United States Environmental Protection Agency

EPA Nutrient Control Webinar:
Nitrogen Control at Wastewater Treatment Plants

U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Water Supply and Water Resources Division

United States Environmental Protection Agency

Webinar Agenda

Welcome and Introduction-Dan Murray

Aging Water Infrastructure Research Program-Dan Murray

Overview of WERF Nutrient Challenge-Amit Pramanik

Fundamental Principles of Biological Nitrogen Removal-Dave Stensel

Process Alternatives-Cliff Randall

Design and Operational Issues for Nitrogen Removal Process Optimization-James Barnard

Design and Process Modeling Considerations-Dave Stensel

Aging Water Infrastructure Research Program

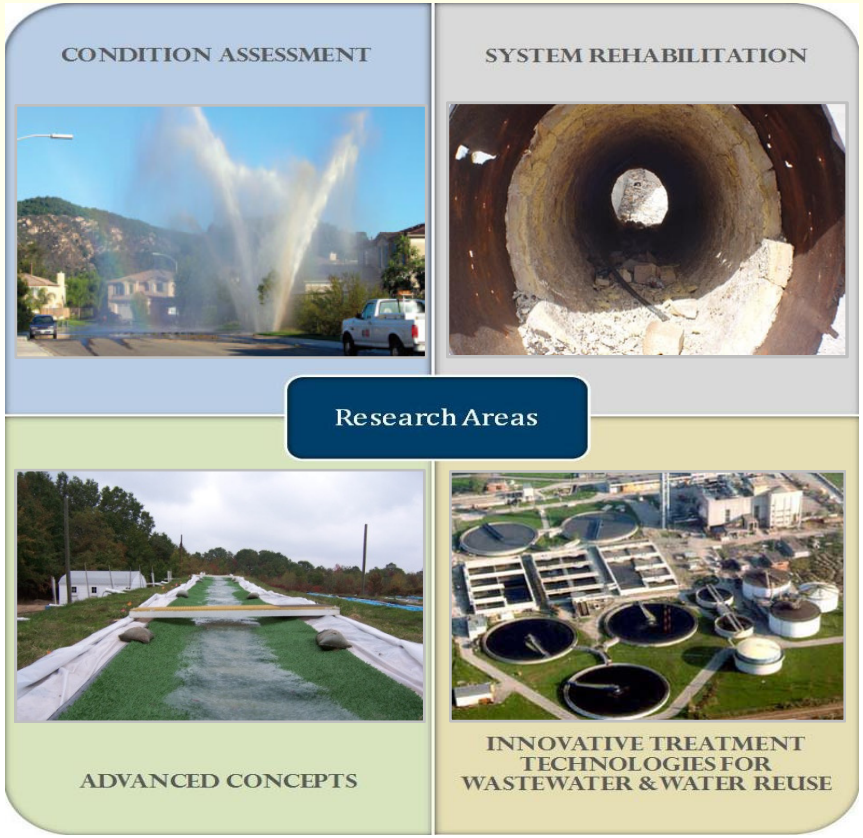
Innovation & Research for the 21st Century

Daniel J. Murray, Jr., P.E., BCEE, M.ASCE
U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Water Supply and Water Resources Division

Aging Water Infrastructure Research Program

Goal: To evaluate and demonstrate innovative technologies, and improve the cost effectiveness of operation, maintenance, and replacement of aging and failing drinking water and wastewater infrastructure.

Encompasses the collection and analysis of data for determining the structural, operational, and performance status of capital infrastructure.



Application of infrastructure repair, renewal, & replacement technologies in an effort to return functionality to drinking water or wastewater systems or sub-systems.

Application or adoption of new and innovative infrastructure designs, management procedures, and operational approaches.

(Green Infrastructure)

Addresses the need for improved water quality and the growing demands for safe and reliable reclaimed wastewater and stormwater.

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Wastewater Technologies

Nutrient Control Design Manual & Seminars

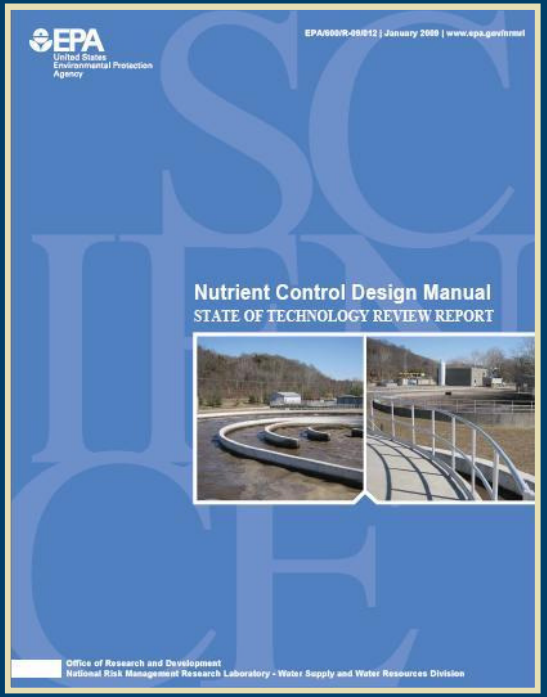
Manual

- Updated engineering design guidance for the treatment of nitrogen and phosphorus at municipal wastewater treatment plants.
- Based on technology innovations that have been developed and applied over the past 20 years.
- Published in August 2010.

Seminars

- Three seminars presented in Regions 1, 5, and 10 in 2009 and 2010.
- Webinar on Nitrogen Control on March 8, 2012

State of Technology Review Report



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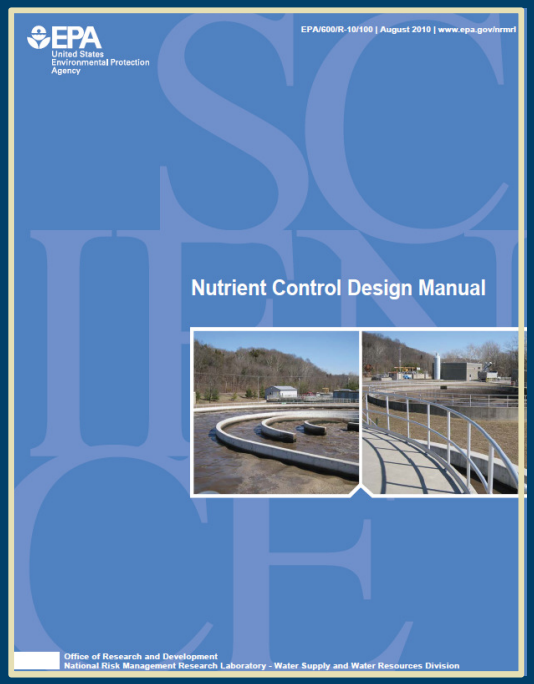
Program Products

AWI Website:

www.epa.gov/awi

Nutrient Control Design Manual



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EPA Nutrient Removal Webinar:

Nitrogen Control at Wastewater Treatment Plants

WERF Nutrient Removal Challenge

Thursday, March 8, 2012, 1:00 p.m. to 4:30 p.m. EST

Amit Pramanik, PhD, BCEEM
Senior Program Director
Water Environment Research Foundation
www.werf.org
apramanik@werf.org

WERF

WERF Nutrient Removal Challenge

- Develop and share credible scientific information about nutrients & their bioavailability to help regulators make informed decisions
- Better understand existing mechanisms of nutrient removal and best available technologies so treatment plants can become more efficient and effective, enabling them to cost-effectively meet permit limits
  - Focus on nitrogen (N) and phosphorus (P)
  - Wastewater treatment related issues

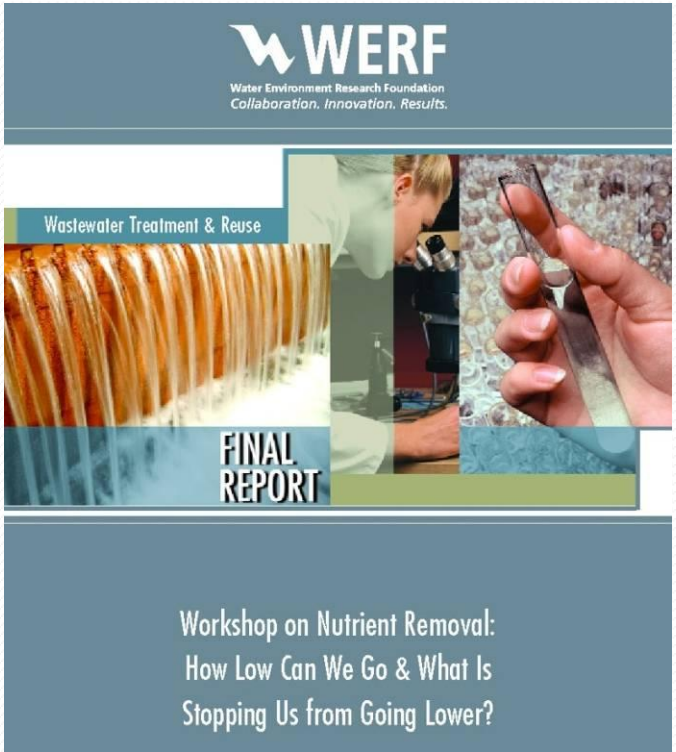
- Status: Ongoing, 5 – 7 year challenge
- Investment: ~$3 million WERF funds (started in 2007)
- In-kind, in-cash: >$10 million
- Leveraged with additional funding, Collaboration, etc.

WERF

Nutrient Removal Challenge Strategy

- Challenge is huge, Funds are limited, Knowledge is available and growing, Need to Collaborate
- Research roadmap developed and refined with industry expert knowledge and guidance
- Experts from utilities, consultants, academia, industry, regulators, *et al*

All working together under one umbrella

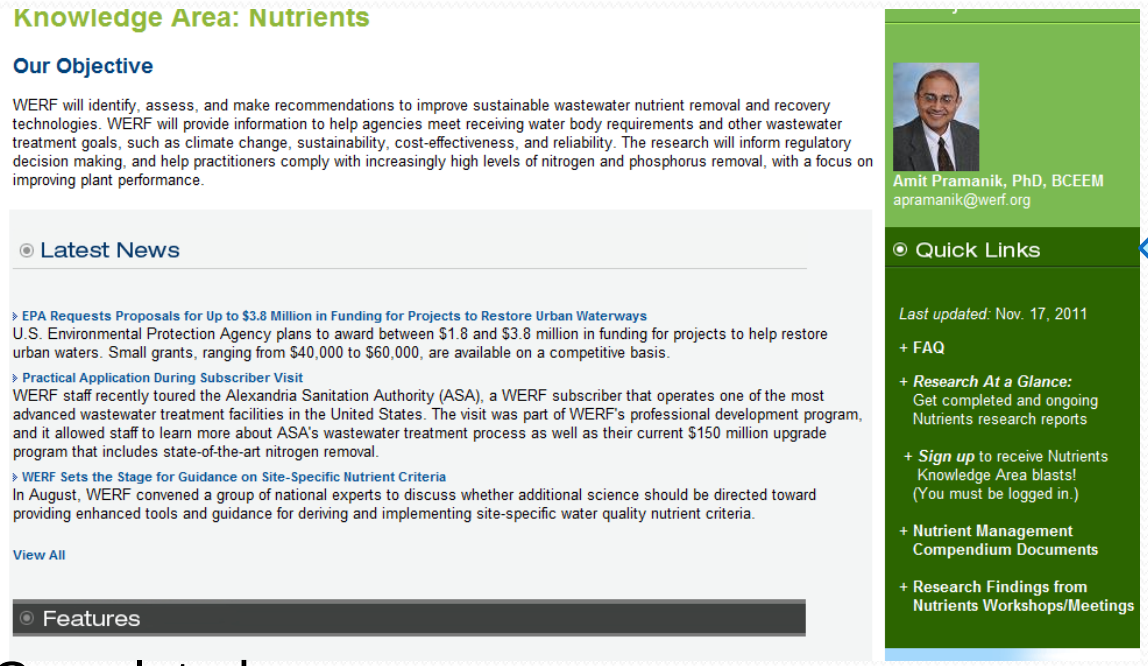


- Focus on collaboration to increase value to profession (instead of single projects)
- Address fundamentals, with strong results focus
- Engage stakeholders to participate in an active role
- Leverage ongoing projects
- Use "Tom Sawyer" principle to paint the fence together

COLLABORATION is the KEY!

Where to get more information

- www.werf.org/nutrients



Go to "Quick Links"

Completed:

- Twelve (12) completed Workshops / meetings
- Eight (8) technology/management "Compendium" documents
- Eight (8) published Final Reports

Plus, Ongoing and Planned WERF research – in this and other programs / challenges, including work funded under EPA – AWI

Principles of Biological Nitrogen Removal

H. David Stensel, PhD, PE
University of Washington

United States Environmental Protection Agency

U.S. EPA Technology Transfer Webinar
Nutrient Webinar on Nitrogen Removal

Fundamental Principles

- Nitrogen constituents
- Biological Removal Mechanisms
- Biological Process Fundamentals
  - Nitrification
  - Heterotrophic Denitrification
- Nitrification to NO2
- Exogenous carbon sources for denitrification
- Simultaneous nitrification/denitrification
- Anaerobic Autotrophic Denitrification -Anammox

Nitrogen in Wastewater

- Ammonia (NH_3)
- Ammonium Ion (**NH_4^+**)

} 60 to 70% of N in WW

- Organic Nitrogen – 30 to 40% of N in WWT
- Influent TKN (NH4 + organic N) -30 to 75 mg/L
- Urea ($(NH_2)_2CO$) hydrolyzes to ammonia

- Products of biological nitrification:
  - Nitrite (NO_2^-)
  - Nitrate (NO_3^-)

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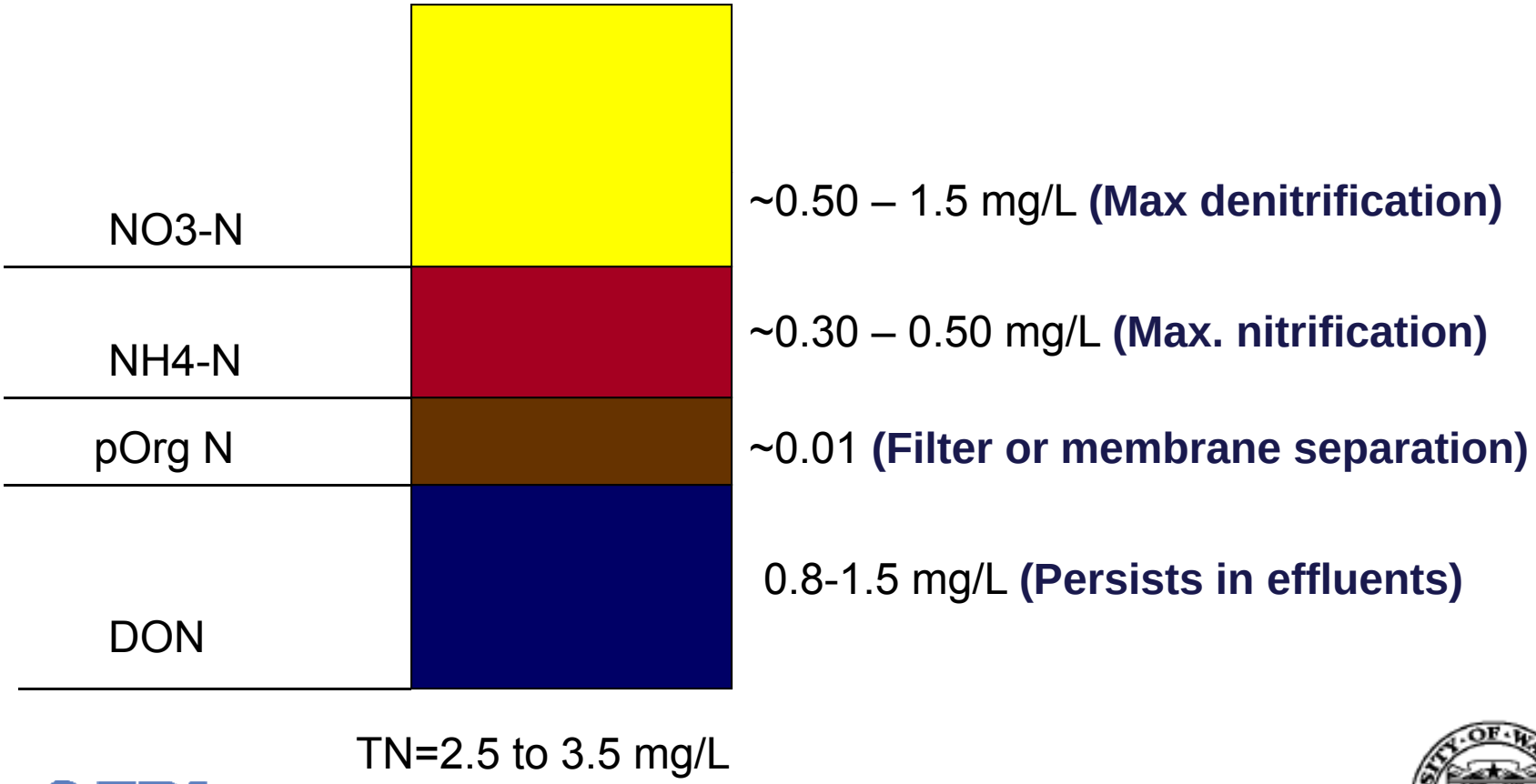
Dissolved organic nitrogen (DON) is an important N species in low effluent TN concentrations?



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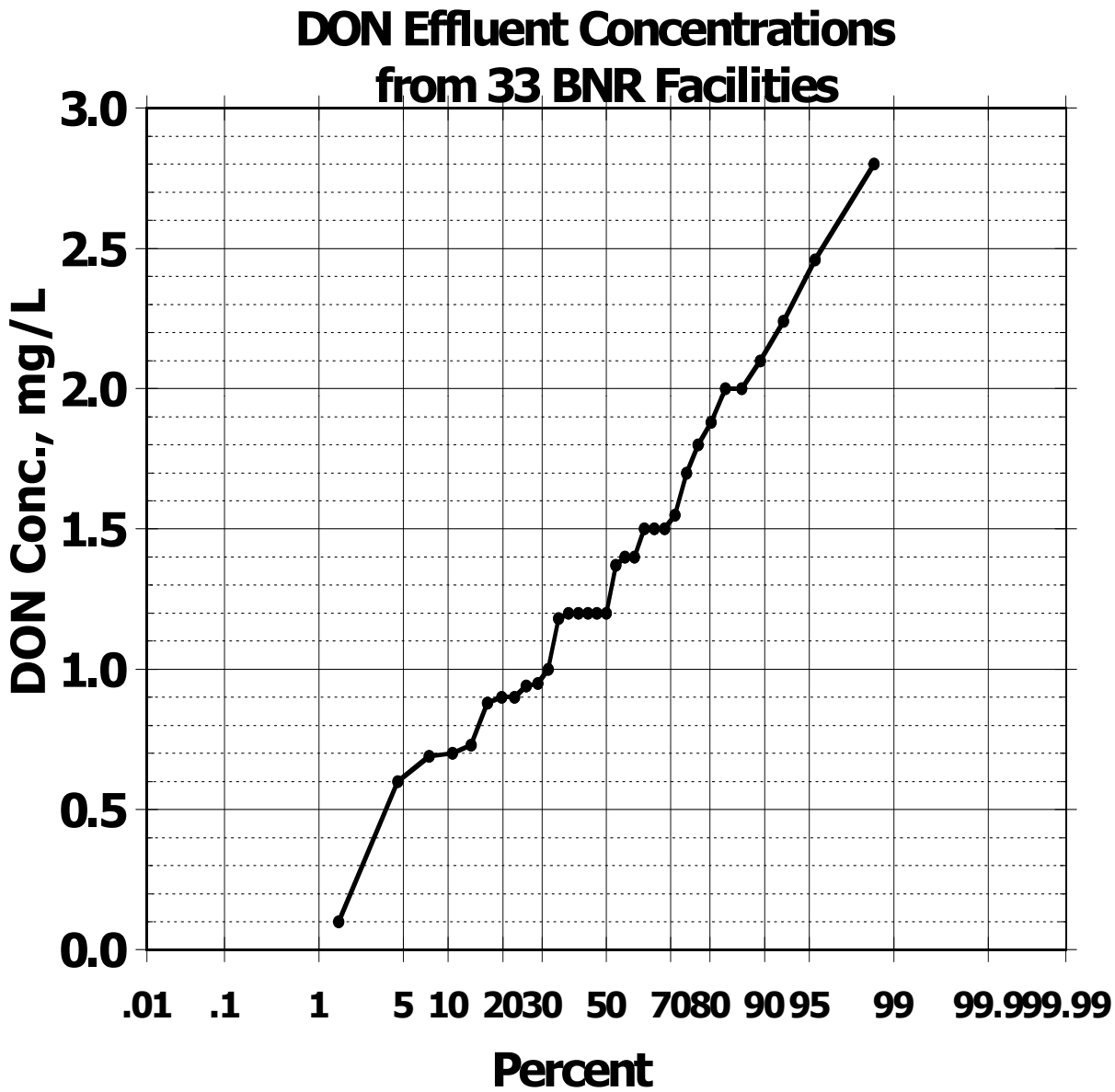
THE DON PROBLEM FOR LOW TN



effluent DON concentration varies for different WWTPs

Impossible to meet TN<3.0 mg/L at higher DON concentrations

WERF STUDY: 20-30% is not readily available to algae

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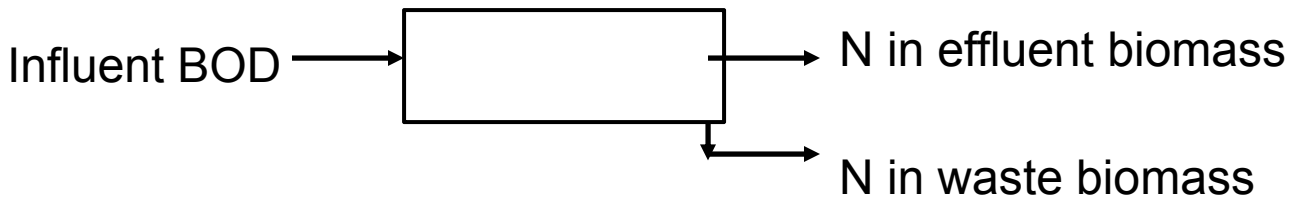
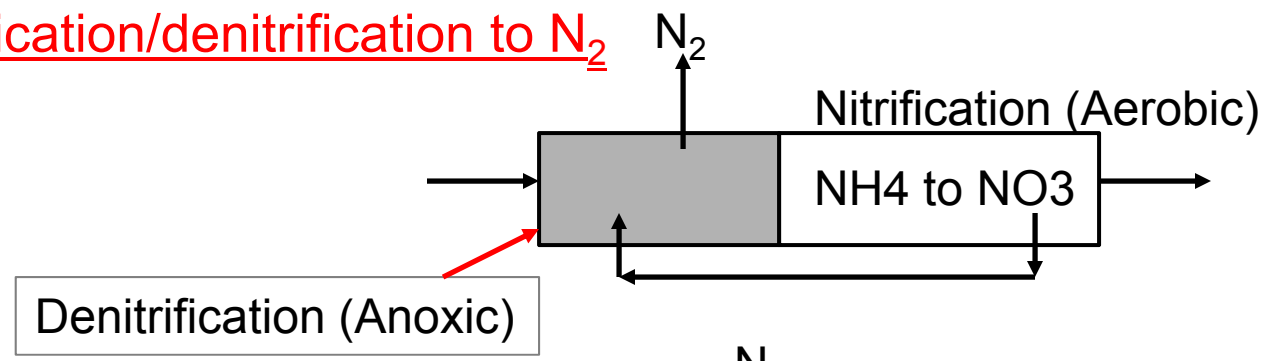
Three Methods of Nitrogen Removal in Biological Treatment Processes

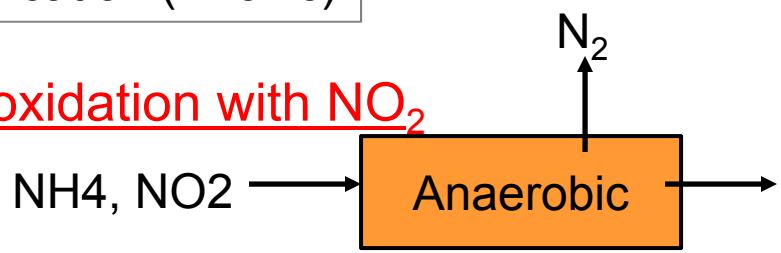
Biomass growth and sludge wasting



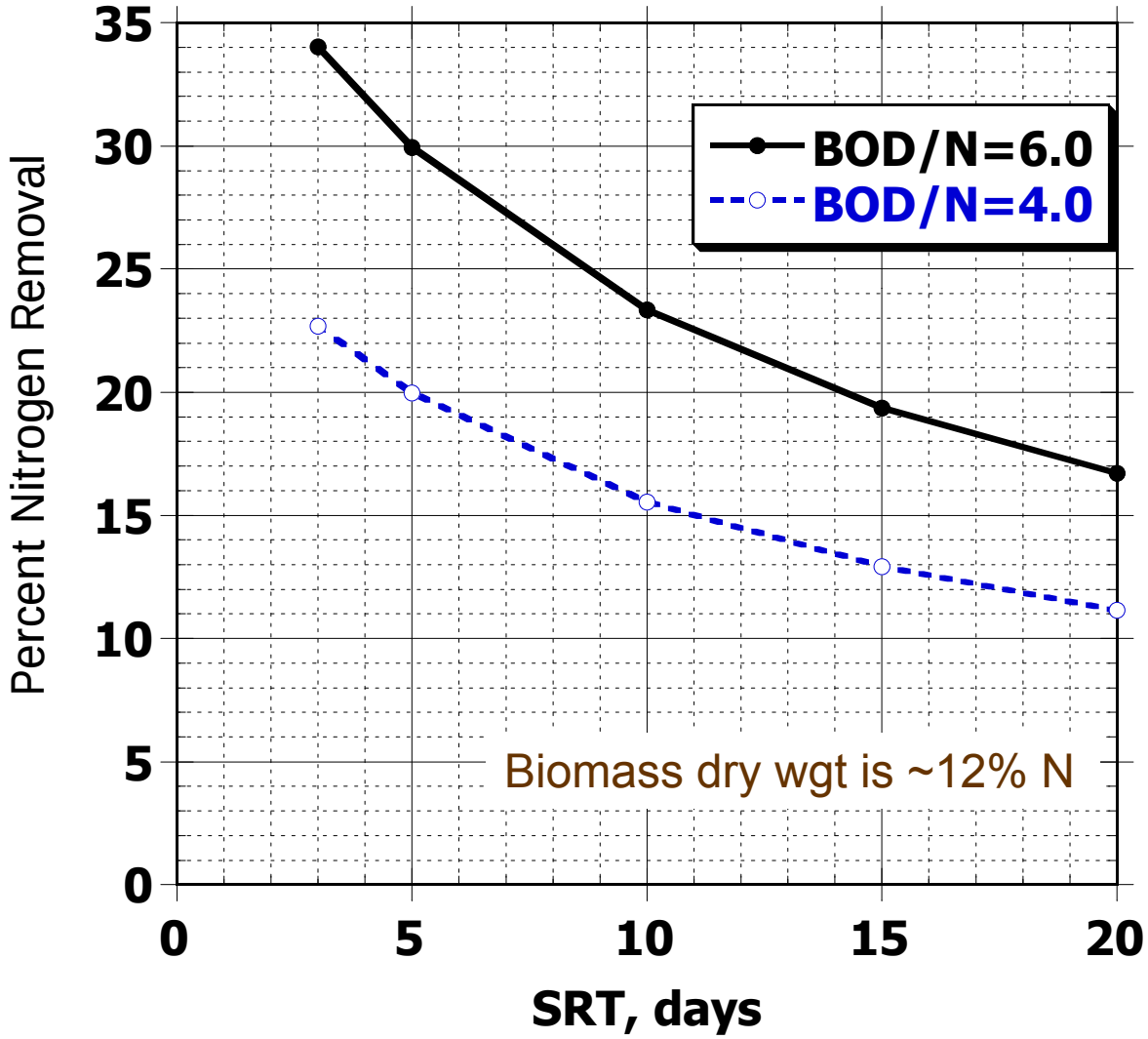
Biological nitrification/denitrification to N_2



Anaerobic ammonia oxidation with NO_2
Anammox



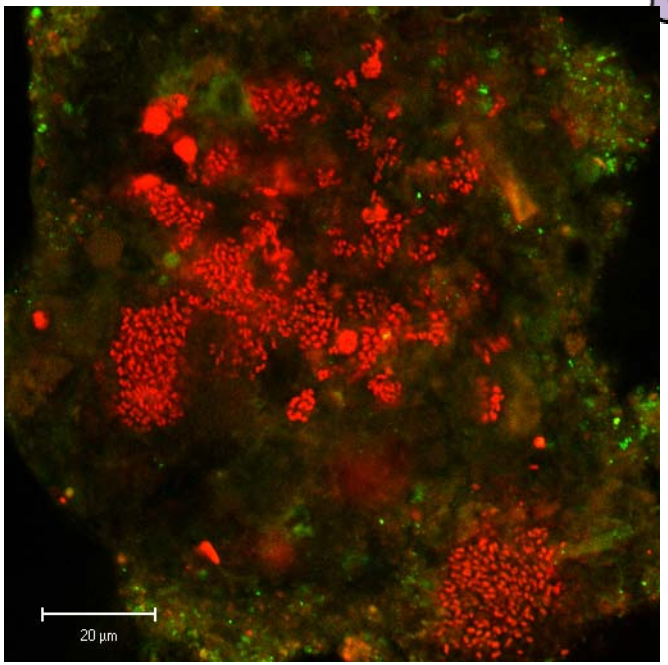
Only ~ 15-25% N removal by biomass growth

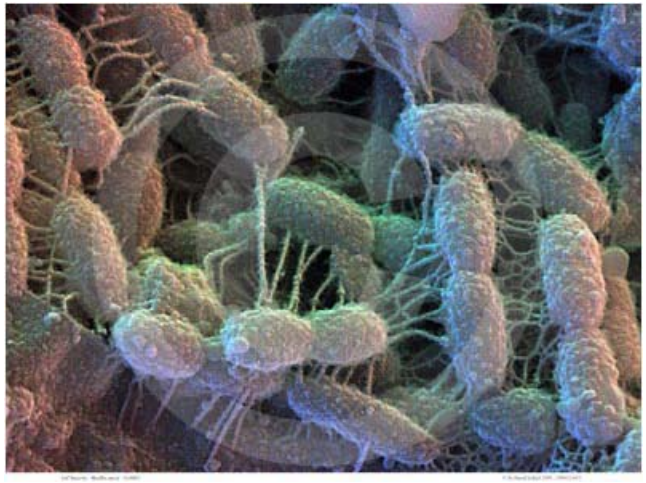


But about half can be released and returned with anaerobic digestion

We need to put the “bugs” to work!!

Aerobic -Nitrifiers
Anoxic -Denitrifiers
Anaerobic -Anammox





Aerobic nitrification is a two-step process with autotrophic bacteria

Nitroso-bacteria

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$$

Nitro-bacteria

$$2NO_2^- + O_2 \rightarrow 2NO_3^-$$

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

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Nitrification needs oxygen and consumes alkalinity

Reaction	g O_2 per g of N oxidized	g VSS per g N oxidized	g alkalinity used (as $CaCO_3$) per g N Oxidized
NH_4 to NO_2	3.43	0.15	7.14
NO_2 to NO_3	1.14	0.04	0
Total	4.57	0.19	7.14

In activated sludge nitrifiers may be only 2-5 % of MLSS

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Many Bacteria Genera Found in WWTPs with Nitrification

NH_4^+ Oxidizers	NO_2^- Oxidizers
Nitrosomonas **	Nitrobacter*
Nitrosococcus*	Nitrococcus*
Nitrosospira*	Nitrospira*
Nitrosorobio	Nitrospina
	Nitroeystis

*-relative frequency More than one type commonly found

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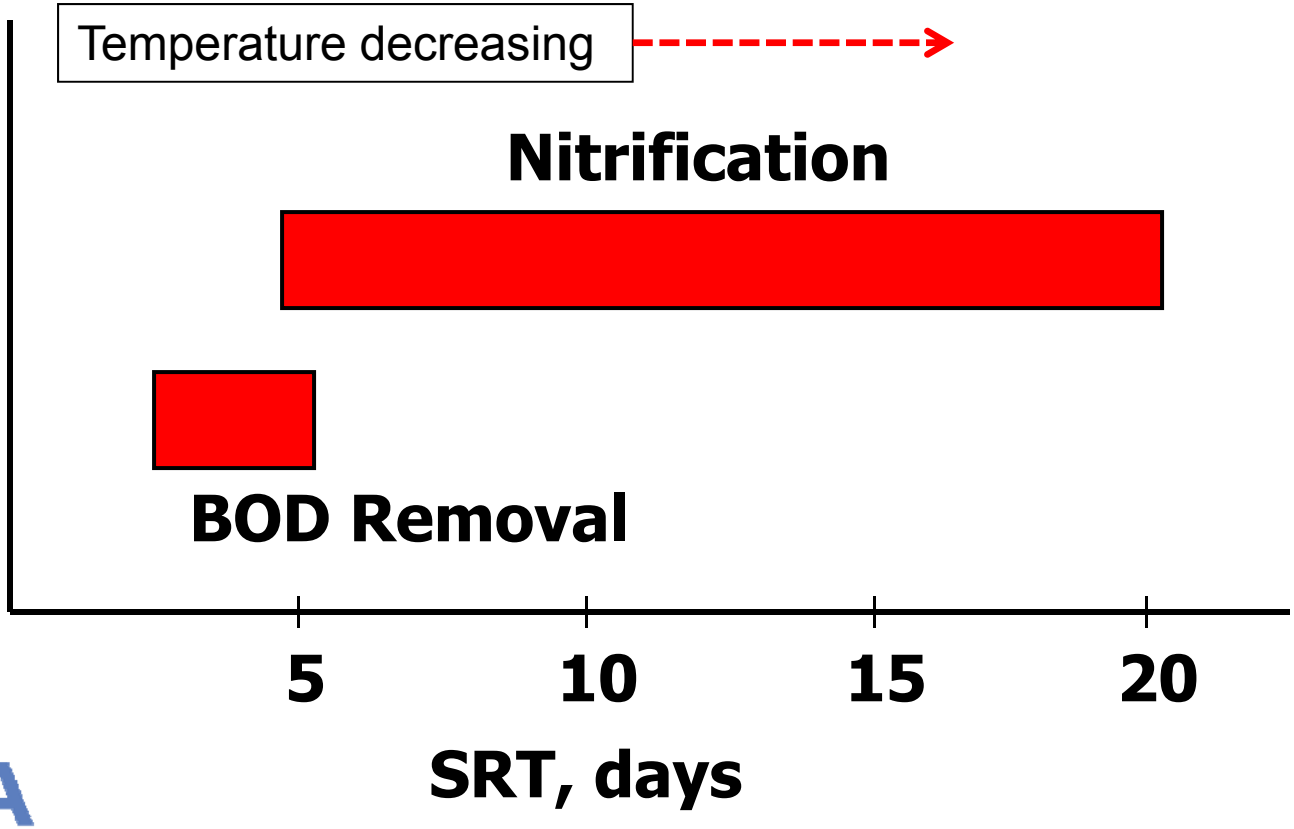
Bacteria are not the only nitrifiers

Archaea Nitrifiers

- Procaryotes - Archaea versus Bacteria
  - Different ribosomal RNA structure, different cell wall and membrane composition, considered extremophiles
- Crenarchaeota in marine and terrestrial environments oxidize ammonia to NO_2-N
- High level of archaea in low DO MBR system – Giraldo et al. (2011)
  - Very competitive at low DO conc., Kdo about 0.01 versus 0.25 to 0.50 mg/L for bacteria
  - Kinetics not as impaired at low DO

Nitrification requires a longer solids retention time (SRT) and larger aeration tank volume than systems needing only BOD removal



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Increase SRT, Then Increase Tank Volume

- SRT ↑, Volume ↑ Detention Time ↑

$$\text{Volume} = \frac{(\text{solids yield})(\text{Flow Rate})(\text{BODremoved})\text{SRT}}{\text{MLSS}}$$

- Effluent NH4-N, DO and temperature affect SRT needed

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Monod kinetic model applied for SRT determination
Coefficient values are key

$$\frac{1}{SRT} = \mu = \frac{\mu_{max} N}{K_n + N}\left[\frac{DO}{K_o + DO}\right] - K_{dn}$$

Where: μ = Specific growth rate of bacteria, g/g-d

μ_{max} = Maximum specific growth rate, g/g-d

Kn = half velocity coefficient, mg/L

N = NH4-N conc., mg/L

DO = Dissolved oxygen conc., m

K_{dn} = Specific endogenous decay rate, g/g-d

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EPA Nutrient Manual Nitrification Kinetic Coefficients

Coefficient	Units	NH_4 oxidation	NO_2 oxidation
μ_{max}	gVSS/gVSS-d	0.90	1.00
K_n	mg/L	0.70	0.20
K_{dn}	gVSS/gVSS-d	0.17	0.17
Y_n	gVSS/g NH4-N	0.15	0.05
Ko	mg/L	0.30	0.90
Θ Value			
μ_{max}	unitless	1.072	1.063
K_n	unitless	1.000	1.000
K_{dn}	unitless	1.029	1.063

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Are these kinetic coefficients applicable in all cases?

- No – can vary with wastewater and process design
  - Wastewater inhibition
  - Floc size effects kinetics
    - MBR with smaller floc size had lower Kn and Ko values – Manser et al. (2005)
  - Internal recycle rate in MLE process affected maximum specific growth rate – Jimenez et al. (2009)
  - Wide range in Ko values – Bratby and Parker (2009)
  - MLSS concentration and volumetric OUR may affect Ko

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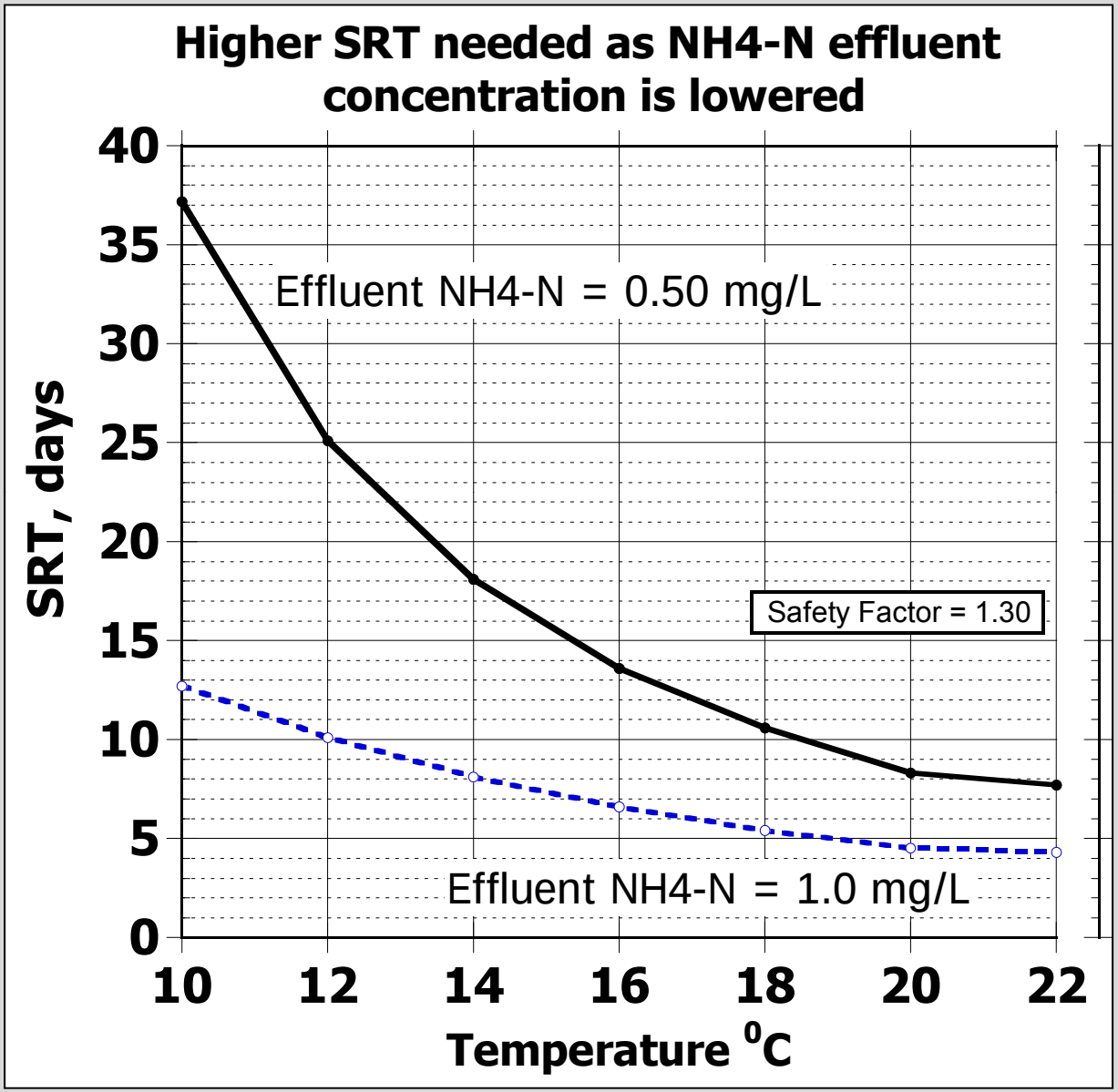
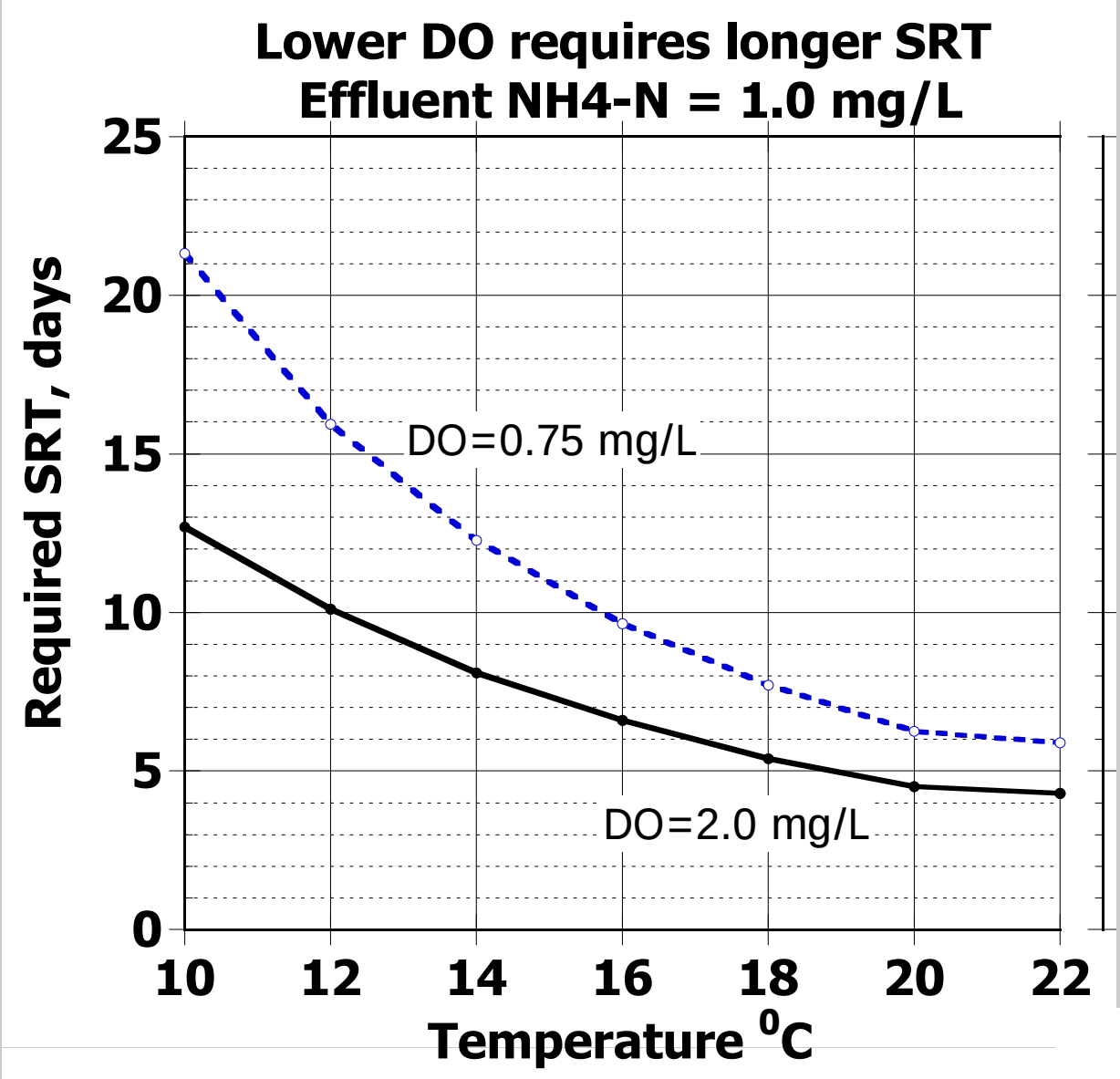
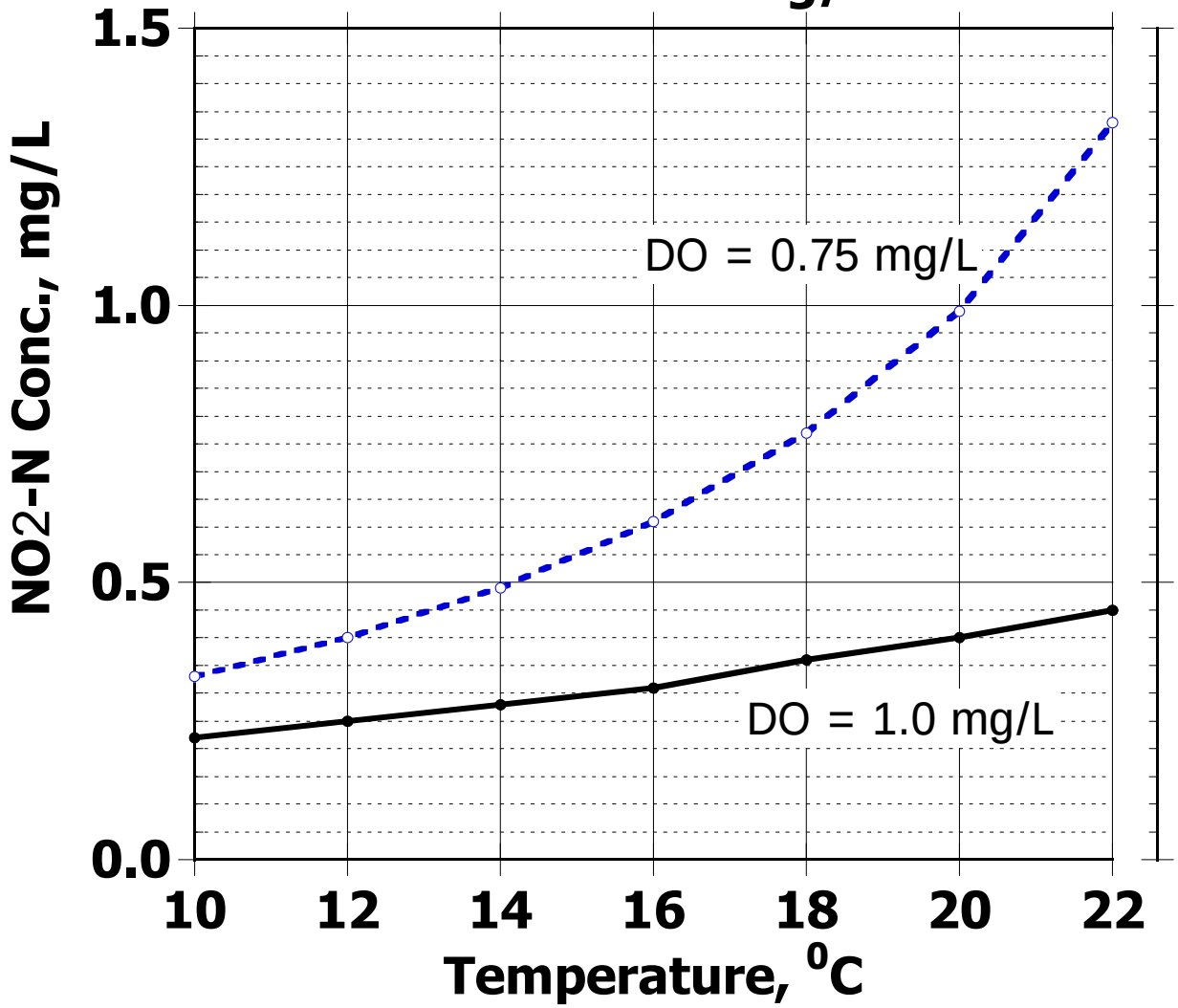

Higher SRT needed as NH4-N effluent concentration is lowered
SRT, days
40
35
30
25
20
15
10
5
0
10
12
14
16
18
20
22
Temperature ^{0}C
Effluent NH4-N = 0.50 mg/L
Safety Factor = 1.30
Effluent NH4-N = 1.0 mg/L


Lower DO requires longer SRT
Effluent NH4-N = 1.0 mg/L
Required SRT, days
25
20
15
10
5
0
10
12
14
16
18
20
22
Temperature ^{0}C
DO=0.75 mg/L
DO=2.0 mg/L

Lower DO concentration may increase effluent NO2-N concentration NH4-N = 1.0 mg/L



Biological Denitrification

- Heterotrophic facultative bacteria
  - Dissimilatory Nitrate or Nitrite Reduction
  - Reduce oxidized nitrogen to nitrogen gas

$$NO^-_3 \longrightarrow NO^-_2 \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2$$

  - Wide range of substrates can be used
  - Produce alkalinity
- Autotrophic bacteria –Anammox
  - Reduce $NO^-_2 \longrightarrow N_2$

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NO_3/NO_2 removed in oxidation of COD and produces alkalinity

Reaction	g O_2 Equivalent per g of N reduced	g alkalinity produced (as $CaCO_3$) per g N reduced
NO_3 to N_2	2.86	3.57
NO_2 to N_2	1.71	3.57

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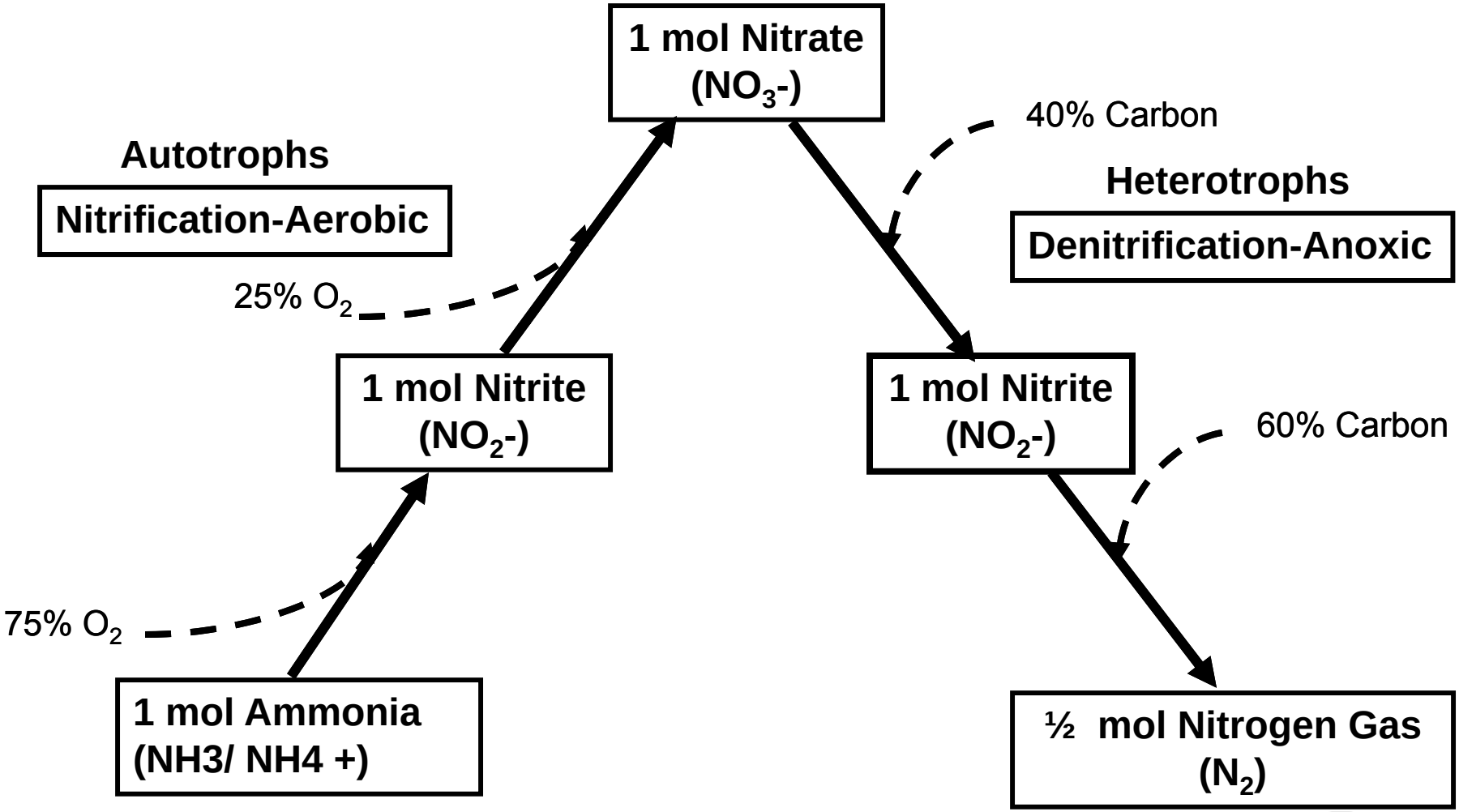
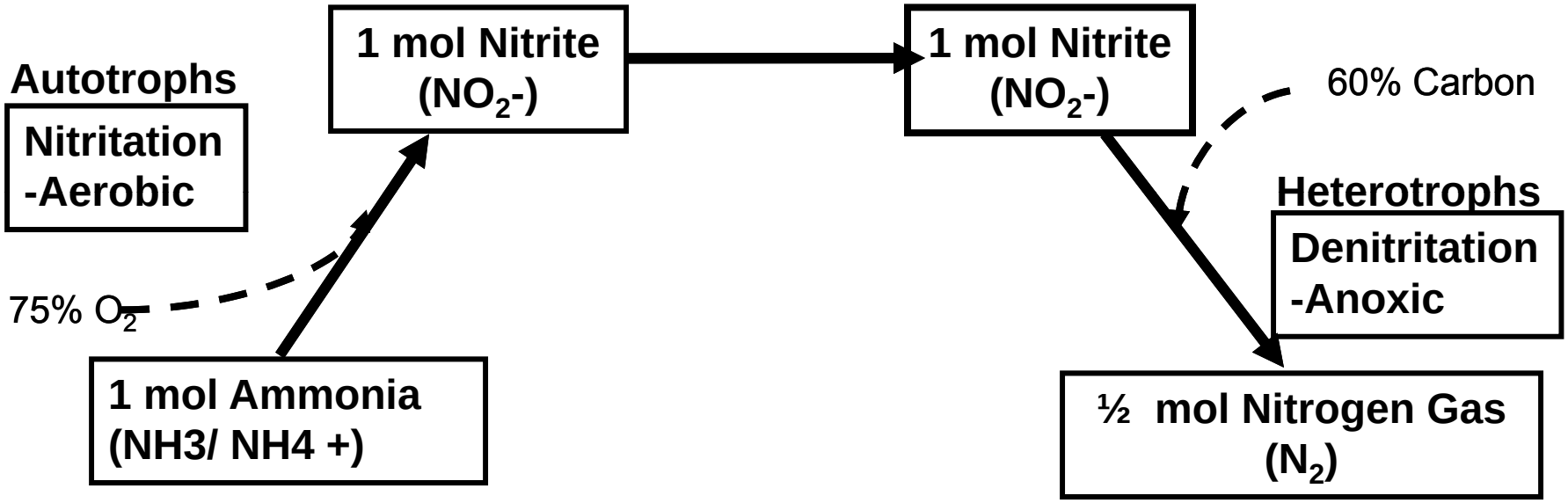
40% less COD needed for NO2 reduction

Nitrification – Denitrification Oxygen and Carbon Needs



4.57 g O2/g NH4-N oxidized
7.2 g COD/g NO3-N reduced

Nitritation – Denitritation needs less carbon



Advantages;
25% Reduction in Oxygen Demand for nitrification
40% Reduction in Carbon (e- donor) Demand
40% Reduced Biomass Production

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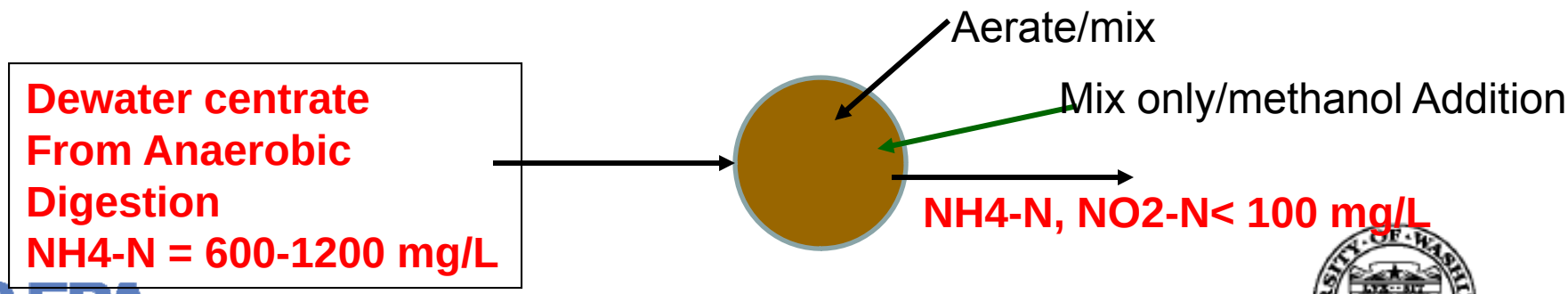
So nitrifying to only NO2-N is GOOD! How can that be done?

- Very low DO in activated sludge nitrification inhibits NO2-N oxidation
- Control SRT in sidestream treatment of digester centrate/filtrate at 25-30^{0}C

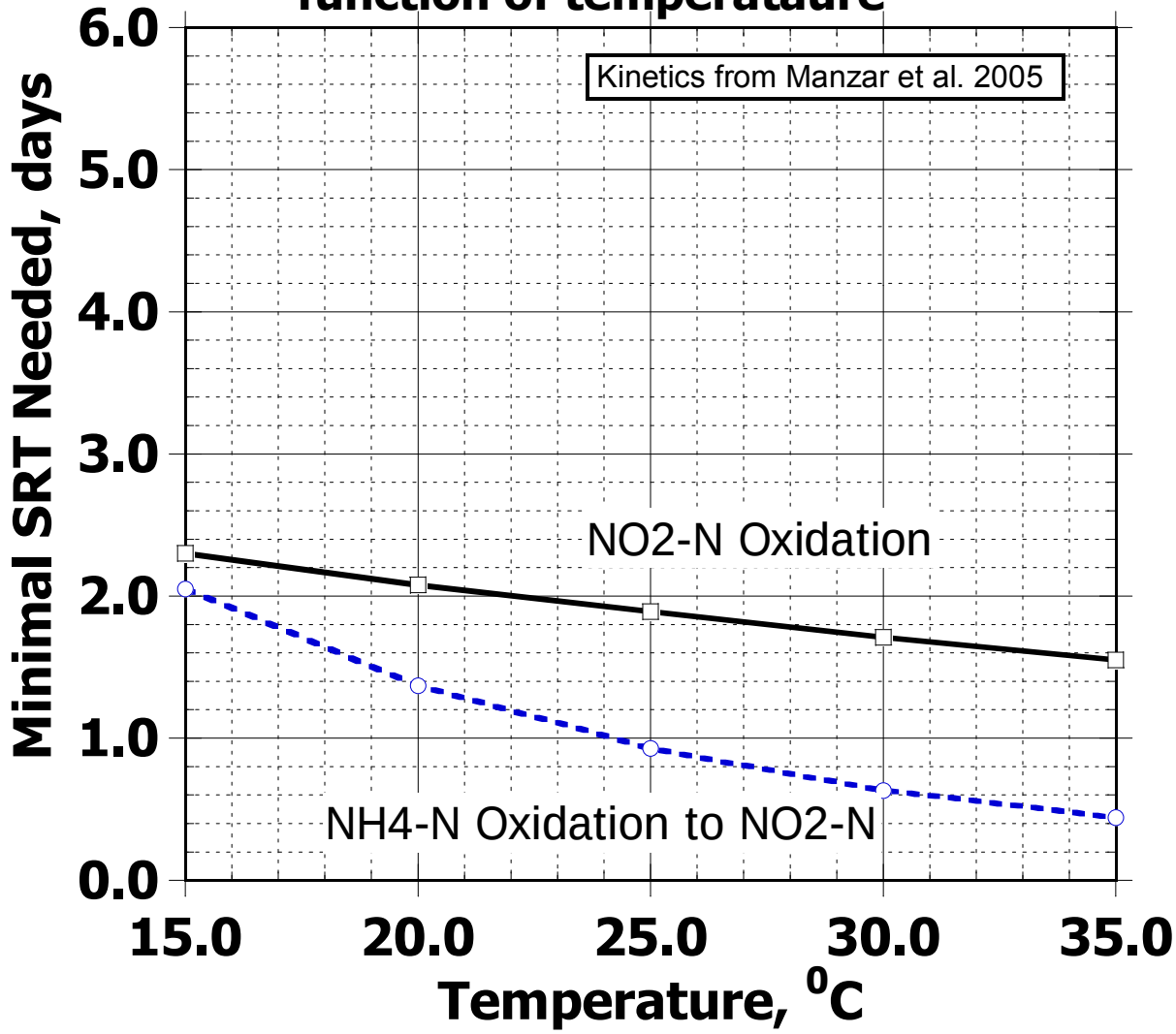
SHARON Process for N removal



SHARON Process

(Single Reactor System for High Activity Ammonium Removal Over Nitrite)

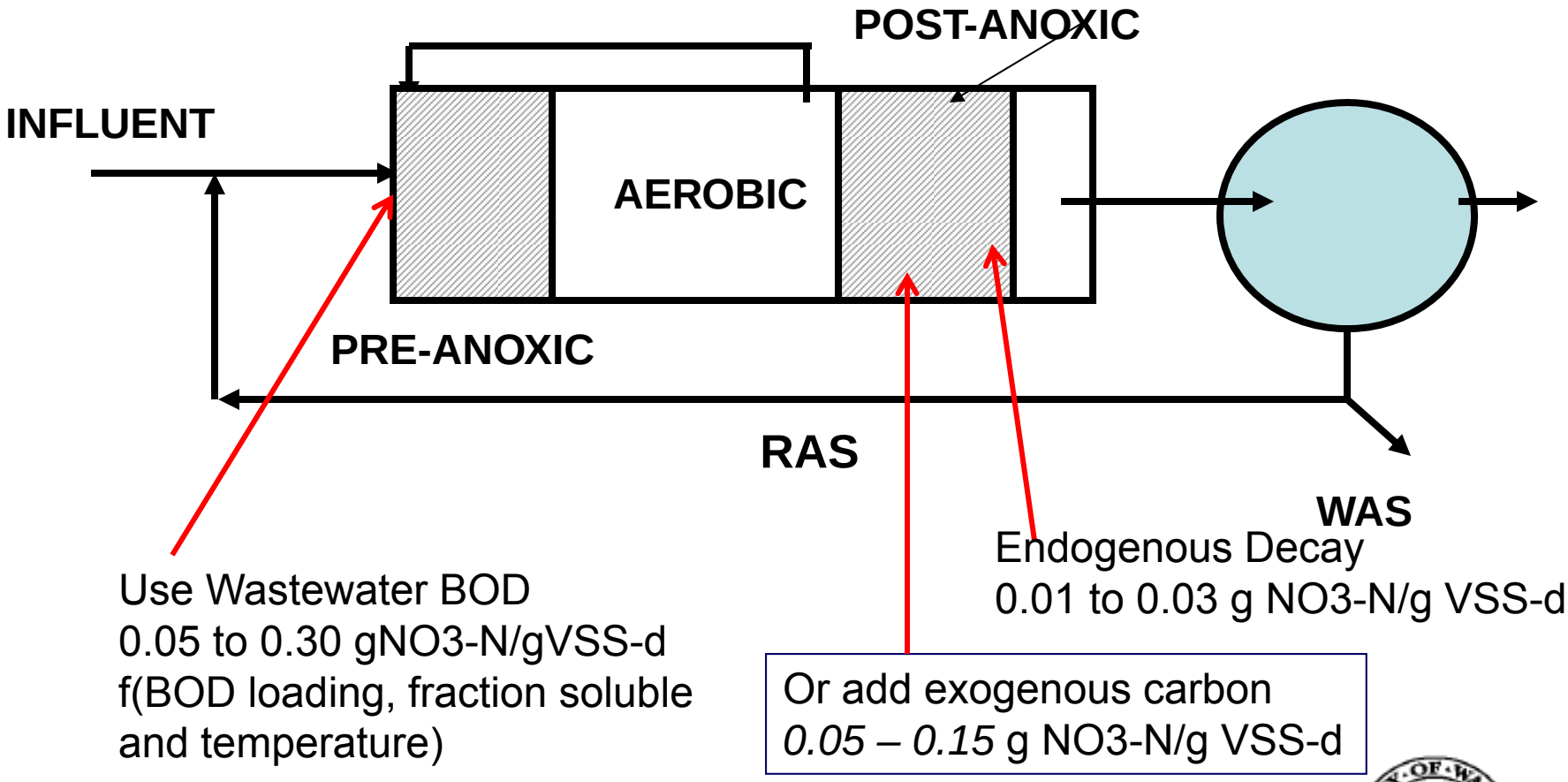
Minimal SRT needed function of temperataure



Heterotrophic Denitrification Needs BOD!- a Carbon Source

- Where from?
  - Influent or exogenous
- How much?
  - depends on influent TN and effluent NO3-N goal
- Exogenous Carbon?
  - Needed for low BOD/N wastewaters
  - for meeting low effluent TN (<6- 8 mg/L)

BARDENPHO PROCESS
Pre and Post Anoxic Zones



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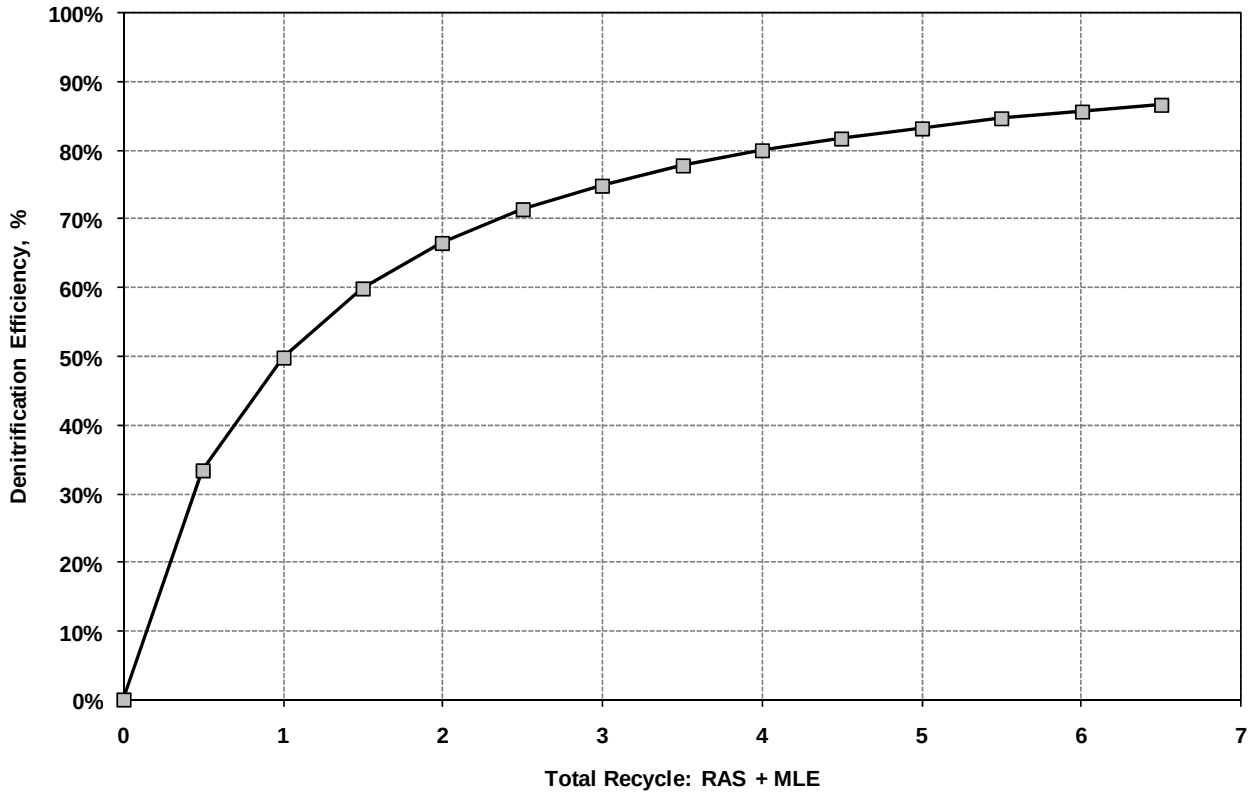
Denitrification Efficiency Can Theoretically Increase with Recycle Rate -but about 3:1 to 4:1 is practical – ~80% removal

Beware of recycle DO!



$$\text{Denitrification Efficiency} = 1 - \frac{1}{1 + \text{RAS} + \text{IR}}$$

RAS = RAS flow ratio

IR = internal recycle flow ratio

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Preanoxic tank designed to remove NO_3/NO_2 to <0.50 mg/L

- Is there enough BOD in the influent wastewater?
  - (rule of thumb BOD:N >4.0
- Is detention time long enough?
- DO added from internal recycle or influent uses BOD –less for Nox reduction
  - 1 mg DO uses BOD for removal of 0.35 mg of NO3-N

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Anoxic Tank Design Volume

- Volume typically in range of 15-30% of total aerobic plus anoxic volume
- Detention times range from 2-5 hours
- Using tanks in series require less volume than single tank

- Design Approaches
  - Mass balance and empirical relationships for denitrification rates
  - Mass balance and biokinetic equations
    - Simulation models

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Denitrification rate in anoxic zone is function of:

- Soluble bCOD concentration
- Kinetic coefficients
- NO3/NO2 concentration
- Heterotrophic denitrifier concentration
- Synthesis yield coefficient
- Temperature

$$r_{NO} = \left(\frac{1-1.42Y_H}{2.86Y_H}\right)\left(\frac{\mu_{max}(S_s)}{K_s + S_s}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\left(\frac{K_{O,H}}{S_O + K_{O,H}}\right)(\eta)X_H$$

Simulation models needed to account for transformations and concentration of all these species

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External Carbon Addition Often Needed To Meet Lower TN Concentrations

- BOD/N < 4.0 and for low effluent TN
- Methanol, Ethanol
- Acetic Acid
- Glycerol
- Industrial By-product (clean source)
  - Pharmaceutical
  - Soft drink bottlers
  - Breweries
  - Yeast factories
  - Fruit juice canneries

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Denitrification rates and amount of carbon needed for NO3/NO2 removal varies with type of exogenous substrate

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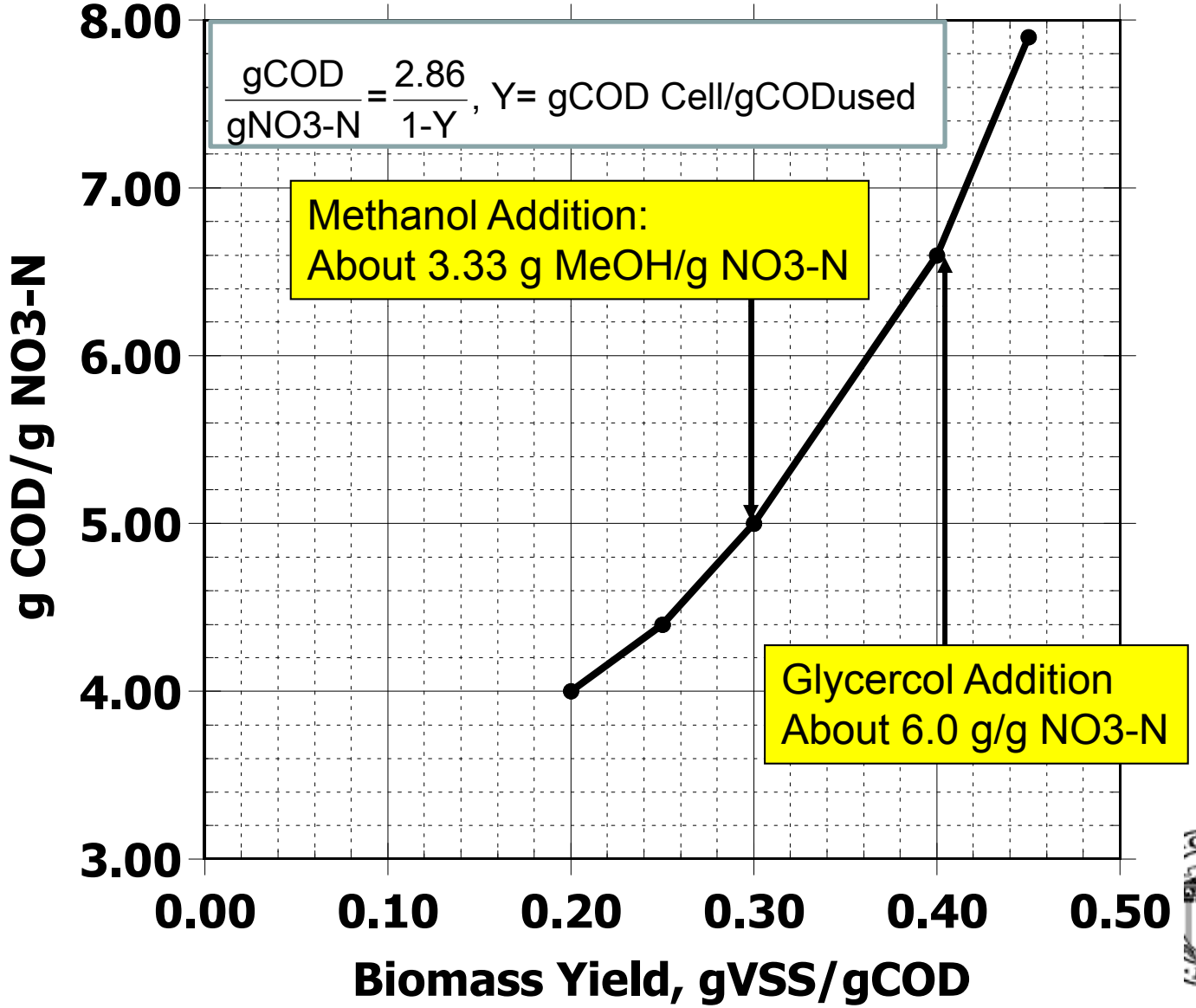
Substrate with lower biomass yields have lower COD dose Per quantity of NO3-N removed



Biological reactions rates vary with type of external substrate

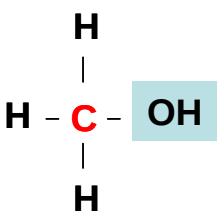
Substrate	u_{max} at 20^0C g/g-day	Temperature θ	Reference
Methanol	1.12	1.12	Mokhayeri et al. (2006)
	1.3	1.1	Christensson et al., 1994
	1.3	1.09	Dold et al. 2008
Acetate	4.46	1.21	Mokhayeri et al. (2006)
Ethanol	3.02	1.1	Christensson et al., 1994
MicroCglycerin	2.05	1.02	Onnis-Hayden et al., 2011
Corn Syrup	4.13	1.18	Mokhayeri et al. (2006)

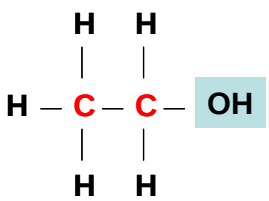
Methanol degraders use less carbon -but are slower and need acclimation time

- bacteria are not common in wastewater
  - May take 1-2 weeks to develop population
- Requires a sufficient anoxic zone SRT to maintain organisms in system
  - Typically 2.5 to 3.0 days

Days added	MeOH	Ethanol
1	1.2	4.0
50	2.0	4.1

Ratio of denite rate in mixed liquor after exogenous carbon addition





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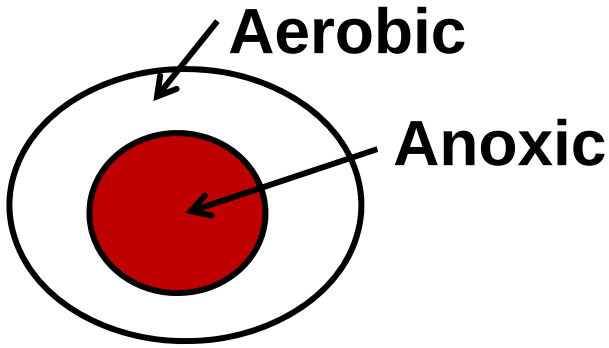
SNdN

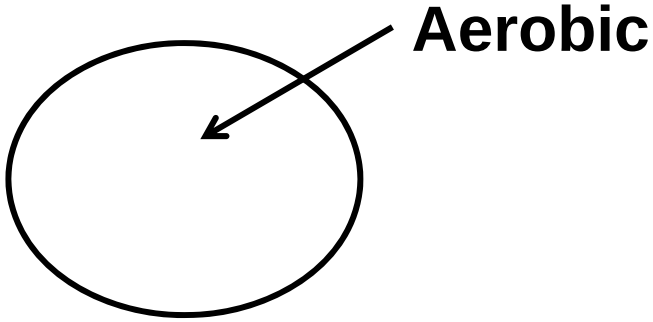
Simultaneous Nitrification and Denitrification can occur in same tank

Low DO control

Cyclic DO



Low DO and/or High F/M



High DO and/or Low F/M

United States Environmental Protection Agency

Effects of DO in SNdN Systems

- Can nitrify and denitrify at low DO conc.
- Lower DO lowers nitrification rate
- Presence of DO lowers denitrification rate
- Nitrifying population can be different for low DO systems and impacts kinetics – Archaea and different bacteria
- Nitrification to only NO_2 may occur
- Needs more volume/longer SRT than if separate nitrification and denitrification

United States Environmental Protection Agency

Nitrogen removal without carbon is possible! -Anammox

- Anaerobic ammonia oxidation
- Autotrophic bacteria
- NH_4-N and NO_2-N present –anaerobic

$$NH_4^+ + 1.32NO_2^{-1} + 0.13H^+ + 0.066HCO_3^{-1} \rightarrow$$
$$1.02N_2 + 0.26NO_3^{-1} + 0.066CH_2O_{0.5}N_{0.15} + 2.03H_2O$$

- About 1.3 moles of NO_2-N reduced per mole of NH_4-N oxidized to N_2
- Full scale plants with digester centrate treatment 30-35^{0}C

EPA United States Environmental Protection Agency

Anammox bacteria

- order *Planctomycetales*
- Species found in wastewater
  - *Candidatus Brocadia anammoxidans*
  - *Candidatus Brocadia fulgida*
  - *Candidatus Kuenenia stuttgartiensis*
  - *Candidatus Scalindua brodae*
  - *Candidatus Scalindua waganeri*
- Organisms found in marine and lake sediments
- Wide temperature range
- Grown in fixed film and also in granulated sludge flocs

United States Environmental Protection Agency

Anammox Growth Considerations

- Kuenenia had maximum activity at 30-35^{0}C
- Growth at 15^{0}C observed
- NO2-N inhibition possible (5-50 mg/L and > 70 mg/L)
- Slow growing bacteria
  - u_{max} ~ 1/5th to 1/20th of that for aerobic nitrifying bacteria
- Low Kn
  - < 0.05 to 0.10 mg/L
- Endogenous decay low
  - ~ 0.005 g/g-d at 35^{0}C
- Cell yield ~ ½ of that for aerobic nitrifying bacteria

Denitrification Summary

- Heterotrophic –Anoxic Conditions
  - Produces alkalinity
  - Provide oxygen equivalence for COD removal
  - Need sufficient carbon (bCOD, BOD)
  - NO3/NO2 reduction rate function of design and wastewater characteristics
  - Exogenous carbon type yield different COD/N ratios, methanol needs acclimation time and is slowest degradation rate

Denitrification Summary

- Process for N removal using less carbon then conventional nitrification-denitrification
  - Ammonia oxidation to only NO2 – SHARON
  - Simultaneous NdN
- Process for N removal using no carbon
  - Anammox
    - Anaerobic NH4-N oxidation with NO2-N
    - Slow growing organisms – need long SRT
    - Demonstrated at 25-35^{0}C

PROCESS ALTERNATIVES
FOR NITROGEN REMOVAL
WASTEWATER TREATMENT

Clifford W. Randall, PhD, Dist.M.ASCE, Hon.M. AAEE

Professor Emeritus

Virginia Tech

NITROGEN REMOVAL ALTERNATIVES

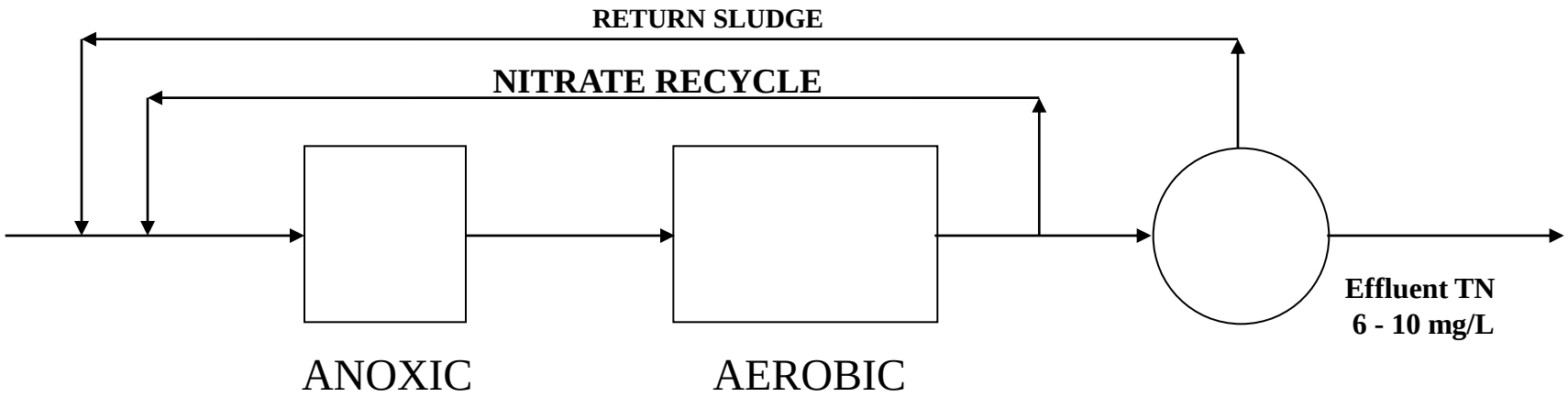
- **BIOLOGICAL**
  - **Biological Wastewater Treatment**
    - **Nitrification - Denitrification**
- **PHYSICAL**
  - **Filtration**
    - **Suspended Solids Removal**
    - **Denite Filter**
- **CHEMICAL**
  - **Ion Exchange & Recovery**
- **PHYSICAL-CHEMICAL**
  - **Air Stripping & Recovery**
  - **Struvite Recovery**
    - **Ostara, etc.**

Biological Nitrogen Removal Processes

- ***Effectively Use Internal Carbon Source***
  - **Two Stage MLE Process**
  - **4-Stage Bardenpho**
  - **Channel Systems (SND), e.g. oxidation ditches**
  - **Step Feed Denitrification**
  - **Sequential Batch Reactors (SBRs)**
  - **Moving Bed Biological Reactors (MBBRs)**
  - **Sidestream Treatment**
- ***Rely on External Carbon Source***
  - **Biological Aerated/Anoxic Filters (BAFs)**
  - **Tertiary Denitrification Filters**
  - **Post Denitrifying MBBRs**

The Basic Configuration for Biological Nitrogen Removal (BNiR)

Single-Sludge Anoxic-Aerobic Sequencing Reactors



MODIFIED LUDZAK-ETTINGER (MLE) CONFIGURATION

Increases Reactor Volume by 10-15% Compared to a Fully Nitrifying Conventional Activated Sludge (CAS) Process, but Decreases Operating Costs

DURING BNiR, NITRATE (NO_3) & NITRITE (NO_2) ARE USED AS ELECTRON ACCEPTORS FOR BOD METABOLISM INSTEAD OF DO

Aerobic reaction:

$$BOD + DO \longrightarrow CO_2 + H_2O + \text{cells} + \text{energy}$$

Anoxic reaction:

$$BOD + NO_x \longrightarrow CO_2 + H_2O + N_2\uparrow + \mathbf{0.75}\ \text{cells} + \mathbf{0.8}\ \text{energy}$$

Denitrification can be used to recover alkalinity, reduce aeration energy requirements and reduce WAS production

Installed Underflow Baffle For Anoxic Zone

Anoxic Zone Mixing by Diffusers With low Air Flow

Cost ≈ $100,000

Re-distributed Diffusers

A few Diffusers Left in Anoxic Zone

No internal Recycle of Nitrates

Nitrates Returned by RAS only

Aeration Basin After Modification for Alkalinity Recovery
Moore's Creek WWTP, Charlottesville, VA

PERFORMANCE AFTER MODIFICATION FOR ALKALINITY RECOVERY

MOORE'S CREEK WWTP

1. Reduced Effluent Nitrogen

	TKN	NH3-N	NO3-N	TN	Nit.	Denit.
Influent, mg/L	25.3	16.6	0	25.3		
Effluent, mg/L	4.5	0.9	8.7	RSN 9.6	95%	47%

2. Eliminated Chemical (Lime) Addition

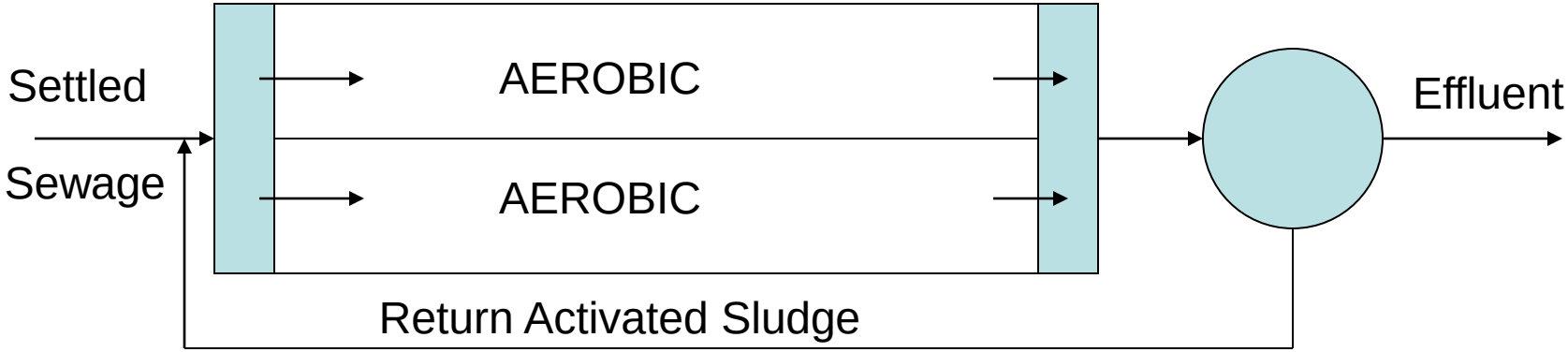
- **Savings of $150/day = $54,750/year**

3. **Improved Sludge Settling:**

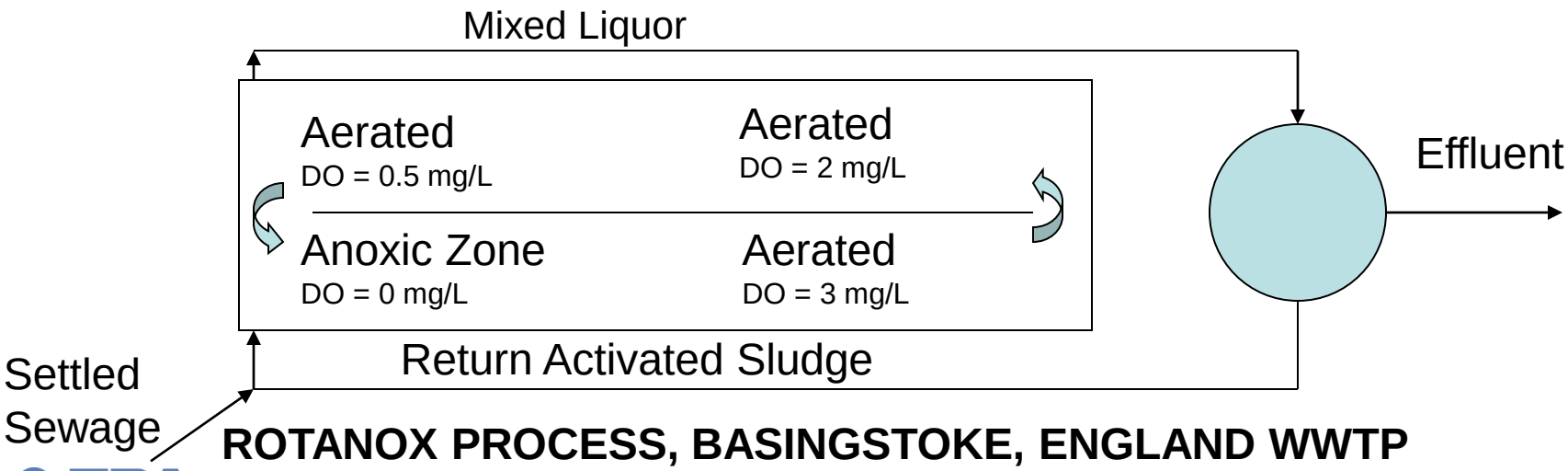
	Before	After
SVI	**180+**	**80-100**

QUANTIFICATION OF AERATION ENERGY SAVINGS

BEFORE MODIFICATION



AFTER MODIFICATION FOR AERATION ENERGY REDUCTION



ROTANOX PROCESS, BASINGSTOKE, ENGLAND WWTP

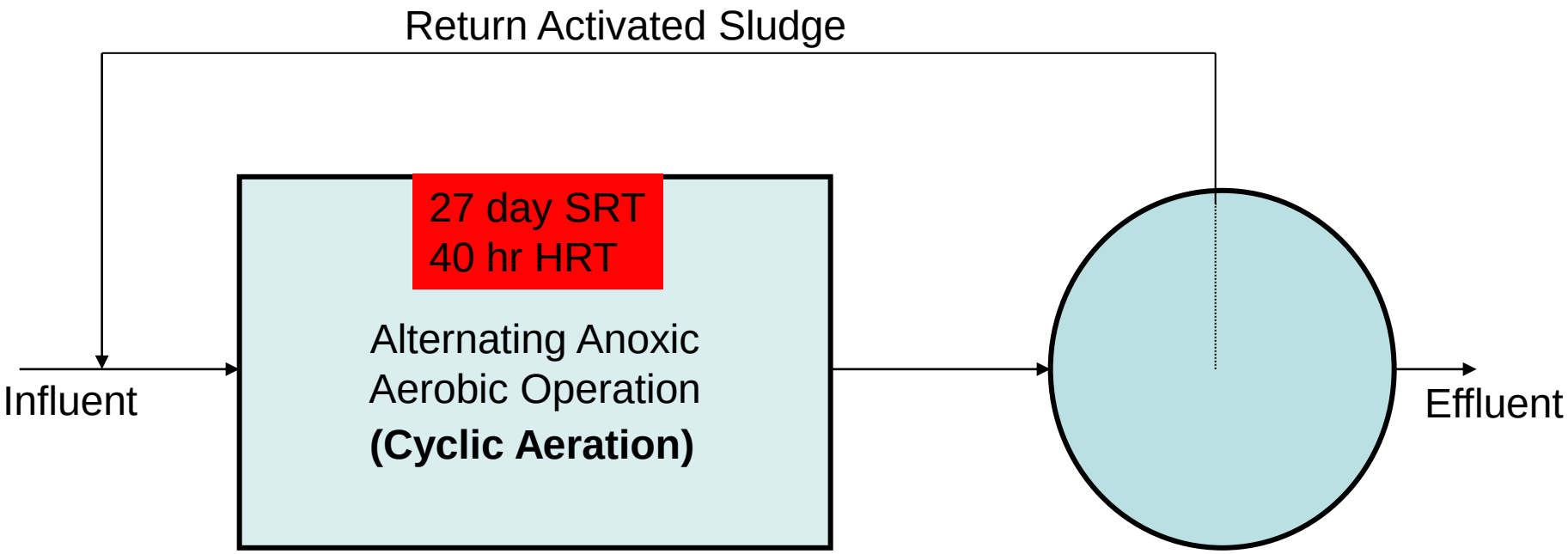
REDUCTION OF AERATION ENERGY REQUIREMENT WITH DENITRIFICATION ROTANOX PLANT, BASINGSTOKE, U.K. (Best, et al., 1984)

Time Period	Parameter	Influent	Effluent or Performance		% Reduction
			Control	Rotanox	
4/82-3/83	BOD_5, mg/L	150	13	4	69
	SS, Mg/L	105	30	11	63
	NH_3-N, mg/L	32	0.5	0.7	(40)
	NO_3-N, mg/L	0	29	7	76
	TN, mg/L	42	30	8	73
	Aeration Energy, kWh/kg BOD_r		1.15	0.9	22
	O_2 Transfer Eff., kg O_2/kg BOD_r		2.1	2.5	(19)
	Mixing Energy, kWh/kg BOD_r			0.2	
	Total Energy, kWh/kg BOD_r		1.37	1.11	19

Flow = 3500 m3/day (0.925 MGD), θ = 7.7 hours, θc = 12-15 days, RAS = 1:1, F/M = 0.11, SS ≈ 4000 mg/L, Sludge Production = 0.7 kg/kg BOD5, RAS NO3N = 6 mg/L, Three Passes per Nominal Retention. Control Flow = 17,500 m3/day

CYCLIC AERATION OPERATION

AERATION ENERGY & BIOMASS REDUCTION



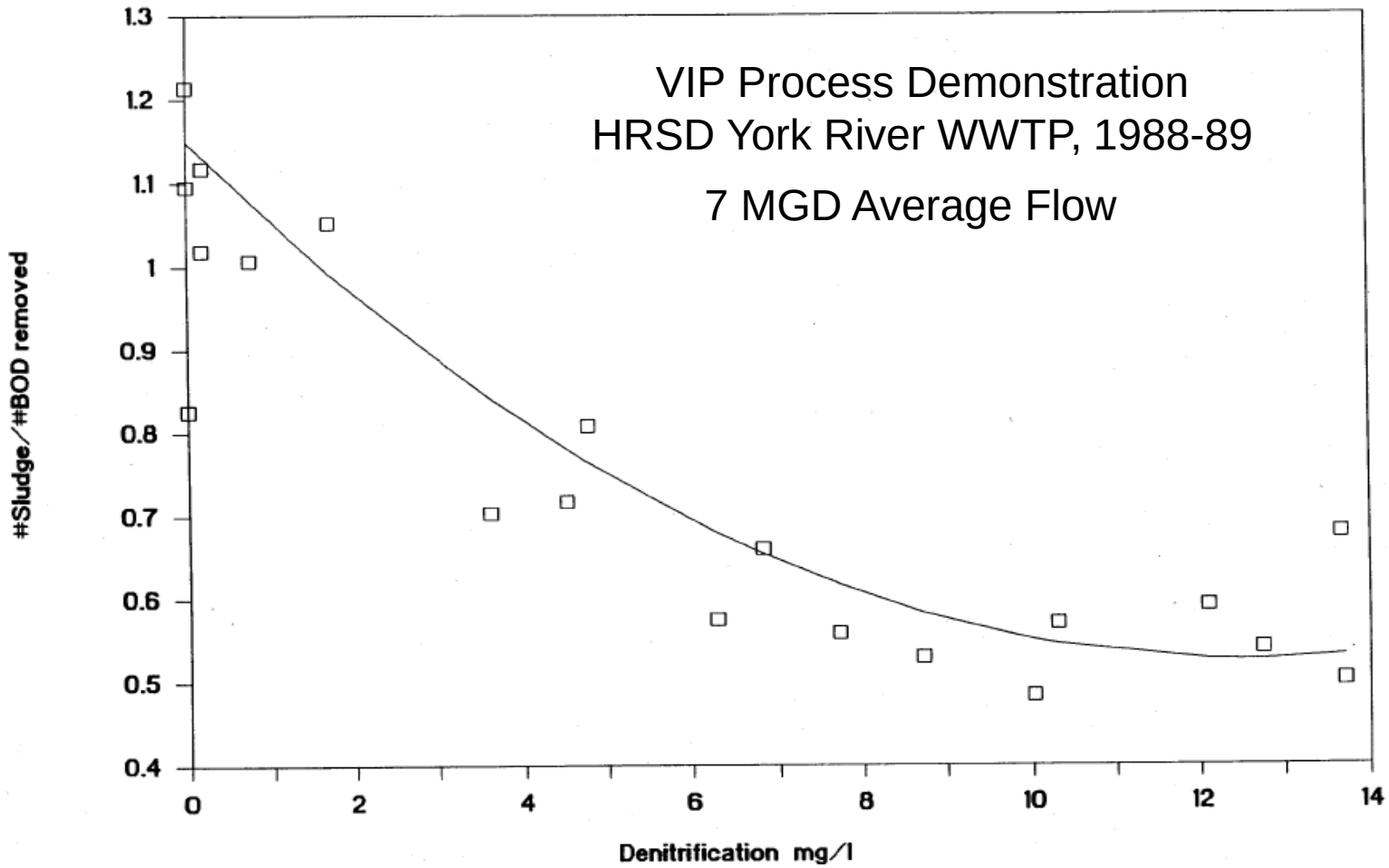
COMPLETELY MIXED ACTIVATED SLUDGE PROCESS
YARRA GLEN WWTP, MELBOURNE, AUSTRALIA

ENERGY & WAS REDUCTION WITH ALTERNATING AERATION

Table 3. Alternating Aerobic Anoxic Performance at Yarra Glen WWTP, Australia
(after Ip, et al. 1986)

Parameter	Influent	CMAS Effluent	AAA Effluent			2/4
			Air On/Off, hours			% Reduction
			3/2	2/3	2/4	
BOD_5, mg/L	396	5	7	3	3	40
SS, mg/L		15	20	15	15	0
TKN, mg/L	76					
NO_3-N, mg/L	0	25	20	10	7	72
MLVSS, mg/L	N.A.	3980	3500	2400	2400	40
Total Energy, kWhr/quarter		3400			2200	35

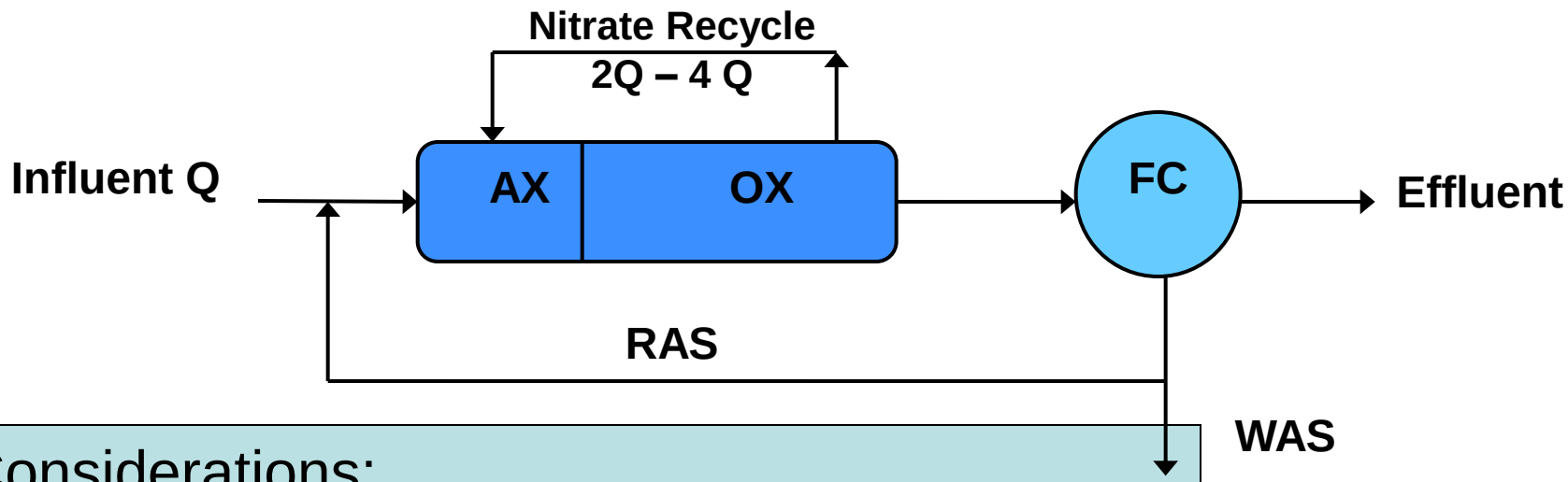
Flow was 21.2 m^3/d (3.9 gpm), Period of Study was 7/83-4/84



REDUCTION OF WAS PRODUCTION WITH INCREASED PRE-DENITRIFICATION

Waltrip, 1990

Two Stage 'MLE' Process for N Removal



Considerations:

- Easily implemented in nitrifying system
- Capacity de-rating may be required
- only ~10 % de-rating if system already nitrifies
- Sensitive to available carbon and MLRecycle

Effluent Quality

NH_3-N < 1 mg/L

TN = 6 - 10 mg/L

Typical Enhanced Nitrogen Removal and Advanced Wastewater Treatment Effluent Requirements

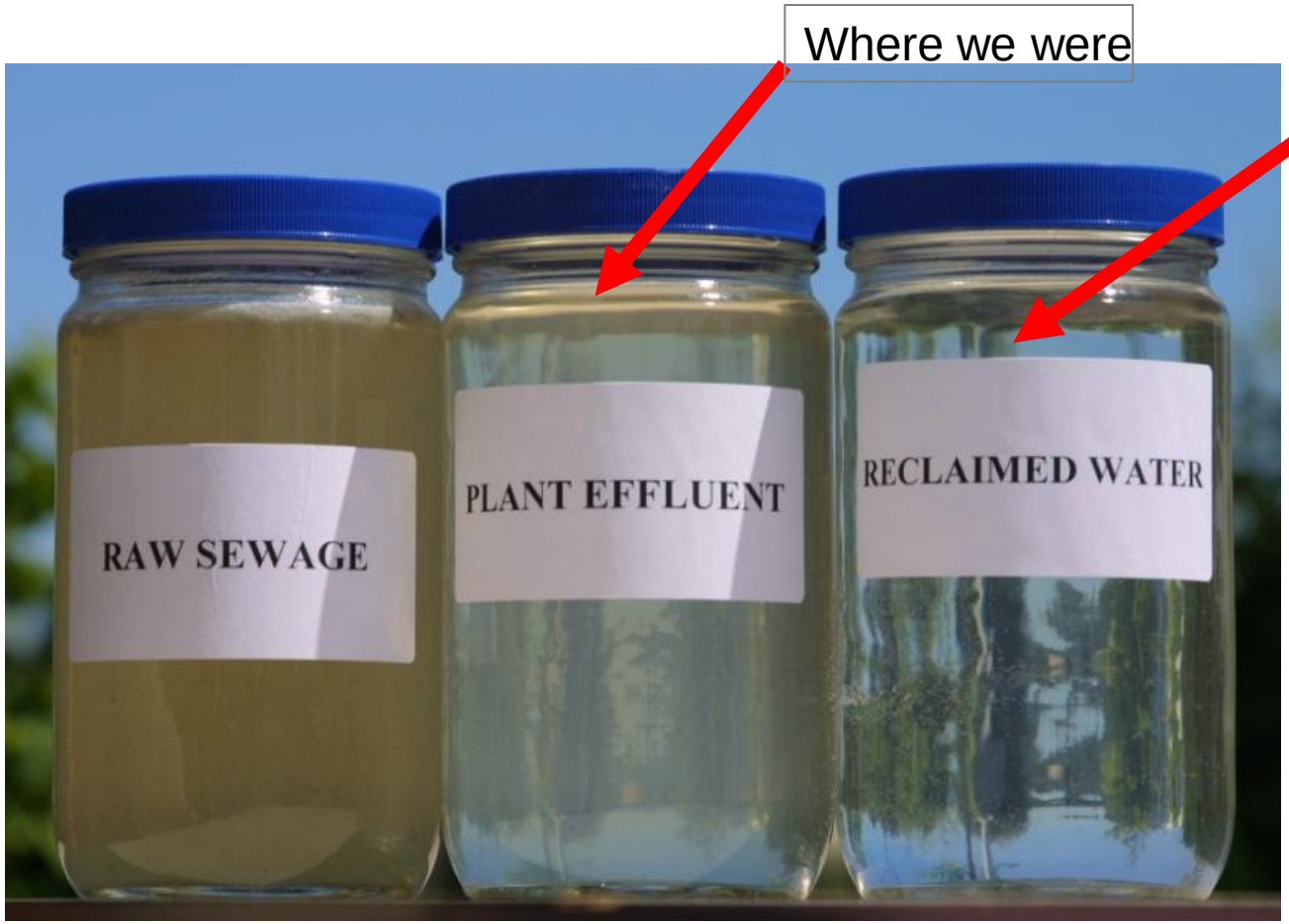
Effluent Parameter	Concentration Range	Typical Averaging Period
BOD_5, mg/L	1-5	Monthly
COD, mg/L	<10	Weekly*
TSS, mg/L	1-5	Monthly
NH_3-N, mg/L	**<1.0****	Monthly/Maximum
TN, mg/L	**3-4**	Monthly/Yearly
TP, mg/L	0.1-0.3	Monthly/Yearly
pH, units	6-9	Instantaneous

***Upper Occoquan AWT Plant** ****Definition of Complete Nitrification**

MLE PROCESS IS UNABLE TO MEET ENR STANDARDS

For ENR Need Excellent Removal of Suspended Solids

Effluent Phosphorus (P) and Nitrogen (N) from the Ruidoso Wastewater Treatment Plant



December 14, 2011

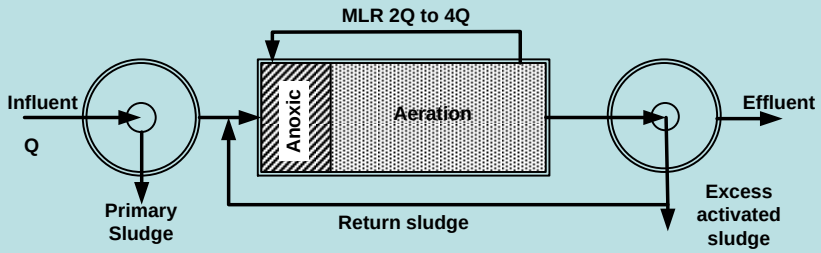
H David Stensel, PhD, PE
University of Washington
Seattle, WA

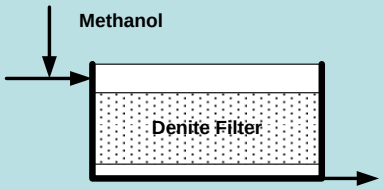
Filtration Alternatives

- Conventional Deep Bed Sand filters
- Traveling Bridge Filters
- Continuous Backwash Deep Bed Filters
- Aqua Disc Filters
- Fuzzy Filters
- Membrane Biological Reactors (MBRs)

Denitrification can be combined with Filtration

Simple "MLE" with Denite Filter

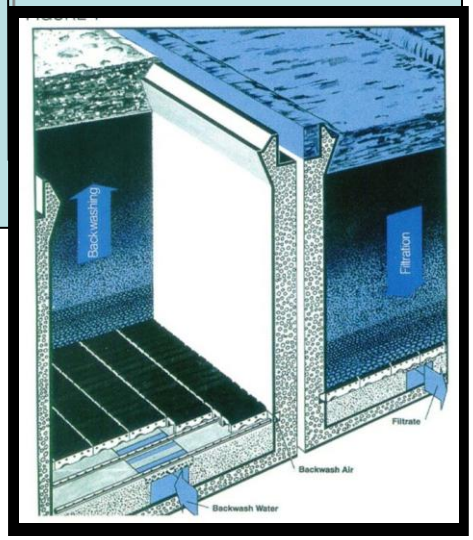




Effluent TN **6-10 mg/L** → **< 3 mg/L** →

Considerations:

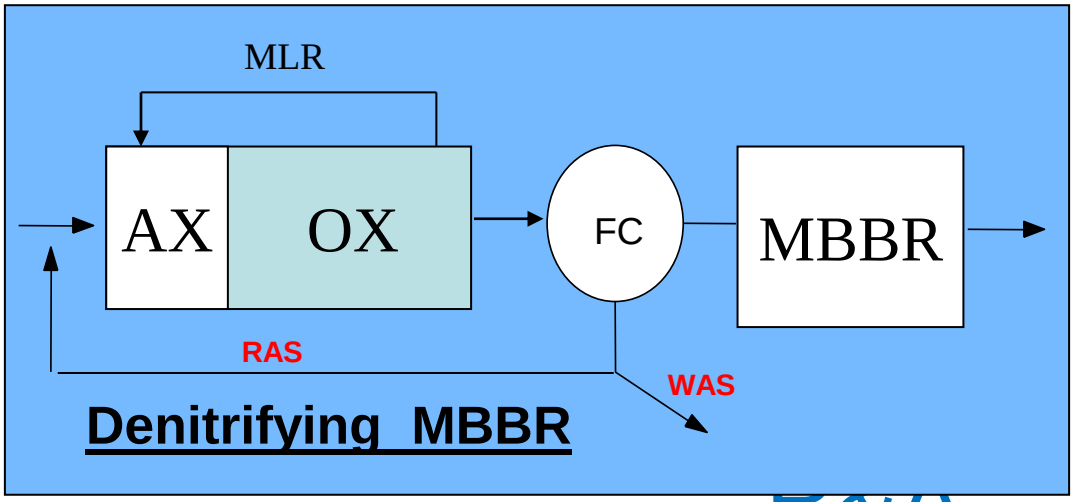
- Removes additional NO_3-N
- External Carbon – e.g. Methanol
- Particulate Nitrogen Removed
- Usually not applied w/ 4-stage process
- Increased Construction & Operating Costs



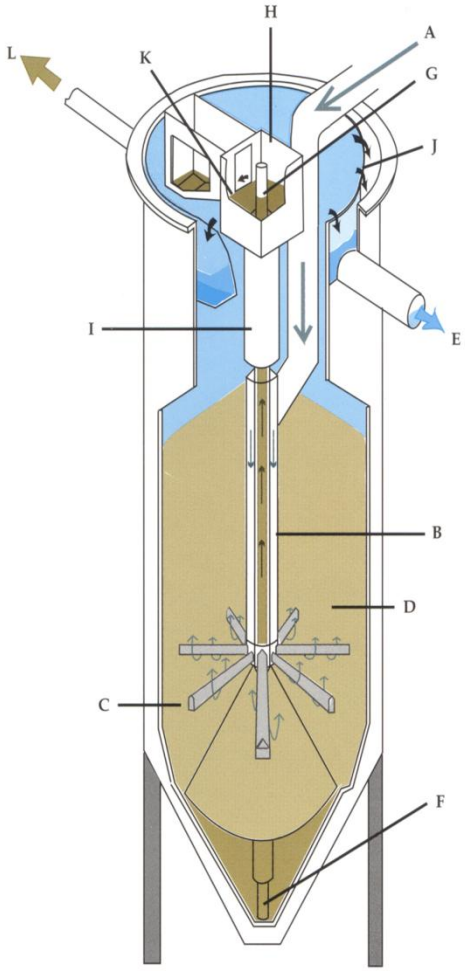
TN < 3 mg/L Frequently Requires Post Treatment with Carbon and Filtration

Denitrification Filter

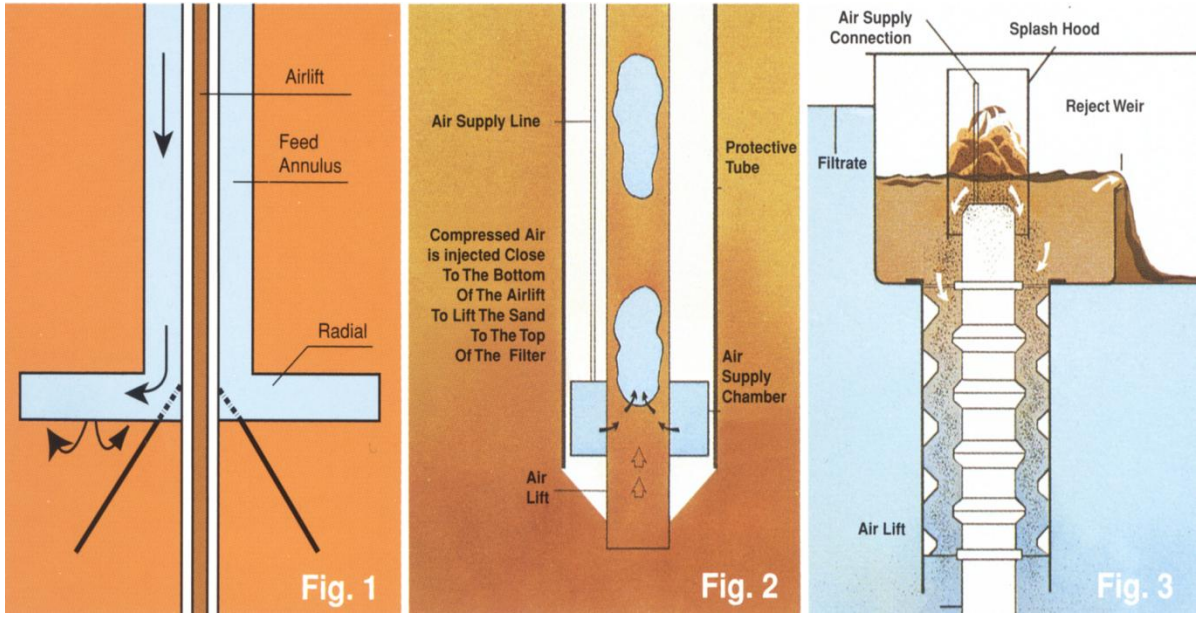
Types Of Filter Media



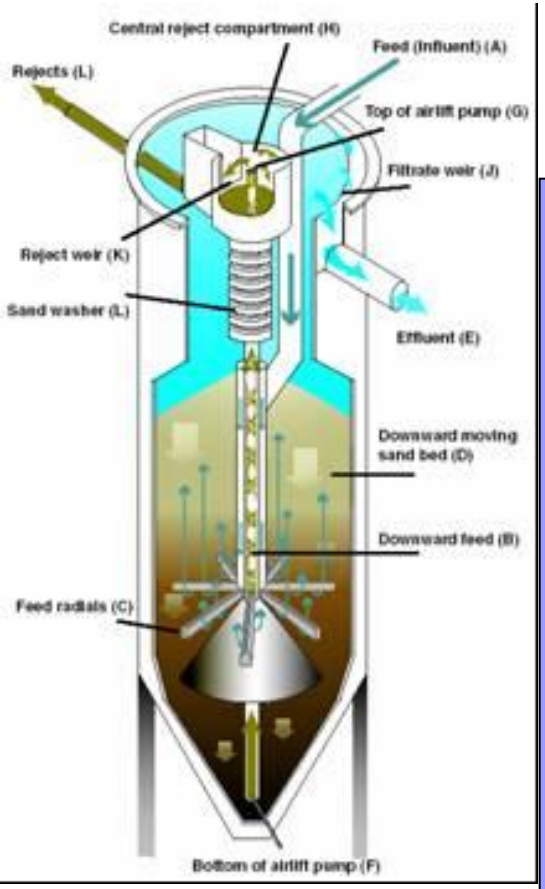
Continuous Backwash Deep Bed Filters



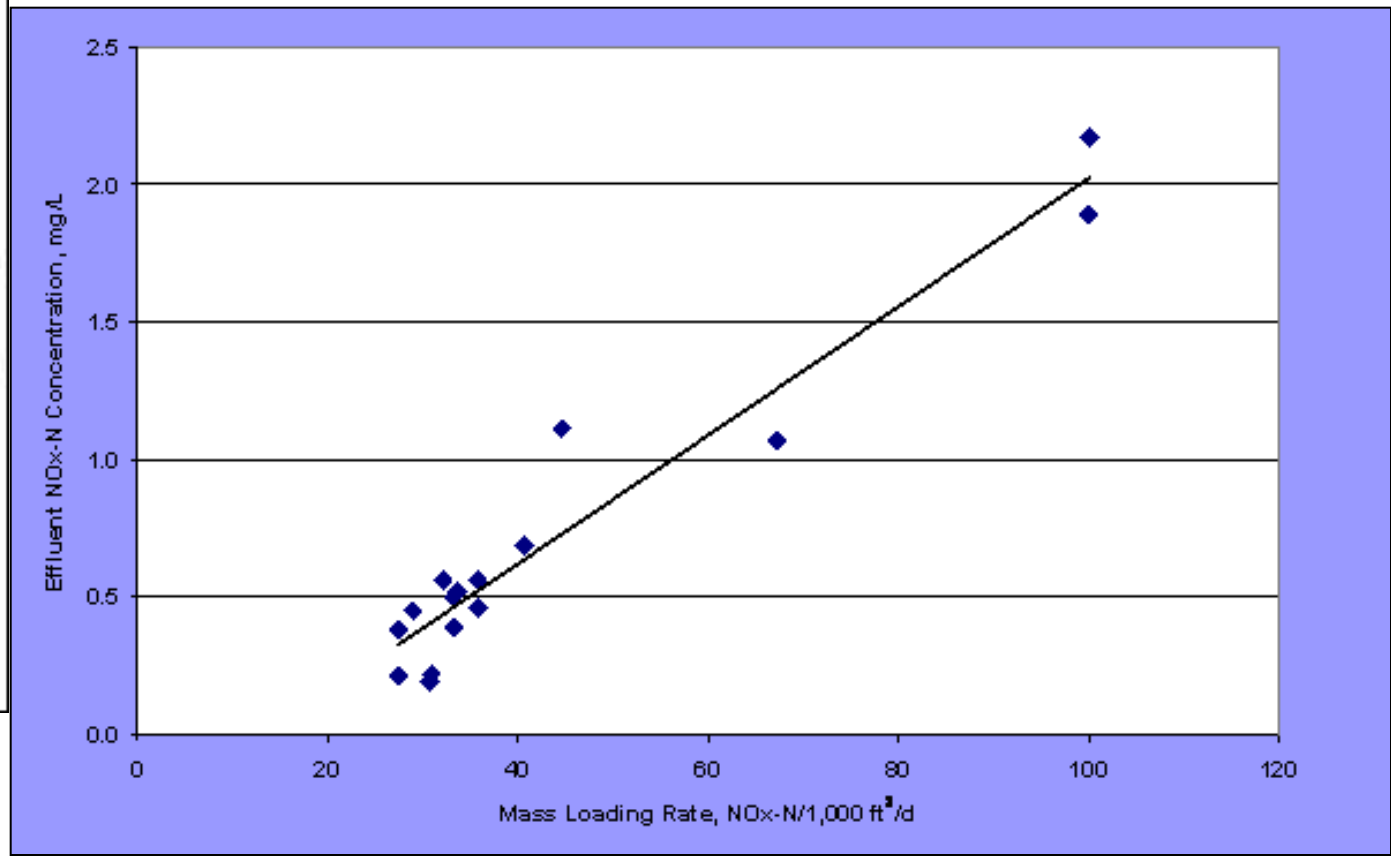
Parkson Dynasand Filter



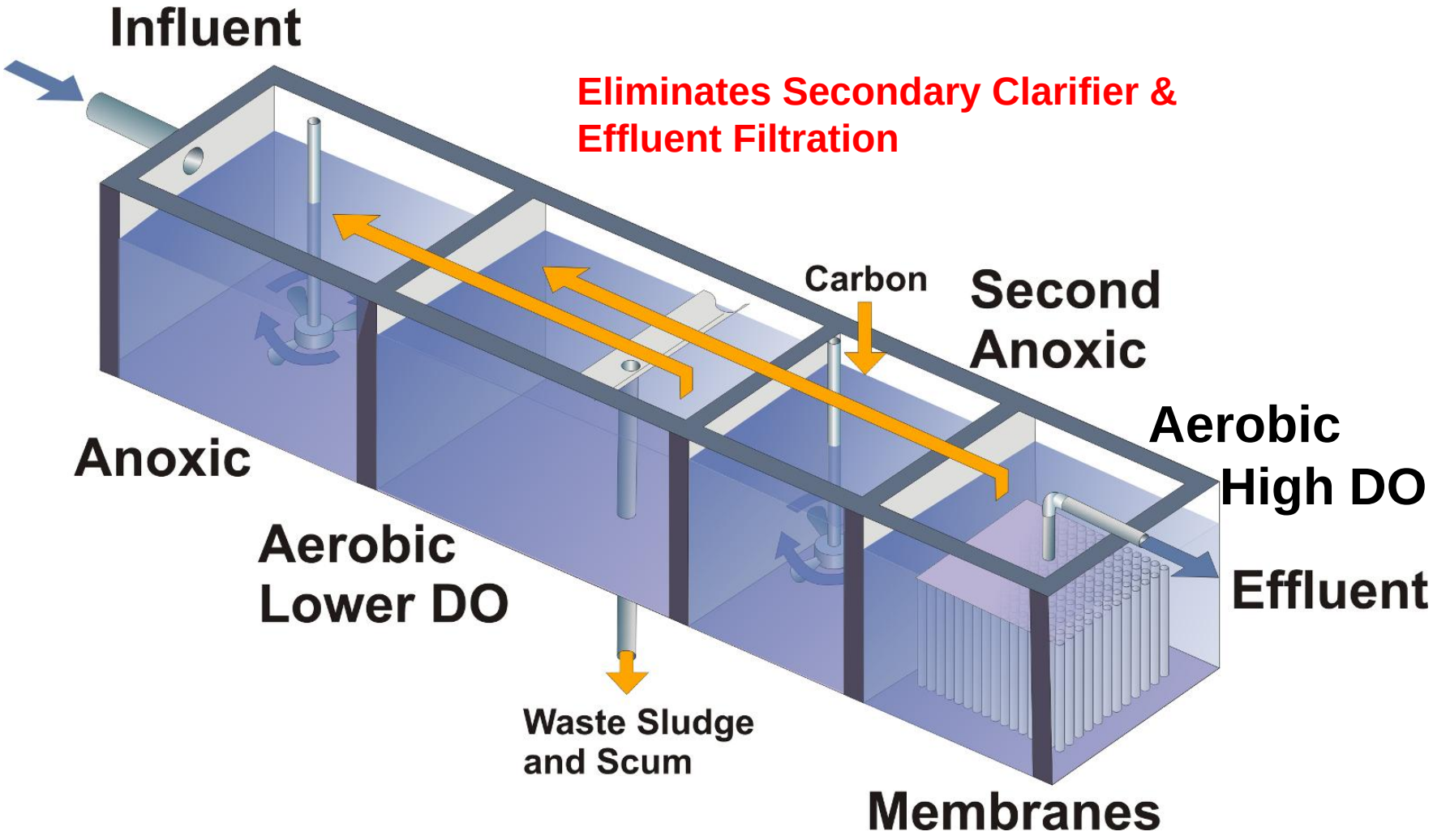
Hagerstown, MD: Effluent TN/TP Minimization



2.5 to 3 mg/L TN

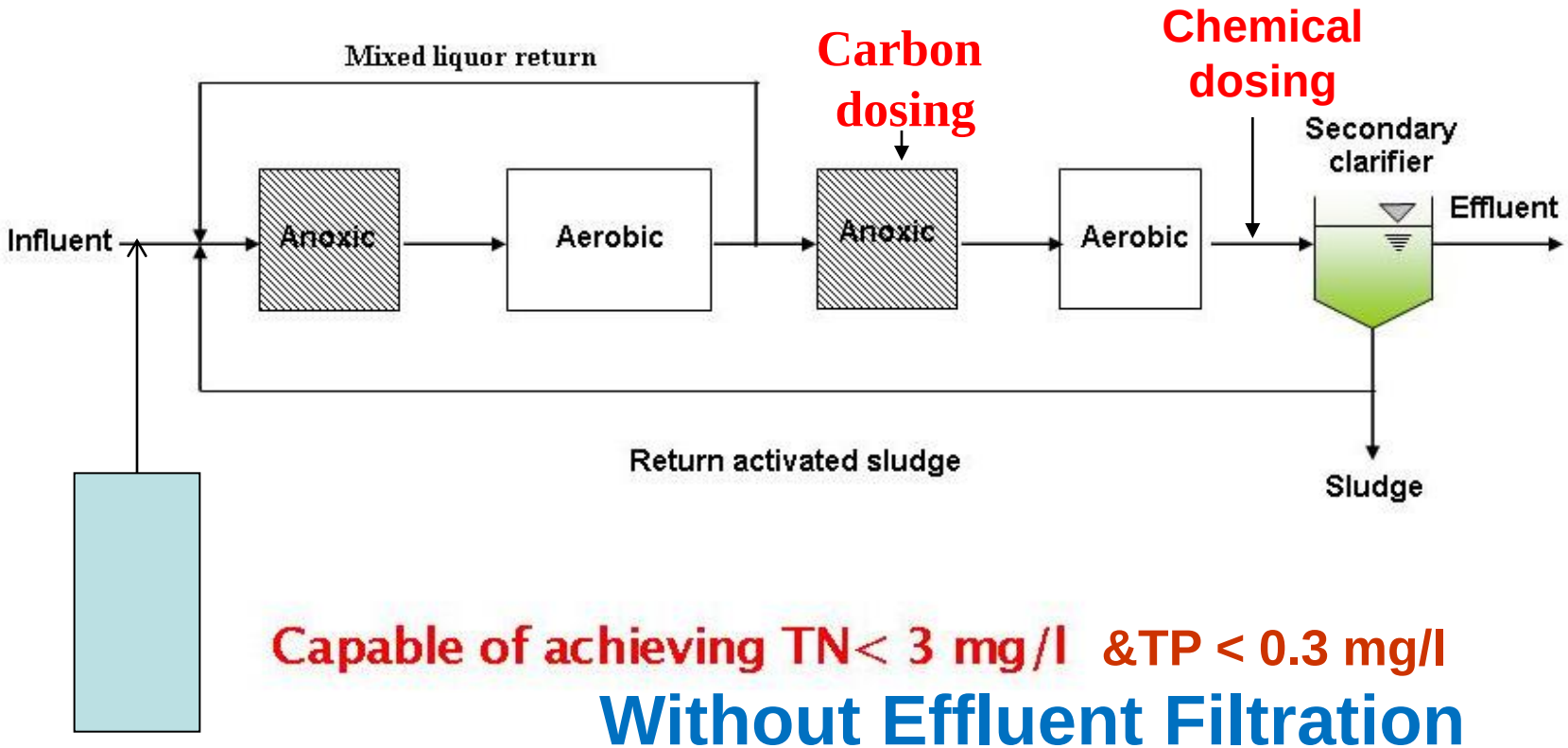


Membrane Bio-reactor for ENR Performance



4-Stage Bardenpho (AOAO)

For lower effluent nitrogen concentrations

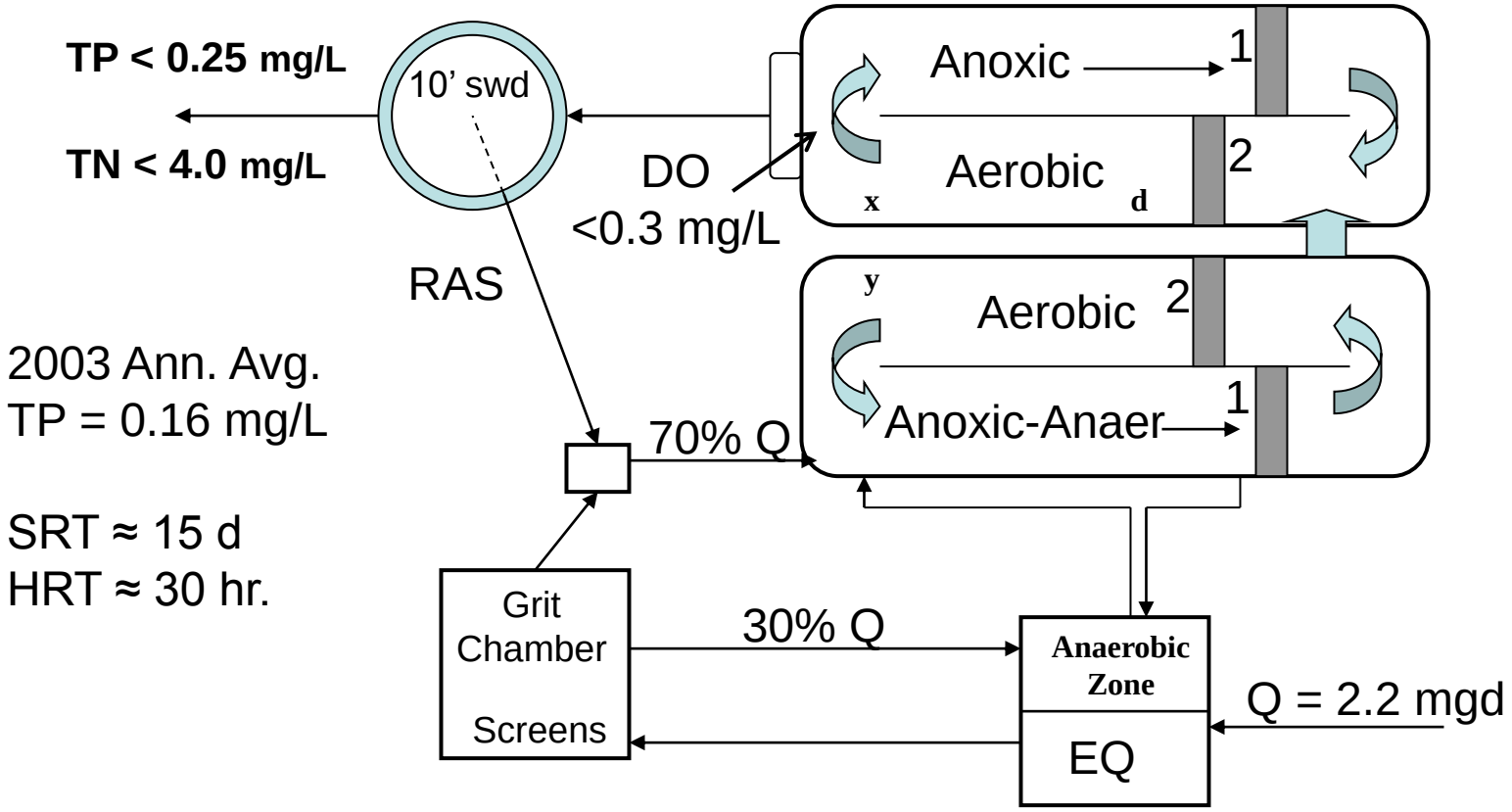


Capable of achieving TN< 3 mg/l &TP < 0.3 mg/l

Without Effluent Filtration

If rDON is low

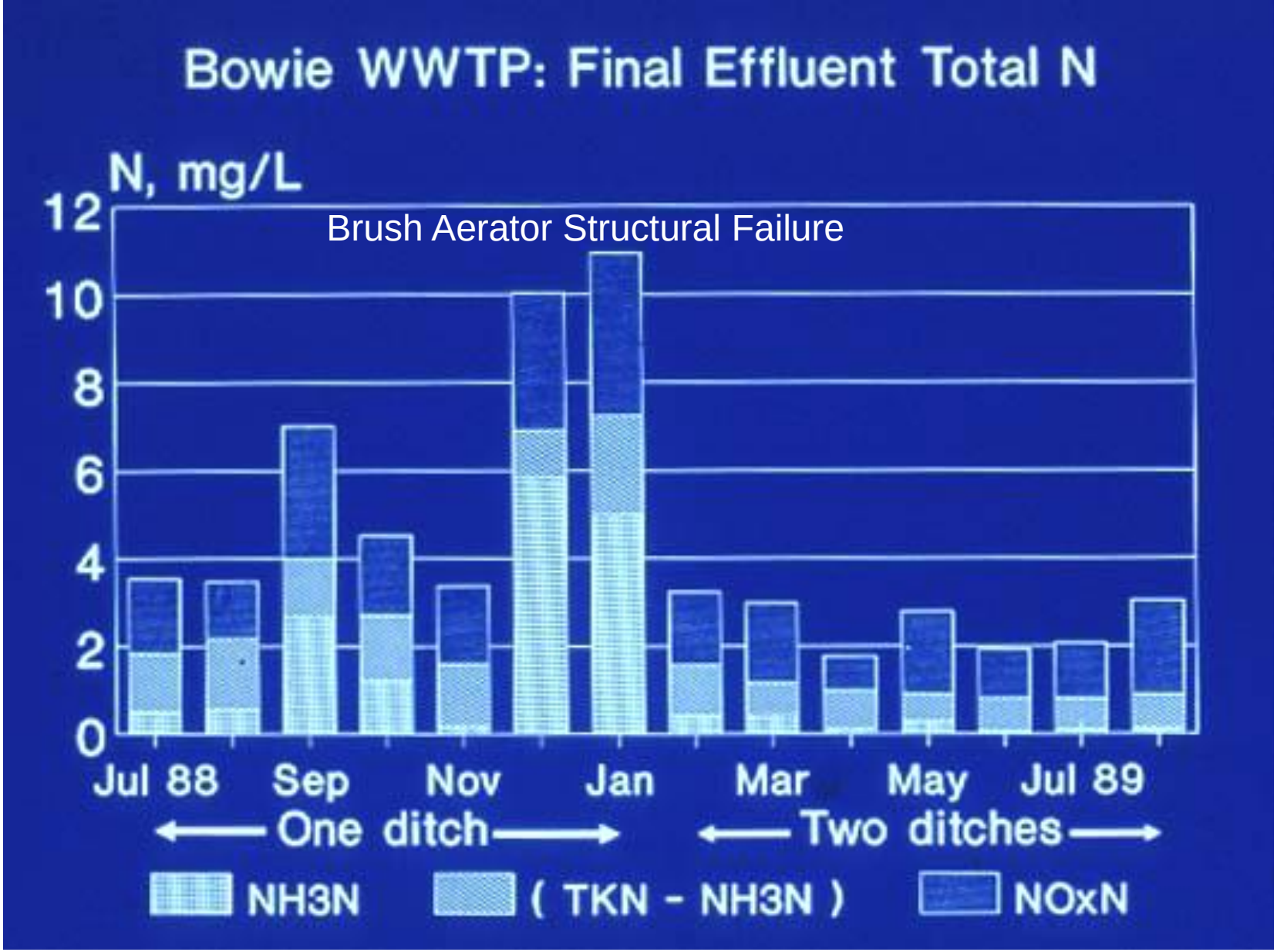
The VT2 Configuration
A Modified Oxidation Ditch BNR Process Operated at Bowie, Maryland, 1988-2008



2003 Ann. Avg.
TP = 0.16 mg/L

SRT ≈ 15 d
HRT ≈ 30 hr.

No Primary Sedimentation, No Chemical Addition, No Effluent Filtration

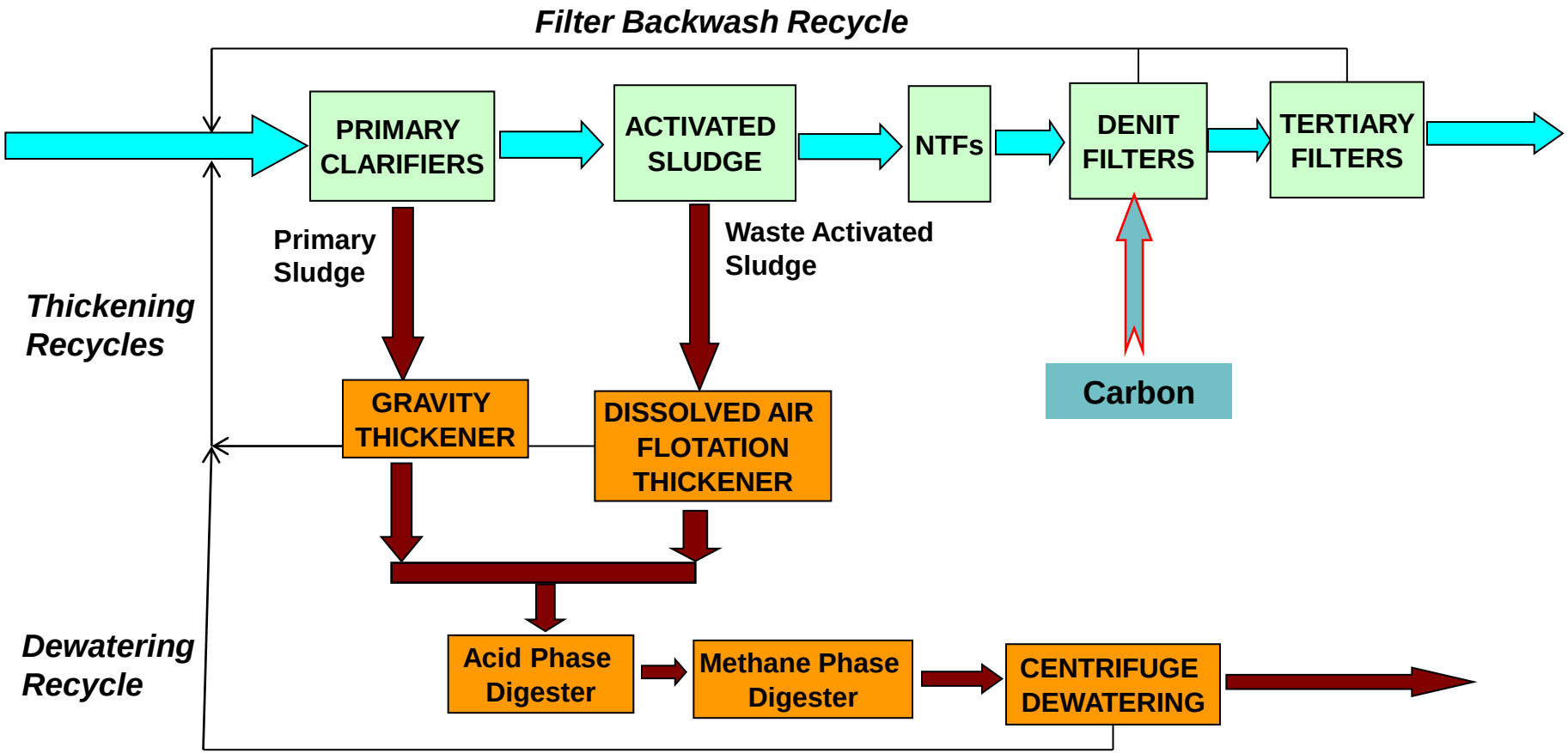

Bowie WWTP: Final Effluent Total N
N, mg/L
12
10
8
6
4
2
0
Brush Aerator Structural Failure
Jul 88
Sep
Nov
Jan
Mar
May
Jul 89
One ditch
Two ditches
NH3N
(TKN - NH3N)
NOxN

HOW LOW CAN WE GO?

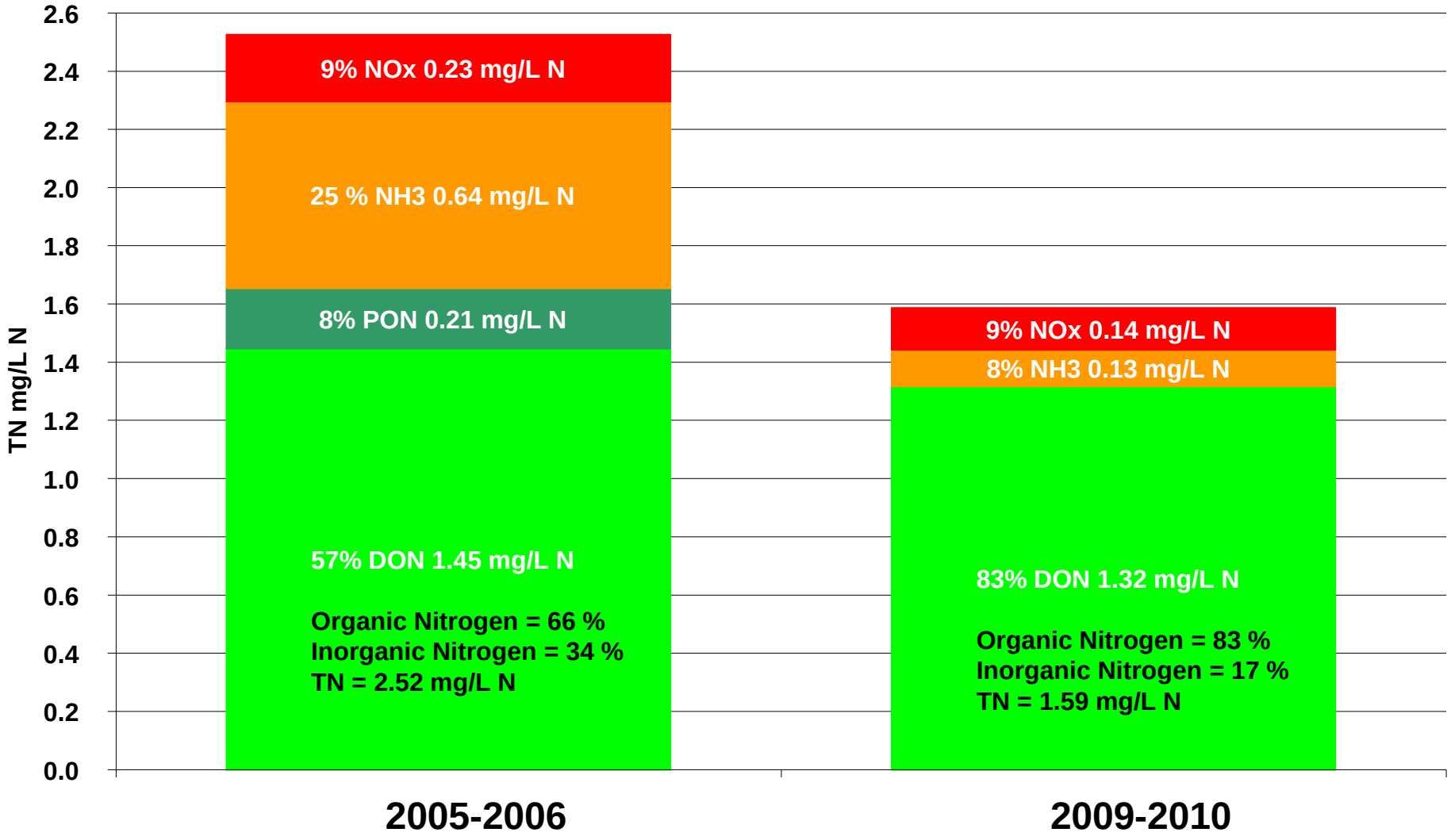
What are the economical limits for Nitrogen Removal?

Truckee Meadows WRF Process Schematic

Lower effluent N system adds carbon to last step



TMWRF AVERAGE EFFLUENT TOTAL NITROGEN



Performance Comparison for Nitrogen Removal Plants

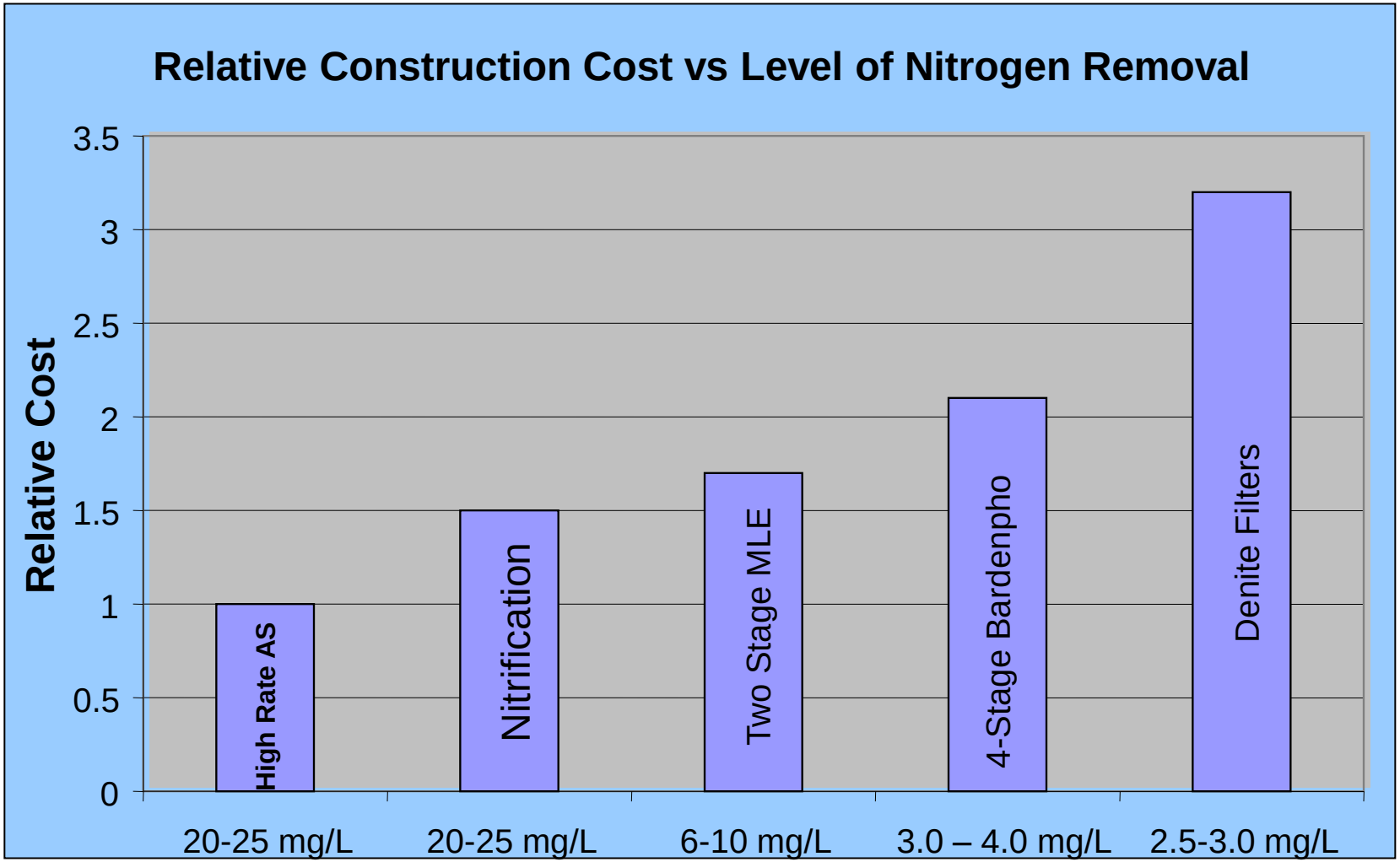
	Process	Permit	TPS-50%	TPS-95%
River Oaks	SepSt	3.75	1.45	2.92
Truckee Meadows	SepSt	2	1.77	4.26
Eastern EWRF Orange Co	Comb	5	3.67	8.18
WSSC	Comb	7	3.40	6.20
DCWASA	BOD/Nit/Denit	7.5 (4.2)	5.33	9.65

Truckee Meadows best (Temp ~ 13-20^{0}C), denitrification filters with Methanol and then polishing filters

<1.0 mg/L TN is not achieved

- Truckee Meadows Water Reclamation Facilities
  - <2.0 mg/L
- Oxidation ditch with filters
  - 2-3 mg/L
- Bardenpho with filters
  - 2-4 mg/L

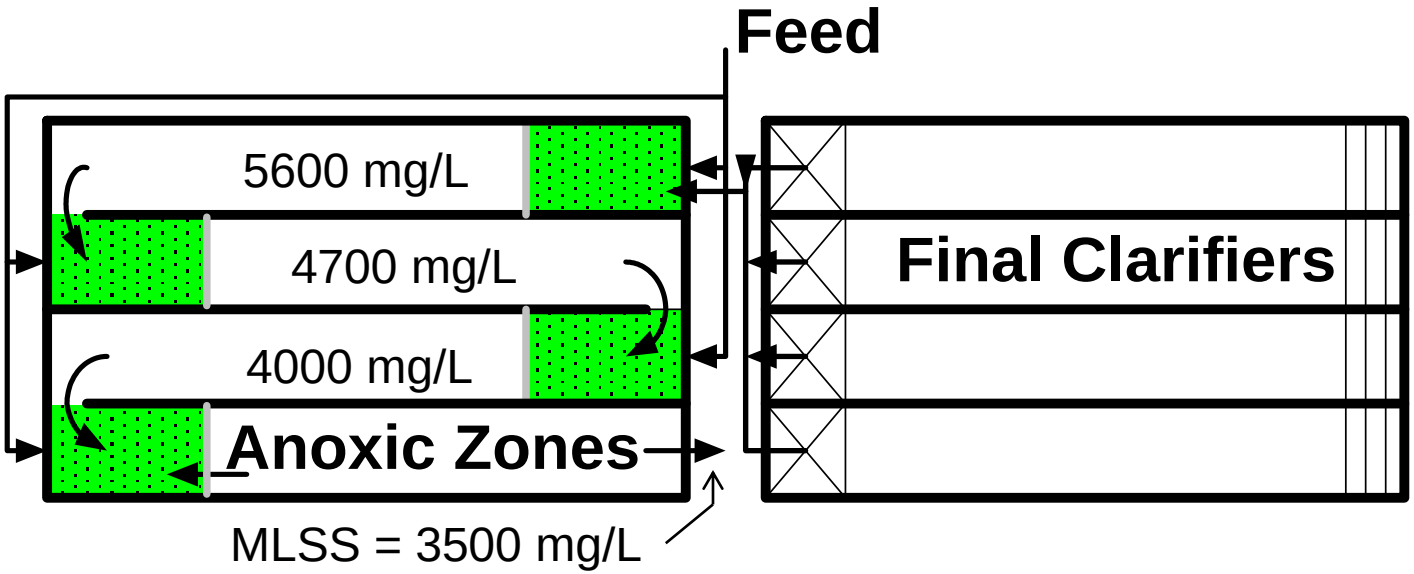
Relative Costs – Site Specific



Effluent Total Nitrogen Limit

Step Feed Denitrification

for Intermediate N Removal



Considerations:

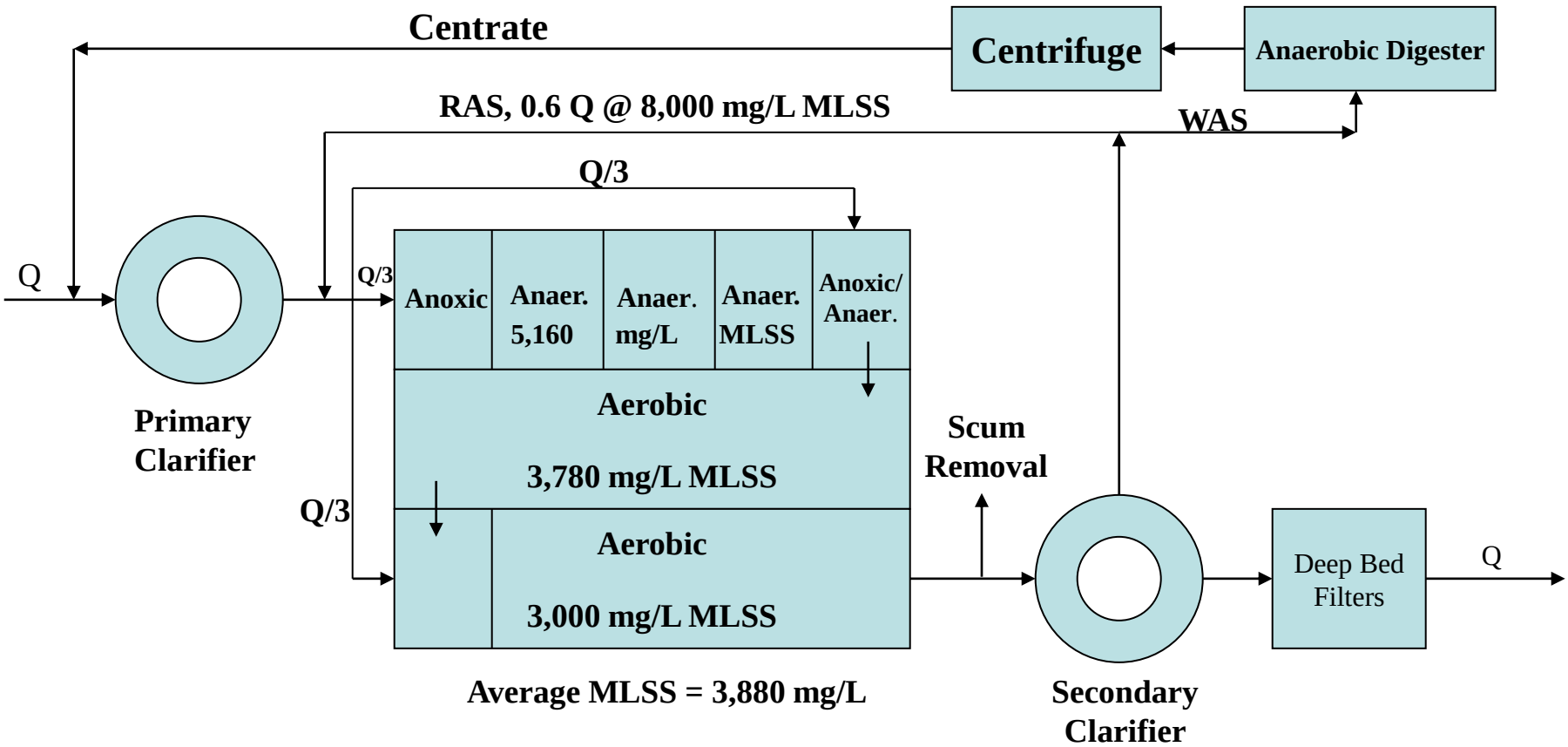
- MLSS Gradient – 15% Capacity Increase.
- NH_3-N Bleed Through
- No MLR pumping, but complex flow dist.

Effluent Quality

NH_3-N < 1.5 mg/L

TN = 8 - 10 mg/L

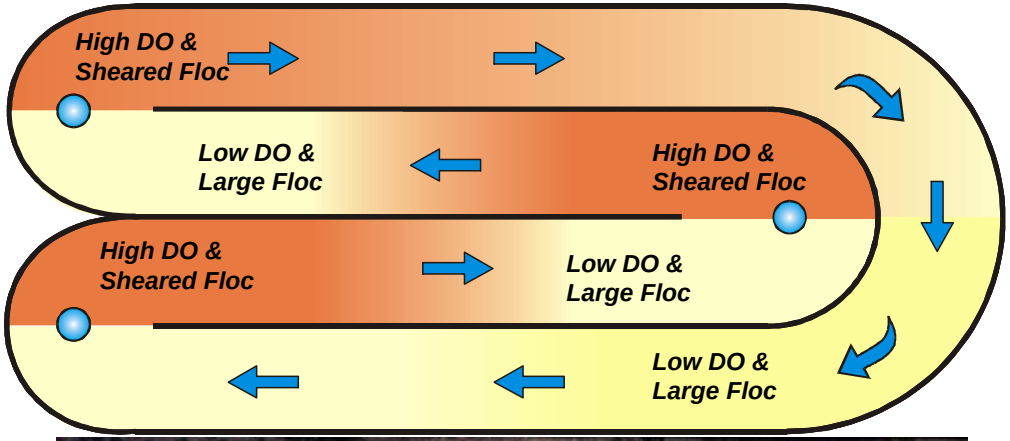
STEP-FEED JOHANNESBURG BNR DESIGN
South River WRC, Atlanta, GA.

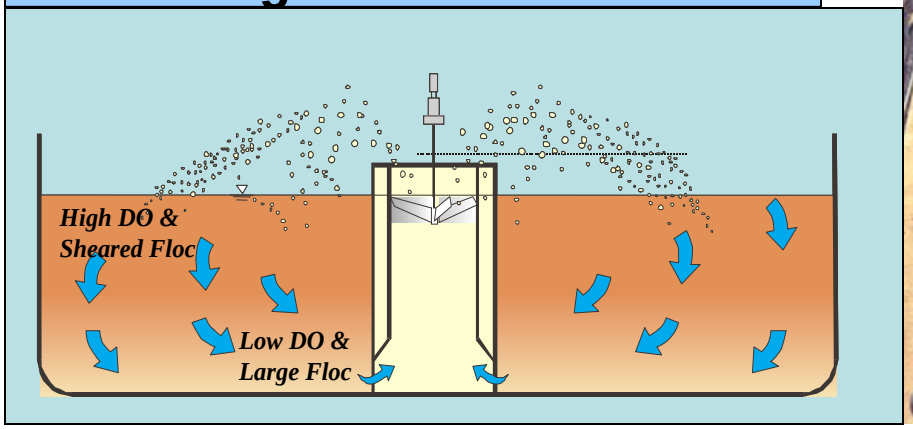


Simultaneous Nite/Den (SND)

Considerations

- Point Source Aeration
- Areas of high and low energy
  - Floc Shear
  - Floc Reformation
- Promotes DO Gradients
  - Floc
  - Bulk Liquid
- 6 to 9 mg/L TN





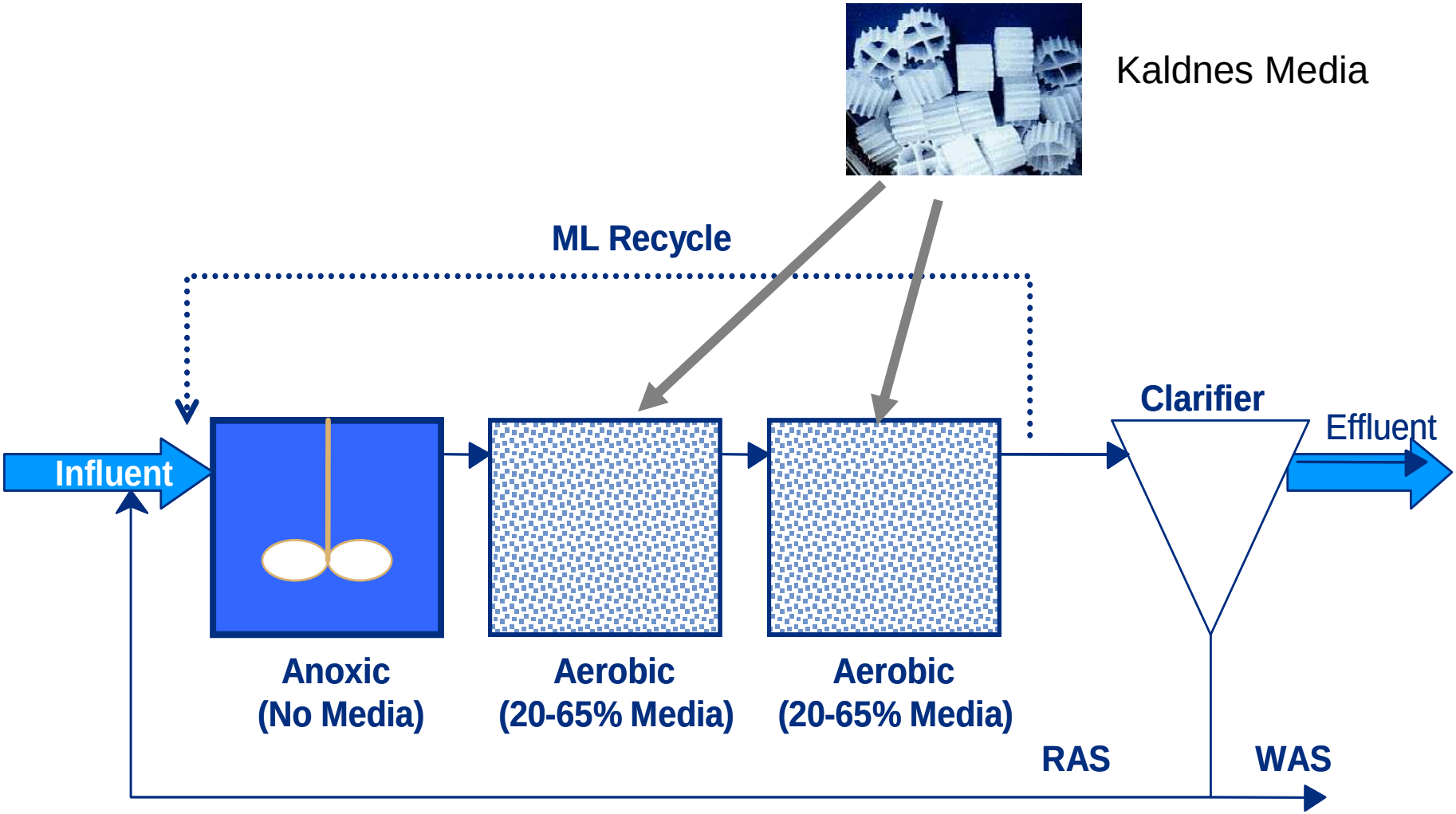
Small Footprint Technologies

- Sequencing Batch Reactor (SBR)
- Integrated Fixed-Film Activated Sludge (IFAS)
- Moving Bed Biofilm Reactor (MBBR)
- Membrane Bioreactor (MBR)

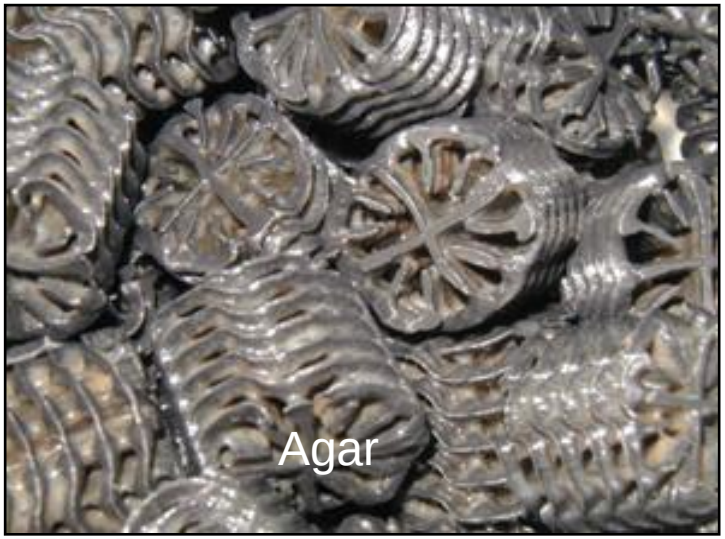
Sequencing batch reactors

- Better utilization of space
- Fits on to odd sized sites
- Can be stacked
- Need a minimum of pipes and boxes
- Can be designed for various levels of nitrogen removal by varying the aeration and anoxic phases

IFAS Example Schematic



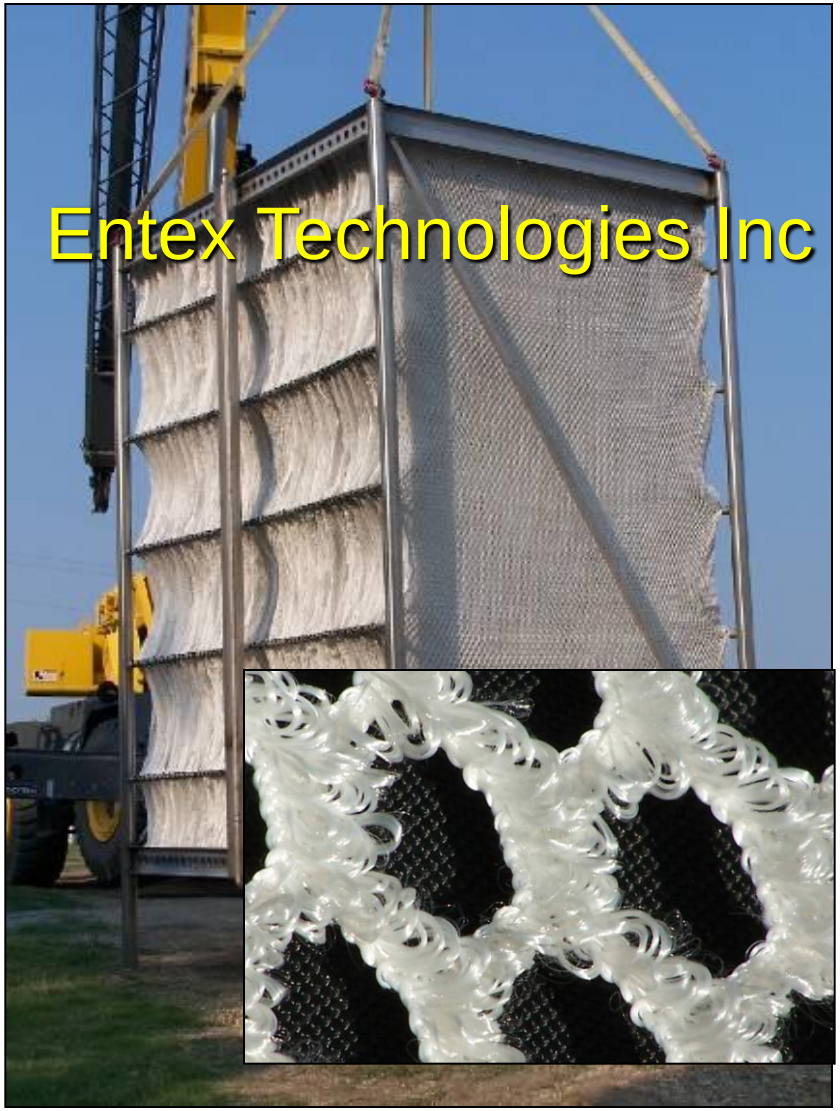
Other Media Types



Media Retention Sieves

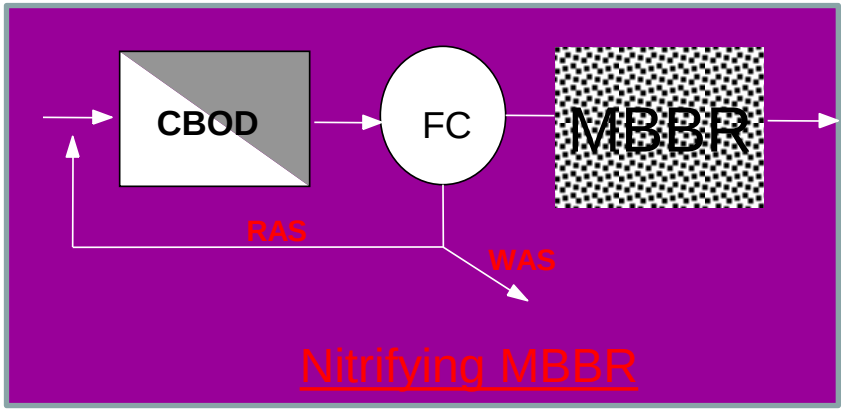
Fixed Media – BioWeb™

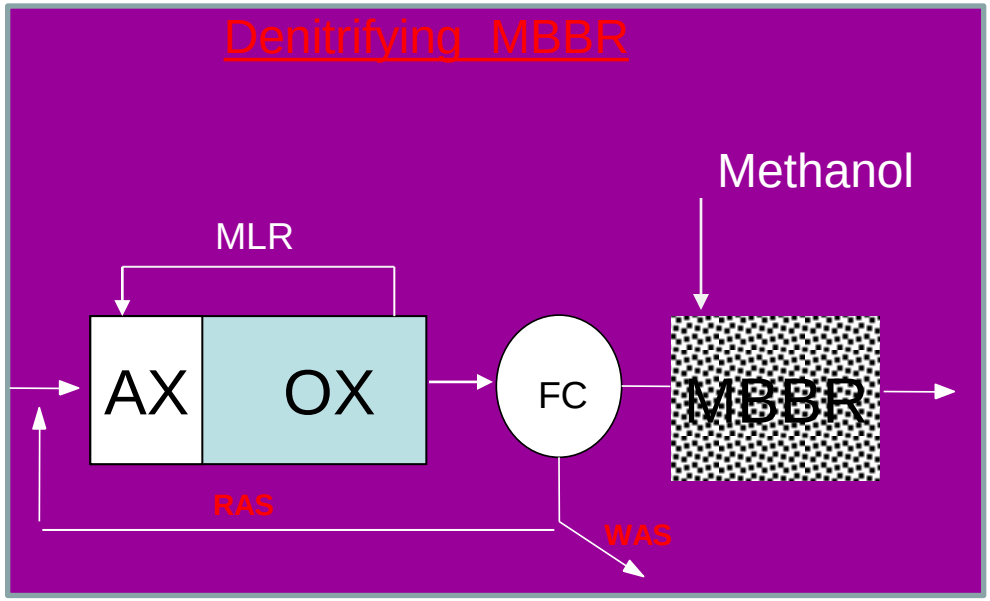
- BioWeb
  - Knitted polyester manufactured in USA
  - Over 1000 pounds per square foot break strength
- Frames
  - Stainless steel
  - Both with and without integral aeration and controlled mixing
- Installation
  - Fully assembled modules shipped to jobsite for simple lift and place



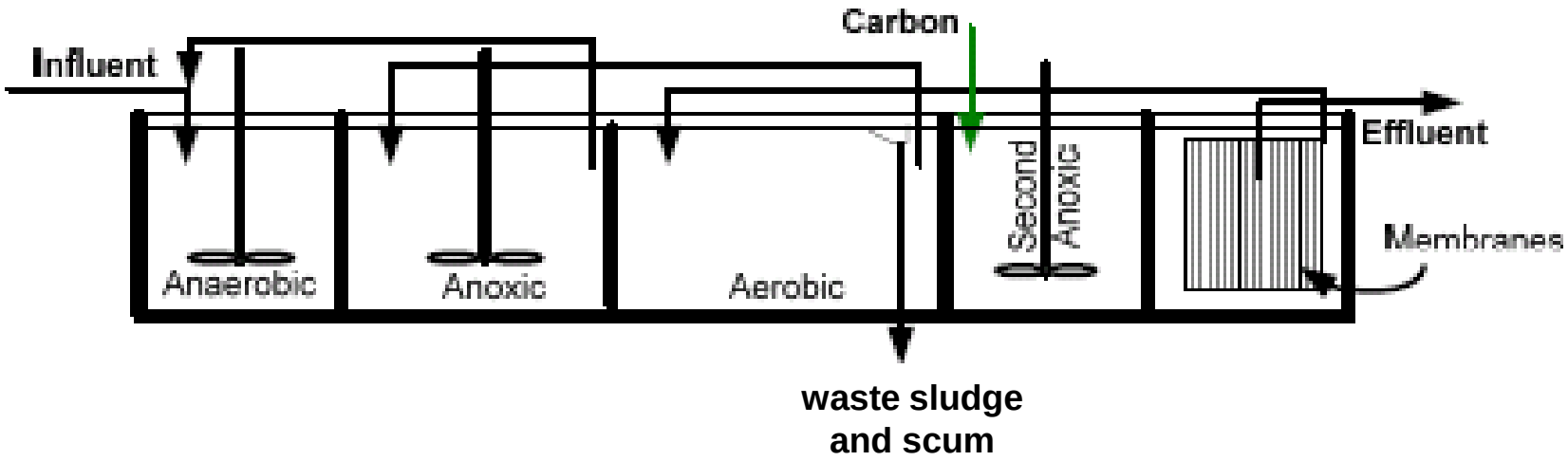
Moving Bed Bioreactor (MBBR)

- Suspended/attached growth system
- High surface area, free floating media
- No RAS – “Once through” process - microbes retained on media





Membrane Bioreactor for very low TN and TP

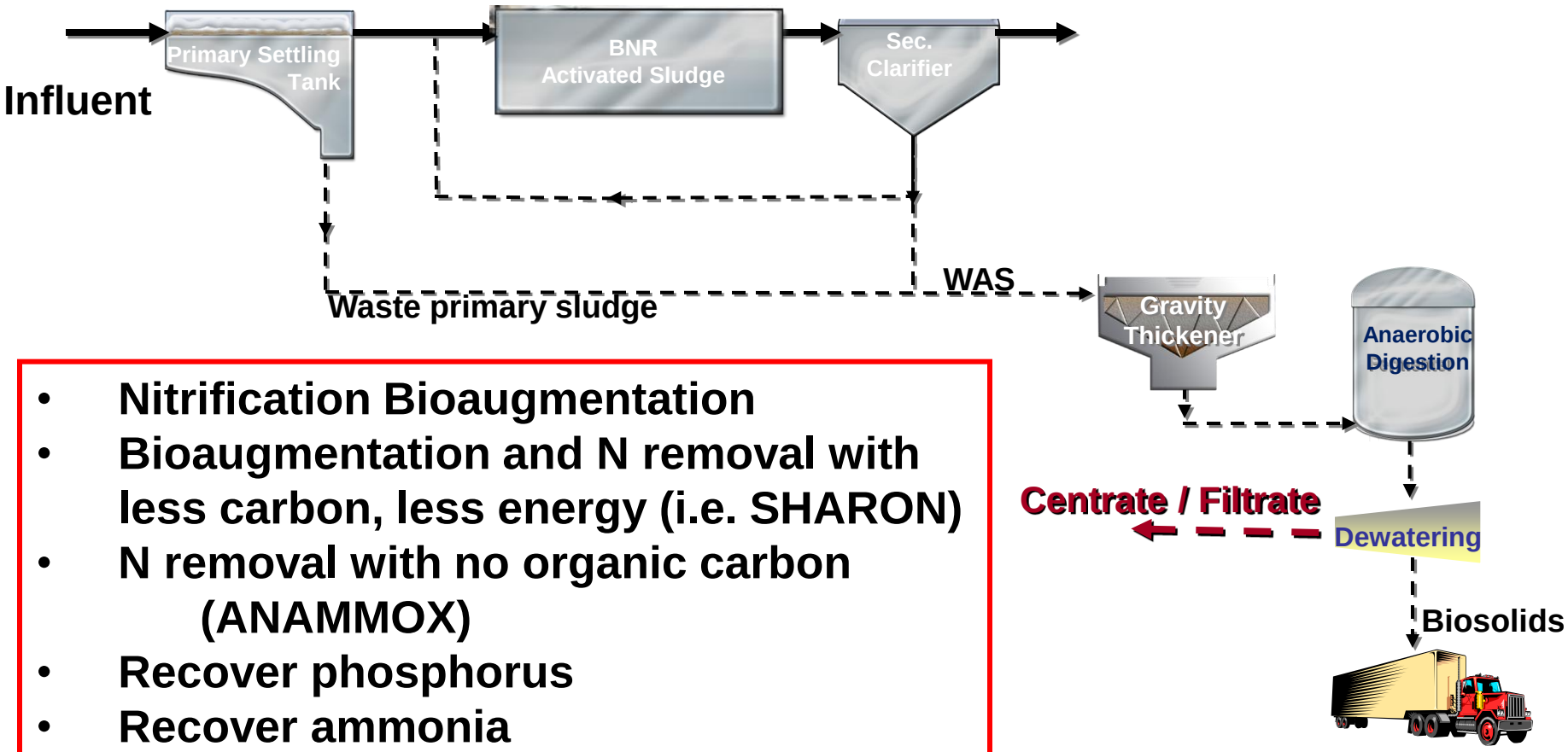


- Membranes replace both secondary clarifiers and filters
- All biological and chemical actions must take place before membranes
- BPR achievable; effluent P concentration a function of rbCOD:P_{ba}
- Nitrogen removal to low levels possible with COD:TKN > 10
- With chemical supplementation, can achieve effluent concentrations of TP <0.05 mg/L and TN around 3 mg/L
- Very good for water recovery & reuse

Membrane Applications

- Membrane Bioreactors
  - BioP with chemical addition
  - Chemical addition only
- Tertiary filtration membranes following N&P treatment
  - with chemical addition

Opportunities with Anaerobic Digestion Sidestreams

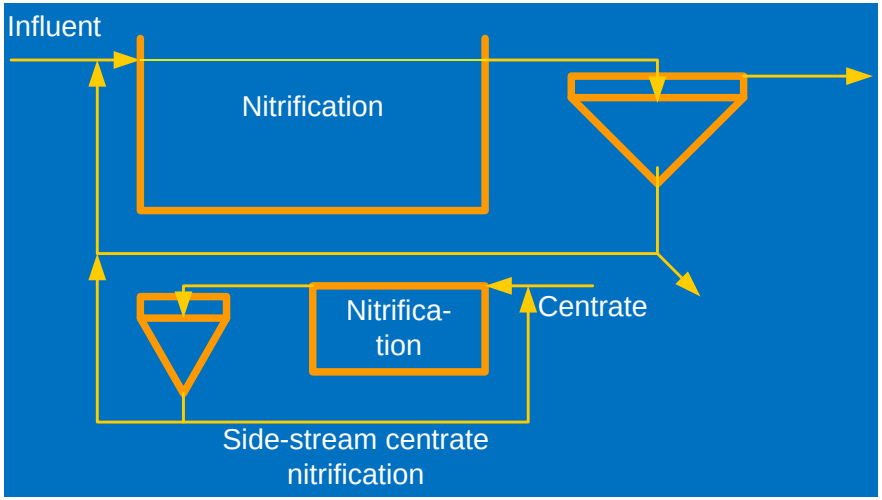


- Nitrification Bioaugmentation
- Bioaugmentation and N removal with less carbon, less energy (i.e. SHARON)
- N removal with no organic carbon (ANAMMOX)
- Recover phosphorus
- Recover ammonia

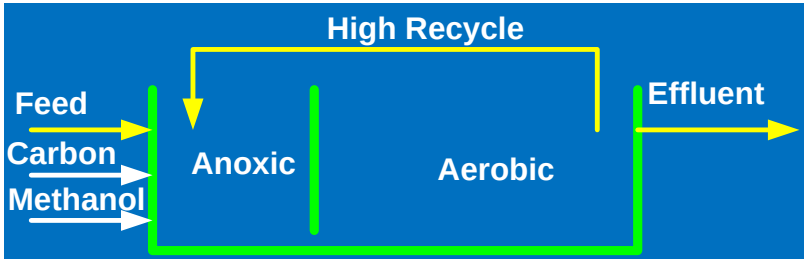
N Removal - Recycle Streams

- When ammonia load is more than 20% of influent load, consider side stream treatment
  - Ammonia stripping and capture
  - Separate nitrification and denitrification – Sharon, Babe , Anammox , Demon, etc. for reduction in carbon requirements
  - Consider struvite recovery for BPR plants – e.g. Ostara which also captures ammonia

In-Nitri and SHARON processes for Centrate/Filtrate Treatment



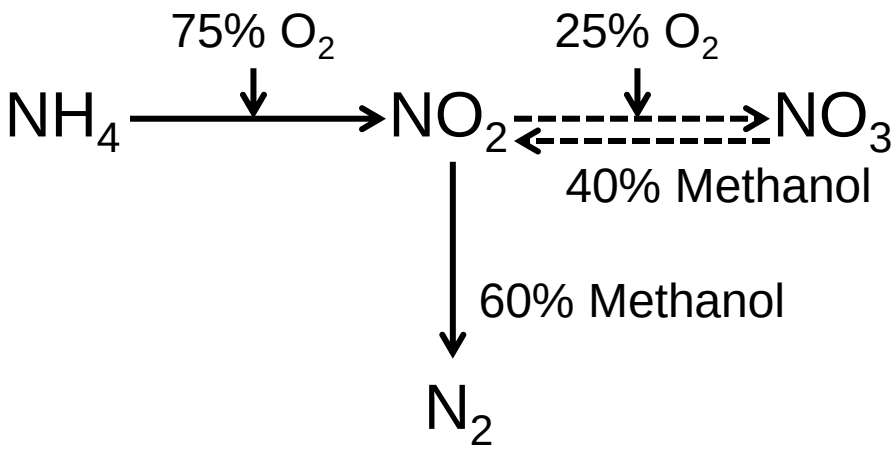
In-Nitri® for Bioaugmentation



SHARON® for Reduction of aeration energy & carbon costs

- In-Nitri has completely separate sludge system to treat the centrate
- High ammonia load leads to high growth of nitrifiers
- Surplus bacteria is wasted to the main aeration for augmentation of nitrification
- Main aeration basin can operate at much lower SRT for nitrification
- SHARON controls process to limit oxidation of ammonium to nitrites, not to nitrates. Nitrites used as electron acceptors and reduced to Nitrogen gas.

SHARON PROCESS FOR N REMOVAL BY NITRITATION



Reduces Oxygen Requirement by 25% & Methanol Requirement by 40%

Controlled by:

1. Maintaining reactor temperature between 30 & 40 ^{o}C
2. Operating the reactor at a one day SRT to washout Nitrate formers
- Therefore, operate reactor at one day HRT without recycle, Δ HRT = SRT
3. Controlling oxygen inputs to maximize denitritation rate

Insufficient Carbon for nitrate reduction

- Purchase additional carbon (methanol, acetate, etc.)
- On-site fermentation of primary sludge
- Use *Nitritation* process in recycle stream
  - SHARON
- Use *De-Ammonification* process in recycle stream
  - ANAMMOX
- Fixed film nitritation and de-ammonification processes
  - OLAND
  - CANON

N REMOVAL BY ANAMMOX

- Anaerobic ammonia oxidation
- Autotrophic bacteria
- NO_2-N used to oxidize NH_4-N

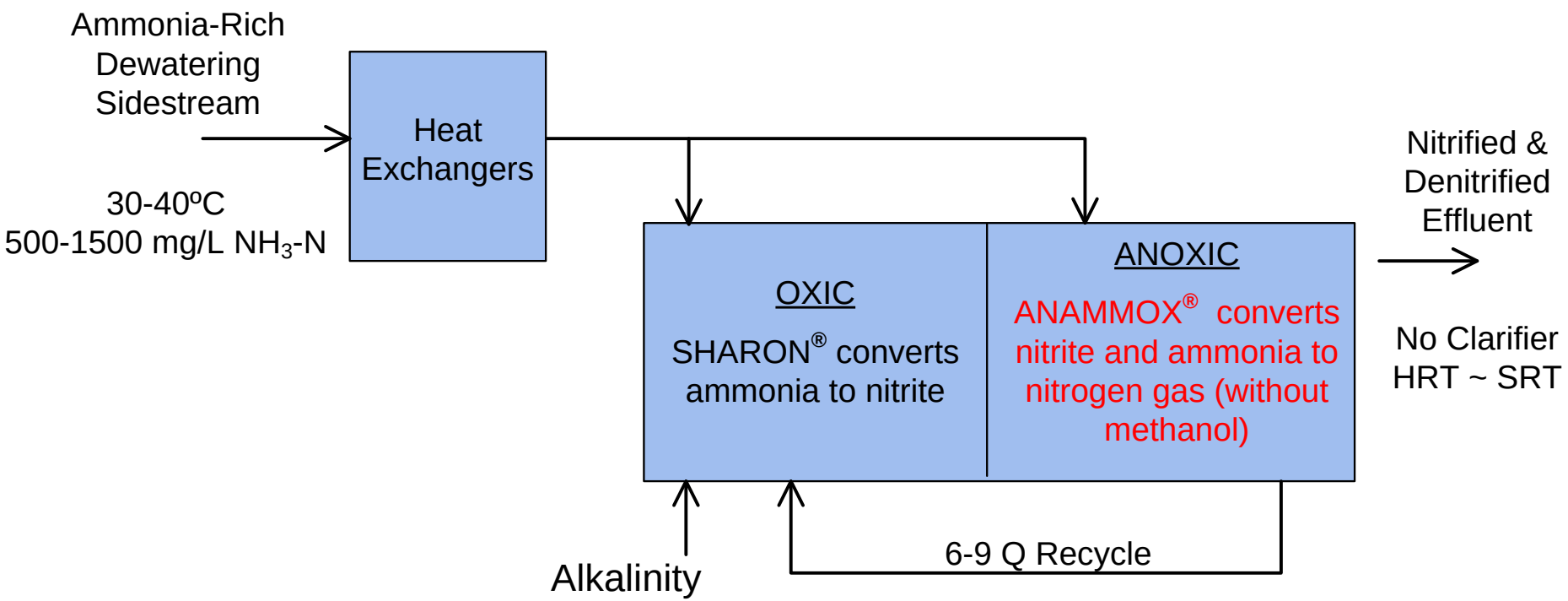
$$NH_4^+ + 1.32NO_2^{-1} + 0.13H^+ + 0.066HCO_3^{-1} \rightarrow$$
$$1.02N_2 + 0.26NO_3^{-1} + 0.066CH_2O_{0.5}N_{0.15} + 2.03H_2O$$

Requires 1.3 moles of NO_2^- -N per mole of NH_4^+-N oxidized to N_2

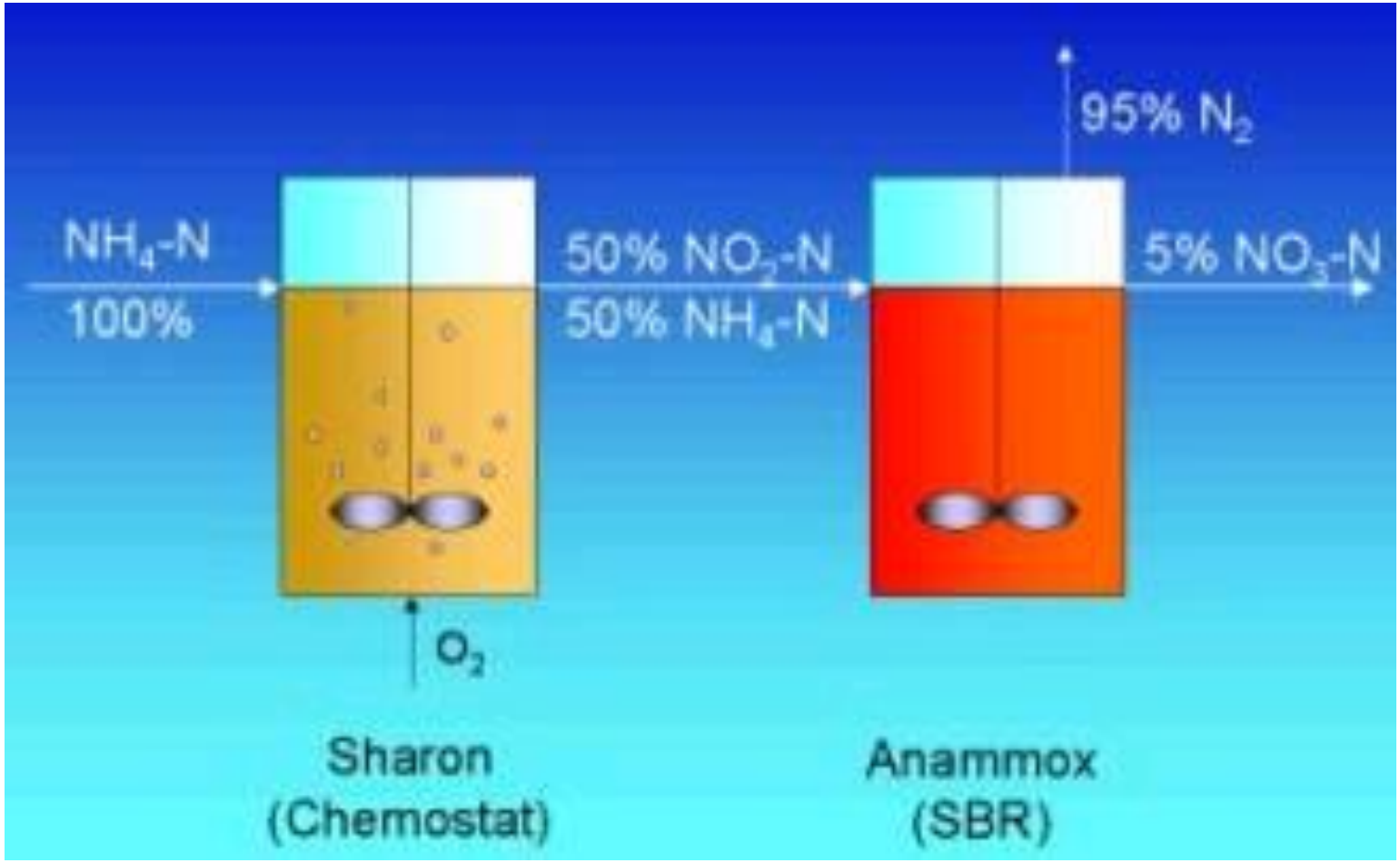
- Nitrogen removal without carbon addition
- Digester centrate treatment @ 30-35 ^oC

SHARON®/ANAMMOX®

ANaerobic AMMonia OXidation



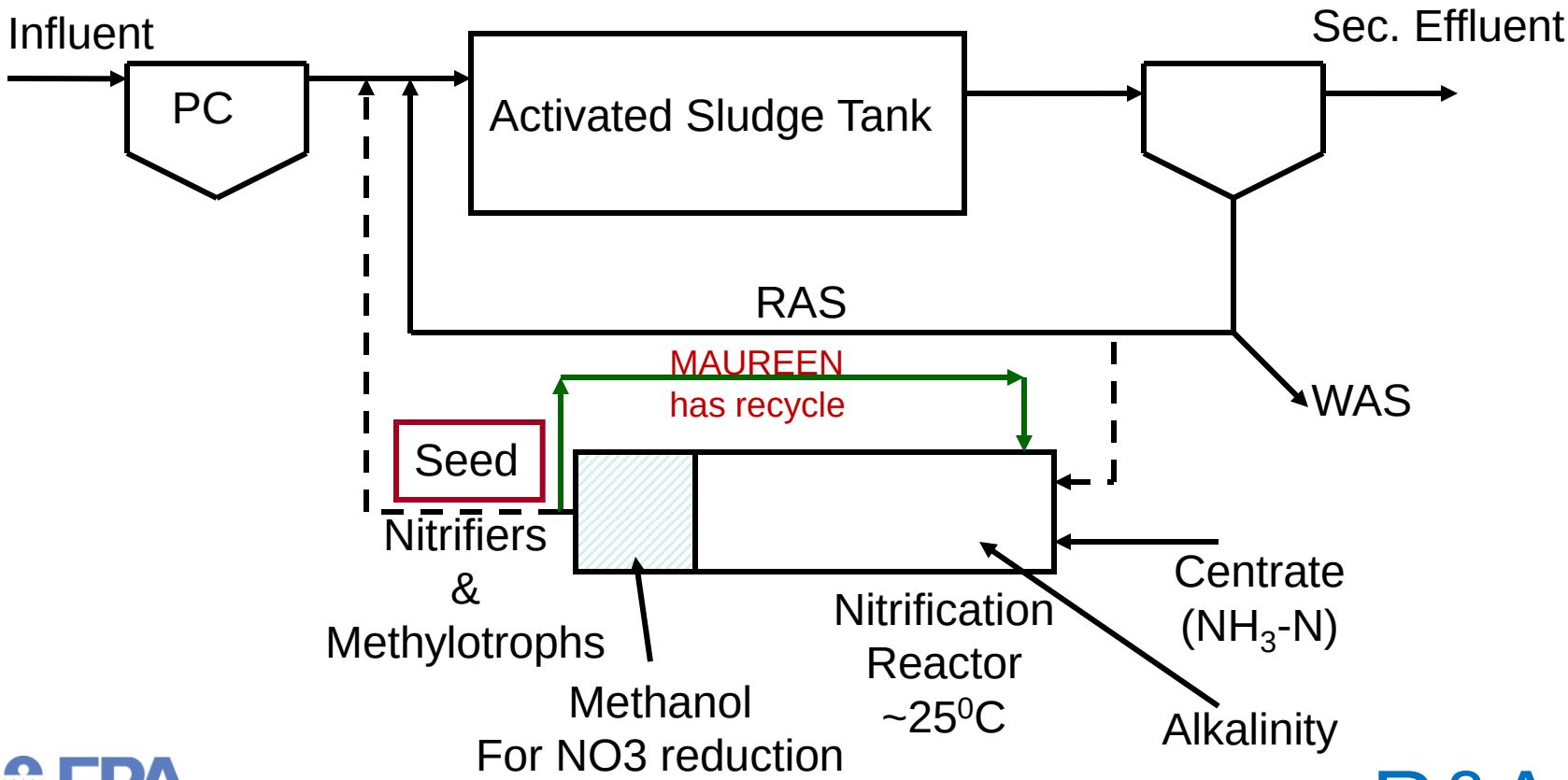
ANAMMOX PROCESS SCHEMATIC



New York City AT-3 Process

MAUREEN IS A MODIFIED VERSION

(**M**ainstream **Au**totrophic **R**ecycle **E**nabling **E**nhanced **N**-removal)



AT-3 Process

- Seeding Effect
  - Nitrifiers allow reduced SRT for mainstream reactors
  - Methylotrophs allow for smaller anoxic zones where methanol is added for mainstream reactors
- Improved sidestream nitrification efficiency
- RAS addition benefits
  - lowers temperature, provides floc to capture nitrifiers, reduces NH4 conc. and potential for free NH3 toxicity
- Operational in 4 New York City plants
- December 2005 Results (W and W/O AT-3)
  - NH4-N, 6.0 to 2.0 mg/L
  - NO3-N, 6.0 to 3.0 mg/L

Summary

- Recycle sidestream treatment can provide more stable and effective nitrification
  - Equalization
- Recycle sidestream treatment can increase nitrification capacity of existing system
  - BABE, InNITRI, AT-3, MAUREEN
- Recycle sidestream treatment can help reduce organic carbon demand for nitrogen removal
  - SHARON, ANAMMOX, OLAND, CANON

Nutrient Recovery – Why?

Benefits for the Treatment Plant

- Reduced Nutrient Loads
- Reduced Phosphate in Biosolids
- Fertilizer Production
- Struvite Control

Lower Costs

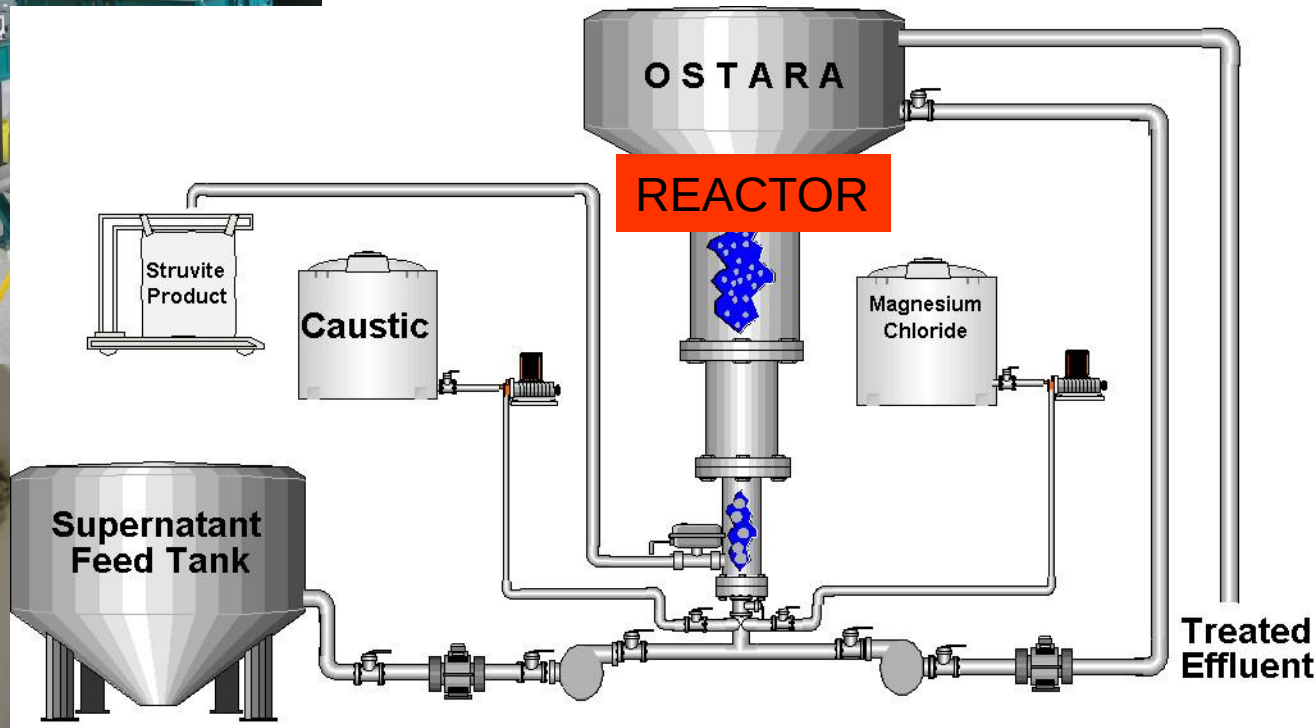
Improved Reliability

Struvite Recovery

Struvite

$Mg.NH_4.PO_4 \cdot 6\ H_2O$

Also recovers up to 20% of nitrogen



Summary of Benefits

- Treatment Plant Capacity Increase
- Struvite Control
- Improved Environmental Stewardship
- Improved Plant Reliability
- Higher Effluent Quality
- Reduced Operating Costs

Cost Savings

THE END

QUESTIONS?

COMMENTS?

Operation and Optimization of BNR plants for Enhanced Nitrogen Removal

James L Barnard

Black & Veatch

U.S. EPA Technology Transfer Seminars
Nutrient Control at Municipal Wastewater Treatment Plants

Typical ENR effluent requirements

Effluent Parameter	Concentration Range	Typical Averaging Period
BOD_5, mg/L	1-5	Monthly
COD, mg/L	<10	Weekly*
TSS, mg/L	1-5	Monthly
NH_3-N, mg/L	<1.0**	Monthly/Maximum
TN, mg/L	3-4	Monthly/Yearly
TP, mg/L	0.1-0.3	Monthly/Yearly
pH, units	6-9	Instantaneous

*Upper Occoquan AWT Plant **Definition of Complete Nitrification

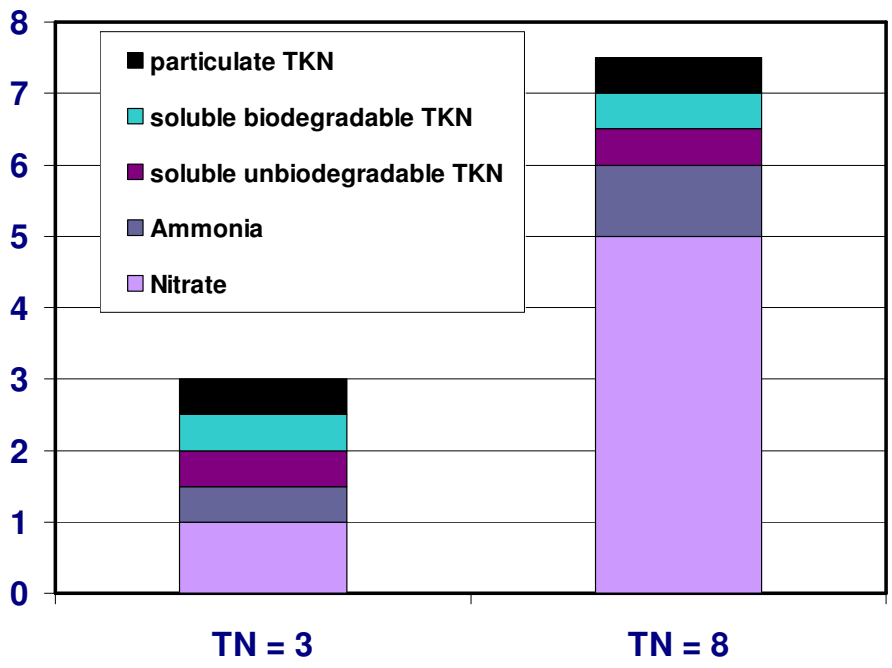
Fundamental ENR Effluent Permit Challenge

- The very high standards leave little room for error
- A single biological process failure can result in violation of any of the concentration limits listed in Table 1, over any of the averaging periods.
- Example: One day excursion of 1.5 mg/L TP averaged with 29 days of 0.08 mg/L results in an average of 0.127 mg/L, which exceeds the monthly limit of 0.1 mg/L

Challenges of ENR Implementation Operating Considerations

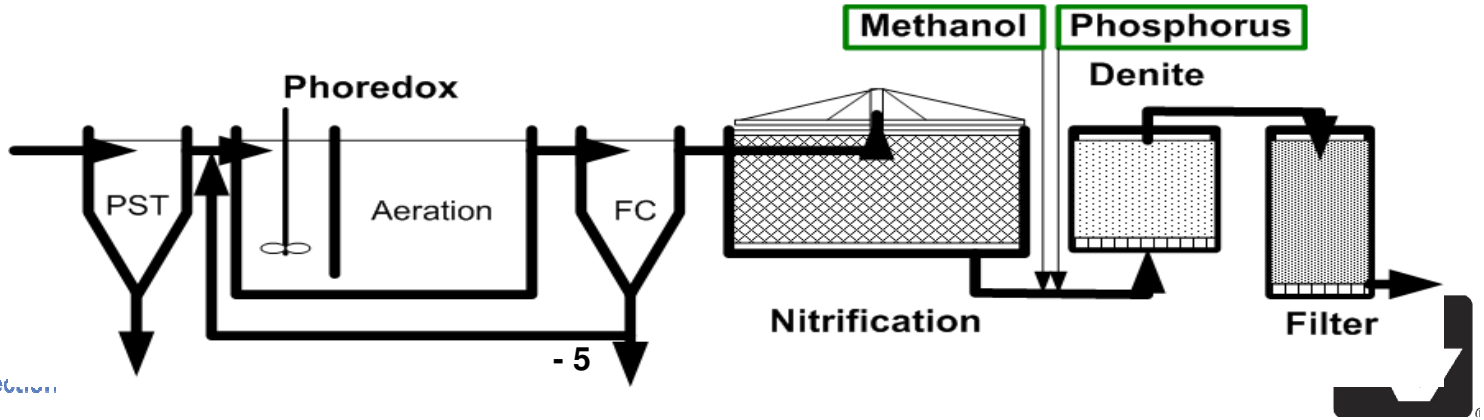
ENR effluent requirements are near the minimum possible with existing affordable wastewater treatment processes.

- Processes must be operated optimally at all times to ensure compliance.
- Influent flows and loads are constantly varying, which tends to make effluent quality variable.
- Flow balancing and/or load balancing is a serious consideration
- So is redundancy



Influential Factors that Affect Nitrogen Removal

- Imposed Nitrogen Limit
- Wastewater Characteristics
- Existing Treatment Processes
- Site Constraints or Restrictions
- Process selection – single of multi-stage



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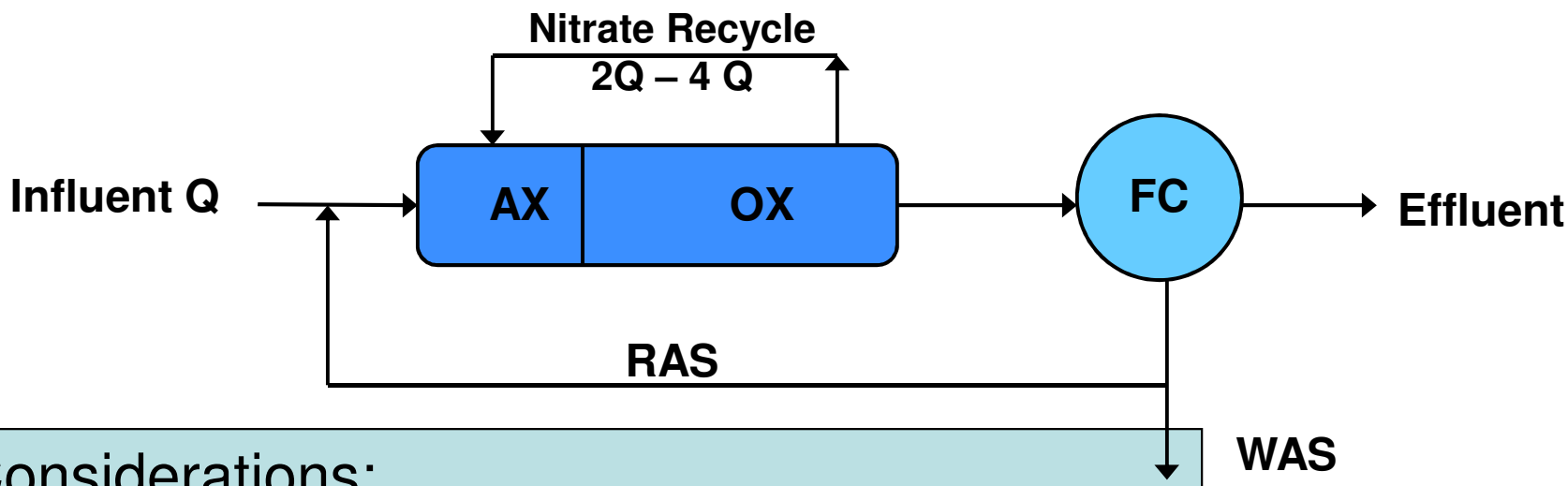
Nitrogen Removal Performance is linked to

- Available COD/BOD loading to the anoxic zone
- Reduced dissolved oxygen to anoxic zones
- Rate of recycle to first anoxic zone
- Temperature affecting both nitrification and denitrification
- SRT to ensure nitrification
- pH and alkalinity
- Load variation

Nitrogen Removal Strategies

- *Effectively Use Internal Carbon Source*
  - Two Stage MLE Process
  - 4-Stage Bardenpho
  - Channel Systems (SND)
  - Step Feed Denitrification
  - Sequencing Batch Reactors
  - MBBR
- *Rely on External Carbon Source*
  - Sidestream Treatment
  - BAF
  - Tertiary Denitrification Filters
  - Post Denitrifying MBBRs
  - Sidestream treatment - Sharron

Two Stage 'MLE' Process



Considerations:

- Easily implemented in nitrifying system
- May increase capacity – 23rd Ave Phoenix
- Maximum 10 % de-rating if system already nitrifies
- Sensitive to available carbon and MLR

Effluent Quality

NH_3-N < 1 mg/L

TN = 6 - 10 mg/L

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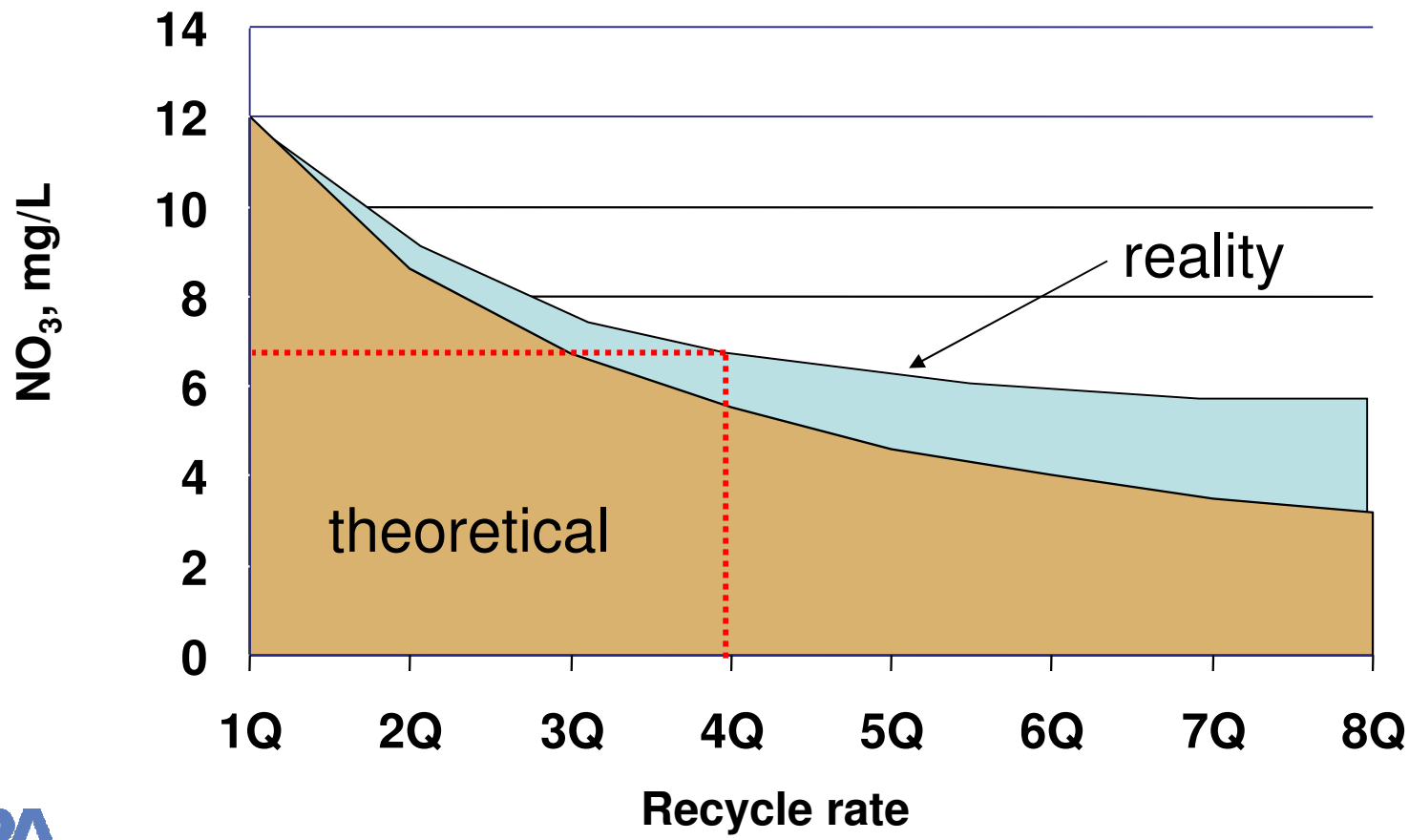
MLE Process Limitation

Inf TKN = 30 mg/L



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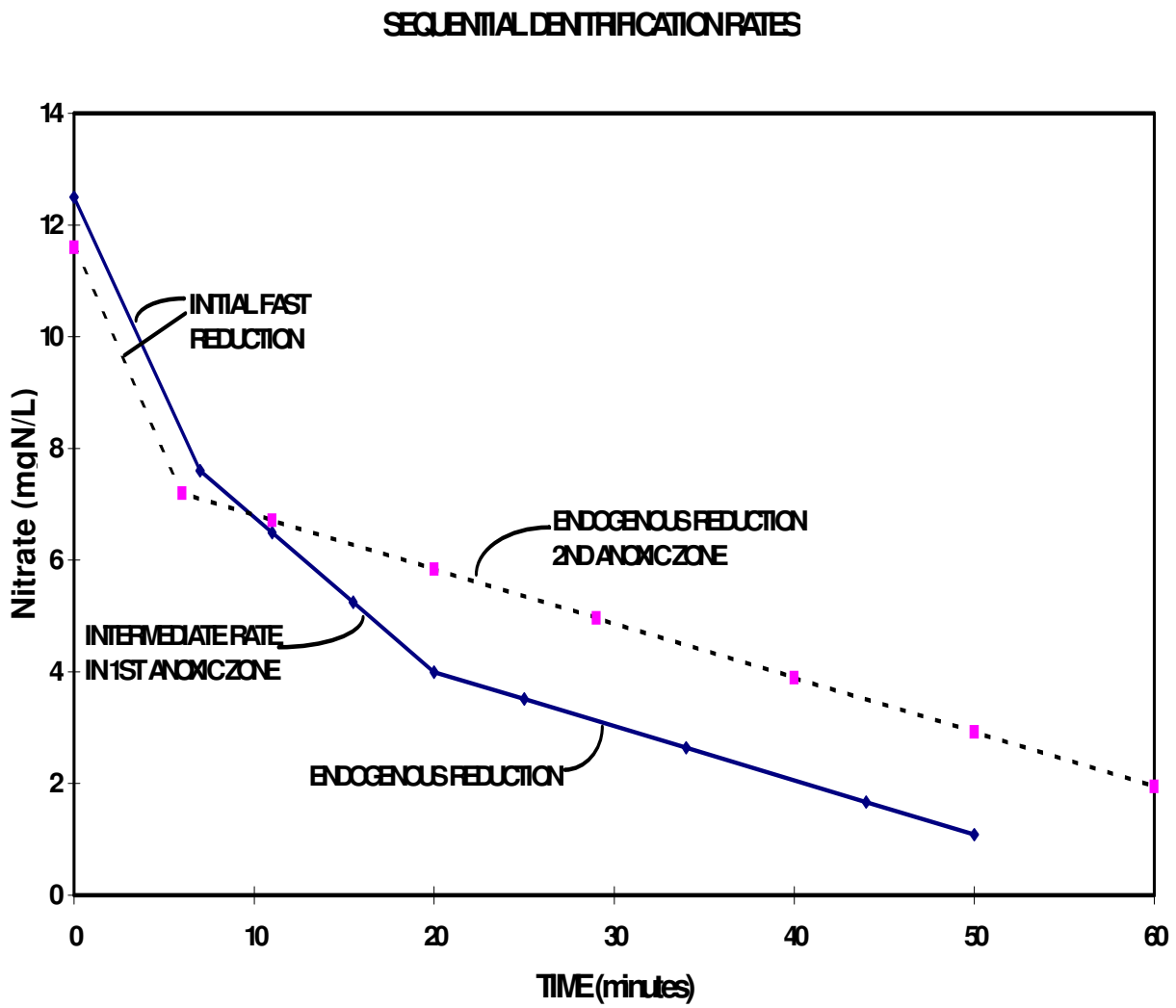
Denitrification Rates



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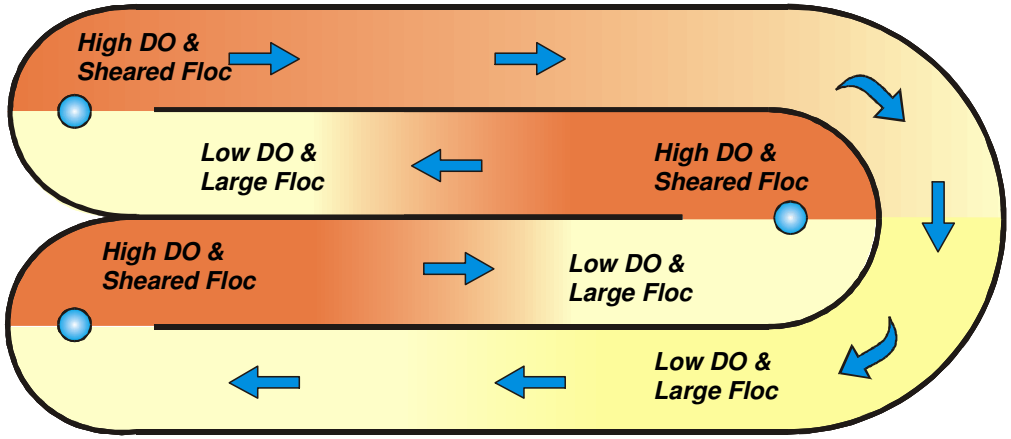
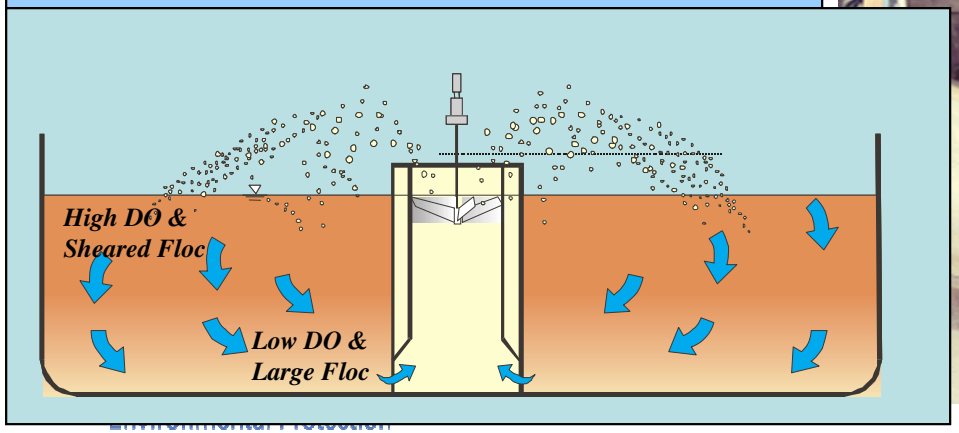
Simultaneous Nitn/Den (SND)

Considerations

- Point Source Aeration
- Areas of high and low energy
  - Floc Shear
  - Floc Reformation
- Promotes DO Gradients
  - Floc
  - Bulk Liquid
- 6 to 9 mg/L TN





Cato Ridge Application

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Troubleshooting Treatment Plants

- Decision Support Systems for Troubleshooting of WWTP Upsets (WERF Project 03-CTS-7S)
- WERF Project 04-CTS-11S - Development of a Decision support system with Corrective Action Strategies for Mitigation of Upset Events
- On-line instrumentation to protect Wastewater Facilities from Toxic Chemicals - Shaw et al, WEFTEC 2006

EPA United States Environmental Protection Agency

Common Operating Changes

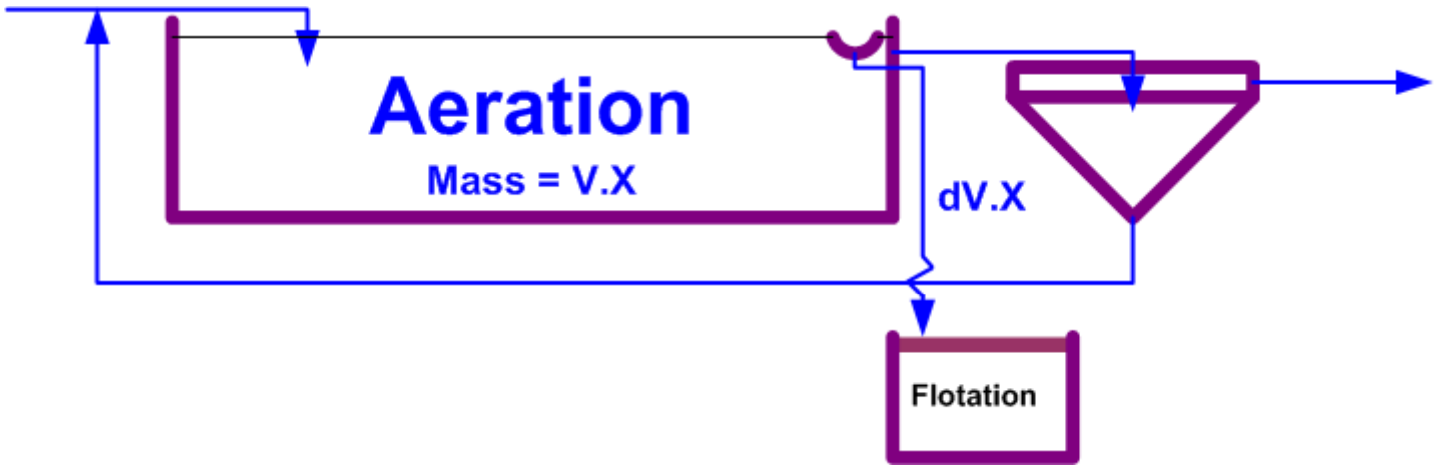
- Adjusting SRT to control Nitrification
- Adjusting aeration rates, sufficient for nitrification. Limited for denitrification
- Optimize anoxic zones, MLR rates
- Hydraulics
- Change operation of collection system
- External carbon sources, fermentation,
- Final clarifiers sludge blanket control and return activated sludge rates

Adjusting SRT

- Maximum possible SRT depends on SVI and final clarifier operation
- The lower the control SRT the more sophisticated instrumentation is required
- Control SRT to minimum required for nitrification at all temperature conditions
- Existing software packages are useful for very tight control of SRT
- Slight drop in SRT may lead to filament growth
- Slight rise in SRT may cause foaming

TaiPo Aeration Basin

Volumetric SRT



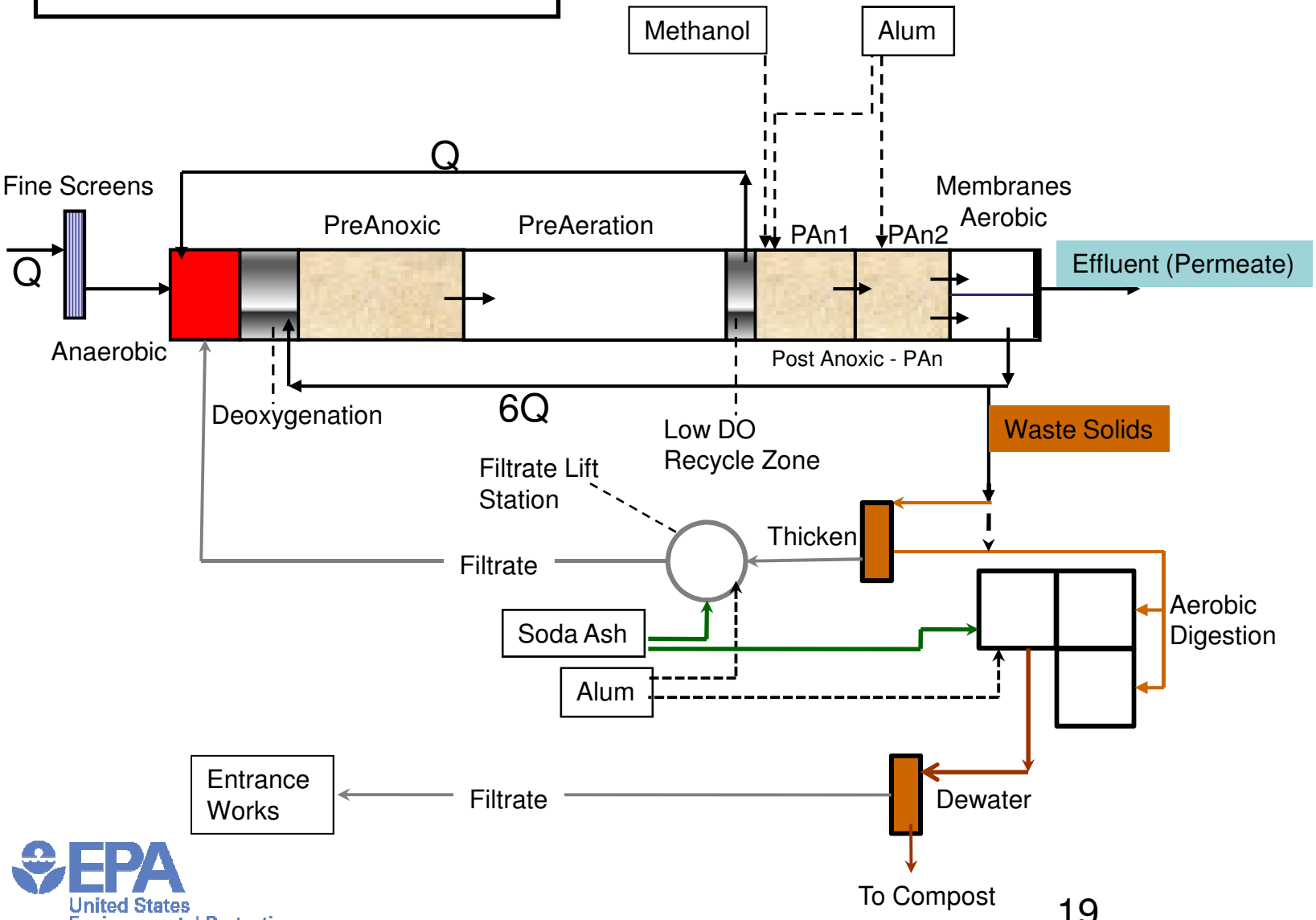
$$SRT = V.X \div dV/X \quad = V/dV \text{ days}$$

Volumetric SRT control & Selective Wastage

- Mixed liquor and scum wasted to satellite clarifier
- Can be wasted to DAF unit
- Accurate control of the SRT
- No scum to the final clarifiers

SRT = V.X/dV/X = V/dV days

RUIDOSO MBR Bardenpho Nitrogen and Phosphorus Removal Process



Daily waste volume from membrane mixed liquor Is function of recycle ratio and aerobic SRT.

If V1 = Volume of bioreactor in m^3
V2 = Volume of membrane reactor in m^3
X1 = MLSS concentration in kg/m^3 (g/L)
X2 = MLSS in membrane reactor in kg/m^3
R = Recycle rate in terms of flow rate
Qw = Volume of mixed liquor wasted per day from bioreactor m^3/d

SRT = Mass under aeration/mass wasted per day (days)

$$= \frac{V1*X1 + V2*X2}{SRT*\ Qw}$$

By mass balance

$$Qw = [V1 + V2(R+1)R]/\ SRT\ m^3/d$$

Adjusting aeration rates

- Aeration profile preferred is DO > 2 mg/L at all times near inlet to DO < 0.5 near end of aeration basin
- For ENR flexibility in control is required
- Mixing requirements at end of the aeration basin sometimes results in DO > 5 mg/L – unacceptable for nitrogen and consequently phosphorus removal
- Consider
  - Mixers at end zone to allow turndown
  - Replacing fine with coarse bubble aeration
  - Turn air low and just bump occasionally
- Reliable DO meters now becoming available – optical sensors
- Example of over-aeration on pH
  - •Ammonia in effluent
  - •Increased DO reduced denitrification
  - •Reduced denitrification - lower pH
  - •Lower pH – more ammonia in effluent

Adjusting aeration rates – cont.

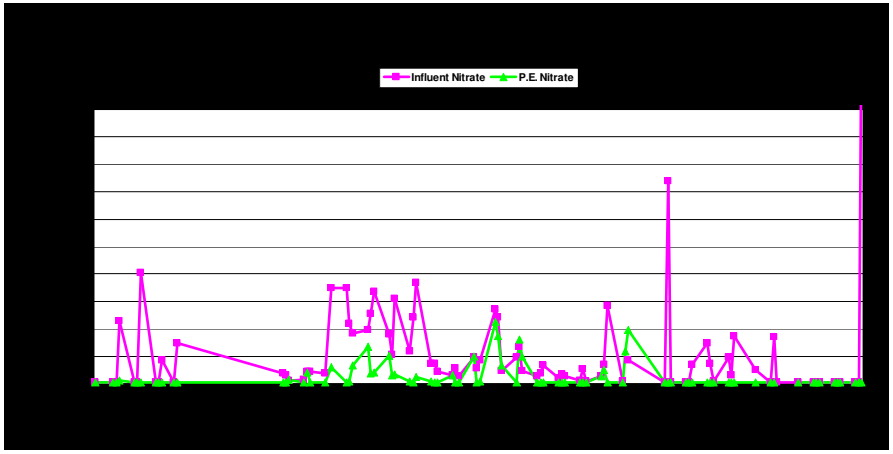
- In channel systems and with other SND reactors, DO metering may not be sensitive enough. Also varies with position in channel.
- Redox meters can perform better
- On-line monitoring becoming essential for tight control
- In plug-flow plants without anaerobic zones switching off aeration at the head end resulted in denitrification and even phosphorus removal
- With surface aerators, switching off some up front can result in good denitrification.

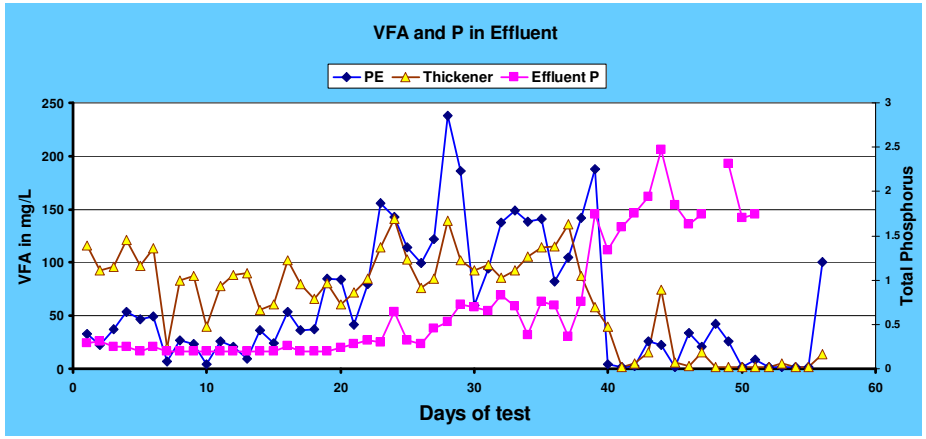
Optimizing Anoxic zone

- Avoid aeration
- Mixing energy low (LT 4 W/m^3 or LT 0.15 hp/kcf) – use mixing chimneys for rapid mix of influent stream then direct to bottom
- Note that slow speed vertical mixers are much more efficient than submersible high speed units – as much as three to 5 times
- Ideal speed for top entry mixers is 20 – 25 rpm
- Sufficient MLR to get some nitrates in effluent to aeration basin – avoid secondary release - with low MLR rate anaerobic conditions may result.

Change Operation of Collection System

- Addition of oxidants remove VFA Consider using $FeSO_4$ for odor control
- Odor extraction rather than aeration
- Avoid discharge of nitrates





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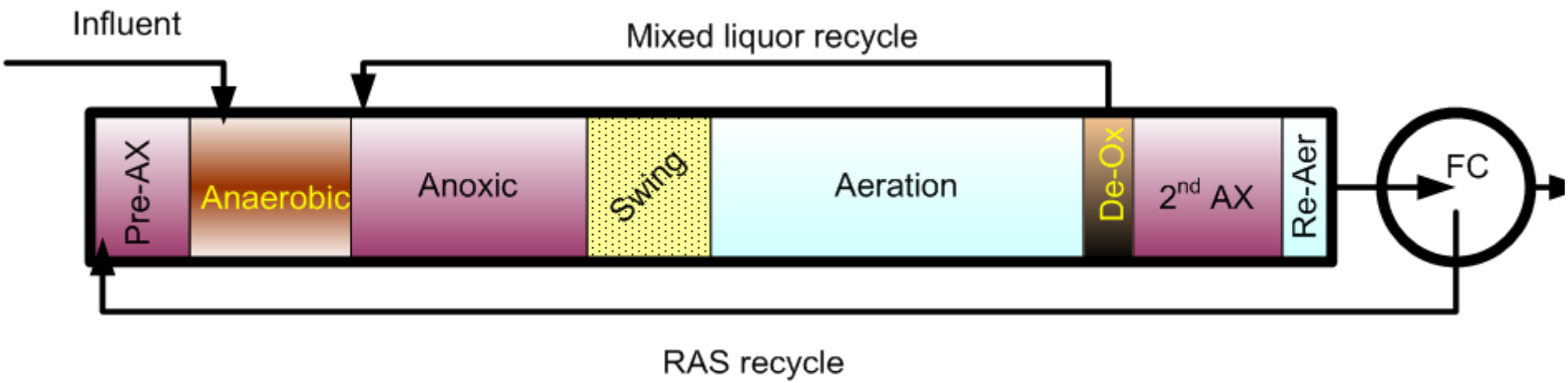
Swing Zones & De-Ox Zones



- Swing zone aerobic or anoxic
- Scum transfer issues
- Mixing issues
- Aeration issues
- De-Ox zone un-aerated

Add fermentation or rbCOD when insufficient

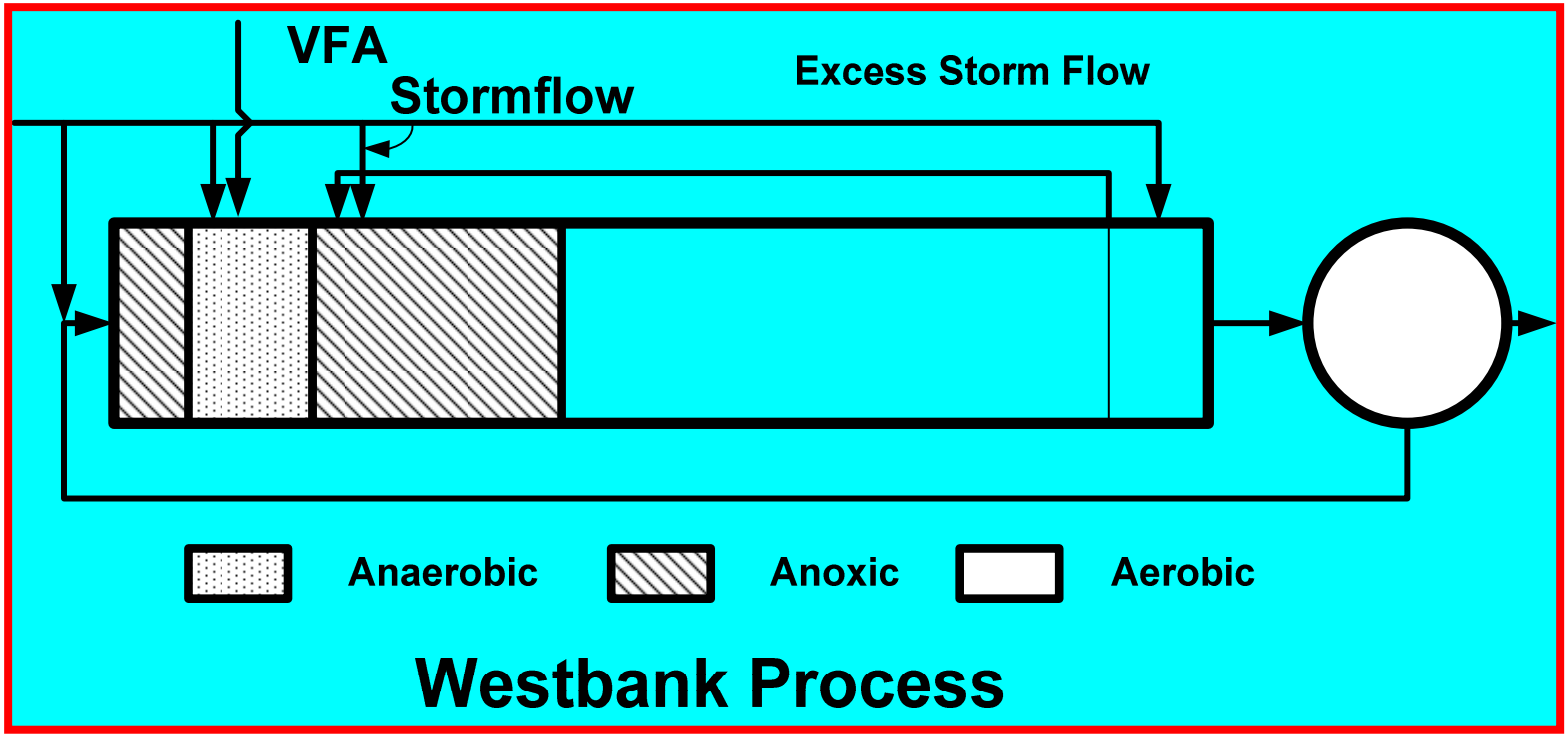
- Operate activated primary tanks – accumulate sludge for fermentation
- Hold sludge in gravity thickener thickeners for advanced fermentation with supernatant to anaerobic zone
- Look for source of rbCOD as industrial by-products – yeast waste, soft drinks acetate products
- Negotiate some by-pass of rbCOD waste where pre-treatment is practiced
- When using acid fermentation of sludge, extract some of the liquor

Standby Chemicals

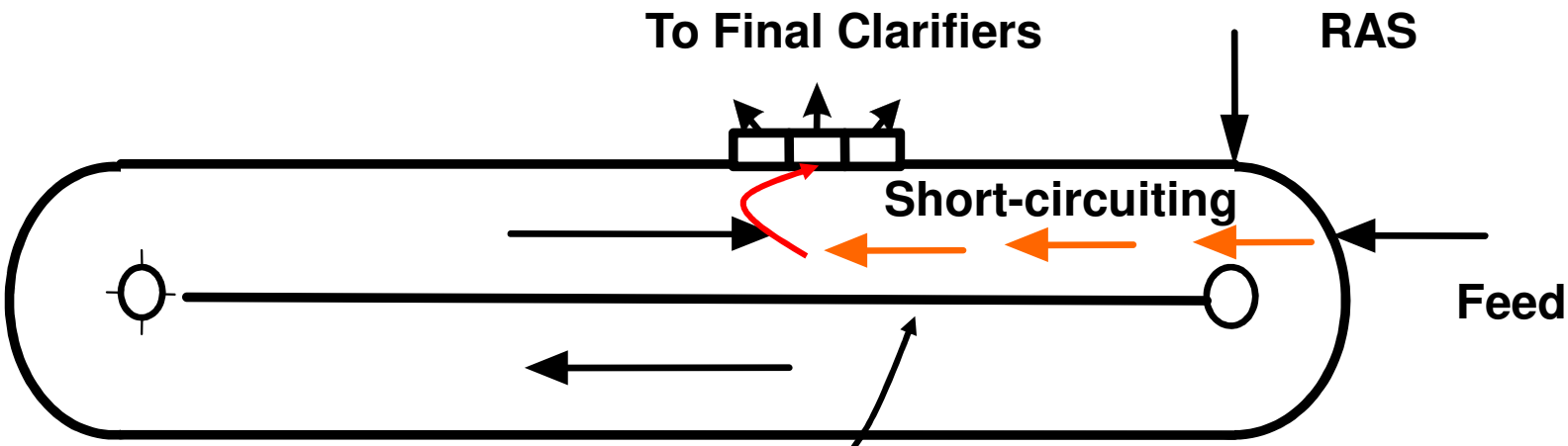
- Methanol or other carbon source may be required for ensuring low effluent Nitrates
- Growth rate of Methanogens is slow and temperature sensitive
- Consider less sensitive carbon sources in winter
- New products on the market such as Micro-C
- Alkalinity may be required to ensure maximum nitrification rate in winter.
- Monitor the effect of lower pH by ammonia profiles during the day
- Never overdose chemicals

HYDRAULIC CONSIDERATIONS

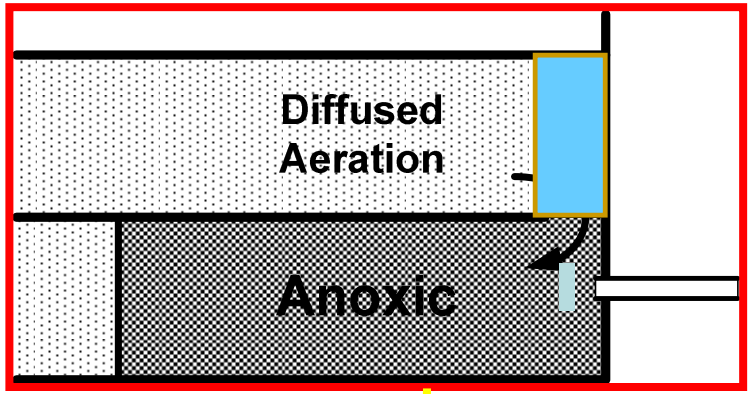
Flow splitting



Short-circuiting in Reactors

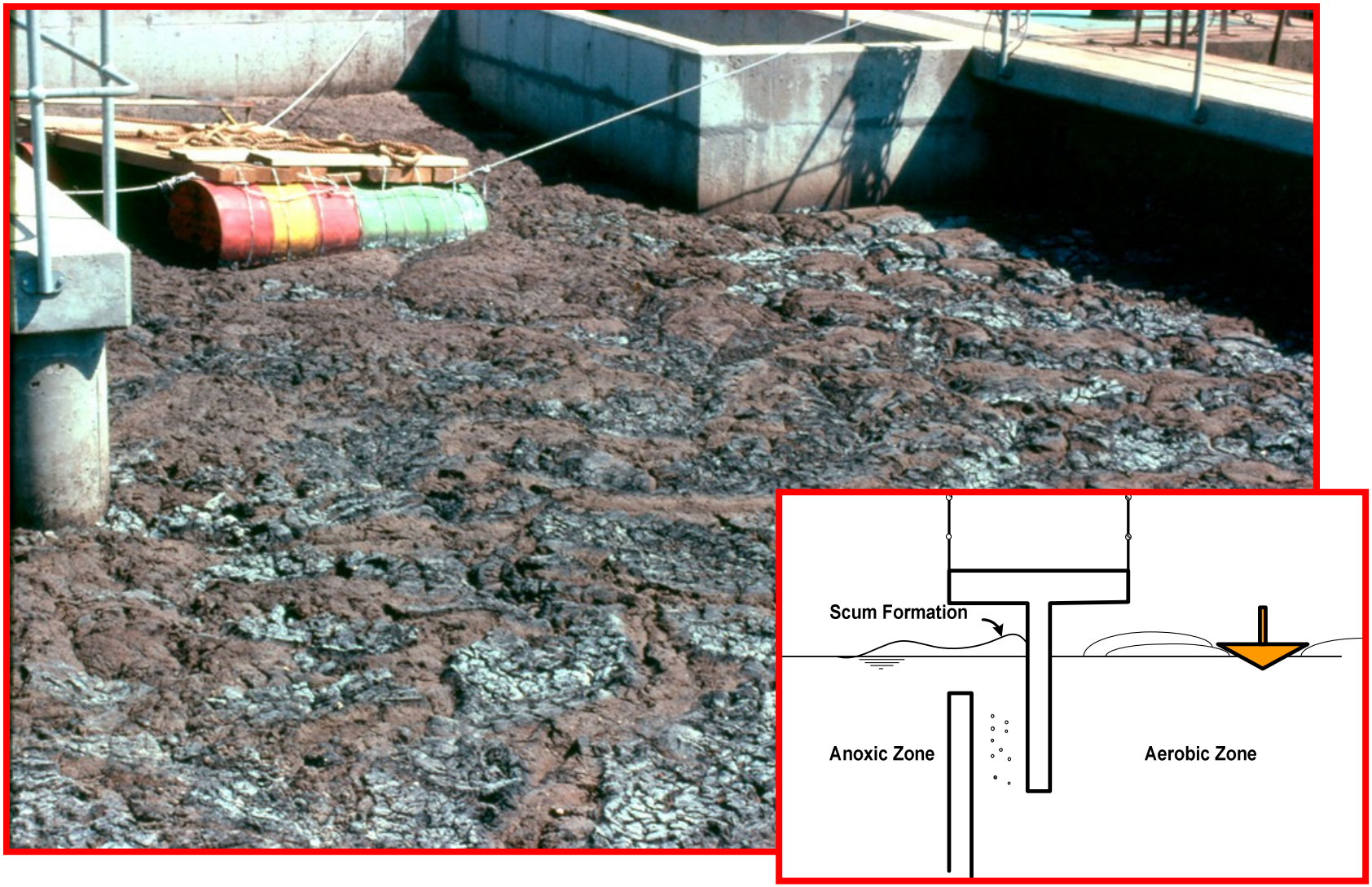


Problem: Ammonia in effluent when right aerator off



Problem: DO in anoxic zone

Trapping scum in the Anoxic zone



Anoxic to Aerobic zone

Baffle between anoxic and aerated zones

- Use only overflow baffles – never top and bottom openings
- Allow small openings on floor for drainage and filling
- Carefully designed bottom openings can reduce head loss for all flows

Mixing influent streams and directing

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Partitions in Anoxic zone

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Application of Chlorine for Filament or Scum Control

- Works best on filaments that cause inter-floc bridging
- Establish a target SVI and reduce/stop dose when target is achieved
- Typical dose is 2 – 10 lbs Cl/1,000 lbs MLSS
- Frequency of exposure should be more than 3 times per day – can apply directly to foams
- Local application concentration should not exceed 15 – 20 mg/L
- Should be added where good mixing occurs, RAS line is most common location

Chlorine Spray Hoods

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Warning Signs for Chlorine Overdosing

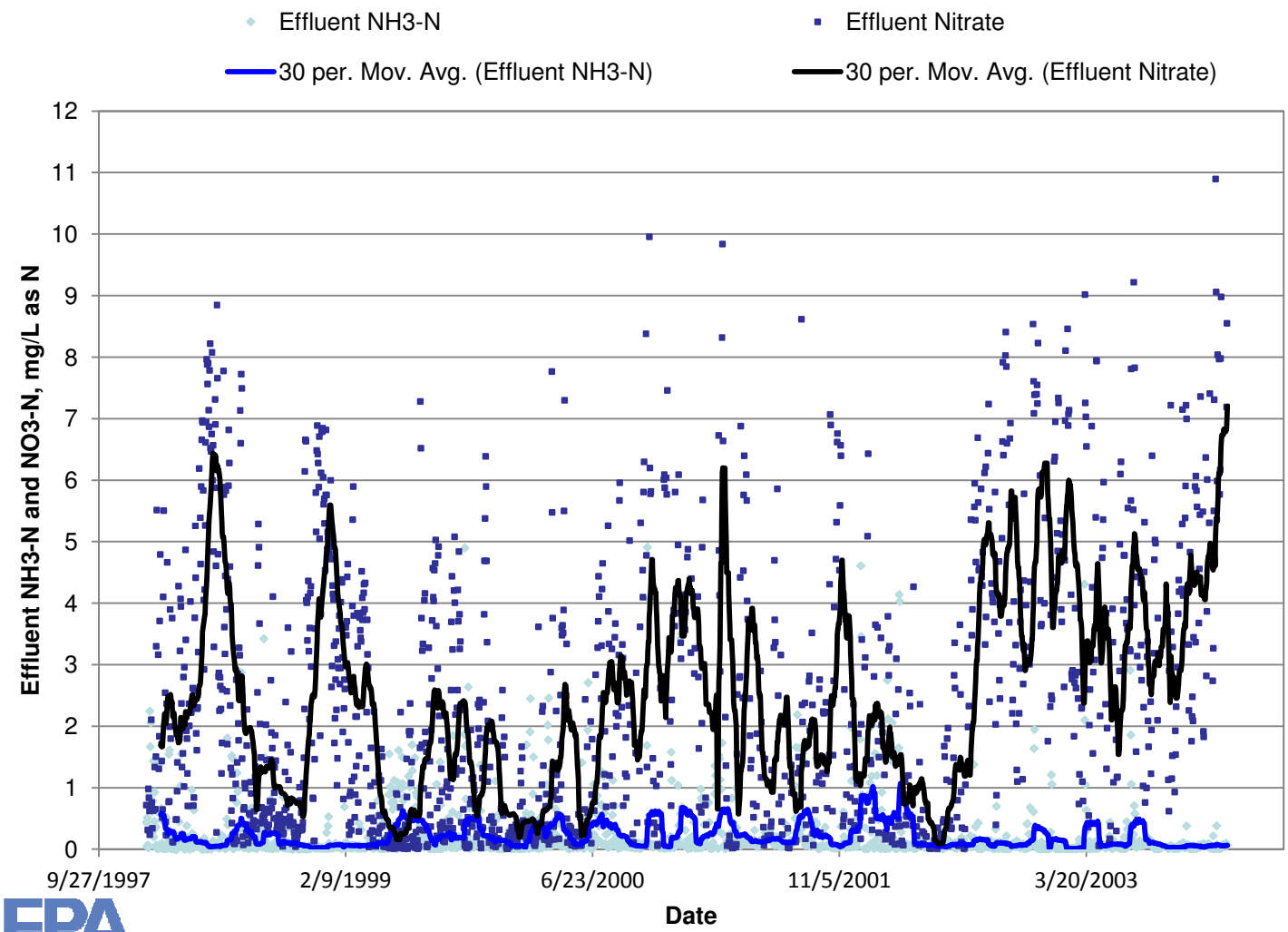
- Disappearance of intracellular storage products like sulphur granules
- Total elimination of filamentous organisms
- Presence of small, broken-up flocs with fine particles
- Complete loss of protozoa and rotifers

Final Clarifiers

- Can remove some NO_3
- Needs thick sludge blanket
- Not advisable when BPR
- Limit return activated sludge to just sufficient to minimize phosphorus release
- High recycle rates can impair BPR

CONTROL SYSTEMS

Rogers Arkansas



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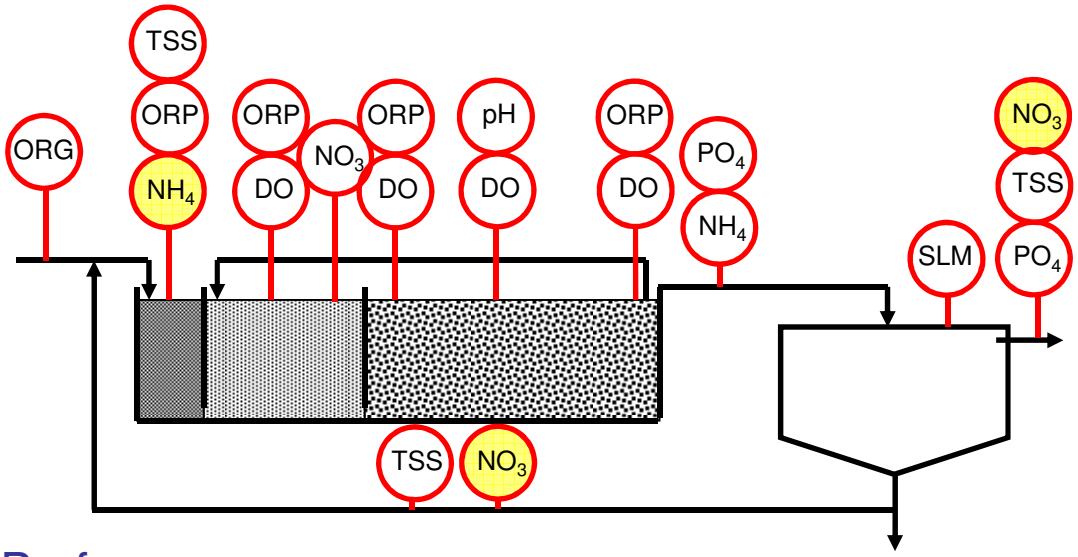
Incorporating Instrumentation and SCADA

It is virtually impossible to comply with ENR requirements without substantial instrumentation and SCADA – later presentation.

Suggested Levels of Instrumentation – Dabrowski (Hach)

MLE	4 Stage Bardenpho	3 Stage Phoredox	5 Stage Bardenpho
Minimum	Minimum	Minimum	Minimum
3 – ORP	3 – ORP	3 – ORP	3 – ORP
1 – pH	1 – pH	1 – pH	1 – pH
2 – DO	2 – DO	2 – DO	2 – DO
Medium	Medium	Medium	Medium
3 – ORP	5 – ORP	4 – ORP	3 – ORP
1 – pH	1 – pH	1 – pH	1 – pH
3 – DO	3 – DO	1 – DO	2 – DO
1 – UV Organics	1 – UV Organics	1 – UV Organics	1 – UV Organics
1 – TSS	1 – TSS	1 – Ammonia	1 – Ammonia
1 – Ammonia	1 – Ammonia	1 – Nitrate	1 – Nitrate
1 – Nitrate	1 – Nitrate	1 – SLM	1 – Phosphate
1 – SLM	1 – SLM	1 – Phosphate	
Maximum	Maximum	Maximum	Maximum
3 – ORP	5 – ORP	4 – ORP	6 – ORP
1 – pH	1 – pH	1 – pH	1 – pH
3 – DO	4 – DO	4 – DO	5 – DO
1 – UV Organics	1 – UV Organics	1 – UV Organics	1 – UV Organics
2 – TSS	2 – TSS	3 – TSS	3 – TSS
2 – Ammonia	2 – Ammonia	2 – Ammonia	2 – Ammonia
2 – Nitrate	2 – Nitrate	3 – Nitrate	4 – Nitrate
1 – SLM	1 – SLM	1 – SLM	1 – SLM
		2 – Phosphate	2 – Phosphate

Three Stage Phoredox



Maximum Performance

- Ammonia in Anaerobic *(NH4Dsc)*
  - Incoming ammonia load
  - Nitrogen removal calculation (mass balance)
- Nitrate in RAS & Secondary Effluent *(NITRATAXsc)*
  - Nitrate in RAS can inhibit Bio-P (anaerobic)
  - Mass balance, effluent quality

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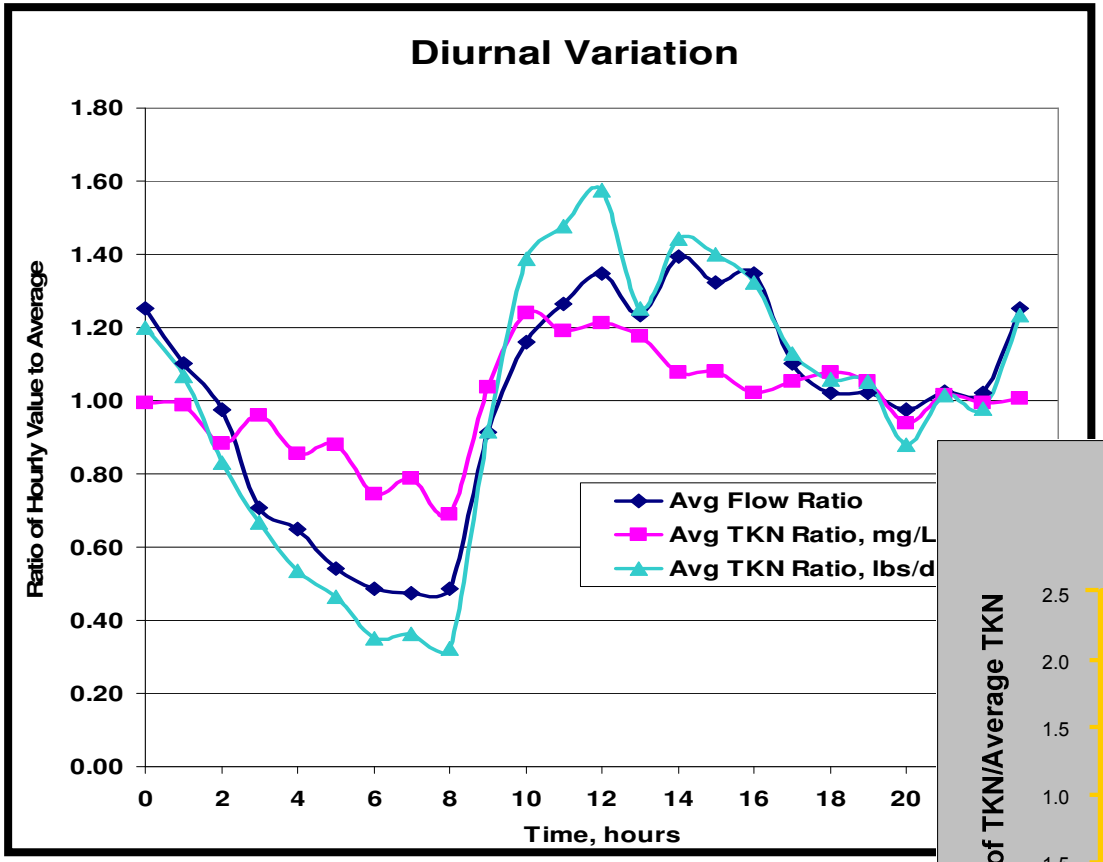
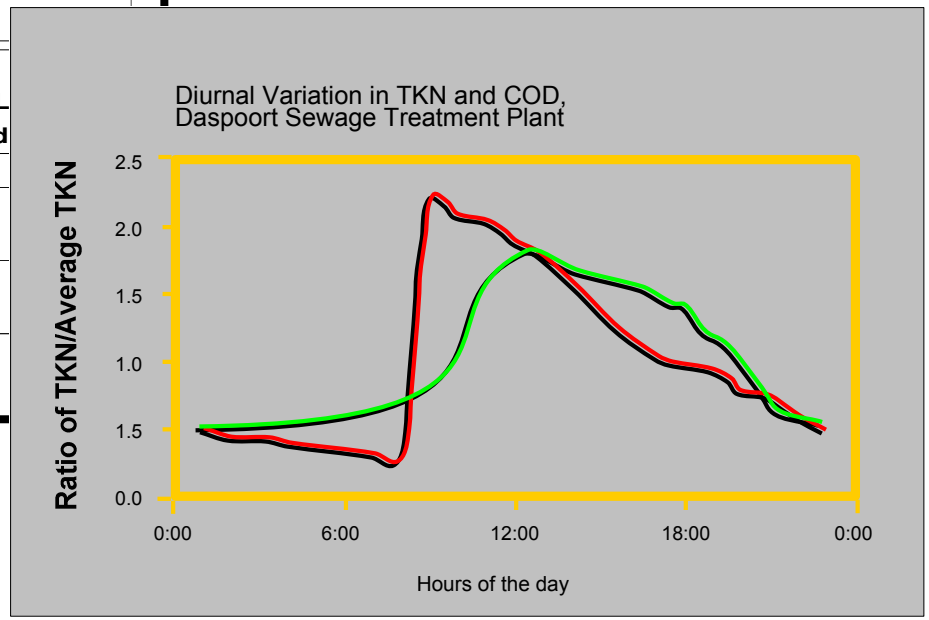
Dabrowski (Hach)

Variation in Influent TKN



Dynamic modeling is required when designing for very low effluent TN.



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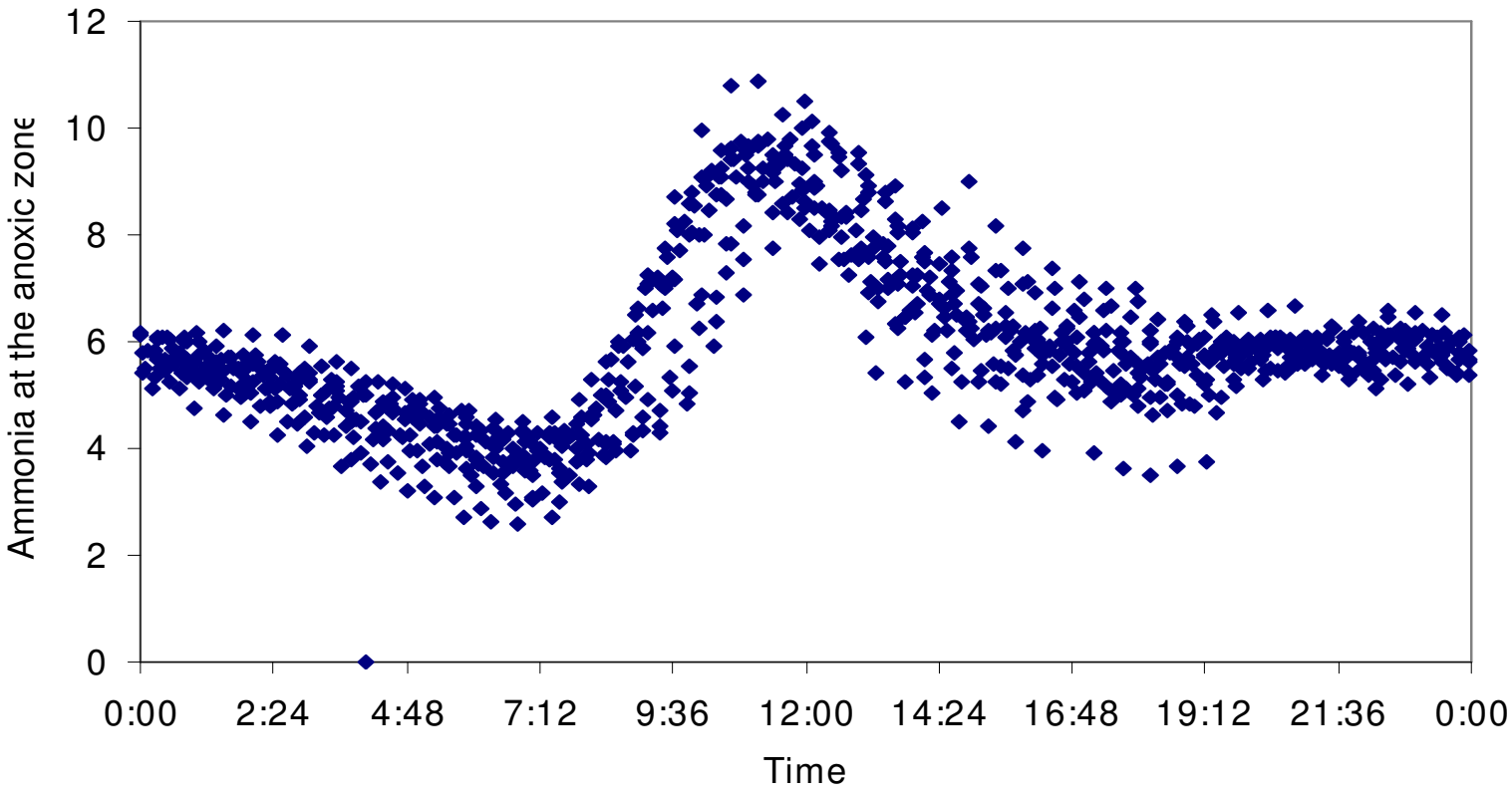
Variation of NH_4^+ Concentration in Anoxic Zone



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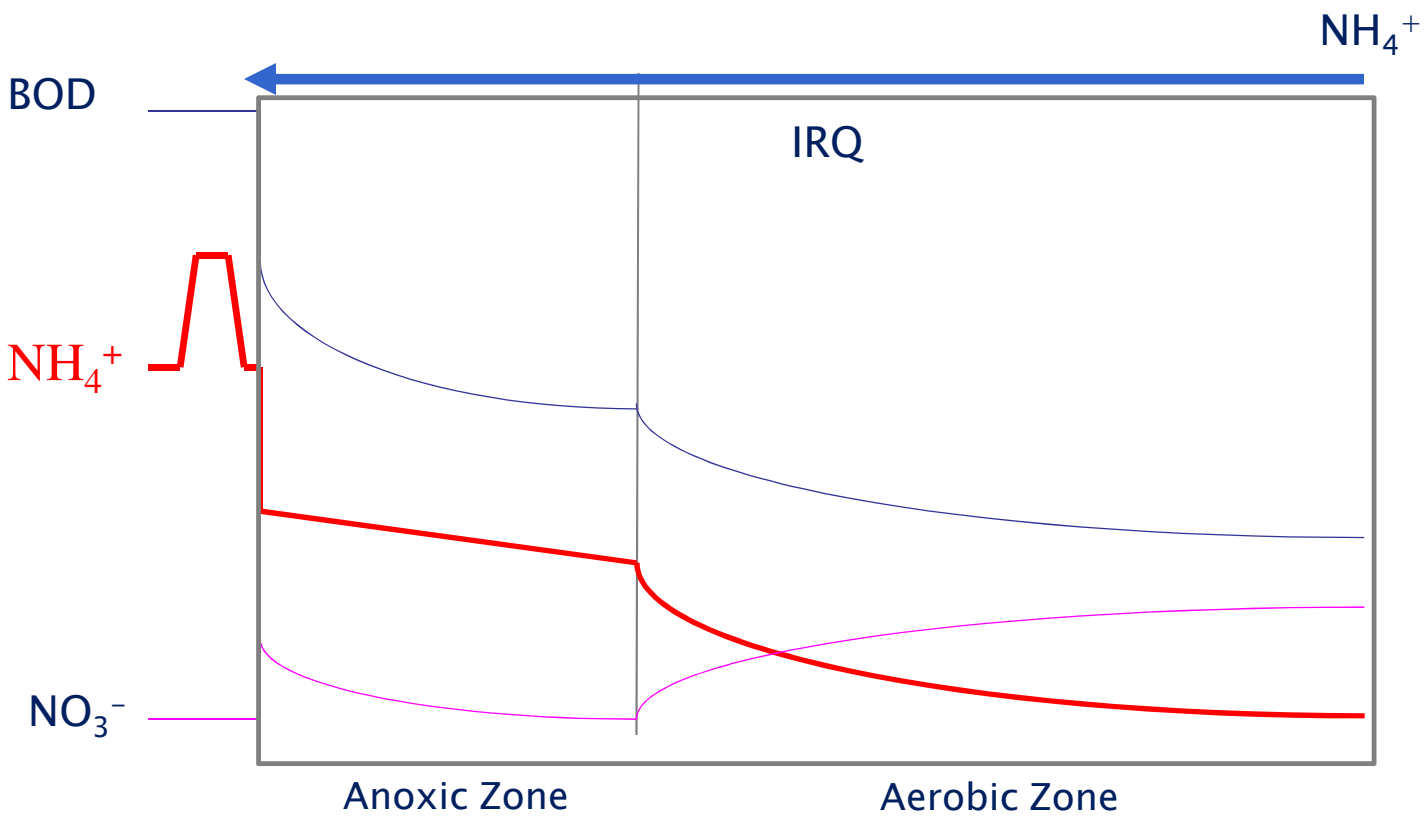
Problem of Feed-Back Control



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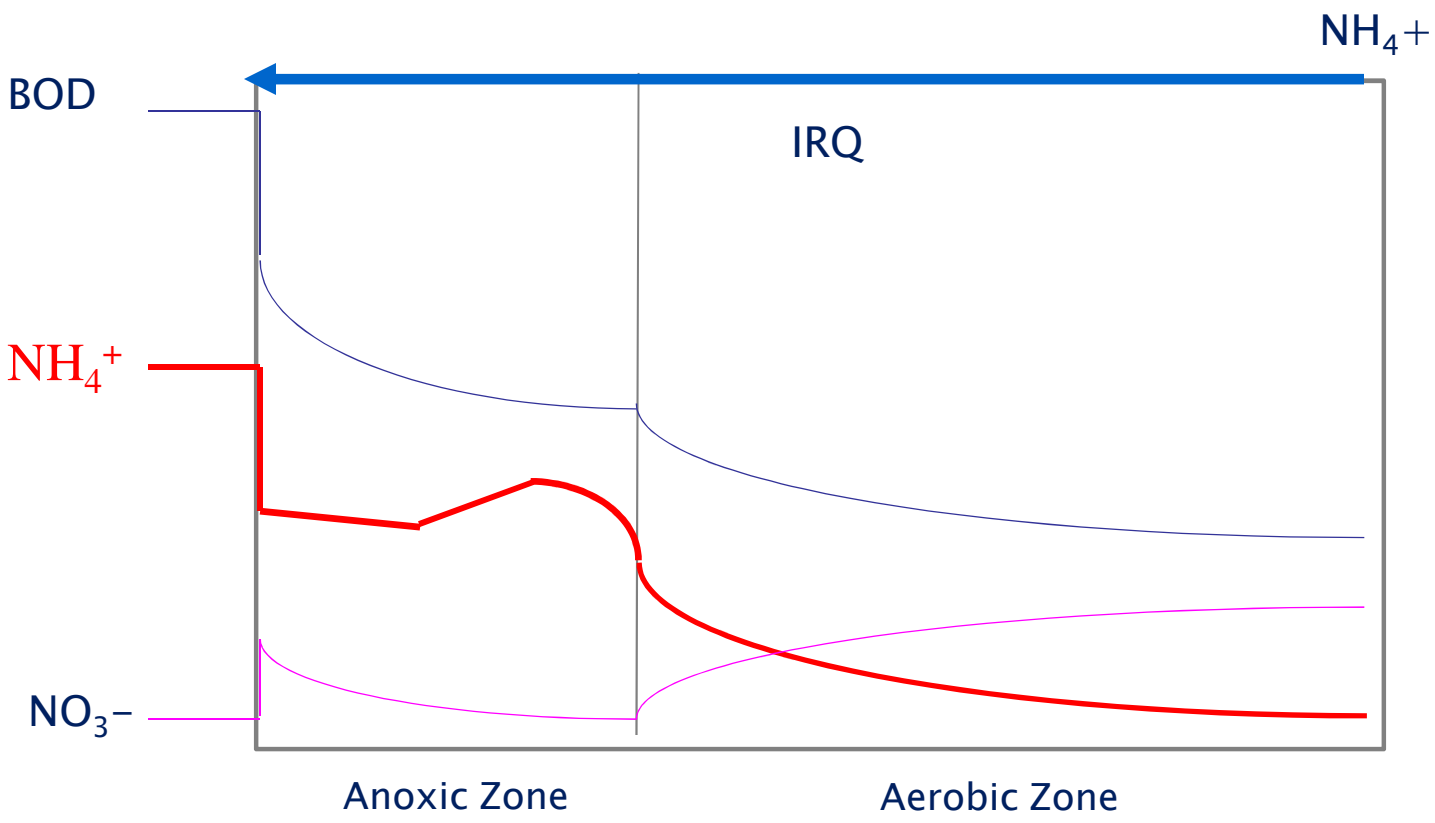
Problem of Feed-Back Control



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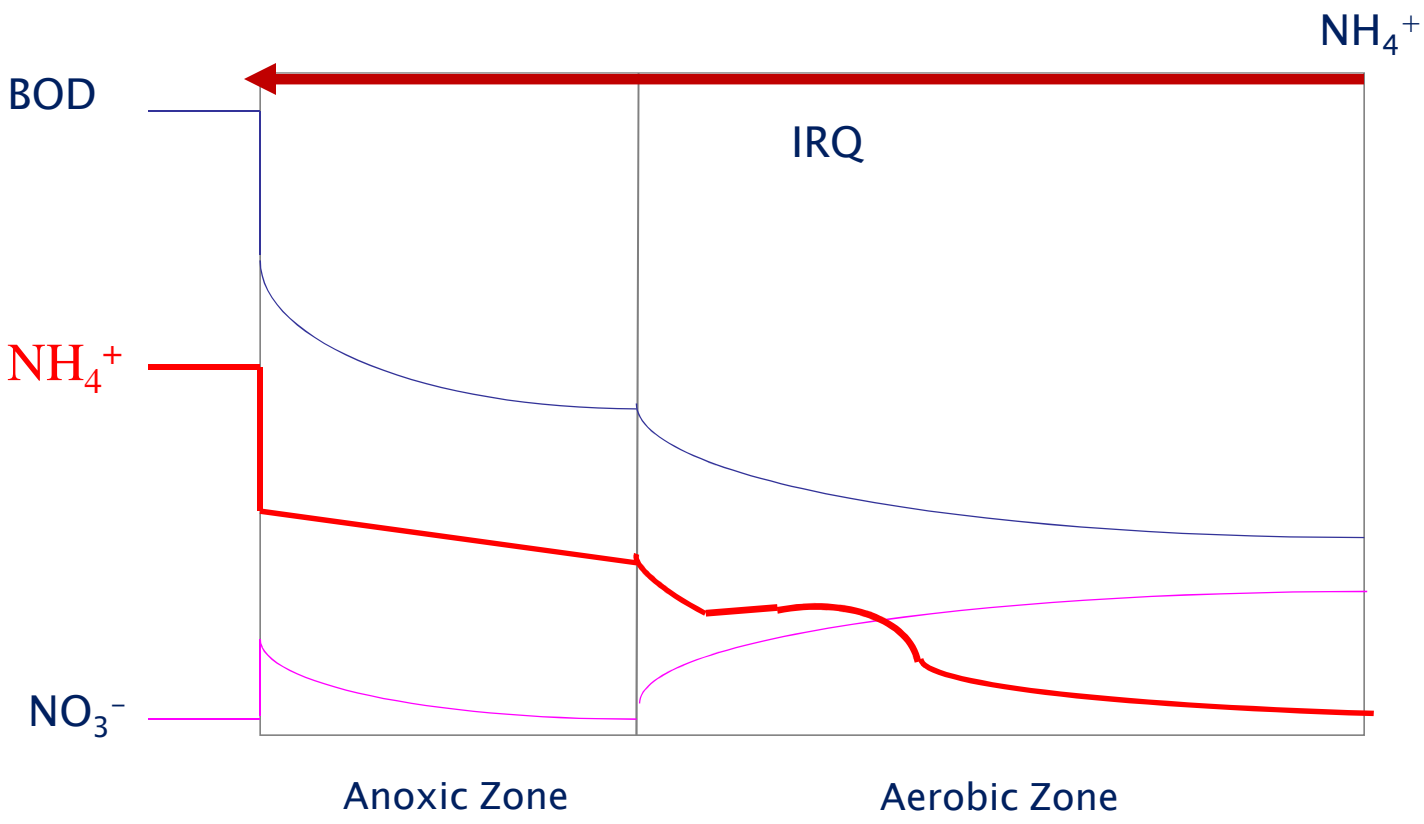
Problem of Feed-Back Control



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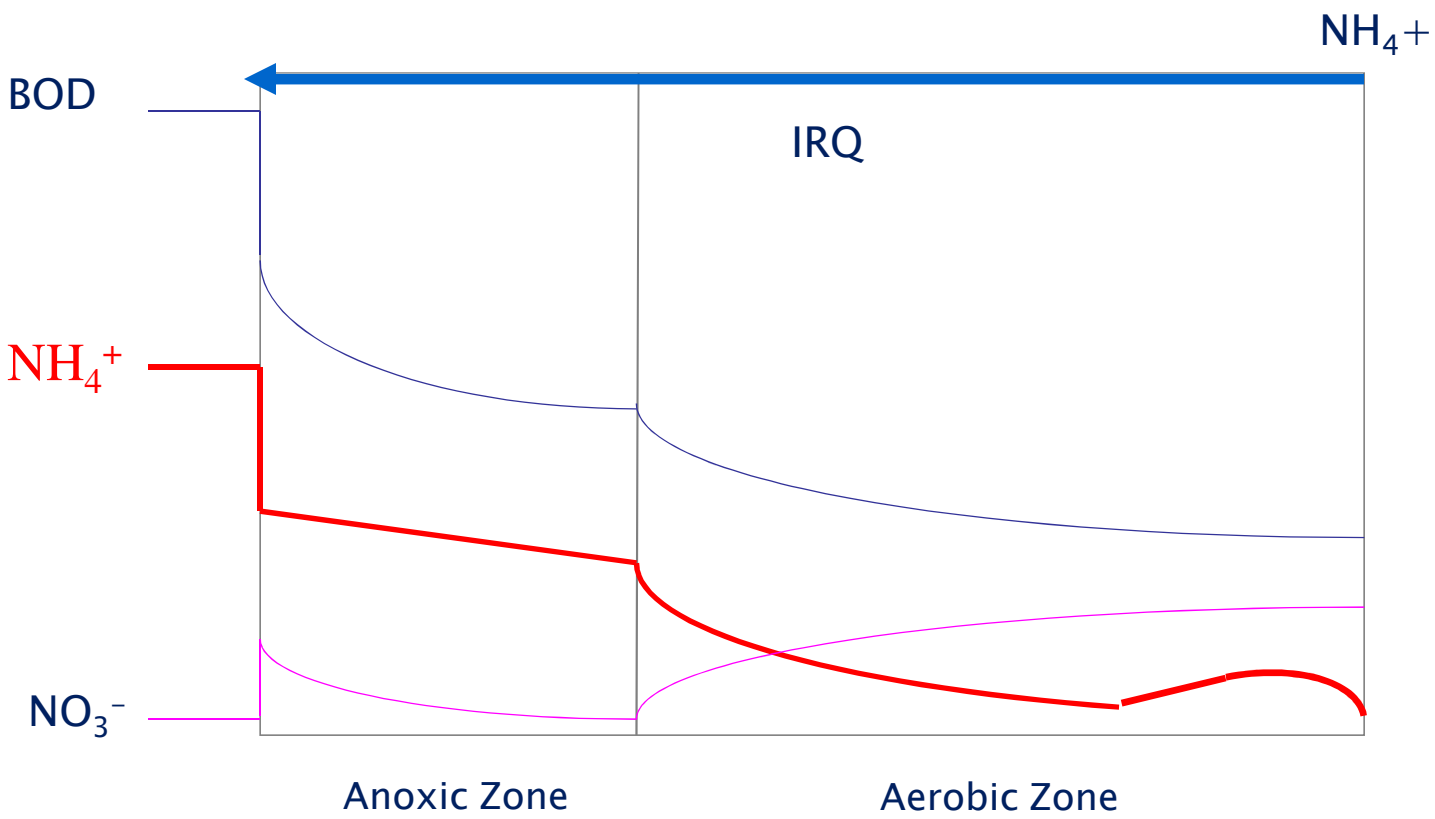
Problem of Feed-Back Control



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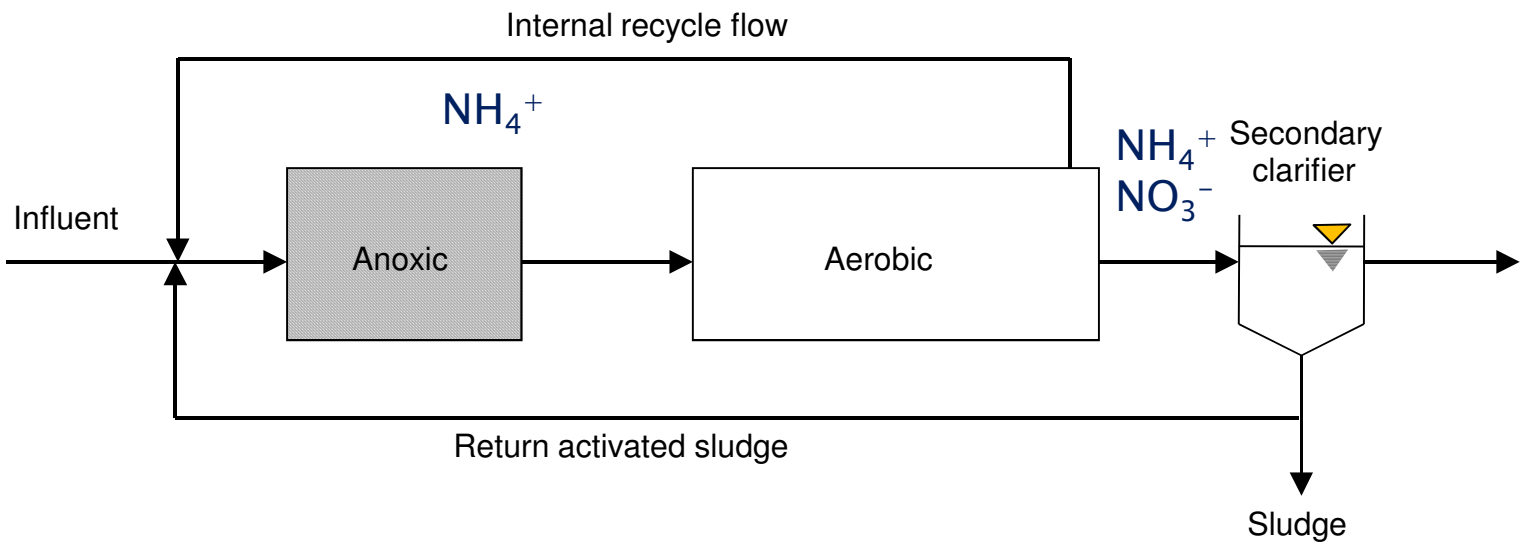
Proactive Control Algorithm needed i.e., a Feed-Forward Approach



Based upon the incoming load, it utilizes a model to calculate suitable DO and IRQ setpoints for the next control step.

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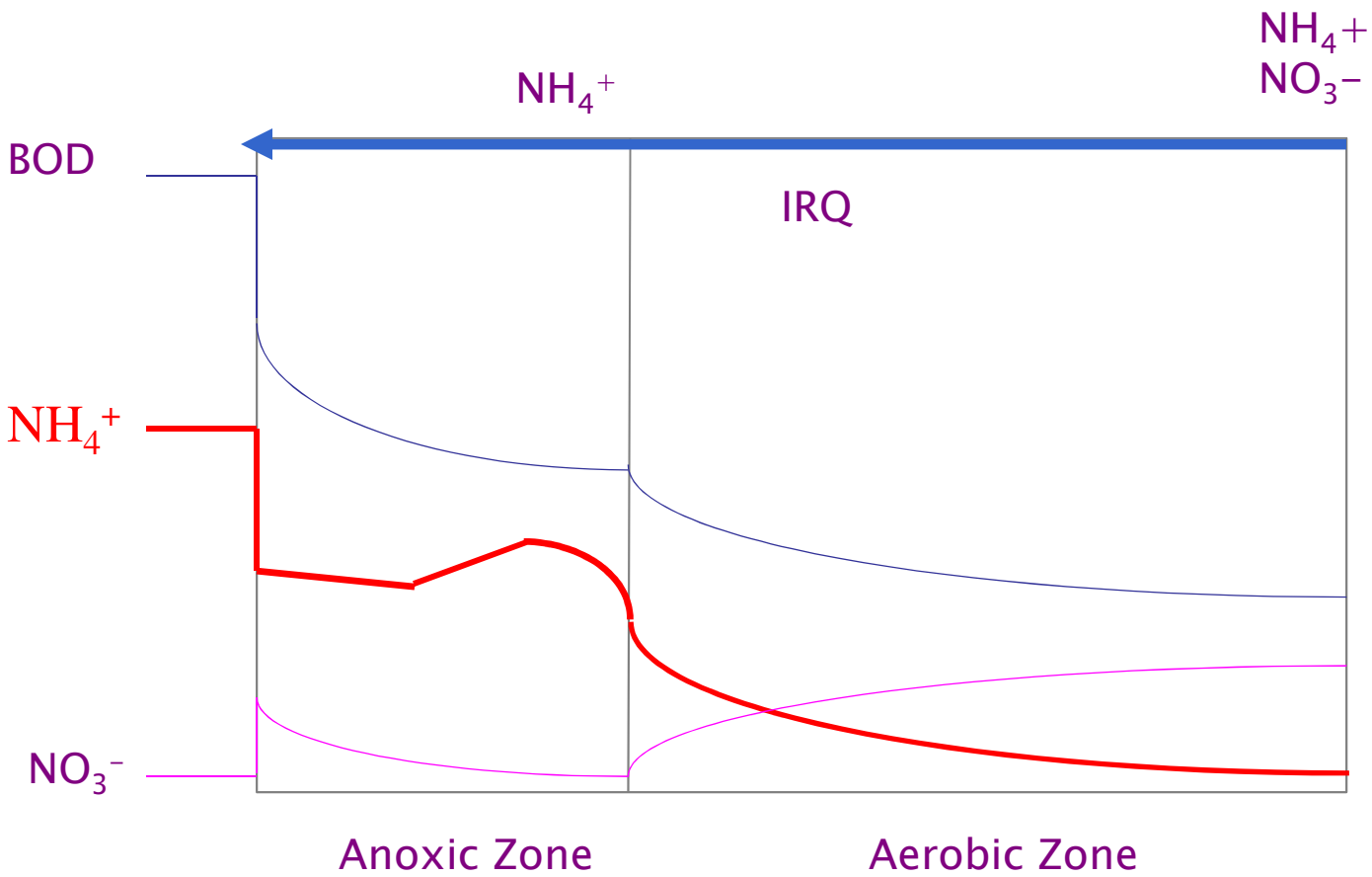
Feed-Forward Control



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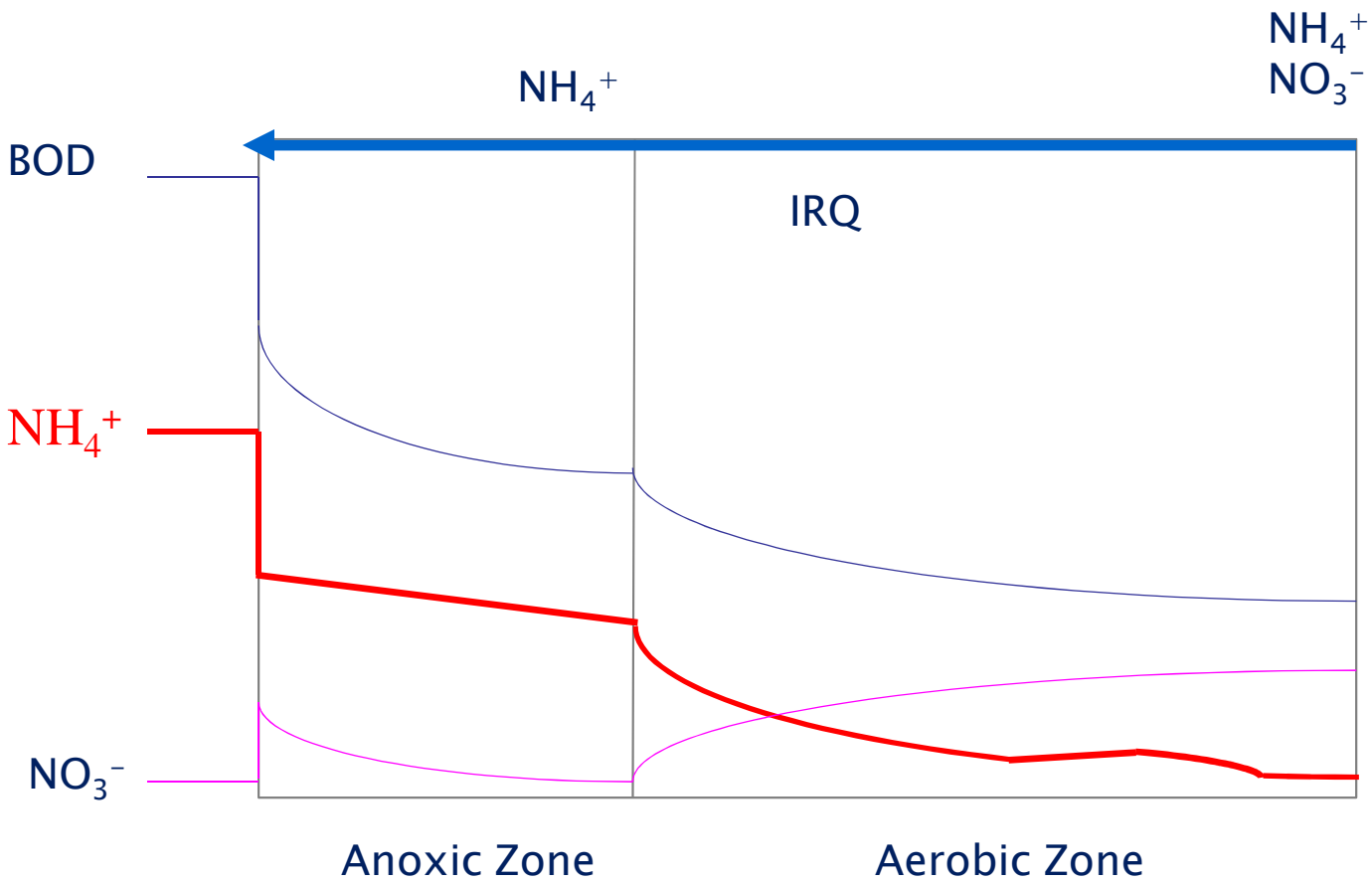
Feed-Forward Control



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Feed-Forward Model

The model must take into account that:

- DO levels need to be set according to the real-time ammonia and COD loadings

- The nitrification rate is a function of:
  - Dissolved oxygen
  - Mixed liquor concentration
  - Aerobic SRT
  - Ammonia concentration

Model (continued)

- The de-nitrification rate is a function of:
  - Nitrate concentration
  - COD concentration
  - Mixed liquor concentration

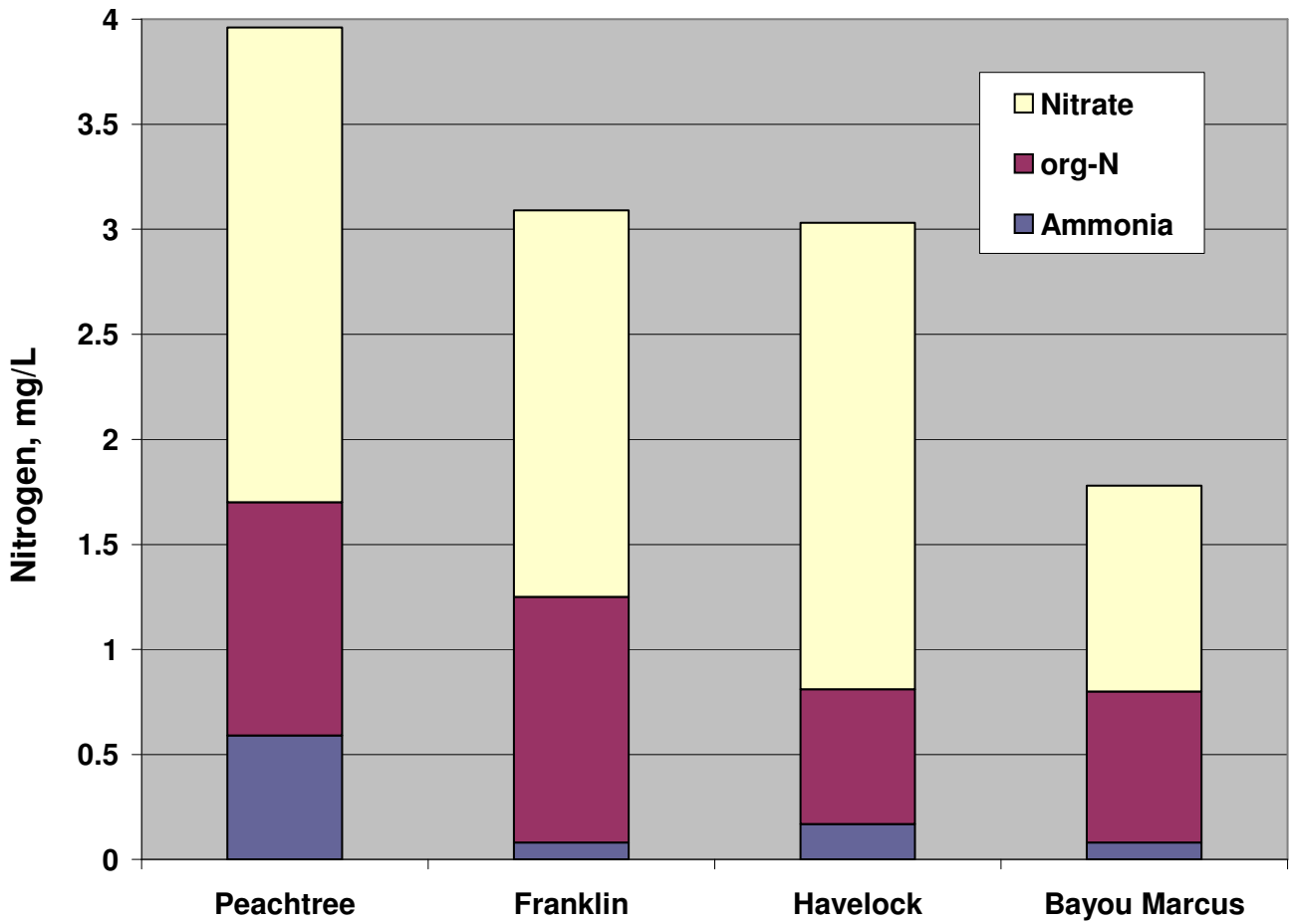
- De-nitrification will provide oxygen credit and reduce the overall oxygen requirements

Process Reliability and Averaging Comparison of Effluent TN

	Avg (mg/L)	50th Percentile	90th Percentile	95th Percentile
Peachtree NC (Hybrid)	4	<3.6	<5.9	<7
Franklin TN (MLE –ditch)	3.1	<2.8	<4.5	<6
Havelock NC DEN-Filters	3	<2.6	<4.4	<5.4
Bayou Marcus FL Bardenpho - Carousel - Filters	1.8	<1.5	<2.7	<3.2

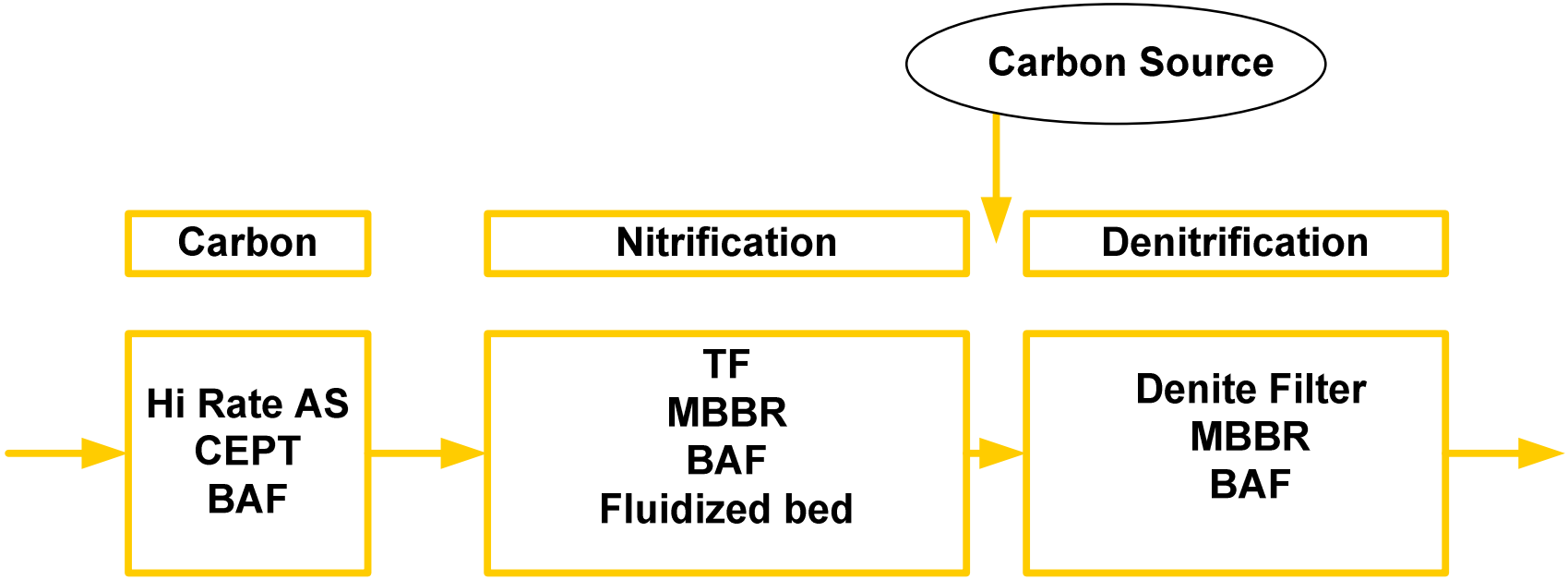
Minimum temperature at Bayou Marcos 20ºC
For other plants around 16ºC

Nitrogen Speciation -- Minimize all constituents

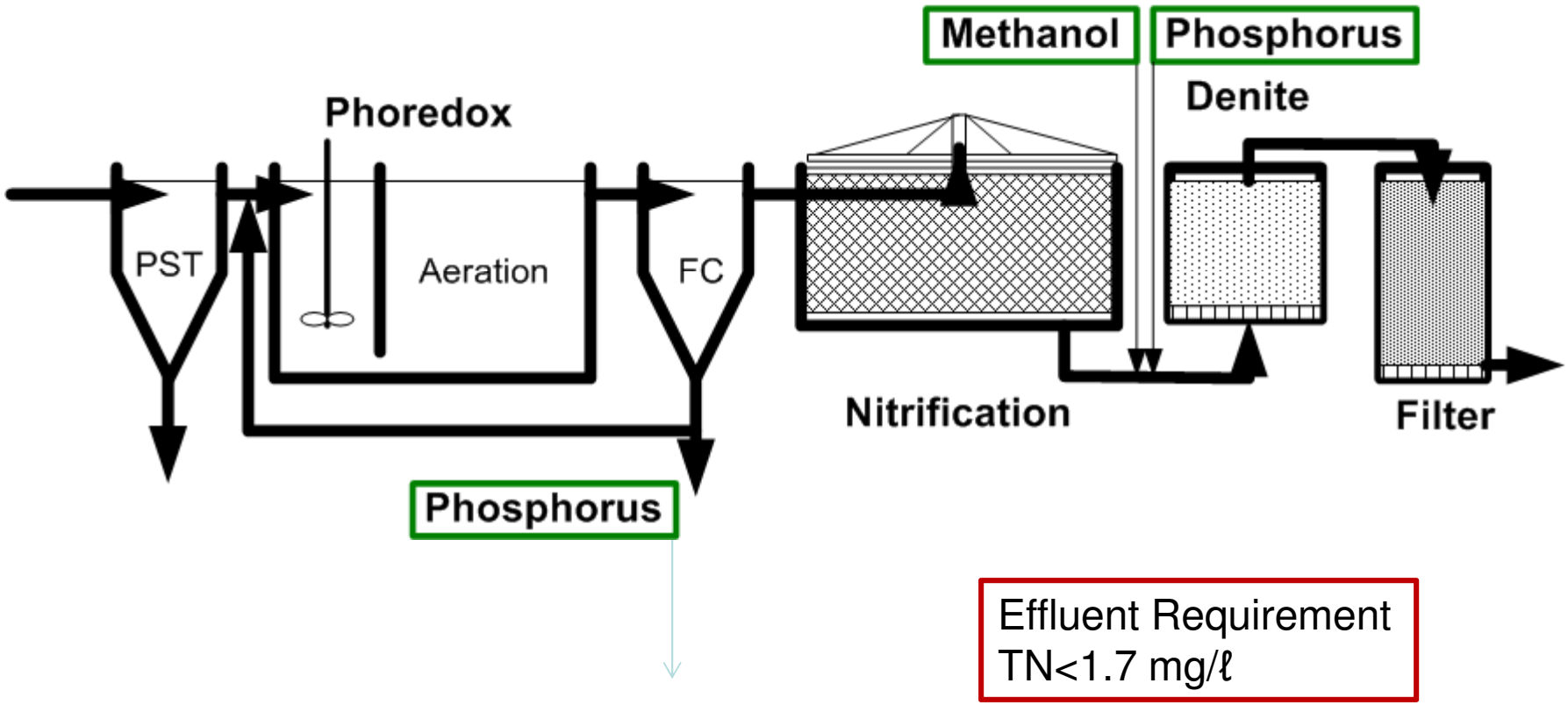


- Reliable N
- Reliable dN
- Filters
- Low Sol. TKN

Multi-stage N/DN



Multi-stage N/DN



Effluent Requirement
TN<1.7 mg/ℓ

How Much Phosphorus is Required for Post Denitrification?

- Methanol is biologically oxidized using NO_3-N
  - 3 mg methanol required per mg NO_3-N
  - COD = 1.5 x methanol
  - Biomass yield for denitrification with methanol 0.4 mg biomass COD/mg COD oxidized
  - 0.022 mg P/mg of biomass COD
- Denitrification of 1 mg/L of NO_3-N
  - Oxidizes 4.5 mg/L COD
  - Produces 1.8 mg/L biomass (as COD)
  - Requires 0.04 mg/L Phosphorus

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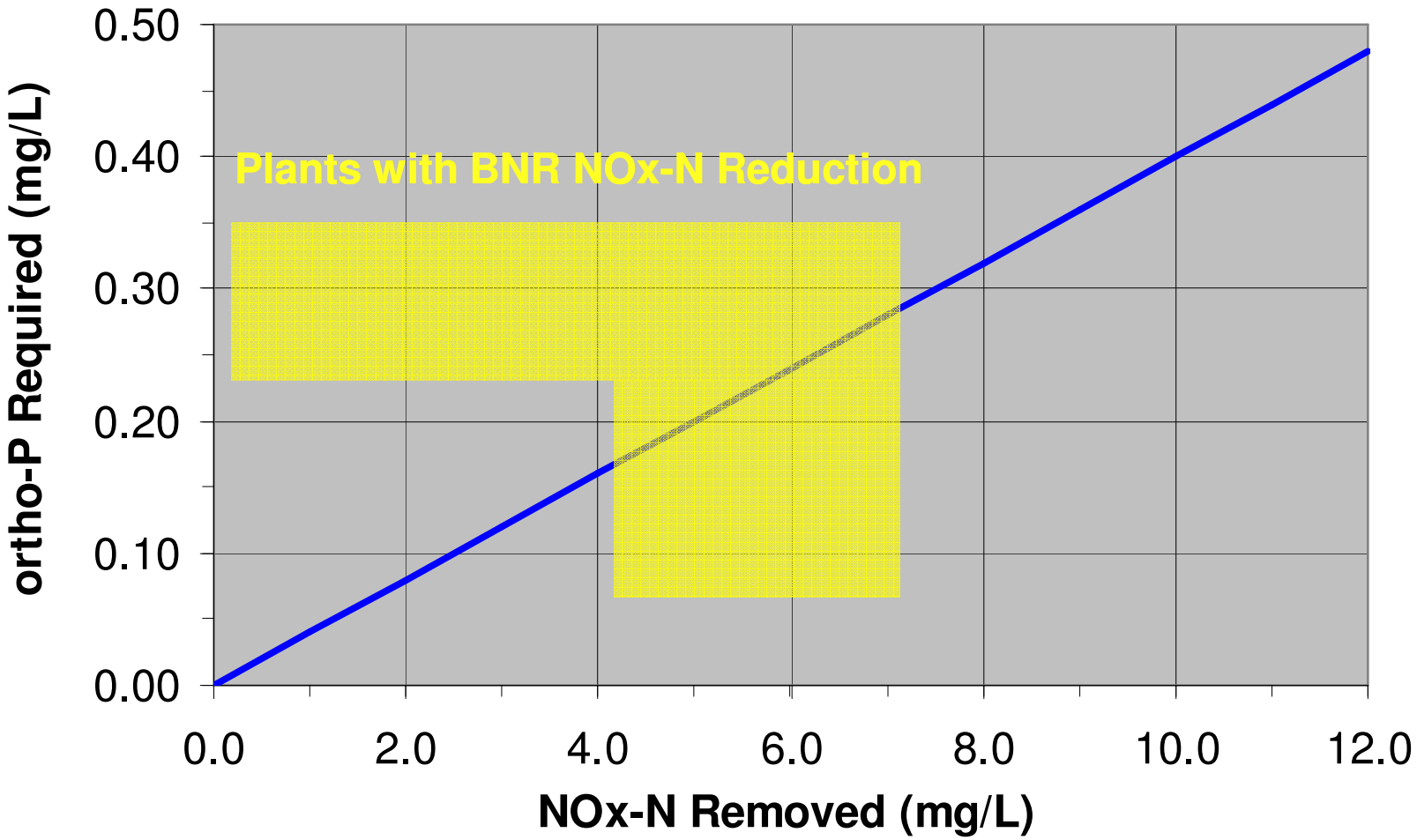
Theoretical ortho-P Requirements for Denitrification Filters following typical BNR process



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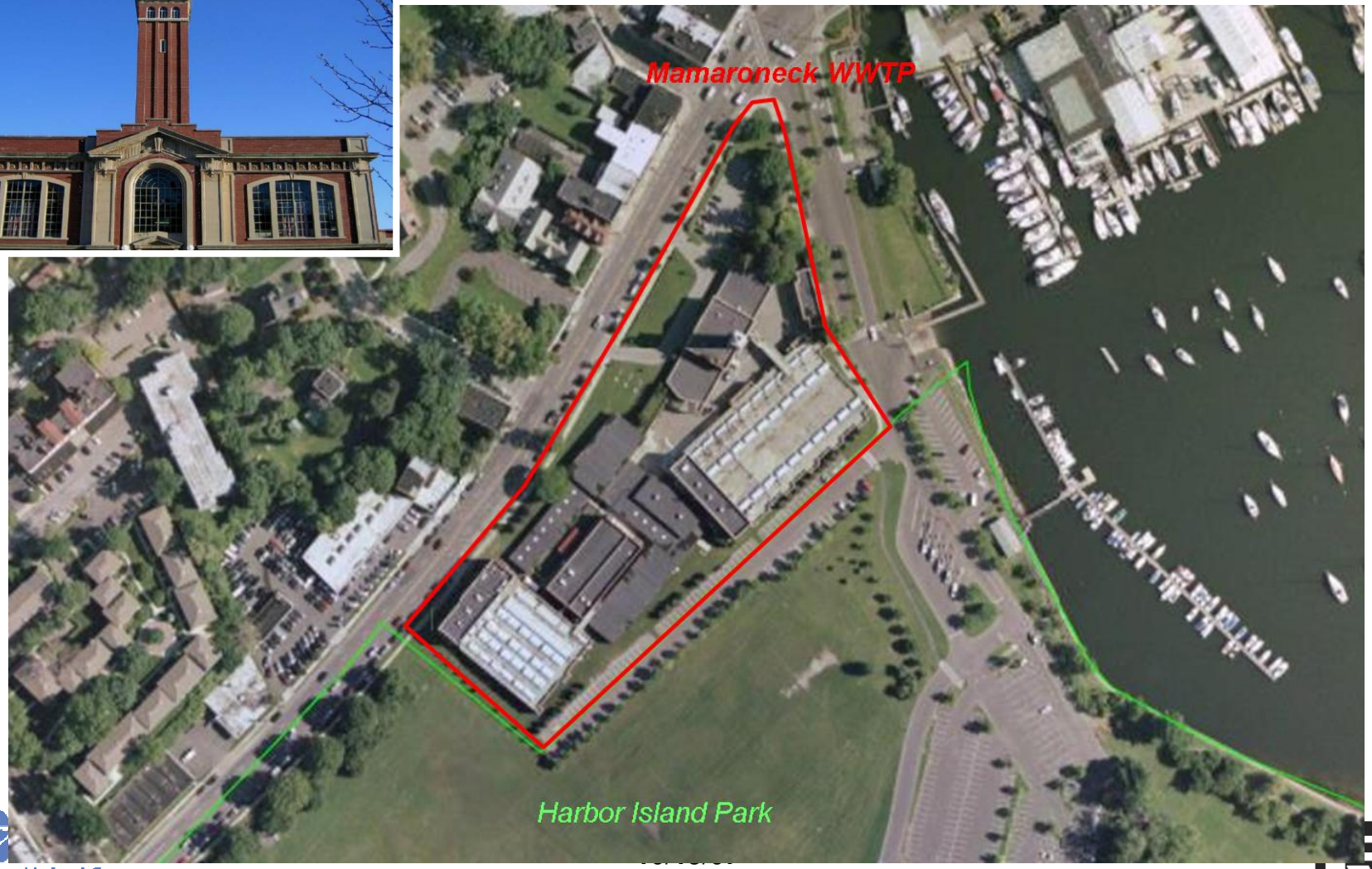
Small Footprint Technologies

- Integrated Fixed-Film Activated Sludge (IFAS)
- Moving Bed Biofilm Reactor (MBBR)
- Membrane Bioreactor (MBR)

Case Study: Westchester Co, NY Mamaroneck WWTP



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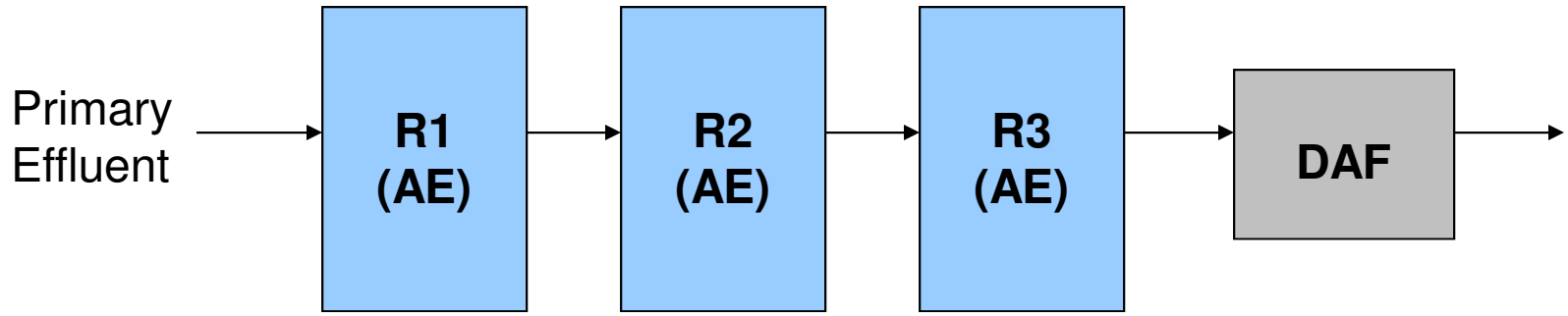
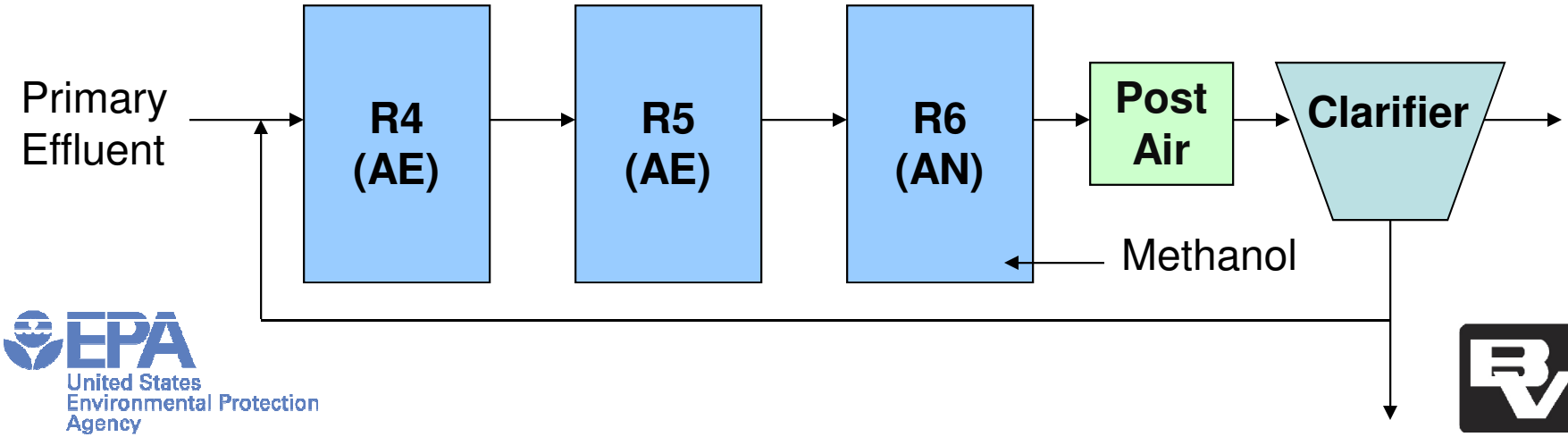
Parallel Pilot-Scale Testing

Train 1: MBBR (Nominal 60% Fill)



Train 2: Hybrid AS with Post-DN (Nominal 50 % Fill)



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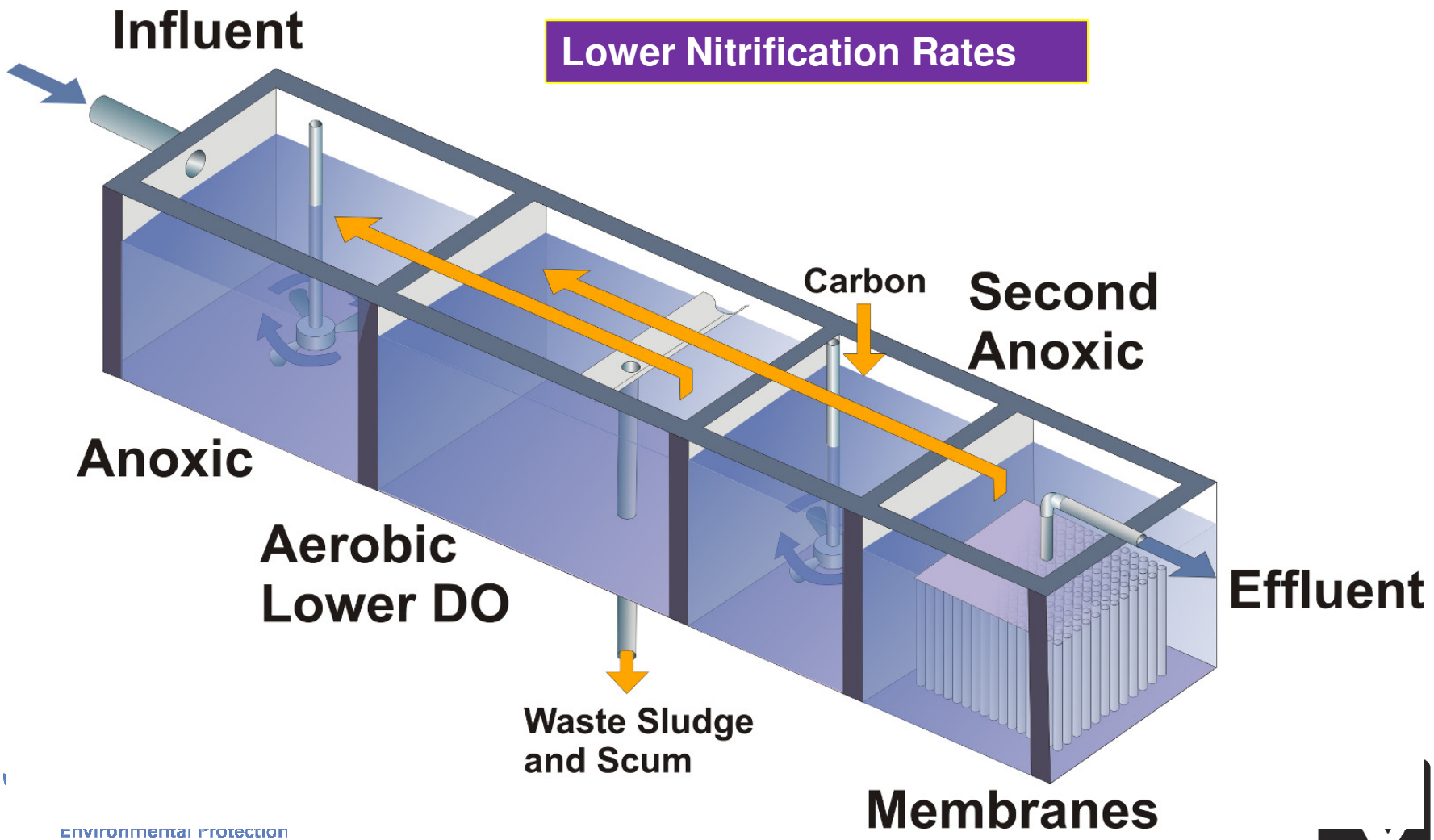
Membrane Bio-reactor for Nitrogen Removal



Side-stream Options

- With digestion 20 to 30% of influent nitrogen could be in return stream after digestion
- Operation of solids dewatering say 5 days @ 8 hours per day
- Consider number of options for side-stream treatment -
- If no side-stream treatment then at least balance the high concentration return stream
- Controlled discharge to inlet works

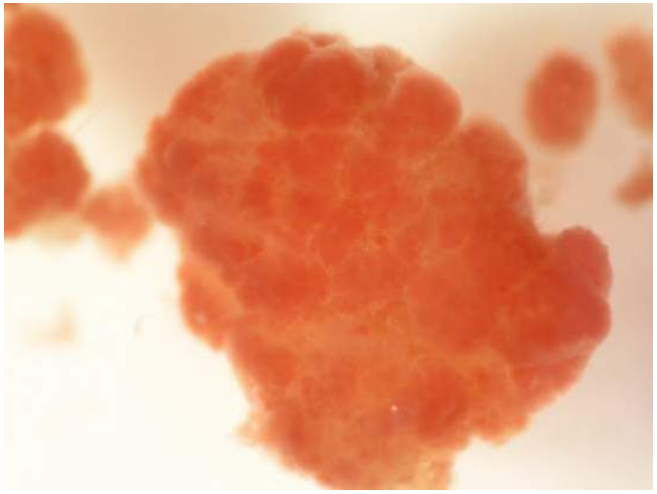
Managing recycle streams

- Preferred to keep ammonia load as constant as possible for treatment in main plant to control feed
- Equalize anaerobic digester centrate to discharge 24/7
- Watch for alkalinity concerns when feeding too much ammonia at night

Recycle Streams

When ammonia load is more than 20% of influent load, consider side stream treatment

- Ammonia stripping and capture
- Separate nitrification and denitrification –Sharron, Babe , Anammox , DEMON etc. for reduction in carbon requirements
- Consider struvite recovery for BPR plants – e.g. Ostara which also captures ammonia



SUMMARY

- ENR discharge permits leave little room for operating failures……
- Real-Time Monitoring and Feed Forward Controls can provide the information needed for reliable, economical compliance with ENR requirements
- Fail-safe Design and redundancy is required
- Flow and load balancing is preferred

SUMMARY (con't)

- Process selection crucial for guaranteed results
- Carbon sources and controls are important
- Understanding the process is essential for optimal operation

Discussions

Design and Process Model Considerations

H. David Stensel, PhD, PE
University of Washington

U.S. EPA Technology Transfer Webinar
Nutrient Webinar on Nitrogen Removal

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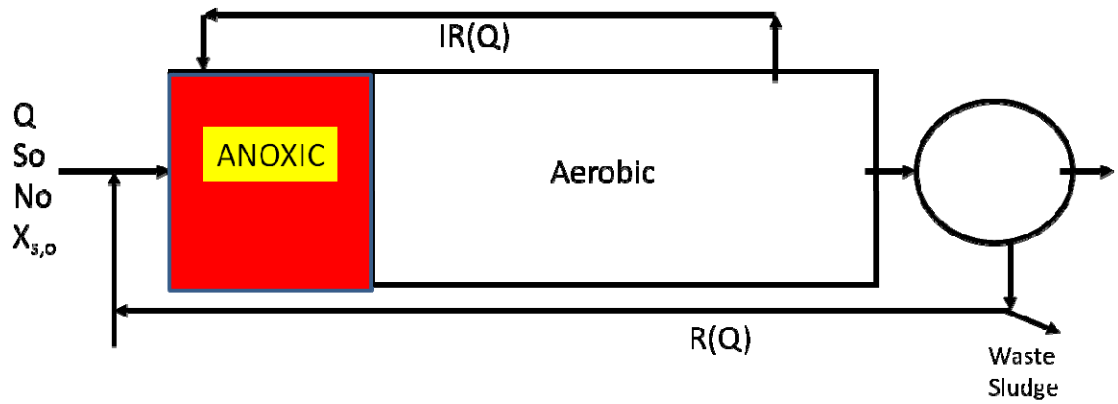
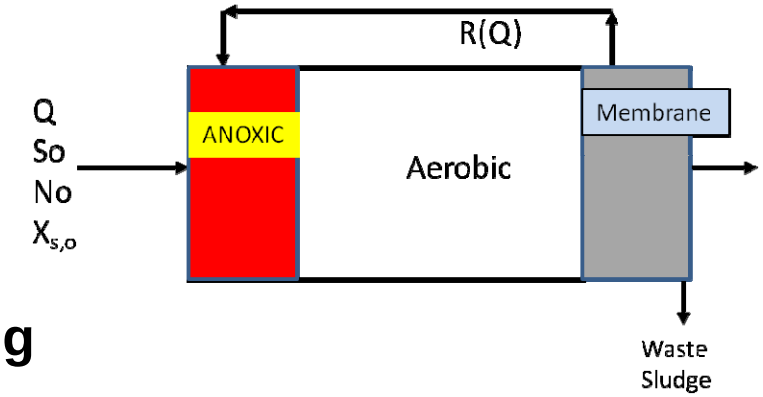
Process Design Needs

- **Tank Volumes**
- **Oxygen Transfer**
- **MLSS concentration**
- **Recycle flowrates**
- **Waste sludge rate**
- **Clarifier or membrane sizing**





Design approach for selected ENR option involves desktop design and simulation models

- Designer should establish wastewater characteristics and flows and effluent goals
- Designer should be familiar with the models and coefficients describing various processes
- A preliminary process design should be done using basic mass balances, spreadsheets, design graphs, and reasonable safety factors

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Simulation Modeling is a Valuable Tool in ENR Design and Analysis

- Results of steady state preliminary design can be incorporated into simulation models for process analysis and design optimization

  - Realistic diurnal variations in flow and loadings
  - Anoxic and aerobic reactors in series vs single stage
  - Effect of recycle flows
  - Evaluate range of loadings
  - Calibrate to existing plant performance

Wastewater characterization very important -affects design outcomes

	Secondary Influent	Effluent
Flow mgd	10	
COD mg/L	265	
rbCOD, mg/L	50	
BOD, mg/L	140	<10
TSS , mg/L	75	<10
VSS, mg/L	60	
TKN, mg/L	30	
Ammonia – N, mg/L	20	<1
Nox, mg/L	0	<6
Total P, mg/L	5	<1
MinimumTemperature	12ºC	
Alkalinity, as CaCO3, mg/L	150	

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Some key steps in Desktop Design

- ✓ Select aerobic SRT for nitrification – add safety factor
- ✓ Production rate of biomass and waste activated sludge
- ✓ Nitrogen balance
  - ✓ TKN minus N in biomass minus (NH4-N+DON) in effluent
  - ✓ =-N oxidized (NO3-N + NO2-N)
- ✓ Oxygen requirements for nitrification and carbon removal
  - NH4-N oxidation, BOD removal, NOx reduction for BOD removal
- ✓ Alkalinity analysis
- ✓ Check spreadsheet model coefficients with simulation model coefficients

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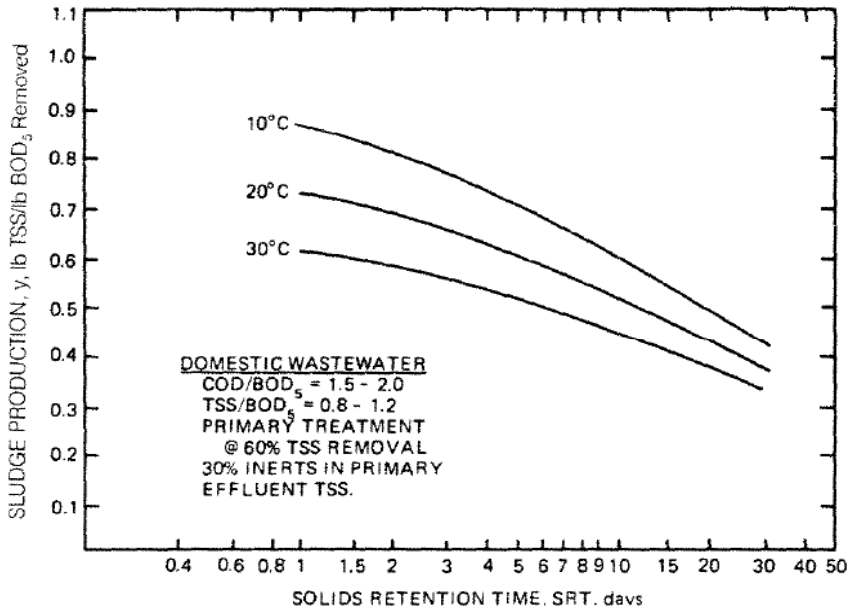
Sludge yield, SRT, MLSS determine Aerobic Volume

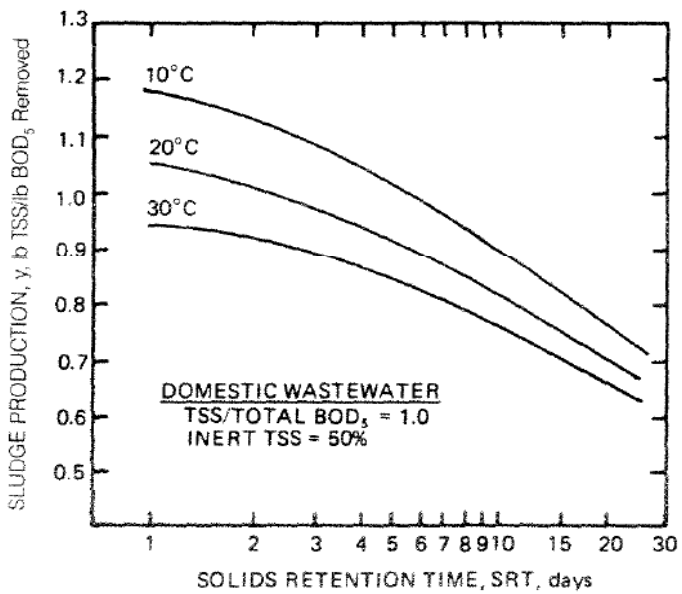
Px = Sludge production rate, (mass VSS/d),

sludge yield, $Yn = \dfrac{\text{net g VSS produced}}{\text{g BOD removed}}$

$$\text{Volume, } V = \frac{Px(SRT)}{MLSS(0.85)} = \frac{Yn(\Delta BOD)Q(SRT)}{MLSS(0.85)}$$



(a)



Yield can be estimated from graphs for domestic wastewater

Activated sludge treatment
with and without primary treatment

WEF, MOP 8

First Anoxic Tank Volume Design Considerations

Dependant on Wastewater Characteristics and N Mass Balance

- Typically in range of 20-30% of total tank volume

- <u>Mass balance on N to determine NOx production</u>
- Amount of NO_3-N removed in first anoxic tank
  - Related to NOx production, internal and RAS recycle ratios and denitrification rates

- Amount of NOx-N removed in 2nd anoxic tank
  - Related to aeration tank Nox, influent and RAS flowrates, and denitrification rates

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Empirical Eqs can approximate specific denitrification rate (SDNR), gNO3-N/gMLVSS-d

$$\text{Anoxic Volume} = \frac{\text{NOx Removed}}{\text{SDNR}(\text{MLVSS})}$$

Anoxic Volume = f(SDNR

First anoxic tank – EPA Nutrient Manual

$$SDNR_T = \left[0.03(F/M)\left(\frac{F_b}{0.30}\right) + 0.029\right]1.07^{(T-20)}$$

$$F_b = \left(\frac{\left[\frac{Y_H}{(1+b_T SRT)}\right]}{\left[\frac{Y_H}{(1+b_T SRT)} + Y_I\right]}\right)$$

Second anoxic tank – WEF Operations Manual

$$SDNR_T = 0.12\left(SRT^{-0.706}\right)\left(1.029^{T-20}\right)$$

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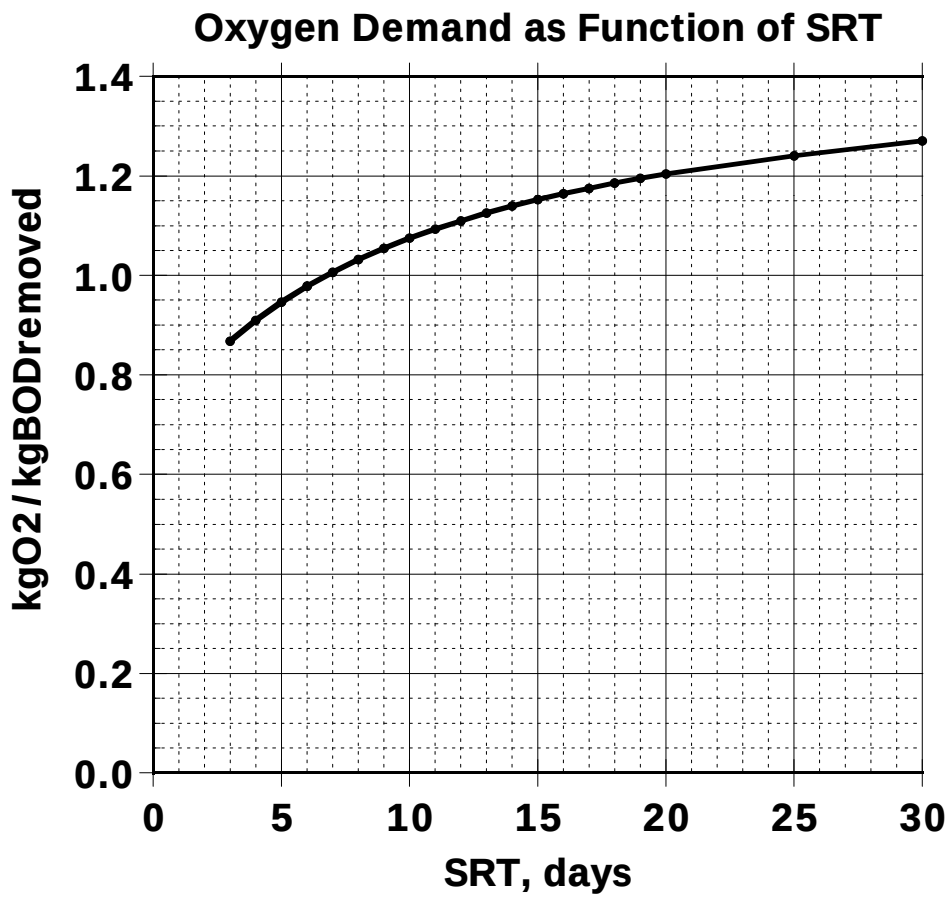
Oxygen needed accounts for BOD removed, NH4 oxidized and NO3 reduced in preanoxic zone

$$\text{Oxygen Required} = (1.0\text{-}1.3)(\text{BODremoval}) + 4.57(\text{Noxidized}) - 2.86(\text{NO3-Nreduced})$$



Alkalinity Balance
(goal is final alkalinity of 70-80)

MLE Process (all as $CaCO_3$)
Assume N oxidized = 30 mg/L
Effluent NO_3-N = 8 mg/L
Influent alkalinity = 180 mg/L

Final =In – consumed + produced + added

80=180 – (7.14)(30) +3.57(30-8) + alkalinity added
Alkalinity added = 80-180+214.2-78.5 = 35.7 mg/L

Internal Recycle rate related to Nox production and effluent NOx

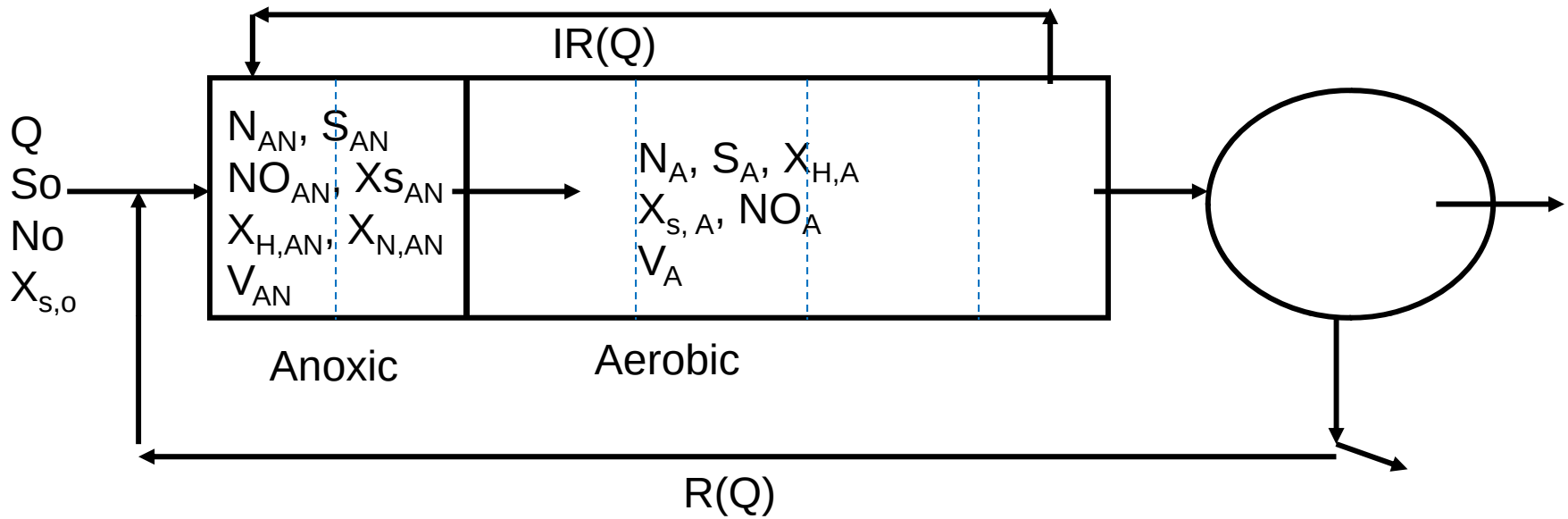
Assume N oxidized = 30 mg/L
Effluent NO3-N = 8 mg/L
Clarifier RAS ratio = 0.50

$$\text{NO effluent, mg/L} = \frac{\text{Nitrate produced in aerobic zone, mg/L}}{1+\text{RAS}+\text{IR}}$$

$$8\ \text{mg/L} = \frac{30\ \text{mg/L}}{1+0.50+\text{IR}}$$

IR = 2.25

Analysis and optimization needs simulation modeling complex process with many constituents in staged reactors



Where:

AN = anoxic tank, V_{AN} = volume
A = aerobic tank, V_A = volume
N = NH4-N
NO = NO3-N
S = soluble bCOD
X_H = heterotrophic biomass
X_N = nitrifier biomass

Q = Flowrate
So = influent bsCOD
N0 = influent TKN
Ss,o = influent particulate degradable COD

Computer Simulation models needed for analysis ad design of complex ENR systems

Commonly used software packages

BioWin (Envirosim)

GPS-X (Hydromantis)

Key simulation modeling capabilities

- Staged reactors and complex reactions
- Effect of soluble and particulates in wastewater
- Diurnal load affects effluent N concentrations
- Designs done with more accurate predictions
- Design analysis can evaluate reactor configurations and recycle flows
- Needs accurate information and knowledge of kinetic coefficients

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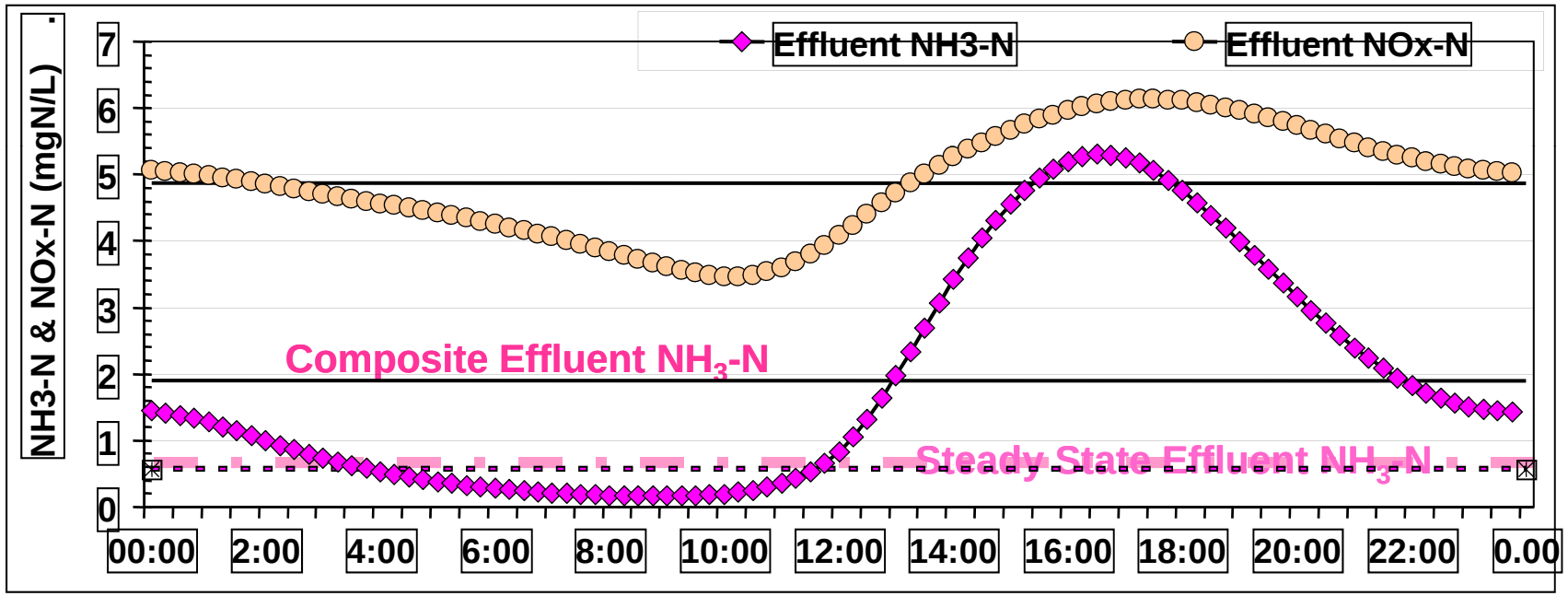
At same SRT steady state performance has lower effluent N than for diurnal loads

- …



If strict effluent goals are to be met, treatment plant dynamics must be considered

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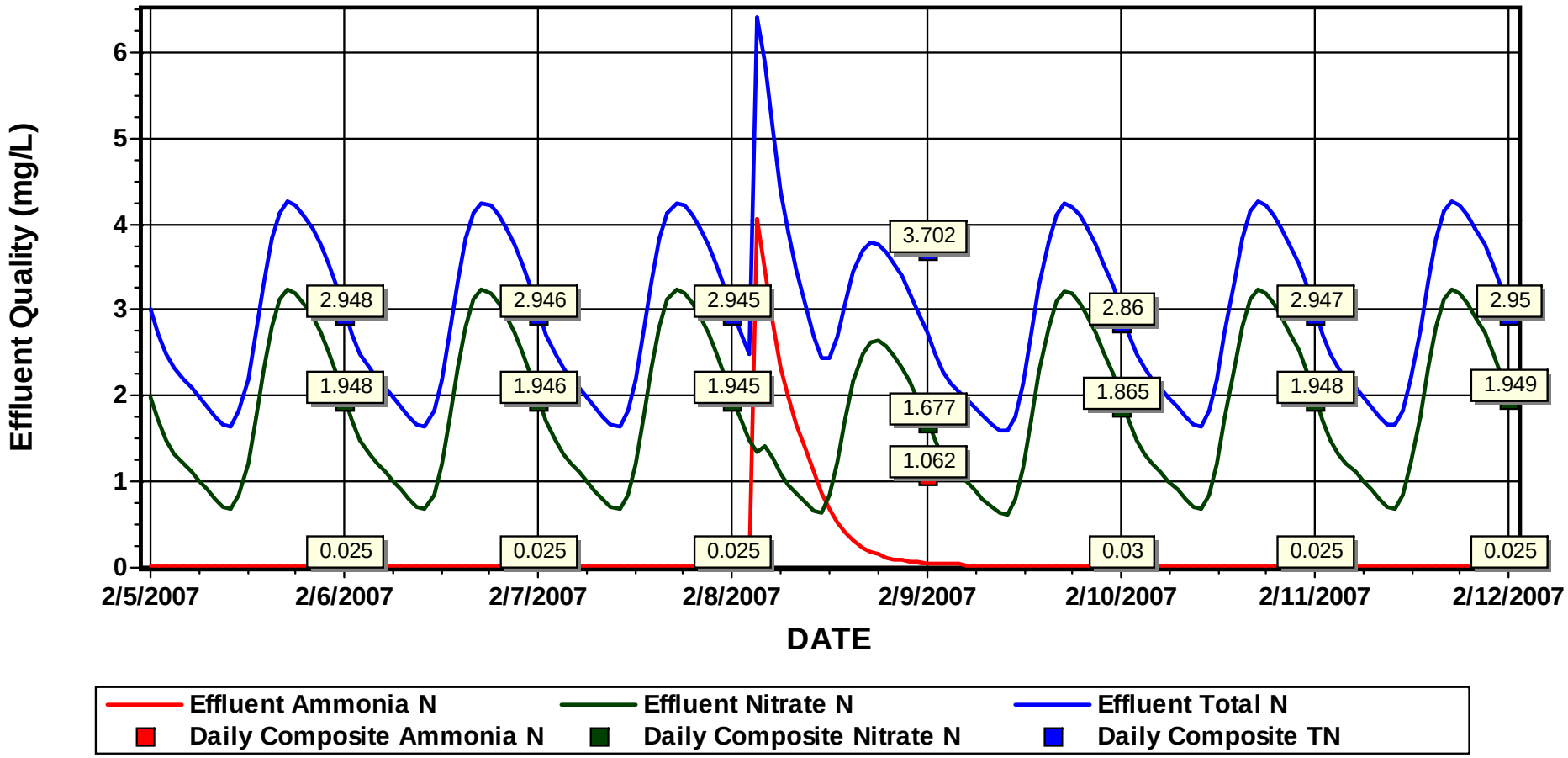
Diurnal Effluent Nitrogen



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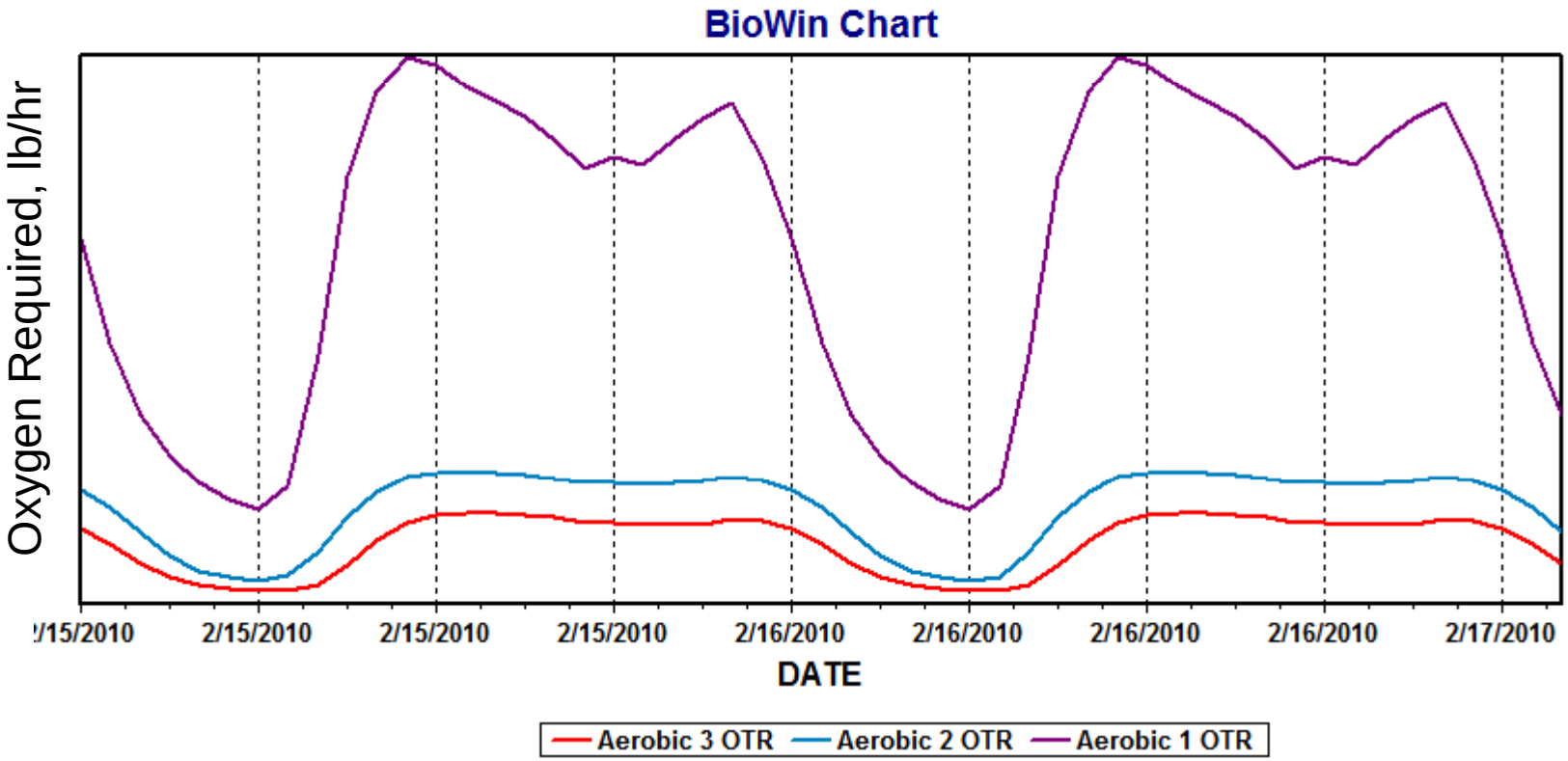
Diurnal variations in oxygen demand



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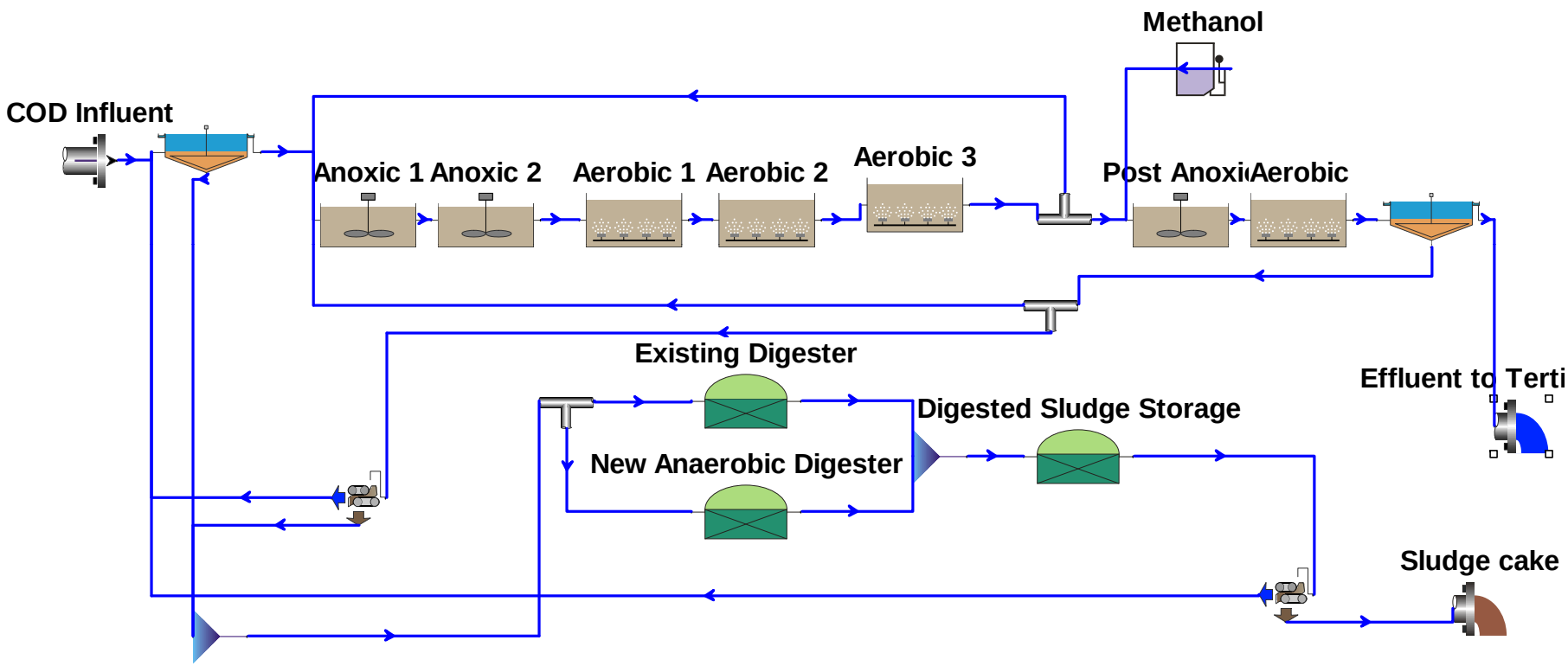
Can model complete to include primary treatment, recycle flows, staged reactors



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GOOD MODELING PRACTICE PROTOCOL

IWA GUIDELINES FOR USE OF ACTIVATED SLUDGE COMPUTER MODELS

The Proposed IWA Protocol Includes
5 Main Steps:

1. Project Definition
2. Data Collection and Reconciliation
3. Model Set-up
4. Calibration and Validation
5. Simulation and Result Interpretation

Be aware of model limitations

- Models consider ideal conditions, i.e. flow splits, DO levels, SRT control etc.
- There are no safety factors built in
- Following variable load simulations, consider the need for safety factors
- Check coefficients in model kinetic and stoichiometric equations
- If diurnal values not available try and establish peak daily loads and mimic diurnal patterns from other plants

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Be Knowledgeable about limitations of models

- Check model results with expectations from simple calculations
  - Sludge production and oxygen demand are key parameters
  - Effluent NO3-N, NH4-N concentrations

Summary

- BNR process designs are more complex with many possible configurations
- Spreadsheets and desktop calculations provide preliminary designs and checks on model results
- Simulation models can account for dynamic flow and load conditions and complex reactions
- Wastewater characterization important
- Calibration of models to existing facilities helps develop more optimal designs