Separate or Combined Sidestream Treatment: That is the Question

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In 2010, municipal wastewater treatment facilities consumed about 25 bil kWh of electricity. Individual facilities use anywhere from 1,000 to 4,000 kWh per mil gal (MG) treated, depending on the level of treatment and the overall efficiency of power use. This represents about 1.5 percent of the total power demand in the United States. About half of the power demand at a wastewater treatment facility is for aeration (10–20 kWh/population equivalent [p.e.]/yr). Further, nitrification constitutes about half the power required for aeration, with the actual fraction depending on the chemical oxygen demand/total Kjeldahl nitrogen (COD/TKN) ratio in the influent to the aeration tank. Thus, the need for nitrification consumes roughly 6 bil kWh per year. While up to 60 percent of this incremental demand can be offset by incorporating a high degree of denitrification into the treatment process, the remainder still represents a huge power demand. Implementation of new techniques for reducing the power requirement for nitrogen removal could significantly lower power demands at municipal wastewater treatment facilities.

While implementation of nitrogen removal at municipal wastewater treatment plants provides significant public health and environmental benefits, nitrogen removal processes also require more electrical power to operate and release more greenhouse gases than a comparable secondary treatment process. A standard Modified Ludzack-Ettinger (MLE) process in Florida using an oxidation ditch with aerobic holding or digestion of the waste sludge will consume about 3,000 kWh per mg of water recovered and release over 4.7 lbs of CO_2 per lb of nitrogen removed. By implementing more efficient aeration and anaerobic digestion, the power demand for this same MLE process can be reduced about 10 to 20 percent, not counting the energy that can be recovered from the biogas generated in the digestion process. Despite the attractiveness of anaerobic digestion from an energy perspective, the destruction of volatile solids during digestion releases significant amounts of nitrogen, which is typically recycled into the mainstream treatment process. This recycle load increases the process air, alkalinity, and carbon requirements for nitrogen removal in proportion to the mass of ammonia recycled.

The magnitude of nitrogen recycle loads from anaerobic digestion depends on the use of primary treatment, the importing of sludge from other facilities, the type of sludge stabilization employed, and the degree of volatile solids destruction achieved. Depending on the plant configuration and dewatering schedule, recycling of sidestream ammonia can result in diurnal spikes in effluent ammonia or total nitrogen (TN). Using a typical Florida wastewater treatment plant with conventional nitrogen removal and mesophilic anaerobic digestion as an example, ammonia recycle will typically be between 10 and 15 percent of the influent nitrogen load. However, with the addition of sludge from other facilities and the use of advanced digestion processes, the recycle load can approach 50 percent of the influent.

Overview of Nitrogen Cycle

Significant developments have occurred over the last ten to fifteen years that have improved the understanding of the nitrogen cycle and opened new opportunities for managing high ammonia sidestreams. One of the most significant advancements in the understanding of the biology of nitrogen transformations is the discovery of a group of microorganisms in the phylum Planctomycetes; these have become better known as anammox bacteria (Anaerobic Ammonia Oxidation). Anammox bacteria are autotrophic organisms capable of converting a mixture of ammonia and nitrite directly to nitrogen gas.

It is now recognized that previously known organisms can transform nitrogen by multiple metabolic pathways, more microorganisms are significantly involved in nitrogen transformations, and the interactions among groups of bacteria are more complex. The following is a brief summary of the three main approaches to using conventional and innovative biology for nitrification and denitrification of sidestreams:

1. *Conventional Nitrification and Denitrification* – Conventional biological nitrogen removal is a multistep process in which a combination of autotrophic and heterotrophic bacteria sequentially converts ammonia to nitrogen gas according to the following equations:
   a. Ammonia is oxidized to nitrite (NO_2^-) by ammonia oxidizing bacteria (AOBs):
   $NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + H_2O + 2\ H^+$
   b. Nitrite is converted to nitrate by nitrite oxidizing bacteria (NOBs):
   $NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$
   c. Nitrate is converted to nitrogen gas by ordinary heterotrophic bacteria (OHOs)
   $6NO_3^- + 5CH_3OH \rightarrow 3N_2 + 5\ CO_2 + 7H_2O + 6OH^-$

   According to these equations for conventional biological nitrogen removal processes, the need to remove ammonia affects oxygen demand and alkalinity. In addition, the relatively slow growth rate of nitrifiers AOBs and NOBs increases the required sludge inventory, but has relatively little effect on sludge production, aside from the decreased yield associated with longer sludge retention time (SRT). Denitrification imposes additional requirements on biological nutrient removal (BNR) processes, including the need to control dissolved oxygen (DO) input, and for additional anoxic sludge inventory and sufficient carbon relative to the nitrogen to be reduced.

   The stoichiometric oxygen requirement for conventional nitrification is $1.5 \cdot 32/14 = 3.43$ mg O_2/mg N for ammonia oxidation and $0.5 \cdot 32/14 = 1.14$ mg O_2/mg N for nitrite oxidation. The first reaction consumes alkalinity. The required COD:N ratio for denitrification is 2.86. Including sludge production, the required COD:N ratio is about 4, depending on the carbon source.
2. *Shortcut Nitrification and Denitrification* – Researchers at the Technical University of Delft discovered that the conventional nitrification process could be stopped halfway; that is, after the formation of nitrite. They gave this first application of partial nitrification (or nitritation) the name Sharon (Single reactor system for High Ammonium Re-

Continued on page 54

Continued from page 52

moval Over Nitrite). Stopping the nitrification reaction at a nitrite endpoint has also become known as shortcut nitrification denitrification (or shortcut NDN) since it bypasses or shortcuts the creation of nitrate. The comparable equations for shortcut NDN are as follows:

d. *Nitritation*:
$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2\ H_2O + 2\ H^+$

e. *Denitritation*:
$NO_2^- + 0.5\ CH_3OH^- \rightarrow 0.5\ N_2 + 0.5\ CO_2 + 0.5\ H_2O + OH^-$

The COD:N ratio is 1.72 for denitritation. Including sludge production, the required COD:N ratio is 2.4 (Mulder et al., 2006), depending on the carbon source, as compared to about 4 for conventional denitrification. Oxygen demand is reduced 25 percent and carbon demand is reduced 40 percent with shortcut NDN as compared to the conventional approach.

3. *Partial Nitritation and Anammox* – Since anammox bacteria require about a 50:50 mix of ammonia and nitrite, it is necessary to do nitritation in combination with anammox. Only about one-half of the ammonia needs to be converted to nitrite to create the right mix of feed.

f. *Nitritation*:
$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2\ H_2O + 2\ H^+$

g. *Anammox*:
$NH_4^+ + NO_2^- \rightarrow N_2 + 2\ H_2O$

h. *Combined Sharon - Anammox*
$NH_4^+ + 0.75\ O_2 + HCO3^- \rightarrow 0.5\ NH_4^+ + 0.5\ NO_2^- + CO_2 + 1.5\ H_2O$

The anammox reaction is autotrophic and has low biomass yield (0.11-0.13 g VSS/g NH_4^+-N), but produces small amounts of NO_3^- (according to the molar ratio $NO3/NH_4^+ = 0.26$). Overall nitrogen removal in the combined (partial nitritation-anammox) process requires less oxygen (1.9 kg O_2/kg N instead of 4.6 kg O_2/kg N), has no carbon source (instead of 2.4 – 4 kg COD/kg N), has low sludge production (0.08 instead of approximately 1 kg VSS/kg N), and reduces CO_2 emission by more than 100 percent because the combined process uses less power and consumes CO_2.

Oxygen requirements, carbon demands, and alkalinity requirements resulting from use of these main groups of biological processes are summarized in Table 1.

Separate Methods of Sidestream Treatment

A variety of treatment processes have been developed using both conventional and innovative biological concepts to treat high ammonia recycle streams. These sidestream treatment processes can be grouped according to the feed streams sent to the sidestream reactor. One group of processes keeps the sidestream separate and treats the sidestream by itself. The other group combines all or a portion of the return activated sludge (RAS) with the sidestream. Mixing RAS and the sidestream allows the use of some biological reactions (conventional, shortcut NDN, and bioaugmentation) and precludes others (anammox at this time).

All but one of the separate methods relies on some sort of biomass retention to develop sufficient biomass for treatment. The exception is the Sharon process, which uses one or two completely mixed stirred tank reactors without recycle (chemostats). By operating at a low hydraulic retention time (HRT), elevated temperature, and high ammonia concentration that results in the washout of NOBs, the Sharon process operates to a nitrite endpoint. With the Sharon process, the nitrites are typically removed by denitrification with methanol. Anammox bacteria grow much slower than nitrifiers, and their natural tendency to form relatively large granules with slightly greater density compared to normal activated sludge provides the basis for retaining these bacteria in the treatment process.

Most separate sidestream treatment processes are well suited for using partial nitritation—anammox. However, two of the separate sidestream processes, short solids retention time (SRT) and Sharon, are not applicable for partial nitritation–anammox. The short SRT process, also known as InNitri™, is a sidestream-nitrifying activated sludge process with an aeration tank and clarifier, where waste sludge from the sidestream process is used to seed the mainstream process. There are no full-scale applications of the InNitri™ process.

Understanding of the characteristics of anammox bacteria and the development of methods for using them for nitrogen removal has evolved over time through research done by numerous groups. Unfortunately, this has resulted in a large number of names and patents for essentially the same biology implemented in different reactor configurations with different control methods. A glossary of terms associated with sidestream treatment is provided at the end of this article.

Current commercially available anammox systems for sidestream treatment include two sequencing batch reactor (SBR) processes, an upflow granular bed process, and a moving bed biofilm reactor (MBBR) process. Depending on the specific process, biomass retention is provided by gravity settling, cyclones, granular sludge, or a fixed film on MBBR media. The SBR processes use pH and DO control to maintain environmental conditions for the anammox bacteria. The MBBR process relies on the biofilm and control of the DO at low concentrations to wash the NOBs out of the process. Unlike the SBR/cyclone process, the MBBR process measures NH_4, NO_2, and NO3, and then uses the ratios of NO_2/NH_4 and NO_3/NH_4 to control aeration. Media fills are typically up to about 50 percent. The long startup times required for the first anammox processes are now avoided by seeding the reactors from other operating systems. The design volumetric loading rate for the MBBR process is about 1 kg N/m³/d. The granular sludge process can be loaded more heavily, up to

Table 1. Comparison of Biological Processes for Nitrogen Removal
(from Jetten et al., 2002 & Ahn, 2006)

Characteristic	Conventional nitrification / denitrification	Nitritation/ denitritation (Sharon)	Partial nitritation (50%) and anammox
Oxygen requirement (g O_2/g N)	4.57 / 0	3.43 / 0	1.71 / 0
% O_2 saving	-	24.9%	62.6%
Alkalinity consumption (g $CaCO_3$/g N)	7.07 / -3.57	7.07 / -3.57	3.57 / 0.24
Carbon requirement (g COD/g N)	3.7	2.3	0
Percent reduction in carbon required	-	37.8%	100%
Main bacteria	Nitrifiers (AOB, NOB) / OHOs	AOB / OHOs	AOB / anammox

about 2 kg N/m³/d, but is reported to be less stable at the higher loading rates. Anammox reactions are inherently limited to a maximum ammonia removal of about 90 percent; however, they are capable of operating consistently at close to this limit.

The advantages of the separate sidestream methods include the ability to use shortcut NDN and anammox bacteria, and to take advantage of the warm temperature and high ammonia concentration to operate at high biological reaction rates. Since the effluent is typically recycled to the mainstream process, higher ammonia concentration reactor effluent is acceptable and enables higher reaction rates.

The main advantages to the separate sidestream treatment process using anammox are their low energy requirement and their ability to denitrify without carbon. Without the addition of an external carbon source, sludge production is lower. As mentioned, the reactor configurations vary, but all use proven rector designs. The main disadvantages of anammox processes are the slow growth rate of anammox bacteria, and the need to inhibit or wash NOBs out of the process. The slow growth rate of anammox bacteria requires seeding for reasonably quick startups, but there are now enough of the systems in existence so that obtaining seed sludge is feasible.

As a result of the need to prevent the growth of NOBs, and to limit the buildup of nitrite concentrations, the process operating requirements are more complex, but the systems are readily automated. While the elevated temperatures of sidestreams are conducive to higher biological reaction rates, the sidestream reactor temperature must be controlled within the range of about 30–40°C. Depending on the situation, this may require heating or cooling of the sidestream. Elevated concentrations of suspended solids in the sidestream can be detrimental to the performance of some separate processes, and possibly require pretreatment. Foaming has been reported at several separate sidestream treatment facilities, and scaling of the media in one MBBR reactor was a problem.

Combined Methods of Sidestream Treatment

The combined sidestream processes are known by many names, including bioaugmentation regeneration (BAR); Aeration Tank No.3 (AT-3), named after work at the New York City 26th Ward Water Pollution Control Plant (WPCP); bioaugmentation batch enhanced (BABE); mainstream autotrophic recycle enabling enhanced N-removal (MAUREEN); and centrate and RAS reaeration basin (CaRRB). The common feature to this group of processes is the mixing of a high ammonia sidestream with RAS in a sidestream reactor, resulting in subsequent return of the sidestream to the main process. The use of RAS adds alkalinity, lowers temperature, and increases the biomass concentration in the sidestream reactor.

While conventional microbial processes do not provide the reduction in oxygen and carbon demands of shortcut NDN and anammox, when used in sidestream reactors they can provide substantial overall facility benefits. These include:

- Bioaugmentation of the mainstream process with nitrifiers resulting in a reduction in the aerobic SRT needed to maintain nitrification, along with elimination of the sudden washout of nitrifiers that can occur under wintertime conditions.
- Increased biomass inventory providing greater overall process stability and reduced effluent nitrogen, while enabling reduced solids loading to secondary clarifiers.
- Reduced carbon requirements and improved mainstream denitrification if denitrification is provided in the sidestream process.
- Ability to increase anoxic volume, at the expense of aerobic volume, to increase denitrification capacity in an existing plant.
- Reduced mixed liquor recycle rates if nitrite or nitrate is returned to a pre-aeration anoxic zone in the mainstream process.
- Potential to inhibit NOBs, thereby combining bioaugmentation with shortcut NDN.

Case Studies

Robert W. Hite Treatment Facility, Denver (CaRRB)

The Metro Wastewater Reclamation District (MWRD) in Denver operates the 220-mgd Robert W. Hite Treatment Facility (Facility), which includes two separate primary and secondary complexes that are served by a common sludge complex, with mesophilic anaerobic digestion and centrifuge dewatering. In 2004, MWRD began planning improvements at the Facility to comply with tighter limits on ammonia, NOx, and phosphorus. The initial strategy in the north secondary complex was based on the addition of two new aeration basins and secondary clarifiers to supplement the existing 12 aeration basins and secondary clarifiers. As an alternative approach, the concept of combined sidestream treatment was evaluated and selected for implementation. The concept envisioned the construction of common CaRRBs instead of two new aeration basins and secondary clarifiers.

Because bioaugmentation reduces the required SRT for nitrification in the mainstream process, the same nitrification performance can be maintained at lower bioreactor MLSS concentrations. This results in lower solids concentrations entering the secondary clarifiers, subsequently increasing clarification capacity. The original improvements strategy would have required two aeration basins with a combined volume of 4.1 MG and two 130-ft diameter secondary clarifiers. The CaRRB approach yielded approximately 20 percent more capacity than the original strategy with the construction of only 2.7 MG of centrate reaeration basins and without any new secondary clarifiers. This increased capacity resulted in a reduction in anticipated capital cost of approximately $17 million when compared to the original strategy.

Combined sidestream treatment also allowed a reduction in the required mixed liquor return (MLR) pumping rate. Due to nitrification of centrate occurring in CaRRB, a significant amount of nitrate is generated and returned to the anoxic zones in the mainstream aeration basins. At MWRD, the CaRRB process generates approximately 6,000 to 8,000 ppd of nitrate as N that is fed to mainstream anoxic zones. This is equivalent to 70 to 100 mgd of MLR, or a reduction of 6 to 8 mgd per aeration basin. This allowed installation of smaller pumps and provides an energy cost savings of approximately $80,000 per year.

Using combined sidestream treatment afforded several important advantages over the original improvements strategy, including increased capacity and performance at a lower cost, reduction in required mixed liquor return pumping, and improved denitrification. The CaRRB process has been in service since August 2009 and performance has exceeded expectations and confirmed the benefits offered by this process. Based on this success, CaRRB is being incorporated into the upgrades to the south secondary complex now under construction.

26th Ward Water Pollution Control Plant, New York City (Aeration Tank 3)

Starting in 1992, as part of its program to eliminate the ocean disposal of sludge, New York City implemented a centralized sludge dewatering scheme where anaerobically digested sludge from the City's 14 WPCPs are pumped or barged to eight centralized dewatering facilities. As a result, the nitrogen loads on the WPCPs that host the centralized dewatering facilities are increased by 30-50 percent from the increased centrate that is returned to the mainstream treatment processes. As centrate was identified as a significant source of nitrogen to the WPCPs, the City undertook investigations to find a feasible treatment method.

Continued on page 56

Continued from page 55

The New York City Department of Environmental Protection (DEP) investigations into centrate treatment began at the City's 26th Ward WPCP, which has a central dewatering facility that receives sludge from up to four other WPCPs. This 85-mgd WPCP, located in Brooklyn and discharging to Jamaica Bay, uses a high-rate, four-pass step-feed-activated sludge process to treat average flows of about 70 mgd. Three step-feed tanks, each with a volume of 5 MG, provide aeration. Primary clarifier effluent is added to Passes B, C, and D of the step-feed aeration tanks, while RAS is added to Pass A. Anoxic zones are present at the beginning of Passes A, B, and C. After experimenting with several configurations, the DEP settled on a combined sidestream treatment process in which AT-3 was dedicated to centrate treatment. All of the centrate (about 1.3 mgd) is sent to AT-3, along with about 0.5-1.0 mgd of RAS (out of 10-15 mgd). The centrate averages about 750 mg/L ammonia with a soluble COD of 270 mg/L, a temperature of 28°C, pH values of 8.3-8.5, and an alkalinity of 2,200 mg/L as $CaCO_3$. The effluent from AT-3 is returned to the RAS channel whereby it enters Pass A of the other two aeration tanks.

The AT-3 combined sidestream treatment process has proven to be very effective, and has provided significant benefits to the City. Bioaugmentation of the mainstream, high-rate, step-feed BNR process (2-3 day SRT) at wintertime temperatures as low as 12°C, allows stable year-round nitrogen removal with lower effluent TN concentrations. A calibrated process simulation model, based on extensive kinetic testing (Ramalingam, 2007), predicts that use of the AT-3 process is lowering the effluent TN during the winter from 16 mg/L to 11 mg/L, and model predictions are in line with current performance. In addition, the combination of high ammonia concentrations and high pH in the centrate tank combined with low DO concentrations in Pass A provides shortcut nitrification (inhibition of NOBs), resulted in a large reduction in process air requirements, and a reduction in carbon requirements in the step-feed BNR, which enhances denitrification. Estimates are that process airflow has been reduced from about 24,000 scfm to 16,000 scfm by using the AT-3 process.

Sjölunda WWTP, Malmo, Sweden (ANITA™ Mox)

The Sjölunda Wastewater Treatment Plant provides wastewater treatment for Malmo, Sweden's third largest city, and surrounding areas. With a design capacity of 550,000 p.e. (about 50 mgd), the plant currently treats about 37 mgd, on average. The plant uses a combination of primary clarifiers with ferrous sulfate addition for phosphorus removal, high-rate activated sludge (3-day SRT) with pre-anoxic zones, nitrifying trickling filters, and denitrifying MBBRs to meet effluent target concentrations of 0.3 mg/L total phosphorous (TP), on a monthly average, and 10 mg/L TN (annual average). Sludge treatment is provided by anaerobic digestion with centrifuge dewatering. The centrifuges operate about 50 percent of the time. When the plant was last upgraded in 1999 to provide nitrogen removal, an equalization tank and a SBR (0.5 mgal) with NaOH addition were added to remove about 1,500 lbs NH_4^-N/d from the centrate and lessen the ammonia load on the nitrifying trickling filters. The centrate nitrogen load is approximately 20 percent of the influent nitrogen load. The centrate flow at Sjölunda averages about 172,000 gal/day, with a mean ammonia concentration of 855 mg/L, a mean soluble COD concentration of 257 mg/L, and a mean total suspended solids concentration of 350 mg/L.

Beginning in August 2010, a new MBBR-based, separate sidestream treatment process, named ANITA™Mox, started operation at Sjölunda. The new system treats about 30 percent of the centrate flow (the design N load equals 440 lb N/d), while the remainder is treated by the existing SBR. The full-scale ANITA™ Mox plant consists of four13,200-gal reactors with three different types of MBBR media (one with BiofilmChip M, two with K3, and one with AnoxK5), with media fills of about 50 percent. The specific surface areas for the three types of media are 500 m^2/m^3, 800 m^2/m^3, and 1200 m^2/m^3 respectively. Continuous aeration is provided by coarse bubble diffusers. DO is controlled to 0.5–1.5 mg/L. Neither temperature nor pH is controlled with pH, varying from 6.7-8.1, while reactor temperatures range from 22–33°C. The system supplier, Veolia, has used this facility to demonstrate its BioFarm concept where media, with established anammox biomass, is used to seed and startup new facilities. Effluent typically contains about 100 mg/L of NH_4 and NO_3, and about 1 mg/L NO_2. The design volumetric loading rate for the ANITA™ Mox process is about 1 kg $N/m^3/d$ and the Sjölunda facility has operated successfully at loadings up to 1.25 kg N/m3/d. The ANITA™ Mox process consumes about 1.4–1.7 kWh/kg N removed. Studies on N2O generation in the MBBR and the SBR process suggest that the MBBR produces less N2O—about 0.75 percent of the TN removed versus about 4.1 percent of the TN removed for the SBR process.

In summary, the new, separate sidestream treatment process removes nitrogen, while using less power without carbon addition, pH, or temperature control and producing less N_2O than the parallel SBR process, which only provides nitrification.

Strass Wastewater Treatment Plant, Strass im Zillertal, Austria (Demon)

The Achental-Inntal-Zillertal Wastewater Board owns and operates the Strass Wastewater Treatment Plant located in Strass im Zillertal (Tirol) Austria. The Strass plant is noted because it has achieved energy self-sufficiency—producing more power than it consumes. Strass is also where the pH controlled DEamMONification (Demon) separate sidestream treatment process was developed and first implemented.

The Demon process has been in operation at Strass since 2004, and currently treats about 440–550 lb/d of nitrogen with maximum influent loads about 900 lb/d. The distinguishing characteristics of the Demon process are 1) pH control, 2) use of cyclones to retain anammox granules in the process, and 3) use of a SBR reactor configuration. No chemicals are added to the Demon process. The Demon is operated as an SBR with four cycles per day. The process is controlled within a very narrow pH band around 7.1. When the pH exceeds 7.1, the air is turned on, and when the pH drops below pH 7.09, the air is turned off.

The Strass plant was commissioned in 1989 to provide wastewater service to the population of three valleys in Austria: the Achental, the Inntal, and the Zillertal. The plant discharges to the Isar River, one of the main tributaries of the Danube. The current ammonia limit is ≤ 5 mg N/L, and ≤ 10 mg/L during peak flows. Typical effluent nitrogen concentrations are 4 mg/L NH_3, 5-12 mg/L NO_3, and 2 mg/L NO_2. The plant achieves 50-60 percent removal of TN in winter, and 80-90 percent removal of TN in the summer. The plant adds sodium aluminate to remove phosphorus. Effluent total phosphorus (TP) concentrations are typically about 0.5 mg/L.

The treatment plant uses an A-B process as the mainstream treatment process. The A stage has a hydraulic retention time of about 15-20 minutes and a SRT of about 0.5 days. The A stage provides about 50 percent removal of BOD_5, and no more than 10-15 percent removal of TKN. Two A-stage aeration tanks were constructed; however, the plant only uses one. The B stage uses a MLE-type process implemented in an oxidation ditch configuration consisting of four rectangular looped reactors, with each pair operating with anoxic and aerobic zones. There is mixed liquor recycle using submersible pumps with a maximum capacity of about 100 percent of design flow.

The plant has two egg-shaped digesters, and is able to produce about 1.8 ft^3 of biogas per p.e. per day. The waste sludge from the A and B stages; internal grease; external fats, oils, and grease (FOG); and external food waste are mixed and then fed to the anaerobic digesters. It is estimated that the plant receives about 3,300 yd^3/year in food waste, and about 1,300 yd^3/year in grease. The digesters operate with an HRT of about 40 days in summer, but only 15 days in winter due to the high tourist loads. The digested sludge is thickened and then dewatered with a plate and frame press to a solids concentration of about 30 percent.

The Demon process was implemented in the second, unused A-stage aeration tank. The ammonia concentration in the Demon feed (filtrate) varies seasonally between 1,600–2,000 mg/L. Filtrate COD concentration varies between 500–1,500 mg/L. Typical effluent from the Demon process consists of 10–100 mg/L NH_3-N, 30–100 mg/L NO_3-N, <2 mg/L NO_2-N, and 300 mg/L COD, with a maximum of 500 mg/L. Operating the Demon process at the Strass plant requires 0.5–1.0 hours per day of labor.

In 2010, the plant generated about 10,900 kWh/d from biogas, which is about 160 percent of the power required to run the plant. Implementation of the Demon process at the Strass plant reduced overall plant power demand by about 8.5 to 12 percent. Overall energy demand at the Strass plant, per unit mass of nitrogen removed, has decreased over time:

- 6 kWh/kg N when operated as a conventional nitrification/denitrification process.
- ~3 kWh/kg N with sidestream nitrogen removal provided by nitritation-denitritation.
- 1.2 kWh/kg N with the current Demon process (nitritation/anammox).

Summary

General guidelines have been published (van Loosdrecht, 2006) on factors to consider when evaluating the potential for implementing sidestream treatment. Depending on site-specific conditions, in particular, the limiting aspects of the treatment process, either a separate or a combined process may be most beneficial. When nitrification or denitrification is limiting in the mainstream process, combined treatment (bioaugmentation) may provide the most benefit, as was demonstrated at both the Facility in Denver and the 26th Ward WPCP in New York. Separate treatment would be indicated if mainstream aeration capacity or carbon is limiting, or to reduce air or energy use, as was demonstrated at the Strass plant.

Whether separate or combined sidestream treatment is best is a question that cannot be

Continued on page 58

Continued from page 57

answered in general, but must be answered for individual facilities. A variety of separate and combined sidestream treatment technologies have been developed and successfully implemented at full-scale municipal wastewater treatment plants. When appropriate circumstances exist, they offer a strong set of tools for reducing the cost of treatment and optimizing nitrogen removal in BNR processes.

A Glossary of Terms for Sidestream Treatment (some appear in the article)

AOBs	ammonia oxidizing bacteria
AOA	ammonia oxidizing archaea
Anammox	anaerobic ammonium oxidation; oxidation of ammonium to nitrogen gas under anoxic conditions with nitrite as the electron acceptor; also a single-stage nitritation-anammox process using granular sludge.
bioaugmentation	seeding of a mainstream process with AOBs/NOBs grown in a sidestream reactor; also known as AT-3, BABE, BAR, CaRRB, and MAUREEN
deammonification	aerobic/anoxic process for autotrophic nitrogen removal where about one-half of the NH_4 is oxidized to NO_2 and the remainder of the ammonia is converted together with the NO_2 to nitrogen gas; also known as DEMON, CANON, OLAND, SNAP, and DIB
denitrification	anoxic process in which nitrite and nitrate are reduced to gaseous nitrogen oxides (nitric oxide (NO), nitrous oxide (N_2O) and free nitrogen (N_2)
denitritation	reduction of nitrite to nitrogen gas
nitrification	aerobic, sequential oxidation of ammonia to nitrite, and nitrite to nitrate
nitritation	aerobic oxidation of ammonia to nitrite; also known as SHARON or shortcut nitrification
NOBs	nitrite oxidizing bacteria

Combined (Bioaugmentation) Processes

AT-3	sidestream treatment process; named after NYC 26th Ward WPCP
BABE	bioaugmentation batch enhanced process
BAR	bioaugmentation regeneration process
CaRRB	centrate and RAS reaeration process
MAUREEN	mainstream autotrophic recycle enabling enhanced N-removal

Separate (Shortcut Nitrification) Processes

Sharon	single reactor for high ammonia removal over nitrite

Separate (Nitritation-Anammox) Processes

Anammox™	nitritation-anammox process using a single-stage granular sludge bioreactor
ANITA™ Mox	nitritation-anammox process using a single-stage MBBR bioreactor
CANON	complete autotrophic nitrogen removal over nitrite
DIB	deammonification in interval-aerated biofilm system
DeAmmon	a nitritation-anammox process using a single-stage MBBR bioreactor
DEMON	pH controlled DEamMONification
OLAND	oxygen-limited autotrophic nitrification-denitrification
SNAP	single-stage nitrogen removal using the anammox and partial nitritation

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