BIOLOGICAL DENITRIFICATION

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OUTLINE (1)
- Benefits
- Design principle
- N removal mechanisms
- The bio-process
- Impact on oxygen demand
- Impact on alkalinity
- Requirements
- Systems
OUTLINE (2)

- Denitrification kinetics
- Denitrification potential
- Principles in design procedure
- Importance of influent TKN/COD ratio
- Effect of oxygen recycling
- Design example
- Reactor volumes and oxygen demand
- Closure

BEENFTITS

- Reduction in effluent nitrate conc
- Reduction of rising sludge in SSTs
- Reduction in oxygen demand
- Recovery of alkalinity
- Higher reactor pH
- Reduced aggression to concrete

Whenever nitrification is possible, include denitrification even if not required!
DISADVANTAGES

- Will require longer sludge age to ensure nitrification. With denitrification:
  - …reactor volume is larger
  - …less WAS produced but more stable
- Mixed liquor recycle pumps
- Slightly more complex system

Benefits of denitrification far outweigh disadvantages!

DESIGN PRINCIPLE (1)

- For aerobic conditions, problem is to calculate mass of oxygen (electron acceptor) required for utilization of known mass of organics (electron donors).

- For anoxic conditions, problem is opposite: Need to calculate mass of electron donors (organics, COD) required for utilization of known mass of electron acceptors (nitrate).
DESIGN PRINCIPLE (2)

- Calculation for nitrate removal is essentially a reconciliation of electron acceptors (nitrate) and donors (WW or dosed organics, COD) taking due consideration of ...
  (1) Biological kinetics of denitrification,
  (2) System operating constraints (anoxic reactor size and recycle ratios).

N REMOVAL FROM WW

Two main processes of N removal –

(1) Sludge production – N incorporated in AS and removed via waste activated sludge (WAS)
(2) Biological denitrification – \( \text{NO}_3^- \to \text{N}_2 \text{ gas.} \)
N REMOVAL VIA WAS

- N content of WAS $\approx 0.10$ mgN/mgVSS.
- Includes N in active ($X_{BH}$), endogenous ($X_E$) and inert solids ($X_i$) of WAS.
- Removes 15-20% of influent TKN –
  - % decreases with increase in
    - sludge age ($\uparrow$),
    - temperature ($\uparrow$),
    - influent TKN/COD ($\uparrow$)
    - and with settled WW.

N REQUIREMENTS FOR SLUDGE GROWTH

(1) FSA not used for sludge growth is nitrified to nitrate.
(2) Influent biodeg OrgN adds to FSA pool in reactor and nitrified.
(3) All nitrate produced available for denitrification.
**THE BIO-PROCESS**

- The process – biological reduction of nitrate ($\text{NO}_3^-$) and nitrite ($\text{NO}_2^-$) to nitrogen gas ($\text{N}_2$) by ordinary heterotrophic organisms (OHOs).
- Consequence of bio-redox reactions to obtain energy for growth (catabolism) under anoxic conditions ($\text{NO}_3^- \text{ & NO}_2^-$ but no DO).
- Called dissimilative denitrification (assimilative denitrification is NO$_3^-$ reduction to NH$_3$ for biomass growth - anabolism).

**STOICHIOMETRY**

**Nitrate to nitrite:**

$$\text{NO}_3^- + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{NO}_2^- + \text{H}_2\text{O} + \text{Energy}$$

**Nitrite to nitrogen gas:**

$$\text{NO}_2^- + 4\text{H}^+ + 3\text{e}^- \rightarrow \frac{1}{2}\text{N}_2 + 2\text{H}_2\text{O} + \text{Energy}$$

Usually nitrate is reduced directly to N$_2$ gas:

$$\text{NO}_3^- + 6\text{H}^+ + 5\text{e}^- \rightarrow \frac{1}{2}\text{N}_2 + 3\text{H}_2\text{O} + \text{Energy}$$

$\text{H}^+$ and $\text{e}^-$ supplied by organics.
**O₂ EQUIVALENT OF NO₃⁻**

- Nitrate reduction to N₂ gas (anoxic):
  \[
  \text{NO}_3^- + 6\text{H}^+ + 5\text{e}^- \rightarrow \frac{1}{2}\text{N}_2 + 3\text{H}_2\text{O} + \text{Energy}
  \]

- Oxygen reduction to water (aerobic):
  \[
  \text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}
  \]

- So e⁻ accepting capacity of nitrate
  \[
  = \left(\frac{32/4}{14/5}\right) \rightarrow 2.86 \text{ mgO/mgNO}_3^-\text{N}
  \]
  (Organics are e⁻ donor)

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**SUBSTRATE UTILIZATION**

- **Yₐ** in COD/COD units!
  - COD or available e⁻
  - Anabolism
  - Catabolism

  - **Aerobic** = 1gCOD
  - **Anoxic** = 1gCOD

  - **Aerobic** **Yₐ** = 0.67
  - **Anoxic** **Yₐ** = 0.56

  - **Aerobic** = **Yₐ** gCOD biomass
  - **Anoxic** = **Yₐ** gCOD biomass
  - \( Y_{HV} = \frac{Y_{HV}}{f_{VSS}} \text{ mgVSS/mgCOD} \)

  - e⁻ passed to e⁻ acceptor to provide energy to make new cell mass

For simplicity, accept **Yₐ** = 0.66 for anoxic
**OXYGEN RECOVERY (1)**

- Nitrification consumes 4.57 mgO/mgN
- Denitrification recovers 2.86 mgO/mgN
- So \( \frac{2.86}{4.57} = 63\% \) of nitrification oxygen demand can be recovered by denitrification.
- Since complete denitrification often is not possible, about 50\% of nitrification oxygen demand can be recovered by denitrification.

**OXYGEN RECOVERY (2)**

Oxygen saving by denitrification
**ALKALINITY GENERATION**

- \( \text{NO}_3^- + 6\text{H}^+ + 5\text{e}^- \rightarrow \frac{1}{2}\text{N}_2 + 3\text{H}_2\text{O} + \text{Energy} \)  
  (5\text{H}^+ \text{from organics} + 1\text{H}^+ \text{from bulk liquid})
- Denitrification uses 1\text{H}^+ per mol NO\textsubscript{3}-N to N\textsubscript{2}  
  \[ = \frac{1}{14} \times 50 \text{ mg/l CaCO}_3 \text{ generated per mgNO}_3^-\text{N/l denitrified.} \]
- Nitrification consumes 7.14 \text{ mg/l CaCO}_3.
- So denitrification recovers half the alkalinity lost in nitrification.

**COMPARISON:**

**NITRIFICATION vs DENITRIFICATION**

<table>
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<tr>
<th>Compnd</th>
<th>NH\textsubscript{4}</th>
<th>NO\textsubscript{3}^-</th>
<th>NO\textsubscript{2}^-</th>
<th>NO\textsubscript{3}^-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cbl No</td>
<td>-3</td>
<td>0</td>
<td>+3</td>
<td>+5</td>
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Nitrification (oxidation)

- Oxidation: \( \text{Ammonia (NH}_3\text{)} \rightarrow \text{Nitrate (NO}_3^-\text{)} \)
- Reactor types: Autotrophic, Aerobic

Denitrification (reduction)

- Reduction: \( \text{Nitrate (NO}_3^-\text{)} \rightarrow \text{Nitrogen gas (N}_2\text{)} \)
- Reactor types: Heterotrophic, Anoxic

Net Gain:

- Nitrification: 4.57 \text{ mgO}_2/\text{mgNH}_4^-N
- Denitrification: 2.66 \text{ mgO}_2/recovered \text{ NO}_3^-\text{N}

Therefore, denitrification allows at best 62.2% (0.8/2.66 x 100) recovery of the nitrification oxygen demand.
REQUIREMENTS FOR DENITRIFICATION

(1) Presence/input of nitrate
(2) Absence of DO (unaerated zone)
(3) Facultative heterotrophic biomass
(4) Suitable electron donor (organics).

(A) PRESENCE OF NITRATE

- Source of nitrate is nitrification.
- Therefore nitrification is prerequisite for denitrification.
- System sludge age $R_s$ must be longer than minimum for nitrification $R_{sm}$, or...
- Anoxic zone must not exceed maximum unaerated sludge mass fraction ($f_{xm}$).
(A) REQ’MTS for NITRIFICATION

The maximum unaerated sludge mass fraction \( f_{xm} \) allowed at a sludge age of \( R_s \) to ensure nitrification with a safety factor of \( S_f \) is –

\[
f_{xm} = 1 - S_f \left( \frac{b_{AT}}{R_s} + \frac{1}{R_s} \right) \mu_{AmT}
\]

and then effluent FSA conc is given by

\[
N_{ae} = \frac{K_n T}{(S_f - 1)}
\]

\( N_{ae} \) lower if \( f_{xt} < f_{xm} \)

(B) ABSENCE OF DO

- DO is inhibitory on denitrification
  
  \[
  DO = 0 \text{ mg/l} \quad \text{Denitrification 100%}
  \]
  \[
  DO = 0.5 \text{ mg/l} \quad \text{Denit < 10%}
  \]
  
  Even if DO conc is zero in reactor, DO entering reactor is used first, reducing the nitrate removal by the reactor.
(B) SOURCES OF DO

- High conc in recycles from aerobic zone (Keep < 1-2 mgO/l). If DO too low in aerobic, will get anoxic pockets – simultaneous denitrification.
- Entrainment at air/liquid interface from high mixing energy
- Entrainment in recycle flows – screw pumps, cascades, hydraulic jumps.

(C) FACULTATIVE BIOMASS

- Ability to denitrify widespread among OHOs
- In AS systems, significant number of OHOs are facultative (can denitrify).
- Little difference in bacterial populations in fully aerobic and anoxic –aerobic systems.
- Aerobic AS requires few days to acclimatize to denitrify at full capacity.
(D) ELECTRON DONOR

- Organics serve as electron donor (ED).
- Sources of organics are:
  - ...(1) Internal ED – present in wastewater
  - ...(2) Self generated (ED) - via endogenous respiration
  - ...(3) External (ED) – dosed to system e.g. methanol or other organics.
- (1) and (2) are of most interest in WWT.
- (3) is used to get very low effluent nitrate.

DENITRIFICATION CONFIGURATIONS

- Different configurations for denitrification have been developed depending on type of electron donor…
  - (1) …Wuhrmann – self generated ED
  - (2) …Modified Ludzack-Ettinger (MLE) – internal ED
  - (3)…4 stage Bardenpho – internal and self generated ED but methanol dosed into 2ary anoxic is external ED.
(A) WUHRMANN SYSTEM

- Post-denit system.
- Secondary anoxic reactor (2<sup>ary</sup>)
- All influent organics utilized in aerobic
- Uses endogenously generated organics
- Methanol often dosed to improve denit.

(B) MLE SYSTEM

- Pre-denit system.
- Primary anoxic reactor (1<sup>ary</sup>.
- Influent organics utilized in anoxic.
- High N removal but effluent NO<sub>3</sub>- > 4 mgN/l because a-recycle has upper limit ≈ 5:1
(C) 4 STAGE BARDENPHO

- Pre+Post denit system.
- 1\textsuperscript{o} + 2\textsuperscript{o} anoxic reactors.
- Influent organics utilized in 1\textsuperscript{ary} anoxic.
- Complete denit possible for low TKN/COD.
- Methanol often dosed to increase denit. rate

DENITRIFICATION MODEL

- Design principle – match supply rate of e\textsuperscript{-} acceptors (NO\textsubscript{3}\textsuperscript{-}) and supply rate e\textsuperscript{-} donors (organics \equiv denit. potential)
  - Find denitrification potential (D\textsubscript{p}) of anoxic reactor
  - Match NO\textsubscript{3}\textsuperscript{-} load on anoxic (N\textsubscript{L}) to this potential
- Need steady state denitrification model to calculate denitrification potential
- Develop model from experimentally observed denitrification behaviour in plug flow primary and secondary anoxic reactors.
**2<sup>ary</sup> ANOXIC DENITRIFICATION**

1. **AERobic REactor**
2. **NO<sub>3</sub> Profile long Reactor**
3. **WASTE FLOW**
4. **Settler**
5. **Effluent**
6. **sludge Recycle s**

- **Observed single continuous decrease in nitrate conc**

**Diagram:**
- Nitrate concentration graph showing a single phase.
- Equations: $K_a$, $K_b$ (Self generated SBOD).

**1<sup>ary</sup> ANOXIC DENITRIFICATION**

1. **AERobic REactor**
2. **NO<sub>3</sub> Profile long Reactor**
3. **WASTE FLOW**
4. **Settler**
5. **Effluent**
6. **sludge Recycle s**

- **Observed two phases:**
  1. **1<sup>st</sup> fast but stopped**
  2. **2<sup>nd</sup> slow and continuous**

**Diagram:**
- Nitrate concentration graph showing two phases.
- Equations: $K_a$, $K_b$ (WW SBOD).
DENITRIFICATION KINETICS (1)

- From literature and data, express denit rate
  \[ \frac{d(\text{NO}_3^-\text{N})}{dt} = -K Xv \text{mgNO}_3^-\text{N}/(l.d) \]
- \( K \) = specific denitrification rate
  \[ \text{mgNO}_3^-\text{N}/(\text{mgVSS}.d) \]
- However, \( K_1 \), \( K_2 \), \( K_3 \) rates varied widely...
- As \( R_s \) increased, \( K \) rates decreased.

DENITRIFICATION KINETICS (2)

- Re-evaluated data by assigning \( K \) rate to OHO conc mediating denitrification...
  \[ \frac{d(\text{NO}_3^-\text{N})}{dt} = -K X_{BH} \text{mgNO}_3^-\text{N}/(l.d) \]
- \( K \) = active OHO specific denitrification rate
  \[ \text{mgNO}_3^-\text{N}/(\text{mgOHOVSS}.d) \]
- \( X_{BH} \) obtained from steady state model.
- \( K \) rates now more consistent with sludge age (\( R_s \)).
DENITRIFICATION K RATES (1)

- Large data base of profiles at 14 and 20°C -
  \[ K_1 = 0.72 (1.2)^{(T-20)} \text{ (halves in 4°C)} \]
  \[ K_2 = 0.101 (1.08)^{(T-20)} \text{ (halves in 9°C)} \]
  \[ K_3 = 0.072 (1.03)^{(T-20)} \text{ (halves in 23°C)} \]
- Note units of K: mgNO_3-N/(mgOHOVSS.d)
- \( K_1 \) = strongly temperature sensitive
- \( K_3 \) = weakly temperature sensitive - as weak as endog. respiration rate.

DENITRIFICATION K RATES (2)

- At 20°C; \( K_{2,20} > K_{3,20} \)
  At 12°C; \( K_{2,12} \approx K_{3,12} \)
- This has implications in design –
  At 20°C; \( K_2 \) denitrifies better than \( K_3 \)
  At 12°C; \( K_2 \) denitrifies same as \( K_3 \)
  but primary anoxic still has \( K_1 \) rate,
  which makes primary anoxic always better than secondary anoxic
BASIS FOR $K_1$ RATE (1)

- From experimental data found that conc of NO$_3$-N removed by $K_1$ rate ($\Delta N_{n1s}$) is proportional to influent biodeg COD ($S_{bi}$).
- This gave clue that $K_1$ rate was due to utilization of influent RBCOD ($S_{bsi}$).

BASIS FOR $K_1$ RATE (2)

- Constant of proportionality between $\Delta N_{n1s}$ and influent biodeg COD ($S_{bi}$) is $\alpha$, so...

$$\Delta N_{n1s} = \alpha S_{bi}$$

where $\alpha = f_{bs} (1-f_{cv} Y_{Hv})/2.86$

$$f_{bs} = \text{influent RBCOD fraction: } S_{bsi} = f_{bs} S_{bi}$$

$$(1-f_{cv} Y_{Hv})/2.86 = e^{-} \text{ to } \text{NO}_3^{-} \text{ (catabolism).}$$
BASIS FOR K RATES

- Concluded from NO$_3^-$ – time profiles that:
  - $K_1$ related to utilization of RBCOD
  - $K_2$ related to utilization of SBCOD
  - $K_3$ related to endogenous respiration rate

- This provided the basis to integrate denitrification into AS kinetic simulation models.

BASIS FOR $K_1$ RATE (3)

- In simulation models, utilization of RBCOD is modeled with the Monod equation – so $K_1$ is

$$K_1 = \frac{(1 - Y_H) f_{cv} \mu_H S_S}{2.86Y_H K_S + S_S} \text{ where } \frac{S_S}{K_S + S_S} \approx 1$$

- mgNO$_3^-$-N/(mgOHOVSS.d)

- So with $K_1 = 0.72$, $Y_H = 0.67$, $\mu_H \approx 2.8/d$.

- In range of $\mu_H$ measured in AS systems - 1 to 4 /d. $\mu_H$ varies with reactor mixing regime – high in plug flow reactors, low in completely mixed.
BASIS FOR K₂ & K₃ RATES

In simulation models utilization of SBCOD is modeled with the saturation kinetics – so K₂ and K₃ are

\[ K_2 = K_{y_2} = \frac{(1-Y_H)}{2.86 Y_H} \left( K_y \left( X_2 / X_{BH} \right) \right) \]

mgNO₃-N/(mgOHVSS.d)

where

\[ \frac{X_2}{X_{BH}} \]

is progressively lower in primary (K₂) secondary (K₃) and anoxic-aerobic digestion (K₄).

Xₜ₂/Xₜ₃ ratio does not change much in anoxic reactors – hence K rates approx. constant.

STEADY STATE MODEL

- From denitrification kinetics...
  \[ \Delta(\text{NO}_3^-\text{N})/\Delta t = - K \ X_{BH} \ \text{mgNO}_3^-\text{N}/(\text{l}.d) \]
- Apply to an anoxic reactor – definitions –
  - \(\Delta N_{nr} = K \ X_{BH} \ R_{ha} = \) reactor nitrate removal mgNO₃-N/(l flow through reactor.d)
  - \(R_{ha} = \) actual ret time of anoxic reactor
  - \(\Delta N_{ns} = K \ X_{BH} \ R_{hn} = \) system nitrate removal mgNO₃-N/(l influent flow through system.d)
  - \(R_{hn} = \) nominal ret time of anoxic reactor.
STEADY STATE MODEL

\[ R_{ha} = \frac{V_{ax}}{(Q_i(a+s+1))} \]

\[ R_{hn} = \frac{V_{ax}}{Q_i} \]

So \( R_{hn} = R_{ha} (a+s+1) \)

\[ \Delta N_{nr} \text{ by } K_2 \]

\[ Q_i = Q_i (a+s+1) \]

\[ \Delta N_{ns} = \Delta N_{nr} (a+s+1) \]

\[ K X_{BH} = \frac{\Delta N_{nr}}{R_{ha}} = \frac{\Delta N_{ns} (a+s+1)}{(a+s+1) R_{hn}} = \Delta N_{ns} / R_{hn} \]

DENIT. POTENTIAL OF SECONDARY ANOXIC (1)

- This is the system NO$_3$–N removal (/litre influent) by K$_3$ rate in 2$^\text{ary}$ anoxic
- \( D_{p3} = \Delta N_{nss} = K_3 X_{BH} R_{hns} \text{ mgNO}_3\text{N/l influent} \)
- But \( R_{hns} = \frac{V_{axs}}{Q_i} \)
- So \( D_{p3} = K_3 (X_{BH} V_{axs})/Q_i \)
  where \( (X_{BH} V_{axs})/Q_i \) is OHO mass in 2$^\text{ary}$ anoxic per l influent flow, which is obtained from COD removal steady state model.
DENIT. POTENTIAL OF SECONDARY ANOXIC (2)

- Defining the $2^{\text{ary}}$ anoxic sludge mass fraction $f_{x3}$ as $(X_{BH}V_{axs})/(X_{BH}V_p)$, then
- $D_{p3} = K_3 f_{x3} (X_{BH}V_p/Q_i)$
- But $(X_{BH}V_p/Q_i) = \text{mass OHOs in system/l } Q_i$
  - which = $S_{bi} Y_{HV}R_s/(1+b_HR_s)$
- So $D_{p3} = S_{bi} K_3 f_{x3} Y_{HV}R_s/(1+b_HR_s)$
  - mgNO$_3$-N/l influent

DENIT. POTENTIAL OF PRIMARY ANOXIC (1)

- This is the system NO$_3$–N removal (/litre influent) by $K_1 + K_2$ rates in $1^{\text{ary}}$ anoxic
- $D_{p1} = \Delta N_{nps} = \Delta N_{n1s} + \Delta N_{n2s}$
- From before $\Delta N_{n1s} = S_{bi} f_{bs} (1-f_{cv}Y_{HV})/2.86$
- And similarly to $K_3$ in $2^{\text{ary}}$ anoxic
  - $\Delta N_{n2s} = S_{bi} K_2 f_{x1} Y_{HV}R_s/(1+b_HR_s)$
  - $f_{x1} = 1^{\text{ary}}$ anoxic sludge mass fraction
DENIT. POTENTIAL OF PRIMARY ANOXIC (2)

- So adding nitrate removal by $K_1$ (RBCOD) and $K_2$ (SBCOD) rates...
  $$D_{p1} = S_{bi} \cdot f_{bs} \cdot (1-f_{cv} \cdot Y_{Hv})/2.86 + S_{bi} \cdot K_2 \cdot f_{x1} \cdot Y_{Hv} \cdot R_s/(1+b_{H} \cdot R_s) \text{ mgNO}_3-\text{N/l influent}$$
- Note $D_{p1}$ depends on…
  1. influent biodeg COD conc ($S_{bi}$),
  2. influent RBCOD fraction ($f_{bs}$) and
  3. primary anoxic mass fraction ($f_{x1}$).

DENIT. POTENTIAL OF PRIMARY ANOXIC (3)

- $D_{p1}$ increases as 1$^{\text{ary}}$ anoxic mass fraction increases,
- but must be larger than minimum ($f_{x1\text{min}}$) to utilize all influent RBCOD.
- It is inefficient to not use all RBCOD in 1$^{\text{ary}}$ anoxic.
MINIMUM 1<sup>ary</sup> ANOXIC

- It can be shown that minimum primary anoxic sludge mass fraction ($f_{x1min}$) is:

$$f_{x1min} = \frac{(1+b_{HT} \cdot R_s)}{(K_{1T} \cdot Y_H \cdot R_s)} \cdot f_{bs} \cdot (1-f_{cy} \cdot Y_H) / 2.86$$

- At 14°C and sludge age ($R_s$) > 10 days,
  $$f_{x1min} \approx 0.08.$$ 
- So primary anoxic reactors must have mass fractions ($f_{x1}$) > 0.10 to ensure all influent RBCOD is utilized to denitrify.

DENIT. POTENTIAL

- $D_p$ = maximum concentration of nitrate per litre influent flow that an anoxic reactor can denitrify.
- Called potential because whether or not it is achieved depends on the nitrate load ($N_L$) on the anoxic reactor….
  - if $N_L < D_p$: performance < potential
  - if $N_L = D_p$: performance = potential (objective)
  - if $N_L > D_p$: performance < potential
DESIGN PROCEDURE (1)

- Depends on objectives – e.g. maximize N removal or protect BEPR from nitrate.
  1. From WW chars ($\mu_{Am20}$, $T_{min}$) determine $f_{xm}$ and $R_s$ interactively to ensure nitrification (most critical decision!).
  2. From $N_{ti}$, $N_{ai}$ and $R_s$, calculate $N_c$
  3. From $S_{ti}$ & $f_{bs}$ and $f_{xm}$ & $R_s$, find $D_{p1}$
  4. is $D_{p1} >$ or $< N_c$
     - Gives idea of extent of N removal.

DESIGN PROCEDURE (2)

- The higher $N_{ti}$, the higher $N_c$
- The higher $S_{ti}$ & $f_{bs}$, the higher $D_{p1}$
- So influent WW TKN/COD ratio gives indication of extent of N removal possible.
- For $R_s >15d$, $T_{min} = 14^\circ C$, $f_{xm} = 0.5-0.6$, extent of N removal depends mainly on WW TKN/COD and RBCOD fraction ($f_{bs}$).
- Guide: If TKN/COD<0.09 for $f_{bs} \approx 0.25$, near complete N removal can be achieved with WW organics only in $1^{\text{any}}$ and $2^{\text{any}}$ reactors.
DESIGN PROCEDURE (3)

- If a very low effluent NO$_3^-$ conc is required (<5 mgNO$_3^-$-N/l) and WW TKN/COD ratio is >0.09, consider subdividing anoxic mass fraction into 1$^a$ and 2$^a$, and dose methanol into 2$^a$.
- With dosing, 2$^a$ acts like a 1$^a$ so add a RBCOD term to $D_p^3$. Eq. Yield ($Y_{Hv}$) for methanol is lower than the usual 0.45 mgVSS/mgCOD AS value.
- Adjust design parameters ($R_s$, $f_{x1}$, $f_{x3}$, $a$) until economical design is obtained.
- This design procedure is demonstrated with some examples.

PROCEDURE DEMO: MLE (1)

- DO in recycles $O_a$ and $O_s$ mg/l
- If NO$_3$ conc exiting anoxic is zero (i.e. $D_{p1} \geq N_L$) then NO$_3$ conc in aerobic is $N_c/(a+s+1)$, i.e. NO$_3$ conc per influent generated in aerobic diluted into flow through aerobic reactor.
PROCEDURE DEMO: MLE (2)

Assume no Denitrification in SST.

- With no denitrification in settling tank, effluent nitrate \( N_{ne} \) and NO\(_3\) in a and s recycles are equal to NO\(_3\) conc in aerobic \( N_{nar} \), which is \( \frac{N_c}{(a+s+1)} \).

PROCEDURE DEMO: MLE (3)

DO in recycles \( O_a \) and \( O_s \) mg/l

- So NO\(_3\) load on 1\(^{ary}\) anoxic \( N_{nlp} \) = \{aerobic NO\(_3\) conc + nitrate equivalent of DO\} x recycle ratios, i.e.

\[
N_{nlp} = \left[ \frac{N_c}{(a+s+1)} + \frac{O_a}{2.86} \right] a + \left[ \frac{N_c}{(a+s+1)} + \frac{O_s}{2.86} \right] s = D_{pt}
\]
For optimum denitrification (lowest $N_{ne}$), set nitrate load ($N_{nlp}$) = denit. potential $D_{p1}$. Only unknown is recycle, so solve for $a_{opt}$. 

$$N_{nlp} = \left[ \frac{N_c}{(a+s+1)} + \frac{O_a}{2.86} \right] a + \left[ \frac{N_c}{(a+s+1)} + \frac{O_s}{2.86} \right] s = D_{p1}$$

$$a_{opt} = \frac{-B+\sqrt{B^2+4AC}}{2A} \quad (5.59)$$

where

$$A = O_s \cdot 2.86$$

$$B = N_c - D_{p1} + ((s+1)O_a + s O_s)/2.86$$

$$C = (s+1)(D_{p1} - s O_s/2.86) - s N_c$$

and

$$N_{nemin} = N_{neopt} = N_c / (a_{opt} + s + 1) \text{ (mgN/l)} \quad (5.60)$$
PROCEDURE DEMO: MLE (6)

- If $a < a_{\text{opt}}$, anoxic is under-loaded with $\text{NO}_3$ and N removal is system (recycle) limited.
- If $a > a_{\text{opt}}$, anoxic is over-loaded with $\text{NO}_3$ above its denitrification potential. N removal is kinetics limited.

MLE: Effluent $\text{NO}_3$ vs $a$

(1) High TKN/COD ratio: Settled
MLE: Effluent NO$_3$ vs a

(2) Low TKN/COD ratio: Raw

- If influent TKN/COD ratio is low, a$_{opt}$ is high (>5).
- Increasing a from 5 to 6:1 only removes 2% (<1 mgN/l) more NO$_3$ – not worth pumping costs.
- Practical upper limit to a (a$_{prac}$) ~ 5:1.
- If a$_{prac}$ < a$_{opt}$, anoxic is under-loaded ($D_{p1}$ not fully used) – options...
  1. reduce anoxic size ($f_{x1}$) → reduction in sludge age ($R_s$) → smaller system volume, or
  2. Keep as safety factor (no change).

MAXIMUM PRACTICAL a
A balanced MLE system is one with a sludge age ($R_s$) and influent TKN concentration ($N_{ti}$) in which $f_{x1} = f_{xm}$ and $a_{opt} = a_{prac}$ (say 5:1) so that this $a_{prac}$ loads the anoxic reactor exactly to its denitrification potential.

Calculation of sludge age ($R_s$) which balances MLE cannot be done directly. Easiest is to use equations we have and calculate $N_{ti}$ for selected $R_s$, plot $N_{ti}$ vs $R_s$, and select $R_s$ for required $N_{ti}$.

Procedure:
1. For selected $R_s$, calculate $f_{xm}$ for $u_{Am20}$, $T_{min}$ and $S_f$.
2. Provided $f_{xm} = f_{x1} > f_{x1min}$, calculate $D_{p1}$.
BALANCED MLE SYSTEM

(3) Select $a_{prac}$ and set $\gamma = a_{opt}$

(4) Calculate nitrification capacity ($N_c$) from NO$_3$ load - denitr potential Eq.:

$$N_{np} = \left[ \frac{N_c}{(a+s+1)} + \frac{O_a}{2.86} \right]a + \left[ \frac{N_c}{(a+s+1)} + \frac{O_s}{2.86} \right]s = D_{p1}$$

(5) Calculate $N_{ti}$ from

$N_{ti} = N_c + N_s + N_{ae} + N_{ousi}$ [$N_{ae} = K_{nT}/(S_f-1)$]

BALANCED MLE SYSTEM

Raw WW TKN/COD 0.08
BALANCED MLE SYSTEM
Settled WW TKN/COD 0.113

EFFECT of TKN/COD on a

- If system $R_s$ is not changed when $a_{prac}$ under-loads anoxic with NO$_3$, it is important to know sensitivity of system to influent TKN/COD ratio variation.

- For accepted $R_s$, plot $a_{opt}$ and $N_{nemin}$ versus TKN/COD ratio for varying influent TKN conc (Need no new equations!)
  
  1. Select $N_{ti}$, calculate $N_c$, $a_{opt}$ and $N_{nemin}$
  2. If $a_{opt} > a_{prac}$, set $a_{opt} = a_{prac}$, else $a_{prac} = a_{opt}$
EFFECT of TKN/COD on a-recycle and Effluent NO\textsubscript{3}

Sludge age = 20d

TKN/COD ratio that balances MLE

(1) If influent TKN/COD ratio is low (<0.10),
- \(a_{\text{opt}}\) is high and > \(a_{\text{prac}}\) (= 5:1)
- effluent NO\textsubscript{3} is low, but not < 4-5 mgN/l.
- If zero effluent NO\textsubscript{3} is required, subdivide anoxic into 1\textsuperscript{ary} and 2\textsuperscript{ary} anoxic reactors and dose methanol into 2\textsuperscript{ary} anoxic – details in notes.
**EFFECT of TKN/COD on a-recycle and Effluent NO₃**

(2) If influent TKN/COD ratio is high (>0.10),
- $a_{opt}$ is low and $< a_{prac} (= 5:1)$
- effluent NO₃ is high, > 5 and up to 15 mgNO₃-N/l depending on influent TKN/COD ratio.
- If low effluent NO₃ is required, subdivide anoxic into 1st and 2nd anoxic reactors and dose methanol into 2nd anoxic – details in notes.

**REACTOR VOLUMES (1)**

- Calculated N removal without knowing anoxic zone volume or retention time, only mass fractions ($f_{x1}$, $f_{xm}$, $f_{x3}$).
- System reactor volume is the same whether fully aerobic or anoxic-aerobic at the same sludge age ($R_s$)!
- System volume is fixed by organic load (kgCOD/d) and sludge age (Chapter 4).
- From definition – 1st anoxic sludge mass fraction $f_{x1} = (X_{tp} V_{axp})/(X_{t} V_{p})$,
REACTOR VOLUMES (2)

- In the MLE, anoxic reactor $X_t$ (MLSS) conc is same as aerobic reactor $X_t$, so volume fractions = mass fractions.
- If $f_{x1} = 0.45$, then 1<sup>anoxic</sup> anoxic volume = 0.45 (45%) of system reactor volume.

OXYGEN RECOVERY (1)

- NO$_3$ mass denitrified = $(N_c-N_{ne})Q_i$ kgN/d.
- Hence Oxygen Demand (OD) saved $MO_d = 2.86(N_c-N_{ne})Q_i$ kgO/d.
- So OD to be supplied to aerobic zone $MO_t = MO_c + MO_n - MO_d$ kgO/d.

OUR in aerobic is higher than for fully aerobic because net OD has to be supplied into a smaller aerobic reactor.
DENIT: SUMMARY (1)

(1) Wastewater characteristics needed for design:

- Influent TKN/COD ratio
- Influent RBCOD fraction
- Wastewater minimum temperature
- Maximum specific growth rate of nitrifiers.

DENIT: SUMMARY (2)

(2) Most important decisions in design:

- Sludge age (R_s) and unaerated (anoxic) mass fraction (f_xm, f_xt) which is done interactively.
- a - recycle ratio.
- Subdivision of anoxic mass fraction into 1^ary and 2^ary - K_3 so low that 2^ary anoxic is only selected if methanol is to be dosed to get very low effluent NO_3 (endogenous respiration releases ammonia, reduces N removal to ~80% of NO_3 denitrified).
DENIT: SUMMARY (3)

(3) Effect of denitrification on system:

- Sludge age will be longer since nitrification is obligatory – larger reactor volume.
- Reduction in oxygen demand over fully aerobic system with nitrification.
- Increase in alkalinity and pH.
- Reduced rising sludge problems in SSTs

Denitrification should always be included where nitrification is possible.

DENITRIFICATION - CONCLUSION

- Design and economics of ND systems are mainly governed by requirement to nitrify – this fixes sludge age of system and hence reactor volume.
- Sludge age and anoxic mass fraction selected interactively, so extent of denit needs to be known.
- Achieving nitrification depends on the maximum specific growth rate of nitrifiers – varies in different wastewaters – measure or choose low value.
- Extent of denitrification (N removal) depends on influent TKN/COD ratio and RBCOD fraction of wastewater – need to be measured on WW!
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