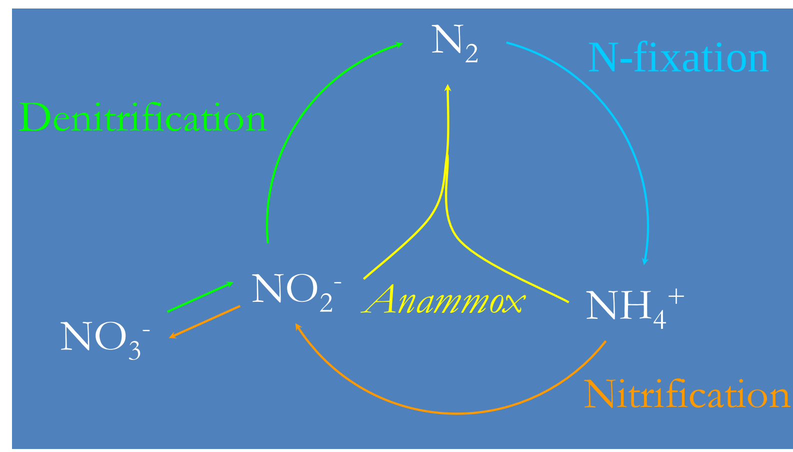
Nitrogen Removal 1.0 to 3.0

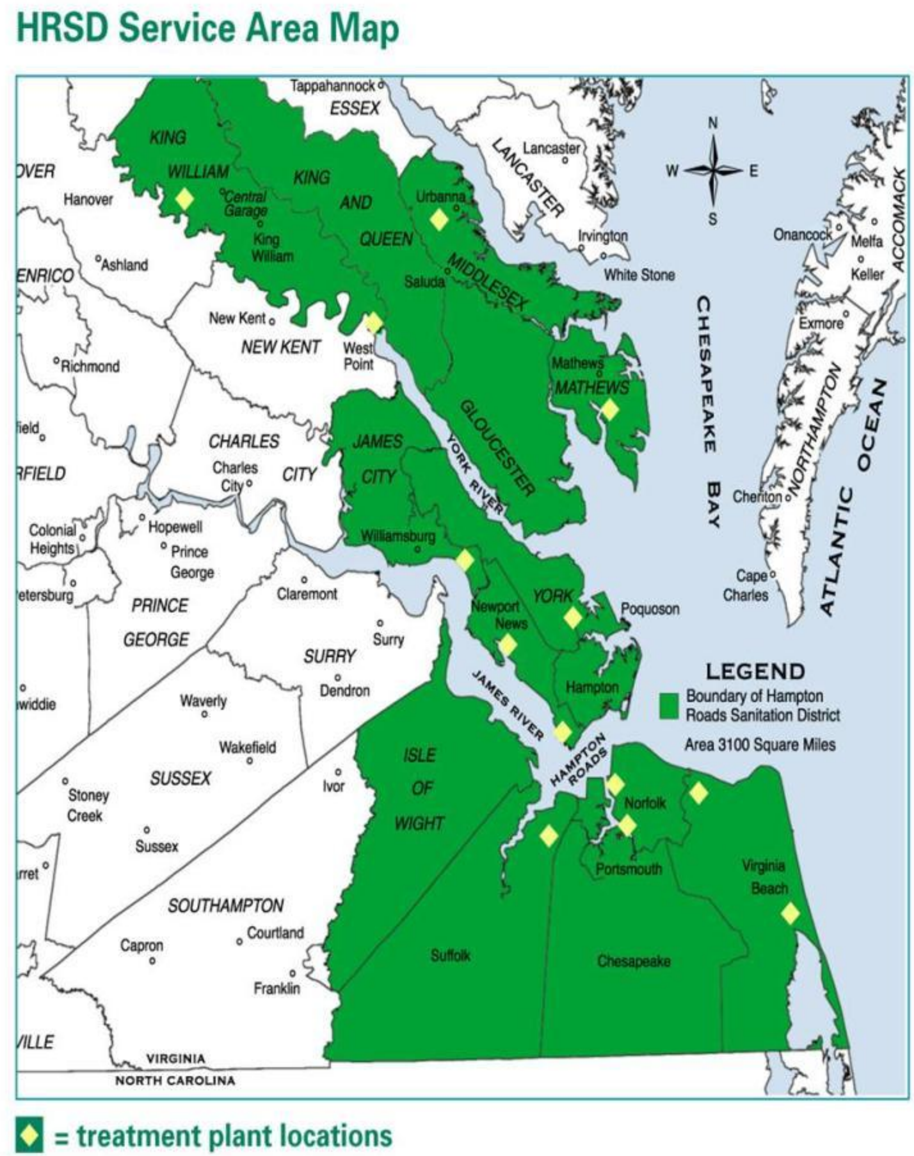
Charles B. Bott, Ph.D., P.E., BCEE
Hampton Roads Sanitation District



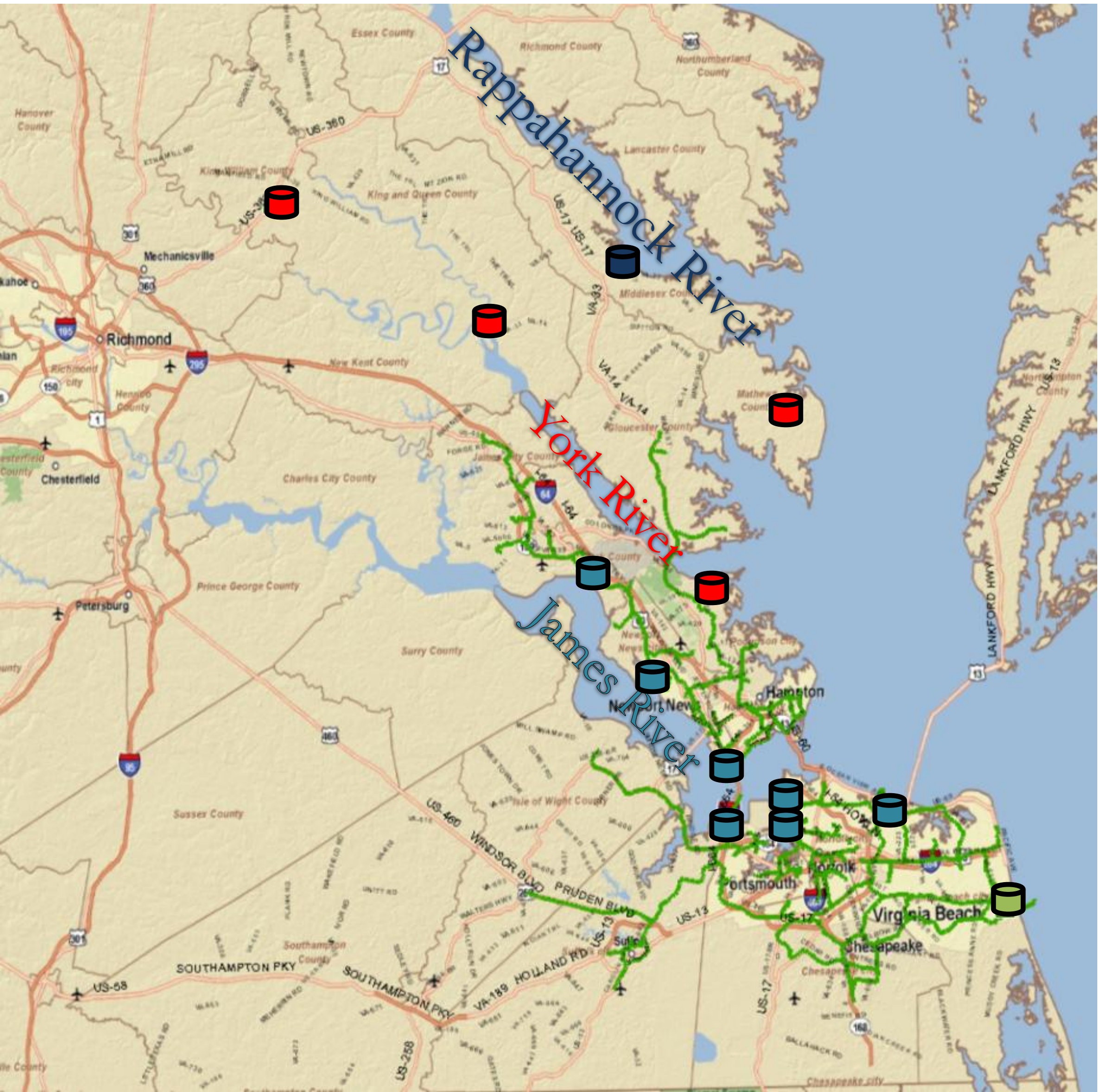
HRSD

Hampton Roads Sanitation District

- Created in 1940
- Serves 1.6 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

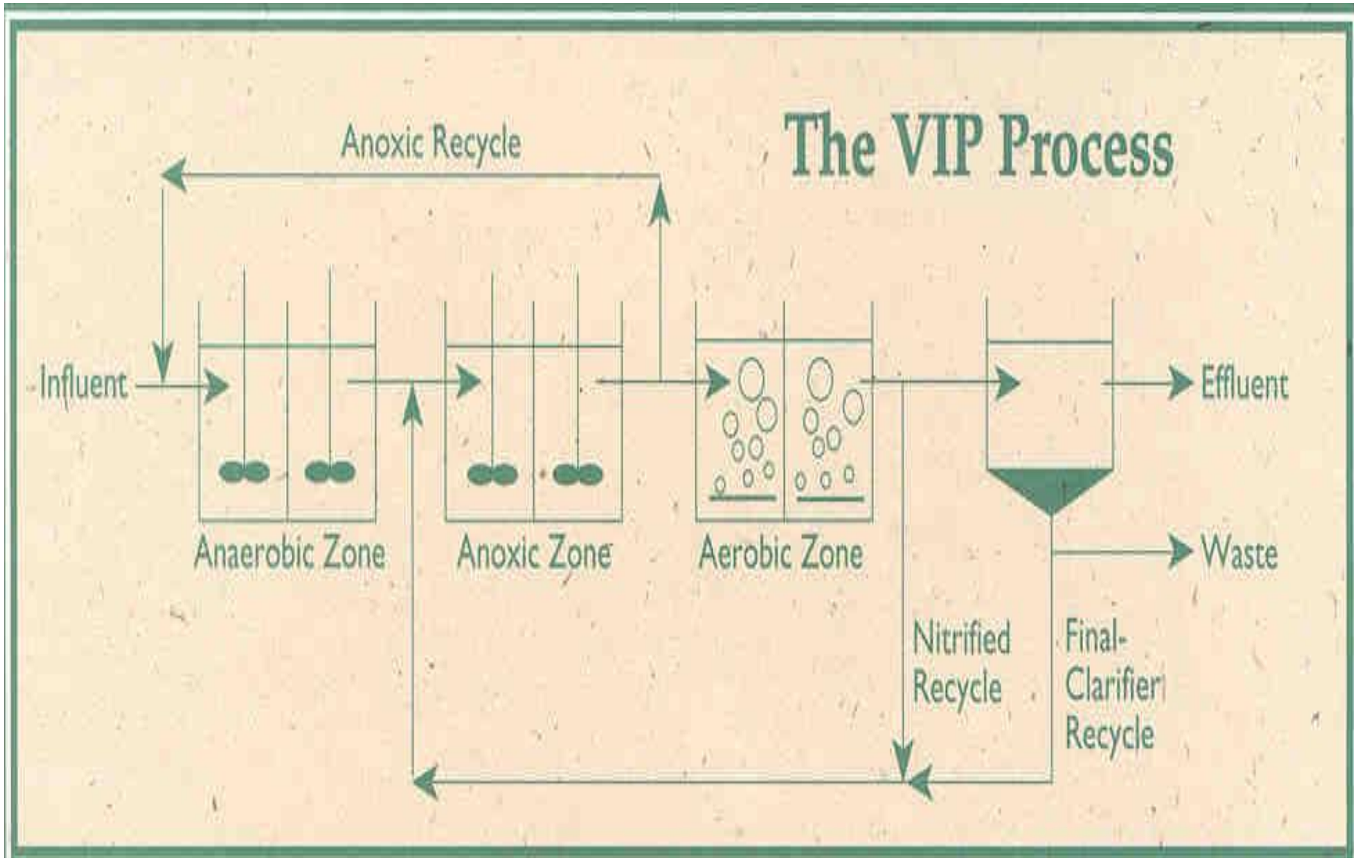
Chesapeake Bay TMDL & VA WIP

- Nitrogen – James River
  - 2011 – 6.0 million pounds/year
    - Major upgrades ongoing at Nansemond, James River, Williamsburg, Army Base,
    - Upgrade at Boat Harbor (minimal N removal)
  - 2017 – 4.4 million pounds/year
    - VIP - biological process upgrade for improved denitrification
    - Small upgrade at Williamsburg possible
  - 2021 – 3.4 million pounds/year
    - Upgrade Chesapeake-Elizabeth (full plant)
- Nitrogen – York River ---- No change?
  - 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
- Resource recovery
  - Water
  - P
  - N (maybe)
  - CH_4 - 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 and CH2M Hill
- Biologically removes Phosphorus and Nitrogen
- Its free for any one to use…

Current HRSD R&D Efforts in BNR:

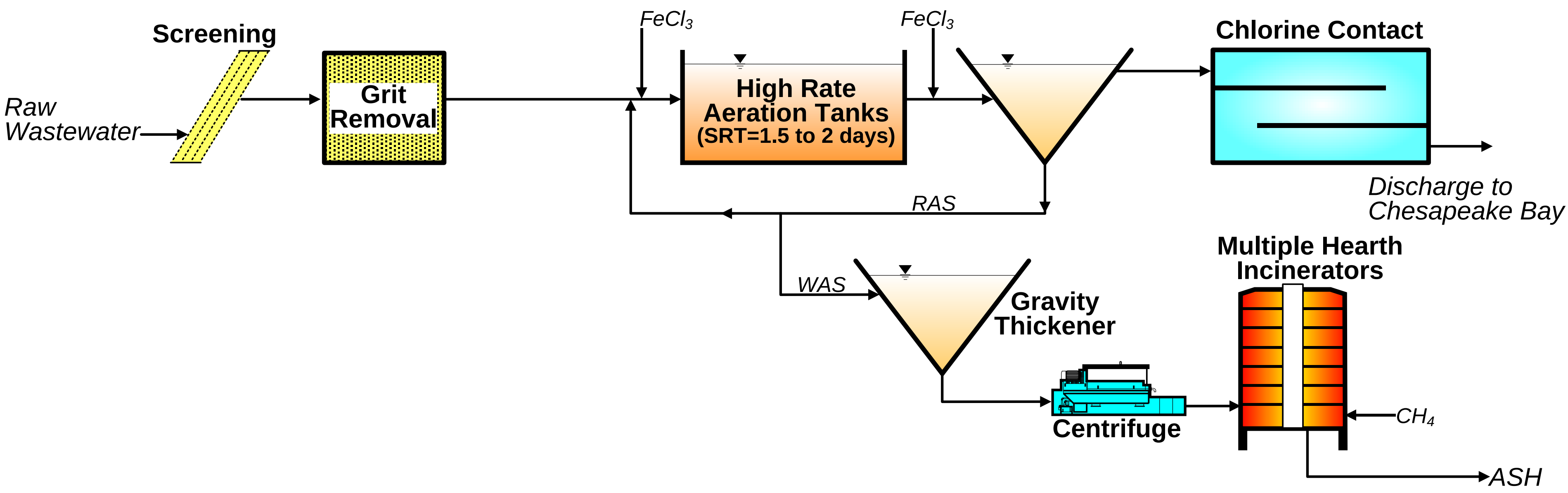
- Supplemental carbon for denitrification (chemicals)
  - AOB conversion of methane to methanol
  - Reduced S compounds
  - Ethanol used for fuel blending
- Ammonia-based DO control systems (energy, chemicals)
- Cost-effective Chemically Enhanced Primary Treatment (chemicals, energy)
- Algae-based nutrient removal (chemicals, energy)
- Centrate treatment – anammox (chemicals, energy)
- Nitrite accum. and excessive chlorine demand (chemicals)
- IFAS process development and modeling (concrete, energy)
- Nitrification inhibition (concrete)
- BNR process reliability and stochastic methods (concrete)
- Improvement of BNR process models (chemicals, energy, concrete)
- Organic nitrogen sources and fate (issue)
- Urine separation (???)

Some Motivation for Pilot Work…

- Nitrogen removal upgrade required by 2021 to meet TN of approximately 5 mg/L
- Capital Cost = $125-150M (conventional process)
- Operating costs will increase dramatically:
  - Incremental Energy for aeration and pumping = $1.0 M/yr
  - Incremental chemicals (caustic and carbon) = $1.0 to 2.0 M/yr
  - Labor & supplies?
- Limited land available
  - Nutrient Removal
  - Biosolids

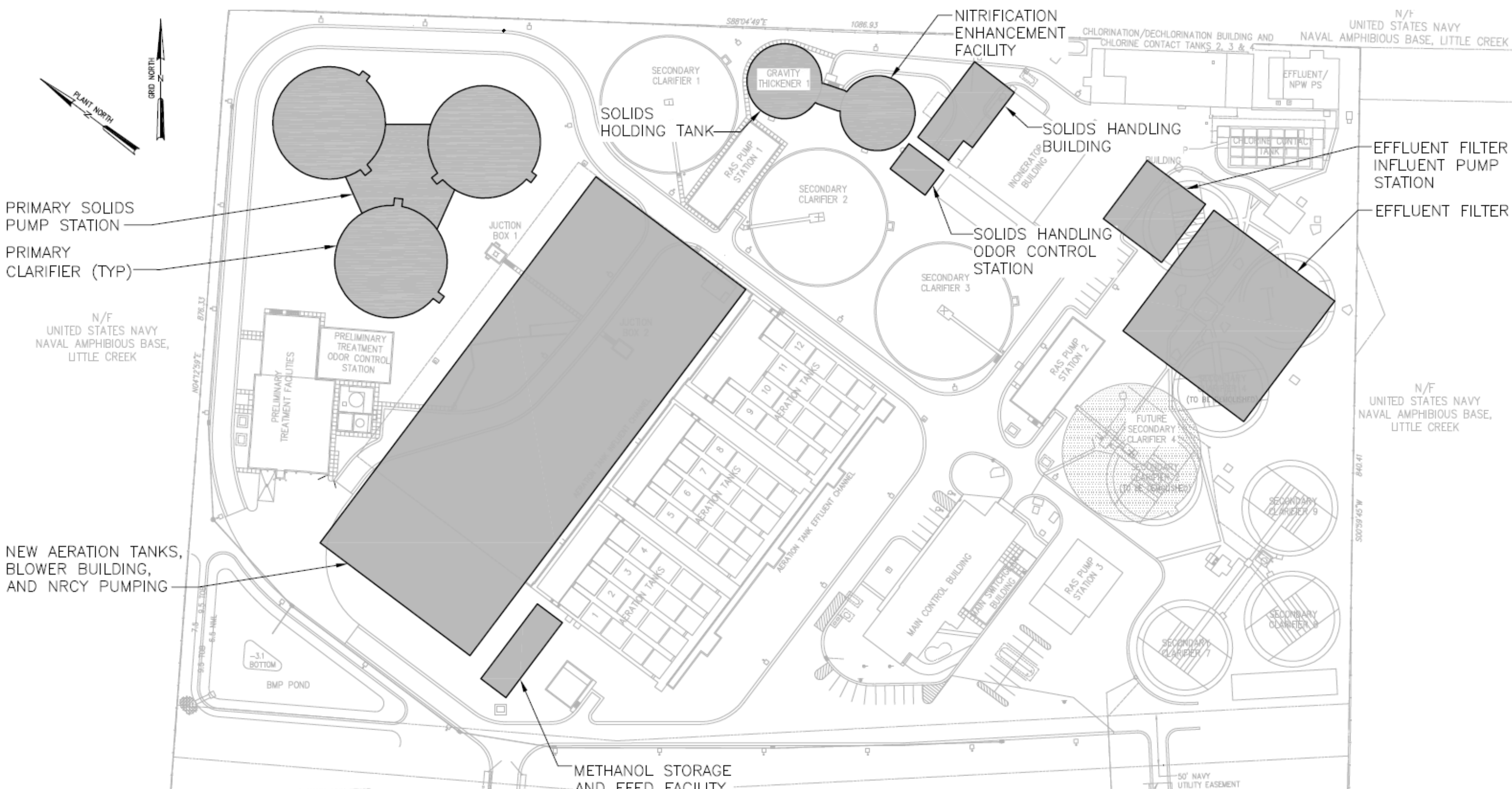
Chesapeake-Elizabeth Treatment Plant

- 24 MGD design, 15-20 MGD operating



Traditional BNR Alternative by 2021

- Construct primary clarifiers
- Construct:
  - 5-stage Bardenpho (+9 MG) & Filters
  - MLE or VIP + Denite Filters
- Incinerator scrubber blowdown treatment
  - Sidestream biological treatment of cyanide
- Thickening improvements
- Full Distributed Control System (DCS)



Pilot Program

- – 4 year study
- – Collaboration through Water Environment Research Foundation (WERF) project:
  - DCWater & HRSD
  - Austrian (Strass) and Swiss wastewater utility
  - Developers of the DEMON process (Wett, et al)
  - ODU, Virginia Tech, Columbia University (NY), University of Innsbruck (Austria)
  - Three US engineering firms – HDR, Black & Veatch, AECOM
  - Several other interested US wastewater utilities

Agenda

- Reactions 1.0, 2.0, 3.0
- Sidestream Treatment of Anaerobically Digested Sludge Dewatering Liquor – 1.0, 2.0, 3.0 (All established)
- Mainstream Treatment 1.0 (established)
- Mainstream Treatment 2.0 (established with caveats)
  - SND (es
  - A/B Process
  - HRSD Pilot A/B Process
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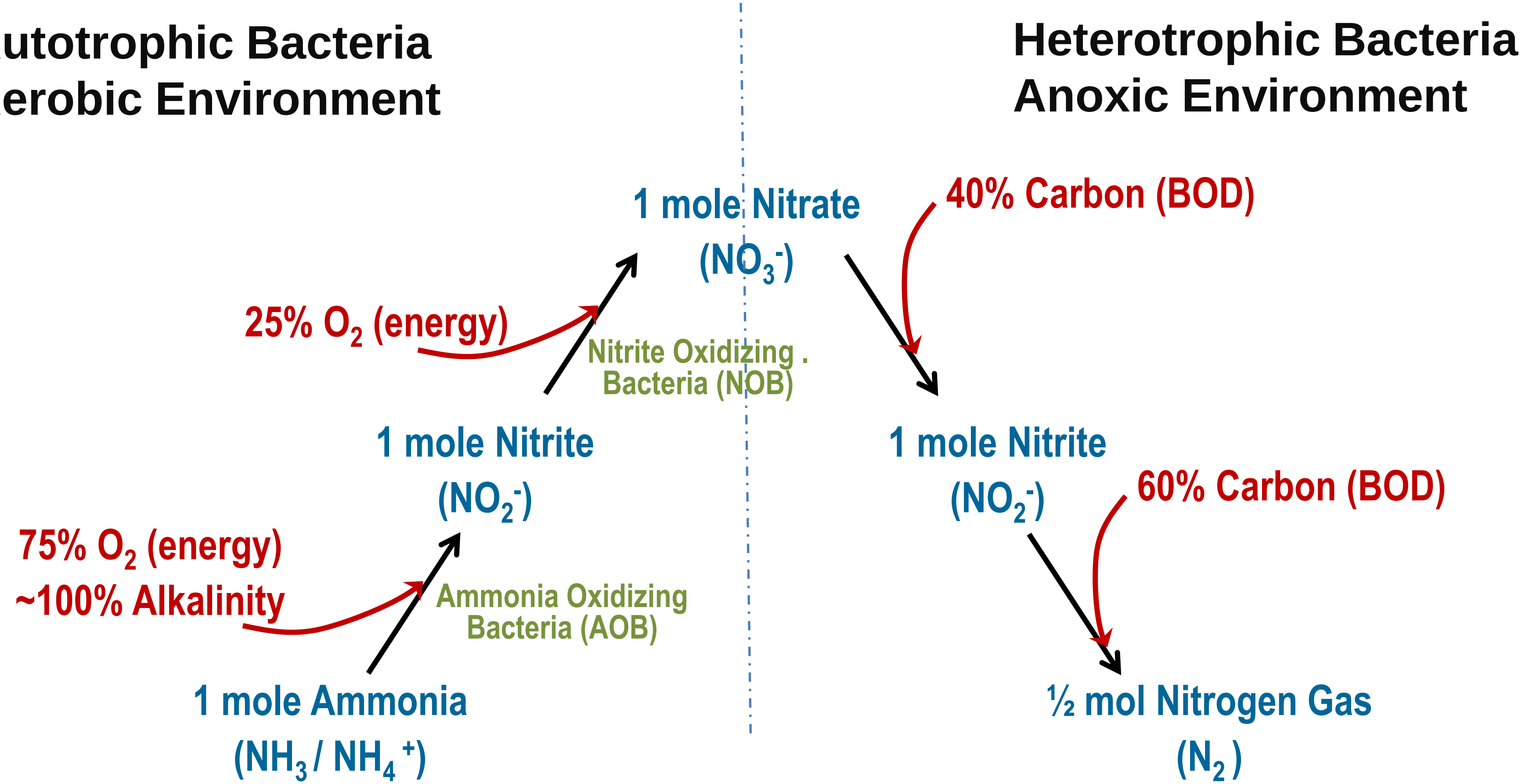
  - NOB Repression
- Mainstream Treatment 3.0 (emerging)
  - Alternative configurations
  - Carbon Flow
  - HRSD Pilot 3.0 – separate stage without bioaugmentation
- Several other emerging ideas (3.1)

Conventional Nitrification-Denitrification (1.0)

Autotrophic Bacteria
Aerobic Environment

Heterotrophic Bacteria
Anoxic Environment



NITRIFICATION **DENITRIFICATION**

Some New Vocabulary….

Autotrophic Bacteria
Aerobic Environment

Heterotrophic Bacteria
Anoxic Environment

1 mole Nitrate
(NO_3^-)

Nitr<u>a</u>tation

Nitrite Oxidizing . Bacteria (NOB)

Denitr<u>a</u>tation

1 mole Nitrite
(NO_2^-)

1 mole Nitrite
(NO_2^-)

Nitr<u>i</u>tation

Ammonia Oxidizing Bacteria (AOB)

Denitr<u>i</u>tation

1 mole Ammonia
(NH_3 / NH_4^+)

½ mol Nitrogen Gas
(N_2)

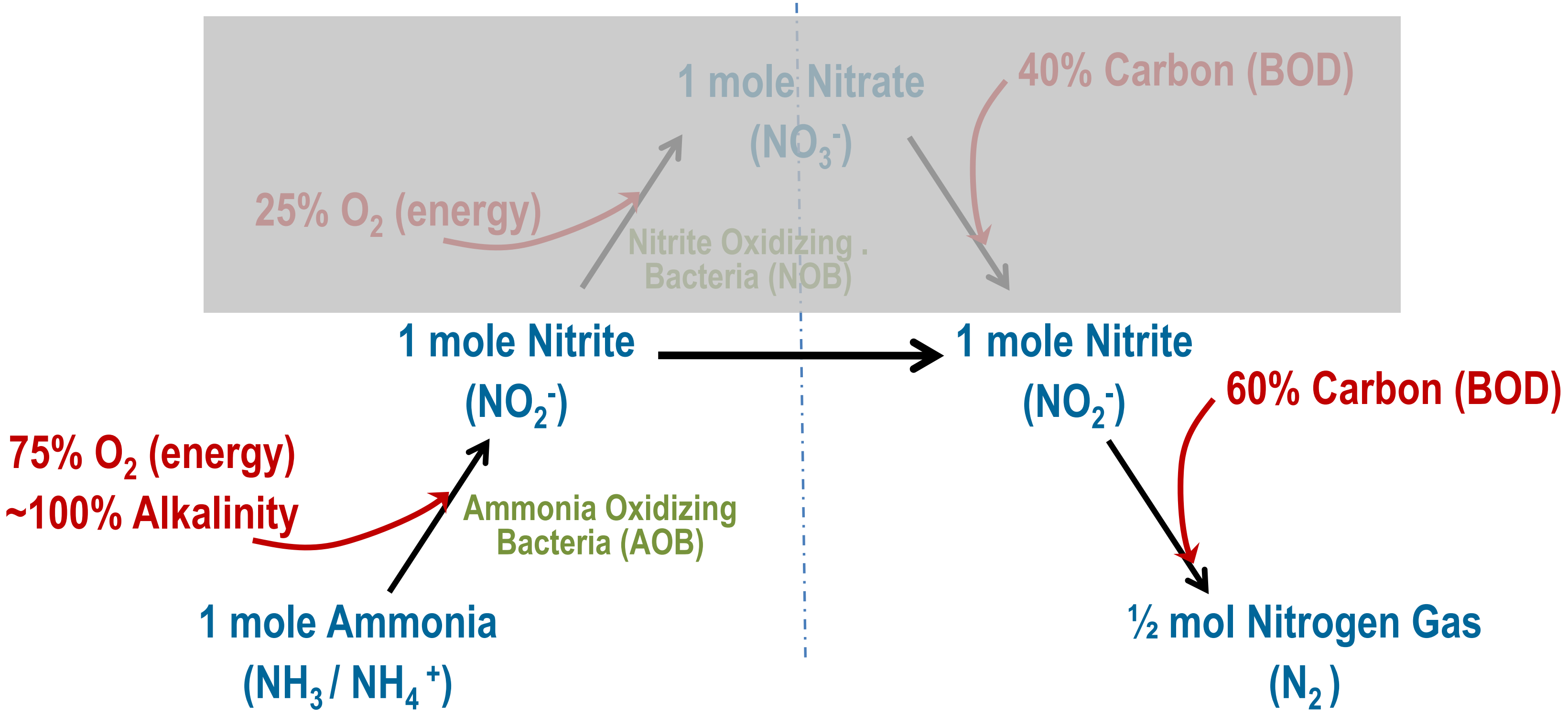
NITRIFICATION

DENITRIFICATION

Nitritation-Denitritation = "Nitrite Shunt" **(2.0)**

Autotrophic Bacteria
Aerobic Environment

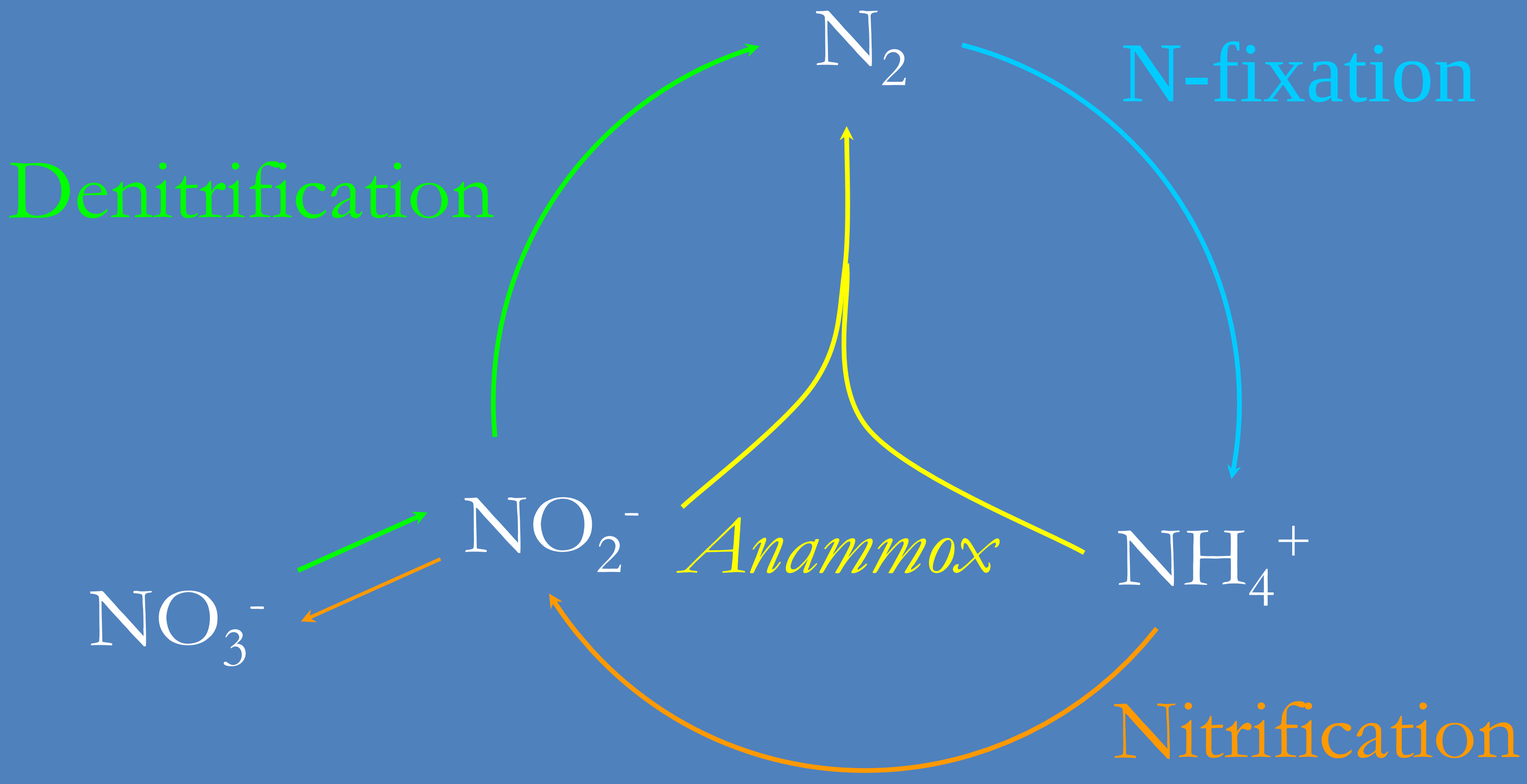
Heterotrophic Bacteria
Anoxic Environment



Advantages:

- **25% reduction in oxygen demand (energy)**
- **40% reduction in carbon (e^- donor) demand**
- **40% reduction in biomass production**

The N-Cycle



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)

$$NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow$$
$$0.26\ NO_3^- + 1.02N_2 + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O$$

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Aerobic Environment

0.5 mole Nitrite (NO_2^-)

37% O_2 (energy)
~50% Alkalinity

Ammonia Oxidizing Bacteria (AOB)

1 mole Ammonia (NH_3 / NH_4^+)

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½ mol Nitrogen Gas (N_2) + a little bit of nitrate (NO_3^-)

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

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  - Carbon Flow
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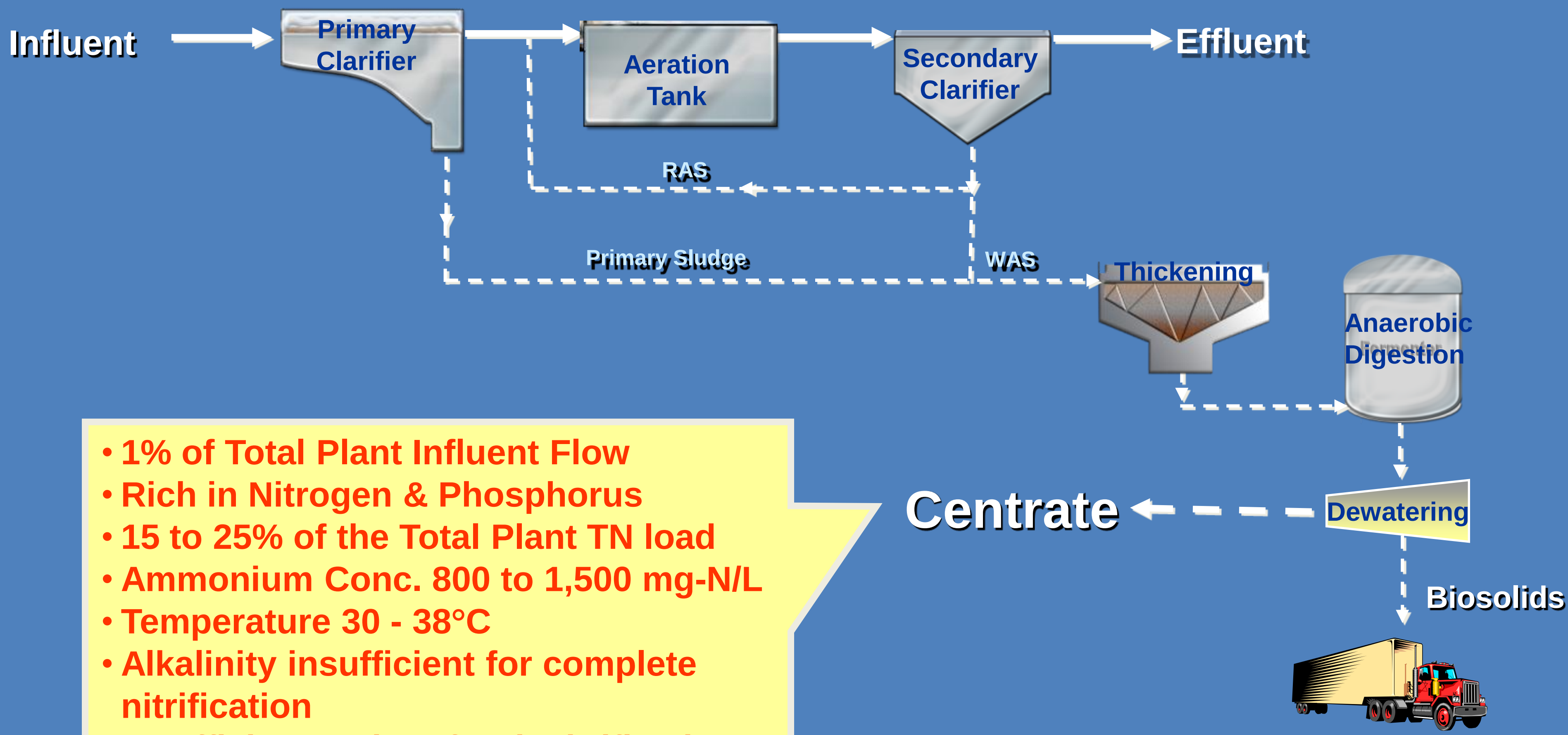
- Several other emerging ideas (3.1)

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

1.0 **Nitrification / Denitrification & Bioaugmentation**
- With RAS & SRT Control
- With RAS
- Without RAS

2.0 **Nitritation / Denitritation**
- Chemostat
- SBR
- Post Aerobic Digestion

3.0 **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

Conventional Nitrification-Denitrification

Autotrophic Bacteria
Aerobic Environment

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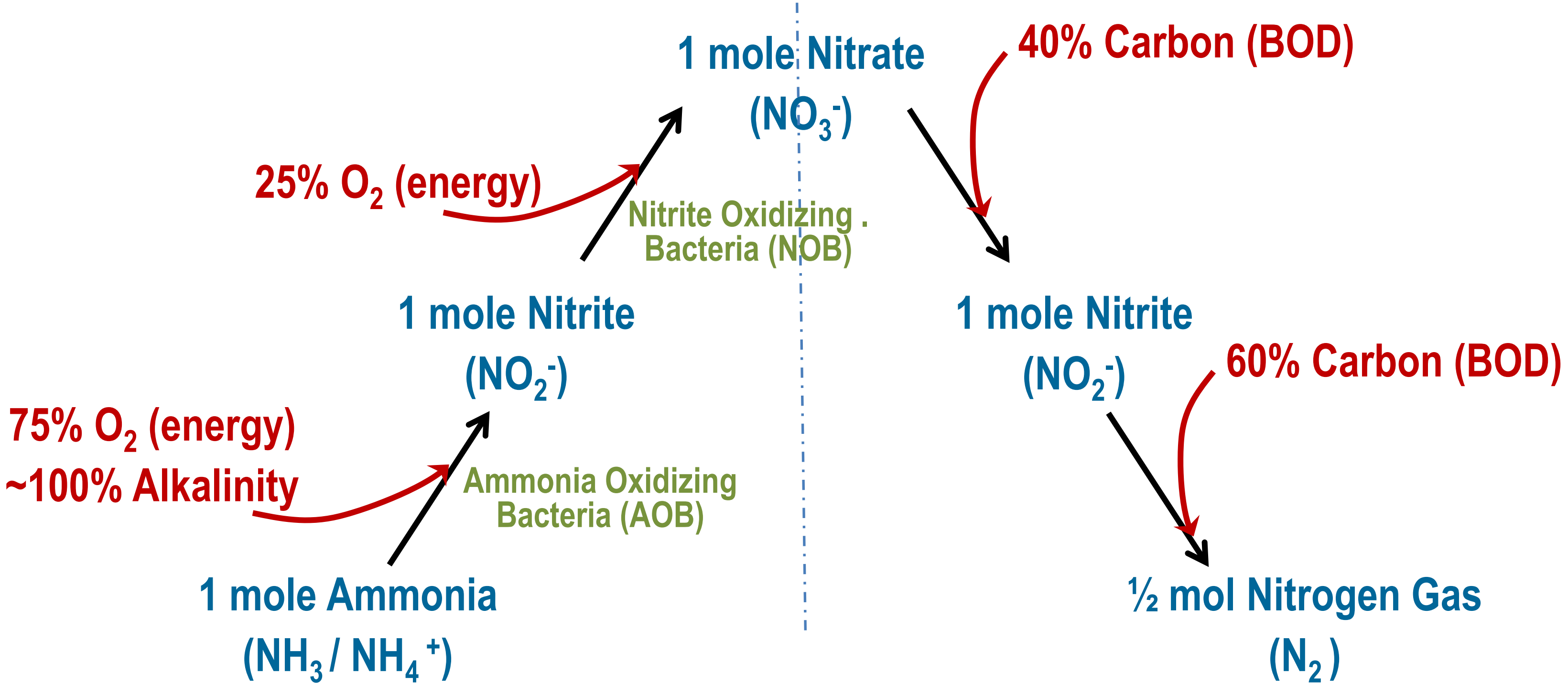
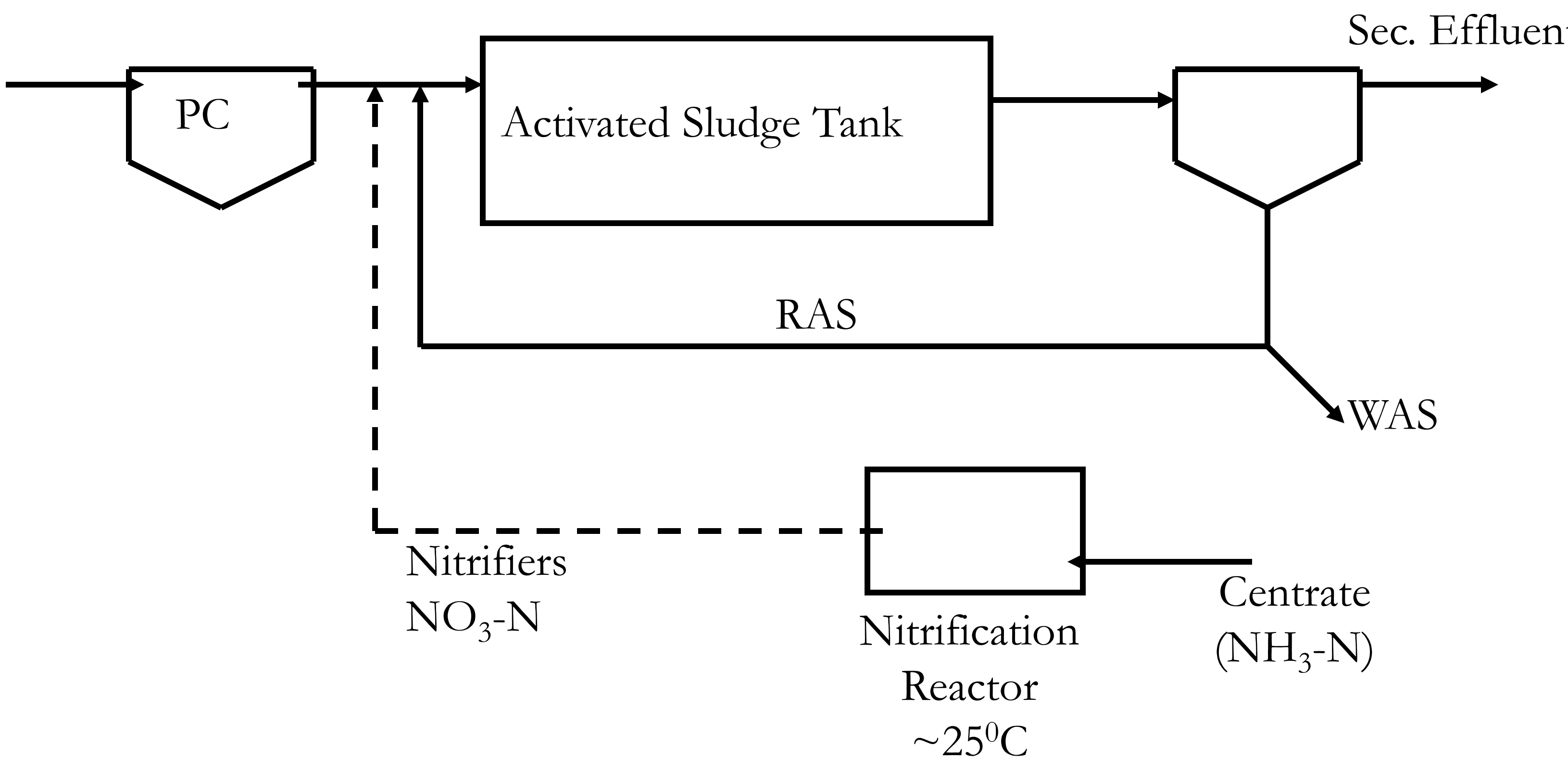


InNitri Process was the First Bioaugmentation Concept



Expected bioaugmentation benefit not fully realized

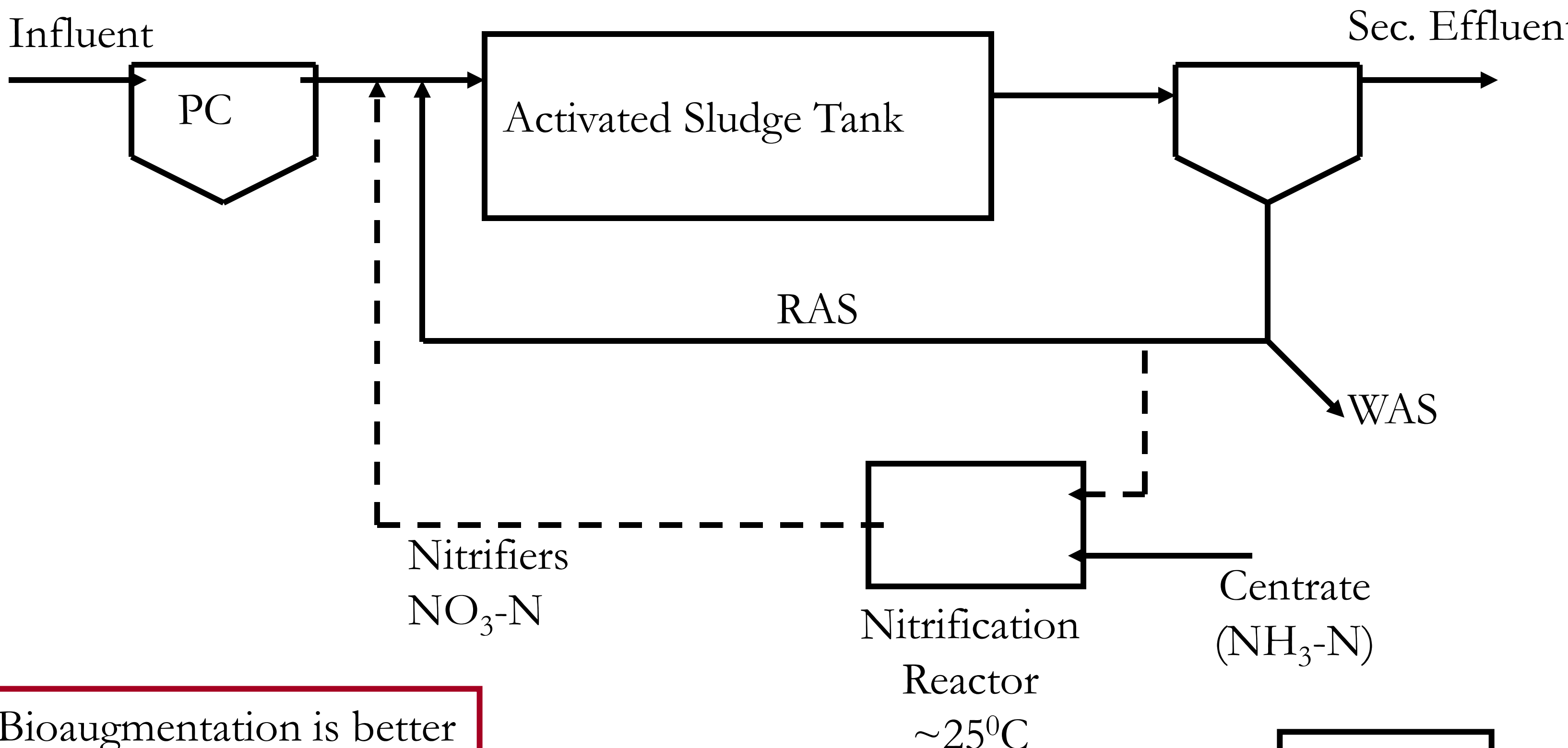
- Temperature change
- Poor capture of recycle stream nitrifiers
- Predation

Peter Kos
M2T Tech License

BABE Process – (SBR Mode of Operation)

Bio**A**ugmentation **B**atch **E**nhanced

AT-3, BAR, CaRRB, Maureen, etc.



Bioaugmentation is better

Delft U.
DHV
STOWA

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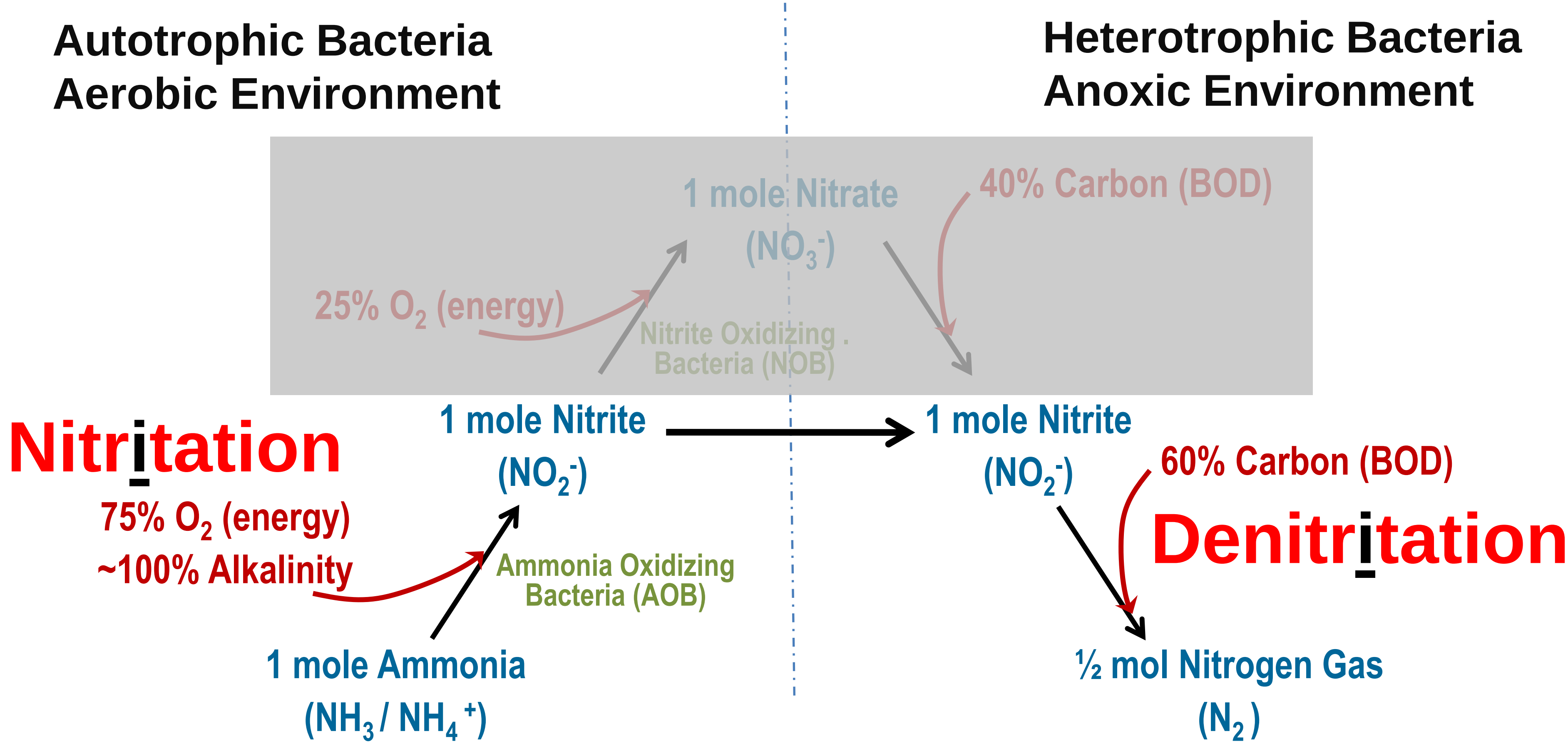

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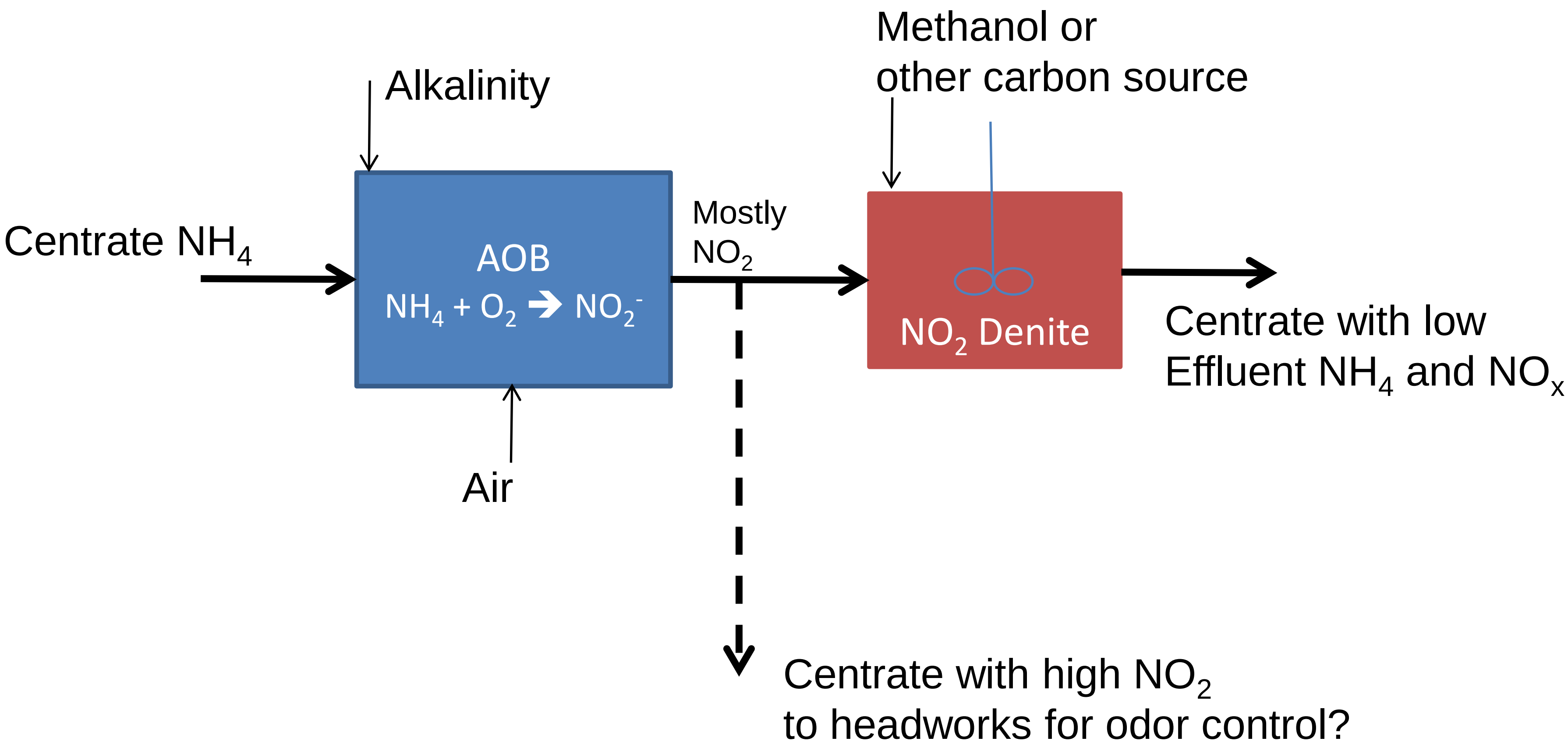
Nitritation - Denitritation



Sidestream Nitritation

- 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
  - AOB DO affinity > NOB DO affinity at high temp
  - Nitrous acid inhibition

Sidestream Treatment Options

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Partial Nitritation-Anammox = "Deammonification" (3.0)

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Advantages:

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- Nearly 100% reduction in carbon demand
- 80% reduction in biomass production
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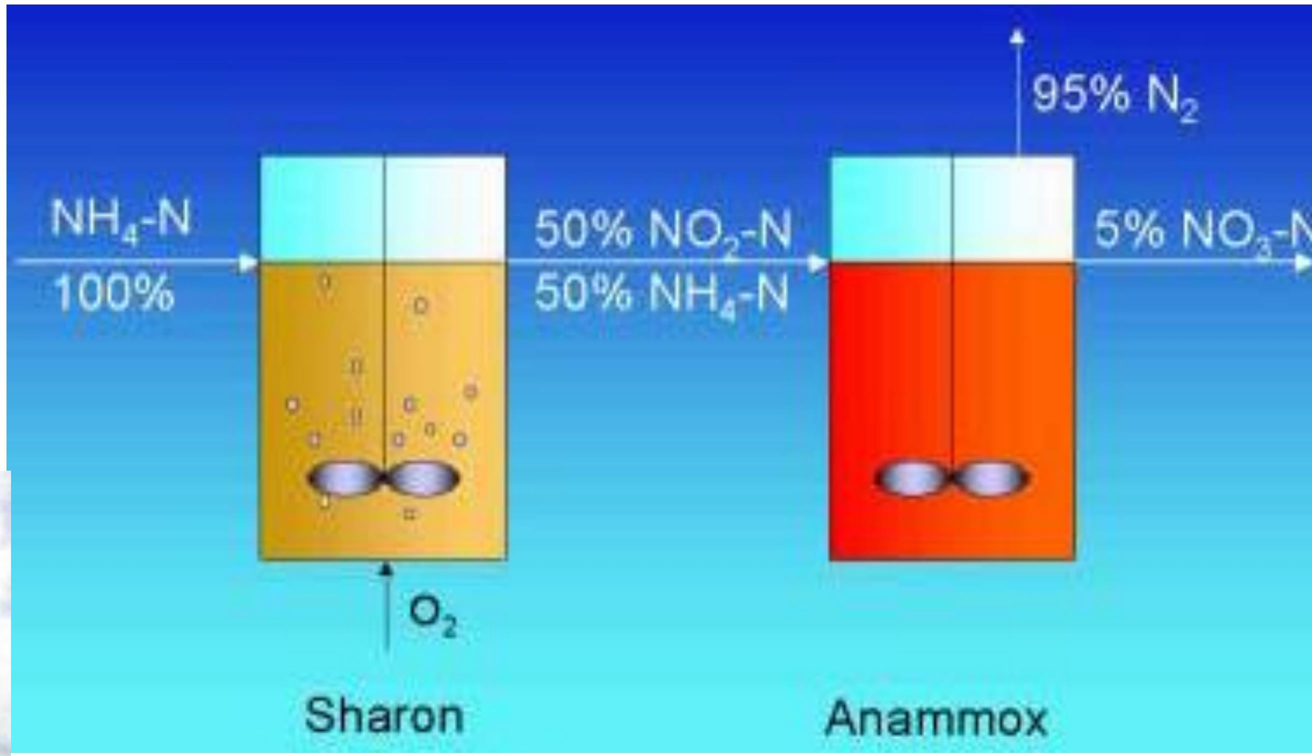
Partial Nitritation – Anammox

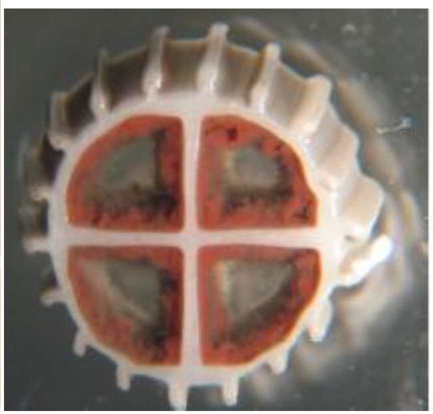
- Two Step Anammox Process
  - Dokhaven, Rotterdam (NL)



One-Step Sidestream Deammonification

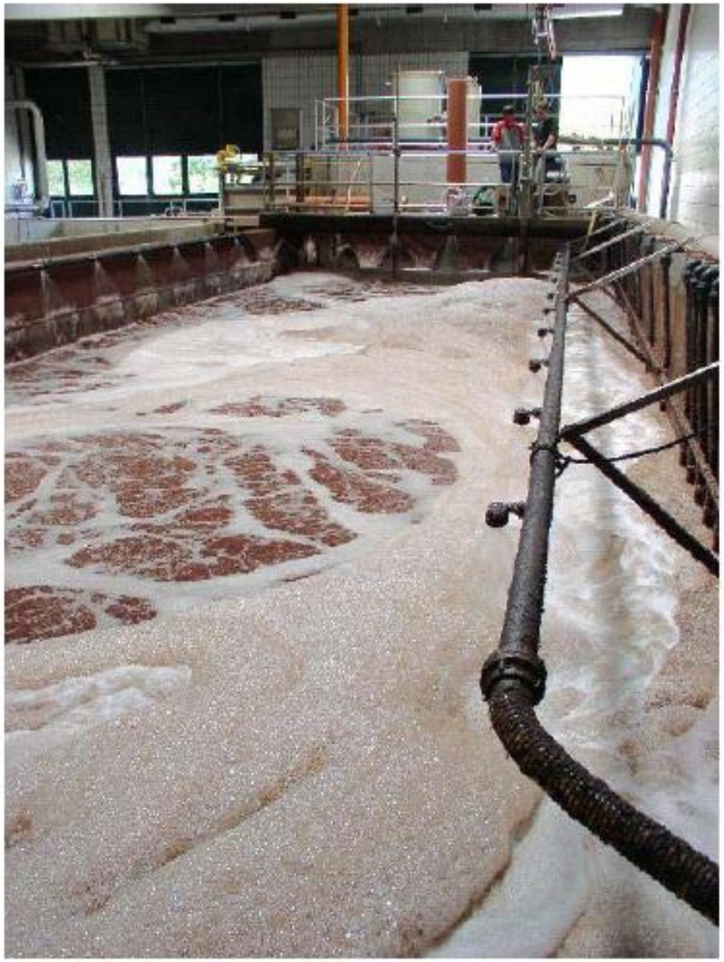
- **SBR + Hydrocyclone Granular Sludge (DEMON)**
  - Strass, Austria + ~18 others
- **Upflow Granular Sludge (CANON)**
  - Olburgen, Netherlands
- **Biofilm process (MBBR-style)**
  - AnoxKaldnes - Malmo, Sweden
    - AnitaMox
  - Hattingen, Germany & Stockholm
    - Deammon (Purac)

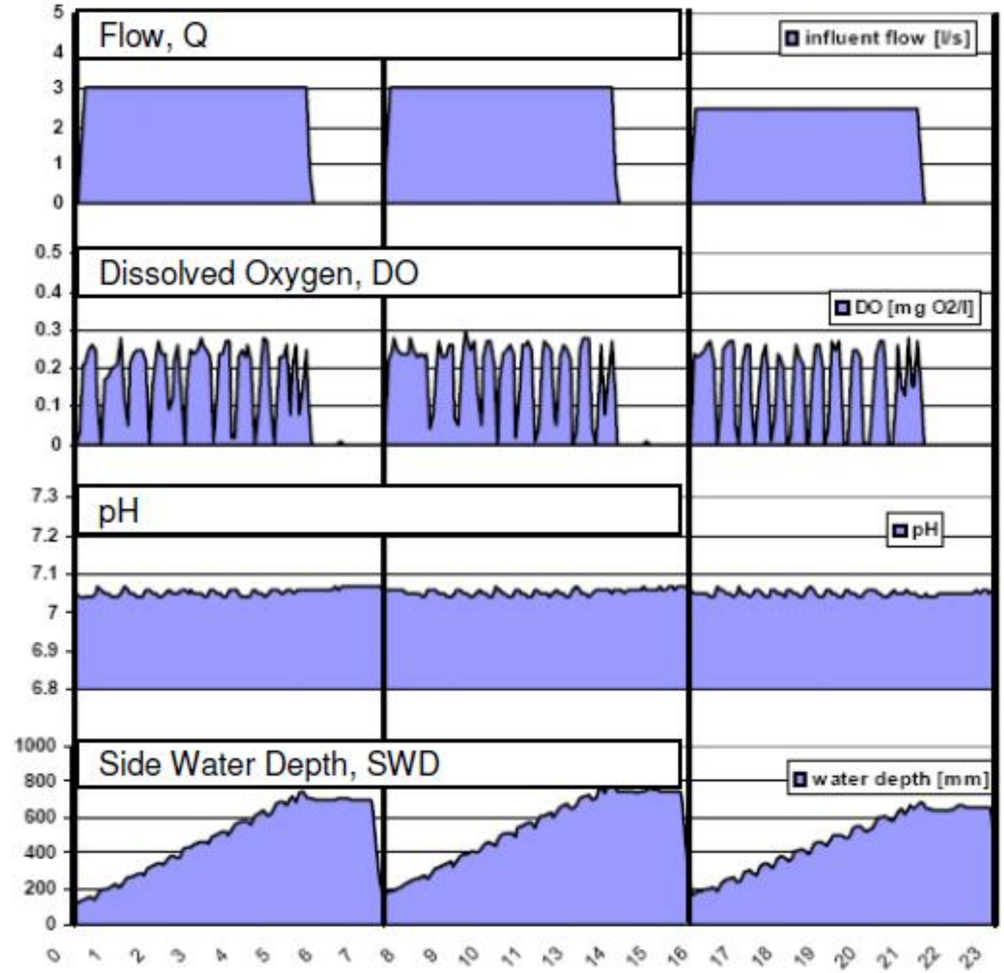
Partial Nitritation and Anammox
- combined in a single reactor



Deammonification SBR – the DEMON™ Process

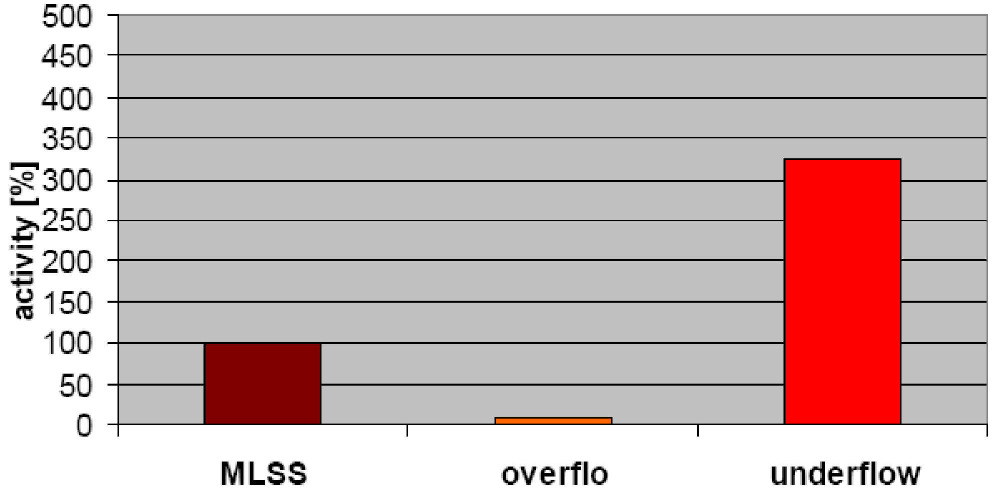
DEMON™ at Strass WWTP, Austria

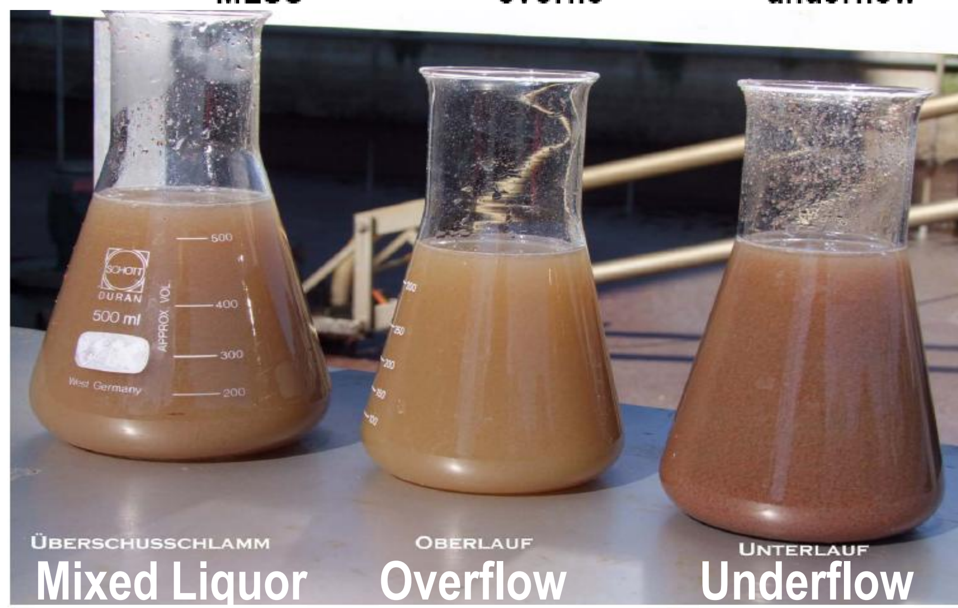




Picture/Figure by: Wett, B., Murthy, S., Takacs, I., Hell, M., Bowden, G., Deur, A., O'Shaughnessy, M. (2007). Key Parameters for Control of DEMON Deammonification Process. Wat. Practice. **1**(5). 1-11.

Cyclone for selecting for DEMON® Granules





Deammonification Experience: DEMON® Process

Operational:

- Strass, Austria
- Glarnerland, Switzerland
- Thun, Switzerland
- Plettenberg, Germany
- Heidelberg, Germany
- Apeldoorn, Netherlands

Several under construction;

- Croatia
- Austria
- Germany

Strass (A)

Apeldoorn (NL)

Heidelberg (D)

Thun (CH)

- By 2012 more centrate Demon facilities (>20) than conventional Nitrification/Denitrification
- Cyklar-Stulz & Grontmij providing turnkey services and now World Water Works, Inc. has US license

Sidestream Deammonification: What's the benefit?

- Remove about 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)
- Risks:
  - Slow process startup (US plant)
  - Requires robust process control, particularly during startup
  - *Process has been adequately demonstrated in Europe*
  - *We need just **one** in North America (anywhere)…*

Sidestream Deammonification Status in North America (3.0)

– DEMON - Alexandria, VA + DCWater Pilot (no cyclone)
– DEMON – New York DEP + DCWater Pilot (no cyclone)
– DEMON – Pierce County, Washington
– Several other DEMON pilot studies pending
– MBBR-style process – New York DEP Pilot
– DEMON – DCWater Blue Plains in design
– DEMON – Alexandria, VA in construction
– DEMON – HRSD York River in construction

HRSD York River Treatment Plant DEMON Under Construction

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Conventional Nitrification-Denitrification **(1.0)**

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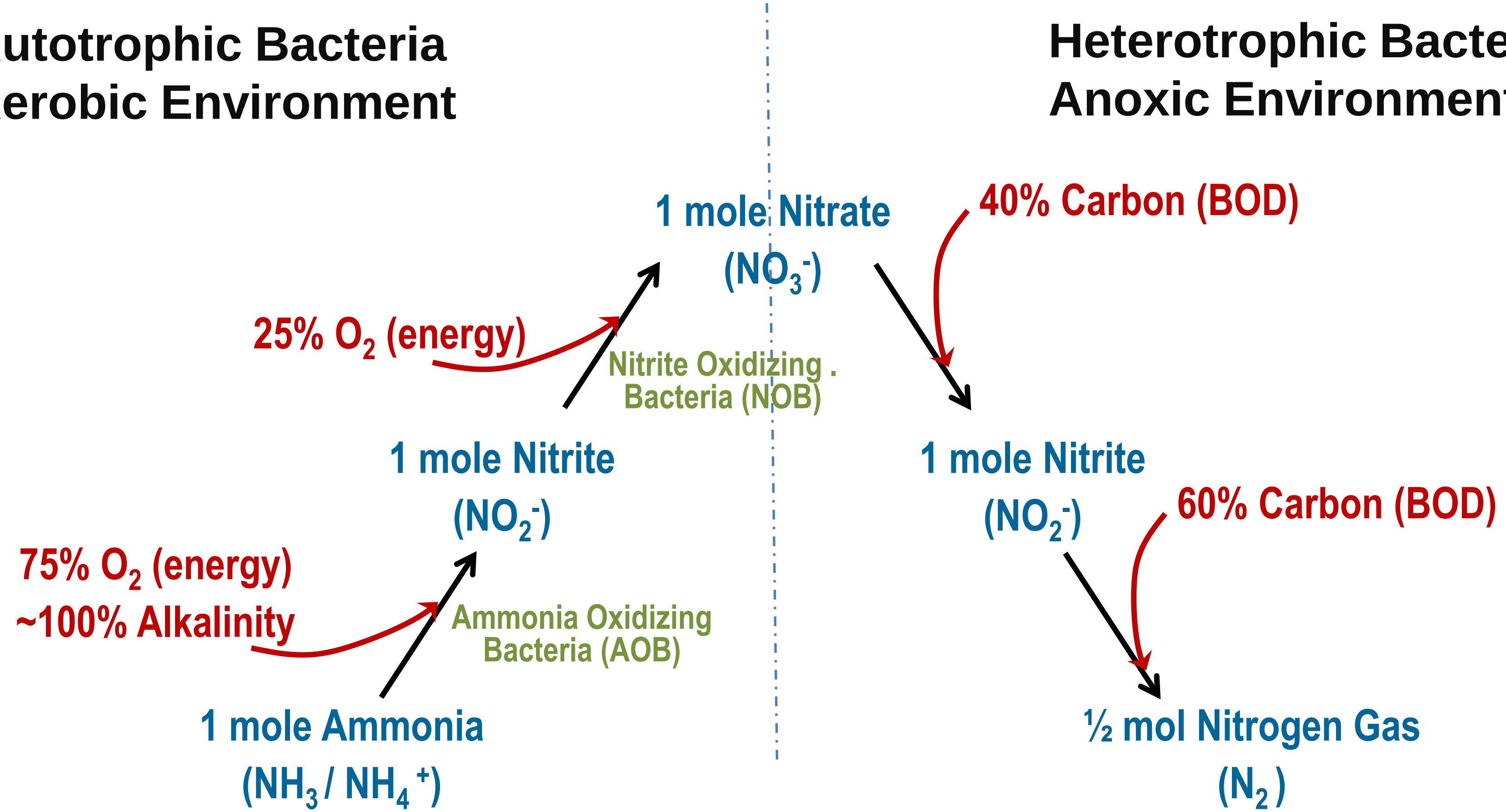
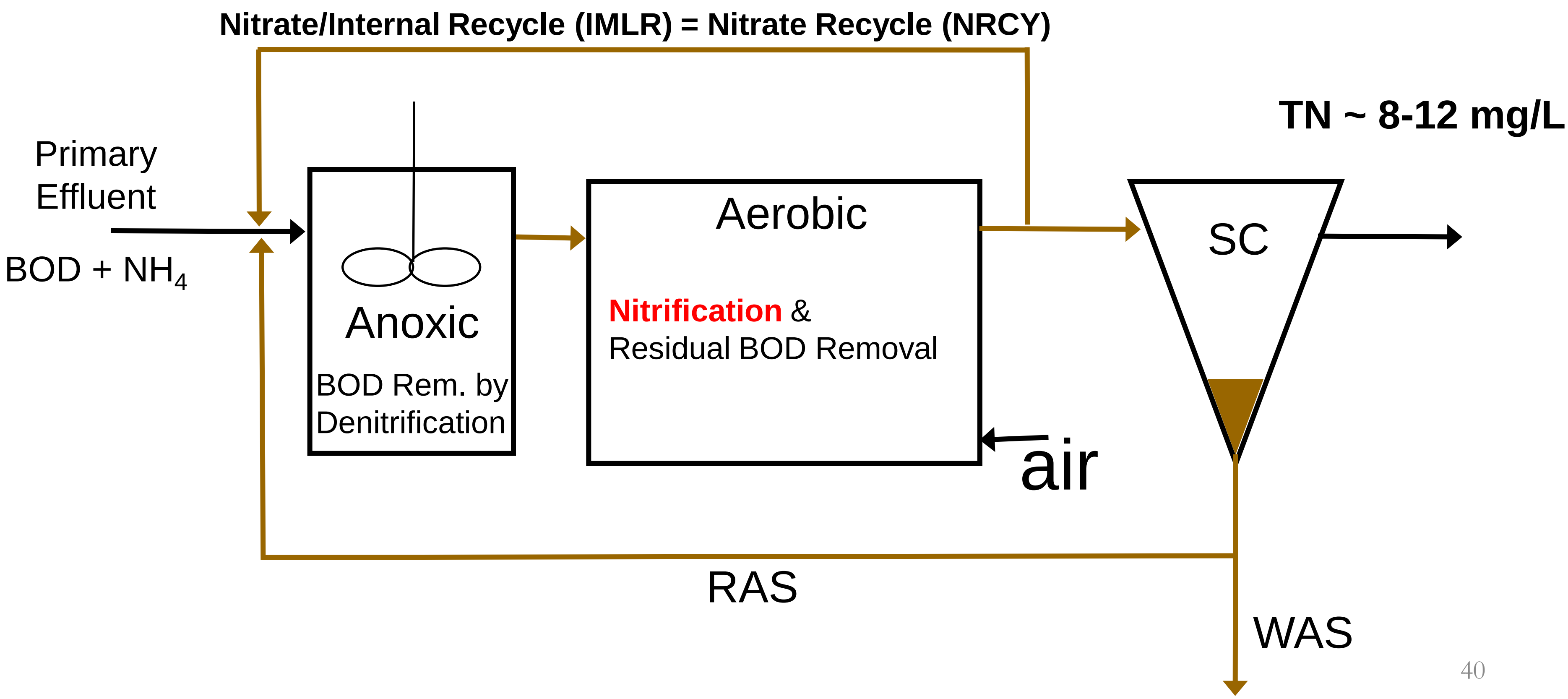
Aerobic Environment

Heterotrophic Bacteria
Anoxic Environment

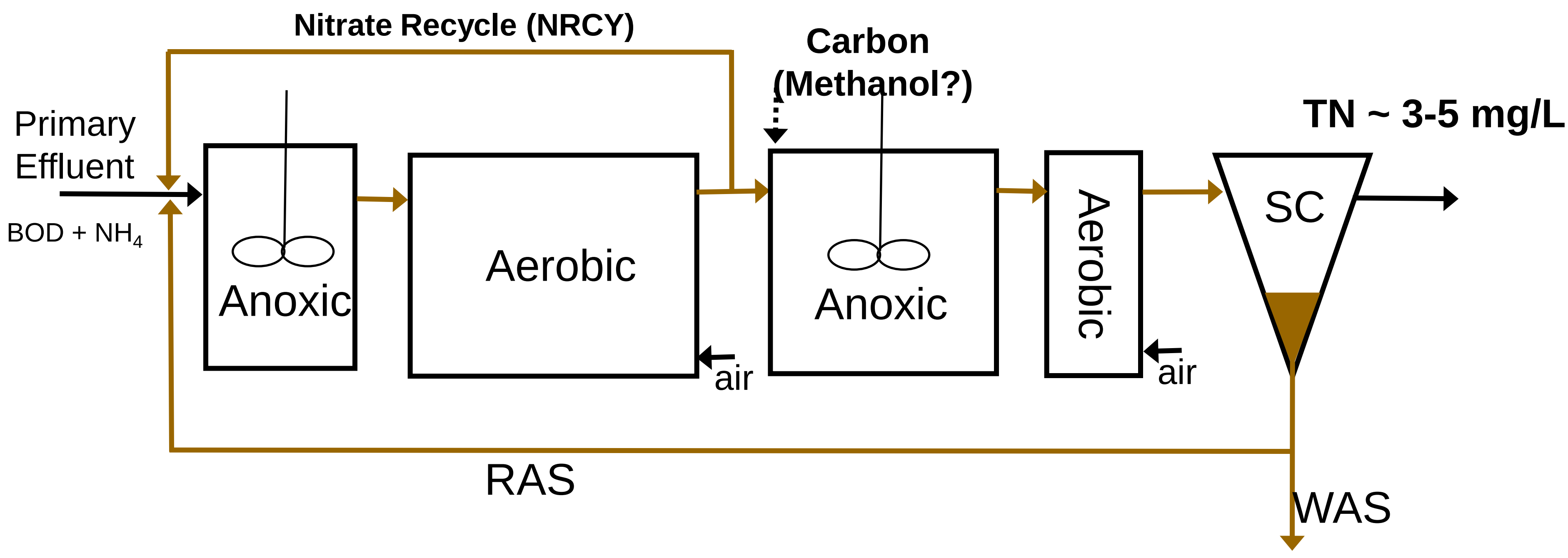


NITRIFICATION **DENITRIFICATION**

MLE Process (N Removal)



4-Stage Bardenpho (Better N Removal)



Agenda

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  - Relationship to SND
  - A/B Process
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- Mainstream Treatment 3.0 (emerging)
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  - Carbon Flow
  - HRSD Pilot 3.0 – separate stage without bioaugmentation
- Several other emerging ideas (3.1)

Can we implement this in the mainstream BNR Process?

"Simultaneous Nitrification/Denitrification(SND)"

Orbal® Oxidation Ditch
Source: Siemens

Process has not been purposefully implemented in larger plants…

- Large aeration tank volume required (perception)
- Sophisticated instrumentation & controls
- Uncertain design
- Uncertain operation
- Risk of poor mixed liquor settling
- **VERY DIFFICULT TO CONFIRM 2.0**

Current Thinking on SND…

- Focus is low DO operation (energy savings)
- NOB repression (2.0) rarely if ever confirmed
- Sludge settling characteristics are a real concern for medium/large plants
- Mechanisms:
  - Micro environment that affects oxygen diffusivity inside the floc
  - Macro environment that is related to mixing (tank configuration)
  - Bulk DO concentration & carbon availability
- Needs:
  - Control strategy
  - NOB repression confirmed and controlled
  - Demonstration in medium/large plants
  - Combine with Bio-P?
- Opportunity is significant, especially if NOB can be repressed

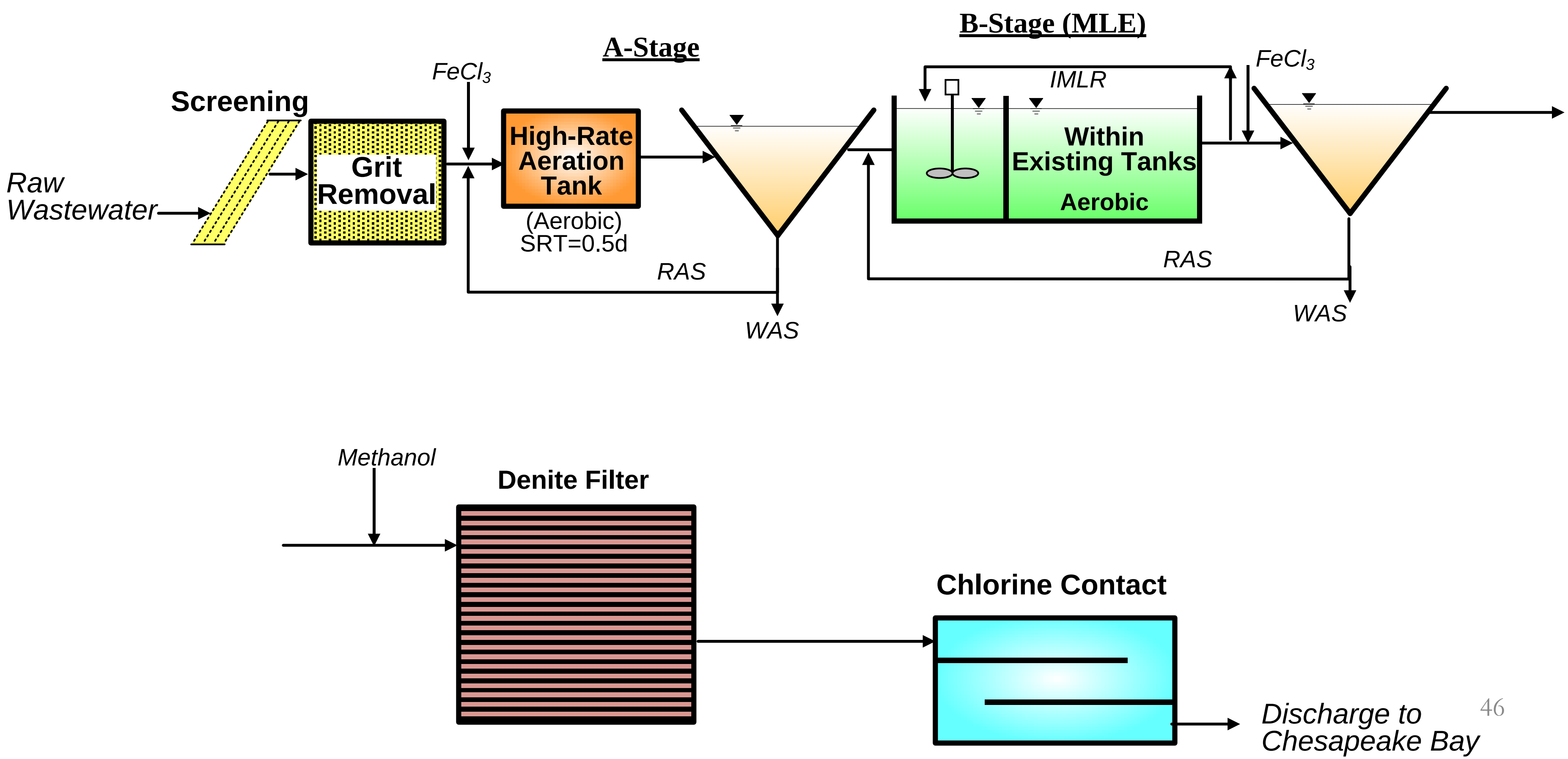
See talk by Jose Jimenez tomorrow

New Tools for SND-Style Processes (2.0)

- Ammonia-based Aeration Control
  - Allows stringent control over DO provided
  - ***See talk by Leiv Rieger tomorrow***
- NOB Repression
  - Rapid transient anoxia seems to be the key
  - Mechanisms?
    - AOB always at maximum growth rate (aerobic SRT control with excess NH4 available)
    - NOB enzyme expression delay
    - Aerobic SRT controlled
    - Nitrite availability delay
    - Oxygen affinity
    - Free ammonia (NH3) inhibition of NOB

Concepts for Pilot Testing

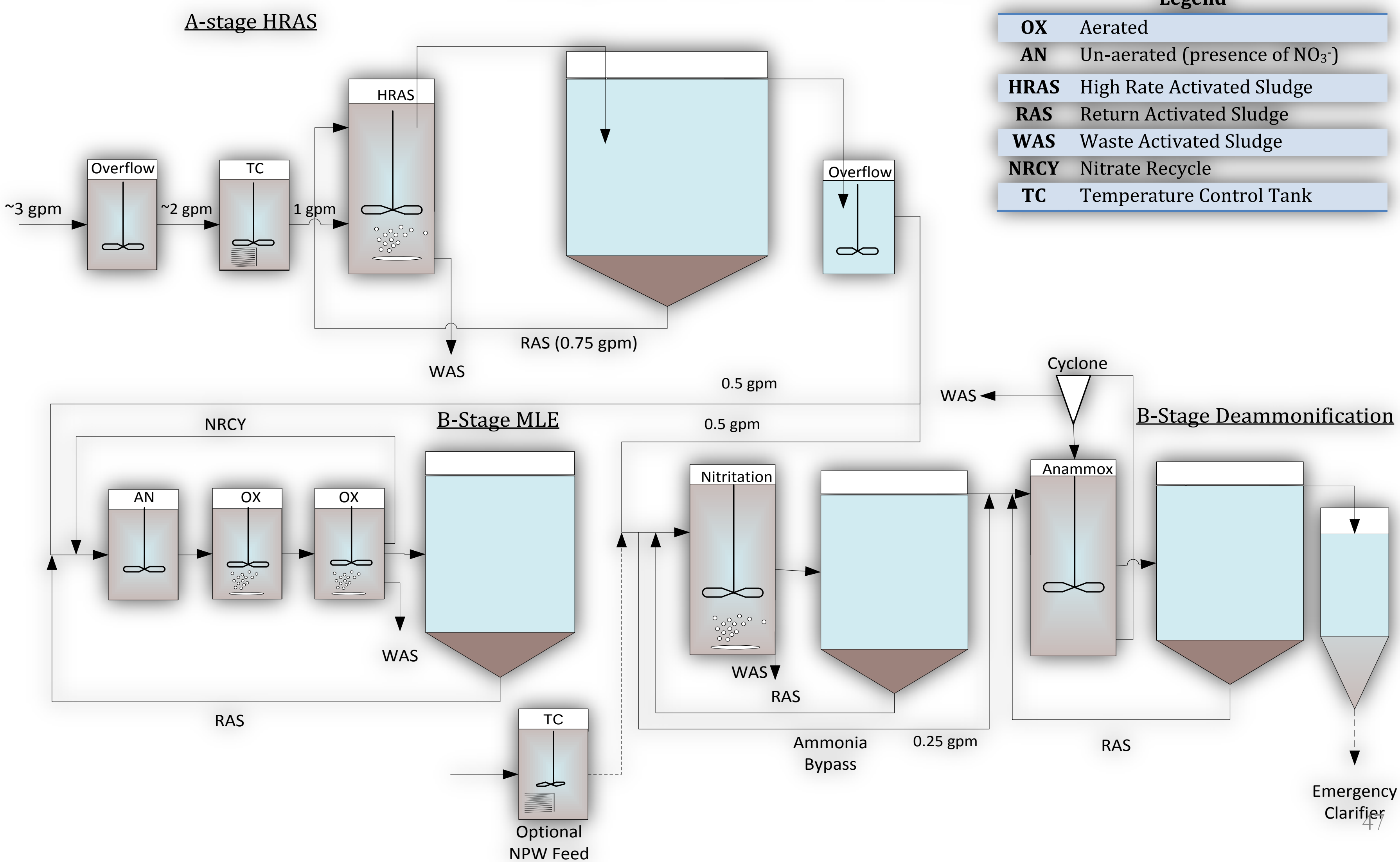
1. Two stage "A/B" process:
   - A stage – high rate activated sludge for 60-70% COD removal (40-50% sCOD removal)
   - B stage – MLE in SND mode (N removal 2.0)



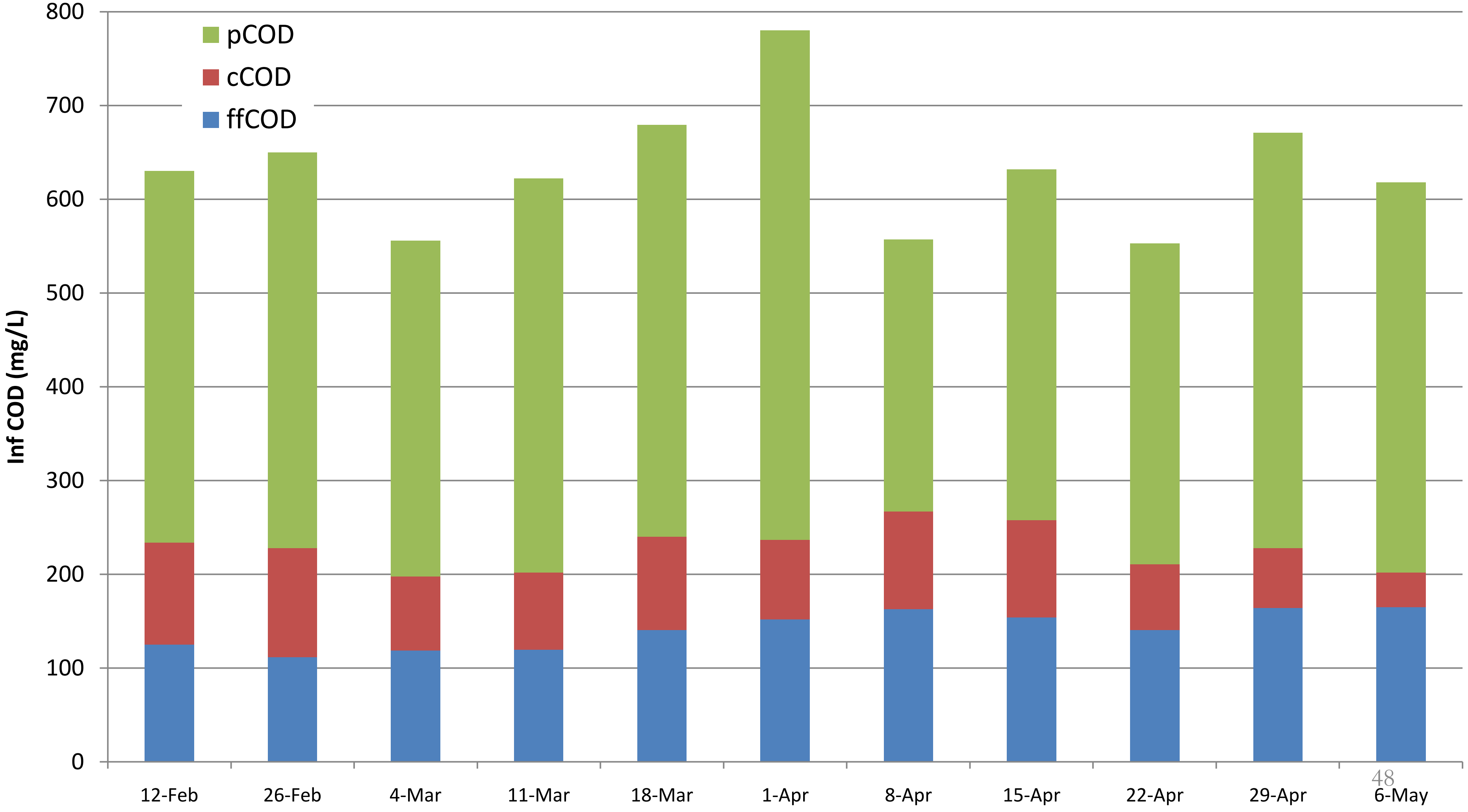
Pilot System Schematic

Hampton Roads Sanitation District
Chesapeake Elizabeth Pilot Study

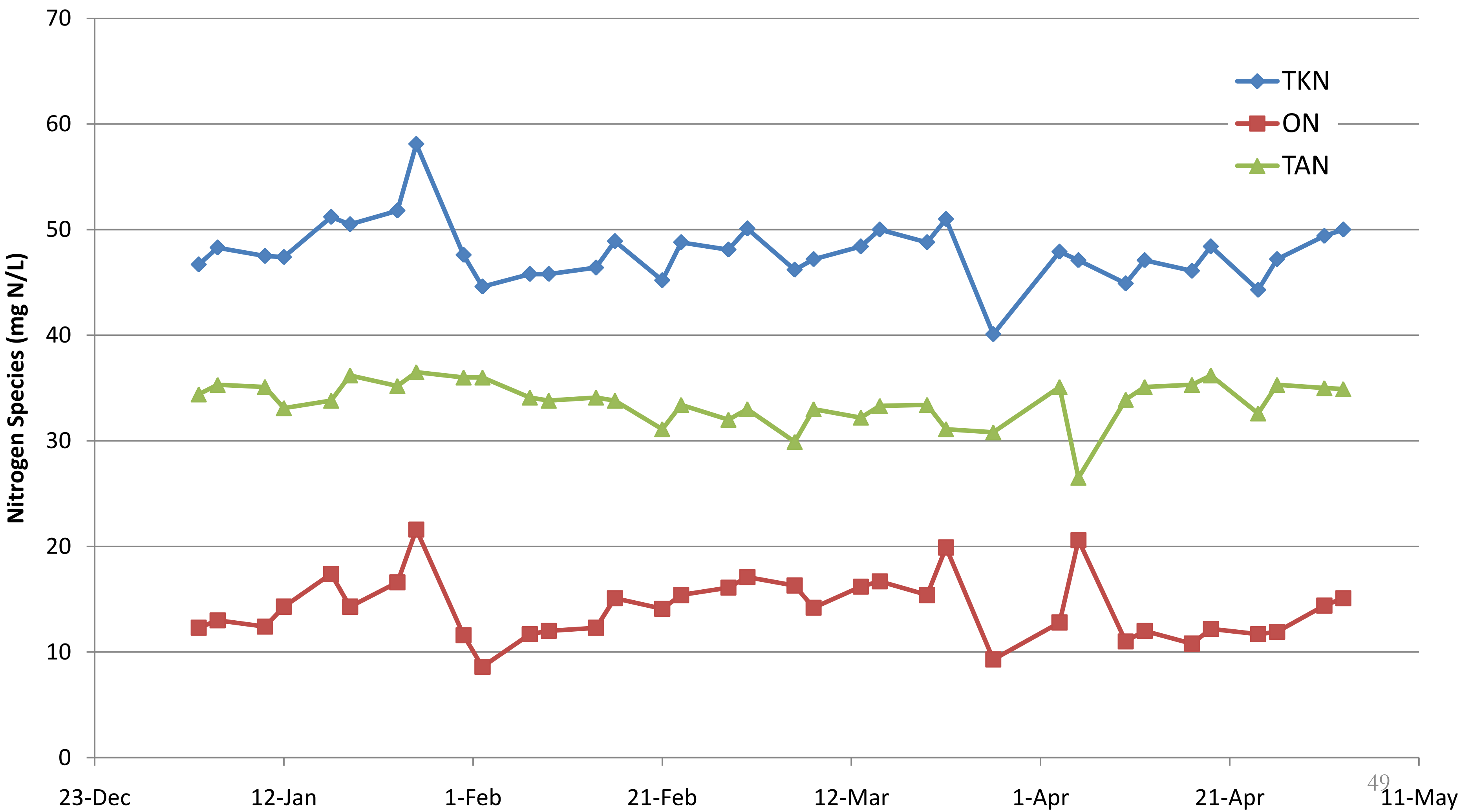
Legend	
OX	Aerated
AN	Un-aerated (presence of NO_3^-)
HRAS	High Rate Activated Sludge
RAS	Return Activated Sludge
WAS	Waste Activated Sludge
NRCY	Nitrate Recycle
TC	Temperature Control Tank



Influent COD



Influent Nitrogen



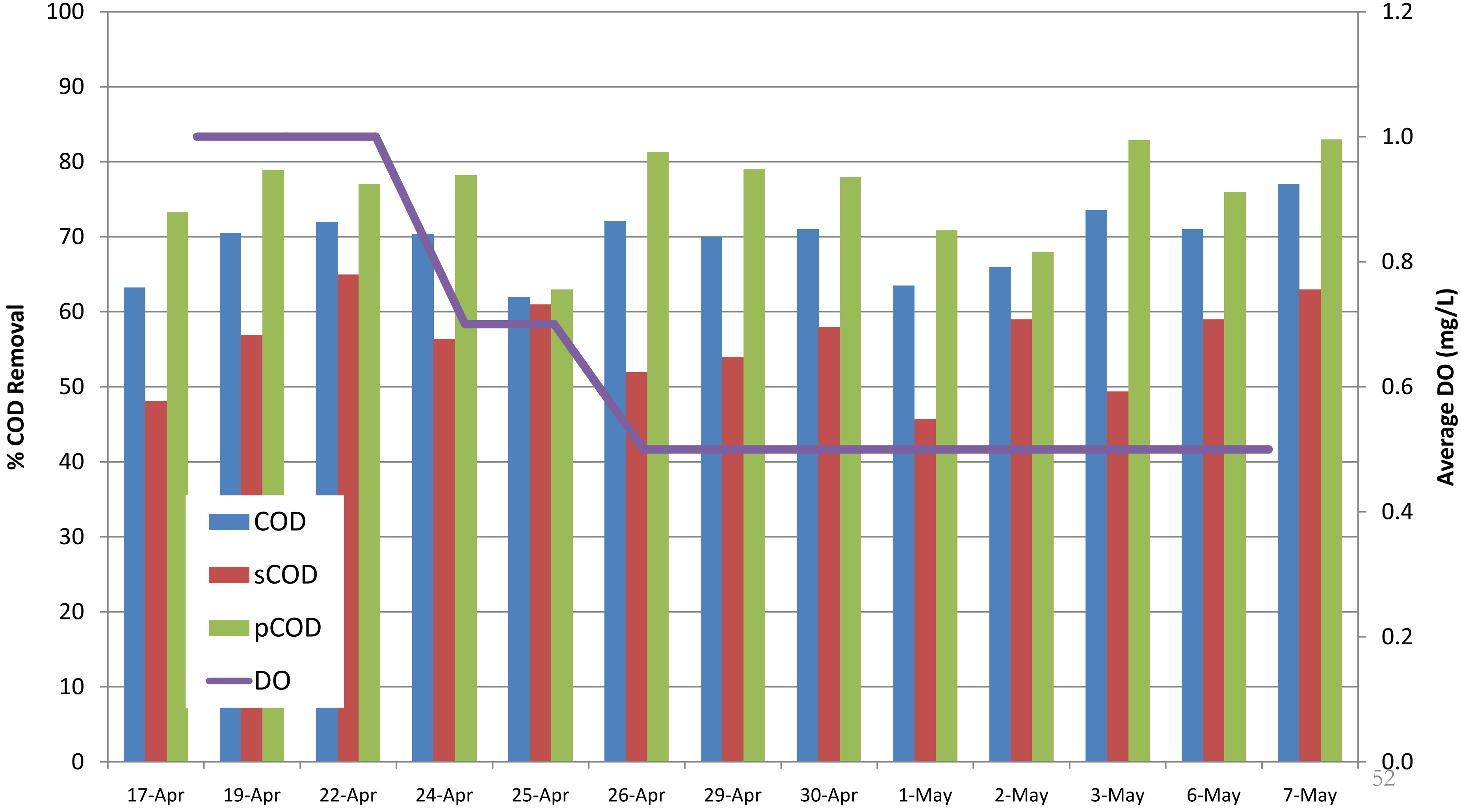
A-stage High-Rate Activated Sludge (HRAS)

- 10 inch diameter pipe reactor at 30 minute HRT
- Single 7 inch high capacity disc diffuser
- SOR = 420 gal/ft^2·day
- SLR = 22 lbs/ft^2·day at 3000 mg/L
- Fixed all Hach LDO probe and MOV/PID issues

Current HRAS Operation

- HRT = 30 min
- MLSS = 2000-3500 mg/L
- DO = 0.5 mg/L
- Influent Temp = 25°C
- Aerobic SRT = 0.20-0.25 days

COD Removal



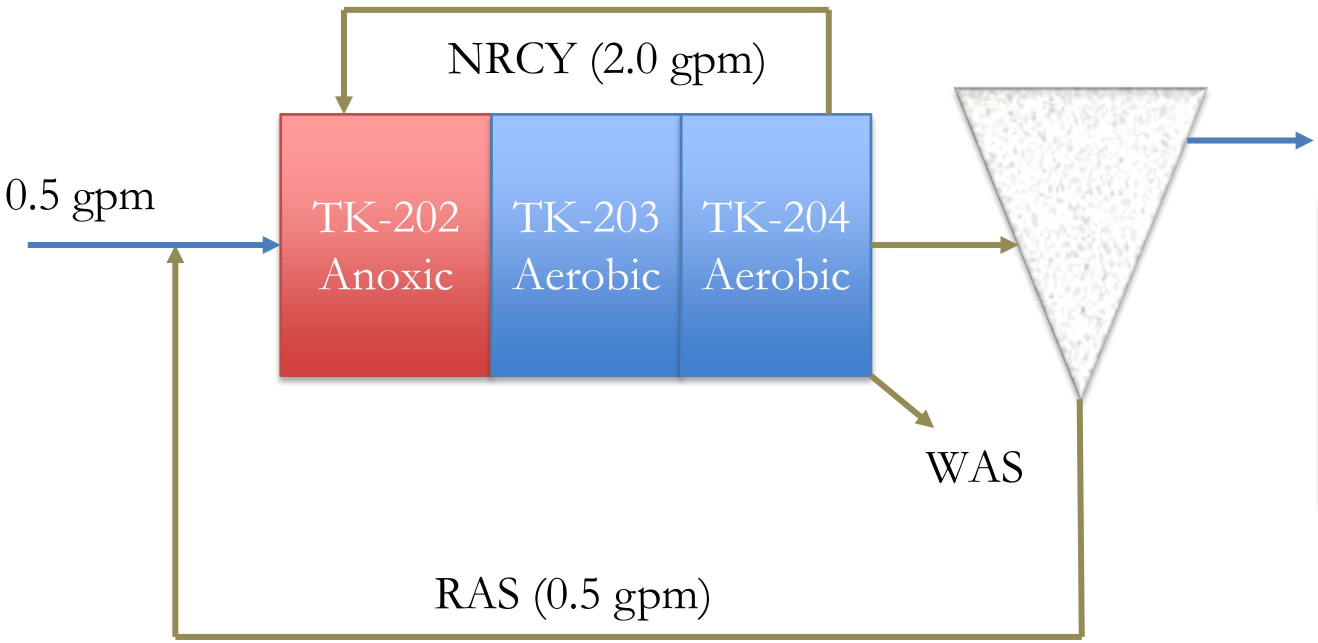
% COD Removal
Average DO (mg/L)
100
90
80
70
60
50
40
30
20
10
0
1.2
1.0
0.8
0.6
0.4
0.2
0.0
17-Apr
19-Apr
22-Apr
24-Apr
25-Apr
26-Apr
29-Apr
30-Apr
1-May
2-May
3-May
6-May
7-May
COD
sCOD
pCOD
DO

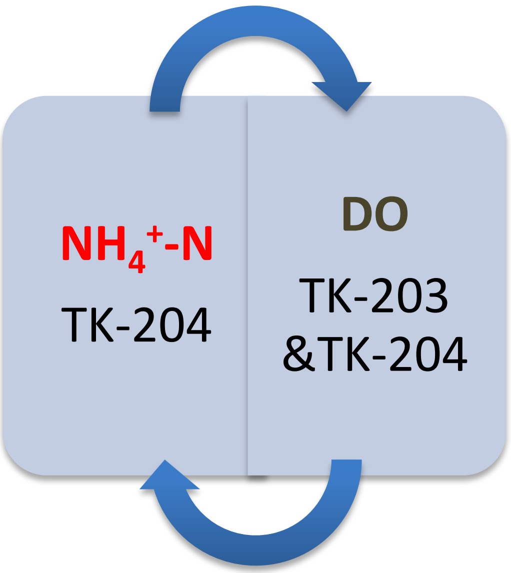
B-Stage MLE

MLE Operational Parameters

- Total SRT = ~10 days
- HRT= 4 hr
- Influent Flow = 0.50 GPM
- Nitrate Recycle = 400%
- RAS = 100%
- Temperature = 24 C
- MLSS = (3500 +/- 750) mg/L

Ammonia Based DO control

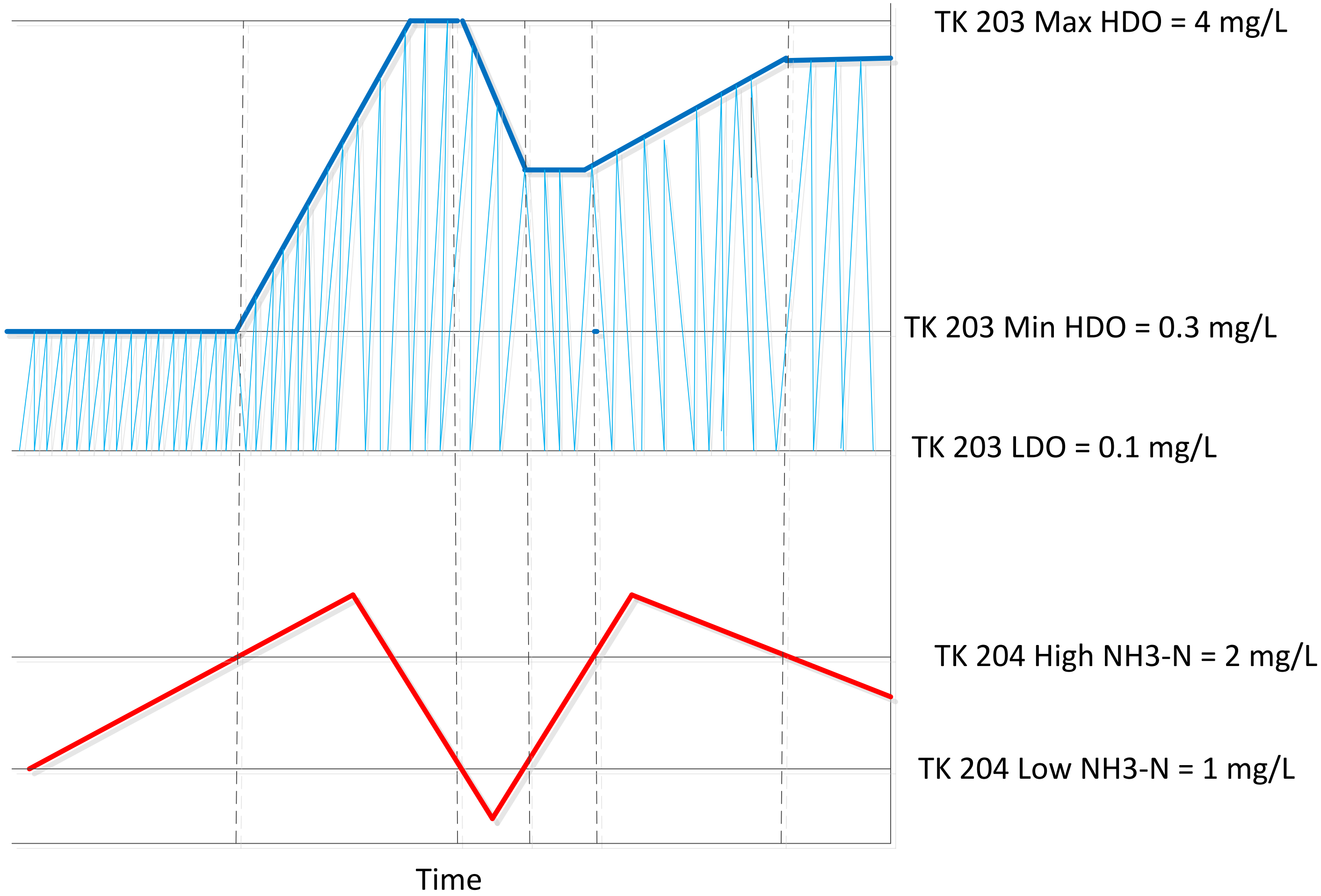




Simultaneous Nitrification and Denitrification (SND)

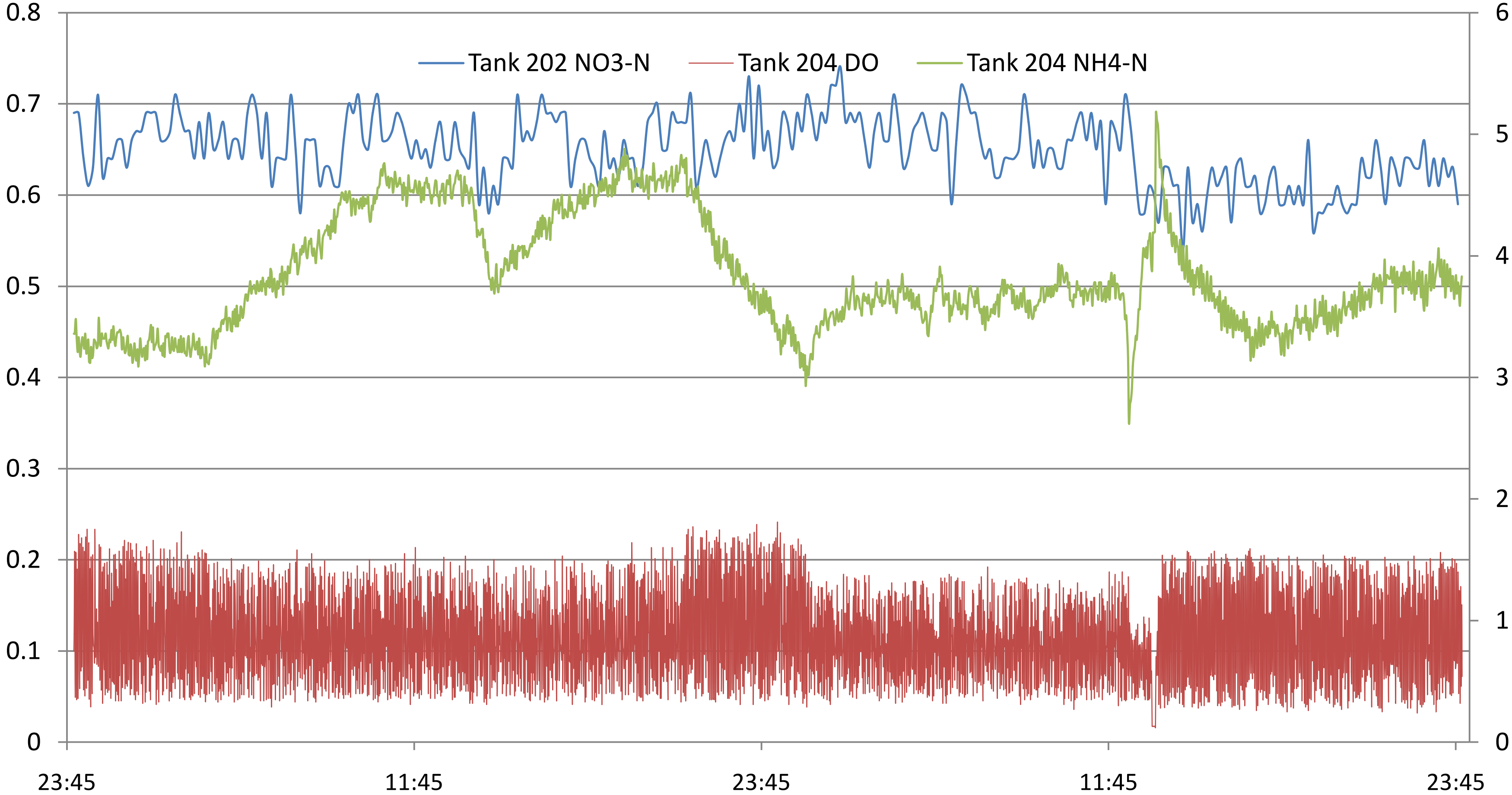
Nitrite Shunt?

Ammonia-Based D.O. Control

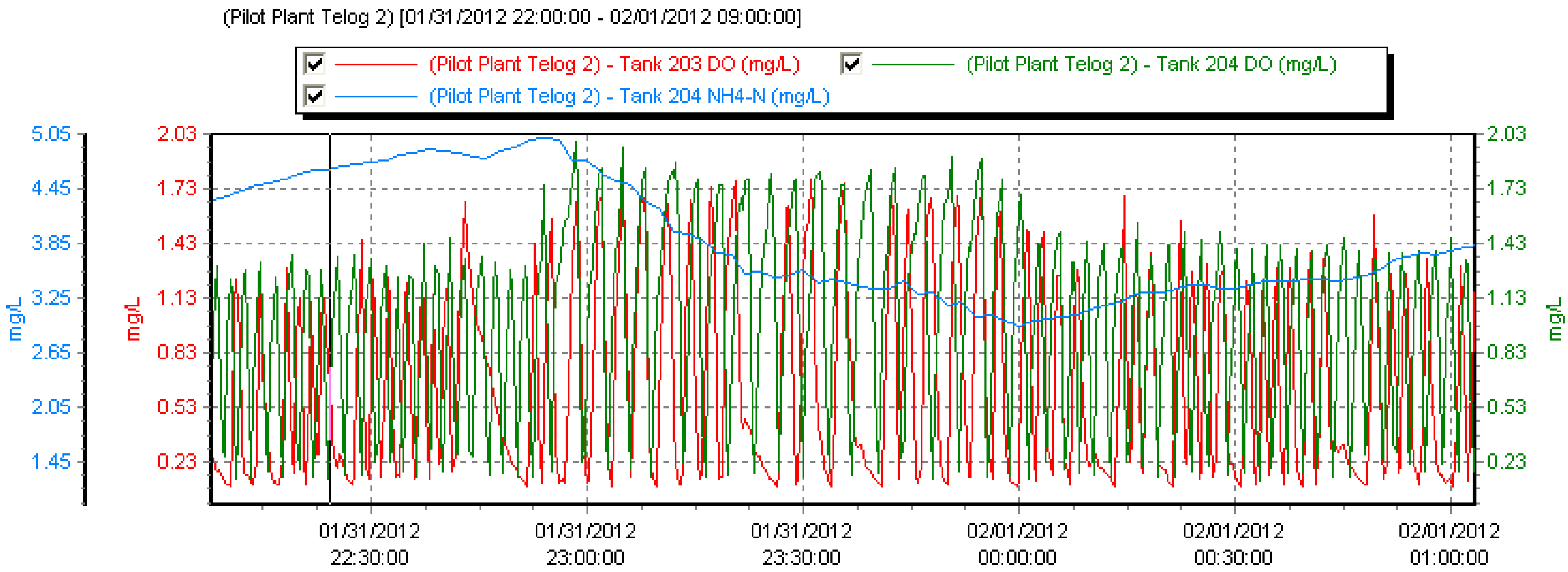


Ammonia-Based DO control

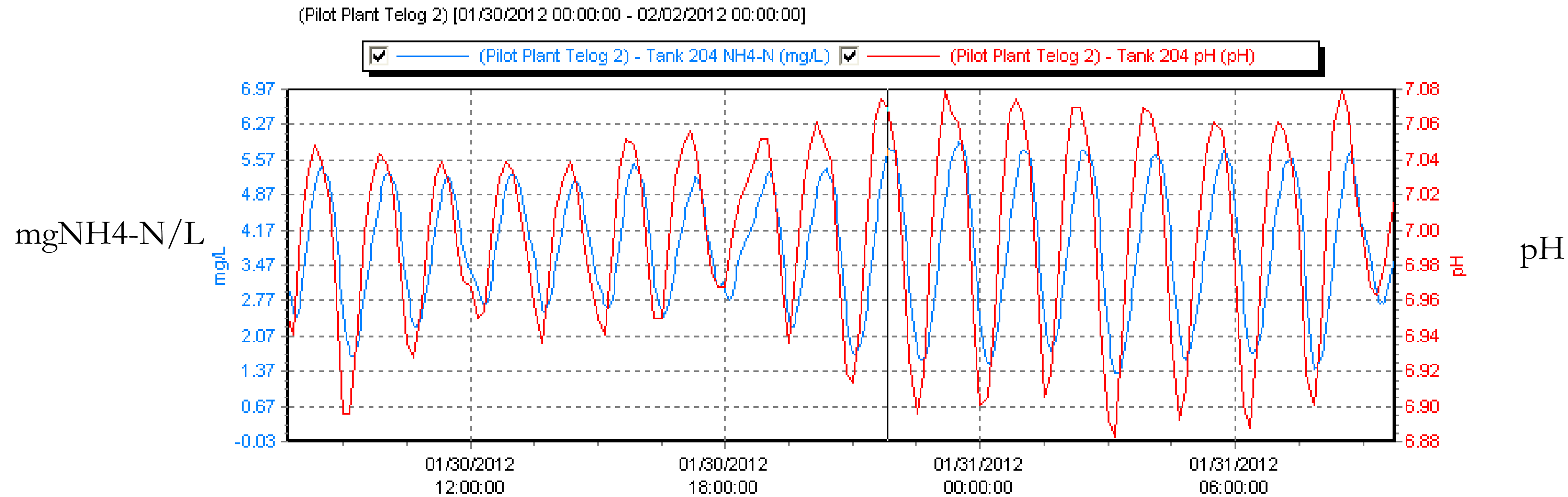
- Ammonia Set Points 3-5 mg-N/L

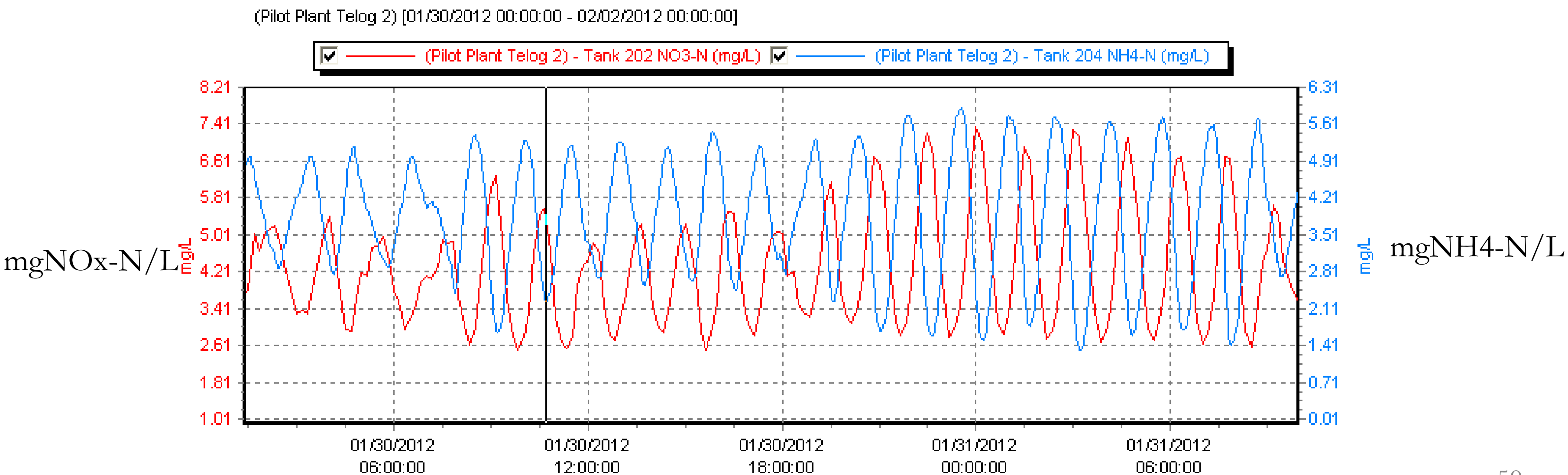


Ammonia Based DO Control in Action

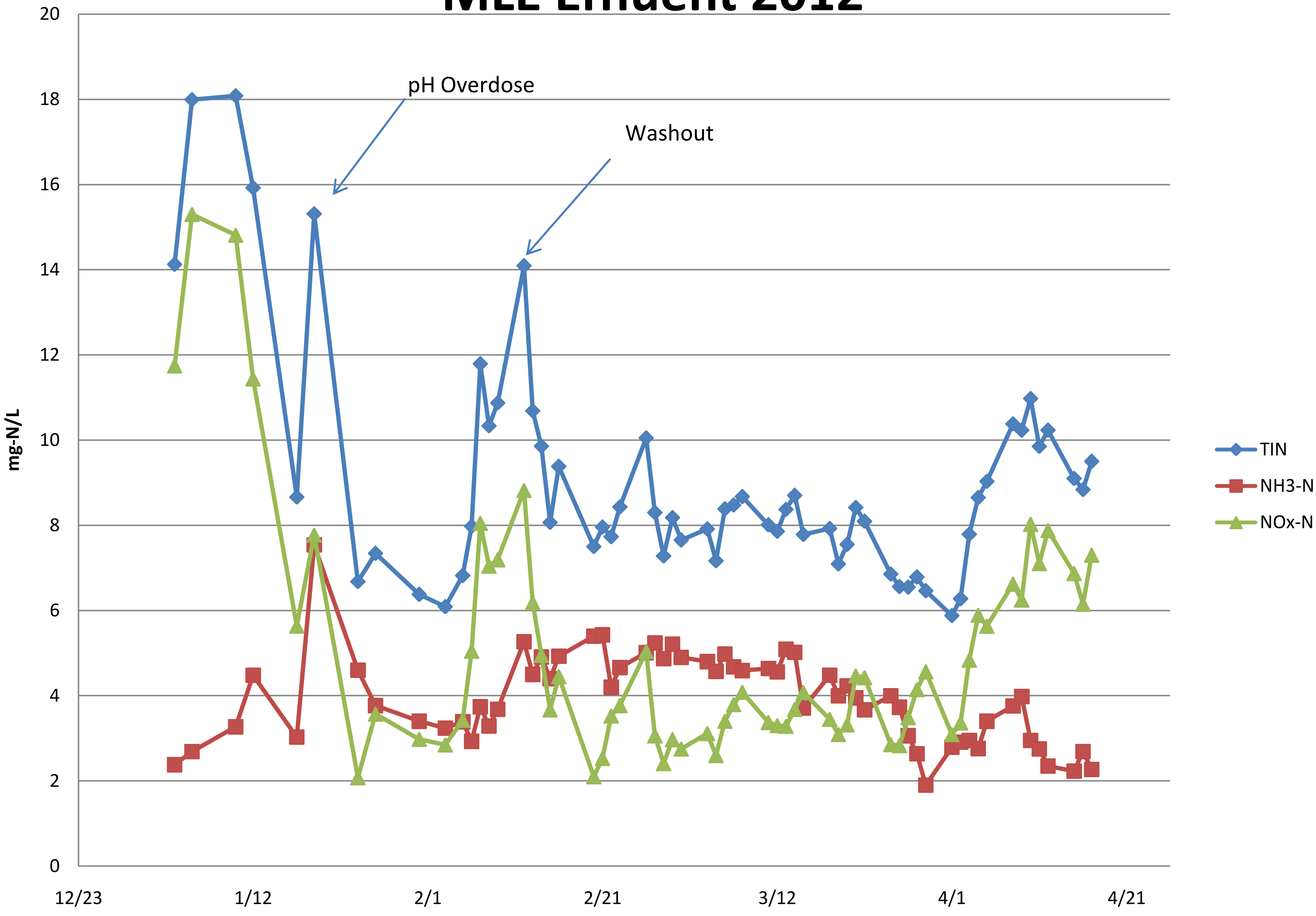


2nd Aerobic pH, Ammonia and Nitrate Trends

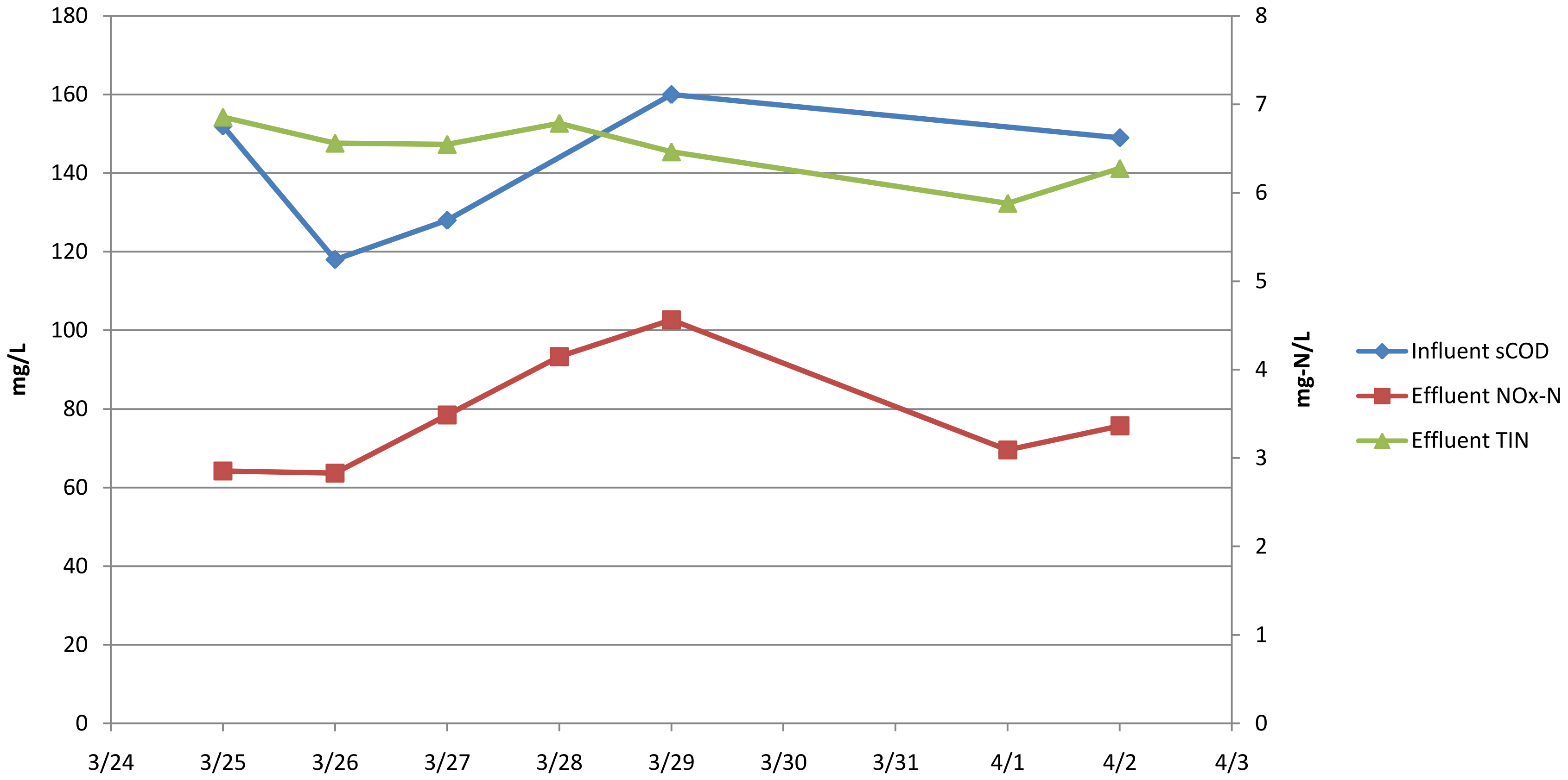




MLE Effluent 2012



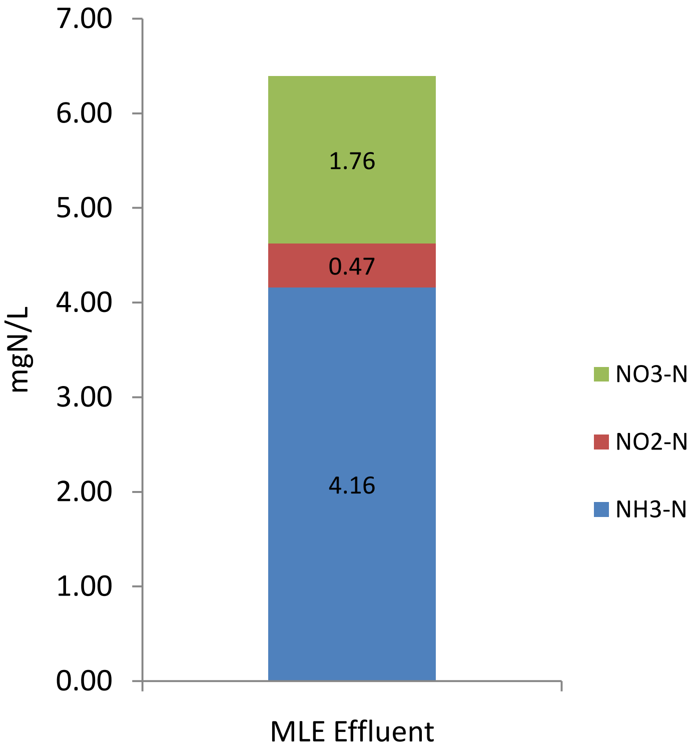
Period of Best MLE Performance



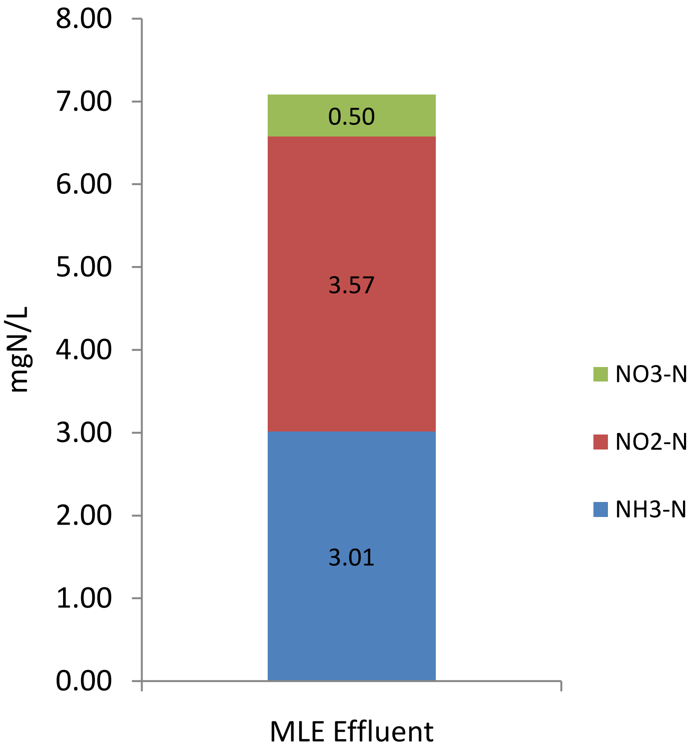
- Influent sCOD between 118 – 160 mg/L
- MLSS between 4000 – 4500 mg/L
- Effluent TIN under 7 mg-N/L
- Effluent NOx as low as 2.83 mg-N/L

DO Control System Led to NOB Repression

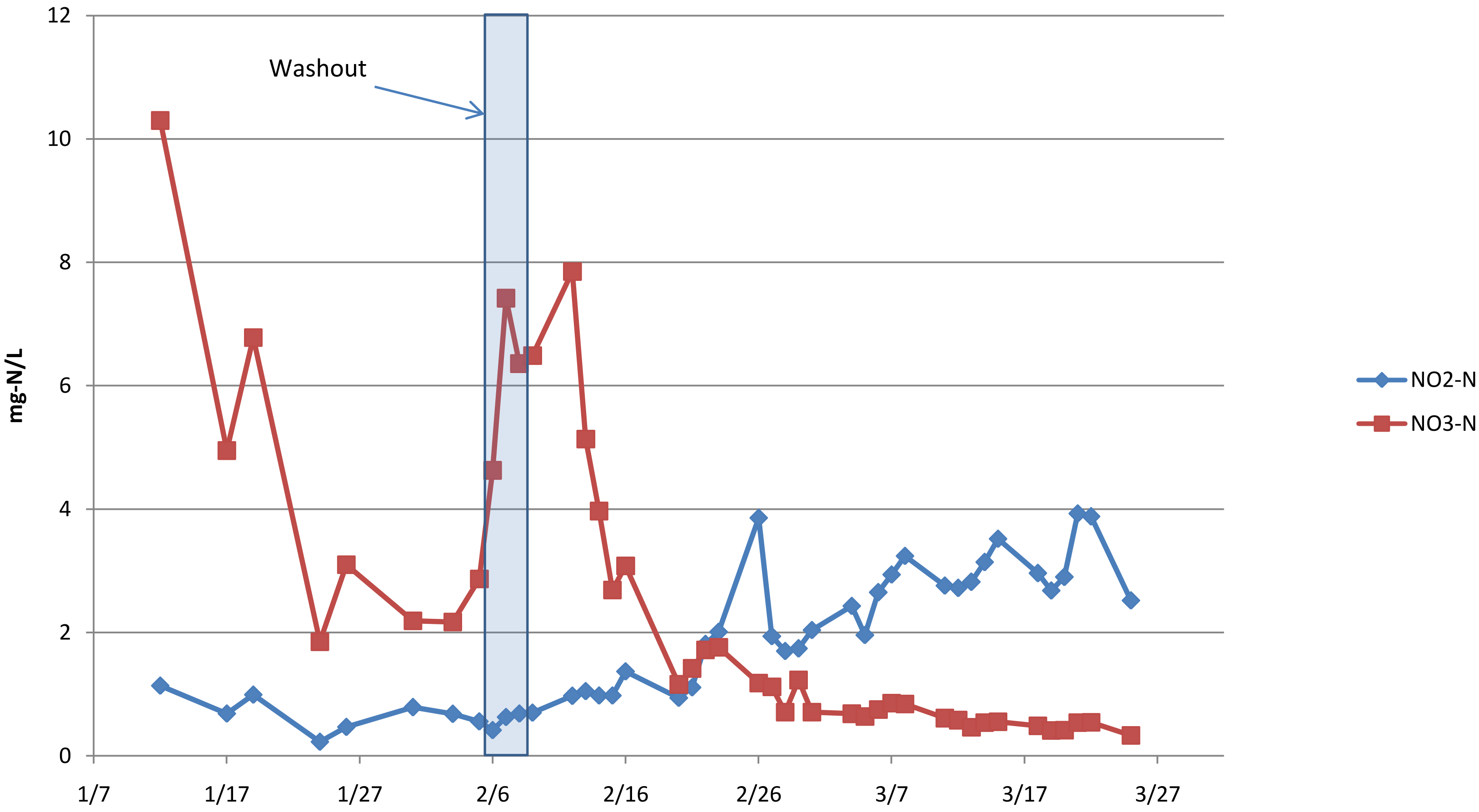
Jan 23 – Feb 2



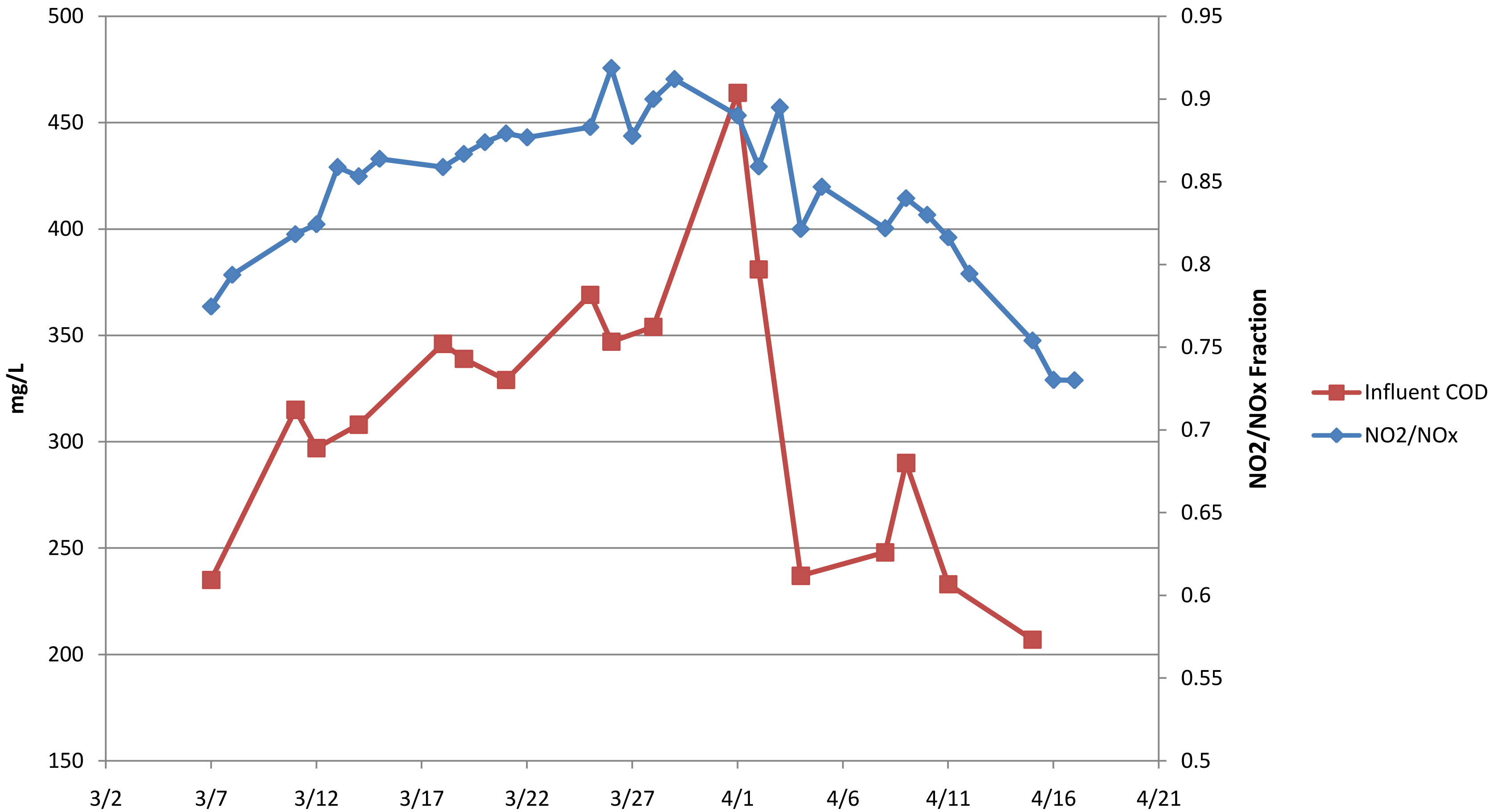
Mar 11 – Mar 25



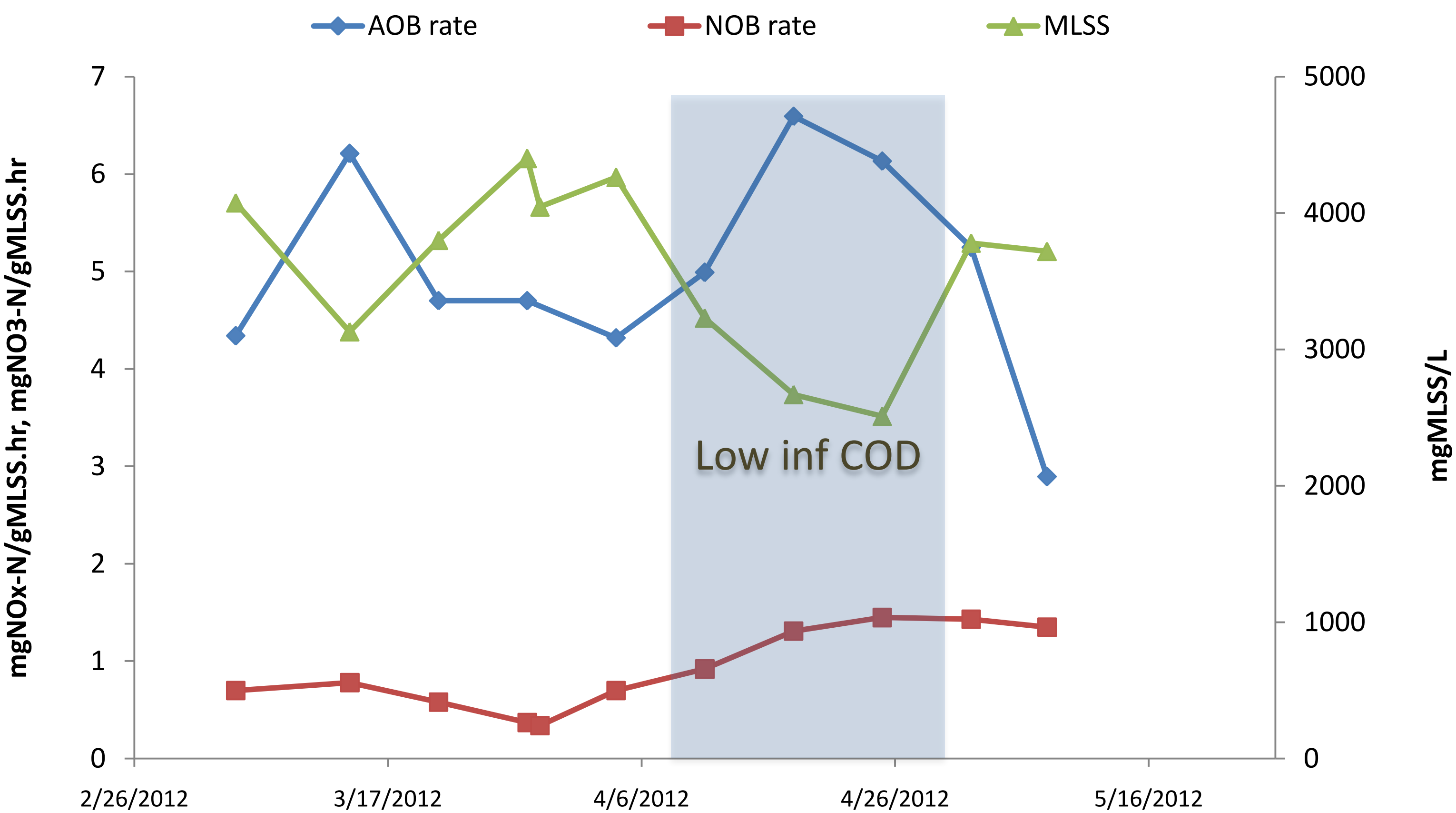
NOB Repression



Influent COD and MLSS (OUR?) were hypothesized to be critical parameters in sustaining NOB repression

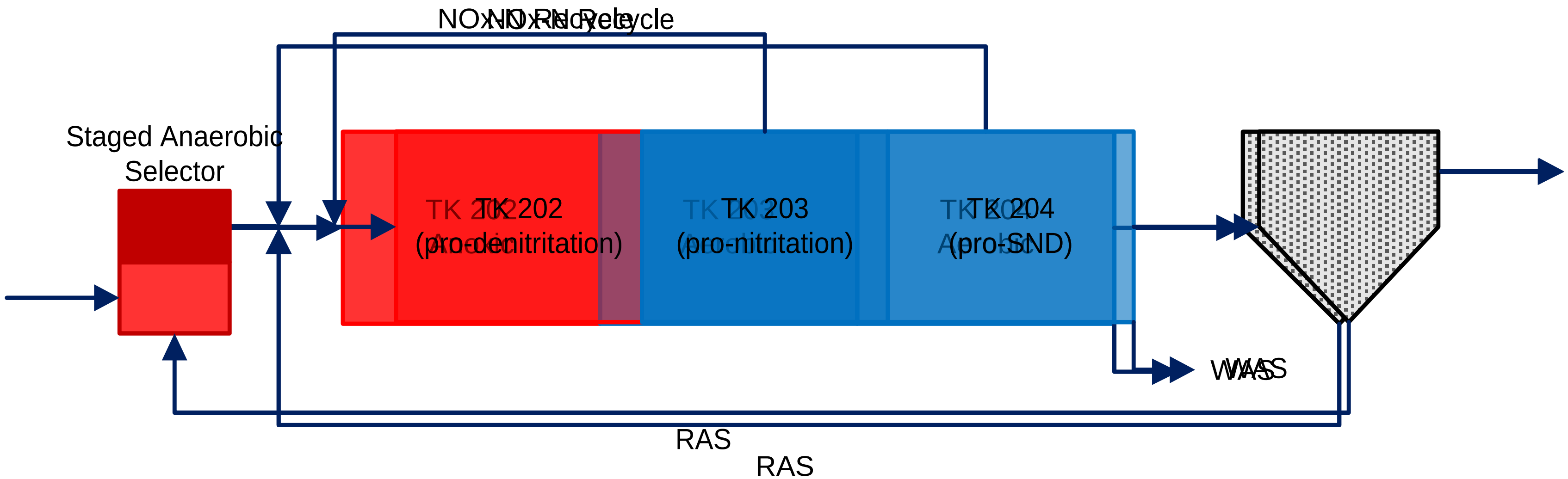


AOB and NOB Specific Nitrogen Processing Rates



Nitritation-Denitritation through Modulating Aeration (NiDeMA)

MLE



- Reactors sized based on Ches-Liz aeration tank volume
- HRT = 4.4 hr (1 aeration tank out of service)
- SLR = <25 lb/ft^2·day
- Target MLSS = 4000 mg/L (maximum 4800 mg/L)
- Anaerobic tank = 16 gallons (separated by baffle)
- **Need of NOx-N Recycle to be determined**

Primary Clarifier

- Independent feeds for each B-stage
- PCE is temperature controlled
- Have the ability to optimize COD concentration and fractions for each B-stage influent
- SOR = 165 gal/ft^2·day
- HRT = 4-5 hrs

Agenda

- Reactions 1.0, 2.0, 3.0
- Sidestream Treatment of Anaerobically Digested Sludge Dewatering Liquor – 1.0, 2.0, 3.0 (All established)
- Mainstream Treatment 1.0 (established)
- Mainstream Treatment 2.0 (established with caveats)
  - Relationship to SND
  - A/B Process
  - HRSD Pilot A/B Process
  - NH4-based Aeration Control
  - NOB Repression
- Mainstream Treatment 3.0 (emerging)
  - Alternative configurations
  - Carbon Flow
  - HRSD Pilot 3.0 – separate stage without bioaugmentation
- Several other emerging ideas (3.1)

Objectives for 3.0

- Redirect Carbon/COD to Anaerobic Digestion/Treatment
  - A-stage HRAS
  - CEPT
  - Anaerobic Treatment (UASB, AnMBR)
  - Primary Clarifier
- Repress NOBs
  - Low temp
  - Low NH4
- Retain Anammox (high SRT for Anammox)

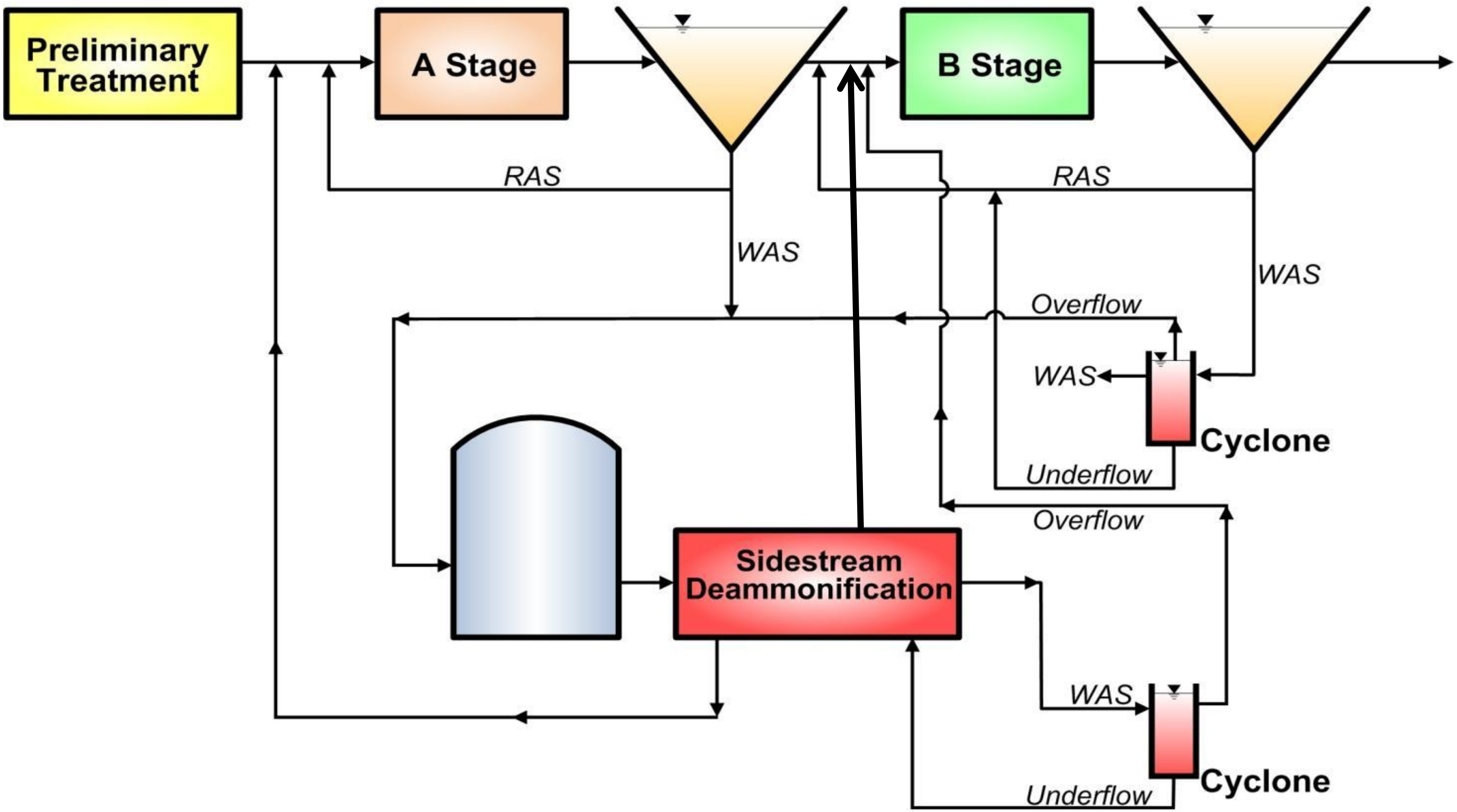
Mainstream Deammonification????

- Very challenging….
  - Lower temperature
  - Lower NH_4 concentration
- Primary objective: Eliminate competition for NO_2^-
  - NOB and Heterotrophs
- Selective retention of Anammox is critical
- Risk is high that this process will not work, but reward is very high…
  - Reduce capital cost by ~$20-40M
  - Reduce chemical cost by $1-2M/yr (no increase above current conditions)
  - Reduce energy cost by ??? (depends on COD redirection)
- This is the clear path to Energy Neutral/Positive treatment…

Several Possible Approaches

A. Bioaugment Anammox and AOB from sidestream deammonification process
   - One step – AOB + Anammox in same reactor
   - SND type reactor with selective Anammox retention

STRASS WWTP DEMONSTRATION (Full-Scale)



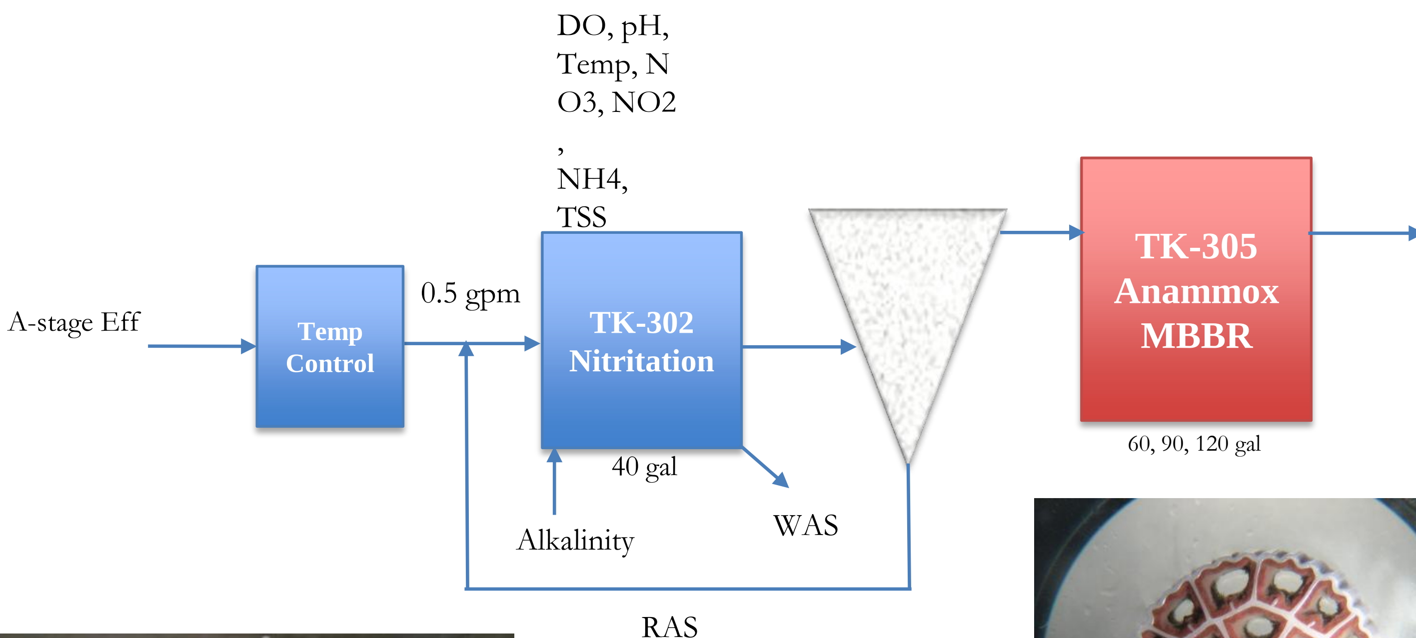
Several Possible Approaches

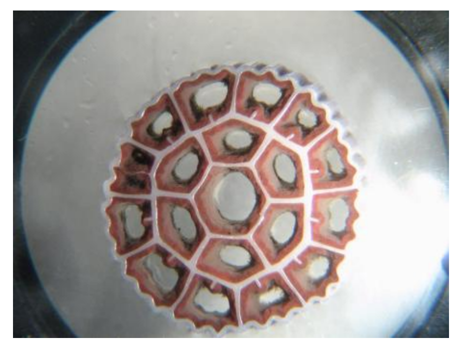
A. Bioaugment Anammox and AOB from sidestream deammonification process
   - One step – AOB + Anammox in same reactor
   - SND type reactor with selective Anammox retention

B. One step process without bioaugmentation
   - Granular sludge process
   - Dutch DHV/TU Delft Nereda Research Program

C. Two step process without bioaugmentation
   - Separate stage partial nitritation
   - Anammox
     - MBBR
     - MBR
     - Granular sludge – cyclone or upflow reactor

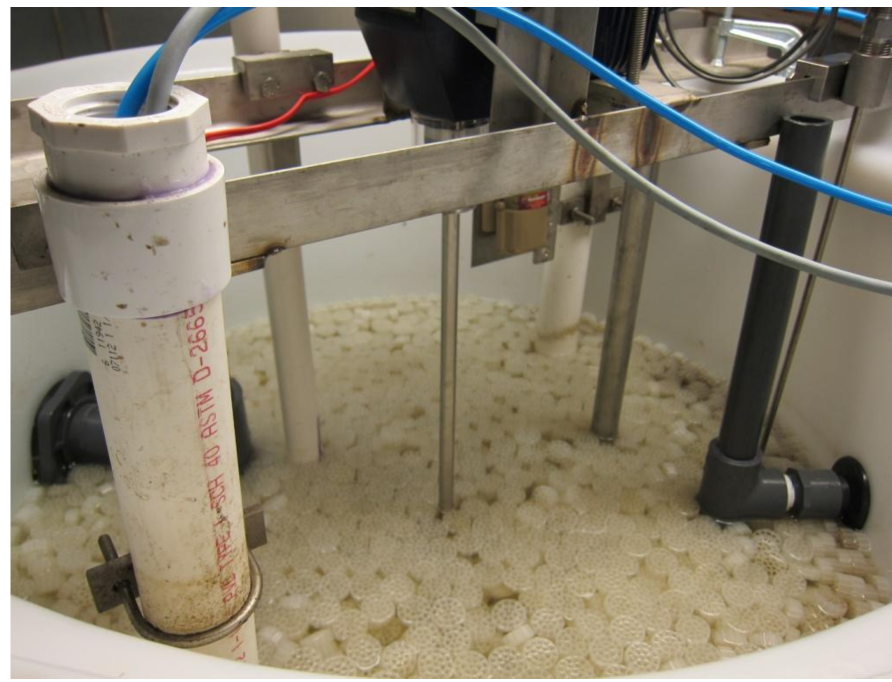
B-stage Nitritation/Anammox





B-Stage Deammonification

Operational w/o Seed Sludge



Nitritation Operational Parameters

- SRT = 7 days
- HRT = 3 hr
- Influent Flow = 0.50 GPM
- RAS = 100 %
- Temperature = 24 C
- pH 6.8-7.0 (Sodium Bicarbonate)
- MLSS = 3000 mg/L (current)

DO controller for Nitritation

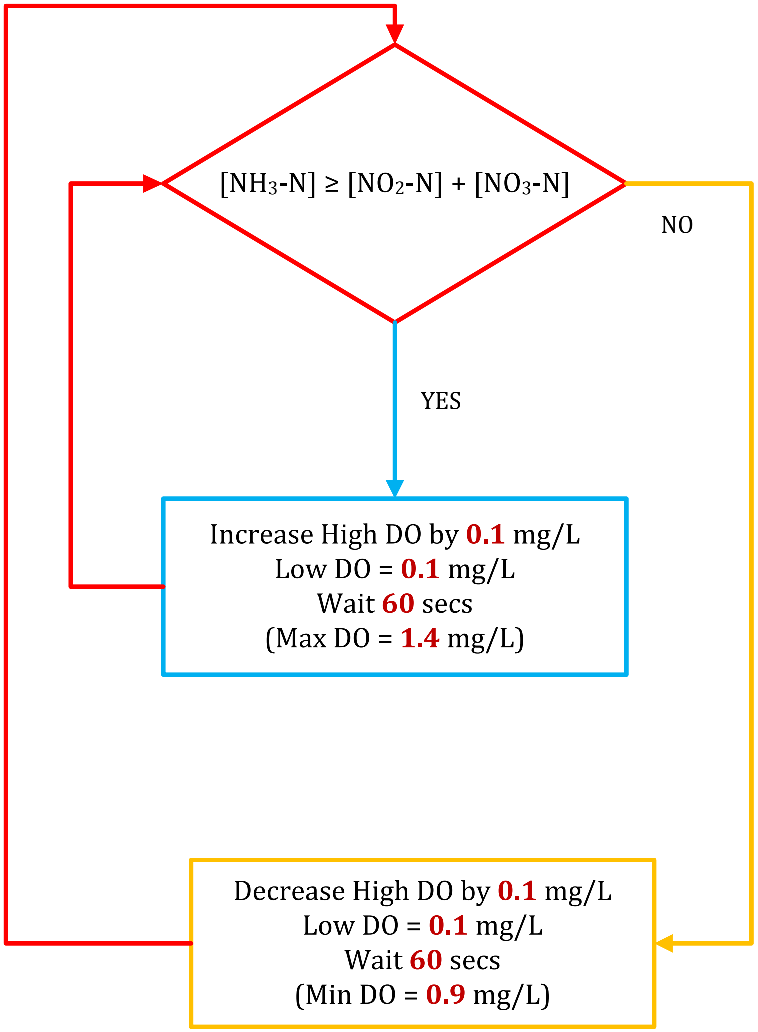
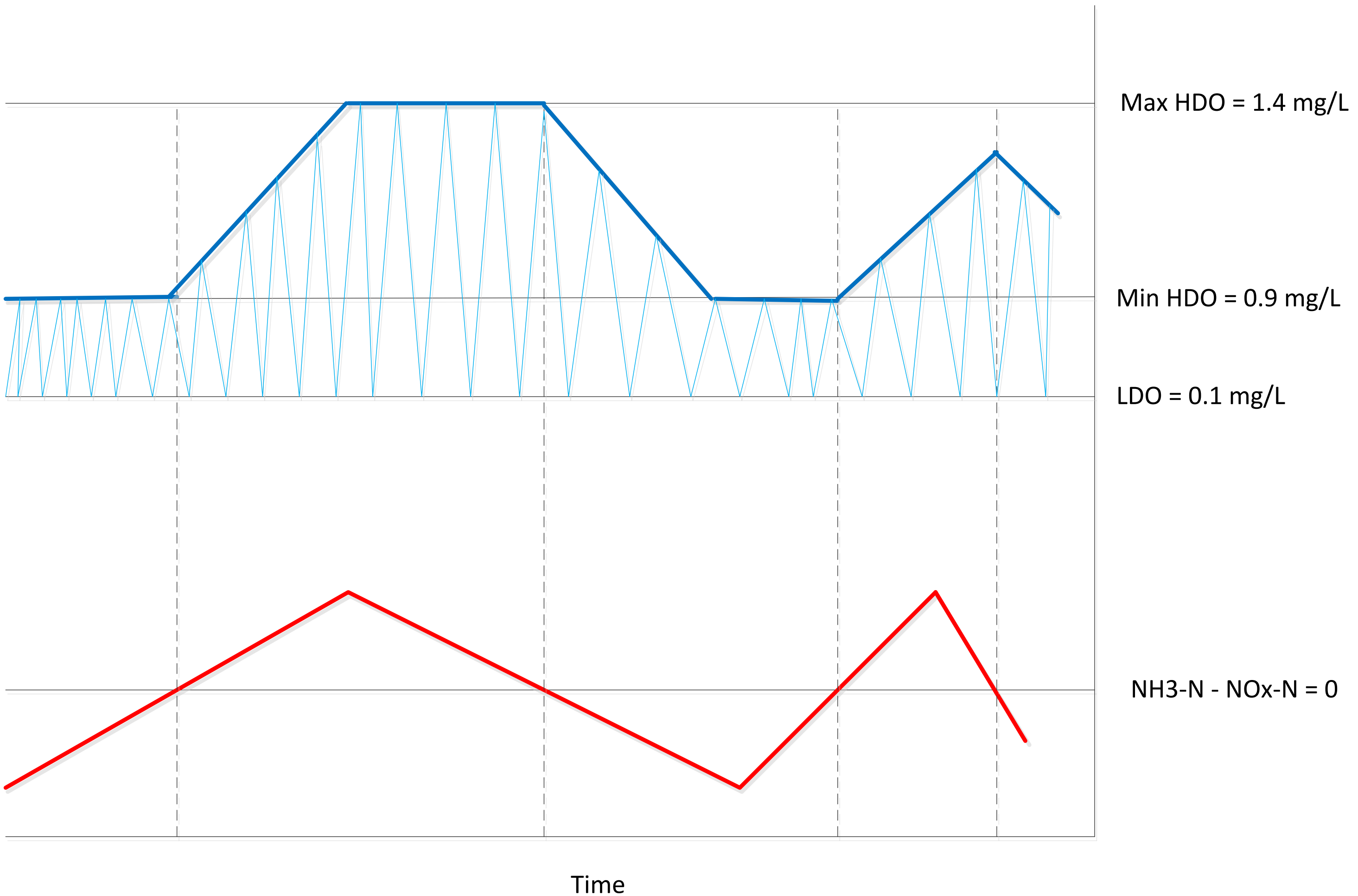
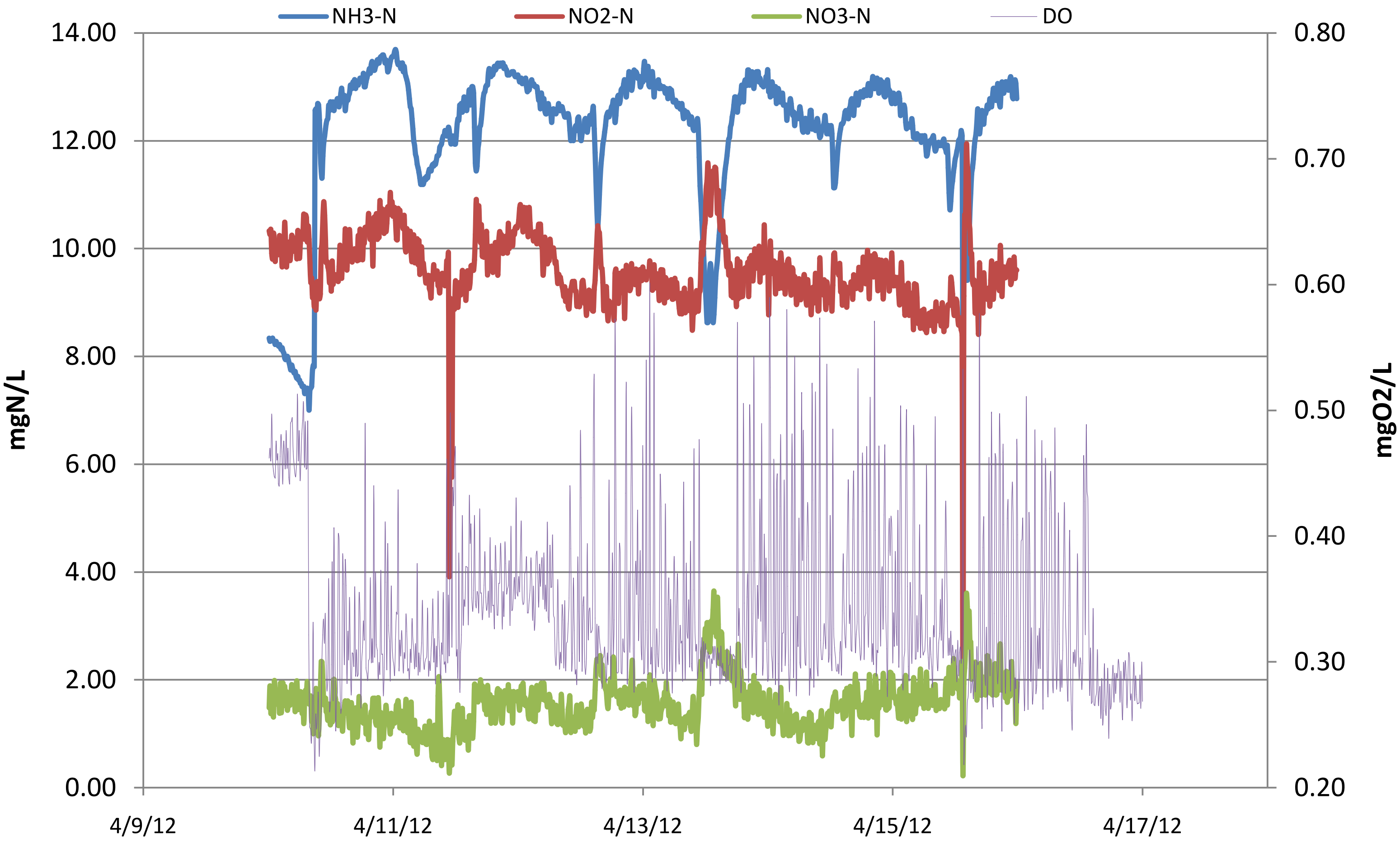


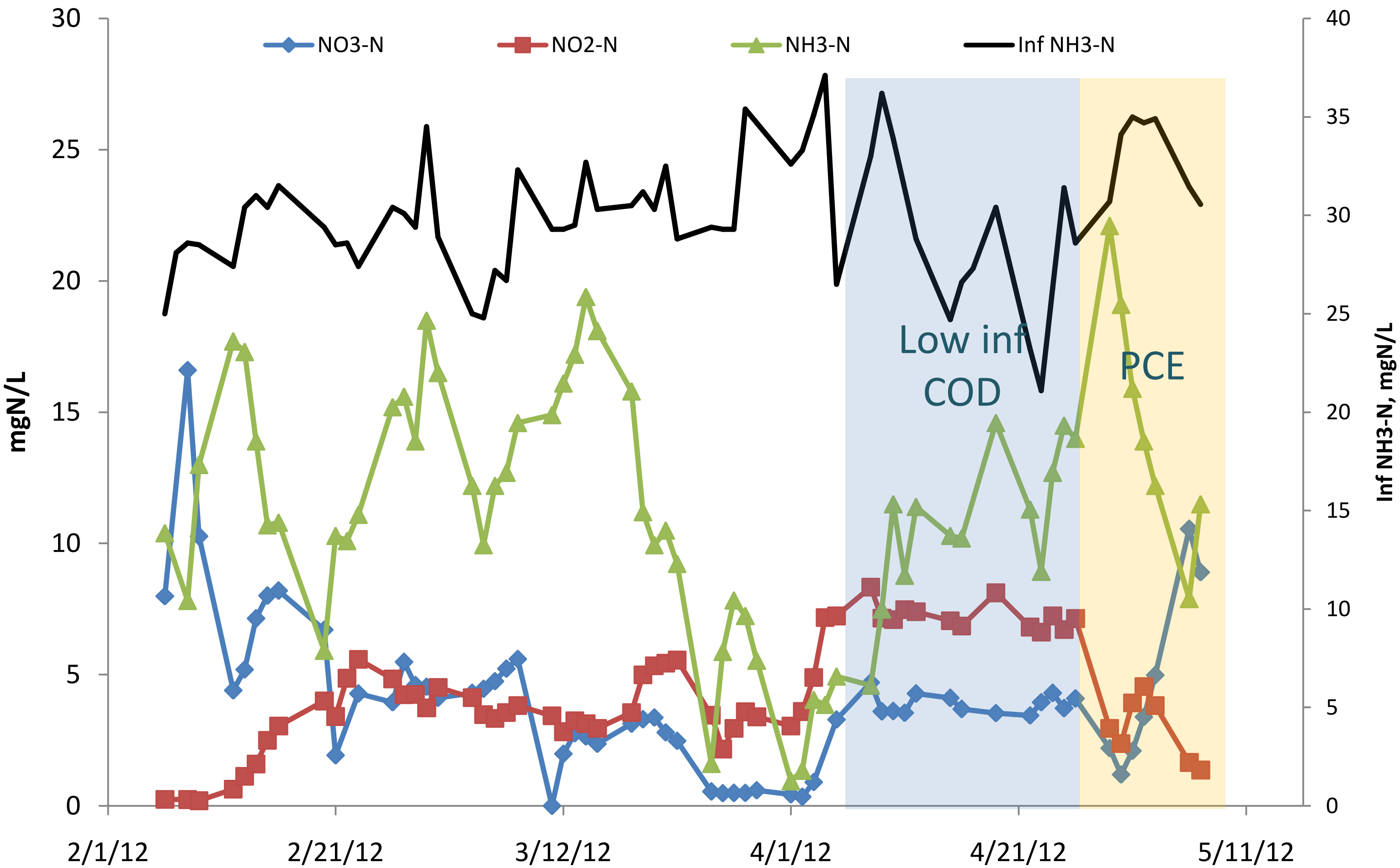
Illustration of NH3-N vs Nox-N (AVN) Control



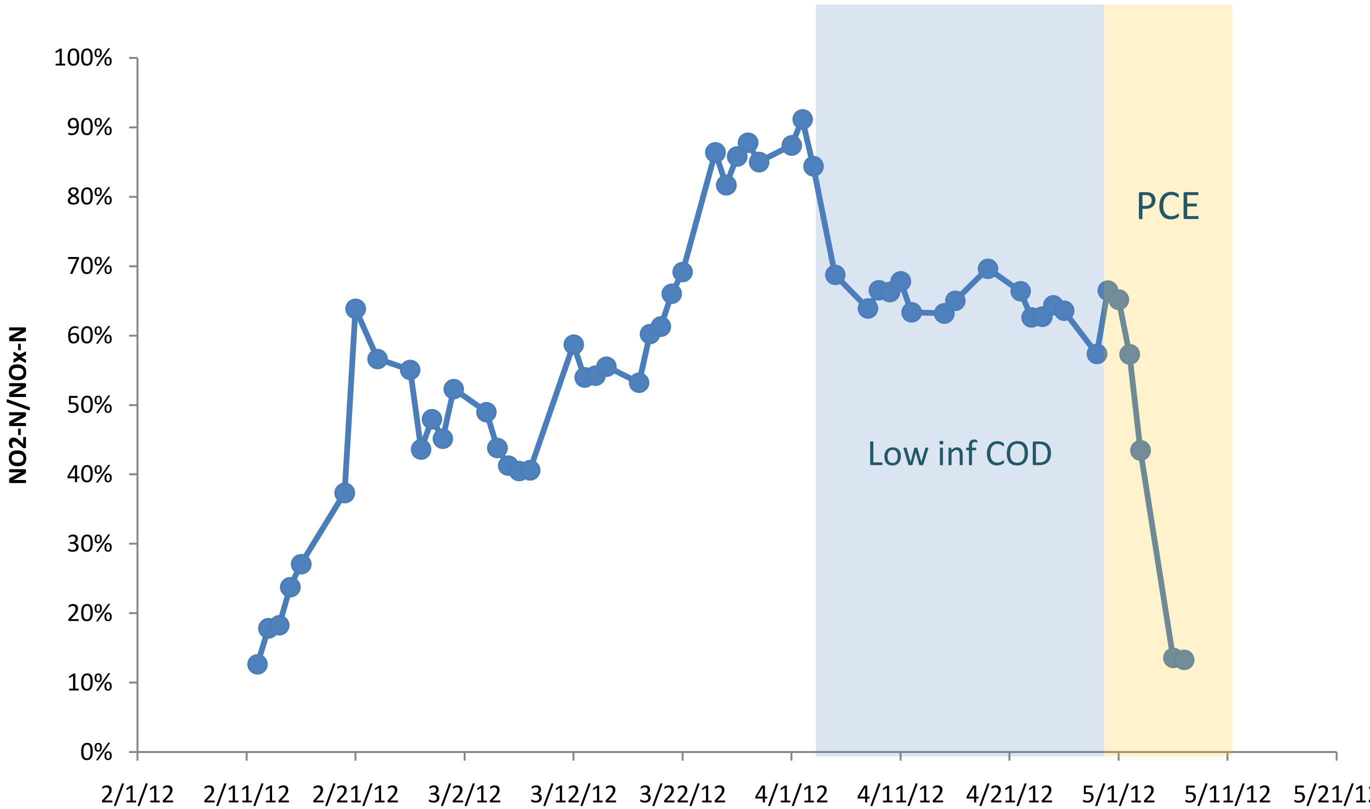
AVN Control in Action



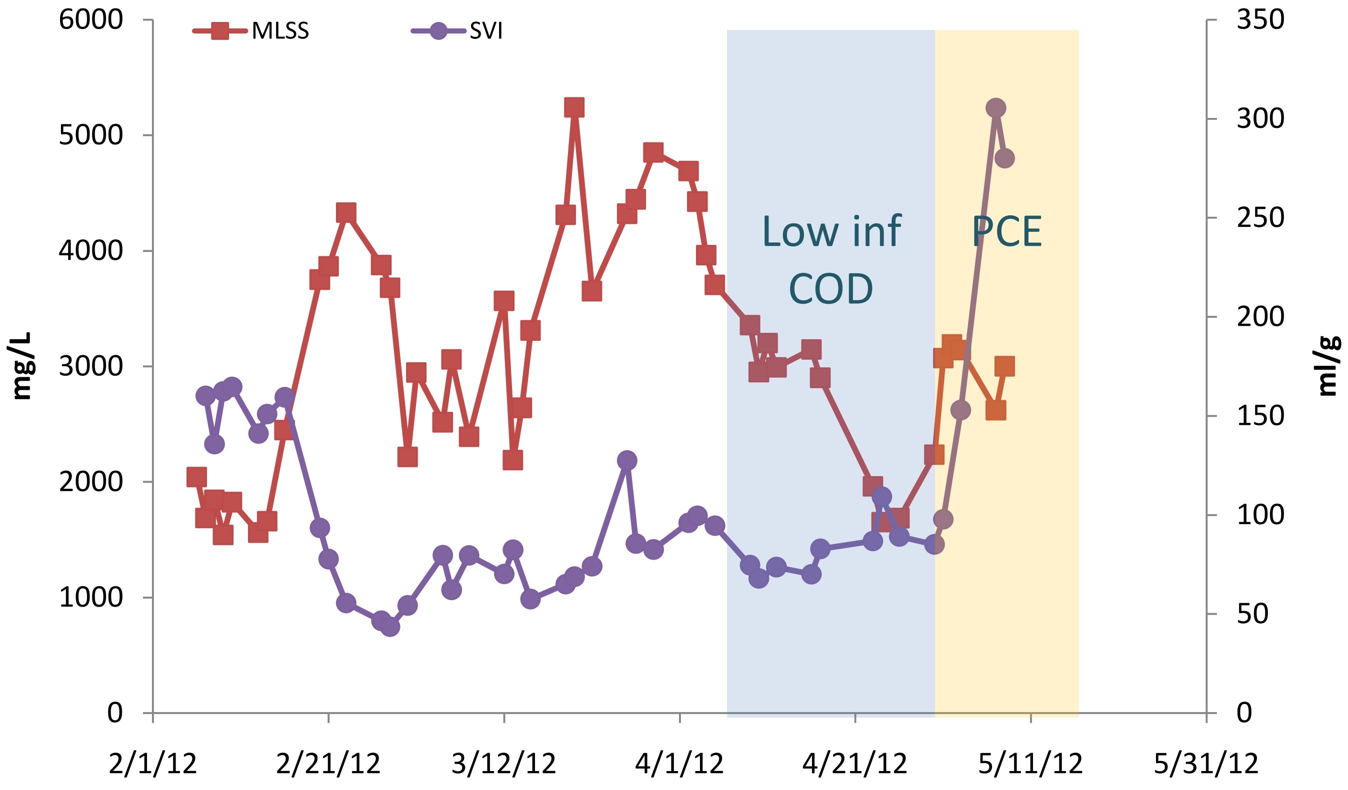
Nitritation Effluent Nitrogen Species and Influent Ammonia



Nitrite Accumulation Rate

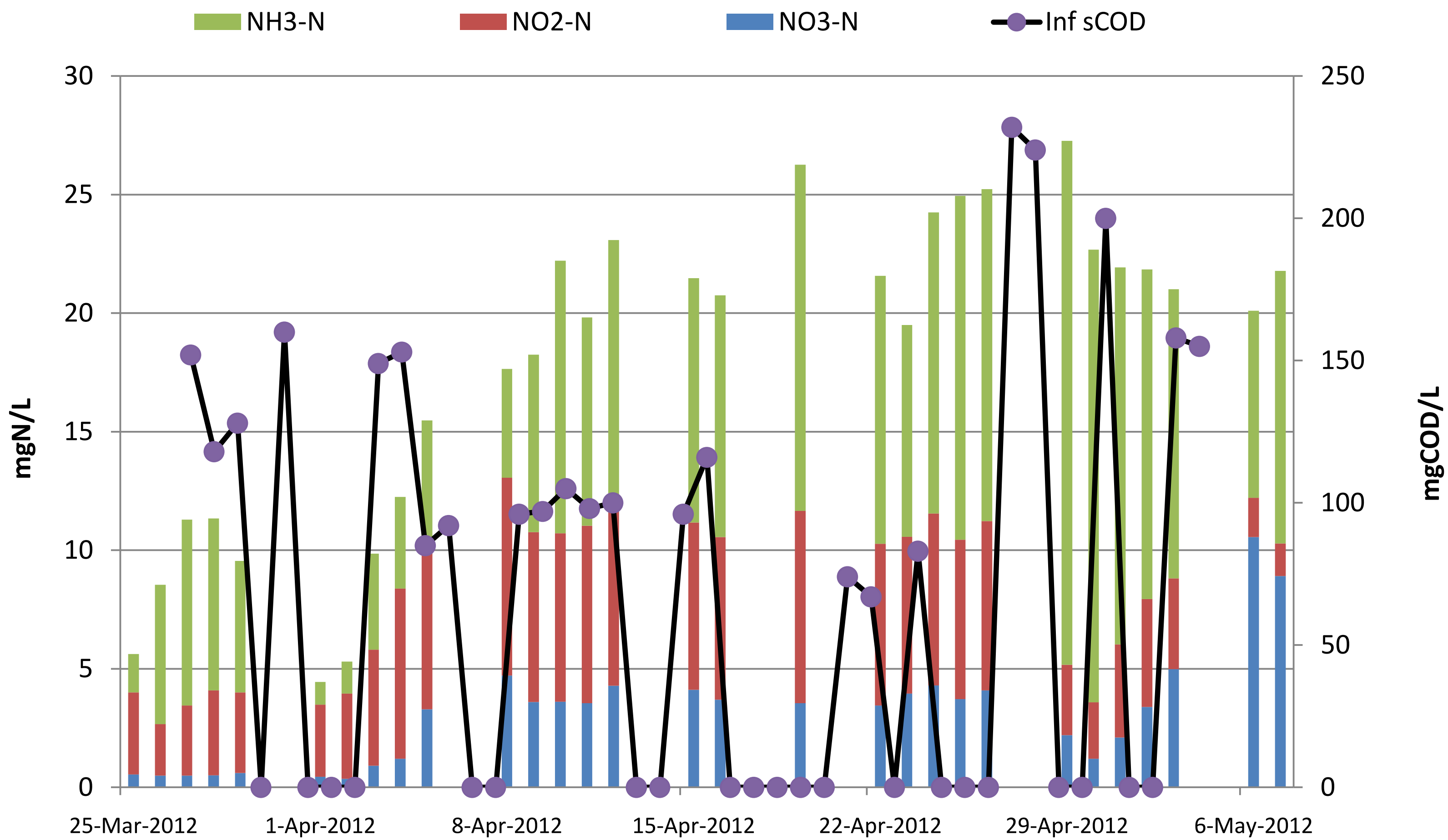


MLSS and SVI

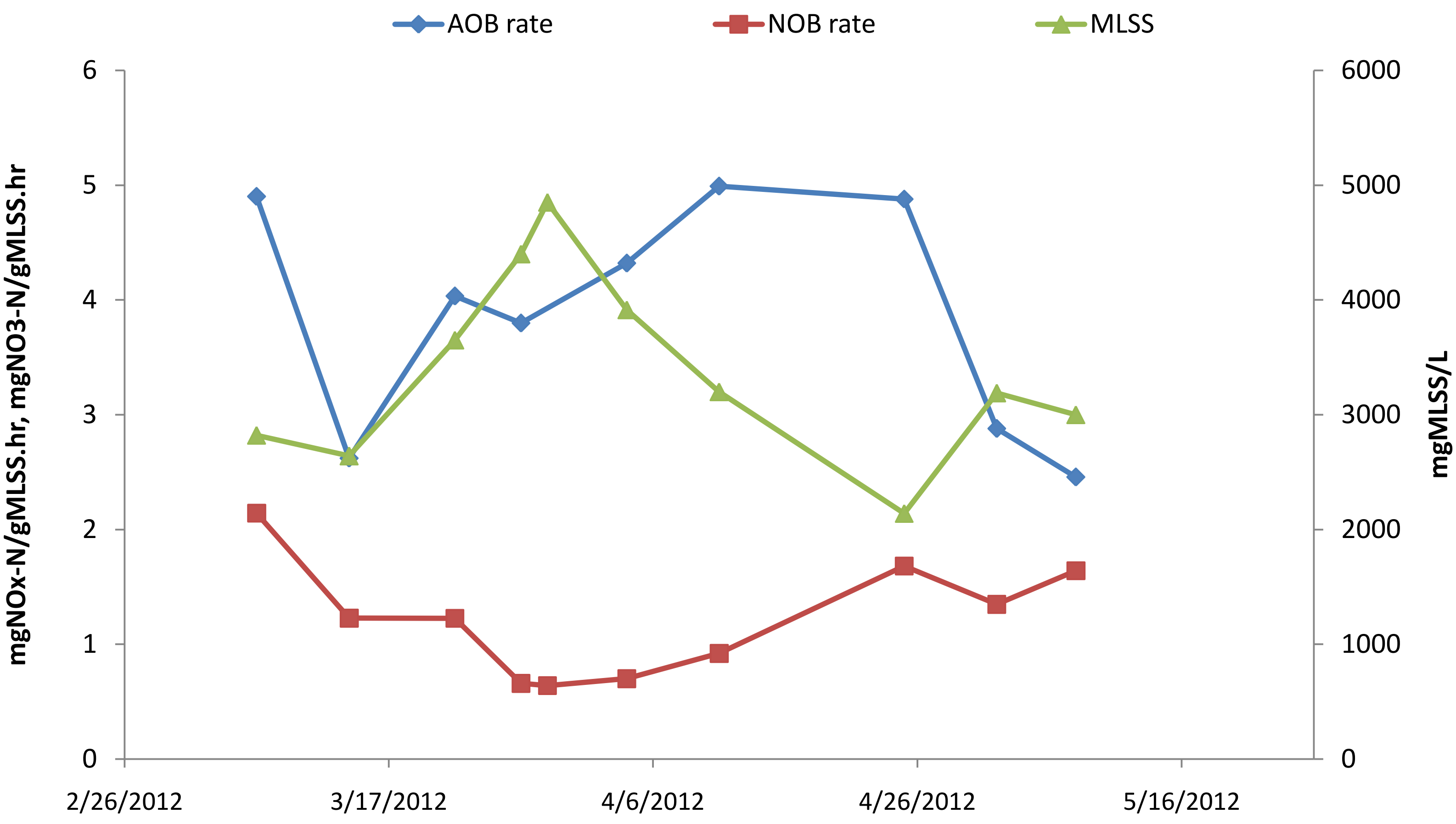


MLSS
SVI
mg/L
ml/g
6000
5000
4000
3000
2000
1000
0
350
300
250
200
150
100
50
0
Low inf
COD
PCE
2/1/12
2/21/12
3/12/12
4/1/12
4/21/12
5/11/12
5/31/12

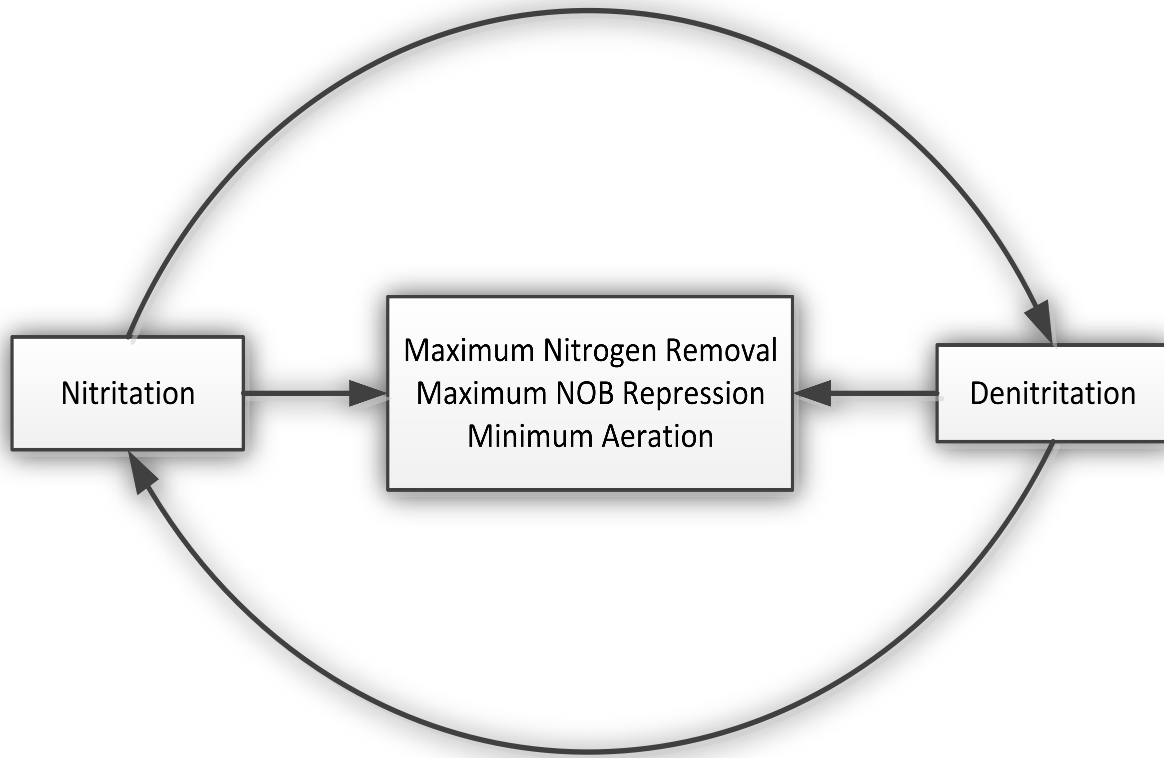
Effect of Inf sCOD on Nitrogen Removal and Species distribution



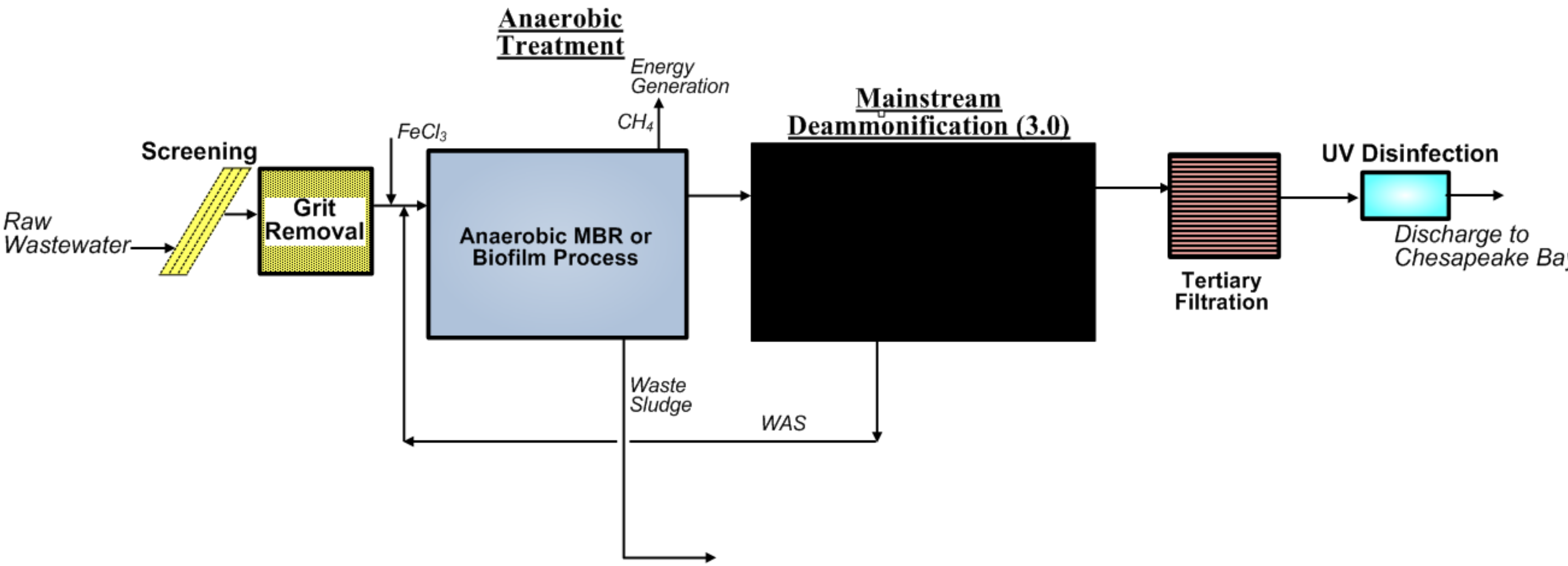
AOB and NOB Specific Nitrogen Processing Rates



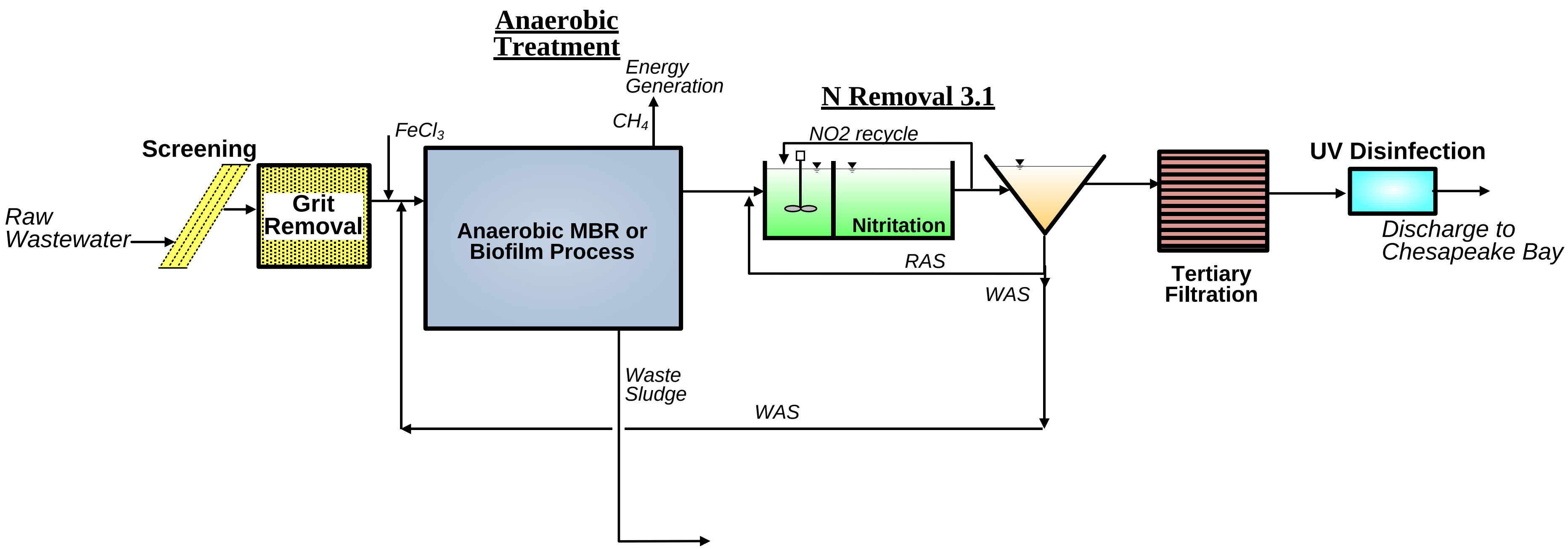
Potential Implication of Nitritation DO Control



Ideal Configuration…



3.1 Ideas….



- Nitrite + Methane – Methanotrophic Denitritation
- Sulfide-driven Autotrophic Denitritation/Denitratation
- Nitritation
- Is Anammox required??

Questions?

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