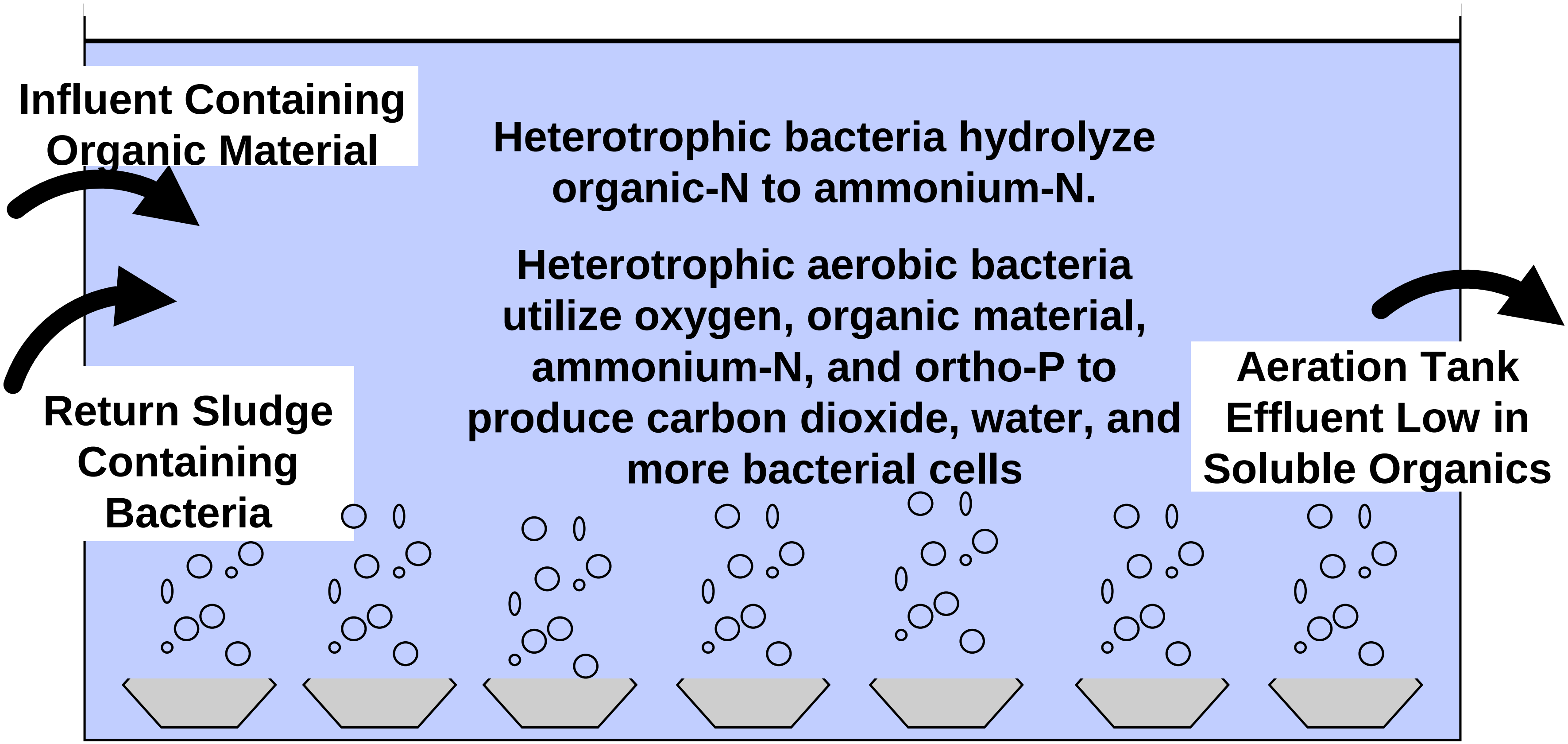
Module 2
Activated Sludge Operational Strategies for Nitrogen Removal

- **Nitrification Fundamentals**
- **Denitrification Fundamentals**
- **Operating Strategies for Nitrification**
- **Operating Strategies for Denitrification**

Nitrification Fundamentals

BOD Removal in the Activated Sludge Process



Minimum Conditions Necessary to Maintain Carbonaceous BOD Removal in the Activated Sludge Process

- **Mean Cell Residence Time - 0.5 to 1 day**
- **pH - 5 to 9**
- **Temperature - above freezing**
- **Dissolved Oxygen - above 0.5 mg/l**

What's Needed to Go From BOD Removal to Nitrification ?

Conditions Necessary to Achieve Nitrification in the Activated Sludge Process

- **Aerobic Mean Cell Residence Time - 4 to 15 days**
- **pH - 6.5 to 8 optimal**
- **Temperature - 25° C for optimal nitrification**
- **Dissolved Oxygen - >2.0 mg/l for optimal nitrification**

What's Different for Nitrification ?

- **Need longer MCRT**
- **Need more oxygen**
- **Need more alkalinity**
- **Need to be careful about inhibitory compounds**
- **Temperature has a greater impact**

Nitrification

$$2NH_4^+ + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+$$

Oxygen Required = 3.43 lb / lb N oxidized

Alkalinity Required = 7.14 lb as $CaCO_3$/ lb N oxidized

$$2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2NO_3^-$$

Oxygen Required = 1.14 lb/ lb N oxidized

For both reactions together:

Total Oxygen Requirement = 4.57 lbs / lb N oxidized

Total Alkalinity Requirement = 7.14 lbs as $CaCO_3$ / lb N oxidized

Simplified Calculation of Oxygen Requirement for Nitrification

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

Simplified Calculation of Alkalinity Requirement for Nitrification

Given:

Plant Influent Flow	**=**	**10 mgd**
Primary Effluent TKN	**=**	**31.5 mg/l**

Alkalinity Consumed by Nitrification :

<u>In lbs/day</u>

(10 mgd) x (31.5 mg/l) x (7.14) x (8.34) = 18,757 lbs alkalinity as $CaCO_3$ per day

(10 mgd)	x	(31.5 mg/l)	x	(7.14)	x	(8.34)	=	18,757 lbs alkalinity as $CaCO_3$ per day
Flow		TKN conc.		lbs. of alkalinity required per lb of ammonia-N nitrified				

<u>In mg/l</u>

(31.5 mg/l) x (7.14) = 225 mg/l alkalinity as $CaCO_3$ consumed

Factors Affecting Nitrification

What is the Key Factor for Achieving Nitrification

?

Factors Affecting Nitrification

What is the Key Factor for Achieving Nitrification?

MEAN CELL RESIDENCE TIME

(MCRT)

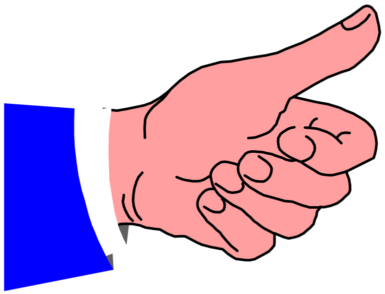
Effect of Temperature on Nitrification

As temperature increases, nitrifier growth rate increases (within the range of 4º C to 35º C).

T ↑ μ ↑

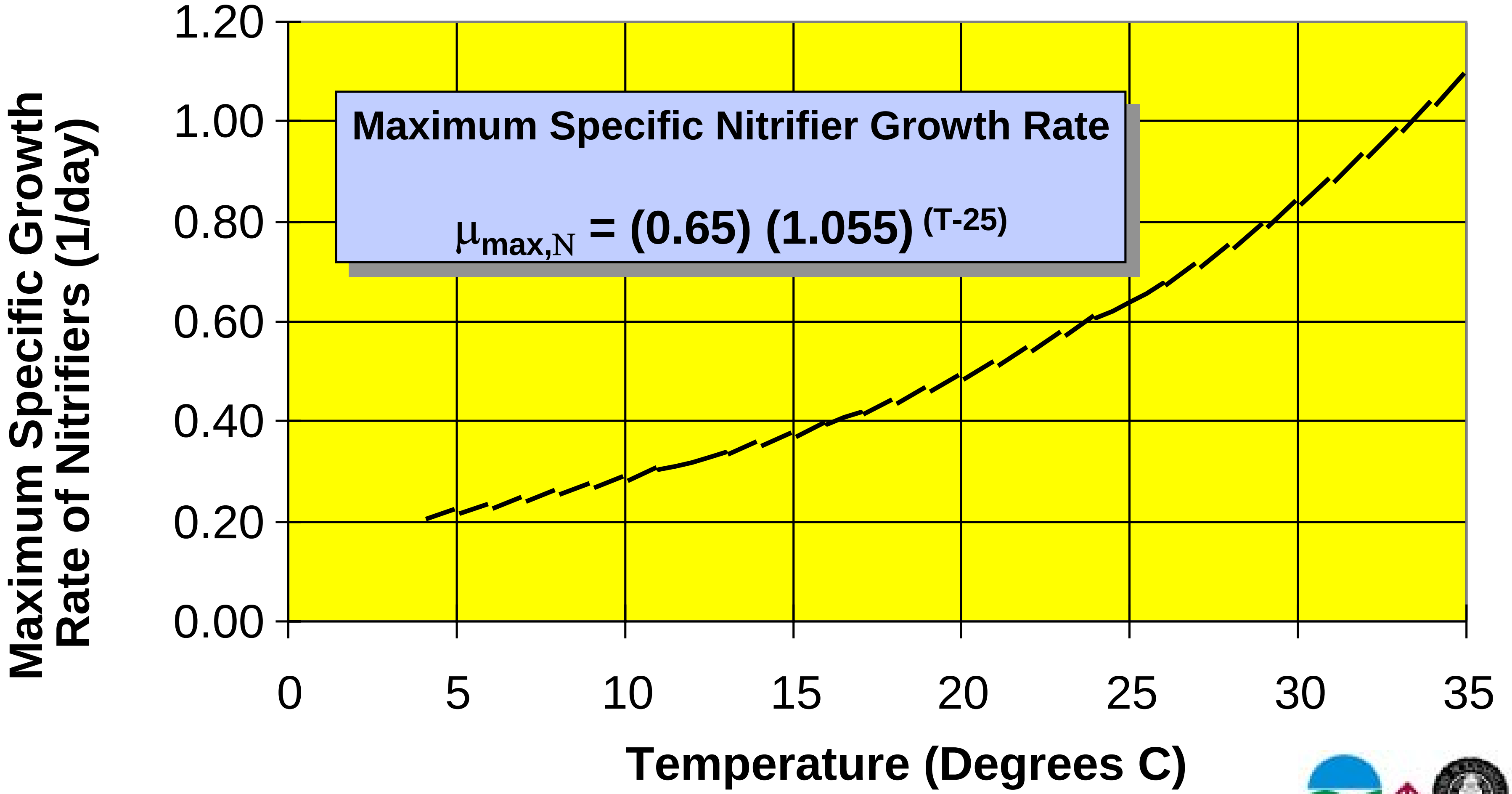
As nitrifier growth rate increases, required MCRT decreases.

μ ↑ MCRT ↓



Rule of Thumb:
For every 10ºC increase in temperature, nitrifier growth rate doubles, required MCRT is cut in half and required MLSS concentration is also reduced.

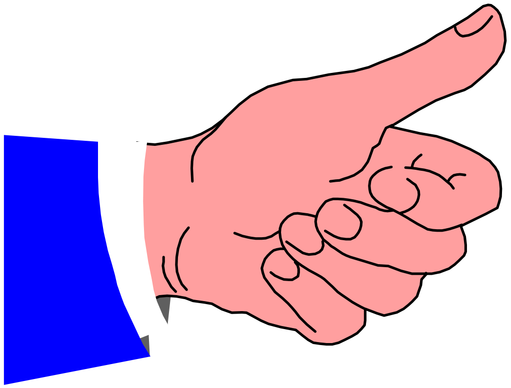
Effect of Temperature on Nitrifier Growth Rate



Effect of Dissolved Oxygen Concentration on Nitrification

As dissolved oxygen increases, nitrifier growth rate increases up to DO levels of about 5 mg/L.

DO ↑ μ ↑

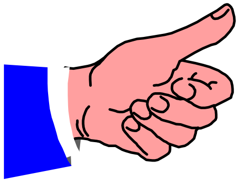


<u>Rule of Thumb</u>:
Maintain dissolved oxygen concentration at
2.0 mg/l or higher for optimum nitrification.

Effect of pH and Alkalinity on Nitrification

Nitrification consumes alkalinity and lowers pH in the activated sludge mixed liquor.

pH below 6.5 or above 8.0 can significantly inhibit nitrification.



<u>Rules of Thumb</u>:
Maintain pH in the range 6.5 - 8.0 for optimum nitrification.

Overall alkalinity consumption is generally less than the theoretical 7.14 lbs as $CaCO_3$ per lb of ammonia-N nitrified.

Compounds Which Inhibit Nitrification

Organic Compounds:

- Acetone
- Carbon Disulfide
- Chloroform
- Ethanol
- Monoethanolamine
- Phenol
- Ethylenediamine
- Hexamethylene Diamine
- Aniline

Metals and Inorganic Compounds:

- Zinc
- Free Cyanide
- Perchlorate
- Copper
- Mercury
- Chromium
- Nickel
- Silver
- Cobalt
- Thiocyanate
- Sodium Cyanide
- Sodium Azide
- Hydrazine
- Sodium Cyanate
- Potassium Chromate
- Cadmium
- Arsenic (trivalent)
- Fluoride
- Lead

Denitrification Fundamentals

Denitrification

Nitrate + Methanol $\longrightarrow$ Carbon Dioxide + Nitrogen Gas + Water + Hydroxide

$$6NO_3^- + 5CH_3OH \longrightarrow 5CO_2 + 3N_2\overset{\text{Gas}}{\uparrow} + 7H_2O + 6OH^-$$

Methanol Utilized = 1.9 lbs methanol per lb nitrate-N denitrified
This is equivalent to 2.86 lbs COD utilized per lb nitrate-N denitrified
(Note: Actual methanol dose required = 2.5 to 3.0 lbs methanol per lb nitrate-N denitrified)

Alkalinity produced = 3.57 lbs as $CaCO_3$ per lb nitrate-N denitrified

$$2NO_3^- + 2H^+ \longrightarrow N_2\overset{\text{Gas}}{\uparrow} + H_2O + 2.5O_2$$

Oxygen recovered = 2.86 lbs per lb nitrate-N denitrified

Simplified Calculation of Oxygen and Alkalinity Recovered by Denitrification

Given: Plant Influent Flow = 10 mgd
Nitrate to be Denitrified = 22 mg/l

Oxygen Recovered

(10 mgd) x (22 mg/l) x 2.86 x 8.34 = 5,248 lbs O_2 recovered per day

- (10 mgd): Flow
- (22 mg/l): Nitrate-N to be Denitrified
- 2.86: lbs O_2 recovered per lb nitrate denitrified

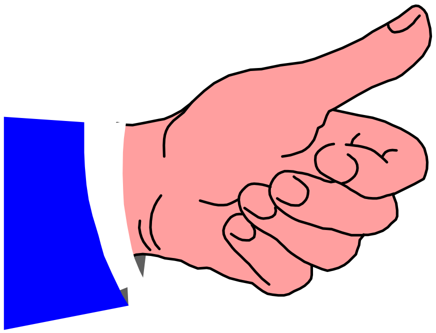
Alkalinity Recovered

(10 mgd) x (22 mg/l) x 3.57 x 8.34 = 6,550 lbs alkalinity as $CaCO_3$ recovered per day

- (10 mgd): Flow
- (22 mg/l): Nitrate-N to be Denitrified
- 3.57: lbs alkalinity recovered per lb nitrate denitrified

Effect of Dissolved Oxygen on Denitrification

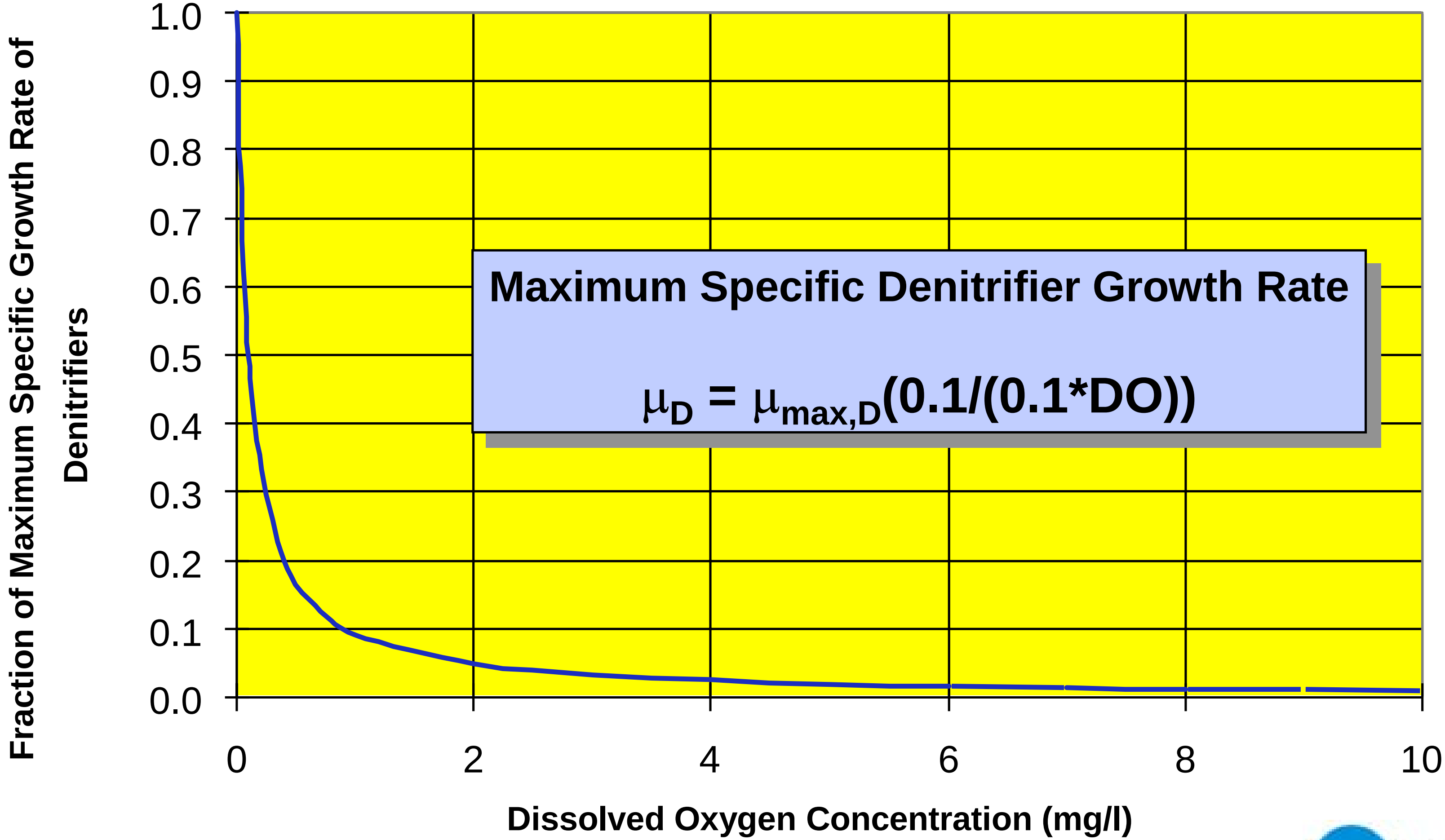
- **Dissolved oxygen inhibits denitrification.**
- **As DO increases, denitrification rate decreases.**



Rule of Thumb:

- **Maintain DO below 0.3 mg/l in anoxic zone to achieve denitrification.**

Effect of Dissolved O_2 on Denitrification Rate

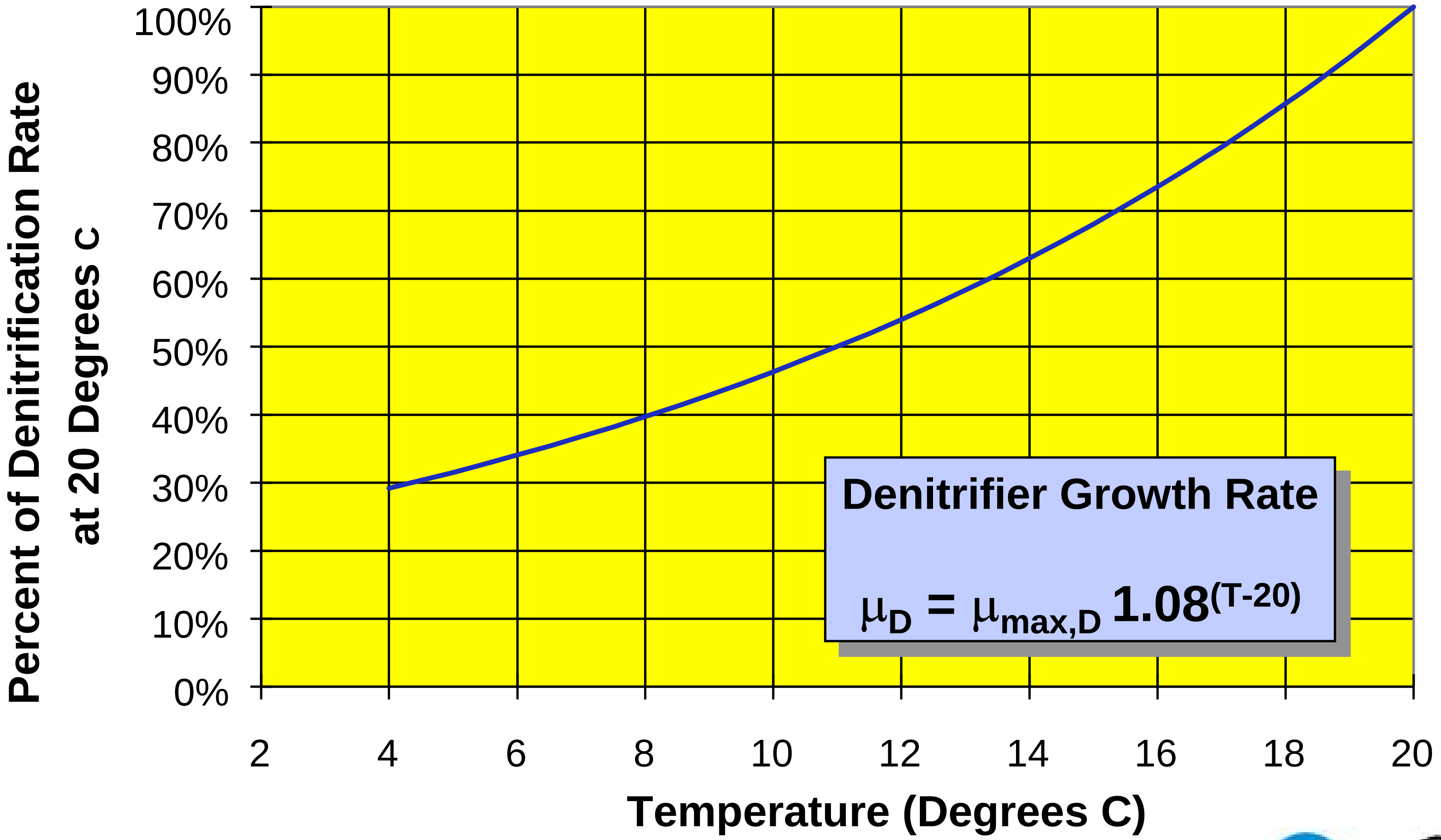


Effect of Temperature on Denitrification Rate

As temperature increases, denitrifier growth rate increases.

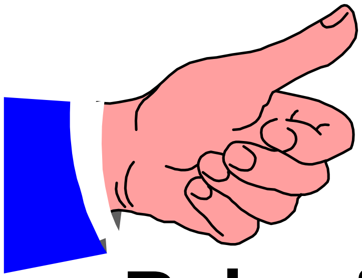
T ↑ μ_D ↑

Effect of Temperature on Denitrification Rate



Effect of pH on Denitrification Rate

- **Denitrifiers are generally less sensitive to pH than nitrifiers.**



<u>Rule of Thumb</u>:

- **If pH is within the recommended range of 6.5 - 8.0 for nitrification, there will be no pH effects on denitrification.**

Effects of Inhibitory Compounds on Denitrification

- **Denitrifiers are generally less sensitive to inhibitory compounds than nitrifiers.**
- **If there are no compounds present which inhibit nitrification, there will probably be no inhibition of denitrification.**

Effects of Available Carbon Source on Denitrification

- **Denitrification rate varies greatly depending upon the source of available carbon.**
  - **Highest rates are achieved with addition of an easily-assimilated carbon source such as methanol.**
  - **Lower denitrification rate is achieved with raw wastewater or primary effluent as the carbon source.**
  - **Lowest denitrification rate is observed with endogenous decay as the source of carbon.**

Denitrification Rates

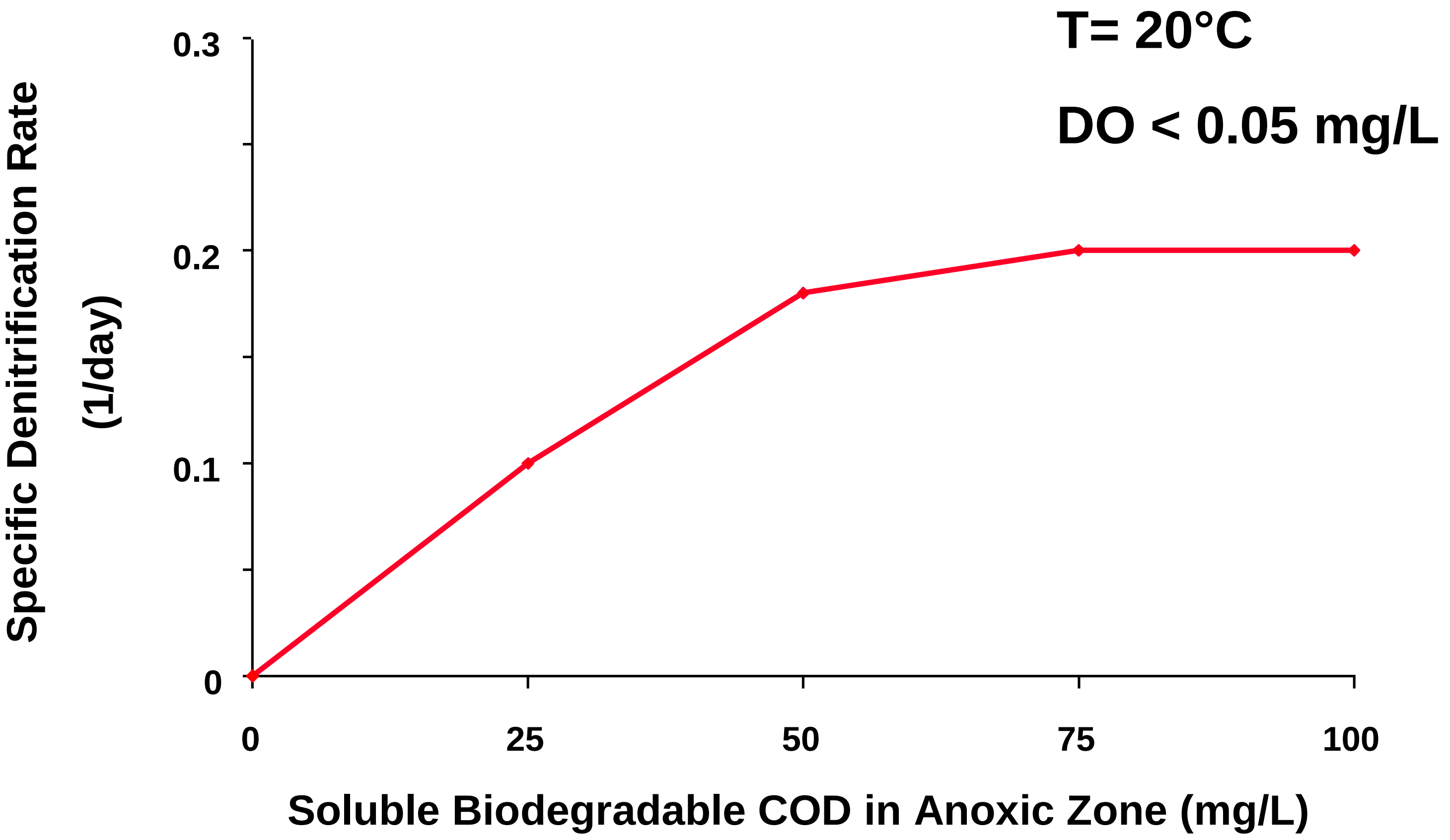
Reported Denitrification Rates

Carbon Source	Denit Rate ($g\ NO_3^-$-N/g VSS-d)	Temp (°C)
Methanol	0.10 to 0.32	10 - 27
Sewage	0.03 to 0.12	10 - 27
Endogenous Decay	0.02 to 0.06	10 - 27

Considerations Regarding Methanol as a Carbon Source

- **Methanol Costs = $0.70 to $3.00 per gallon**
- **Storage Requirements**
  - **National Fire Protection Agency (NFPA) requirements**
  - **Dike around each above ground tank (125% of tank volume)**
  - **Tank fittings should include:**
    - Inlet with dip tube to prevent splash and static electricity
    - Anti-siphon valve of hole on the inlet to prevent back siphoning
    - Vent pipe with pressure vacuum release valve with flame arrester
    - Outlet connection
    - Drain connection
    - Various opening for depth gauges, sample points, and level switches
  - **Tanks must be grounded**

Effect of Biodegradable SCOD in Anoxic Zone on Specific Denitrification Rate



Range of Variation of K_S
K_S = 20 - 50 mg/L SCOD at 12°C

Operating Strategies for Nitrification

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So, what do we need to do to get my plant to nitrify

?

Operating Strategies for Nitrification

So, what do we need to do to get my plant to nitrify?

Establish sufficient mean cell residence time (MCRT).

Approach to Establishing Nitrification

1. **Confirm adequate alkalinity[1]**
2. **Confirm adequate oxygen[1]**
3. **Calculate target MCRT[1]**
   - **Determine growth rate at desired temperature**
   - **Adjust growth rate for ammonia and DO concentrations**
   - **Use corrected growth rate to determine target MCRT**
4. **Calculate current actual MCRT**
5. **Adjust MCRT to try to reach target**

(1) Include Denitrification for TN removal

Relationship Between Growth Rate and MCRT

$$\text{Minimum MCRT} = \frac{1}{\mu_{max} - k_d}$$

μ_{max} = maximum nitrifier growth rate, 1/day

k_d = endogenous decay coefficient, 1/day

Correcting Growth Rate For Temperature

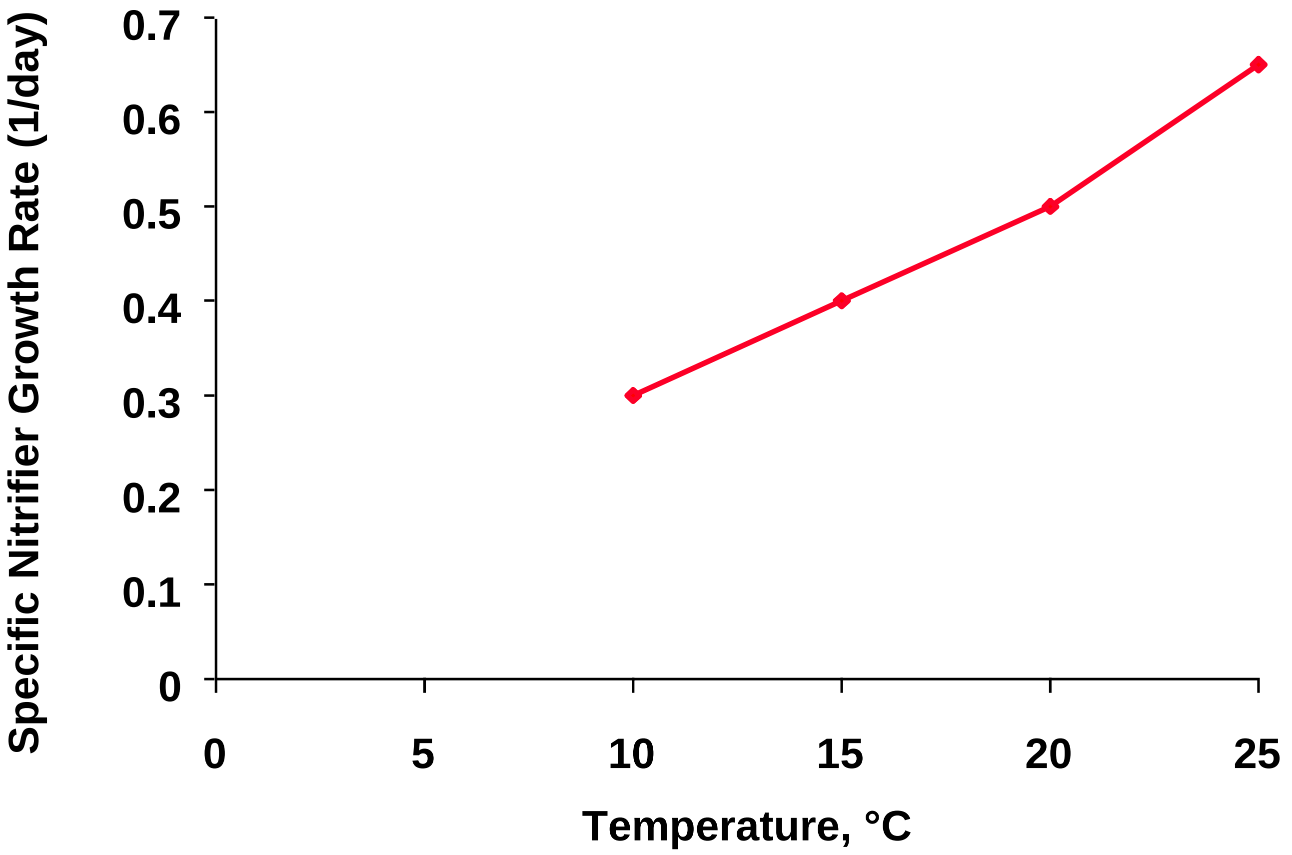
Correction for Temperature

$$\mu_{max,\, T} = (\mu_{max,\, 25°C})\,(1.055)^{(T-25)}$$

$$= (0.65)\,(1.055)^{(T-25)}$$

T = Temperature in ° C

Specific Nitrifier Growth Rate vs. Temperature



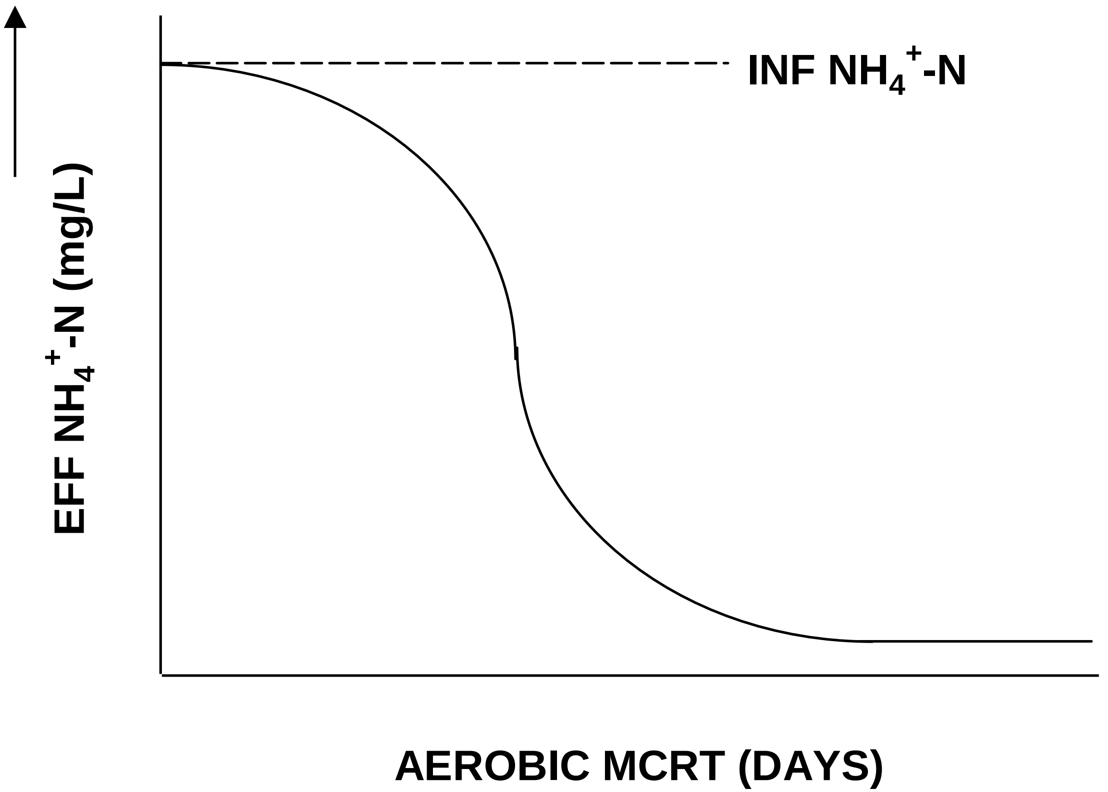
Growth Rate and Target MCRT as a Function of Temperature

Temp	Max Specific Growth Rate μ_{max} (days^{-1})	Death & Decay Rate k_d (days^{-1})	Min MCRT (days)
10°C	0.29	0.02	3.7
15°C	0.38	0.03	2.8
20°C	0.50	0.04	2.2
25°C	0.65	0.05	1.7

Correcting Growth Rate for Ammonia Concentration

$$\mu_{NH_4^+} = (\mu_{max}) \frac{NH_4^+}{K_N + NH_4^+}$$

Relationship Between Effluent Ammonia Concentration and Required MCRT

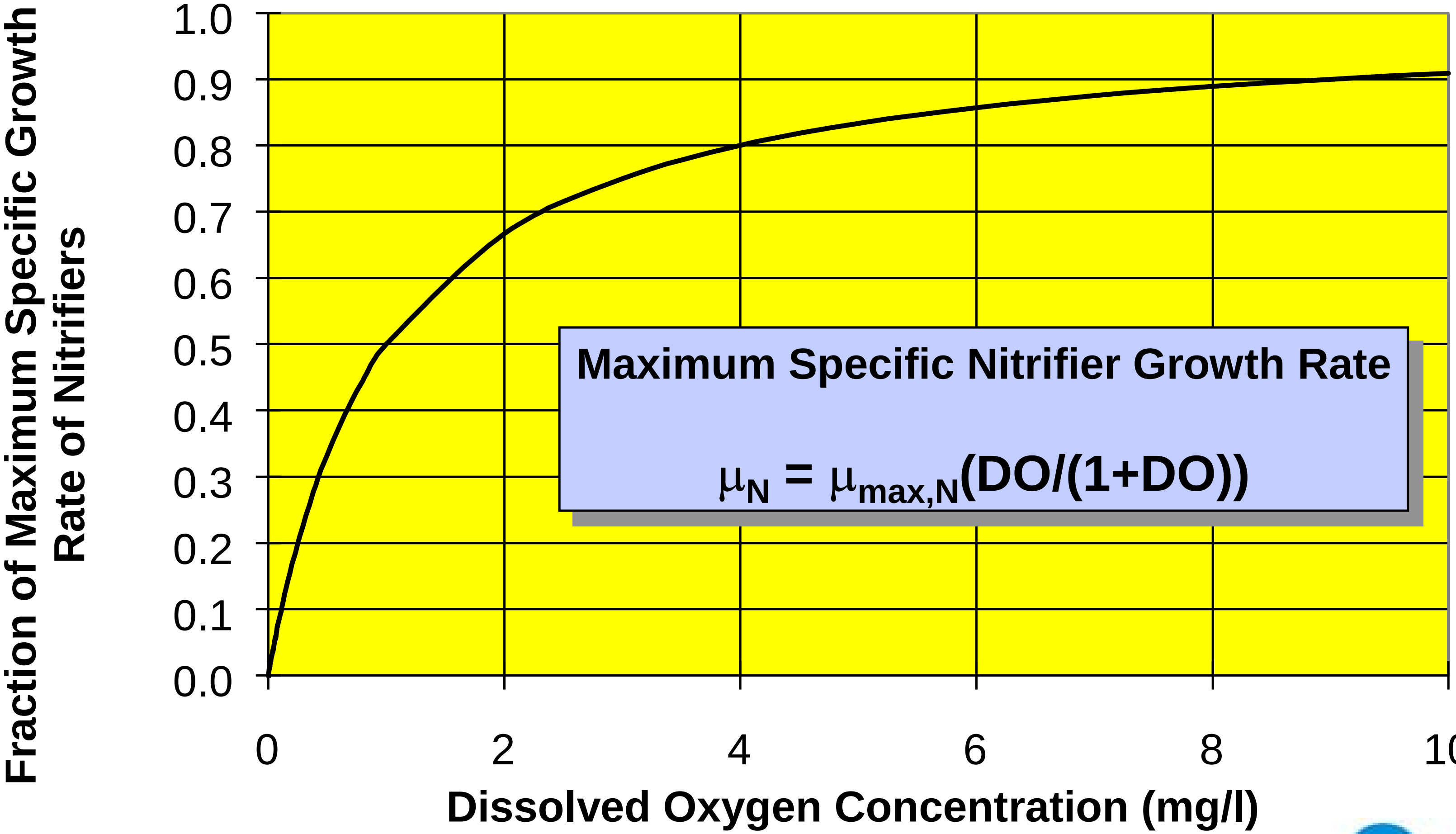


Correcting Growth Rate for Dissolved Oxygen Concentration

$$\mu_{DO} = (\mu_{max}) \frac{DO}{K_{DO} + DO}$$

Use K_{DO} = 1.0 mg/l

Effect of Dissolved Oxygen on Nitrification Rate



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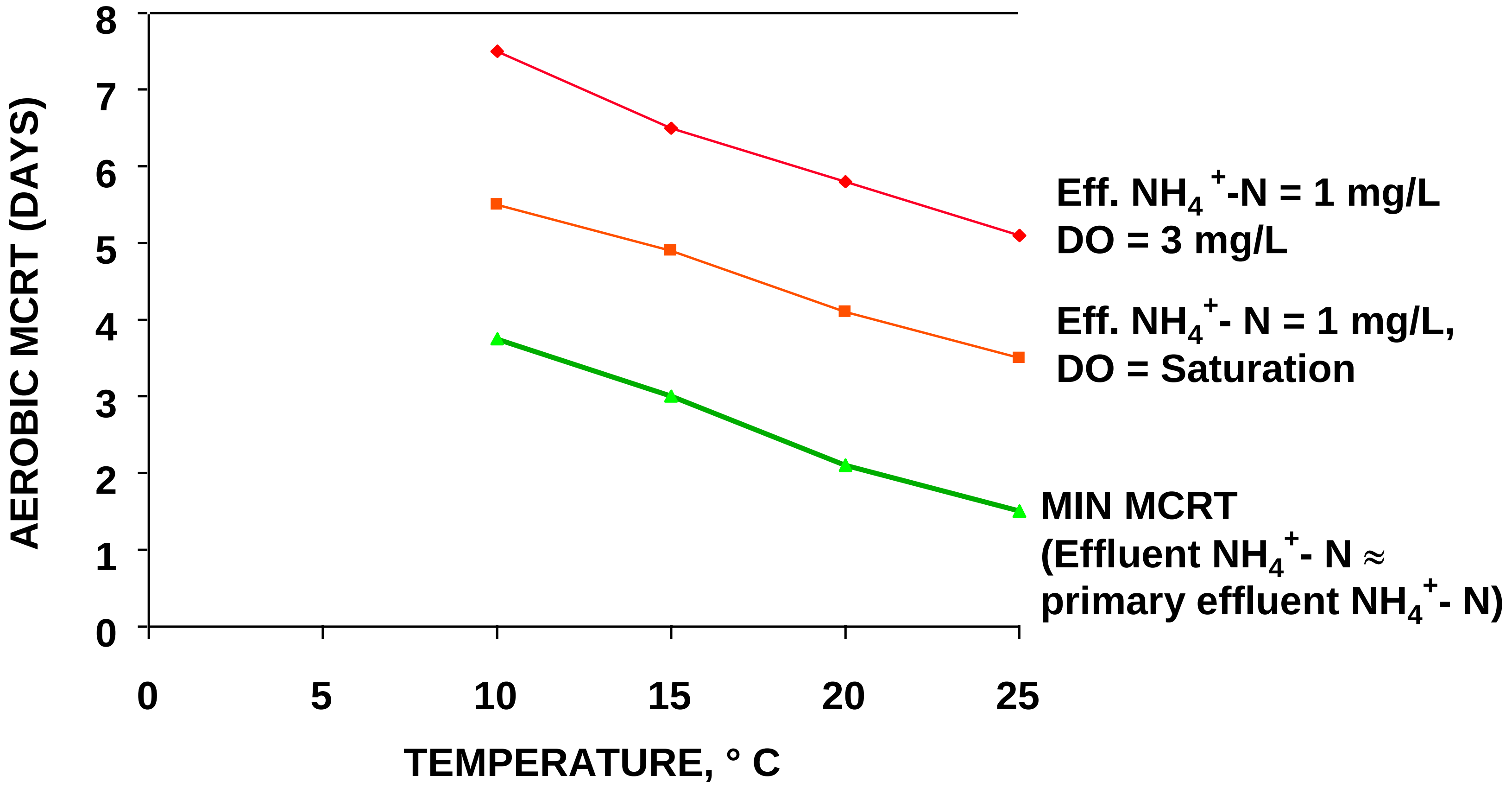
Target MCRT as a Function of Ammonia and DO

Temp	K_N (mg/l as NH_4^+-N)	MCRT Corrected for NH_4^+-N (days)	MCRT Corrected for DO (days)
10°C	0.45	5.6	7.8
15°C	0.59	4.7	6.6
20°C	0.77	4.1	5.8
25°C	1.0	3.6	5.2

Note: Based on complete mix system, Eff. NH_4^+-N = 1 mg/l, DO = 3 mg/l

Relationship Between MCRT, Temp, DO, and NH_4^+-N



Determining Required MCRT

How do I determine the MCRT required to get my plant to nitrify?

Determination of Actual Operating MCRT

How do I determine the MCRT at which my plant is actually operating ?

What is MCRT ?

$$\text{MCRT (days)} = \frac{\text{Biomass in system (lbs)}}{\text{Biomass wasted (lbs per day)}}$$

= average number of days that solids remain in system

Varying Approaches to Calculating MCRT

- **Include biomass in aeration tanks only**
- **Include biomass in aeration tanks and clarifiers**
- **Aerobic MCRT**
- **Anoxic MCRT**

Calculating Mean Cell Residence Time

$$\text{MCRT (days)} = \frac{\text{Biomass in system (lbs)}}{\text{Biomass wasted (lbs per day)}}$$

$$\text{Biomass in System (lbs)} = \text{Aeration Tank Volume (million gallons)} \times \text{MLSS (mg/l)} \times 8.34$$

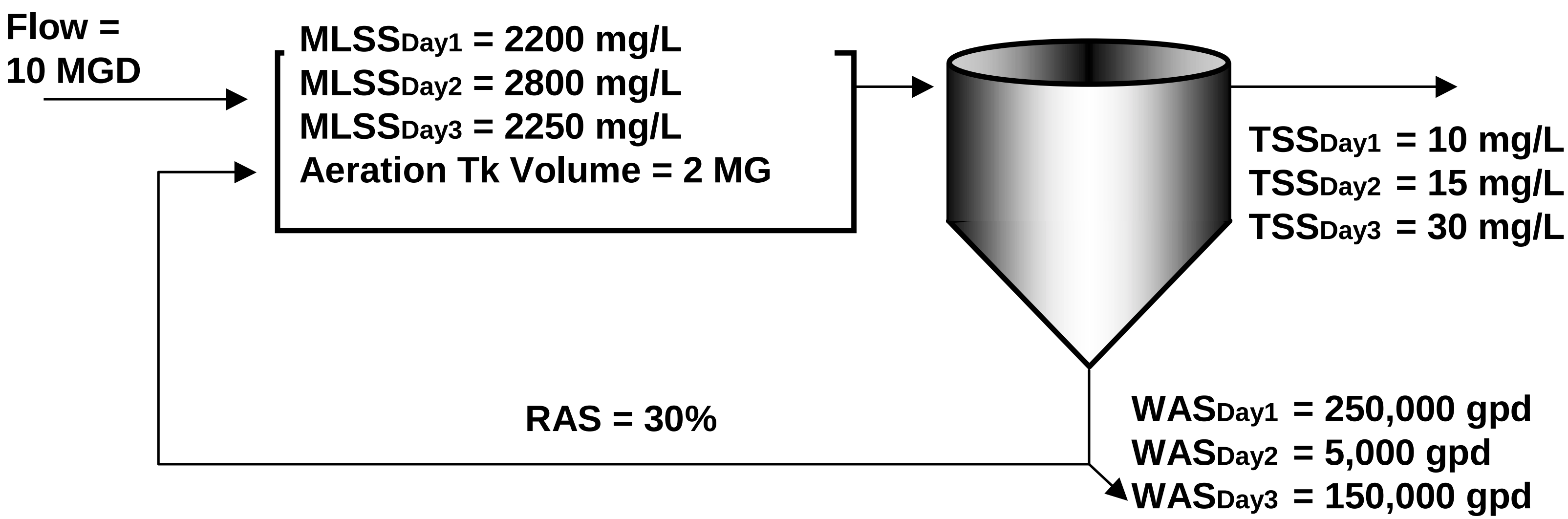
$$\text{Biomass Wasted (lbs per day)} = \left[\left(\text{WAS Flow (mgd)}\right)\left(\text{WAS MLSS (mg/l)}\right) + \left(\text{Secondary Effluent Flow (mgd)}\right)\left(\text{Secondary Effluent SS (mg/l)}\right)\right] \times 8.34$$

Calculating Aerobic Mean Cell Residence Time

Aerobic MCRT

$$= (\text{Total MCRT}) \; \frac{(\text{Aerobic Volume})}{(\text{Aeration Tank Volume})}$$

MCRT Calculation Problem



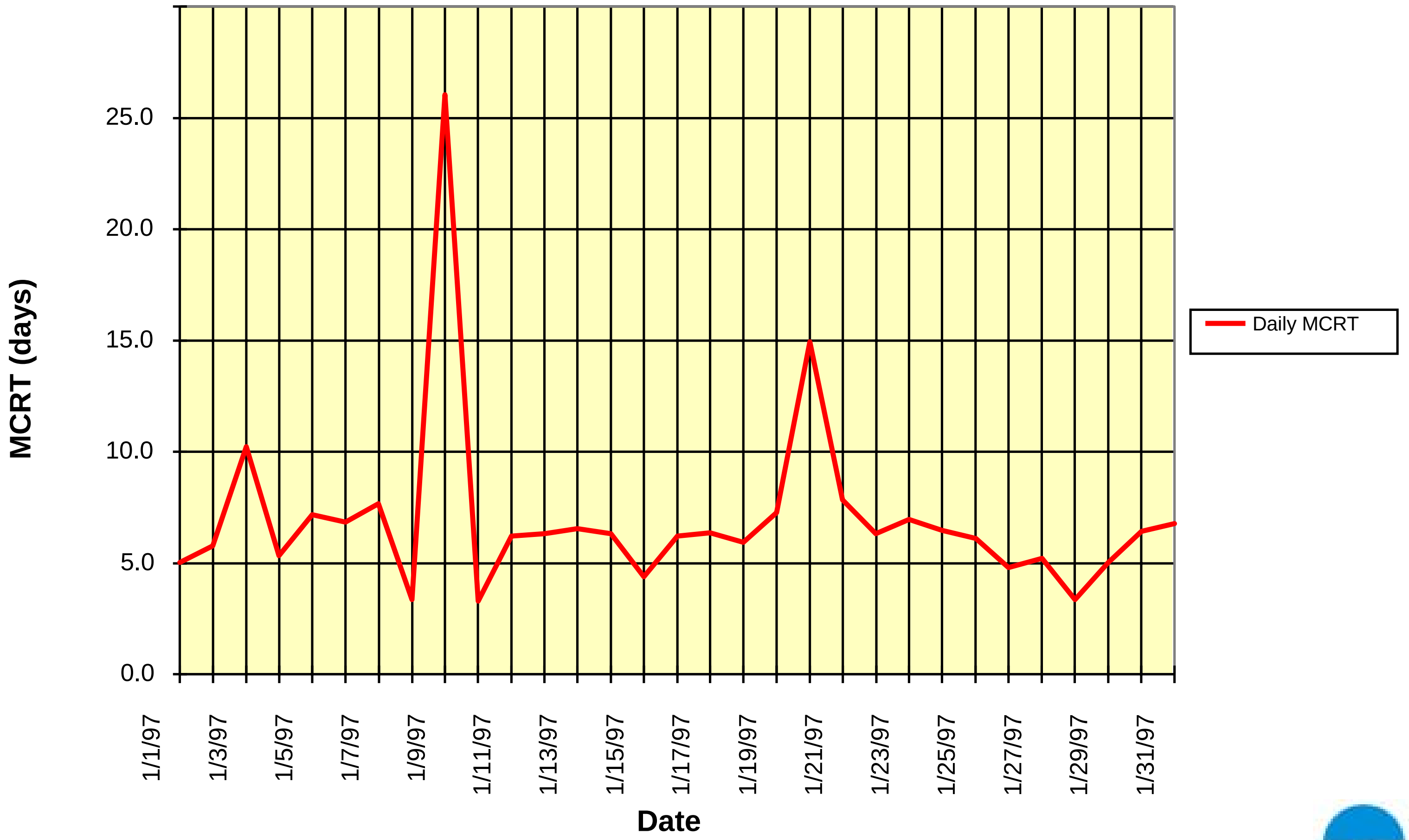
$TSS_{W,Day1}$ = 4,800 mg/L
$TSS_{W,Day2}$ = 10,000 mg/L
$TSS_{W,Day3}$ = 7,100 mg/L

What is the calculated MCRT each day ?

What are the problems with this calculation?

What can be done to correct it?

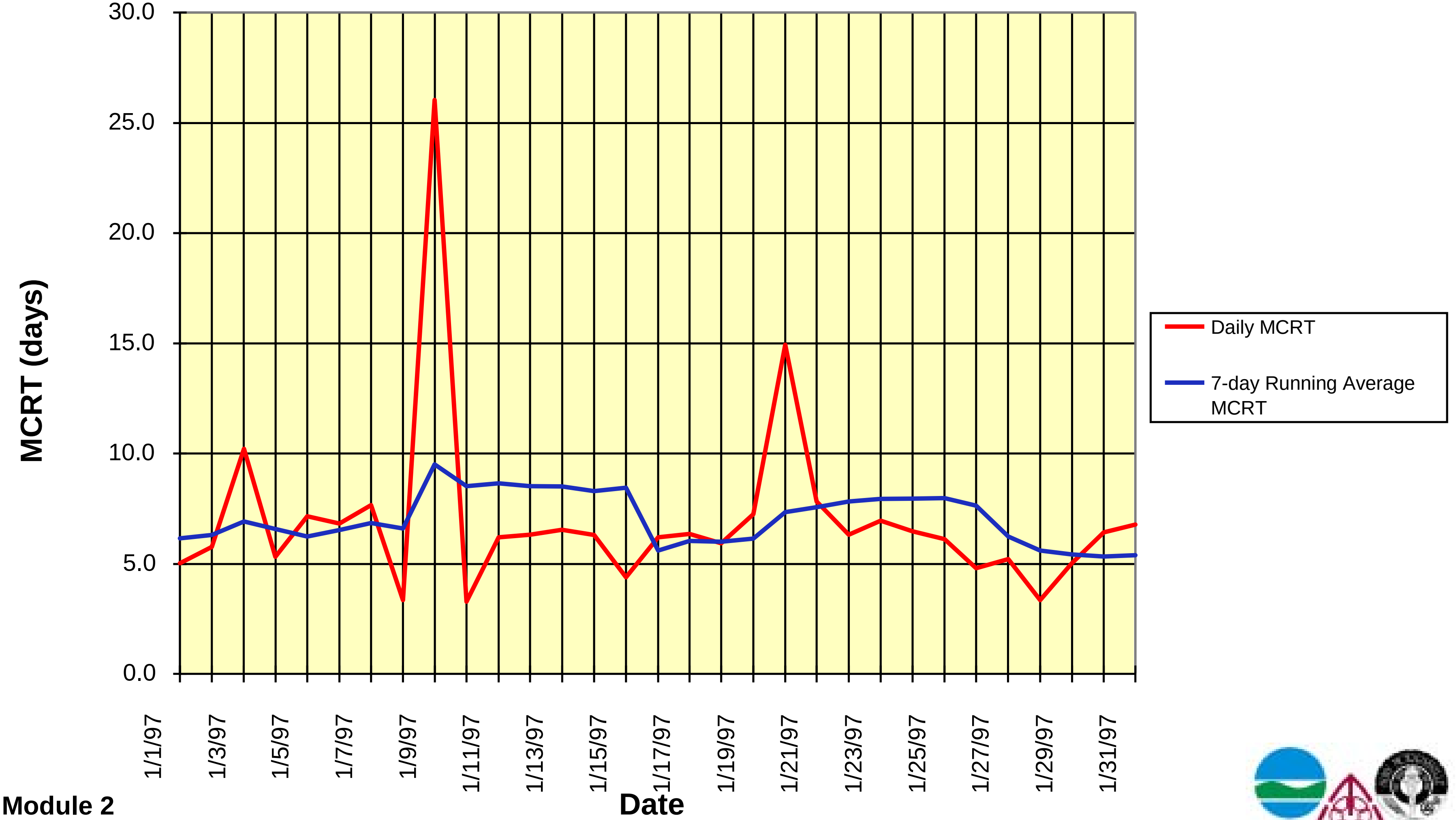
MCRT Plot


25.0
20.0
15.0
10.0
5.0
0.0
MCRT (days)
1/1/97
1/3/97
1/5/97
1/7/97
1/9/97
1/11/97
1/13/97
1/15/97
1/17/97
1/19/97
1/21/97
1/23/97
1/25/97
1/27/97
1/29/97
1/31/97
Date
Daily MCRT

Running-Average MCRT Calculation

- **Don’t rely on a single day’s MCRT calculation**
- **Use a running average over a period approximately equal to the MCRT. For example, if MCRT is about 7 days, use a 7-day running average**

Daily and 7-day Running Average MCRTs



Performing a Nitrogen Balance In a Nitrifying Plant

Where Does Nitrogen End Up In A Nitrifying Plant ?

- **In the Sludge**
- **In the Effluent**
- **In the Atmosphere**

How Much Secondary Sludge Is Produced ?

$$\text{Sludge Yield (Y)} = \frac{\text{0.67 lbs VSS}}{\text{lb BOD}_5\text{ consumed}}$$

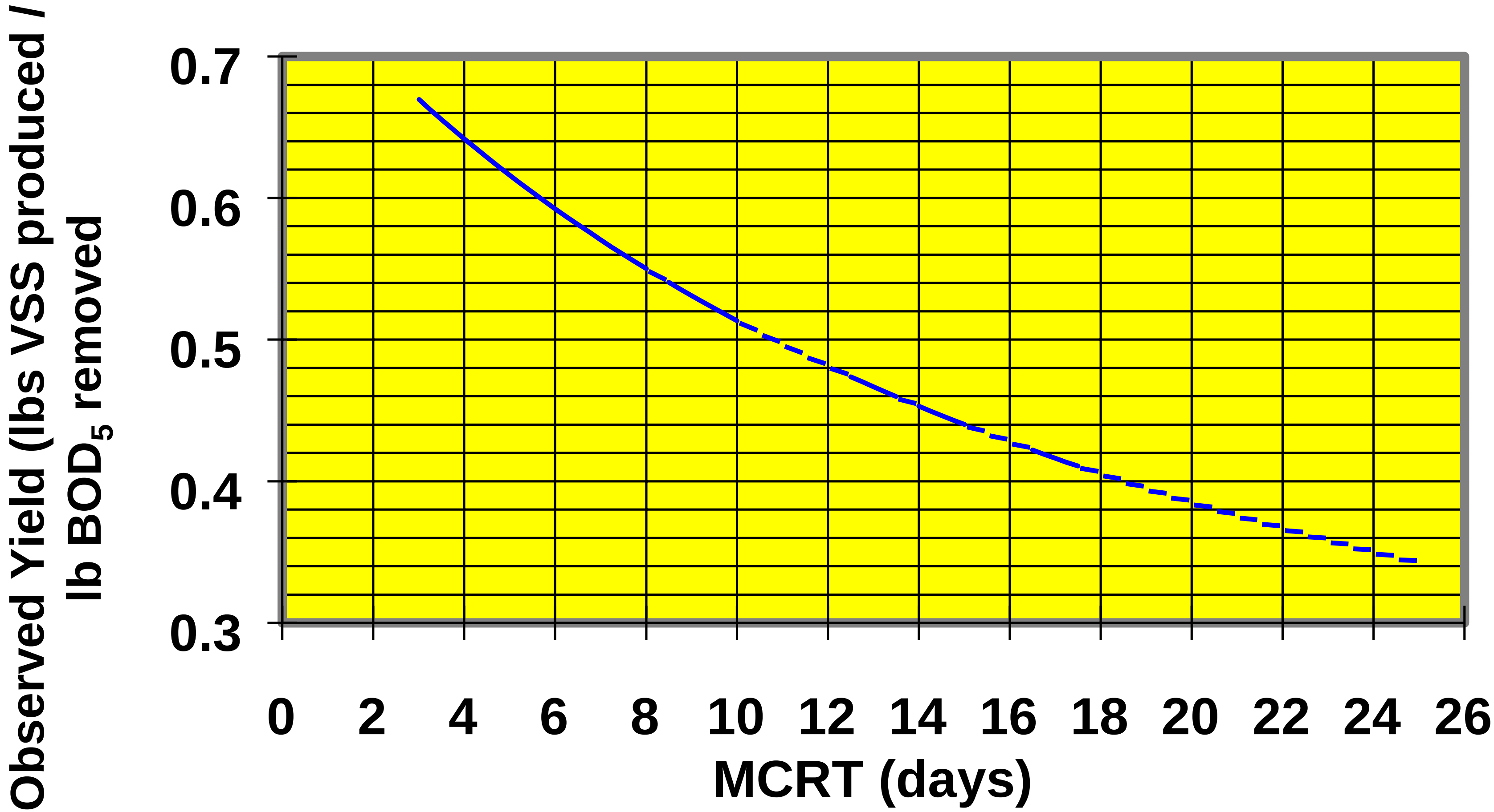
$$\text{Observed Yield } (Y_{obs}) = \frac{Y}{1 + (k_d)(\theta_c)}$$

Secondary Sludge Produced

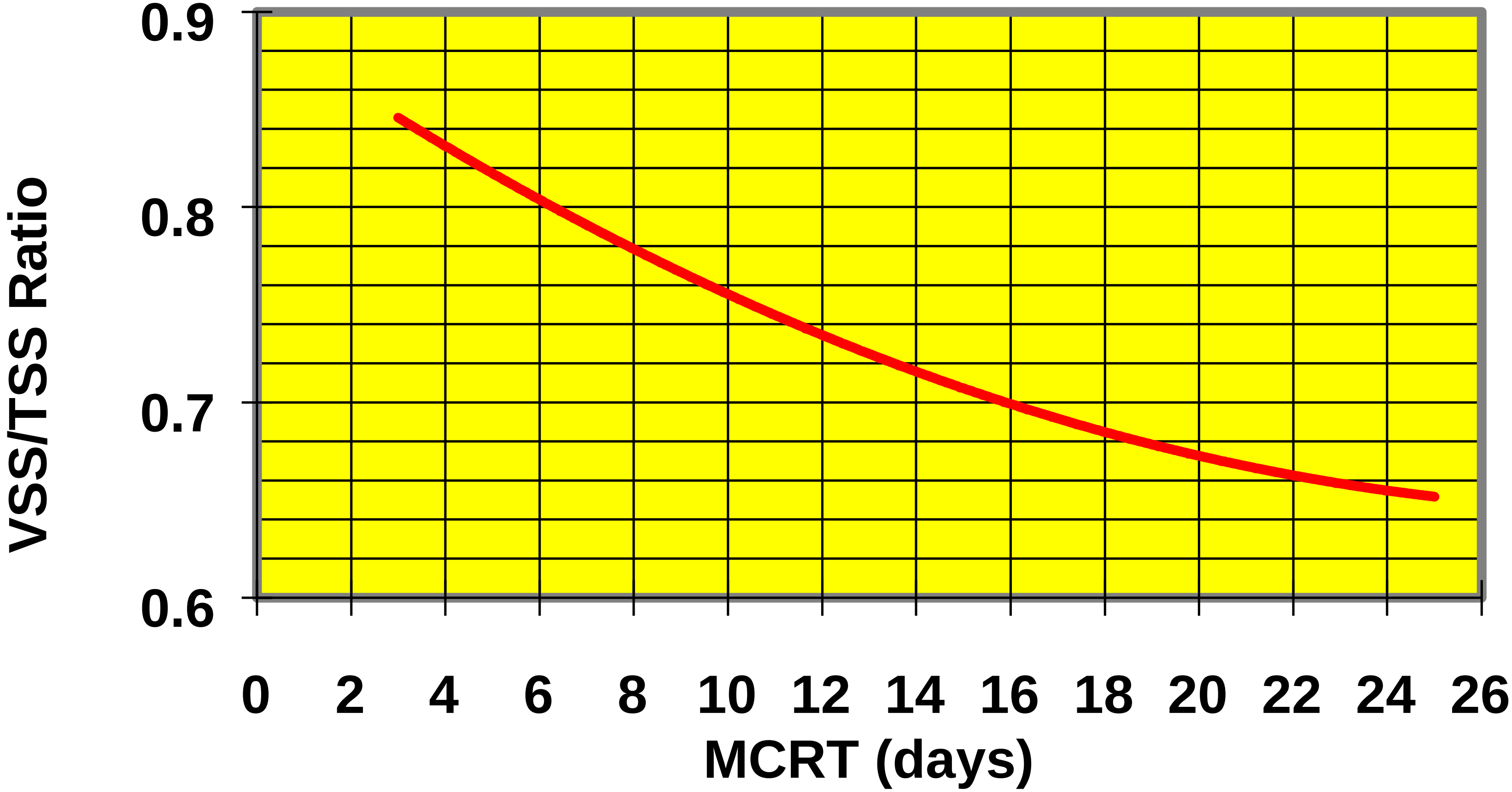
$$= Y_{obs}\,(S_0 - S)$$

Y_{obs} = Observed Sludge Yield
S_0 = Aeration Tank Influent BOD_5
S = Secondary Effluent $SBOD_5$

Typical VSS Production Versus MCRT



Typical Mixed Liquor VSS/TSS Ratio Versus MCRT



Calculation of Required MLSS at a Given MCRT

- Calculate BOD consumed in Activated Sludge Process
- Determine VSS produced using typical production value from preceding chart
- Multiply MCRT x daily sludge production to determine required VSS mass in aeration basin
- Divide VSS mass by basin volume to determine MLVSS concentration
- Divide MLVSS concentration by VSS/TSS ratio from preceding chart to determine MLSS concentration

How Much Nitrogen is in the Sludge ?

Primary Sludge	**-**	**About 2.5% of Total Solids is Nitrogen**
Secondary Sludge	**-**	**8 - 12% of Total Solids is Nitrogen on VSS basis**

Nitrification

What if I can't achieve the MCRT necessary to nitrify

?

Alternatives to Achieve Nitrification

- **Build more aeration tanks**
- **Add nitrifying filters**
- **Add fixed media to the existing aeration tanks (Integrated Fixed Film Activated Sludge, IFAS)**

Why Use An IFAS Process ?

- **Increase capacity without more tankage**
- **Achieve nitrification in tankage which could not otherwise nitrify**
- **Achieve nitrogen removal in tankage which could not otherwise nitrify and denitrify**

Benefits of IFAS Processes

- **Increase total solids inventory without increasing solids loading to clarifier**
- **Minimize effects of solids washout under high hydraulic loadings**
- **Avoid cost of construction of new tankage**
- **Decrease required recycle rates**

IFAS Processes - Media Comparison

	Rope-type	Sponge-type
Advantages	Simplicity - No moving parts Easily relocated Can vary media density along length of reactor	Up to 80% nitrification in suspended growth Higher rate of nitrification per unit volume
Disadvantages	Minimum aerobic MCRT for 50% nitrification in suspended growth	More pumps and appurtenances Potential for screen clogging Periodic supplement of media required

IFAS Criteria for 10°C

Feasible Aerobic Zone MCRT (days)	Feasible IFAS Alternatives
7.5+	•Nitrify in activated sludge system •*All nitrification in mixed liquor*
4.5 to 7.5	•Woven cord (rope) media •Sponge media •Plastic cylinders or spheres •*At least 50% of nitrification in mixed liquor*
3.0 to 4.5	•Sponge media in entire tank •Plastic cylinders in entire tank •*Only 20% of nitrification in mixed liquor*
Below 3	•Nitrification filters following activated sludge

IFAS Nitrification Rates

- **Max 0.45 lb/day/1000 cu. ft. at 10°C, 5 mg/L DO, 5 mg/L NH_4^+-N, $SBOD_5$<10 mg/L**
- **Rate decreases at lower DO, lower NH_4^+-N, and higher $SBOD_5$ levels**
- **Actual rates in nitrifying IFAS systems will be 30 to 80 percent of maximum rates**

Operating Strategies for Denitrification

Operating for Denitrification

Now that my plant is nitrifying, what do I need to do to make it denitrify

?

Operating for Denitrification

Now that my plant is nitrifying, what do I need to do to make it denitrify

?

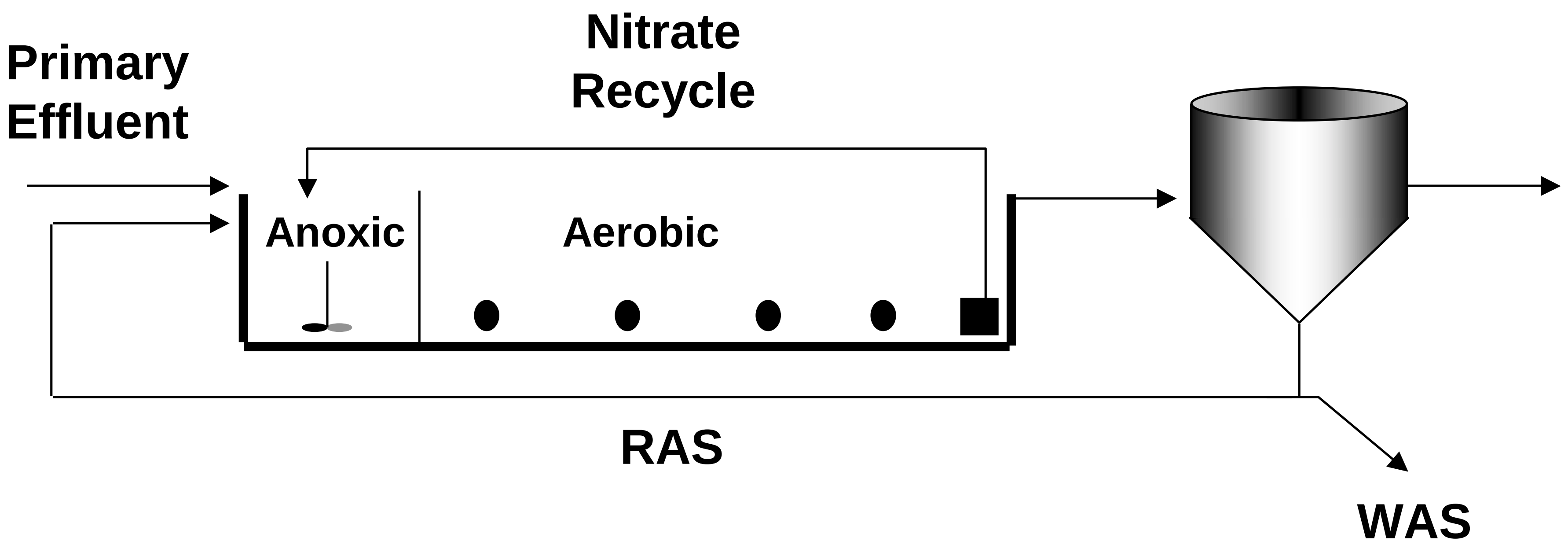
Establish anoxic conditions somewhere in the activated sludge process

Pre-denitrification

Pre-denitrification uses an anoxic zone at the beginning of the activated sludge tanks.

An example is the Modified Ludzack-Ettinger (MLE) process.

Modified Ludzack-Ettinger (MLE) Process



Post-denitrification

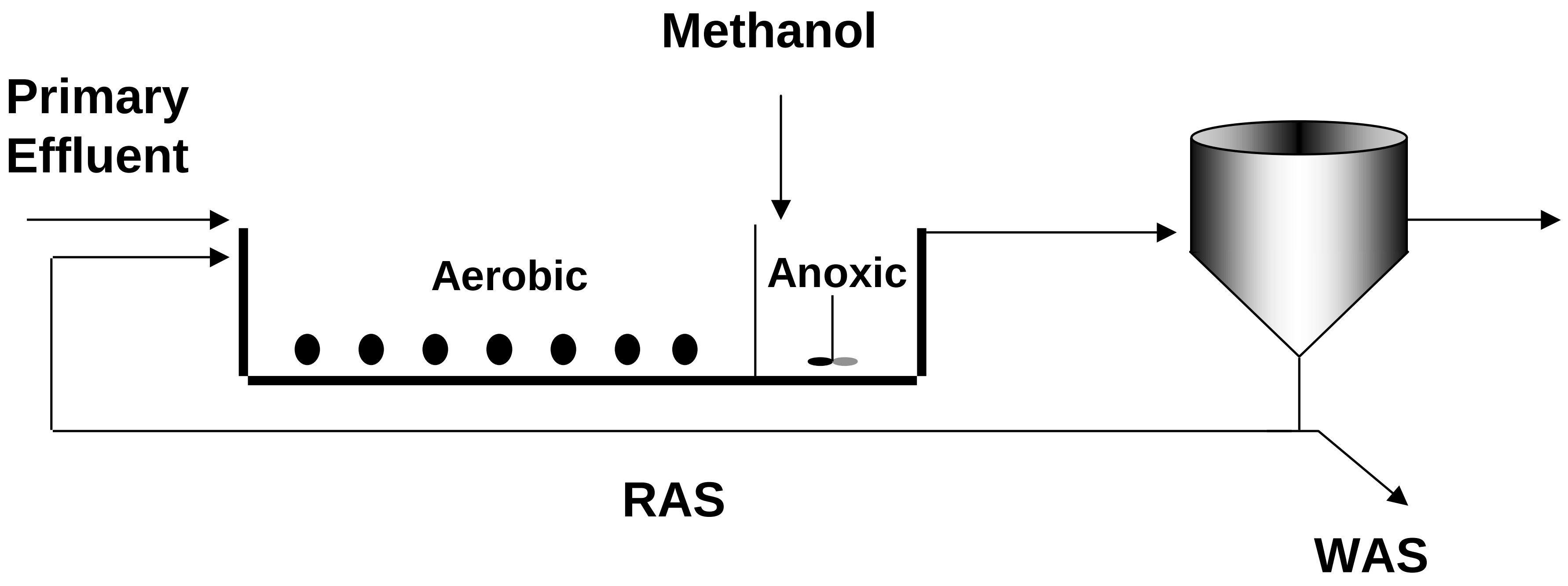
Post-denitrification uses an anoxic zone at the end of the activated sludge tanks.

Denitrification is slower in a post-denitrification zone than in a pre-denitrification zone.

Why ?

What could be done to increase the denitrification rate in a post-denitrification zone ?

Post-denitrification

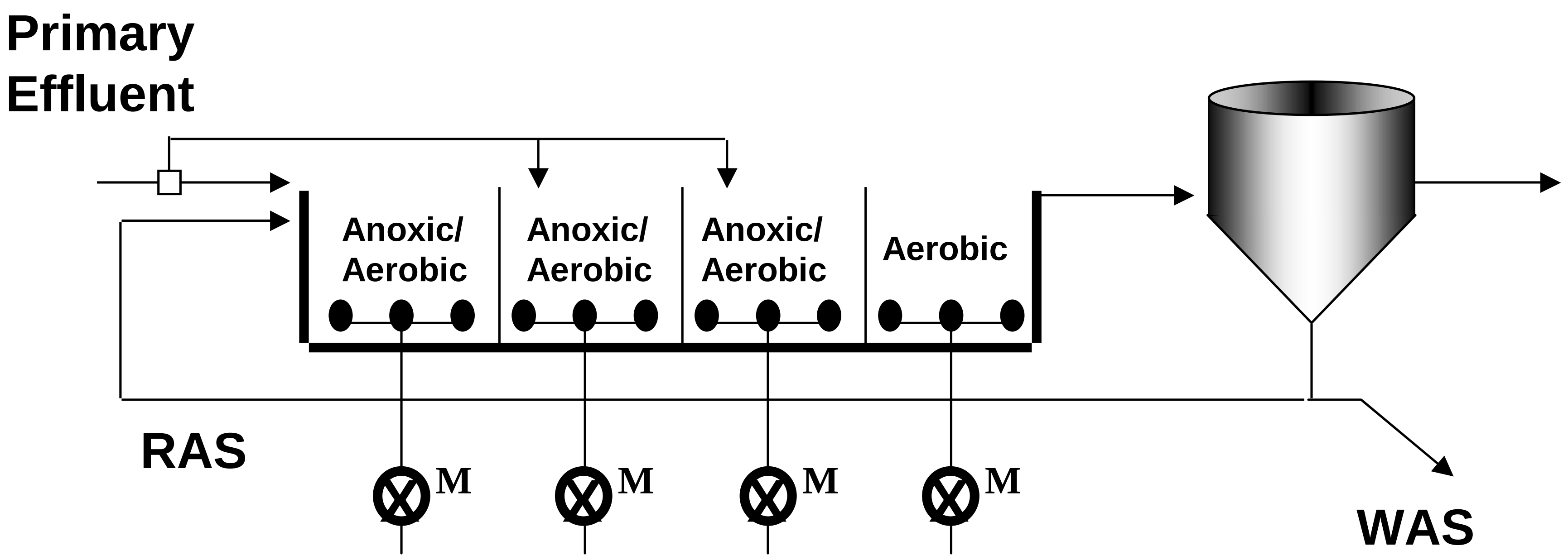


Step Feed Denitrification With Cyclical Aeration

Step-Feed Denitrification uses alternating periods of aerobic and anoxic conditions. Primary effluent is fed at multiple points along the tank to provide a carbon source for denitrification.

What advantages would this arrangement have over pre- or post-denitrification ?

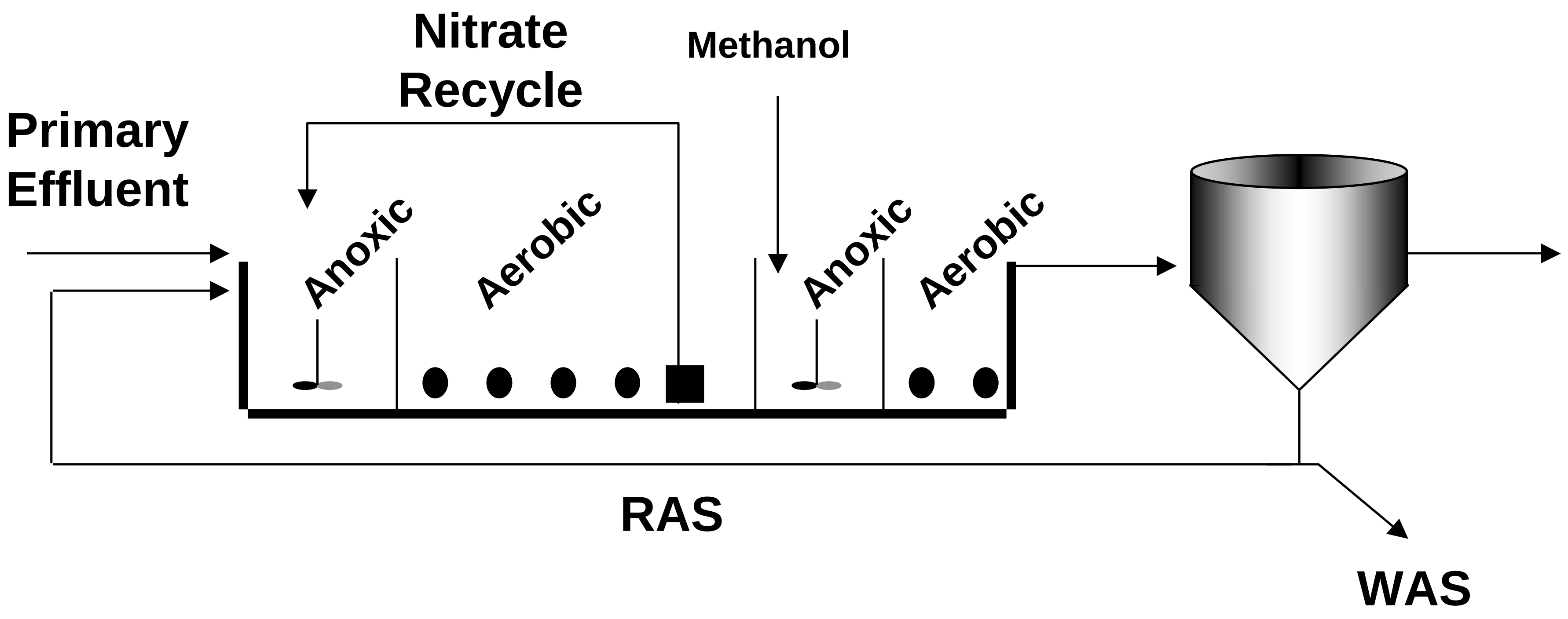
Step Feed Denitrification With Cyclical Aeration



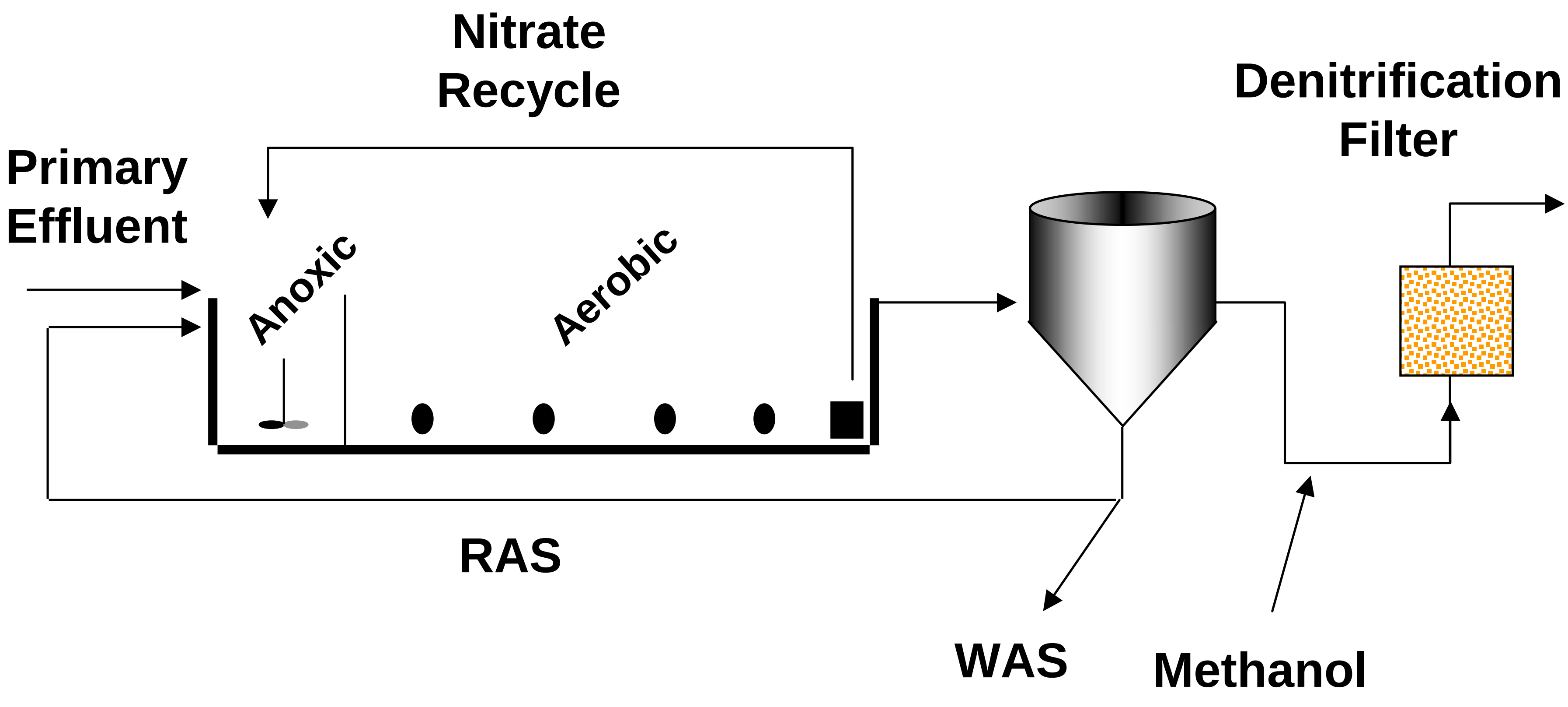
Other Denitrification Configurations

- **Enhanced MLE**
- **MLE With Denitrification Filter**
- **Step Denitrification**
- **A^2/O**
- **Bardenpho**
- **Sequencing Batch Reactor**

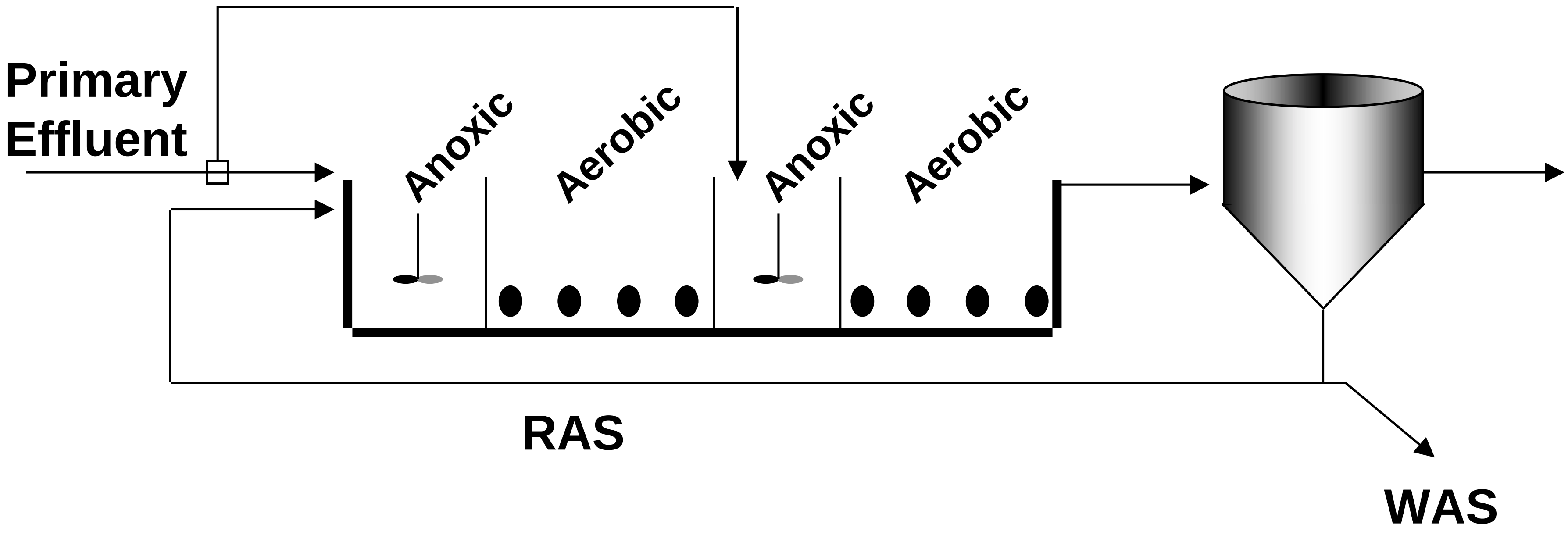
Enhanced MLE Configuration



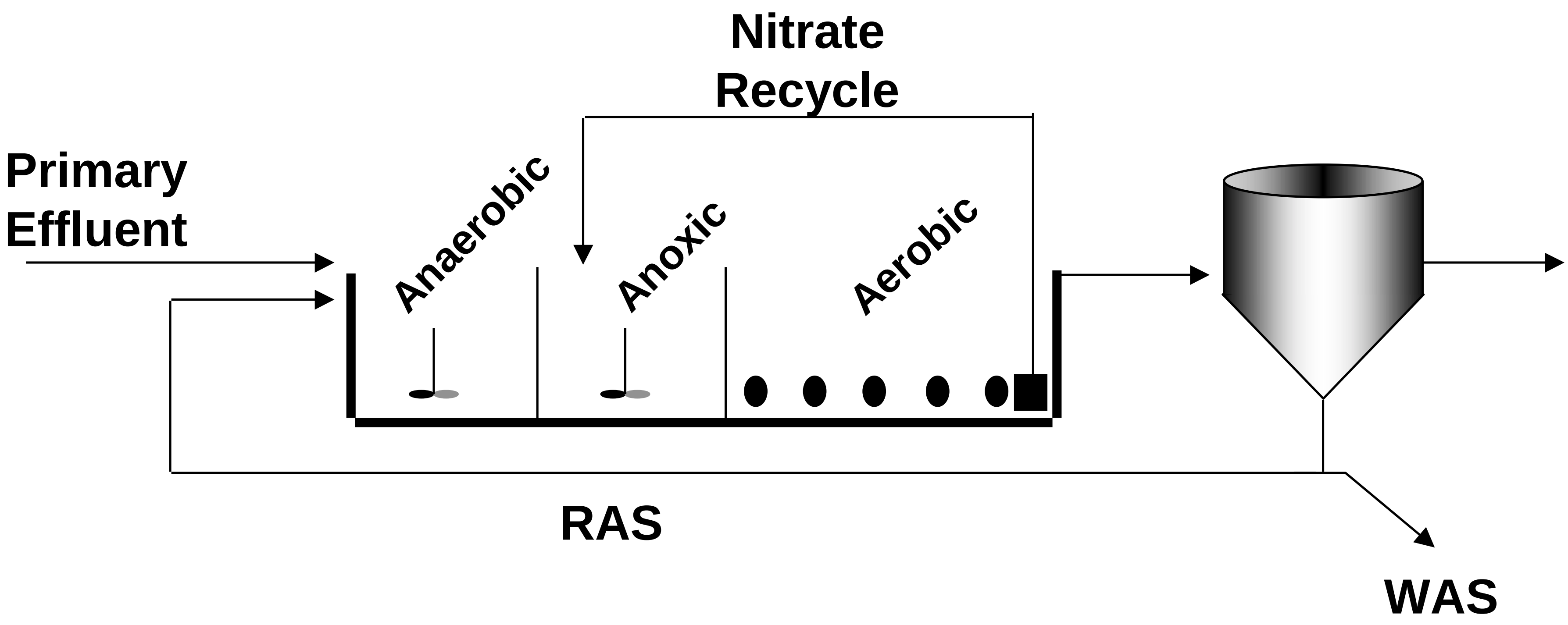
MLE With Denitrification Filter



Step Denitrification

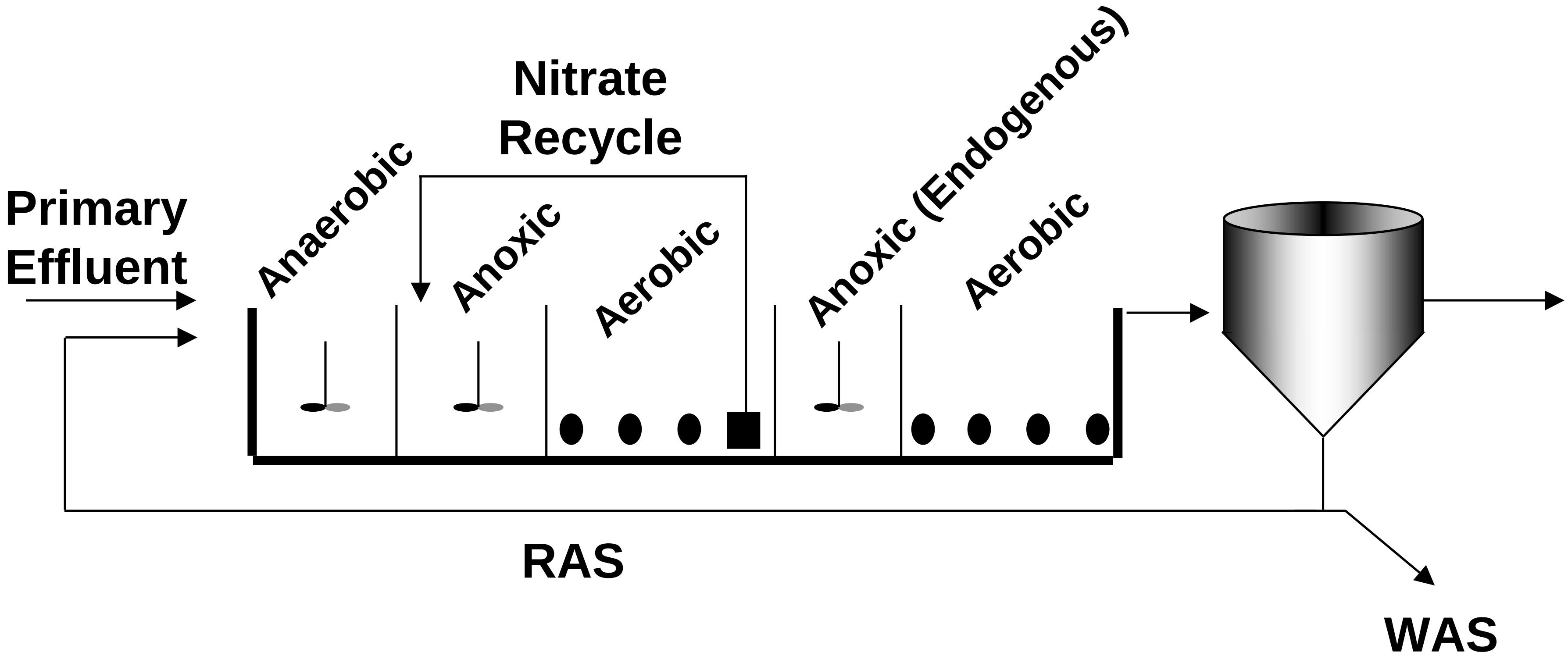


A^2/O Process

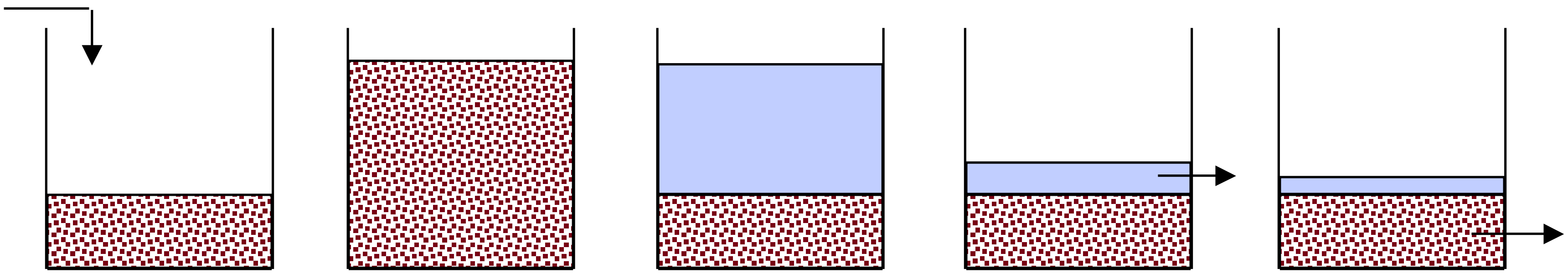


Nitrate
Recycle
Primary
Effluent
Anaerobic
Anoxic
Aerobic
RAS
WAS

5-Stage Bardenpho Process



Sequencing Batch Reactor



Fill	React	Settle	Draw	Idle
Add Substrate	Reaction Time	Clarify	Decant Effluent	Waste Sludge
Air: On/Off	Air: On/Off	Air: Off	Air: Off	Air: Off

Creating an Anoxic Zone

- **What conditions are needed in the anoxic zone ?**
- **What nitrate recycle rate is needed ?**
- **How much anoxic volume is needed ?**

Conditions in the Anoxic Zone

- **DO less than 0.3 mg/l**
  - **No aeration**
  - **Low aeration**
  - **Cyclical Aeration**
- **Carbon source**
  - **Primary Effluent**
  - **Endogenous**
  - **Methanol**
- **Mixing**
  - **Pulsed or cycled air**
  - **Submersible mixers**
  - **Vertical mixers**

Nitrate Recycle Rate

- **Determine desired effluent nitrate**
- **Determine amount of nitrate to be denitrified**
- **Determine total recycle rate including RAS flow**

Calculation of Required Recycle Rate

Required Recycle Rate

$$RAS + NR = Q[N/N_e - 1]$$

RAS + NR = Total recycle rate

RAS = Return activated sludge flow rate

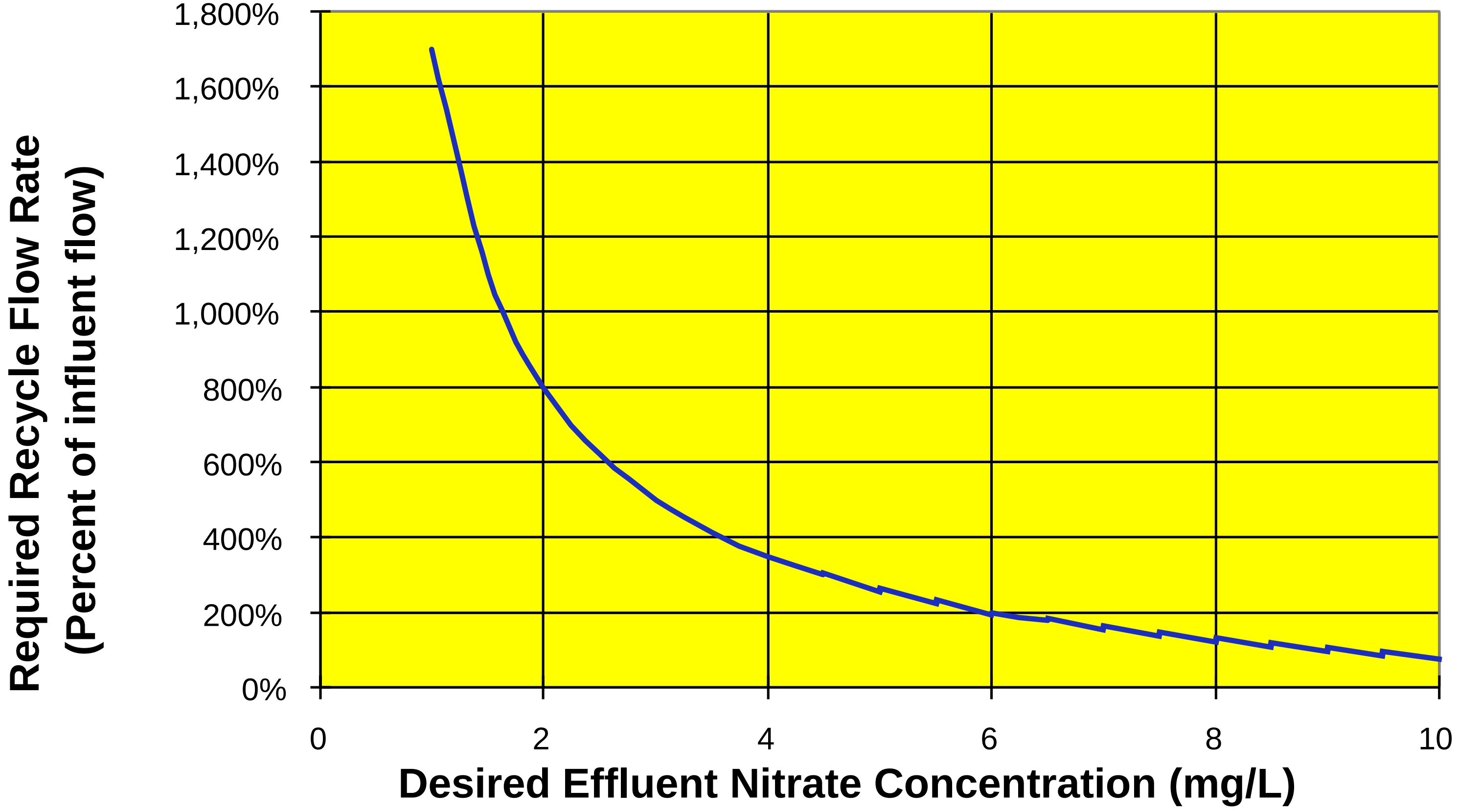
NR = Nitrate recycle flow rate

N = Concentration of nitrate to be denitrified

N_e = Concentration of nitrate in effluent

Q = Plant flow rate

Impact of Effluent Nitrate Requirement on Nitrate Recycle Flow Rate



Determination of Required Anoxic Volume

- **Determine mass of nitrates recycled**
- **Estimate denitrification rate**
- **Calculate required anoxic volume**

Mass of Nitrates Recycled

Nitrates Recycled to Anoxic Zone

$$= N_e(NR + RAS)$$

Estimated Denitrification Rate at Various Temperatures

Estimated Specific Denitrification Rate

$$SDNR = 6.40 \times 10^{10} e^{-15880/RT}$$

$$T(°K) = T(°C) + 273$$

$$R = 1.987 \text{ kcal/(mole °K)}$$

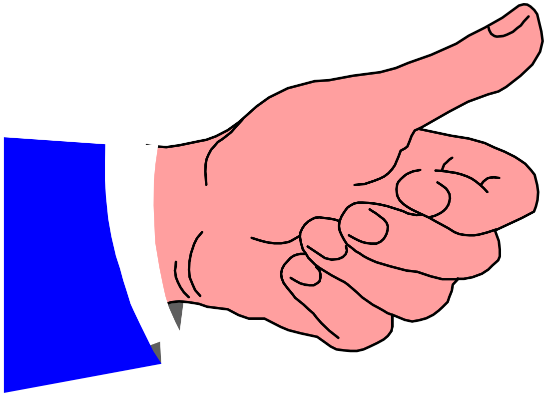
SDNR as lbs NO_3^--N/day/lb MLVSS for single sludge nitrification-denitrification systems with primary effluent as carbon source

Estimated Specific Denitrification Rates

Temp ° C	Estimated SDNR	Temp ° C	Estimated SDNR
10	0.035	18	0.076
12	0.042	20	0.091
14	0.052	22	0.110
16	0.063	24	0.132

SDNR as lbs NO_3^--N/day/lb MLVSS for single sludge nitrification-denitrification systems with primary effluent as carbon source , using equation on previous slide.

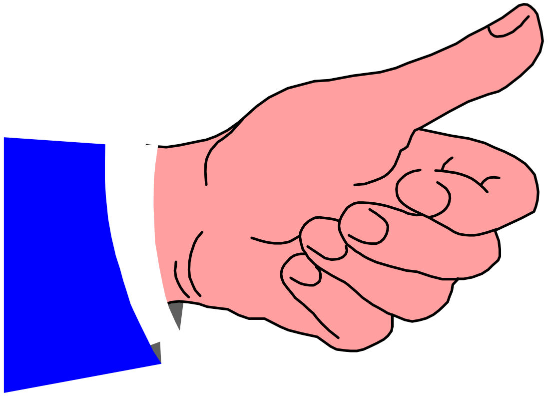
Denitrification Volume Required



<u>Rule of Thumb</u>:

- **Required anoxic zone volume will be about one third of the aerobic volume**

Anoxic Zone Mixing



<u>Rule of Thumb</u>:

- **Required mixing power will be about 1 HP per 15,000 gallons of anoxic zone volume**