Technical Series

BACWA Nitrogen Removal Seminar

BACWA
BAY AREA
CLEAN WATER
AGENCIES

Nitrogen Removal Fundamentals

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Nevada Water
INNOVATION INSTITUTE

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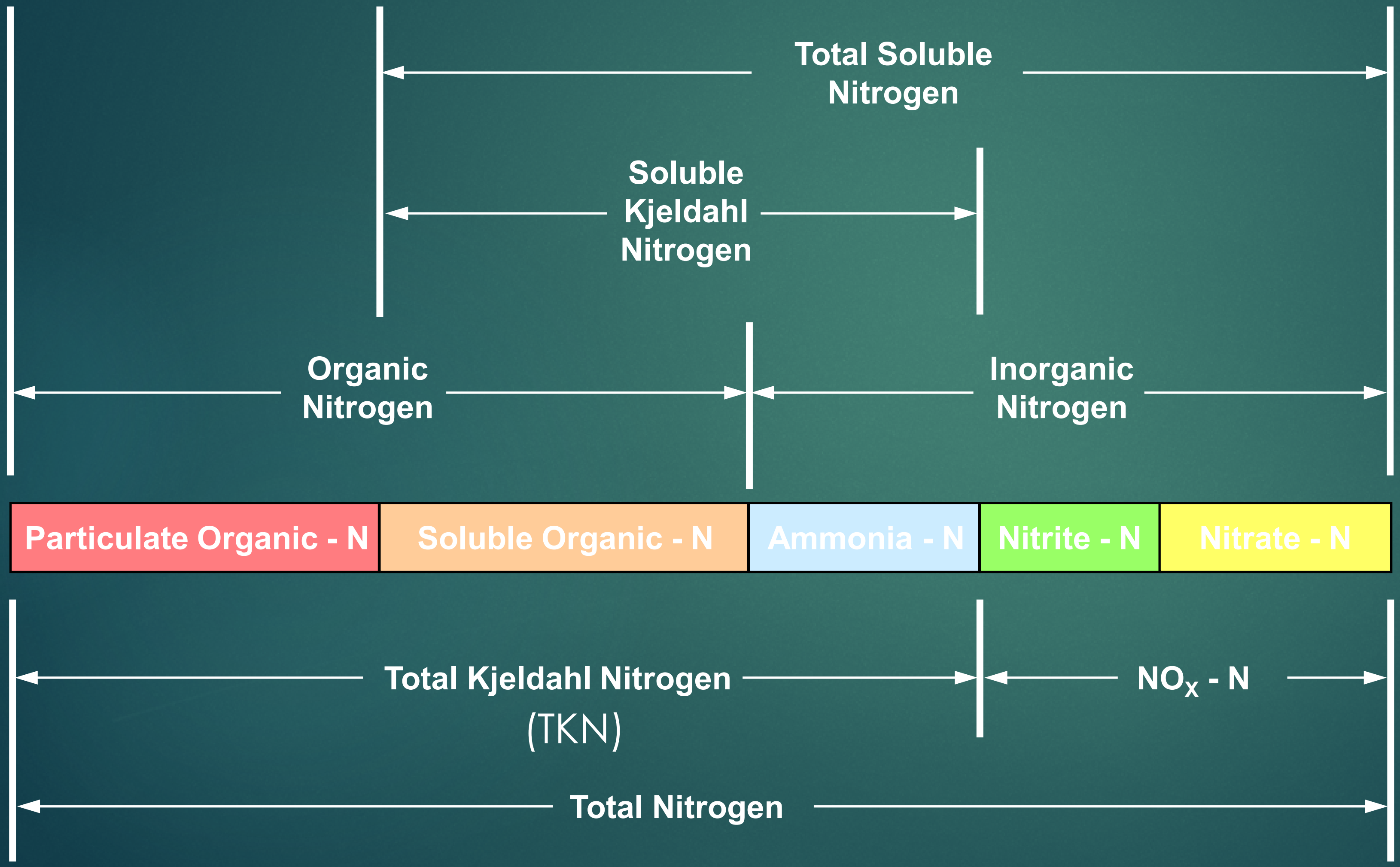
Learning Objectives

- Attendees at this presentation will be able to :
  - Develop greater understanding of the theory of nitrogen removal
  - Be able to describe the nitrification and denitrification processes and their key features
  - Analyze and distinguish between various nutrient removal processes to retrofit or add to existing plants
  - Describe operational consequences of N removal processes (oxygen requirements, potential solid-liquid separation problems, etc.)

Nitrogen Pollution – Introduction

Forms of Nitrogen in Wastewater



Total Soluble Nitrogen

Soluble Kjeldahl Nitrogen

Organic Nitrogen

Inorganic Nitrogen

Particulate Organic - N
Soluble Organic - N
Ammonia - N
Nitrite - N
Nitrate - N

Total Kjeldahl Nitrogen (TKN)

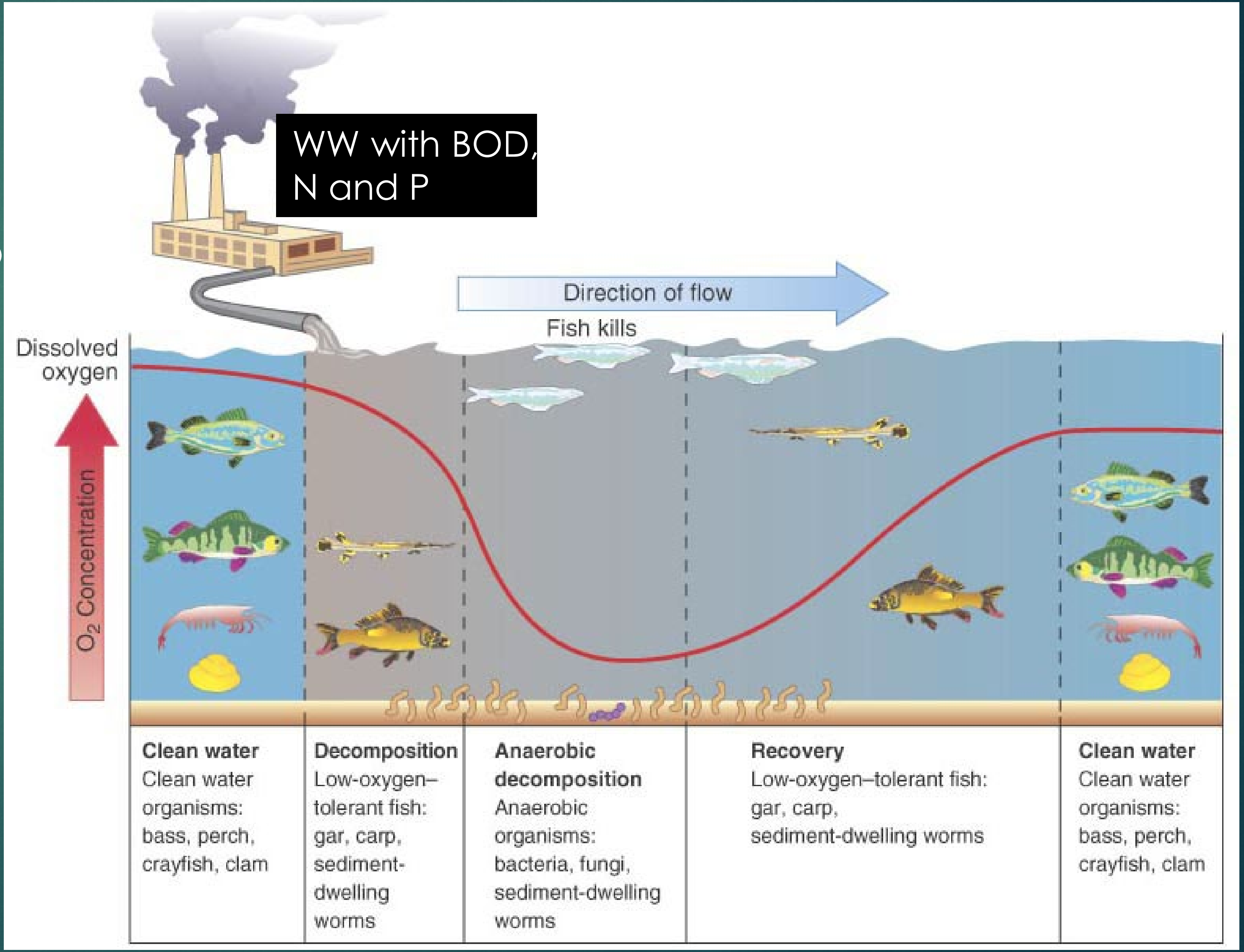
NO_X - N

Total Nitrogen

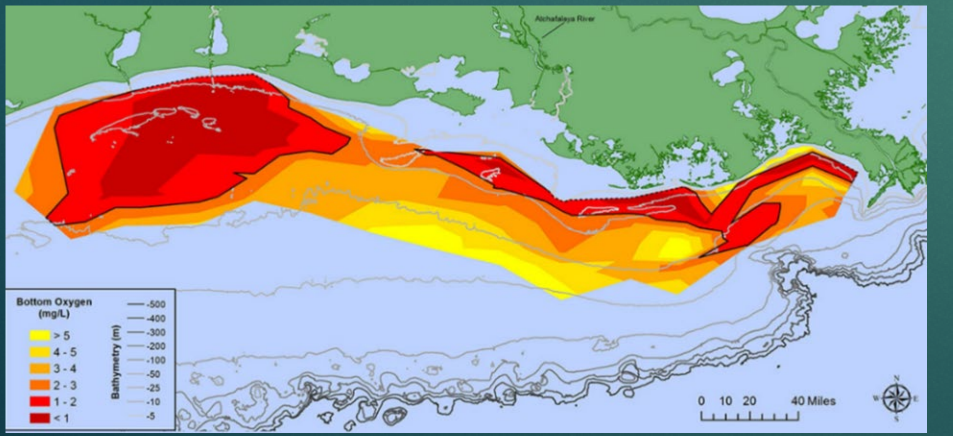
- $TKN = NH_4^+\text{-}N + Org\text{-}N$
- $TN = TKN + NO_3^-\text{-}N + NO_2^-\text{-}N$
- $TN = TKN + TIN$
- $TIN = NH_4^+\text{-}N + NO_3^-\text{-}N + NO_2^-\text{-}N$

Why Remove Nitrogen from Wastewater

- Excess nitrogen in aquatic systems causes eutrophication
- Hypoxia can lead to fish kills and reduce eco-diversity
- Unionized Ammonia (NH_3) is toxic to aquatic animals at low concentrations



WW with BOD, N and P



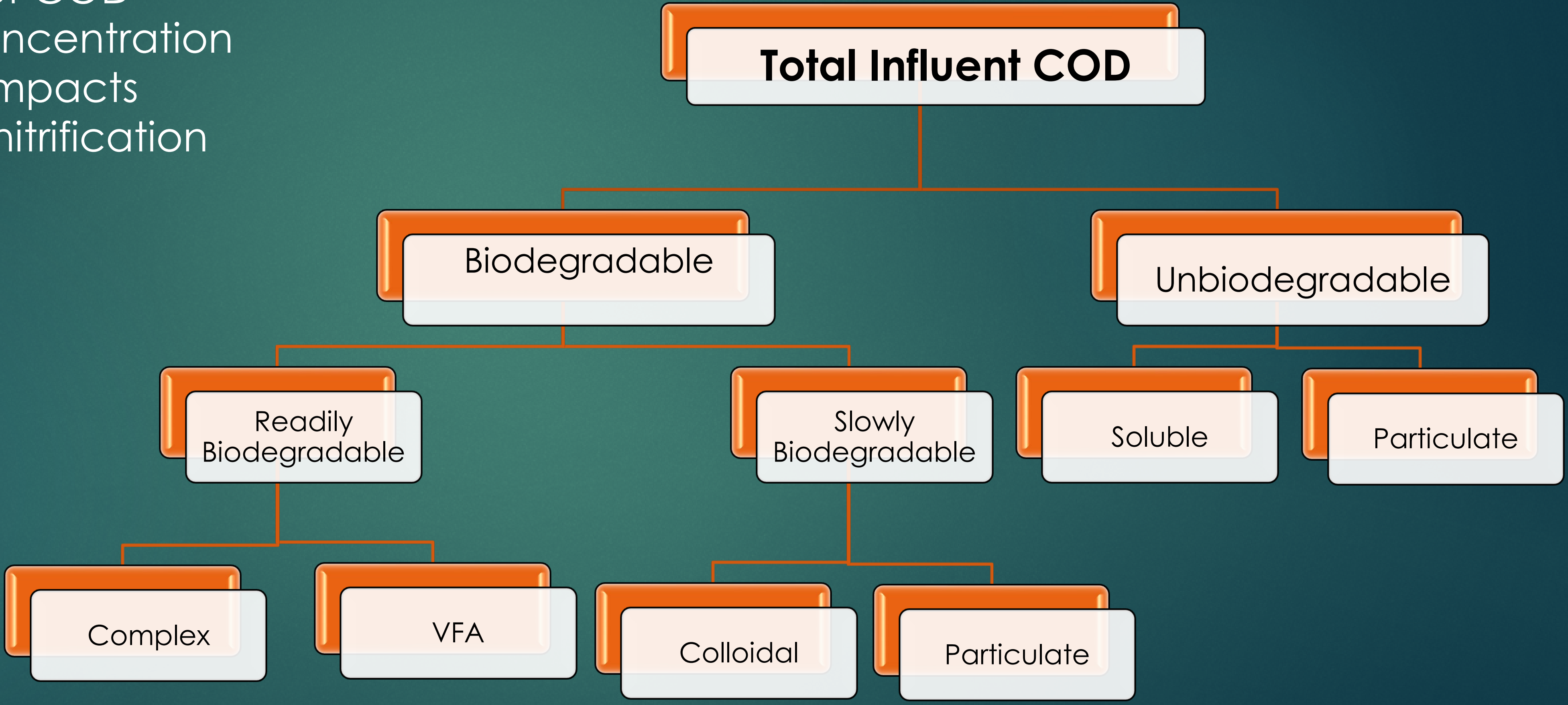
Louisiana Gulf Coast - EPA

Wastewater Characteristics – Why They Matter

Influent Wastewater Organics/COD

WW characteristics can have significant impact on BNR

- C/N ratio (Need > 4.0 for N removal)
- Fractionation of COD
- Influent TKN concentration
- Sidestream N impacts
- Carbon for denitrification



Total Nitrogen

Influent Total Nitrogen

Nitrate/Nitrite Nitrogen
~ 0 – 5%

TKN
~ 95 – 100%

Ammonia Nitrogen
~ 65 – 75%

Organic Nitrogen
~ 25 – 35%

Most of influent Org N biologically converted to Ammonia Nitrogen

Biomass growth (assimilation) removes ~ 25 to 30% of TN, rest must be nitrified to Nitrate

BNR Effluent Total Nitrogen

Nitrate/Nitrite Nitrogen
~ Varies

TKN
~ 1 - 1.5 mg/L

Ammonia Nitrogen
< 1 mg/L

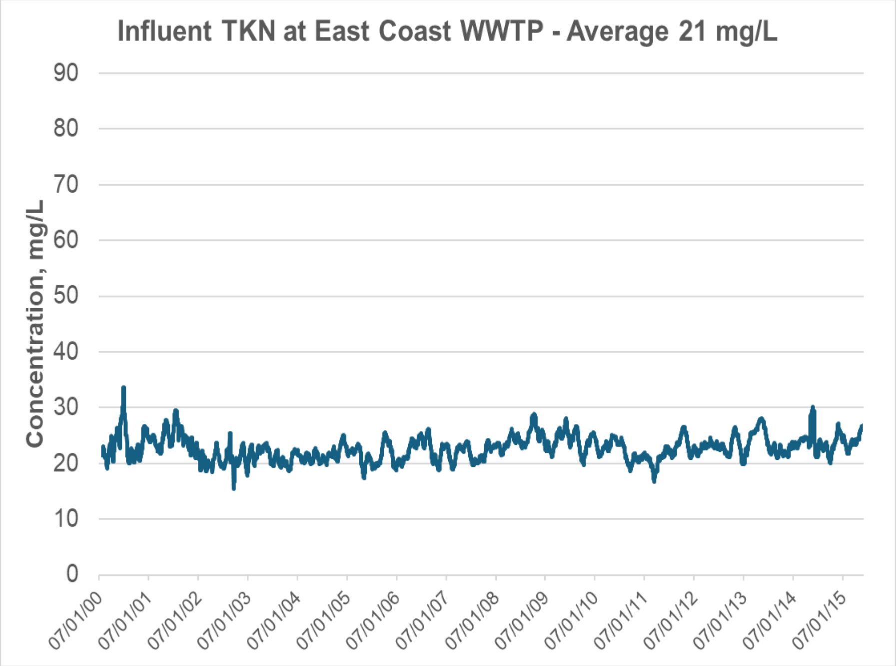
Organic Nitrogen
~ 0.5 mg/L

TN Limits will require nitrification and reducing NOx through denitrification

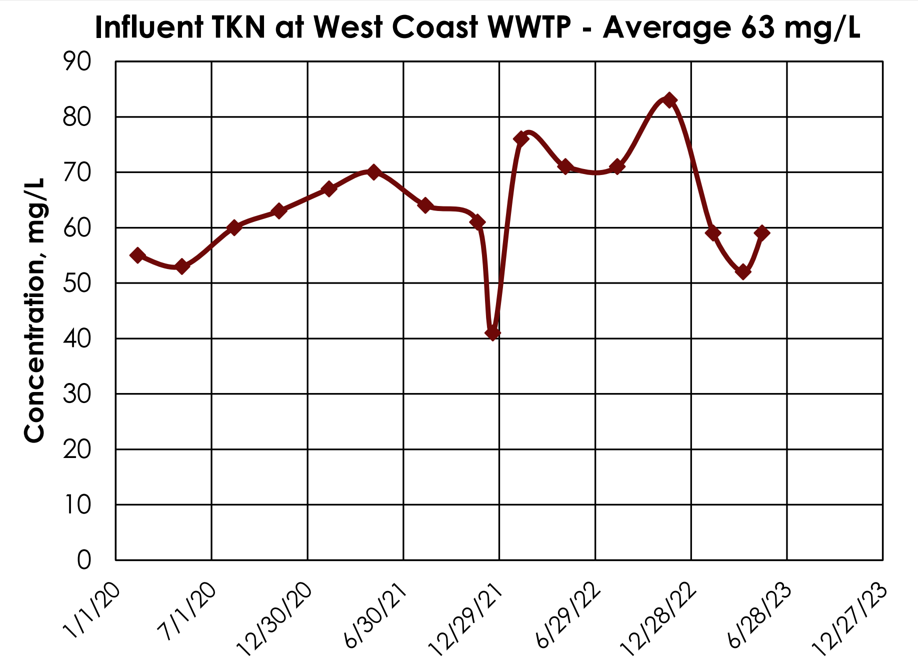
BOD + NOx → N_2 gas ↑

Wastewater Characteristics

- Wastewater characteristics can vary significantly based on watershed
- Site Specific Data is Critical!



Influent TKN at East Coast WWTP - Average 21 mg/L



Influent TKN at West Coast WWTP - Average 63 mg/L

Low flows leads to higher concentrations.

California Residential Water Use regulation keep getting tighter

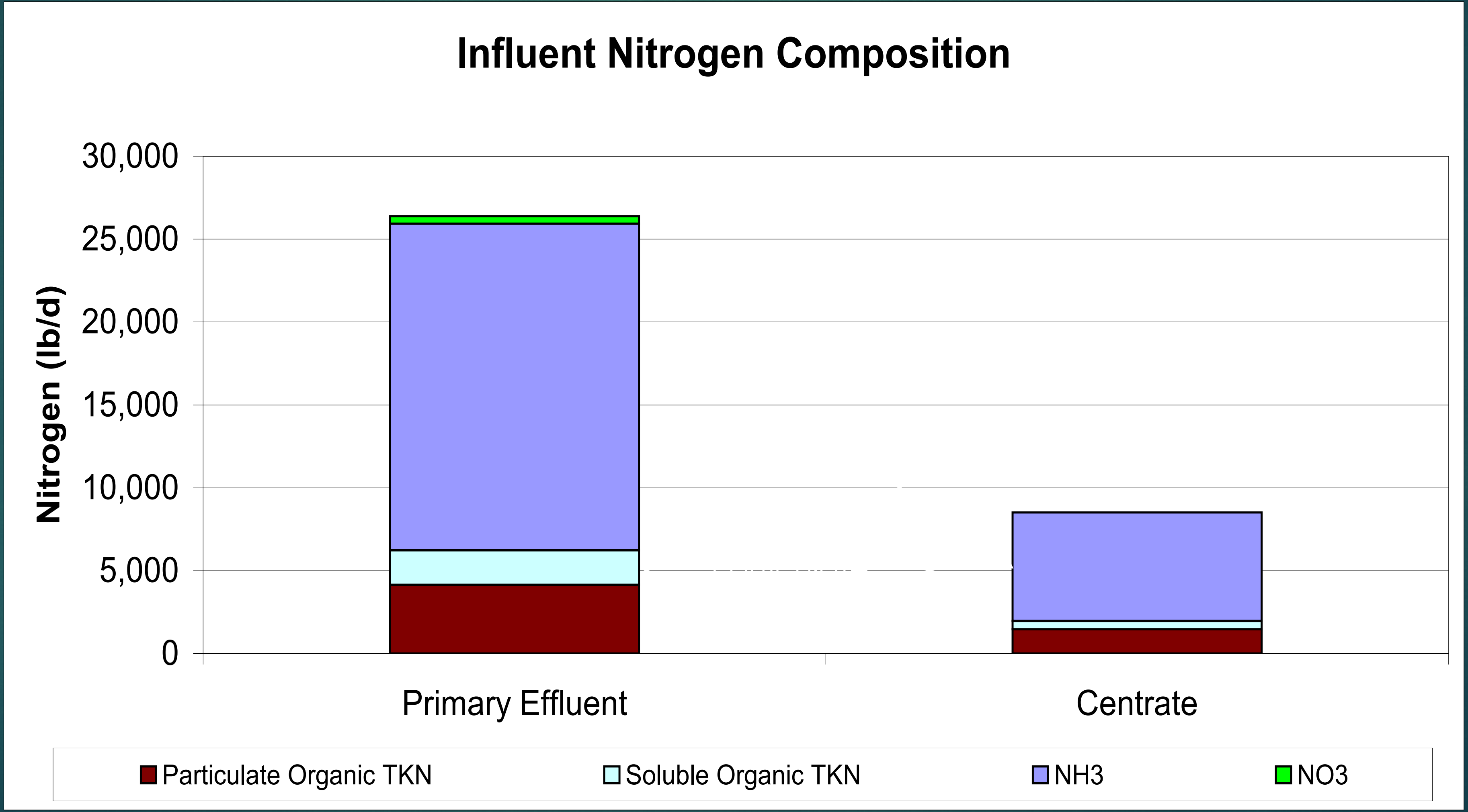
Year	Per Capita flow, gpd
2023	55
2025	47
2030	42

California Indoor Residential Water Use Standard is lower; and getting lower
Impact on influent concentrations and key ratios that drive nutrient removal

NYC ~ 115 GPD

Influent and Centrate Nitrogen Load Composition

- Centrate or filtrate from dewatering of anaerobically digested sludge
- Centrate Recycle/Filtrate Nitrogen Loads Typically Make up 10-20% of Influent Loads
- Can be higher if dewatering is centralized (NYC, Philadelphia)



Nitrification – Denitrification

Biological Nitrogen Removal

BNR processes remove Ammonia (TKN) and Total Nitrogen (Organic N + Inorganic N)

BNR for TN removal requires a two processes:

Step 1: Nitrification $NH_4 \rightarrow NO_2 \rightarrow NO_3$

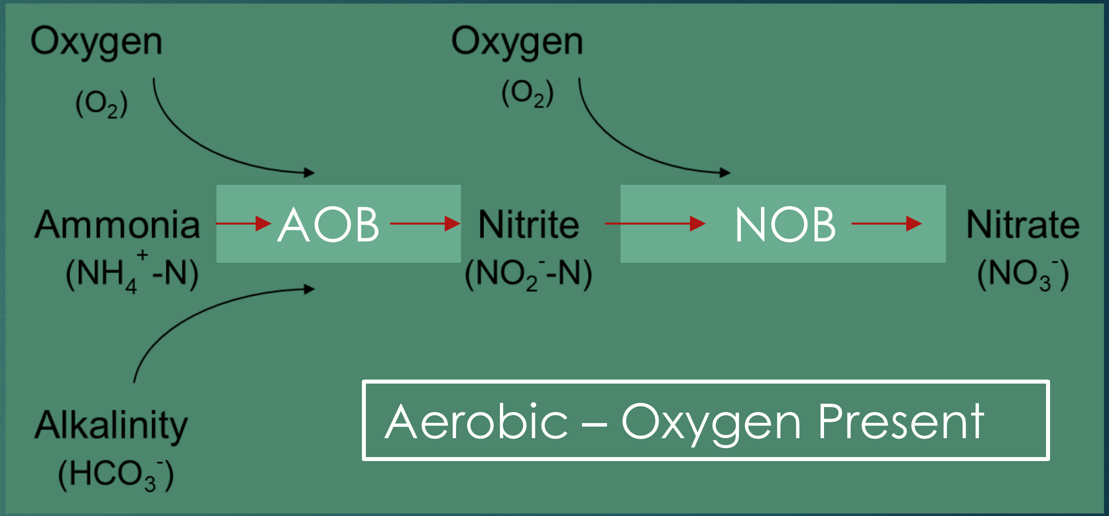
Ammonia-N in WW + Biomass + O_2 + Alkalinity

= NO_3^- + Biomass (++) + H_2O

Step 2: Denitrification $NO_3 \rightarrow NO_2 \rightarrow N_{2(g}$

NO_3^- + Waste(BOD) in WW + Nutrients + Biomass

= N_2 + CO_2 + Biomass (++) + H_2O



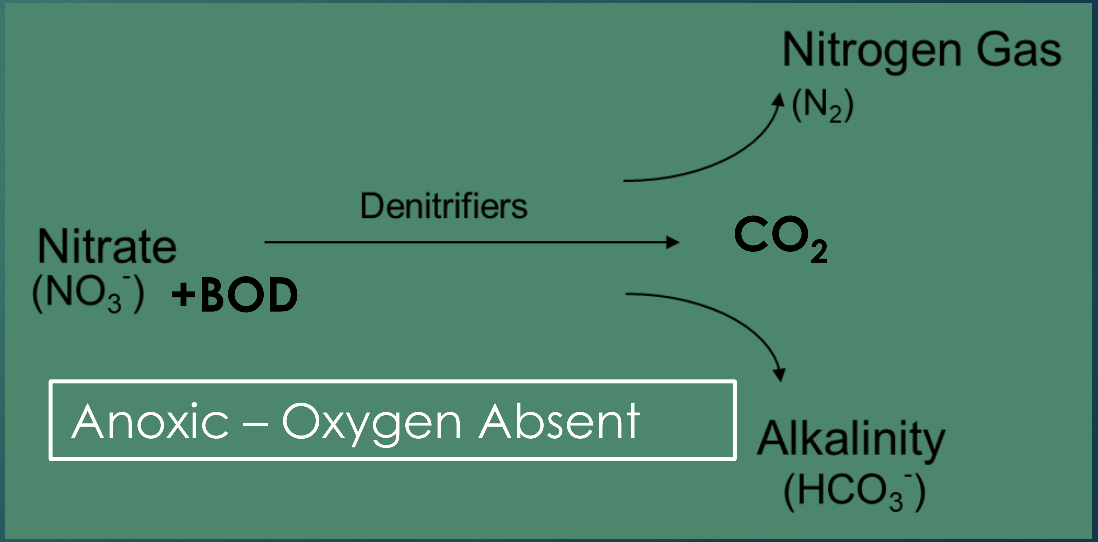
Oxygen (O_2)

Oxygen (O_2)

Ammonia (NH_4^+-N) → AOB → Nitrite (NO_2^--N) → NOB → Nitrate (NO_3^-)

Alkalinity (HCO_3^-)

Aerobic – Oxygen Present



Nitrogen Gas (N_2)

Nitrate (NO_3^-) **+BOD**

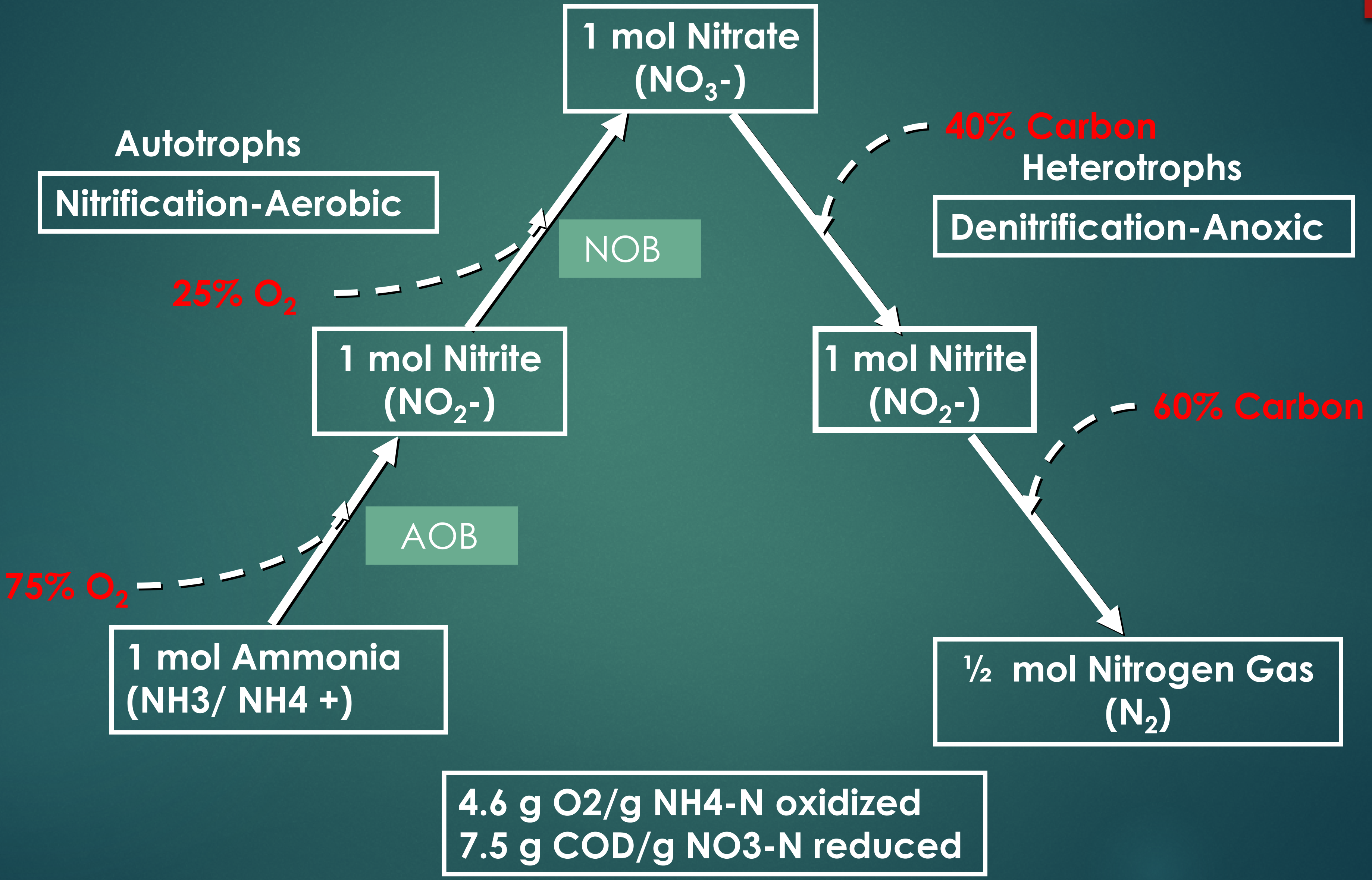
Denitrifiers

CO_2

Anoxic – Oxygen Absent

Alkalinity (HCO_3^-)

Nitrification - Denitrification



1 mol Nitrate (NO_3-)

Autotrophs

Nitrification-Aerobic

NOB

25% O_2

1 mol Nitrite (NO_2-)

AOB

75% O_2

1 mol Ammonia (NH3/ NH4 +)

40% Carbon

Heterotrophs

Denitrification-Anoxic

1 mol Nitrite (NO_2-)

60% Carbon

½ mol Nitrogen Gas (N_2)

4.6 g O2/g NH4-N oxidized
7.5 g COD/g NO3-N reduced

Nitrification Process

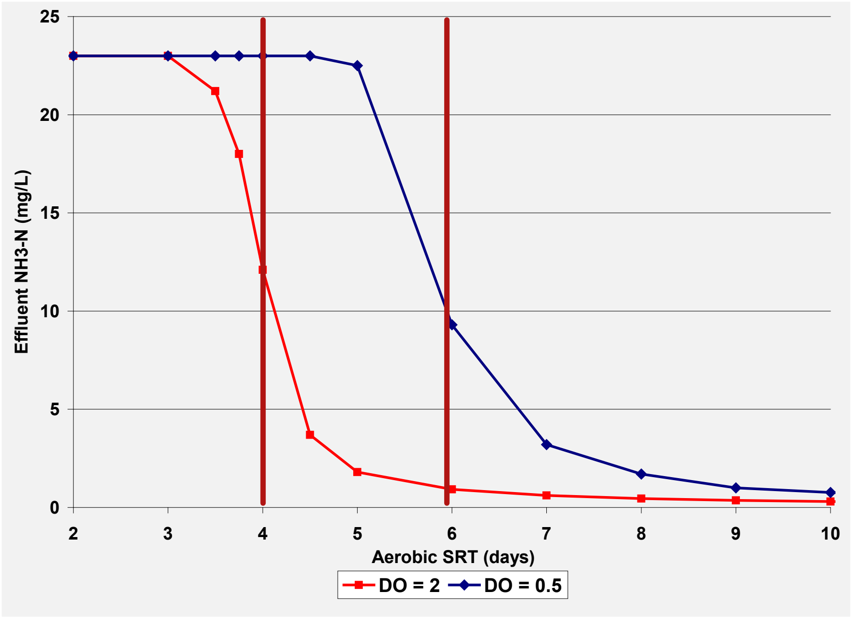
- Needs longer SRT or MCRT
- Need more oxygen (4.6 lb O_2/lb N oxidized
- Need more alkalinity
- Need to be careful about inhibitory compounds (heavy metals, toxics)
- Temperature has a greater impact

	BOD Removal	Nitrification
Aerobic SRT	0.5-1 day	4-15 days
pH	5-9	6.5-8
Temperature	Above freezing	25 °C (Optimum)
Dissolved Oxygen	Above 0.5 mg/L	Above 2.0 mg/L

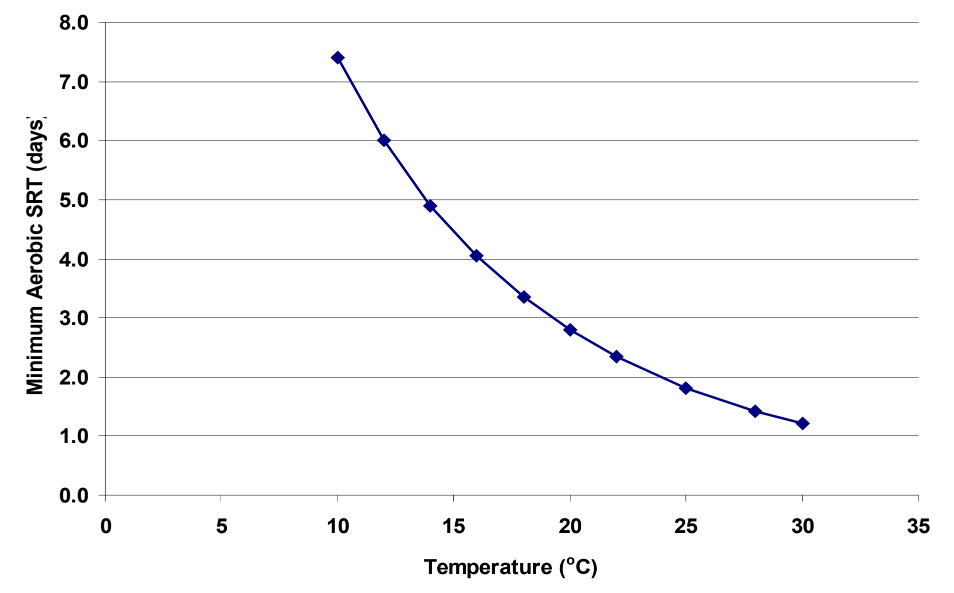
$$SRT = \frac{V * X_{mlvss}}{P_x} = \frac{V * X_{MLVSS}}{X_{WAS} * Q_{WAS}}$$

$$SRT_{AER} = \frac{V_{AER} * X_{mlvss}}{P_x} = \frac{V_{AER} * X_{MLVSS}}{X_{WAS} * Q_{WAS}}$$

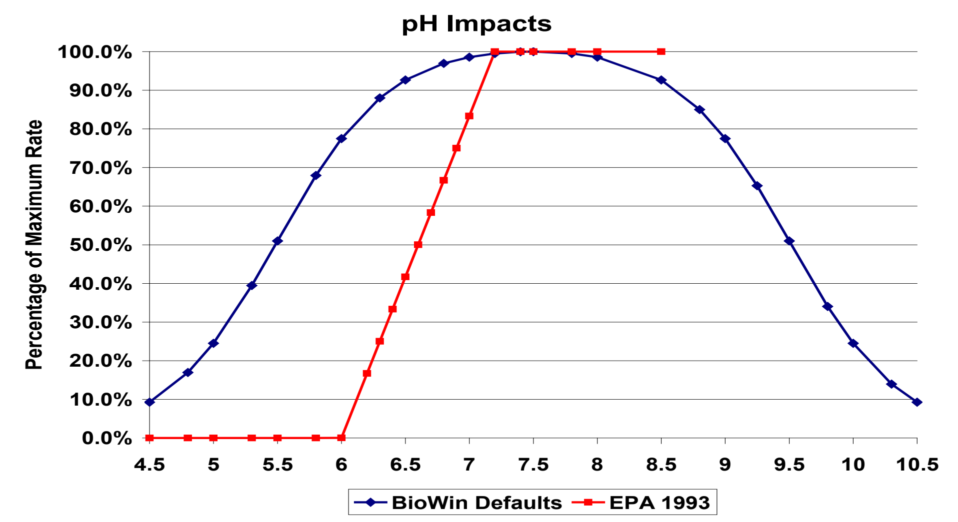
DO and Aerobic SRT Impact on Effluent NH_4^+-N



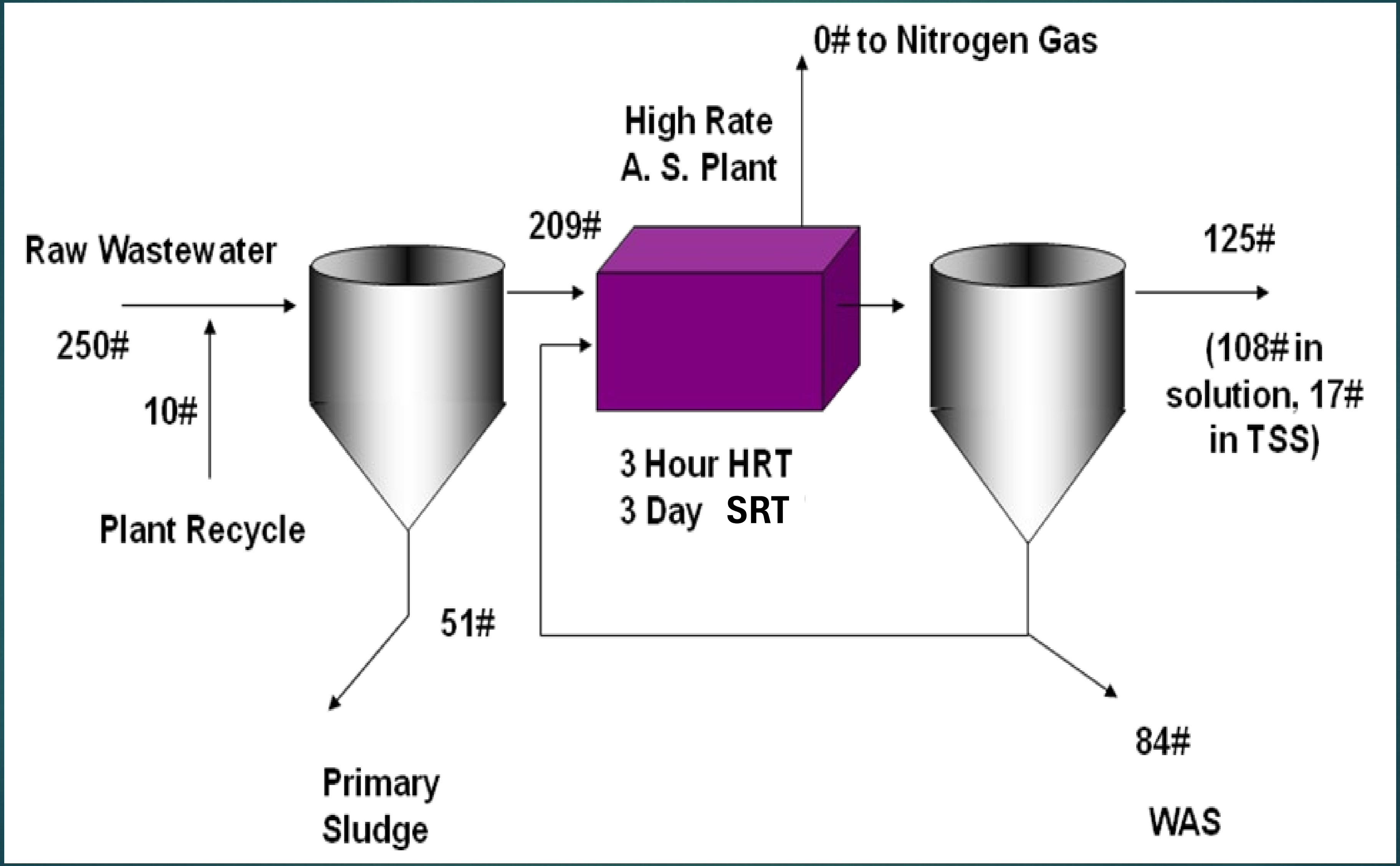
Temperature Impacts on Minimum Aerobic SRT



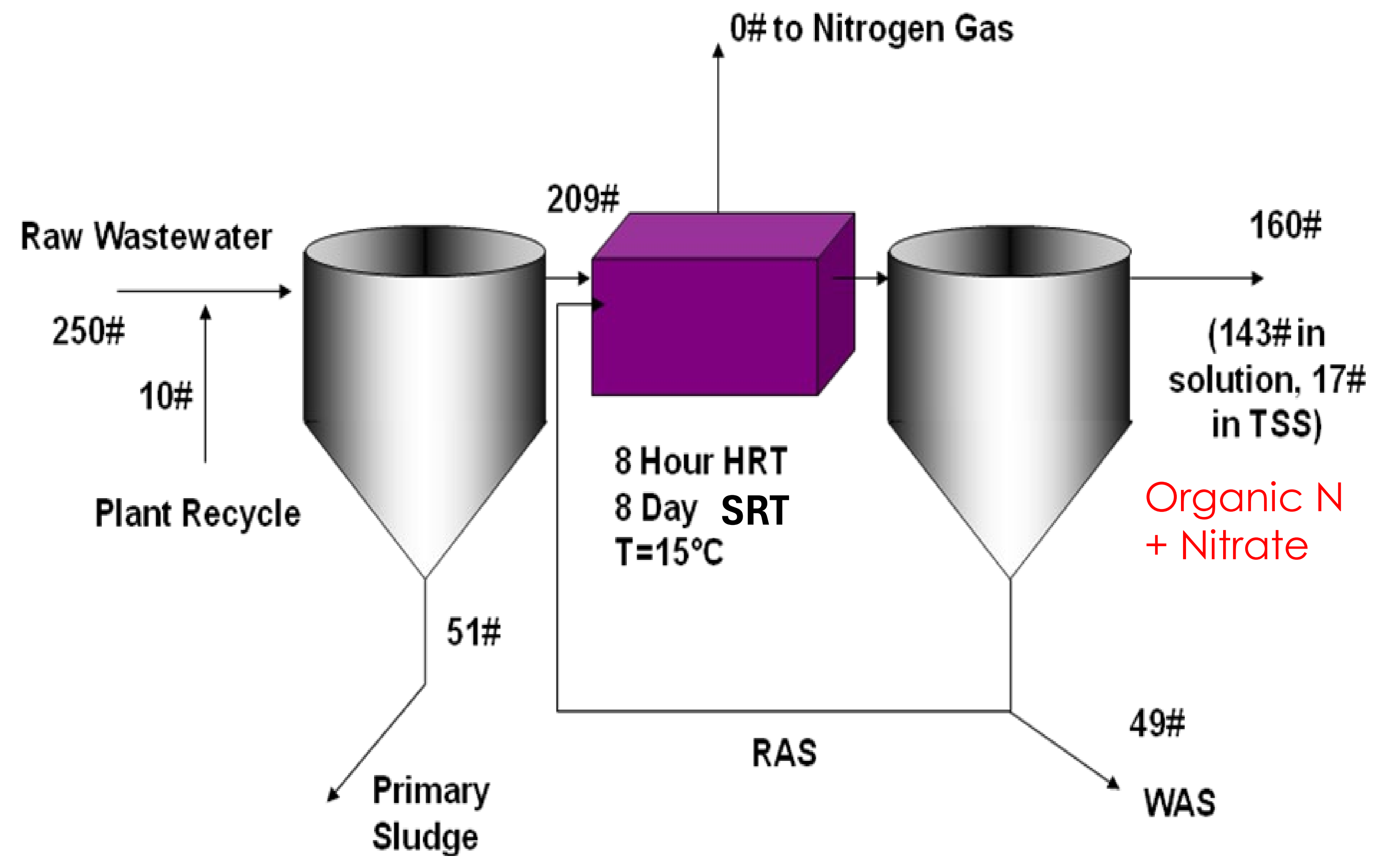
pH Impacts on Nitrification Rate



Fate of Nitrogen in BOD Removal Plant (1 MGD)



Fate of Nitrogen in BOD Removal and Nitrification Plant (1 MGD)



Assumes 100% Nitrification

Denitrification Process

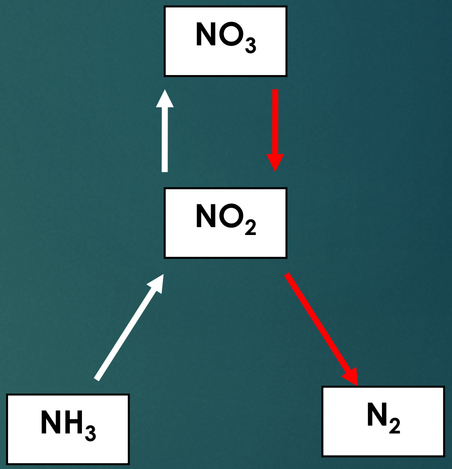
The reduction of Nitrate to Nitrogen gas

NO_3 + BOD ⟶ N_2 + CO_2 + Alk + Biomass

Modeled as Two-Step process

- Oxygen credit and Alkalinity Recovery
  - 2.86 lbs O2 credit/lb NO_3-N denitrified
  - 3.6 lbs Alk produced/lb NO_3-N denitrified

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

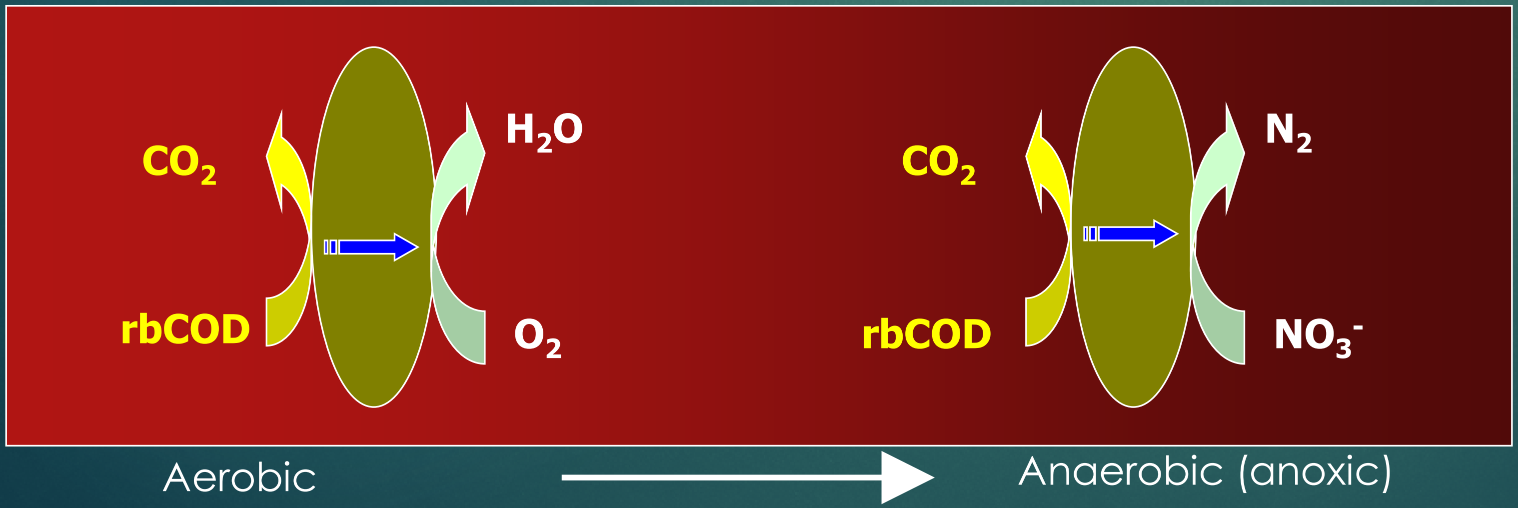


NO_3

NO_2

NH_3

N_2



Denitrification Requirements

- Nitrification to produce nitrite/nitrate
- Anoxic zones with low/no DO
    - Baffling and zone segregation
    - Minimize DO carryover from previous zones
- Readily biodegradable carbon (rbCOD)
    - Raw Influent BOD (~ 5 lbs BOD/lb NO3-N denitrified)

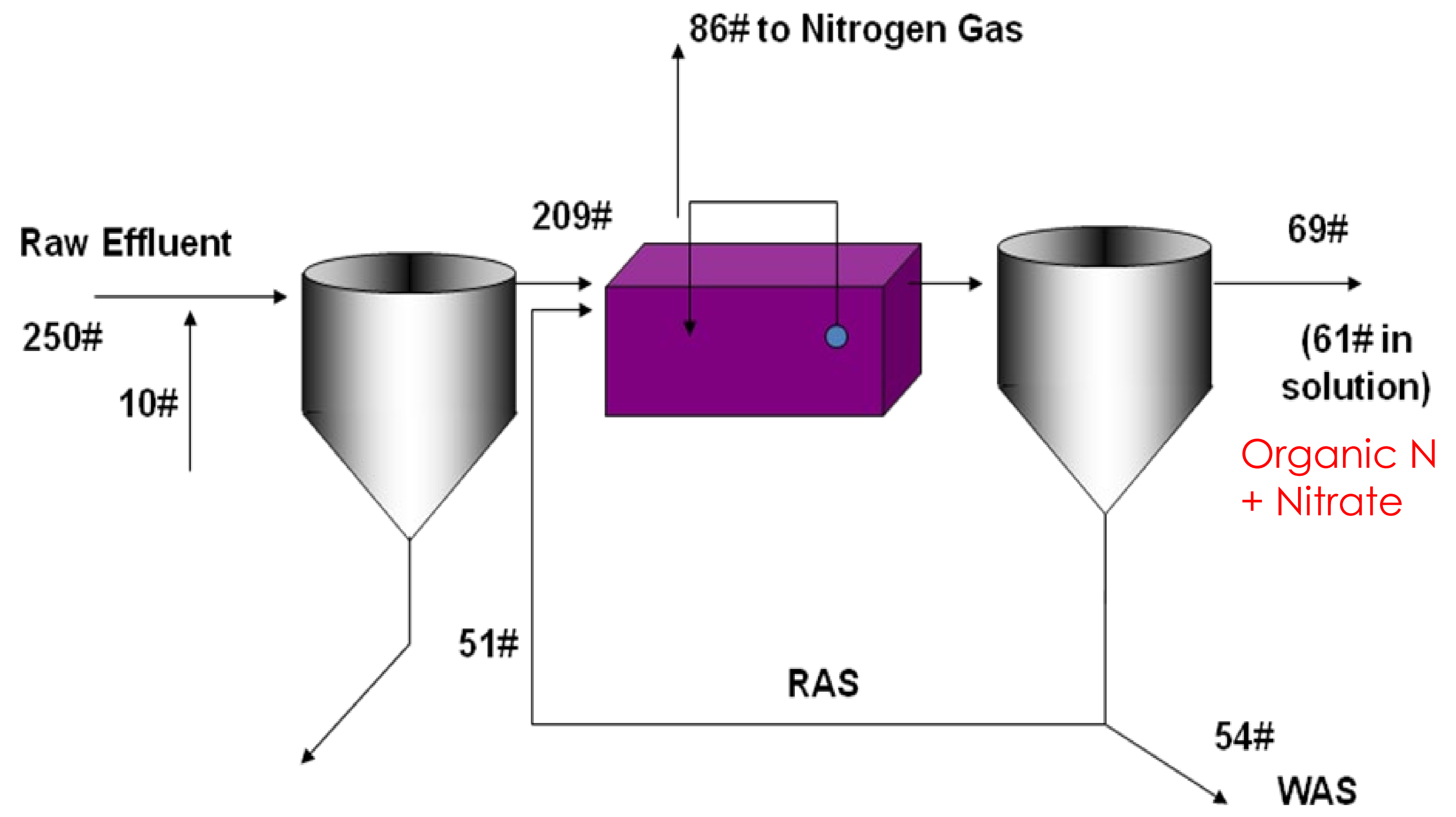
Impact on Oxygen and Alkalinity:

- Oxygen
    - 50% oxygen demand removed
- Alkalinity produced via Denitrification
    - 50% alkalinity recovered

Electron Donor Required

- Influent WW carbon
- Endogenous carbon
- Supplemental carbon

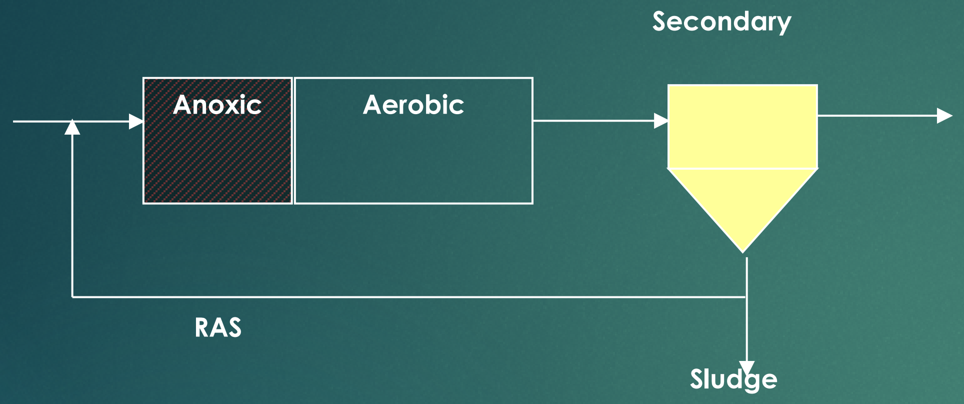
Fate of Nitrogen in BOD Removal and N Removal Plant (1 MGD)



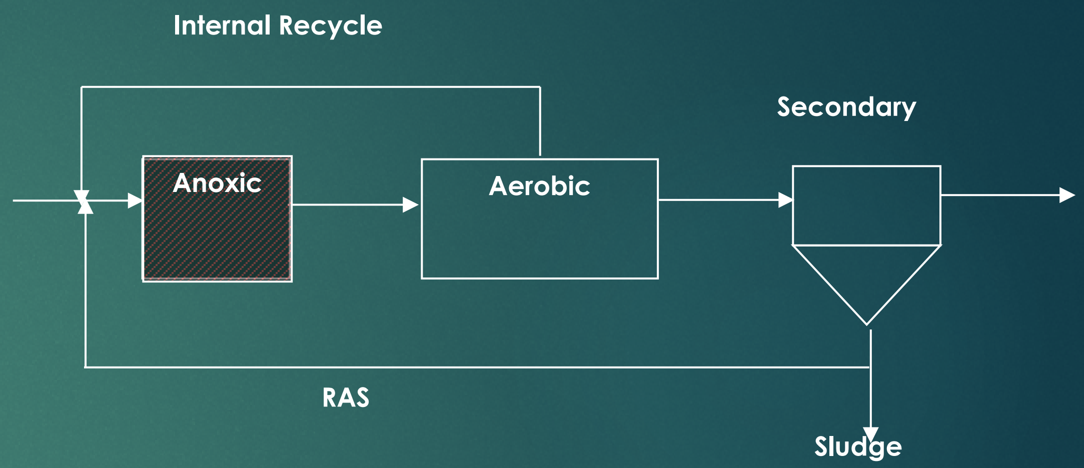
Organic N
+ Nitrate

General Types of BNR Activated Sludge Processes

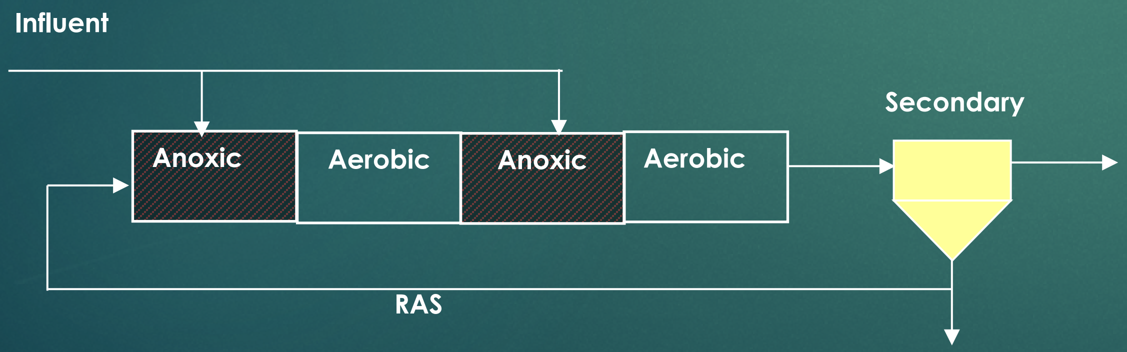
Ludzack-Ettinger Process



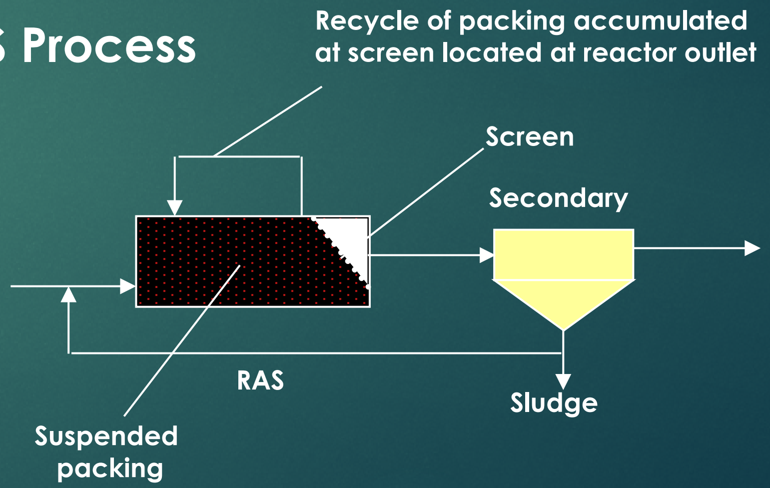
Modified Ludzack-Ettinger (MLE)Process



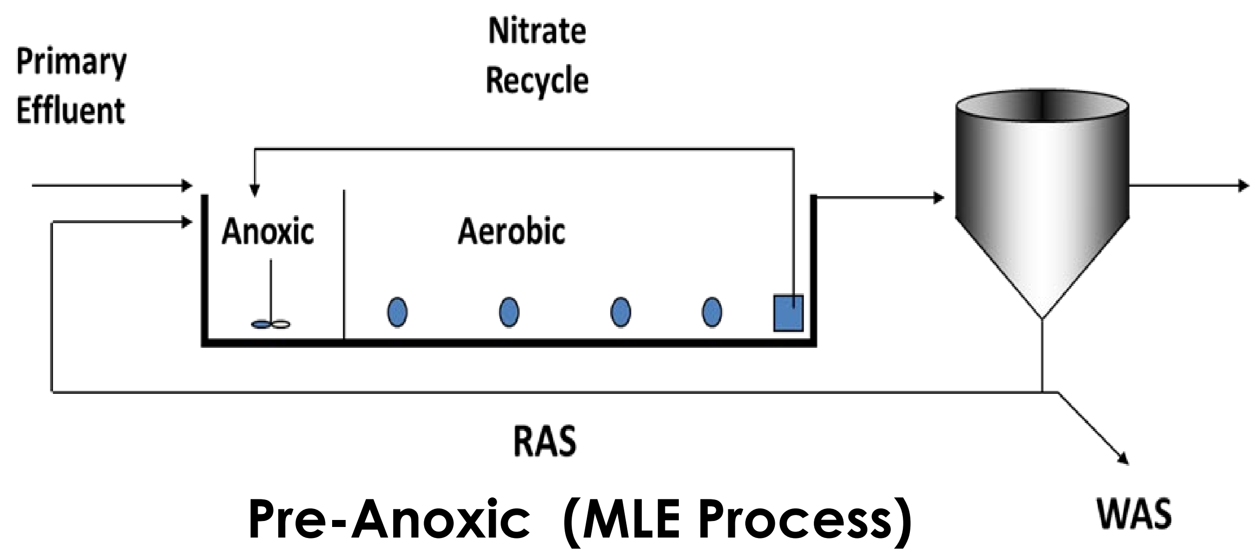
Step-Feed BNR Process



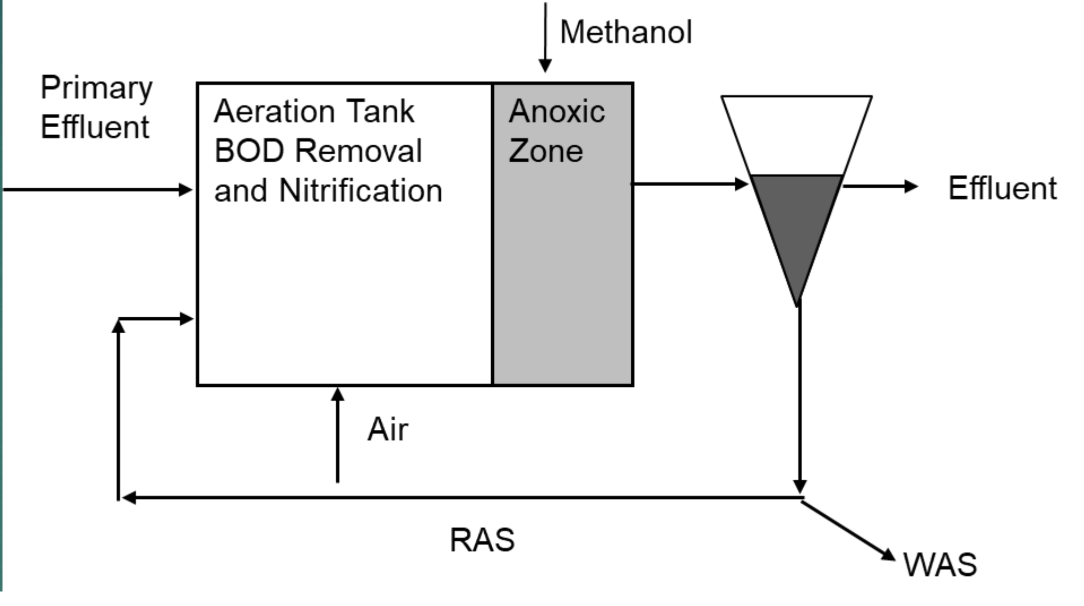
IFAS Process



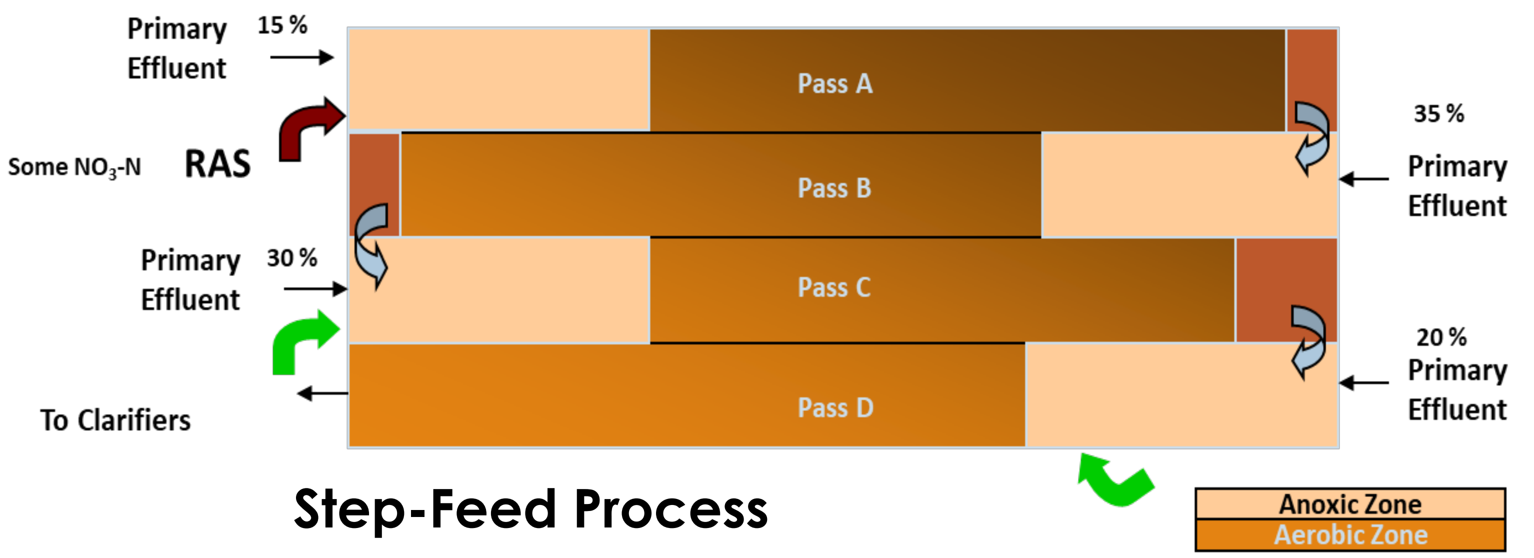
General Types of BNR Activated Sludge Processes



Pre-Anoxic (MLE Process)



Post-Anoxic (Wuhrmann Process)



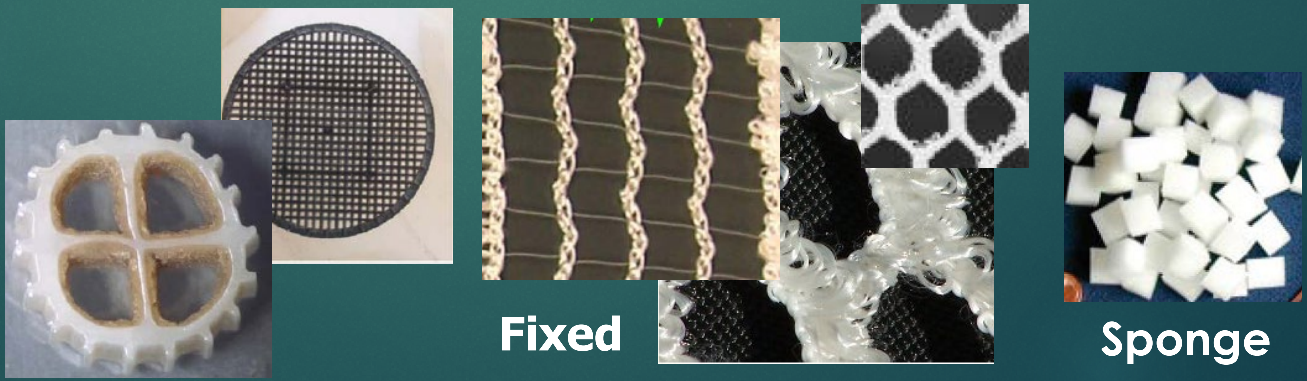
Step-Feed Process

Hybrid BNR

Activated Sludge and Fixed Film Processes

IFAS – Integrated Fixed Film/Activated Sludge
MBBR- Moving Bed Biofilm Reactor

- Advantages of IFAS and MBBR
  - Retrofit or New Construction
  - Higher "MLSS" without need for additional AT Volume
  - Increase plant capacity on same footprint
  - Phased construction
- Multiple Media Types



IFAS Aeration and Media Retention

Aeration

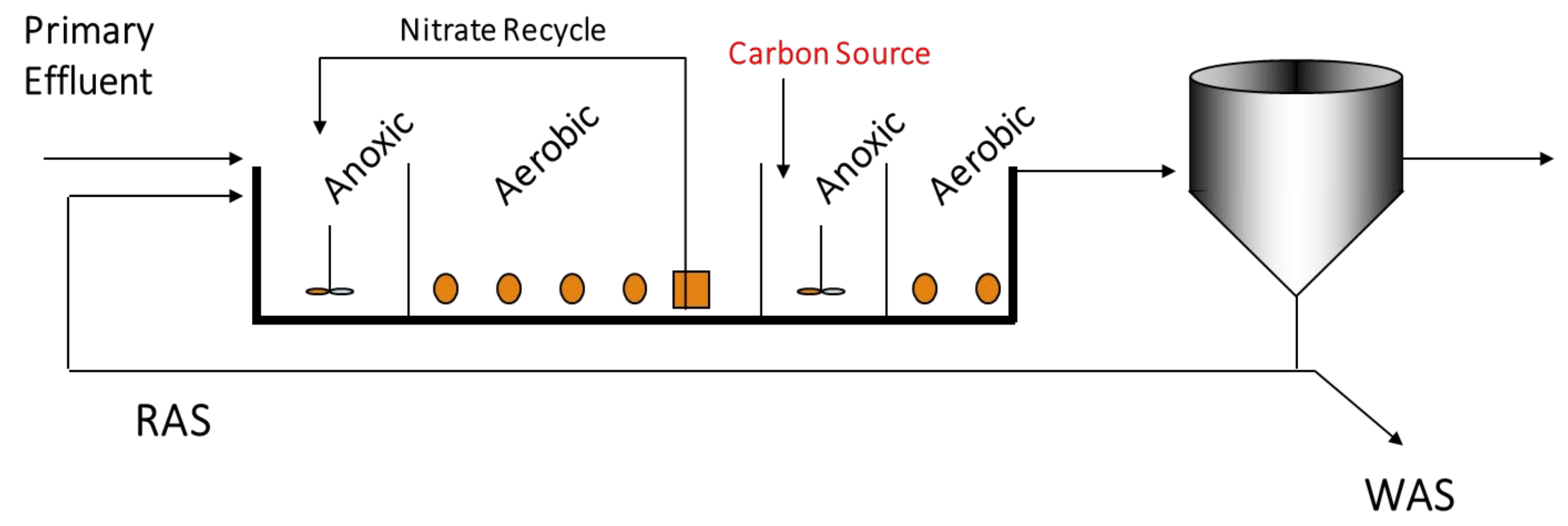
- Plastic – coarse bubble
- Fixed – fine bubble
- Normally supplied as part of package for plastic
- No additional air for main tank
- Air knife / additional air at screens

Media Retention Screens

- Headloss – 2-4 inches
- 6 mm screens general rule of thumb
- Cylindrical at effluent / vertical at anox
- Higher MLSS – consider additional air / flushing at screens

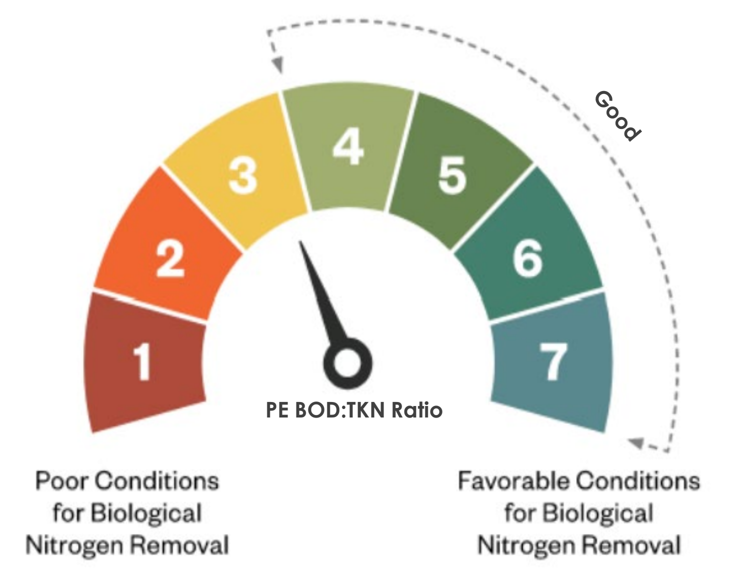



4-Stage BNR w/Supplemental Carbon



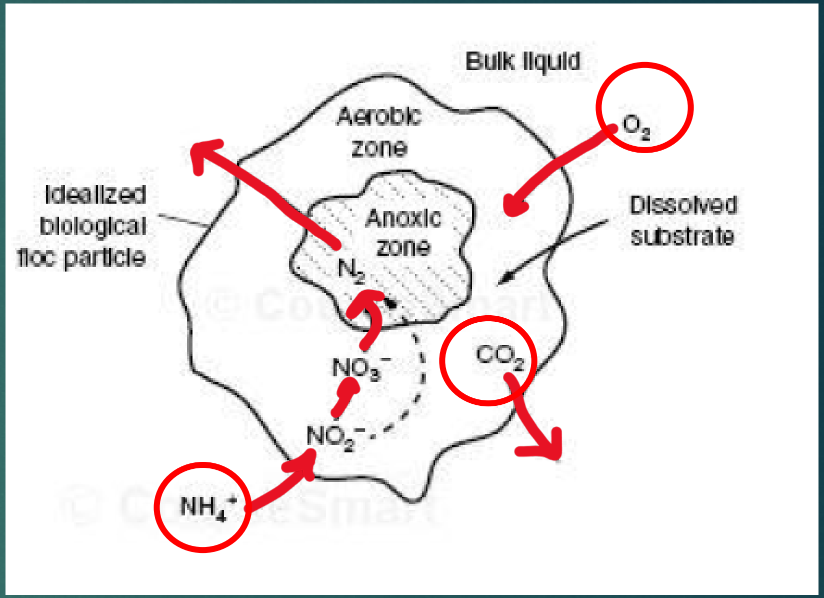
- Post-anoxic Zone
  - BOD/COD removed in aerobic zone
  - Very little remaining
- C/N ratio
  - Theory 2.55 g C/g N
  - Practice about 5 g C/gN
- Supplemental Carbon
  - Increase nitrate removal
  - Accelerates denitrification
- Carbon Compounds Used
  - Methanol
  - Glycerol
  - Acetate
  - Proprietary products

BOD:TKN Ratio for Effective Denitrification



Simultaneous Nite/Denite - SND

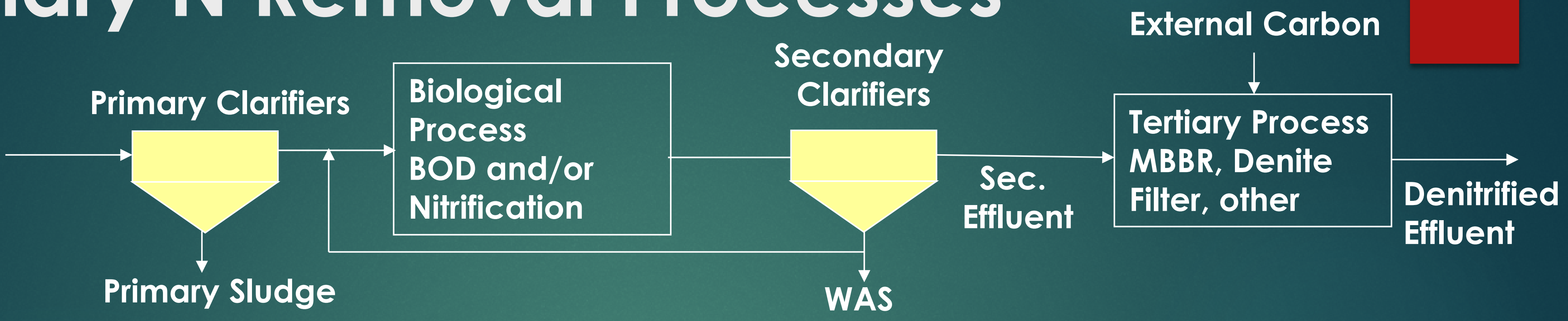
- Accomplished by operation at low DO
- Produce activated sludge floc with both aerobic and anoxic zones
- Oxygen depleted within the floc
- DO cannot penetrate the entire floc depth and anoxic zones occur in inner floc
- Not captured in process models
- Can be significant in systems with poorly defined Anoxic/Aerobic zones or periodic aeration
- Engineered via fine DO control
- Aerobic Granular Process works on this principle



- DO and substrates outside floc diffuse into the aerobic zone
- Dependent on DO, ammonia and bCOD availability

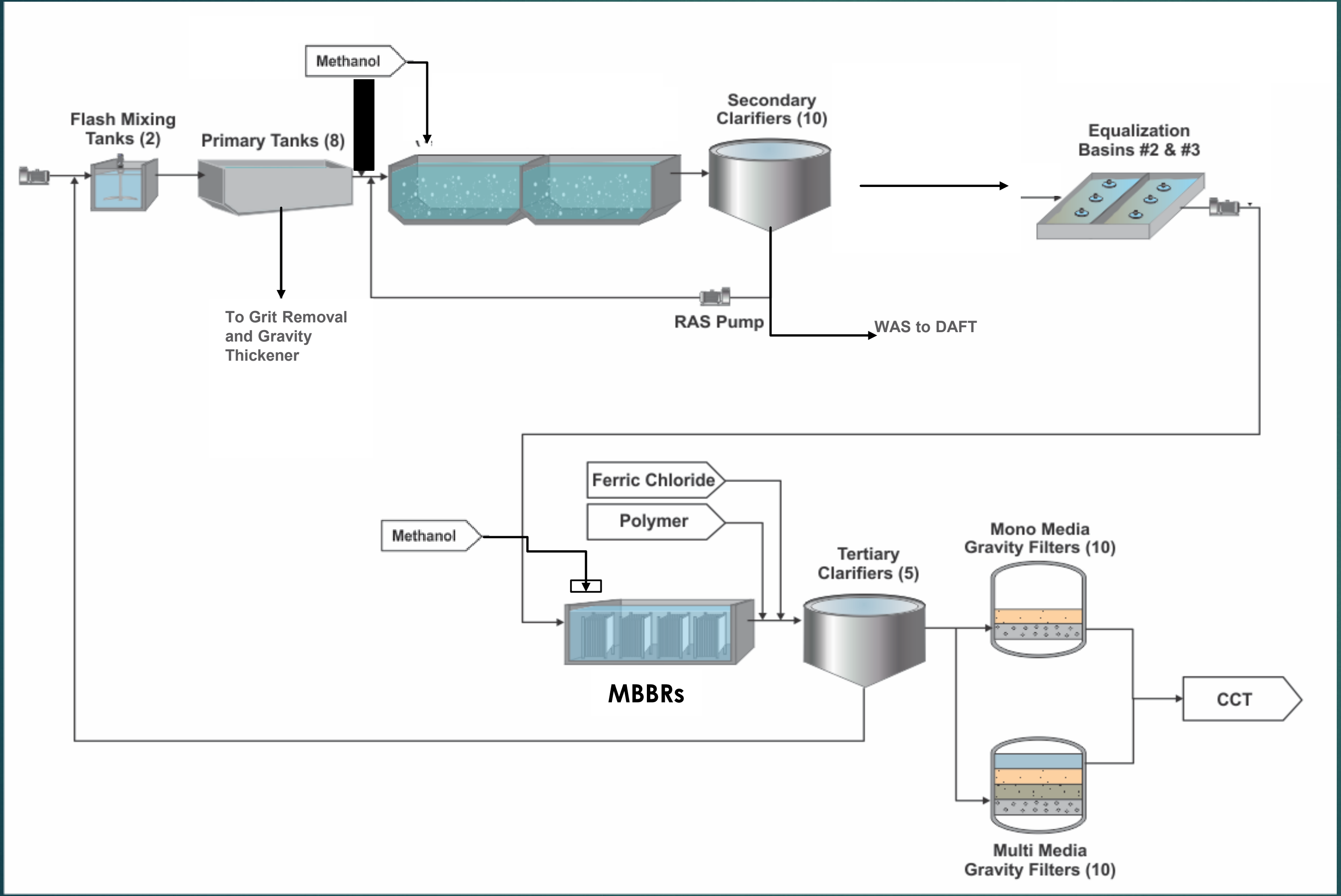
Tertiary and Sidestream N Removal Processes

Tertiary N Removal Processes



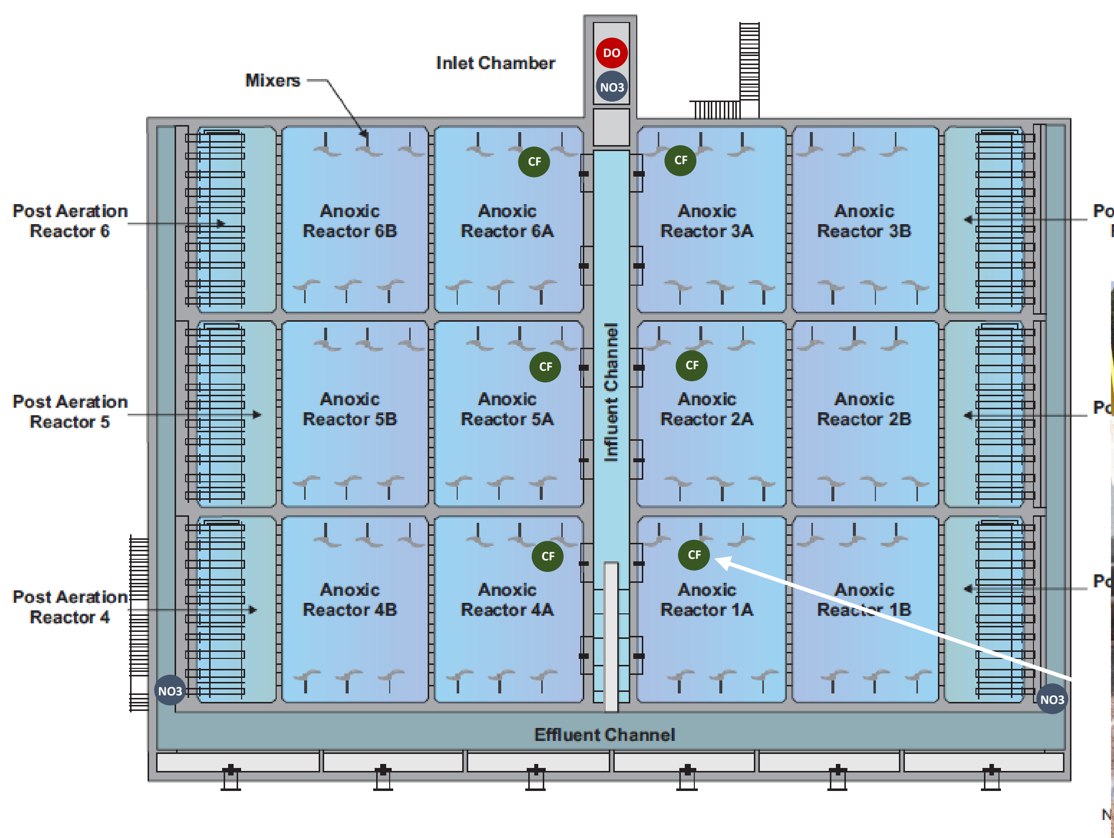
- N Removal in Tertiary Process as an add-on to the existing facility
- Common processes include MBBRs, Trickling Filters (only for tertiary nitrification), Denitrification Filters
- If the main process performs nitrification, only denitrification with external carbon source is needed in tertiary treatment
- Can achieve very low TIN < 3 mg/L

Noman Cole Jr. Pollution Control Plant – Tertiary MBBR



- Currently 67 mgd
- Step-feed BNR followed by tertiary denitrification MBBR
- TN < 3 mg/L

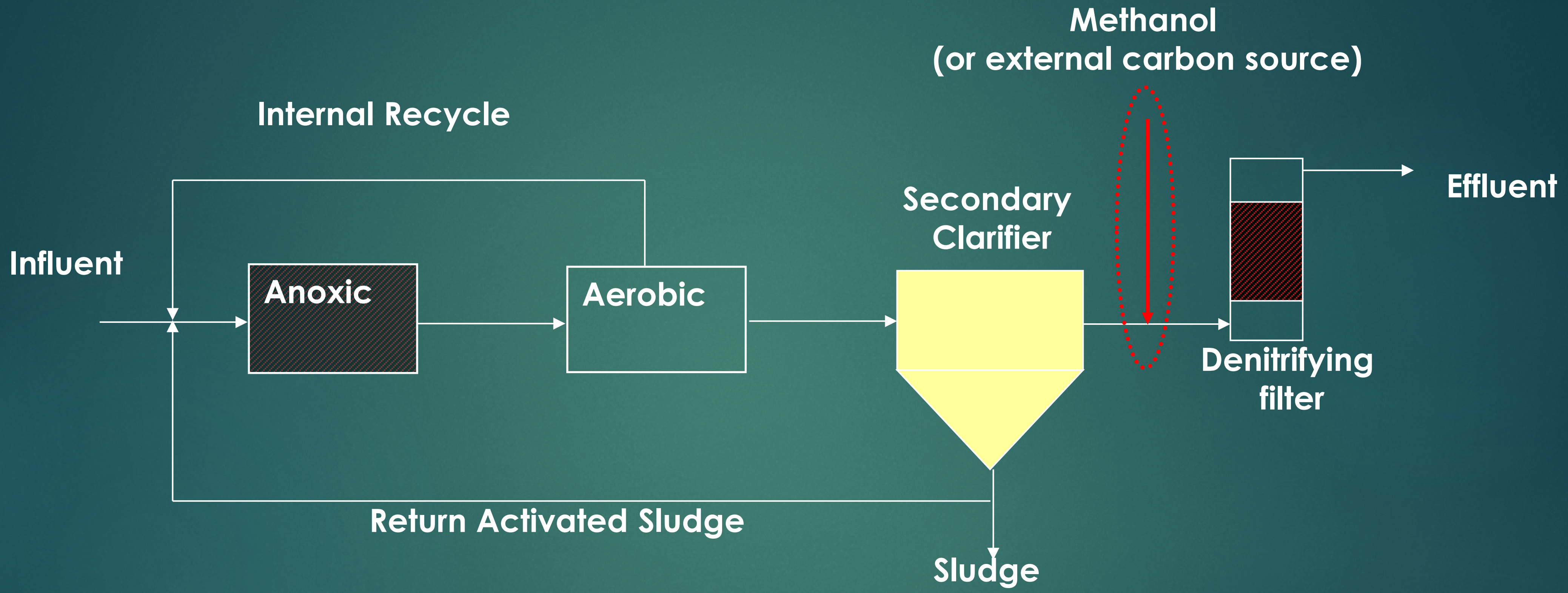
Tertiary Denitrification MBBR



DO DO probe
NO3 NO3 probe
CF Carbon feed location

- Q = 80 mgd capacity
- N Removal = 4,000 lb NOx-N/day capacity
- Requires supplemental carbon - methanol
- Design HRT = 35-45 min

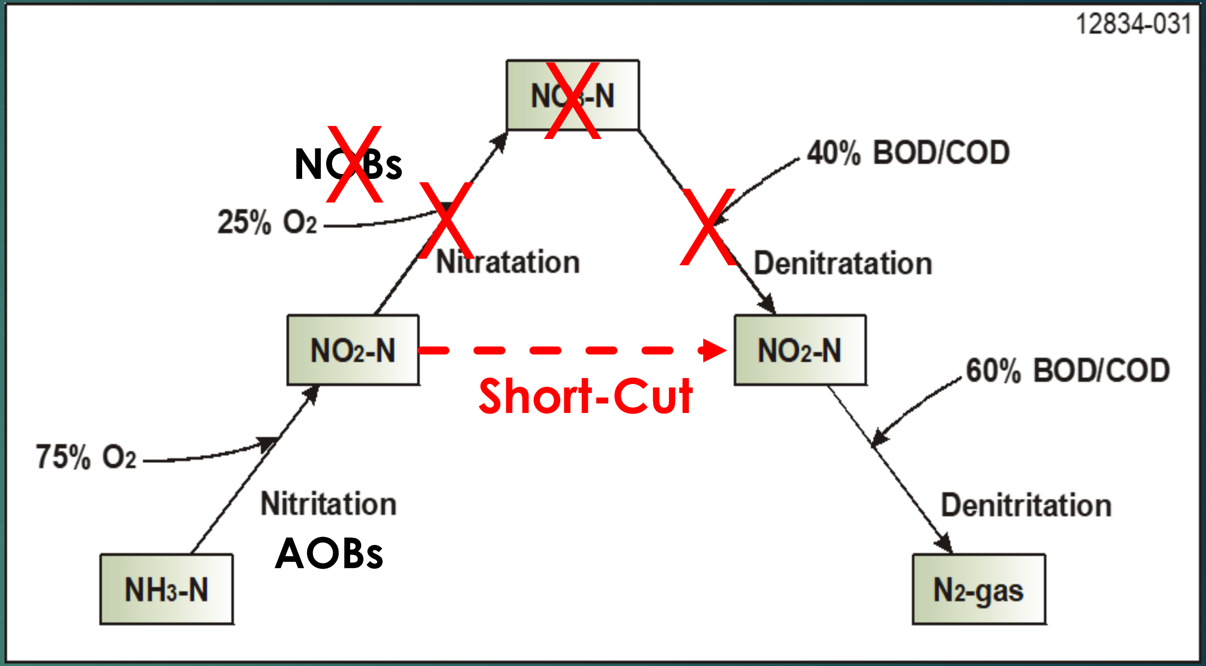
Tertiary Denitrification Filter



- It is possible to retrofit existing effluent filters to denitrification filters provided they are deep enough (> 6 ft bed depth)
- Need external carbon (i.e. methanol) for effective denitrification

Short-cut BNR

- Less organic carbon consumption
- > 50% reduction in aeration costs
- ~50% reduction in alkalinity
- Reduced sludge production
- NOB suppression
- Required step in traditional deammonification (Anammox)



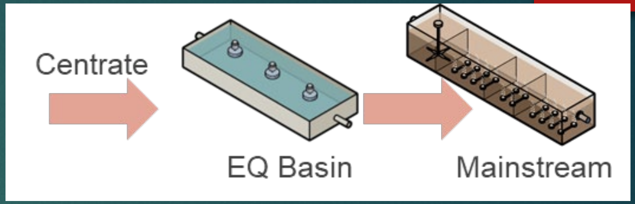
- 1st step – Nitritation $NH_4 \rightarrow NO_2$
  - AOBs convert ~ 1/2 of the ammonia into nitrite
  - Partial nitritation is common in WW treatment specially as part of **deammonification** process

- 2nd step – Denitritation NO2 → NO3
  - NOB not used to convert nitrite to nitrate

Sidestream Treatment

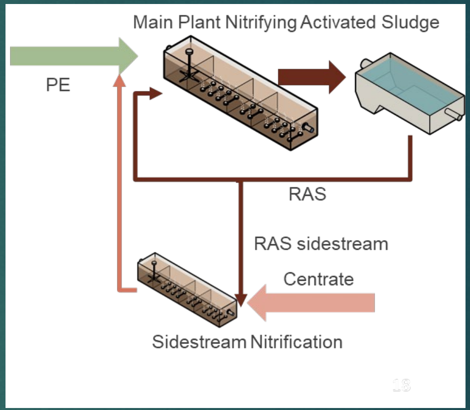
Equalization provides a simple solution for facilities with periodic dewatering

- Dependent on mainstream facility nitrogen removal



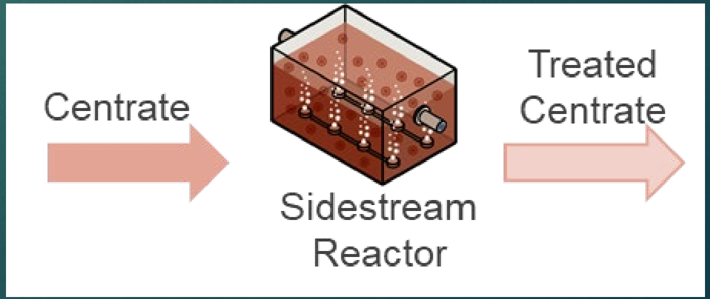
Centrate nitrification is seldom used today for reasons including:

- Limited N removal
- Highly dependent on available alkalinity
- Large volumes and operational costs



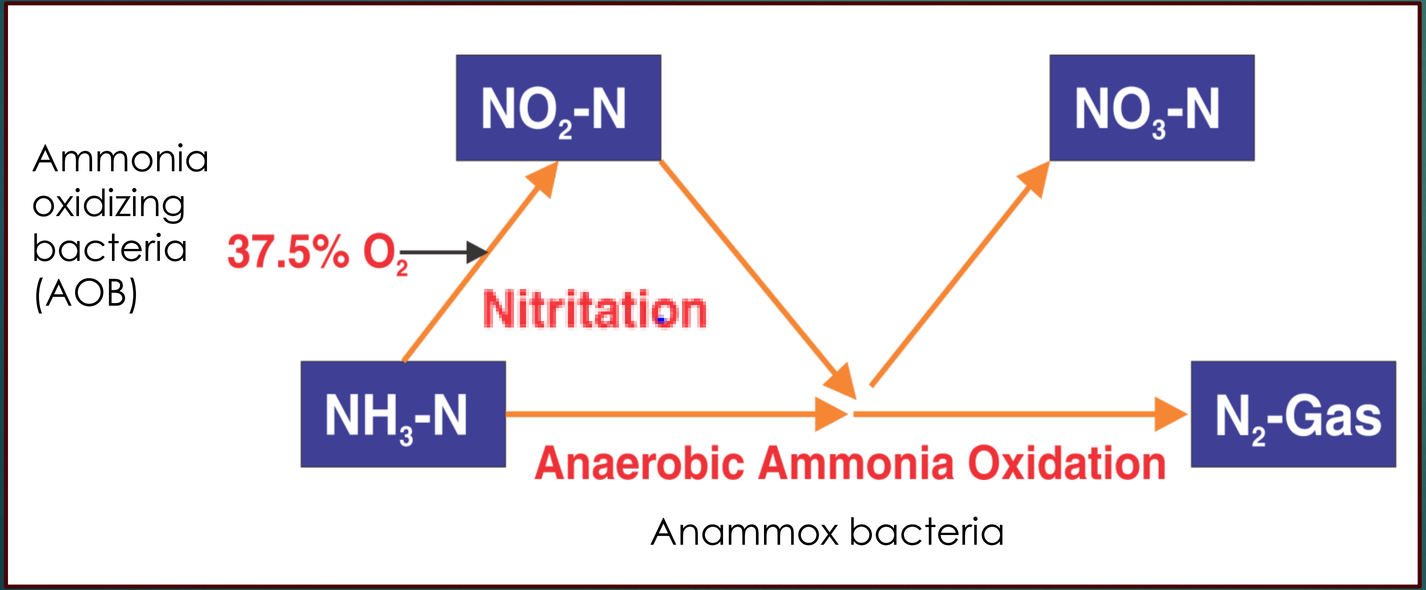
Sidestream deammonification is a demonstrated technology (15+ years). Implemented at numerous facilites around the country:

- Provides effective N removal in small footprint
- Simple process
- Demonstrated success
- Robust



Sidestream Treatment - Deammonification

- Centrate/Filtrate from Dewatering of AD Sludge can be significant source of Ammonia load
- Sidestream treatment can reduce that load in a compact process
- Has become standard for SS treatment
- Three primary vendors in US – AnitaMox, DEMON,



NO_2-N

NO_3-N

Ammonia oxidizing bacteria (AOB)

37.5% O_2

Nitritation

NH_3-N

N_2-Gas

Anaerobic Ammonia Oxidation

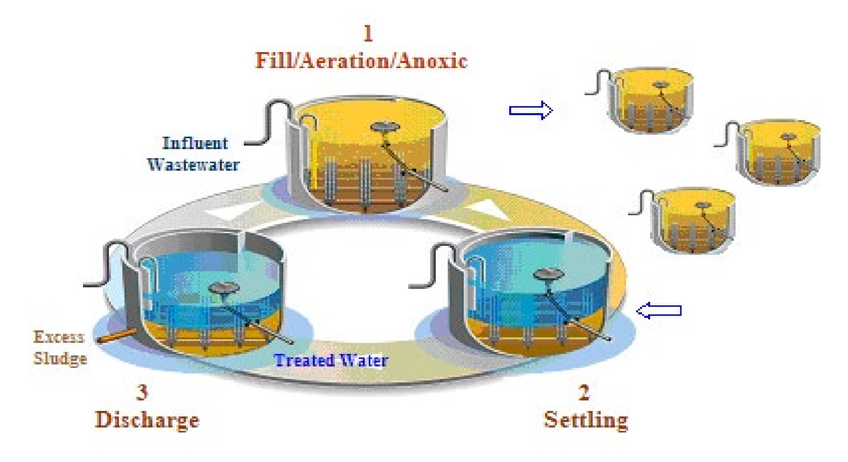
Anammox bacteria

$NH_3 + NO_2 + \text{Alkalinity} \rightarrow N_2 + NO_3$

Anammox Biomass

- Slow growing organisms – Long SRT
- Preferential selection of Anammox and AOBs – NOB supression
- Requires approach to maintain biomass in the system
  - Granular reactor or CSTR
  - Fixed film approach
  - SBR
  - Hydrocyclones or screens

Courtesy DEMON



Courtesy Degremont

Courtesy Paques

Courtesy Veolia

Benefits of Sidestream Deammonification?

Can increase N treatment capacity, reliability and overall flexibility

- Intercept and treat 15 to 30% of Ammonia load in compact footprint

Reduce load impacts on mainstream biological process

- Decreases intensity and duration of recycle nutrient load
- Stabilized nitrogen removal and also benefit disinfection stability

Cost effective for nutrient removal

- High temperature, low flow, high concentrations allow for compact footprint
- ~ 30 to 50% of the cost to treat nutrients in mainstream

Seeding benefits

- Nitrifiers or Anammox bacteria can be seeded
- Increases nitrogen removal robustness in the mainstream

Robust process when sized appropriately

- Set it and forget it
- Routine maintenance → probes/analyzers

BNR Operational Considerations

Oxygen Requirements: Nitrification vs. BOD Removal

Given: Plant Influent Flow = 10 MGD
Plant Influent TKN = 35 mg/l
Plant Influent BOD_5 = 180 mg/l

BOD_5 Removal in Primary Clarifier = 30%
TKN Removal in Primary Clarifier = 10%

Oxygen Required for BOD Removal

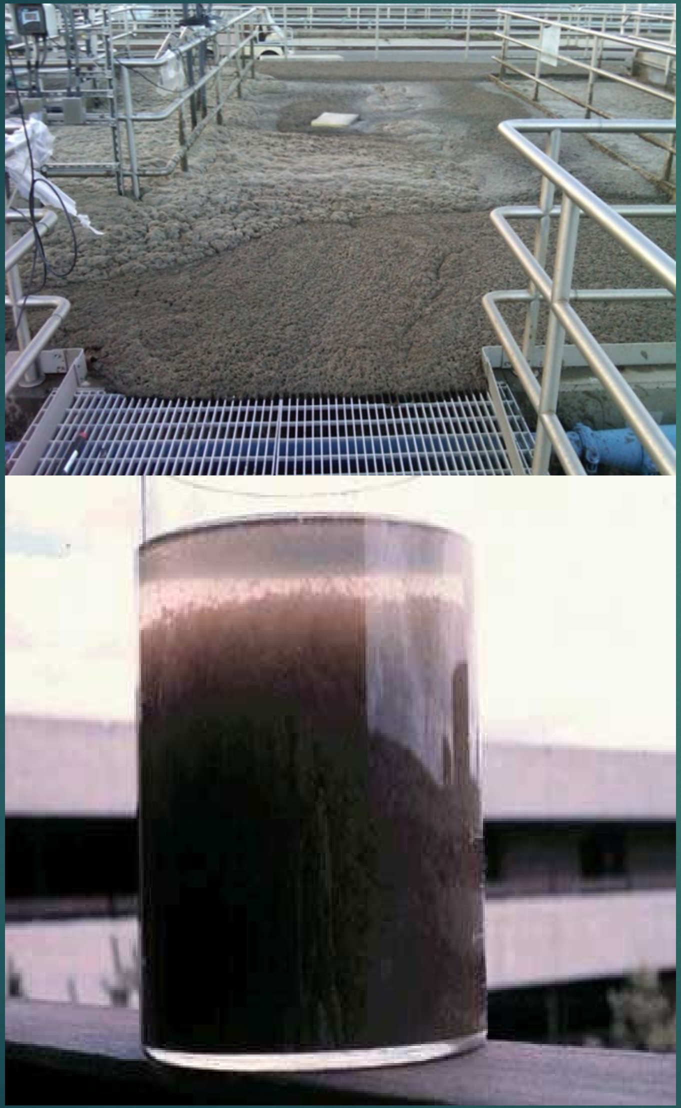
(10 mgd)	x	(180 mg/l)	x	(0.7)	x	(1.1)	x	(8.34)	= **11,559 lbs O_2/day**
Flow		BOD_5 conc.		fraction of BOD remaining after primary clarifiers		lbs of oxygen required per lb of BOD_5 removed			

Oxygen Required for Conversion of Ammonia to Nitrate

(10 mgd)	x	(35 mg/l)	x	(0.9)	x	(4.57)	x	(8.34)	= **12,006 lbs O_2/day**
Flow		TKN conc.		fraction of TKN remaining after primary clarifiers		lbs of oxygen required per lb of ammonia-N nitrified			

Nitrification Can Double Your Oxygen Requirement.

Bulking and Foaming



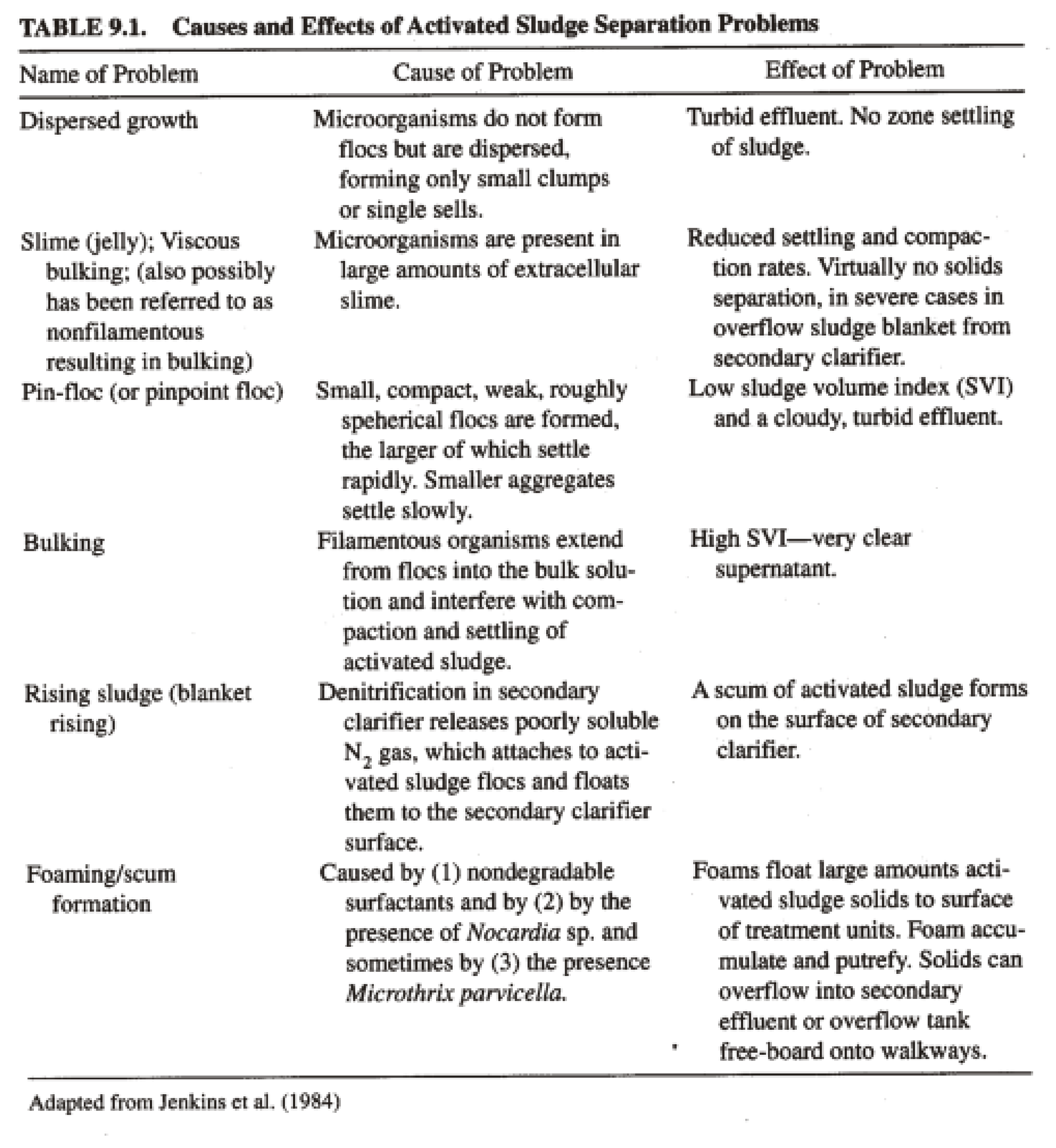
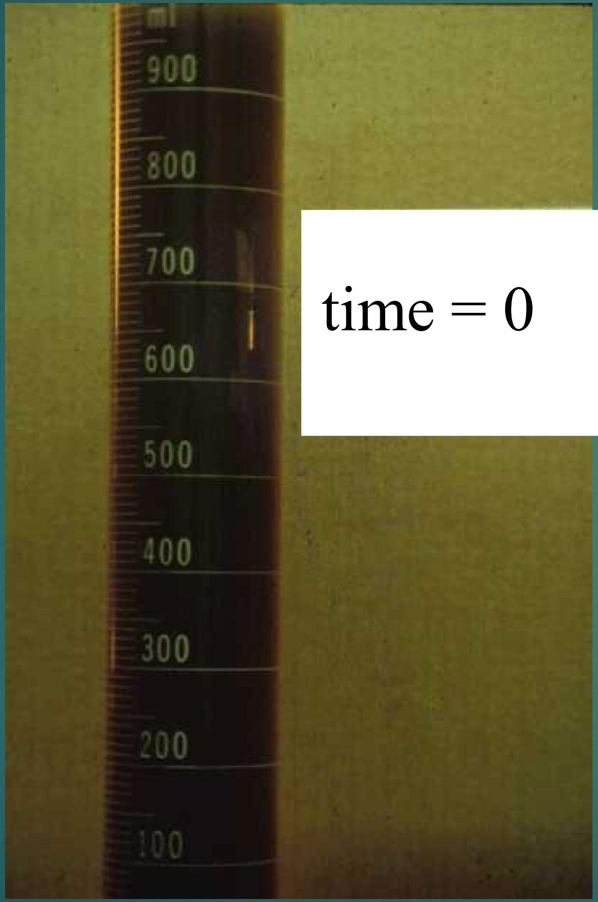


TABLE 9.1. Causes and Effects of Activated Sludge Separation Problems

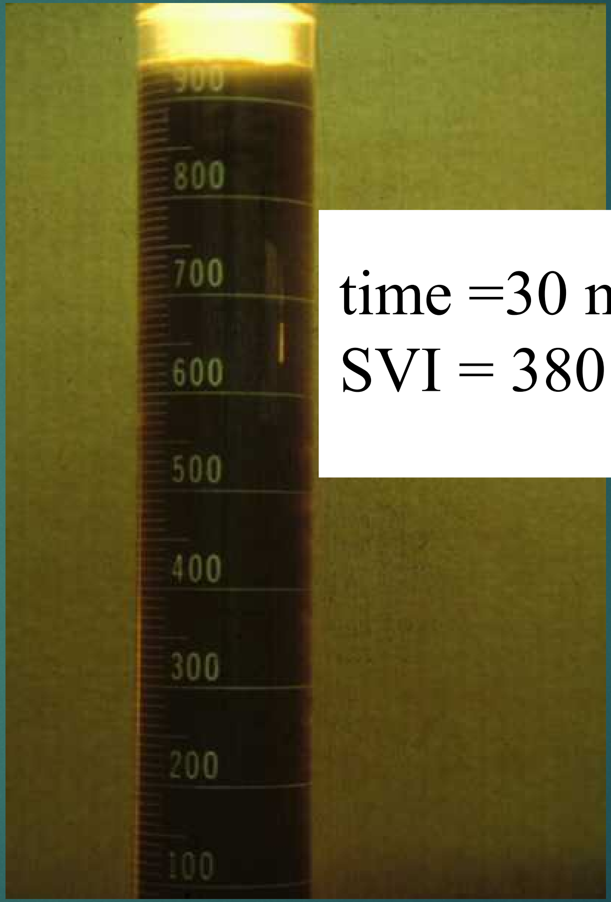
Name of Problem	Cause of Problem	Effect of Problem
Dispersed growth	Microorganisms do not form flocs but are dispersed, forming only small clumps or single sells.	Turbid effluent. No zone settling of sludge.
Slime (jelly); Viscous bulking; (also possibly has been referred to as nonfilamentous resulting in bulking)	Microorganisms are present in large amounts of extracellular slime.	Reduced settling and compaction rates. Virtually no solids separation, in severe cases in overflow sludge blanket from secondary clarifier.
Pin-floc (or pinpoint floc)	Small, compact, weak, roughly speherical flocs are formed, the larger of which settle rapidly. Smaller aggregates settle slowly.	Low sludge volume index (SVI) and a cloudy, turbid effluent.
Bulking	Filamentous organisms extend from flocs into the bulk solution and interfere with compaction and settling of activated sludge.	High SVI—very clear supernatant.
Rising sludge (blanket rising)	Denitrification in secondary clarifier releases poorly soluble N_2 gas, which attaches to activated sludge flocs and floats them to the secondary clarifier surface.	A scum of activated sludge forms on the surface of secondary clarifier.
Foaming/scum formation	Caused by (1) nondegradable surfactants and by (2) by the presence of *Nocardia* sp. and sometimes by (3) the presence *Microthrix parvicella.*	Foams float large amounts activated sludge solids to surface of treatment units. Foam accumulate and putrefy. Solids can overflow into secondary effluent or overflow tank free-board onto walkways.

Adapted from Jenkins et al. (1984)

Sludge Bulking



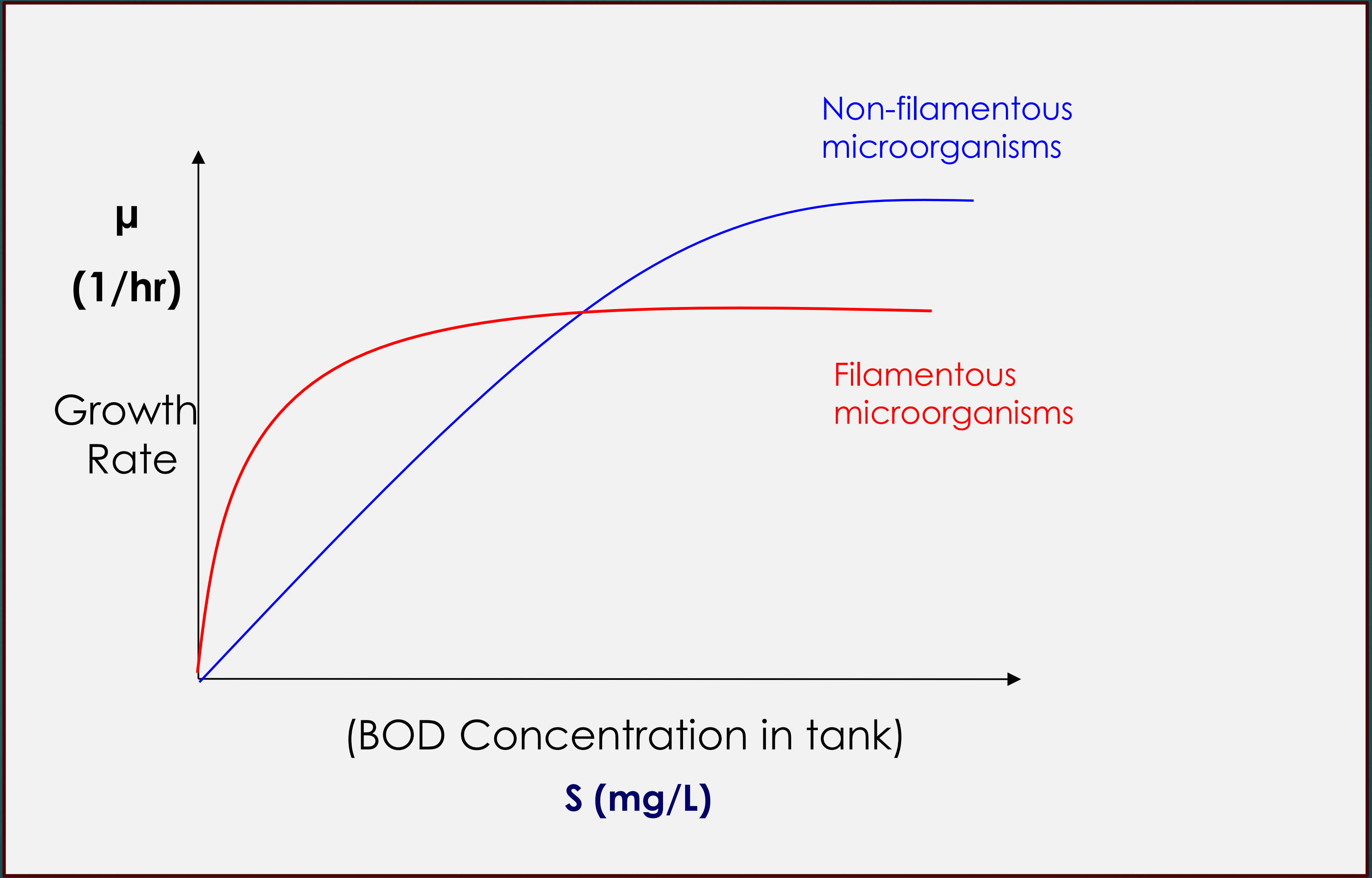
time = 0



time =30 min
SVI = 380 mL/g

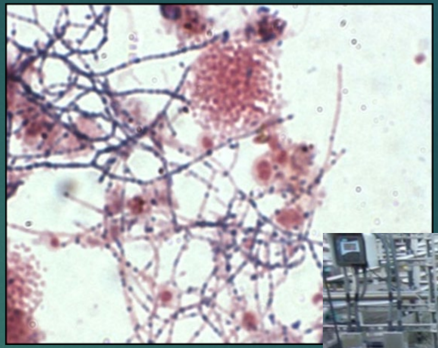
Bulking = SVI > 150 mL/g

Growth Advantage for Filamentous vs. Non-Filamentous



Biological Foam

- Often caused by proliferation of *Microthrix* and *Nocardia* biomass
- Very common in BNR systems
- Often Seasonal
- Plant hydraulics/design - surface trapping



Effective Controls

- Surface Wasting (SWAS)
- RAS chlorination
- Vigilance and wasting strategy
- Chlorine Hoods/Surface Sprays
- Defoamant (Emergency)

Causes Of Bulking/Foaming

1. DO concentration

Four filamentous bacteria proliferate with low DO.

- At low to moderate sludge age: type 1701, S. natans and *Haliscomenobacter hydrossis*
- At high sludge age: ***Microthrix parvicella***

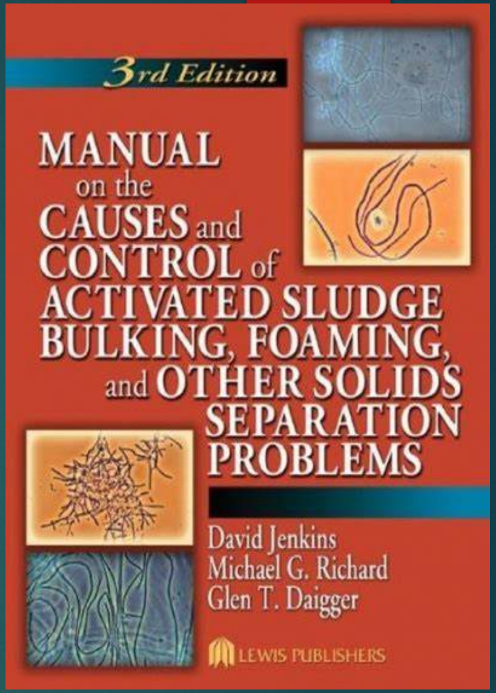
All of these microorganisms usually respond well to increases in DO.

2. Nutrient deficiency

Type 021N, *Thiothrix spp.*, type 0041 and type 0675 grow with nitrogen and/or phosphorus deficiencies. Biological slime often accumulates as well with the growth of these microorganisms. If chronic issue, adding nutrients to the aeration tank may be required.

3. Low pH

Fungi can proliferate under low pH conditions – especially if influent pH is low. However, may occur in nitrifying systems or oxygen-AS systems with low alkalinity WW. Addition of alkalinity to the system may be required.



3rd Edition

MANUAL
on the
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ACTIVATED SLUDGE
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PROBLEMS

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LEWIS PUBLISHERS

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By ***David Jenkins***, *Michael G. Richard*, *Glen Daigger*

Causes Of Bulking

4. Sulfide

Thiothrix spp., type 021N, Beggiatoa spp. and type 0914 can oxidize sulfide to elemental sulfur and incorporate the sulfur into the cell. The sulfur can be seen in the cell via microscopy. Eliminate sulfide source or the chemically treat sulfide.

5. rbCOD

Many problem organisms grow well on readily biodegradable, soluble materials. Including: **S. natans, type 021N, Thiothrix spp., H. hydrossis, Nostocoida limicola and type 1851**. Reducing the sludge age and installing a selector often help to control filaments.

6. Slowly metabolized food

Types 0041, 0092, and 0675 and M. parvicella are able to grow on slowly biodegradable COD and are prevalent in BNR systems. Growth can be enhanced by complete mixing in the aeration tank. Control by reducing the sludge age, plug-flow operation if possible, and maintaining a uniform DO.

Diagnostics

- Plant Performance
  - BOD removal Efficiency
  - TSS in effluent

- Visual
  - Foaming in aerators
  - Pin-floc in clarifiers
  - Sludge color

- Settling Tests
  - SVI
  - Supernatant clarity
  - Settling tests

- Microscopy
  - Inventory
  - Sludge Health
  - Floc Structure/activity
  - Filaments
  - Toxicity

- Oxygen Uptake Studies
  - OUR – Oxygen Uptake Rate
  - SOUR
  - Tracking

World of BNR Options

- Conventional BNR
  - Multi-Stage BNR
  - Step-feed
  - Two-sludge
  - Nite Trickling filters
- Intensified BNR
  - IFAS
  - MABR
  - Biomag™
  - BIOCOS®
  - Granular Sludge
  - MBR
  - DAS
- Tertiary Denite
  - MBBR
  - Biocatalysts
  - Biologically Active Filtration
- Next Gen N-Removal
  - SND
  - Nitritation/ Denitritation
  - Mainstream Deammonification
  - PANDA
- Advanced
  - Microalgae
  - Advanced Floc/Sed
  - Ozone/ BAC
  - Post Filtration GAC
  - RO
- Sidestream
  - Deammonification
  - Chemical P removal
  - P recovery

Thank You!

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Questions?