

# Development of Enhanced Deammonification Selector

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## ABSTRACT

Deammonification (i.e. combined partial nitrification and anaerobic ammonia oxidation) is known as an efficient and resource saving sidestream process option to remove high strength nitrogen load from sludge dewatering liquors. The process uses less energy, 1.2 kWh/kg N removed versus 5-6 kWh/kg N removed for conventional nitrification/denitrification in the mainstream and requires no carbon dosage. The paper describes a cyclone-device as a significant feature of the DEMON-process for additional enrichment of anammox biomass in the system. Model results supported by activity measurements indicate almost doubling of the anammox- to aerobic AOB mass ratio improving the robustness against disturbances. Ongoing full-scale experiments explore the potentials for anammox retention in the main liquid train by cyclone operation.

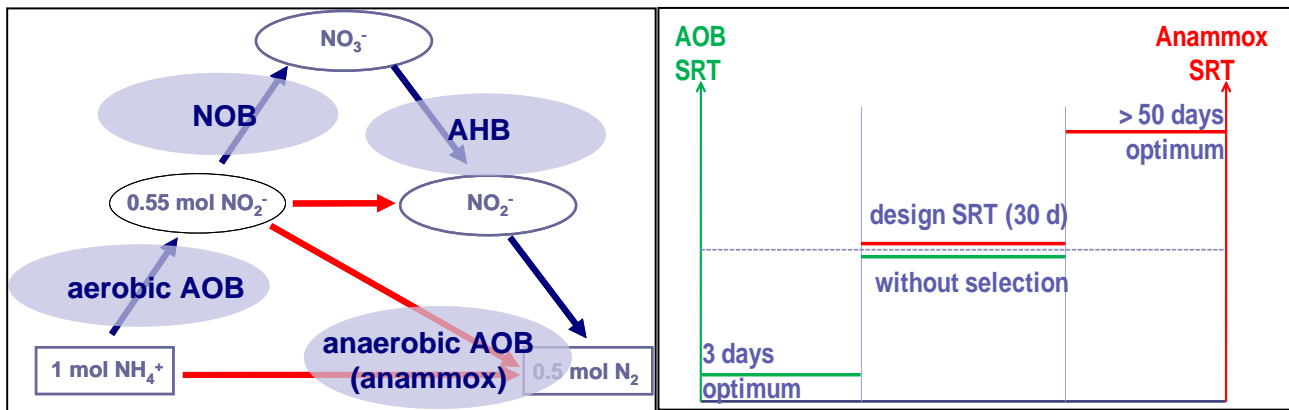
## KEYWORDS

Deammonification, sidestream treatment, ammonia, DEMON, anammox, cyclone

## INTRODUCTION

The DEMON® process is a suspended growth deammonification process that is operated in a sequencing batch reactor and has been installed at 9 full-scale locations in Austria (1), Germany (3), Switzerland (3), Hungary (1) and Netherlands (1) with 6 more under construction or start-up in Austria (2), Serbia (1), Netherlands (1) and Germany (2). Valuable experience is collected with each new successful installation which provides a deeper understanding of how to design and operate these facilities. The success of the DEMON® process for the energy-efficient suspended growth deammonification depends on the control of following four different microbial consortia (Fig.1a):

- Aerobic ammonia oxidizers (aerobic AOB – one of the main players in deammonification process) produce nitrite which serves as substrate for anammox but is a toxic compound when in excess. The DEMON®-process controls the duration of each aeration interval based on the pH-signal (Fig.2) in order to prevent nitrite accumulation (Wett, 2007).
- Anaerobic ammonia oxidizers (anammox – the other main player) are extremely slow growing autotrophic organisms and therefore a higher solids retention time is required for these organisms to fully establish in the system (Fig.1b).
- Nitrite oxidizers (NOB) need to be repressed by taking advantage of higher oxygen half saturation and different temperature sensitivity compared to aerobic ammonia oxidisers AOB. Importantly, free ammonia inhibition can out-compete NOB (Turk & Mavinic, 1989). Low SRT increases the pressure on the NOB-population (Fig.1b).
- Another group – anoxic heterotrophic biomass (AHB) – plays a minor role due to limited availability of organic carbon but can help reduce residual nitrate concentration (nitrate is produced in 11% stoichiometric ratio from deammonification according to Strous et al., 1998). However presence of excess carbon can increase their activity significantly to out-compete the anammox organisms.



**Figure 1.** Functional groups of organisms catalysing nitrogen removal processes (1a; left) and difference in SRT requirements for anammox and AOB (1b; right)

This paper explores how to apply a deammonification ‘Selector’ and the use of the selection to ‘stretch’ the limits of operation of the deammonification process. Four examples are provided below for enhancement (AOB and anammox), repression (NOB) or accommodation (AHB) of each of the four organism groups mentioned above.

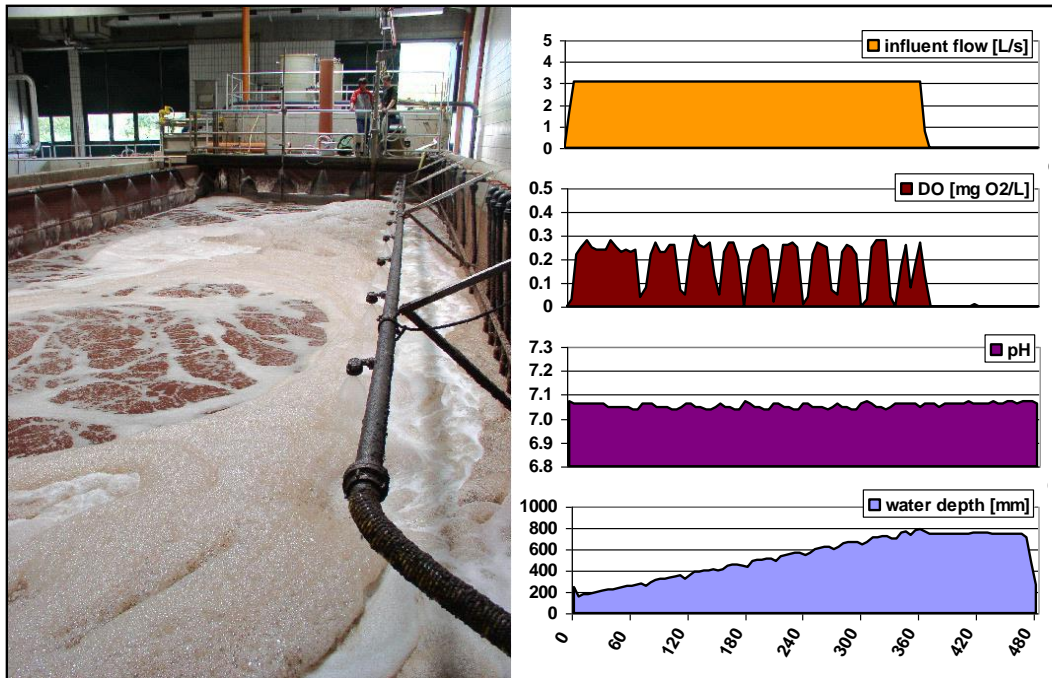
Limit of Operation - AOB: Inadequate alkalinity will limit the growth of AOBs, especially since these organisms depend on bicarbonate to convert into organic mass. A *solution* is to enable the process to operate under pH conditions that maximize the availability of inorganic carbon.

Limit of Operation - Anammox: A decrease in temperature will significantly slow down the anammox activity. A *solution* is to decouple the anammox SRT from the other organism groups by using a classifying selector. Since anammox is predominantly aggregated in the heavy granular fraction, Innerebner et al. (2007), a cyclone can be applied for the DEMON process making use of centrifugal forces to select the appropriate SRT separately for AOB and anammox populations. The sludge recycle flow is fed to the cyclone and the overflow is wasted while the cyclone underflow showing high anammox activity is returned to the reactor (Fig.3).

Limit of Operation – NOB: High SRT or a decrease in influent ammonia concentration or temperature will increase NOB activity. A *solution* is to maintain low DO conditions to outcompete NOBs.

Limit of Operation – AHB: An increase in organic substrate will increase the activity of AHB. A *solution* is to balance the mass ratio of AHB and anammox, using the anammox selector (as above).

The following case studies include DEMON plants in Switzerland and Austria that have been equipped with a classifying cyclone (to separate more densely aggregating anammox organisms from other organisms) to improve process robustness.

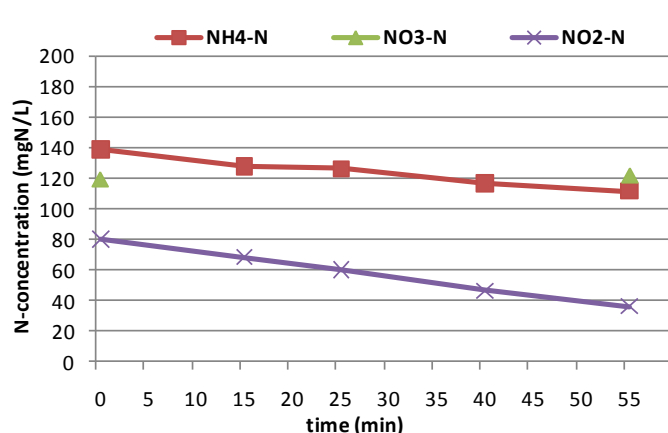


**Figure 2.** Photograph of the full-scale DEMON-system Strass (left; 500 m<sup>3</sup> maximum volume) and typical process variables during 1 SBR cycle (right; flowrate, DO, pH and liquid level; Wett 2007)

## METHODS

**Anammox activity tests.** The mass of active anammox organisms is quantified indirectly by ex-situ tests determining degradation rates of spiked nitrite loads. Activity measurements are conducted in combination with periodical sludge wastage according to the following protocol:

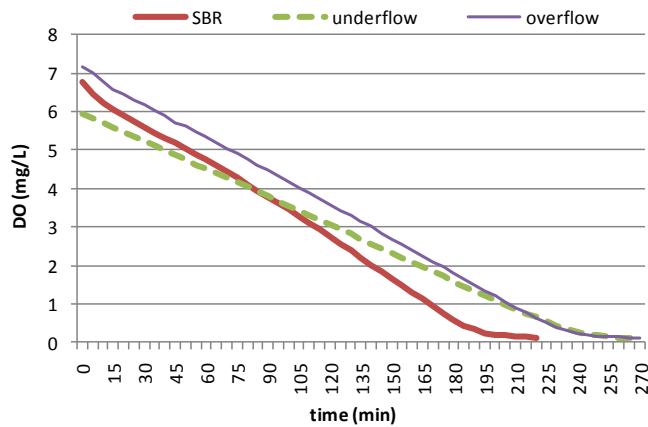
- 1) Sampling of 5 L of sludge and spiking with NaNO<sub>2</sub> (results NO<sub>2</sub>-N > 50 mg/L)
- 2) Cover vessel, start mixing and wait 5 minutes for complete dissolution of salt
- 3) Measurement from filtered samples every 15 minutes: 5 data points for NH<sub>4</sub>-N, NO<sub>2</sub>-N, NO<sub>3</sub>-N, temperature, DO, time (Figure 3)
- 4) Determine TSS concentration and calculate nitrite depletion and total N-turnover per g TSS and hour: [g N \* g TSS<sup>-1</sup> \* h<sup>-1</sup>]



**Figure 3.** Set-up for ex-situ anammox activity tests in the lab (3b; right) and measured removal of N-compounds (3a; left)

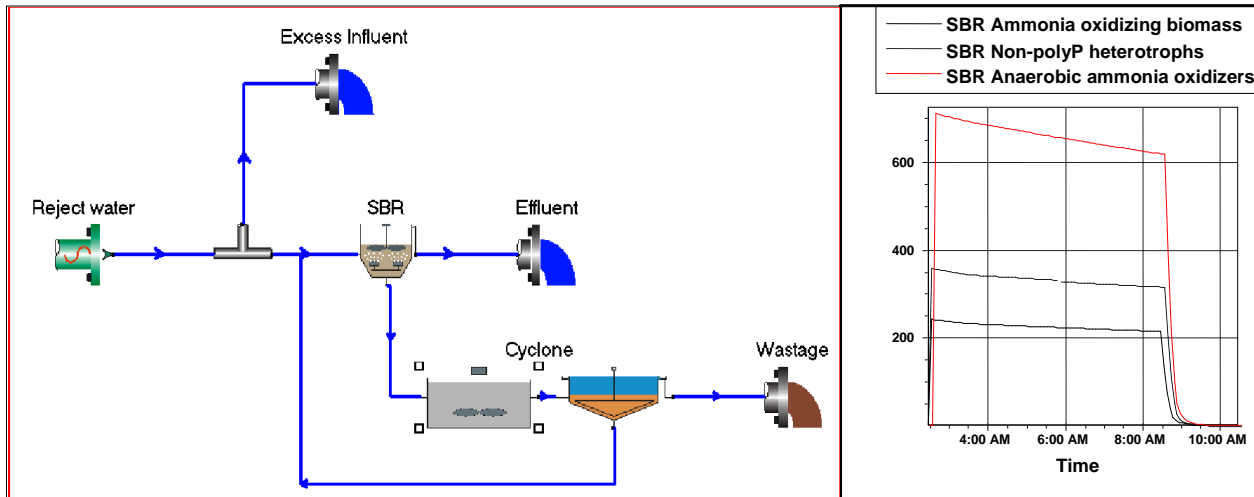
### **AOB-activity test.**

- 1) Same sample of 5 L as before (aerobic test after the anaerobic test)
- 2) Start mixing and aerating and wait at least 5 minutes for stable DO-level (at least 3 mg DO/L)
- 3) Measurement from filtered samples every 15 minutes: 5 data points for NH<sub>4</sub>-N, NO<sub>2</sub>-N, NO<sub>3</sub>-N, temperature, DO, time
- 4) Determine TSS concentration and calculate nitrite production  $dNO_2\text{-N}$  per g TSS and hour:  $[g\ N * g\ TSS^{-1} * h^{-1}]$
- 5) Additional OUR-test (DO-depletion profile after aeration has been turned off) to quantify AOB-activity (Figure 4)



**Figure 4.** Set-up for ex-situ AOB-activity tests in the lab (4b; right) and measured OUR (4a; left)

**Deammonification Modeling.** Implementation of a 2-step nitrification model and the anammox reaction (Jones et al., 2007; Sin et al., 2009) leads to a model description of relevant population dynamics. The process configuration including the pH-controlled SBR and the cyclone has been implemented in the environment of the BioWin simulator. The cyclone is represented by a model builder unit which allows the removal of different solids fractions to a defined extent (Wett et al., 2010). By definition of certain removal rates – so called selectivity parameters – a target retention of individual solids fractions in the cyclone underflow back to the reactor can be defined (Figure 5). These selectivity parameters are calibrated to the mass-specific activity measured in the underflow or overflow versus the feed-flow to the cyclone.



**Figure 5.** Model flow scheme and simulated biomass composition after anammox enrichment

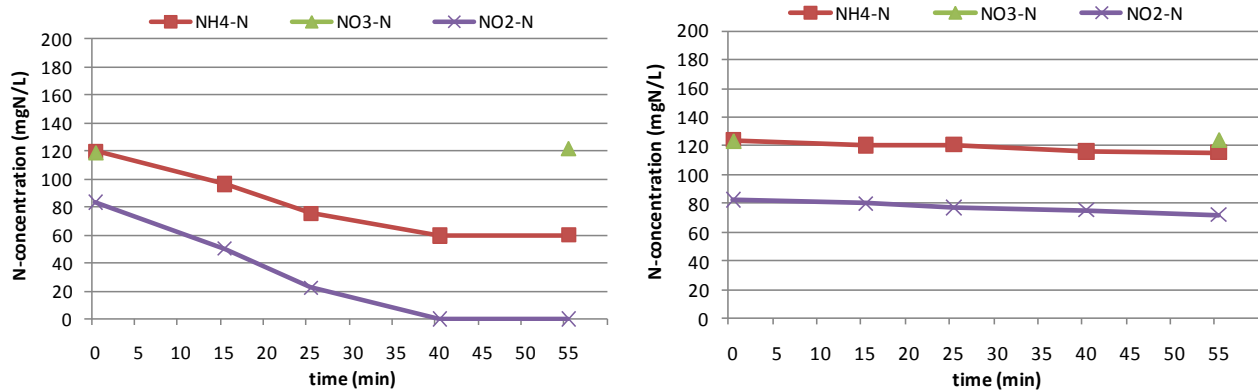
## RESULTS AND DISCUSSION

**Initial anammox activity without cyclone at WWTP Strass (A).** At the WWTP Strass activity tests have been conducted in order to evaluate the quality of the seed sludge since the first biomass transport to support start-ups for other DEMON plants, i.e. the Swiss plant Glarnerland in 2006. Table 1 summarizes activity measurement results from that period without cyclone application indicating an average anammox activity of 15.9 mgN/gTSS/h.

	ammonia	nitrate	nitrite	stoichiometry	<b>N-conversion</b>
	d NH <sub>4</sub> -N/gTS/h	d NO <sub>3</sub> -N/gTS	d NO <sub>2</sub> -N/gTS	dNO <sub>2</sub> /dNH <sub>4</sub>	<b>dNO<sub>2</sub>+dNH<sub>4</sub></b>
<b>19.07.2006</b>	7.58	1.67	8.52	1.12	<b>16.10</b>
<b>25.07.2006</b>	7.10	-0.60	8.50	1.20	<b>15.60</b>

**Table 1.** Early anammox activity test results expressed as N-conversion rates specific to the MLSS-concentration in the SBR

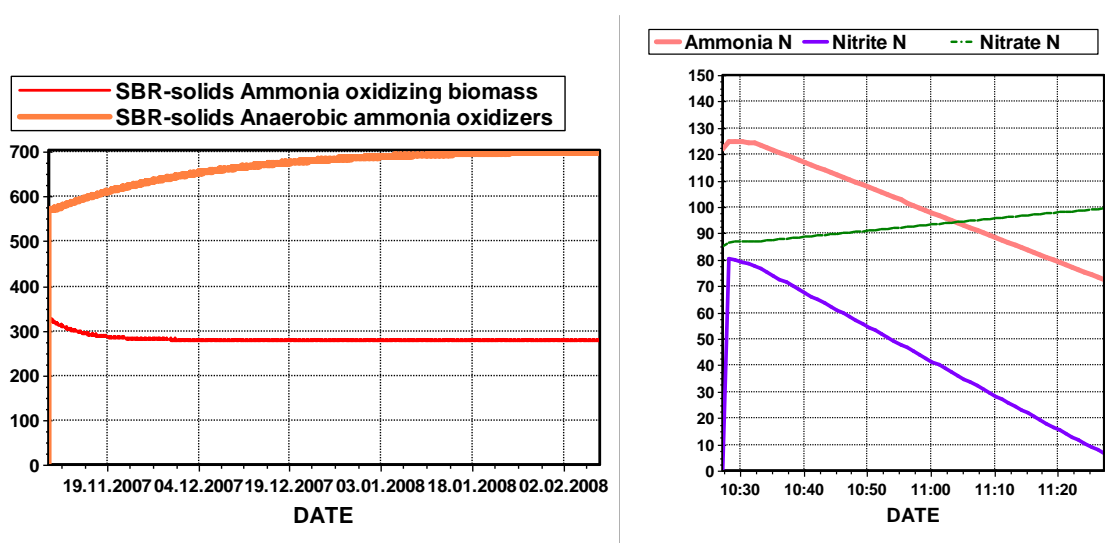
**Enhanced anammox activity with a cyclone device at the WWTP Strass.** The cyclone-application in Strass had a visible impact on sludge composition towards a more reddish and granular appearance although the size of granules remained in the range smaller than 1 mm. Activity measurements indicate a substantial increase of the anammox fraction. The activity test for the underflow-sample had to be performed at 5-fold dilution and still then the spiked nitrite concentration was depleted in about 30 minutes (Figure 6a). The cyclone overflow exhibited a completely different behaviour showing almost horizontal (negligible) N-conversion profiles (figure 6b). Ratios of measured removal rates for nitrite and ammonia of 1.37 and 1.21, respectively, reflect stoichiometry of the Strous equation (1.32; Strous 1998). The comparison of the measured anammox activity in the SBR employing the cyclone (28.6 mgN/gTSS/h; table 2) and of the initial system (15.9 mgN/gTSS/h; table 1) demonstrates an 80% improvement.



**Figure 6.** Ammonia- and corresponding nitrite removal during parallel ex-situ activity tests for an underflow- (6a; left) and an overflow sample (6b; right) of the cyclone in Strass

	OUR	ammonia	nitrate	nitrite	stoichiometry	N-conversion	flow Q	solids	anammox	AOB
	d DO/gTS/min	d NH4-N/gTS	d NO3-N/gTS	d NO2-N/gTS	dNO2/dNH4	dNO2+dNH4	L/s	gTSS/L	activity flux N*Q*TSS	activity flux OUR*Q*TSS
SBR cyclone feed	0.67	10.95	-1.10	17.65	1.61	28.60	1.5	2.72	116.7	2.72
underflow	0.24	18.35	-0.56	25.15	1.37	43.51	0.09	21.60	85.5	0.48
overflow	1.16	6.50	-0.60	7.85	1.21	14.35	1.41	1.46	29.5	2.40
% waste flux									0.25	0.88

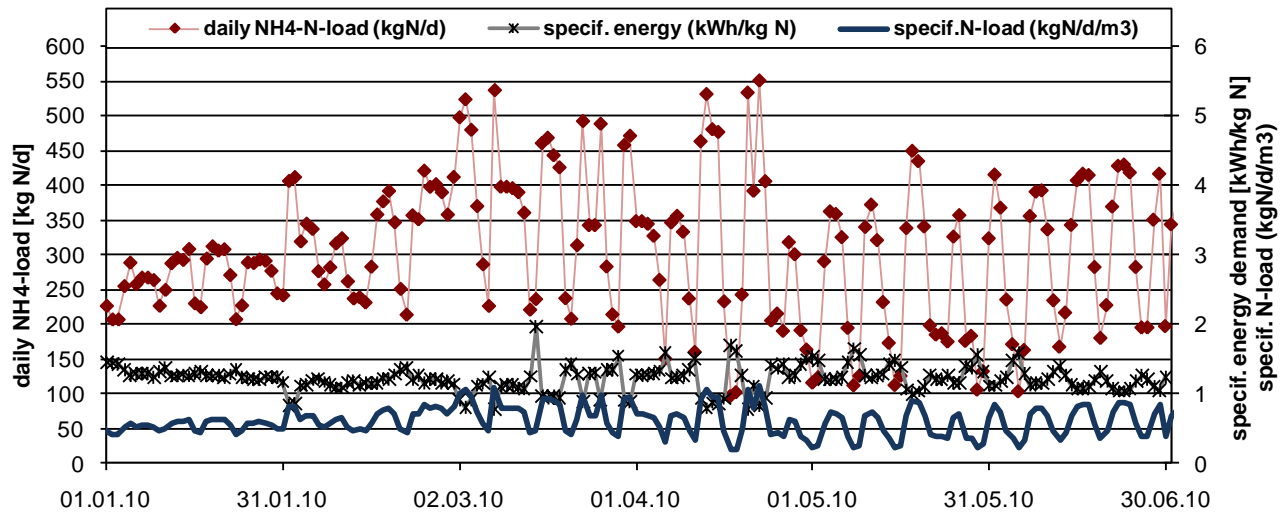
**Table 2.** Measured specific oxygen depletion and nitrogen conversion (per g solids), calculated activity fluxes contained in each cyclone flow and AOB- and anammox-share in the waste flow (overflow)



**Figure 7.** Simulated anammox enrichment due to cyclone operation at dropping MLSS concentration (7a, left) and final ammonia- and nitrite removal in an anammox activity batch test (7b, right; compare measurements in Figure 3)

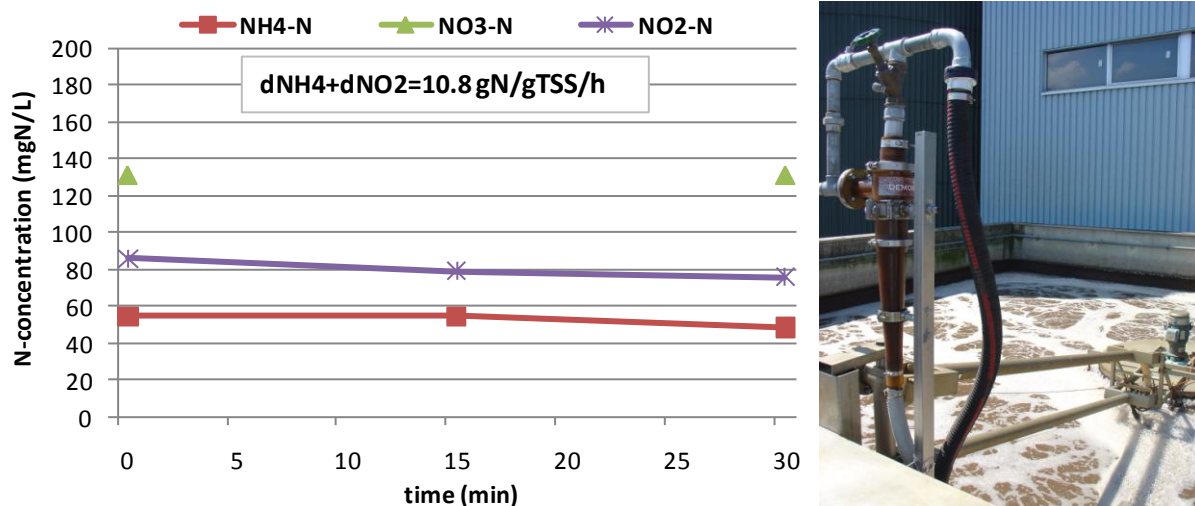
Simulations of the DEMON-system including the cyclone application in Strass under an ammonia loading of 350 kg N per day reproduce the enrichment of anammox biomass during a period of increased sludge wastage when MLSS dropped from 5 to 4 g/L. Increased anammox concentration

(figure 7a) means high activity in the simulated batch test (figure 7b). In general the higher mass of active nitrite consumers (anammox) versus nitrite producers (AOB) improves robustness of the process against disturbances like over-aeration or temperature drop. The substantially higher accumulated mass of anammox in the system compensates for slower kinetics of these organisms compared to AOBs. In Figure 8 the monitored process performance in Strass is shown with a specific loading rate (blue profile) up to 1.0 kg N/m<sup>3</sup>/d (6-months average of 0.61) and a specific energy demand of 1.2 kWh/kgN.



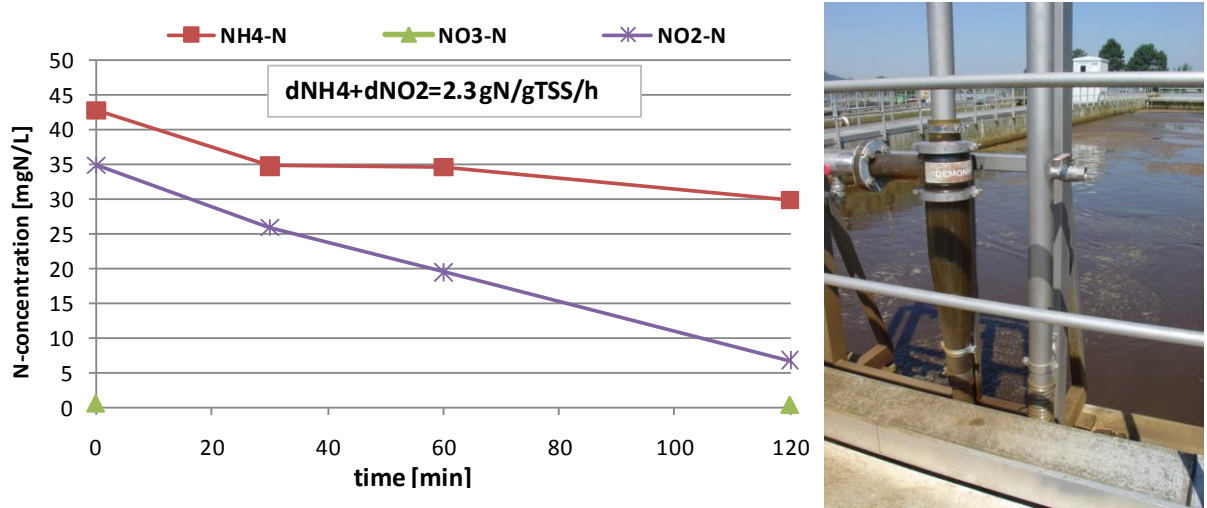
**Figure 8.** Daily sidestream ammonia load, volumetric ammonia loading and specific energy uptake of the DEMON unit during 6 month 2010 at WWTP Strass

**Cyclone performance at the DEMON Glarnerland (CH).** The DEMON-plant Glarnerland achieves similar ammonia removal efficiency beyond 90%. It is a smaller system designed for a maximum load of 200 kg NH<sub>4</sub>-N. The operating MLSS-concentrations is significantly lower – around 1.5 g/L – and also the measured specific anammox activity (Figure 9) is lower mainly due to one reason: A major part of the produced waste sludge in the sidestream is transferred to the mainstream in order to enhance anammox activity there.



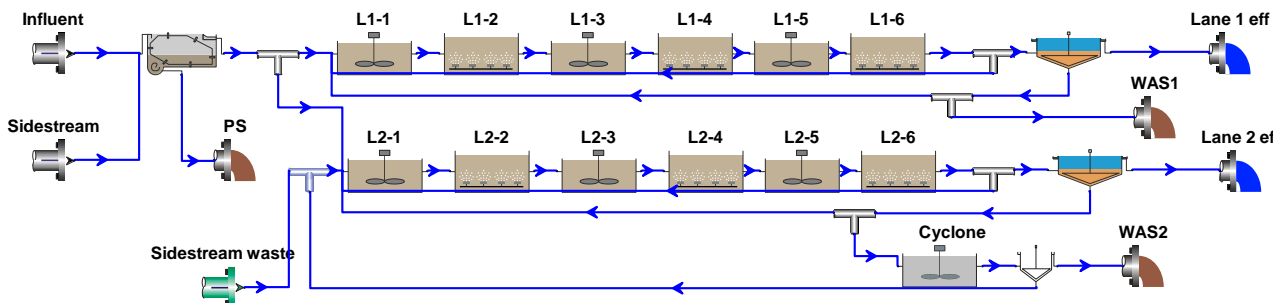
**Figure 8.** Anaerobic ammonia oxidation performance measured in a sidestream mixed liquor sample with 1.5 g TSS/L and an operating temperature of 27°C (8a; left) and a photo of the DEMON-system Glarnerland (8b; right)

**Preliminary tests for anammox retention in the mainstream liquid train.** In the waste sludge pipe of the main liquid train in Glarnerland a similar cyclone device (Figure 9b) has been installed as in the sidestream. Accumulated red granules are visible in the underflow as well as in the activated sludge of the aeration tank. Activity of this biomass has been demonstrated by a 2-hour batch-test using an underflow-sample heated to the same temperature of 27°C as measured in the sidestream. Three months after the seeding procedure has been started the measured activity was 2.3 g N/gTSS/h (Figure 9a).



**Figure 9.** Anaerobic ammonia oxidation performance measured in a mainstream cyclone underflow sample after heating to 27°C (9a; left) and a photo of the DEMON-system Glarnerland (9b; right)

Figure 10 displays the flow-scheme of the main plant including the set-up of the cyclone. The BioWin-model of this configuration has been used to evaluate all key factors on anammox accumulation – i.e. seeding, cyclone-recovery, growth and temperature. Table 3 summarizes the individual impacts of these factors: Starting from the control case-study assumed anammox trace—concentrations of 0.05 mgCOD/L in the raw wastewater yields 0.5 mg/L in the mixed liquor. Seeding as operated in Glarnerland adds another 4.2 mg/l and the cyclone doubles this contribution. Growth- and temperature impacts depend heavily on operation mode and nitrite availability.



**Figure 10.** Configuration of 2 independent mainstream liquid lanes in Glarnerland, lane 2 with anammox accumulation by seeding from the sidestream and by the cyclone

	scenarios	key-factors for anammox accumulation			biomass composition	
		seeding yes/no	cyclone selectivity (%)	temperature (°C)	anammox (mg/L)	AOB (mg/L)
0	control scenario	no	0	16.5	0.5	51.2
1	seed scenario	yes	0	16.5	4.7	54.1
2	cyclone scenario	yes	75	16.5	8.7	54.1
3	growth scenario	yes	75	16.5	9.11	54
4	temperature scenario	yes	100	25	10.77	50

**Table 3.** Evaluation of individual impact factors on anammox accumulation

## CONCLUSIONS AND OUTLOOK

The explanation of the deammonification selector and limits of operations through case studies and modeling helps a designer determine how and where to apply this energy efficient technology that is increasingly widespread in Europe. Selective sludge wasting as demonstrated by the cyclone operation plays a major role in establishing the anaerobic ammonia oxidation pathway in the main liquid train. The first results presented in this paper from an anammox seeding pilot using a DEMON-cyclone in the mainstream process are considered preliminary and need further development.

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