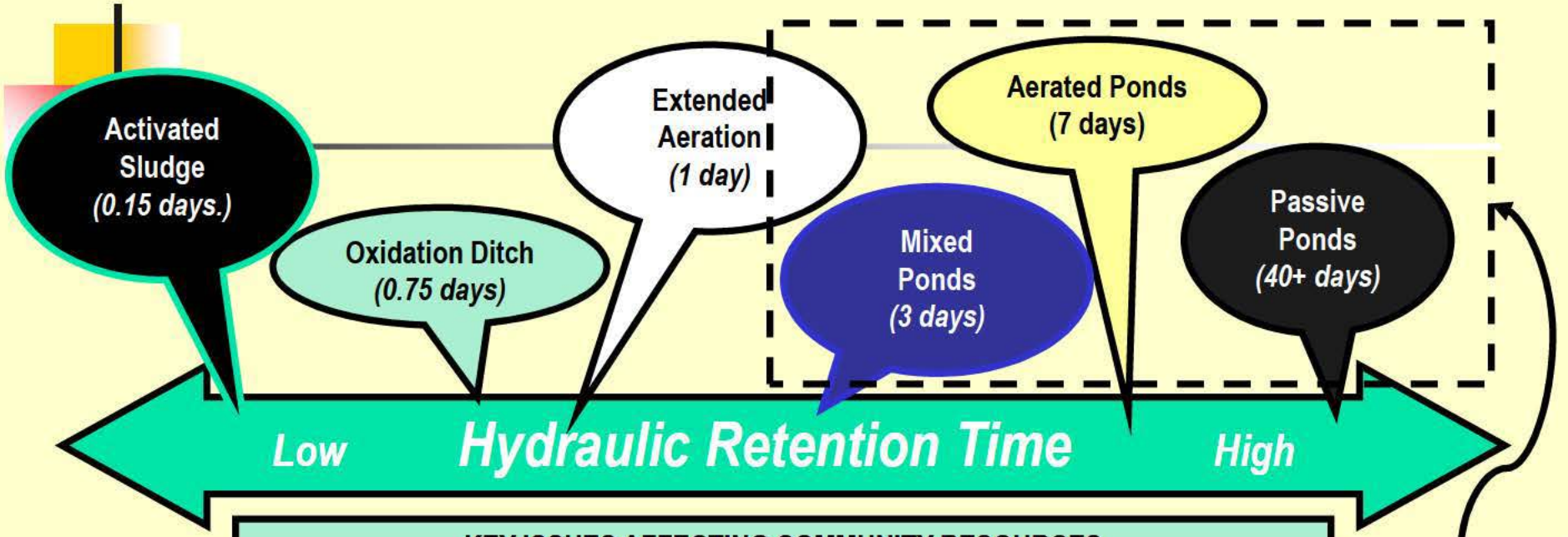
Nitrogen Removal in Wastewater Ponds

Nitrogen Removal in Ponds is not well understood.

"Various investigators have suggested: algal uptake, sludge deposition, adsorption by bottom soils, nitrification/denitrification, and loss of ammonia as a gas to the atmosphere (volatilization). …a combination of factors may be responsible, with the dominant mechanism under favorable conditions being losses to the atmosphere." (WEF 2010, pg. 278)

A Wide Range of WW Treatment Solutions



KEY ISSUES AFFECTING COMMUNITY RESOURCES		
Large	Sludge Production	Small
Consistent	Effluent Quality	Variable
Large	Power Required	Small
Small	Land Area Required	Large
Large	O & M Effort Needed	Small
Good	Nitrogen Removal ★	Poor

What do you do with the solids? Huge Cost!

Range of Technology Considered Today

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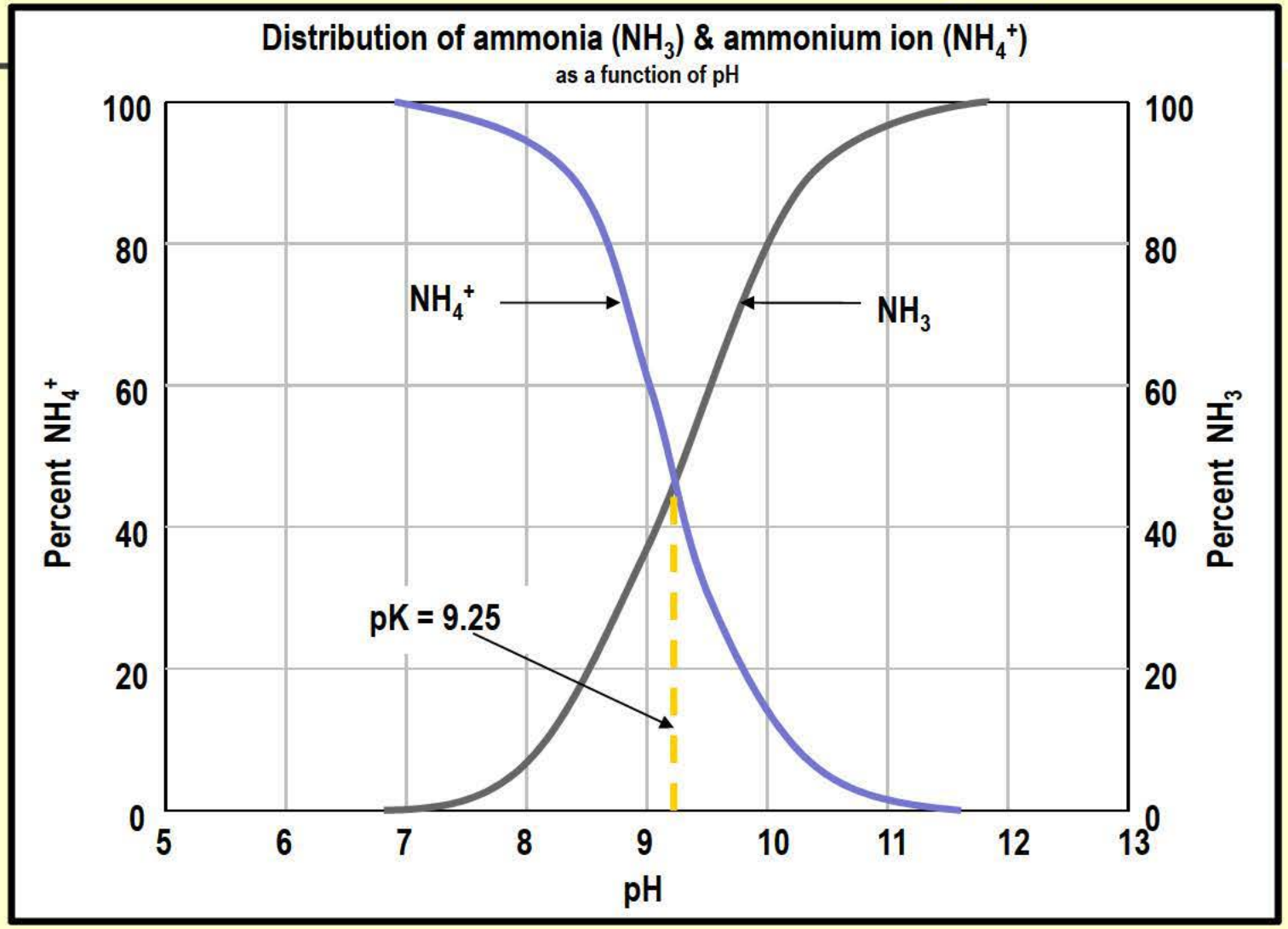
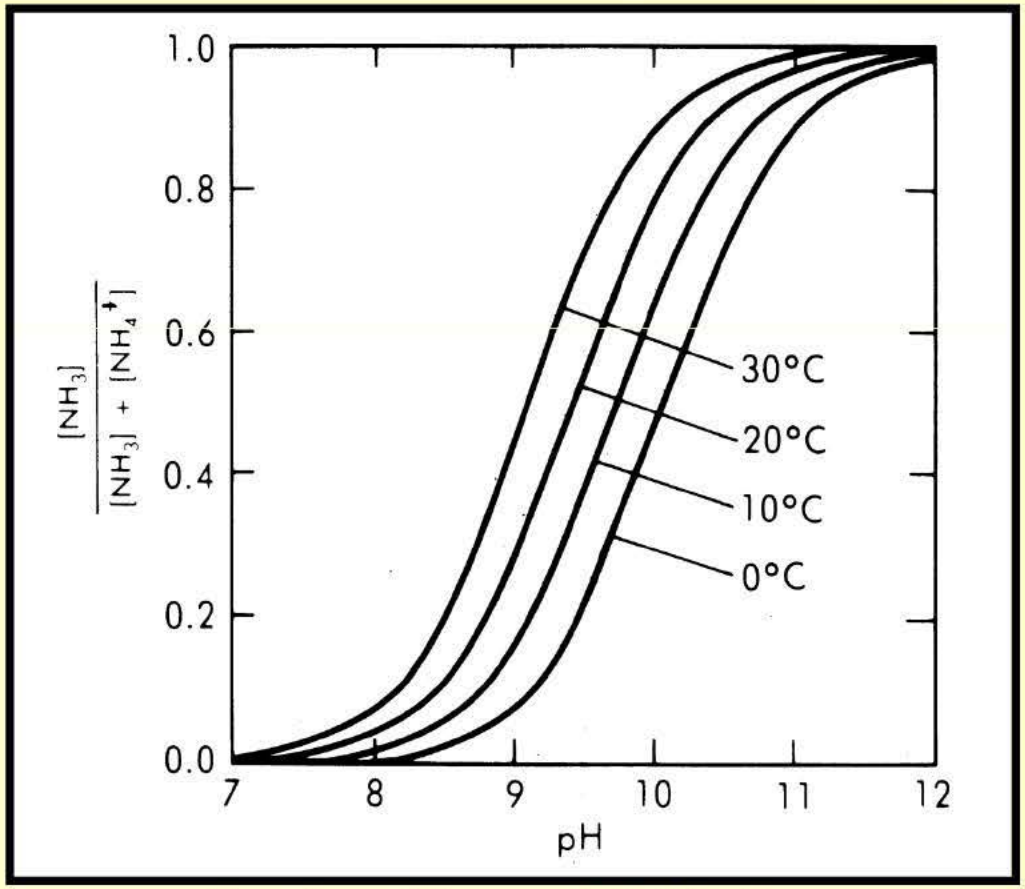
Volatilization
Ammonia Equilibrium
according to pH in Water



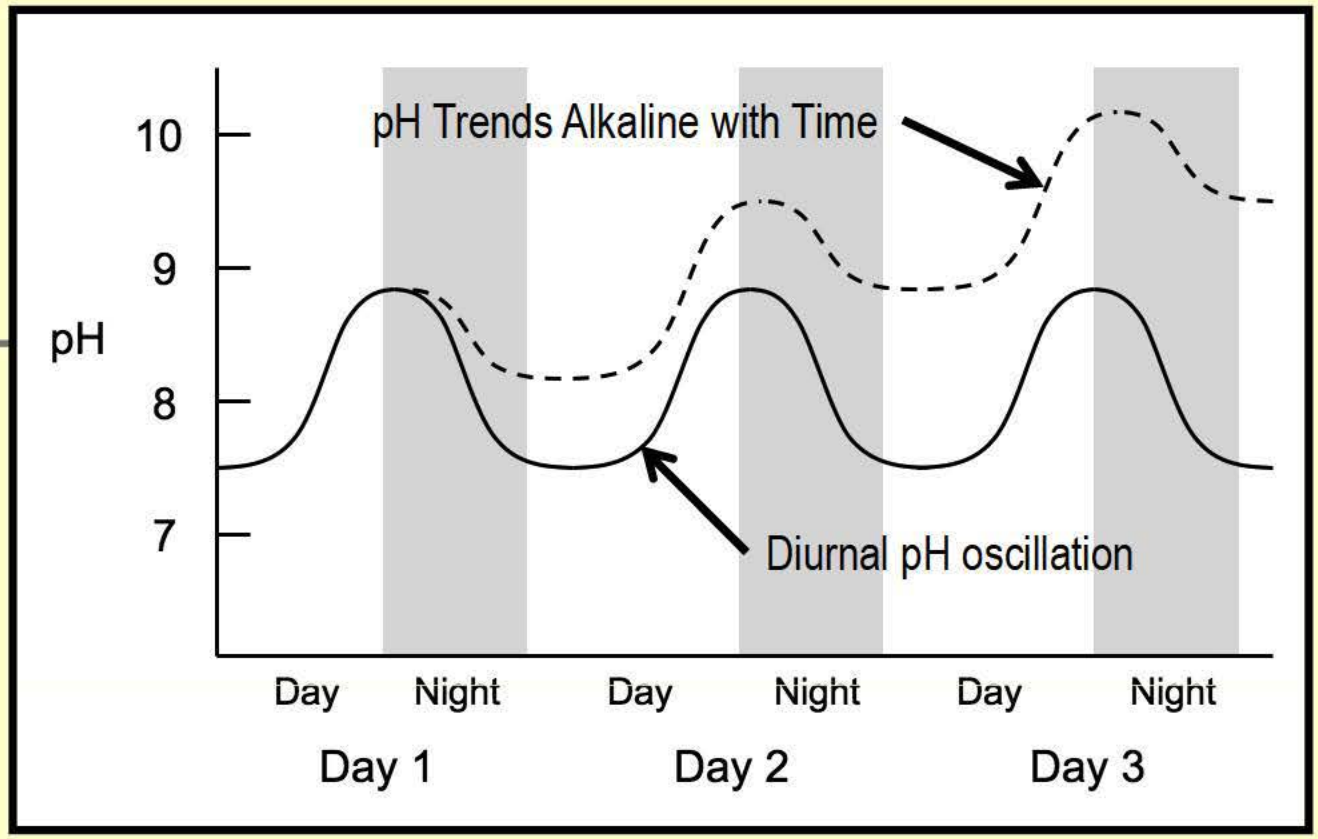
Volatilization
Ammonia Fraction Varies
Depending on pH and Temperature

- Ammonia (NH_3) is gaseous and will volatize
- Ammonium (NH_4^+) is ionically held in solution
- High rate ammonia air strippers are usually designed for use on water with a pH > 10.
- In a pond volatilization is slow. 80% nitrogen removal requires over 200 days hydraulic retention time (HRT) *[Reed 2003, Table A.49]*



Fraction of Ammonia in NH_3 Form
as a function of temperature and pH (Tchobanaglous 1987, Figure 12.40)

Volatilization
pH Trends
Alkaline
in ponds w/Time



- When is comes to the volatilization of ammonia, algae are our friends.
- Carbon dioxide consumed by actively photosynthesizing algae exceed that produced by organic degradation, resulting in an increase in pH.
- Alkaline pH shifts ammonia/ammonium equilibrium towards ammonia.
- The volatilization of ammonia to the atmosphere depends on the aeration, mixing and temperature, in addition to pH.

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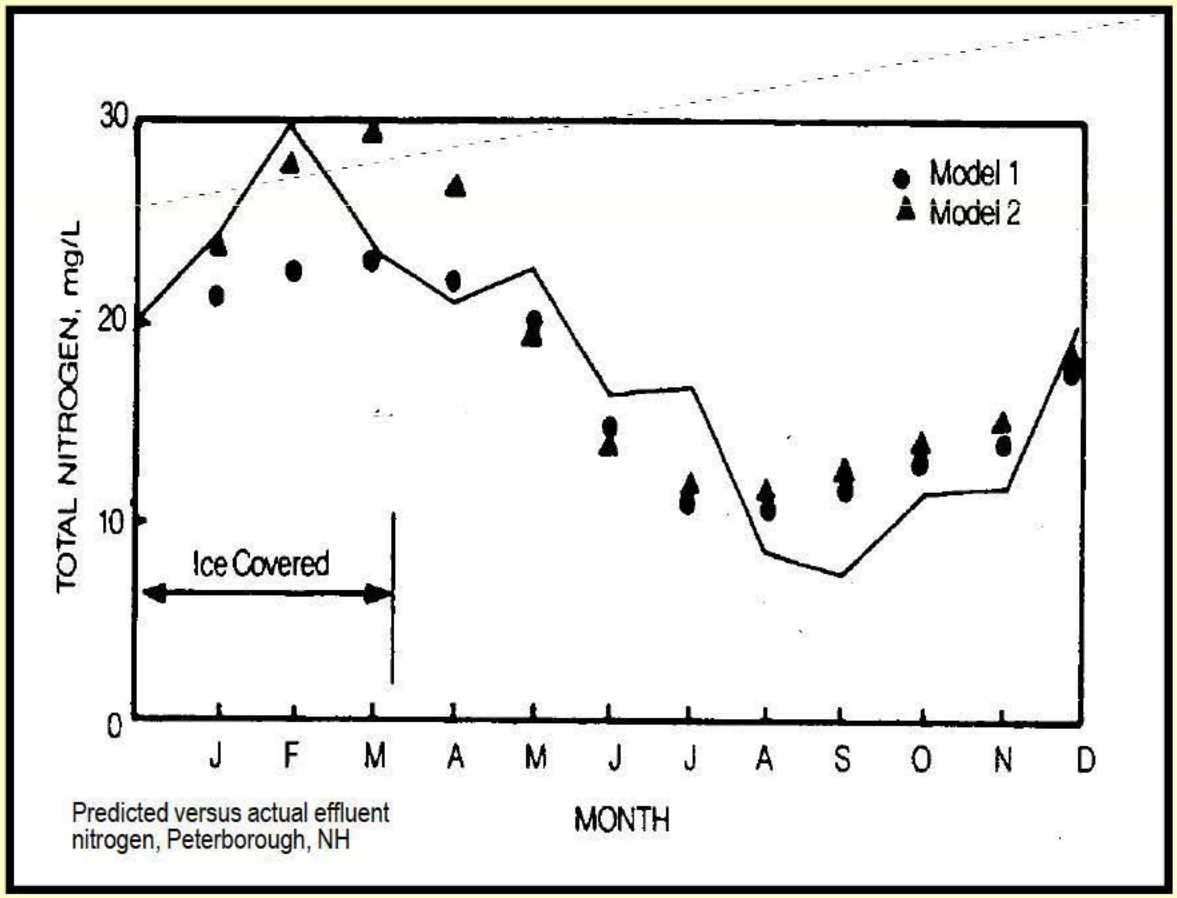
Volatilization
Proposed Empirical Relationships[1]
to Predict Ammonia Concentrations

- Model 1: $N_e := N_o \cdot \exp(-k) \cdot T^{[t + 60.6 \cdot (pH - 6.6)]}$

[1]From EPA Study (Reed 1985)

- Model 2: $N_e := N_o \cdot \left[\frac{1}{1 + t \cdot (0.000576T - 0.00028) \cdot \exp(1.080 - 0.042T) \cdot (pH - 6.6)} \right]$



Predicted versus actual effluent nitrogen, Peterborough, NH

- N_e = effluent total nitrogen (mg/L)
- N_o = influent total nitrogen (mg/L)
- k_t = temperature-dependent rate constant (day^{-1}, pH^{-1}) = $k_{20}(\theta)^{T-20}$
- $\theta = 1.039$
- T = water temperature
- $k_{20} = 0.0064$
- t = time (days)

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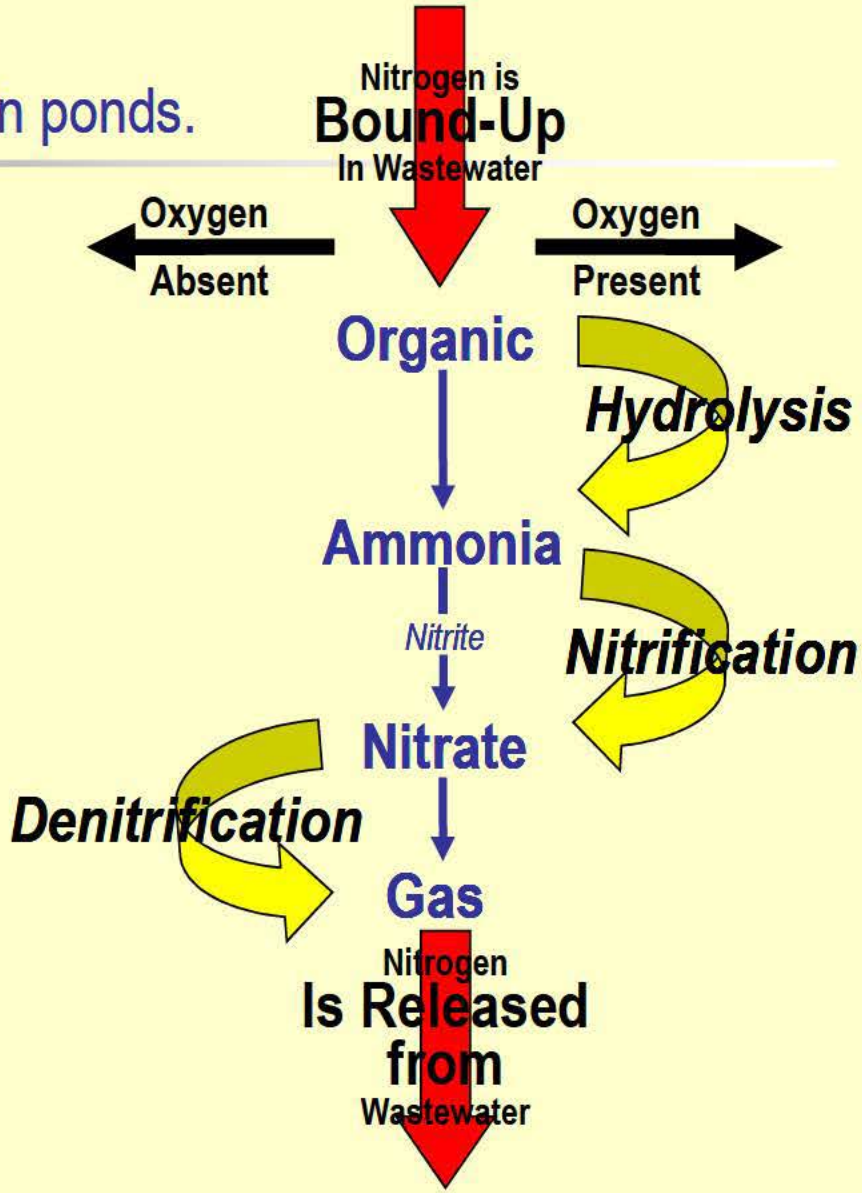
Biological Nitrogen Removal
3 Steps
Only one step readily occurs in ponds.

- Normally only the first step in this process "hydrolysis" occurs in ponds.
- A Pond's primary means of removing nitrogen is through volatilization of ammonia.
- Therefore, in most cases, lagoons are poor at removing nitrogen.
- However, lagoons can be a part of a good biological nitrogen removal system.



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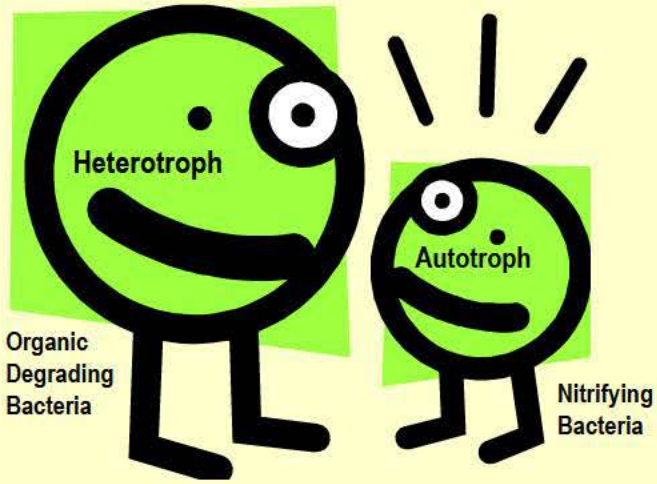
Biological Nitrification
Problems/Obstacles
Microbial Competition & Adverse Environments

- Nitrifiers are autotrophs, deriving their energy ammonia and nitrites, and their carbon from carbon dioxide.
  - They do not **compete** well with organic degrading bacteria (heterotrophs) for things like nutrients and oxygen.
  - They have relatively low energy, slow metabolisms and are more affected by **adverse conditions/environments** than organic degrading bacteria.
- Competition from heterotrophs is not unique to pond systems.
- But some of the adverse conditions/environments found in ponds are.
- Consequently, specific attention must be paid to the factors that influence the behavior of nitrifiers if nitrification is to be achieved in lagoons.



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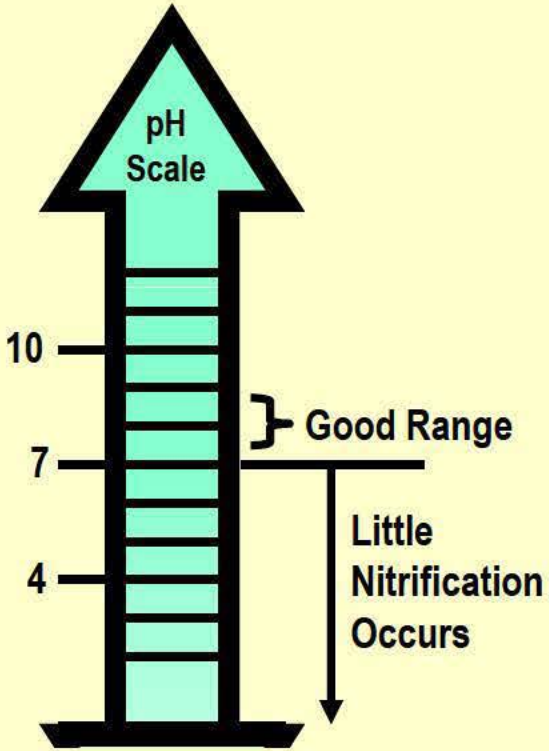
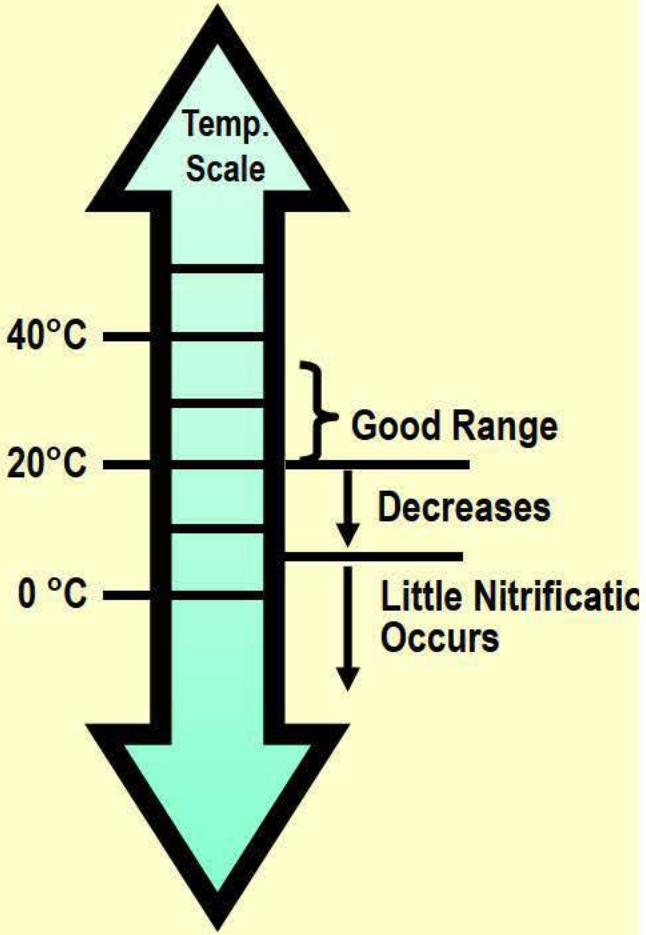
Biological Nitrification
Adverse Environments
Conditions in Pond that Limit Nitrification

- Food/Microorganism Contact – Ponds provide insufficient opportunities for food and microorganisms to come into contact.
  - Ponds have low MLSS (often between 250 and 500 mg/L).
  - Ponds have poorly mixed water columns.
- Dissolved Oxygen – Ponds have uneven aeration throughout their water columns, including areas with very low dissolved oxygen.
- pH and Alkalinity – Ponds, usually due to local environmental influences, can have acidic pH and low alkalinity.
- Temperature – Ponds are uncovered and exposed to the elements, subjecting them to cold temperatures. Ponds can ice over in winter.
- Limit Toxic Materials – As with any wastewater management system ponds can be subjected to toxic discharges. (Toxic discharges into wastewater systems is not discussed here. See other sources for a discussion e.g. Mectalf and Eddy.)

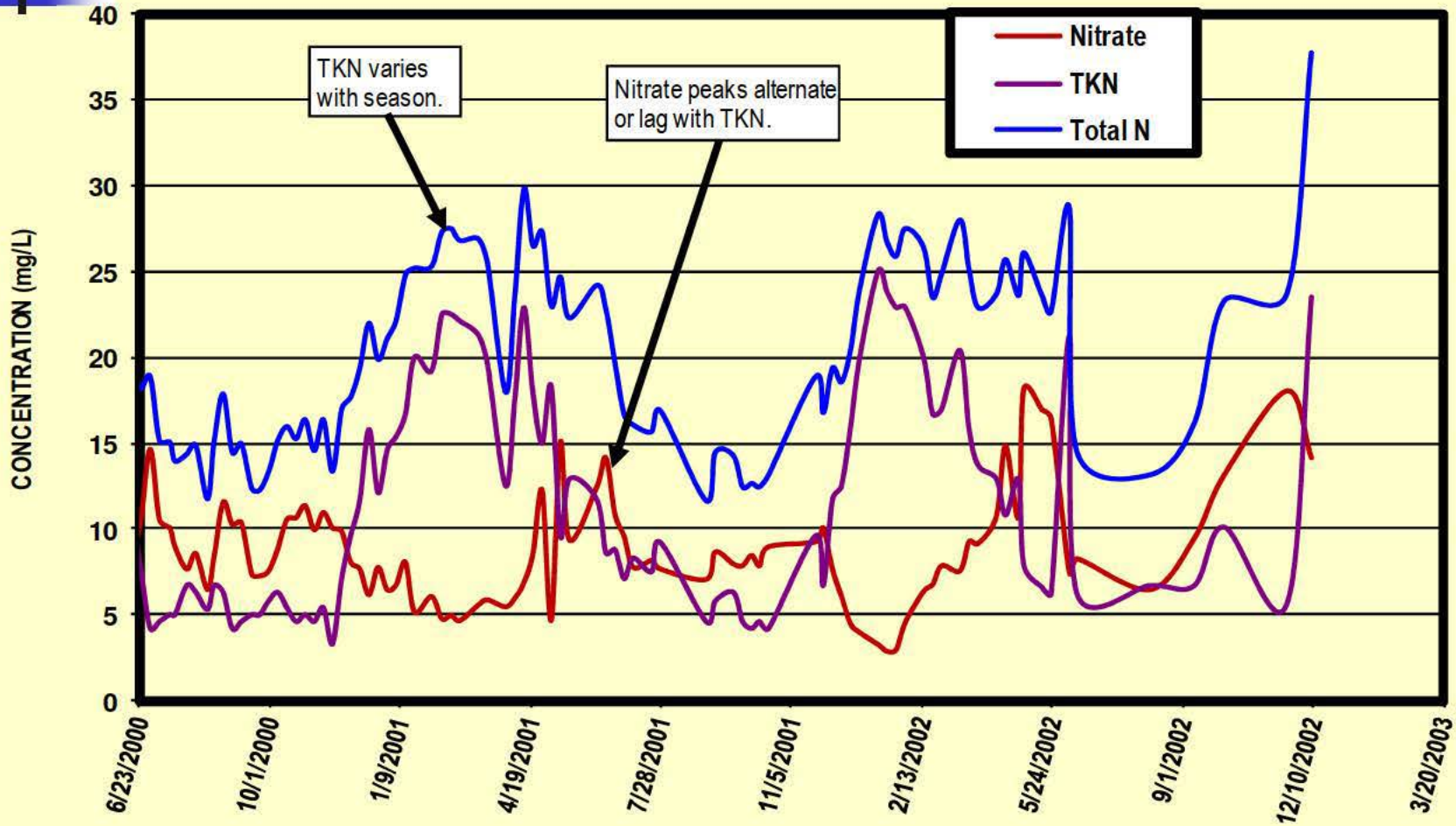
Biological Nitrification
pH, Alkalinity, & Temperature
Favorable Ranges

- pH & Alkalinity; Biological Nitrification
  - Is enhanced at higher pH's; 7.5 to 8.5 is ideal
  - Is drastically reduced when pH < 7.2
  - Produces acids and consumes about 7 lbs. of alkalinity for each 1 lb. of ammonia converted
  - Requires sufficient alkalinity to buffer the acids produced
  - Algae trend ponds alkaline
- Temperature
  - Optimal when between 20°C and 35°C
  - Little occurs below 7°C





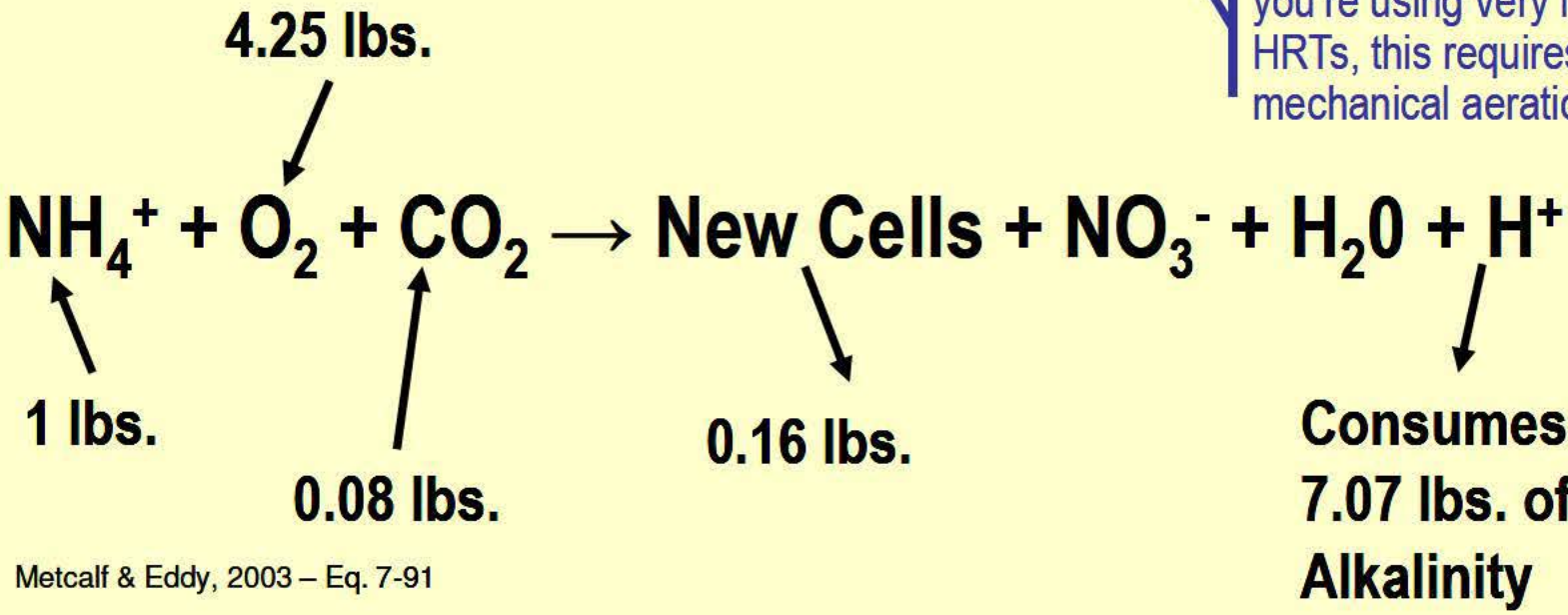
Biological Nitrification
Temperature Affects
Deming, NM - WWTP



Biological Nitrification
Dissolved Oxygen
Stoichiometric Requirements

- Whereas only 1 lb. of O_2 is required to remove the organics that cause 1 lb. of *CBOD (design for about 1.5 lb. O_2 per lb. of CBOD)*,
- Over 4 lbs. of O_2 are required to convert 1 lb. of ammonia to nitrate *(design for about 4.6 lbs. O_2 per lb. of TKN)*,
- The concentration of O_2 in water should be above 2 mg/L.
- About 7 lbs of alkalinity are consumed.

Normally, unless you're using very long HRTs, this requires mechanical aeration.



Metcalf & Eddy, 2003 – Eq. 7-91

Biological Nitrification
Aeration/Mixing Power
Floating Surface Aerators

To determine the amount of mechanical aeration required:

1. Determine the rate at which oxygen will be required to convert the incoming organics to biomass – *1.5 lbs. O_2 per lb. incoming $CBOD_5$*
2. Determine the rate at which oxygen will be required to convert the ammonia produced to nitrates (nitrification). – *Use 4.6 lbs. O_2 per lb. ammonia that will be generated*
3. Add the organic conversion and the nitrification oxygen requirements together to determine the total lbs. oxygen required per hour.
4. Divide the total oxygen required by the applied aeration rate of a selected aerator to determine the horsepower needed.
5. Select individual aerators that can be spaced on the pond for good mixing-aeration throughout and provide the total horsepower needed.

Applied Mixing *(Power required for complete solids suspension)*	Applied Aeration*	Aerator Type
135 hp/Mgal	2.5 to 3.5lbs O_2/hr Use 3.0 for preliminary sizing.	Slow Speed
30 hp/Mgal	1.5 to 2.5 lbs O_2/hr Use 2.0 for preliminary sizing.	High Speed
10 hp/Mgal	1.0 to 2.0 lbs O_2/hr Use 1.5 for preliminary sizing.	Aspirating

*Varies – Check with the manufacturer

Aeration & Mixing

Floating Surface Aerators

3 Main Types

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Biological Nitrification

Food & Microorganism Contact

Using the Right Tools

Provide more opportunity for food & microorganisms to come into contact.

- ~~Use very long HRTs (> 40 days).~~
- Prevent short-circuiting.
  - Use strategic pond configurations (e.g. series instead of parallel), including careful placement of inlets and outlets.
  - Use baffles.
- Increase mixing with mechanical aerators.

This is costly and allows algae to propagate. Algae are counter productive to meeting TSS requirements.

Biological Nitrification

Pond Baffle

Reduce Short-circuiting

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Biological Nitrification
Mixing Power
High Speed Surface Aerators

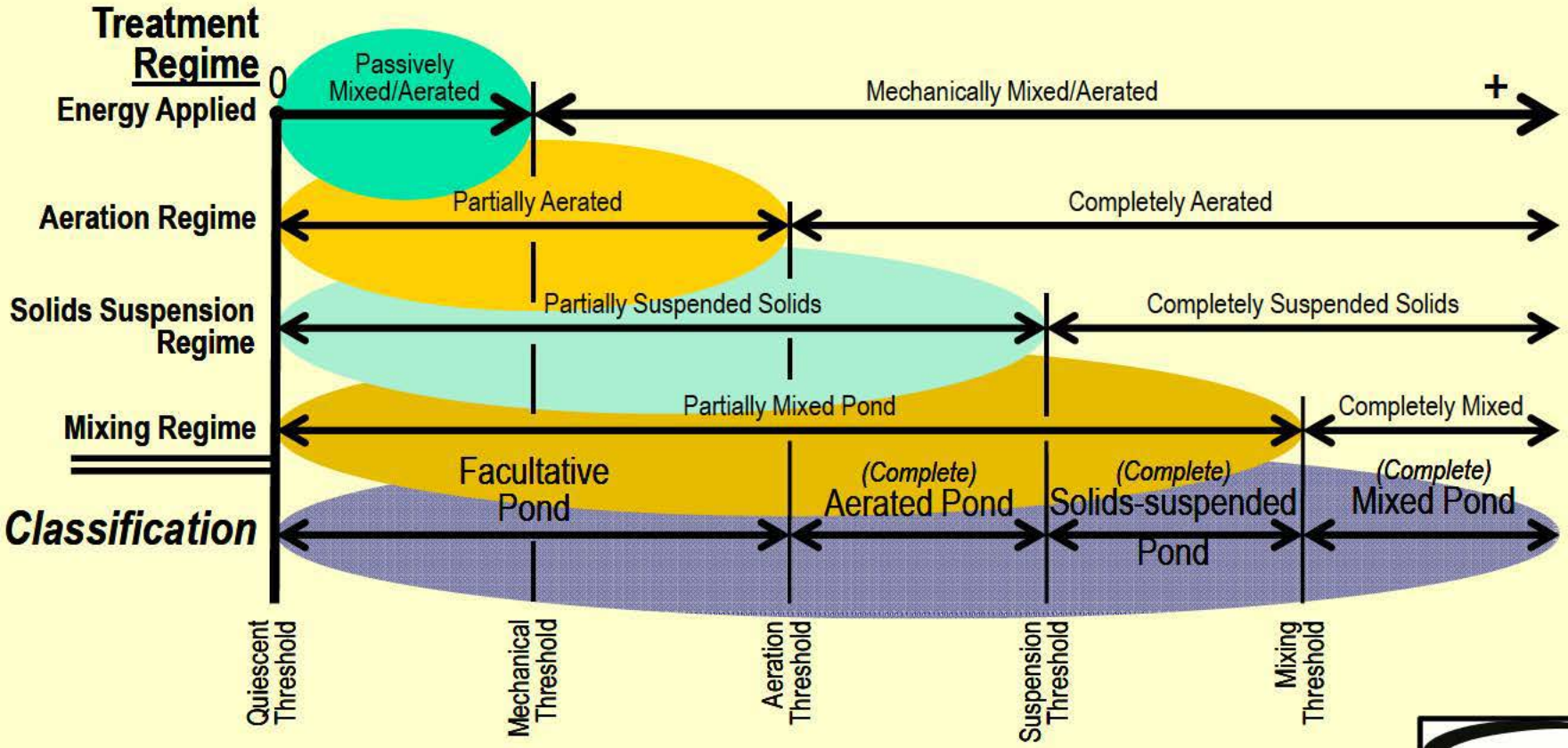
Applied Mixing/Aeration Power*	Solids Suspension Regime
Less than **7.5 hp/Mgal** *(1.5 kW/1000m^3)*	Minimal Suspension: Particulate organics settles out of solution and are stabilized on pond bottom. Only soluble organics in the water column.
Between **7.5-15 hp/Mgal** *(1.5-3 kW/1000m^3)*	Partial Suspension: Most particles settle to pond bottom. Concentration of particles varies throughout pond. Soluble, together with some particulate organics, are treated in water column.
Between **15-30 hp/Mgal** *(3-6 kW/1000m^3)*	Substantial Suspension: Large solids settle and are not resuspended. Uniform concentration of other particles is maintained throughout pond. Both soluble and particulate organics are treated in the water column.
Greater than **30 hp/Mgal** *(6 kW/1000m^3)*	Complete Suspension: All solids are suspended uniformly throughout pond. Both solid and soluble BOD is treatment in water column.

*Varies – check with the manufacturer

Classification of Wastewater Ponds

Treatment Regimes

Based on Energy Applied



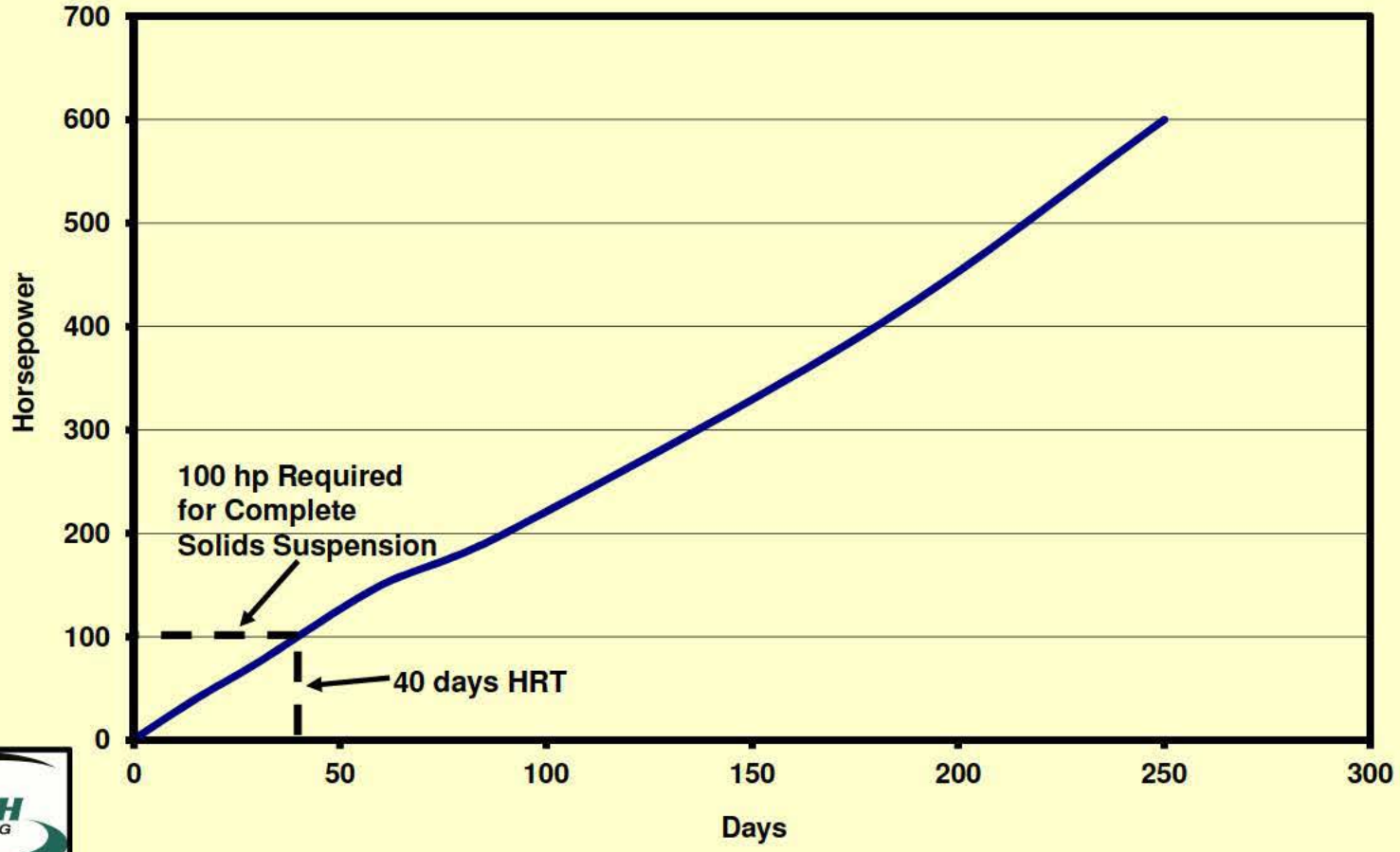
Classification of Wastewater Ponds

HRT & Mixing Power

Solids-suspended Pond for a Small *Community*

High-speed Floating Aerators

(1,000 people generating ≈80 gpcd of wastewater)



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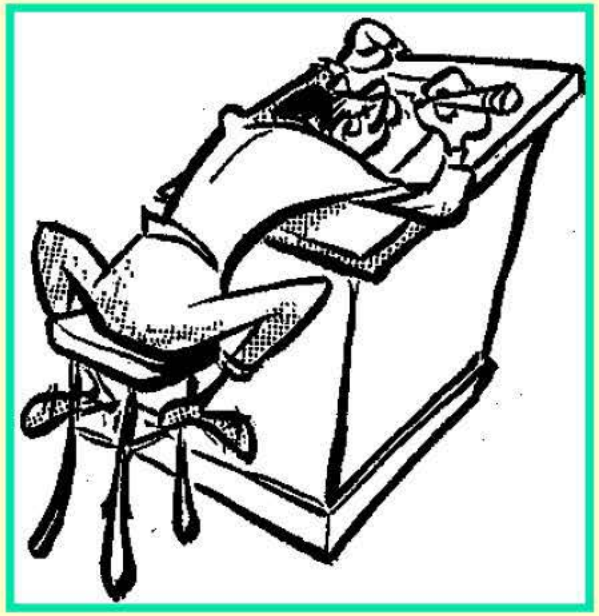
Biological Nitrification
Managing Microbial Competition
Reducing Heterotrophs

When large amounts of organics (food) are present large numbers of heterotrophs (organic degrading microorganisms) exist and out-compete Nitrifiers for nutrients and oxygen. Therefore you must reduce the number of heterotrophs in solution to allow nitrifies to prosper. You can do this by:

High Cost + Algae/TSS problems

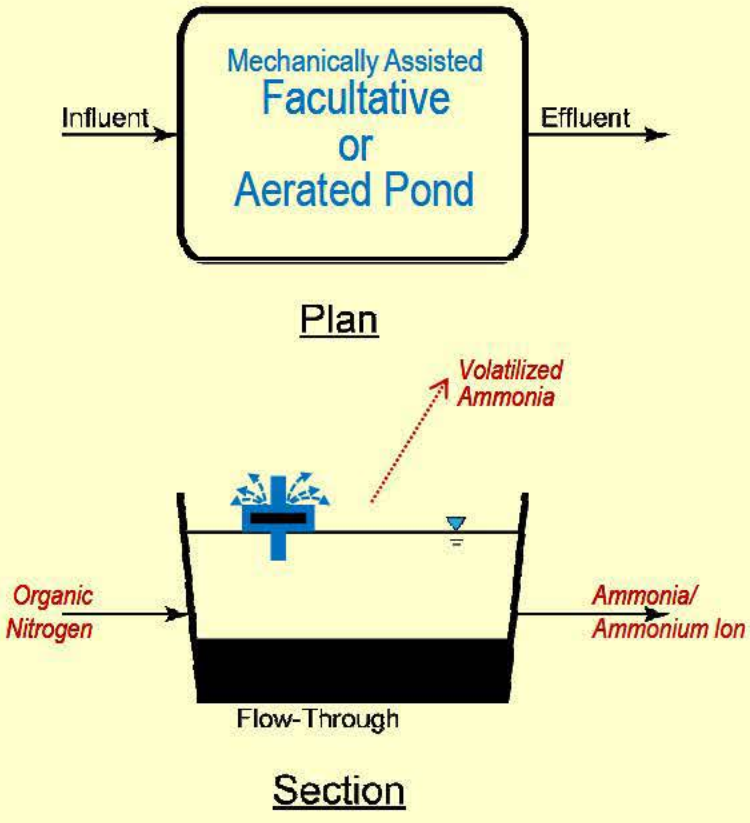


- Use **long hydraulic retention times** (HRTs). After 36 hours most of the readily available organics will have been depleted.
  - Solids-suspended Pond - 5 to 7 days HRT
  - ~~Aerated Pond – 40+ days HRT~~
  - ~~Passive Pond – 240+ days HRT~~
- Prevent **short-circuiting**. Short HRTs caused by short-circuiting allow heterotrophs to exist through to pond outlets.
  - Strategically locate inlets/outlets.
  - Install baffles.
  - Use ponds in series.
- Use **separate reactors**. Deplete readily available organics in a primary pond and nitrify in a subsequent reactor or pond where organics and heterotroph concentrations are smaller. Attached growth reactors (biotowers, MBBRs, and sand filters etc.) are particularly effective.

Nitrification Problems

Facultative and Aerated Ponds

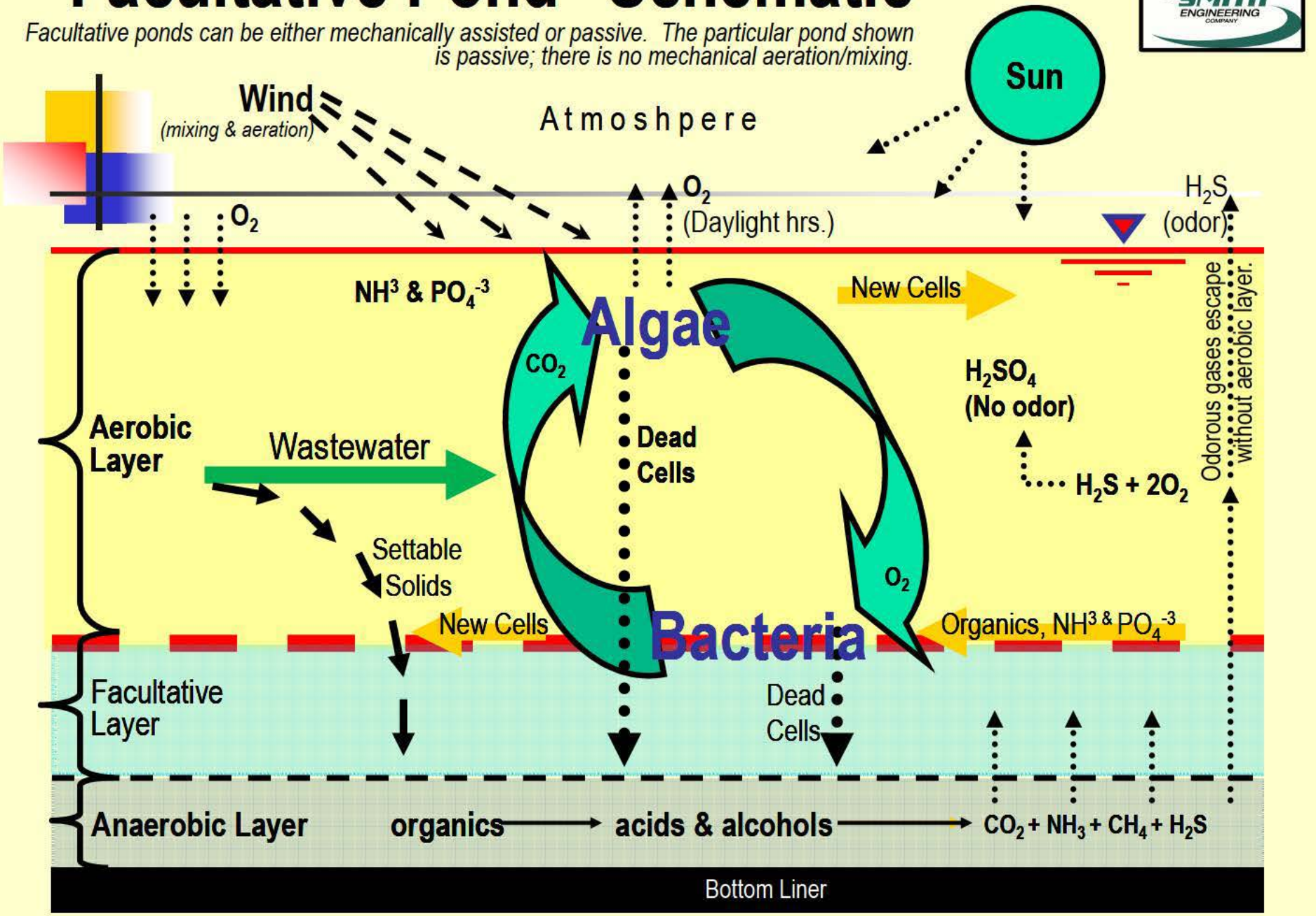
Pond Effluents are High in Ammonia

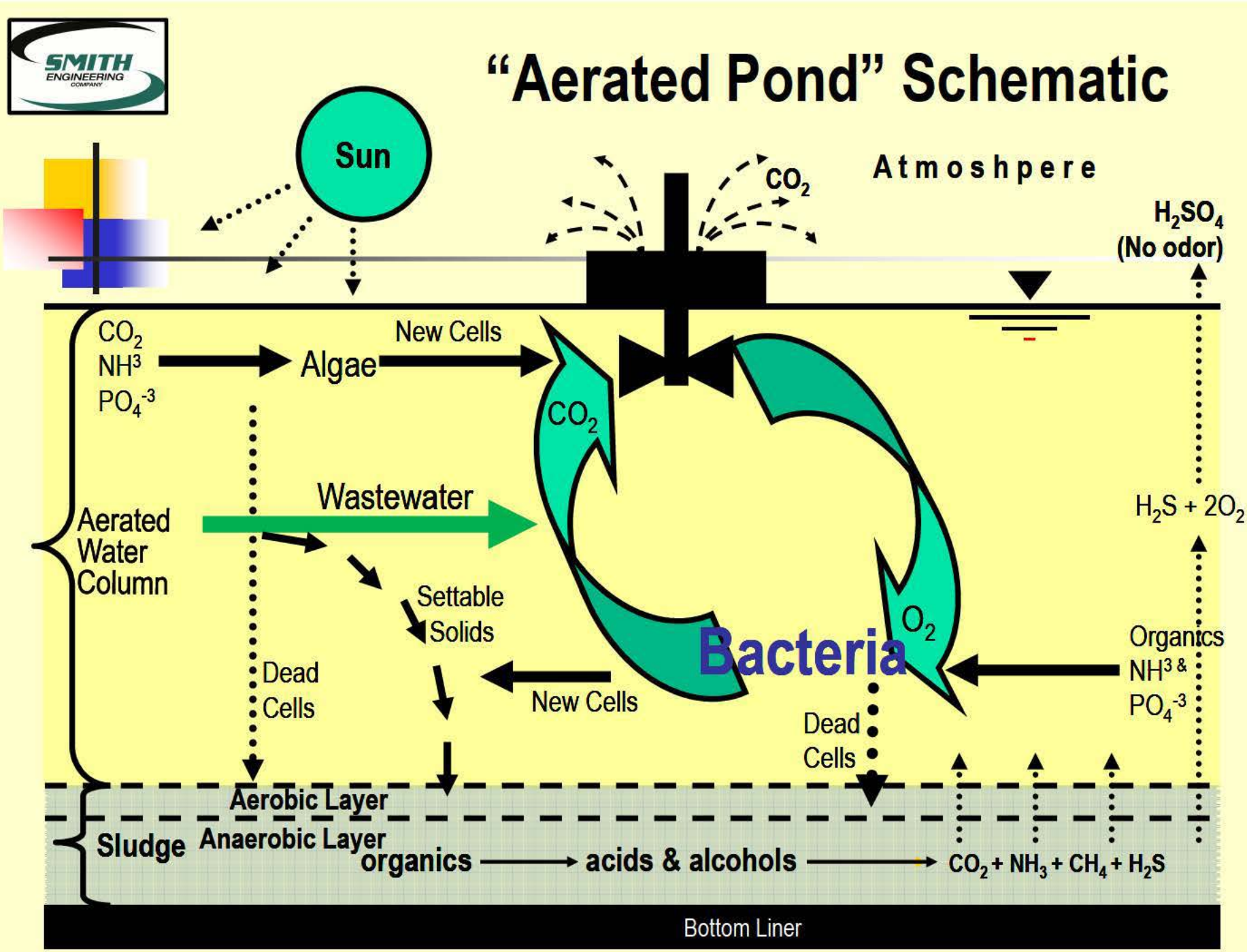


- ✓ Influent organic nitrogen gets converted to ammonia via hydrolysis
- ✓ But… nitrification (conversion of ammonia to nitrates does) does not occur
- ✓ Reasons why nitrification does not occur:
  - ✓ Too many organics remain in suspension
  - ~~Inadequate oxygen in the water column~~
  - ✓ Inadequate contact between nitrifying organisms and ammonia in solution
    - ✓ Low MLSS
    - Poor mixing and/or short-circuiting
    - Improved
  - ✓ Winter temperatures cause poor seasonal performance
  - ✓ Biomass assimilated nitrogen is re-released from sludge

"Facultative Pond" Schematic

Facultative ponds can be either mechanically assisted or passive. The particular pond shown is passive; there is no mechanical aeration/mixing.

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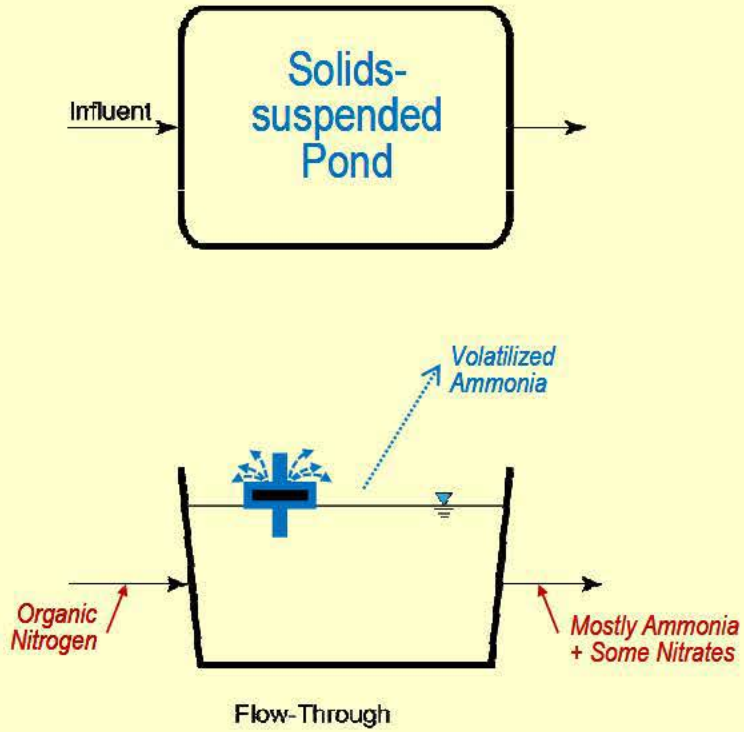
"Aerated Pond" Schematic
Sun
Atmoshpere
CO_2
H_2SO_4
(No odor)
CO_2
NH^3
PO_4^{-3}
Algae
New Cells
CO_2
Wastewater
Aerated
Water
Column
Settable
Solids
Bacteria
O_2
$H_2S + 2O_2$
Organics
NH^3 &
PO_4^{-3}
Dead
Cells
New Cells
Dead
Cells
Aerobic Layer
Sludge
Anaerobic Layer
organics
acids & alcohols
$CO_2 + NH_3 + CH_4 + H_2S$
Bottom Liner

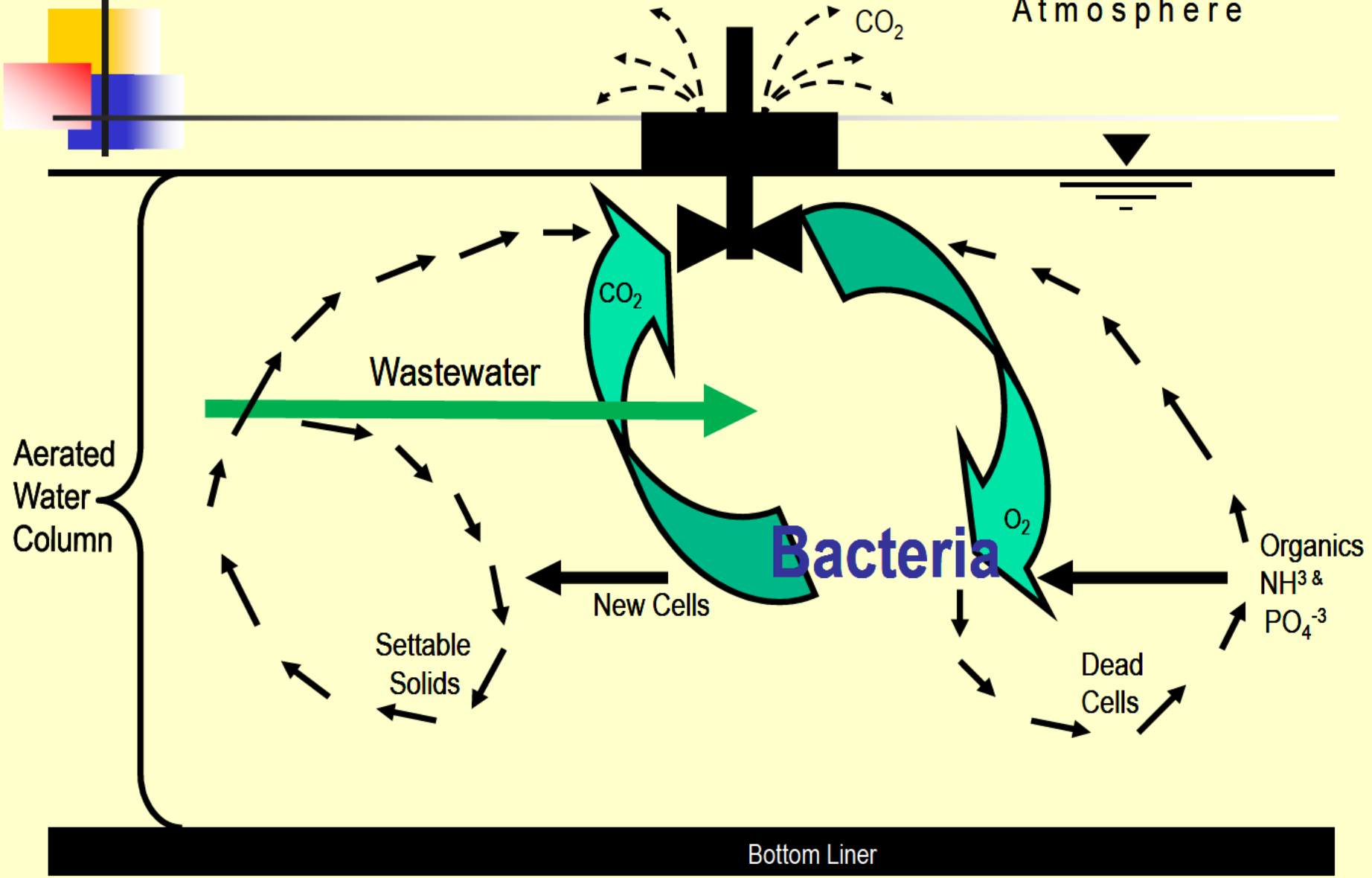
Nitrification Problems
Solids-suspended Ponds
Pond Effluents are High in Ammonia



- ✓ Influent organic nitrogen gets converted to ammonia via hydrolysis
- ✓ Large amounts of ammonia is converted to nitrate ions.
- ✓ Reasons why nitrification might not be a robust as you'd like:
  - ~~Too many organics remain in suspension~~
  - ~~Inadequate oxygen in the water column~~
  - ✓ Inadequate contact between nitrifying organisms and ammonia in solution
    - ✓ Low MLSS
    - ~~Poor mixing and/or short circuiting~~
  - ~~Biomass assimilated nitrogen is re-released from sludge~~
  - ✓ Winter temperatures cause poor seasonal performance

"Mixed Pond" Schematic

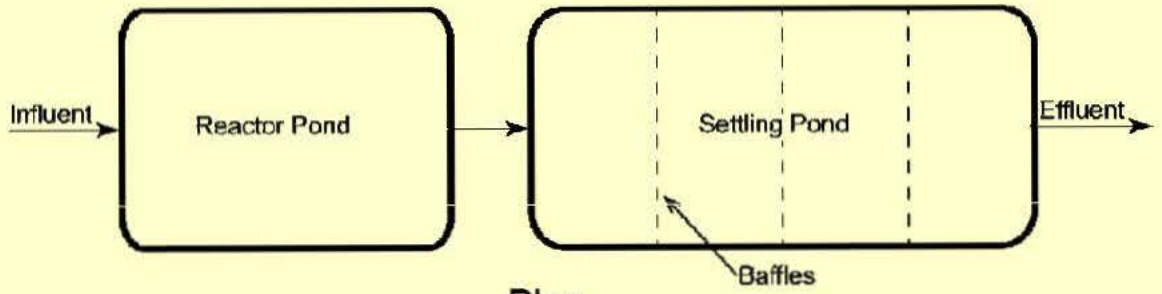
Complete Suspension NOT Complete-Mix



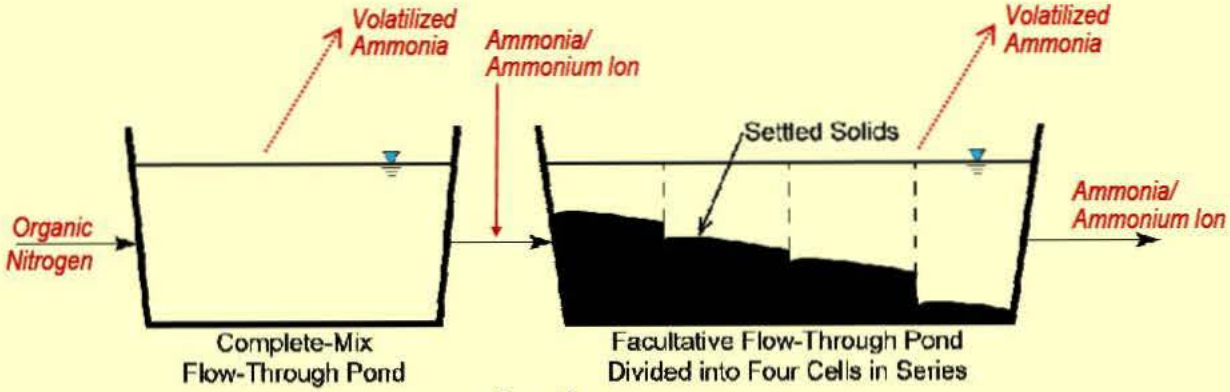
Nitrification Problems
Dual-Powered Multi-Cellular (DPMC) Ponds*

Pond Effluents are High in Ammonia

* As proposed by Rich (1999)



Plan



Section

Elemental Composition of Microbial Cells

Element	Variations in Composition of Microbial Cells, dry weight %
Carbon	45 – 55
Oxygen	16 – 22
Nitrogen	12 – 16
Hydrogen	7 – 10
Phosphorus	2 – 5
Sulfur	0.8 – 1.5
Potassium	0.8 – 1.5
Sodium	0.5 – 2.0
Calcium	0.4 – 0.7
Magnesium	0.4 – 0.7
Chlorine	0.4 – 0.7
Iron	0.1 – 0.4
All others**	0.2 – 0.5

** Includes trace elements

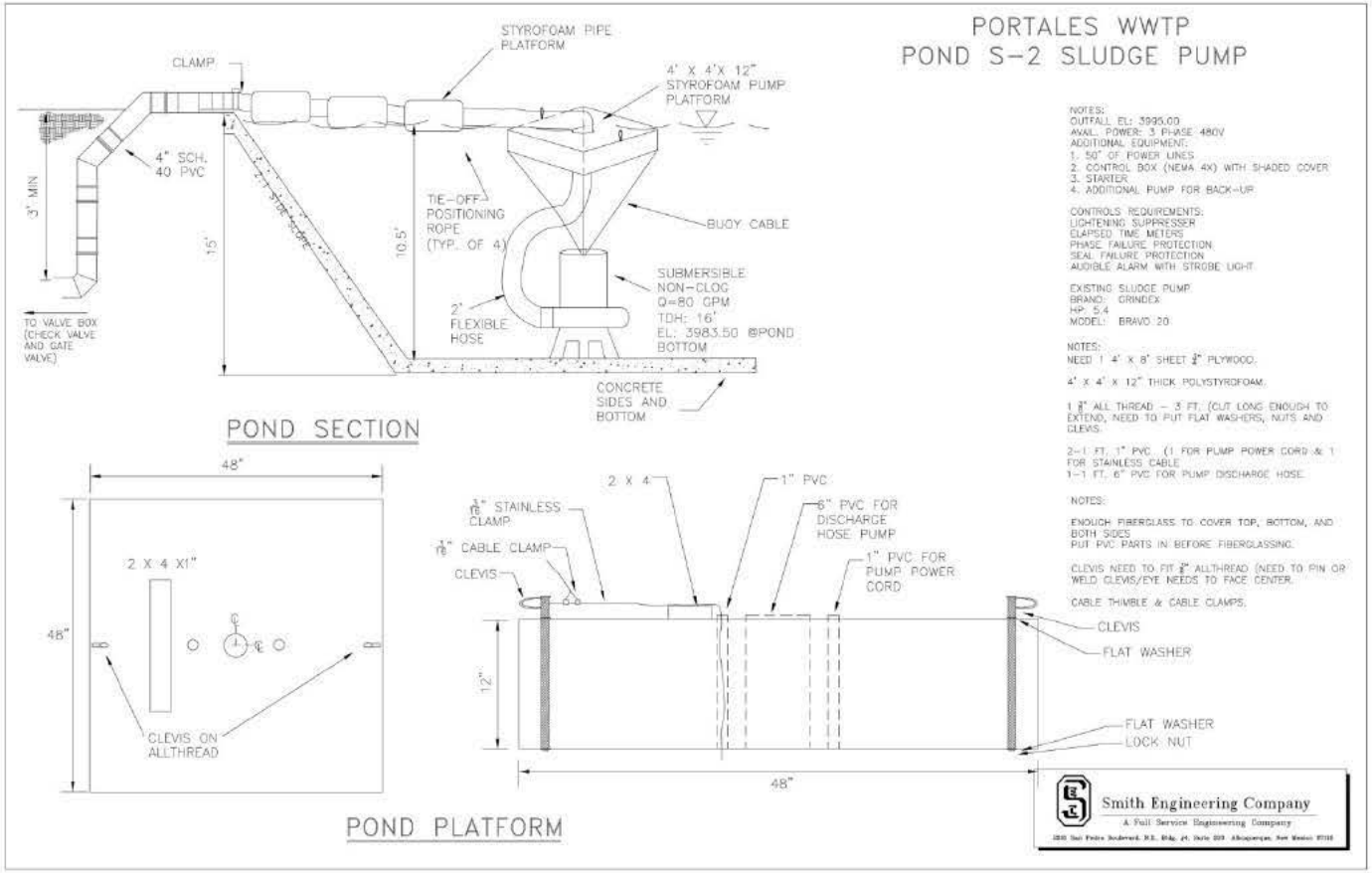
Separating Solids

Pond Sludge Pump

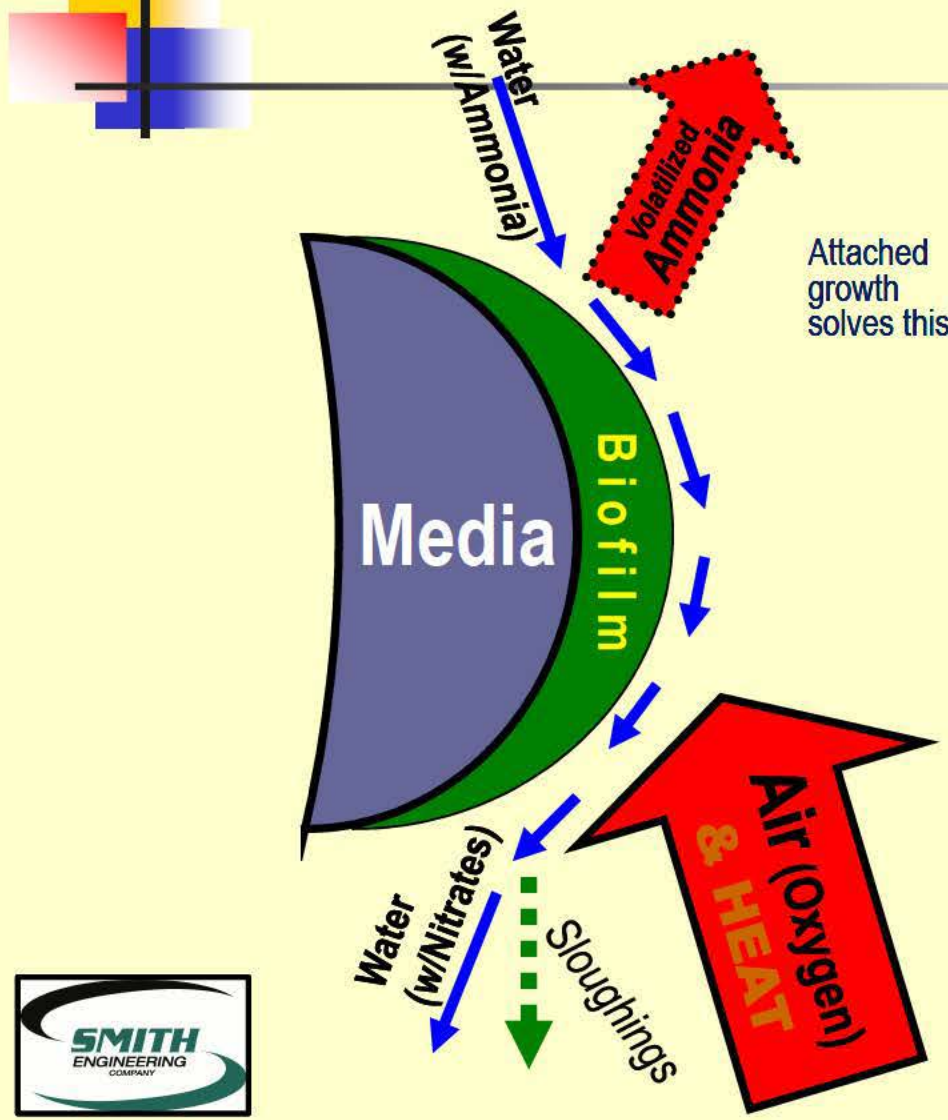
Remove Sludge & Remove Nitrogen

Portales, NM

Separating Solids
Pond Sludge Pump
Remove Sludge & Remove Nitrogen



Biological Nitrification
Attached Growth Reactor
High Performance Separate Reactors



Using a separate reactor can solve this.

Attached growth solves this.

- Remember why Ponds Don't Work?
  - Nitrifiers don't compete well with heterotrophs
  - Food & Microorganisms Don't Get Together
- Attached Growth Nitrification Characteristics.
  - Food is brought into contact with a dense culture of Nitrifiers
  - High Hydraulic Loading Rates (HLRs)
  - Passive Venting is Usually Not Adequate
  - Sensitive to Cold
  - High Performance (Really Converts Ammonia!)

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Biological Nitrification

Dosing Sand Filter

Cuba, NM

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Biological Nitrification

Small System Biotower

Capitan, NM

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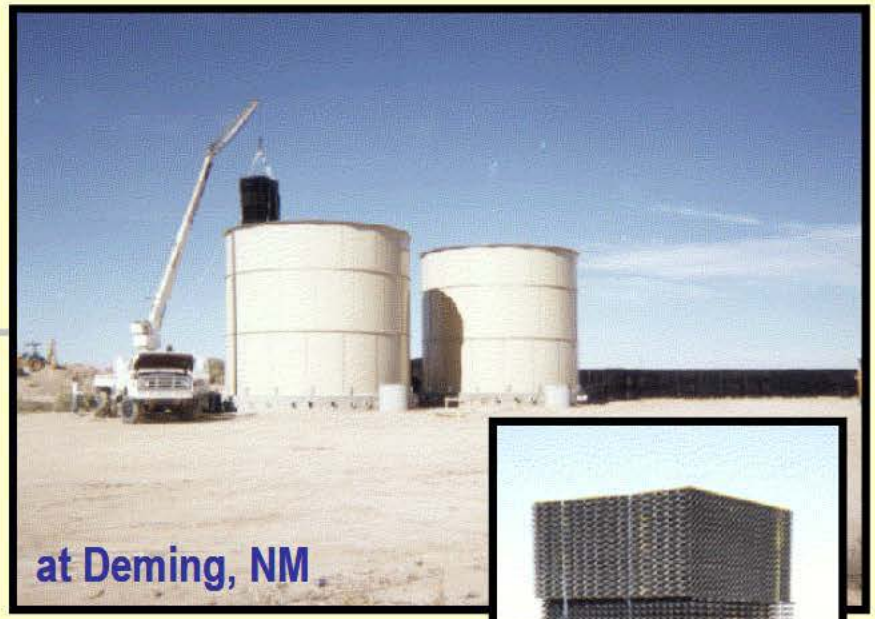
Biological Nitrification
Biotowers
Design (simplified)



- If
  1. $CBOD_5$:TKN ≤ 1.0
  2. $SCBOD_5$ ≤ 12 mg/L
  3. q ≥ 47 [m^3/m^2 d]
  4. $CBOD_5$ & TSS ≤ 30 mg/L
  5. Forced Ventilation ≥ 50 kg O_2/kg O_2 required
- Then you can reliably design a biotower using
  - $K_n = 1.2(1.045)^{T-10}$, *Nitrification rate constant [g N/m^2 d]*
  - $A_s = Q(N_0/k_n)$, *Surface Area of the media [m^2]*
  - $V_m = A_s/a$, *Volume of the media [m^3]*
  - $A_x = Q/q$, *Cross-sectional area of the biotower [m^2]*
  - $D_{min} = V_m/A_x$, *Depth of the biotower [m]*
  - $R_v = 50\,Q(1.5\,CBOD_5+4.6\,TKN)/1000$, *Ventilation rate of the biotower [kg O_2/hr)*
- *Where*
  - T = water temperature *[°C]*
  - Q = flow *[m^3/d]*
  - N_0 = effluent ammonia concentration *[mg/L]*
  - A = media specific surface area, from the manufacturer *[m_2/m_3]*
  - q = limiting hydraulic loading intensity *[m^3/m^2 d]*

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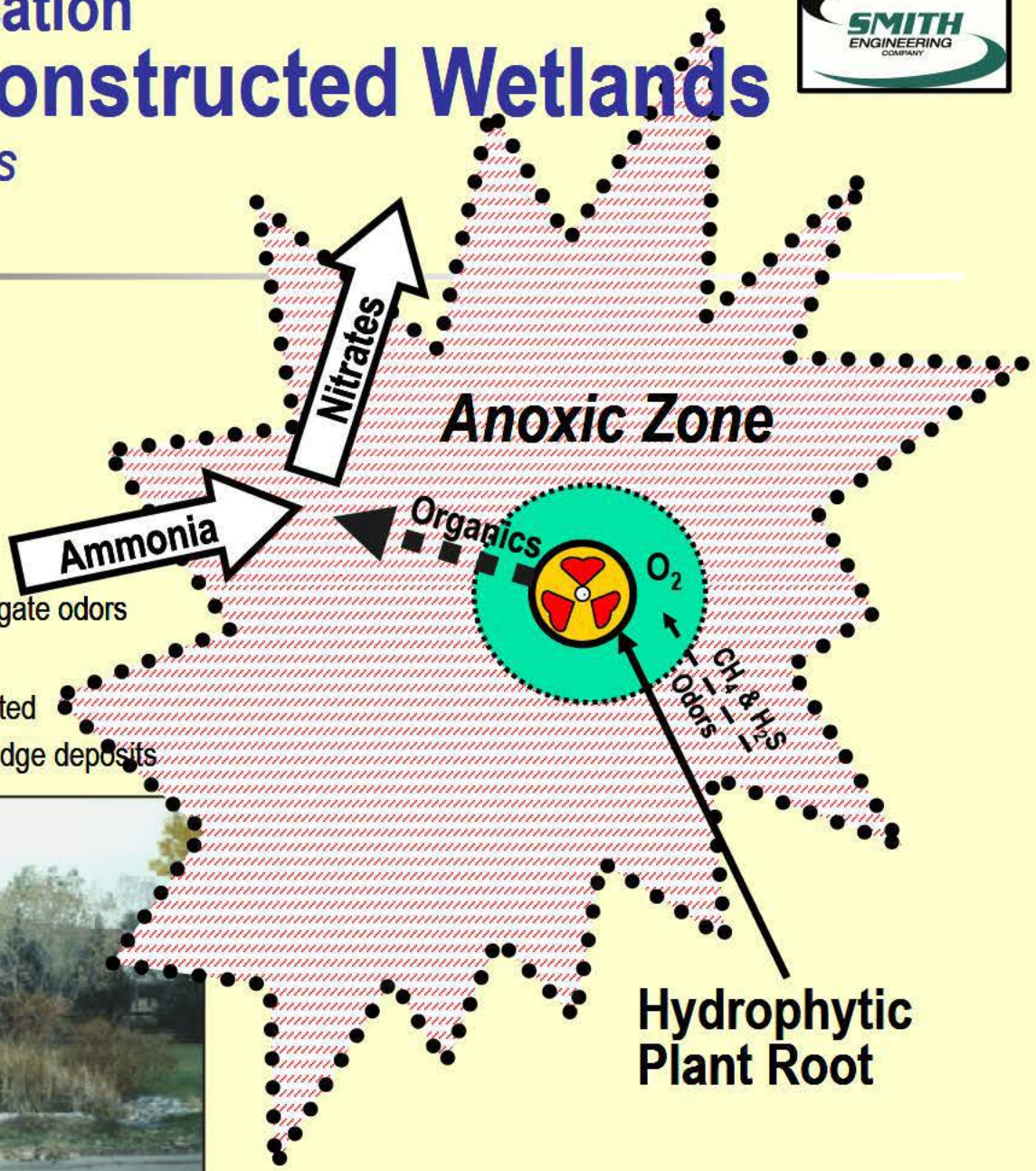
Biological Nitrification

Biotower Venting

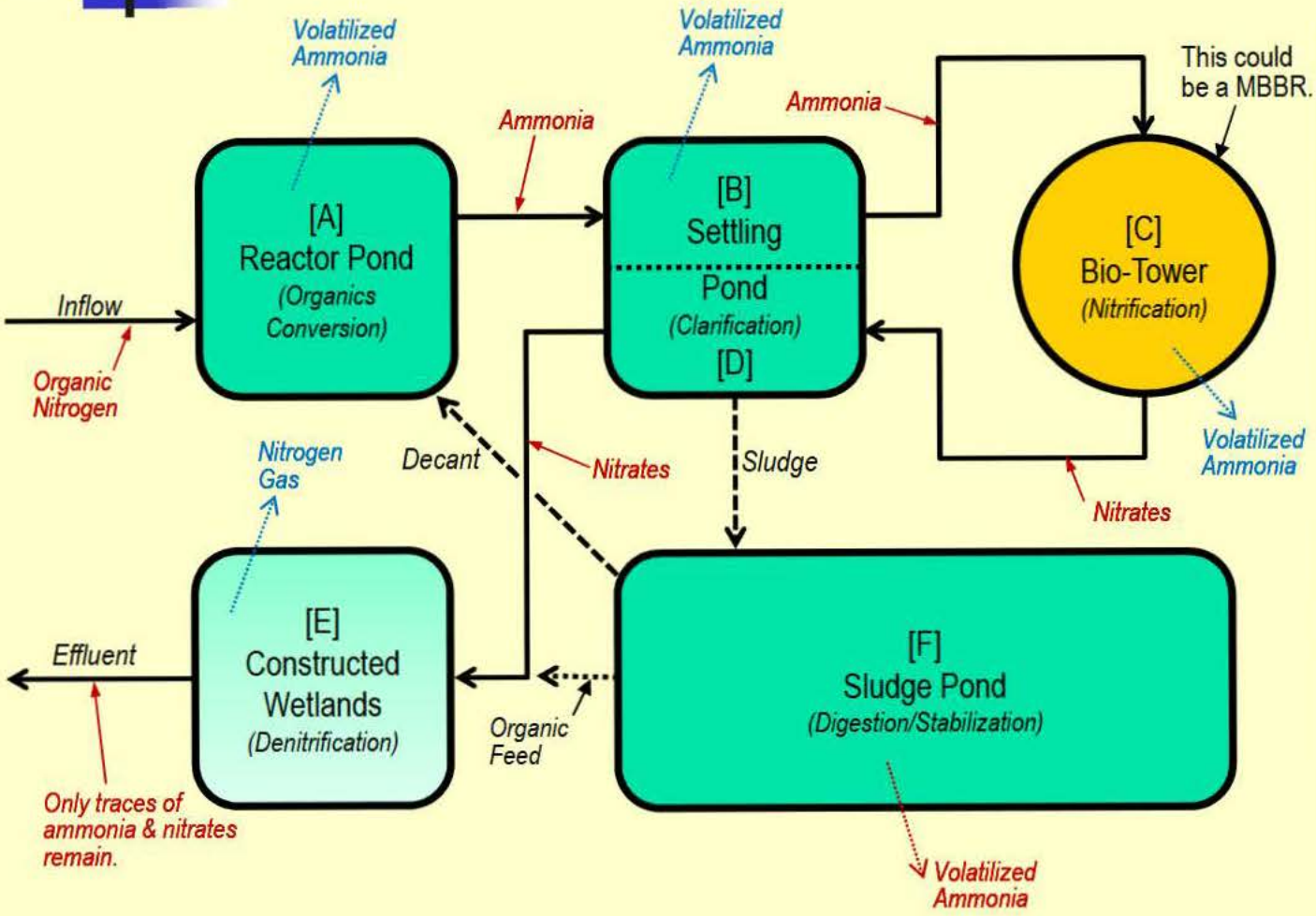
Deming, NM

Biological Denitrification
Subsurface Constructed Wetlands
Anoxic Polishing Process

- Items required for denitrification
  - Organics
  - Absence of oxygen
- Plants contribute
  - Some organics shed from roots
  - A small amount of oxygen to help mitigate odors
- Organics
  - At startup may need to be supplemented
  - During maturity will be supplied by sludge deposits

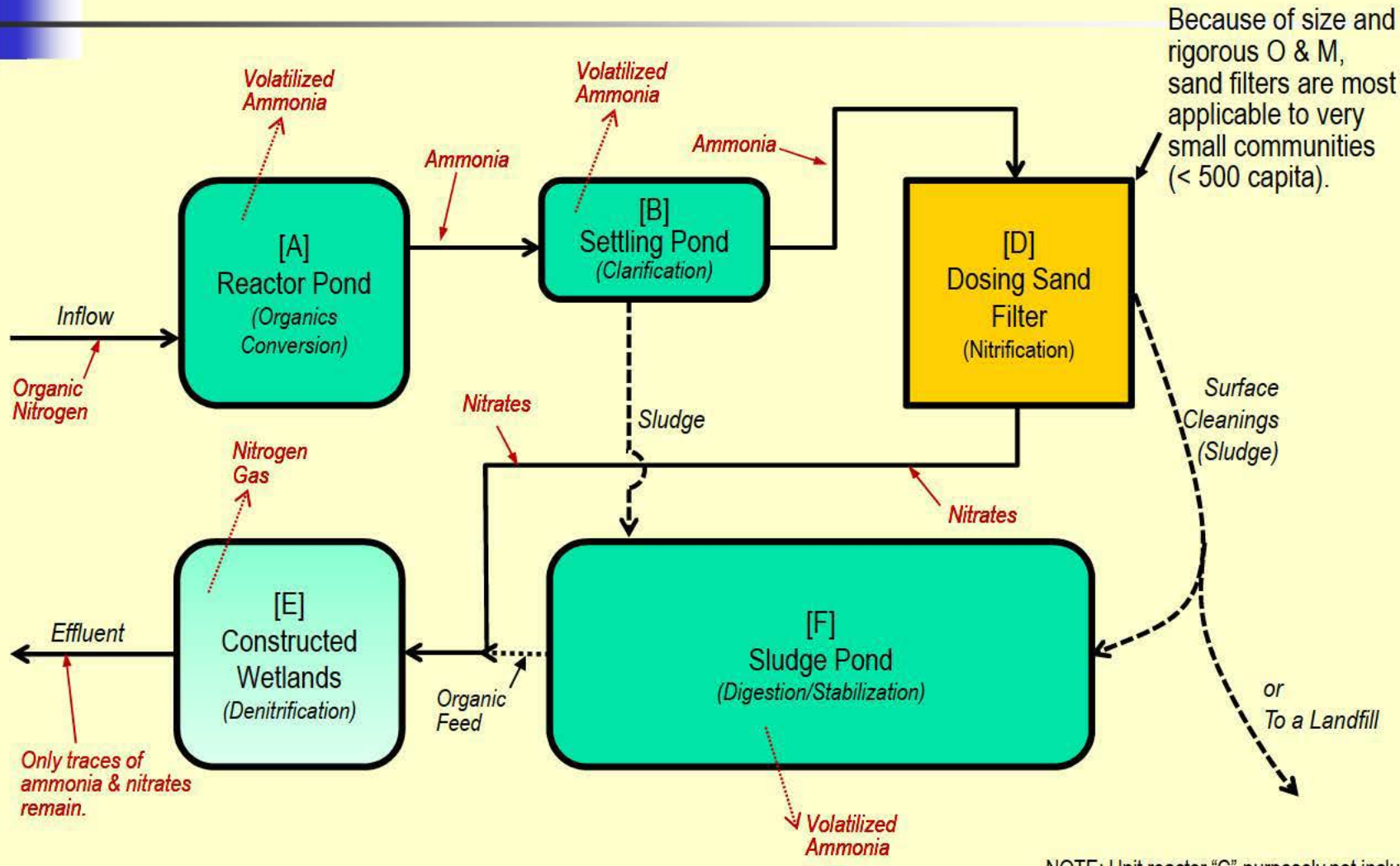


Biological Nitrogen Removal
High Performance Pond
Biotower Nitrification & SFCW Denitrification



Process	Description
A	Organics converted to biomass. Ammonia released.
B	Organics depleted. Biomass settled out and removed to sludge pond.
C	Nitrifiers established. Conversion of ammonia to nitrates.
D	Nitrifiers settled out. Sludge removed to sludge pond.
E	Heterotrophs re-establish with organics from plants and sludge. Convert nitrates to nitrogen gas.
F	Sludge is digested and stabilized.

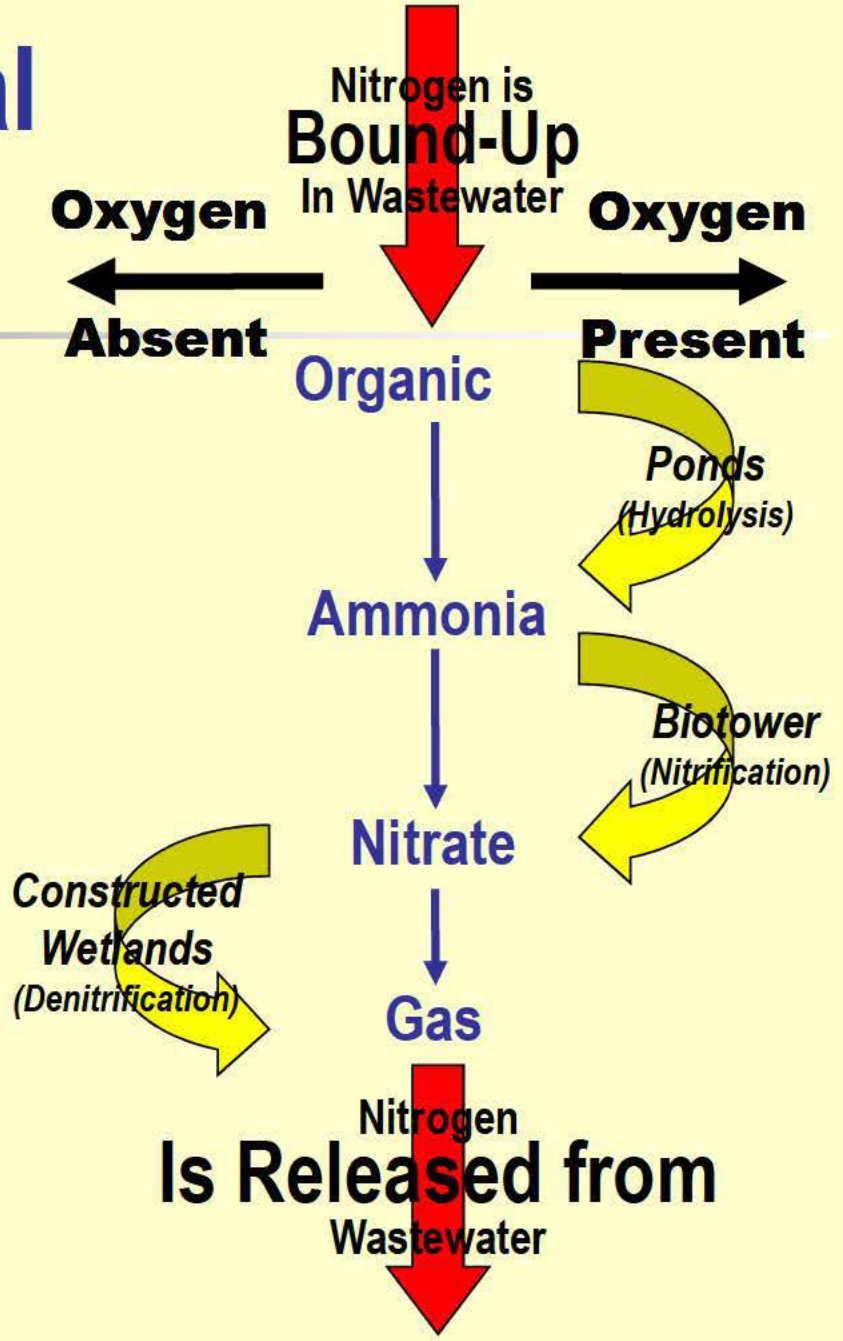
Biological Nitrogen Removal
High Performance Pond
Sand Filter Nitrification & SFCW Denitrification



NOTE: Unit reactor "C" purposely not included.

Nitrogen Removal

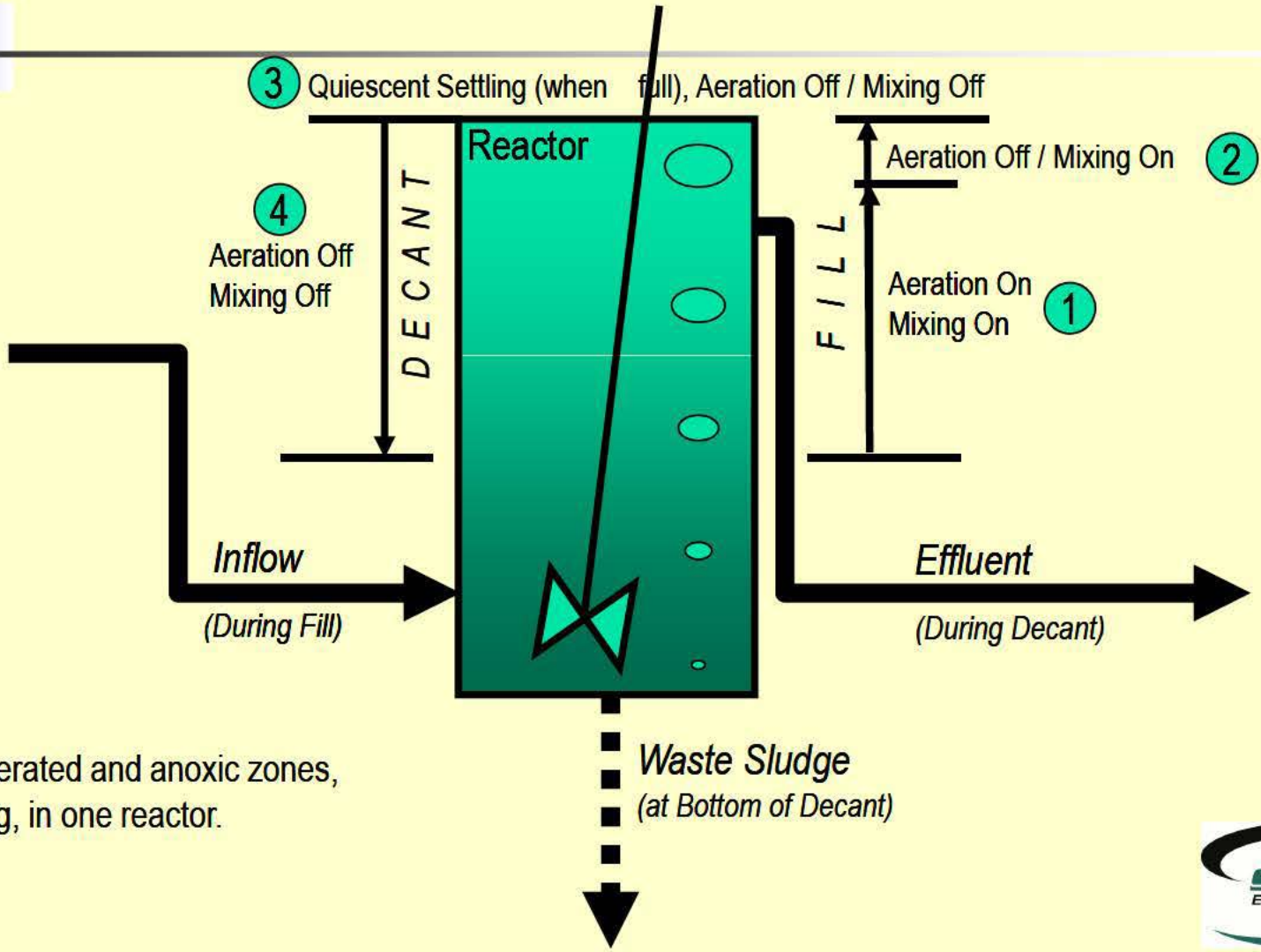
- Pond
- Biotower, MBBR, or Sand Filter
- Wetlands



Secondary/Tertiary Treatment + Clarification

Batch Process

Sequencing Batch Reactor (SBR)



Provides aerated and anoxic zones, plus settling, in one reactor.

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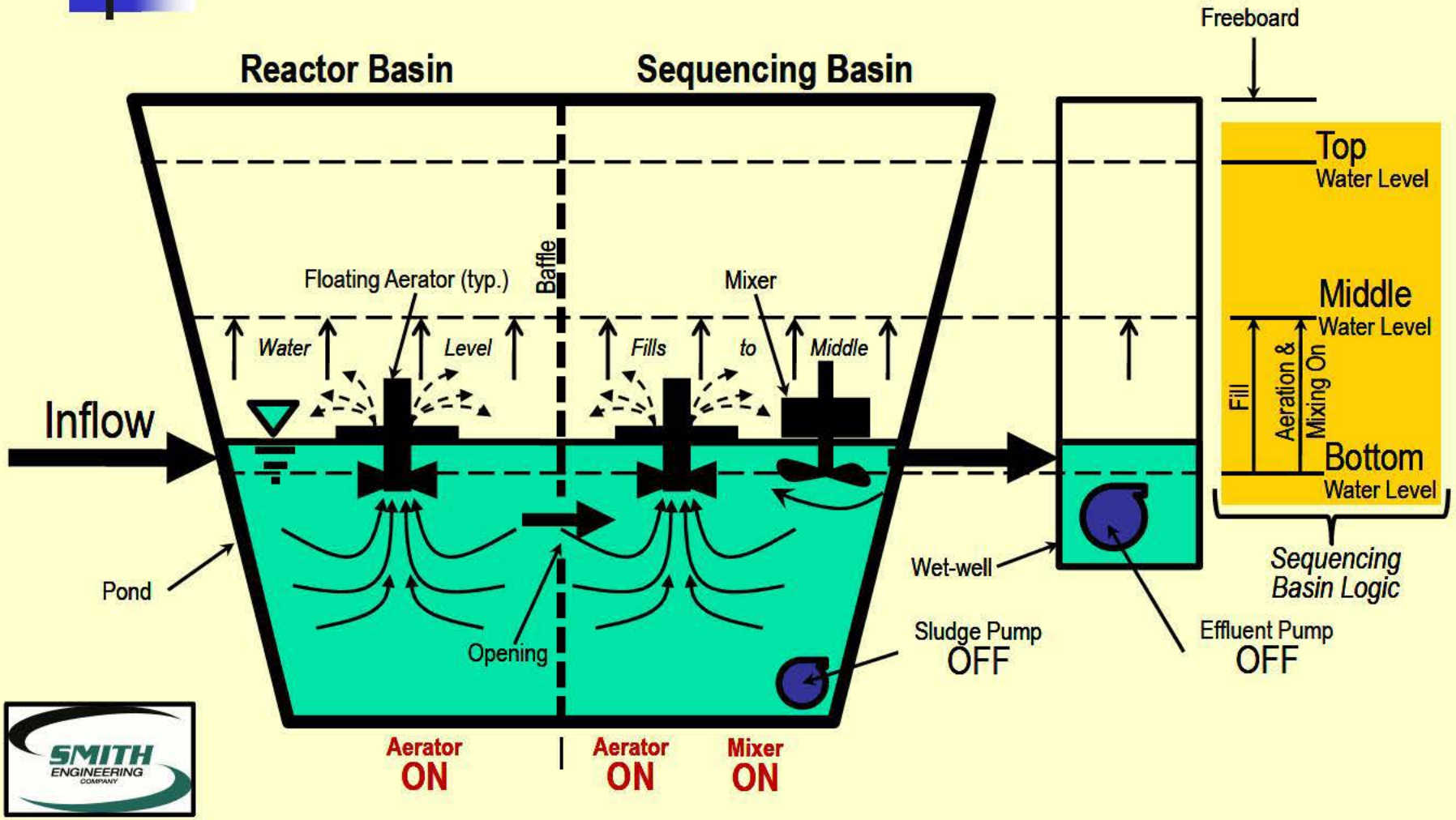
CFID Pond
Stage 1 – Turbulent Filling
Filling - with Aeration & Mixing

Θ = 4 hours (6-hour cycle)

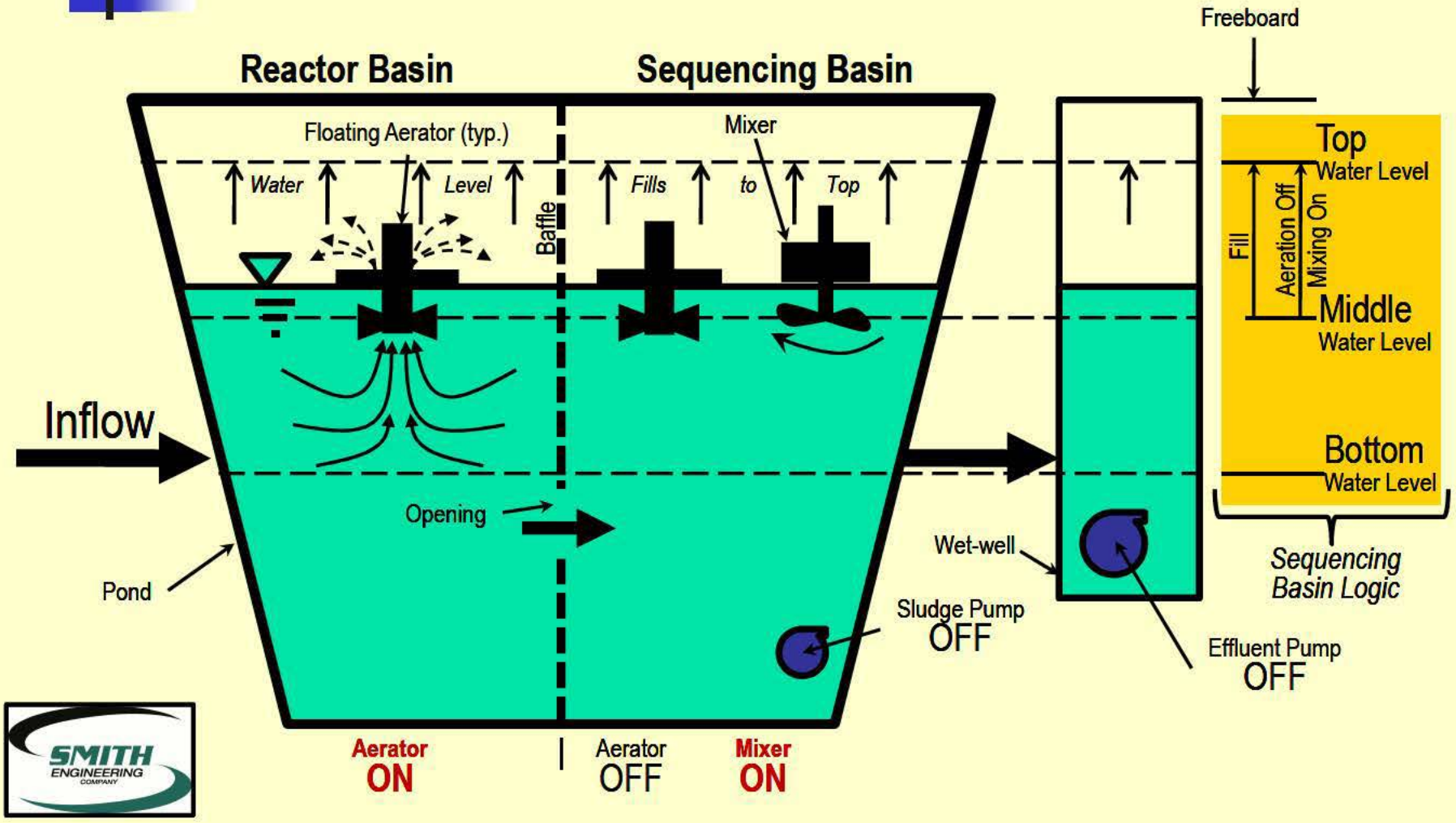
No Outflow



CFID Pond
Stage 2 – Quiescent Filling
Filling - without Aeration or Mixing

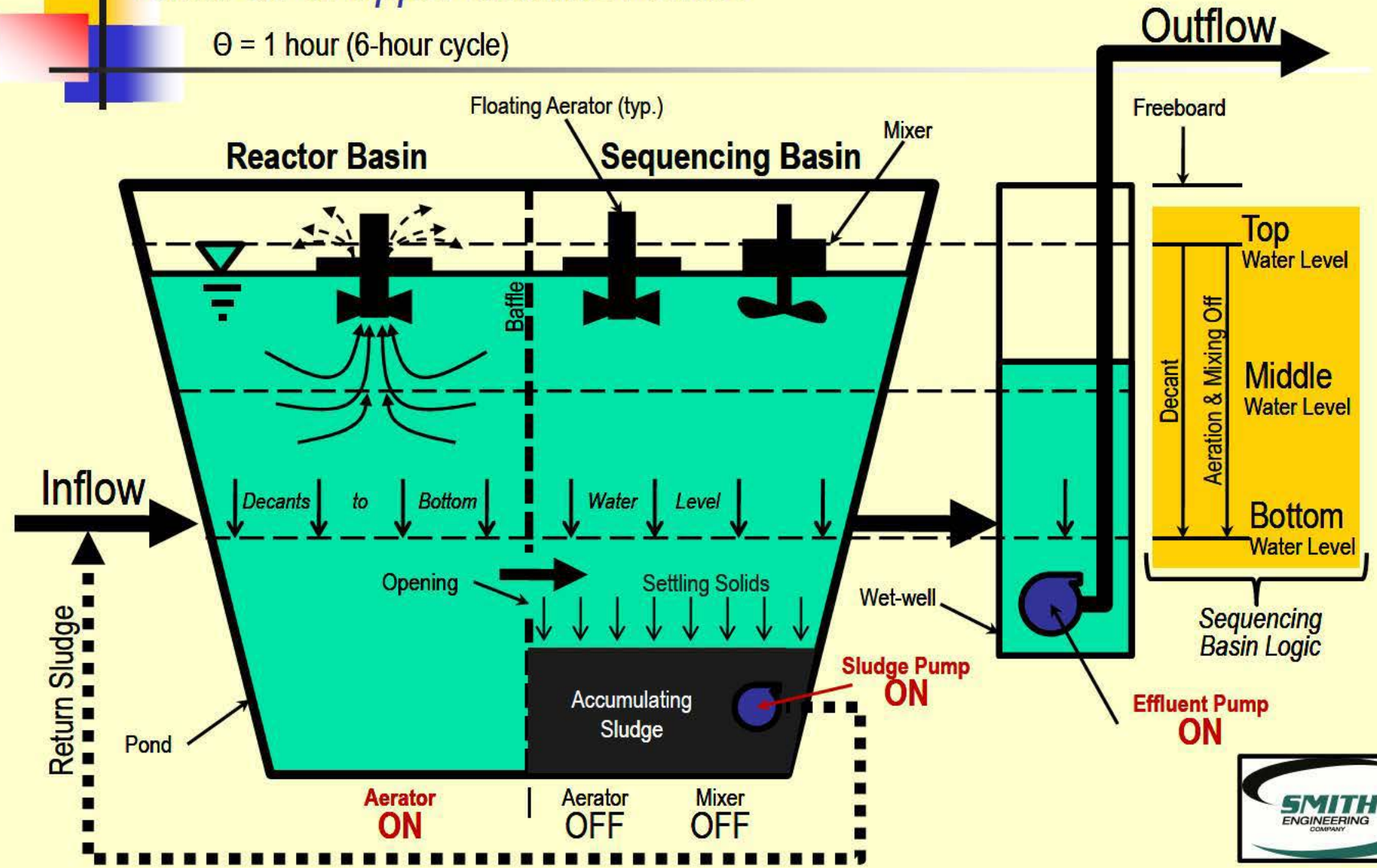
Θ = 1 hour (6-hour cycle)

No Outflow

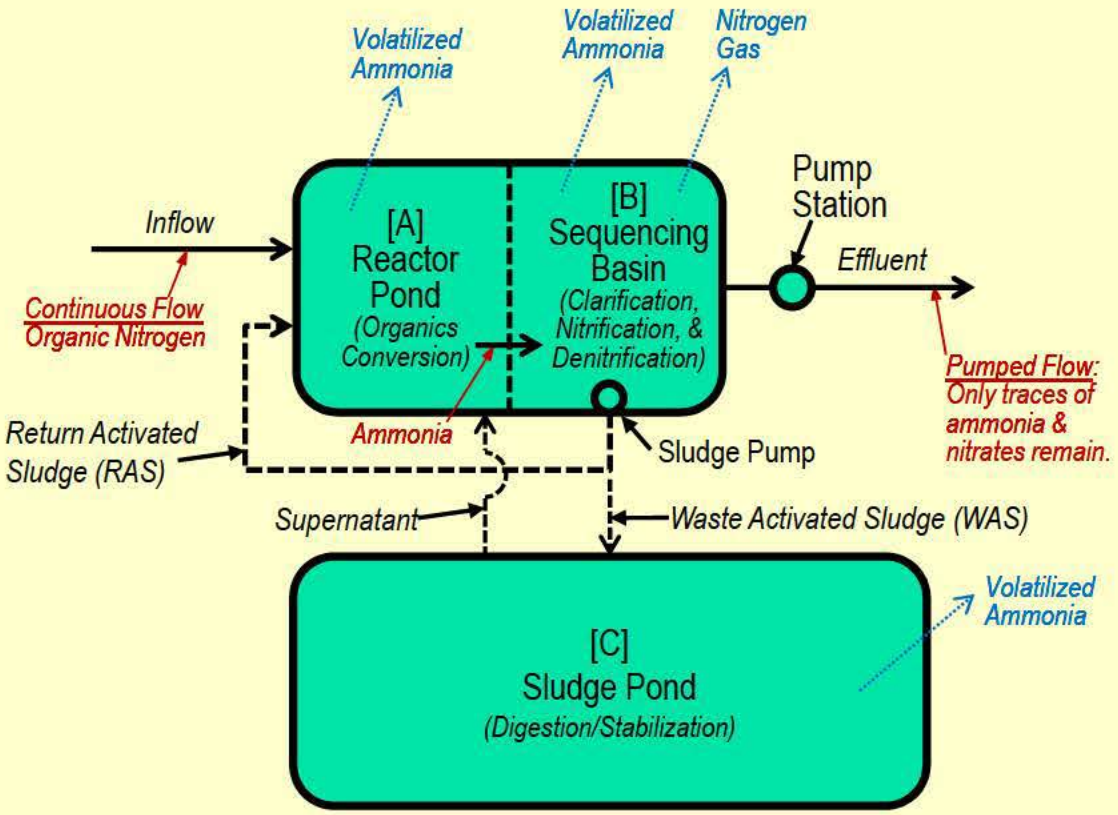


CFID Pond
Stage 3 – Decant
Draw-off of Upper Clarified Levels

Θ = 1 hour (6-hour cycle)

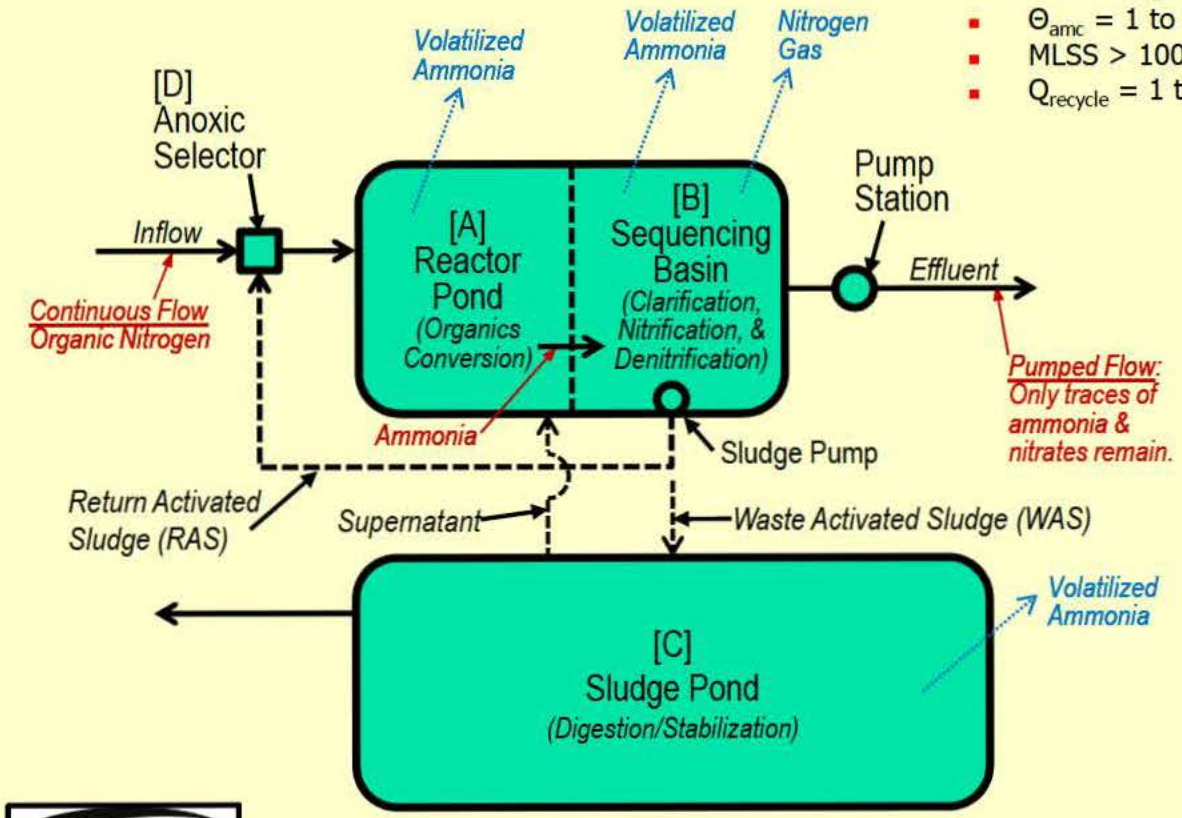


Biological Nitrogen Removal
CFID Pond
Nitrification & Denitrification



Process	Description
A	Organics converted to biomass. Ammonia released. Incoming organics depleted.
B.1	Nitrifiers established. Ammonia converted to nitrates.
B.2	Incoming organics continue to be depleted; resulting in nitrates converted to nitrogen gas.
B.3	Biomass settled-out and recalculated to reactor pond or removed to sludge pond.
C	Sludge is digested and stabilized.

Biological Nutrient Removal
CFID Pond
Nitrogen & Phosphorus



Process	Description
A	Organics converted to biomass. Ammonia released. Incoming organics depleted. Poly-P bacteria begin luxury uptake of phosphates.
B.1	Nitrifiers established. Ammonia converted to nitrates.
B.2	Incoming organics continue to be depleted; resulting in nitrates converted to nitrogen gas.
B.3	Biomass settled-out and recalculated to reactor pond or removed to sludge pond.
C	Sludge is digested and stabilized.
D	Poly-P bacteria starve and shed phosphates.

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Overcoming Obstacles to Nitrification

Factors	Suspended Growth (CFID Pond)	Attached Growth	Comments
Remove Organics	Increase mixing and aeration in pond where organics are removed and then settle-out bacterial floc.		It only takes 1.5 days for organics to be converted to biomass in most ponds. Therefore, longer HRT are usually not required for converting organics.
Increase Nitrifying Biomass	Use different areas (reactors) for organics and ammonia removal. Afford nitrifiers a long time to convert ammonia.	Provide surfaces on which nitrifiers can attach and grow.	Large HRT's require huge amounts of mixing and aeration. Uncoupling SRT from HRT can be a key to better exposure of nitrifiers to ammonia.
Increase contact between Nitrifiers and Ammonia.	Increase mixing in area where ammonia is removed.	Use high specific areas and high hydraulic loading rates (HLR).	Synthetic particle or crossflow matrix media are acceptable.
Supply Large Amounts of Oxygen	Increase aeration in area where ammonia is removed.	Forced ventilation will likely be required	If annual averaging is allowed by NM Discharge Plan then ventilation may not be required.
Temperature	Minimize heat lost to evaporation. Use aspirating or slow speed aerators (in that order) if possible.	Heat may be required.	If annual averaging is allowed by NM Discharge Plan then winter temperatures may not be required.
pH & Alkalinity	Add lime, soda ash, or caustic soda.	Add lime, soda ash, or caustic soda.	Insufficient alkalinity is rare in NM.
Toxicity	Create industrial wastewater ordinance. Educate the public on proper materials for sewer disposal.		Ponds are the best possible reactor for industrial shock loads, but nitrifiers can still be impacted.