Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

MONITORING AND RESEARCH DEPARTMENT

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SHORTCUT BIOLOGICAL NITROGEN REMOVAL METHODOLOGIES: MAINSTREAM PARTIAL NITRITATION/DEAMMONIFICATION AND NITRITATION/DENITRITATION:

A LITERATURE REVIEW

September 2014

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SHORTCUT BIOLOGICAL NITROGEN REMOVAL METHODOLOGIES: MAINSTREAM PARTIAL NITRITATION/DEAMMONIFICATION AND NITRITATION/DENITRITATION:

A LITERATURE REVIEW

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DISCLAIMER

Mention of proprietary equipment and chemicals in this report does not constitute endorsement by the Metropolitan Water Reclamation District of Greater Chicago.

INTRODUCTION

In 2012, the District initiated a strategic plan to achieve energy neutrality in ten years' time. As such, two mainstream shortcut biological nitrogen (N) removal (SCBNR) strategies, partial nitritation/deammonification and nitritation/denitritation, were selected for evaluation as part of this initiative due to their energy savings with respect to N removal in the mainstream process. The benefits of SCBNR through nitritation/denitritation by suppressing the growth of nitrite-oxidizing bacteria (NOB) have long been known (Turk and Mavinic, 1986) for cost-effective biological N removal (BNR). The discovery of the deammonification process by Mulder et al. (1995) and later identification of ANAMMOX bacteria by Strous et al. (1999), which are capable of transforming ammonium to N gas with nitrite (NO_2), has made SCBNR through partial nitritation/deammonification by the suppression of NOB even more attractive. Partial denitritation/deammonification, which relies on ammonia (NH_3) oxidizing bacteria (AOB) to partially convert NH_3 to NO_2 and ANAMMOX bacteria to convert the remaining NH_3 and NO_2 to N gas (N_2), has emerged as an innovative and efficient SCBNR alternative. Partial denitritation/deammonification has successfully been implemented in over 50 sidestream treatment facilities (Neethling et al., 2012). The District will have its first sidestream partial nitritation/deammonification moving bed biofilm reactor (MBBR) system, ANITA™ Mox, online at the Egan WRP in 2014.

Following the success of sidestream shortcut N removal systems, there has been great interest in mainstream application. Table 1 lists all bench-, pilot- and full-scale implementations of mainstream partial nitritation/deammonification and nitritation/denitritation identified during our literature review. These implementations have thus far provided promising results to support the concept of mainstream nitritation/denitritation and/or partial nitritation/deammonification. According to the Interim Annual Report from the Water Environmental Research Federation (WERF) under Project INFR6R11 funded by the United States Environmental Protection Agency (USEPA) through Assistance Agreement No. 83419205, mainstream deammonification is a promising new treatment concept that has the potential to revolutionize the way in which BNR is achieved at wastewater treatment facilities. Its success represents a paradigm shift for the industry, offering the opportunity for sustainable wastewater treatment, energy-neutral or even energy-positive facilities, and dramatic reductions in treatment costs, which has widespread environmental, economic, and societal benefits. It should be noted that though the report uses the term mainstream "deammonification," it actually refers to both partial denitritation/deammonification and nitritation/denitritation as discussed in this literature review. For existing mainstream systems, the microorganisms for nitritation/denitritation and partial nitritation/deammonification are often found to coexist (Stinson et al., 2013, and Cao et al., 2013).

The WERF study and the experiences of other researchers around the world have provided a clearer understanding of the fundamental issues discussed herein that must be overcome to apply and ultimately optimize mainstream partial nitritation/deammonification and nitritation/denitritation. Various solutions and mitigation approaches to those issues have been developed, but all focus on operating strategies to achieve and improve upon four process objectives: (1) growth and retention of AOB; (2) growth and retention of a robust ANAMMOX population; (3) suppression or management of the ordinary heterotrophic organism (OHO) population; and (4) suppression of the NOB population. Objective 4 is the most critical and challenging step,

TABLE 1: MAINSTREAM PARTIAL NITRITATION/DEAMMONIFICATION AND NITRITATION/DENITRITATION PILOT- AND FULL-SCALE APPLICATIONS*

Facility or Researcher	Strategies Utilized	Location	Year	Scale
Blue Plains AWTP	Intermittent aeration + sidestream bioaugmentation for deammonification.	Washington, DC	2010	Pilot Scale
Strass WWTP	Carousel type aeration tank provide a DO-range of 0.00 – 0.55 mg/L along the flow path + Bioaugmentation from side stream + cyclone for ANAMMOX retention for deammonification.	Austria	2011–present	Full-Scale Demonstration
Glarnerland WWTP	HRAS + Cyclone for ANAMMOX retention for deammonification.	Switzerland	2012–present	Full-Scale Demonstration
Chesapeake-Elizabeth Treatment Plant	HRAS + Suspended Growth using Nitritation/ Denitritation using AVN control + Biofilm ANAMMOX Polishing	Hampton Road Sanitation District, Virginia	2012–present	Pilot Scale
Changqi WRP	Nitritation/Denitritation and Partial Nitritation/ deammonification by step-feed BNR operation.	Singapore	2011–2013	Full Scale – 211 MGD
Veolia Water	CEPT and MBBR with sidestream bioaugmentation for deammonification	Paris, France	Started in Nov, 2013	Pilot Scale
Veolia Water	Primary + HRAS + IFAS with sidestream bioaugmentation for deammonification	Sweden	Started in Aug, 2013	Pilot Scale
Veolia Water	UASB+ HRAS + MBBR with sidestream bioaugmentation for deammonification	Emirates, Middle East	Started in June, 2013	Pilot Scale

TABLE 1 (Continued): MAINSTREAM PARTIAL NITRITATION/DEAMMONIFICATION AND NITRITATION/ DENITRITATION PILOT- AND FULL-SCALE APPLICATIONS*

Facility or Researcher	Strategies Utilized	Location	Year	Scale
Beijing University of Technology	Nitritation/Denitritation using SBR	Beijing, China	2012	Pilot scale
LabMet	Nitritation/Denitritation using RBC	Ghent Univ, Belgium	2012	Pilot scale
Delft Technical University/ Paqus/WSHD	1-stage granular ANAMMOX for deammonification	Netherlands	NA	Pilot scale
Biofilter	Laboratory-scale single-step N removal biological filter with oxygen supply control	Inha Univ, Korea & Stanford Univ, USA et al.	2012	Bench scale

*Information from this table covered both pilot and full scale implementations identified during literature review (see References).
Note: AVN = Ammonia vs. NOx control.
BNR = Biological nutrient removal.
CEPT = Chemically enhanced primary treatment.
DO = Dissolved oxygen.
HRAS = High-rate activated sludge process.
IFAS = Integrated fixed-film activated sludge.
MBBR = Moving-bed biofilm reactor.
RBC = Rotating biological contactor.
SBR = Sequencing batch reactor.
UASB = Upflow anaerobic sludge blanket reactor.
WSHD = Hollandse Delta Water Board.
NA = Not applicable.

because the low effluent NH_3-N concentration requirements, low operating temperatures, and higher influent carbon:nitrogen (C:N) ratio often observed in mainstream processes are not well suited for suppression of NOB.

In light of this, the Monitoring and Research (M&R) Department initiated this SCBNR study to understand how these two SCBNR methodologies can best be applied to the District's facilities and tie into our future enhanced biological phosphorus (P) removal (EBPR) processes. This literature review includes:

1. Background, including the fundamentals of the two SCBNR methodologies, key process considerations, and challenges.

2. Strategies or recipes developed based on the two SCBNR methodologies for successful mainstream implementation.

3. Existing successful SCBNR processes and implementations.

4. The District's challenges and options of implementing SCBNR.

5. Summary and future steps.

BACKGROUND

There are three common methodologies for total N (TN) removal in wastewater treatment. Figure 1 illustrates the fundamentals of these methodologies: traditional nitrification/denitrification, nitritation/denitritation, and partial nitritation/deammonification. Conventional NH_3 removal from wastewater through nitrification (NH_3 converted to NO_2, then to nitrate [NO_3]) and denitrification (NO_3 converted to NO_2, then to N_2) is a proven and stable technology. However, the process is costly, owing to the use of alkalinity and extensive aeration energy for the nitrification process for NH_3 removal, and often external C needs for the denitrification process. Moving from nitrification/denitrification to the other two SCBNR methodologies offers many benefits in terms of C requirement reduction, energy requirements, and greenhouse gas emissions (Stinson et al., 2013; Kartal et al., 2010; Peng et al., 2006).

Nitritation/denitritation is the two-step N removal pathway where all NH_3 is first oxidized by AOB to NO_2 under aerobic conditions (nitritation), then NO_2 is denitrified by heterotrophic bacteria to N_2 under anoxic conditions (denitritation); the NO_2 must be converted to N_2 due to the instability of NO_2.

The fundamentals of partial nitritation/deammonification refers to the two-step N removal pathway where only about half of the NH_3 is oxidized by AOB to NO_2 in a first step (partial nitritation), then the autotrophic bacteria, ANAMMOX, uses the NO_2 generated from the first step and oxidizes the remaining NH_3 under anaerobic conditions to N_2 (deammonification).

The key process considerations to facilitate these two SCBNR methodologies are explained in Figure 1, and can be summarized as follows:

1. Growth and retention of a robust AOB population for both methodologies.

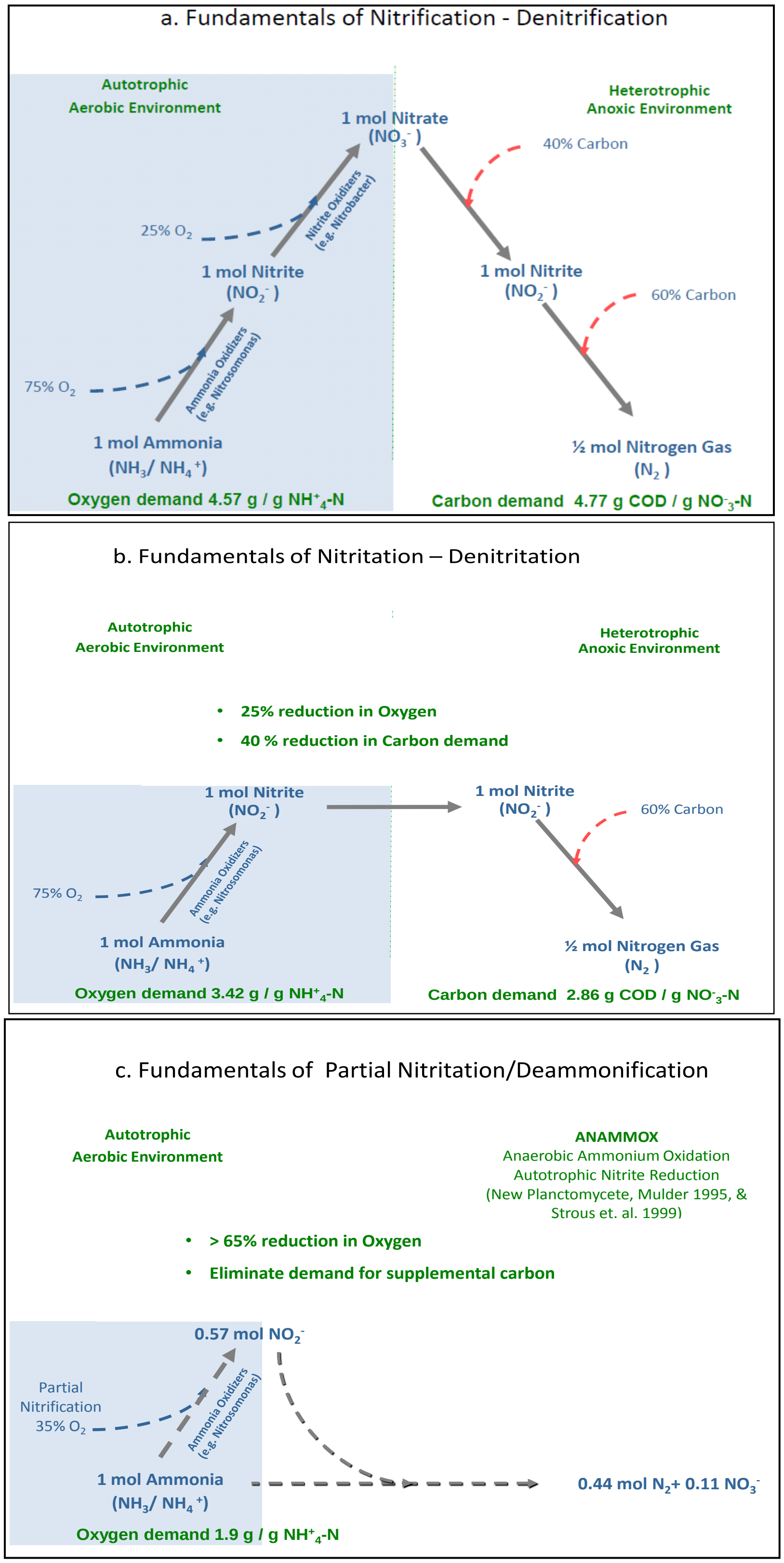
2. Suppression of the NOB population for both methodologies.

3. Growth and retention of a robust ANAMMOX population for the deammonification process.

4. Suppression or management of the OHO population. OHO growth should be suppressed if the second step targets deammonification, but should be maintained and managed if denitritation is the second step.

It should be emphasized that the first step of both methodologies is nitritation, although less oxygen is needed for partial nitritation/deammonification. It is the second step conversion of NO_2 to N_2 where the methodologies diverge. Controlling the growth of OHO depending on whether there is available C for OHO in the system could shift the process from nitritation/denitritation to partial nitritation/deammonification; the latter could achieve more energy savings, but relies on the availability and activity of ANAMMOX and carbon. In reality, these two N removal processes often occur simultaneously in any mainstream system. The challenge for both processes is preventing the NOB from converting the NO_2 to NO_3. Mitigating the growth and

FIGURE 1: FUNDAMENTALS OF THREE BIOLOGICAL NITROGEN REMOVAL APPROACHES (FIGURES COURTESY OF STINSON WATER ENVIRONMENT RESEARCH FOUNDATION PROJECT INFR6R11)



activity of the NOB has indeed become the greatest challenge in reliably accomplishing either of these processes.

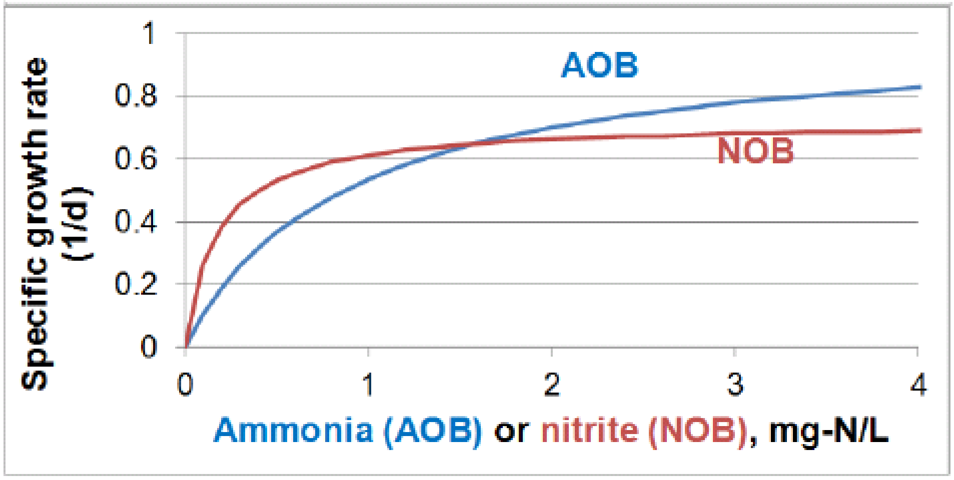
While deammonification for N removal pathway has been successfully implemented in sidestream systems, it is challenging in mainstream systems for the following reasons:

1. Lower N concentrations in mainstream wastewater. Influent N concentrations are in the range of 20 to 75 mg/L (Metcalf & Eddy 2003) vs. sidestream concentrations which are often on the order of 800 to 3,000 mg/L (Stinson et al., 2013). Furthermore, the required effluent NH_3-N concentrations are generally lower in mainstream than sidestream. The challenge here is therefore twofold: (1) lack of inhibition pressure on the NOBs due to the presence of free NH_3, which contributes significantly to the success of the sidestream system, and (2) reduced relative competitiveness of the AOBs to outcompete the NOBs at the low effluent NH_3-N concentrations. As the concentration of NH_4-N drops below 2 mg/L, the growth rate of the AOB declines relative to that of the NOB for similar NH_4-N and NO_2-N concentrations as indicated in Figure 2 (Stinson et al., 2013). It may be very difficult to get to very low effluent NH_4-N concentrations in a typical system due to this limitation without a subsequent polishing step. Higher dissolved oxygen (DO) concentration can help compensate for the low AOB growth rate but may also serve to enhance the growth of the NOB and thus can be counterproductive.

2. Lower operating temperatures. Many wastewater treatment plants (WWTPs) operate at wastewater temperatures in the range of 10° to 15°C in winter compared to sidestream systems that operate at relatively high temperatures in the range of 32 to 38°C (Stinson et al., 2013). The challenge is the slower growth rate of AOBs at low temperatures relative to NOBs. There have been several studies on the growth rates of the various organisms (Hellinga et al., 1998; Vazquez-Padin et al., 2011; Winkler et al., 2011), but few have studied the combined effect of sustained low temperature and low N concentration. According to De Clipperlier et al. (2012), as the temperature drops below about 15°C, the growth rate of the NOB begins to exceed the growth rate of the AOB and so it is difficult to outcompete the NOB and maintain an acceptable AOB/NOB balance even through the use of aggressive sludge retention time (SRT) control alone.

3. Higher C:N ratios. The influent C:N ratio is important in shifting the N removal between the pathway of nitritation/denitritation and partial nitritation/deammonification. The challenge here is to manage the growth of the OHO that will compete with the AOB for oxygen under aerobic conditions and with the ANAMMOX for the NO_2 under anoxic conditions. Furthermore, the OHO will also compete with the AOB for organic substrate, as it is now understood that certain AOB can denitrify using organic acids (Stinson et al., 2013). Reducing the influent C:N ratio therefore is important in shifting the N removal between the pathways of denitritation and deammonification and even conventional denitrification if NO_3 is present.

FIGURE 2: SPECIFIC GROWTH RATES OF AMMONIA-OXIDIZING BACTERIA AND NITRITE-OXIDIZING BACTERIA AT LOW AMMONIA AND NITRITE CONCENTRATIONS, RESPECTIVELY (STINSON ET AL., 2013)



STRATEGIES FOR SUCCESSFUL MAINSTREAM PARTIAL NITRITATION/ DEAMMONIFICATION AND NITRITATION/DENITRITATION

Through bench- and pilot-scale research and full scale demonstrations done around the world, a recipe for successful mainstream SCBNR has emerged based on the processes/ challenges identified and is summarized below:

Growth and Retention of a Robust Ammonia-Oxidizing Bacteria Population

Growth and retention of AOB is the first important step for both SCBNR technologies. This could be achieved by:

1. Bioaugmentation from a sidestream system. Full scale demonstration at Strass (Wett et al., 2012) has confirmed that AOB in the mainstream can successfully be bioaugmented from a sidestream system where the conditions of high ammonium load and warmer temperature favor the growth of AOB over NOB. This strategy can be particularly helpful at low mainstream operating temperatures below 15°C and can maintain the competitive advantage of the AOB over NOB at these lower operating temperatures.

2. Growth and retention of AOB in a biofilm. The use of MBBRs, rotating biological contactors (RBCs), or a dense granular sludge has been proven successful even at lower temperatures (De Clippelier et al., 2013). Several previous and ongoing studies found that the diffusion rate through the biofilm of electron donors/acceptors such as ammonium, nitrite and DO from the bulk liquid to the organisms can be effectively used to outcompete the NOB while AOB and ANAMMOX can thrive in a symbiotic environment (Stinson et al., 2013).

Growth and Retention of a Robust ANAMMOX Population

Successful mainstream deammonification must retain the slow–growing ANAMMOX bacteria in the system. Two methods are generally used.

1. Bioaugmentation from the sidestream system. While the growth rate of ANAMMOX organisms is slow, especially at lower temperatures, they are resilient. Sidestream bioaugmentation of ANAMMOX has been successfully demonstrated at the full scale level at Strass (Wett et al., 2012) and is recommended to accelerate the startup of a new system and to maintain activity through colder seasons. The ANAMMOX bioaugmentation helped maintain ANAMMOX activity in the system. The bioaugmentation efficiency was found to be sensitive to the seeded reactor operating temperature. Wett et al. (2010) suggested that the temperature sensitivity was reduced when the

difference in temperature between the sidestream seed source and mainstream, was minimized.

2. ANAMMOX retention. Another way to retain the ANAMMOX in the system is to decouple the ANAMMOX SRT from the nitrifier/heterotroph sludge SRT by selectively wasting the light floc sludge but keeping ANAMMOX. The ANAMMOX demonstrate a propensity to develop in larger denser granules than the typical AOB, NOB and OHO flocs. This facilitates the selective retention of ANAMMOX. Several technologies have been used successfully to decouple the two sludges (Stinson et al., 2013): (a) Hydro cyclone – demonstrated at full scale at Strass and Glarnerland WWTPS; (b) Sieve/fine screen based technologies – under evaluation at Blue Plains AWTP; (c) Granular Sludge – studied by Delft University of Technology, Royal Haskoning DHV, and the Dutch Foundation for Applied Water Research; (d) MBBR Media – pilot testing at Hampton Road Sanitary District (HRSD) and Veolia Water; (e) Integrated Fixed-Film Activated Sludge (IFAS) Media – under evaluation by Veolia Water; (f) RBC biofilms – Ghent University; (g) Membrane – under evaluation by American Water.

Suppression or Management of Ordinary Heterotrophic Organism Populations

As discussed earlier, controlling the growth of OHO could shift the process from nitritation/denitritation to partial nitritation/deammonification; the latter could achieve more energy savings. This can be accomplished by removing biodegradable organic C. The influent COD:N ratio is a key factor in pressing the system move toward deammonification by limiting the available C for OHO denitrification. Reducing the influent C has successfully been accomplished with the use of either chemical enhanced primary treatment (CEPT) or high-rate activated sludge (HRAS) processes (Stinson et al., 2013). Wastewater characteristics will play a key role in determining which processes are optimal for each plant. While colloidal material can be thoroughly removed with CEPT, the truly soluble C will not be removed. Blue Plains WWTP removes as much as 60 percent of the organics via CEPT with good colloidal enmeshment/capture. A HRAS system has great potential to capture both colloidal and particulate organics and can also take up, store, or assimilate some of the soluble COD. The Strass HRAS system captures between 55 to 75 percent of influent organics through enmeshment, colloidal bioflocculation, and uptake/storage of some of the soluble COD. Adding the HRAS or CEPT process will also provide opportunity to capture and divert more influent C to the anaerobic digesters to generate methane gas for energy recovery.

Suppression of Nitrite-Oxidizing Bacteria Populations

This is the most challenging step in accomplishing either partial nitritation/deammonification or nitritation/denitritation. The activity of NOB must be effectively suppressed without reducing the activity of AOB. Numerous studies have been done to investigate methods for suppression or washout of NOB, including free NH_3 and nitrous acid inhibition, low DO, and the combination of high temperatures and low SRT. While these methods have been employed to varying degrees of success, they are generally not suited for treating low temperature, low N mainstream municipal wastewaters. Several mechanisms have been evaluated that help to wash out, outcompete, or inhibit NOB in the mainstream and are summarized below:

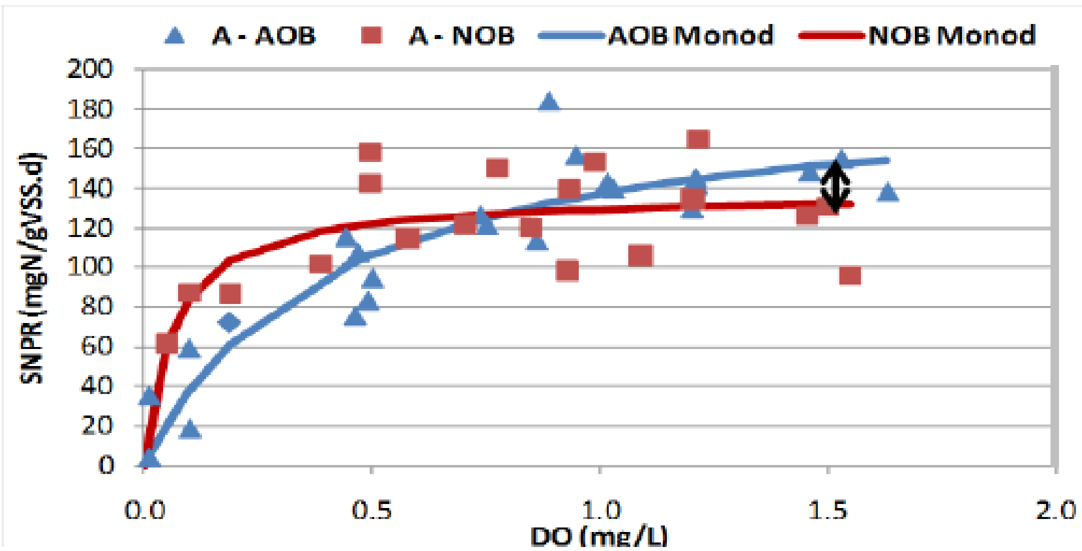
1. Aggressive short SRT operation to wash out the NOB. This strategy is effective at warmer temperatures, generally above 17°C (Stinson et al., 2013) because the AOB growth rate is higher than the NOB growth rate at this temperature regime.

2. Maximize the growth rate for the AOB. While operating at short SRTs, the growth rate of the AOB should be maximized at high DO in the aerobic zones and a high residual NH_4-N concentration > 2 mg/L.

3. Transient anoxia has emerged as being one of the most effective mechanisms by which to suppress NOB growth (Al-Omari et al., 2012; Kornaros et al., 2010). Turk and Mavinic (1986) demonstrated that when transitioning from anoxic to aerobic conditions, NOB experienced a metabolic lag of several hours behind AOB. Research by Pollice et al. (2002) supports this theory. They found that while SRT control can be used to suppress NOB at higher temperatures in a continuously aerated sequencing batch reactor (SBR), operating with a 10 minute on/10 minute off aeration pattern was successful at suppressing NOB regardless of SRT (Pollice, Tandoi, and Lestingi, 2002). Peng et al. (2004) have also used intermittent aeration to successfully suppress NOB in an SBR. The experimental work reported on by Omari et al. (2012) indicates that the DO has to fluctuate between a high DO (> 2 mg/L) and then reduce rapidly to anoxic. Figure 3 shows a comparison of specific N processing rates for both AOB and NOB at different DO levels from the work at Blue Plains which has subsequently been confirmed by work at HRSD and Strass.

4. Use of nitric oxide (NO) is also an interesting concept if an effective mechanism could be developed. NO is quite toxic to most bacteria (Mancinelli and McKay, 1983) and highly inhibitory to NOB even at very low concentrations. NO, however, is an intermediate product for AOB metabolism, and high NO concentrations do not detrimentally impact their activity (Kartal et al., 2010). Therefore, in conditions of high NO concentrations, AOB could have a competitive advantage over NOB. It has been shown, however, that it is a reversible inhibition and that as the NO concentrations decline, NOB activity can increase again (Starkenburg et al., 2008). Another concern with facilitating NO occurrence is NO emission.

FIGURE 3: NITROGEN PROCESSING RATE FOR AMMONIA-OXIDIZING BACTERIA AND NITRITE-OXIDIZING BACTERIA AS OBSERVED AT BLUE PLAINS AND CONSISTENT WITH DATA REPORTED BY STRASS AND HAMPTON ROAD SANITARY DISTRICT (STINSON ET AL., 2013)



PARTIAL NITRITATION/DEAMMONIFICATION AND/OR NITRITATION/ DENITRITATION – CURRENT IMPLEMENTATION

Numerous processes are emerging to support partial nitritation/deammonification and/or nitritation/denitritation implementation in the mainstream around the world and are summarized below based on the above approaches.

Deammonification with Bioaugmentation of ANAMMOX Organisms

This concept is being tested at pilot scale and demonstrated at full scale (WERF, 2012). The pilot-scale work is being conducted at Blue Plains WWTP, in Washington D.C. (with a target TN limit of 3 mg/L). This pilot scale work led to the development and implementation of two full-scale demonstrations at the Strass WWTP in Austria and the Glarnerland WWTPs in Switzerland. Both the pilot- and full-scale work have provided promising results to support the concept of mainstream deammonification. The bench-scale testing was conducted in two phases, the first operating at temperature of 15°C and the second at 25°C. The evaluation was conducted in two 10-L sequencing batch reactors (SBRs). Both SBRs were operated at 4 cycles per day (6 hours per cycle) initially, but were increased to 6 cycles per day (4 hours per cycle). Each cycle included: fill phase (7 minutes), react-aeration phase (4 hours for 4 cycle operation and 2 hours for 6 cycle operation), react-post anoxic phase (35 minutes for 4 cycle operation and 40 minutes for 6 cycle operation), re-aeration phase (5 minutes), settle/decant phase (75 minutes for 4 cycle operation and 70 minutes for 6 cycle operation), and idle phase (5 minutes) as detailed in Figure 4. SBR A was operated in continuous aeration mode in the react-aeration phase with constant low DO concentrations (target DO was reduced systematically from 0.1 mg/L to as low as 0.03 mg/L). SBR B operated in intermittent aeration mode for transient anoxia during the react-aeration phase with various aeration/non-aeration intervals (20 min/10 min, 4 min/2 min, 2 min/4 min, 2 min/6 min) and with target DO levels varying from 0.06 – 0.3 mg/L during aeration. Both reactors were bioaugmented with ANAMMOX sludge on a weekly basis using the sludge from the Strass WWTP (20-30 mL/week). The ammonia in the feed was adjusted daily to a target of 20 mg/L concentration. The effluent ammonia concentration was not discussed. The performance profiles in both SBRs showed that constant low DO operation was less effective in repressing the NOB when compared to intermittent aeration control.

Full scale trials at the Strass and Glarnerland WWTPs were conducted to evaluate the feasibility of ANAMMOX enrichment in the mainstream. This was achieved by seeding active biomass from a sidestream SBR (Demon process) to the mainstream, and by retaining the ANAMMOX biomass in the mainstream system using a cyclone system. Two different approaches were used to transfer seed from the sidestream to the mainstream: (1) the waste sludge of the sidestream DEMON was pumped to the mainstream system to bioaugment as much biomass as possible during every SBR cycle; and (2) periodic seeding of mixed liquor to transfer a defined mass of ANAMMOX granules (see attached Figure 5 for seeding schedule). The process at the Strass WWTP was intermittently aerated for NOB suppression and controlled using an online NH_4-N signal at the effluent of the tank with a DO range of 0.00 to 0.55 mg/L along the flow path. The total SRT varied between 5 and 20 days throughout the year. The aerobic SRT was difficult to quantify. In general, aerobic SRT was about 50 percent of total

FIGURE 4: SEQUENCING BATCH REACTOR CYCLE FOR THE MAINSTREAM DEAMMONIFICATON BENCH SCALE PILOT TEST DONE AT THE BLUE PLAINS WASTEWATER TREATMENT PLANT (WATER ENVIRONMENT RESEARCH FOUNDATION, 2012)

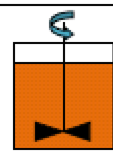
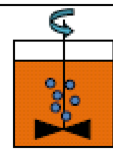
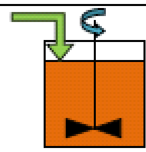
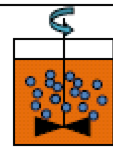
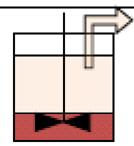
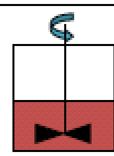
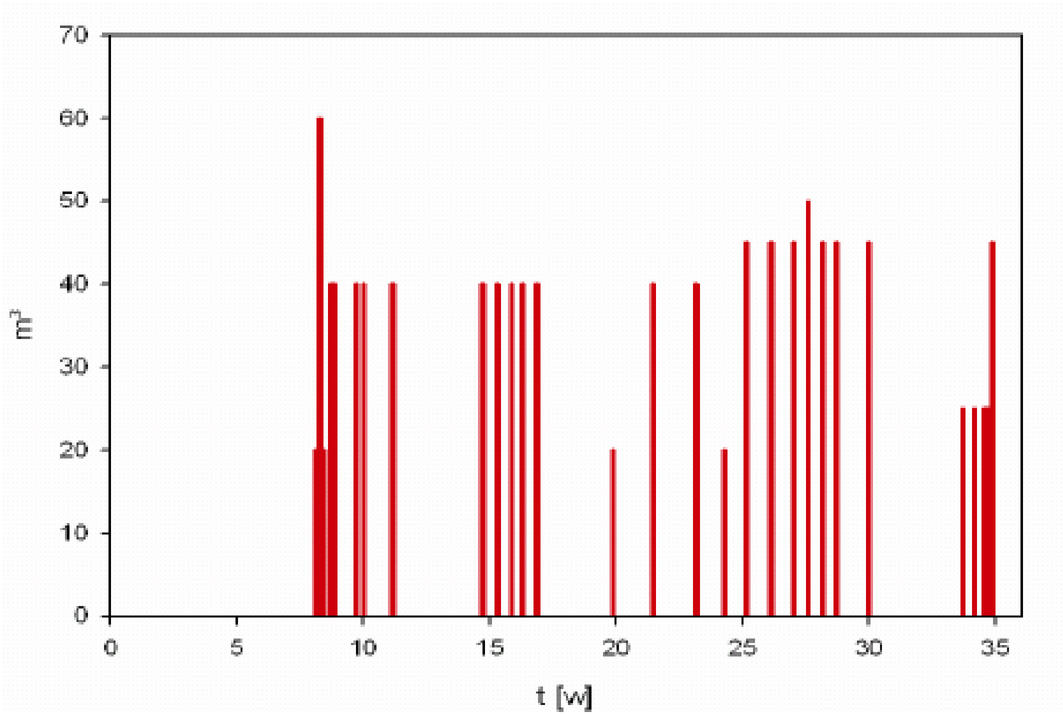
Phase	Duration	Reactor Condition	Action
Fill	7 min		Mixer is on. Reactor Volume is at maximum level. Reactor A is filled with 5.25L. Reactor B is filled with 3.5L.
React – aeration	4-cycle -4 hrs 6-cycle – 2 hrs		Mixer is on. Air is controlled.
React – post anoxic	4-cycle - 35 min 6-cycle – 40 min		Mixer is on. Air is off. Carbon substrate is added.
Re-aeration	5 min		Mixer is on. Air is on.
Settle/Decant	4-cycle - 75 min 6-cycle – 70 min		Mixer is off. Air is off. Decant pump is on.
Idle	5 min		Mixer is on. Reactor Volume is at minimum level.
Total Cycle Time	4-cycle - 6 hr 6-cycle – 4 hr		

FIGURE 5: SEEDING VOLUMES FROM THE SIDESTREAM DEMON TO MAINSTREAM (CUBIC METERS PER DAY) SEQUENCING BATCH REACTOR CYCLE FOR PILOT TEST DONE AT THE BLUE PLAINS WASTEWATER TREATMENT PLANT (WATER ENVIRONMENT RESEARCH FOUNDATION, 2012)



*The sidestream system where the seed comes from is a Demon SBR tank with a maximum volume of 500 m^3 and loading rate up to 450 kg of ammonia nitrogen per day. The mainstream system is the Strass WWTP B stage Carousel type aeration tank (capacity is not indicated from the source documentation).

SRT during low ammonia loading season and reached up to 100 percent of total SRT during high ammonia loading season. One of the crucial goals for this test is the suppression of NOB, which is indicated by increasing nitrite levels. During the Strass WWTP piloting period, the average nitrate level of approximately 2 mg/L (varied between 1 – 5 mg/L) were observed. Approximately 25 percent of ammonia oxidation produced nitrate while the majority portion, 75 percent, was converted via nitritation/denitritation. Effluent NH_4-N concentrations of approximately 2.0 – 3.0 mg/L were observed (ammonia spiked to around 4-8 mg/L during the pilot test, but reasons were not given).

The key findings from both pilot scale and full scale studies were identified as: (1) Successful NOB repression has been demonstrated in the full-scale mainstream system, as indicated by measurement of higher concentrations of NO_2 rather than NO_3 in the effluent and as quantified by aerobic activity tests. It seems that the enrichment or bioaugmentation strategy of both the AOB and ANAMMOX organisms from the sidestream supports AOB activity over NOB activity and also enhances the opportunity for the ANAMMOX to outcompete the NOB for NO_2. (2) Although significant quantities of ANAMMOX biomass granules were transferred from the sidestream to mainstream, the NH_4 removal capacity of the sidestream was maintained and even improved (from an average of 95 percent to 96 percent).

Dual-Stage Mainstream Deammonification Without Bioaugmentation

This concept has been tested at the pilot scale at the HRSD in Virginia (with a target TN limit of 5 mg/L). The process is a modified European style A/B process, which includes an initial "A" stage HRAS process followed by a "B-stage" SCBNR process without bioaugmentation from a sidestream process. The SCBNR stage was piloted using modulating aeration to achieve N removal using the nitritation/denitritation pathway and a fully anoxic ANAMMOX MBBR for nitrogen polishing. The AB process provides an overall TKN removal ranging from 85-90 percent with an average effluent total NH_4-N concentration of 4.2 mg/L, which is between the setpoints of 3-5 mg/L. Average effluent NO_3-N and NO_2-N concentration of 1.76 mg/L and 0.4 mg/L were also observed. The pilot study process flow diagram and operational parameters are depicted in the attached Figure 6 and Table 2, respectively. The results from this pilot study may be applied at the full scale-level in the future at the 24-MGD Chesapeake-Elizabeth Treatment Plant. The ammonia versus NO_x (NO_2 + NO_3) (AVN) control strategy was evolved from this pilot study.

The HRSD AVN control strategy is a real-time aeration control strategy using online monitoring of NH_4-N and NO_x-N concentration in the continuous-stirred tank reactor (CSTR) to prevent overaeration and balance the ammonium and NO_2/NO_3 throughout the process. As demonstrated in Figure 7, under the AVN strategy, the aeration controller maintains the target DO set point through the use of a motorized operating valve (MOV) when aerated. The ammonium concentration is compared to the NO_x-N. If NH_4-N is higher, then aerobic duration is increased. When NH_4-N is less than NO_x-N, aerobic duration is decreased. When aerated, the MOV maintains a target DO set point of 1.6 mg/L through the use of a proportional-integral-derivative (PID) controller (Regmi et al., 2013). The effluent NO_x-N depends on denitrification. Following favorable conditions for denitrification, the NO_x-N concentration in the effluent can get low, whereby the AVN controller will allow more ammonium oxidation to match the NO_x-N

FIGURE 6: TWO-STAGE PILOT STUDY PROCESS FLOW DIAGRAM FOR MAINSTREAM NITRITATION AND DENITRITATION PILOT TEST CONDUCTED BY THE HAMPTON ROAD SANITATION DISTRICT
(REGMI ET AL., 2013)

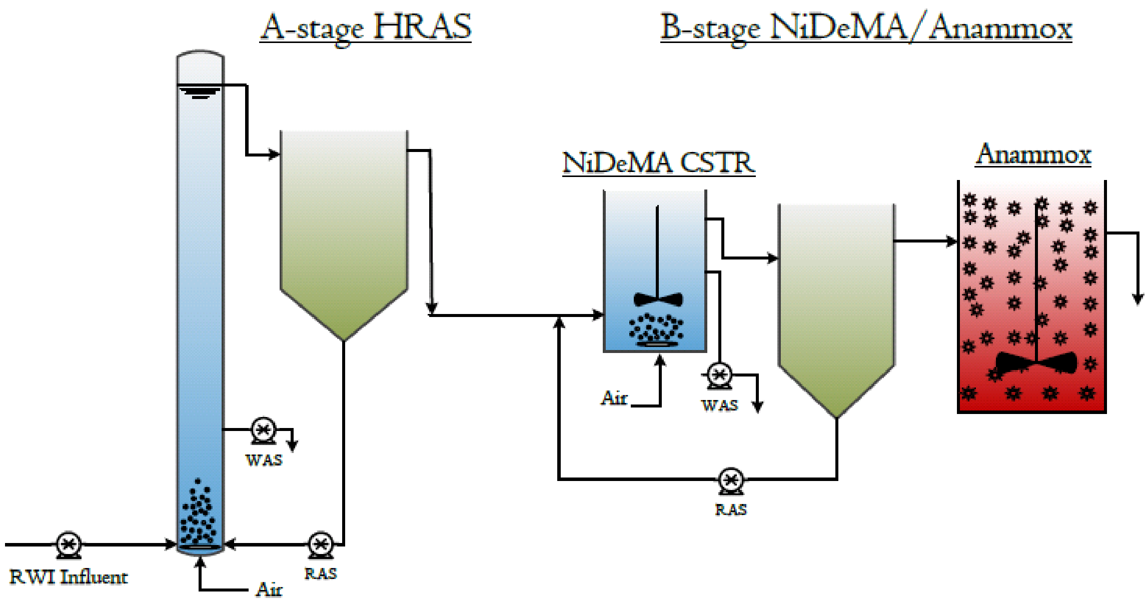
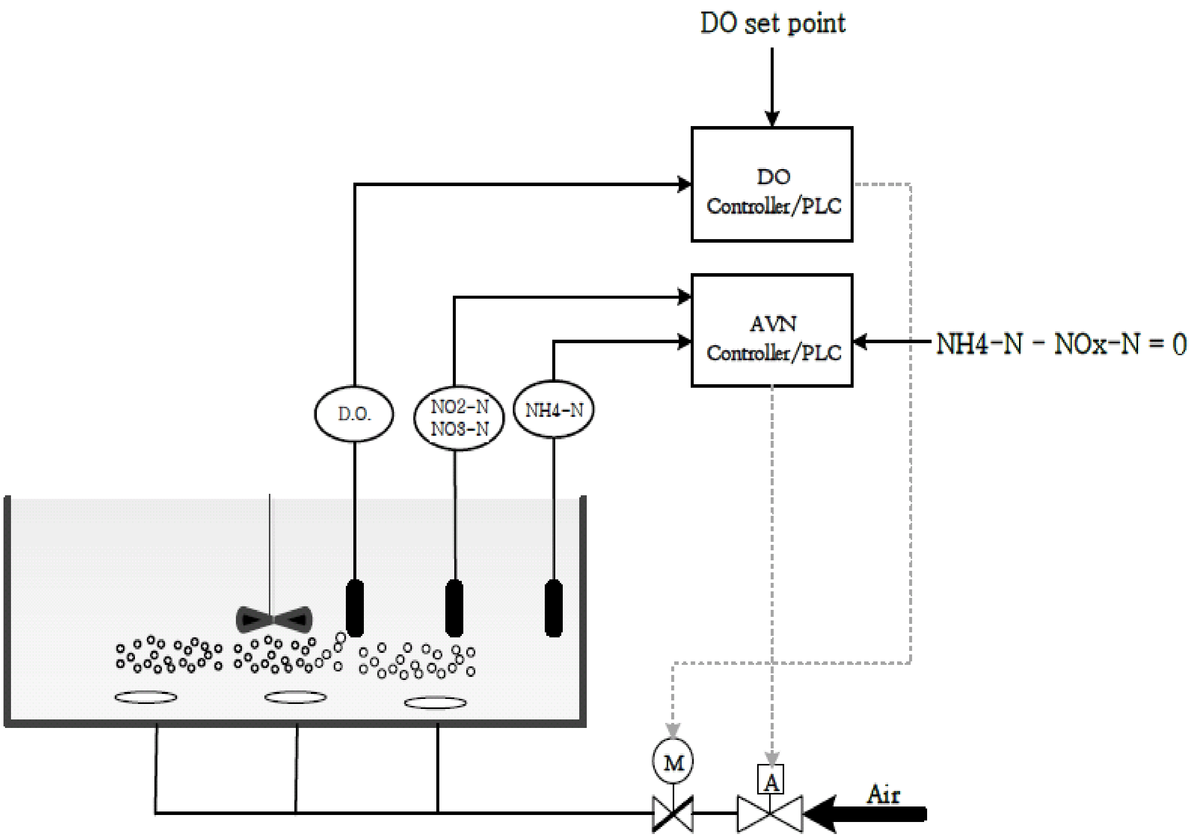


TABLE 2: OPERATING PARAMETERS FOR TWO-STAGE SHORTCUT BIOLOGICAL NITROGEN REMOVAL PROCESS FOR THE PILOT TEST DONE AT THE HAMPTON ROAD SANITATION DISTRICT

	Volume Liter	HRT hr	Influent Flow liter/min	Total SRT days	Aeration Pattern	Target DO mg/L	MLSS g/L	Temperature ºC	pH
A-stage	107	0.5	5.7	0.2–0.3	Intermittent	0.2–0.6	1.5–3	25	7.2–7.4
NiDeMA CSTR	340	2–3	1.9	4–7	Intermittent	1.6	3–4	25	6.7–6.9
AMX MBBR	454	4	1.9	N/A	Un-aerated		N/A	25	6.8–7

Source: Regmi et al., 2013.

FIGURE 7: AMMONIA VERSUS NITRITE/NITRATE CONTROLLER DEPICTING AEROBIC DURATION CONTROLLER RECEIVING AMMONIA NITROGEN (WTW AMMONIUM SELECTIVE ELECTRODE, GERMANY), NITRITE AND NITRATE NITROGEN (S::CAN SPECTRO::YSER, AUSTRIA) SIGNALS AND DISSOLVED OXYGEN CONTROLLER RECEIVING DISSOLVED OXYGEN (HACH LDO, USA) SIGNAL – FOR MAINSTREAM NITRITATION/DENITRITATION PILOT TEST DONE AT THE HAMPTON ROAD SANITATION DISTRICT (REGMI ET AL., 2013)



Ⓜ = Motor Operating valve

Ⓐ = Aeration controller

level, thus driving the overall TN lower. This is achieved by increasing the aeration duration. If conditions are not favorable for good denitrification NO_x-N will be high and less ammonium oxidation will be allowed by the AVN controller through lowering the aeration duration. Therefore, the controller is constantly changing the process depending on the conditions (influent C:N, oxygen uptake rate, mixed liquor suspended solids [MLSS]) to maximize the TN removal. Since the controller is always optimizing NH_4-N oxidation and NO_x-N reduction during the aerated and unaerated periods, respectively, NOB competing for common substrate in both environments are not favored. This helps realize mainstream nitritation/denitritation.

Step-Feed Biological Nitrogen Removal Process

The Singapore Changqi WRP reported the first full-scale autotrophic N removal process without sidestream seed augmentation in the world, and demonstrated the feasibility and benefits of mainstream autotrophic SCBNR in a large 212 MGD municipal wastewater treatment facility in a warm climate using a step-feed BNR process. Figure 8 shows the configuration of the step–feed BNR process at the Changqi WRP. For each reactor, the primary effluent (PE) was split into six basins, and each basin has an anoxic and an aerobic pass. The anoxic pass consists of four compartments separated by physical partitions. Five basins are normally operating, while one is off-line. The PE flow was split evenly between basins with flow measurement control. The recycled return activated sludge (RAS) was fed into the first anoxic zone at 50 percent of influent flow. Partial nitritation/deammonification and nitritation/denitritation were observed by monitoring the NH_4-N, NO_2-N, and NO_3-N profile in the individual zones. The fluorescence in situ hybridization pictures in the study showed ANAMMOX bacteria were small floc sludge or free cell rather than granular or aggregate. The BNR step–feed activated sludge (AS) process at the Changqi WRP demonstrated excellent N removal efficiency. Table 3 (attached) summarizes the major process and operating parameters, and the characteristic of the primary effluent and final effluent of the step feed BNR AS process. The autotrophic N removal contributed to 100 percent removal of ammonium and 75 percent removal of TN in the primary effluent with a average PE C:N ratio of 7. EBPR was active in the process and accounted for 68 percent total-P removal from the process influent compared to a typical 10–30 percent removal in conventional AS process without EBPR. According to the author, the short aerobic SRT (2.5 days) under the high operating temperature (28°C–32°C) and alternating aerobic/anoxic environment could be the main conditions to achieve stable partial nitritation/deammonification and nitritation/denitritation (Cao et al., 2013).

Attached Growth (Hybrid and Granular) System

Attached growth and hybrid systems provide a means by which organisms can be retained in the system. It has been demonstrated that the NOB can be outcompeted in an attached growth system, while multiple organisms including AOB and ANAMMOX can thrive in the system (Stinson et al., 2013). Either the size or the mass of the media can be used to facilitate intensification of the processes. Studies done by Clippeleir et al. (2013) have demonstrated that RBCs could be reliable reactors to ensure ANAMMOX retention at shorter HRT operation. Moreover, NOB can be out-selected based on space in the biofilm due to very rapid transient anoxia, high DO exposures due to atmospheric contact, and ammonium residual,

FIGURE 8: STEP-FEED ACTIVATED SLUDGE PROCESS CONFIGURATION AT THE CHANGQI WATER RECLAMATION PLANT
(FROM CAO ET AL., 2013)

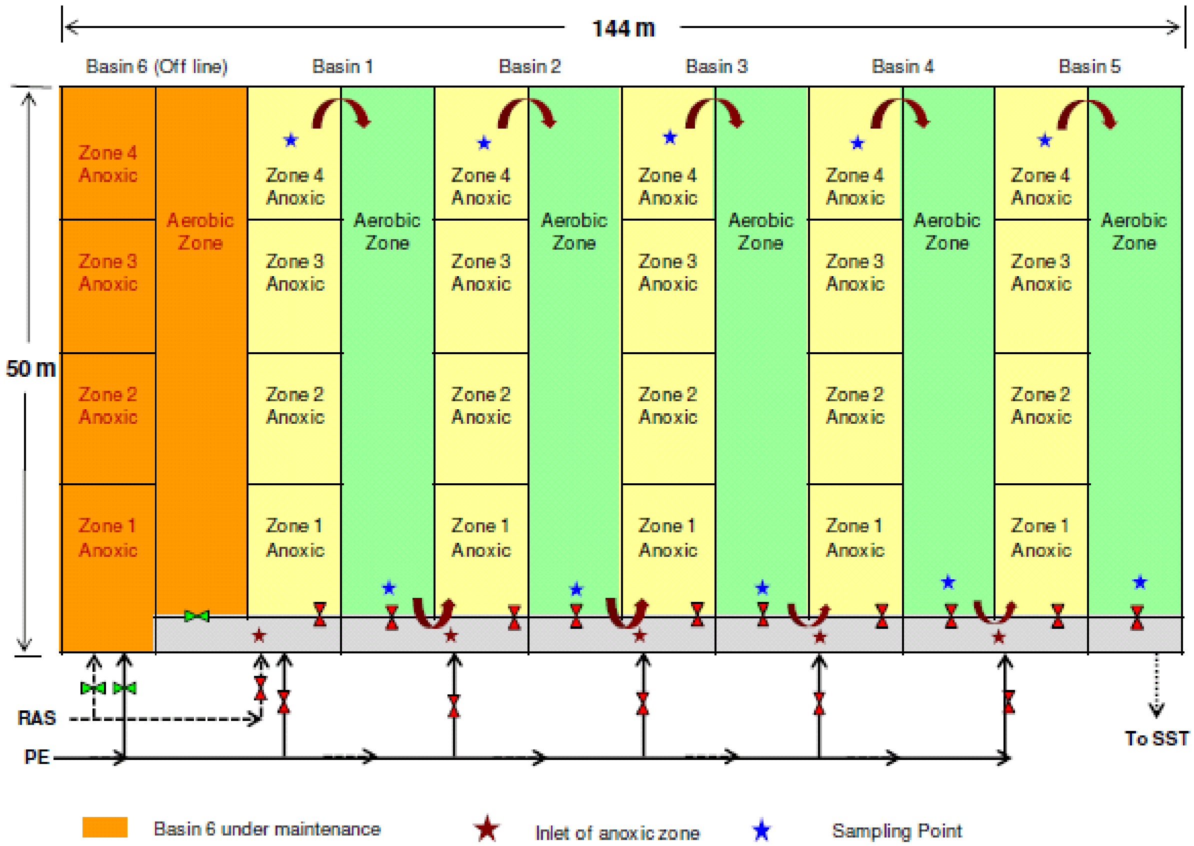


TABLE 3: STEP-FEED BIOLOGICAL NITROGEN REMOVAL ACTIVATED SLUDGE PROCESS AT THE CHANGQI WATER RECLAMATION PLANT

Major Process, Operating Parameters

Hydraulic Flow, m^3/d	HRT, hr	SRT, day	Sludge Inventory in the Five Basins, mg/L	DO, mg/L
200,000	5.8	5	4,500, 4,200, 3,500, 3,000, and 2,500	1.4 - 1.8 in Aerobic Zone, 0.08 - 0.12 in Anoxic Zone

Characteristics of Primary Effluent, Final Effluent, and Removal Efficiency

	COD	sCOD	TSS	TN	NH_4-N	NO_2-N	NO_3-N	TP	Ortho-P	pH
Primary effluent, mg/L	306	175	87	41	30	~0	~ 0	5.9	5	7.2
Final effluent, mg/L	33	23	5.6	4.8	1.7	1.1	0.8	1.9	1.6	6.8
Removal Efficiency, %	89.2%	86.9%	93.6%	88.3%	94.3%	NA	NA	67.8%	68.0%	NA

Source: Cao et al., 2013

allowing for high AOB growth rates. The latter organisms produce NO, allowing for a second competition for space in the biofilm between NOB and AOB.

Veolia Water has successfully implemented MBBR and IFAS configuration for sidestream treatment. A recent full-scale implementation done by Veolia Water (Lemarie et al., 2013) has shown that an IFAS configuration resulted in an increase in N-removal rate of up to three times than usually achieved by a pure MBBR in a sidestream system. Based on the experience learned from sidestream, IFASs are currently being tested for the mainstream with different configurations and climates at the pilot scale at three WWTPs (i.e. after primary settler + HRAS in Sweden, after UASB + HRAS in the Middle East, after CEPT + HRAS in France). IFAS is also currently being tested in several parallel bench-scale units at different COD/N ratios (from 0.5 to 3) to investigate the maximum COD/N ratio that can be applied on the IFAS and the impact on the overall performance and design. In the mainstream, the IFAS solution has the advantage of being more easily retrofitted in the existing AS systems (Lemaire et al., 2013).

MBBR and IFAS have also been considered in several facilities as a polishing step to remove remaining NO_x and ammonium, e.g. HRSD is piloting an MBBR for this purpose. Denver is evaluating the option to operate their existing BNR basin optimally using Nitritation/Denitritation through modulating aeration (NiDeMa) for nitritation/denitritation and installing IFAS media in a post-anoxic zone for ANAMMOX polishing.

THE METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO'S CHALLENGES AND RECOMMENDED STRATEGIES FOR IMPLEMENTING SHORTCUT NITROGEN REMOVAL

Table 4 is a decision matrix developed by the WERF Mainstream Deammonification Study for implementing the two SCBNRs in the mainstream (WERF, 2013). The main challenges/factors that should be considered for the District to implement SCBNR in our existing facilities are summarized below.

Challenges

Carbon:Nitrogen Ratio. As shown in Table 4, a low influent C:N ratio (0–5:1) favors the partial nitritation/deammonification process; a moderate C:N ratio (5–8:1) will shift the process toward nitritation/denitritation; and a high C:N ratio (8–15:1) will shift the process toward the nitrification/denitrification process. The District is currently operating seven WRPs with single stage AS processes. For all District WRPs, the C:N ratio in the wastewater feeding the secondary process is close to or higher than 10 (please note that C:N ratios are calculated using COD and TKN concentrations as suggested through personal communication with a consultant from Black and Veatch.). Based on the WERF-recommended C:N ratio in Table 4, it will be challenging to implement nitritation/denitritation, especially partial nitritation/deammonification, at the District's facilities without reducing the COD loading to the secondary treatment process by implementing either HRAS or CEPT. Adding the HRAS or CEPT process would provide an opportunity to capture and divert more influent C to the anaerobic digesters to generate methane gas for energy recovery. Adding HRAS to existing facilities may have hydraulic limitations and will also involve costly capital investment if the facility does not currently have a two stage AS system. Adding chemical feed to implement CEPT will remove some P through chemical precipitation in primary clarifiers, which is not desirable for the District's P recovery goal. Pilot tests using District wastewater and facilities have to be conducted to evaluate the best process that can be implemented for SCBNR in the District's facilities considering our C:N ratios.

Wastewater Temperature. Generally, the optimum temperature for ANAMMOX activity is in the range of 30–35°C (Wett et al., 2006, 2010; Bowden et al., 2007). Denitritation using OHOs can occur between 5 and 30°C, with rates increasing with temperature (Bertino et al., 2010). In addition, as discussed previously, as the temperatures drop below about 15°C, the growth rate of the NOB begin to exceed the growth rate of the AOB; thus, it is difficult to outcompete the NOB and maintain an acceptable AOB/NOB balance. The wastewater temperature at the District's WRPs is as low as 10–15°C in winter, which poses a great challenge to grow and retain ANAMMOX and out select NOB for an SCBNR process. Installing cyclones, sieve/fine screen for ANAMMOX retention, bioaugmentation from a sidestream process, and/or utilizing aeration control methods for NOB out selection would be necessary for the mainstream process, especially during low-temperature operations.

TABLE 4: DECISION MATRIX FOR IMPLEMENTING SHORTCUT NITROGEN-REMOVAL METHODOLOGIES

	C/N Ratio				
Effluent Drivers	Low C/N (0–5)	Moderate C/N (5–10)	High C/N (8–15)	Very high C/N (15+)*	
Low ammonia No TN	NiDeMA with ABAC				*Bioaugmentation* *Control* *Polishing*
No/high ammonia limit Moderate TN	Bioaugmentation NiDeMA with AVN				*Bioaugmentation* *Control* *Polishing*
Low ammonia Moderate TN	Bioaugmentation NiDeMA with AVN ANAMMOX Polishing or Reaeration		NiDeMA with AVN & Reaeration or ABAC		*Bioaugmentation* *Control* *Polishing*
Low ammonia Low TN	Bioaugmentation NiDeMA with AVN ANAMMOX Polishing				*Bioaugmentation* *Control* *Polishing*

*Note: Consider carbon diversion:

NiDeMA = nitritation denitritation through modulating aeration
AVN = Ammonia vs NO_x control
ABAC = Ammonia-based aeration control (must include robust control for low ammonia limits)

"Low Ammonia" limit = limit <2 mg/L (limits less than 1 mg/L may have other considerations)
Moderate TN = limit 6 -12 mg/L
Low TN = limit <6 mg/L

Effluent Nitrogen Limits.

1. TN Limit. Facilities with a TN limit could benefit from either SCBNR methodology. However, the District currently does not have a TN limit at any plant.

2. NH_3-N limit. For a facility with a low NH_3-N limit (<2 mg/L), deammonification or re-aeration for ammonia polishing may be needed. Several District WRPs have NH_3-N limits as low as a monthly average of 1.5 mg/L, which could become lower with the implementation of new USEPA NH_3-N criteria.

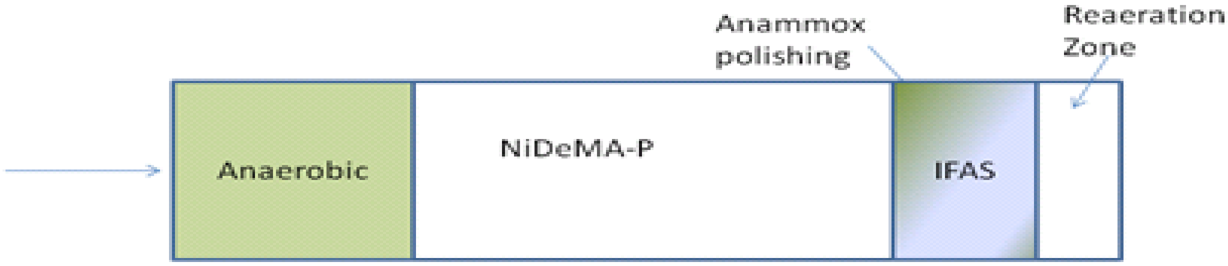
Enhanced Biological Phosphorus Removal. Very little research has been done to investigate how partial nitritation/deammonification and nitritation/denitritation can tie into the EBPR process in the mainstream. Singapore's Changqi plant experience (Cao et al., 2013) demonstrated a TP removal efficiency of approximately 68 percent from the plant primary effluent in their mainstream hybrid partial nitritation/deammonification and nitritation/denitritation process; this is compared to typical 10-30 percent TP removal in a conventional AS process without EBPR. Their studies indicated that soluble biodegradable C in the anoxic zones was first being utilized for P release by organisms for the EBPR process with the leftover COD for denitrifiers. This was considered to be an important factor that kept their process from being affected by the high C:N ratio in their plant influent (Cao et al., 2013). It is suggested that there is a synergistic effect between EBPR and the two shortcut N removal methodologies. However, the Changqi plant effluent TP level is high (average of 1.9 mg/L). As the District will likely have a low TP limit (monthly average <1.0 mg/L) in the new NPDES permits at four WRPs, we are committed to remove P through EBPR whenever possible. Whether mainstream nitritation/denitritation or partial nitritation/deammonification can fit into our EBPR process will be the key factor for our future studies.

Based on the experience gained from this literature review and given the District's existing facilities, wastewater, and permits, the following four options should be further researched and evaluated for future bench scale and/or full scale pilot tests.

Recommendations

Option 1 – Anaerobic + Nitritation/Denitritation Through Modulating Aeration + Integrated Fixed-Film Activated Sludge + Reaeration. The schematic for this process is shown in Figure 9 below. This process could be implemented at almost all District facilities if it is proved to work. This process is to operate the existing aeration basin optimally for nitritation/denitritation based on NiDeMa, modified to operate at short sludge age for NOB out-selection, but still maintaining EBPR. IFAS media in a post-anoxic zone and/or re-aeration should be evaluated for NH_3 polishing. This process is similar to the B-stage piloted at the HRSD in Virginia discussed previously, but with an anaerobic zone added to the beginning of the aeration tank for EBPR. PAO in the anaerobic zone will uptake carbon, which will help reduce the carbon level entering the NiDeMa process. In addition, IFAS, instead of MBBR, is used for

FIGURE 9: SCHEMATIC FOR OPTION 1 - ANAEROBIC + NITRITATION/ DENITRITATION THROUGH MODULATING AERATION + INTEGRATED FIXED FILM ACTIVATED SLUDGE + REAERATION FOR SHORTCUT BIOLOGICAL NITROGEN REMOVAL PROCESS



ammonia polishing. If sidestream treatment is available, it might be an option to occasionally transfer sludge from the sidestream system to the mainstream system to ensure the ANAMMOX and AOB population is maintained. Challenges for this configuration include: (1) if the intermittent aeration in the NiDeMa zone impacts P uptake for the EBPR process; (2) need to investtigate secondary P release potential in the anoxic IFAS system; (3) the increased NO_2-N level in the effluent may increase chlorine consumption in the downstream disinfection. Upon further discussion, this process could be piloted at bench scale using a series of SBRs to simulate plug flow for EBPR and NiDeMA, followed by a small-scale IFAS tank. If successful, it then could be piloted at one of the District facilities.

Option 2 – Step-Feed Biological Nitrogen Removal Activated Sludge Process (Singapore Changqi Experience). The schematic for this process is shown Figure 10. This is similar to Singapore Changqi experience discussed previously. This process involves step feed operation with an aggressive aerobic SRT to keep the NOB population low. This process would involve minimum change to the existing facilities that already have step feed ability in the AS process. If a partial nitritation/deammonification sidestream system is implemented, feeding this sludge to maintain ANAMMOX and AOB population, especially in cold weather, will be necessary. The main challenges for this process are: (1) whether the process will be able to constantly meet the effluent P limit (monthly average of 1.0 mg/L) and ammonia-N limit. The ammonia-N level in the final effluent from Singapore Changqi varied between 0.5 to 5.0 mg/L with an average of 1.7 mg/L (94 percent removal). The average TP level in the final effluent was 1.9 mg/L (68 percent removal) as a side bonus without any consideration given to controlling EBPR. Aerobic and anaerobic SRT, ORP/DO levels in different zones, and alternating aerobic and anoxic environment should be investigated through pilot study for NOB out selection and EBPR optimization; (2) how the process will respond in cold weather; and (3) the increased NO_2-N level in the effluent may increase chlorine consumption in the downstream disinfection. Upon further discussion, this process could be piloted in one of the District facilities that has step feed ability. The District facilities with step feed ability that have been evaluated for pilot testing include: Egan (3 passes), Kirie (3 passes), and Stickney (4 passes). The Egan WRP is selected for piloting study because (1) Egan WRP has extra aeration tank capacity to allow converting one aeration tank for step feed BNR AS process. As a matter of fact, one of the North aeration tanks has been converted to the step feed anoxic/aeration process for biological nitrogen removal and chemical P removal piloting under WERF 02-CTS-1 project in 2004/2005; (2) Effluent from the ANITA™ Mox process, which is enriched with ANAMMOX and AOB, could be used to seed and bioaugment the pilot tank; (3) effluent from the ANITA™ Mox process has low C:N ratio (relative high ammonia, low carbon), which can be used to balance the influent C:N ratio to the pilot tank to shift BNR removal toward nitritation/denitritation and partial nitritation/deammonification process.

Figure 11 illustrates the proposed pilot tank conversion schematic for one of the north aeration tanks in Egan WRP. The pilot aeration tank will be operated in step feed mode, where primary effluent is split and distributed to all three passes of the pilot tank. Effluent from the ANITA™ Mox process and RAS will be fed to the beginning of the first pass. Three anoxic/anaerobic zones will be generated by adding mixers and baffle walls in each of the three passes. The future design detail should consider the flexibility to allow changing the volume split between the aerobic and anoxic/anaerobic zones. Initially, the first and second anoxic/anaerobic

FIGURE 10: SCHEMATIC FOR OPTION 2 - STEP-FEED SHORTCUT BIOLOGICAL NITROGEN REMOVAL PROCESS

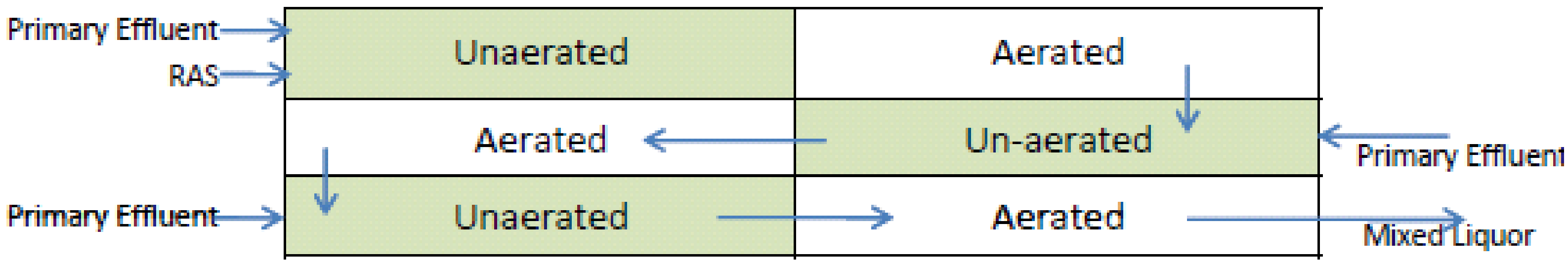
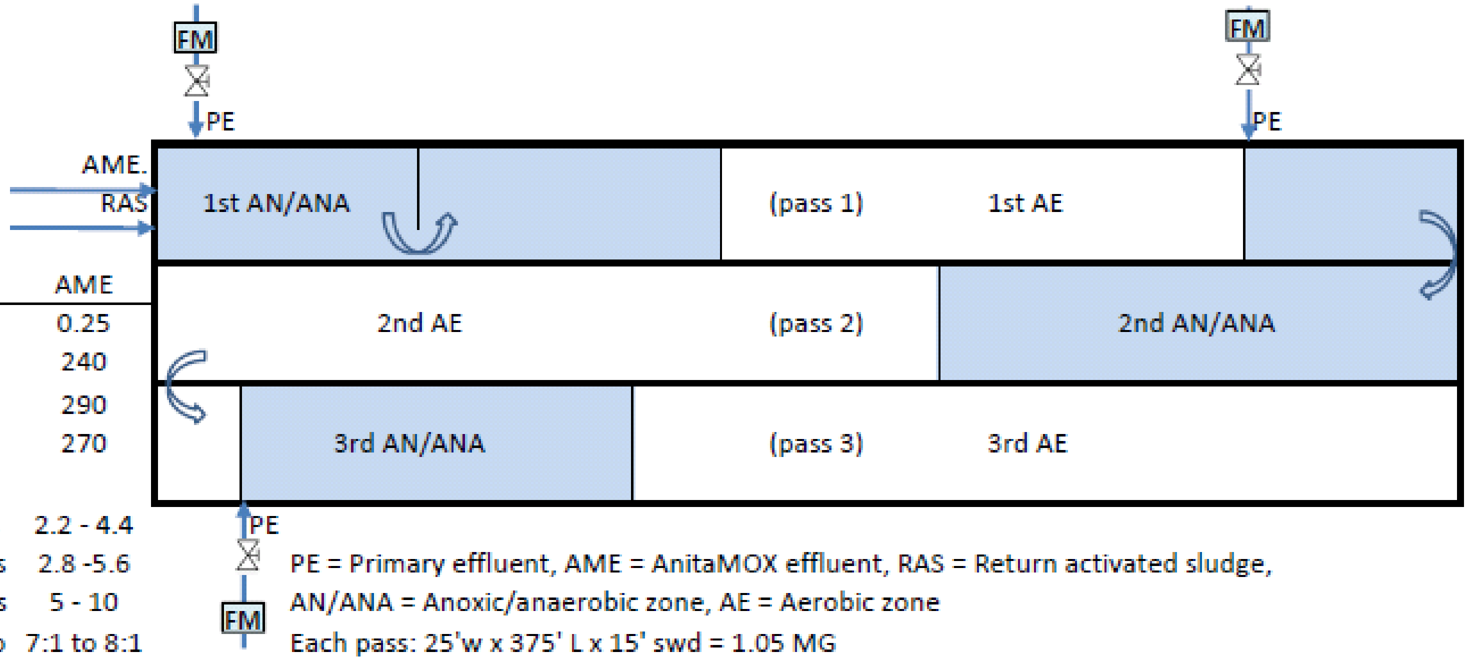


FIGURE 11: EGAN WATER RECLAMATION PLANT STEP FEED BIOLOGICAL NITROGEN REMOVAL AS PROCESS PILOT STUDY – PROPOSED TANK CONVERSION SCHEMATIC



	PE	AME
Flow, mgd	7.5 -15	0.25
COD, mg/L	226	240
TKN, mg/L	23	290
NH3-N, MG/L	21	270

AN/ANA HRT,hrs	2.2 - 4.4
AE HRT, hrs	2.8 -5.6
Total nominal HRT, hrs	5 - 10
COD:TKN ratio	7:1 to 8:1

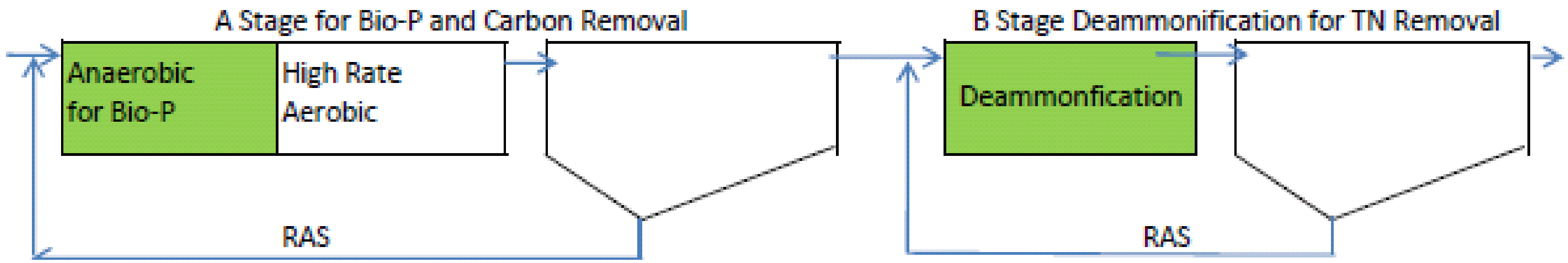
PE = Primary effluent, AME = AnitaMOX effluent, RAS = Return activated sludge,
AN/ANA = Anoxic/anaerobic zone, AE = Aerobic zone
Each pass: 25'w x 375' L x 15' swd = 1.05 MG
Mixers should be provided in each AN/ANA zone.
1st AN/ANA zone volume = 1st AE zone 2nd AN/ANA zone volume = 2nd AE zone
3rd AN/ANA zone volume = half of 3rd AE zone, additional AE volume is provided in the 3rd pass for ammonia polishing

zones will each have equal volume as the first and second aerobic zone. The third anoxic/anaerobic zone volume will be half of the aerobic zone to provide more aeration for ammonia polishing to meet the effluent ammonia limit. The plant traditionally operates the aeration tanks with MLSS of 2000 – 3000 mg/L, SRT of 8 (warm days) to 15 days (cold days) and relatively constant RAS rate at about 70 percent of the plant flow. According to the literature review, in order to wash out NOB but still maintain AOB, the total SRT should be around 4-7 days (with half for anaerobic SRT and half for aerobic SRT). For the EBPR process, the recommended anaerobic SRT is 0.3 – 2 days and aerobic SRT was generally not a concern and most plants were designed to meet the nitrification needs. For this pilot testing, we will try to maintain a pilot tank SRT of 4 – 7 days. The corresponding anoxic/anaerobic and aerobic SRT will be 1.8 – 3.1 days and 2.2 – 3.9 days, respectively.

As mentioned above, effluent from the ANITA™ Mox process is enriched with ANAMMOX and AOB and has a low C:N ratio. Diverting a portion or all of the ANITA™ Mox effluent to the beginning of the pilot aeration tank would provide an opportunity to seed and bioaugment the pilot tank and balance the influent C:N ratio to maintain ANAMMOX and AOB populations to outcompete NOB, which is important in cold weather when low water temperature favors NOB growth. Under the current ANITA™ Mox design, the effluent from the ANITA™ Mox process will be discharged to the plant drain. Diverting ANITA™ Mox effluent to the pilot aeration tank would involve pump and pipe installation, which could be costly and time consuming. If this is not practical, we may need to consider other options to retain ANAMMOX population if the pilot test encounters difficulty to maintain ANAMMOX population in cold weather.

Option 3 – Two-Stage Process with First Stage to Maintain Short Solids Retention Time for Enhanced Biological Phosphorus Removal and High-Rate Activated Sludge to Remove Carbon and Phosphorus and Second Stage for Deammonification for Ammonia and Total Nitrogen Removal. The schematic for this process is shown in Figure 12. This two stage process is similar to the A/B process piloted at the HRSD in Virginia. Anaerobic zone will be provided in stage A for EBPR. This concept could be researched for implementation at the Egan and Kirie WRPs. Both Egan and Kirie can be operated as two-stage activated sludge processes. Stage A could be modified to maintain a short SRT for EBPR and HRAS process to remove P and carbon, but without nitrification for ammonia removal, while stage B is optimized to facilitate SCBNR either using aeration control/bioaugmentation for nitritation/denitritation and/or partial nitritation/deammonification to remove ammonia in the suspended growth AS process and/or using IFAS to remove ammonia through partial nitritation/deammonification. Reaeration may be needed for NH_3 polishing. For facilities with aerated grit and primary clarifiers (such as Stickney, Lemont, Calumet, Egan, and O'Brien), there is potential to convert aerated grit tanks and primary clarifiers to stage A processes for carbon removal. However, this concept needs further evaluation on retention time, air supply capacity, combination with EBPR, and retrofit possibilities. If implemented successfully, this process offers the most energy benefit, because it diverts more C to anaerobic digesters for gas production. The main challenges to this process include: (1) balancing SRT in stage A for EBPR and HRAS; (2) maintaining DO level in stage A in the aerobic zone for P uptake and C removal through enmeshment, colloidal bioflocculation and soluble COD uptake/storage; and (3) the increased NO_2-N level in the effluent may increase chlorine consumption in the downstream disinfection. Upon further

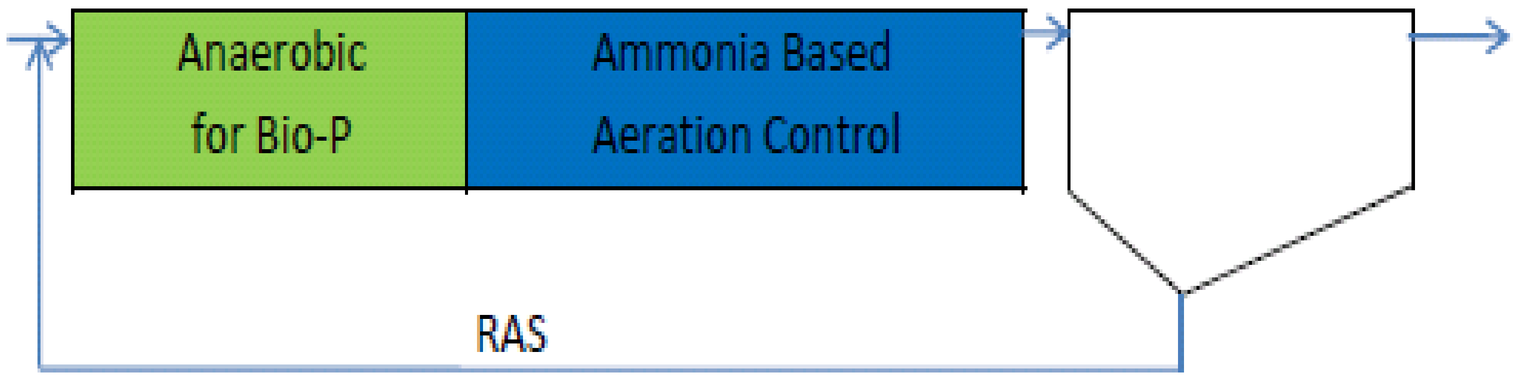
FIGURE 12: SCHEMATIC FOR OPTION 3 - TWO STAGE SYSTEM FOR SHORTCUT BIOLOGICAL NITROGEN REMOVAL PROCESS



discussion, this process should be piloted through a bench scale study. If successful, it then could be piloted in one of the District facilities that are best suited for a 2-stage AS process.

Option 4 – Other Options for Reducing Energy Consumption. The schematic for this process is shown in Figure 13. The aeration process at all District plants is currently operated either at a fixed rate or to seek a constant DO level (2.0 mg/L or higher), which are susceptible to over-aeration when influent ammonia levels. Over-aeration wastes energy. By controlling air flow based on ammonia measurements, it can be ensured that no more than the minimum air requirements for nitrification are being met at all times (Bunce et al., 2013). Ammonia control would allow maintenance of low DO levels to reduce air supply requirement (possibly less than 1 mg/L) in aeration tanks, but still achieve nitrification to meet effluent ammonia limit. In addition, low DO levels maintained in the aeration tank will increase the oxygen transfer efficiency, which could further reduce air supply requirement. With low DO maintained in the aeration tank, it encourages the oxidation of ammonia to NO_x-N followed by reduction to N_2 at the same time in the same reactor without going through clearly defined aerobic and anoxic zones. This is defined as simultaneous nitrification–denitrification (SND) process. While uneven oxygen distribution throughout the bulk liquid of the aeration tank as well as novel microorganisms have been shown to play a role in SND, the mechanism responsible in most cases is the oxygen gradient that exists within biological floc (Diagger & Littleton, 2000). The advantage of SND includes more complete nitrogen removal and reduced aeration requirements (Bunce et al., 2013). Even though SCBNR through SND happens in this ammonia based aeration control option because of the low DO maintained in the aeration zone, there will be no control in this process to encourage partial nitritation/deammonification or nitritation/denitrification. However, this process could be implemented in all District facilities and potentially involves the least modification to the existing facilities. In addition, this process could be efficiently combined with the EBPR process. Currently the District is planning to pilot this process in one of the aeration tanks in Battery D at the Stickney WRP November 2014 through June 2015 as part of the Aeration Reduction Task Force led by the Maintenance and Operations (M&O) Department. DO and ammonia probes have been already installed in a selected aeration tank, and baseline data will be calculated. A process control algorithm will then be developed, and use the feedback information from the real-time ammonia probes to modulate aeration for pilot testing. The M&R Department will work closely with the M&O Department to conduct ammonia based aeration control pilot study. The pilot study results will be used to determine air savings through ammonia based aeration control, cost savings, and feasibility for full-scale implementation. Battery D is currently operated as an EBPR process, and implementing ammonia-based control will also help reduce the oxygen in RAS recycled back to the influent, which can help improve the EBPR process.

FIGURE 13: SCHEMATIC FOR OPTION 4 – OTHER OPTIONS FOR REDUCING ENERGY CONSUMPTION



SUMMARY AND FUTURE STEPS

Mainstream partial nitritation/deammonification and nitritation/denitritation, together with other renewable energy technologies, offers the opportunity for sustainable wastewater treatment and energy-neutral or even energy-positive facilities. Table 5 summarizes all benefits these two mainstream methodologies can offer. However, current full-scale implementation is very limited around the world and there is no full-scale implementation in the U.S. as of October 2013, but process models and operational schemes are under development. In addition, the interest that drives current studies is to meet TN limits rather than NH_3-N limits. Finally, little practice has been made on how to tie mainstream partial nitritation/deammonification or nitritation/denitritation in with an EBPR process.

To evaluate if and how these shortcut N-removal processes can be cost-effectively applied to District facilities given our current infrastructure, capability, and NPDES permit limits for TP and NH_3-N in parallel with EBPR improvements, we would need to conduct a series of investigational research programs. The previous sections have identified two processes that could be pilot tested through bench-scale study and two processes that could be pilot tested in full-scale at District facilities. The District is currently planning to pilot test **Option 4** – Other Options for Reducing Energy Consumption at Stickney using ammonia based aeration control. NH_4-N and DO probes required for the pilot test have already been installed. The background data will be collected; and the NH_4-N based control strategy will be developed, implemented, and pilot tested afterwards. For the other three options, the level of effort, resources, and time scales based on the current understanding of the technologies are summarized below.

1. Form teams to conduct selected piloting of different SCBNR technologies/ approaches. These efforts will be led by the M&R Department and are expected to take place between June 2014 and November 2014.

   a. Bench-scale Study: **Option 1** and **Option 3** – These two-stage processes discussed in the previous sections are processes that have a great potential to be implemented in the District facilities to achieve energy savings, but require significant modification to the existing infrastructure. Therefore, bench-scale studies are recommended to verify the design and operating parameters for the processes. We expect to team up with regional universities under the District's master agreements for the study. The M&R Department would work together with the selected university to evaluate the recommended technologies and select suitable ones for further studies. The universities will design the bench scale tests, develop test protocols, and conduct pilot testing, analyze the data, and prepare a report. The M&R Department will review the pilot test design and test protocols, supervise the pilot-test process, and review pilot test results, analysis, and report.

   b. Full-scale Study: **Option 2** discussed in the previous section has been selected for a full-scale pilot study, because it requires

TABLE 5: THE BENEFITS OF MAINSTREAM NITRITATION/DENITRITATION AND PARTIAL NITRITATION/ DEAMMONIFICATION RELATIVE TO NITRIFICATION/DENITRIFICATION

Moving from Conventional Nitrification/Denitrification to Nitritation/Denitritation	Moving from Conventional Nitrification/Denitrification to Partial Nitritation/Deammonification Process
25 percent reduction in oxygen (electron acceptor) demand in the nitrification step	65 percent reduction in oxygen (electron acceptor) demand in nitrification step
40 percent reduction in carbon (electron donor) demand for the denitrification step	90 percent less carbon demand (ANAMMOX bacteria use CO_2 as carbon source)
33–35 percent reduction in sludge production in nitrification step and 55 percent reduction in the denitrification step	Even less sludge production because ANAMMOX are slow growing autotrophic bacteria
63 percent improvement in the denitrification rate leading to a decrease in size of anoxic reactor by 30–40 percent.	Not applicable
20 percent reduction in CO_2 emissions due to the denitrification from NO_2 instead of nitrate.	90 percent reduction in greenhouse gas emissions (CO_2 consumption mentioned above and potentially no N_2O emission)
	Better sludge settleability because of the ANAMMOX bacteria

*Source: Roadmap toward energy neutrality & chemical optimization at Enhanced Nutrient Removal Facilities, Stinson et al., 2013.

minimal modification to the existing infrastructure and has the potential to achieve energy savings. The M&R Department will work with Engineering and the M&O Department to select aeration tanks for full-scale pilot testing. The M&R Department will prepare the pilot test conceptual design, develop test protocol, conduct the pilot study, sample collection, and data analysis, and prepare reports.

2. Prepare for bench-scale and field–scale studies. We expect that the selected bench-scale studies will be conducted by local universities. The contract process may take several months and be completed by spring 2015. Meanwhile, for field-scale studies, the M&O, Engineering, and M&R Department team will design, select, procure, and install equipment, material, and instruments to convert the selected aeration tank(s) for the studies, and prepare experimental work plan. We expect this process may take approximately 10-20 months, and the field-scale facility may be ready for testing between September 2015 and July 2016.

3. Conduct bench-scale and field scale studies in parallel. We expect the bench-scale studies may last anywhere between one to two years. We expect to receive the final study reports in 2016 or 2017. For the field-scale tests, we expect to run the processes for a minimum of 1.5 years to cover the periods for startup and seasonal variation. Semi-annual status reports will be provided throughout the testing period. The final study report is expected sometime in 2018.

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