Advances in Point Source Nutrient Removal Technologies: Doing more with less...

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Chief of Research and Development
Hampton Roads Sanitation District
Hampton Roads Sanitation District

- Created in 1940
- Serves 1.7 million people
- Includes 17 jurisdictions – 3,100 square miles
- 9 major plants, 4 small plants
- Capacity of 249 MGD
HRSD’s Bubble Permit - 2011

- **James River**
  - 6,000,000 lbs/yr TN
  - 573,247 lbs/yr TP

- **York River**
  - 288,315 lbs/yr TN
  - 33,660 lbs/yr TP

- **Rappahannock River (one plant)**
  - 1,218 lbs TN
  - 91 lbs/yr TP
Chesapeake Bay TMDL & VA WIP

• Nitrogen – James River
  – 2011 – 6.0 million pounds/year
    • Major upgrades ongoing at Nansemond, James River, Williamsburg, Army Base
  – 2017 – 4.4 million pounds/year
    • VIP - biological process upgrade for improved denitrification
    • Small upgrade at Williamsburg possible
  – 2021 – 3.4 million pounds/year (possible?)
    • Upgrade or Close Chesapeake-Elizabeth?

• Nitrogen – York River
  – Rapid upgrade to add denite filters for 2011 compliance
  – Additional upgrade needed for cost-effective BNR and reliability
HRSD R&D Program Focus

• Resource utilization:
  – Energy
  – Chemicals
  – Labor (operations, maintenance, instrumentation...)
  – Concrete, footprint, land area

• Resource recovery
  – Water
  – P
  – N (maybe)
  – CH₄ - biogas
  – Heat
  – Hydraulic energy
  – Chemicals of interest (maybe)
  – Biosolids (N, P, organics)
  – Etc, etc, etc
The VIP® Process

- It was developed and patented by HRSD, VT, and CH2M Hill
- Biological N and P removal
- Its free for any one to use...
Recycle Streams with High Ammonia - Sidestream

• 1% of Total Plant Influent Flow
• Rich in Nitrogen & Phosphorus
• 15 to 25% of the Total Plant TN load
• Ammonium Conc. 800 to 1,500 mg-N/L
• Temperature 30 - 38°C
• Alkalinity insufficient for complete nitrification
• Insufficient carbon for denitrification

• For a Bio-P plant with no iron addition:
  • Centrate TP = 200-800 mg/L
Sidestream Treatment Options

Biological - N
- Nitrification / Denitrification & Bioaugmentation
  - With RAS & SRT Control
  - With RAS
  - Without RAS
- Nitritation / Denitritation
  - Chemostat
  - SBR
  - Post Aerobic Digestion
- Deammonification
  - Suspended Growth SBR
  - Attached Growth MBBR
  - Upflow Granular Process

Physical-Chemical – N&P
- Ammonia Stripping
  - Steam
  - Hot Air
  - Vacuum Distillation
- Ion-Exchange
  - ARP
- Struvite Precipitation
  - Ostara Process
  - PhosPaq Process
  - Etc
HRSD Nansemond Treatment Plant Upgrade
Nansemond Plant Process Flow Diagram
What is Struvite?

\[ \text{Mg}^{2+} + \text{NH}_4^+ + \text{PO}_4^{3-} \rightarrow \text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O} \]
What is the Ostara® Process?
Struvite Facility Construction Schedule

- Proposal Submitted July 2009
- Commission Approval October 2009
- Contract Signed November 2009
- Operational May 2010
- Ribbon-cutting May 27, 2010
Struvite Recovery Facility

- Sorting, product Storage and bagging
- Dewatering and Drying
- 3 - 500 kg/day fluidized bed reactors
Struvite Facility Cost

Project Cost $5.6 M

Building and Sitework 40%
Process Equipment and Technology license 56%
Design 4%

Total 100%
Product Production/Sales

HRSD Bagged Production - 2013 and 2014

Calendar Year 2013
Calendar Year 2014

January
February
March
April
May
June
July
August
September
October
November
December

198
142
194
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  - Etc
Conventional Nitrification-Denitrification

**Autotrophic Bacteria**

**Aerobic Environment**

- 1 mole Ammonia ($\text{NH}_3 / \text{NH}_4^+$)
- 25% O$_2$ (energy)
- 75% O$_2$ (energy)
- ~100% Alkalinity

**Heterotrophic Bacteria**

**Anoxic Environment**

- 1 mole Nitrite ($\text{NO}_2^-$)
- 40% Carbon (BOD)
- 60% Carbon (BOD)

**Ammonia Oxidizing Bacteria (AOB)**

**Nitrite Oxidizing Bacteria (NOB)**

- 1 mole Nitrate ($\text{NO}_3^-$)
- $\frac{1}{2}$ mol Nitrogen Gas ($\text{N}_2$)
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Nitritation-Denitritation = “Nitrite Shunt” (2.0)

**Nitritation**
- **75% O₂ (energy)**
- **~100% Alkalinity**
- **1 mole Ammonia**
  \(\text{NH}_3 / \text{NH}_4^+\)
- **1 mole Nitrite**
  \(\text{NO}_2^-\)

**Denitritation**
- **40% Carbon (BOD)**
- **1/2 mol Nitrogen Gas**
  \(\text{N}_2\)

**Advantages:**
- 25% reduction in oxygen demand (energy)
- 40% reduction in carbon (e⁻ donor) demand
- 40% reduction in biomass production
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 (all the possibilities)
  – AOB max growth rate > NOB max growth rate at high temp
  – Free NH3 inhibition of NOB > AOB
  – AOB DO affinity > NOB DO affinity (r-strategist *Nitrobacter*...)
    • For mainstream: AOB DO affinity < NOB DO affinity (K-strategist *Nitrospira*...)
  – Nitrous acid inhibition of NOB > AOB

• Processes:
  – SHARON – Continuous flow MLE with supplemental carbon
  – Strass - SBR
Nitritation – Denitritation - SHARON

Nitritation:
\[ \text{NH}_4^+ + O_2 \rightarrow \text{NO}_2^- \]

Denitritation:
Methanol or other carbon source
Alkalinity
Air

Centrate with low Effluent NH\(_4^+\) and NO\(_x\)

Centrate NH\(_4^+\)

NO\(_2^-\) Denite

AOB

\[ \text{NH}_4^+ + O_2 \rightarrow \text{NO}_2^- \]
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The N-Cycle

Denitrification

$\text{NO}_3^-$ → $\text{NO}_2^-$ → $\text{NH}_4^+$ → $\text{N}_2$

Anammox

$\text{N}_2$ → $\text{NO}_2^-$

Nitrification

$\text{NH}_4^+$ → $\text{NO}_3^-$

E. Broda (1977): „missing lithotroph“ ... „might have existed or still exists“

free enthalpy -360 kJ/mol
Partial Nitritation-Anammox = "Deammonification" (3.0)

ANAMMOX
"Anaerobic" Ammonia Oxidation - (New Planctomycete - Strous et al, 1999)

\[
\begin{align*}
\text{NH}_4^+ + 1.32 \text{NO}_2^- + 0.066 \text{HCO}_3^- + 0.13 \text{H}^+ & \rightarrow \\
0.26 \text{NO}_3^- + 1.02\text{N}_2 + 0.066 \text{CH}_2\text{O}_{0.5}\text{N}_{0.15} + 2.03 \text{H}_2\text{O}
\end{align*}
\]

Advantages:
- 63% reduction in oxygen demand (energy)
- Nearly 100% reduction in carbon demand
- 80% reduction in biomass production
- No additional alkalinity required
One-Step Sidestream Deammonification

- **SBR + Hydrocyclone Granular Sludge (DEMON)**
  - Strass, Austria
  - Demon GmbH – World Water Works, Inc.

- **Upflow Granular Sludge (CANON/ANAMMOX)**
  - Olburgen, Netherlands
  - Paques (NL)

- **Biofilm process (MBBR-style)**
  - ANITA Mox
    - AnoxKaldnes – Kruger - Veolia
  - Deammon -- Hattingen, Germany & Stockholm
    - Purac

Partial Nitritation and Anammox - combined in a single reactor
Sidestream Deammonification: What’s the benefit?

• Remove ~20% of the N load to the plant by treating the centrate separately
• Do it with:
  – No chemicals (caustic & methanol)
  – < 40% of the energy cost
  – (as compared to traditional nitrification-denitrification)
• Business case is very good, particularly if existing tanks can be used
• Risks:
  – Requires robust process control, particularly during startup
  – Process has been adequately demonstrated
  – Seeding required for fast startup
S-curve for Sidestream Deammonification

100 Full-scale Installations

Industrial

25%

Municipal

75%

In the US

Scientific Publications

Full-scale Installations

Year


Publications

Installations
DEMON at HRSD York River (15 MGD)

DEMON

ANAEEROBIC DIGESTION

THICKENING

DEWATERING

AERATION BASINS

HEADWORKS

DENITE FILTERS
Implementation of DEMON at York River
DEMON Seed Sludge
Hydrocyclone for Biomass Wasting

- Retain anammox in small dense granules
- SRT of anammox granules >> SRT of AOB, NOB, heterotrophs, debris
- Create “washout” conditions for NOB
- Control activity of AOB population
ANITA™ Mox Sidestream Deammonification MBBR

- Seeding strategy to help speed up startup
  - 10% pre-colonized media
- 3 plants in Europe, this is the first in the US
- DO control based off of NH4 and NO3 sensors
Process Components

Aeration System
Instrumentation
Centrate Feed

Mixers and Heaters
K5 Media
Media Retention
Seeding and Startup
Biofilm Growth

New media
12/12/13

Seed media
12/12/13

New media
2/26/14

Seed media
2/26/14

New media
4/10/14

Seed media
4/10/14

New media
7/15/14

Seed media
7/15/14
Short-Cut Nitrogen Removal Processes: Transitioning to Mainstream 2.0 & 3.0
Mainstream Deammonification Project
3 different sites and scales
Challenges

1. Mainstream NOB suppression (out-selection)
2. Selective anammox retention
3. Wastewater carbon (COD) diversion & control
Conventional Nitrification-Denitrification (1.0)

**Autotrophic Bacteria**
- Aerobic Environment
  - 1 mole Ammonia ($\text{NH}_3 / \text{NH}_4^+$)
  - 25% $\text{O}_2$ (energy)
  - 75% $\text{O}_2$ (energy)
  - ~100% Alkalinity
- Ammonia Oxidizing Bacteria (AOB)

**Heterotrophic Bacteria**
- Anoxic Environment
  - 1 mole Nitrite ($\text{NO}_2^-$)
  - 40% Carbon (BOD)
  - 60% Carbon (BOD)
- Nitrite Oxidizing Bacteria (NOB)

**Chemical Reactions**
- 1 mole Nitrate ($\text{NO}_3^-$)
- ½ mol Nitrogen Gas ($\text{N}_2$)
4-Stage Bardenpho
(Better N Removal)

Primary Effluent
BOD + NH₄

Anoxic

Aerobic

Anoxic

Aerobic

氮酸再循环 (NRCY)

Methanol

TN ~ 3-5 mg/L

RAS

SC

WAS
Adsorption/Bio-oxidation (A-B) Process

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low overall volume</td>
<td>Requires ammonia-based aeration control</td>
</tr>
<tr>
<td>Good nitrogen removal</td>
<td>Not operated to achieve complete nitrification</td>
</tr>
<tr>
<td>Redirect carbon to anaerobic digestion</td>
<td></td>
</tr>
<tr>
<td>Low aeration energy requirement</td>
<td></td>
</tr>
</tbody>
</table>
CONVENTIONAL

A-STAGE
Simulated COD Balance of the AIZ Strass WWTP

- Influent: 100.0%
- A-stage: 60.7%
  - SBR: 1.3%
  - Thickener: 36.3%
- B-stage: 36.3%
- Effluent: 4.7%
- Dewatering: 37.6%
- Digester: 38.9%
- Methane: 35.4%
- Waste Sludge: 80-90%
- Waste Sludge: 10-20%

Ammonia-Based Aeration Control
Feedback Control
Limiting aeration: *Cascaded NH\textsubscript{4}/DO control*

Aeration intensity control (or intermittent aeration)
Feedback+Feedforward control

- **NH₄ Feedforward Controller**
- **Maximum-criteria**
- **Ref. variable**
- **DO Controller**
- **Manipulated variable**
- **Measured variable**
- **NH₄ Feedback controller**

Variables:
- NH₄
- Q
- O₂
- M

Feedback control is represented by the blue arrow, feedforward control by the red arrow, and both combined by the green arrow.
Reducing ammonia effluent peaks

- **Intensity control**: Manipulate aeration intensity early to create buffer for incoming peak

- **Volume control**: Change aerated volume by switching on/off swing zones
Ammonia-based aeration control

**Limiting aeration:**

- Reduce energy consumption
  - less NH4 converted, aerating at lower DO, less COD oxidized aerobically
- Increase denitrification – SND
- Improve usage of sbCOD, reduce need for supplemental carbon
- Decrease ALK demand
- Decrease chlorine demand – NH4 is present
- Maybe improve bio-P performance

**Decreasing effluent ammonia peaks:** Reduce the extent of effluent ammonia peaks
Nitritation-Denitritation = “Nitrite Shunt” (2.0)

**Nitritation**
- 75% O₂ (energy)
- 100% Alkalinity
- 1 mole Ammonia (NH₃ / NH₄⁺)

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

**Advantages:**
- 25% reduction in oxygen demand (energy)
- 40% reduction in carbon (e⁻ donor) demand
- 40% reduction in biomass production
Partial Nitritation-Anammox = “Deammonification” (3.0)

ANAMMox
“Anaerobic” Ammonia Oxidation - (New Planctomycete - Strous et al, 1999)

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\]

Autotrophic Bacteria
Aerobic Environment

37% O₂ (energy)
~50% Alkalinity

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

0.5 mole Nitrite
\((\text{NO}_2^-)\)

Ammonia Oxidizing Bacteria (AOB)

Autotrophic Anoxic Environment

½ mol Nitrogen Gas \((\text{N}_2)\) + a little bit of nitrate \((\text{NO}_3^-)\)

Advantages:
- 63% reduction in oxygen demand (energy)
- Nearly 100% reduction in carbon demand
- 80% reduction in biomass production
- No additional alkalinity required
Plants with Anaerobic Digestion

- Incentive for C-redirection

Key Features:
1. Bioaugment AOB in the sidestream cyclone overflow to the mainstream
2. Bioaugment anammox from sidestream to mainstream
3. Cyclone for anammox retention in mainstream
4. Repress NOB in mainstream (and sidestream)

Being piloted at DC Water and tested full-scale at Strass, AT and Glanerland, CH
S-select – Cyclone installation for settleability improvement
HRSD James River Plant - S-Select
HRSD Mainstream Approach

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
- AVN control system for NOB out-selection
- Remove remaining nitrogen autotrophically without additional aeration energy and supplemental carbon
- Meet very low effluent TIN limits
Pilot 2.0

A-stage

HRAS

B-stage (AvN+)

AvN

Anammox MBBR

https://vimeo.com/92084803
A Few Conclusions...

• NOB out-selection is possible in mainstream (sensors and novel control systems are unavoidable)

• Separate stage C and N removal is back...
  – Energy benefit
  – BNR volume and footprint benefit

• Anammox polishing in the mainstream is feasible and simple

• NOB out-selection is really tough...

• The AVN control strategy provides excellent N removal even in conventional 1.0 nitrification-denitrification mode – *technology is adequately incremental and transferable to existing infrastructure*
Questions?

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