Short-Cut Nitrogen Removal: A State of the Art Review

Jose Jimenez, Ph.D., P.E.
Brown and Caldwell
Outline

• Introduction

• Overview of nitrogen (N) removal in wastewater
  • Conventional N removal
  • Nitritation-Denitritation/ Nitrite-Shunt
  • Partial Nitritation- Deammonification

• Case studies – potential savings
Introduction
Sidestream Short-Cut N Removal
Established Technology
Sidestream Short-Cut N Removal
Established Technology
Energy Savings

![Typical Energy Demand Ranges](chart.png)
# Carbon Requirements for Mainstream Biological Nitrogen Removal Processes

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Nitrification-denitrification</th>
<th>Nitritation-denitritation</th>
<th>Partial nitritation-deammonificaiton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon required for nitrogen removal (mg COD /mg N)</td>
<td>3.5 – 4.0</td>
<td>2.0 – 2.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Net Process Oxygen Requirement (mg O2/mg N Converted to N2):**

1.71

**C:N ratio may be a key control factor in defining predominant pathway for TN removal**

**Diagram:**
- Conventional Nitrification / Denitrification
- Nitrite Shunt
- Deammonification

**Higher C:N ratio**
- 6-10 :1 range?
- OHO Outcompete
- Anammox

**Medium C:N**
- 3 –5 :1 range?

**Lower C:N ratio**
- 1-3 :1 range?
- Anammox Outcompete
- OHO
Nitrogen Removal
Short Cut Nitrogen Removal Processes
Conventional Nitrification-Denitrification

**Autotrophic Bacteria**
- **Aerobic Environment**
  - 1 mole Ammonia (NH₃ / NH₄⁺)
  - 25% O₂ (energy)
  - 75% O₂ (energy)
  - ~100% Alkalinity

**Heterotrophic Bacteria**
- **Anoxic Environment**
  - 1 mole Nitrite (NO₂⁻)
  - 40% Carbon (BOD)
  - 60% Carbon (BOD)

**Bacteria**
- Ammonia Oxidizing Bacteria (AOB)
- Nitrite Oxidizing Bacteria (NOB)

**Yield**
- Oxygen Required: 3.3 lb O₂/lb N
- Carbon Required: 6.6 lb COD/lb N
- Yield: 1.9 lb VSS/lb N
N Removal Process

NITRITE OXIDIZING BACTERIA (NOB)

AMMONIA OXIDIZING BACTERIA (AOB)

OHO DENITRIFYING BACTERIA
Conventional Nitrogen Removal Processes

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW carbon utilized for denitrification</td>
<td>Large BNR volume</td>
</tr>
<tr>
<td>Alkalinity recovered</td>
<td>Nitrogen removal limited by IMLR</td>
</tr>
<tr>
<td></td>
<td>WW carbon is difficult to manage</td>
</tr>
</tbody>
</table>
Conventional Nitrogen Removal Processes
Effect of C:N Ratio on Denitrification

Jimenez et al. (2010)
Nitritation-Denitritation = “Nitrite Shunt”

**Nitritation**
- 75% O₂ (energy)
- ~100% Alkalinity
- 1 mole Ammonia (NH₃ / NH₄⁺)
- 1 mole Nitrite (NO₂⁻)
- Ammonia Oxidizing Bacteria (AOB)

**Denitritation**
- 60% Carbon (BOD)
- ½ mol Nitrogen Gas (N₂)
- 40% Carbon (BOD)

Advantages:
- 25% reduction in oxygen demand (energy)
- 40% reduction in carbon (e⁻ donor) demand
- 40% reduction in biomass production

**Autotrophic Bacteria**
- Aerobic Environment

**Heterotrophic Bacteria**
- Anoxic Environment

- 1 mole Nitrite (NO₂⁻)
- 25% O₂ (energy)
- Nitrite Oxidizing Bacteria (NOB)
- 1 mole Nitrite (NO₂⁻)
- 40% Carbon (BOD)
- 1 mole Nitrate (NO₃⁻)
Nitrite-Shunt

- Nitrite Oxidizing Bacteria (NOB)
  - Inhibited by high ammonia conc.
  - Compete for nitrite
  - Grows faster than NOB

- Ammonia Oxidizing Bacteria (AOB)

- Heterotrophic Denitrifying Bacteria
  - Outcompete NOB for nitrite

At low to no DO, NOB outcompete NOB for nitrite.
Carbon Requirements for Mainstream Biological Nitrogen Removal Processes

![Graph showing effluent NO$_x$-N (mg/L) vs. Soluble COD:NH$_4$ Ratio]

- SND
- Shunt

Brown and Caldwell  Internal Data 15
NOB Outselection

- Competition with OHOs for Nitrite at low DO operation
- AOB always at maximum growth rate (aerobic SRT control with excess NH$_4$ available)
- Aggressive SRT control
- Oxygen affinity
- Free ammonia inhibition of NOB
Nitrite-Shunt

- In a fully nitrifying system (no nitrite-shunt), the ratio of NOB/AOB should equal the ratio of the respective yield coefficients.

  For example, if $Y_{NOB} = 0.09$ and $Y_{AOB} = 0.15$, then $NOB/AOB = 0.6$

- The plant mixed liquor NOB/AOB ratio can be estimated from a fully-aerated SNR test.

  $NO_3PR/NOxPR$ is linked directly to the ratio NOB/AOB.

- If a lower value is measured in a fully-aerated SNR test on plant mixed liquor, then it is likely that the NOB population is suppressed and nitrite shunt is occurring.
St. Petersburg FL – Low DO Mainstream Nitrite Shunt
St. Petersburg FL - Inorganic Nitrogen Profile

Unaerated
DO = 0.02 ± 0.01 mg/L

Aerobic 1
DO = 0.22 ± 0.15 mg/L

Aerobic 2
DO = 0.12 ± 0.08 mg/L

Aerobic 3
DO = 0.08 ± 0.05 mg/L

NH3-N

0.8

NO2-N

0.2

NO3-N

0.12 0.1
HRSD Pilot Plant - AvN Control

DO = set point

NH4-N - NOx-N = setpoint

Regmi et al., 2014
AvN Aeration Advantage

Model-based evaluation of mechanisms and benefits of mainstream shortcut nitrogen removal processes (2014), Ahmed Al-Omari, Bernhard Wett, Ingmar Nopens, Haydee De Clippeleir, Mofei Han, Pusker Regmi, Charles Bott, Sudhir Murthy. WWTMOD
Partial Nitritation-Anammox = “Deammonification”

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

Partial Nitritation
Aerobic Environment

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

0.57 mol NO$_2^-$

Partial Nitritation 40% O$_2$
50% Alkalinity

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

Ammonia Oxidizers
(e.g. Nitrosomonas)

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

Oxygen demand 1.9 g / g NH$_4^+$-N oxidized

Oxygen demand 1.9 g / g NH$_4^+$-N oxidized
Mainstream Deammonification
Four Groups Of Bacteria Involved

- **NITRITE OXIDIZING BACTERIA (NOB)**
- **AMMONIA OXIDIZING BACTERIA (AOB)**
- **HETEROTROPHIC DENITRIFYING BACTERIA**
- **ANAMMOX BACTERIA**
Mainstream Deammonification
Four Groups Of Bacteria Involved

NITRITE OXIDIZING BACTERIA (NOB)
- Inhibited by high ammonia conc.
- Favored by low DO

AMMONIA OXIDIZING BACTERIA (AOB)
- Grows faster than NOB at low DO
- Compete for nitrite

HETEROTROPHIC DENITRIFYING BACTERIA
- Favored by low DO
- Favored by no DO

ANAMMOX BACTERIA
- Inhibited by nitrite

Requires process control to prevent growth of competing organisms.
Challenges of Nitrite Shunt/ Mainstream Deammonification

1. AOB Growth & Retention
2. Anammox Growth & Retention
3. Control OHO Activity
4. Limit NOB Growth
Approaches to Mainstream Nitrite Shunt/Deammonification

- Small Flocculant & Suspended Growth Anammox Granules
  - e.g. Activated Sludge Systems

- Attached Growth Biofilm
  - e.g. RBC, MBBR, Biofilter

- Hybrid Suspended & Attached Growth
  - e.g. IFAS

- Large Anammox Granules
  - e.g. granular sludge systems

Increasing diffusivity or mass transfer resistance
Strass WWTP – Single Stage Full Scale Mainstream Nitrite Shunt/ Deammonification

Full-scale installations in Strass:
Cyclons to select granules out of the wastelines of side-stream and main-stream
Strass WWTP – Single Stage Full Scale Mainstream Nitrite Shunt/ Deammonification
HRSD Mainstream Nitrite-Shunt + Anammox Polishing

Anaerobic digestion is not necessary

- Minimum aeration and volume for C-removal
- Reduce volumetric requirement for nitrogen removal
- Promote nitrite shunt pathway to achieve more nitrogen removal for a given influent C/N
- Produce effluent containing ammonia and nitrite for anammox polishing
- Remove remaining nitrogen autotrophically without additional aeration energy and supplemental carbon
- Meet very low effluent TIN limits
HRSD Mainstream Nitrite-Shunt + Anammox Polishing

The goals:
Nitritation/Denitritation Process:
• Maximum TN removal possible
• Effluent = half ammonia + half nitrite

Anammox MBBR
• Polish residual ammonia and nitrite

Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRT</td>
<td>2 - 3 hr</td>
</tr>
<tr>
<td>Influent Flow</td>
<td>114-159 liter/hr</td>
</tr>
<tr>
<td></td>
<td>(0.5-0.7 gpm)</td>
</tr>
<tr>
<td>SRT</td>
<td>5 days (Target)</td>
</tr>
<tr>
<td>Temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>RAS</td>
<td>100%</td>
</tr>
<tr>
<td>pH</td>
<td>6.8-7.0</td>
</tr>
<tr>
<td>MLSS</td>
<td>3500±500 mg/L</td>
</tr>
</tbody>
</table>
HRSD Mainstream Nitrite-Shunt + Anammox Polishing

- Nitrogen removal in nitrite-shunt
- Anammox Polishing

![Graph showing nitrogen concentrations over time.](image-url)
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