

# Single-Stage Nitrogen Removal Using Anammox and Partial Nitrification (SNAP) for Treatment of Synthetic Landfill Leachate

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## Abstract

In the process named SNAP (Single-stage Nitrogen removal using Anammox and Partial Nitrification), influent ammonium was removed as nitrogen gas by the combination of two autotrophic steps, partial nitrification and anammox, in one unit process. The reactors were packed with acryl-resin fiber biomass carriers and gently aerated. The synthetic influent, simulating secondary-treated landfill leachate, contained ammonium concentrations of 240 mg-N/l and 500 mg-N/l for reactors named SN-2 and SN-3, respectively. Data from 300 days of SNAP operation using reactor SN-2 showed ammonium conversions of 47.7~88.1% with nitrogen removal rates of 0.31~0.45 kg-N/m<sup>3</sup>/d under various operational conditions. The best performance with loading rate of 0.6 kg-N/m<sup>3</sup>/d was obtained at 35°C, pH 7.8, and aeration rate of 0.10 vvm (volume per volume per minute), with 88.1% ammonium conversion and 78.5% nitrogen removal. The results of about 100 days of operation for reactor SN-3 confirmed the treatment capability of SNAP process, with about 80% nitrogen removal with loading rates up to 1.0 kg-N/m<sup>3</sup>/d. Some important characteristics of the SNAP process are discussed.

**Key words:** acryl fiber biomass carrier, landfill leachate, nitrogen removal, SNAP, wholly autotrophic

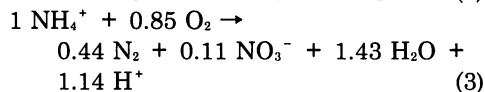
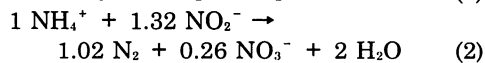
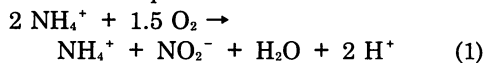
## INTRODUCTION

Nitrogen removal from wastewater is traditionally based on the combination of nitrification and denitrification steps. The first step consumes large amounts of oxygen for the oxidation of ammonium to nitrate while the second step requires addition of an external organic carbon source for the reduction of nitrate to dinitrogen gas. These requirements make full-scale nitrification-denitrification systems quite expensive, especially for the treatment of wastewaters containing high nitrogen concentrations such as sludge digester supernatant and secondary-treated landfill leachate. In addition, nitrification and denitrification are

carried out under different culture conditions and by different microorganisms, so that complicated process controls are required.

Over the past decades, several ways to overcome the disadvantages of conventional nitrogen removal technology have been considered, which can be classified into two approaches. One of these is the shortcut biological nitrogen removal (SBNR) process<sup>1-3)</sup>. The principle of SBNR is to denitrify from nitrite instead of from nitrate. The second approach is a wholly autotrophic process; i.e., removal of ammonium in the absence of organic carbon. This approach has been widely developed since anammox reaction was discovered in the mid-1990s. In this approach, ammonium is converted

ultimately to dinitrogen gas by two sequential reactions: partial nitrification (eq. 1) and anammox (eq. 2). The overall reaction is described in equation 3.



Compared to conventional nitrification-denitrification, this way saves 100% of the external organic carbon source for denitrification and more than 50% of the oxygen supply for nitrification. This leads to a significant reduction in the operational costs and a decrease in the energy demand. The principal steps of traditional and novel nitrogen removal processes are partially depicted in Fig.1.

In wholly autotrophic processes, the combination of two conversion steps can be done in separate reactors or in a single reactor. Typical systems with separate reactors include SHARON-ANAMMOX<sup>9)</sup> and partial nitrification-ANAMMOX<sup>5, 6)</sup>. For single-stage processes, OLAND (Oxygen-Limited Autotrophic Nitrification-Denitrification) and CANON (Completely Autotrophic Nitrogen removal Over Nitrite) are widely known.

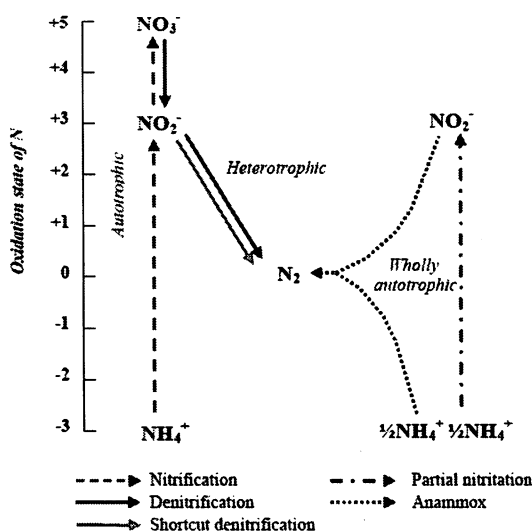
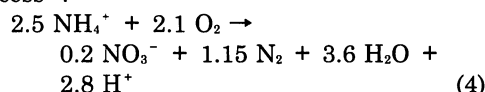


Fig. 1 Principal steps of N-removal processes

The original OLAND process was done in a sequencing batch reactor (SBR) seeded with nitrifying sludge. A specific removal rate of 16 mg-N/gVSS/d was obtained with a loading rate of 0.13 kg-N/m<sup>3</sup>/d. The responsible microorganisms were assumed to be nitrifiers dominated by ammonium oxidizers<sup>7)</sup>. In a high-load RBC reactor based on the OLAND principle with an addition of a granular anaerobic sludge, a removal rate as high as 1.058 kg-N/m<sup>3</sup>/d was attained with a loading rate of 1.189 kg-N/m<sup>3</sup>/d<sup>8)</sup>.

The CANON process was originally developed for SBR using a specific start-up pattern consisting of anoxic inoculation with anammox biomass followed by oxygen supply to develop nitrifying microorganisms. Ammonia was mostly converted to  $\text{N}_2$  (85%) and the remainder (15%) was recovered as  $\text{NO}_3^-$ . However, the treatment efficiencies were still low with a nitrogen removal rate of only 0.064 kg-N/m<sup>3</sup>/d and an ammonium conversion of 57%. FISH analysis confirmed the absence of nitrite oxidizers and the presence of bacteria belonging to the genus *Nitrosomonas* (45%) and anaerobic ammonium oxidizing planctomycetes (40%) in the CANON biomass<sup>9)</sup>. The CANON process was easily maintained in a gas-lift reactor with high conversion rates of up to 1.5 kg-N/m<sup>3</sup>/d<sup>10)</sup>.

The following equation was empirically developed for describing the CANON process<sup>11)</sup>:



So far, studies have been continued for getting better achievements in a wholly autotrophic nitrogen removal process. Under oxygen-limiting conditions with high ammonium concentrations, the competition between ammonium-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria is minimized. The use of biomass carriers would increase the sludge retention time which is important for both slowly growing bacteria, i.e. aerobic and anaerobic ammonia oxidizers, and increase the treatment efficiency of a wholly autotrophic nitrogen removal processes.

Some biomass carriers made from synthetic resin fiber have demonstrated effectiveness

in nitrification and partial nitrification processes in our previous studies<sup>12, 13</sup>. This type of biomass carrier possesses advantages such as light weight, high specific surface area, durability, etc. During the experiments on partial nitrification of an ammonium-containing medium using an acryl resin fiber carrier, wholly autotrophic nitrogen removal was confirmed and subsequently named as SNAP (Single-stage Nitrogen removal using Anammox and Partial nitrification)<sup>14</sup>. Establishment of the SNAP process has also been recognized in partial nitrification reactors treating synthetic landfill leachate. This paper introduces the development of SNAP process and its treatment performance using synthetic landfill leachate.

## MATERIALS AND METHODS

**Reactor set-up** The reactor system, shown in Fig.2, was designed to allow for control in hydraulic retention time (HRT), aeration rate, temperature and pH. Two identical reactors named SN-2 and SN-3 with liquid volumes of 4.65 l were used for two systems. A net type acryl resin fiber material (Biofix; NET Co., Ltd.; Japan) shown in Fig.3 was used as the biomass carrier.

**Reactor start-up and operation** The reactors were seeded with 14 g (MLSS) of activated sludge. This sludge had been cultivated using a synthetic medium (containing peptone, meat extract,  $\text{NaHCO}_3$ ,  $\text{MgSO}_4$ ,  $\text{CaCl}_2$ ,  $\text{NaCl}$ , and  $\text{KCl}$ ) by the fill-and-draw method for a long-time under total oxidation conditions. The seeding sludge, therefore, was rich in heterotrophic bacteria and slowly growing nitrifiers.

During the start-up phase, an inorganic medium containing ammonium, bicarbonate and phosphate was supplied. The nitrogen loading rate was increased stepwise by increasing influent concentration and decreasing HRT. Reactor SN-3 was started 6 months later than reactor SN-2.

After start-up, synthetic landfill leachate influent was introduced to the reactors and both reactors were operated to achieve partial nitrification and then SNAP. Reactor SN-2 was used for detail study on

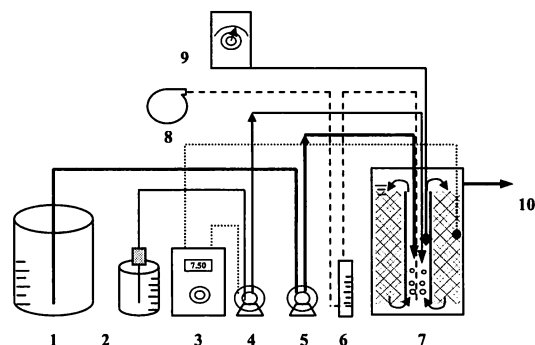


Fig. 2 Schematic diagram of reactor system

- (1) Influent tank (2)  $\text{NaHCO}_3$  solution
- (3) pH controller (4)  $\text{NaHCO}_3$  pump
- (5) Influent pump (6) Airflow meter (7) Reactor
- (8) Air pump (9) Heater (10) Effluent

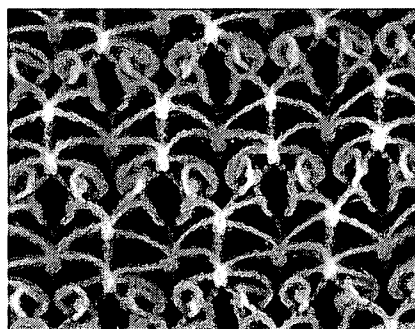


Fig. 3 Photograph of the acryl resin biomass carrier

performance, while reactor SN-3 followed the operational conditions used for reactor SN-2. Details on start-up and nitrification phases of reactor SN-2 were described in a previous report<sup>13</sup>.

**Influent** Landfill leachate is characterized by high concentration of organic, nutrient as well as inorganic constituents. Leachates from mature landfill or after secondary treatment contain relatively low degradable organic matter but still high ammonium concentration. Synthetic wastewater simulating pre-treated landfill leachate, with the assumption that organic carbon is effectively removed after pretreatment, was used as influent for the experiments. The influent compositions, which were defined from the typical data<sup>15</sup>

and various data on leachate composition, are listed in Table 1. Tap water was used for dilution in all cases.

**Experimental plan** Different experimental periods with various sets of operational conditions were assigned as described in Table 2. Reactor SN-3 has also operated for about 100 days under conditions as in period 5 of reactor SN-2.

**Anaerobic batch tests** After 4 months of SNAP operation, loosely attached sludge (including sludge accumulated at the bottom of the reactor and other free spaces) was removed from the reactor SN-2. A portion of this sludge was used for 3 consecutive anaerobic batch tests. The medium contained  $\text{NH}_4\text{Cl}$  (50 mg-N/l),  $\text{NaNO}_2$  (50 mg-N/l),  $\text{NaHCO}_3$  and  $\text{KHCO}_3$  (total 7.5 mM  $\text{HCO}_3^-$ ) and a trace element solution (1 ml/l). The 300-ml Erlenmeyer flasks with rubber stopper and gas-tight syringe were used. The sludge concentration was 2.2 g MLVSS/l. The test bottles were flushed with nitrogen gas and incubated at 35°C and shaken at 100 rpm.

**Chemical analyses**  $\text{NO}_2\text{-N}$  was determined by the colorimetric method,  $\text{NO}_3\text{-N}$  was quantified by the UV screening method with a correction for  $\text{NO}_2\text{-N}$  interference, and alkalinity was measured by the titration method; in accordance with Standard Methods<sup>16</sup>.  $\text{NH}_4\text{-N}$  was determined by the modified phenate method using ortho-phenyl phenol (OPP) instead of phenol<sup>17</sup>. Absorbance was measured using a U-2010 Spectrophotometer (HITACHI). A Mettler 320 pH meter (TOLEDO) was used for measure pH. DO was measured using a 782 Oxygen Meter (STRATHKELVIN INSTRUMENTS).

## RESULTS AND DISCUSSION

**Nitrogen losses and the occurrence of SNAP** For the reactor SN-2, during partial nitrification experiments with influent containing organic carbon (TOC = 25~30 mg/l), the mass balance showed that the average nitrogen unbalance was not significant (around  $\pm 5\%$ , see Fig. 4). However, during a short time (14 days) in

Table 1 Composition of synthetic influents (in mg/l)

Composition	Reactor SN-2	Reactor SN-3
1. $\text{NH}_4\text{Cl}^{(a)}$	916 (240 mg-N/l)	1908.5 (500 mg-N/l)
2. $\text{KH}_2\text{PO}_4^{(a)}$	43.4	43.4
3. $\text{NaHCO}_3^{(a)}$	530	1480.5
4. $\text{KHCO}_3^{(a)}$	630	1762.5
5. $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	328	328
6. $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	235.2	235.2
7. $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	16	16
8. $\text{Na}_2\text{-EDTA}$	16	16
9. $\text{C}_8\text{H}_5\text{O}_2\text{K}^{(b)}$	37.5	N.A

<sup>(a)</sup> Lower concentrations at start-up phase

<sup>(b)</sup> Potassium Hydrogen Phthalate, only applied in nitrification phase

Table 2 Experimental periods for reactor SN-2

Period (term)	Operational conditions			
	HRT (h)	Temp. (°C)	pH	Aeration rate (vvm)
1 (0~17)	6	35	7.5	0.10
2 (18~31)	6	35	7.5	0.06
3 (32~45)	8	35	7.5	0.06
4(46~67)	8	35	7.8	0.06
5 (68~82)	10	35	7.8	0.10
6 (83~88)	10	35	$\geq 8.0^{(a)}$	0.10
7 (89~103)	10	32.5	7.8	0.06
8 (104~113)	10	35	7.5	0.14
9 (114~127)	10	35	7.5	0.10
10 (128~191) <sup>(b)</sup>	10	35	7.5	0.10
11 (192~209) <sup>(c)</sup>	—	—	—	—
12 (210~242) <sup>(d)</sup>	12~10	30~35	7.5	0.06~0.10
13 (243~298)	6	35	7.5	0.10

<sup>(a)</sup> Not controlling pH but increasing influent bicarbonate

<sup>(b)</sup> After removing loosely attached sludge

<sup>(c)</sup> Stop operation, store SNAP sludge in refrigerator

<sup>(d)</sup> Restart-up reactor, operational conditions varied

which organic carbon was not supplied and HRT increased and varied from 10 to 12 h, nitrogen losses more than 80% were observed as shown in Fig.4.

Similarly, significant N-losses were also observed in the reactor SN-3 after about 130 days of operation under partial nitrification conditions.

**Performance of SNAP process under different conditions** Influences of

operational conditions on performance of the SNAP process were assessed by ammonium conversion (difference between influent ammonium nitrogen and effluent ammonium nitrogen), N-removal (difference between influent total nitrogen and effluent total nitrogen) and effluent nitrate concentrations. These results during 10 periods for reactor SN-2 are shown in Fig.5 (refer to Table 2 for operational conditions of each period).

Firstly, it can be seen that higher values of ammonium conversion and N-removal were obtained with longer HRTs (periods 5 to 10). This can be understood considering low growth rates of AOB and anammox bacteria.

The SNAP process was enhanced when pH increased from 7.5 to 7.8 (period 3 to 4), but not higher than 8.0. When pH was equal to or higher than 8.0 in period 7, both ammonium conversion and N-removal decreased. This may be due to the inhibition of AOB by free ammonia.

An increase in aeration (period 8) could have contributed to the increases in ammonium conversion; however, effluent nitrate concentrations also increased. This might be due to the favored condition for nitrite oxidation with higher oxygen concentrations (bulk DO in this period was about 2.2 to 2.5 mg/l compared to 0.5 to 2.0 mg/l in other periods). Regarding the effect of temperature, higher nitrogen removals were obtained at 35°C than at 32.5°C.

The changes in both HRT and aeration rate from periods 4 to 5 led to a pronounced

change in SNAP performance. The best SNAP performance was obtained in period 5 with the average N-removal of  $78.5 \pm 2.8\%$  and ammonium conversion of  $88.1 \pm 3.1\%$  ( $n = 15$ ). The operational conditions in this period were 10 h HRT, 35°C, pH 7.8 and 0.10 vvm aeration rate.

Data in Table 3 show a comparison of results of the SNAP process with other single-reactor autotrophic processes such as CANON and OLAND.

The ammonium conversion and N-removal obtained for the SNAP process are comparable with the original CANON process in terms of percentage and are much higher in terms of loading rate. The CANON process with the gas-lift reactor could operate at higher loading rates than the SNAP; however, both ammonium conversion and N-

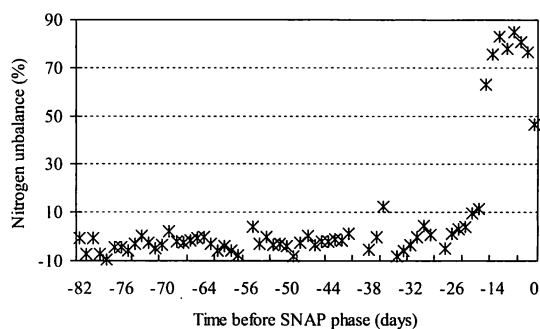


Fig. 4 N-losses at the end of partial nitrification phase of reactor SN-2

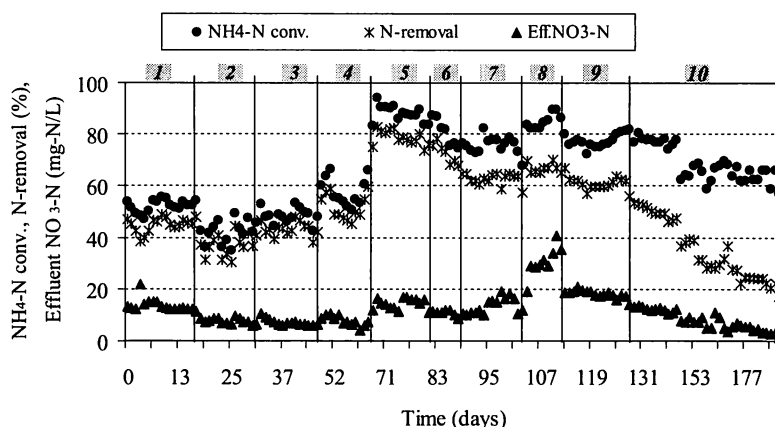


Fig. 5 Effects of operational conditions on the SNAP process performance (reactor SN-2)

removal (of the applied load) on a percentage basis were still low at 42.0% and 39%, respectively. These parameters are important for evaluation of treatment efficiency.

Compared to SNAP, the original OLAND process, in which nitrifying sludge was used as seed sludge, worked only at lower applied loadings. However, noticeably higher loadings were possible in a SBR reactor which was modified by adding anaerobic sludge as a second biocatalyst.

From data of total weight of biomass in the reactor, the specific ammonium conversion rate and specific N-removal rates of the SNAP process were estimated to be 110 mg-N/gVSS/d and 96 mg-N/gVSS/d, respectively. While these values are lower than those of the high-rate OLAND process (192.4 mg-N/gVSS/d and 179.3 mg-N/gVSS/d), further study on the SNAP process to optimize performance at higher loading rates is going on.

In reactor SN-3, the SNAP process occurred from day 200 after which N-removal continuously increased. The recent 50-day averages for ammonium conversion and N-removal were  $65.9 \pm 12.0\%$  and  $56.3 \pm 12.2\%$ , respectively. The highest N-removal of about 80% was obtained at an applied loading rate of 1.0 kg-N/m<sup>3</sup>/d (see Fig 6).

**DO and alkalinity consumption** The bulk DO of reactor SN-2 and SN-3 varied between 0.5 to 2.5 mg/l, while the DO inside carrier block and close to biomass surface was consistently almost zero. Although changes in air flow rate clearly affected liquid circulation, DO levels did not change significantly.

Alkalinity consumption during the SNAP phase was  $3.5 \pm 0.78$  mg CaCO<sub>3</sub>/mg NH<sub>4</sub>-N converted or  $4.2 \pm 1.0$  mg CaCO<sub>3</sub>/mg-N removed. These data are in good agreement with the theoretical value from equation 3 (4.07 mg CaCO<sub>3</sub>/mg-N removed).

Data obtained in this study were in good agreement with the CANON process as calculated by equation 4<sup>11)</sup> and experimental

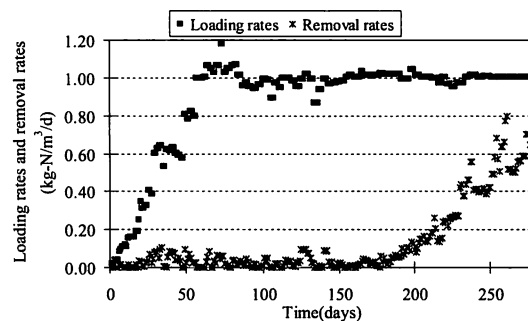


Fig. 6 Performance data of reactor SN-3 in 300-day operation

Table 3 Performance data of SNAP and other single-reactor processes

System	Applied load (kg-N/m <sup>3</sup> /d)	Ammonium conversion		N-removal			Reference
		kg-N/m <sup>3</sup> /d	%	kg-N/m <sup>3</sup> /d	% of N-load	% of N-conversion	
SNAP, reactor SN-2, (periods 1~2)	0.96	0.46	47.7	0.40	41.4	86.8	This study
SNAP, reactor SN-2, (periods 3~4)	0.72	0.38	52.7	0.31	47.2	89.8	This study
SNAP, reactor SN-2, (periods 5~9)	0.58	0.47	81.0	0.39	67.9	84.0	This study
SNAP, reactor SN-2, (periods 5)	0.58	0.51	88.1	0.45	78.5	89.4	This study
CANON (SBR)	0.131	0.075	57.2	0.064	48.9	85.3	<sup>9)</sup>
CANON(Gas-lift)	3.70	1.50	42.0	1.44	39.0	93.0	<sup>10)</sup>
OLAND (SBR)	0.13	0.08	62.0	0.05	40.0	64.5	<sup>7)</sup>
	0.25	0.07	26.2	0.04	15.2	58.0	
OLAND (SBR, high rate)	1.189	1.135	95.5	1.058	89.0	93.2	<sup>8)</sup>

results of the OLAND process (4.1 mg  $\text{CaCO}_3/\text{mg NH}_4\text{-N removed}$ )<sup>7</sup>.

The alkalinity consumption in SNAP, as well as other wholly autotrophic processes, was only half of the theoretical value for nitrification or nitritation (7.1 mg  $\text{CaCO}_3/\text{mg NH}_4\text{-N converted}$ ). The subsequent anammox reaction that slightly consumes hydrogen ions explains this reduction of alkalinity consumption. Therefore, together with the saving in oxygen demand, the saving in alkalinity consumption is also an advantage of wholly autotrophic processes, in general, and of the SNAP process, in particular.

**Sludge quantity** The amount of sludge in the reactor seemed to have an effect on process performance. From day 128, after removing loosely attached sludge from reactor SN-2, ammonium conversion did not change much but N-removal continuously decreased for about 20 days. Then ammonium conversion decreased and was almost stable around 65% while N-removal varied and dropped to about 20%. In addition, around day 170, the loosely attached sludge appeared again and was as full as before day 127.

From days 192 to 209, operation of reactor SN-2 was stopped. The carrier was taken out and all biomass was detached. Total amount of sludge in reactor was determined to be 34.0 g-SS including 28 g well attached to material and 6.0 g loosely attached. The VSS was  $68.7 \pm 0.7\%$  of the SS. This low fraction of

VSS was due to the accumulation of minerals in influent during long term operation. From these results, it would appear that loosely attached sludge contributes to the SNAP process, and an accumulation of excess sludge leads to a decrease in treatment performance.

There were no experiments to determine exactly the optimum amount of sludge in the reactor; however, it could be estimated that the total amount of sludge in the reactor should be kept below 34 g-SS and higher than 28 g-SS, with some loosely attached sludge. This amount was equal to an overall concentration of about 7.0 g-SS/l of reactor or a specific sludge attachment of 0.02 g-SS/g biomass carrier.

#### Anaerobic activity of loosely attached sludge

It is assumed that flocs formed by loosely attached sludge provide the anoxic condition for anammox bacteria. In fact, all DO values inside flocs were nearly 0 mg/l. The anaerobic tests were conducted to confirm the role of loosely attached sludge and results are shown in Fig 7. Symbols ABT1 ~ ABT3 refer to the order of consecutive test.

Experimental data showed a stable N-removal rate, with an average value of  $0.6 \pm 0.1$  mg-N/gVSS/h. This value was 15% of the specific N-removal rate for continuous operation (96 mg-N/gVSS/d). This result is reasonable considering that the batch tests were carried out with the loosely attached

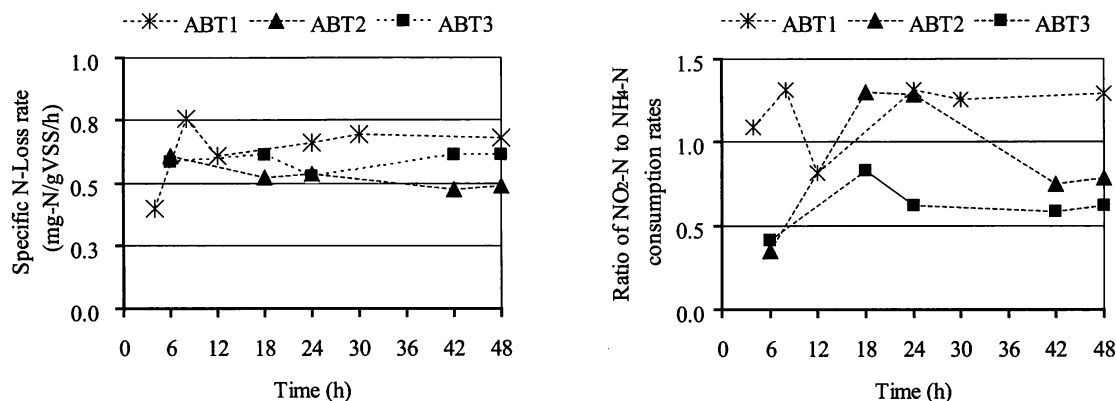


Fig. 7 Results of anaerobic activity test of the SNAP sludge

sludge under anaerobic conditions, while continuous process was carried out with attached and loosely attached sludge and was aerated.

The specific consumption rate of ammonium was  $0.28 \pm 0.07$  mg-N/gVSS/h and of nitrite was  $0.24 \pm 0.07$  mg-N/gVSS/h. Ratio of these consumption rates does not match the nitrite-to-ammonium ratio for anammox reaction of 1.32, and could be explained by the high fraction of AOB beside anammox bacteria in SNAP sludge<sup>10</sup> and the possible presence of a trace amount of oxygen in the batch tests.

**Restart of reactor and repeatability of SNAP process** As mentioned above, it took about 200 days for reactors SN-2 and SN-3 to demonstrate the peculiar nitrogen losses when activated sludge had been used as seed sludge. However, a significantly shorter time was required to establish the SNAP process by using SNAP sludge as seed.

From day 210, reactor SN-2 was re-started with the SNAP sludge that had been detached and stored in refrigerator for 18 days. The amount of sludge re-attached to biomass carrier was 16 g-SS. Operational conditions were varied slightly as indicated in Table 3. Performance data in periods 12~15 after restarting are presented in Fig. 8.

N-removal was quickly detected and increased. Even when HRT was down to 6 h from day 242, N-removal still increased for 15 days then decreased and stabilized. From days 256 to 301, the reactor was subjected to the same operational conditions as the period

1. The average ammonium conversion and N-removal efficiency for 40 days were  $58.9 \pm 5.2$  % and  $51.4 \pm 4.8$  %, respectively. These data were about 12% higher than those of the period 1 (52.2 and 44.9 %). This fact may be attributed to the long-term adaptation and compositional optimization of the SNAP sludge.

**Nitrogen-based stoichiometry** Assuming that fraction of removed nitrogen used for biomass synthesis is neglected and all N-removals are to dinitrogen gas, the mass balance for nitrogen or nitrogen-based stoichiometry of the SNAP process could be calculated as shown in Table 4. Similar calculations for CANON and OLAND processes are cited for comparison.

The equations in left column give easy assessments of ammonium conversion and relative composition of the effluent, while the ones in right column clearly reflect the fate of removed nitrogen. For example, the SNAP process of reactor SN-2 in period 5, which had the best performance, demonstrated an ammonium conversion of  $(1-0.119) \times 100 = 88.1\%$  and yielded 11.9%  $\text{NH}_4\text{-N}$ , 3.7%  $\text{NO}_2\text{-N}$ , 5.8%  $\text{NO}_3\text{-N}$  and 78.6%  $\text{N}_2\text{-N}$  as end-forms of nitrogen. In addition,  $0.446 \times 2 \times 100 = 89.2\%$  of  $\text{NH}_4\text{-N}$  was removed in the form of nitrogen gas. These data were already shown and discussed in Table 3.

Taking the best result of each process for evaluation, the high rate OLAND process had the highest treatment efficiency, then the SNAP and the CANON processes, in order. It is interested to see that the CANON, OLAND and SNAP processes were not much different with respect to reaction coefficients for nitrate and nitrogen gas but considerably different for nitrite. The CANON process had the lowest effluent nitrite while some rather high nitrite did appear with SNAP. This may be due to the difference in bacterial compositions of the sludges. A relatively higher fraction of anammox bacteria in the CANON sludge (40%)<sup>9</sup> than that in the SNAP sludge (15%)<sup>10</sup> can explain for the lower effluent nitrite of the first process. Nitrite produced by AOB would have been consumed by more symbiotic anammox bacteria in the CANON process; hence, the

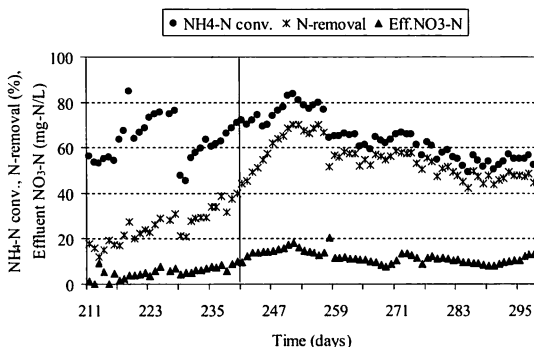


Fig. 8 Restart of the SNAP process (reactor SN-2)



Table 4 Nitrogen-based stoichiometry of SNAP process(\*)

System	Nitrogen-based stoichiometry	
	For 1 mole $\text{NH}_4^+$ applied	For 1 mole $\text{NH}_4^+$ removed
SNAP, Reactor SN-2 Periods 1~4 (n=58)	$1 \text{ NH}_4^+ \rightarrow 0.499 \text{ NH}_4^+ + 0.023 \text{ NO}_2^-$ $+ 0.038 \text{ NO}_3^- + 0.220 \text{ N}_2$	$1 \text{ NH}_4^+ \rightarrow 0.045 \text{ NO}_2^-$ $+ 0.077 \text{ NO}_3^- + 0.439 \text{ N}_2$
SNAP, Reactor SN-2 Periods 5~9 (n= 60)	$1 \text{ NH}_4^+ \rightarrow 0.190 \text{ NH}_4^+ + 0.060 \text{ NO}_2^-$ $+ 0.071 \text{ NO}_3^- + 0.339 \text{ N}_2$	$1 \text{ NH}_4^+ \rightarrow 0.075 \text{ NO}_2^-$ $+ 0.088 \text{ NO}_3^- + 0.419 \text{ N}_2$
<b>SNAP, Reactor SN-2 Period 5 (n=15)</b>	$1 \text{ NH}_4^+ \rightarrow 0.119 \text{ NH}_4^+ + 0.037 \text{ NO}_2^-$ $+ 0.058 \text{ NO}_3^- + 0.393 \text{ N}_2$	$1 \text{ NH}_4^+ \rightarrow 0.042 \text{ NO}_2^-$ $+ 0.066 \text{ NO}_3^- + 0.446 \text{ N}_2$
SNAP, Reactor SN-3 (n=42)	$1 \text{ NH}_4^+ \rightarrow 0.335 \text{ NH}_4^+ + 0.034 \text{ NO}_2^-$ $+ 0.052 \text{ NO}_3^- + 0.290 \text{ N}_2$	$1 \text{ NH}_4^+ \rightarrow 0.051 \text{ NO}_2^-$ $+ 0.077 \text{ NO}_3^- + 0.436 \text{ N}_2$
CANON (SBR)	$1 \text{ NH}_4^+ \rightarrow 0.427 \text{ NH}_4^+ + 0.002 \text{ NO}_2^-$ $+ 0.084 \text{ NO}_3^- + 0.244 \text{ N}_2$	$1 \text{ NH}_4^+ \rightarrow 0.003 \text{ NO}_2^-$ $+ 0.146 \text{ NO}_3^- + 0.425 \text{ N}_2$
CANON(Gas-lift)	$1 \text{ NH}_4^+ \rightarrow 0.582 \text{ NH}_4^+ + 0.004 \text{ NO}_2^-$ $+ 0.029 \text{ NO}_3^- + 0.193 \text{ N}_2$	$1 \text{ NH}_4^+ \rightarrow 0.009 \text{ NO}_2^-$ $+ 0.070 \text{ NO}_3^- + 0.461 \text{ N}_2$
OLAND (SBR)	$1 \text{ NH}_4^+ \rightarrow 0.380 \text{ NH}_4^+ + 0.133 \text{ NO}_2^-$ $+ 0.087 \text{ NO}_3^- + 0.200 \text{ N}_2$	$1 \text{ NH}_4^+ \rightarrow 0.215 \text{ NO}_2^-$ $+ 0.140 \text{ NO}_3^- + 0.323 \text{ N}_2$
OLAND (SBR, high rate)	$1 \text{ NH}_4^+ \rightarrow 0.045 \text{ NH}_4^+ + 0.010 \text{ NO}_2^-$ $+ 0.056 \text{ NO}_3^- + 0.445 \text{ N}_2$	$1 \text{ NH}_4^+ \rightarrow 0.010 \text{ NO}_2^-$ $+ 0.059 \text{ NO}_3^- + 0.466 \text{ N}_2$

(\*) Data sources were already indicated in Table 3.

accumulation of this compound would be higher in the SNAP process.

## CONCLUSIONS

In a long-term study, the effective performance of SNAP was demonstrated and the advantages and potential applications of this process were discussed. With both aerobic and anaerobic ammonium bacteria enriched on the same acryl-resin fiber carrier, most of the influent ammonium could be removed as nitrogen gas under mild aeration conditions in a two-in-one process. At a loading of 0.6 kg-N/m<sup>3</sup>/d, the SNAP process attained 81~88% ammonium conversion of which 84~89% was expelled as nitrogen gas. At this loading, the best performance of 88.1% ammonium conversion and 78.5% nitrogen removal was obtained at 35°C with a pH of 7.8 and aeration rate of 0.10 vvm. At higher loading rates of up to 1.0 kg-N/m<sup>3</sup>/d, approximately 80% nitrogen removal was also obtained. Interestingly, these results were obtained using influent containing high levels of inorganic salts to simulate the composition of landfill leachate. Experimental data from batch and continuous-flow tests were corroborative with theory and comparable to performance levels reported for other wholly autotrophic

processes – namely, CANON and OLAND. For further characterization of SNAP, treatment performance is being evaluated at higher nitrogen loadings and with addition of organic substrates.

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