Advances in Sidestream Ammonia Removal Strategies

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AECOM Wastewater Practice Leader

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Overview

- Sidestream characteristics
- Fundamentals of biological nitrogen removal
- Innovative sidestream treatment options
  - Nitrification / denitrification
  - Nitritation/ denitritation
  - Deammonification
Sidestream Characteristics

- 1% plant influent flow
- High in nitrogen and phosphorus
- 15 to 25% plant influent total nitrogen load
- Ammonia-N = 800 to 2,500 mg/L
- Total phosphorus = 200 to 800 mg/L
- Temperature = 30 to 38°C
- Alkalinity insufficient for complete nitrification
- Insufficient carbon for denitrification

Reduce Effluent TN by ≈ 20%

• Phosphorus Recovery
• Beneficial Reuse of Biosolids
• Dewatering
Advantages of Separate Sidestream Treatment

- **Improved Reliability**
  - Removes 20 to 40% of nitrogen load even during main plant process upsets
  - Protects the main plant from process upsets due to variability in sidestream characteristics
  - Can provide source of nitrifiers for seeding of main activated sludge process

- **Cost Effective**
  - Optimize treatment based on the unique sidestream characteristics
  - Facilities have a small footprint

- **Sustainable**
  - Nutrient recovery
  - Reduced energy and chemical use
Novel Sustainable Sidestream Management

Sidestream Management Options

Nitrogen Removal Focus

Biological
- Nitrification / Denitrification and Bio-augmentation
- Nitritation / Denitritation
- Deammonification

Physical-Chemical
- Ammonia Stripping
  - Steam
  - Hot Air
  - Vacuum Distillation
- Ion-Exchange
  - ARP
- “Struvite” Precipitation
  - MAP Process

Nutrient Recovery Focus

- Reduced energy and chemical demands – more sustainable
- Perceived increase in operational complexity
Fundamentals of Biological Nitrogen Removal
Biological Nitrogen Removal Terms

- **Nitrification** – biological oxidation of ammonia under aerobic conditions
  - Nitritation – oxidation of ammonia to nitrite
    - Ammonia oxidizing bacteria (AOBs) – *Nitrosomonas*
  - Nitratation – oxidation of nitrite to nitrate
    - Nitrite oxidizing bacteria (NOBs) – *Nitrobacter*

- **Denitrification** – biological reduction of nitrate and nitrite by heterotrophic bacteria in absence of dissolved oxygen

- **Deammonification** – biological oxidation of ammonia under anaerobic conditions (*Anammox*)
Fundamentals of Nitrification - Denitrification

**Autotrophic Nitrification**
- Aerobic Environment
- 1 mole Nitrate ($\text{NO}_3^-$)
- Oxygen demand 4.57 g / g $\text{NH}_4^+$-N oxidized
- Alkalinity demand 7.14 g / g $\text{NH}_4^+$-N oxidized
- Carbon demand 4.77 g COD / g NO$_3^-$-N reduced
- 25% $\text{O}_2$
- 75% $\text{O}_2$
- 100% Alkalinity

**Heterotrophic Denitrification**
- Anoxic Environment
- 1 mole Nitrite ($\text{NO}_2^-$)
- ½ mole Nitrogen Gas ($\text{N}_2$)
- 40% Carbon
- 60% Carbon

**Ammonia Oxidizers**
- (e.g. Nitrosomonas)

**Nitrite Oxidizers**
- (e.g. Nitrobacter)

1 mole Ammonia ($\text{NH}_3/$ $\text{NH}_4^+$)

1 mole Nitrite ($\text{NO}_2^-$)
Growth Rates of Nitrosomonas and Nitrobacter
Fundamentals of Nitritation - Denitritation

Autotrophic Nitritation
Aerobic Environment

- 25% reduction in Oxygen
- 40% reduction in Carbon demand
- 40% reduction in Biomass production

Oxygen demand 3.42 g / g NH$_4^+$-N oxidized
Carbon demand 2.86 g COD / g NO$_3^-$-N reduced

1 mole Nitrite (NO$_2^-$)

Ammonia Oxidizers (e.g. Nitrosomonas)

75% O$_2$
100% Alkalinity

1 mole Nitrite (NO$_2^-$)

Heterotrophic Denitrification
Anoxic Environment

½ mole Nitrogen Gas (N$_2$)

60% Carbon

1 mole Ammonia (NH$_3$/ NH$_4^+$)

1 mole Nitrate (NO$_3^-$)

25% reduction in Oxygen

40% Carbon
Sidestream Nitritation – NOB Repression

- **Control**
  - Elevated temperature (30-35 deg C)
  - Low SRT (1-2 days)
  - Low DO (~0.5 mg/L)

- **NOB Repression Mechanisms**
  - Free NH$_4$–N inhibition of NOB > AOB
  - Nitrous acid inhibition of NOB > AOB
  - AOB max growth rate > NOB max growth rate at high temp
  - AOB DO affinity > NOB DO affinity (perhaps only at high temp)
Inhibition of Nitrification by \( \text{NH}_3 \) and \( \text{HNO}_2 \)
Fundamentals of Deammonification

Partial Nitritation
Aerobic Environment

ANAMMOX Deammonification
Anaerobic Ammonium Oxidation Autotrophic Nitrite Reduction
(New Planctomycete, Strous et. al. 1999)

• > 60% reduction in Oxygen
• Eliminate demand for supplemental carbon
• 50% of the alkalinity demand

Partial Nitritation 40% O$_2$
50% Alkalinity

1 mole Ammonia (NH$_3$/ NH$_4^+$)

0.57 mole NO$_2^-$

0.44 mole N$_2^+$ 0.11 NO$_3^-$

Oxygen demand 1.9 g / g NH$_4^+$-N oxidized
Overall Benefit of Deammonification Processes

- Elimination of supplemental carbon source (such as methanol)
- Significant reduction in energy demand possible
- Reduction in alkalinity demand possible

![Typical Energy Demand Ranges](image_url)
Nitrification / Denitrification
Nitrification/denitrification - continuous

- Sidestream treated in small separate tank (~ 4 day HRT)
- Divert portion of mainstream RAS to sidestream tank
- Seeds nitrifiers, adds alkalinity and controls temperature
  - Introduces nitrite oxidizing bacteria
- Can add methanol for denitrification and methanol degrader seeding
- Achieve *bioaugmentation* by returning sidestream mixed liquor to main process
Nitrification/denitrification - batch

- SBR – built in clarifier
- Control on SRT
- WAS/effluent back to main activated sludge process
- Effluent NO\textsubscript{x} to head of plant for odor control

✓ High MLSS – approximately 7,000 mg/L
✓ Mass loading rate – 15 lb N per 1,000 cubic feet
Sidestream SBR Process

Influent $\text{NH}_3$-$\text{N} = 2,500 \text{ mg/L}$
Effluent $\text{NH}_3$-$\text{N} < 10 \text{ mg/L}$
Without Sidestream Treatment

- Winter TN Removal Varied from 43% - 80%
- Avg. 60%

With Sidestream Treatment

- Winter TN Removal Varied from 60% - 90%
- Avg. 75%

Operational Benefits - NYCDEP 26th Ward WPCP

- HRT < 4.5 Hrs; SRT < 5 -8 days
- “Nitrifier incubator” enhanced operational reliability
  - Enhanced winter performance
  - Mitigated storm washout impacts
  - Mitigated centrate inhibition impacts
- Mitigated aeration limitations
  - Off-Loaded 30% TKN Load
  - Oxidized 70-95% Centrate TKN
  - Denitrified in main plant anoxic zone using wastewater COD
- >70% TN removal plant-wide
- Effluent TN 5-8 mg/l
**Nitritation / Denitritation Process Control**

- **Temperature (30-38°C)** favors growth kinetics of AOBs

- **SRT** = HRT Sludge Age;
  - Minimum for ammonia oxidizers, but < minimum for nitrite oxidizers
  - Selects for ammonia oxidizers (AOBs) and de-selects for nitrite oxidizers (NOBs)

- **pH** in 6.6 to 7.2 range
  - Optimal range for AOBs
  - Methanol for denitrification and alkalinity recovery

- **DO** in the 0.3 to 2 mg/L range

![Graph showing the relationship between temperature and minimum SRT for different bacteria](image)
Chemostat Tank Configurations - SHARON Process

- Completely mixed tank with cyclical aeration – pH controlled
- Plug flow with internal recycle
  - Accommodates modifications for ANAMMOX process in the future
- Concentric circles – feed the anoxic zone to utilize COD in sidestream first
**SHARON Process (Chemostat)**

- **Small Footprint**
  - 2.5 day SRT = HRT
    - Oxic SRT = 1 - 1.5 days
    - Anoxic SRT = 0.5 - 0.75 days
  - No clarifiers
  - No pretreatment

- **90% NH$_3$-N removal**

- **Cost Reductions**
  - 25% Oxygen demand
  - 40% COD demand
  - 30% sludge
  - 20% CO$_2$ emission

![Graph showing N-concentration over time](Image)
SHARON Experience

- 7 operational >10 years experience
- 4 planned
- NYC DEP Wards Island
  - First in USA & largest in world

≈ 30 - 40% TKN-load

<table>
<thead>
<tr>
<th>WWTP</th>
<th>Capacity (pe)</th>
<th>SHARON kgN/day</th>
<th>Operational</th>
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<tbody>
<tr>
<td>Utrecht</td>
<td>400,000</td>
<td>900</td>
<td>1997</td>
</tr>
<tr>
<td>Rotterdam-Dokhaven</td>
<td>470,000</td>
<td>850</td>
<td>1999</td>
</tr>
<tr>
<td>Zwolle</td>
<td>200,000</td>
<td>410</td>
<td>2003</td>
</tr>
<tr>
<td>Beverwijk</td>
<td>320,000</td>
<td>1,200</td>
<td>2003</td>
</tr>
<tr>
<td>Groningen-Garmerwolde</td>
<td>300,000</td>
<td>2,400</td>
<td>2005</td>
</tr>
<tr>
<td>The Hague - Houtrust</td>
<td>430,000</td>
<td>1,300</td>
<td>2005</td>
</tr>
<tr>
<td>New York-Wards Island</td>
<td>~2,000,000</td>
<td>5,770</td>
<td>2009</td>
</tr>
<tr>
<td>Whitlingham, UK</td>
<td>275,000</td>
<td>1,500</td>
<td>2009</td>
</tr>
<tr>
<td>MVPC Shell Green, UK</td>
<td>~</td>
<td>1,600</td>
<td>2009</td>
</tr>
<tr>
<td>Geneva – Aïre 2</td>
<td>600,000</td>
<td>1,900</td>
<td>2010</td>
</tr>
<tr>
<td>Paris Seine Grésillons</td>
<td>3,500</td>
<td></td>
<td>2010</td>
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Deammonification
Challenges of Sidestream Deammonification

- **Low Growth Rate**
  - approximate 10 day doubling time at 30°C
  - <10 day has been reported (Park et. al - 5.3 - 8.9 days)
  - SRT (>30 days)

- **Sensitive to**
  - Nitrite
    - Toxic - irreversible loss of activity based on concentration and exposure time
    - $\text{NH}_4^+ : \text{NO}_2^-$ ratio 1 : 1.32
  - DO - reversible inhibition
  - Free ammonia (<10 -15 mg/l)
  - Temperature >30°C preferred
  - pH (neutral range)
Deammonification Experience

- Over 50 plants in operation, construction, or commissioning
- Experience dates to 2002
- Most plants are in Europe
- 5 in United States
  - James River, Virginia (ANITA™Mox)
  - South Durham, North Carolina (ANITA™Mox)
  - York River, Virginia (DEMON)
  - Blue Plains, Washington DC (DEMON)
  - Alexandria, Virginia (DEMON)
Keys to success

Ability to manage competing demands:

**SRT**

- *Aerobic SRT* long enough to support AOB growth but short enough to wash out NOBs (2<SRT<3) and
- *Anaerobic SRT* long enough to support ANAMMOX growth (>30)

**DO**

- High enough to support partial nitritation
- But low enough to suppress NOB growth (Ks AOB< Ks NOB)
- And also low enough so that it does not inhibit ANAMMOX (reversible)

**Nitrite concentration**

- Sufficient nitrite to support ANAMMOX growth (electron acceptor)
- But low enough to avoid ANAMMOX inhibition (irreversible)

**Ammonium concentration**

- Sufficient ammonium to serve as energy source for ANAMMOX
- But avoid free ammonia inhibition of AOBs (<15 mg/l)
Operational Experience

- DEMON® Suspended Growth SBR
- Cleargreen® Suspended Growth SBR
- Terra-N Hybrid Suspended and Attached
- Anita® MOX Attached Growth MBBR
- ANAMMOX® Upflow Granular
Demon® Operational Philosophy

Each DEMON cycle involves 3 time-controlled phases:
1. Fill / React – cyclical aeration and mixing
2. Settling phase
3. Decant / Discharge phase
Demon® Operational Philosophy

Graph showing trends in Reaction, Settling, and Decant with specific data points and values.

Table showing trend, tag connection, value, and date/time.

Graph with level m and numbers for reference.
Overview of Several DEMON® Plants

- Typical volumetric design criteria = **0.7 kg / m³ / day**
- Typically ~90% NH₃-N and ~85% TN removal
- Effluent NO₃-N ~10% of NH₃-N removed; less if bCOD available

<table>
<thead>
<tr>
<th>Facility</th>
<th>Load (kg N / d)</th>
<th>Tank Vol. (m³)</th>
<th>Design Loading Rate (kg N / m³ / d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apeldoorn</td>
<td>1900</td>
<td>2900</td>
<td>0.66</td>
</tr>
<tr>
<td>Thun</td>
<td>400</td>
<td>600</td>
<td>0.67</td>
</tr>
<tr>
<td>Glarnerland</td>
<td>250</td>
<td>360</td>
<td>0.69</td>
</tr>
<tr>
<td>Strass</td>
<td>600</td>
<td>500</td>
<td>1.20</td>
</tr>
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</table>
Operational Cost Savings

- $8.5M / yr (methanol, alkalinity, sludge processing)
- 9 year payback
- Risk mitigation for effluent TN

Sidestream Treatment
20,200 lbs /day NH$_3$-N

Mainstream Treatment
105,000 lbs /day TKN
SRT Control – Cyclone retains DEMON® Granules and Wastes NOBs

Greatest anammox activity in the cyclone underflow

MLSS Overflow Underflow

Greatest activity [%]

MLSS Overflow Underflow

MLSS Overflow Underflow

AECOM
Robust System – More Reliable Operations and Faster Startup

• Initially the startup period for DEMON was slow
• Strass started up over a 2 year period
• Startup of Glarnerland, Switzerland occurred within 50 days using Strass seed and a cyclone
Lessons Learned from Discussions with Operators

- Robust and reliable process
- Confidence and comfort level with the process
- No failures - more resilient than anticipated to elevated NO₂–N and DO concentrations
- Simple design – aeration, mixing, decant, cyclone, 6-8 m SWD
- Controlled primarily with on-line pH and DO probes
  - Bi-weekly to monthly cleaning
  - Drift in calibration not fatal, just reduces efficiency
- Grab samples for NO₂-N, NO₃-N
- Control logic has numerous safety nets built in
  - Prevent over aeration or elevated DO
  - Prevent NO₂-N accumulation
- **Pre-settling to remove heavy material beneficial**
  - Cyclone tends to select for heavy inert material. Difficult to remove.
Strass Full Scale DEMON® – Energy Savings

- 84% TN Removal at design loading rate of 0.7 kg/ m³ / day
- 1.0 - 1.3 kW-hr / kg N removed

Bernhard Wett, March 2009
Strass undertook many energy efficiency activities
With the introduction of DEMON® it became a net energy producer
## Comparative Summary of Deammonification Processes

- **Pros:** energy efficient, widely used
- **Cons:** operator attention, NO₂⁻-N tolerance

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• **Pros:**
  - Energy efficient
  - Widely used

• **Cons:**
  - Operator attention
  - NO₂⁻-N tolerance

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**NO₂⁻-N (< 5 mg/l) in Pre-settling**
Operational Experience

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- ANAMMOX® Upflow Granular
Simultaneous aerobic and anaerobic conditions in biofilm layers
- NH$_3$-N, alkalinity and DO in the bulk liquid
- AOBs on the outer aerobic layer
- ANAMMOX on the inner anaerobic layer
ANITA™ Mox – MBBR process

- ANAMMOX organisms in attached growth are protected from high concentrations in the bulk liquid
- Less vulnerable to inhibitory compounds
  - DO: 3 mg/L vs. 0.3 mg/L suspended
  - NO$_2$-N: 50 mg/L vs. 5 mg/L suspended
ANITA™ Mox – Different Media

K3
500 m²/m³

K5
800 m²/m³

BiofilmChip M
1200 m²/m³

MBBR = Media + Grid + Aeration

Mitigate risk of losing Anammox biomass

Media Retention Grid
ANITA™ Mox MBBR Deammonification

- Soljunda WWTP, Malmo, Sweden
  - Pilot → “BioFarm”
  - Tested carrier media, mixing, aeration
- Patented aeration control to prevent NO$_3$-N production <10% without supplemental mixing
- Continuous aeration 0.6 – 1.6 mg/L DO
- Demonstrated energy demand of 1.45 – 1.75 kWh / kg NH$_3$-N removed (Christesson et al., 2011)
ANITA™ Mox Performance – Soljunda BioFarm

- ~90% NH₃-N removal; ~85% TN removal
- Patented DO control strategy reduce NO₃ production <11%
- 1.4 – 1.7 kWh/kgN-NH₄ removed

BiofilmChip™
Best Performer

(Christesson et al., 2011)
Ongoing Technology Development

MBBR

IFAS 3X the loading rate of MBBR

Aerobic

Anoxic

Biofilm

Media

Liquid

Nitritation

$\text{NH}_4^+ + \text{NO}_2^- \rightarrow \text{AOB}$

Anammox

$\text{N}_2$

$\text{O}_2 = 0.5-1.5 \text{ mg/L}$

$\text{NO}_2^-$

Flocs (1-3 g/L)

Aerobic

Anoxic

Biofilm

Media

Liquid

Nitritation

$\text{NH}_4^+ + \text{NO}_2^- \rightarrow \text{AOB}$

Anammox

$\text{N}_2$

$\text{O}_2 < 0.5 \text{ mg/L}$

$\text{NO}_2^-$

AOB in biofilm = $\text{NO}_2^-$ limitation

AOB in flocs = less $\text{NO}_2^-$ limitation

IFAS 3X the loading rate of MBBR
Higher NH₄ removal after switching to IFAS (x3)
Good sludge quality so far (SVI <100)
Lower energy consumption 1.2 kWh/kg NH₄-N removed
# Comparative Summary of Deammonification Processes

- **Pros:** NO$_2$-N tolerance; low operator demand
- **Cons:** Not most energy efficient; less widely demonstrated

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DEMON®, Cleargreen, Terra-N
ANITA™ MOx MBBR
ANAMMOX® Upflow Granular Process
Principle One Step ANAMMOX®

\[
\begin{align*}
N_2 & \quad \text{anammox} \\
\text{NH}_4^+ & \quad \text{NO}_2^- \quad \text{aob} \\
\text{O}_2 &
\end{align*}
\]

FISH picture: Mari Winkler
Principle One Step ANAMMOX®

2 NH₃ + 1.7 O₂ → 1.14 NO₂⁻ + 0.86 NH₃ → 0.88 N₂ + 0.24 NO₃⁻
Benefits of AOB-AMX granules?

- Rapid settling velocities 5 – 10 m/h
- Less sensitive to NO$_2$-N inhibition
- Better separation from influent TSS
- Compact reactors
Upflow Granulation Process: ANAMMOX®

- Most notable WWTPs:
  - Rotterdam (NL), Niederglatt (CH)
- Numerous industrial facilities
- Rotterdam ANAMMOX startup 2002
- Initially designed as a two-step process
  - SHARON - 1800 m³
  - ANAMMOX – 72 m³ (compact!)
- >2 yrs before ANAMMOX activity was detected
- >3.5yrs to reach full capacity
- Removal rate 7.1 - 9.5 kg/m³/day
  - Refers to second stage
- TN removal ~90%
- Effluent NO₂-N < 10 mg/l

Upflow Granulation Process: ANAMMOX®

- **Next generation design: single stage**
  - Both nitritation and deammonification

- **Controlled by:**
  - $O_2$ - continuous aeration DO ≈ 5 mg/l
  - $NO_2$ - N
  - Upflow velocity (shear)

- **Granular biomass beneficial**
  - Low sensitivity to inhibition e.g. $NO_2 > 30$ mg/L

- **Rendac performance**
  - Startup 1 month with seeding
  - Removal rates 1.4 – 1.6 kg N/m³/d
  - 85% TN removal

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ammonia load (kg/m³.d) vs ammonia removed (kg/m³.d)

- 27-Mar
- 16-Apr
- 6-May
- 26-May
- 15-Jun

~1mm Dia. Granules
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Summary – Sidestream Deammonification

- 30 operational facilities / 25 in construction / commissioning
- Proven process
- Sustainable, small footprint and cost effective
- 60% less oxygen
- 90% less carbon
- 50% less alkalinity
- 40% less biomass
Acknowledgements

- Beverley Stinson, P.E., Ph.D., AECOM
- Greg Bowden, P.E., Ph.D., AECOM
Questions

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