A Case for Low Return Sludge Flow Rates

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ABSTRACT

A common problem encountered by traditional activated sludge systems involves failure to develop biomass that separates efficiently from the liquid, leaving behind a clear effluent that is low in BOD_5 and suspended solids. Another problem is the bleed-through of ammonia due to low detention time in the aeration tank. Oftentimes, failure may be attributed to high return sludge flow rates (RSF) that affect not only clarifier hydraulics, but also the growth of bacteria in the system. In order to promote efficient separation and nitrification, system conditions should be maintained that favor the growth of floc-forming bacteria and nitrifiers over nuisance microorganisms that may include filaments. Favorable conditions are encouraged by a regime of higher detention time and feast and famine experienced by the bacteria in the system. By viewing system operation through this lens, the following paper proposes that many activated sludge treatment systems can achieve significant operational improvement through reduction in RSF. This paper further provides a method for minimizing RSF and presents examples of successful application of this method.

KEYWORDS: Activated sludge, return sludge flow rate, feast/famine, microbiology, bioreactor, sludge settleability, specific oxygen uptake rate, respiration rate, state-point analysis

INTRODUCTION

In their work on optimizing secondary clarifiers performance, Griborio et al (2009) state that "In well designed secondary clarifiers, sludge settleability is the single most important factor affecting clarifier capacity and performance." Therefore, achieving and maintaining good sludge settleability is the best way to minimize clarifier problems.

Many conditions may lead to poor sludge settleability. Growth of filamentous microorganisms and "slime bulking" are prime examples. Jenkins et al (2004) address these issues quite well, noting conditions that include low dissolved oxygen (DO), low pH, septicity, low food to microorganism ratio (F/M), nutrient deficiency, readily metabolized substrate, and continuously fed/completely mixed reactors. Fundamentally, each of these issues relates to microorganism growth and may be controlled by addressing the conditions experienced by the activated sludge during wastewater treatment. Of the factors promoting filament growth, the least considered in practice is probably the "continuously fed/completely mixed" condition. However, as will be seen, this condition is itself related to the feast/famine regime and may be effectively controlled via RSF.

Feast/Famine

Feast/famine is a concept that was proposed by Chudoba et al (1973a), in an attempt to identify causes of sludge bulking. In their view, “feasting” relates to keeping the concentration of food as high as possible at the point of feeding to control filamentous growth and enhance floc-former proliferation. This idea was furthered by the work of Albertson (2007) and others where benefits of high initial substrate concentration from bioreactor compartmentalization were promoted. Chudoba et al (1973b) also presented the kinetic theory of selection and suggested that the initial part of the aeration tank could be used to suppress the growth of filamentous microorganisms grown in mixed cultures. As illustrated in Figure 1, the typical floc former exhibits higher growth rates than the typical filament at increasing concentrations of 5-day biochemical oxygen demand (BOD_5), thereby providing a competitive advantage to floc formers over filaments in systems where “feasting” occurs at high BOD_5 concentrations. Conversely, systems in which BOD_5 application occurs at lower concentrations will tend to provide competitive advantage to filaments. Later, Chudoba (1985) summarized his “basic principles for control of filamentous bulking” and included:

> “The micro-organism which accumulates (or simply consumes) most of the amount of substrate in….an inlet part of the aeration system will be dominant in this system provided the regeneration period for exhaustion of all the accumulated substrate is sufficient.

By diluting the concentration of substrate at the head of the aeration tank, high RSF tends to move a system toward “continuously fed/completely mixed reactor” conditions, thereby reducing the initial BOD_5 concentration to the range that may encourage filamentous growth. In other words, by diluting the initial BOD_5 concentration high RSF reduces the degree of “feasting” for the microorganisms. Figure 2 illustrates the effect of RSF on initial substrate concentration at the head of the aeration tank. For instance, at an initial substrate concentration of 250 mg/L, a return sludge recycle ratio (R) of 0.3 will produce an actual substrate concentration (S) of about 192 mg/L; however, an R of 1.0 will result in an S of 125 mg/L, or a 35 percent reduction in S.

Of course, per Chuboda’s concept, the complement to “feasting” is “famine” or “fasting.” Tay et al (2001) have noted the importance of providing a “period of aerobic substrate starvation” in order to benefit from the noted tendency of many bacteria to modify cellular surface characteristics. Most important, it has been noted that starvation tends to promote microbial adhesion as the microorganisms become increasingly hydrophobic during periods absent of growth substrate. Bossier and Verstraete (1996) noted similar effects. In a manner analogous to feasting, fasting conditions are negatively impacted by high RSF.

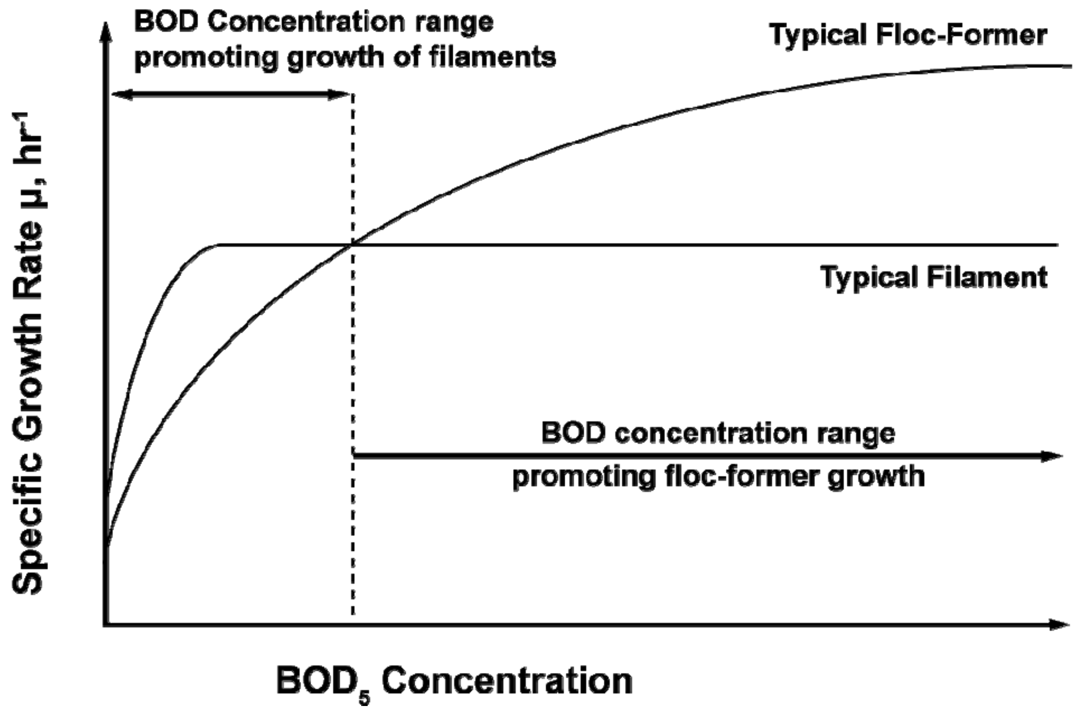

Figure 1. Kinetic theory of selection for filaments vs. floc-formers.

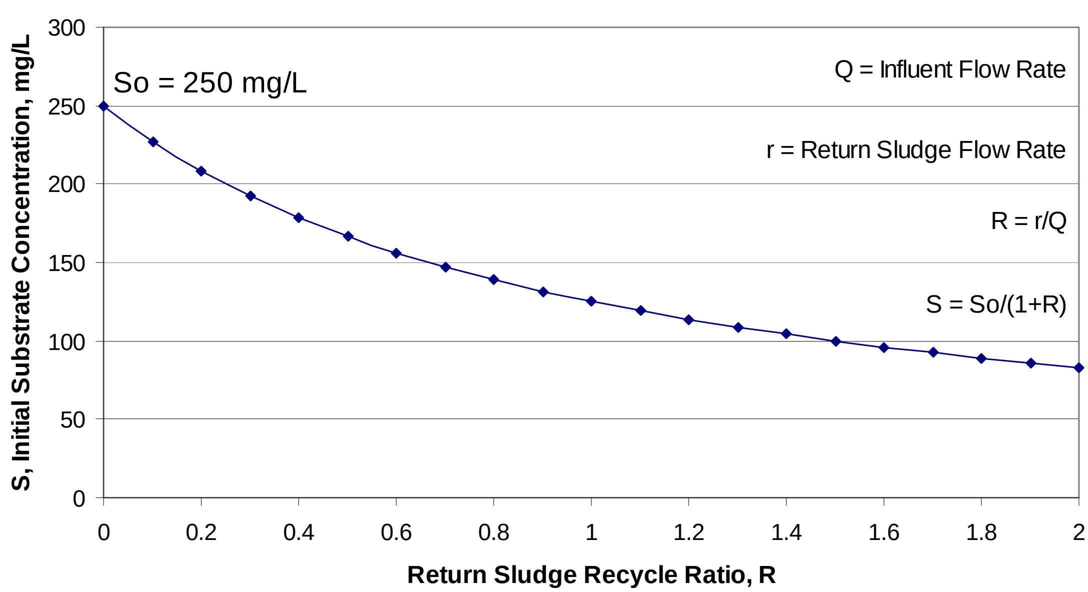

Figure 2. Effect of high RSF on initial substrate concentration in the aeration tank.

High RSF minimizes the degree of fasting or famine experienced by the sludge by reducing the actual time available per pass for the microorganisms to stabilize the food accumulated during feasting. To see the influence of RSF on fasting, it is beneficial first to discuss the concept of solids detention time (SDT), which itself can be further broken down into solids detention time in the aerator (SDT_A) and solids detention time in the clarifier (SDT_C).

SDT_A is the amount of time that an organism takes to travel through the aerator. (For ease of discussion, the bioreactor is termed "Aerator". SDT_A is equal to the hydraulic detention time unless step-feed is used, in which case the SDT_A will increase. For non-step-feed plants, the SDT_A can be determined by calculating the per-pass hydraulic detention time in hours:

$$SDT_A = \frac{\text{Vol of the aerator}}{\text{Flow to the aerator}} = \frac{Vol_A * 24}{Q+RSF} \qquad (2)$$

Where

Vol_A = volume of the bioreactor as configured. The solids detention time can also be calculated through any of the individual sections, e.g. anaerobic or anoxic sections.
Q = influent flow rate, m^3/d (MGD), and
RSF = return sludge flow rate, m^3/d (MGD).

Similarly, SDT_C is viewed as the time that a particle stays in the clarifier and can be calculated by the following equation:

$$SDT_C = \frac{\text{Mass in the Clarifier}}{\text{Rate Mass is Removed from the clarifier}} = \frac{CSC * Vol_C}{RSC * RSF} \qquad (3)$$

Where

CSC is the average clarifier solids concentration, mg/L. CSC is typically determined from a core-sample taken 1/3r in from the outside edge of a circular clarifier or at 1-3 points along the flow path in a rectangular clarifier.
Vol_C is the volume of the clarifier, m^3 (MG),
RSF is the return sludge flow rate, m^3/d (MGD), and
RSC is the return sludge concentration, mg/L.

Returning now to the discussion of fasting, Figure 3 illustrates the actual time, SDT_A, which microorganisms have to feast and to reach complete famine before discharging to the clarifier. Two examples are given: first, a 3 MGD extended aeration plant designed for 18-hour detention time and running at 3 MGD; and a 10 MGD conventional activated sludge plant designed for 6-hour detention time, running at 10 MGD. The extended-aeration process example shows that a recycle ratio of 1.0 provides only nine hours of contact time while a ratio of 0.3 increases the time for fasting metabolism to almost 14 hours. Similarly, the conventional activated sludge example reduces the stabilization time from 4.5 hours at recycle ratio of 0.3 to 3.0 hours at a ratio of 1.0. Thus, it is obvious that reduced RSF, by increasing SDT_A, increases the potential to reach starvation conditions prior to biomass discharge to the clarifier.

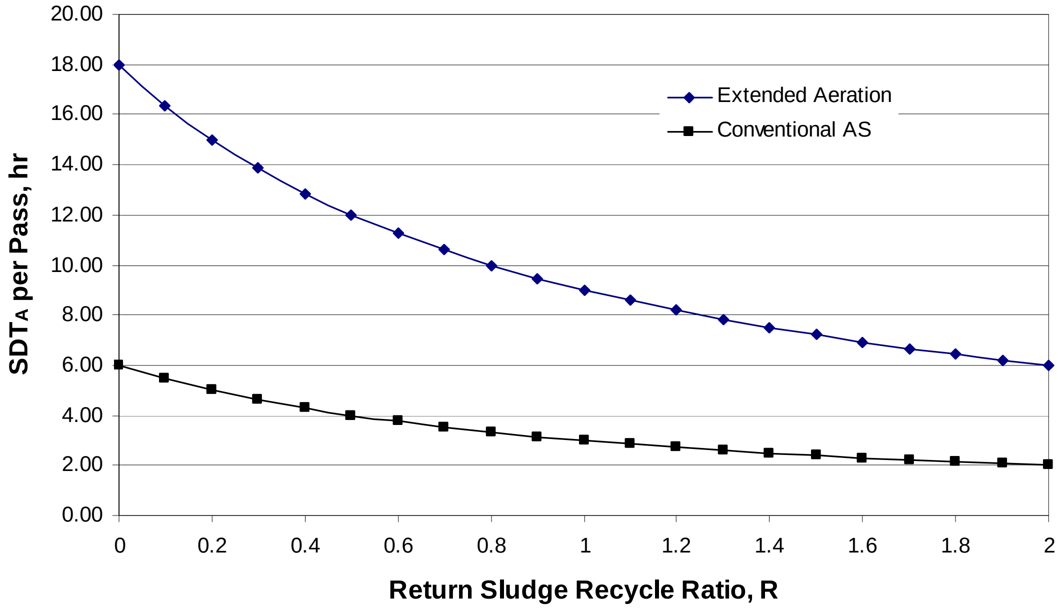

Figure 3. Effect of high RSF on actual solids detention time in the aerator.

Feast/famine has also been referred to as "accumulation" and "regeneration" by Grau et al (1982). Their work suggests that high food to microorganism ratio (i.e., feasting) in the initial contact zone followed by complete stabilization of the stored food (i.e., famine) could be used to promote growth of floc-forming organisms while minimizing the growth of filamentous microorganisms. Consequently, a number of researchers and operators have sought to mitigate bulking problems by favoring plug-flow over complete-mixing in their basin configurations. Plug flow was recommended by Ardern (1917) who suggested that narrow tanks provide "a long length of travel." Length:width ratios as high as 38:1 were utilized. Hazeltine (1932) discussed operating with plug-flow to combat bulking. Compartmentalization to produce plug-flow characteristics was practiced as early as 1916 (Bartow, 1917). Donaldson (1932a and 1932b) recommended compartmentalization to promote plug-flow conditions to combat growth of the organisms that caused bulking. Staging of biological reactors is still promoted today (Albertson, 2007). Staging or compartmentalization is a way to optimize the conditions of microorganism "feasting" on BOD_5 at the head of the bioreactor and "famine" for them in the remainder of the bioreactor. In any case, Figures 2 and 3 demonstrate that high RSF minimizes the effectiveness of plug-flow systems by reducing the initial substrate concentration and minimizing the time available per pass for stabilization.

Impact of High RSF Operation

As a matter of practice, RSF tends towards values above 50% of influent flow and oftentimes reaches values of 100% or more. This tendency arises from numerous causes that can range from poor turndown capability on return sludge pumps to an ill-founded belief that rising clarifier blankets can always be combated by increasing RSF. Regardless, return rates are generally turned up with some frequency, but rarely turned down – resulting in a ratcheting effect and a bias towards high RSF.

Perhaps in response to this tendency, it has been stated that hydraulic detention time is not affected by RSF. To support this statement, it has been argued that, over the course of a day, activated sludge solids reside in the aeration tank the same period independent of RSF (Wahlberg, 2000). Mathematically, the total sludge-aeration-hours concept may be correct when viewed in the context of SDT_A. However, this logic does not take into account the per-pass *biological* requirements of the microorganisms with respect to the feast/famine regime or the time necessary to complete nitrification.

In their initial experiments while developing the activated sludge process, Ardern and Lockett (1914a) allowed "complete oxidation of the sewage" and defined that sludge condition as "activated sludge." Viewed through the lens proposed earlier in this paper, it appears that famine is required to "activate" the sludge. In contrast to Wahlberg (2000), Chudoba's (1985) feast/famine theory suggests that a more important parameter than sludge aeration time over an entire day is the time that an organism has to travel through the aeration tank *during each pass* – a similar concept to Ardern and Lockett (1914a). In other words, there must be enough time on each pass through the aeration tank for the organisms to feed on high-concentration substrate, to completely stabilize the ingested foodstuffs, and finally to experience starvation.

Ardern and Lockett (1914a) defined "activated sludge" as "the deposited solids resulting from the complete oxidation of sewage." The time required to completely stabilize the mixed liquor, or to activate the sludge, can be determined by performing a specific oxygen uptake rate (SOUR) stabilization test. This test (Water Pollution Control Federation, 1989) measures the time it takes after feeding for the respiration rate of fed-microorganisms to return to the endogenous respiration rate, or the base respiration rate upon complete oxidation of all nutrients. Ardern and Lockett (1914a) found that, for a given activated sludge, the time to achieve complete stabilization depends on the organic and/or ammonia loading to the system. Achievement of the endogenous respiration rate suggests that complete stabilization of ingested substrate has occurred and can be verified by performing a SOUR test on the mixed liquor discharged to the secondary clarifier. To maintain the feast/famine feeding regime as suggested by Chudoba (1985), the process including feasting and complete famine must be established during each pass through the bioreactor. If the famine condition is not reached on a pass through the aeration tank, heterotrophic bacteria will not take up as much food upon return to the bioreactor (Chudoba, 1989). The overall result is that the degree of feasting is reduced and the potential accumulation/regeneration effect is minimized or lost.

Per pass aerator or bioreactor detention time not only affects the feast/famine regime related to BOD_5, but in a similar manner it also impacts ammonia. Effluent BOD_5 problems are rare unless suspended solids are lost, since heterotrophic microorganisms can accumulate substrate in storage compounds such as polyhydroxybutyrate or glycogen. Therefore, even if BOD_5 may not be completely stabilized during a single pass through the aeration tank, heterotrophs can nonetheless complete the stabilization in future passes through the aeration tank (even though their subsequent substrate uptake of would be reduced on later passes). However, nitrifying microorganisms cannot store ammonia. Therefore, successful and complete nitrification requires that nitrifiers ingest and metabolize NH_3 completely to NO_2^- and then to NO_3^- before the organisms are sent to the clarifier. If nitrification is not completed prior to discharge to the clarifier, the potential for discharge of ammonia, NO_2^-, or N_2O is greatly increased. Experience suggests that if the SDT_A is great enough for BOD_5 famine, it is usually long enough for nearly complete nitrification provided that mean cell residence time (MCRT) is high enough to support nitrifier growth and suitable overall environmental conditions are provided.

From a hydraulic perspective, it should be remembered that RSF not only returns settled sludge from the clarifier to the bioreactor, but also controls the time that sludge resides in the clarifier. This concept should be obvious in light of the discussion above regarding SDT_C. During this detention time, particles will settle and the entire biomass may compact depending on the amount of time is resides in the clarifier. Logically, higher RSF corresponds to decreased SDT_C – which in turn corresponds to decreased time available for compaction or sludge thickening. Consequently, it should be clear that increased RSF leads to decreased sludge thickening.

THE LOW-RSF APPROACH

The author's sludge return control philosophy is patterned after West (1973): Under normal operating conditions, keep the sludge in the clarifier as long as it will concentrate, then return it to the bioreactor. Using the clarifier for both clarification and thickening will provide the highest return sludge concentration (RSC) and use the lowest return sludge flow rate (RSF).

The following approach allows the operator to estimate the maximum value, termed target settled sludge concentration (SSC_t) to which the sludge will concentrate. Once the SSC_t is identified, it is compared to the actual return sludge concentration (RSC). Based on the comparison, the return sludge flow rate (RSF) is adjusted to minimize discrepancies between RSC and SSC_t. Figure 4 depicts the approach.

To obtain SSC_t, a settleometer test is run using a wide-mouthed, 2-L Mallory settleometer graduated in 1,000 units. The settling test (West, 1974) is run until the sludge stops concentrating. Settled sludge volume (SSV) values are recorded for various settled sludge times (SST) up to the point in time when the sludge stops settling and compacting. The settled sludge concentration (SSC) in the blanket in the settleometer is calculated from the following:

$$SSC = \frac{1000}{SSV} \qquad (1)$$

Where

SSC = settled sludge concentration at a specific settling time (mg/L) and
SSV = settled sludge volume at the same time (units).

As the sludge settles, the SSC increases to a maximum value. The curve of SSC vs. time can be plotted as shown in Figure 4. A knee will form as the sludge stops concentrating. A point on the knee of the curve will be used to determine the target concentration, SSC_t.

Once the SSC_t is established, the approximate sludge settling time (SST) can be estimated. The operator can then adjust RSF down to increase RSC or up to reduce RSC so as to obtain an actual RSC from the clarifier that more closely approximates SSC_t.

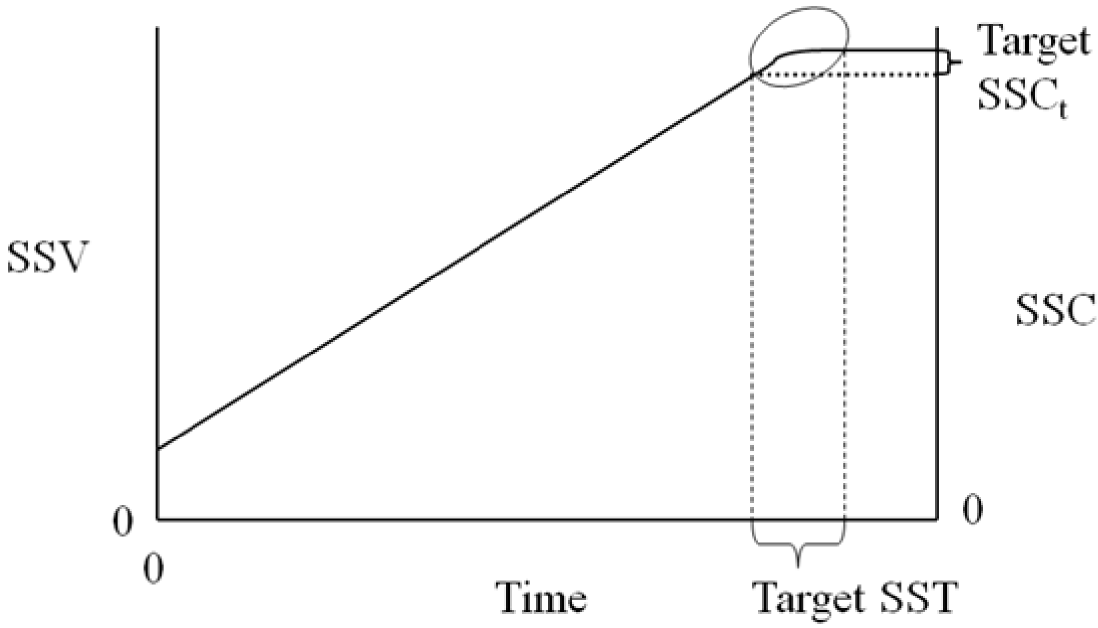

Figure 4. Definition of the target settled sludge concentration, SSCt.

That approach usually provides a low sludge blanket and is depicted in Figure 5a. Figure 5a shows that as return sludge flow rate (RSF) increases from zero, the sludge blanket thickness will decrease to a minimum and then begin to expand. The author has generally found success using this approach. However, it should here be noted that two operational situations can indicate implementation of higher RSF on a short-term basis. The first situation involves excessive clarifier denitrification resulting from high SDT_C with concomitant high SOUR conditions. The second situation involves organic-acid production due to fermentation of high-SOUR settled sludge causing growth of septicity-type filamentous microorganisms such as *Thiothrix* and type 021N. In those two cases, some increased RSF may be required until the situation can be controlled through other control mechanisms.

Some investigators, e. g., Keinath (1985), have suggested that if RSF is allowed to increase significantly, a turning point will occur and the blanket thickness will decrease to zero as might be represented by Figure 5b. For example, many papers can be found that discuss clarifier failure as a major cause of poor effluent quality, e. g., Wahlberg

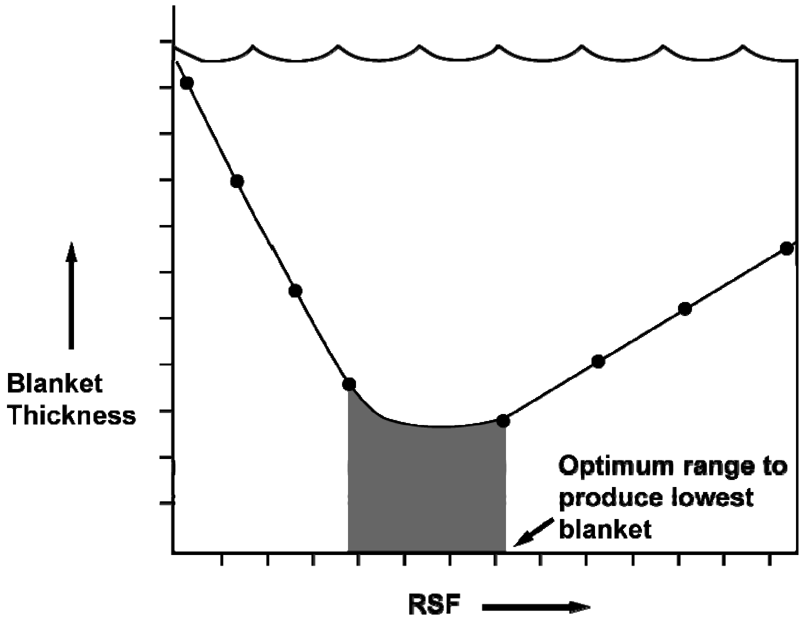

Figure 5a. Blanket thickness vs. return sludge flow rate (RSF)

(2001), and propose the use of state-point-analysis to define the proper solution. The state-point-analysis approach is used to determine when a sludge blanket will form due to the clarifier being overloaded with respect to thickening (Wahlberg, 2001), or in other words, experiencing thickening failure. Some like Wahlberg (2002) have advocated that as a consequence clarifiers should be used only for clarification, not thickening, and should therefore maintain no clarifier sludge blanket. According to Figure 5b, this would require use of high RSF. For slow settling sludges, this requires higher and higher RSF. However, as discussed earlier in this paper, controlling clarifier sludge blanket thickness with higher RSF cannot avoid interfering with good feast/famine conditions and therefore can lead to problems with respect to filament growth and incomplete nitrification.

ADVANTAGES OF THE LOW-RSF APPROACH

Low RSF helps develop an activated sludge that properly treats BOD_5 and/or ammonia while developing a sludge that settles efficiently and produces a clear effluent. Sludge quality is developed in the bioreactor where growth occurs: where microorganisms feed upon and stabilize organic and certain inorganic constituents of wastewater. Low RSF provides a higher initial substrate concentration for better feasting while maximizing the time available for famine and the consequent return to endogenous respiration prior to sludge entry to the clarifier. Such operating conditions decrease the potential for filament growth and lead to more complete nitrification.

While certain industrial wastes and requirements for nitrification may cause substrate uptake and stabilization problems, most activated sludge systems have no problem converting soluble and insoluble BOD_5 to cell mass, CO_2, and H_2O. However, a biomass

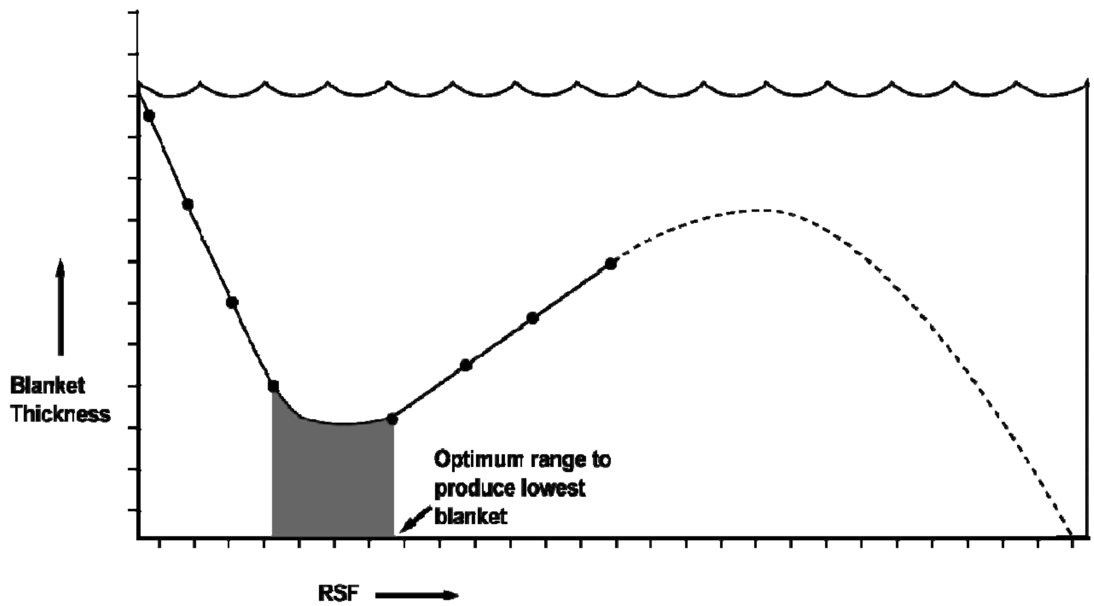

Figure 5b. Blanket thickness vs. return sludge flow rate, revised.

exhibiting good BOD_5 and/or ammonia uptake and stabilization does not necessarily provide good sludge settleability or solids removal capability in the clarifier. If the biomass that grows does not settle well, the success of the activated sludge system may be in jeopardy if the consumed BOD_5 discharges as cellular suspended solids in the effluent.

Review of the literature points to increasing discontent with the high RSF conditions seen in operational practice. For example, Kinnear (2004 and 2005) indicated that RSF higher than about 50% of influent flow rate (Q) may not provide treatment benefit, and may adversely affect secondary clarifier performance. Lynggaard-Jensen et al (2009) suggested that RSF is "seldom controlled by any other means than as a (typically too high) percentage of the inlet to the wastewater treatment plant – giving a varying and too-low solids concentration in the return sludge…"

Not only does lower RSF optimize bioreactor conditions, it also has positive effects on the clarifier. The solids load to the clarifier is reduced, the time available to settle is maximized, and clarifier hydraulic disturbances may be reduced.

EXAMPLES OF LOW-RSF USE

Three examples will be used to demonstrate successful use of low RSF. The first, in Boonton, NJ, is an over-loaded, medium-sized oxidation ditch system while the second is a small, significantly under-loaded conventional activated sludge plant at La Junta CO. The last is the Fresno, CA, plant, a large, conventional activated sludge plant that was typically loaded at or above capacity.

Rockaway Valley Regional Sewerage Authority, Boonton, NJ

Rockaway Valley Regional Sewerage Authority (RVRSA) treats wastewater collected from the area around Boonton, NJ. The oxidation ditch process was originally designed for 1,892 m^3/m^2.d (12 MGD) capacity, but recently has been reevaluated and estimated to have a capacity of 2,508 m^3/m^2.d (15.9) MGD based on actual influent characteristics and permitted effluent quality at that time. The plant processes include headworks with influent grit removal, coarse screening, and comminution; four 3,785 m^3 (2.75) MG oxidation ditch aeration tanks with four 75 kW (100 hp) brush-type aerators each; four 30.48 m by 30.48 m (100 ft by 100 ft) “squircle” clarifiers with multiple-tube rapid sludge-removal; waste sludge dewatering and subsequent disposal at a nearby treatment plant. A State-DEP-sponsored project in 1999 was implemented to see if plant operation could be modified to allow the existing facilities to get some degree of denitrification while continuing to meet nitrification requirements.

Initial inspection suggested that turning off appropriate rotors at the correct times of the day could allow significant denitrification. However, the operational methodology used at the plant at that time would not allow use of the new approach. The plant was having trouble nitrifying consistently with two oxidation ditches and was using high MCRTs, over 20 days which typically produced MLSS values of 3,000-4,000 mg/L, and RSF’s well over the influent flow rate, Q. The result was greater than nine-foot sludge blankets in three clarifier (sometimes four clarifiers had to be placed on line). Mr. Ed Ho, Authority Manager, felt that the new approach was worth investigating and implemented changes: lower MCRT to 15 days or less, cut RSF to approximated 50-70 percent of Q, turn one rotor per ditch for a test, then two rotors per ditch. The new Operations Manager, Mr. Bob Sobeck and his staff, immediately set-out to optimize the process by reducing RSF to approximately 50-70% of Q, controlling MCRT, and taking the necessary ammonia data to determine when and how long aeration rotors should be turned off and left off. RVRSA was able to take the third clarifier off-line and have not used it since. Just two ditches and two clarifiers have been used since 1999, even though loading have increased during the 10 year period to an average daily flow of 1,653 m^3/m^2-d (10.48 MGD) from 1,514 m^3/m^2-d (9.6 MGD) and influent BOD_5 from 168 mg/L to 238 mg/L, or an organic load increase of 54.6% based on influent BOD_5 (6,107 kg/d (13,451 lb/d) to 9,444 kg/d (20,802 lb/d)). Table 1 summarizes the data for the last five years while the plant is loaded on average at approximately 31% above design capacity. Data on F/M, space loading, surface overflow rate (SOR) and solids loading rate (SLR) are included to provide information on the relative degree of plant loading.

As load increased from 1999 to 2005 process demands required increasing RSF from the 50 per cent range to an average of 72 per cent of influent Q over the five years. The ideal 30-40 percent of Q RSF rates would cause plugging of the hydraulically inefficient clarifier sludge collector tubes, and the operators would respond with higher RSF. Even so, at the lower RSF used, only two clarifiers have been required for the last 10 years. Recent process control optimization has resulted in reducing the RSF to the 50-60 per cent range again while maintaining very good effluent quality, well within permit limits.

Table 1. Wastewater Characteristics and Loading/Operating Parameters for RVRSA.*

Parameter	**Min.**	**Average**	**90th Percentile**	**Max.**	**Typical Extended Aeration Design Criteria****
Influent Flow, m^3/hr (MGD)	1325 (8.4)	1650 (10.46)	1890 (11.98)	2539 (16.1)	
Influent $CBOD_5$, mg/L	138	238	278	300	
Effluent $CBOD_5$, mg/L	3	5	6	9	
Effluent TSS, mg/L	3	7	9	12	
Effluent NH_3-N, mg/L	0.1	0.58	0.97	1.5	
Effluent Total P, mg/L	0.6	1.61	2.24	2.5	
SVI, mL/g	107	151	206	267	
RSF, m^3/d (MGD)	931 (5.9)	1166 (7.39)	1311 (8.31)	1341 (8.5)	
RSF/Q, %	47	72	85	90	
HRT, hr (RSF not included)	**8.2**	**12.8**	**14.5**	**15.7**	>16
SDT_A, hr (RSF included)	5.6	7.5	8.3	8.9	
F/M, kg BOD_5/kg MLVSS	**0.26**	**0.31**	**0.34**	**0.36**	<0.2
Space Loading, kg/m^3.d (lb BOD_5/1000 ft^3)	0.368 (23.0)	**0.045 (27.8)**	**0.48 (30.1)**	**0.51 (31.9)**	<0.04 (25)
SOR, m^3/m^2.d (gal/d-ft^2)	21.9 (535)	27.3 **(666)**	**31.2 (762)**	**42 (1025)**	<28 (600)
SLR, kg/m^2.d (lb/ft^2-d)	78 (16)	122 (25)	**152 (31)**	**172 (35)**	<144 (30)

* **Bold** indicates values which are higher than some typical extended aeration design criteria.
**Metcalf and Eddy, 2003

Since RVRSA's system uses alternating aerobic/anoxic zones within their oxidation ditches, it is important to allow as much time as possible each time a microorganism travels through the ditch. Since nitrifiers do not store substrate, they need to completely nitrify the incoming ammonia while also denitrifying the produced nitrate. SDT_A is little affected by internal recycles such as travel around an oxidation ditch or mixed liquor recycle for denitrification through an anoxic section, since the microorganisms continue feeding and stabilizing substrate in the bioreactor prior to discharge to the clarifier. (However, internal recycle does negatively affect the "feasting" at the head of the first bioreactor by lowering the concentration of available BOD.)

Even though there is not a nitrate permit limit, controlling the nitrate concentration helps control clarifier denitrification. Table 2 shows the effect of RSF on the actual SDT_A allowed per pass for the microbes to complete BOD_5 removal, nitrification and denitrification. Microorganisms at an endogenous respiration level will use minimal oxygen since there is no food to stabilize; during endogenous respiration, they are merely staying alive. Therefore, when organisms are at endogenous respiration, it is possible to experience little or no secondary clarifier denitrification even if there is nitrate available as an electron acceptor. Further, since there is no food to stabilize, there would be little fermentation even if DO was depleted, and septicity issues should be avoided. Further, with no fermentation, there is little or no BOD_5 uptake and the potential for phosphorus release from phosphorus accumulating organisms (PAOs) is minimal. If low bioactivity is achieved at the end of the aeration tank, settled sludge could remain in the clarifier for a prolonged amount of time with minimal negative effect on the biomass, clarifier, or effluent conditions. Thus, one can keep the endogenous biomass in the clarifier to thicken and concentrate, not cause clarifier problems. This is typically the author's objective.

As can be seen, reducing the RSF from the 5-year average of 72 per cent to 50 per cent increased the SDT_A by over an hour. If lower RSF could approach 25 percent, the time would be increased 2.76 hours or 37 per cent above the historical average.

Table 2. SDT_A for various RSF at Q = 10.46, average flow since January, 2005.

RSF as % of $Q_{Average}$	SDT_A (hr)
72 (actual average over 5 years)	7.5
50	8.55
40	9.16
35	9.5
30	9.87
25	10.26

Reducing the RSF and providing additional time for nitrification and denitrification has allowed reduced aerator run time. At the time the project started, at least two – 75 kW (100 hp) aerators were turned off in each ditch, saving an estimated $500/d in electrical cost. Further, by running in an overloaded condition, the staff has deferred the time at which an additional oxidation ditch must be placed on line. This eliminates the electrical power required to drive two-75 kW (100 hp) aerators and saves upwards of $275/d depending on the amperage-draw on the aerators.

La Junta, CO

The La Junta wastewater treatment plant was overloaded for years while receiving wastes from a pickle processor. For at least the last 15 years the La Junta staff has used the low RSF approach to help them handle the high organic loads from the pickle waste. When the pickle processor left the City, the wastewater treatment plant immediately became significantly under-loaded. Based on the major change in loading, the city requested an evaluation of wastewater treatment plant capacity based on post pickle-plant influent loadings. The evaluation started with an on-site evaluation followed by analysis of data recorded by the plant staff. The plant is a conventional activated sludge plant with three aeration tanks, each with different size and shape and constructed at different times throughout the long life of the plant. Only two of the parallel aeration tanks are in use under the present low-load scenario along with one of the two secondary clarifiers. Even so, the process operates in a loading range between conventional activated sludge and extended aeration.

Table 3 shows the wastewater characteristics and loading/operating parameters for the period from June, 2006, through July 2008, the period from the time that the pickle factory ceased discharging up to the point in time that the evaluation was initiated. All data was collected while using only the two aeration tanks and the single secondary clarifier.

While the previous data from RVRSA showed overloading and many parameters outside typical design values, the La Junta data show just the opposite, significant underloading, even operating just the two aeration tanks and one clarifier. In this case many would think that low RSF would certainly lead to clarifier denitrification since, although not designed to do so, the process totally nitrifies. However, the very low SOUR values indicate the potential for denitrification to be very low. The average RSF/Q ratio of 27 percent allows the MLSS to thicken from an average 2,996 mg/L to an RSC averaging 12,664 mg/L. Activated sludge is wasted from the return sludge line, so the waste sludge concentration is the same as the RSC. The biomass growth produces a relatively fast-settling sludge with low sludge volume index (SVI) less than 100 mL/g. The system averages BOD_5 and TSS values of 5 and 6 mg/L, respectively, while nitrifying to less than 0.2 mg/L NH_3-N.

This shows that low RSF can be effectively used not only in an over-loaded situation such as RVRSA, but also in an under-loaded situation such as La Junta.

Fresno, CA

In 2001 organic loading to the Fresno wastewater treatment plant began increasing. This exacerbated already prevalent problems of low DO in the aeration tanks, growth of low-DO and septicity-type filaments that caused poor settling and high SVI’s. The system was loaded near design capacity hydraulically and above design capacity organically. The B-Side of the plant tended to function better with a long-narrow, partial step-feed aeration tank design, so significantly more flow was treated on the B-Side. A-Side was originally a complete-mix system with aeration using turbine mixers and spargers. It was later converted to diffused aeration to improve oxygen transfer efficiency and reduce aeration costs. But, in doing so, the system lost complete-mix capabilities, and even though the tanks were square (51.8 m (170 ft) by 51.8 m (170 f)t with sloping sides, 4.6 m (15) feet deep), the influent came in on one side and was not completely-mixed as it traveled through the aeration tank to the opposite side. Thus, the system could be defined as being somewhere between complete-mix and plug flow. The four 45.7 m (150 ft) by 45.7 m (150 ft) squircle clarifiers were 4.4 m (14) feet deep and susceptible to solids washout even though surface overflow rates were less than 24.6 m^3/m^2-d (600 g/d/ft^2). This treatment regime never performed as well as the more plug-flow B-Side, and operators typically loaded it at a lower rate in the 20,430 kg BOD_5/d (45,000 lb/d) range with which it could properly perform. However, when the organic load increased

Table 3. Wastewater characteristics and loading/operating parameters for La Junta

Parameter	**Min.**	**Average**	**90th Percentile**	**Max.**	**Typical Extended Aeration Design Criteria***
Influent Flow, m^3/hr (MGD)	126 (0.86)	157 (1.0)	170 (1.08)	185 (1.17)	
Influent BOD_5, mg/L	84	112	133	158	
Effluent BOD_5, mg/L	2	5	6	8	
Effluent TSS, mg/L	2	6	12	13	
Effluent NH_3-N, mg/L	0.06	0.13	0.19	0.23	
SVI, mL/g	59	80	92	97	
SOUR, mg O_2/hr/g MLVSS	1.09	1.85	2.39	2.88	
MLSS, mg/L	2,353	2,996	3,563	3,747	
RSC, mg/L	10,279	12,664	14,276	16,274	
Blanket Depth, m (ft)	0.02 (0.06)	0.09 (0.31)	0.15 (0.5)	0.2 (0.66)	
RSF, MGD	0.34	0.37	0.42	0.44	
RSF/Q, %	24	27	29	33	
HRT, hr (RSF not included)	11.9	14.0	15.6	16.1	5-8
SDT_A, hr (RSF included)	9.0	10.3	11.1	11.3	
F/M, kg BOD_5/kg MLVSS	0.07	0.08	0.09	0.11	<0.2
Space Loading, kg/m^3-d (lb BOD_5/1000 ft^3)	7.8	12.1	15.5	19.8	<25
SOR, m^3/m^2-d (gal/d-ft^2)	7.1 (172)	8.1 (198)	8.9 (216)	9.5 (232)	< 28 (600)
SLR, kg/m^2-d (lb/ft^2-d)	23.5 (4.8)	32.8 (6.7)	41.6 (8.5)	47.0 (9.6)	<144 (30)

**Metcalf and Eddy (2003)

significantly in the late summer of 2001, additional hydraulic and organic load had to be shifted to the A-Side due to high loading of B-Side. The load increased in early September to over 24,516 kg BOD_5/d (54,000 lb/d) and the SVI responded by reaching 589 mL/g. The A-Side flow rate continued to increase from 4,745 m^3/hr (27 MGD) to 6,467 m^3/hr (41 MGD), and the BOD_5 load soared to an average 46,238 kg/d (101,845 lb/d) in September.

A modified operations plan was developed to control the process under these significantly changed loading conditions through March of 2002. The first action was an increase in MCRT from 1.6 days to greater than 4 days to significantly slow the biomass growth rate. However, with higher MCRT came enhanced nitrification that had historically resulted in significant clarifier denitrification and floating sludge- blankets. Lower DO values were anticipated, because the aeration system was not designed for such high organic loads and partial nitrification. Since DOs could not be maintained above 1.0 mg/L and significant clarifier denitrification occurred whenever the MCRT reached approximately 2.0 days, DO was slashed to approximately 0.1 mg/L. This action held complete nitrification in check while minimizing clarifier denitrification and growth of *Sphaerotilus natans* and *Haliscommenobacter hydrossis*, organisms commonly referred to as “low-DO filaments.” Even though 0.1 mg/L DO is “low DO” it appears that such low DO provides a growth environment that is too anoxic to support the low-DO filaments which are aerobic organisms (Schuyler, et al 2008). These initial actions brought the SVI down to the range of 181-438 mL/g from September, 2001 to March, 202. However, the clarifier blankets remained high at about 2.32-3.41 m (7.6-11.2 ft) with a RSF of 70-82 percent of Q.

In March of 2002 the third action was implemented; reduce RSF to the range of 40-60 percent of Q. Prior to this, the operations staff had been reluctant to reduce RSF based on past catastrophic clarifier denitrification experiences. The reduced RSF approach immediately brought the blankets below 1.83 m (6.0 ft) and with operator experience down to 0.79 m (2.6 ft) by October, while allowing the plant to weather another high organic-load season in August-September, 2002. The low-DO helped control the nitrate level by maintaining simultaneous nitrification/denitrification and helped control the degree of nitrification at an MCRT high enough to provide good sludge quality. While the BOD_5 load increased about one percent and kept the plant loaded at or above typical maximum F/M and space-loading values, the hydraulic loading increased approximately five percent. With a slight increase in MCRT from 3.75 to 4.33 days, the ammonia discharged remained nearly unchanged while effluent BOD_5 and TSS concentrations were reduced by 21 and 45 percent, respectively. Even though the influent flow rate increased five percent the lower RSF provided an additional seven percent SDT_A for biomass stabilization and nitrification/denitrification while maintaining a low clarifier solids loading. An average sludge blanket depth of 0.98 m (3.2 ft) was realized while effluent TSS improved to 17.6 mg/L, mainly due to reduced clarifier denitrification.

From the end of 2002 through February, 2004 the staff tried variations of DO, MCRT, and RSF, but by March, 2004, had settled on DO of 0.1-0.2, MCRT of about 4.5 days, and RSF below 0.4Q. Even though the influent still contained relatively high BOD_5 loads, including organic acids, this operational strategy has helped maintain the SVI within a tolerable range. Table 4 presents a comparison of A-Side conditions from January, 2001 through February, 2004 and March, 2004 through October, 2006. Most values have changed little since October 2006 to present. The system has been relatively stable since 2006, even though the SVI’s will probably never be what would be considered “normal” due to the filament growth related to high organic loadings and very high concentrations of organic acids. The BOD_5 values are relatively high due to nitrogenous BOD_5, and the ammonia values are mid-range; however, the plant has no ammonia limitation. Not only was satisfactory treatment realized, but by controlling DO at low values, the oxygen transfer efficiency of the diffusers was estimated to increase approximately 29 percent from that used if a DO of 2.0 mg/L was used (Schuyler et al 2008).

SUMMARY AND CONCLUSIONS

As observed in the examples provided, operating at lower RSF maximizes not only feast/famine conditions but also nitrification. In practice, it is important to note that proper application of feast/famine strategies requires that food concentration be as high as possible initially and all accumulated substrate be exhausted before discharge of mixed-liquor to the clarifier. Implementing such a strategy leads to full consumption and exhaustion of BOD_5 in the feasting area prior to return of the organism to the bioreactor. By using the approach recommended for RSF control to maximize return sludge concentration and solids detention times in the aerator and clarifier (SDT_A and SDT_C), the three plants referenced were able to overcome historical problems and improve effluent quality. Of note, this same approach worked equally well for three very different types of facilities with respect to loading and scale: 1) an overloaded, medium-sized facility, 2) an underloaded, small facility, 3) and an overloaded, large facility.

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Table 4. Wastewater characteristics and loading/operating parameters from January 2001, to October, 2006 for Fresno, CA.*

Parameter	**Jan. 01- Feb. 04**		**Mar. 04 - Oct. 06**		**Typical Conventional AS Design Criteria****
	Avg.	90th Percentile	Avg.	90th Percentile	
Influent Flow, m^3/hr (MGD)	5,446 (34.53)	6,423 (40.72)	5,710 (36.2)	6,311 (40.01)	
Influent BOD_5, mg/L	202	230	193	218	
Influent BOD_5, lb/d	57,691	73,046	58,334	66,767	
Effluent BOD_5, mg/L**	33.75	48.67	26.62	35.59	
Effluent TSS, mg/L	32.28	68.3	17.6	25.77	
Effluent NH_3-N, mg/L	12	23.6	11.55	17.86	
SVI, mL/g	390	568	175	232	
MCRT, d	3.75	5.04	4.33	4.74	
MLSS, mg/L	1757	2425	2236	2618	
RSC, mg/L	4,521	5,780	6,490	8,000	
Blanket Depth, m (ft)	1.65 (5.4)	2.5 (8.2)	0.98 (3.2)	1.58 (5.2)	
RSF, m^3/hr (MGD)	3,107 (19.7)	4,292 (27.21)	2,207 (13.99)	2,448 (15.52)	
RSF/Q, %	58	76	39	43	
DO, mg/L	0.42	0.85	0.12	0.17	
HRT, hr (RSF not included)	7.5	7.9	7.2	7.9	5-8
SDT_A, hr (RSF included)	4.8	5.06	5.16	5.76	
F/M, kg BOD_5/kg MLVSS	**0.58**	**0.88**	**0.39**	**0.45**	0.2-0.4
Space Loading, kg/m^3-d (lb BOD_5/1000 ft^3)	0.64 **(40)**	**0.82 (51)**	**0.64 (40)**	**0.74 (46)**	<0.7 (40)
SOR, m^3/m^2-d (gal/d-ft^2)	20 (489)	23.6 (576)	21.0 (512)	23.2 (566)	<28 (800)
SLR, kg/m^2-d (lb/ft^2-d)	54.4 (11.4)	83.8 (17.1)	59.8 (12.2)	71.5 (14.6)	<144 (30)

***Bold** indicates values outside standard design criteria.
**High effluent BOD_5 values are mainly due to nitrogenous BOD_5 from partial nitrification.
***Metcalf and Eddy (2003)

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