Designing Single-Sludge Bionutrient Removal Systems

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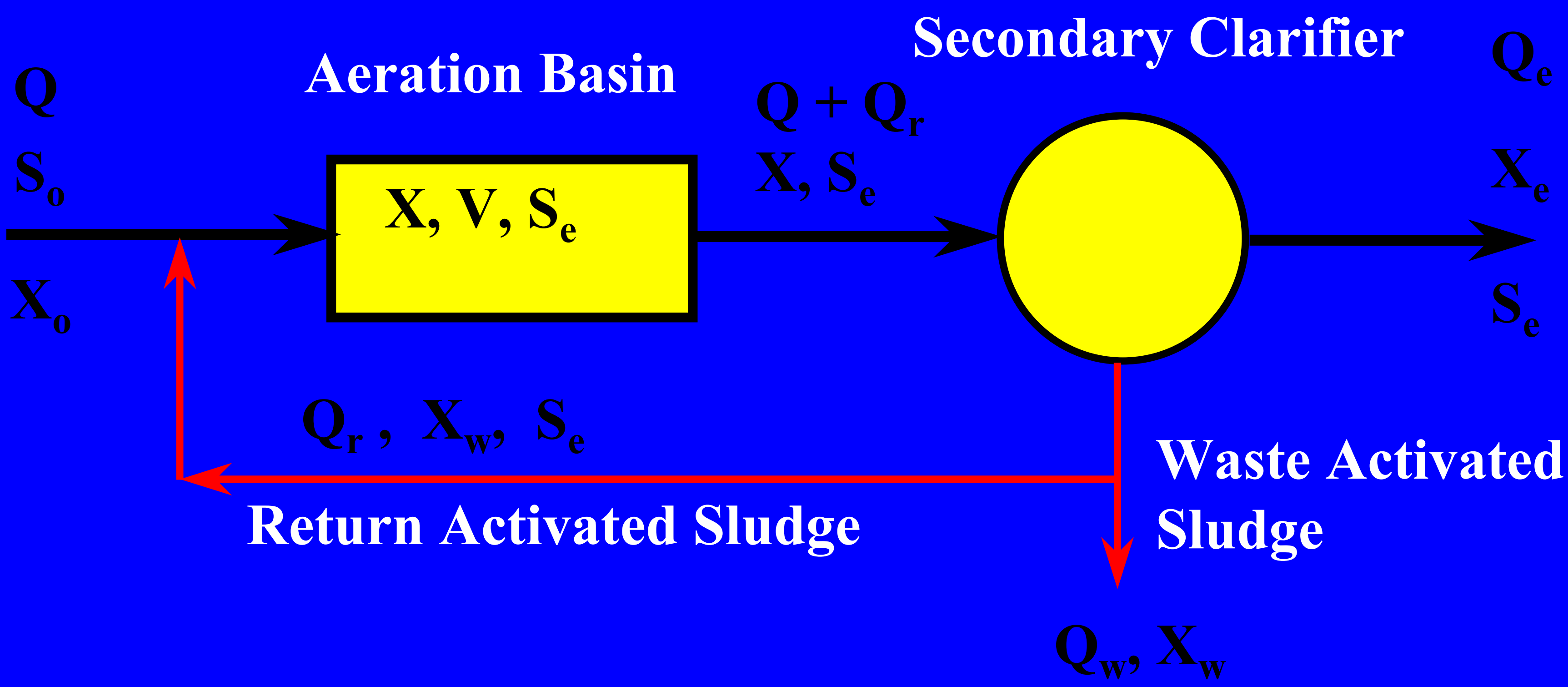
Activated Sludge Background

- Activated Sludge
  - Schematic
  - Microbial composition
  - Substrate utilization
  - Solids retention time (SRT)
  - Nitrification stoichiometry

Activated Sludge Background Continued

- Biokinetic Equations
  - Substrate
  - Biomass
  - Sludge Production
  - Oxygen Requirements

ACTIVATED SLUDGE FLOW SCHEMATIC



Microbial Composition

$$C_{60} H_{87} O_{23} N_{12} P_1$$

$$MW = 1374$$

$$12.2\% \ Nitrogen \quad by \ Weight$$

$$2.3\% \ Phosphorus \quad by \ Weight$$

Substrate Utilization

$$C + O_2 \xrightarrow{Heterotrophs} CO_2 + Energy$$

$$C + N + P + C_{60}H_{87}O_{23}N_{12}P \rightarrow New\ Biomass \quad C_{60}H_{87}O_{23}N_{12}P$$

$$+ \quad CO_2 \quad + \quad NH_3 \quad + \quad PO_4^-$$

Solids Retention Time (SRT)

$$SRT\,(days) = \frac{Total\ Biomass\ in\ System}{Biomass\ Wasted\ from\ System}$$

Nitrification
(neglecting synthesis)

$$NH_4^+ + 2O_2 \xrightarrow{Nitrifiers} NO_3^- + 2H^+ + H_2O$$

4.57 kg of oxygen required per kg of NH_4^+ - N oxidized

7.14 kg of alkalinity as $CaCO_3$ consumed per kg of NH_4^+ - N oxidized.

Effluent Soluble Substrate Concentration

$$S_e = \frac{K_S \, (1 + b\, SRT\,)}{SRT\,(Y\,k - b) - 1}$$

Biomass Concentration

$$X = \frac{Y\,(S_o - S_e)\;\; SRT}{(\,1 \,+ b\,SRT)\quad \theta}$$

Waste Sludge Production

$$P_X = \frac{Y\,Q\,(S_o - S_e)}{1 + b\,SRT}$$

O_2 Requirements

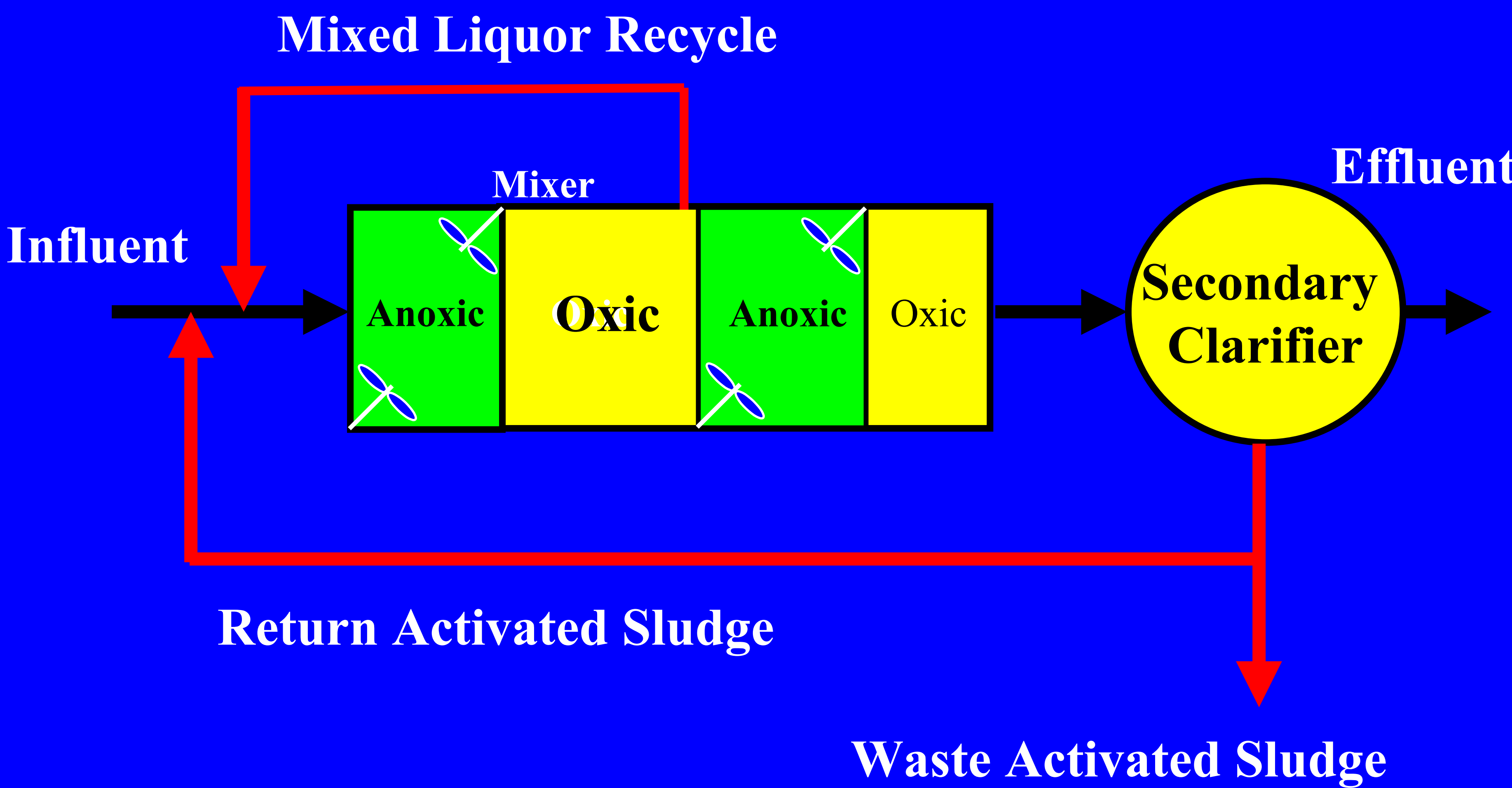
$$O_2 = Q(1+1.42Y)(S_o - S_e) + 1.42\,b\,XV + NOD$$

$$NOD = Q\,(TKN_o)\,(4.57)$$

Biological Nitrogen Removal

- Schematic
- Denitrification stoichiometry
- Pre-anoxic zone sizing
- Post-anoxic zone sizing

Pre- & Post-Denitrification Systems



Denitrification

$$6\,NO_3^- + 2\,CH_3OH \rightarrow 6\,NO_2^- + 2\,CO_2 + 4\,H_2O$$

$$6\,NO_2^- + 3\,CH_3OH \rightarrow 3N_2 + 3\,CO_2 + 3\,H_2O + 6\,OH^-$$

$$6\,NO_3^- + 5\,CH_3OH \xrightarrow{Denitrifiers} 3N_2 + 5\,CO_2 + 7\,H_2O + 6\,OH^-$$

3.57 kg of alkalinity produced per kg of NO_3^- N reduced.

2.86 kg of oxygen available per kg of NO_3^- N reduced.

Pre-Anoxic Zone Sizing

$$SDNR_1 = 0.03\left(F/M\right)_1 + 0.029$$

$$\left(F/M\right)_1 = Q\,S_o/\left(X\,V_1\right)$$

(Burdick *et al., 1982)*

$$SDNR_1 = Specific\ denitrification\ rate(pre-anoxic), days^{-1}$$

$$V_{ANOXIC} = \frac{TNOR(1000\ g/kg) - 0.03(S_o)(Q)(1.06)^{T-20}}{0.029(X)(1.06)^{T-20}}$$

Post-Anoxic Zone Sizing

$$SDNR_2 = 0.12\left(SRT\right)_{Overall}^{-0.706}\left(1.02\right)^{\left(T^\circ C - 20^\circ C\right)}$$

(Burdick *et al., 1982)*

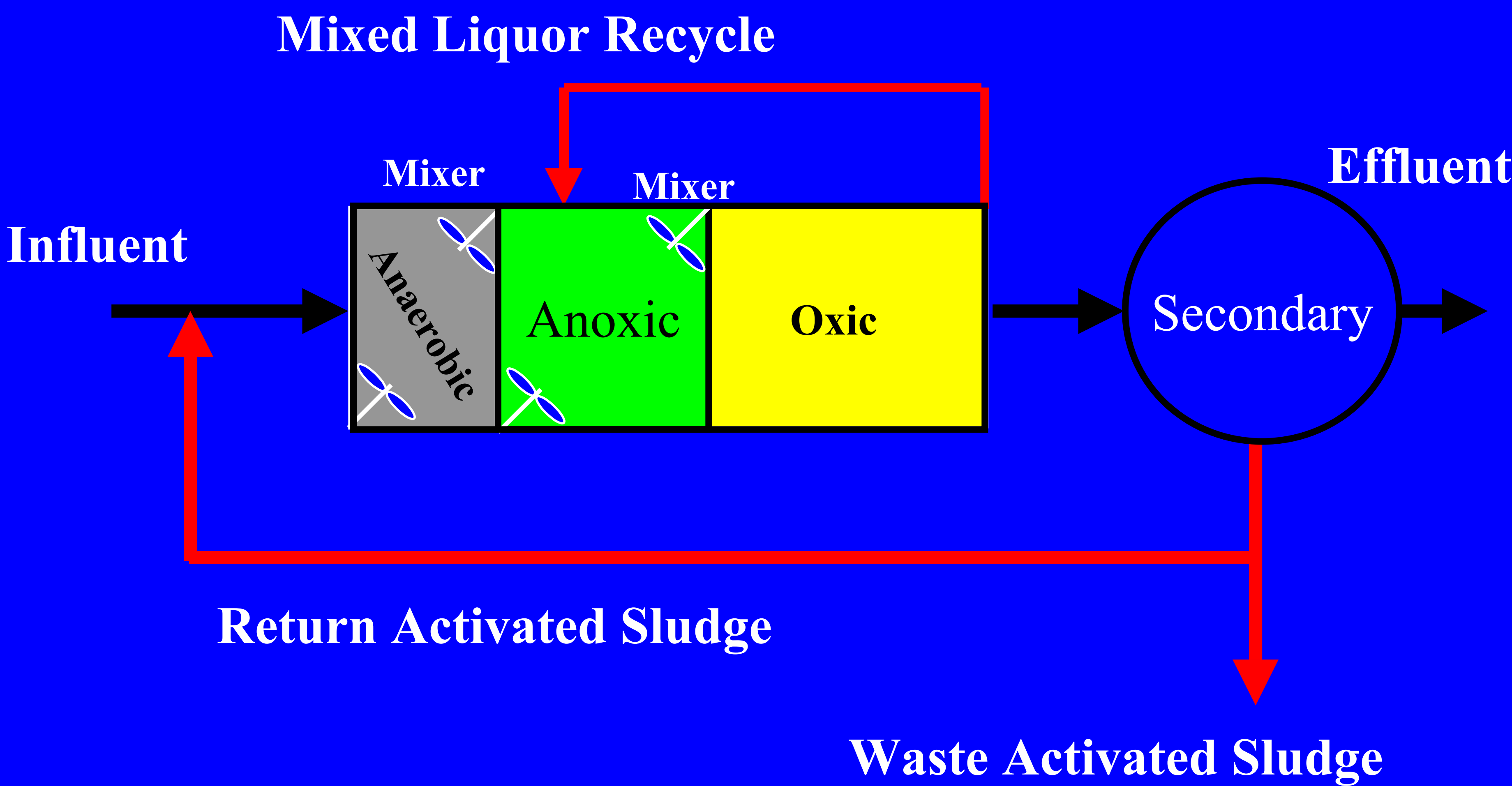
$$SDNR_2 = Specific\ denitrification\ rate, d^{-1}$$

$$V_{Anoxic_2} = \frac{TNOR_2\left(1000\ g/kg\right)}{\left(X\right)\left(SDNR_2\right)}$$

Enhanced Biological Phosphorus Removal (EBPR)

- Schematic: anaerobic zone precedes aerobic zone.
- ***Acinetobacter*** phosphorus composition
- Anaerobic or fermentation zone sizing

Anaerobic/Anoxic/Oxic System



Acinetobacter Composition

4 to 8 % Phosphorus by weight

Anaerobic/Fermentation Zone Sizing

P Removed = TP_o – SP

P Removed = mg/L of phosphorus removed,

TP_o = Influent total phosphorus concentration into biological process, mg/L, and

SP = Effluent soluble phosphorus from process, mg/L.

Volume of Anaerobic Zone
COD:TP ratio = 20:1 to 43:1

$$V_{Anaerobic} = Q\left[0.2557\left(P\,\mathrm{Re}\,moved\right) - 0.7242\right]\left(\frac{1\,d}{24\,h}\right)$$

$V_{anaerobic}$ = Volume of anaerobic zone, m^3

Equation developed from the data developed by Randall et al., 1992.

Volume of Anerobic Zone COD:TP ratio = 40:1 to 69:1

$$V_{Anaerobic} = Q\left[0.8850(P\mathrm{Re}\,moved) - 2.3742\right]\left(\frac{1d}{24h}\right)$$

$V_{anaerobic}$ = Volume of anaerobic zone, m^3

Equation developed from the data developed by Randall et al., 1992.

Design Procedure

- Size the aerobic zone based on the "washout" point of *Nitrosomonas*.
- Size the pre-anoxic zone using the specific denitrification equation developed by Burdick et al., 1982.
- Size the anaerobic zone using the equations developed by Randall et al., 1992.

Heterotrophic Biokinetic Coefficients

Heterotrophic Biokinetic Constants at 20EC

Y	**= 0.6 g VSS/g BOD_5**	**b**	**= 0.06 $days^{-1}$**
k	**= 5 $days^{-1}$**	**K_s**	**= 60 mg/L BOD_5**

Heterotrophic Biokinetic Constants at 15EC

Y	**= 0.6 g VSS/g BOD_5**	**b**	**= 0.05 $days^{-1}$**
k	**= 3.2 $days^{-1}$**	**K_s**	**= 39 mg/L**

A temperature correction coefficient (1) of 1.04 was used for correcting b whereas a 1 of 1.09 was used for correcting k and K_s.

Autotrophic Biokinetic Coefficients

Nitrosomonas Biokinetic Constants at 20EC

Y_{NS} = 0.15 g VSS/g NH_4^+ - N

b_{NS} = 0.05 $days^{-1}$

k_{NS} = 3 $days^{-1}$

K_{NS} = $10^{0.051T-1.148}$ = 0.74 mg/L

Nitrosomonas Biokinetic Constants at 15EC

Y_{NS} = 0.15 g VSS/g NH_4^+ - N

b_{NS} = 0.04 $days^{-1}$

k_{NS} = 1.95 $days^{-1}$

K_{NS} = $10^{0.051 T-1.148}$ = 0.41 mg/L

A temperature correction coefficient (1) of 1.04 was used for correcting b whereas a 1 of 1.09 was used for correcting k and K_s.

Calculate *Nitrosomonas* Growth Rate

$$\left(\mu_{MAX}\right)_{NS} = 0.47e^{0.098(T-15)}\left[\frac{DO}{K_{DO} + DO}\right]\left[1 - 0.833\left(7.2 - pH\right)\right]$$

$$\frac{1}{(SRT)_{\mathrm{MIN}}} = \frac{(\mu_{\mathrm{MAX}})_{NS}(NH_4^+ - N)_O}{K_{NS} + (NH_4^+ - N)_O} - b_{NS}$$

Calculate Design & Overall SRTs

$$(SRT)_{DESIGN} = (SRT)_{\mathrm{MIN}}(SF)(PF)$$

$$(SRT)_{OVERALL} = (SRT)_{DESIGN}(MF)$$

Multiplication Factor (MF)

$$MF = \frac{1}{[1-A][1-B]}$$

A = Anaerobic zone fraction of total reactor volume

B = Anoxic zone fraction of total reactor volume

Calculate Effluent Substrate Concentration (S_e)

$$S_e = \frac{K_s\left[1 + b(SRT)_{OVERALL}\right]}{\left[(SRT)_{OVERALL}\left(Yk - b\right) - 1\right]}$$

Calculate Effluent NH_4^+- N Concentration

$$(NH_4^+ - N)_e = \frac{K_{NS}[1 + b_{NS}(SRT)_{DESIGN}]}{(SRT)_{DESIGN}[Y_{NS}\ k_{NS} - b_{NS}] - 1}$$

Calculate Nitrogen to be Oxidized (NO)

$$NO = TKN_o - (NH_4^+)_e - N_{SYN}$$

$$N_{SYN} = \frac{Y(S_o - S_e)F_N}{[1 + b(SRT)_{OVERALL}]} + (X_e)F_N$$

Calculate Oxic Volume

$$V_{OXIC} = \frac{Q(SRT)_{DESIGN}}{X}\left[\frac{Y(S_o - S_e)}{1 + b(SRT)_{DESIGN}} + X_L\right]$$

Anoxic Zone Calculations

$$N = \frac{NO(Q)}{(MLR + RAS + Q)}$$

N = Effluent & MLR nitrate concentration, mg/L

Mass of Nitrates to be Removed in Anoxic Zone

$$\left(NO_3^- - N\right)_{EQ} = (DO)_{MLR}\left(0.35\ \frac{g\ NO_3^- - N}{g\ O_2}\right)(MLR)\left(\frac{1kg}{1000g}\right)$$

$$NOR = [\left(RAS + MLR\right)N]\left(\frac{1\ kg}{1000g}\right)$$

$$TNOR = NOR + (NO_3^- - N)_{EQ}$$

Calculate Anoxic Volume

$$V_{ANOXIC} = \frac{TNOR(1000\ g/kg) - 0.03(S_o)(Q)(1.06)^{T-20}}{0.029(X)(1.06)^{T-20}}$$

Sludge Production & New Overall SRT

$$P_X = \left[\frac{Y\left(S_o - S_e\right)}{1 + b\,(SRT)_{OVERALL}} + X_L \right] (Q) \left(\frac{1kg}{1000g} \right)$$

$$\left(SRT\right)_{OVERALL} = \frac{X\left(V_{OXIC} + V_{ANOXIC} + V_{ANAEROBIC}\right)}{P_X}$$

Check SRT values

If the new overall SRT is not within 5% of the old overall SRT, the procedure should be repeated.

Oxygen Requirements

$$O_2 = CBOD + NOD - DOC$$

$$CBOD = \{Q[(1-1.42\,Y)(S_O - S_e)] + 1.42\,(b)(X)(V_{OXIC})\}\left(\frac{1\,kg}{1000\,g}\right)$$

$$NOD = Q(4.57)(NO)\left(\frac{1\,kg}{1000\,g}\right)$$

$$DOC = Q\left(2.86\frac{g\,O_2}{g\,NO_3^- - N}\right)\left[NO - (NO_3^- - N)_e\right]\left(\frac{1\,kg}{1000\,g}\right)$$

Alkalinity Requirements

$$ALK_e = ALK_o - 7.14\left(NO\right) + 3.57\left[NO - N\right]$$

Conclusions

- A step-by-step procedure has been presented for designing a three-stage, nitrogen and phosphorus removal system.
- Biokinetic equations developed by ***Lawrence & McCarty (1970)*** were used for sizing the aerobic zone with ***Nitrosomonas*** being the growth limiting microbe.

Conclusions continued

- The pre-anoxic zone was sized based on the specific denitrification equation developed by ***Burdick et al., 1982***.

- The anaerobic or fermentation zone was sized based on the equations developed from data presented by ***Randall et al., 1992.***

Conclusions continued

- The 4-stage, pre- and post- anoxic BNR system has been validated and presented in the following paper: ***Mines, R.O.(1997)*** "Design and Modeling of 4-Stage Single-Sludge Systems", ***Advances in Environmental Research,*** **1** (3) 323-332.

- Plans are to validate the anaerobic equations after collecting data from an **A^2/O** facility.