Pilot-Scale Evaluation of ANITA™ Mox for Centrate Nitrogen Removal at the Joint Water Pollution Control Plant

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ABSTRACT

The Sanitation Districts of Los Angeles County (Districts) evaluated two variants of Kruger/Veolia's ANITA Mox process for removing centrate nitrogen at the Joint Water Pollution Control Plant (JWPCP) in Carson, California. One variant was based on the Moving Bed Biofilm Reactor (MBBR) technology, while the other was based on the Integrated Fixed-Film Activated Sludge (IFAS) technology. Two different centrate streams ("Pre-DAF" and "Post-DAF") were tested as feed to the MBBR pilot; one ("Pre-DAF") was tested with the IFAS pilot. Due to dilution by other process water, both centrate streams contained lower concentration of NH_4 than typical centrate. Median feed NH_4 concentrations during this study were 634 mgN/L (Pre-DAF) and 469 mgN/L (Post-DAF).

Despite its low strength, JWPCP centrate was treatable by ANITA Mox. With Post-DAF as feed, the MBBR pilot demonstrated removal rates of 1.3 gN/m^2-d (NH_4) and 1.1 gN/m^2-d (TIN), with corresponding removal efficiencies of 85% (NH_4) and 70% (TIN). With Pre-DAF as feed, after process optimization, the MBBR pilot achieved higher removal rates of 2.1 gN/m^2-d (NH_4) and 1.9 gN/m^2-d (TIN), with corresponding removal efficiencies of 75% (NH_4) and 68% (TIN). Removal rates showed attenuated response to operating temperature. The IFAS pilot demonstrated significantly higher rates than the current generation of single-stage deammonification technologies. With Pre-DAF as feed, removal rates of 7.8 g/m^2-d (NH_4) and 6.7 g/m^2-d (TIN), with corresponding removal efficiencies of 78% (NH_4) and 68% (TIN), were achieved.

Robustness of the MBBR pilot was evaluated in six scenarios designed to simulate various commonly-encountered operational outages/events: (1) Power Outage; (2) No Feed NH_4; (3) Overfeed; (4) Excess Mannich Polymer in Feed; (5) No Aeration; and (6) Over-aeration. Of these scenarios, "No aeration", "Overfeed", and "Excess Mannich Polymer in Feed" resulted in temporary performance loss. Even in the worst case, performance fully recovered within 2 days. No special shut-down/start-up procedure was necessary.

The offgas of both pilots were analyzed for two potent greenhouse gases, N_2O and CH_4. The MBBR pilot emitted 0.52% of the influent TKN as N_2O, substantially lower than had been reported for the competing DEMON process (1.3%). The IFAS pilot emitted 1.7% of the influent TKN as N_2O.

KEYWORDS

Deammonification, Anammox, Nitrogen, Sidestream Treatment, Biofilm/Fixed Film

INTRODUCTION

The Sanitation Districts of Los Angeles County (Districts) operate the Joint Water Pollution Control Plant (JWPCP), a 400 mgd design flow ocean-discharging secondary-treatment plant in Carson, California. While nitrogen removal is not required at the plant presently, it may become necessary in the future due to regulatory drivers and/or demands for effluent reuse. If such a need arises, implementation of nitrogen removal via a tertiary conventional nitrification/denitrification (NDN) process is expected to be very costly. One approach to lower this cost is by removing centrate nitrogen via deammonification. To aid future planning and implementation of such technologies, the Districts decided to evaluate commercially-available deammonification technologies for treating JWPCP centrate.

Deammonification technologies currently being marketed can be classified by their reactor configuration: (1) Granular Sludge Reactor; (2) Sequencing Batch Reactor (SBR); or (3) Moving-Bed Biofilm Reactor (MBBR). Each configuration offers its own unique strategy for dealing with a common challenge in deammonification: how to retain the critical, but very slow growing, anaerobic ammonia oxidizing (Anammox) bacteria (AnAOB) in the reactor. The ANITA Mox process maintains AnAOB within the biofilm on plastic media which are retained in the reactor by screens. In the MBBR-variant, a thick ammonia-oxidizing bacteria (AOB) biofilm overlays AnAOB, the former producing the NO_2 required by the latter (Figure 1, left). In the Integrated Fixed-Film Activated Sludge (IFAS) variant, a thinner AOB biofilm still overlays AnAOB, but most of the AOBs are located in flocs for improved mass transfer (Figure 1, right).

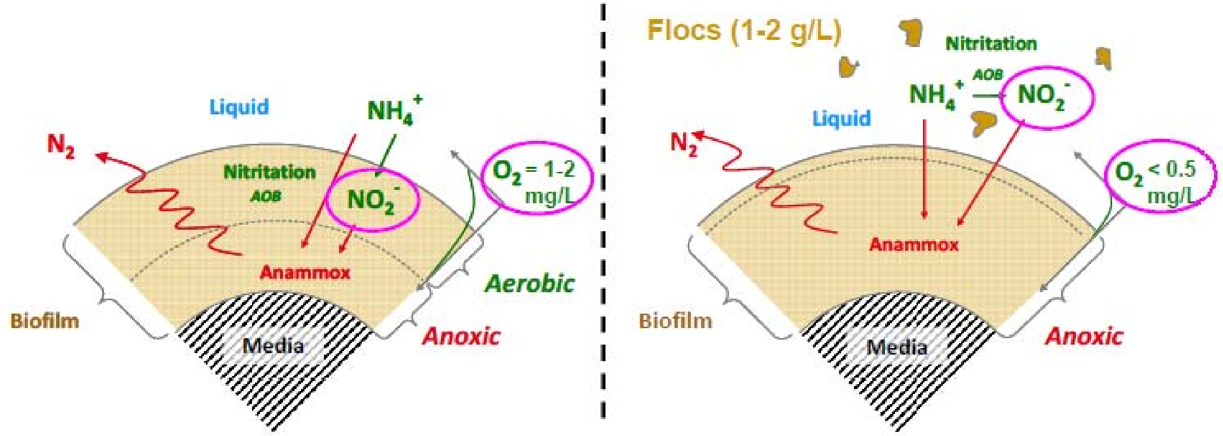


Figure 1. Simplified ANITA Mox Models. Left: MBBR; Right: IFAS. (Kruger/Veolia)

Localizing AnAOB within the biofilm likely improves its retention, and provides the critical organism better protection from inhibitors and washout. As such, ANITA Mox is potentially a more stable process which may favor its deployment at the Districts, if such installation becomes necessary. However, the limited number of full-scale ANITA Mox installations (4 in Europe; 2 in the US) translates to a higher risk of deployment relative to its more prominent peers such as World Water Works' DEMON process. To reduce this risk, the Districts conducted a pilot study of the MBBR-variant of ANITA Mox at the JWPCP between April 2013 and April 2014. During this period, Kruger/Veolia made available for testing a second pilot system based on the IFAS variant. The IFAS system was tested between October 2013 and April 2014, with a more limited scope.

OBJECTIVES

The objects of the Districts' testing at the JWPCP included the following:

(1) Evaluate ANITA Mox's capacity for treating JWPCP centrate;
(2) Evaluate ANITA Mox's robustness against common operational events;
(3) Identify any potential operational issues with ANITA Mox.

METHODOLOGY

Pilot Systems Description

The two pilots systems were arranged in a parallel configuration as illustrated in Figure 2. Each component is described in more detail below.

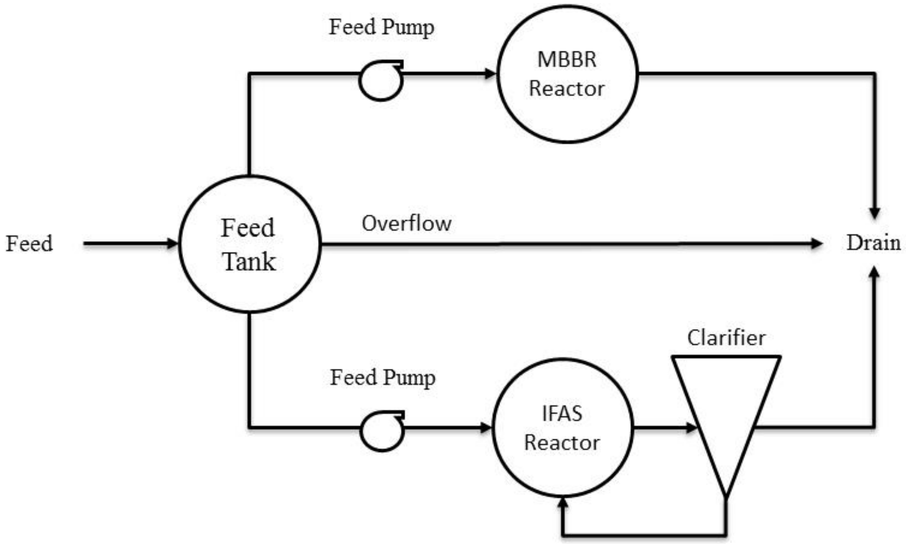


Figure 2. ANITA Mox Pilot Systems Schematic

Feed Tank

Feed for the testing flowed by gravity from nearby full-scale centrate lines into a feed tank shared by both pilot systems. The tank was a 55-gal HDPE cylindrical vessel (ID=21.5", h=35") with a working volume of 35 gal (h=22"). Flow rate into the tank was unregulated, but overflow condition was maintained. A submersible pump within the tank facilitated mixing of the tank content. Feed delivery into each downstream reactor was achieved by a progressive cavity pump (Moyno 300-series) and verified by an inline flow meter (Endress-Hauser Promag) located between the pump and the reactor.

MBBR Reactor

The reactor was a 1,400 gallon HDPE cylindrical vessel (ID=5'9", h=7'2") with a working volume of 950 gallons (side water depth (SWD)=5'2"). During startup, 450 gallons of seeded AnoxKaldnes K5 media (specific surface area: 800 m^2/m^3), equivalent to a media fill of 47% by volume, were transferred into the reactor. The media and the reactor had previously been in operation at Metro Wastewater Reclamation District's (MWRD) Robert W. Hite Treatment Facility (RWHTF) in Denver, Colorado (Hollowed et al., 2013). Media retention was achieved by screens installed on the tank outlets. Aeration was provided via plant process air, through a medium-bubble aeration grid located at the bottom of the reactor. Air flow rate was regulated by an inline air mass flow controller (Alicat). Mechanical mixing was available via a four-blade mixer, but it was typically not used. Process DO, pH, and temperature were continuously monitored by online analyzers (Hach LDO2 and pHD).

IFAS Reactor

The reactor was a 1,030 gallon stainless steel cylindrical vessel (ID=5', h=7') with a typical working volume of 803 gallons (SWD=5'6"). During startup, approximately 295 gallons of seeded AnoxKaldnes K5 media, equivalent to a media fill of 37% by volume, were transferred into the reactor. The media were obtained from a full-scale reactor at the Sjölunda Wastewater Treatment Plant in Malmö, Sweden. Media retention was achieved by screens installed on the tank outlets. Aeration was provided via a mobile air compressor (Kaesar), through a medium-bubble aeration grid located at the bottom of the reactor. Air flow rate was regulated by an inline air mass flow controller (Alicat). Mechanical mixing was available via a four-blade mixer, but it was typically not used. Process DO, pH, and temperature were continuously monitored by online analyzers (Hach LDO2 and pHD). During stable operation, reactor mixed liquor suspended solids (MLSS) was typically between 4,000 to 6,000 mg/L.

IFAS Clarifier

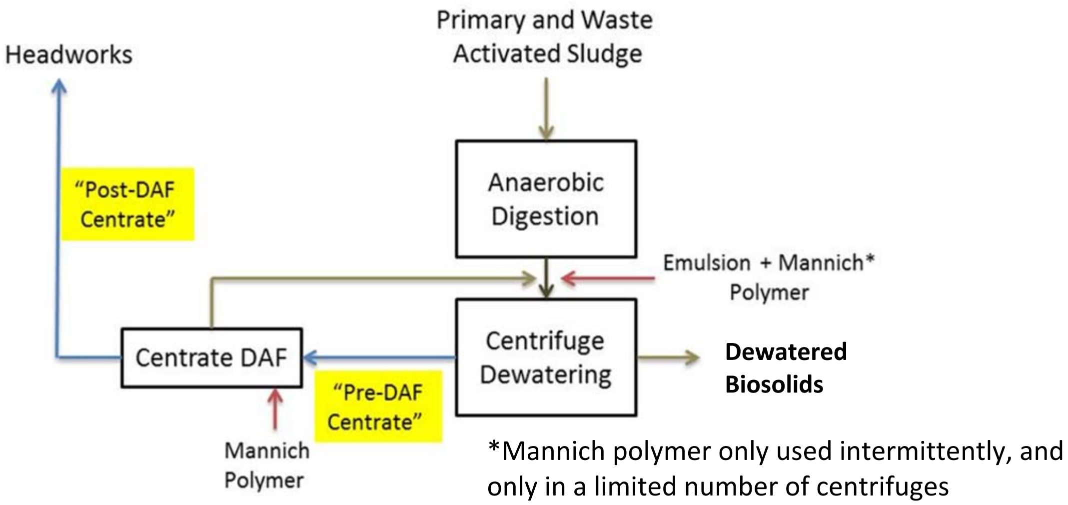
A lamella clarifier was installed downstream of the IFAS reactor. The clarifier had a working volume of 480 gallons with four distinct zones: an influent distribution zone, a lamella settling zone, a sludge collection zone, and an effluent collection box. The lamella settling zone consisted of 20 lamella plates with approximate total plate surface area of 80 ft^2 and volume of 85 gallons. Sludge recycle was achieved with a progressive cavity pump (Moyno 300-series), typically at 100% of the feed rate. Sludge wasting was not routine/active; only via passive loss through clarifier overflow.

Control Systems

Real-time data (feed rate, air flow rate, pH, DO, temperature) from each reactor were monitored by a Programmable Logic Controller (PLC) which maintained feed and air rates according to the set points. In addition, in the event that the process pH fell below the alarm condition (MBBR: 6.7; IFAS: not set), the system would stop aeration and engage the mechanical mixer until the condition was cleared. The pH-based alarm served as a convenient indicator for limiting alkalinity condition during which additional aeration would be unproductive.

Feed Sources

JWPCP centrate is typically treated by dissolved air flotation (DAF) before being returned to the plant's headworks. As such two centrate streams were available for testing: (1) centrate upstream of the DAF ("Pre-DAF") and (2) centrate downstream of the DAF ("Post-DAF"). Compared to digested sludge, Pre-DAF typically contained substantially lower concentrations of constituents, due to dilution by centrifuge cooling water. Post-DAF contained even lower concentrations of constituents, due to dilution by plant wash water introduced for Mannich polymer delivery, and particulate removal by DAF. Figure 3 illustrates the flow of the relevant processes, and highlights the feed sources for this study. Note that both Pre-DAF and Post-DAF were tested as feed to the MBBR pilot, while only Pre-DAF was tested as feed to the IFAS pilot.



*Mannich polymer only used intermittently, and only in a limited number of centrifuges

Figure 3 Simplified Solids/Centrate Processing Flow Diagram (JWPCP)

Sampling and Analysis

Samples were collected regularly from four locations: (a) "Feed" samples, from the feed tank; (b) "MBBR Effluent" samples, from the MBBR reactor; (c) "IFAS Mixed Liquor", from the IFAS reactor; and (d) "IFAS Clarified Effluent" samples, from the IFAS clarifier overflow. Table 1 summarizes the analyses performed, including the methods and frequencies. Analyses denoted by "(L)" were performed by the Districts' JWPCP Laboratory; those denoted by "(F)" were performed by JWPCP Research staff. For statistical analysis purposes, results below the detection limit were treated as 50% of the detection limit.

Table 1. Sample Analysis and Frequency

Group	Parameter	Method	Feed	MBBR	IFAS	
				Effluent	Mixed Liquor	Clarified Effluent
Nitrogen	TKN	SM 4500 NH3 C (L)	C-W	C-W	--	G-W
	NH_4-N	SM 4500 NH3 C (L)	C-D	C-D	--	--
		Hach TNT+ 832 (F)	G-D	G-D	G-D	--
	NO_2-N	SM 4500 NO2 B (L)	C-D	C-D	--	--
		Hach TNT+ 840 (F)	G-D	G-D	G-D	--
	NO_3-N	SM 4500 NO3 E (L)	C-D	C-D	--	--
		Hach TNT+ 836 (F)	G-D	G-D	G-D	--
Organics	tCOD	SM 5220D (L)	C-W	C-W	--	G-W
	sCOD	SM 5220D (L)	C-W	C-W	--	--
	tBOD	SM 5210B (L)	C-W	C-W	--	--
	sBOD	SM 5210B (L)	C-W	C-W	--	--
Solids	TSS	SM 2540D (L)	C-D	C-D	G-D	G-D
	VSS	SM 2540E (L)	C-D	C-D	--	--

C-W: 24-hr composite; weekly
G-W: Grab, weekly
C-D: 24-hr composite; daily
G-D: Grab; daily
--: Not Analyzed
O: Online/Continuous

Others	PO_4-P	SM 4500P-E (L)	C-W	C-W	--	--
		Hach TNT+ 846 (F)	--	--	G-D	--
	Alkalinity	SM 2320B (L)	C-D	C-D	--	--
	Biomass Density	Kruger Method (L)	--	C-W	--	--
	pH	Hach pHD (Online)	--	O	O	--
	DO	Hach LDO2 (Online)	--	O	O	--
	Temperature	Hach pHD (Online)	--	O	O	--

C-W: 24-hr composite; weekly
C-D: 24-hr composite; daily
--: Not Analyzed
G-W: Grab, weekly
G-D: Grab; daily
O: Online/Continuous

Performance Metrics

System nitrogen removal performance was characterized by two metrics: Removal Efficiency (RE) and Surface Area Removal Rate (SARR). Definitions of these metrics are given below. SARR is a key design parameter for biofilm-based systems such as ANITA Mox.

$$RE_N = 1 - \frac{[N]_{eff}}{[N]_{inf}} \qquad (1)$$

$$SARR = \frac{Q\ ([N]_{inf} - [N]_{eff})}{V * FR * SSA} \qquad (2)$$

Where
$[N]_{inf}$ = Influent N (e.g., NH_4 or TIN) concentration
$[N]_{eff}$ = Effluent N (e.g., NH_4 or TIN) concentration
Q = Volumetric feed rate
V = Reactor volume
FR = Media fill ratio
SSA = Media specific surface area
TIN = Total inorganic nitrogen

Using the bulk reactor rates (SARR) described above, in combination with stoichiometry, one can calculate the nitrogen utilization rate (NUR) of each microbial group involved in the process. Formulas for calculating the individual NURs are given below.

$$NUR_{AOB} = SARR_{NH4} - \frac{SARR_{TIN}}{2.04} \qquad (3)$$

$$NUR_{NOB} = -SARR_{NO3} - \frac{SARR_{TIN}}{2.04} * 0.26 \qquad (4)$$

$$NUR_{AnAOB} = \frac{SARR_{TIN}}{2.04} * 2.32 \qquad (5)$$

Test Phases

Initial Start-up (MBBR and IFAS)

Once the test systems were delivered, they were re-assembled and checked for leaks and mechanical/electrical problems. Then each reactor was filled with the feed and plant wash water, such that the blend contained 200~250 mgN/L of NH_4. Next, seed media were transferred into the reactor in quantities described by "Pilot Systems Description". Initially, intermittent/limited aeration was supplied and the mechanical mixer was operated, while mixed liquor nitrogen species were intensively (at 15-min intervals) monitored. Aeration was increased incrementally as long as reactor NO_2 concentration remained low. After the mixed liquor NH_4 dropped below 100 mgN/L, feed was started at a rate corresponding to the observed NH_4 consumption rate.

Capacity Building (MBBR and IFAS)

System feed and aeration rates were adjusted, in consultation with Kruger, to maximize the reactor's treatment capacity (based on SARR). The general approach was that given a particular feed rate, the aeration rate was adjusted such that the nitrogen load could be removed (NH_4: 80~90% RE; TIN: 70~80% RE) without excess NO_3 production (<10% of NH_4 consumed). If stable operation could be achieved, the feed rate was raised and the procedure repeated.

Capacity Testing (MBBR and IFAS)

Reactor capacity was reached when additional nitrogen loading could not be removed despite aeration adjustments. This capacity was verified by stable operation at this loading/removal rate for at least two weeks.

Robustness Testing (MBBR-Only)

Process robustness refers to a system's ability to maintain and regain treatment performance in the event of a perturbation. Figure 4 shows a hypothetical performance-time curve for a reactor encountering a perturbation from time t_0 to t_1. Baseline is defined as the 14-day median performance before the perturbation. Performance reduction (Δp) is defined as the maximum performance loss from baseline. A small Δp indicates minimal effect from the perturbation; a large Δp indicates the opposite. Recovery time ($t_{recovery}$) is defined as the time required to regain performance to a recovery threshold, defined as a percentage (e.g., 95%) of baseline. A small $t_{recovery}$ indicates the process recovers rapidly from the particular perturbation; a large $t_{recovery}$ indicates the opposite. A robust process exhibits both small Δp and $t_{recovery}$.

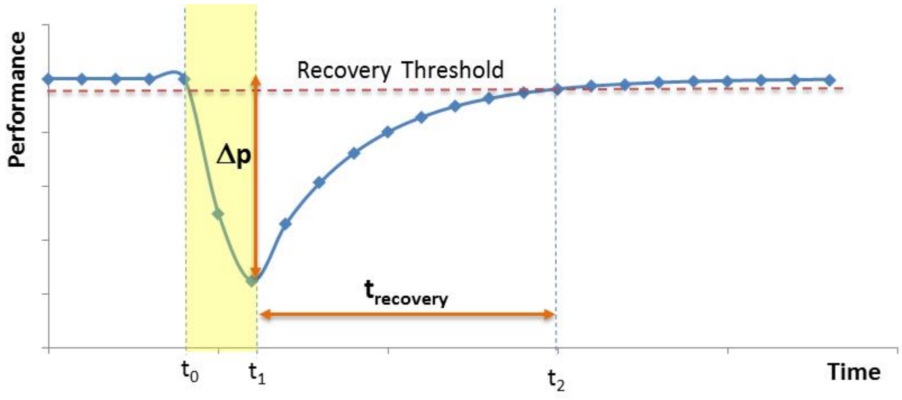


Figure 4. Performance Recovery for a Hypothetical Perturbation

This study aimed to assess ANITA Mox's robustness to perturbations commonly encountered, albeit infrequently, at a large treatment plant like the JWPCP. These perturbations can include power failure, equipment failure, and changes in feed quality. Table 2 summarizes the perturbations tested, as well as the corresponding real-world scenarios simulated and other test details. Perturbation period of one day was selected for most tests, as in the Districts' experience, power/equipment failures are typically resolved within that timeframe. After the perturbation period, the process was returned to normal operation without special start-up procedure. Process performance was monitored intensively (at 8-hour intervals) until the recovery threshold (selected as 95% of the baseline) was met or exceeded. In this study, each test was conducted once, and only the MBBR system was tested.

Table 2. Robustness Testing – Perturbations Tested

Perturbation Type	Subtype	Simulated Scenario	Perturbation Period	Performance Metric	Recovery Threshold
Power Outage		Planned and unplanned power outages	1 day	NH_4 and TIN SARR	95% of baseline
Feed Variance	No feed NH_4	Centrifuge offline	1 day		
	Overfeed	Feed meter failure	1 day		
	Excess Mannich polymer	Centrifuge start-up condition	Various		
Aeration Variance	No aeration	Air compressor failure	1 day		
	Over-aeration	DO sensor/Air flow meter failure	1 day		

GHG Emissions Testing (MBBR and IFAS)

Each system's offgas was analyzed for two greenhouse gases (GHG): N_2O and CH_4. The sampling train consisted of a sampling hood, a water trap, and a gas analyzer arranged according to Figure 5. The sampling hood was fabricated from a HDPE bottle with two holes drilled at the bottom/closed-end: one was fitted a tank adapter for connecting to the sampling train; another acted as a vent hole to prevent back pressure from blocking gas flow into the hood. The water trap was a 50 mL Teflon impinger designed to knock out moisture but not to dry the sample. The gas analyzer (Innova 1412, LumaSense Technology) was a photoacoustic infrared analyzer equipped with optical filters for measuring N_2O and CH_4 at the ppm/sub-ppm levels. The sampling train components were connected by ¼" polyethylene tubing.

During use, the sampling hood was oriented with its open-end (3¼" diameter) submerged approximately 1~2" below the water surface. Reactor offgas continuously passed through the hood and exited via the vent hole. Every two minutes, a sampling pump built into the analyzer drew sample through the sampling train for line flushing and measurement. Collected data were stored on a laptop computer for subsequent data analysis.

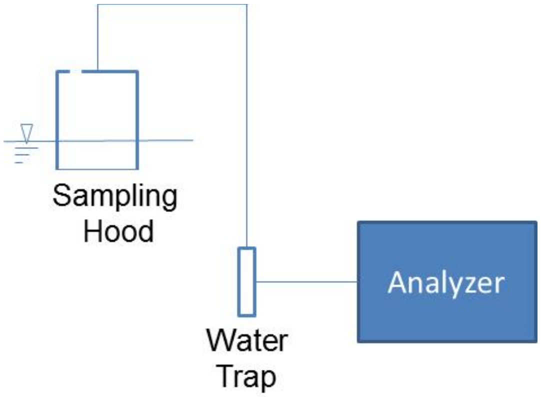


Figure 5 GHG Emission Testing Sampling Train

RESULTS AND DISCUSSION

Feed Characteristics

Feed used during this study was routinely analyzed as described in "Sampling and Analysis." Table 3 presents a statistical summary for these analyses.

Table 3 Feed Characteristics[1]

Group/Parameter	Unit	Pre-DAF (8/21/13-4/18/14)	Post-DAF (5/20/13-8/20/13)
Nitrogen			
TKN	mg N/L	634 (117)	469 (10)
NH_4	mg N/L	620 (84)	463 (22)
NO_2	mg N/L	3.5 (1.7)	0.6 (0.7)
NO_3	mg N/L	0.1 (0.5)	0.1 (0.2)
Organics			
tCOD	mg/L	365 (254)	181 (23)
sCOD	mg/L	153 (29)	128 (11)
tBOD	mg/L	53 (37)	21 (4.1)
sBOD	mg/L	21 (8.8)	17 (1.8)
Suspended Solids			
TSS	mg/L	195 (326)	64 (67)
VSS	mg/L	150 (216)	55 (48)
Other Constituents			
Alkalinity	mg $CaCO_3$/L	2,435 (314)	1,930 (66)
Orthophosphorus	mg P/L	12 (4.5)	4.7 (0.6)

[1] Median values; standard deviation in parentheses.

Capacity Testing (MBBR)

Initial Capacity Testing

After initial start-up, the MBBR system was operated with Post-DAF as feed from 05/20/14 through 08/20/14, followed by Pre-DAF as feed from 08/21/14 through 09/12/14. The system's performance during these two periods is summarized in Table 4, along with results of the previous test (using the same pilot) at the RWHTF:

Table 4 Initial Capacity Testing (MBBR)[1]

Site	Feed	Date Range	NH_4		TIN	
			Removal Efficiency	SARR (g/m2-d)	Removal Efficiency	SARR (g/m2-d)
JWPCP[1]	Post-DAF	7/22/13~8/20/13	85%	1.3	70%	1.1
	Pre-DAF	8/26/13~9/12/13	84%	1.7	71%	1.5
RWHTF[1] (MWRD)			81%	2.0	75%	1.9

[1] Medians

As can be seen above, the pilot's N removal rates at JWPCP (in particular, with Post-DAF as feed) were much lower than at RWHTF. In addition, the pilot required significantly higher DO (3.5 mg/L vs. 1~2 mg/L) to maintain this level of N removal rates; at a lower operating DO, reactor performance degraded. These observations suggested that RWHTF's experience may not be transferable to JWPCP.

Per Kruger/Veolia's suggestion, bench-scale batch activity tests were conducted using media from the reactor. Results indicated that the biomass could sustain significantly higher performance than was observed in the pilot reactor (data not shown), even in the same matrix. It was concluded that the biomass' full potential was not being realized, possibly due to mass transfer limitation of substrates such as dissolved oxygen, NH_4, and/or bicarbonate. Due to the potential of mass transfer limitations, additional work was done to determine if the process performance could be improved.

Process Optimization

During this phase, the effects of three parameters on system performance were explored: (1) Biomass Density; (2) Operating DO, and (3) Centrate Loading. For biomass density, it was thought that inactive biomass and/or polymer might have accumulated on the outer layer of the biofilm, thereby reducing mass transfer and consequently the system performance. By applying mechanical shear, this outer layer may be removed, and system performance may improve. For operating DO, it was thought that the high operating DO resulted in high nitrite-oxidizing bacteria (NOB) activity, which then competed with AnAOB and repressed the associated NH_4 removal. If oxygen mass transfer limitation could be addressed by biomass density, then the operating DO could be lowered to suppress NOBs to improve performance. For centrate loading, it was thought that if NH_4 mass transfer was limiting, raising the loading rate would increase the mixed liquor NH_4 concentration and overcome the NH_4 mass transfer limitation.

Biomass Density The reactor's mechanical mixer was operated periodically from 9/12/13 through 10/4/13, with the intention of shearing biomass off the media. This practice proved effective, as the mean media biomass density declined by nearly 50% during this period (Figure 6). As shown in Table 5, the lower biomass density increased AOB activity by 7% and NOB activity by 133%, and decreased AnAOB activity by 2%. The overall effect on system performance was a 4% increase in NH_4 SARR and a 3% decrease in TIN SARR. These observations were consistent with improved DO mass transfer raising AOB and NOB activities, the latter of which repressed AnAOB activity.

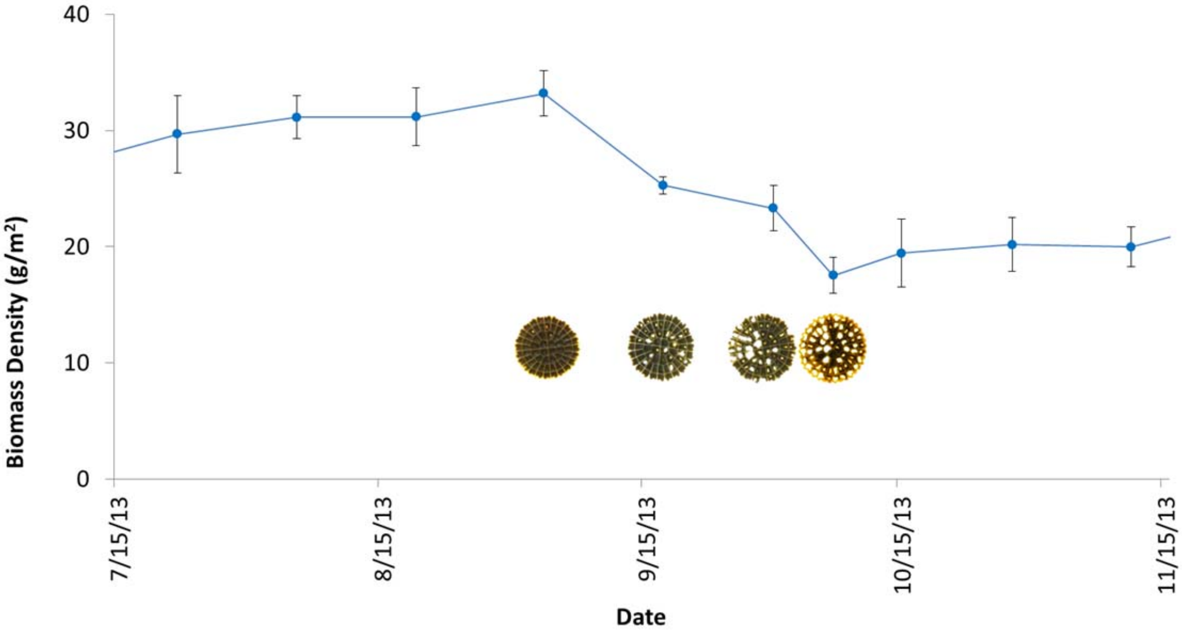
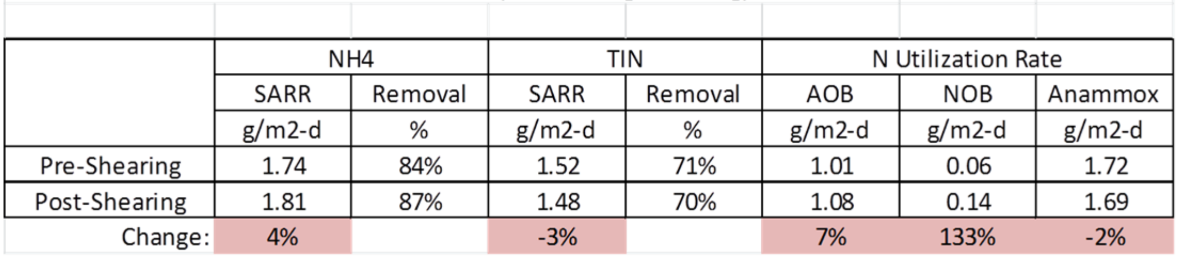


Figure 6 Mean biomass density and images of media chip over time during the biomass density reduction experiment

Table 5 Effect of Biomass Density Reduction on Performance

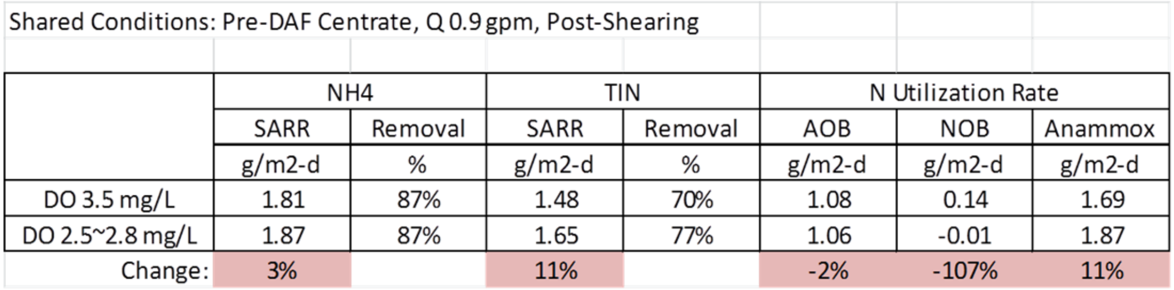


Shared Conditions: Pre-DAF Centrate, DO setpoint 3.5 mg/L; Q 0.9 gpm

	NH4		TIN		N Utilization Rate		
	SARR	Removal	SARR	Removal	AOB	NOB	Anammox
	g/m2-d	%	g/m2-d	%	g/m2-d	g/m2-d	g/m2-d
Pre-Shearing	1.74	84%	1.52	71%	1.01	0.06	1.72
Post-Shearing	1.81	87%	1.48	70%	1.08	0.14	1.69
Change:	4%		-3%		7%	133%	-2%

Operating DO The DO set point was lowered stepwise from 3.5 mg/L to 2.5 mg/L, at which point the system's NH_4 SARR declined sharply. In response, the DO set point was raised and maintained at 2.8 mg/L. As shown in Table 6, the lower operating DO suppressed NOB activity significantly while only minimally affected AOB activity. As a result of NOB suppression, AnAOB activity improved by 11%. The overall effect on system performance was a 3% increase in NH_4 SARR and an 11% increase in TIN SARR. These observations were consistent with lower DO availability leading to NOB suppression, and consequently higher AnAOB activity.

Table 6 Effect of Operating DO on Performance

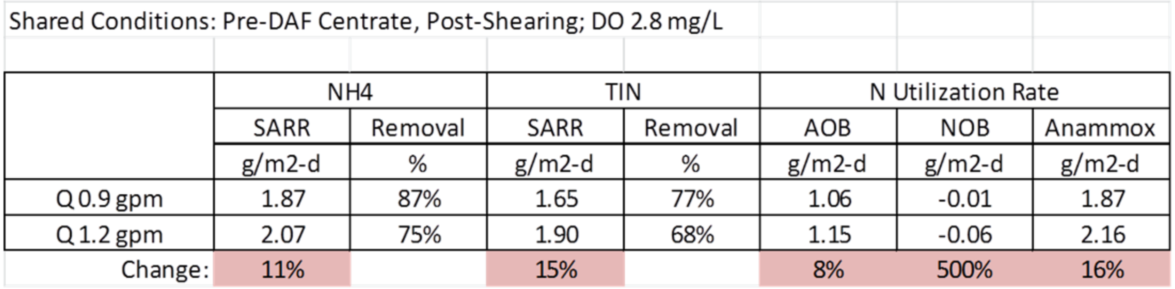


Shared Conditions: Pre-DAF Centrate, Q 0.9 gpm, Post-Shearing

	NH4		TIN		N Utilization Rate		
	SARR	Removal	SARR	Removal	AOB	NOB	Anammox
	g/m2-d	%	g/m2-d	%	g/m2-d	g/m2-d	g/m2-d
DO 3.5 mg/L	1.81	87%	1.48	70%	1.08	0.14	1.69
DO 2.5~2.8 mg/L	1.87	87%	1.65	77%	1.06	-0.01	1.87
Change:	3%		11%		-2%	-107%	11%

Centrate Loading Reactor feed rate was increased from 0.9 to 1.2 gpm. As shown in Table 7, the higher feed rate increased AOB and AnAOB activities, and further repressed NOB activity. The overall effect on system performance was increases of 11% (NH_4) and 15% (TIN) in SARRs. These observations were consistent with improved NH_4 mass transfer resulting in higher AOB and AnAOB activities, the latter repressed NOB activity via competition.

Table 7 Effect of Centrate Loading on Performance



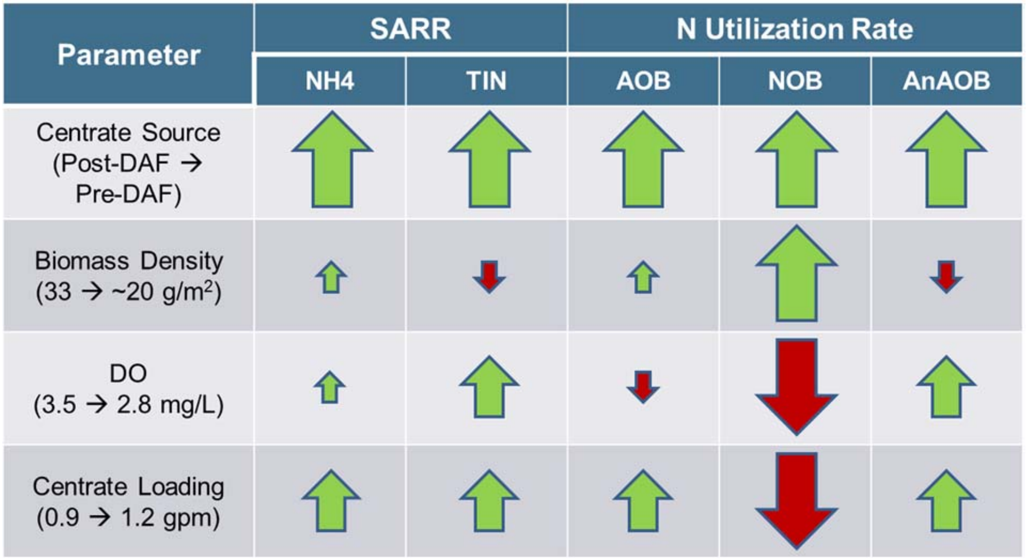
Shared Conditions: Pre-DAF Centrate, Post-Shearing; DO 2.8 mg/L

	NH4		TIN		N Utilization Rate		
	SARR	Removal	SARR	Removal	AOB	NOB	Anammox
	g/m2-d	%	g/m2-d	%	g/m2-d	g/m2-d	g/m2-d
Q 0.9 gpm	1.87	87%	1.65	77%	1.06	-0.01	1.87
Q 1.2 gpm	2.07	75%	1.90	68%	1.15	-0.06	2.16
Change:	11%		15%		8%	500%	16%

The three operating parameters explored (biomass density, operating DO, and centrate loading), in combination with the switch from Post-DAF to Pre-DAF as feed, brought the pilot's performance to similar level observed at RWHTF. This optimization exercise demonstrated that such efforts can be a good investment of time, especially when other evidence suggests that the maximum capacity has not been realized.

Table 8 qualitatively compares each parameter's effect on the system N removal rates and each microbial group's NUR. Switching from Post-DAF to Pre-DAF yielded the greatest improvement, suggesting that something added/removed during DAF (e.g., Mannich polymer) contributed the most to the reactor's poor performance during initial testing. Significant improvement from higher centrate loading suggested that mass transfer limitation (MTL) of a feed component (e.g., NH_4, bicarbonate) was also a major factor. Gain in TIN removal rate via a lower operating DO indicated that oxygen MTL was not a problem (at least not after biomass density was reduced), and that in fact excess aeration led to NOB proliferation and became a part of the problem. Finally, while reducing biomass density did not appear to help performance much, it should not be completely dismissed as it might have enabled improvements attributed to the other parameters.

Table 8 Summary of Process Optimization



Parameter	SARR		N Utilization Rate		
	NH4	TIN	AOB	NOB	AnAOB
Centrate Source (Post-DAF → Pre-DAF)	⬆	⬆	⬆	⬆	⬆
Biomass Density (33 → ~20 g/m²)	↑	↓	↑	⬆	↓
DO (3.5 → 2.8 mg/L)	↑	⬆	↓	⬇	⬆
Centrate Loading (0.9 → 1.2 gpm)	⬆	⬆	⬆	⬇	⬆

Summary

Table 9 summarizes the NH_4 and TIN removal efficiencies and SARRs observed during the MBBR capacity testing. With Pre-DAF as feed and the system optimized, the SARRs were in line with the vendor's expectations and similar to experiences reported elsewhere. Removal efficiencies, however, were slightly lower as higher centrate loading was necessary to sustain the SARR levels.

Table 9 Summary of Capacity Testing (MBBR)[1]

Feed	Date Range	NH_4		TIN	
		Removal Efficiency	SARR (g/m2-d)	Removal Efficiency	SARR (g/m2-d)
Post-DAF	7/22/13~8/20/13	85%	1.3	70%	1.1
Pre-DAF	8/26/13~9/12/13	84%	1.7	71%	1.5
Pre-DAF (optimized)	10/28/13~11/22/13	75%	2.1	68%	1.9

[1] Medians

Specific alkalinity consumption and NO_3 production during capacity testing are summarized in Table 10. According to deammonification stoichiometry, specific alkalinity consumption should be approximately 3.86 gram of alkalinity (as CaCO3) per gram of NH_4-N consumed, and specific NO_3-N production should be approximately 11% of NH_4-N consumed.

Table 10 Alkalinity Consumption and NO_3 Production (MBBR)[1]

Feed	Date Range	Specific Alkalinity Consumption ($g\text{-}CaCO_3/g\text{-}N$ consumed)	Specific NO_3 Production (% of N consumed)
Post-DAF	7/22/13~8/20/13	4.11	14.7%
Pre-DAF	8/26/13~9/12/13	4.15	14.4%
Pre-DAF (optimized)	10/28/13~11/22/13	3.90	8.9%

[1] Medians

During initial testing (Post-DAF and Pre-DAF), median specific alkalinity consumption was ~4.1 $g\text{-}CaCO_3/g\text{-}NH_4\text{-}N$, about 6% greater than predicted by the stoichiometry. A similar pattern was also observed with the specific NO_3 production. These observations were consistent with excessive NOB activity, which oxidized additional NO_2 to NO_3. The latter, as it could not be metabolized by denitrifiers due to the lack of COD, became a terminal product and consequently raised the specific NO_3 production. The diversion of NO_2 to NO_3 (instead of N_2) also prevented alkalinity recovery, consequently resulting in higher specific alkalinity consumption. With more optimal operation during "Pre-DAF (optimized)", NOB activity was repressed, and the two ratios approached values predicted by stoichiometry.

Following capacity testing, the system was operated at the peak feed rate for nearly 6 months. Figure 7 shows SARRs plotted against operating temperatures during this period, excluding data collected during unstable conditions. Using Arrhenius constant typical for nitrification ($\theta=1.072$), the observed temperature span ($\Delta\sim5°C$) would have produced a rate difference of ~42%, which was not observed during this study. This attenuated temperature response is similar to observations in nitrifying biofilters (Zhu and Chen, 2002). It must be emphasized that attenuated temperature response does not mean no response; as with all biological processes, the operating temperature should still be considered during ANITA Mox design.

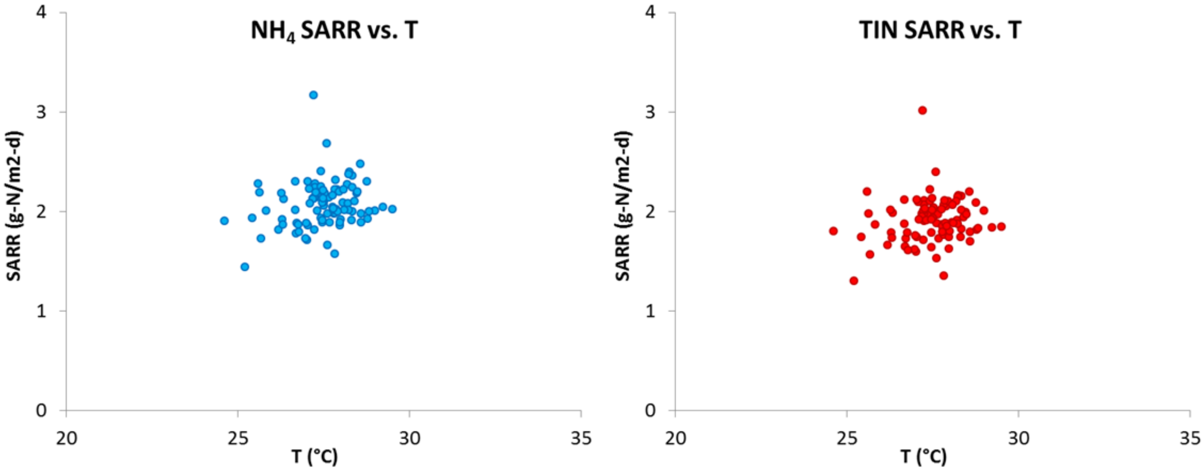


Figure 7 NH_4 and TIN SARR versus operating temperature (10/28/13-04/18/14)

Capacity Testing (IFAS)

The IFAS system was operated from 10/9/13 through 07/11/14 using Pre-DAF as feed. During this time, mixed liquor biomass was grown entirely from the process, without external seeding. After capacity building and process optimization, the maximum capacity was reached on 1/23/14. The period of 1/23/14 and 2/12/14 was selected for capacity testing purposes, as reactor operation was stable with minimal planned or unplanned outages/disturbances.

Table 11 summarizes the system's N removal efficiencies, SARRs, and NO_3 production during this period. Compared to the MBBR system, the IFAS system exhibited substantially higher (greater than 3-fold) SARRs while maintaining similar removal efficiencies. The higher design SARR is expected to translate into smaller footprint requirement and lower capital cost. However, actual saving would be less than indicated by the SARRs, as the IFAS variant would require additional tankage for clarification. The specific NO_3 production was slightly lower than observed on the MBBR pilot. The less-than-predicted-by-stoichiometry value was likely due to the reactor's limited but present denitrification activity fueled by COD released from biomass endogenous decay.

Table 11 Summary of Capacity Testing (IFAS)[1]

Feed	Date Range	NH_4		TIN		Specific NO_3 Production (% NH_4-N consumed)
		Removal Efficiency	SARR (g/m2-d)	Removal Efficiency	SARR (g/m2-d)	
Pre-DAF	1/23/14~2/12/14	78%	7.8	68%	6.7	8.1%

[1] Medians

Another interesting characteristic of the IFAS pilot was its higher reactor NO_2 concentration. Whereas mixed liquor NO_2 concentration stayed in the 3~5 mg/L range for the MBBR pilot, it ranged from 10~30 mg/L for the IFAS pilot (Figure 8), with peaks as high as 70 mg/L. Surprisingly, the high bulk NO_2 concentration did not inhibit AnAOB activity; in fact it was likely necessary to support the higher mass transfer rate required for the higher removal rate.

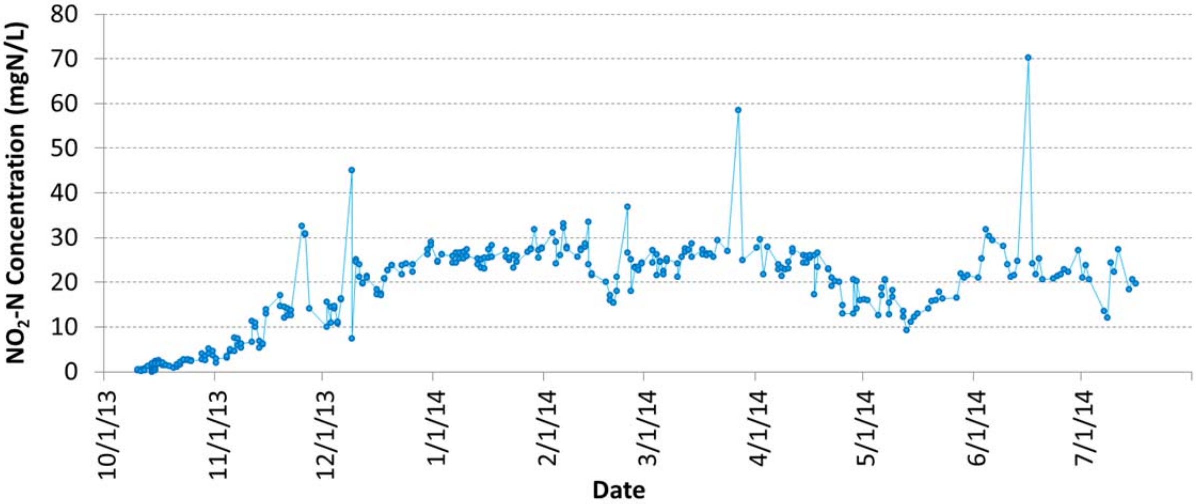


Figure 8 Reactor NO_2-N Concentration (IFAS)

Robustness Testing (MBBR)

Power Outage

This test was to assess the effect of power outages, which can occur from time to time. During the 24-hour perturbation period, power to the reactor was shut off, resulting in no feed, air, or mixing (via aeration or mechanical) being delivered. During the power shutoff, the reactor surface was covered completely by floating media, though it was unclear if all the media floated. After restoration of power, system performance was monitored for 48 hours at 8-hour intervals to evaluate the recovery behavior. Figure 9 shows the system's NH_4 and TIN SARRs during this test.

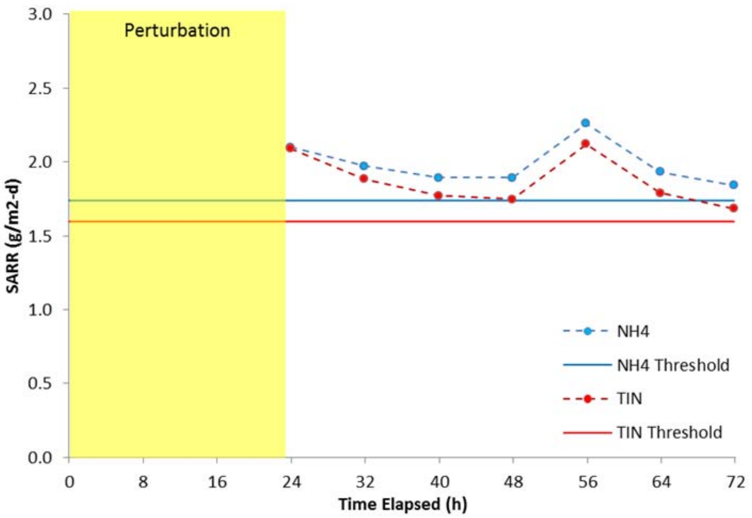


Figure 9 Robustness Test (Power Outage)

During the perturbation period, as there was no influent and effluent, the reactor's SARRs could not be evaluated. During the recovery period, system SARRs did not drop below the baseline, defined as the 14-day median SARR before the perturbation (see Methods: Robustness Testing). As such, there was no performance reduction ($\Delta p=0$) and no recovery time ($t_{recovery}=0$).

Feed Variance (No Feed NH_4)

This test was to assess the effect of feed NH_4 outages, which can occur when centrifuges are taken offline, resulting in the centrate stream being primarily dominated by centrifuge cooling water. During the 24-hour perturbation period, feed to the MBBR system was replaced by plant wash water. After resumption of centrate as feed, system performance was monitored for 48 hours at 8-hour intervals to evaluate the recovery behavior. Figure 10 shows the system's NH_4 and TIN SARRs during this test.

During the perturbation period, system SARRs were limited by the loading rate, so the low apparent SARRs in this period were not considered. During the recovery period, system SARRs stayed above the baseline from the first monitoring time point. As such, there was no performance reduction ($\Delta p=0$) and no recovery time ($t_{recovery}=0$).

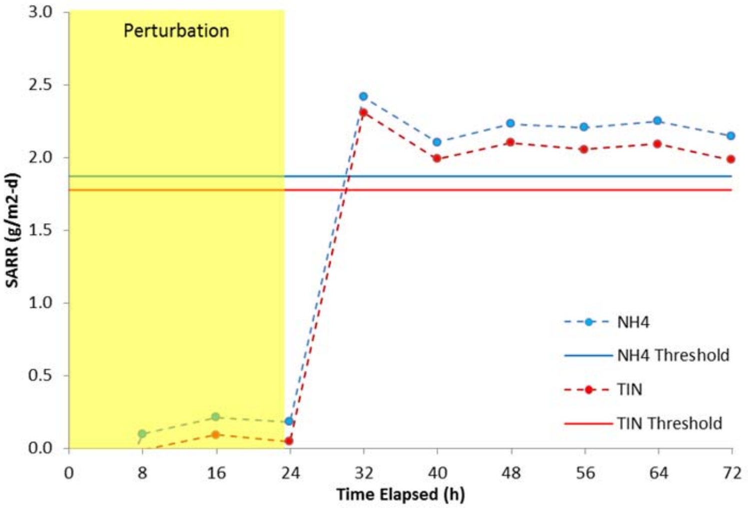


Figure 10 Robustness Test (Underfeed)

Feed Variance (Overfeed)

This test was to assess the effect of centrate overfeeding events, which can occur when the feed flow meter malfunctions. During the 24-hour perturbation period, feed to the MBBR system was doubled. After returning to the normal feed rate, system performance was monitored for 48 hours at 8-hour intervals to evaluate the recovery behavior. Figure 11 shows the system's NH_4 and TIN SARRs during this test.

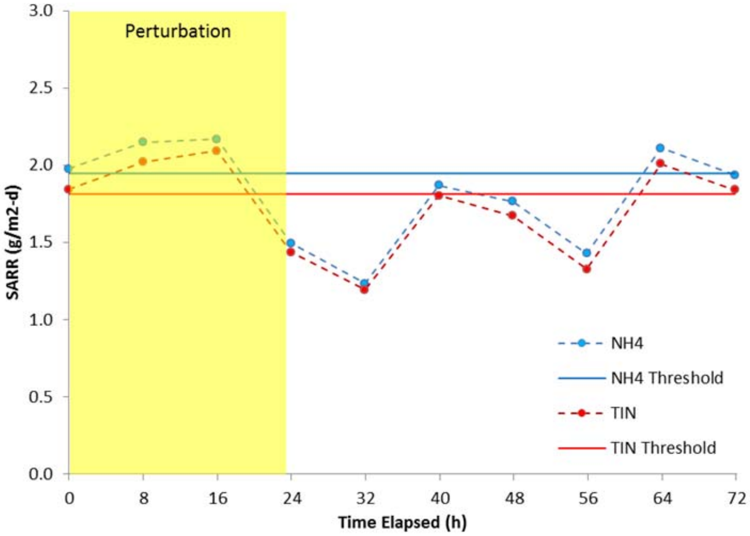


Figure 11 Robustness Test (Overfeed)

During the perturbation period, system SARRs stayed near the baseline until the end of the period, when the reactor NH_4 concentration peaked at 460 mg/L. The high NH_4 concentration resulted in a 40% loss in NH_4 SARR during the initial recovery period. However as NH_4 concentration declined, without special attention or recovery procedure, system SARRs recovered gradually and were fully restored by hour 64 ($t_{recovery}$=40 h).

Feed Variance (Excess Mannich Polymer)

This test was to assess the effect of excess Mannich polymer in the feed, which can occur during centrifuge start-up conditions. In addition, Mannich polymer is used in DAF operation to help improve thickening performance. Excess polymer was speculated to cause the performance disparity between Pre-DAF and Post-DAF operation. During the initial 72-hour perturbation period, the MBBR system received Mannich polymer at a dose of 13 ppm, or approximately 3 times the typical DAF dose. Then, the polymer dose was raised to 44 ppm, or approximately 10 times the typical DAF dose, for 10 days. Afterward, polymer feed stopped (unplanned) for 1.5 day, resumed for about a day, and stopped again. System performance was monitored for the entire duration, typically at 8-hour intervals. Figure 12 shows the system's NH_4 and TIN SARRs during this test.

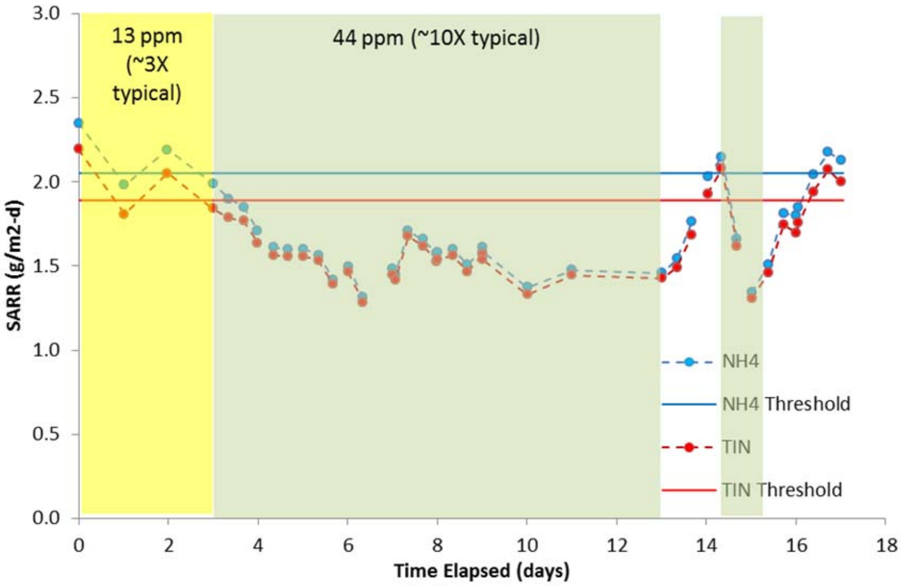


Figure 12 Robustness Test (Excess Polymer)

At the lower dose (13 ppm), Mannich polymer addition resulted in ~9% reduction in SARRs after 3 days, though the small reduction could have been just experimental noise. At the higher dose (44 ppm), system SARRs deteriorated by 39% after about 3 days. Notably, even though dosing continued at the same level for nearly a week afterward, performance remained stable. During the first (unplanned) recovery period, system SARRs recovered fully after ~32 hours. Interestingly, resumption of polymer addition triggered performance decline much quicker than the first time, though the second (planned) recovery was similar to the first ($t_{recovery}$=32 h).

Aeration Variance (No Aeration)

This test was to assess the effect of aeration outage, which can occur when the process air compressor fails. During the 24-hour perturbation period, aeration to the MBBR system was shut off, while mechanical mixer was engaged to maintain mixing. After aeration was restored, system performance was monitored for 48 hours at 8-hour intervals to evaluate the recovery behavior. Figure 13 shows the system's NH_4 and TIN SARRs during this test.

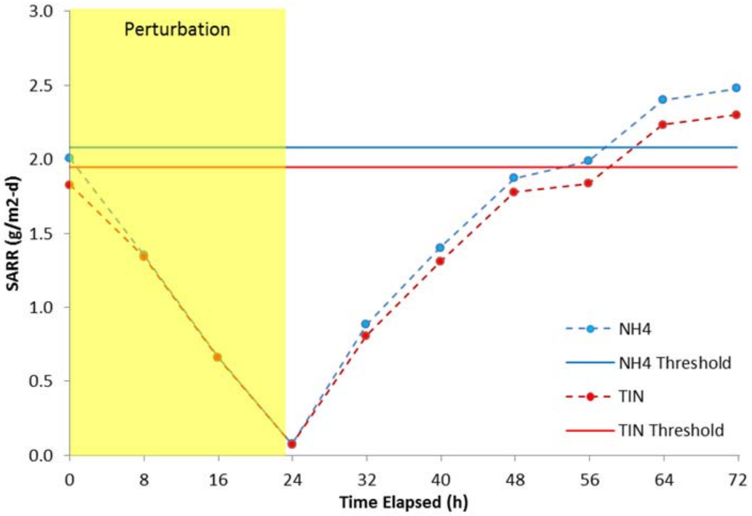


Figure 13 Robustness Test (Under-aeration)

During the perturbation period, system SARRs declined as much as 96% by hour 24. The apparent gradual performance loss in the absence of aeration countered the premise that oxygen is required for the process, and was likely an artifact of the non-steady state condition and reflected a limitation of the method. After aeration was restored, system SARRs were fully restored by hour 64 ($t_{recovery}$=40 h).

Aeration Variance (Over-aeration)

This test was to assess the effect of over-aeration, which can occur when air flow metering fails or malfunctions. During the 24-hour perturbation period, air flow rate to the MBBR system was increased by 23% (maximum that could be achieved by the test equipment). After aeration was restored to normal levels, system performance was monitored for 48 hours at 8-hour intervals to evaluate the recovery behavior. Figure 14 shows the system's NH_4 and TIN SARRs during this test.

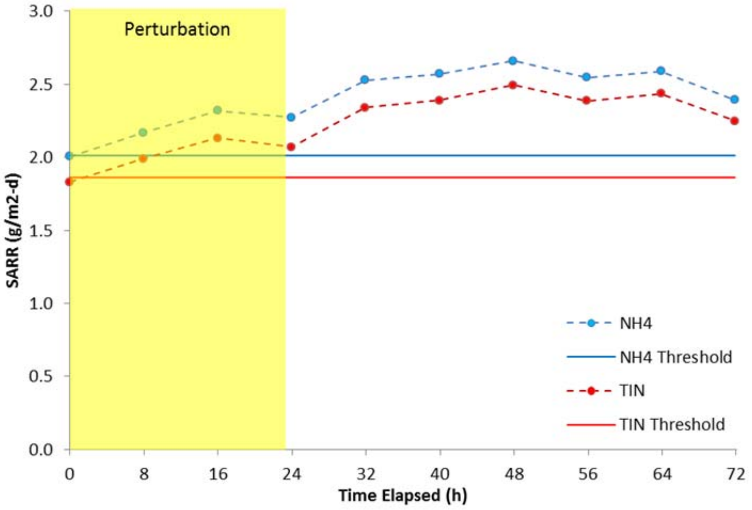


Figure 14 Robustness Test (Over-aeration)

During both the perturbation and the recovery periods, system SARRs did not drop below the baseline. As such, there was no performance reduction ($\Delta p=0$) and no recovery time ($t_{recovery}=0$).

Robustness Testing Summary

Robustness of the MBBR variant was evaluated with six different scenarios designed to simulate various commonly-encountered operational events/outages. The results of the testing are summarized in Table 12. Of the scenarios tested, no aeration resulted in the largest performance reduction (96%), which is understandable as oxygen is required for the reaction. Overfeed and excess Mannich Polymer also resulted in substantial performance reductions (~40%). In all scenarios, the system recovered completely within 2 days. The process' excellent recovery characteristics should comfort those considering the process but are wary of its sensitivity and ability to recover from common operational events/outages.

Table 12 Robustness Testing Summary

Test	Scenario	Perturbation Period	Performance Reduction (Δp)	Recovery Time ($t_{recovery}$)
1	Power Outage	24 hr	None	None
2	No Feed NH_4	24 hr	None	None
3	Overfeed (2X)	24 hr	40%	40 hr
4a	Excess Mannich Polymer (13 ppm)	72 hr	9%	Not Tested
4b	Excess Mannich Polymer (44 ppm)	240 hr	39%	32 hr
5	No aeration	24 hr	96%	40 hr
6	Over-aeration (+23%)	24 hr	None	None

Greenhouse Gas Emissions

Offgas from the MBBR reactor was sampled from 4/15/14 through 4/21/14 and analyzed for N_2O and CH_4 as described in the Methods section. During this period, the sampling train experienced blockage by condensate between 4/17/14 and 4/18/14, so this data subset was excluded. The measured analyte concentrations, combined with the reactor's air flow rate which was estimated to approximate the reactor offgas rate, were used to calculate the Mass Emission Rate (MER) for each analyte. The calculated MER for N_2O and CH_4 over time are shown in Figure 15 (panels A and B). Median MER for N_2O was 36 g/d; for CH_4, 26 g/d.

Similar measurements were collected with offgas from the IFAS reactor from 3/10/14 through 3/17/14. The calculated MER for N_2O and CH_4 over time are shown in Figure 15 (panels C and D). Median MER for N_2O was 230 g/d; for CH_4, 120 g/d. Interestingly the IFAS pilot exhibited diurnal pattern in N_2O and CH_4 MERs that correlated with the reactor's temperature, whereas the MBBR pilot did not.

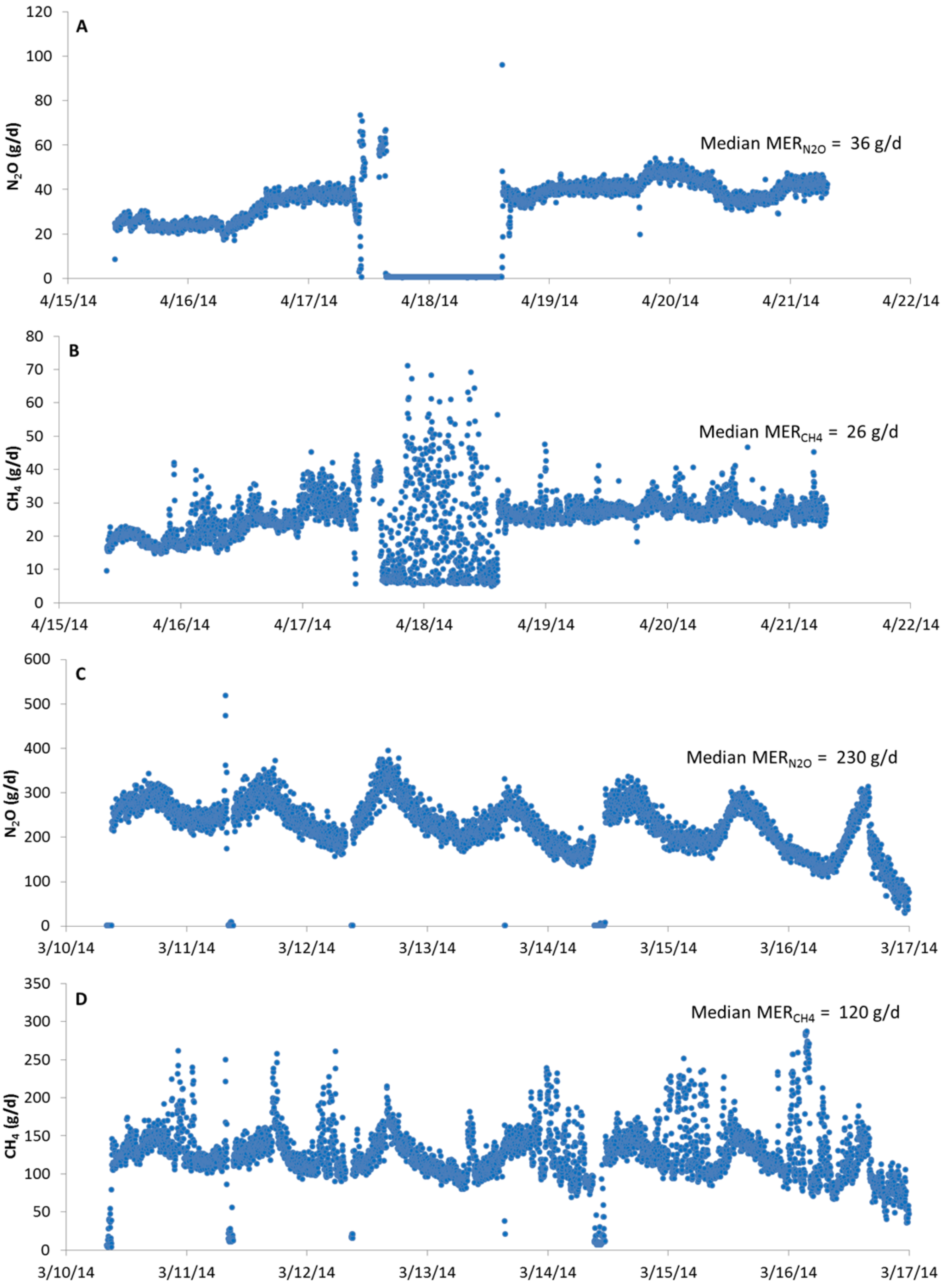


Figure 15 Mass Emission Rates over Time
(A) MBBR/N_2O; (B) MBBR/CH_4; (C) IFAS/N_2O; (D) IFAS/CH_4

As the two pilots were operated with different flow rates and nitrogen loading rates, a more meaningful comparison of the two ANITA Mox variants require their MERs be normalized on the same basis. To this end, the N_2O MERs were normalized by the TKN loading, and the CH_4 MERs were normalized by the flow rate (Table 13). On such normalized basis, the IFAS pilot emitted 3.3 times more N_2O and 2.5 times more CH_4 than the MBBR pilot. For comparison, Weissenbacher et al. (2010) reported that the DEMON process, a competing technology to ANITA Mox, emitted 1.3% of the influent TKN as N_2O.

Table 13 Normalized N_2O and CH_4 MERs

System (Date Range)	N_2O MER / TKN Loading (g-N/g-N)[1]	CH_4 MER / Flow Rate (mg-CH_4/gal)[1]
MBBR (4/15/14-4/21/14)	0.52%	15
IFAS (3/10/14-3/17/14)	1.7%	38

[1] Medians

Operational Issues

One operational problem encountered during this evaluation involved the equipped DO probe (Hach LDO2). With the standard issue, the probe was exposed directly to the media. The scouring action by the media appeared to damage the sensor coating (Figure 16, left), resulting in erratic readings and potentially shorter sensor life. Installation of a probe guard (Figure 16, middle) offered some protection for the sensor, but surprisingly media chips were often found lodged between the sensor and the probe guard. When this occurred, DO readings tended to under-report the actual DO, consequently leading to over-aeration. Retrofitting the probe guard with an air scouring device (Figure 16, right) reduced the frequency of media trapping, but did not completely eliminate the problem. In full-scale installation, special care is recommended in the selection/design for probe protection. Installation of redundant probes can also be a cost-effective solution to ensure the operator has accurate DO information to operate the process optimally.

Figure 16 Left: DO Sensor lens scratching by media; Middle: Media trapped between probe and probe guard; Right: Probe/Probe guard retrofitted with an air scouring device.

CONCLUSIONS

Two variants of the ANITA Mox process (MBBR and IFAS) were evaluated for treating two JWPCP centrate streams (Pre-DAF and Post-DAF). The study's major findings were:

- JWPCP centrate nitrogen can be removed by ANITA Mox at the following rates/efficiencies:

Centrate Stream	Removal Rate[1] (Removal Efficiency)	
	MBBR-variant	IFAS-variant
Pre-DAF	NH_4: 2.1 (75%) TIN: 1.9 (68%)	NH_4: 7.8 (78%) TIN: 6.7 (68%)
Post-DAF	NH_4: 1.3 (85%) TIN: 1.1 (70%)	Not Tested

[1] Median surface area removal rate, in gN/m^2-d

- Robustness of the MBBR-variant was evaluated in six scenarios:
    - Three scenarios (No aeration, overfeed, and excess Mannich polymer) showed performance reduction;
    - Even in the worst case, full recovery was achieved within 2 days without special shutdown/startup procedures;
- GHG (N_2O, CH_4) emissions of both pilots were measured:
    - MBBR-variant showed lower N_2O MER than the competing DEMON process.
    - IFAS-variant showed higher N_2O and CH_4 MERs than the MBBR-variant;

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