Sustainable Aeration Design: Right-Sizing Aeration Systems and Other Methods to Facilitate Energy Efficient Operation of Wastewater Treatment Plants

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Electricity comprises a significant portion of operating costs for the water industry in the United States, with approximately 3 percent of energy consumed by water and wastewater treatment plants (Krause et al., 2010). It is well known that the aeration treatment process is typically the largest consumer of energy at conventional wastewater treatment plants; 70 percent of plants exceeding 2.5 mil gal per day (mgd) utilize activated sludge secondary treatment, and 45 to 75 percent of electricity use is consumed for aeration treatment (Rosso and Stenstrom, 2006). Improving the efficiency of aeration can result in significant cost and energy savings to utilities in Florida—and beyond.

The sizing of aeration systems is often based on maximum flow and load in worst-case scenarios, whereas actual conditions are typically far below design conditions. Aeration blowers are often oversized and cannot efficiently operate under low loading conditions. Aeration basins are also often oversized, with excessive diffusers installed, and aeration system operation can be driven by mixing requirements rather than process aeration demands.

Sustainable aeration system design requires that the full range of flow, load, and ambient temperature conditions be considered. Changes in aeration efficiency over time due to diffuser fouling and wear also need to be considered. Key elements of sustainable aeration system design include:

- Providing flexible aeration basin designs to match volumetric capacity to influent flows throughout the life of the system
- Providing multiple sizes of blowers to ensure adequate turndown and optimal efficiency throughout the range of operation
- Providing an effective control system to match blower operation to process aeration and mixing requirements

Most of the sustainable design methods discussed in this article, including anoxic zones and activated sludge foul air diffusion, were installed at the Broward County North Regional Wastewater Treatment Plant (WWTP) Module C in 2004. Based on the successful track record of operation of this WWTP, the nearby Plantation Regional WWTP decided to implement a similar sustainable system and has recently completed the design phase for conversion from mechanical aeration to fine bubble diffused aeration. The Plantation Regional WWTP system, which incorporates the recommendations discussed in this article, is illustrated in Figure 1.

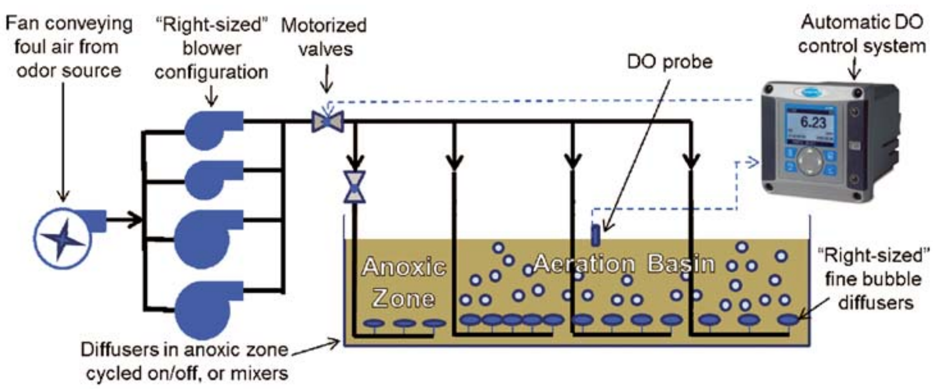

Figure 1. Plantation Regional Wastewater Treatment Plant Right-Sized Aeration System

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Fine Bubble Diffusers

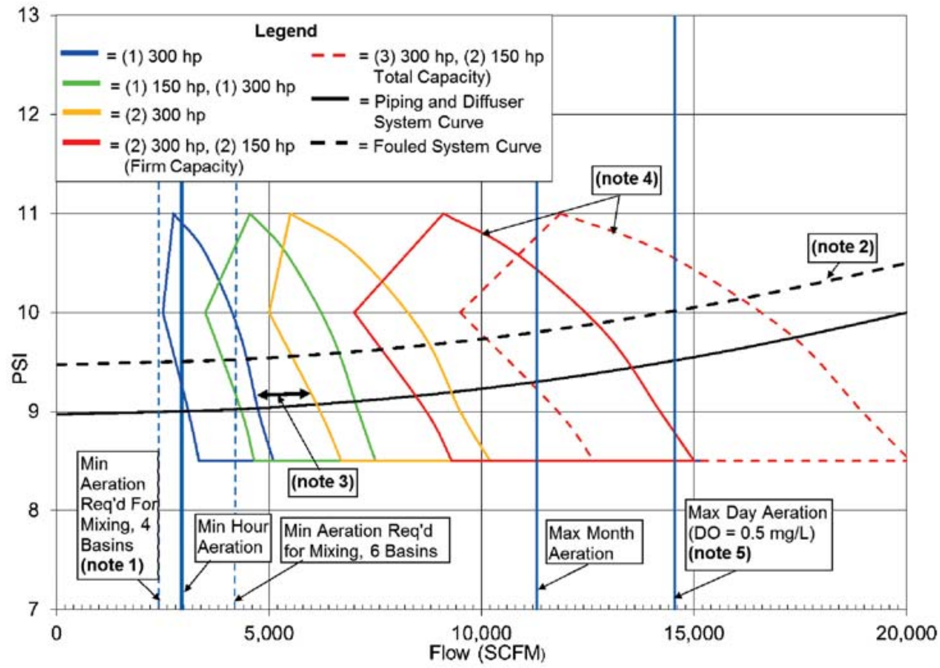
Fine bubble diffused air systems are typically more efficient at oxygen transfer than mechanical aeration or coarse bubble diffused air technology. The reason for this is that the smaller bubble size produced by fine bubble diffusers has a higher surface-area-to-volume ratio, which allows much higher oxygen transfer per unit volume of air than other technologies. Design considerations for right-sizing fine bubble diffuser systems include:

Diffuser Tapering - Each zone/cell in an aeration basin has a specific air demand as the oxygen demand varies due to changes in organic load down a plug flow biological reactor. Alpha, or the ratio of oxygen transfer between dirty and clean water, will also typically vary along the reactor length. A tapered aeration diffuser layout configures the diffusers to follow the oxygen demand profile in the reactor. Thus, more diffusers should be located at the influent end (i.e., highest load and oxygen demand) and be tapered or reduced towards the effluent end of the reactor. Process simulation software, such as BioWin™, can be used to simulate oxygen uptake rates for each cell to determine the oxygen demand among the zones/cells of the aeration basin.

Diffuser Density - Because diffuser systems are often created for a design flow that will not occur until 20 or more years in the future, they can sometimes be oversized. In general, the lower the airflow per diffuser, the greater the standard oxygen transfer efficiency (SOTE). A higher diffuser coverage on the basin floor, also known as diffuser density, also results in a greater SOTE. This may lead some designers to provide too many diffusers in current conditions, which may result in uneven air distribution, especially during nighttime and early morning low-flow conditions as the airflow struggles to overcome the head loss across the diffuser membrane. In the case of 9-in. membrane disc diffusers, uneven air distribution occurs below approximately 0.5 cu ft per minute (cfm) per diffuser. This condition is worsened with fouling. To remedy this, diffuser grids should be designed with spare saddles to add diffusers for future loadings. Existing diffuser systems that are determined to currently have too many diffusers can have surplus diffusers plugged.

Avoid Minimum Mixing Limitations - It is required to maintain a minimum level of aeration at all times to maintain minimum mixing requirements. For a full-floor grid, 0.1 cfm/sf of basin floor area is a typical value for providing adequate mixing (Mueller et al., 2002; Krause et al., 2010). During low-flow and loading conditions, the air demand can often drop below the minimum mixing level. At this point, it is necessary to provide air beyond that demanded for adequate wastewater treatment, which results in wasted energy. If the same wastewater loading could be achieved in a lower aeration basin volume/floor area, the minimum mixing airflow requirement would be reduced and the aeration demand of the wastewater would be controlled. Sustainable aeration system design consideration should balance the "more and smaller" basin approach with the "less and larger" basin approach to prevent the need to operate in minimum mixing mode as best as possible. Note 1 in Figure 2 demonstrates the minimum mixing requirements of an aeration system with six basins online, versus an aeration system with four basins online. In this example, it is apparent that if four basins are operated, the system can operate at a substantially lower-flow rate during low air demand periods, resulting in substantial energy savings.

Reduce Fouling - Diffuser fouling can significantly reduce oxygen transfer by affecting bubble geometry and increasing the pressure loss in the system, resulting in decreased diffuser efficiency. Fine bubble membrane diffuser manufacturers typically recommend that aeration basins be taken out of service annually to have the diffusers hosed down and any biofilm brushed off. Studies have shown that the cost and energy savings achieved by a biannual or annual regular diffuser cleaning routine more than compensate for the time and material investment by plant owners. Note 2 in Figure 2 shows the effect of a nonmaintained diffuser system. Note that the amount of pressure required to meet the same flow rate can be increased by as much as 0.5 pounds per sq in. (psi) according to diffuser manufacturers, resulting in wasted energy.



Notes:

1. "More and smaller" instead of "less and larger" basins are provided, allowing basins to be brought offline to meet current or low-season design loadings and preventing wasted energy to provide minimum mixing of 0.1 cfm/sf
2. Fouled, nonmaintained diffusers can raise the pressure requirement of the system, resulting in wasted energy
3. With both "small" and "large" blowers, a gap in airflow is avoided and a more efficient operation results
4. Maximum-month average daily loading is met with one unit out of service, and maximum-day loading with all units in service
5. The system is designed to only provide 0.5 to 1.0 milligrams per liter (mg/L) dissolved oxygen (DO) concentration during maximum-day loadings

Figure 2. Typical Sustainable Aeration System Blower Curve Plot for Multistage Centrifugal Blowers

Blower Systems

Traditional blower technologies used for aeration in biological treatment processes include positive displacement, multistage centrifugal, and single-stage integrally geared centrifugal blowers. Hybrid rotary lobe-screw positive displacement blowers and high-speed single-stage centrifugal blowers have been introduced into the municipal wastewater market as more energy efficient alternatives to traditional rotary-lobe positive displacement and multistage centrifugal blowers.

The appropriate blower technology for each facility depends on multiple factors, and is best determined on a case-by-case basis. Hazen and Sawyer has conducted several studies evaluating performance and capital/operation and maintenance (O&M) costs for multistage centrifugal blowers, turbo blowers, and single-stage integrally geared blowers. These studies have resulted in the following general conclusions:

- Turbo blowers are generally more efficient than multistage centrifugal blowers, although the advantage is not nearly as pronounced when multistage blowers are allowed to run near their design capacity for maximum efficiency.

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- Turbo blowers are typically not as efficient as single-stage integrally geared blowers.
- Turbo blowers, multistage blowers, and integrally geared blowers are generally competitive against one another in terms of total net present-worth costs, depending on specific project conditions and capacity requirements.
- Replacement of existing blowers with new, more efficient blowers, just for the sake of improving efficiency, generally does not have a favorable payback period due to the high capital cost involved. Once a blower is at the end of its service life, it makes sense to consider replacement with a more efficient technology available at that time.

Considerations for sustainably designing blower systems include:

Blower Configuration to Avoid Performance Gaps - The ratio of minimum-to-maximum oxygen demand within a typical activated sludge process varies from approximately 3:1 to 5:1 between the peak and off-peak hours. For smaller plants the ratio can be as much as 16:1 (Tchobanoglous et al., 2003). As wastewater flow and strength fluctuate, there is a corresponding fluctuation in the amount of oxygen required to provide treatment over the course of the day. As a result, aeration blowers that are sized to meet average and maximum daily loads may not efficiently operate under low loading conditions.

A sustainable blower system should be capable of providing the entire range of required airflows with minimal gaps in coverage, from maximum-day to minimum-day design flow. Multistage centrifugal and high-speed direct drive blowers often cannot be turned down lower than 50 percent of their design flow rate, which results in gaps in the blower system's air flow rate capacity. A solution to this is to install two separate size blowers when using multistage centrifugal or a high-speed direct drive blower, with the smaller blower having 50 to 80 percent capacity of the larger blowers. At least two blowers of each size should be provided for redundancy and to maintain full coverage. Turndown to minimum mixing should also be considered, as this often controls during low overnight flows.

Note 3 in Figure 2 demonstrates that with only large 300 hp blowers installed, an operational gap of 1,200 cfm is encountered between the one- and two-blower operating condition. If the system is frequently operating within this lower airflow range, anytime the airflow demand falls within this range, energy is wasted. With both small and large blowers, the gap in airflow is avoided, and a more efficient operation results.

Defer Installation of Equipment - Blower systems are often created for a design flow that will not occur until 20 years, or more, in the future. This can result in a blower system with multiple idle blowers, incurring unnecessary capital and maintenance costs. Sometimes regulations require adequate blower capacity to be installed, even if this results in idle equipment. If permit conditions allow, it is good practice to provide enough blower capacity to meet intermediate flow and loading rates, while leaving room on the blower pad or blower building for installation of future blowers. Figure 3 demonstrates a blower system at the City of Plantation Regional WWTP, with planned room for a future fifth blower; it also shows the typical layout of two large 350 horsepower (hp) and two small 200 hp blowers at the plant.

Avoid Oversizing the System by Setting Appropriate Key Design Criteria - The blower system should be sized so that with the largest unit out of service, it can still satisfy the oxygen requirement of the system under most conditions. To reduce capital costs and the need for extraneous blower capacity, it may be permissible to allow the system to satisfy maximum-month or maximum-week average daily loading with one unit out of service, and maximum-day loading with all units in service. As an additional way to reduce the size of the aeration system, it is typical to allow the system to provide 0.5 to 1.0 mg/L of oxygen concentration in the aeration basins during design maximum-day loadings, as opposed to the typical 2 mg/L DO for lesser loadings (Mueller et al., 2002). The example in Figure 2, Note 4 demonstrates that maximum-month loading is met with the largest unit out of service, while maximum day is met with the largest unit in service. Note 5 in Figure 2 indicates that the maximum-day aeration capacity calculated is based on 0.5 mg/L. Note that increasing the DO requirement at maximum-day loading would result in the need for an additional blower.

Determine Appropriate Design Weather Conditions - The maximum-day design flow and associated head loss through the piping and diffuser system define the design point for the blowers. Because hotter air is less dense and has less oxygen per unit volume, the blower system must provide a high enough flow rate to supply adequate oxygen for the hottest summer day. Because colder air contracts, but blowers intake a constant volume of air, the blower motors should also be sized to handle denser winter air so that they are nonoverloading over the entire range of operation. Also affecting oxygen transfer is humidity, because moisture contained in a unit volume of air displaces oxygen. If a blower is sized for correct inlet temperature and pressure, but does not consider humidity, the blower will deliver the correct maximum volume of air but will be undersized to deliver the design maximum oxygen flow rate. However, incorrectly using relative humidity can also result in oversized blowers.

A common mistake when sizing blowers is to use a high or maximum relative humidity, such as in the range of 90 to 100 percent, in combination with a maximum design temperature. Relative humidity in this range is possible, but only at temperatures much lower than the maximum design temperature. A psychrometric chart should be used with the design dry bulb temperature and wet bulb temperature to determine design relative humidity. Design wet bulb data for representative cities of a geographical location are available from the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). The design dry bulb temperature should be the design maximum temperature for the system, which in this case is also taken from the ASHRAE charts. Based on the preceding discussion, typical design

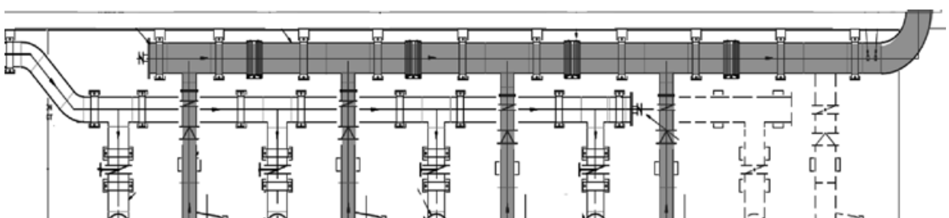

Figure 3. Typical Sustainable Blower System Layout at Plantation Regional Wastewater Treatment Plant

weather conditions for a blower system in south Florida are provided in Table 1.

An existing blower system was recently evaluated at a large WWTP in Florida. The existing blower system was installed in the 1980s, and upgraded in the 1990s. The ceramic fine bubble diffusers are located in basins that require dewatering of the shallow underlying aquifer (approximately 5 ft below grade) to prevent flotation of the thin concrete floors of the basins. Because of the difficulty in dewatering, the diffusers are generally not cleaned or maintained, which increases the head loss due to fouling. Upon examination of the blower curves, it was apparent that the existing blowers were both pressure-limited at hot weather conditions and the motors were undersized for cold weather conditions. Indeed, the plant staff reported that, in the summertime, surge conditions occasionally occurred during hot weather, making it necessary to shut down the blowers. Furthermore, plant staff reported that, during cold weather, the horsepower limitation of blowers is reached due to the increased air density, making it necessary to limit blower flow rate by inlet throttling to prevent the blower motors from overloading. The evaluation resulted in a recommendation to right-size the system by installing new blowers, or to potentially modify the existing blowers with new impellers and/or motors.

Table 1. National Oceanic and Atmospheric Administration (NOAA) and ASHRAE Weather Design Conditions for West Palm Beach

Data Source	Parameter	Value
ASHRAE Extreme (1%) Conditions	Design Temperature (Wet Bulb) (°F):	80
	Maximum Design Dry Bulb Temperature (°F):	92
	Minimum Design Dry Bulb Temperature (°F):	42
ASHRAE Psychrometric Chart	Resulting Relative Humidity:	41%

Table 2. WEFTEC Paper Survey of Energy Savings Available Through Implementing Automatic Dissolved Oxygen Control

Plant	Flow (mgd)	Energy Savings	Description	Source
Florence WWTP Demonstration (AL)	9	17%	Add luminescent DO probes and master control panel to control (3) existing 350 hp multistage and (1) 150 hp multistage centrifugal blowers with fine bubble diffusers by throttling intake valve, DO maintained at 2 mg/L	Brogdon et al., 2008
Poultry Processing Facility (MS)	1	22%	Add luminescent DO probes and VFD to existing centrifugal blower with fine bubble diffusers	Brogdon et al., 2008
Oxnard WWTP (CA)	22	20%	Install (2) influent total suspended solids (TSS) meter, update DO probes to luminescent probes, implement model-predictive control strategy to continuously modify DO set point based on influent TSS and DO with existing single stage integrally geared blowers and fine bubble diffusers	Moise and Morris, 2005
Phoenix 23rd Ave WWTP (AZ)	48	15%	Install feed-forward BIOS system (BioChem Technology Inc.) with DO, flow, TSS, temperature, nutrient, and flow measurement to control DO set points in different zones, with minimum DO set point of 2.0, 1.3, and 0.7 mg/L in three zones of a modified Ludzack-Ettinger process, compared to fixed DO set points of 2.5, 2.0, and 2.0 mg/L, respectively	Walz et al., 2009
Abington WWTP (PA)	2	6%	Install feed-forward/feedback model predictive control system, with BOD, TSS, nutrient, flow, and DO measurement in a preanoxic selector/aeration process for a reduction of DO from 2 mg/L set point to average adjustable set point of 1.5 mg/L with minimum and maximum set points of 1.0 and 2.0 mg/L, respectively	Liu et al., 2005
Enfield WWTP (CT)	5	3%	Install feed-forward BIOS system (BioChem Technology Inc.) with DO, flow, TSS, temperature, nutrient and flow measurement to control DO set points in different zones of a modified Ludzack-Ettinger process to unreported values, compared to fixed DO set points of 2.75, 2.0, and 0.5 mg/L, respectively	Liu et al., 2005

Controls

As wastewater flow and strength fluctuate, there is a corresponding fluctuation in the amount of oxygen required to provide treatment. It is common to maintain a DO level of 1 to 3 mg/L in aeration basins to ensure that adequate oxygen is supplied to sustain the microorganisms in the wastewater. The most simple DO control strategy is manual control, where operators take periodic manual readings of DO or other related parameters, then manually adjust valve or blower settings to meet the required oxygen level. However, because operators typically conservatively set the airflow to the maximum worst-case airflow demand incurred during peak flow and wastewater strength, the result is that, during many times of the day, DO levels higher than 1 to 3 mg/L are supplied, resulting in wasted energy.

A typical automatic DO control strategy utilizes DO sensors to continuously take readings and feedback signals to a controller that automatically adjusts airflow to maintain a predetermined set point (typically 1 to 3 mg/L) by continuously adjusting the blowers and/or air distribution control valves to each basin. As such, implementing automated DO control can greatly reduce electricity costs, operator workload, and help to maintain consistent effluent quality. A literature review of DO control implementation papers presented at the Water Environment Federation Technical Exhibition and Conference (WEFTEC) was recently compiled. A summary of the various strategies implemented are presented in Table 2 to demonstrate various methods of implementing aeration controls and the energy savings achieved.

Anoxic Zones/Denitrification

Incorporation of anoxic zones upstream of aerated zones can provide substantial benefits to conventional nitrification facilities that are not yet required to meet nutrient limits. Since many facilities in Florida that are not required to nitrify do so anyway, due to the year-round high temperatures and resulting increased microbial kinetics, why not reap the benefits of subsequent denitrification? These benefits include decreased aeration requirements, improved solids settleability, and alkalinity recovery as described:

Denitrification in an Anoxic Zone Reduces the Aeration Requirements of the System - Implementing and/or improving the denitrification capability of the secondary process will result in a reduction in process aeration demands. Conversion of ammonia to nitrate-nitrogen (NO_3-N) requires 4.57 lbs oxygen per lb ammonia-nitrogen (NO_3-N) oxidized to NO_3-N. Denitrification of nitrate to nitrogen gas under anoxic conditions reduces oxygen requirements through consumption of influent readily biodegradable carbon as an electron donor. This reduction in organic carbon loading decreases the amount of oxygen required in the aerobic zone by 2.86 lb of oxygen per lb

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NO_3-N reduced to nitrogen gas (N_2). Significant savings in aeration can be achieved by providing an anoxic zone upfront of an aerobic zone for denitrification of the return activated sludge.

Denitrification in an Anoxic Zone Reduces the Overall Consumption of Alkalinity (and Subsequent pH Suppression) - The nitrification process consumes 7.1 grams of alkalinity (as CaCO3) per gram of NH3-N oxidized to NO_3-N. This alkalinity is partially recovered through denitrification at a rate of 3.6 grams of alkalinity (as CaCO3) per gram of NO_3-N reduced to N_2, resulting in a net loss of 3.5 grams of alkalinity (as CaCO3) per gram of nitrogen removed through the nitrification/denitrification process. Nitrification without subsequent denitrification will decrease alkalinity almost twice as much as nitrification, followed by denitrification. A reduction in alkalinity results in a decrease in the wastewater pH, which may decrease the nitrification capacity of the process, in addition to potential effluent quality violations.

Denitrification in an Anoxic Zone can Increase the Settleability of the Mixed Liquor - Implementation of an initial unaerated zone can also improve secondary solids settleability by providing an anoxic selector to preclude the growth of filamentous bacteria and select for bacteria that form tight, dense flocs with good settling properties. Filamentous bacteria can form bridges between flocs, keeping them in suspension and decreasing secondary clarifier performance. Many filamentous bacteria use readily biodegradable carbon very efficiently, but cannot utilize these substances under anoxic conditions where nitrate (and not oxygen) is an electron acceptor (Grady et al., 1999). The anoxic selector allows for the removal of readily biodegradable organic matter under conditions where filamentous organism growth is restricted.

Aerated zones with membrane fine bubble diffusers can be converted to an anoxic zone with relatively little capital investment. A motor-operated modulating valve can be installed on the aeration piping drop leg to the anoxic zone, and the valve can be programmed to periodically open and bump the anoxic zone for a short period of time to maintain mixing. Valves in the anoxic zones for each basin can be programmed to operate sequentially to avoid sudden destabilizing increases in aeration demand. Ceramic diffusers may be more prone to fouling in this situation.

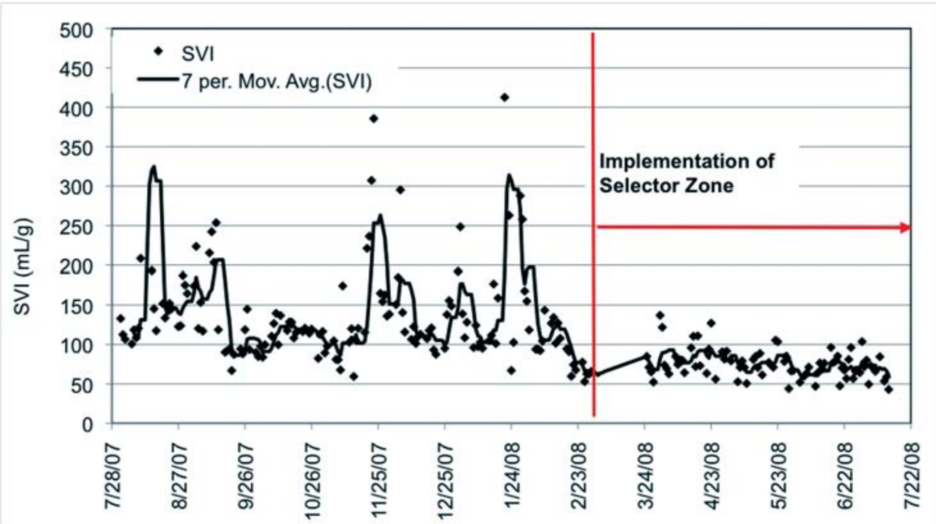

Figure 4. Broward County North Regional Wastewater Treatment Plant Sludge Volume Index Before and After Anoxic Zones

Table 3. Broward County North Regional Wastewater Treatment Plant Estimated Savings Due To Reduction in Oxygen Demand

Trains 1 and 4 NOx-N (mg/L)	Trains 2 and 3 NOx-N (mg/L)	Average Flow (mgd)	Reduction in Average Airflow	Reduction in power (hp)	Yearly Energy Savings	20-Year NPV Savings
14.9	7.4	16.6	1,390	57	$25,600	$413,000

Table 4. Plantation Regional Wastewater Treatment Plant Activated Sludge Foul Air Diffusion Savings

	Capital Cost	20-Yr Present Value O&M	Total Present Value ($2012)
Chemical scrubber system	$911,000	$665,000	$1,576,000
Activated sludge diffusion	$118,000	$ 44,000	$162,000
Total Savings	**$793,000**	**$621,000**	**$1,414,000**

Anoxic Zones at Broward County North Regional Wastewater Treatment Plant

The Broward County North Regional WWTP is rated to treat an average flow of 100 mgd and is composed of five individual activated sludge modules (20 mgd/module), each comprising four aeration trains. A pilot program was conducted from February through July of 2009 to evaluate the ability of the facility to operate with an anoxic zone with no physical improvements and only process modifications. The pilot study also tested the effectiveness of the anoxic selector to improve the settleability of the activated sludge.

As a part of this study, air was turned off to the first grid of membrane fine bubble diffusers to create an anoxic selector at the front of Module C. Operations staff turned on the first diffuser grid for 10 minutes every two hours to bump the basin and keep the solids in suspension. The upstream cell of trains 2 and 3 of the four trains in Module C were operated in the unaerated mode for six weeks, with trains 1 and 4 operated in fully aerated mode, and the performance of Module C was monitored for nitrogen removal. Sludge volume index (SVI) values were monitored during the pilot operation. The SVI trend presented in Figure 4 confirms that the anoxic selector zone considerably improved the settleability of the activated sludge in Module C. Further details of this evaluation and pilot study are available (Griborio et al., 2009).

The results of the nitrogen removal in the trains with the anoxic zones, compared to the fully aerated trains, was significant, as demonstrated in Table 3. Assuming an average multistage centrifugal blower efficiency of 62 percent operating 10 minutes every two hours it is anticipated that this level of denitrification would account for a reduction in airflow and power, resulting in over $25,000 per year of annual savings for Module C alone.

Activated Sludge Foul Air Diffusion for Odor Control

Activated sludge foul air diffusion is a rarely used, but viable, option for odor control in lieu of conventional odor control, such as chemical scrubbers or bioscrubbers. Utilization of activated sludge foul air diffusion can result in significant savings in capital, operation, and maintenance costs by avoiding the need for odor control vessels and chemicals and has been implemented successfully at many locations throughout the country.

The diffusion involves conveying foul air to the suction of aeration blowers and diffusing it through the fine bubble diffuser system into the mixed liquor. The odors are removed by a combination of mechanisms including absorption, adsorption, condensation, and biological oxidation in the basins. Typical odor removal efficiencies are reported in the 80–99 percent range for moderate- to high-strength odors. Odorous contaminants are absorbed into the activated sludge mixture due to the fine bubble diffusion and microorganisms present in the activated sludge, converting the hydrogen sulfide (H_2S) into the sulfate (SO_4^{2-}) form. This process is limited by the efficiency of the absorption of the gases from the vapor phase into the liquid phase and pH.

Under the activated sludge diffusion scenario, there are several design considerations to keep in mind:

- A fan should be provided near the source of odor to convey air to the blower system through the suction piping.
- Aeration blowers and any equipment located within 3 ft of foul air may be required to be explosion-proof-rated (subject to interpretation and local code requirements) since they may be handling odorous foul air from a classified area.
- Grease filter/mist eliminators should be provided upstream of the blowers to protect the blower components.
- Aeration blowers should be constructed of materials or provided with coatings (such as heresite) on internal surfaces to prevent corrosion. Additionally, aeration piping should be made of 316 stainless steel to help prevent corrosion.

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Activated Sludge Foul Air Diffusion at Plantation Regional Wastewater Treatment Plant

Based on the successful operation of an activated sludge foul air diffusion system at the Broward County North Regional WWTP Module C in 2004, the nearby Plantation Regional WWTP decided to investigate the benefits of installing a similar system. A capital cost analysis presented in Table 4 predicted that the City of Plantation will realize a net present worth savings of over $1.4 million by implementing an activated sludge foul air diffusion system instead of chemical scrubbers.

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