Modeling Suspended Growth Systems
– see Grady, Daigger & Lim

Environmental Biotechnology
CE421/521
Tim Ellis
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Monod Equation and Unified Model

- Reactor performance as a function of SRT.
- Fails to account for:
  - Particulate removal rate
  - Anaerobic/anoxic conditions
  - Variable flow and loading
  - Biological nutrient removal

$$S = \frac{k_s(1 + b\theta_c)}{\theta_c(\hat{\mu} - b) - 1}$$

$$X = \frac{Y(S_0 - S)}{1 + b\theta_c}\frac{\theta_c}{\theta}$$

International Association on Water Quality Activated Sludge Model 1 (IAWQ-ASM 1)

- In 1983, IAWQ appointed a task group to develop a model.
- In 1986, ASM 1 was completed.
- ASM 1 able to predict performance of soluble and particulate substrate removal, nitrification and denitrification under steady state and dynamic conditions.

Traditional vs. Lysis-regrowth

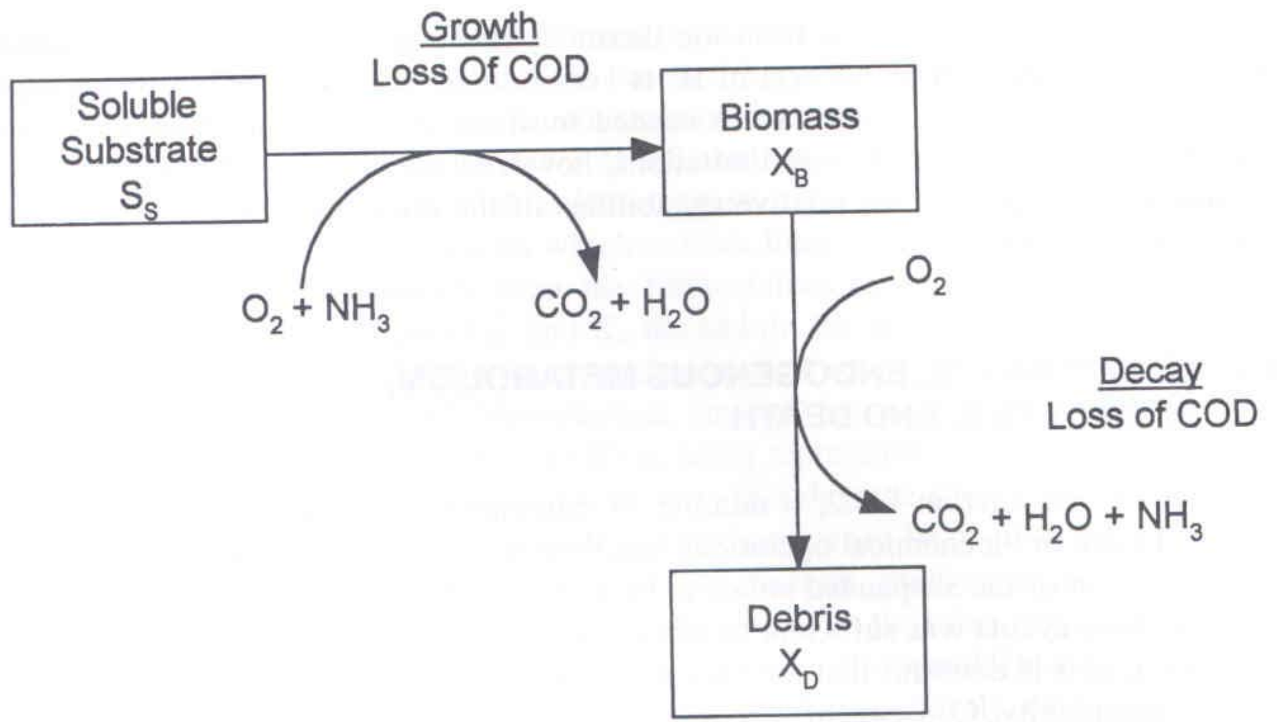


Figure 3.5 Schematic representation of the traditional approach to modeling biomass decay and loss of viability.

Traditional vs. Lysis-regrowth

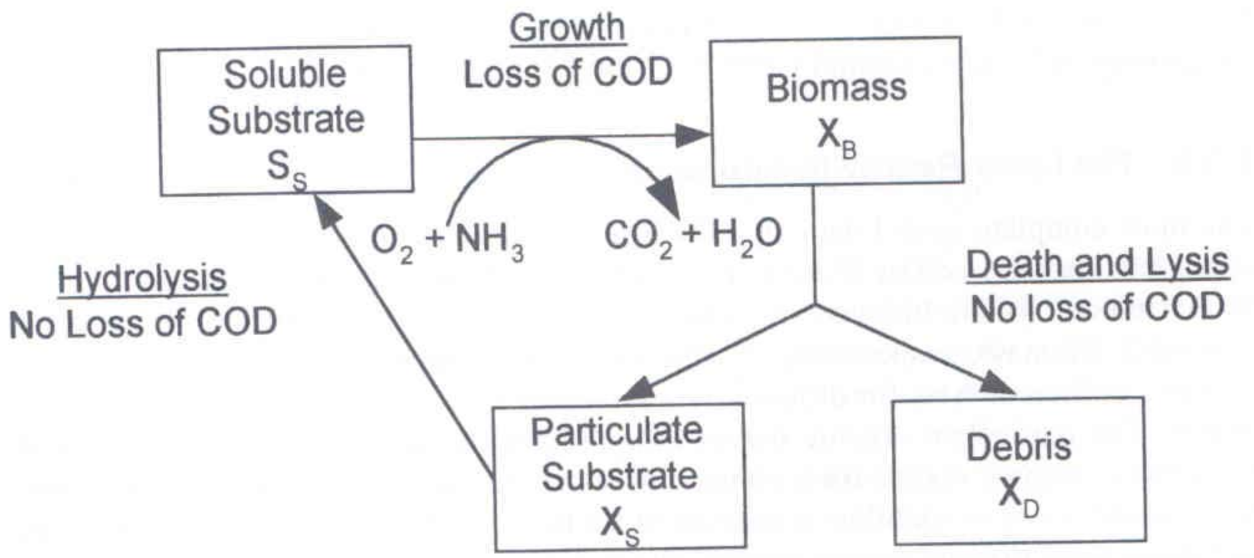


Figure 3.6 Schematic representation of the lysis:regrowth approach to modeling biomass decay and loss of viability.

ASM 1

- Tracks 13 individual components through eight separate processes.
- Assumes heterotrophic growth under anoxic conditions.
- Limited anaerobic activity.
- Uses lysis-regrowth approach

Table 6.1 Process Kinetics and Stoichiometry for Multiple Events in Suspended Growth Cultures as Presented by IAWQ Task Group on Mathematical Modeling[16,17]

	Component[a] → i	1	2	3	4	5	6	7	8	9	10	11	12	13	
j	Process ↓	X_I	X_S	$X_{B,H}$	$X_{B,A}$	X_D	S_I	S_S	S_O[b]	S_{NO}	S_{NH}	S_{NS}	X_{NS}	S_{ALK}	Process rate, r_j, $ML^{-3}T^{-1}$
1	Aerobic growth of heterotrophs			1				$-\frac{1}{Y_H}$	$\frac{1-Y_H}{Y_H}$		$-i_{N/XB}$			$-\frac{i_{N/XB}}{14}$	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{O,H}+S_O}\right)X_{B,H}$
2	Anoxic growth of heterotrophs			1				$-\frac{1}{Y_H}$		$-\frac{1-Y_H}{2.86\ Y_H}$	$-i_{N/XB}$			$\frac{1-Y_H}{14(2.86\ Y_H)}$ $-\frac{i_{N/XB}}{14}$	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\cdot\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\eta_g X_{B,H}$
3	Aerobic growth of autotrophs				1				$\frac{4.57-Y_A}{Y_A}$	$\frac{1}{Y_A}$	$-i_{N/XB}-\frac{1}{Y_A}$			$-\frac{i_{N/XB}}{14}-\frac{1}{7Y_A}$	$\hat{\mu}_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{O,A}+S_O}\right)X_{B,A}$
4	Death and lysis of heterotrophs		$1-f'_D$	−1		f'_D							$i_{N/XB}-f'_D i_{N/XD}$		$b_{L,H}X_{B,H}$
5	Death and lysis of autotrophs		$1-f'_D$		−1	f'_D							$i_{N/XB}-f'_D i_{N/XD}$		$b_{L,A}X_{B,A}$
6	Ammonification of soluble organic nitrogen										1	−1		$\frac{1}{14}$	$k_a S_{NS} X_{B,H}$
7	"Hydrolysis" of particulate organics		−1					1							$k_h\frac{X_S/X_{B,H}}{K_X+(X_S/X_{B,H})}\left[\left(\frac{S_O}{K_{O,H}+S_O}\right)+\eta_h\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]X_{B,H}$
8	"Hydrolysis" of particulate organic nitrogen											1	−1		$r_7(X_{NS}/X_S)$
	Observed conversion rates, $ML^{-3}T^{-1}$								$r_i=\sum_{j=1}^{n}\Psi_{ij}r_j$						

[a] All organic compounds (1–7) and oxygen (8) are expressed as COD; all nitrogenous components (9–12) are expressed as nitrogen.
[b] Coefficients must be multiplied by −1 to express as oxygen.

IAWQ – ASM 2

- In 1995, ASM 2 was released capable of tracking biological phosphorus flows.
- Now able to model enhanced biological phosphorus removal.

ASM 2

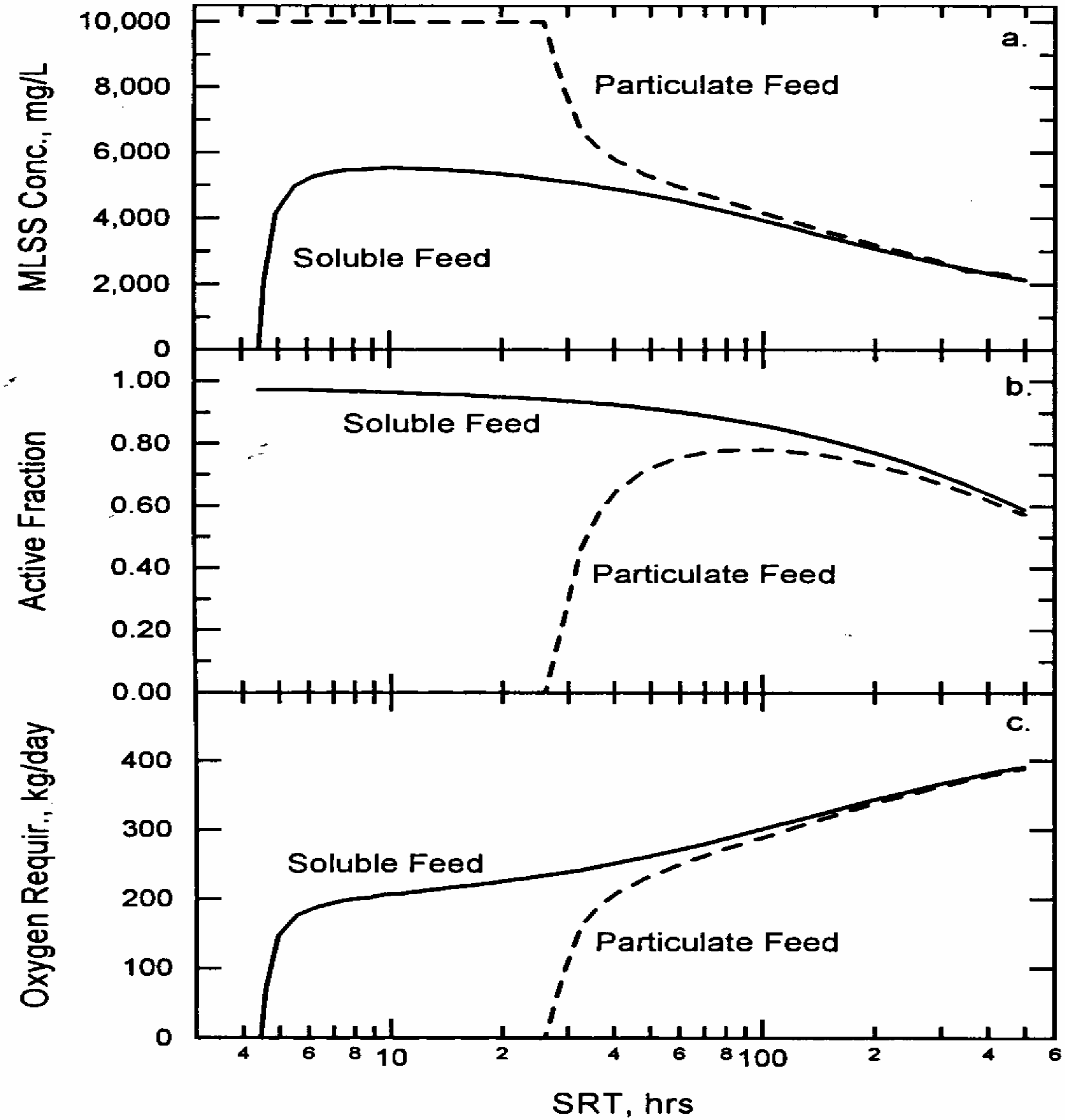
- Tracks 19 separate components through 19 processes.
- 22 stoichiometric coefficients and 42 kinetic parameters
- Ammonification and hydrolysis simplified to stoichiometric terms; i.e. rates implicit.
- Includes anaerobic fermentation, uptake of acetate, formation of PHB and PHAs, and release of soluble phosphate from hydrolysis of polyphosphate.
- Several assumptions made that constantly need revision as knowledge evolves.

Activated Sludge Models

- Cannot solve analytically.
- Use computer algorithm based on numerical techniques
  - SSSP, Bidstrup and Grady (MS-DOS based, ASM 1)
  - GPS-X, Hydromantis, Inc.
  - BioWin, EnvironSim Associates Limited.
  - ASIM & AQUASIM, Swiss Federal Institute of Aquatic Science and Technology, EAWAG.
  - EFOR, DHI, Inc.
  - STOAT, WRc Group.
  - WEST, Hemmis N. V.
  - SIMBA, IFAK-System GmbH.
- ASM 2 integrated into software algorithm provides a powerful tool.

Steady-state performance – Particulate versus Soluble

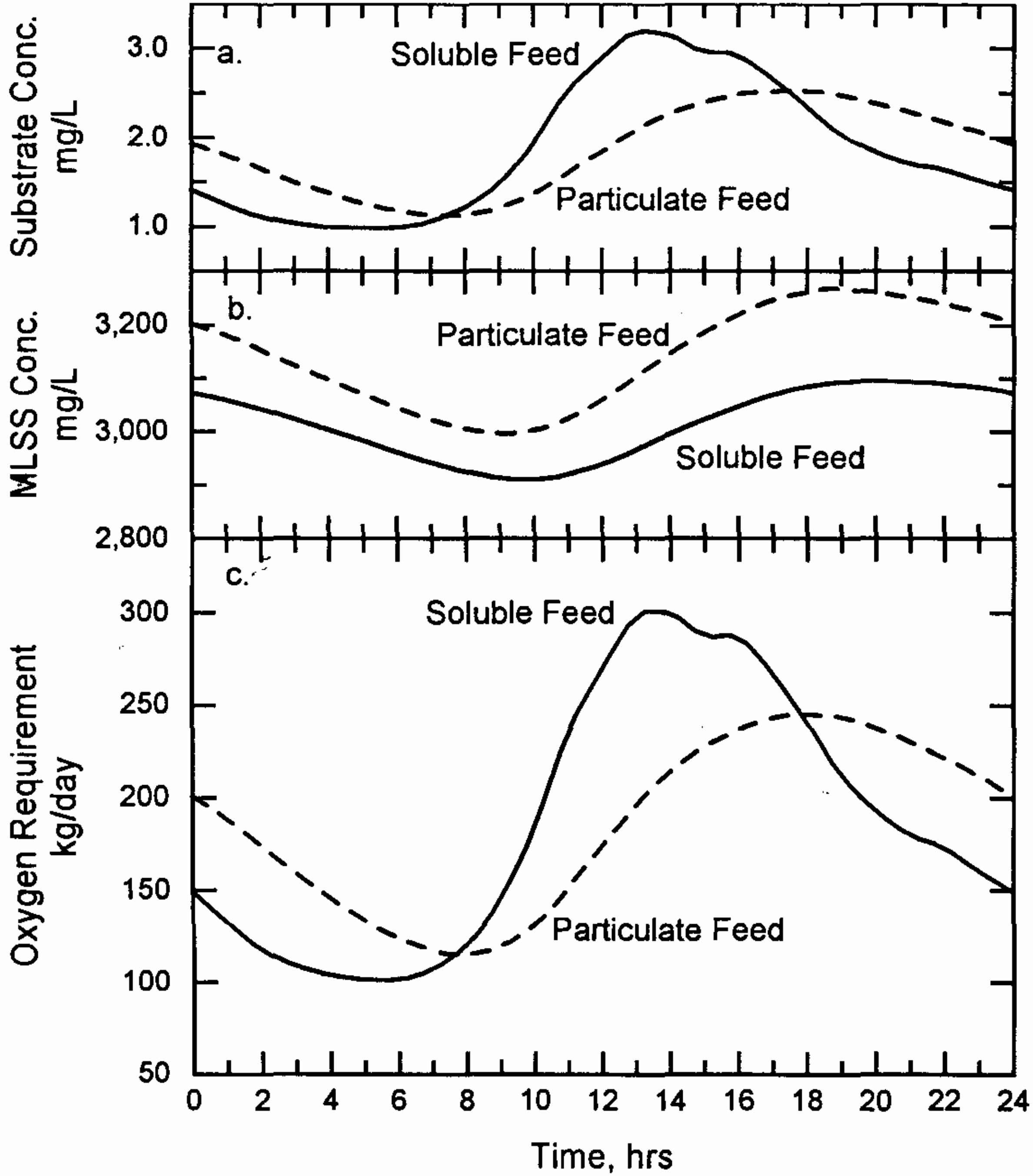
- Particulate hydrolysis is a rate limiting step.
- A particulate feed requires a longer SRT to achieve treatment.
- Particulates compose all of MLSS at low HRTs and active fraction is washed out.



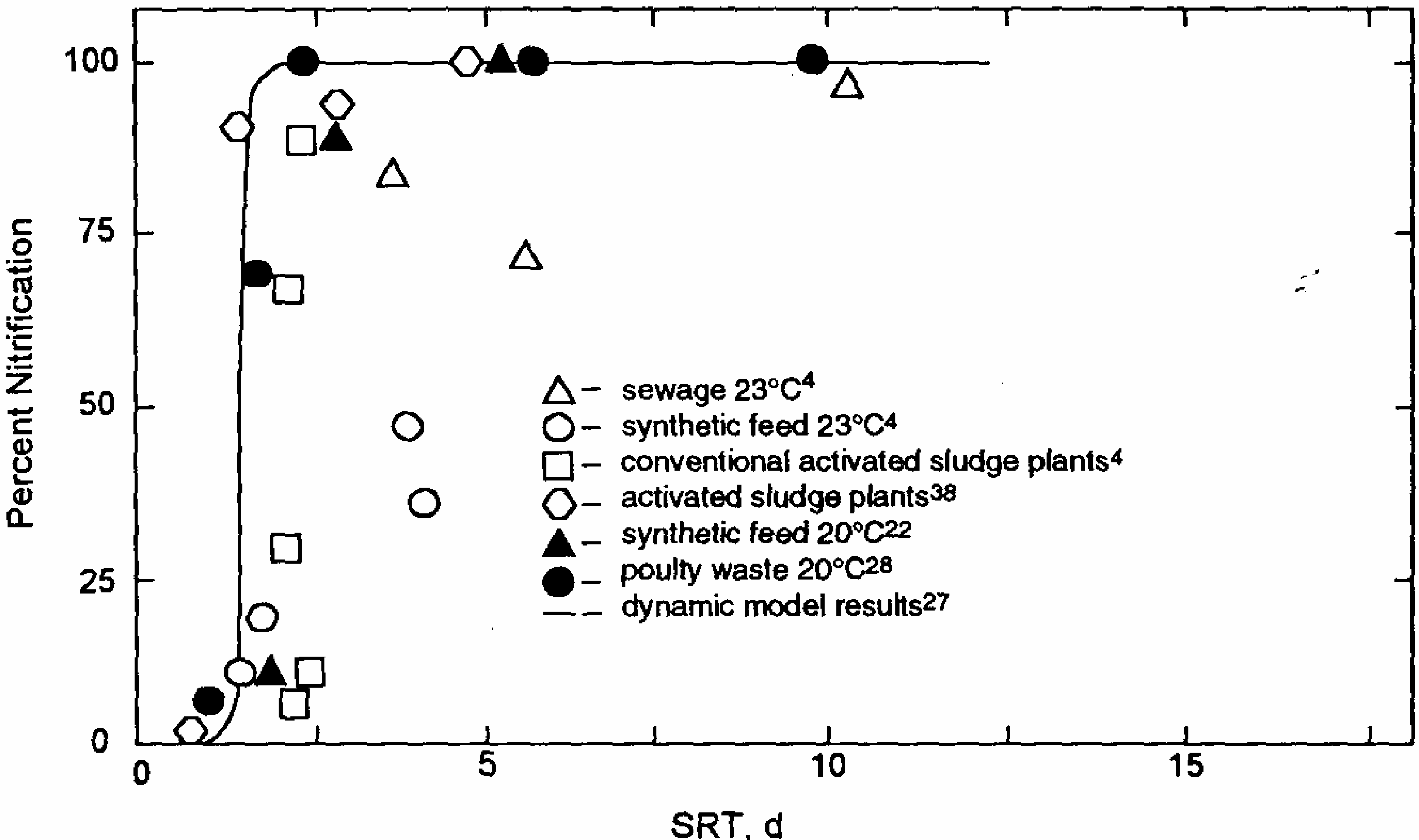
MLSS Conc., mg/L
10,000
8,000
6,000
4,000
2,000
0
a.
Particulate Feed
Soluble Feed
Active Fraction
1.00
0.80
0.60
0.40
0.20
0.00
b.
Soluble Feed
Particulate Feed
Oxygen Requir., kg/day
400
300
200
100
0
c.
Soluble Feed
Particulate Feed
4
6
8
10
2
4
6
8
100
2
4
6
SRT, hrs

Dynamic performance – Particulate and Soluble

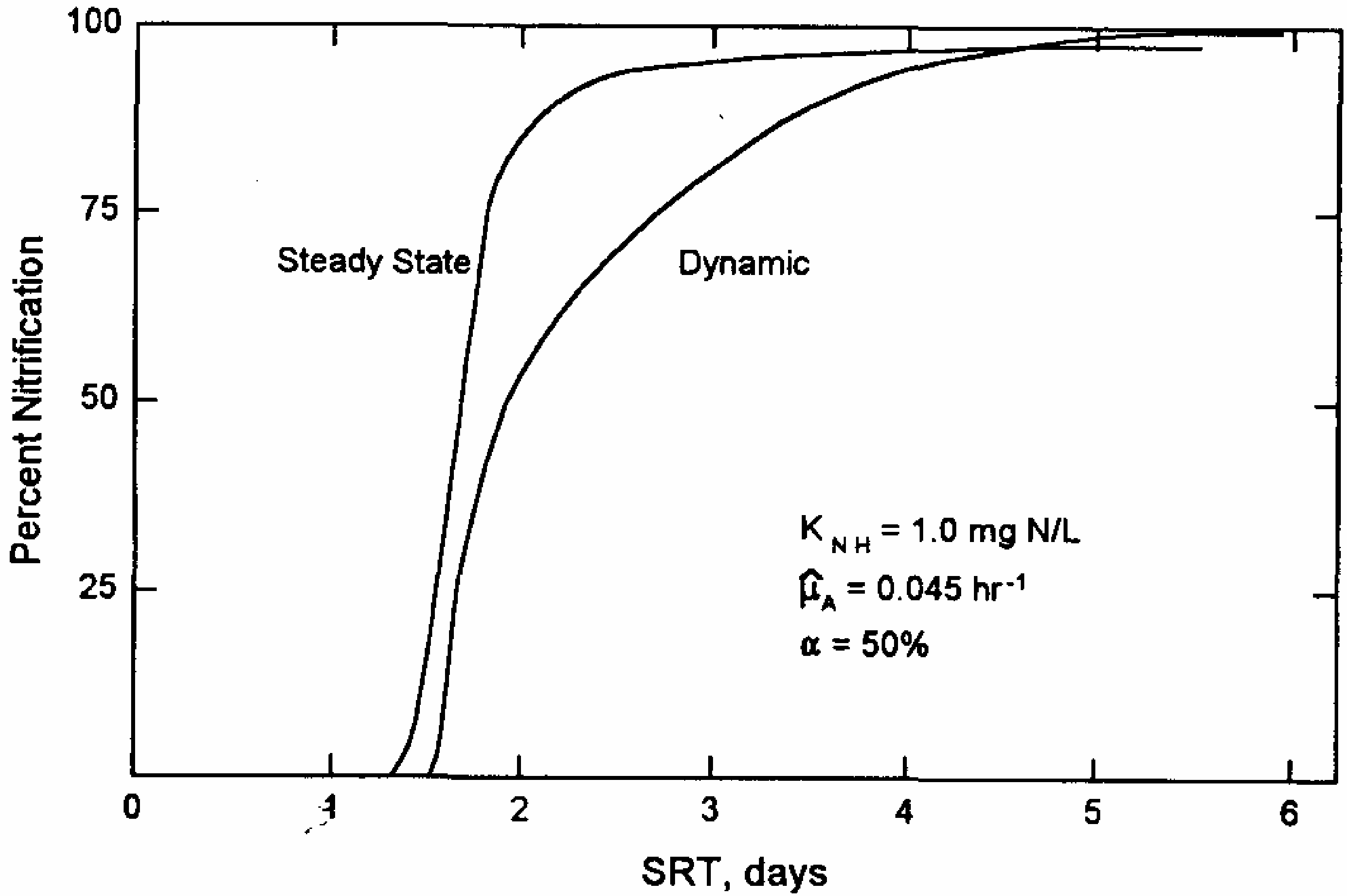
- Flow & substrate concentrations vary during diurnal pattern.
- Particulate and soluble feeds have different effects on performance.


Substrate Conc.
mg/L
3.0
2.0
1.0
a.
Soluble Feed
Particulate Feed
MLSS Conc.
mg/L
3,200
3,000
2,800
b.
Particulate Feed
Soluble Feed
Oxygen Requirement
kg/day
300
250
200
150
100
50
c.
Soluble Feed
Particulate Feed
0
2
4
6
8
10
12
14
16
18
20
22
24
Time, hrs

Nitrification – low μ_{max} and K_S

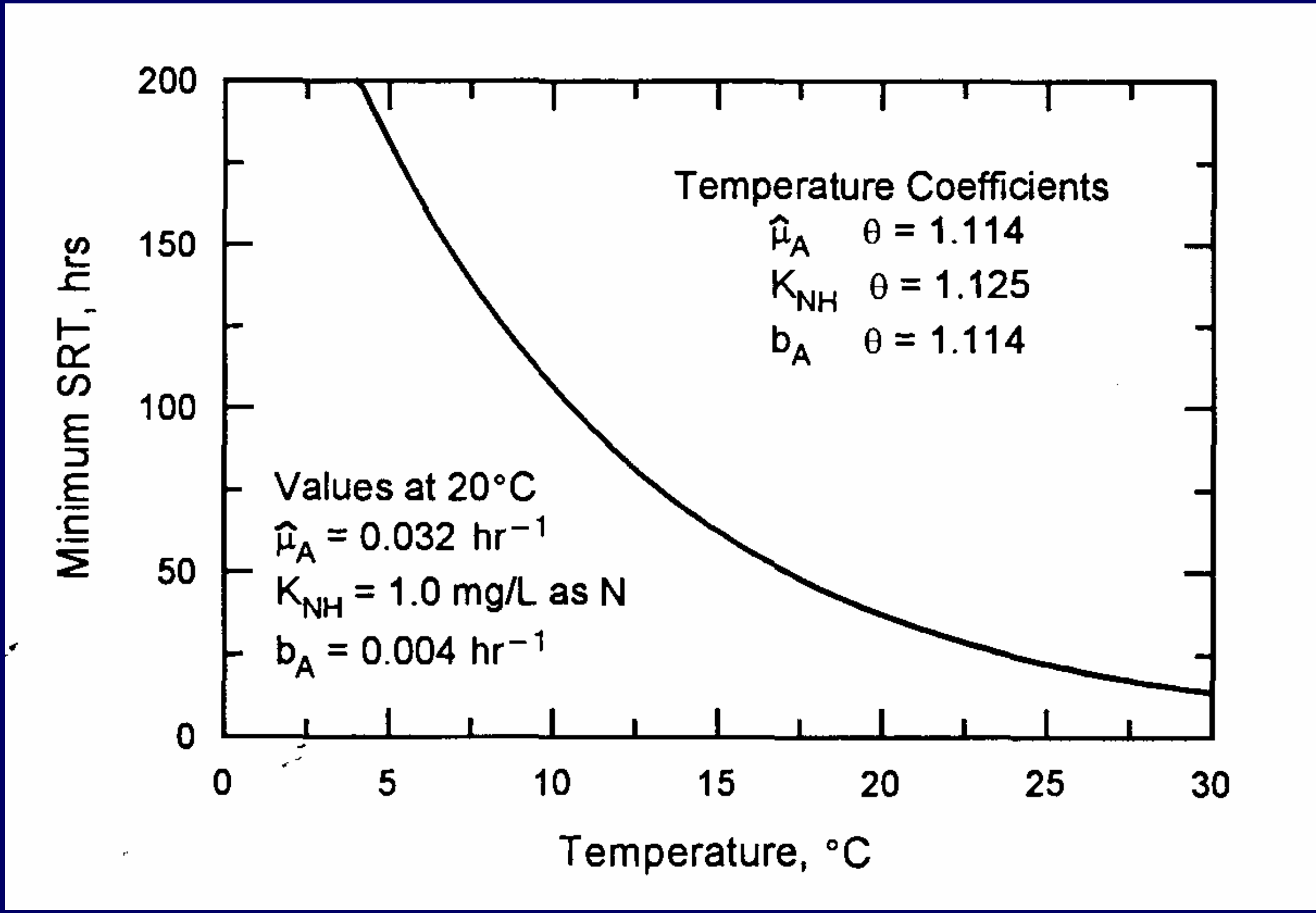


Diurnal flow has a negative effect on nitrification



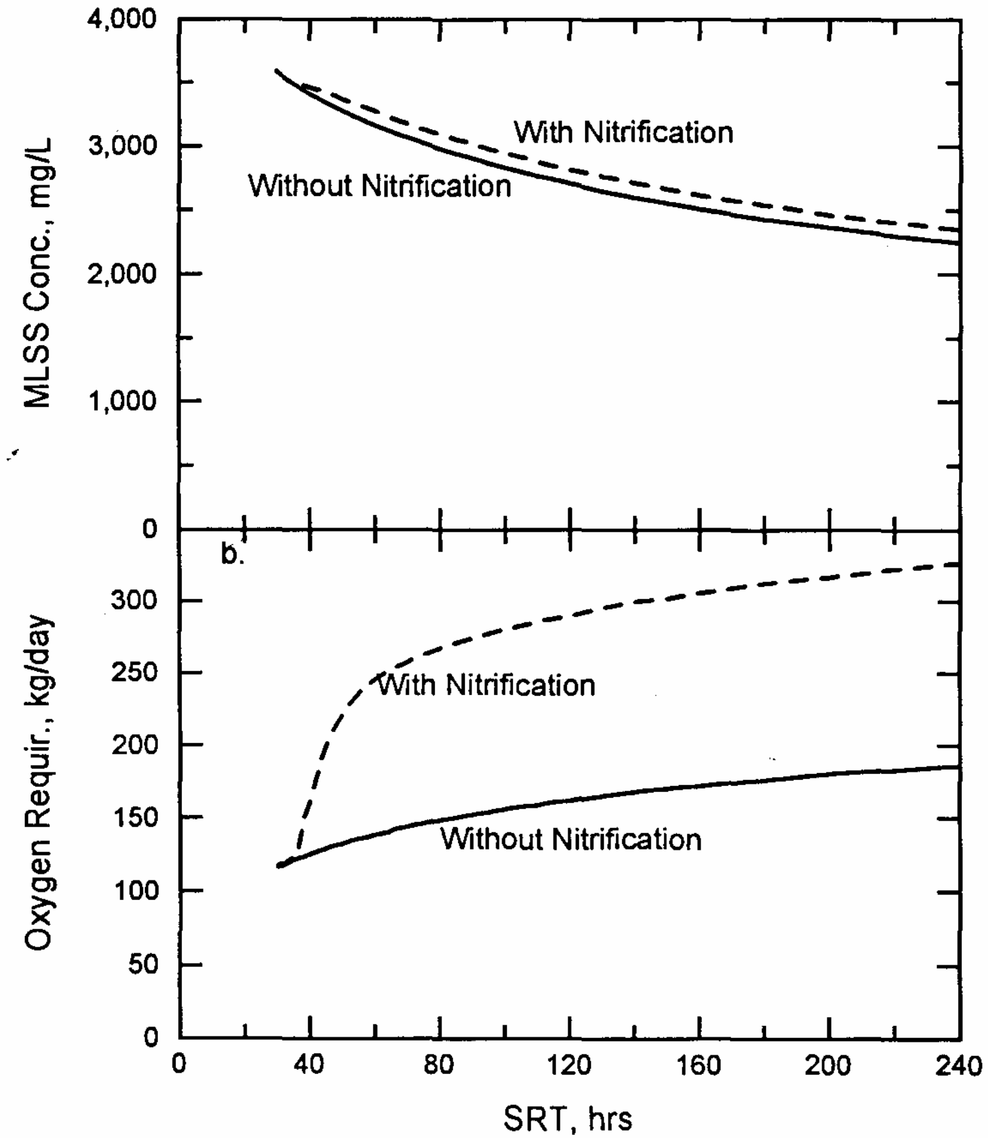
Nitrification

- Nitrifiers are affected by:
  - Temperature
  - Low oxygen concentrations
  - Inhibition by some organics



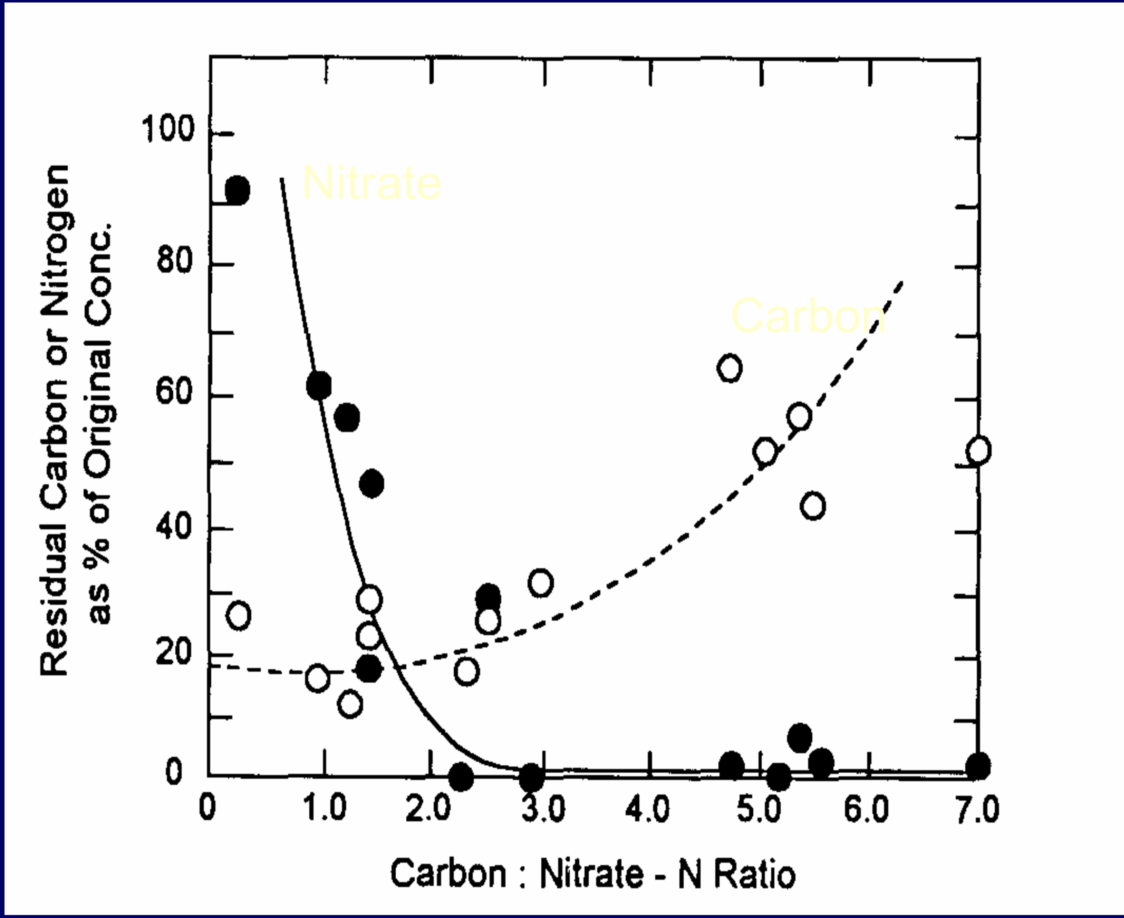
Nitrification

- Autotrophs are a small fraction of MLSS.
- Nitrification consumes large amount of oxygen.



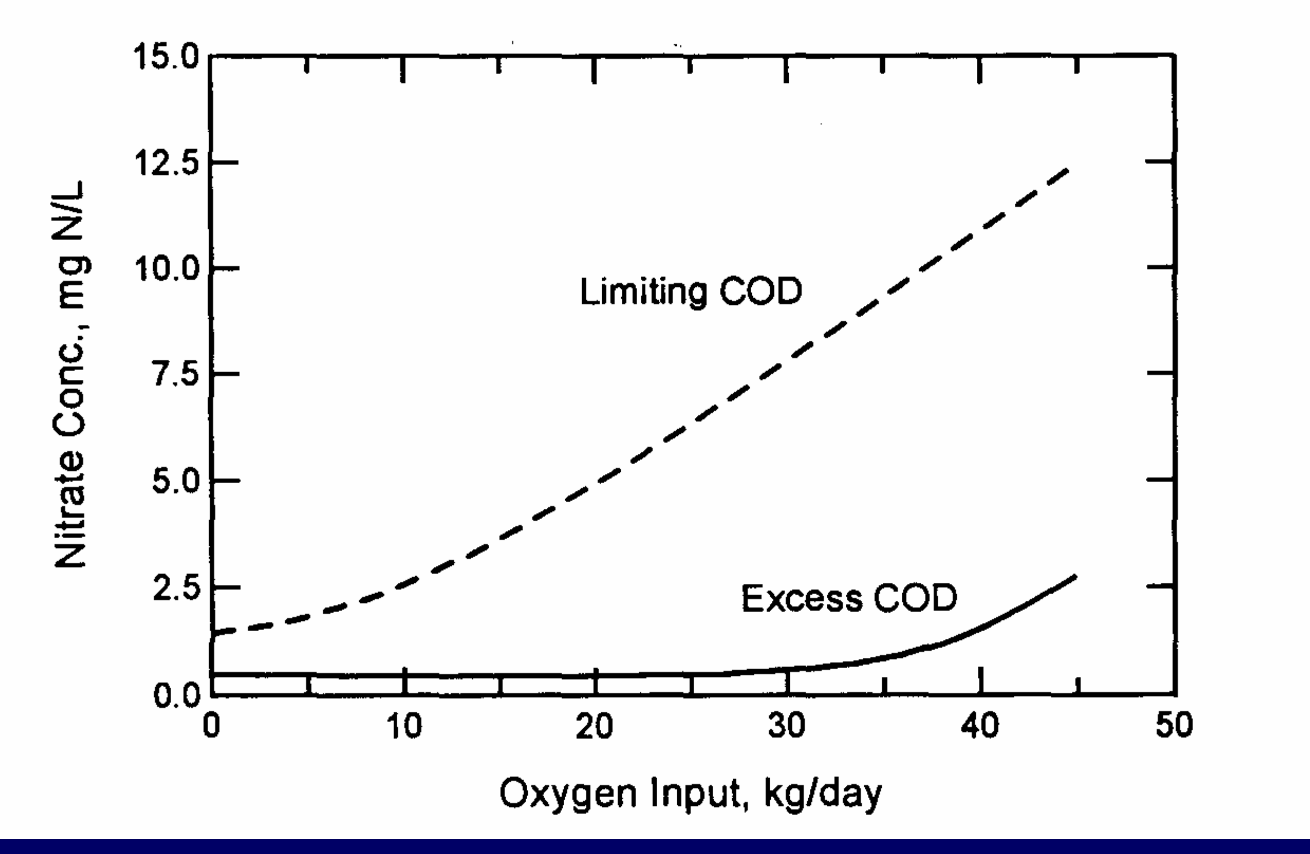
Denitrification

- Denitrification –
  - Organics are electron donor
  - Nitrates are electron acceptor
- Optimum Carbon to Nitrate ratio based on balance between electron donor and acceptor.



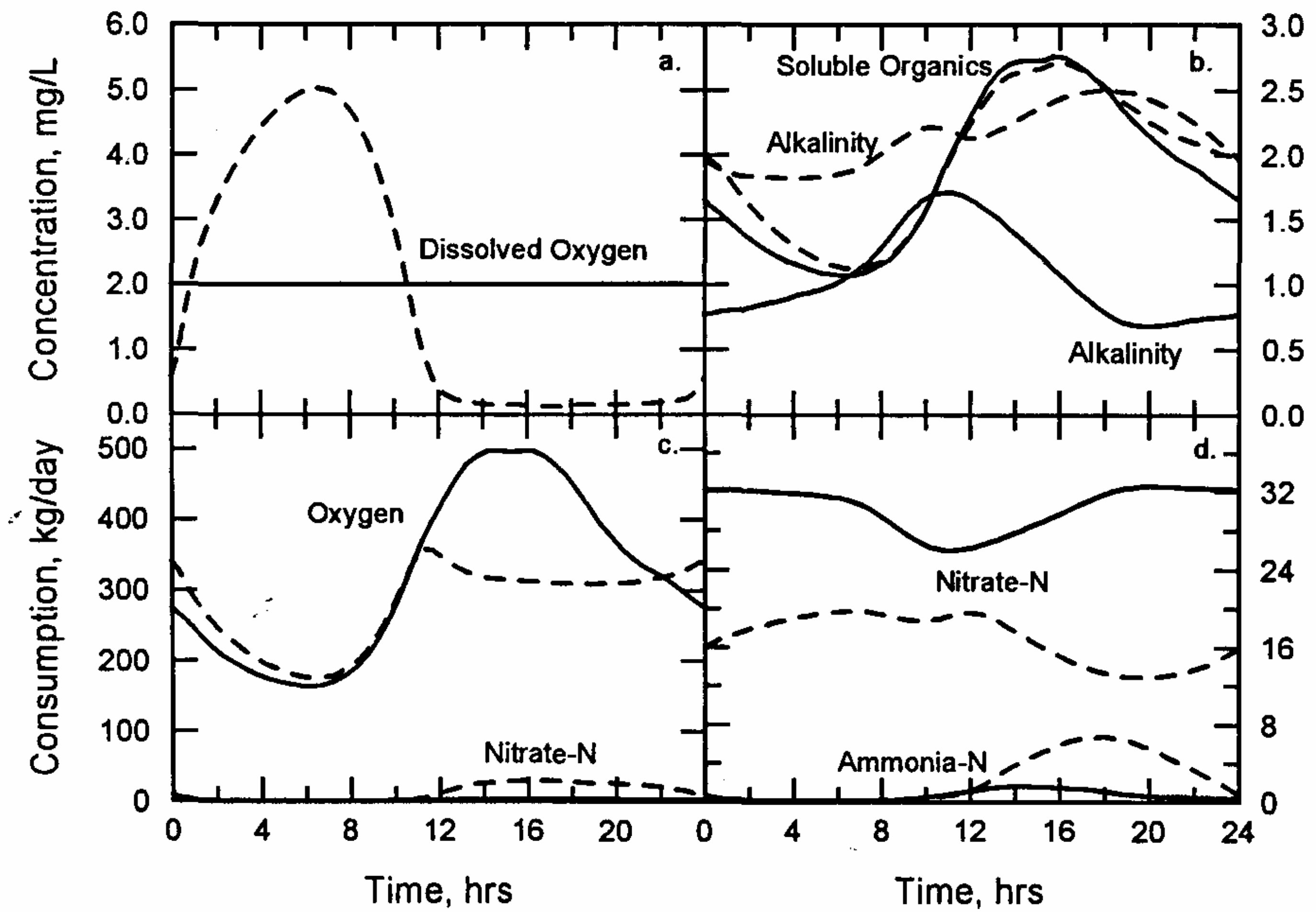
Denitrification

- Oxygen is preferred electron acceptor…



Diurnal flow with different aeration strategies

- Single CSTR may be set to:
  - Maintain a constant dissolved oxygen concentration in the tank
  - Constant oxygen flow into tank

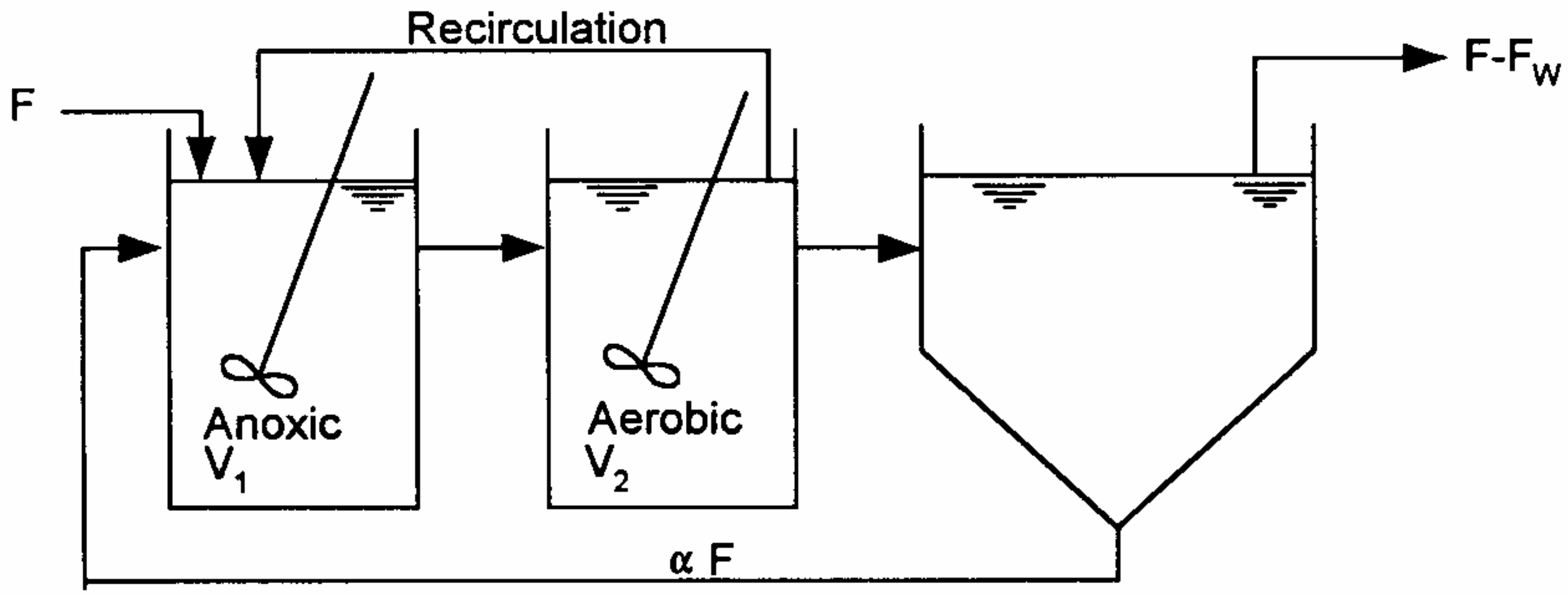


a.
b.
c.
d.
Dissolved Oxygen
Soluble Organics
Alkalinity
Alkalinity
Oxygen
Nitrate-N
Nitrate-N
Ammonia-N
Concentration, mg/L
Consumption, kg/day
Time, hrs
Time, hrs

Modified Ludzack Ettinger

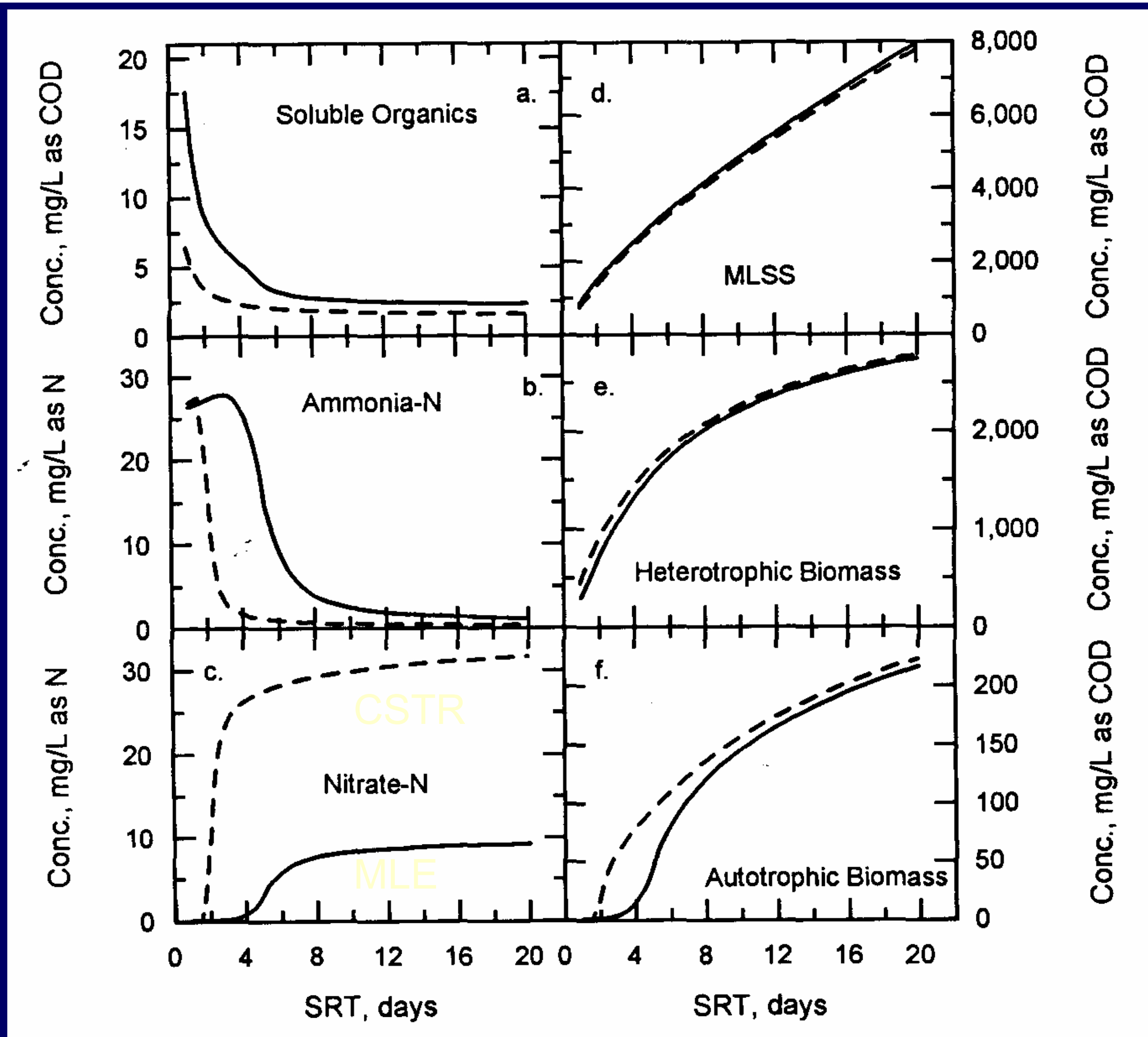
- Use an anoxic basin and an aerobic basin to select for denitrification after nitrification…

- Why denitrify?
- Where would you place anoxic selector in flow scheme?


Recirculation
F
F-F$_W$
Anoxic
V_1
Aerobic
V_2
α F

Effect of SRT on MLE

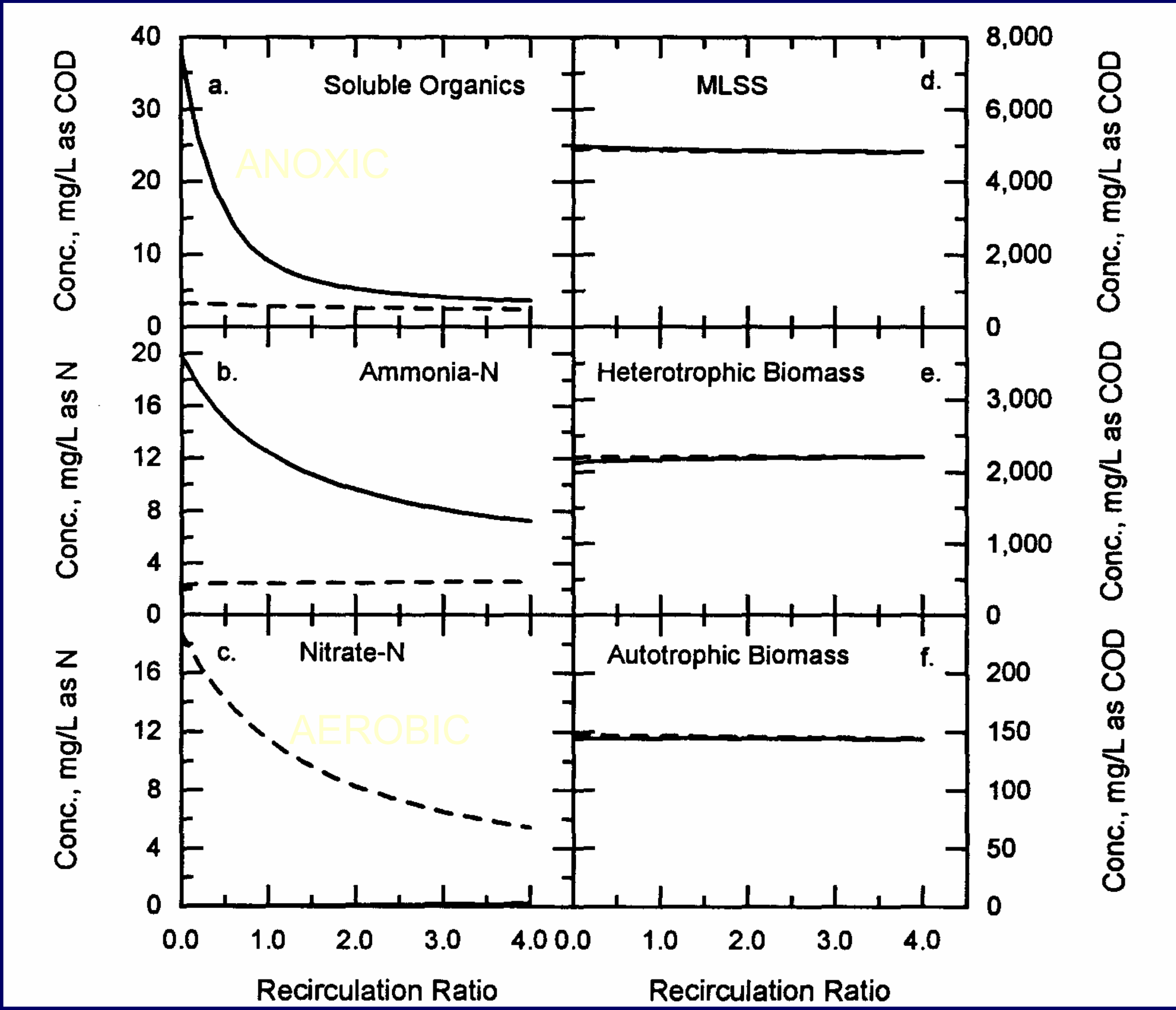
- SRT is biomass in system divided by biomass wasted from system where system includes both aerobic and anoxic basins…



Dashed lines indicate performance of a single CSTR of the same volume as the anoxic and aerobic reactors.

MLE

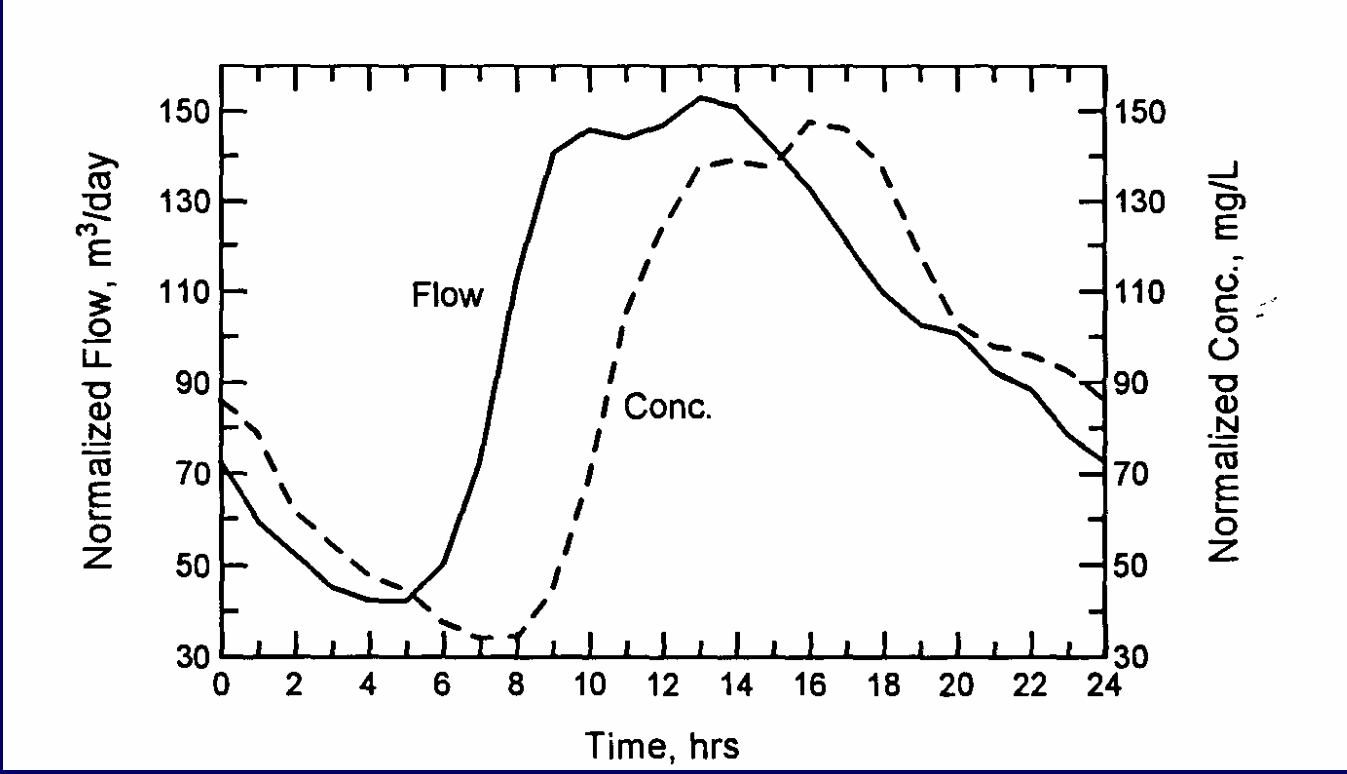
- Recycle affects performance in MLE
- Greater recycle leads to:
  - Nitrate flow into anoxic reactor and thus higher consumption of nitrates and organics.
  - Dilution of ammonia in anoxic reactor.



Solid lines indicate the anoxic (first) reactor and the dashed indicate The second (aerobic) reactor.

Diurnal Flow

- Wastewater flow and strength reflect activity of population.
- Expect diurnal flow pattern.



Diurnal Flow

- Dynamic flow results in lower performance.
- Performance not solely a function of SRT.
- Also depends on biomass change as a result of changing input.

Steady-state equation

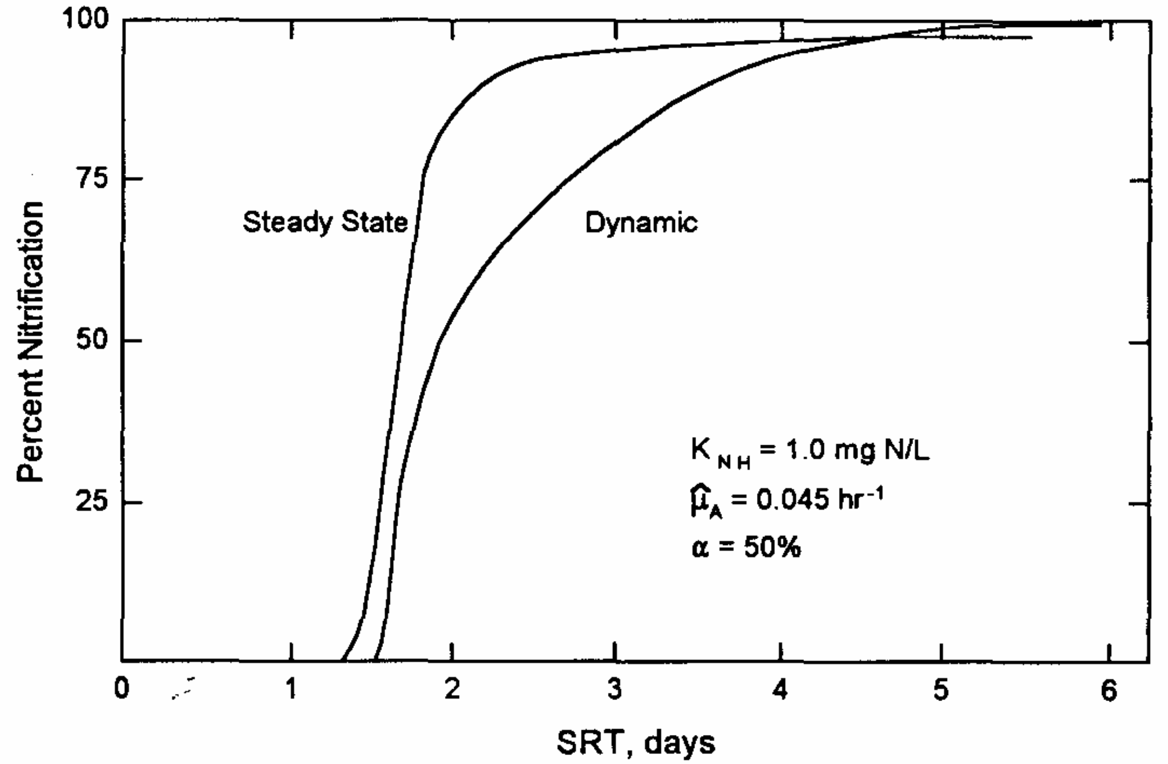
$$S = \frac{K_s(1 + b_H \theta_c)}{\theta_c(\hat{\mu}_H - b_H) - 1}$$

$$S = \frac{K_s(1 + b_H \theta_c + \frac{\theta_c}{X}\frac{dX}{dt})}{\theta_c(\hat{\mu}_H - b_H - \frac{1}{X}\frac{dX}{dt}) - 1}$$

Dynamic equation

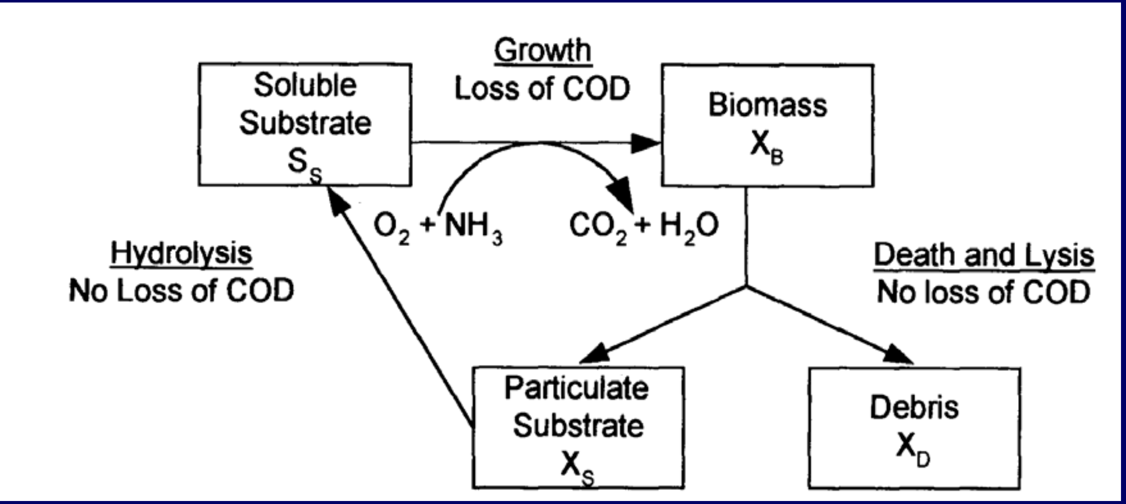
Diurnal Flow

- Recall effect of diurnal flow on flow weighted nitrification in CSTR.
- Must increase SRT to compensate for dynamic condition.



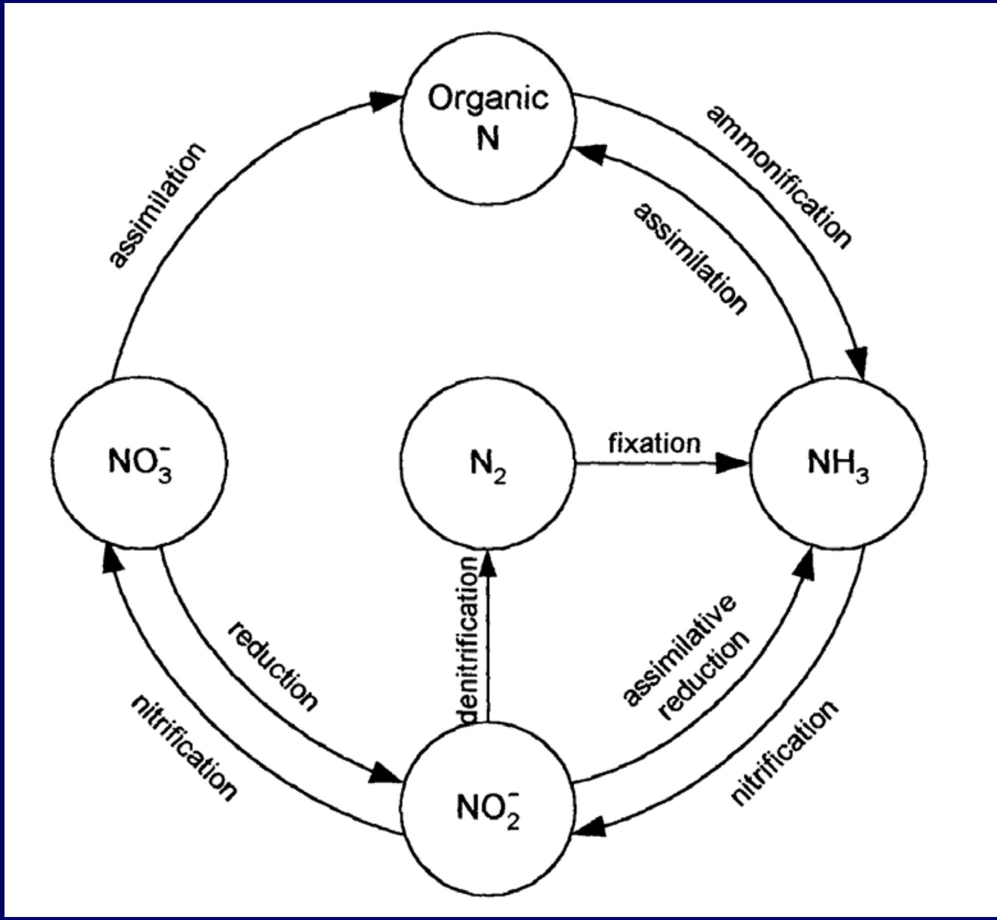
Active Populations

- Heterotrophs
  - Environment=Aerobic
- Electron Donor
  - Organics
- Electron Acceptor
  - Oxygen
- Benefits
  - Removes organics that suffocate or are toxic to the environment
- Drawbacks
  - Consumes Oxygen (Costs money)
  - Produces large amounts of sludge



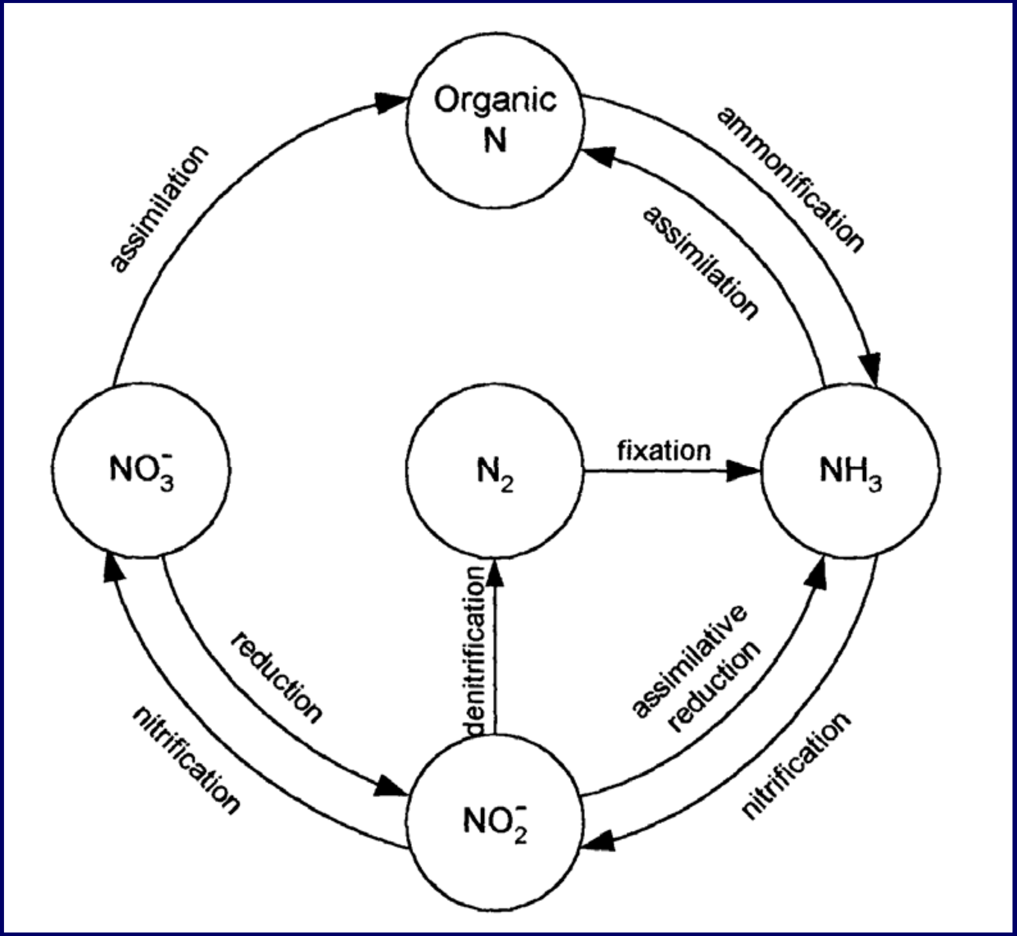
Active Populations

- Heterotrophs
  - Environment=Anoxic
- Electron Donor
  - Organics
- Electron Acceptor
  - Nitrates
- Benefits
  - Removes nitrates
  - Reduces oxygen use
  - Generates alkalinity
- Drawbacks
  - Anoxic environment may be difficult to create



Active Populations

- Autotrophs
  - Environment =Aerobic
- Electron Donor
  - Ammonia
- Electron Acceptor
  - Oxygen
- Benefits
  - Removes ammonia
- Drawbacks
  - High oxygen consumption
  - Reduces alkalinity

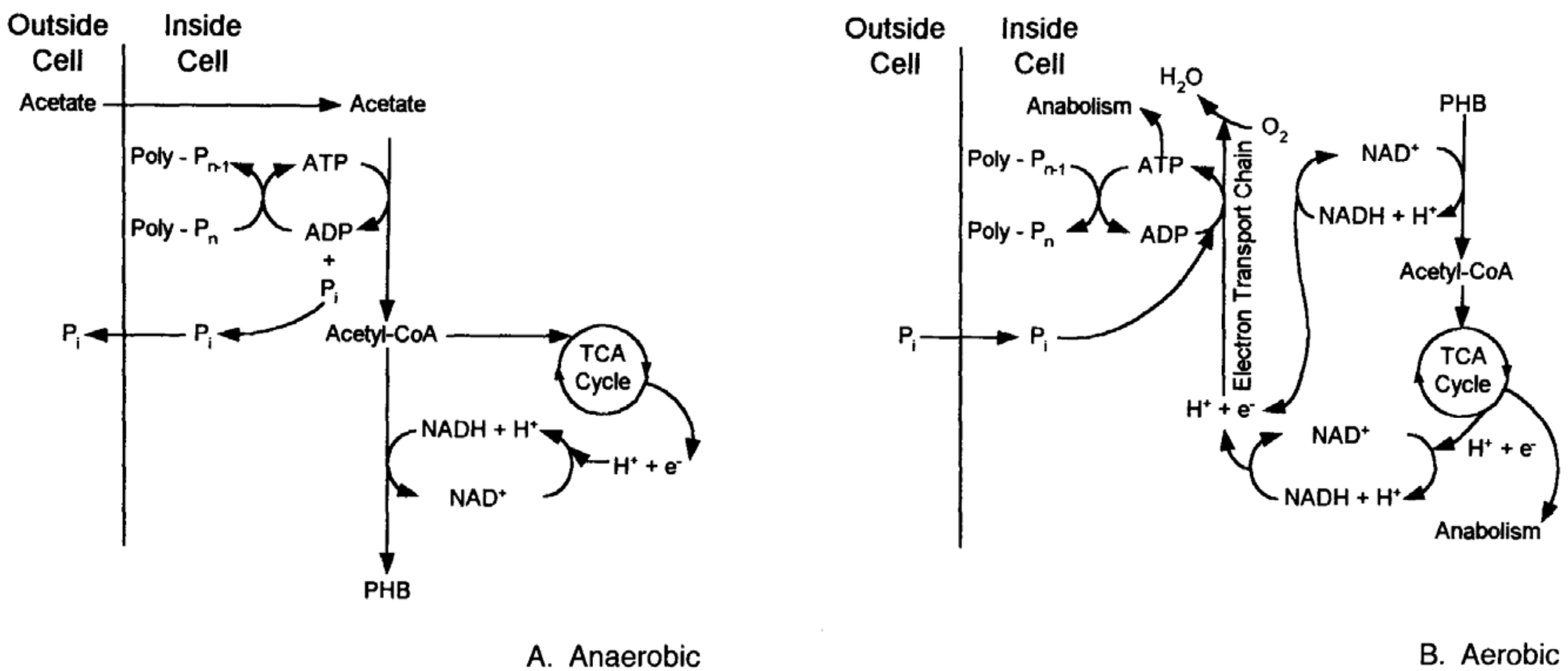


Active Populations

- Phosphate Accumulating Organisms
  - Environment=Anaerobic/Aerobic

- Benefits
  - Removes Phosphorus
- Drawbacks
  - Complex life cycle
    - Requires numerous recycle lines
  - Phosphorus rich sludge

EBPR


Outside Cell
Inside Cell
Acetate
Acetate
Poly - P_{n-1}
ATP
Poly - P_n
ADP
+
P_i
P_i
P_i
Acetyl-CoA
TCA Cycle
NADH + H^+
H^+ + e^-
NAD^+
PHB
A. Anaerobic
Outside Cell
Inside Cell
H_2O
Anabolism
O_2
PHB
Poly - P_{n-1}
ATP
NAD^+
NADH + H^+
Poly - P_n
ADP
Electron Transport Chain
Acetyl-CoA
P_i
P_i
TCA Cycle
H^+ + e^-
NAD^+
H^+ + e^-
NADH + H^+
Anabolism
B. Aerobic

Virginia Initiative Plant

- System to remove:
  - Organics
  - Nitrogen
    - Ammonia
    - Nitrates
  - Phosphorus
- Environments needed:
  - Aerobic
  - Anoxic
  - Anaerobic
- System configuration?

Virginia Initiative Plant

- System configuration:
  - Anaerobic
  - Anoxic
  - Aerobic

  - Recirculation
    - RAS to Anoxic
    - MLR from Aerobic to RAS
    - MLR from Anoxic to Anaerobic

VIP

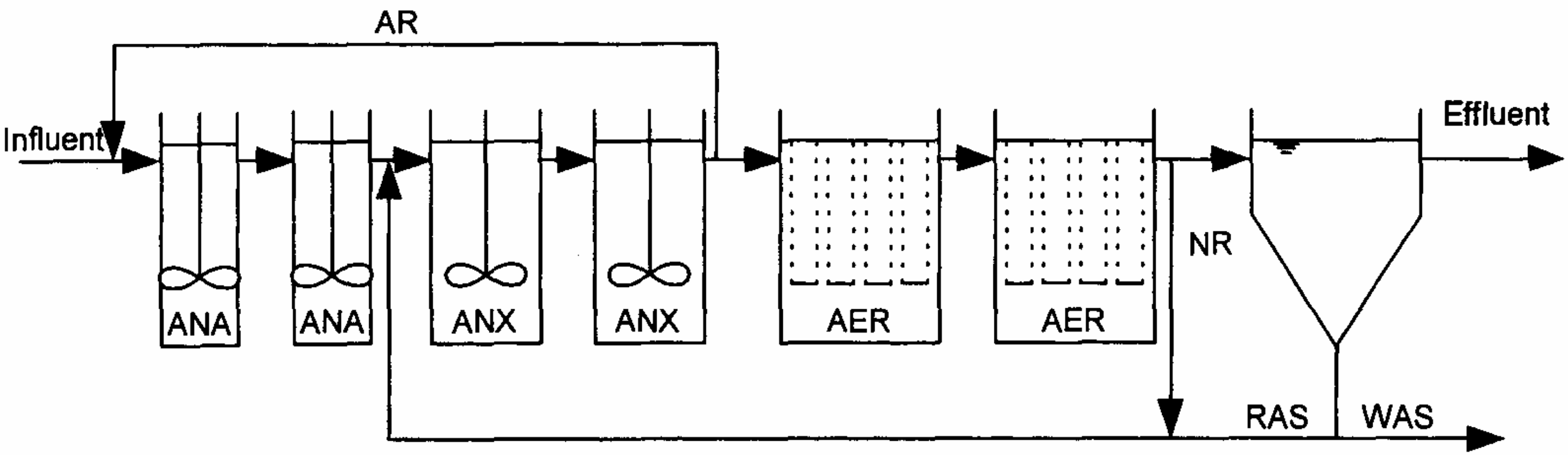


Figure 11.13 VIP process.

VIP

- Benefits?
- Drawbacks?

Table 11.2 Biological Nutrient Removal Process Comparison

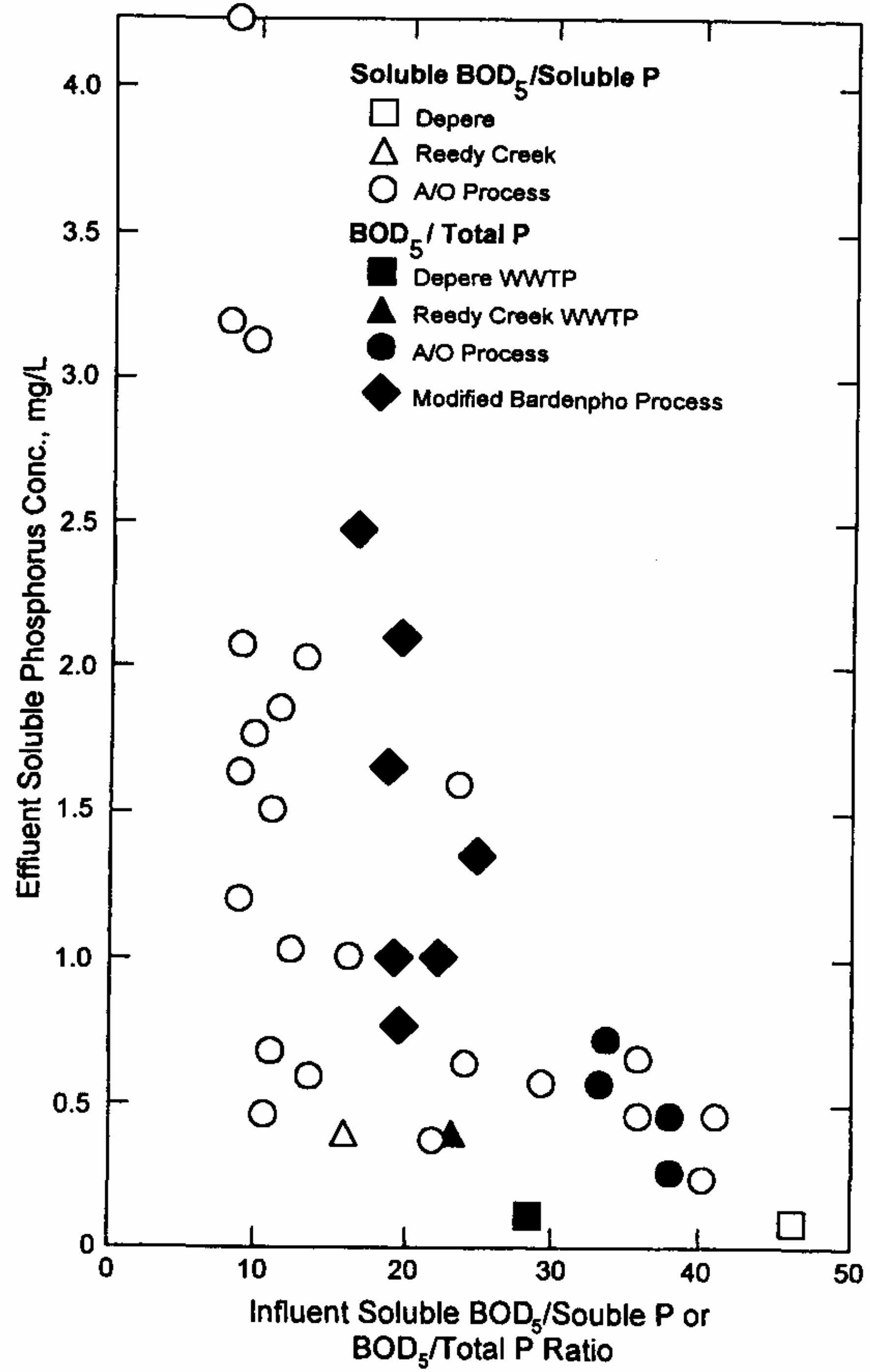
Process	Benefits	Drawbacks
Nitrogen Removal		
MLE	• Good nitrogen removal • Moderate reactor volume • Alkalinity recovery • Good solids settleability • Reduced oxygen requirement • Simple control	• High level of nitrogen removal not generally possible
Four-stage Bardenpho	• Excellent nitrogen removal • Alkalinity recovery • Good solids settleability • Reduced oxygen requirement • Simple control	• Large reactor volume
Denitrification in aerobic reactor	• Alkalinity recovery • Reduced energy requirement • Easily applied to some existing facilities	• Large reactor volume • Complex control • May result in poor sludge settleability
Separate stage suspended growth denitrification	• Excellent nitrogen removal • Minimum reactor volume	• Requires upstream nitrification • Supplemental electron donor required • High energy requirement
Phosphorus Removal		
A/O™	• Minimum reactor volume • Good phosphorus removal • Good solids settleability • Simple operation	• Phosphorus removal adversely impacted if nitrification occurs
Phostrip®	• Excellent phosphorus removal	• Complex operation • Phosphorus removal adversely impacted if nitrification occurs
Nitrogen and Phosphorus Removal		
A^2/O™	• Good nitrogen removal • Moderate reactor volume • Alkalinity recovery • Good solids settleability • Reduced oxygen requirement • Simple control	• High level of nitrogen removal not generally possible • Moderate phosphorus removal
VIP and UCT	• Good nitrogen removal • Good phosphorus removal • Moderate reactor volume • Alkalinity recovery • Good solids settleability • Reduced oxygen requirement • Simple control	• High level of nitrogen removal not generally possible • An additional MLR step is required
Five-stage Bardenpho	• Excellent nitrogen removal • Alkalinity recovery • Good solids settleability • Reduced oxygen requirement	• Large reactor volumes • Moderate to poor phosphorus removal

VIP

VIP and UCT	• Good nitrogen removal • Good phosphorus removal • Moderate reactor volume • Alkalinity recovery • Good solids settleability • Reduced oxygen requirement • Simple control	• High level of nitrogen removal not generally possible • An additional MLR step is required

VIP

- Important consideration:
  - BOD_5/Total P ratio



Virginia Initiative Plant

- $BOD_5/\Delta P$ ratio needed for VIP Process?
  - 15-20 mg BOD_5/mg P

Table 11.4 BOD_5 and COD to Phosphorus Removal Ratios for Various BPR Processes

Type of BPR process	$BOD_5/\Delta P$ ratio (mg BOD_5/mg P)	$COD/\Delta P$ ratio (mg COD/mg P)
High efficiency (e.g., A/O™ without nitrification, VIP, UCT)	15–20	26–34
Moderate efficiency (e.g., A/O™ and A^2/O™ with nitrification)	20–25	34–43
Low efficiency (e.g., Bardenpho)	>25	>43