# Wastewater Process Design with Energy Savings in Mind

*Sam Jeyanayagam and Ifetayo Venner*

*Sam Jeyanayagam, Ph.D., P.E., BCEE, is a senior associate in the Columbus, Ohio, office of the environmental engineering firm Malcolm Pirnie. Ifetayo Venner, P.E., is a process engineer in the firm's Tampa office.*

Energy costs represent a considerable portion of a treatment facility's annual operation and maintenance expenses, with the activated sludge process accounting for 50 to 60 percent of them. In the backdrop of escalating energy costs, a high energy use pattern is anticipated to strain operating budgets of wastewater treatment plants.

Threatened by this eventuality, many utilities are looking for opportunities for reducing energy use. This article reviews energy-saving strategies that could be implemented during the design and operation of an activated sludge process.

## Oxygen Demand and Credit

In nitrifying facilities, portions of influent organic and nitrogen compounds are oxidized. The associated oxygen requirements are called the carbonaceous biochemical oxygen demand (CBOD) and nitrogenous oxygen demand (NOD). Included in the CBOD are the oxidation of the influent substrate and endogenous decay.

If an anoxic zone is incorporated into the bioreactor for total nitrogen removal or improving sludge settleability, the resulting denitrification will provide an "oxygen credit." Depending on the extent of denitrification, it is possible to recover up to 63 percent of the oxygen consumed for ammonia oxidation.

The sources of oxygen demand and credit in an activated sludge process are summarized in Table 1. The net oxygen demand is expressed as follows:

**Net Oxygen Demand**
*= CBOD + NOD - Denitrification Credit*

## Net Oxygen Demand Distribution

Over-aeration represents an energy waste and may be minimized by better "matching" of air supply to the required oxygen demand.

Based on full-scale experience, a plug-flow aeration basin may be divided into equal zones and the net oxygen demand profile developed as outlined in Table 2. Denitrification credit is typically realized in the anoxic zone but is applied equally across all three zones of the aeration basins.

To meet the decreasing oxygen requirement along the length of the tank, air supply may be tapered by varying the number of diffusers in proportion to the net demand in the zone. If a uniform diffuser arrangement is used, droplet valves must be adjusted and the air pressure increased to achieve the desired oxygen distribution.

A tapered diffuser arrangement is the first step in providing oxygen where it is needed without increasing blower pressure, which represents higher aeration cost. Care should be exercised in designing tapered aeration systems to ensure that the reduced energy input provided at the end of a plug-flow basin to maintain low dissolved oxygen (DO) is sufficient for mixing.

## Factors Affecting Oxygen Demand

**Nitrification**. Some treatment plants are not required to nitrify, so unwanted nitrification is a significant source of energy waste. Typically, nitrification represents about 30 to 50 percent more oxygen than required for satisfying CBOD alone.

Unwanted nitrification can be minimized by lowering solids retention time (SRT). This can be accomplished by reducing aeration basin mixed liquid suspended solids (MLSS) concentration or by using fewer aeration tanks.

Nitrification may also be reduced by maintaining low mixed liquor DO, approximately 1 mg/L, since low DO conditions inhibit nitrifiers but not heterotrophs (BOD-removing organisms); however, this strategy could promote filamentous growth. The resulting poor settleability would require increased RAS pumping energy, as discussed later.

**Denitrification**. Part of the oxygen used during nitrification may be recovered by incorporating an anoxic zone at the beginning of the aeration tank for denitrifying the return activated sludge (RAS). Additional denitrification credit is achieved in a process

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**Table 1**
**Sources of Oxygen Demand and Credit**

| Process | Oxygen Demand | Oxygen Credit |
|---|---|---|
| Carbon Oxidation | | |
| Substrate Oxidation | X | |
| Endogenous Decay | X | |
| Nitrification (ammonia oxidation) | X | |
| Denitrification (nitrate reduction) | | X |
| Enhanced Biological Phosphorus Removal | No additional demand or credit | |

**Table 2**
**Spatial Distribution of Oxygen Demand and Credit**

| Process | Guideline | Aeration Zone Distribution (%) | | | Total (%) |
|---|---|---|---|---|---|
| | | Zone 1 | Zone 2 | Zone 2 | |
| Substrate Oxidation | 60% of CBOD or 0.7 lb $O_2$ per lb BOD removed | 66 | 33 | 0 | 100 |
| Endogenous Decay | 40% CBOD or 0.5 lb $O_2$ per lb BOD removed | 33 | 33 | 33 | 100 |
| Nitrification | 4.6 lb $O_2$ per lb Ammonia-N oxidized | 40 | 40 | 20 | 100 |
| Denitrification Credit* | 2.9 lb $O_2$ per lb Nitrate-N reduced | 33 | 33 | 33 | 100 |
| Approximate Zone Total, % of Basin Total | | 45 | 35 | 20 | |

*Only in nitrogen removal systems. Occurs in anoxic zone but applied equally across all zones

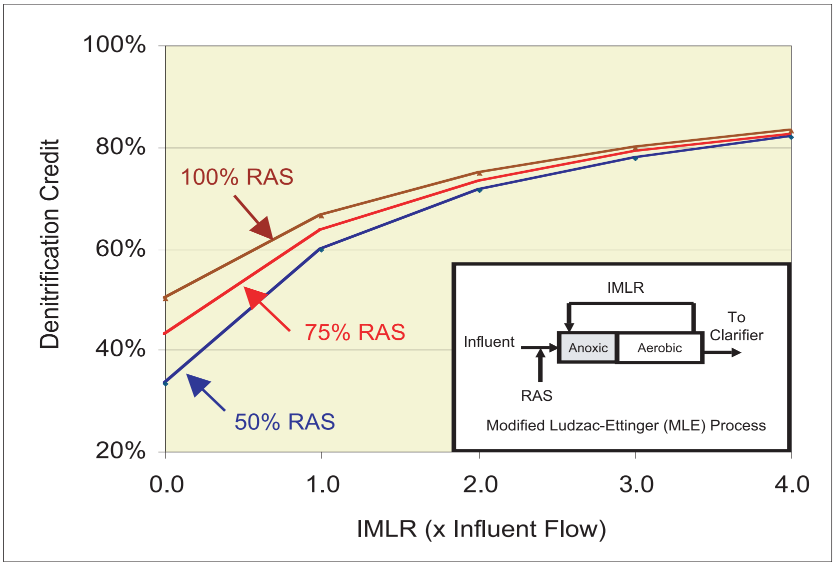

Figure 1: Effect of Recycle Flows on Denitrification Credit

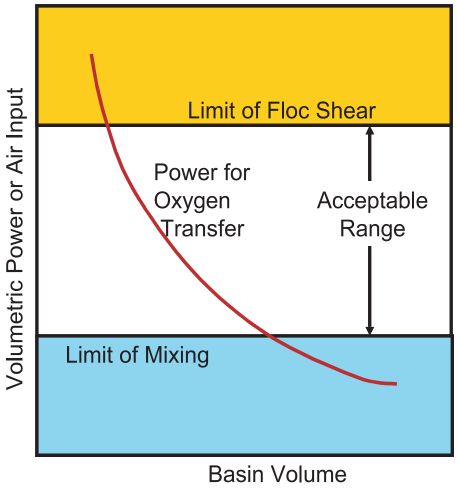

Figure 2: Limits of Volumetric Power/Air Input
Adopted from Grady *et al.*, 1999

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designed to achieve total nitrogen removal, such as the Modified Ludzack-Ettinger (MLE) process, where an internal mixed liquor recycle (IMLR) is used. A review of the impact of RAS and IMLR flows on the denitrification credit, shown in Figure 1, reveals the following:

- In a nitrifying activated sludge process with no internal recycle (IMLR=0), RAS denitrification is the only source of denitrification credit. For example, a 50-percent RAS flow would provide approximately 30 percent of the maximum available denitrification credit, while a 100-percent RAS rate would provide 50 percent denitrification credit.
- As the IMLR flow increases, the difference in the denitrification credits provided by the various RAS rates decreases.
- In theory, an IMLR rate of approximately three times Q (influent flow) provides approximately 80 percent of the denitrification credit. IMLR rates greater than 3Q to 4Q provide marginal increase in denitrification credit.

While IMLR provides increased aeration credit in nitrogen removal systems, it requires internal pumping, which represents an additional capital and energy cost.

**Solids Retention Time**. The solids retention time (SRT) dictates the extent of the fundamental processes that consume oxygen, which includes microbial growth and decay. For a specific wastewater, selecting a design SRT establishes the process oxygen requirement. Organic (CBOD) removal can be achieved at very low SRT values (two to four days).

Because nitrifiers grow more slowly than heterotrophs, nitrification requires longer SRTs. Once nitrification is initiated, the NOD will increase very rapidly with the increase in SRT. At very long SRTs, both CBOD and NOD increase marginally.

One significant oxygen demand is endogenous respiration, or cell decay, which is a characteristic of long SRT systems. At very high SRTs, the aeration basin begins to operate as an aerobic digester, and additional oxygen is required to support endogenous decay. Some facilities intentionally operate at very long SRTs in order to reduce sludge production to achieve lower overall operating cost. At these facilities, the resulting sludge disposal cost savings is greater than the increased cost of aeration to satisfy endogenous demand, but this will not always be the case.

Since shorter SRTs are generally associated with lower oxygen demand, effort should be made to operate the system at the minimum SRT required to meet effluent limits.

**Primary Treatment**. Enhancing primary treatment can reduce oxygen demand. Low-cost strategies for improving primary clarifier performance, such as flow balancing, baffles, and inlet energy dissipation, can result in increased CBOD removal with an associated decrease in aeration demand in the bioreactor; however, in biological nutrient removal plants, enhanced CBOD removal in the primary clarifiers may lower the denitrification and enhanced biological removal capabilities.

## Factors Affecting Oxygen Transfer

The driving force for oxygen transfer is the DO differential, which is the difference between the saturation DO (Csat) and mixed liquor DO (Cmlss):

Oxygen Transfer Efficiency a $(C_{sat} - C_{mlss})$

The saturation DO depends on wastewater temperature and mixed liquor DO. Due to reduced oxygen solubility, $C_{sat}$ values are lower in the summer, resulting in reduced DO differential (transfer efficiency) for a given $C_{mlss}$. For example, in order to maintain 2.0 mg/L DO, approximately 25 percent more air is required at 23°C than at 12°C.

At many facilities, the lack of automation or the practice of "safe" operation causes over-aeration. The resulting high $C_{mlss}$ lowers the DO differential, which causes lower oxygen transfer rates and increased energy use. For example, a system operating at a DO of 4.0 mg/L will require approximately 35 percent more air than a system operated at a DO of 2.0 mg/L.

A good DO control strategy can provide considerable energy savings, either manually or automatically. In manual DO control, operators measure basin DO levels and adjust air supply a few times a day. As a result, over/under-aeration can occur between manual sampling episodes. Less energy is wasted when air supply is automatically controlled to maintain a preset DO level in the aeration basin.

As noted earlier, a tapered diffuser arrangement is the first step in providing oxygen where it is needed without increasing blower pressure. A more refined strategy involves the use of motorized valves to independently control airflow to the different zones to maintain DO set points. The blower output is controlled based on a discharge pressure setpoint, which is the lowest pressure commensurate with the most-open valve position. On-line DO meters are typically used with this setup.

More sophisticated instrumentation,

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such as on-line nutrient analyzers, oxidation-reduction potential (ORP) probes, and nicotinamide adenine dinucleotide – reduced (NADH) probes, have also been used quite successfully for achieving tight DO control, particularly in nitrification/denitrification processes.

Air can be delivered to the aeration basin using surface aerators or diffusers. The amount of oxygen that can be transferred by a surface aerator is a function of its design as well as the operating conditions. On-site oxygen transfer tests and aerator power draw measurements would allow surface aerator oxygen transfer rates under actual operating conditions to be determined.

Diffused aeration systems are classified as fine (porous) or coarse (nonporous) bubble systems. Fine bubble diffusers produce bubbles in the range of two to five millimeters in diameter when new. The resulting high surface-area-to-volume ratio of the bubbles allows relatively high oxygen transfer efficiencies to be attained.

In contrast, coarse bubble diffusers produce significantly larger bubbles (six to 10 millimeters) and are associated with lower transfer efficiencies. Many facilities have realized significant energy cost savings by replacing coarse bubble diffusers with fine bubble devices.

Aeration basin configuration affects the “alpha” factor, which is a measure of oxygen mass transfer in wastewater relative to that in clean water. Increased alpha could result in energy savings. The oxygen transfer rate and alpha factor typically increase along the length of the aeration tank in plug-flow systems.

Activated sludge systems are often underloaded during initial years of use or during certain seasons. Consideration should be given to taking aeration basins off-line to minimize aeration costs, but process parameters such as food-to-microorganism (F:M) ratio, SRT, and hydraulic retention time should be checked to ensure that they are within the facility's recommended design range.

**Table 3**
**Limiting Values of Volumetric Power/Air Input for Activated Sludge Systems**

| Air Delivery System | Limit of Mixing | Limit of Shear |
|---|---|---|
| Diffused Aeration (Spiral Roll) | 2.7 scfm/$10^3$gal | 12.0 scfm/$10^3$gal |
| Diffused Aeration (Full floor) | 4.9 scfm/$10^3$gal | 12.0 scfm/$10^3$gal |
| Mechanical aeration | 0.53 hp/$10^3$ft$^3$ | 2.3 hp/$10^3$ft$^3$ |

Adopted from: Grady, C.P.L; G.T.Daigger; and H.C.Lim *Biological Wastewater Treatment*. 1999

## *Mixing Requirements*

The activated sludge is a suspended growth process, so sufficient power must be provided for mixing. The objective is to keep the solids in suspension without causing significant floc shear, which would impact settling.

In an activated sludge basin, in order to simplify operations and to minimize cost, the same equipment is used to keep the solids in suspension and to transfer the required oxygen. As stated before, the process oxygen requirement is determined by the SRT, as is the power needed to transfer this oxygen.

As shown in Figure 2 (Adopted from Grady et al. 1999), for a given SRT and oxygen transfer device, the volumetric power input (hp/1,000 ft$^3$ in mechanical aerators) or volumetric air input (m$^3$/min. 1,000 m$^3$ in diffused aeration) decreases with increasing basin volume. This value should not be so low as to cause the solids to settle (mixing limited) or so high as to cause the solids to shear (shearing limited). The approximate limiting values for an activated sludge system are provided in Table 3.

As illustrated in Figure 3, good engineering design is an iterative process involving the use of several interrelated factors in order to size the activated sludge basin to achieve optimum energy savings. Once the SRT has been selected and the necessary solids inventory determined, the size and cost of the activated sludge basin may be minimized by using the highest possible MLSS concentration. Doing so, however, will require the use of larger clarifiers at a higher cost, so the designer should consider an MLSS concentration that achieves a trade-off between the volume of the activated sludge basin and the size of the clarifier to minimize the total system cost.

The next step is to use the activated sludge basin volume to determine the volumetric power/air input. If the basin volume is too large, the volumetric power/air input may be less than the limit of mixing, so the power/air input will have to be increased beyond the input required for oxygen transfer in order to keep the solids in suspension—a waste of power. Conversely, if the basin volume is too small, the volumetric power/air input may exceed the limit of shear, causing floc breakup.

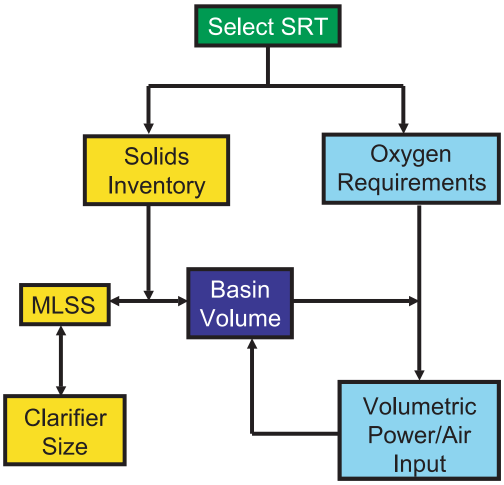

Figure 3: The Iterative Process Design Approach

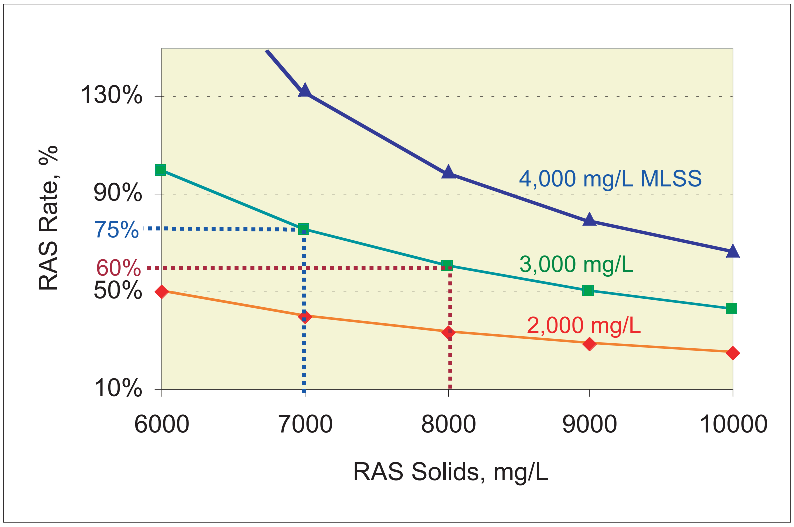

Figure 4: Impact of RAS Solids on RAS Pumping Rate

The designer should adjust the basin volume to ensure that the volumetric power/air input is within acceptable limits. This may require revising the MLSS concentration and clarifier size requirements.

Conventional activated sludge systems are typically not mixing limited. This means the energy required for oxygen transfer is less than that required for adequate mixing. On the other hand, extended aeration systems, which are operated at relatively long hydraulic retention times (around 24 hours HRT), utilize large basin volumes and are likely to be mixing limited. For this reason, oxidation ditches are designed as looped reactors with high mixed liquor recirculation rates to maintain a velocity of around one foot per second, which is sufficient to keep the solids in suspension. Such a design eliminates the need for additional energy input for mixing.

## Pump Selection & Operation

Pumping systems used in the activated sludge process can be designed with energy saving features. Some examples include:

- Proper sizing of pumps to operate at optimum efficiency over the operating range.
- Use of high efficiency motors.
- Use of variable speed drives.
- Correcting power factor to avoid utility penalties.

In addition, the following strategies specific to the application have energy-saving potential:

<u>RAS Pumps</u>: These are low-head, high-flow units that operate continuously at the required return rate. The RAS flow rate (percent of influent flow) can be calculated as follows using aeration basin MLSS (X) and the RAS solids concentration ($X_{ras}$):

$Q_{ras} = X/(X_{ras}-X)$

A plot of the above equation shown in Figure 4 reveals that the RAS pumping rate can be lowered by increasing $X_{ras}$. The RAS concentration that can be attained in a well designed clarifier is function of sludge settleability. For example, by increasing the RAS solids from 7,000 to 8,000 mg/L, a facility operating at 3,000 mg/L MLSS can reduce the RAS rate from 75 to 60 percent, which represents an approximate power savings of 20 percent, assuming no change in motor efficiency and headloss.

In order to achieve this goal, sludge settleability (or ability to compact) should be improved. Strategies that can use used to enhance sludge settleability include (i) avoiding operating conditions that favor excessive filament growth, such as low DO, low F:M, and long SRT; (ii) use of anoxic/anaerobic selectors; and (iii) use of chemicals such as RAS chlorination and polymer addition to final clarifiers.

These alternatives should be carefully assessed to ensure no other process impacts. For instance, reducing the SRT may compromise nitrification. Likewise, RAS chlorination, if not controlled, may inhibit nitrification and biological phosphorus removal.

It should be noted that increasing the sludge blanket to achieve higher RAS solids concentration is not recommended, since this approach can cause denitrification and secondary phosphorus release in final clarifiers. Operating at a high sludge blanket would also restrict the ability of the clarifier to accommodate increased solids loading during peak flow conditions, leading to potential biomass washout.

In the case of a multipass pass plug flow basin, conversion to a step-feed configuration would allow the same average MLSS to be maintained at lower RAS rates, achieving energy savings. For example, if a facility operating at 75 percent RAS rate and 3,000 mg/L MLSS (7,000 mg/L RAS solids) has the flexibility to be converted to a four-pass, step-feed configuration, it would be possible to reduce the RAS rate to 42 percent to achieve the target average MLSS of 3,000 mg/L. Again, it is important to ensure that this conversion would not impact nitrification.

<u>WAS Pumps</u>: Waste pumps are typically fixed-speed units that operate intermittently. Although the amount of sludge wasted daily is small (1 percent to 3 percent of influent flow), the wasting rate (gpm) is relatively high.

Energy-saving approaches includes eliminating WAS pumps and wasting from the RAS discharge line using timer-operated valves and operating pumps during off-peak hours. The operation of WAS pumps should be coordinated with the upstream activated sludge process requirements (SRT, MLSS, etc.) and downstream sludge operations.

<u>IMLR Pumps</u>: These pumps, used in nitrogen removal processes, are typically low-head, high-flow (100 percent to 400 percent of influent flow) pumps that operate continuously. Although variable-speed pumps provide greater process flexibility, two-speed units are adequate for many facilities. The use of IMLR pumps may be avoided by implementing a step-feed configuration with multiple anoxic zones.

## Equipment Maintenance

Performing preventive maintenance according to manufacturers' recommendations will enable equipment to function at optimum operating efficiency, realizing maximum energy savings. Examples of key maintenance tasks include:

- Cleaning and replacing air filters and diffusers routinely.
- Cleaning and calibrating on-line analyzers regularly.
- Servicing blowers, mixers, and pumps regularly.

## Conclusion

Achieving energy savings at a wastewater treatment plant is the responsibility of both the designer and the operator. Engineers should identify available energy-saving approaches during the design phase and collaborate with plant staff to evaluate and select the most appropriate strategies to implement. The operating staff's role is to use the features provided to maximize energy savings. ◊