ENERGY-SAVING BENEFITS OF DENITRIFICATION

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ABSTRACT

Nitrogen removal in wastewater treatment can be achieved by introducing anoxic zones in biological reactors within an activated sludge process, operating at medium or long mean cell retention time (MCRT). Anoxic zones at the head of the process also function as biological selectors and provide benefits in addition to nitrogen removal, including improved stability by avoiding filamentous bulking, enhanced removal of many recalcitrant pollutants and reduced energy consumption due to the oxygen credit and higher oxygen transfer efficiency. Improved oxygen transfer occurs because the readily biodegradable organic compounds are used by the denitrifiers for nitrate reduction. These organic compounds, which are surfactants, would otherwise reduce oxygen transfer efficiency, increasing plant operating costs. We tested 22 treatment plants which included either conventional, nitrifying-only, or nitrifying-denitrifying (NDN) operations. Off-gas tests confirm that oxygen transfer efficiency for NDN operations is higher. Our economic analyses show that NDN operation can have the lowest aeration costs, contrary to long-standing beliefs. The net operating costs can be lower than conventional, short MCRT operation and are always lower than nitrifying-only operation. However, depending on the local plant situation, expansion of aeration volume and/or clarifier area might be necessary, and the operating savings could be offset by debt service on plant expansion.

INTRODUCTION

The Need for Nitrogen Removal

Urban areas in the United States have generally implemented full secondary treatment and in some cases more advanced treatment, depending on the needs of the receiving waters. Typically, plants on the West Coast that discharge to ocean waters are generally designed to remove only carbon and do not remove nutrients. Recently, inland plants have been required to upgrade for biological nutrient removal (BNR). Water reclamation is often the motivation for upgrading, and a greater fraction of the wastewater treatment plant effluents are now being recycled. Wastewater reclamation, which can be achieved by recharging ground water basins or augmenting drinking water reservoirs and rivers, is viewed as a new water source either by displacing potable water for lesser uses of through indirect potable reuse. Nitrogen removal can be a strict requirement for water reclamation, depending on the application. Therefore, treatment plants that are candidates for reclamation are being upgraded to remove nitrogen.

Nitrogen removal can be achieved by modifications to effect nitrification and denitrification (NDN) in existing activated sludge plants, and many existing facilities are currently undergoing upgrades. New designs typically include NDN and may also provide for phosphorus removal. Phosphorus removal is generally not required in California but is required in the Great Lakes basin and is common in the Eastern United States.

Stability and Performance of NDN

The inherent characteristic of NDN processes is operation at high mean cell retention time (MCRT), which is required to maintain the slower growing nitrifiers. Typically the range of MCRT for NDN plants is 4.5-30 days. Plants in warmer regions benefit from higher microbial reaction rates, and can operate in NDN mode at lower MCRT values. Plants operating at low loading rates (i.e., high MCRT or low food-to-microorganism ratio [F/M]) are generally better in removing recalcitrant organic compounds and may produce lower effluent soluble COD or organic carbon (Babcock et al, 2001). Here-to-fore, the benefits of operation at high MCRT conditions have not been great enough to convince plant managers to operate at these conditions. The additional of selectors to increase process stability as well as the improved oxygen transfer rates associated with the higher MCRT (Fisher and Boyle, 1999) are now well known and provide new incentive to operate at high MCRT conditions.

Parker et al. (2003) surveyed 21 plants with anoxic and anaerobic selectors, and reported that all plants showed improvement after selector installation. Among the plants with anoxic selectors, 70% had sludge volume index (SVI) lower than 200 ml/g. Plants using anaerobic selectors were even better and more than 90% of the plants had SVIs less than 150 ml/g. Martins et al (2004) reported similar results and concluded that better operation is achieved if there is a first anaerobic stage. The benefit of selectors is the reduction of filamentous organisms (Harper and Jenkins, 2003), which improves SVI and reduces the probability of sludge bulking and rising sludge blankets in secondary clarifiers (Jang and Schuler, 2007). The activity of phosphorus accumulating organisms (PAO) was reported to increase even when operating a strictly anoxic selector, with PAO improving the floc structure and biomass density (Tampus et al, 2004).

In addition to these advantages, there is growing evidence that processes operating under high MCRT conditions are more efficient in removing anthropogenic compounds, such as pharmaceuticals (Soliman et al., 2006; Goebel et al, 2007). Andersen et al (2003) reported removals up to 90% for the endocrine disruptor 17a-ethinylestradiol (EE3) after a wastewater treatment plant was retrofit to remove nutrients at MCRT of 11-13 days. Operation at high MCRT conditions in order to enhance removal of trace organics will become more important as wastewater water reclamation becomes more widely practiced.

Advantageous Economics of Denitrification

Aeration is the most energy-intensive unit operation in wastewater treatment plants, amounting to 45-75% of plant operating costs (Reardon, 1995). Treatment plants operating with NDN typically show improved oxygen transfer efficiency (OTE), with consequent lower energy requirements (Groves et al, 1992; Rosso and Stenstrom, 2005). This improved transfer efficiency results mainly because of higher MCRT operation, which is associated with increased a factors (0.2-0.5 for conventional treatment, 0.4-0.7 for nitrification-only, 0.5-0.75 for NDN), but has not always been recognized by design engineers. An advantage of selectors is the removal or sorption of a fraction of the carbonaceous load, i.e. the readily biodegradable COD (rbCOD). The rbCOD is partially composed of surface active agents or surfactants, which are typically discharged as fatty acids, oils, soaps and detergents. The surfactants, because of their amphiphilic nature, accumulate at the air-water interface of rising bubbles, reducing oxygen transfer efficiency. Removal of the rbCOD can improve oxygen transfer efficiency and can reduce operating costs for aeration (Rosso and Stenstrom, 2006a). The increase in transfer efficiency is in addition to the reduction in oxygen demand due to denitrification.

The economic advantages of NDN are discussed in detail in this paper. We performed mass- and energy- balances over NDN processes, and quantified unit operating costs and credits. We compare conventional treatment, nitrifying-only, and NDN, showing the advantageous economics of NDN. Differences in capital cost, such as the possible need for increased aeration tank volume and clarifier area, are too site-specific to be quantified here. Although the influence of capital cost is not included in our calculations, it is discussed.

BACKGROUND

Oxygen Transfer and Aeration Efficiency

Fine-pore diffusers are now the most commonly used aeration technology in municipal wastewater treatment in the United States. They have higher efficiencies on the basis of energy consumption (standard aeration efficiency [SAE], measured in lb O_2/hp-hr or kg O_2/kWh). Fine-pore diffuser systems strip the fewest volatile organic compounds by virtue of their increased efficiency, which results in lower airflow rates (Hsieh et al., 1993a and b). Fine-pore diffusers also have reduced heat losses for the same reason (Sedory and Stenstrom, 1995; Talati and Stenstrom, 1990).

Two important disadvantages must be taken into consideration when operating fine-pore diffusers: the need for periodic cleaning and the deleterious effect on oxygen transfer efficiency from wastewater contaminants, which is most often quantified by the a factor (ratio of process water to clean water mass transfer coefficients, or K_La_{pw}/K_La_{cw}). The economic implications of fine-pore diffuser ageing have been recently quantified by the authors (Rosso and Stenstrom, 2005). In general, fine-pore diffusers show lower a factors than coarse-bubble diffusers or surface aerators (Stenstrom and Gilbert, 1981; Rosso and Stenstrom, 2006a). Differences in a factors among aeration systems were observed as early as in the 1930s by Kessener and Ribbius (1935), but were generally forgotten until the early 1980s, when fine-pore diffusers became popular again due to increased energy cost. Many plants were initially designed with arbitrarily chosen a factors of 0.8 for all aeration technologies (i.e., fine- vs. coarse-bubbles vs. surface aerators), which resulted in under-designed aeration systems and considerable controversy among competing manufacturers. In our experience we have measured a factors for fine-pore diffusers in the range of 0.2 to 0.7 (with rare exceptions), and in the range of 0.6 to 0.9 coarse bubble diffusers and surface aerators.

The standardized oxygen transfer efficiency in process water (αSOTE) and the a factor are functions of mean cell retention time (MCRT) or sludge age, of the air flow rate (AFR), and of tank geometry (diffuser submergence, number, and unit area), as previously discussed and quantified (Rosso *et al*., 2005). Fine-bubble aeration systems in activated sludge processes operating at low loading rates (i.e., high MCRT or low F/M) are generally associated with higher a factors (Groves et al., 1992).

Measuring Aeration Efficiency with the Off-Gas Technique

First developed by Redmon *et al.* (1983) in conjunction with the U.S. Environmental Protection Agency (EPA)-sponsored American Society of Civil Engineers (ASCE) Oxygen Transfer Standards Committee, the off-gas technique has become the method of choice for process water testing of subsurface aeration systems. Testing protocols are described in detail in ASCE publications (ASCE, 1997). By performing off-gas testing, we can accurately and precisely measure oxygen transfer for diffused aeration systems (coarse-bubble diffusers, fine-pore diffusers, turbines, and jets) at virtually all process conditions. The dissolved oxygen concentration, or the oxygen uptake rate, or the aeration system air flow rate do not interfere with or limit the test procedure. Off-gas measurements over long periods of time have proven useful for plant performance improvement (Libra et al., 2002). Recently, a low-cost automated real-time off-gas analyzer was developed and deployed in municipal treatment plants in Southern California, and its design will be released to the public domain in 2007 (Leu et al., 2007).

Clean water test results are necessary to calculate the effect of process water on oxygen transfer efficiency, i.e. to calculate the a factor. Clean water results can be reported as standard oxygen transfer efficiency (SOTE, %), standard oxygen transfer rate (SOTR, kgO_2/h or lbO_2/h), or standard aeration efficiency (SAE, kgO_2/kW-h or lbO_2/HP-h). Standard conditions are defined in a protocol (ASCE, 1991) and correspond to 20°C, mean atmospheric pressure, zero dissolved oxygen, and zero effect of salinity or other contaminants (e.g., α factor =

1.0, β factor = 1.0). Because it is generally not possible or easy to measure a factors, process water transfer efficiencies are generally reported as αSOTE, which includes all adjustments (DO, temperature, barometric pressure, salinity), except the α factor. We also use this approach, which is convenient because the other non-standard conditions are easily measured. The α factor can be calculated from off-gas results when clean water data are available:

$$\alpha=\frac{\alpha SOTE}{SOTE} \qquad (1)$$

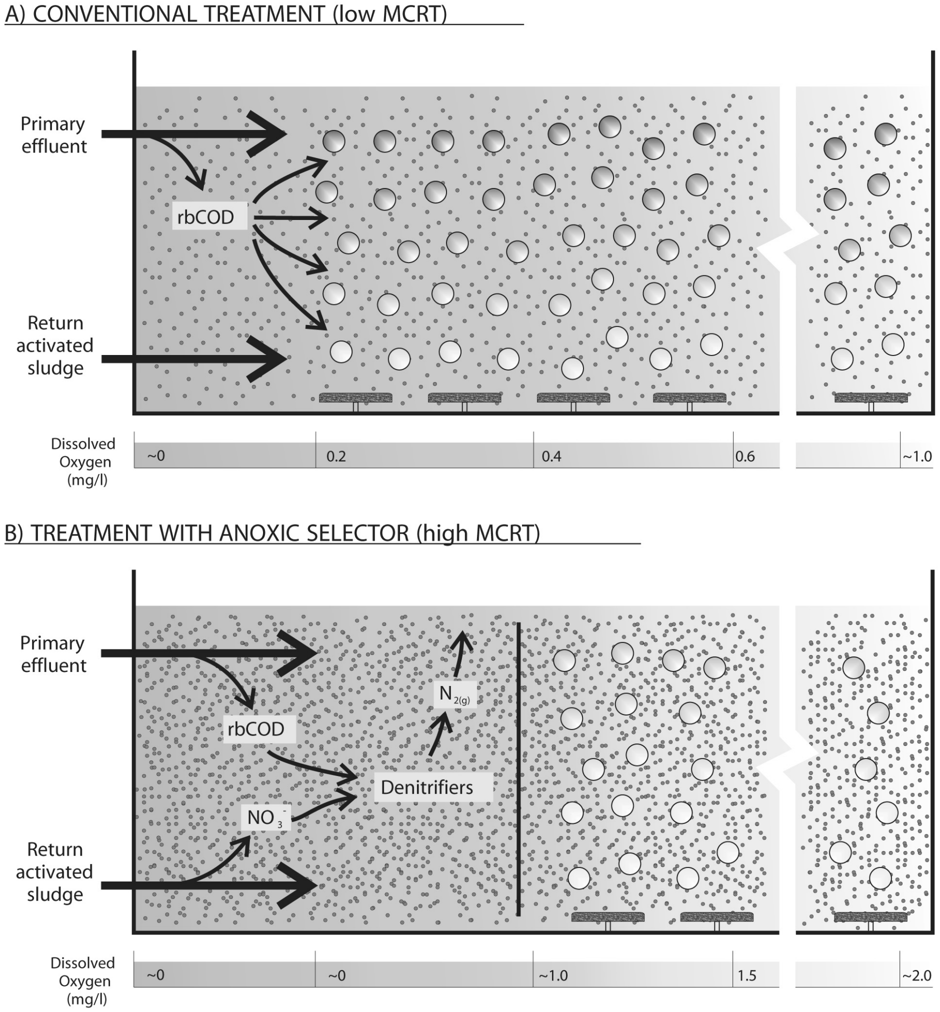
When it is desirable to differentiate the effects of wastewater contaminants and fouling, an αF factor is often used. In this work we use α for new or recently cleaned fine-pore diffusers, and αF for fouled fine-pore diffusers. Since coarse-bubble diffusers do not show significant effects of fouling, α may be used in lieu of αF for coarse-bubble diffusers which have been in operation for long time. When calculating SAE or power consumption, care is necessary because different power measurements may be used. In general, "wire" power is preferable, but requires site-specific information. Wire power is used in this paper.

FIELD OBSERVATIONS

The current database and analyses include data from 113 tests at 22 treatment plants conducted over the last 25 years using the off-gas procedure. Fourteen of the plants were conventional, three plants were operating as nitrifying-only, and five plants were operating in NDN mode. Eighty-four of the tests were for conventional treatment operations, nine tests were for nitrifying-only plants and twenty tests for NDN operation. The MCRT range for conventional plants was 1.2 to 8.5 days. In Southern California, as well as in other warm regions, nitrification can be achieved at the lower MCRTs because wastewater temperatures are typically between 26 and 28°C in the summer and seldom below 20°C during winter. In the current database, the range of MCRTs for nitrification-only was 12 to 21 days and for NDN was 5 to 22 days.

All plants tested were equipped with fine-pore diffusers which included: ceramic discs and domes, membrane discs, tubes and panels, and plastic discs and tubes. Equipment from eleven different manufacturers was included in our dataset. The range of diffuser ages varied from new (less than 1 month of operation) to used (within the first 24 months of operation) to old (greater than 24 months operation). Diffusers that had been cleaned within one month of testing were classified as cleaned. Diffuser cleaning can be achieved by tank-top hosing, mechanical scrubbing, or chemical cleaning (with liquid or gaseous acid). We grouped all cleaning methods together because the effects of different methods, at least within the present dataset, were too small to quantify.

FIGURE 1 Pathway and Fate of Readily Biodegradable COD (Mostly Surfactants) In Conventional Tanks and Anoxic Selectors.



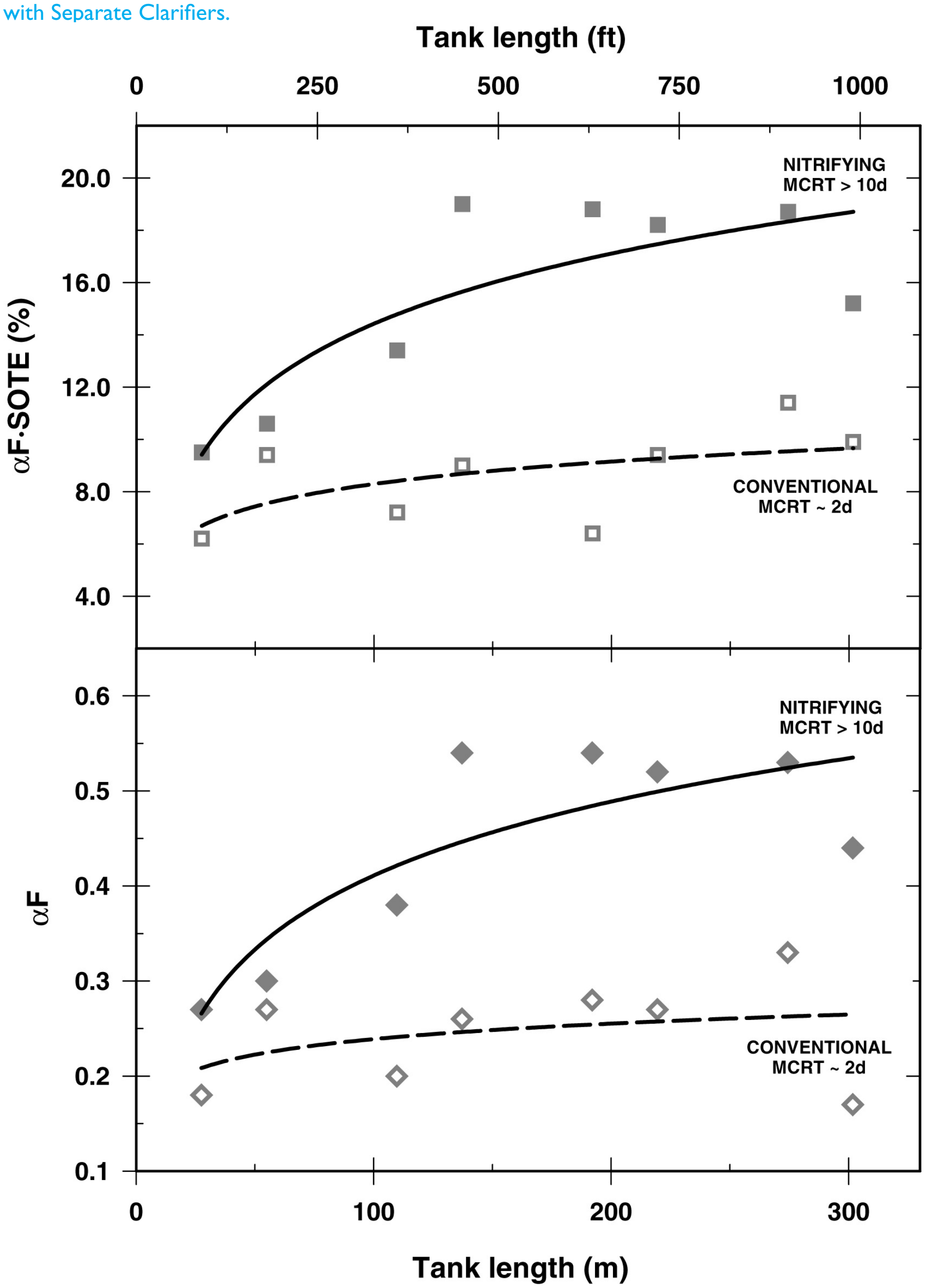
The plants had a range of construction features that may impact process operation. Baffle design, in particular, can impact operation. Baffles with submerged tops were generally effective in separating the anaerobic or anoxic mixing zones without selecting for foam producing organisms and creating nuisance and odor problems with dried spray. Baffles that extended well above the surface were the worst performing and invariably retained foam and had the worst nuisance and odor problems, often requiring manual, periodic scum removal. The ideal baffle design is discussed later and created a small water fall that prevented backflow while ensuring that scum was transported out of the selector zones (Narayanan et al, 2003).

DISCUSSION

Process Considerations

Conventional treatment is typically operated at lower MCRT conditions with lower biomass concentrations and offers less opportunity for dissolved substrate to be sorbed by the biomass. Higher MCRT operations have the advantage of higher biomass concentration. Given the same average MCRT, treatment systems using anaerobic selectors or coupling nitrification and denitrification

FIGURE 2 A Tale of Two Side-by-side Tanks Treating the Same Wastewater with Separate Clarifiers.



have the additional advantage of partially removing or sorbing readily biodegradable substrate (rbCOD) in the selector zone. This is beneficial because of decreased overall oxygen requirements (in the case of anoxic or nitrate-reducing selectors), and increased oxygen transfer efficiency (Eckenfelder and Ford, 1968; Rosso and Stenstrom, 2006a). The expected pathway and fate of rbCOD in conventional tanks and anoxic selectors are illustrated in Figure 1 where dots represent contaminants, and circles are air bubbles. Anoxic selectors have the potential to partially remove rbCOD, which otherwise would accumulate onto fine-bubbles and reduce oxygen transfer. This is the reason for improved efficiency in denitrification plants, when compared to nitrifying-only operating at same MCRT.

Figure 2 illustrates the impact of higher MCRT values on oxygen transfer. These data came from a plant operating two side-by-side tanks with serpentine layout (4 passages of 75 m each), one operating with conventional process (MCRT ~ 3.2 days; 1900 mg_{MLVSS}/l) and the other with nitrification-only (MCRT ~16 days; 2500 mg_{MLSS}/l).For both tanks, aeration was performed with fine-pore ceramic disc diffusers, influent BOD_5 was 180 mg/l, and influent NH_4^+-N was 27.2 mg/l. The tank operated in conventional mode shows consistently lower α factors and αFSOTE throughout the process. By comparing the flow-weighted averages for α and αFSOTE over the entire tanks, the overall improvement of operating at higher MCRT is about a two-fold increase in the aeration efficiency. Note that a two-fold increase in efficiency may not correspond to a 50% reduction in surfactant concentration, as the "faster" surfactants (i.e. lower molecular weight) have much more severe impact on efficiency than the "slower" surfactants (i.e., higher molecular weight). Direct surfactant removal measurements are therefore required, and may not be inferred from the variation in efficiency.

Figure 3 shows the improvement in OTE attained by introducing an anoxic selector in a high MCRT activated sludge process. This is another treatment plant with side-by-side aeration tanks and separate clarifiers with one with conventional layout (MCRT ~ 3.1 d; 1130 mg_{MLSS}/l) and one with NDN (MCRT ~ 13.8 d; 3610 mg_{MLSS}/l). Both tanks were equipped with fine-pore ceramic disc diffusers, BOD_5 influent concentration was 132 mg/l, and NH_4^+ influent concentration was 25.3 mg/l. At the head of the aeration tank, where the greatest oxygen uptake rate occurs, the oxygen transfer rate is most depressed by low α factors. The first 30% of the NDN aeration tank was not aerated and functioned as an anoxic selector. The NDN tank has no α defined in the anoxic zone, but consistently higher values for α along the entire aerated zone. In cases where the process operates at high MCRT, the average α factor will be greater and if there is internal mixed liquor recirculation, the gradient is reduced. Internal recirculation is normally used to improve nitrogen removal, but also distributes load, reducing amount of aeration tapering that is required.

The effect of dissolved contaminants on aeration efficiency is shown in Figure 4. In this figure, a subset of the entire dataset was plotted. Aeration efficiency is reported as standardized aeration efficiency in process water or αFSAE for fine-pore diffusers and αSAE for coarse-bubbles, turbines, jets, and surface aerators (all not prone to fouling).

FIGURE 3 Effect of Tank Length and Anoxic Selectors on α for Side-By-Side Treating the Same Wastewater with Conventional and NDN Operations.

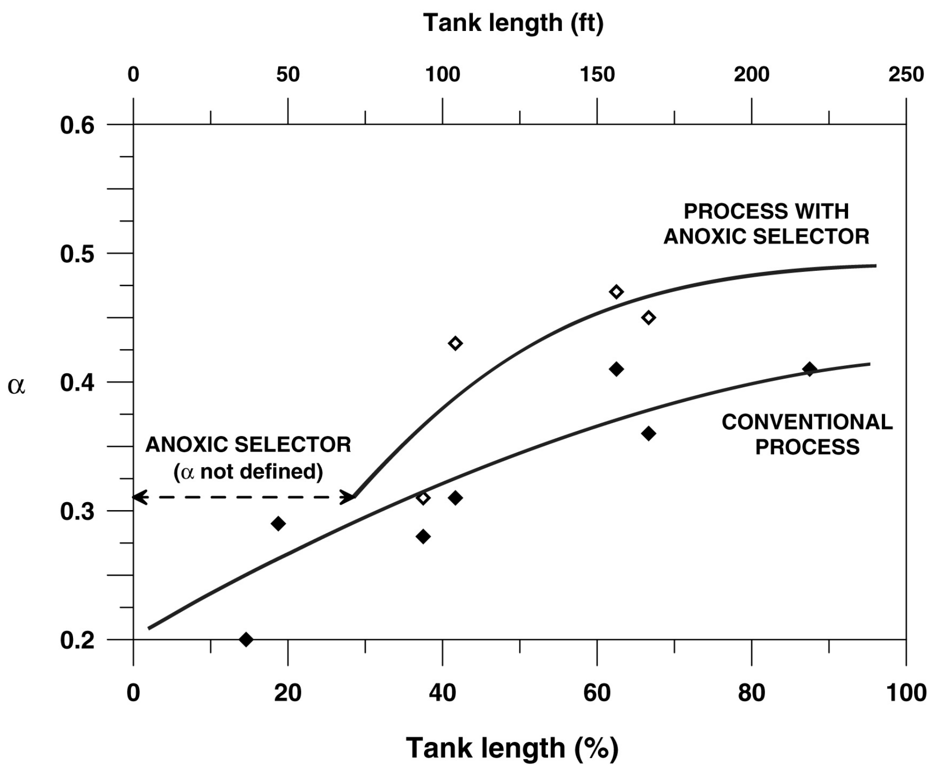
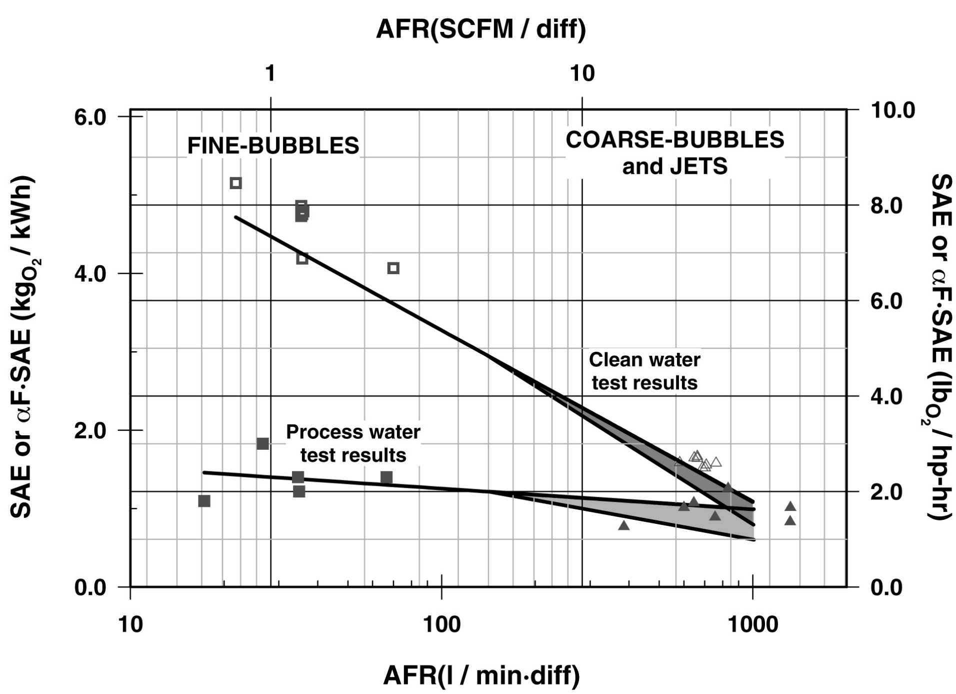


FIGURE 4 Standard Aeration Efficiency In Clean-(SAE) and Process-(αFSAE) Water for Fine-Pore and Coarse-Bubble Diffusers (data after Yunt and Stenstrom, 1996).



Clean water test results as well as results from process water testing are plotted. The horizontal axis is air flow per diffuser. At low air flow, fine bubbles are created while at high flow coarse bubbles occur. Higher air flow rates, in general, correspond to lower aeration efficiency. This is because at higher air flow rate more energy per unit oxygen transferred is required to meet the uptake rate. Bubble surface-to-volume ratio improves at low air flow rates, where bubbles are formed with small diameters. Smaller bubbles also have lower rise velocity and increased time available for gas transfer. At low air flow rates, the bubbles are released with lower initial velocity, which further increases the time available for gas transfer. The shaded areas at high air flow rates represent the range of values that can be observed for coarse-bubbles, turbines, jets, or surface aerators. In general, turbines and jets tend to be at the top of the shaded range, while coarse-bubbles and surface aerators at the bottom. Note that for the same unit power required, the oxygen transferred by a fine-pore diffuser is typically about twice as great as can be obtained by coarse bubble diffusers, jets, turbines, or surface aerators.

Figure 5 shows the trend of a with increasing Reynolds Number (Re) and compares different aeration technologies in a series of laboratory-scale experiments. The Reynolds number is defined as:

$$(Re) = \frac{du}{v} \tag{2}$$

with:

$$d = \begin{cases} \dfrac{d_{column} = \dfrac{d_{eq}}{\phi}}{d_{bubble}} \end{cases} \tag{3}$$

where:

- d = characteristic length (i.e., bubble diameter, L)
- u = bubble rising velocity (L/T)
- v = kinematic viscosity (L^2/T)
- d_{eq} = diameter of the water column above the fine-bubble diffuser (L)
- ϕ = volume fraction of liquid in the water column above the diffuser (-).

The trend lines in Figure 5 confirm the behavior of a versus turbulence predicted by Eckenfelder and Ford (1968). Figure 5 also shows the impact on clean water of 50mg/l of two different surfactants, a "fast" with high diffusivity (sodium dodecyl sulfate, m.w. ~ 10^2) such as rbCOD, and a "slow"

FIGURE 5 The Effect of Turbulence on α Factors

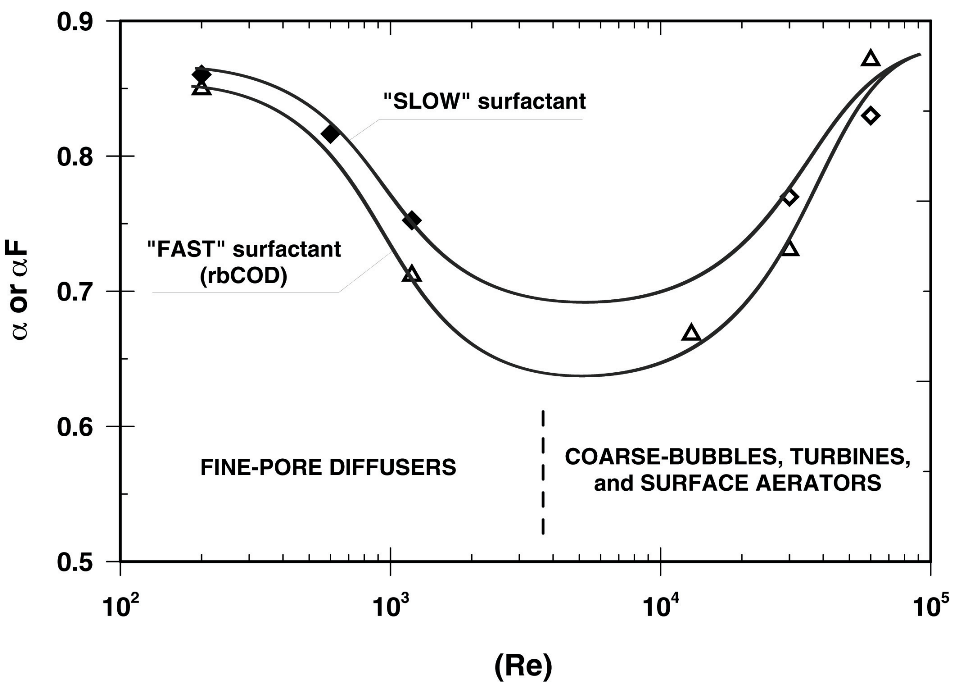


TABLE 1 Average values of off-gas tests for fine-pore and jet diffusers.

			AFR		αFSAE		αFSOTE	
Aerator	Bubbles	Water	(l/min-diff)	(scfm/diff)	(kg_{O2}/kWh)	(lb_{O2}/hp-hr)	(%)	(% ft)
Disks	Fine	Clean	39.8	1.40	4.72	7.76	30.7	2.05
Disks	Fine	Process	36.0	1.27	1.39	2.28	8.66	0.67
Jets	Fine	Clean	663	23.4	1.65	2.70	16.9	1.13
Jets	Fine	Process	756	26.7	1.01	1.66	9.50	0.63

with lower diffusivity (polyvinylpyrrolidone, m.w. ~ 10^4) surfactant. At this concentration, both surfactants were below the critical micelle concentration. The fast surfactant suppressed the transfer rate more because of its greater diffusion rate and greater accumulation at the bubble surface (lower trendline). This supression could be mitigated by the partial removal of rbCOD in the anoxic selector, before it has the chance to accumulate onto fine-bubbles. The difference between slow and fast surfactants is much less for coarse-bubbles, turbines, jets, and surface aerators. This is because the very high interfacial velocity between air and liquid maintains the renewal of oxygen molecules at the liquid surface. This explains why fine-bubble diffusers have lower α factors. Note that even though the α factors are lower for fine-bubble diffusers, they are still more energy efficient, with αFSAE of 1.38 kg_{O2}/kWh as opposed to 1.00-0.70 kg_{O2}/kWh αSAE for all other aeration technology (see Figure 4). For reference, average values of αFSAE and αSAE for different aeration technologies are reported in Table 1. Also note that the fine-bubble data presented in Figure 4 are for a low density fine-pore diffuser system, and the more recently developed high density systems have higher SAE.

The central portion of the trend lines (i.e., where the curve is minimum) shows an interfacial flow regime that is usually not encountered in commercially available aeration systems. At extremely high energy densities (energy supplied per unit volume of water, or kWh/m^3), corresponding to (Re) > 10^5, the higher interfacial shear rate reduces the thickness of the interfacial film to a few layers of water molecules, and the phenomenon of liquid vaporization will be dominant, in a similar fashion to turbines or pumps cavitating. The far-right portion of the trend lines in Figure 5 corresponds to a region where mass transfer is affected by local energy density, corresponding to the shaded areas in Figure 4. In this region, (Re) and the energy density may be independent and produce different mass transfer rates. This means that high a factors can be achieved, at the expense of much reduced αSAE.

Figure 6 shows the results of 28 off-gas tests at plants that are low MCRT, carbon-only removal, nitrifying only and nitrifying-denitrifying (NDN, such as the MLE process). All values are flow-weighted averages over the entire tank area. This figure also shows the effect MCRT and diffuser condition (new, used, old, and cleaned) on transfer rate. Both diffuser condition and MCRT affect transfer rates. The average MCRT increased from approximately 5 days for conventional to approximately 15 days for both nitrifying and NDN treatment plants. The average α factor increases from 0.37 to 0.48 to 0.59 for conventional, nitrifying and NDN systems, respectively. The change in α from nitrifying to NDN can be attributed to the rbCOD removal in the selectors. Also note the effect of diffuser condition. Points in the upper range for each process are tests of new or recently cleaned diffusers (i.e., α factors), while the lower numbers are for used (< 24 months operation) and old (> 24 months) diffusers and include the impacts of fouling (i.e., αF factors).

Economic Considerations

To quantify the benefits of denitrification on plant economics, the major operating costs from the three types of plants were calculated. Oxygen requirements, aeration efficiency, sludge disposal cost, and digester biogas credit were considered. Other operating costs, such as labor cost, while still important, were not considered either because they play a minor role on plant energy costs, or because they do not vary significantly among the three process layouts.

The cost-analysis results for the three scenarios are reported in Table 2 in costs and credits per unit volume treated, both in metric and US customary units. The net cost was calculated as:

$$\text{NET COST}=\left(\frac{\text{Aeration Sludge Disposal Cost}}{\text{Cost}}\right)\left(CH_4\text{production credit}\right) \qquad (4)$$

FIGURE 6 α Factor vs. Process Layout

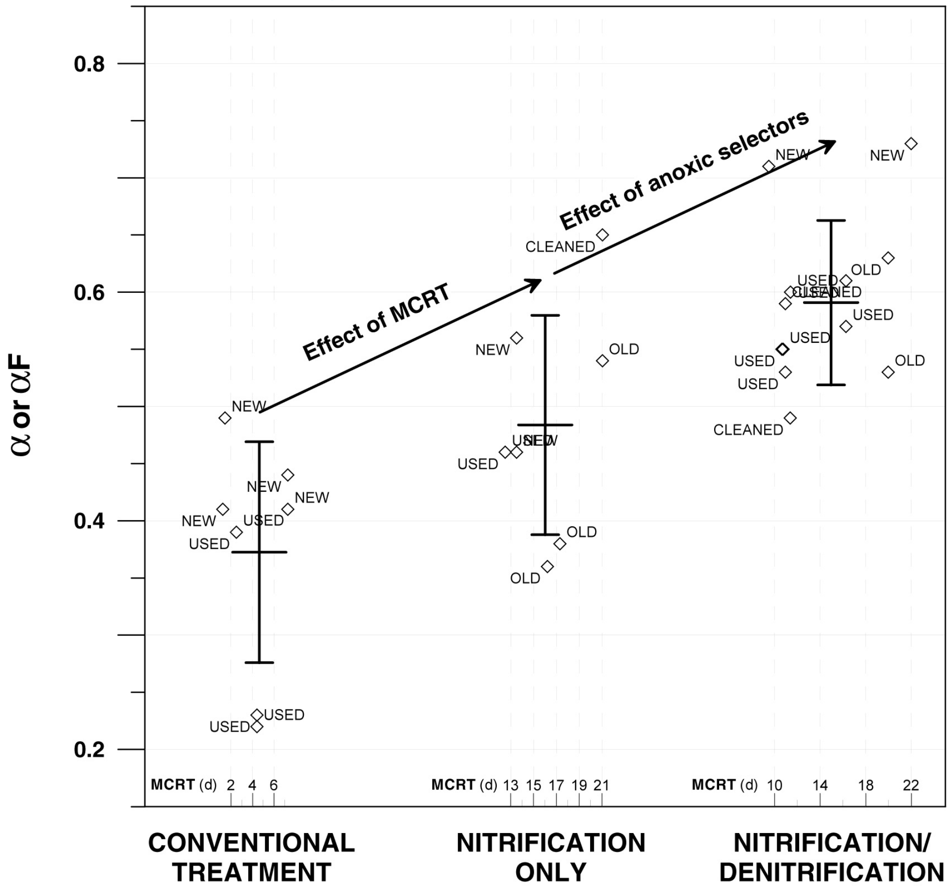


TABLE 2 Comparative Unit Costs and Requirements for Conventional Treatment, Nitrification Only, and Nitrification/Denitrification Processes.

	Conventional	Nitrifying-Only	Nitrifying/ Denitryfing
field transfer efficiency %	15.3	17.6	18.8
sludge disposal cost (USD/1000m^3)	7.0	3.9	3.5
O_2 requirement (kg$_{O2}$/1000m^3)	79	105	72
aeration cost (USD/1000m^3)	2.0	2.6	1.8
CH_4 production credit (USD/1000m^3)	4.8	1.8	1.6
net cost (USD/1000m^3)	4.2	4.7	3.7
sludge disposal cost (USD/MG)	26.5	14.7	13.0
O_2 requirement (lb$_{O2}$/MG)	659	872	601
aeration cost (USD/MG)	7.37	9.83	6.80
CH_4 production credit (USD/MG)	18.1	6.80	6.05
net cost (USD/MG)	15.7	17.8	13.8

These costs are based upon values that are typical for large municipal treatment plants (~ 100 MGD and larger), and implicitly include economies of scale. Care must be used when comparing these costs to small facilities, which typically have greater unit costs, due to the loss of economies of scale.

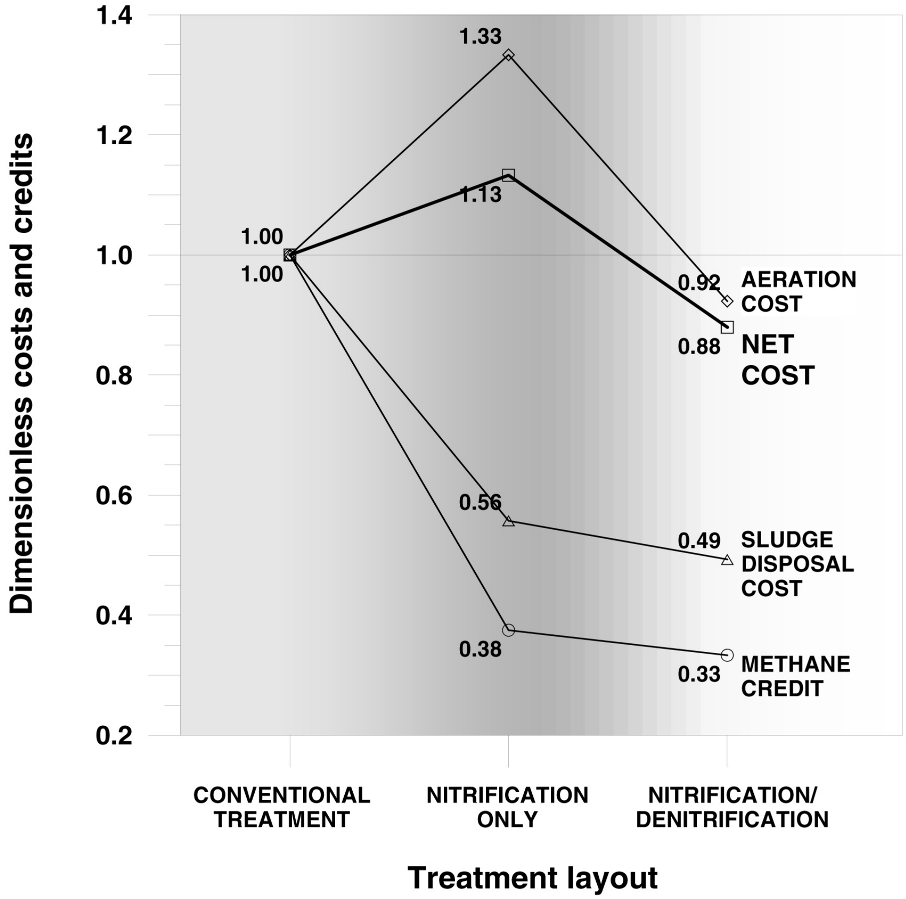
In order to calculate oxygen requirements and required airflow rate, a process temperature is 20°C and 2mg/l of dissolved oxygen (DO) was selected for all three scenarios (no aeration occurs in the anoxic zones). In order to adjust efficiency values to field conditions, a common depth of 5 m was assumed and an internal recirculation pump was included in the process layout. Note that, due to site-specific costs and requirements, the results reported in Table 2 should be used for comparison between the different layouts, and should be considered as sub-totals for each separate layout.

Nitrifying-only operations, with higher MCRT, result in higher oxygen requirements. However, higher MCRT operations are also associated with higher field transfer efficiencies. The results show a comparable airflow rate for conventional and NDN layout, this being due to the oxygen denitrification credit and to the higher efficiencies at higher MCRTs. The highest required airflow rate is for the nitrification-only layout, although the increase is not as much as the increase in oxygen requirement, due to the increased oxygen transfer efficiency. The minimum oxygen requirement, and therefore the minimum aeration burden and cost, occurs during NDN operation.

Sludge production values vary among layouts and are lowest for NDN operations. Therefore, assuming the digesters operating at the same retention time in all three cases, sludge disposal costs will be highest for conventional operations. Due to higher methane production yields, conventional operations will result in higher methane production. It is assumed that 50% VSS destruction occurs in the anaerobic digester and methane production ranges from 0.75 to 1.12 m^3/kg-VSS destroyed, the biogas composition is 65% methane on a dry basis, methane gas is valued at 5.4 \$/106 kJ (14 US cents per m^3, current methane value in Southern California), and 25% discount due to gas processing costs (scrubbing, adsorption, combustion, etc.), hence the final methane gas value is calculated as 0.06 \$/m^3 of biogas. The assumed sludge disposal cost is 20 \$/t$_{wet}$, and the calculated required blower energy is 1.17 kW/m^3. The power cost was assumed to be 0.15 \$/kWh, which is the typical cost for large treatment plants in the United States. The sum of costs minus credits is here referred to as net cost. Table 2 shows that NDN operations are the most cost-effective on the basis of net costs as well as aeration costs alone.

Costs, credits and their case combinations were normalized to relative ratios in order to eliminate currency or inflation effects (Figure 7). The costs for conventional

FIGURE 7 Relative Costs and Credits for Conventional Treatment, Nitrification Only, and NDN Processes.



operations were used as baseline; therefore, all relative costs and credits related to conventional operations amount to 1.00. In terms of net cost, nitrifying-only operations will be 1.13 times (113%) the net cost of conventional operations, while NDN will total 0.88 (88%) of conventional net cost. Aeration costs are highest for nitrifying-only operations, as expected. Costs and credits associated with solid-handling (i.e., sludge disposal cost and methane credit) have lower magnitude for nitrifying-only and NDN operations, due to the smaller amounts of sludge produced per unit time.

Design Recommendations

Our analysis was restricted to operating costs. A detailed analysis of potential changes in process sizes is beyond the scope of this paper. However, depending on the local plant situation, expansion of aeration volume and/or clarifier area might be necessary, and the operating savings could be offset by debt service on plant expansion.

The change from conventional to NDN mode requires increased MCRT, which will necessitate retaining higher mixed-liquor suspended solids (MLSS) mass in the aeration tank. This may be achieved with greater aeration tank volume or higher MLSS concentrations, resulting in higher solids flux to the secondary clarifiers. Note that the increased MLSS concentrations to achieve NDN in an activated sludge process are not expected to impact α. The typical MLSS concentrations for the processes discussed here (2-4 g/l) are much lower than concentrations used in membrane bioreactors (8-20 g/l), which have demonstrated low a factors ($\alpha = 0.4$ at $17 g_{MLSS}/l$) due to viscous transport limitations (Wagner, et al., 2002). The retrofit to NDN operations typically creates better settling sludge (Harper and Jenkins, 2003), which increases the limiting secondary clarifier solids flux. The actual capital improvements required to support higher MLSS mass will be different for each plant, and are too site-specific to be quantified here. Several agencies in Southern California have found that no additional tank volume was required, due to the elevated temperatures and to the use of reserve capacity included in conservative designs.

The design and construction of the baffle separating anoxic and aerated zone to prevent scum accumulation is important for "healthy" plant operations. Figure 8 shows a schematic of the baffle's hydraulic requirements. The anoxic tank water level should always have a hydraulic gradient to the aerated zone, i.e. the water level in the anoxic zone should be at least higher than the aerated zone in operation (this must include the expansion due to the bubble volume, typically 4 to 6 inches for a 15 ft deep tank). An opening between the baffle bottom and the tank bottom allows enough flow to guarantee proper hydraulic transit of the wastewater, and ease in draining the tanks for maintenance.

Implications of baffling on foaming and foam selection are shown in Figure 9. The figure on the left shows a conventional treatment (MCRT = 1.2 days) during an off-gas testing. In this case, the foam is so thick (~2ft !) that completely obscures the off-gas hood. The figure in the center shows a treatment plant with an anoxic selector, but with poor baffle design/construction: the hydraulic gradient between the anoxic and aerated zones is not sufficient, and the net result is foam flowing backwards into the anoxic tank (the dark surface in the center of the image, i.e. where the tank is equipped with surface mixers). This selects for foam-forming organisms, and requires periodic manual removal of the foam. The figure on the right shows a correctly designed and constructed baffle: the hydraulic gradient is sufficient, and no foam is retained in the selector zone. The baffle functions as a submerged weir. During these "healthy" operations, the foam and foam-forming organisms are continuously wasted into the aerobic tank, and not allowed to accumulate. This increases the sustainability of the process, as well as reducing labor costs associated with periodic manual foam disposal.

SUMMARY AND CONCLUSIONS

The activated sludge process, operated with anoxic selectors has several operational advantages:

FIGURE 8 Requirements for Correct Baffle Design and Construction

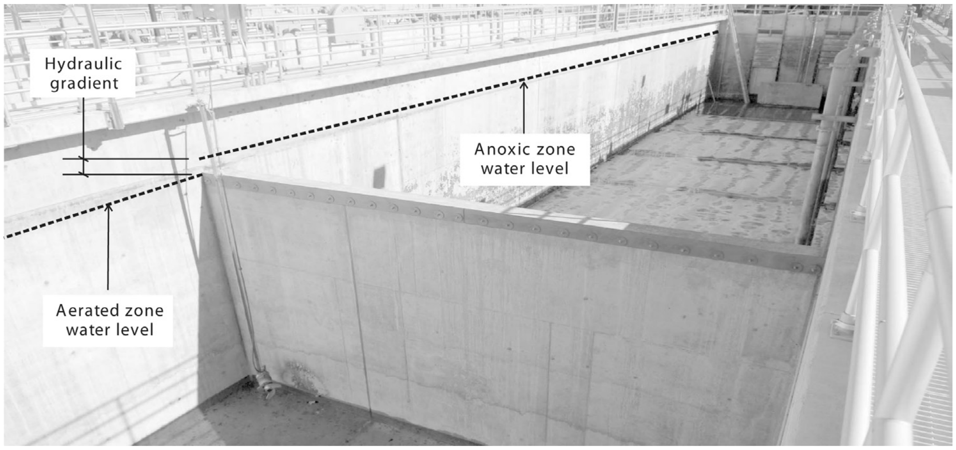


FIGURE 9 Baffle Installation and Its Implications on Foaming and Foam Selection

CONVENTIONAL TREATMENT (Low DO; no chance for surfactants to be removed before accumulating onto bubbles; high propensity for foaming and filamentous growth)

NITRIFICATION/DENITRIFICATION (retention of scum and filamentous organisms [dark, in the center] within the anoxic zone, due to improper baffle design and construction)

NITRIFICATION/DENITRIFICATION (the image above shows no retention and filamentous organisms in the anoxic tank, due to correct baffle design and construction)

- Improved nitrogen removal
- Increased stability of biological treatment operations
- Improved removal of recalcitrant COD
- Advantageous economics due to oxygen credit and higher OTE

We tested 22 treatment plants which included either conventional, nitrifying-only, or nitrifying-denitrifying (NDN) operations. The average oxygen transfer efficiency for NDN operations was consistently higher. This is because the rapidly degradable COD (i.e., the rbCOD) may be removed in the anoxic selector and used by the denitrifiers for nitrate conversion. This fraction of rbCOD would otherwise accumulate onto fine-bubbles in the aerated zone, with dramatic reduction of oxygen transfer efficiency and severely increased plant operating costs. Our economic analyses quantify and show that NDN has lowest operating costs, when compared to conventional and nitrifying-only operations. Capital costs were not included in this analysis. Depending on the local plant situation, expansion of aeration volume and/or clarifier area might be necessary, and the operating savings could be offset by debt service on plant expansion.

New designs and upgrades should consider the benefits of operating in NDN mode, even if the permit does not require nitrogen removal. During the initial stages of a plant operation, the plant is typically underloaded, benefiting of the spare capacity available for operating in NDN mode. The designer should always consider the economic benefit of operating in NDN mode during the initial years. The initial design requirements to include NDN (e.g., mixers, anoxic zones, baffles, etc.) can be included, in most cases, with marginal additional costs, and will in the long run save substantial amounts of operating costs. The overall conclusion is that design engineers and plant owners should no longer assume that NDN operation will always be more expensive than conventional, low MCRT operation.

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