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

Aeration Basin

Return Activated Sludge

Q

S_o

X_o

Q_r, X_w, S_e

Q + Q_r

X, S_e

Secondary Clarifier

Q_e

X_e

S_e

Waste Activated Sludge

Q_w, X_w

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Microbial Composition

\[ C_{60} \quad H_{87} \quad O_{23} \quad N_{12} \quad P_{1} \]

\[ MW = 1374 \]

12.2 \% Nitrogen \quad by \quad Weight

2.3 \% Phosphorus \quad by \quad Weight
Substrate Utilization

\[ C + O_2 \xrightarrow{\text{Heterotrophs}} CO_2 + \text{Energy} \]

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

\[ + \quad CO_2\quad + \quad NH_3\quad + \quad PO_4^- \]
Solids Retention Time (SRT)

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

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

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

\[ X = \frac{Y (S_o - S_e) \ SRT}{(1 + b \ SRT)} \ \theta \]
Waste Sludge Production

\[ P_X = \frac{Y Q (S_o - S_e)}{1 + b SRT} \]
$O_2$ Requirements

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

\[ NOD = Q (TKN_o) (4.57) \]
Biological Nitrogen Removal

• Schematic

• Denitrification stoichiometry

• Pre-anoxic zone sizing

• Post-anoxic zone sizing
Pre- & Post-Denitrification Systems

Influent ➔ Mixed Liquor Recycle ➔ Anoxic ➔ Oxic ➔ Anoxic ➔ Oxic ➔ Secondary Clarifier ➔ Effluent

Return Activated Sludge ➔ Waste Activated Sludge

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Denitrification

\[ 6 \text{NO}_3^- + 2 \text{CH}_3\text{OH} \rightarrow 6 \text{NO}_2^- + 2 \text{CO}_2 + 4 \text{H}_2\text{O} \]

\[ 6 \text{NO}_2^- + 3 \text{CH}_3\text{OH} \rightarrow 3 \text{N}_2 + 3 \text{CO}_2 + 3 \text{H}_2\text{O} + 6 \text{OH}^- \]

\[ 6 \text{NO}_3^- + 5 \text{CH}_3\text{OH} \xrightarrow{\text{Denitrifiers}} 3 \text{N}_2 + 5 \text{CO}_2 + 7 \text{H}_2\text{O} + 6 \text{OH}^- \]

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

\[ SDNR_1 = 0.03 \left( \frac{F}{M} \right)_1 + 0.029 \]

\[ \left( \frac{F}{M} \right)_1 = \frac{Q S_o}{(X V_1)} \]

(Burdick et al., 1982)

\[ SDNR_1 = \text{Specific denitrification rate}(pre – anoxic), \text{days}^{-1} \]

\[ V_{ANOXIC} = \frac{TNOR(1000 \text{ g/kg}) - 0.03(S_o)(Q)(1.06)^{T-20}}{0.029(X)(1.06)^{T-20}} \]
Post-Anoxic Zone Sizing

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

(Burdick et al., 1982)

\[SDNR_2 = \text{Specific denitrification rate, d}^{-1}\]

\[
V_{\text{Anoxic}_2} = \frac{TNOR_2 \left( 1000 \text{ g / kg} \right)}{(X)(SDNR_2)}
\]
Enhanced Biological Phosphorus Removal (EBPR)

- Schematic: anaerobic zone precedes aerobic zone.

- *Acinetobacter* phosphorus composition

- Anaerobic or fermentation zone sizing
Anaerobic/Anoxic/Oxic System

Influent -> Anaerobic -> Anoxic -> Oxic -> Secondary

Mixed Liquor Recycle

Return Activated Sludge

Effluent

Waste Activated Sludge
Acinetobacter Composition

4 to 8 % Phosphorus by weight
Anaerobic/Fermentation Zone Sizing

P Removed = TP₀ – SP

P Removed = mg/L of phosphorus removed,

TP₀ = 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

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

\[ V_{anaerobic} = \text{Volume of anaerobic zone, m}^3 \]

Equation developed from the data developed by Randall et al., 1992.
Volume of Anerobic Zone
COD:TP ratio = 40:1 to 69:1

\[ V_{Anaerobic} = Q \left[ 0.8850 \left( P_{Removed} \right) - 2.3742 \right] \left( \frac{1 \text{ d}}{24 \text{ h}} \right) \]

\[ V_{anaerobic} = \text{Volume of anaerobic zone, m}^3 \]

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 20°C

\[ Y = 0.6 \text{ g VSS/g BOD}_5 \]
\[ b = 0.06 \text{ days}^{-1} \]
\[ k = 5 \text{ days}^{-1} \]
\[ K_s = 60 \text{ mg/L BOD}_5 \]

Heterotrophic Biokinetic Constants at 15°C

\[ Y = 0.6 \text{ g VSS/g BOD}_5 \]
\[ b = 0.05 \text{ days}^{-1} \]
\[ k = 3.2 \text{ days}^{-1} \]
\[ K_s = 39 \text{ mg/L} \]

A temperature correction coefficient (1) of 1.04 was used for correcting b whereas a \( l \) of 1.09 was used for correcting k and Ks.
Autotrophic Biokinetic Coefficients

Nitrosomonas Biokinetic Constants at 20°C

\[ Y_{NS} = 0.15 \text{ g VSS/g NH}_4^+ - N \]
\[ k_{NS} = 3 \text{ days}^{-1} \]
\[ b_{NS} = 0.05 \text{ days}^{-1} \]
\[ K_{NS} = 10^{0.051T-1.148} = 0.74 \text{ mg/L} \]

Nitrosomonas Biokinetic Constants at 15°C

\[ Y_{NS} = 0.15 \text{ g VSS/g NH}_4^+ - N \]
\[ k_{NS} = 1.95 \text{ days}^{-1} \]
\[ b_{NS} = 0.04 \text{ days}^{-1} \]
\[ K_{NS} = 10^{0.051T-1.148} = 0.41 \text{ mg/L} \]

A temperature correction coefficient \( T \) of 1.04 was used for correcting \( b \) whereas a \( T \) of 1.09 was used for correcting \( k \) and \( K_s \).
Calculate *Nitrosomonas* Growth Rate

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

\[
\frac{1}{(SRT)_{MIN}} = \frac{(\mu_{MAX})_{NS} (NH_4^+ - N)_O}{K_{NS} + (NH_4^+ - N)_O} - b_{NS}
\]
Calculate Design & Overall SRTs

\[ (SRT)_{\text{DESIGN}} = (SRT)_{\text{MIN}} (SF)(PF) \]

\[ (SRT)_{\text{OVERALL}} = (SRT)_{\text{DESIGN}} (MF) \]
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 ($S_e$)

\[
S_e = \frac{K_s \left[ 1 + b(SRT)_{OVERALL} \right]}{\left[ (SRT)_{OVERALL} (Y_k - b) - 1 \right]}
\]
Calculate Effluent
\( \text{NH}_4^+ - N \) Concentration

\[
(\text{NH}_4^+ - N)_e = \frac{K_{NS} [1 + b_{NS} (\text{SRT})_{\text{DESIGN}}]}{(\text{SRT})_{\text{DESIGN}} [Y_{NS} k_{NS} - b_{NS}]} - 1
\]
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

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

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

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

\[
TNOR = NOR + \left( NO_3^- - N \right)_{EQ}
\]
Calculate Anoxic Volume

\[ V_{ANOXIC} = \frac{TNOR (1000 \text{ g/kg}) - 0.03(S_o)(Q)(1.06)^{T-20}}{0.029(X)(1.06)^{T-20}} \]
Sludge Production & New Overall SRT

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

\[ (SRT)_{OVERALL} = \frac{X (V_{OXIC} + V_{ANOXIC} + V_{ANAEROBIC})}{P_X} \]
Check SRT values

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

\[ O_2 = CBOD + NOD - DOC \]

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

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

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

\[ ALK_e = ALK_o - 7.14 (NO) + 3.57 [NO - N] \]
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 A²/O facility.