Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

MONITORING AND RESEARCH DEPARTMENT

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SIDESTREAM NITROGEN REMOVAL AT THE JOHN E. EGAN WATER RECLAMATION PLANT BY DEMON® PROCESS

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Metropolitan Water Reclamation District of Greater Chicago
100 East Erie Street Chicago, Illinois 60611-2803 (312) 751-5600

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By

Dongqi Cindy Qin
Associate Environmental Research Scientist

Joseph A. Kozak
Supervising Environmental Research Scientist

Heng Zhang
Assistant Director of Monitoring and Research
Environmental Monitoring and Research Division

Thomas C. Granato
Director of Monitoring and Research Department

Monitoring and Research Department
Thomas C. Granato, Director

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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

The conveyance of the centrate from the John E. Egan (Egan) Water Reclamation Plant (WRP) to the Terrence J. O'Brien (O'Brien) WRP (formerly the North Side WRP) has historically caused odor problems in the sewer lines. This ammonia (NH_3)-rich centrate cannot currently be recycled at the Egan WRP due to limited nitrification capacity in its aeration basins. In order to mitigate the odor problem in the sewer lines by recycling the NH_3-rich centrate at the Egan WRP without imposing harm on the existing operations, sidestream NH_3 removal treatment technologies were reviewed for potential application.

There are three types of biological sidestream treatment methods for nitrogen (N) removal, i.e. nitrification-denitrification, nitritation-denitritation, and partial nitritation-deammonification (ANAMMOX), of which ANAMMOX has been widely used in recent years due to its great energy saving and no need of carbon addition. The ANAMMOX technologies include but are not limited to Demon® (DE-amMONification), OLAND (Oxygen-Limited Autotrophic Nitrification-Denitrification), CANON (Completely Autotrophic Nitrogen removal over Nitrite process), ANITA Mox, and the Pacques process. Among these, the Demon® process (patented by the University of Innsbruck, Austria) has proven to be one of the most promising ANAMMOX technologies. Significant advantages of the Demon® process over other sidestream treatment processes are the technology's maturity and energy savings. As such, a Demon® sequencing batch reactor (SBR) suspended growth process pilot was procured from World Water Works, Inc. (WWW) for a five-month study at the Egan WRP to evaluate its ability to remove NH_3 from an NH_3-rich centrate and to assess the technology's ease of operation and robustness.

Background

Egan Water Reclamation Plant Centrifuge Operations. The Metropolitan Water Reclamation District of Greater Chicago's (District's) Egan WRP operates three 25 dry ton per day capacity solid-bowl centrifuges which dewater anaerobically digested sludge. Prior to centrifuge feeding, both ferric chloride ($FeCl_3$) and Mannich polymer are added to the digester draw for conditioning. Based on a preliminary characterization study in 2011, the centrate from the process has an average ammonia N (NH_3-N) concentration of 956 milligrams (mg) N per liter (L), and contributes up to 42 percent of the total N load to the main treatment system at the facility. Raw centrate is discharged from each centrifuge and enters a temporary 1,000-gallon holding tank before it is pumped to the O'Brien WRP. Normally, the centrate lines feeding the holding tank and the tank itself are flushed with process water to reduce struvite formation, clogging, and odors.

Demon® Technology. Demon® is a sequencing batch bioreactor that supports a mixed bacterial biomass to perform aerobic nitrification to nitrite (NO_2^-) and anaerobic NH_3 oxidation under controlled dissolved oxygen (DO) and pH conditions. The process includes a hydrocyclone to separate the granular ANAMMOX bacteria from the floc-forming bacteria (Wett B., 2007a); the heavier ANAMMOX granules are returned to the reactor while the nitrifying flocs are separated and wasted. This allows the system to control the accumulation of NO_2^--oxidizing bacteria (NOBs) and enrich ANAMMOX biomass, thereby stabilizing performance.

Theoretically, only NO_2^- is produced aerobically by controlling the aerobic NH_3-oxidizing bacteria (AOBs) and NOBs in the bioreactor in the first step. However, a minor amount of nitrate (NO_3^-) is still produced in this first step through NOB oxidation. In the second step, NH_3 is converted to N gas (N_2) directly by ANAMMOX bacteria that uses NO_2^- as an electron acceptor under anaerobic conditions. In this process, the fundamental control parameters are: aeration and anaerobic times; solids retention times (SRTs); temperature; pH; DO; and NH_3-N and nitrite N (NO_2-N) concentrations. Initial seed concentration is also vital to the time needed for start-up. Among these fundamental control parameters, the Demon® process operates between pH set-points and is very sensitive to the resulting pH bandwidth. Destabilization has been noted if the bandwidth is greater than 0.02 units (Wett et al., 2007b). Also, DO above 0.5 mg/L may lead to NO_2^- accumulation and substantial activity loss of the ANAMMOX bacteria. The system may also destabilize and cause subsequent irreversible damage when accumulation up to 80 mg NO_2-N/L in concentration is observed (Jaroszynski et al., 2011). It is also known that the process can be slowed down when temperatures are changed from 35 to 37°C (O'Shaughnessy et al., 2008); the optimum operational range is normally considered to be 30 to 35°C.

Compared to conventional nitrification/denitrification, Demon® can reduce energy costs by 60 percent (Wett et al., 2007a). Furthermore, no organic carbon substrate is required in the process, because NH_3 itself is an electron donor. Other advantages include: (1) the process is a net consumer of carbon dioxide (CO_2), compared to a release of CO_2 from carbon oxidation by heterotrophic bacteria in the conventional nitrification/denitrification process; (2) the alkalinity (ALK) demand for N removal is reduced by 45 percent; (3) reduction in sludge production; and (4) reduction in greenhouse gas emmision.

In 2004, the first full-scale Demon® reactor was implemented at the wastewater treatment plant (WWTP) in Strass, Austria. By 2012, Demon® has been applied to treat the high-NH_3 side streams at more than 36 full-scale facilities in Europe. The first full-scale Demon® plant in North America began operation on October 7, 2012, at the York River WWTP, Seaford, Virginia. Two more Demon® reactors are in final design in Pierce County, Washington, and Washington, DC, respectively. It has been documented that the existing installations operate well and require only a modest level of operator attention (Bagchi et al., 2012; Wett et al., 2007a). Over 85 percent total N removal has consistently been reported on the treatment of high-strength NH_3 wastewater at the plants currently in operation.

So far, there have been no documented failures from these facilities due to elevated NO_2-N or DO concentrations. Given Demon®'s viability and cost effectiveness, the Environmental Monitoring and Research Division staff recommended and have recently completed pilot-testing the Demon® process treating centrate at the Egan WRP. The objectives and results are summarized in this report.

Objectives

The specific objectives of the study were as follows and the time schedule for the corresponding stress testing are shown in Table 1:

1. To investigate the loading rate and N removal of centrate at the Egan WRP by the Demon® pilot.

2. To examine the effect of alkalinity on pilot operation performance.

3. To investigate the impact of temperature on pilot operation performance.

4. To examine the effect of polymer on pilot operation performance.

5. To test the system in mixing mode (idle) for 72 hours to simulate a weekend or repair shutdowns.

6. To identify the problems and lessons learned during the pilot operation, changes made during operation, and the factors that affect process efficiency and performance.

7. To evaluate the stability and robustness of the process during changes in key parameters such as suspended solids (SS) with respect to solids washout, NO_2^- spikes, and NH_3 overload.

8. To assess the overall ease of the Demon® process operation.

Methods and Materials

The pilot reactor was installed at the end of August 2012 at the Egan WRP outside the Dewatering Building. It then was seeded with 40 gallons of sludge from Glanerland, Switzerland, and operation and monitoring started on September 11, 2012. The pilot was operated for five months to assess the NH_3 removal efficiency through monitoring of the influent and effluent through normal operation and under a number of stress-testing scenarios. Special consideration was given to length of start-up time; process control including fill, react, and decant cycles and extent of aeration and mixing times; ease of operation; and effect of influent characteristics including but not limited to NH_3-N, temperature, alkalinity, SS, NO_2-N, excess polymer, and organics.

Demon® Pilot Plant Description. The Demon® pilot was constructed at the Egan WRP by WWW of Oklahoma City. Figure 1 is a photograph of the Demon® pilot system. The pilot consists of a 6,900-gallon day tank (black) for centrate pre-settling, storage, and alkalinity addition, and a 1,900-gallon Demon® reactor (white); the effective volume of the reactor is 1,445 gallons for centrate treatment. The design volumetric load of the pilot is 800 gallons per day, but the practical maximum loading is determined by the amount of N in centrate and volumetric

TABLE 1: TIME SCHEDULE FOR THE DEMON® PILOT SYSTEM TESTING AT THE JOHN E. EGAN WATER RECLAMATION PLANT

Test	Test Period
Start-up Period	9/12/12–12/6/12
Idle	12/7/12–12/10/12
Stable Operation	12/11/12–12/23/12
Alkalinity Test	12/24/12–1/4/13
Temperature Test	1/7/13–1/20/13
Polymer Test	2/1/13–2/11/13

FIGURE 1: DEMON® PILOT SYSTEM AT THE JOHN E. EGAN WATER RECLAMATION PLANT

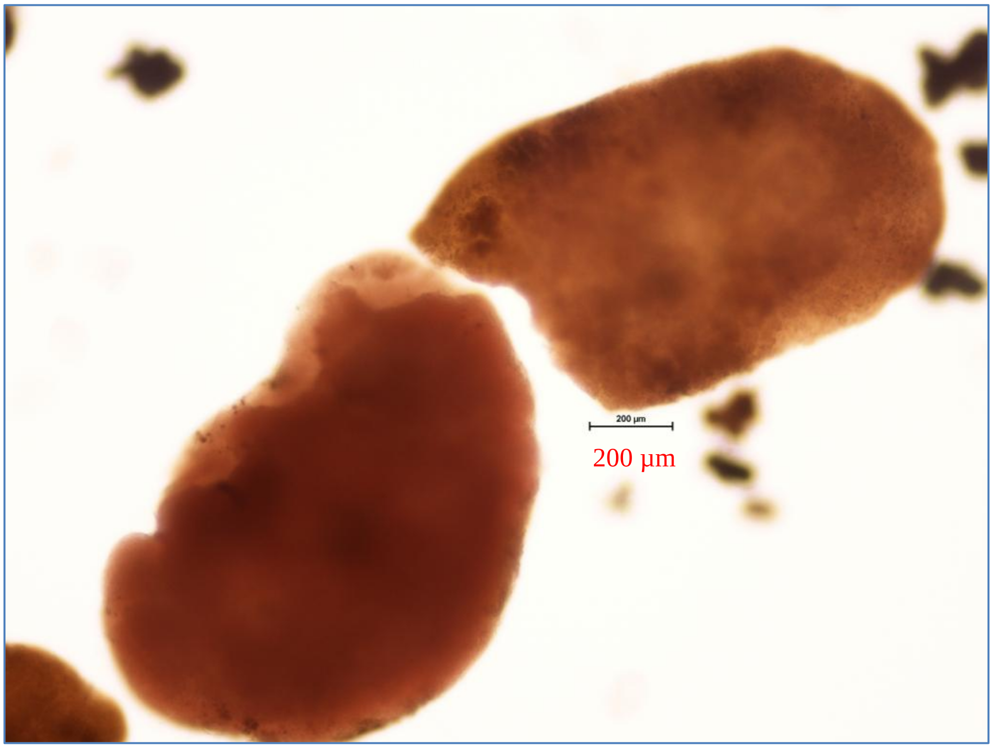
feeding rate. The reactor is equipped with feed and cyclone pumps inside the trailer to control influent centrate flow and to separate ANAMMOX granules from nitrifying flocs, respectively. The treated effluent flow is drained by gravity through a decant valve. A blower is employed for periodic aeration and mixing purposes along with diffusers within the reactor tank. A vertical mixer is positioned immediately below the minimum liquid level in the reactor to provide mixing during the anoxic fill and react times. Heat is provided through two wall-mounted immersion heaters, and temperature in the tank is regulated through a temperature sensor. A hydrocyclone (shown in Figure 2) is used to separate the granular ANAMMOX bacteria from the floc-forming bacteria in the mixed liquor (ML). The heavier ANAMMOX granules are recycled to the reactor while the flocs including AOBs and NOBs can be separated and wasted. Accumulated red granules are visible in the underflow of cyclone waste. As shown in Figure 3, ANAMMOX granules from cyclone underflow are reddish in color and sized about 1 to 1.5 millimeter. This practice allows the system to control the accumulation of AOBs and NOBs and enrich ANAMMOX, thereby stabilizing performance. Due to the recycled underflow of the hydrocyclone, total solids in the reactor are expected to increase over time. The cyclone run time determines the SRT of bacteria; the optimum SRT for AOBs is five days, and for ANAMMOX is approximately 40 days.

Online probes for pH (Hach, 6120218) and DO (Hach, 57900-18) measurement are installed and connected to the programmable logic control system (Siemens). For monitoring purposes (outside the control loops), ammonium nitrogen (Hach, DOC026.53.00745), NO_3-N (Hach, NITRATAX sc DOC023.54.03211), and conductivity are measured on-line. Water level is measured by a pressure meter. All the probes are located in a measurement loop inside the reactor. The DO probe has an air blast kit which operates four times per day to help keep the DO sensor clean from biofilm build-up over time. The pH probe was calibrated at the beginning of pilot set-up and cleaned after two months of operation. The other probes were not calibrated before installation and were cleaned on an as-needed basis.

Demon® Pilot Operation. The Demon® day tank was filled periodically by Maintenance and Operations Department staff. Centrate left the centrifuges and entered a 1,000-gallon storage tank in the Dewatering Building basement. During a fill event, centrate was pumped from the 1,000-gallon storage tank into the day tank. Upon settling of the centrate to reduce the solids entering the reactor, the centrate from this day tank then was fed to the pilot reactor via a centrifugal pump (feed pump). The reactor was loaded based on target N loading. Feed rates varied during the start-up period and were adjusted manually as summarized in the Results and Discussion section below. Centrate in the reactor was treated by the mixed biomass through multiple feed, react, and decant cycles which will be discussed in detail below. The feed was considered alkalinity-limited due to $FeCl_3$ addition to the centrifuge feed. Thus, sodium bicarbonate ($NaHCO_3$) was added to the day tank prior to reactor feeding on certain occasions. Additionally, a sump pump was installed later during the start-up period (November 1, 2012) for mixing of the added $NaHCO_3$, by drawing centrate from two feet above the bottom of the day tank and circulating/discharging it at the top of the day tank. After treatment, the pilot effluent was discharged to a nearby manhole through the decant valve and was recycled to the head of the plant.

FIGURE 2: HYDROCYCLONE ON THE DEMON® PILOT TO RETAIN ANAMMOX AND REMOVE COMPETING BACTERIA SUCH AS NITRITE-OXIDIZING BACTERIA AND ANOXIC HETEROTROPHIC BIOMASS

FIGURE 3: PICTURE OF ANAMMOX BACTERIA FROM CYCLONE UNDERFLOW



Sequencing Batch Reactor Cycles. The Demon® process strategy performed four SBR operation cycles per day. The theoretical duration of each operational cycle was six hours, which included in general five hours of reaction (aeration or mixing) and feeding, 30 minutes of settling, and 30 minutes of decanting, but the actual settling time varied from 8 minutes to 40 minutes based on results of settling tests (discussed in the Settleability section). Although the reaction and feeding phase was scheduled within a fixed time frame of five hours in each cycle, the actual reaction time was subject to a simple on-off controller based on the pH signal. The reaction phase consists of the initial mixing period and several mini-cycles of aeration and fill/ mix periods.

The centrate was usually fed during a fill/mix period. Aeration was initiated at an upper pH set-point. Nitritation by the AOBs led to hydrogen ion (H^+) production and drove down the pH value to a lower point where aeration stops. In the subsequent anaerobic step, which is considered as a react period, accumulated NO_2^- was used for oxidization of NH_3 by the ANAMMOX bacteria. In the course of this biochemical process the recovered alkalinity from limited denitrification as well as the continuous feed of alkaline centrate led to an increase in pH to the upper set-point where aeration was switched on again.

Several short partial nitritation/ANAMMOX cycles occurred during the fill/react phase, which served to limit the buildup of NO_2^- in the reactor. The NO_2-N concentration was monitored daily to ensure low concentrations and avoid NO_2^- toxicity to the ANAMMOX bacteria.

Demon® Process Control. Control of the Demon® process was refined to address three elements: (1) time control to allow the fill and draw operation of the SBR; (2) pH control; and (3) DO control.

1. Time control defined operation cycles of six hours each, involving a fill/react phase, a settle phase, and a decant phase as described above.

2. For pH control, the partial nitritation reaction depressed the pH and the anaerobic NH_3-oxidation reaction elevated the pH. Thus, aeration was initiated at the upper pH and stopped at the lower pH set-point to maintain a pH bandwidth of 0.02 units. The actual duration of aeration intervals were controlled by the pH signal through the on-line pH probe.

3. For DO control, DO was controlled to a low value (around 0.3 mg/L) during the aeration times to prevent rapid NO_2^- production by AOBs and repress NOBs that convert NO_2^- to NO_3^-.

The monitoring program entailed three daily grab samples collected from the Demon® system five days a week during the day shift. An influent sample was collected from the inlet of the feed pump anytime during a monitoring day during the feed/react phase; a reactor sample was taken from the sampling port located in the middle of the reactor during the pause phase (well mixed after decant phase, but before next cycle starts); and an effluent sample was collected from the decant valve during the decant phase. As shown in Table 2, average concentrations of the effluent and reactor samples were similar during the time period of September 12,

TABLE 2: AVERAGE CONCENTRATION DATA OF EFFLUENT AND REACTOR SAMPLES IN DEMON® PILOT SYSTEM TESTING FROM SEPTEMBER 12, 2012, TO OCTOBER 29, 2012

Sample	NH_3-N (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	Alkalinity (mg/L)	Sol-COD (mg/L)
Effluent	79.2	61.2	4.41	828	107
Reactor	78.4	57.9	2.53	840	104

2012, to October 29, 2012. In the later stages of the study, the sampling plan was modified to take only reactor and influent samples while the reactor was in aeration mode in order to see the actual concentration of NO_2-N in the system. Effluent samples were replaced by reactor samples on October 30, 2012, and forward, because of their similarity.

The concentrations of NH_3-N, NO_2-N, nitrate N (NO_3-N), volatile SS (VSS), total SS (TSS), chemical oxygen demand (COD), soluble COD (sol-COD), orthophosphate (ortho P), and alkalinity were determined by using the standard methods (American Public Health Association, American Water Works Association, Water Environment Federation, 1998). Alkalinity is expressed as mg/L calcium carbonate throughout the report. The wastewater quality was characterized for process control and to evaluate pilot performance.

Due to the loss of biomass caused by excessive floating sludge identified during the pilot testing, periodic settling tests were performed to ensure a clean supernatant was discharged. For this test, a grab sample was taken from the reactor, put in a glass quart jar, sealed, and mixed. The sample was allowed to settle. Settling time and time to sludge flotation were recorded. This information was used to change the settle phase time of the reactor.

The pilot system was alkalinity-limited due to $FeCl_3$ addition to the centrifuge feed. Thus, $NaHCO_3$ was added to the pilot day tank most of the time to make up the lack of alkalinity for efficient removal performance. Stress testing of no $NaHCO_3$ addition was performed for two weeks to evaluate the effect of alkalinity on the pilot performance (Table 1).

Low temperature effects on the performance were investigated for two weeks. In the first week, a sudden temperature drop from 30 to 25°C was made and maintained; in the following week temperature in the reactor was decreased one degree per day to reach 20°C by the end of the study (Table 1).

Effect of polymer dosage on the performance was also tested. Mannich polymer was dosed to the Egan centrifuge at a higher concentration of 255 parts per million (ppm) instead of the normal dosage of 203 ppm, resulting in a 26 percent increase during the polymer stress testing (Table 1).

Egan WRP centrifuges operate only five days a week, Monday through Friday. In order to simulate a weekend or repair shutdown at the Egan WRP, the Demon® pilot system was operated in mixing mode (idle) for 36 to 72 hours (Table 1).

Weekly conference calls with the vendor representative, Mr. Chandler Johnson, and Dr. Bernard Wett, were also held to discuss operational changes and problems encountered during the pilot study. The vendor summarized and sent out operational data during the week, includ¬ing flow rates, probe data, and screenshot information of unusual incidents. Operational changes were made based on discussion through these conference calls and emails. The flow rate and influent NH_3 concentration were used to determine the loading rate on the pilot.

Results and Discussion

Loading Rate and Nitrogen Removal Efficiency. The pilot reactor was operated for five months starting from September 11, 2012, to assess the NH_3 removal efficiency and capacity through monitoring of the influent and effluent. The initial loading rate was kept low in order to minimize NO_2-N and NO_3-N effluent concentrations and also to avoid NH_3 shock feed to the system. NO_3-N is monitored as an indication of NOB inhibition. Based on the deammonification stoichiometry, 10.6 percent of the incoming ammonium is converted to NO_3^-. Greater than 10.6 percent NO_3^- production would indicate unwanted NOB activity.

Table 3 summarizes the number of samples taken and a statistical analysis of the influent, reactor, and effluent water quality of the pilot. Wide ranges of TSS, VSS, and COD concentrations were observed due to high solids entering the reactor occasionally during the test period. Influent alkalinity also fluctuated in a wide range. Alkalinity needs and additions were roughly estimated based on single grab samples of the raw centrate. All other analytical parameters of influent and effluent showed relatively stable characteristics.

Table 4 summarizes the average and some percentile influent and effluent characteristics and removal data from the pilot reactor in the five-month study; an average of 76 percent total N and 85 percent NH_3-N removal with average influent NH_3-N concentration of 952 mg/L were observed. Please note this average removal efficiency also includes values from stress testing without alkalinity addition, in which the average NH_3-N removal efficiency was only 44 percent.

The NH_3-N loading rate was gradually increased approaching the design point of 0.6 kg N/cubic meters (m^3)-day by the end of two months. Figure 4 illustrates the loading rate and average NH_3-N removal efficiency with time. The system had typically been loaded in the range of 0.5 to 0.6 kg/m^3-day after the start-up period while maintaining an average NH_3-N removal efficiency of over 85 percent. As observed in Figure 4, an increase of 400 percent (0.1 kg N/m^3-day up to 0.4 kg N/m^3-day) in loading was achieved during the first month of the operation. The percentage removal of NH_3-N during this period of time was greater than 90 percent. Loading was slowed in late October due to the alkalinity limitation as discussed in detail below and poor NH_3-N removal (75 percent); overloading can occur if the AOBs do not have enough alkalinity to nitrify the NH_3 to NO_2^-, causing poor NH_3 removal during deammonification by the ANAMMOX bacteria. As mentioned above, the alkalinity imbalance was remedied through $NaHCO_3$ addition. This allowed a parallel increase in the N loading. The percent removal increased from 75 percent to 88 percent after this adjustment in early November 2012.

Other adjustments to loading were made throughout the terminus of the study. After a NO_2^- spike of 161 mg/L on November 9, the volumetric loading of the system was reduced to 0.2 kg/m^3-day in order to address potential toxicity on the ANAMMOX bacteria. Starting on December 24, 2012, no external alkalinity was added to the day tank for stress testing, causing the removal efficiency to decrease from over 80 percent to around 50 percent. The average loading rate was increased to 0.7 kg N/m^3-day and even up to 0.9 kg N/m^3-day to achieve the same treatment capacity (2.7–3.6 kg NH_3 removed per day) at this lower removal efficiency.

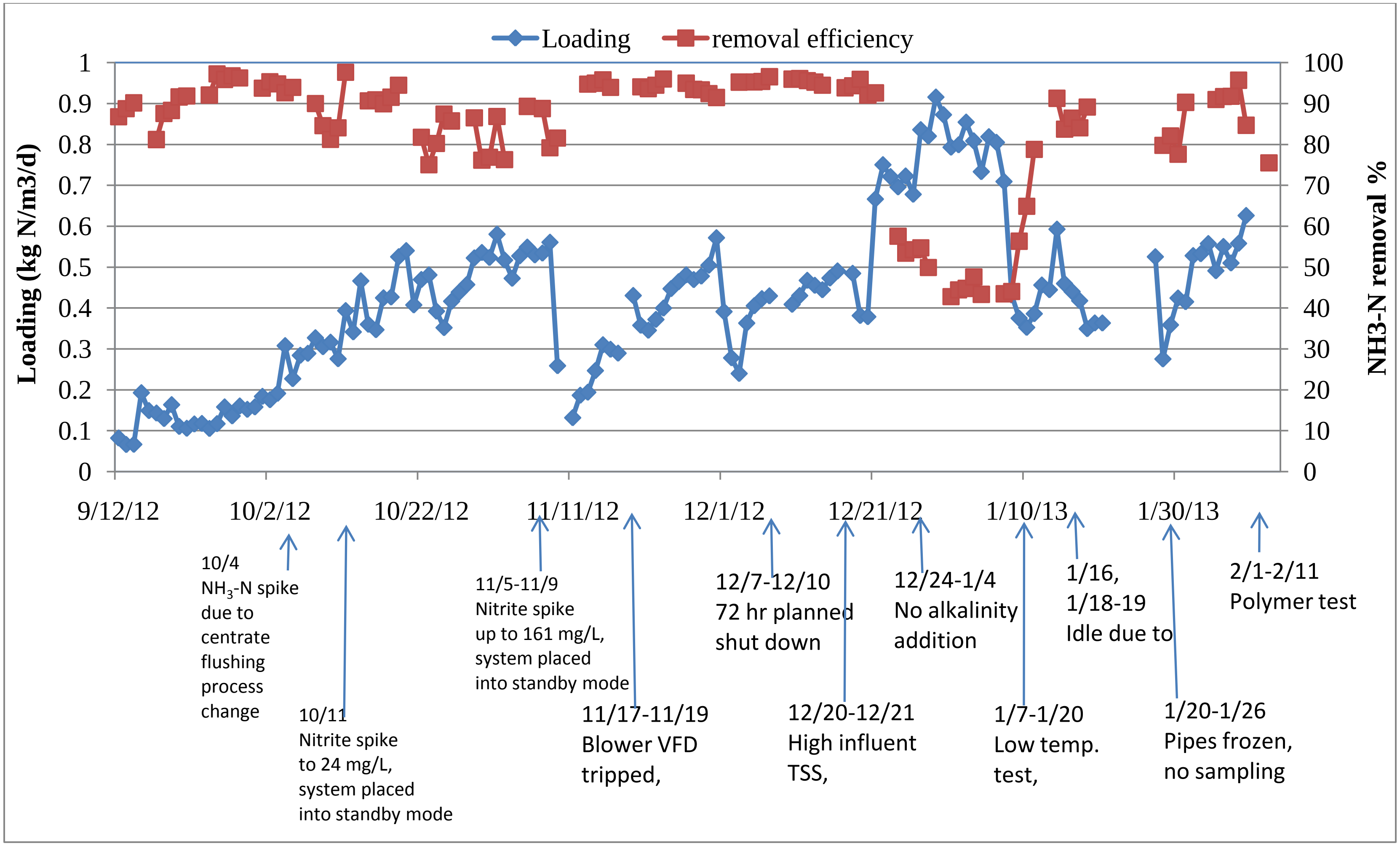
TABLE 3: STATISTICAL DATA OF THE INFLUENT REACTOR AND EFFLUENT OF THE DEMON® PILOT SYSTEM AT THE JOHN E. EGAN WATER RECLAMATION PLANT DURING THE FIVE-MONTH STUDY

	TSS (mg/L)	VSS (mg/L)	NO_2-N (mg/L)	NO_3-N (mg/L)	NH_3-N (mg/L)	COD (mg/L)	sol-COD (mg/L)	ortho-P (mg/L)	ALK (mg/L)
					Influent				
No. Samp.	100	100	100	100	100	72	72	100	100
Min	33	21	0.04	0.2	607.6	226	149	0.1	1,923
Max	19,140	12,860	0.95	1.8	1,299.1	14,142	720	11.6	8,311
Aver	1,628	1,093	0.10	0.5	951.5	1,330	279	2.0	3,838
Stdev	4,033	2,698	0.11	0.5	204.5	2,834	99	2.1	1,227
					Effluent				
No. Samp.	35	35	35	35	9	34	30	–	6
Min	28	20	1.07	18.2	18.6	96	58	–	689
Max	1,550	1,250	24.25	90.0	213.0	2,005	201	–	1,026
Aver	286	227	4.35	61.6	78.9	392	128	–	909
Stdev	431	343	4.12	17.2	47.4	471	32	–	141
					Reactor				
No. Samp.	100	100	100	100	100	–	37	100	100
Min	892	775	0.17	2.5	33.4	–	70	0.1	133
Max	10,740	7,140	161.00	123.2	688.6	–	576	6.1	1,871
Aver	3,022	2,136	8.02	68.8	192.8	–	197	1.0	723
Stdev	1,701	1,096	22.66	21.9	203.5	–	93	1.0	364

TABLE 4: AVERAGE AND PERCENTILE DATA OF THE INFLUENT AND EFFLUENT OF THE DEMON® PILOT SYSTEM AT THE JOHN E. EGAN WATER RECLAMATION PLANT DURING THE FIVE-MONTH STUDY

	Inf NH_3-N (mg/L)	Eff NH_3-N (mg/L)	NH_3-N Rem %	Eff NO_3-N (mg/L)	Eff NO_2-N (mg/L)	TN Rem %	Inf sCOD (mg/L)	Eff sCOD (mg/L)	Inf PO_4-P (mg/L)	Eff PO_4-P (mg/L)
Average	951.5	192.8	85	69.1	9.9	76	284.0	179	2.0	1.1
10th Percentile	685.2	39.3	55	47.2	2.0	50	191.2	104.1	0.3	0.3
25th Percentile	813.8	50.2	81	55.3	2.4	73	219.5	125.0	0.7	0.4
50th Percentile	929.9	88.8	91	64.3	3.6	82	263.5	165.0	1.4	0.6
75th Percentile	1,159.4	187.9	94	74.5	5.0	86	337.0	201.0	2.7	1.4
90th Percentile	1,215.0	519.2	96	97.4	15.1	87	367.0	283	4.0	2.2

FIGURE 4: DAILY AVERAGE AMMONIA NITROGEN LOADING RATE AND REMOVAL EFFICIENCY OF THE DEMON® PILOT AT JOHN E. EGAN WATER RECLAMATION PLANT



A factor affecting the maximum load and removal efficiency is the percent aeration time per overall cycle. According to a discussion with the vendor, the percent aerobic time per cycle needs to be between 60 percent to 70 percent in order to achieve the maximum loading rate while still maintaining performance. Therefore, as shown in Figure 5, the pilot reactor loading rate at the Egan WRP was increased slowly and achieved its maximum loading rate on November 9 (NO_2^- spike day), and then again in late December.

Figure 6 provides added detail of the daily performance of the Demon® pilot with time. The maximum removal efficiency of the pilot was up to 97 percent of NH_3-N and 92 percent of total N, and the average removals were 85 percent of NH_3-N and 76 percent of total N, respectively (Table 3). The relatively lower N removal efficiency points can be attributed to many variables during the start-up period, e.g. limited alkalinity in the centrate, elevated NO_2^- concentration, or solids wash-out from the reactor. These factors will be discussed later in the "Effect of Alkalinity" and the "Problems Encountered During the Demon® Pilot Operation and Lessons Learned" Sections.

As stated above, the NO_3^- produced in the pilot should be 10.6 percent of influent ammonium concentration. However, the NO_3^- produced in the process can be denitrified during the anaerobic step by heterotrophic biomass utilizing the organic content of the reactor feed. Figure 7 shows the NO_3-N concentration over the pilot-test period varying from 0.2 percent to 12.8 percent of influent NH_3-N. By comparing NH_3-N and total N removal in the pilot, a final NO_3^- average production rate of 8.7 percent was determined. Given the stoichiometry, we can therefore assume that only 1.9 percent of the generated NO_3^- was denitrified. The average influent and reactor sol-COD were 281 mg/L and 183 mg/L, respectively. These low concentrations suggest that denitrification was minimized due to limited substrate for the denitrifiers.

Effect of Alkalinity. Nitrification requires sufficient alkalinity to buffer acidification and to supply bicarbonate as substrate for the autotrophic nitrifying biomass. Inadequate alkalinity will limit the growth of AOBs, especially since these organisms depend on bicarbonate for cell synthesis. A solution is to enable the Demon® process to operate under pH conditions that maximize the availability of inorganic carbon. The optimum alkalinity-to-NH_3-N concentration ratio is 3.6:1 for partial nitritation/deammonification. With an influent NH_3-N concentration of 1,000 mg/L, the alkalinity needed for 90 percent NH_3-N removal is calculated to be realistically in the range of 3,000–3,500 mg/L. Centrate influent at the Egan WRP had an average alkalinity of 2,597 mg/L, which illustrates a lack of approximately 1,000 mg/L alkalinity for efficient NH_3 removal.

The pilot system was alkalinity-limited due to low alkalinity in the centrate as a result of $FeCl_3$ addition to the centrifuge feed. Thus, $NaHCO_3$ was added to the feed to the pilot unit when the monitoring data suggested the centrate was lacking in alkalinity, and performance was observed to drop off. When the system is alkalinity-limited, the first step of the process, i.e.partial nitritation of NH_3, is not efficient, resulting in not enough NO_2^- substrate for ANAMMOX bacteria. Therefore, low removal performance would be observed in parallel with a NH_3-N spike. Figure 8 illustrates low NH_3-N removal efficiency due to an alkalinity limitation, especially on days without external alkalinity addition. It also shows that alkalinity in the reactor was fluctuating during the test period. The reason for this was a time lag between

FIGURE 5: PERCENT AERATION TIME PER CYCLE OF THE DEMON® PILOT AT THE JOHN E. EGAN WATER RECLAMATION PLANT

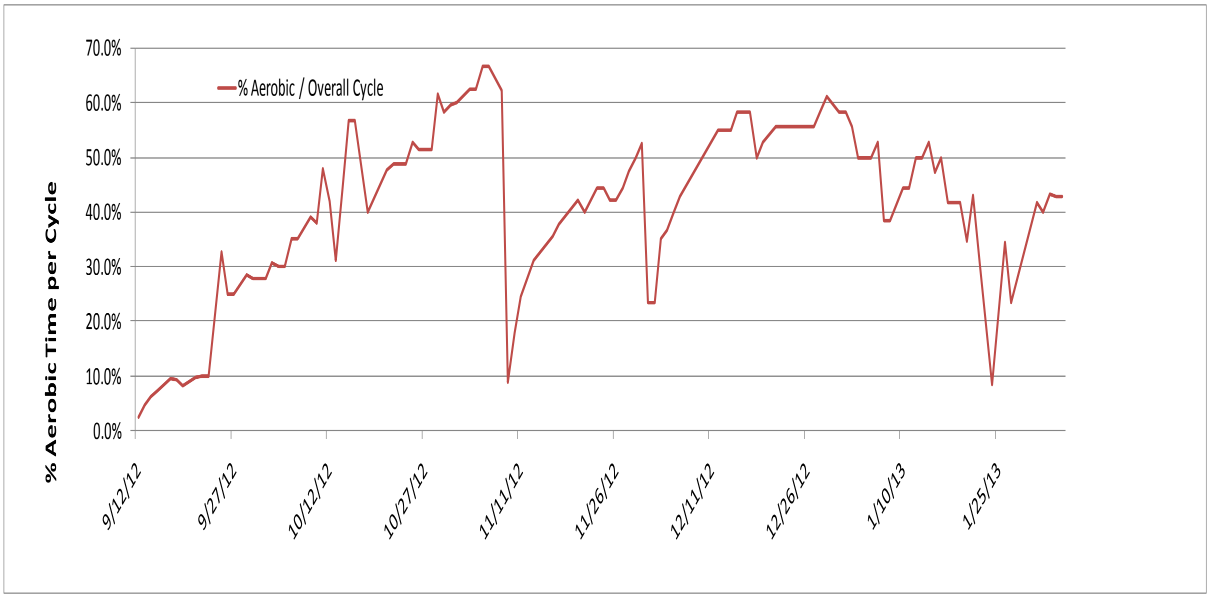


FIGURE 6: AMMONIA NITROGEN AND TOTAL NITROGEN REMOVAL EFFICIENCIES OF THE DEMON® PILOT OPERATION

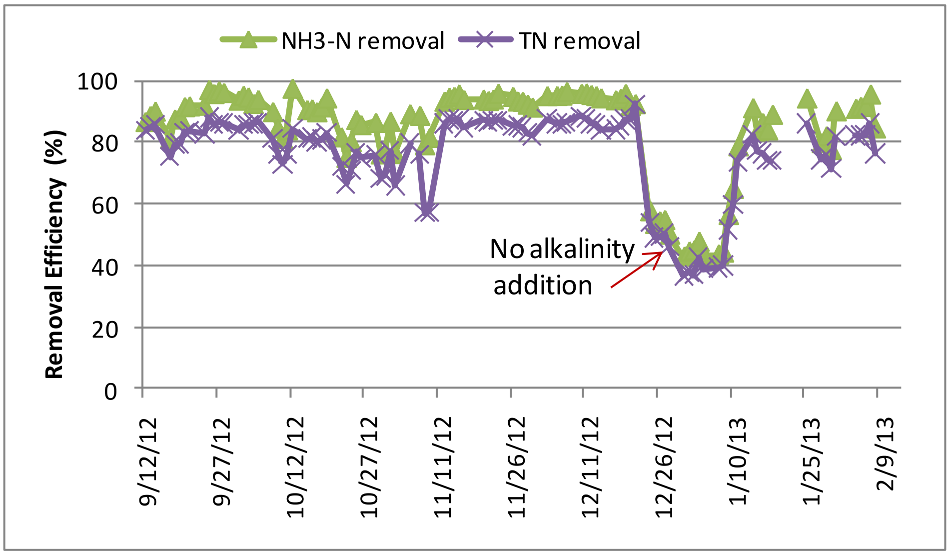


FIGURE 7: NITRATE NITROGEN PERCENTAGE IN THE DEMON® PILOT REACTOR OVER THE PERIOD OF THE STUDY

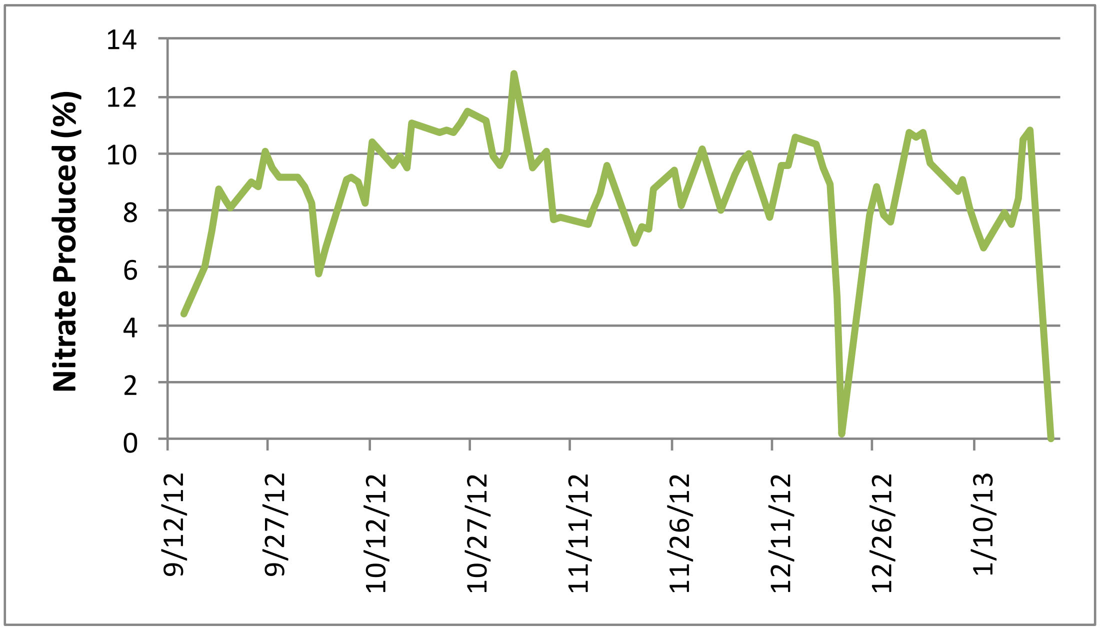
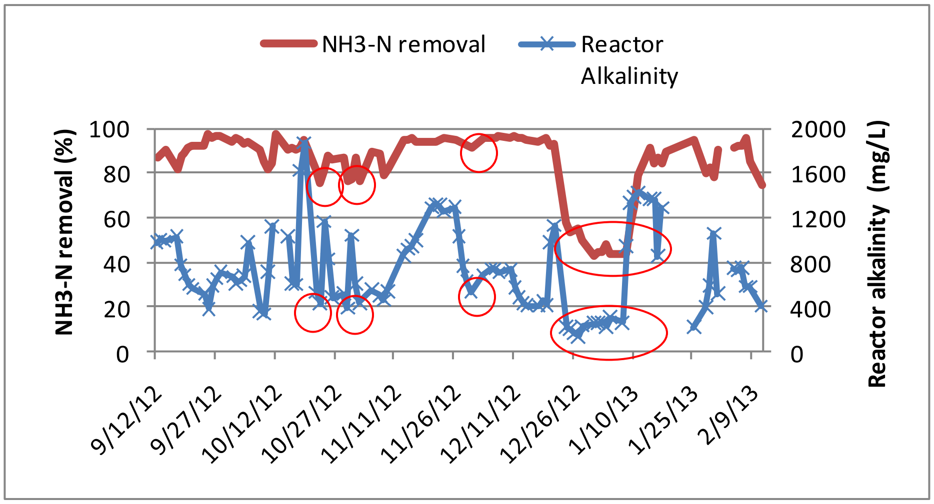


FIGURE 8: ALKALINITY AND AMMONIA NITROGEN REMOVAL IN THE DEMON® PILOT REACTOR OVER THE PERIOD OF THE STUDY*



*Effluent alkalinity data were used before October 30, 2012; then effluent samples were replaced by reactor samples after October 30, 2012.

obtaining the alkalinity data of raw centrate and calculation of the correct amount of $NaHCO_3$ to add. In addition, bicarbonate powder was used instead of solution which causes dissolution and homogeneity issues; this is more of a pilot-test problem in which the full-scale Demon® process would use an alkalinity solution to constantly feed into the reactor.

Figure 9 shows the influent and reactor alkalinity and NH_3 removal efficiency in the system during the alkalinity stress-testing period. With no alkalinity addition, the maximum NH_3 reduction potential is a function of the alkalinity in the feed wastewater. In this two-week period of no alkalinity addition, the average influent alkalinity was 2,597 mg/L and average influent NH_3-N concentration was 1,195 mg/L, resulting in an average NH_3-N removal efficiency of 44 percent. Once alkalinity was restored to the system, removal efficiency increased slowly from 43 percent to 79 percent NH_3-N removal over a period of four days as shown in the rectangle frame. The delayed recovery of removal efficiency may be due to the following reasons: (1) after two weeks of operation at low alkalinity, AOBs needed three to four days to recover their full activity and population; (2) the reactor had a buildup of NH_3-N (688 mg/L) due to the low removal observed during the alkalinity stress testing; when adding the NH_3-rich influent flow upon conclusion of the stress testing, NH_3 overload could have occurred.

However, it should be noted that overload of alkalinity should also be avoided to not leave ANAMMOX in a starving situation, i.e. too much alkalinity will cause too much nitritation of NH_3. Residual NH_3-N concentration needs to be at least 10 mg/L to provide enough food for ANAMMOX bacteria, according to personal communication with Chandler Johnson (WWW, Oklahoma City, Oklahoma).

Effect of Temperature. ANAMMOX bacteria are strongly influenced by temperature. A higher temperature can result in higher ANAMMOX bacteria activity within a certain range. Generally, the optimum temperature for ANAMMOX activity is in the range of 30–35°C (Strous et al., 1999). However, Demon® reactors have been reported to operate in a wider temperature range, i.e. 20 to 37°C (Wett et al. 2006, 2010a; Bowden et al., 2007).

As shown in Figure 10, we investigated a temperature decrease from 30 to 20°C in the reactor over a period of two weeks. In the first week, a sudden decrease from 30 to 25°C was made and maintained; in the following week it was decreased one degree per day from 25 to 20°C. The volumetric loading rate during the temperature test averaged 0.44 kg N/m^3/d, similar to the loading rate at 30°C. The temperature decrease in this mode caused rapid NO_2^- accumulation during the second week when it was operated in the lower 20s; the temperature decrease caused an imbalance between NO_2^- production and NO_2^- consumption rates and consequently increased the vulnerability of operation stability. Wett et al. (2010) reported that this imbalance of NO_2^- can be partially compensated for by reducing the DO level from 0.3 to 0.2 mg/L during the aerobic cycle in parallel with a temperature decrease. Our temperature stress-testing results showed that when the Demon® pilot operated at low temperature (20°C) and a relatively high NO_2-N concentration (up to 61 mg/L), good performance with an average NH_3-N removal of 85 percent was maintained (excludes points from limited alkalinity recovery area as discussed above in the "Effect of Alkalinity" section).

FIGURE 9: INFLUENT AND REACTOR ALKALINITY AND AMMONIA NITROGEN REMOVAL OF THE DEMON® PILOT REACTOR DURING ALKALINITY STRESS TESTING

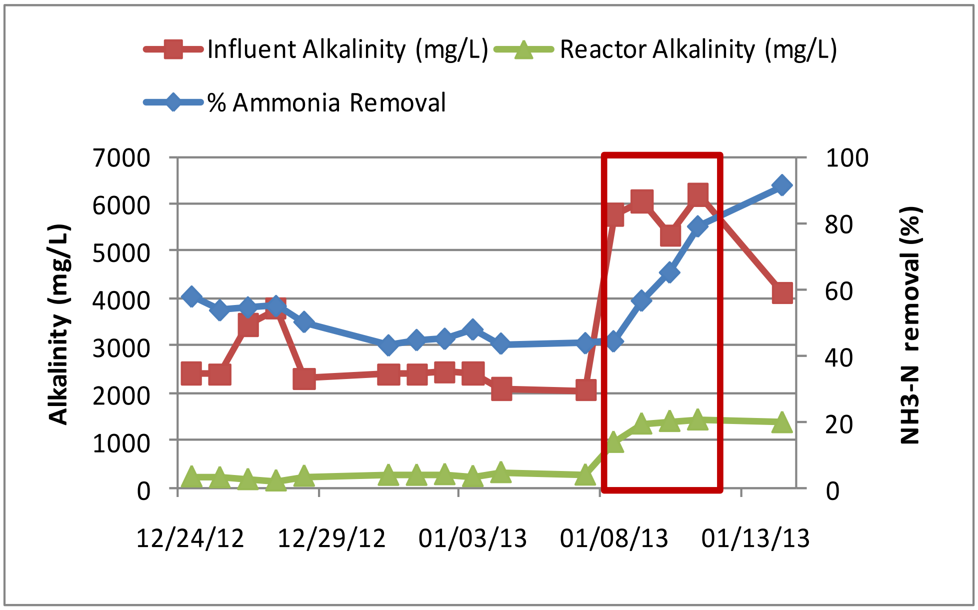
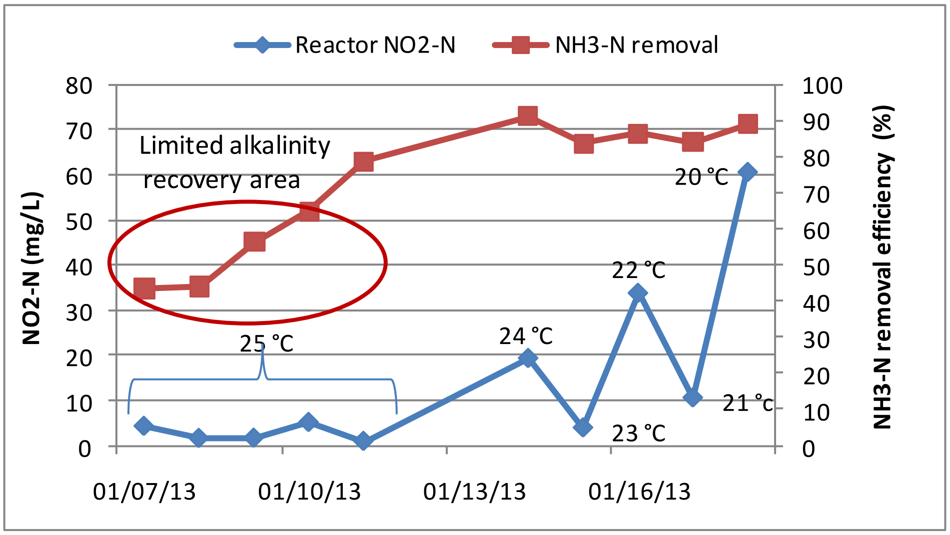


FIGURE 10: NITRITE NITROGEN CONCENTRATION AND AMMONIA NITROGEN REMOVAL IN THE DEMON® PILOT REACTOR DURING TEMPERATURE STRESS TESTING



As reported in the literature, low-temperature operations can also be accommodated by ANAMMOX enrichment to overcome temperature sensitivity of these anaerobic organisms. With the help of cyclone operation to enrich ANAMMOX biomass, the Demon® system in Thun, Switzerland, where an uncovered sidestream reactor is in place, has operated at a temperature of 20°C without loss of operational stability (Wett, B., personal communication with G. Nyhuis, 2009). For the Ruhrverband plant in Germany, the design temperature was set at 25°C (Jardin and Hennerkes, 2012).

Effect of Polymer. Polymer was added to help improve dewatering characteristics of the centrifuge feed. Therefore, residual polymer is usually in the centrate entering the Demon® reactor. Yamamoto et al. (2008) tested the treatment of digester liquor and synthesized wastewater by using partial nitritation followed by a deammonification reactor. While this was not a Demon® reactor, the study indicated a decrease of ANAMMOX activity in digester liquor compared to the synthesized wastewater. This was thought to be due to high amounts of cationic polymers in the digester liquor (Yamamoto et al., 2008). It was assumed that the polymeric organic coagulant that remained in the wastewater attached to the ANAMMOX bacteria caused a decrease in activity. It was later indicated by Jardin and Hennerkes (2012) that the polymers in the reactor's wastewater feed could have an inhibitory effect on the transfer of electron acceptors at the ANAMMOX cell wall. However, separate pilot tests performed by Wett for Ruhrverband, Germany, with seed sludge from the Strass Demon® plant did not show any significant influence of polymer dosage on NH_3 oxidation and NO_2^- reduction (Wett B., 2009).

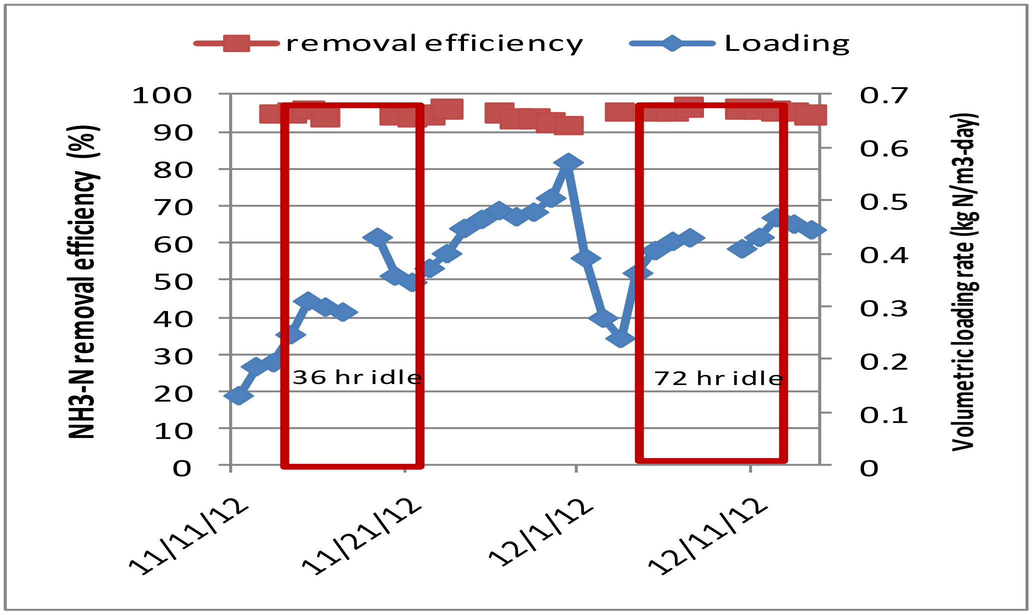
Effect of polymer dosage on the performance was tested at the Egan WRP Demon® pilot. Mannich polymer was dosed to the Egan centrifuge at a higher concentration of 255 ppm instead of the normal dosage of 203 ppm, resulting in a 26 percent increase during the polymer stress testing. NH_3-N removal results showed that this change in polymer dosage had no significant impact on pilot performance. The system was able to maintain an average of 80 percent NH_3-N removal rates with good settling characteristics at the same time.

Operation in Idle Mode. Egan WRP centrifuges operate only five days a week, Monday through Friday. In order to simulate a normal or repair shutdown at the Egan WRP, the Demon® pilot system was placed in mixing mode (idle) for 36 to 72 hours. Figure 11 shows the daily average NH_3-N volumetric loading and removal efficiency during two idle operation periods. It shows no sacrifice of loading rate and removal efficiency two to three days upon restarted operation. Generally, with idle operation for less than five days, the AOBs have a recovery period of one to two days. Additionally, a significant downtime of the system will require starting out at a 20 percent lower loading while closely monitoring the NO_2^- and oxygen (O) level during restart (Johnson, 2012).

Problems Encountered During the Demon® Pilot Operation and Lessons Learned

Solids Washout. Solids washout is defined as unintentional loss of active biomass. In Demon®, the potential for solids washout could occur by two ways: (1) increased hydrocylone

FIGURE 11: DAILY VOLUMETRIC LOADING RATE AND AMMONIA NITROGEN REMOVAL EFFICIENCY OF THE DEMON® PILOT DURING TWO IDLE OPERATION PERIODS



operation to maintain a target ML SS (MLSS) in the reactor during periods of increased solids entering the reactor; and (2) floating sludge exiting the reactor during the decant cycle.

MLVSS or MLSS were measured to evaluate biomass accumulation over the course of the study. Due to the recycled underflow of the hydrocyclone and enrichment of ANAMMOX during the start-up period, total active solids in the reactor were expected to increase over time until a target MLSS concentration is reached. For this pilot study, the MLSS target during stable operations was 3,000 mg/L with an MLVSS of 2,000 mg/L. If high solids are present in the reactor feed, the MLSS concentration can instantly increase. This can cause a number of problems: (1) non-active solids are entering the bioreactor, which can reduce ammonia removal performance; and (2) a large portion of this TSS is usually COD, which can be hydrolyzed to sol-COD and used by anoxic heterotrophic biomass causing denitrification and possibly floating sludge.

During the startup phase of the Demon® reactor, the centrate holding tank in the Dewatering Building basement was initially flushed to dilute the centrate and decrease odor-causing potential. This practice was stopped after October 4, 2012, thereby producing a centrate with higher NH_3-N as well as solids entering the day tank and subsequently the pilot. Between October 4, 2012, and the end of November 2012, in four out of nine fill events, influent with high TSS (>1,000 mg/L) entered the Demon® reactor.

Figure 12 illustrates samples from October 11, 2012, with high TSS flushed into the Demon® reactor. The influent TSS (right bottle) was 9,270 mg/L compared to the normal daily average influent TSS of 55 mg/L. In order to remove the high solids, cyclone operations were increased to five then three minutes per cycle instead of one minute per cycle. This practice was continued until October 24, even after the feed solids concentration reduced to normal levels. MLSS in the reactor subsequently decreased gradually from over 3,000 mg/L to 892 mg/L due to a delay in reviewing monitoring results. As such, the NH_3-N removal efficiency decreased from an average of 91 percent to an average of 85 percent due to solids wash-out. Once these low MLSS values were observed, the hydrocylone operation was reduced in order to build the active biomass. Additionally, in late November, the operation of the day tank was changed to let the centrate settle for a few hours prior to filling the Demon® reactor. This practice helped prevent high SS from entering the Demon® reactor and excessive operation of the hydrocyclone.

Concurrently, periodic settling tests were performed to evaluate whether floating sludge and subsequently solids washout was also problem. If the settling time during the decant phase is too long, ANAMMOX granules can be enmeshed in the flocculated biomass, and loss of both active bacteria can occur. While the consultant normally performed the settling tests, on one occasion on October 12, 2012, settling problems were identified by M&R. Figure 13 shows a ML sample from the Demon® reactor after five minutes of settling; a clear interface between the supernatant and sludge blanket on the bottom of the container is observed, indicating good settling. However, an increasing amount of sludge started floating to the surface between 8 to 15 minutes. The floating sludge contained some of the red granulated ANAMMOX bacteria. Since the settling time for the reactor was set at 25 minutes, if floating problems observed in the test were occurring in the reactor itself, wash-out could have occur, affecting the ANAMMOX SRT, i.e. the decant sample would have a substantial amount of solids. Figure 14 shows the visual comparison of normal effluent (left) and darker solid wash-out effluent (right).

FIGURE 12: PHOTO OF THE OCTOBER 11, 2012, SAMPLES INDICATING HIGH SOLIDS ENTERING THE DEMON® PILOT

FIGURE 13: PHOTOS OF THE MIXED LIQUOR DURING PERIODIC SETTLING TESTS AT SETTLING TIMES OF FIVE, EIGHT, AND FIFTEEN MINUTES, RESPECTIVELY

5 min 8 min 15 min

FIGURE 14: NORMAL EFFLUENT SAMPLE (LEFT) AND SOLIDS WASH-OUT EFFLUENT SAMPLE (RIGHT) FROM THE DEMON® PILOT

As mentioned above, this floating phenomenon may be due to following reasons: (1) denitrification: an increased amount of influent COD occurred whereby heterotrophic denitrification caused N_2 bubbles to form and subsequent sludge flotation, i.e., the sludge floats due to N_2 bubbles created by the ANAMMOX bacteria; and (2) deammonification: N_2 produced from deammonification process lifted sludge to the surface.

Regarding the first reason above, anoxic heterotrophic biomass (AHB) is another organism which competes with ANAMMOX for NO_2^- with the exception of NOBs. Higher TSS entering the equalization tank normally yields higher total COD entering the reactor. The presence of excess amounts of organic carbon will increase the denitrifiers' activity significantly to outcompete the ANAMMOX organisms, although limited availability of organic carbon can also help reducing residual NO_3^- concentration through denitrification by this same AHB. Over the course of the pilot study, we assumed that two percent NO_3^- removed by denitrifiers, which indicates negligible AHB activity and a decrease in potential of floating sludge via this mechanism

Generally, the biomass produced by the Demon® pilot indicated good settling. The reason for a severe loss of solids at the beginning of October 2012 was assumed to be caused by the excessive floating sludge and increased hydrocylone operation. To combat the floating sludge concern, the settling phase time was adjusted in accordance with the performed settling tests of ML, e.g. reduced settling time from 40 minutes to 25 minutes, then to as low as eight minutes.

Table 5 shows the results of VSS portion in MLSS before and after washout problems on October 12, 2012, i.e. 83.1 percent before and 76.7 percent after the first time floating sludge was observed. In another circumstance of four days (January 8 through 11, 2013) consecutive high TSS entering the reactor (averages of 8,065 mg/L influent TSS), the VSS portion in MLSS averaged 66.2 percent, which indicated biomass was washed out due to increased but not closely monitored cyclone operation on floating sludge.

Solids wash-out contributed to low MLSS levels in the reactor during the study period. During the start-up period, when conditions in the reactor, e.g. flow rate, feed solids concentration, and biomass concentration, etc., fluctuate, washout via floating sludge with poor settling properties and increased in hydrocyclone operations is more likely to happen. When the system approaches steady state conditions, higher MLSS concentrations with improved settling properties are expected.

Chronic high solids entering the reactor and loss in active biomass was not observed. This was due to the change in operations of allowing the centrate in the day tank to settle before feeding the reactor, close attention and change in operation of the hydrocyclone, and modification of settling times. However, even with these measures in place, washout and lower ammonia removal performance did occur as identified above and shown in Table 5. While the pilot was able to operate even under elevated feed solids concentrations, ease of reactor operation would benefit from a pre-solids removal treatment.

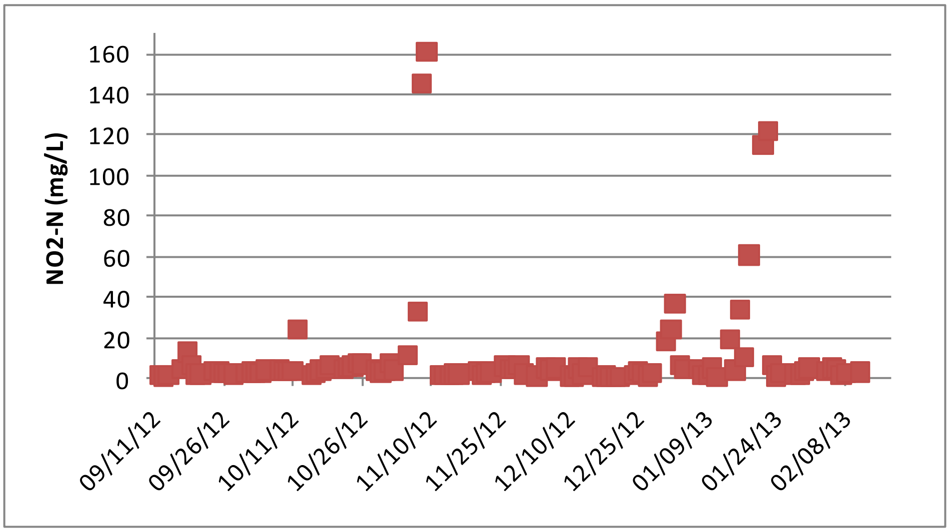
Robustness of Demon® Pilot. Due to damage to a pressure sensor in the reactor on Thursday, October 11, 2012, the Demon® system was set to idle, i.e. no feed, for eight hours at a residual elevated NO_2-N concentration of 24 mg/L (Figure 15). The system still maintained

TABLE 5: VOLATILE SUSPENDED SOLIDS PORTION IN MIXED LIQUOR SUSPENDED SOLIDS BEFORE AND AFTER FLOATING SLUDGE EPISODES IN THE DEMON® PILOT STUDY

Time	Influent TSS	NH_3-N Removal	VSS/TSS in MLSS
Before floating sludges (9/12/12–10/10/12)	45	91%	83.1%
First time high influent TSS observed (10/11/12)	9,270	84%	76.7%
Consecutive high TSS entering (1/8/13–1/11/13)	12,205	61%*	66.2%

*Low NH_3-N percent removal was partially due to low alkalinity recovery period as discussed in the "Effect of Temperature" section.

FIGURE 15: NITRITE NITROGEN CONCENTRATION IN THE DEMON® PILOT REACTOR DURING PILOT STUDY



good NH_3 oxidation treatment, i.e. maintaining 84 percent NH_3-N removal during this downtime. A sample collected 72 hours after the spike indicated that the effluent NO_2-N concentration decreased to 3.6 mg/L. On November 6, 2012, the system experienced a week-long NO_2^- spike, increasing from 10 to 161 mg NO_2-N/L due to system overload and delay in laboratory data reporting. Once the NO_2-N data was provided, the feeding was immediately shut down to allow the system to recover and reduce the NO_2^- in the reactor. The feeding was stopped, and the reactor was mixed for 24 hours. Then it was placed back into service at a lower loading rate (0.15 kg N/m^3-day versus 0.55~0.6 kg N/m^3-day before the NO_2-N spike). A sample collected 72 hours after the spike was detected indicated that the NO_2-N decreased to 1.5 mg/L, which indicated that the elevated NO_2-N concentration over an extended period of time did not affect deammonification performance after inhibition of the ANAMMOX activity as long as feeding was suspended and loading during restart was kept at a minimum.

Two more NO_2-N spikes were observed during the low-temperature stress testing in January 2013. ANAMMOX activity decreased in the early stages of sudden reduced temperature from 30 to 20°C, resulting in a NO_2^- spike episode. From January 10 to 15, 2013, reactor NO_2^- increased from 9 to 121 mg N/L but an NH_3-N removal efficiency of 80 percent was still maintained. In order to handle the NO_2^- spike without causing irreversible toxic effects on the ANAMMOX, the feeding ceased for a short period followed by feeding at a lower loading rate. Our experience with NO_2^- spikes at the Egan pilot is that the system showed great ability to handle large NO_2^- spikes over a period of five days and was able to recover in a few days' time.

Conductivity was found to be a good parameter to monitor the performance of the process and the NO_2^- spike, but only when the system has low NH_3-N concentrations in the reactor. Its advantage is that it can be easily measured giving immediate real-time feedback. Figure 16 shows the increased conductivity due to elevated NO_2^- concentrations on November 5 through 9, 2012. Once elevated NO_2-N levels were detected, the system was put into mixing mode for 24 hours; during this time the conductivity dropped steadily as NO_2^- and NH_3 were being consumed by ANAMMOX bacteria. On November 10, 2012, a small amount of raw centrate was fed to the reactor to increase the NH_3 concentration and help reduce the NO_2^- still present. By the evening of November 10, 2012, a reduced loading rate of 0.15 kg N/m^3-day was introduced to the system rather than the target load of 0.55–0.6 kg N/m^3-day. A grab sample taken 72 hours later showed that NO_2-N lowered to 1.4 mg/L in the system; conductivity decreased as well.

On October 4, 2012, NH_3-N concentration in the reactor spiked to 280 mg/L due to a sudden increase in both flow rate and centrate NH_3-N concentration. As shown in Figure 17, the influent NH_3-N concentration jumped from 612 mg/L to 802 mg/L primarily due to a change in the reduced centrate flushing procedures on October 4, 2012. At the same time, the flow rate was increased, causing the loading rate to instantly double. This resulted in too much NH_3 for the active biomass to treat, resulting in lower removal efficiency. The problem was solved by lowering the influent feed rate to allow the biomass to adjust to the high NH_3-N concentrations in the reactor before continuing. Effluent NH_3-N concentration leveled off to 48 mg/L within 24 hours, and the NH_3-N removal efficiency was 92 percent. Again, the Demon® pilot showed tolerance to a high shock of NH_3 influent during a short period of time as long as feeding was postponed until the NH_3 in the reactor was treated. As shown in Figure 17, the ten-day moving average influent NH_3-N shows a steady increase throughout the testing period; the ANAMMOX

FIGURE 16: CONDUCTIVITY AND pH TREND LINES DURING NITRITE SPIKE IN NOVEMBER 2012

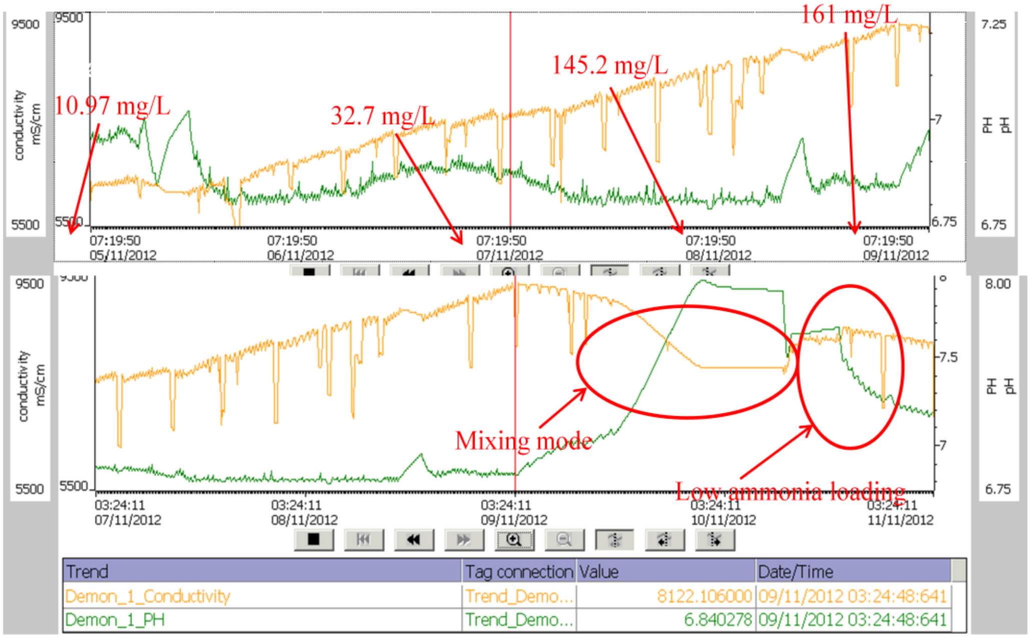
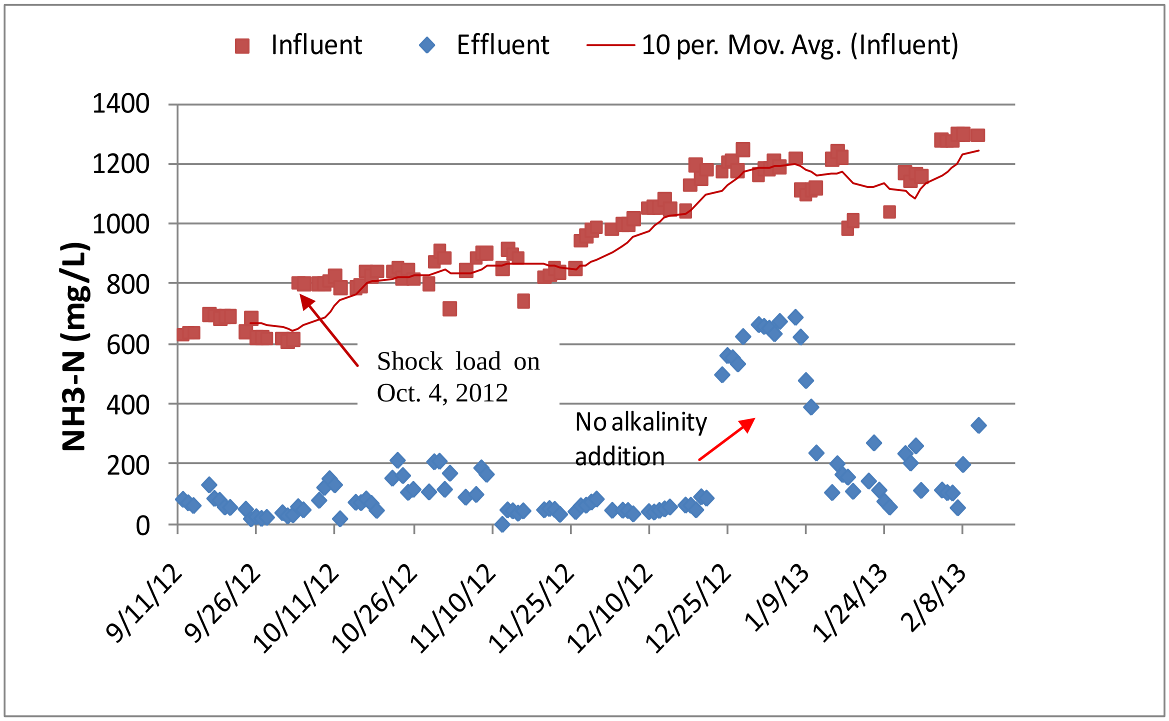


FIGURE 17: AMMONIA NITROGEN CONCENTRATION OF THE DEMON® PILOT INFLUENT AND IN THE EFFLUENT OVER THE PERIOD OF THE STUDY*



*Effluent samples were replaced by reactor samples on October 30, 2012.

bacteria showed great ability to cope with this increase and were able to maintain a low NH_3-N effluent concentration (100 to 200 mg/L NH_3-N). It is critical to develop the operation ranges for pH, DO and temperature, which allows reliable and stable performance if the system is subjected to variable influent characteristics and NH_3-N loadings.

The pilot has also proved to have a great ability to cope with the high TSS entering the DEMON® reactor. The cyclone was used to waste the excess solids with only a little effect on the performance, i.e. 91 percent NH_3-N removal down to 85 percent during a high-TSS episode on October 11, 2012.

When the MLSS in the reactor decreased down to 892 mg/L on October 25, 2012, due to the wash-out problems cited above, the system still produced over 80 percent NH_3-N removal. This indicates that the system still had excess capacity and a very active population of ANAMMOX bacteria. Please note that the target MLSS in the reactor was 2,500 to 3,000 mg/L.

Polymer stress tests showed that an increase of 26 percent in polymer dosage to the digester sludge had no significant impact on pilot performance. The system was able to maintain an average of 80 percent NH_3-N removal with good settling characteristics at the same time.

We have not seen any significant loss in treatment during the pilot test. The system has shown to be robust and quickly returns to normal operation after NO_2^- spikes, shock loads of NH_3, high TSS entering the reactor, low temperatures, increased polymer concentrations, and low MLSS concentrations.

Ease of Operation. District staff did not operate the Demon® pilot. This section is based on the information the vendor provided. It was classified into two steps for set-points – initial start-up and stable load/operation.

On the set-point page of the pilot's control panel there are a total of 45 parameters which can be changed and modified, but only a handful of parameters were modified during initial start-up and stable operation. These parameters are listed below.

Initial Start-Up.

1. **Time for Aeration** – Time for aeration was increased during the initial start-up phase in concurrence with the growing AOBs, i.e. aeration times could increase when the AOBs could accept higher loads. For the Egan pilot study, aeration times started 0.3 minutes in September 2012 and increased to 10 minutes by the end of December 2012. Likewise, the load increased from 0.1 kg N/m^3-day to 0.5 – 0.6 kg N/m^3-day during this same time period.

2. **Time for Mixing at the Beginning of a Six-Hour Cycle** – Time for mixing was decreased as loading increased during start-up. Lowering the mixing time allows more mini-cycles to occur within the entire cycle period. An initial

mixing time of 10 minutes of mixing in the beginning of the study was decreased down to less than four minutes at the end of December 2012.

3. **Time for Fill/Mix During a Mini-Cycle** – Once the time for mixing in the beginning phase has been reduced, the time for filling/mixing in the multiple mini-cycles will increase to help increase the loading to the system, i.e. the ANAMMOX bacteria populations were high enough to accommodate a higher load. The pilot system started with a fill/mix time of 0.3 minutes and increased up to one minute near the end of December 2012. The overall time allocation for a Demon® treatment system in stable operation was 60–65 percent for aeration, 25–30 percent for mixing, and 10–15 percent for settling/decanting.

4. **Percent Blower Speed** – As the loading and activity in the Demon treatment system increases, the speed of the blower needs to be increased to accommodate the higher O demand by the AOB bacteria. The Demon® control program has interlocks to provide for minimum and maximum blower operation speeds. At the beginning of the pilot, the maximum blower speed was four percent, and by the end of December 2012 it was 14 percent.

5. **Sludge Removal Time** –The degree of sludge wasting is determined by the load and the NOB population. If the NOB population increases, the system needs to waste so NOBs will not outcompete the ANAMMOX bacteria. In the case of high influent TSS entering the pilot reactor, the sludge-wasting time was typically increased with new batches of centrate.

6. **Low pH Set-Point** – Due to the constant addition of alkalinity to the equalization (EQ) tank, the low pH set-point was being change typically right after addition of pretreated centrate. Once the pH set-point was set, it was not changed until a new batch of centrate was added. During the two-week no-alkalinity addition test, the low pH set-point was only changed three times though.

7. **Percent Speed of Feed Pump** – Due to the changing head pressure on the feed pump from the level of centrate in the EQ tank, the percent speed of the feed pump needed almost daily attention to ensure the system would treat the same load in the reactor. On days when new centrate was added to the EQ tank, the set-point was 80 percent; when the level in the tank decreased, the percent speed would be increased by five percentage points each day until 100 percent pump speed was met, and the tank level was at its lowest.

Stable Operation.

1. **Time for Fill/Mix** – Time for fill/mix does not need to change during stable operation. If the concentration of the influent NH_3 fluctuates, this time would change to provide for proper loading.

2. **Sludge Removal Time** – If the influent TSS is fairly consistent, changing the sludge-wasting rate is not needed. It would need to change if the NO_3^- concentration indicates that the NOB populations were increasing.

3. **Low pH Set-Point** – During the stable operation period, the low pH set-point will only need to be changed a few times per week. If the pH starts to increase from the low pH set-point, it would indicate the system is being overloaded. As such, the following would need to be done: (1) increase the aeration to accommodate the increase in load; or (2) decrease the flow rate if the blowers are at 100 percent already.

Based on the discussion above, the Demon® system requires only a modest level of operator attention especially in stable operation mode.

Conclusions and Recommendations

Based on the results obtained during the pilot study, the following conclusions are drawn and recommendations made:

1. The pilot study demonstrated the effectiveness of the Demon® process at the Egan WRP for removing NH_3 from the centrate during the study.

2. With the external alkalinity addition, the pilot achieved a loading rate of 0.55 kg/m^3-day with an average NH_3-N removal efficiency of 90 percent; without alkalinity addition, the pilot reached a volumetric loading rate of 0.7 to 0.9 kg/m^3-day with an average NH_3-N removal of 44 percent.

3. Alkalinity adjustments to the centrate are required for effective ammonia removal if $FeCl_3$ dosing to the centrifuge feed continues. In order to increase centrate alkalinity without chemical addition, the benefits of CO_2 sparging should be explored to replace $FeCl_3$ addition for sludge conditioning and struvite control before dewatering.

4. The Demon® pilot could be operated at low temperatures such as 20 to 25°C with an average NH_3-N removal efficiency of 85 percent and maintain a similar volumetric loading rate as when it was operated at 30°C.

5. An increase in polymer dosage by 26 percent in the digested sludge had no effect on the Demon® system performance during the 11-day test in this study.

6. Putting the system in mixing mode (idle) for 72 hours had no noticeable effect on the loading rate and system performance after the system restarted.

7. The pilot study has demonstrated the robustness of the Demon® process with respect to short term elevated NO_2^- concentrations, shock loads of NH_3, and low MLSS concentrations in this study.

8. High solids entering the Demon® reactor could cause floating sludge and increased hydrocyclone operation; therefore, for ease of operation of a full-scale system, pre-treatment is strongly recommended.

9. Operational control demands could be minimized during stable operation.

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APPENDIX AI

DEMON® (DEamMONification) LITERATURE REVIEW

DEMON® (DEamMONification) LITERATURE REVIEW

Introduction

The conveyance of the centrate from the John E. Egan (Egan) Water Reclamation Plant (WRP) to the Terrence J. O'Brien WRP has historically caused odor problems in the sewer lines. This ammonia-rich centrate cannot currently be recycled at the Egan WRP due to limited nitrification capacity in its aeration basins. In order to mitigate the odor problem in the sewer lines by recycling the ammonia-rich centrate at the Egan WRP without imposing harm on the existing operations, sidestream ammonia removal treatment technologies were reviewed.

There are three common sidestream treatment methodologies for ammonia and complete nitrogen (N) removal, i.e. nitrification-denitrification, nitritation-denitritation, and partial nitritation-deammonification (ANAMMOX). ANAMMOX has been widely used due to its low energy consumption and no organic chemical requirement. A number of ANAMMOX technologies exist, including DEMON® (DEamMONification), OLAND (Oxygen Limited Autotrophic Nitrification-Denitrification), CANON (Completely Autotrophic Nitrogen removal over Nitrite process), ANITA Mox, and Pacque.

Among these, the DEMON® process (patented by the University of Innsbruck, Austria) has proven to be one of the most promising processes for sidestream N removal. Significant advantages of the DEMON® process over other sidestream treatment processes are maturity and energy savings. As such, a DEMON® sequencing batch reactor (SBR) suspended-growth process pilot was procured from World Water Works, Inc., for a four-month study at the Egan WRP to evaluate its ability to remove ammonia from an ammonia-rich centrate and to assess the technology's ease of operation and robustness per a Monitoring and Research Department memorandum entitled "John E. Egan Water Reclamation Plant Centrate Characterization" dated July 7, 2012. The full-scale applications, process controls, and limitations of DEMON® are discussed herein.

Background

During the anaerobic digestion of sludge, the destruction of organic substances results in the release of significant amount of organic-bound N. The released N immediately binds with the hydrogen ion (H^+), forming ammonium (NH_4^+) and causing an increase in alkalinity. The centrate from dewatered anaerobically digested solids therefore can contain a high concentration of ammonium and can represent a significant N load if recycled directly to the main liquid process train. Separate sidestream treatment to remove the ammonia in the sidestream allows for a significant reduction in this N recycle.

Conventional ammonia removal from digested sludge dewatering liquor, i.e., nitrification and/or denitrification, is a proven and stable technology. However, the process is costly owing to the use of alkalinity, extensive energy from aeration, and/or external carbon for denitrification if complete N removal is desired. The discovery of ANAMMOX bacteria has led to the development of a fully autotrophic process which uses much less energy for ammonia removal, offering the potential for a plant to achieve energy self-sufficiency.

In general, ANAMMOX is a process of anaerobic ammonia oxidation by autotrophic bacteria. First only nitrite (NO_2^-) is produced aerobically by controlling the ammonium-oxidizing bacteria (AOB) and NO_2^--oxidizing bacteria (NOB) in a bioreactor by a partial nitritation process. Ammonia is then converted to nitrogen gas (N_2) directly by using NO_2^- as an electron acceptor, which is accomplished under anaerobic conditions by ANAMMOX bacteria (Figure AI-1). The overall partial nitrification-deammonification reaction occurring in the ANAMMOX process, accounting for cell synthesis (Strous *et al*., 1998), is:

$$NH_4^+ + 0.806O_2^- + 0.066HCO_3^- \rightarrow 0.106NO_3^- + 0.44N_2 + 0.0132C_5H_7O_2N + 2.638H_2O + 0.106H^+$$

(Reaction 1)

Compared to conventional nitrification/denitrification, the ANAMMOX process can use 60 percent less energy (Table AI-1). Furthermore, no carbon substrate is required in the process, because ammonia itself is used as an electron donor. Other advantages include: (1) the process is a net consumer of carbon dioxide (CO_2), compared to a release of CO_2 from carbon oxidation by heterotrophic bacteria in the conventional nitrification/denitrification process; (2) the alkalinity demand for N removal is reduced by about 45 percent; (3) reduction in sludge production; and (4) reduction in greenhouse gases (GHG) due to lower energy use.

The ANAMMOX process has mainly been configured as either a one- or a two-reactor system. Examples of a two-reactor system are the SHARON-ANAMMOX (Single-Reactor High-Activity Ammonia Removal Over Nitrite-Anaerobic AMMonium Oxidation) process and Pacque (a fluidized bed reactor process). The most popular single-reactor processes are OLAND, CANON, DEMON® (a suspended-growth SBR), and ANITA Mox (an attached-growth moving bed bioreactor process).

CANON is a combination of partial nitrification and deammonification in a single reactor, employing two groups of bacteria, namely, *Nitrosomonas*-like aerobic microorganisms and Planctomycete-like anaerobic bacteria (Gong et al., 2007). The concept of CANON was proposed for treatment of low carbon to N wastewaters. OLAND and DEMON® share similar approaches and process mechanisms to CANON as they employ a suspended mixed biomass in a single reactor. The ANITA Mox process employs polyethylene biofilm carriers operating in mixed motion within an aerated wastewater treatment basin. For ANITA Mox, there is a two-layer biofilm system with ANAMMOX bacteria forming an interior layer where anaerobic conditions exist for deammonification around the carrier and an outer layer of nitrifiers where aerobic conditions exist for partial nitrification. The Pacque process is a multireactor system whereby nitritation occurs in a suspended-growth reactor, followed by a settling tank to remove the biomass solids, followed by upflow of the nitrite- and ammonia-rich effluent through a granular ANAMMOX bed reactor for deammonification.

FIGURE AI-1: NITROGEN TRANSFORMATIONS EXPLOITED BY THE ANAMMOX PROCESS (LEFT)

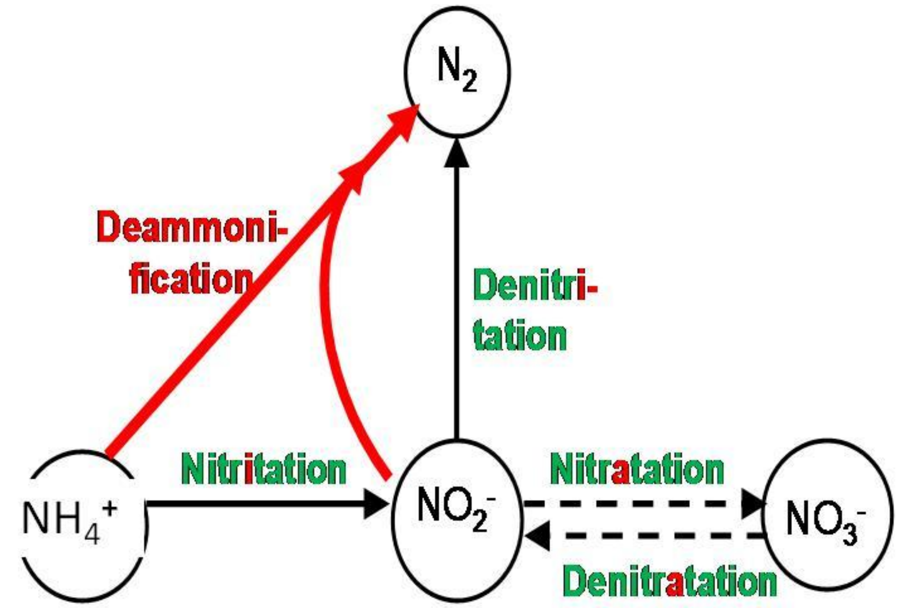

TABLE AI-1: COMPARISON OF CONVENTIONAL NITRIFICATION/DENITRIFICATION AND PARTIAL NITRITRATION/DEAMMONIFICATION

Removal Method	Oxygen $g\ O_2/g\ N$	Alkalinity g/g N	Carbon g COD/g N*	Biomass g COD/g N
Conventional Nitrification/Denitrification	4.6	7.1	2.86	0.5–1.0*
Partial Nitritation/Deammonification	1.89	3.9	0	0.06

*Depends on carbon used.
**COD = Chemical oxygen demand.

Among the technologies mentioned above, DEMON® is the most widely used (Murthy, 2011). In 2004, the first full-scale DEMON® reactor was implemented at the wastewater treatment plant (WWTP) in Strass, Austria. By 2012, DEMON® has been applied to treat higher-strength sidestreams at more than 36 full-scale facilities in Europe. Table AI-2 highlights some of the constructed DEMON® facilities as well as their start dates and treatment capacities (Johnson, C., 2012). The first full-scale DEMON® plant in North America began operation on October 7, 2012, at the York River WWTP in Seaford, VA. Two more DEMON® reactors are in final design in Pierce County, Washington, and Washington, D.C. The aforementioned full-scale DEMON® plants have been reported to treat ammonia-rich wastewater with mass loading rates in the range of 0.7 to 1.2 kg N/m^3/day and an energy demand of 1.0 to 1.3 kWh/kg ammonia nitrogen (NH_3-N) treated. Additionally, over 85 percent total N removal has consistently been reported on the treatment of high-strength ammonia wastewater. Finally, it has been well documented that the existing installations operate efficiently and require a modest level of operator attention (Bagchi et al., 2012; Wett et al., 2007a).

The DEMON® process is a suspended-growth SBR maintained to support both nitrifying and ANAMMOX biomass. The reactor is operated through multiple feed/react (both aerobic and anaerobic), settling, and decant cycles. The process strategy performs three or four SBR operation cycles per day. These cycles involve a feed/react phase (~5 hours), a settling phase (~0.5 hours), and a decant phase (~0.5 hours). The feed/react phase is composed of multiple mini-cycles; the duration of each mini-cycle is a function of the wastewater characteristics, but is usually between 5–30 minutes. High-ammonia concentration wastewater is fed during a mini-cycle. Aeration is first initiated at an upper pH setpoint. During the aeration step of the mini-cycle, the nitritation by the AOBs leads to H^+ production, which drives down the pH value to a lower pH setpoint where aeration stops. In the subsequent anaerobic step of the mini-cycle, more high-ammonia wastewater is fed to the reactor, and all accumulated NO_2^- from the aeration step is used for the oxidation of the incoming ammonia by the ANAMMOX bacteria. In the course of this anaerobic step, the recovered alkalinity as well as the feed of an alkaline wastewater leads to an increase in pH to the upper pH setpoint, where aeration is switched back on again. Therefore, the process operates within a pH bandwidth. These aerobic/anaerobic mini-cycles serve to limit the build-up of NO_2^- in the reactor. NO_2-N concentration is monitored frequently to avoid NO_2^- build-up, which can be toxic to the ANAMMOX bacteria.

Periodically, a hydrocyclone is used to separate the granular ANAMMOX bacteria from the floc-forming AOB and NOB bacteria that coexist in the SBR. The heavier ANAMMOX granules are recycled back to the reactor, while the flocculated biomass is separated and wasted. Accumulated red ANAMMOX granules are often visible in the underflow of cyclone waste. The hydrocyclone operation controls the accumulation of NOBs and enriches ANAMMOX, allowing process stabilization. The cyclone running times determine the solids retention time (SRT) of each bacterium, in which the optimum SRT for AOBs is approximately 5 days, and the optimum SRT for ANAMMOX bacteria is approximately 40 days.

Overall, the fundamental control parameters in the DEMON® process are aeration and anaerobic times, SRTs, temperature, pH, dissolved oxygen (DO), and NH_3-N and NO_2-N concentrations. Real-time control of the DEMON® process through programmed logic controls has been refined to address three elements: (1) time control to allow fill (react)/settling/decant operations; (2) DO; and (3) pH control.

TABLE AI-2: DEMON® PLANTS IN OPERATION

Facility	Year	Flow Rate (m^3/day)	Plant Flow (GPD)	Total Nitrogen Treated (mg/L)
Strass, Austria	2004	250	66,000	2,000
Glarnerland, Switzerland	2007	100	26,400	800
Plettenberg, Germany	2007	100	26,400	800
Heidelberg, Germany	2008	480	126,000	1,300
Thun, Switzerland	2008	300	79,250	1,300
Gengenbach, Germany	2008	50	13,200	1,000
Etappi Oy, Finland	2009	330	87,200	3,000
Balingen, Germany	2009	400	105,700	480
Apeldoorn, Netherlands	2009	1,270	335,500	1,300
Zalaegerszeg, Hungary	2010	160	42,300	1,000
Limmattal, Switzerland	2010	250	66,000	1,000
Alltech, Serbia	2010	NA	NA	NA
York River, VA, USA	2012	297	78,500	NA

Given DEMON®'s viability and cost-effectiveness, Environmental Monitoring and Research Division staff recommended and are currently pilot-testing a DEMON® reactor at the Egan WRP. The literature review herein is a discussion of the influential factors affecting performance and process control from published DEMON® studies and personal communications.

Factors That Affect the Demon® Process Efficiency and Performance

Nitrite. NO_2^- is an essential substrate for ANAMMOX bacteria, but can be highly toxic, causing irreversible inhibition. The effect of NO_2^- on ANAMMOX metabolism depends on the concentration of the NO_2^- as well as the time of exposure. One key variation that has been debated in the literature is the degree to which NO_2^- inhibits ANAMMOX, and how to monitor the inhibition quantitatively. For DEMON®, the main control target is to avoid accumulation of toxic NO_2^- by controlling concentration. The resulting concentration of the NO_2^- in the reactor might be affected by many parameters including DO above 0.5 mg/L or an increase in the pH bandwidth from 0.02 to 0.04 (Wett, 2007).

The maximum allowable concentration of NO_2^- at which ANAMMOX performance will be significantly reduced has been reported in various ranges. By using biomass from the Alexandria Sanitation Authority Wastewater Treatment Facility (ASA) DEMON® pilot, Musabyimana et al. (2008) evaluated the effect of NO_2-N concentration on ANAMMOX activity. The seeded bench-scale bioreactor was spiked with a target NO_2-N concentration of 50–400 mg/L for two hours. The results showed that the short-term effect of NO_2^- exposure to ANAMMOX is fully recoverable in situations when the NO_2^- concentration is not sustained. This study also suggested the threshold sustained concentration that results in detrimental impact on ANAMMOX activity can be between 50 and 100 mg/L NO_2-N for DEMON® biomass (Musabyimana et al., 2008). Other reports of a pilot study suggested that the detrimental concentration of NO_2-N is as low as 5 mg/L (Wett, 2007). One study suggested that the DEMON® system may destabilize for a week and cause subsequent irreversible damage when NO_2-N concentrations increased up to 80 mg/L; this occurred during the start-up period of a DEMON® pilot study at the Applied Research Facility located at the 26th Ward Water Pollution Control Plant in Brooklyn, NY (Bowden et al., 2007).

Though elevated NO_2^- concentrations cause system toxicity, nitritation is the critical step of the DEMON® process. The nitritation step in the ASA pilot study showed that nitritation inhibition leads to process instability. The reason for inhibition was not determined, but the problem was overcome by creating more favorable conditions for growth of AOBs by raising the DO setpoint from 0.3 mg/L to 0.6 mg/L. The elevated DO concentration did, however, also produce higher effluent nitrate nitrogen (NO_3-N) concentrations, e.g. sometimes up to 400 mg/L, compared to the expected 100 mg/L. During these periods of elevated NO_3^- concentrations, the overall N removal efficiency was reduced by 10 percent, as NO_3^- cannot be removed by ANAMMOX during deammonification.

Overall, the stability and removal efficiency of the DEMON® process depends on controlling the feed rate, pH, and DO in the reactor to control the extent of nitritation and ANAMMOX reactions (Shaughnessy et al., 2008).

Nitrate. From the DEMON® process stoichiometry (Reaction 1), a NO_3^- production of 10.6 percent relative to ammonia treated is expected. However, the NO_3^- produced in the process can be denitrified during the anaerobic step by heterotrophic biomass grown on the organic content of the reactor feed. In Wett at al. (2007a), a final NO_3^- production rate of only 4.6 percent was observed, which indicates subsequent reduction of more than half of the generated NO_3^- through denitrification.

A case study in Ruhrverband, Germany, reported a system failure during the start-up phase due to elevated NO_3-N concentrations, which indicated the growing activity of NOBs. When NOBs take over the aerobic phase, lower removal efficiencies by the ANAMMOX bacteria are observed. Several efforts were used to suppress the NOBs without success, e.g. low oxygen levels and high free NH_3 concentrations. Jardin et al. (2012) later found that compared to AOBs, NOBs need a longer period of time to reacclimate themselves to oxic conditions after transition from the anaerobic to the aerobic phase to fully ramp up their metabolism. As such, the aeration time was reduced from 18 minutes to 9 minutes in order to suppress NOB activity and restore nitritation. At the same time, DO was increased from 0.5 to 1 mg/L to assure sufficient AOB activity. With this operation mode, the suppression of NOBs was successfully restored, with NO_3-N concentrations dropping from 200 mg/L to 38 mg/L (Jardin et al., 2012). In summary, Jardin et al. (2012) found that once NO_2^- oxidation occurs in the system, reduction of aerobic cycle length at elevated DO levels proved to be effective in order to suppress growth of NOB. This operation is unique for the case study. The general practice to suppress NOBs is to lower the oxygen level. Another approach to suppression of NOBs was based on the reported selective inhibition of NOBs compared with AOBs using sodium azide at a concentration of 50 μmol/L (Ginestet et al., 1998; Jardin et al. 2012).

Temperature. Generally, the optimum temperature for ANAMMOX activity is in the range of 30–35°C (Strous et al., 1999). However, DEMON® reactors have been reported to operate in a wider temperature range, i.e. 20 to 37°C (Wett et al. 2006, 2010; Bowden et al., 2007).

In a DEMON® pilot reactor study of biological treatment of landfill leachate, Wett et al. (2010a) reported that a sudden temperature drop from 30 to 20°C caused rapid NO_2^- accumulation. This temperature drop caused an imbalance between NO_2^- production and NO_2^- consumption rates and consequently increased the vulnerability of operation stability. This imbalance was partially compensated for by reducing the DO level from 0.3 to 0.2 mg/L during the aerobic cycle.

Viable low-temperature operations can also be reached by ANAMMOX enrichment to overcome temperature sensitivity of these anaerobic organisms. With the help of cyclone operation to enrich ANAMMOX biomass, the DEMON® system in Thun, Switzerland, where an uncovered sidestream reactor is in place, has operated at a temperature of 20°C without loss of operational stability (Wett, personal communication with G. Nyhuis, 2009). For the Ruhrverband plant in Germany, the design temperature was set at 25°C, but the variability of the actual operating temperature is unknown (Jardin et al., 2012).

The impact of elevated temperature on performance was also evaluated at ASA and Strass by operating a kinetics reactor at temperatures ranging from 30 to 39°C. The pilot reactor at ASA was mostly operated at 35°C, and for a short period of time, i.e., 5 days, the temperature was increased to 37°C and even further to 39°C. Under these conditions, the AOB rates increased. However the pH was shown to decrease slowly during the aeration phase and increase quickly during the anaerobic phase, which leads to longer aeration times and shorter anaerobic times. This temperature change from 35 to 37°C tended to slow down the process and produce less-than-desirable process stability (Bowden et al., 2007). The DEMON® pilot reactor was still operational, but it was inconclusive whether a loading bonus by increased AOB activity can be realized at these high temperatures due to the resulting process instability (Shaughnessy et al., 2008). Once the temperature setpoint was reduced to 35°C, it led to improved process stability.

Dissolved Oxygen. One of the most critical factors in the DEMON® process is to maintain an appropriate concentration of DO during the aerobic phase, which has to be sufficient for the growth and activity of AOBs, while being insufficient for the survival of NOBs and nontoxic to the ANAMMOX bacteria. The DO setpoint is usually specified at a low range, close to 0.3 mg/L, in order to prevent rapid NO_2^- accumulation and to maintain a continuous repression of the second oxidation step of NO_2^- to NO_3^-. A DO concentration above 0.5 mg/L may lead to NO_2^- accumulation and substantial ANAMMOX activity loss (Bagchi et al., 2012).

pH. Wett et al. (2007b) reported that the DEMON® process is very sensitive to the pH bandwidth, and that destabilization will occur if the bandwidth is greater than 0.02. When the pH bandwidth was increased from 0.02 to 0.04 units, it resulted in an increase in the mean NO_2^--N concentration in the reactor from 1.7 to 4.8 mg NO_2-N/L and a reduction in the specific ANAMMOX activity from ~13 to ~8 mg N removed/g total suspended solids-hour due to an extended aeration period. This NO_2^- level of 4.8 mg/L NO_2-N resulted in a continuous decrease in ANAMMOX activity, but no failure was indicated, suggesting a resilience of a system operated with excess ANAMMOX inventory. This observation points out that a solid biological reserve capacity increases confidence in the operational safety of the system (Wett et al., 2007b).

The studies at ASA and Strass indicated that the pH setpoint around which the bandwidth is controlled in the DEMON® operation is a function of the alkalinity of the incoming wastewater (upper pH limit) and the bicarbonate limitation for AOB growth (lower pH limit). However, in Bowden's modeling of a DEMON® reactor, as the upper pH setpoint approaches the pH of the wastewater, the performance is reduced due to extended anoxic/anaerobic phases (Bowden et al., 2007).

Alkalinity. Nitrification requires sufficient alkalinity to buffer acidification and to supply bicarbonate as substrate for the autotrophic biomass. However, at lower pH values, the DEMON® aeration process causes CO_2 stripping and consequently a decrease of the available inorganic carbon for nitrification. Inadequate alkalinity will limit the growth of AOBs, especially since these organisms depend on bicarbonate for cell synthesis. A solution is to enable the DEMON® process to operate under pH conditions that maximize the availability of inorganic carbon.

The pH value in the reactor is determined by the balance of the added alkaline of the feed wastewater, e.g. centrate, and the hydronium ion production during nitrification (Wett et al., 2003). Hence, nitrification is interrupted by the pH control, i.e. the lower setpoint, as soon as the available alkalinity is consumed. No further oxidation of ammonia is possible until alkalinity is recovered by the addition of new wastewater and the limited denitrification that can occur. In most cases, the maximum ammonia-elimination rate is determined by the alkalinity in the feed wastewater unless an external alkalininty source is added.

Anoxic Heterotrophic Biomass. Anoxic heterotrophic biomass (AHB), a denitrifier biomass, competes with ANAMMOX for NO_2^- along with NOBs if a carbon source is available. In the second step of deammonification, NOBs compete with ANAMMOX for NO_2^- to produce NO_3^- in the system. NOB activity can be efficiently suppressed at elevated temperatures and low DO levels during the aerobic cycle. When limited organic carbon is available, AHBs can help reduce residual NO_3^- and NO_2^- concentrations. However, the presence of excess carbon can increase AHB activity significantly to outcompete the ANAMMOX organisms, thereby reducing the overall N removal efficiency by the ANAMMOX bacteria.

Solids Retention Time. Due to significant difference in growth rate (AOB rates are 10 times higher than ANAMMOX rates; Sin et al., 2008), a corresponding difference in SRT is necessary for a balanced biomass composition in a DEMON® reactor. This balance is realized by using a hydrocyclone to separate the granular ANAMMOX bacteria from the floc-forming nitrifier bacteria (Figure AI-2). The heavier ANAMMOX granules can be returned to the reactor while the nitrifying flocs are separated and wasted. This also allows the system to control the accumulation of NOBs and stabilize performance.

Cyclone operation plays a major role in establishing the anaerobic ammonia oxidation pathway (Wett et al., 2010b). Stable deammonification operation requires a long SRT to sustain a large population of the slow-growing ANAMMOX bacteria (the doubling time is approximately 10 days at 30°C). A minimum SRT for ANAMMOX is approximately 30 days; AOB and NOBs are at five days SRT. Due to the ability to decouple the bacteria via the hydrocylcone, ANAMMOX concentrations will show a steep increase during the startup period. A simulated calculation of a DEMON® cyclone system suggests that once stable, the final SRT for ANAMMOX (53 days) was almost six times higher than that for aerobic AOB (nine days) when a hydrocylone is used as shown in Table AI-3 (Wett et al., 2010a).

Greenhouse Gases. Compared to conventional nitrification/denitrification, a reduction of GHGs has been observed in DEMON® systems mainly due to the energy savings and net CO_2 consumption. Studies have been performed to assess the GHG emissions from the DEMON® system at the Strass WWTP in Austria. Results show that nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O) are emitted from the deammonification process in trace amounts. It is generally known that N_2O is produced by AOBs, NOBs, and denitrifying organisms; however, ANAMMOX bacteria can be an indirect source of N_2O since they produce NO, which could be converted to N_2O by AOBs. In the Weissenbacher et al. (2011) study, the measured online N_2O data showed comparable emission dynamics for both a pilot- and a full-scale plant.

FIGURE AI-2: HYDROCYCLONE TO RETAIN ANAMMOX AND WASH OUT COMPETING BACTERIA

TABLE AI-3: SELECTED SOLIDS RETENTION TIME AND DISTRIBUTION OF BACTERIA DUE TO SIMULATED CYCLONE OPERATION

	Without Cyclone – Share in Solids (%)	SRT (d)	With Cyclone – Share in Solids (%)	SRT (d)
AOB	5	28	5	9
Anammox	8	28	15	53

The change of the DO and pH setpoints had no significant impact on the N_2O emissions (1.4 ± 0.2 percent of N loading). From a NO_2^- accumulation test at the pilot plant, the only significant increase of N_2O emissions was observed under high NO_2^- accumulation; NO_2-N concentrations greater than 10 mg/L resulted in an increase of N_2O. This addresses the importance of lower NO_2^- concentrations through pH-dependent aeration and a small pH bandwidth providing the conditions for rapid consumption of the produced NO_2^- by the ANAMMOX bacteria to avoid toxic effects as well as elevated GHG emissions (Weissenbacher et al., 2011).

Polymer. Yamamoto et al. (2008) tested the treatment of digester liquor and synthesized wastewater by using partial nitritation followed by a deammonification reactor. While this was not a DEMON® reactor, the study indicated a decrease of ANAMMOX activity in digester liquor compared to the synthesized wastewater. This was thought to be due to high amounts of cationic polymers in the digester liquor (Yamamoto et al., 2008). It was assumed that the polymeric organic coagulant that remained in the wastewater attached to the ANAMMOX bacteria caused a decrease in activity. It was later indicated by Jardin (2012) that the polymers in the reactor's wastewater feed could have an inhibitory effect on the transfer of electron acceptors at the ANAMMOX cell wall. However, separate pilot tests performed by Wett for Ruhrverband, Germany, with seed sludge from the Strass DEMON® plant did not show any significant influence of polymer dosage on ammonia oxidation and NO_2^- reduction (Wett B., 2009). Polymers were dosed to a DEMON® pilot system at increasing rates to evaluate the effect on ammonia removal. Even when overdosing, ammonia removal rates were maintained.

Start-up Time. It took a period of three years for the first full-scale DEMON® treatment plant at Strass, Austria, to reach its capacity of 340 kg-N/d. As ANAMMOX bacteria are slow-growing organisms, a stepwise strategy for enrichment was applied. At the beginning, a 300-L reactor was seeded with four liters of inoculum taken from the pilot plant operated by Eawag Aquatic Research at Zurich. The seed was then transferred to increasing reactor sizes of to 2,400 L and finally to 500,000 L to enrich the biomass. The enrichment period took two years, and the actual startup of the full-scale reactor took another six months, until the end of 2004. It should also be noted that the first full-scale DEMON® reactor was started without cyclone to enrich ANAMMOX biomass.

Conversely, it took only 55 days to reach a N load of 64 kg-N/d with a reactor volume of 134 m^3 for the second full-scale DEMON® reactor in Ruhrverband, Germany, to start up, because a substantial amount of seed sludge (500 kg) was transferred from Strass plant. Jardin et al. (2012) reported it took only one day to observe nitrogen removal at Ruhrverband, Germany, but high NO_3^- accumulation slowed the start-up. As such, ANAMMOX seed is essential to a quick start-up of the deammonification process. Additionally, the European DEMON® plants indicated in <u>Table AI-2</u> were started with ANAMMOX-enriched seed sludge from previous operated DEMON® plants, which reduced their startup period to few months (personal communication with Mr. Johnson and Dr. Wett). The challenge for starting up a new DEMON® system is the availability of a substantial amount of seed sludge.

Summary of Literature Review

The DEMON® process is a robust, mature, and energy-efficient technology; more than 80 percent of nitrogen removal has been consistently reported in current DEMON® plants. The key elements to successfully operate a DEMON® reactor, especially during the start-up period, are as follows:

1. The optimum pH level in the DEMON® reactor is neutral, and the pH band-width used during the feed/react cycles should be less than 0.02 units.

2. DOs are usually maintained to less than 0.3 mg/L. DO concentrations should be high enough to support partial nitritation, but low enough to suppress NOB growth and also low enough so that they do not inhibit ANAMMOX activity

3. The optimum operation temperature for a DEMON® system is 30 to 35°C.

4. Operating at a low NO_2^- concentration will avoid NO_2^- toxicity as well as minimize GHG emissions. Generally speaking, NO_2-N concentrations should be kept at concentrations of less than 7 mg/L. This can be controlled through aeration time, loading rates, and DO levels.

5. Denitrifiers help reduce NO_3^-/NO_2^- concentrations in the effluent, but their populations need to be controlled to prevent outcompeting ANAMMOX bacteria. Avoiding feed with high biodegradable organics will limit denitrifier growth.

6. The maximum ammonia-elimination rate is determined by the alkalinity in the feed wastewater unless an external alkalininity source is added to improve nitritration.

7. Polymers in the wastewater may inhibit the ANAMMOX activity.

8. The start-up time of a DEMON® reactor will be significantly shortened by using substantial amounts of seed sludge from currently operating DEMON® plants.

9. Sufficient ammonia needs to serve as an energy source for ANAMMOX, but free NH_3 should be controlled through pH control, as levels above 10–15 mg/L are toxic to ANAMMOX.

10. ANAMMOX SRTs should be long enough, which is at a minimum of 30 days, but nitrifier SRTs are around five days.

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