Energy-Efficient

Existing aeration basins at the Lake Bradford Road Water Reclamation Facility in Tallahassee, Fla. Since their structural integrity is good, the team proposed that they receive only minimal modifications.

MBRs

A well thought-out design can minimize a membrane bioreactor's energy demand

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Although membrane bioreactors (MBRs) continue to gain popularity because of their compact size and exceptional-quality effluent, these systems tend to be energy hogs. So, when upgrading the Lake Bradford Road Water Reclamation Facility (Tallahassee, Fla.) to an MBR, the project team implemented measures that could reduce the facility's overall energy use by 20% while still meeting effluent requirements.

Energy Diet Needed

MBRs combine low-pressure membrane filtration with activated sludge treatment. According to literature on the energy consumption of various wastewater treatment processes, MBRs require significantly more energy than conventional treatment processes. They tend to use more energy because

- a separate aeration or pumping system is required to scour the membranes (to control fouling);
- return activated sludge (RAS) rates typically must be kept between 300% and 400% of influent flow to maintain the solids balance between membrane tanks and bioreactors at 6000 to 12,000 mg/L of mixed liquor suspended solids (MLSS); and
- another pumping system usually is needed to move water through the membranes.

With this in mind, the project team looked for ways to reduce the overall energy use of an immersed MBR system retrofitted into the existing Lake Bradford facility. The facility was being upgraded to produce an effluent containing less than 5 mg/L of carbonaceous biochemical oxygen demand (CBOD), 5 mg/L of total suspended solids (TSS), 3 mg/L of total nitrogen, and 2.5 mg/L of total phosphorus (on an annual average basis).

The team found that an MBR facility's overall energy consumption is significantly affected by

- preliminary and primary treatment processes;
- membrane selection;
- the configuration of the biological nutrient removal (BNR) process;
- the design of the process aeration system; and
- the control strategy for both process and scouring airflows.

Preliminary and Primary Treatment

Preliminary treatment processes typically include screening (coarse, fine, or both) and grit removal. Primary clarification is an optional process for treating raw wastewater or preliminary treatment effluent before it enters a biological process. Its use primarily depends on economics and the facility's solids-handling processes. Properly designed and operated primary clarifiers have been reported to remove 50% to 70% of suspended solids (grit, rags, and other colloidal, inert, and biodegradable suspended solids) that otherwise would increase the solids yield and interfere with its aeration system. Primary clarification also removes 25% to 50% of BOD from raw wastewater.

Design engineers should seriously evaluate how primary clarifiers affect both costs and overall operations. Primary clarifiers use little energy, and if they remove 30% to 50% of BOD, then a downstream activated sludge process will need less aeration capacity, bioreactor volume, and power to do its job (see Table 1, p. 48).

The Lake Bradford facility has primary clarifiers, which historically removed an average of 66% of TSS, 47% of BOD, and 15% of total Kjeldahl nitrogen from wastewater. The project team designed the subsequent BNR process with these removals in mind. The team also decided to degrit primary solids before pumping them into the collection system, where they will be sent to Tallahassee's other water reclamation facility for further treatment.

Membrane Selection

The project team selected an immersed MBR because a relatively large number of successful municipal installations use this technology. However, depending on the membrane configuration, as well as aeration intensity and duration, the energy demand for membrane scouring varies considerably.

The project team used an evaluated bid process to select the most energy-efficient membrane system. Equipment vendors were required to provide not only a competitive capital cost but also guaranteed operating costs (power, chemical use, typical maintenance labor, etc.). Three membrane manufacturers submitted bids, and Membrane A used the least power (see Table 2, p. 49).

BNR

The Lake Bradford facility has undergone many changes over the years. Originally designed with Imhoff tanks, it switched to rock trickling filters, whose final clarifiers later became intermediate clarifiers when the plant was converted to a trickling filter/activated sludge process. The intermediate clarifiers were abandoned when the plant was converted to an activated sludge process.

For this metamorphosis, the project team chose a four-stage biological treatment process coupled with an immersed MBR, because the process had met advanced wastewater treatment limits at other Florida facilities, and retrofitting an MBR minimized new tank construction. If necessary, phosphorus will be chemically precipitated via alum addition upstream of the membrane tanks.

The team plans to convert the intermediate clarifiers into the first anoxic tanks and to convert the rectangular final clarifiers into second anoxic tanks. Meanwhile, the aeration tanks will receive minimal modifications (because their structural integrity is good). The team proposed adding a pump station between the aeration and first anoxic tanks to recycle enough flow for denitrification. The team also proposed adding another pump station and aboveground membrane filtration tanks after the second anoxic tanks. A new combined operations/blower building would house new process air blowers, positive-displacement blowers (for scouring air), and membrane permeate pumps. The permeate pumps would apply a slight vacuum to pull water through the membranes and transfer it to new chlorine contact tanks for final disinfection. Meanwhile, RAS would overflow the membrane filtration tanks, enter a flow-splitter box, and then be sent to the aeration tanks.

The configuration of a BNR/MBR process affects both nitrogen-removal efficiency and energy demand. Team members chose a process configuration that balanced pumping energy with the effects of recycle magnitude and location (air demands, nitrogen removal, and supplemental carbon). They chose a "pump to" configuration for RAS pumping to allow for an aboveground membrane tank and competitive bidding of membrane equipment.

The membrane tanks' RAS is saturated with oxygen due to scouring air. Sending it to the first anoxic tanks would minimize pumping but decrease nitrogen-removal potential or increase the need for external carbon supplements (by preferentially removing chemical oxygen demand from primary effluent). On the other hand, sending RAS to the

Table 1. Predicted Aeration Energy Consumption With and Without Primary Clarification

Parameter	Without primary clarification	With primary clarification	
		Current performance[a]	Typical performance[b]
Total actual oxygen demand [kg/d (lb/d)]	7152 (15,789)	4456 (9837)	5562 (12,278)
Total SOR required [kg/d (lb/d)]	19,380 (42,782)	12,074 (26,654)	15,072 (33,271)
Estimate of required bioreactor volume [m^3 (ft^3)][c]	4702 (166,043)	2555 (90,241)	3577 (126,337)
Required airflow rate [Nm^3/h (ft^3/min)][d]	10,575 (6151)	6588 (3832)	8225 (4784)
Total blower power [kW (hp)][e]	216 (289)	134 (180)	167 (224)
Annual power consumption (kWh)	1,886,000	1,175,000	1,466,000

[a] Based on historical performance and bench testing: 47% BOD and 15% TKN removal.

[b] Based on typical performance of primary clarifiers: 30% BOD and 7.5% TKN removal.

[c] MLSS concentration = 8000 mg/L, aerobic SRT = 12 days.

[d] Alpha = 0.50; spatial dissolved-oxygen concentration = 2.0 mg/L; AOR/SOR = 0.38.

[e] Blower efficiency = 70%, blower suction pressure = 99 kPa (14.4 lb/in.^{2}), blower discharge pressure = 157 kPa (22.8 lb/in.^{2}).

SOR = standard oxygenation rate.
BOD = biochemical oxygen demand.
TKN = total Kjeldahl nitrogen.
MLSS = mixed liquor suspended solids.
SRT = solids retention time.
AOR = actual oxygenation rate.

aeration tank would offset process air demands.

Modeling results indicated that RAS would contain about 6 mg/L of dissolved oxygen (DO). If the RAS flow rate is four times the facility's influent flow rate (68,100 m^3/d [18 mgd] under average day flows and 90,800 m^3/d [24 mgd] under maximum day flows), then about 410 kg/d (900 lb/d) of DO would be returned to the aeration tanks, or 540 kg/d (1200 lb/d) of DO would be returned to the first anoxic tanks. Modeling results also showed that effluent quality would be the same, but air and energy demands would be higher if RAS were sent to the first anoxic tanks.

MBR Aeration

Blower and diffuser selection. Aeration efficiency greatly affects the overall facility's power use, so the project team carefully selected the process air blowers and diffusers. Team members considered four types of process air blowers: positive-displacement, single-stage centrifugal, multistage centrifugal, and turbo with and without variable-speed drives. They conducted a present-worth analysis to select the most efficient type of blower. The team also considered two types of fine-pore diffusers: 230-mm (9-in.) ethlyene propylene diene membrane disc diffusers and 150-mm polyurethane strip diffusers.

The project team also carefully evaluated the effects of high MLSS concentrations on oxygen-transfer efficiency and the effects of reduced aeration tank volume on diffuser density.

Alpha. *Standard oxygen transfer* is a variable used to size aeration equipment (blowers and piping). Design engineers often calculate it using manufacturer-suggested standard oxygen-transfer rates for aeration equipment (diffusers) and apply correction factors, such as alpha (α), beta (β), and theta (θ), to account for the effects of various wastewater characteristics.

Setting a value for alpha is one of the more challenging aspects of designing aeration systems, because inaccurate alpha assumptions can result in a drastically under- or overdesigned system. It depends on such parameters as MLSS concentration, location in the aeration tank, and bubble size (type of diffuser). However, alpha does not seem to vary among different fine-bubble diffusers. Theoretically, a 10% variation in alpha results in an almost equal variation in oxygen-transfer efficiency and, thus, power consumption. In other words, a 10% higher alpha used in the design could predict lower air demand because of 10% higher oxygen-transfer efficiency, while the actual field transfer efficiency could be lower and cause an oxygen-deficient system that will affect nitrification.

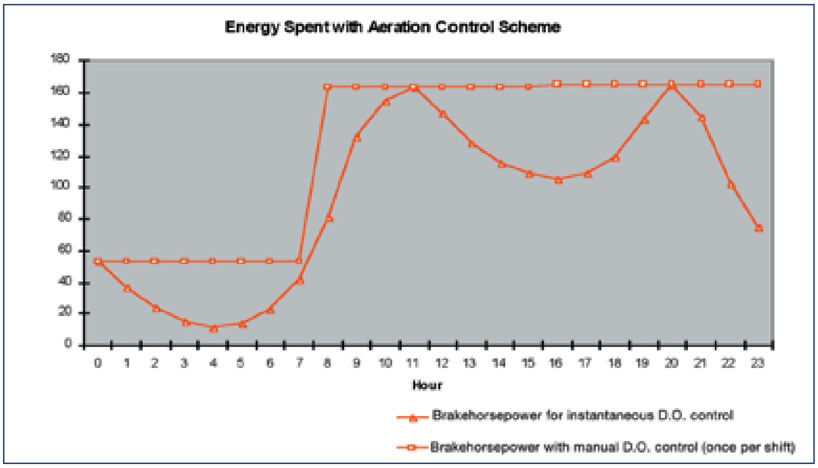
Oxygen-transfer efficiency. The project team compared two diffuser systems' energy consumption and found that as floor coverage increased, transfer efficiency increased and power cost dropped.

To estimate annual energy consumption, team members first needed a more accurate representation of the aeration system's operating conditions over a year. So, they created a yearlong schedule of five operating conditions based on a frequency analysis of daily peaking factors for oxygen demand during a 3-year period. Then, they asked blower manufacturers to provide the brake horsepower and overall wire-to-water efficiencies for each operating condition. They used this information to calculate the total wire power

Table 2. Summary of Bids for Membrane Systems

Parameter	Membrane A	Membrane B	Membrane C
Total membrane surface area [m^2 (ft^2)]	31,334 (348,160)	32,637 (362,632)	30,989 (344,320)
Total system average scour air [Nm^3/h (ft^3/min)]	11,966 (6960)	10,685 (6215)	10,806 (6285)
Scour air [$Nm^3/h/m^2$ ($ft^3/min/ft^2$) of membrane surface area]	0.38 (0.020)	0.33 (0.017)	0.35 (0.018)
Scour air daily effective operating hours	12	24	19
Average operating power for scour air (kW)	117.9	89.4	156.7
Annual power demand for scour air (kWh)	516,271	783,144	1,086,715
Average specific energy (kWh/1000 gal; scouring)	0.314	0.476	0.661
Filtrate/backpulse pumps	345,941	345,941	345,941
Membrane filtration feed pumps	967,712	967,712	967,712
Miscellaneous components	1000	1785	0
Total power consumption	1,830,924	2,098,582	2,400,368
Specific energy (kWh/1000 gal)	1.11	1.27	1.46

Diurnal Variation of Airflow and Blower Power Demand for Manual Versus Automated Air Control



demand (kW) and annual energy consumption.

Results showed that single-stage centrifugal blowers had the lowest net present worth, and turbo blowers had the highest (per the supplier's capital cost quotation). Turbo blowers are more efficient than other blower types. However, properly sizing blowers for an aeration system is critical, because blower efficiency is a function of blower output. Installing fewer, larger blowers could result in blowers that must operate outside their best efficiency zone for longer periods, thus making the overall system less energy-efficient.

There was little competition for small, single-stage blowers, however, so the project team selected rotary positive-displacement blowers with variable-frequency drives (which had the third-lowest net present worth). Constant-speed units would have made it more difficult to meet the nitrogen limit.

Airflow Control

Process-air control strategy. Facilities can optimize operations and improve energy efficiency via an automated control system. An effective control system is operator friendly, with on-line instruments that are inexpensive, reliable, and easy to maintain. The Water Environment Research Foundation (Alexandria, Va.) report *Online Nitrogen Monitoring and Control Strategies* (03-CTS-8) identifies five basic aeration-control strategies for nitrification. They are

- control based on DO;
- control based on ammonia;
- control based on both DO and ammonia (cascade loop);
- phase-length control (intermittent aeration); and
- control based on oxidation–reduction potential.

The most common control strategy involves a DO setpoint and manual or automatic adjustments of blower airflows. Effluent nitrogen levels are monitored to refine blower airflows as needed to increase or decrease DO.

The project team compared the aeration energy requirements for automated, real-time DO control versus manually adjusting airflow once every 8-hour shift (see figure, left). The team extrapolated typical hourly flow and load variations to determine diurnal variations in air demand.

The goals were to minimize both effluent nitrogen and energy demand. The project team evaluated two aeration-control strategies: DO-based control and cascade control based on both DO and ammonia setpoints. Both strategies require *in situ* or on-line instrumentation to monitor the control parameter(s). The cascade control method also involved two proportional-integral-derivative (PID) controllers arranged so Controller A managed ammonia concentrations, while Controller B used Controller A's output to manage DO levels. PID controllers are designed to correct the "error" between a variable's measurement and a desired setpoint by calculating and implementing appropriate corrective actions.

The Lake Bradford facility has three aeration tanks. Each will have an air header with a flow-control valve and a flowmeter. Each also will have four zones. The first and last will be swing zones (swing zones 1 and 2) so operators can vary aerobic and anoxic volumes in accordance with seasonal changes in flow, load, and temperature. The middle two zones (aeration zones 1 and 2) will be strictly aerobic. Luminescent DO probes will be installed in Aeration Zone 2 and Swing Zone 2, and inorganic nitrogen species (ammonium, nitrate, and nitrite) will be monitored in Swing Zone 2. The programmable logic controllers will give operators three airflow choices:

- *Aeration Zone 2 DO.* In this option, operators provide the DO setpoint, and then a reverse-acting PID controller will adjust airflow in response to shifts in DO concentrations in Aeration Zone 2.
- *Swing Zone 2 DO.* In this option, operators provide the DO setpoint, and then a reverse-acting PID controller will adjust airflow in response to shifts in DO concentrations in Swing Zone 2.
- *Swing Zone 2 ammonia control with Swing Zone 2 DO max.* In this option, operators provide the ammonia and maximum DO

Table 3. Predicted Effluent Quality and Aeration Demand Using Automatic Aeration Control, Using DO and Ammonia–Nitrogen Concentrations as the Control Parameters

Permit effluent total nitrogen limit = 3 mg/L							
Setpoint = DO in Aeration Zone 2				Setpoint = ammonia–nitrogen in Swing Zone 2			
DO setpoint (mg/L)	Effluent ammonia–nitrogen (mg/L)	Effluent total nitrogen (mg/L)	Air supply [Nm^3/h (ft^3/min)]	Ammonia–nitrogen setpoint (mg/L)	DO in aeration zone (mg/L)	Effluent total nitrogen (mg/L)	Air supply [Nm^3/h (ft^3/min)]
3.0	0.47	2.98	6708 (3902)	0.25	4.14	2.30	7745 (4505)
2.5	0.47	2.78	5830 (3391)	0.50	1.85	2.44	4166 (2423)
2.0	0.49	2.64	5101 (2967)	0.75	0.85	2.69	3353 (1950)
1.5	0.53	2.58	4489 (2611)	1.00	0.5	2.94	3095 (1800)
1.0	0.60	2.6	3958 (2302)	1.25	0.41	3.36	2923 (1700)
0.5	0.83	2.83	3389 (1971)				
0.25	1.53	3.61	2771 (1612)				

DO = dissolved oxygen.

setpoints, and a direct-acting PID controller will adjust airflow in response to the ammonia concentration in Swing Zone 2. The controller also will limit airflow based on a maximum DO concentration in Swing Zone 2.

The project team used a process simulation model to estimate the aeration energy demands under each control strategy. Results indicated that aeration control based on both DO and ammonia–nitrogen used excess energy to keep a higher-than-desired DO level in the aeration tank without exceeding the total nitrogen limit of 3 mg/L (see Table 3, above). Sometimes, extra capacity may be necessary to meet certain peak conditions, but it is more energy-efficient to control aeration during the rest of the time. This is possible with an automated control system.

Scouring-air control strategy. Both hollow-fiber and flat-plate MBRs use coarse-bubble aeration to scour the membranes to control fouling. Air-scouring systems may be constant or intermittent. For example, one manufacturer uses an intermittent aeration system in which airflow alternates among two or four sets of modules, so the membranes are aerated for either one-half or one-quarter of the time.

Air-scouring intensity significantly affects both membrane performance and energy demand, so design engineers should pay careful attention to the scouring system. Researchers have found that the existence and thickness of the cake layer on the membrane surface depend on air-scour intensity and MLSS concentration. Higher scouring rates are needed when MLSS and soluble microbial product concentrations are high; otherwise, a "thick" cake layer (with a higher transmembrane pressure) is more likely to form. To obtain a balance, researchers suggest a feed-forward control of air-scour intensity that is proportional to the facility's influent flow rate. In addition, researchers have suggested that flat-plate MBRs have higher air-scour demands than hollow-fiber MBRs.

Membrane filtration technology is still maturing. Rising energy costs and sustainability concerns certainly will prompt manufacturers to make their systems more energy-efficient in the future.

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At press time, the project had been put on hold indefinitely because of budget constraints.

Further Reading

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