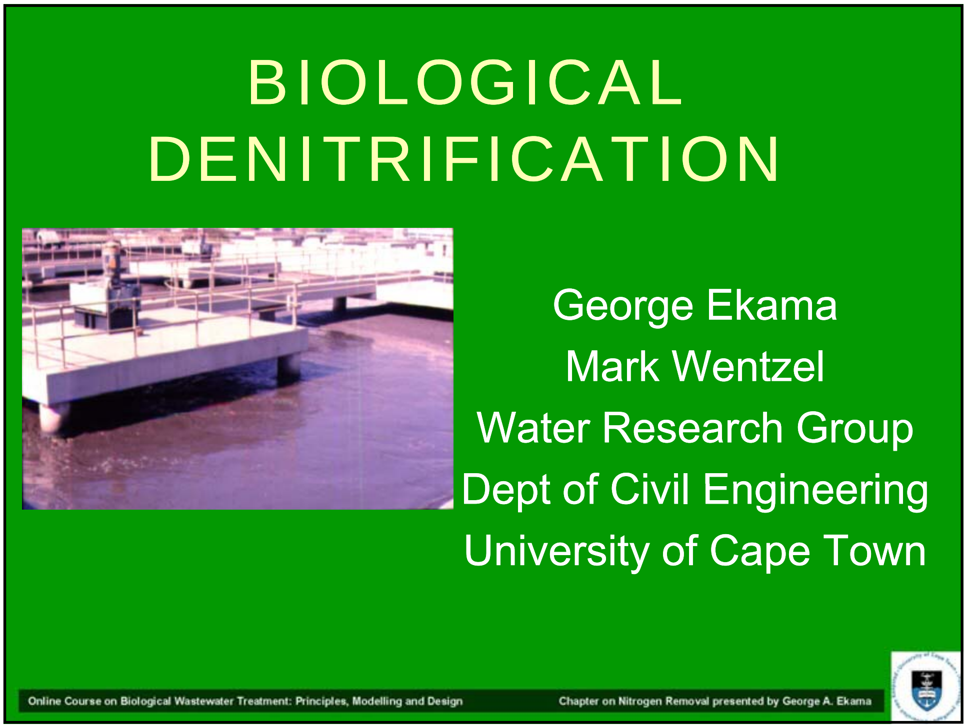

BIOLOGICAL DENITRIFICATION

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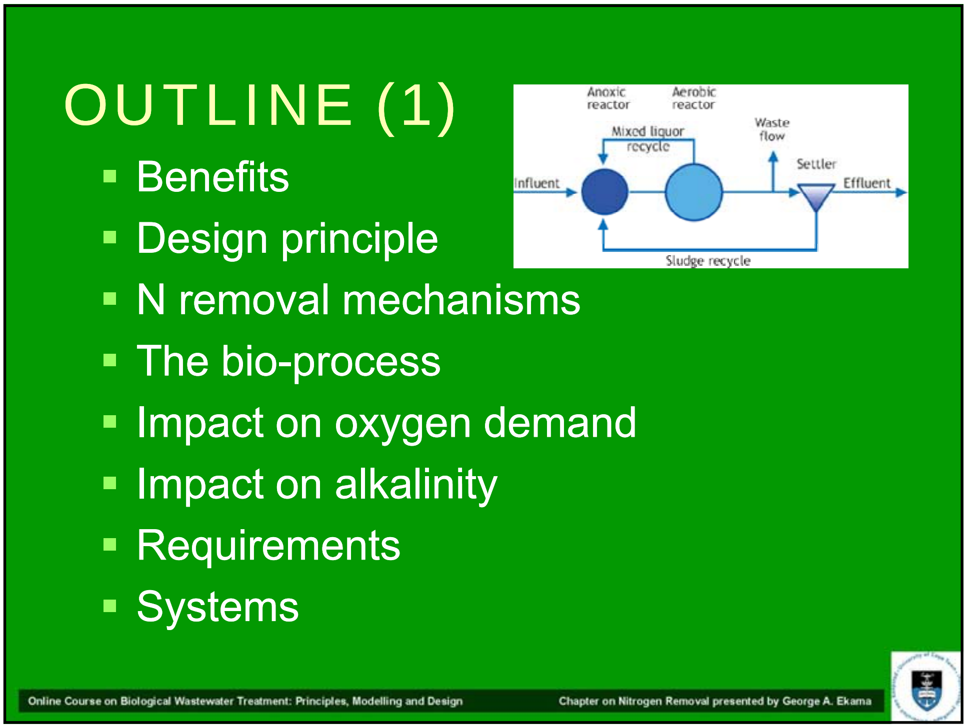
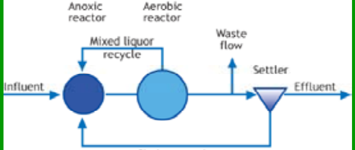


OUTLINE (1)

- Benefits
- Design principle
- N removal mechanisms
- The bio-process
- Impact on oxygen demand
- Impact on alkalinity
- Requirements
- Systems

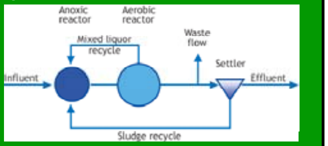
OUTLINE (2)



- 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

BENEFITS

- 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 –

$NO_3^- \rightarrow N_2$ gas.

N REMOVAL VIA WAS

- N content of WAS ≈ 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

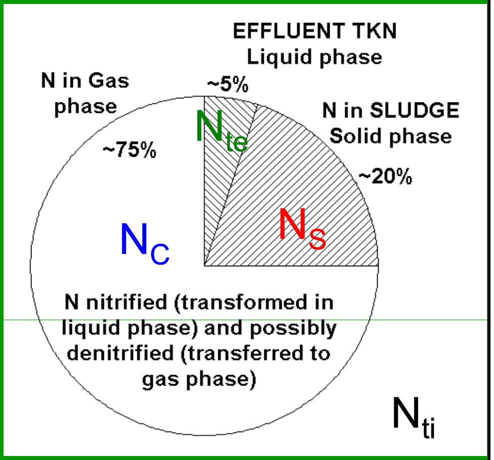
    - sludge age (↑),
    - temperature (↑),
    - influent TKN/COD (↑)
    - and with settled WW.

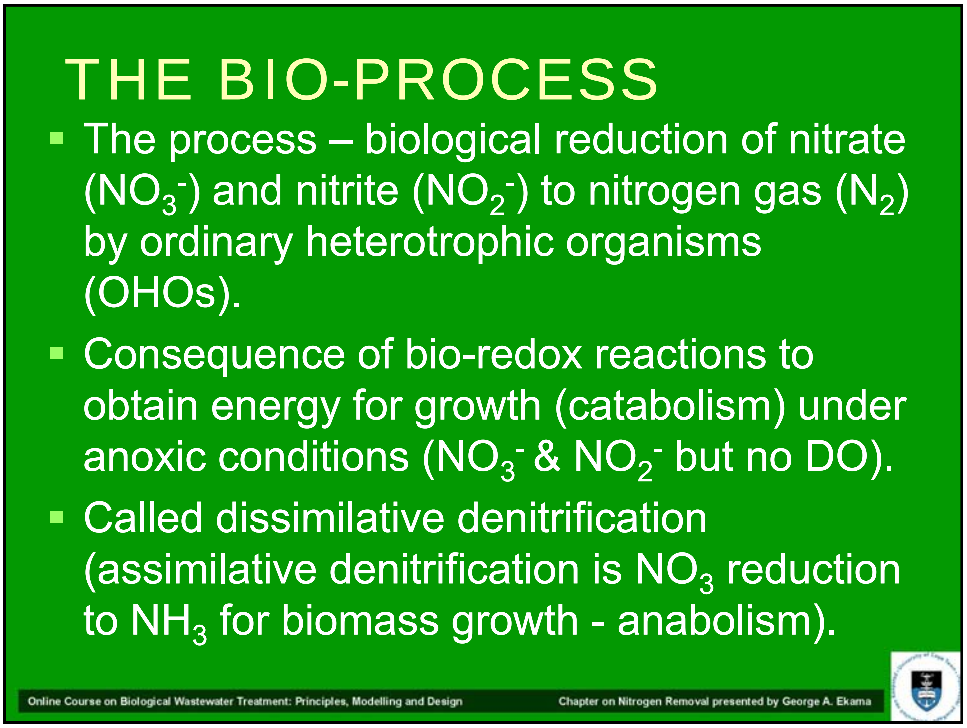
N REQUIREMENTS FOR SLUDGE GROWTH

(1) FSA not used for sludge growth is nitrified to nitrate.

(2) Influent biodeg OrgN adds to FSA pool in reactor and nitrified.

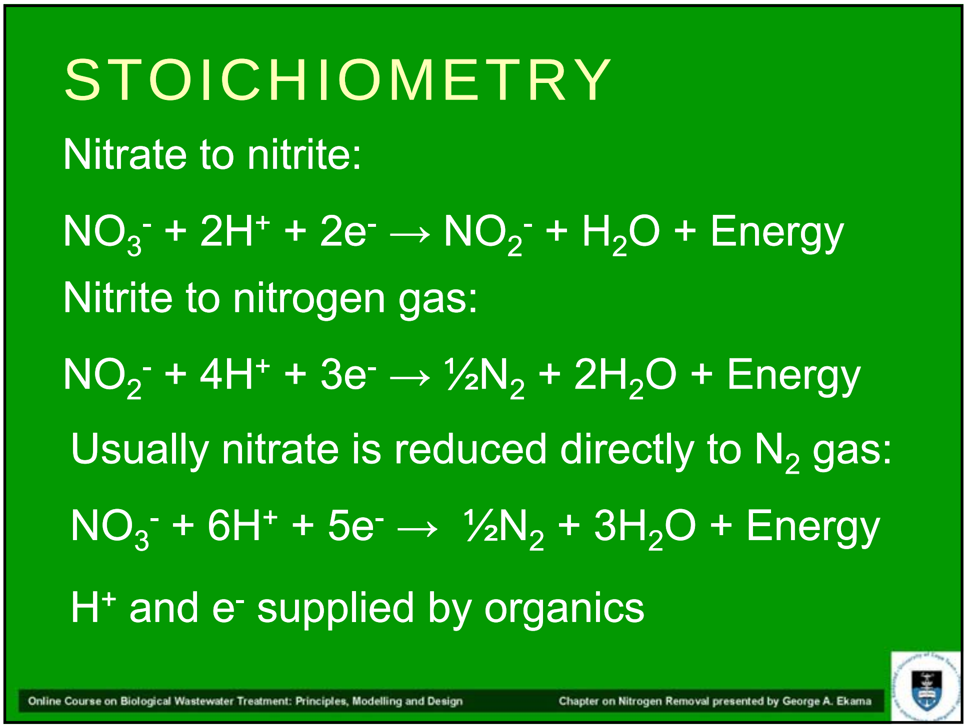
(3) All nitrate produced available for denitrification.





THE BIO-PROCESS

- The process – biological reduction of nitrate (NO_3^-) and nitrite (NO_2^-) to nitrogen gas (N_2) by ordinary heterotrophic organisms (OHOs).
- Consequence of bio-redox reactions to obtain energy for growth (catabolism) under anoxic conditions (NO_3^- & 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:

$$NO_3^- + 2H^+ + 2e^- \rightarrow NO_2^- + H_2O + \text{Energy}$$

Nitrite to nitrogen gas:

$$NO_2^- + 4H^+ + 3e^- \rightarrow \tfrac{1}{2}N_2 + 2H_2O + \text{Energy}$$

Usually nitrate is reduced directly to N_2 gas:

$$NO_3^- + 6H^+ + 5e^- \rightarrow \tfrac{1}{2}N_2 + 3H_2O + \text{Energy}$$

H^+ and e^- supplied by organics

O_2 EQUIVALENT OF NO_3^-

- Nitrate reduction to N_2 gas (anoxic):

$NO_3^- + 6H^+ + 5e^- \rightarrow \frac{1}{2}N_2 + 3H_2O$ + Energy

- Oxygen reduction to water (aerobic):

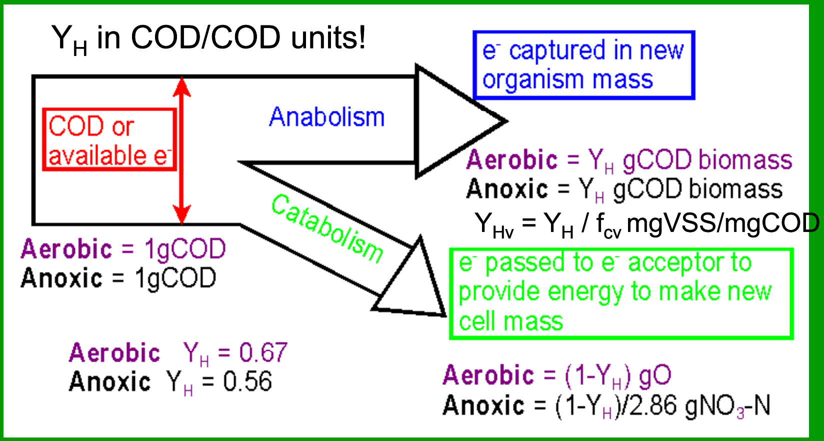
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

- So e^- accepting capacity of nitrate

= (32/4) / (14/5) → 2.86 mgO/mgNO_3^-N

(Organics are e^- donor)

SUBSTRATE UTILIZATION



Y_H in COD/COD units!

COD or available e^-

Aerobic = 1gCOD
Anoxic = 1gCOD

Aerobic Y_H = 0.67
Anoxic Y_H = 0.56

e^- captured in new organism mass

Aerobic = Y_H gCOD biomass
Anoxic = Y_H gCOD biomass
$Y_{Hv} = Y_H / f_{cv}$ mgVSS/mgCOD

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

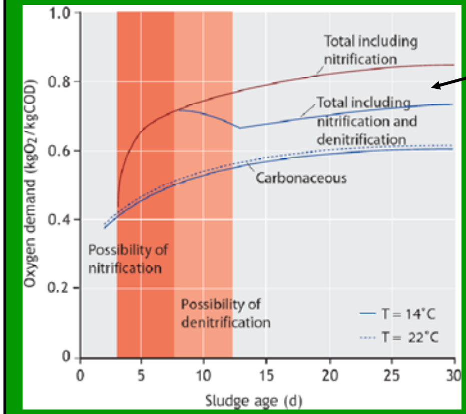
Aerobic = $(1-Y_H)$ gO
Anoxic = $(1-Y_H)/2.86$ gNO_3-N

For simplicity, accept Y_H= 0.66 for anoxic

OXYGEN RECOVERY (1)

- Nitrification consumes 4.57 mgO/mgN
- Denitrification recovers 2.86 mgO/mgN
- So 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

- $NO_3^- + 6H^+ + 5e^- \rightarrow \frac{1}{2}N_2 + 3H_2O$ + Energy

($5H^+$ from organics + $1H^+$ from bulk liquid)

- Denitrification uses $1H^+$ per mol NO_3-N to N_2

  = 1/14*50 = 3.57 mg/l $CaCO_3$ generated per mgNO_3-N/l denitrified.
  - Nitrification consumes 7.14 mg/l $CaCO_3$.
  - So denitrification recovers half the alkalinity lost in nitrification.

COMPARISON: NITRIFICATION vs DENITRIFICATION

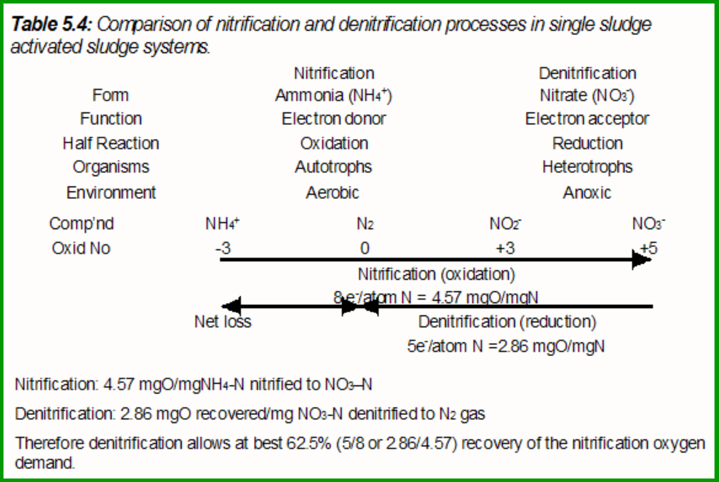


Table 5.4: *Comparison of nitrification and denitrification processes in single sludge activated sludge systems.*

	Nitrification	Denitrification
Form	Ammonia (NH_4^+)	Nitrate (NO_3^-)
Function	Electron donor	Electron acceptor
Half Reaction	Oxidation	Reduction
Organisms	Autotrophs	Heterotrophs
Environment	Aerobic	Anoxic

Comp'nd	NH_4^+	N_2	NO_2^-	NO_3^-
Oxid No	-3	0	+3	+5

Nitrification (oxidation)

$8e^-$/atom N = 4.57 mgO/mgN

Net loss

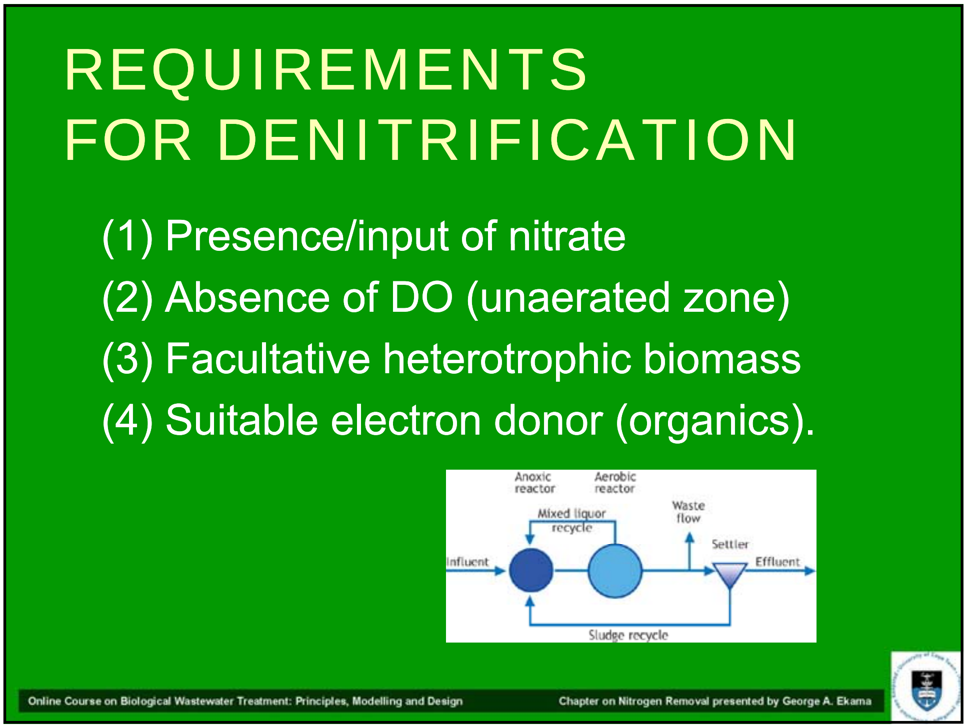
Denitrification (reduction)

$5e^-$/atom N =2.86 mgO/mgN

Nitrification: 4.57 mgO/mgNH_4-N nitrified to NO_3–N

Denitrification: 2.86 mgO recovered/mg NO_3-N denitrified to N_2 gas

Therefore denitrification allows at best 62.5% (5/8 or 2.86/4.57) recovery of the nitrification oxygen demand.



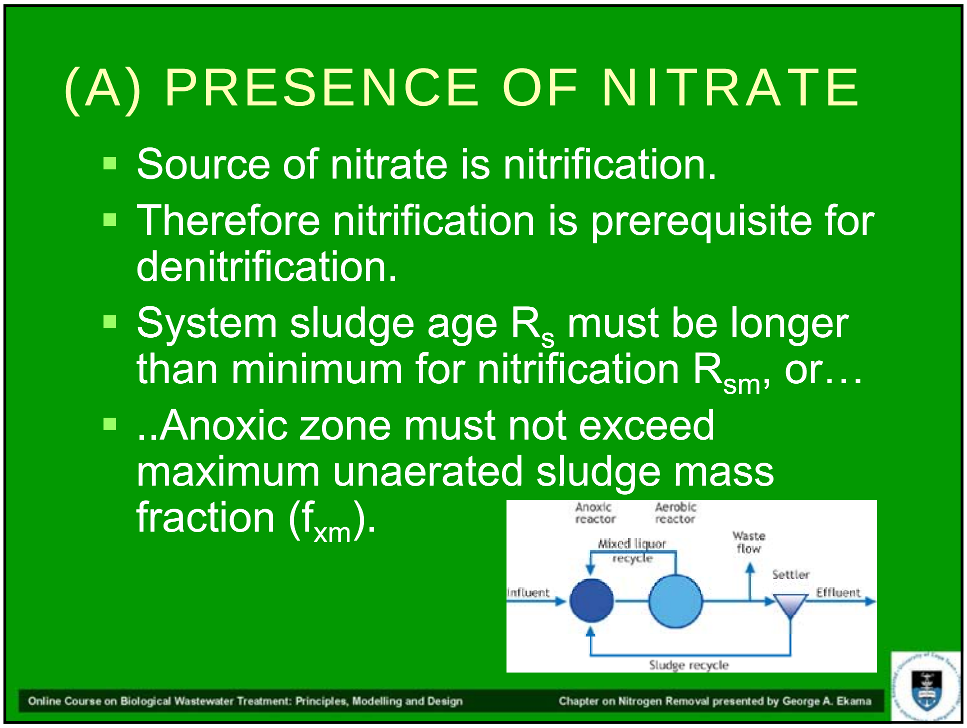
REQUIREMENTS FOR DENITRIFICATION

(1) Presence/input of nitrate

(2) Absence of DO (unaerated zone)

(3) Facultative heterotrophic biomass

(4) Suitable electron donor (organics).



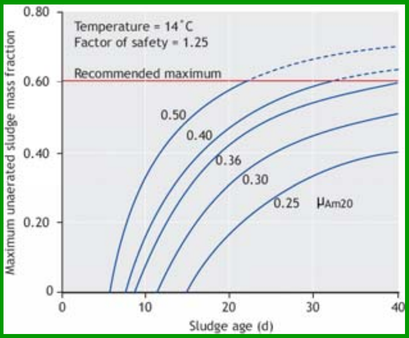
(A) PRESENCE OF NITRATE

- 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 –

$$f_{xm} = 1 - S_f\,(b_{AT} + 1/R_s)/\mu_{AmT}$$



and then effluent FSA conc is given by

$$N_{ae} = K_{nT} / (S_f - 1)$$

N_{ae} lower if $f_{xt} < f_{xm}$

(B) ABSENCE OF DO

- DO is inhibitory on denitrification

  DO = 0 mg/l -- Denitrification 100%

  DO = 0.5 mg/l – 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

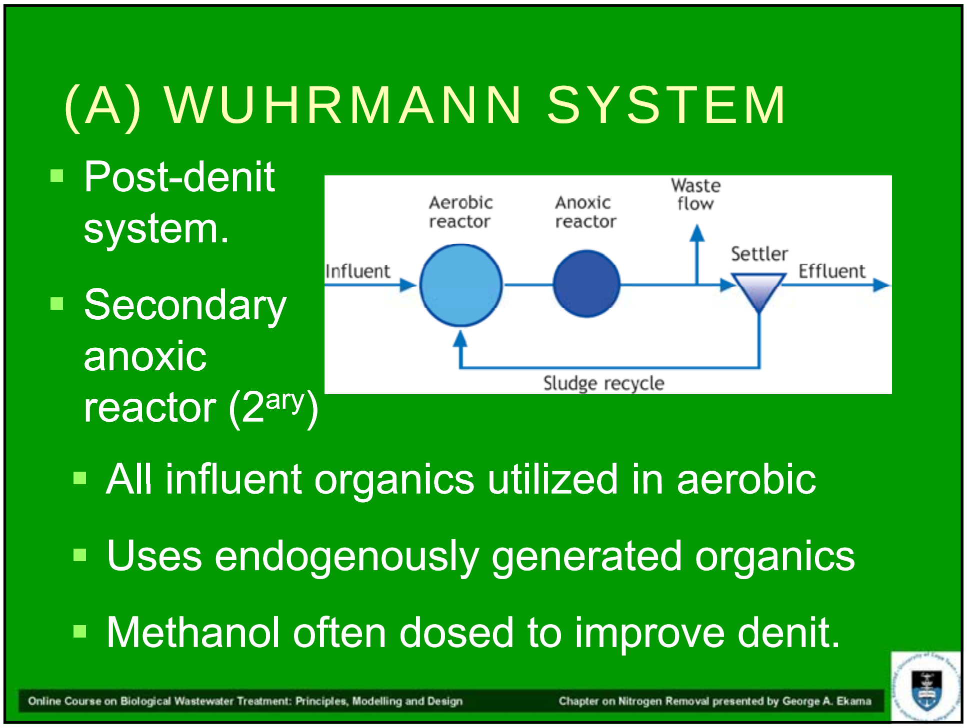
- Ability to denitrify widespread among OHOs
- In AS systems, significant number of OHOs are facultative (can denitrify).
- Little difference in bacterial populations in fully aerobic and anoxic –aerobic systems.
- Aerobic AS requires few days to acclimatize to denitrify at full capacity.

(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

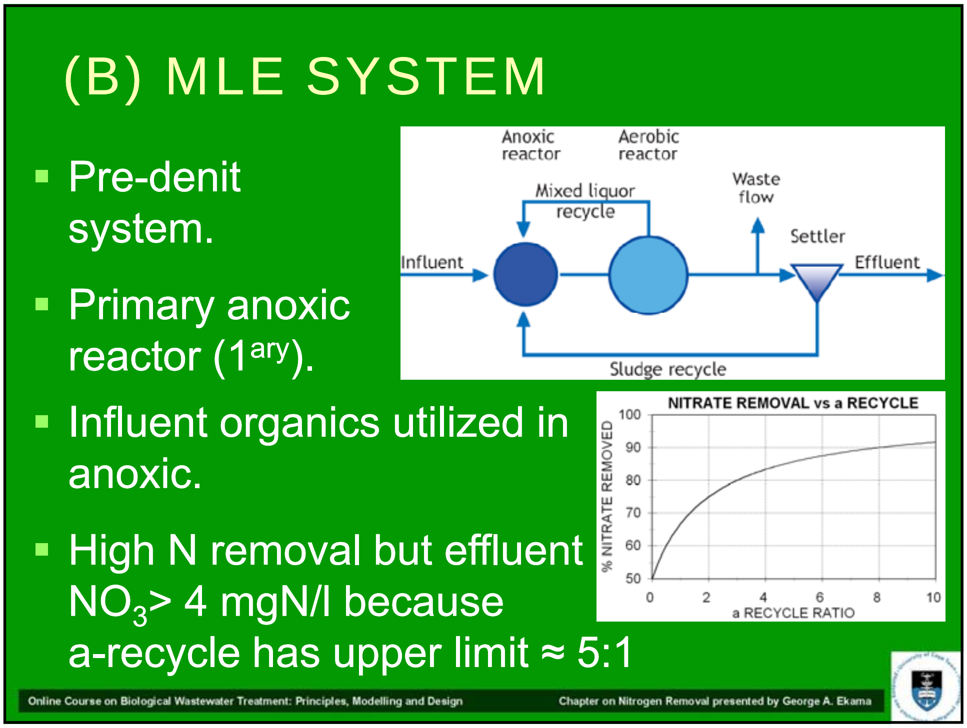
- Different configurations for denitrification have been developed depending on type of electron donor…
  - (1) …Wuhrmann – self generated ED
  - (2) …Modified Ludzack-Ettinger (MLE) – internal ED
  - (3)…4 stage Bardenpho – internal and self generated ED but methanol dosed into 2ary anoxic is external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



(A) WUHRMANN SYSTEM

- Post-denit system.
- Secondary anoxic reactor (2^{ary})

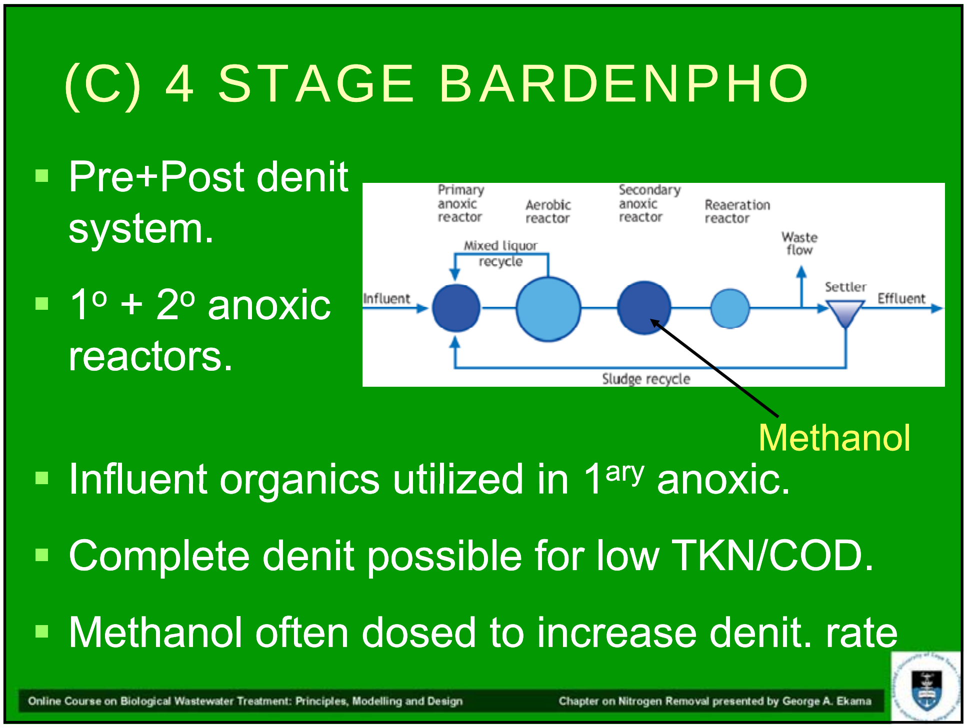
- All influent organics utilized in aerobic
- Uses endogenously generated organics
- Methanol often dosed to improve denit.



(B) MLE SYSTEM

- Pre-denit system.
- Primary anoxic reactor (1^{ary}).

- Influent organics utilized in anoxic.
- High N removal but effluent NO_3> 4 mgN/l because a-recycle has upper limit ≈ 5:1



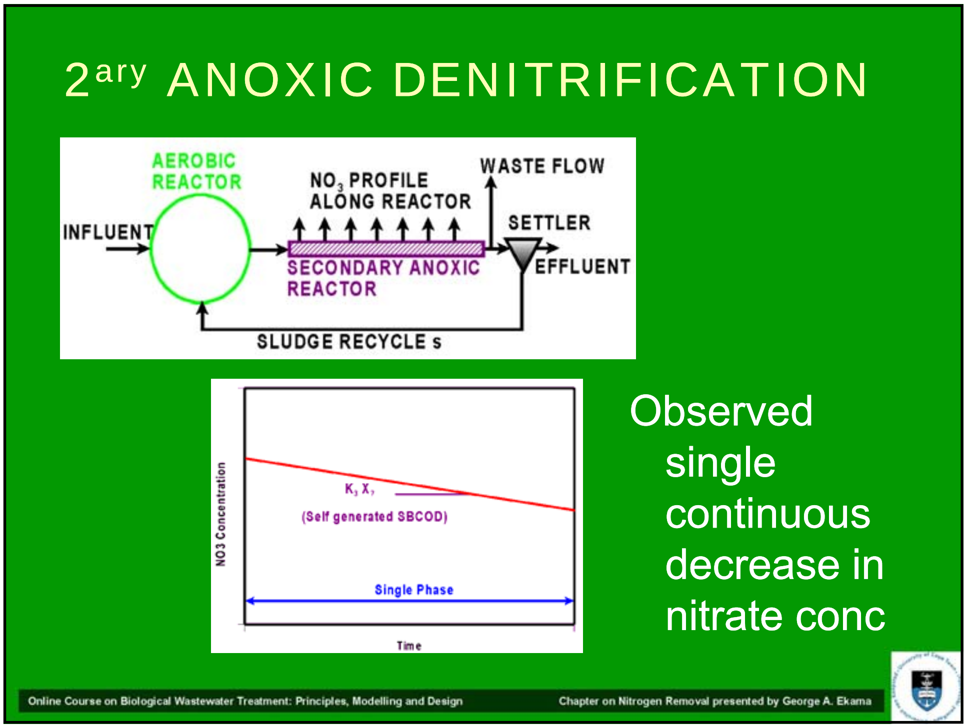
(C) 4 STAGE BARDENPHO

- Pre+Post denit system.
- 1^o + 2^o anoxic reactors.

- Influent organics utilized in 1^{ary} anoxic.
- Complete denit possible for low TKN/COD.
- Methanol often dosed to increase denit. rate

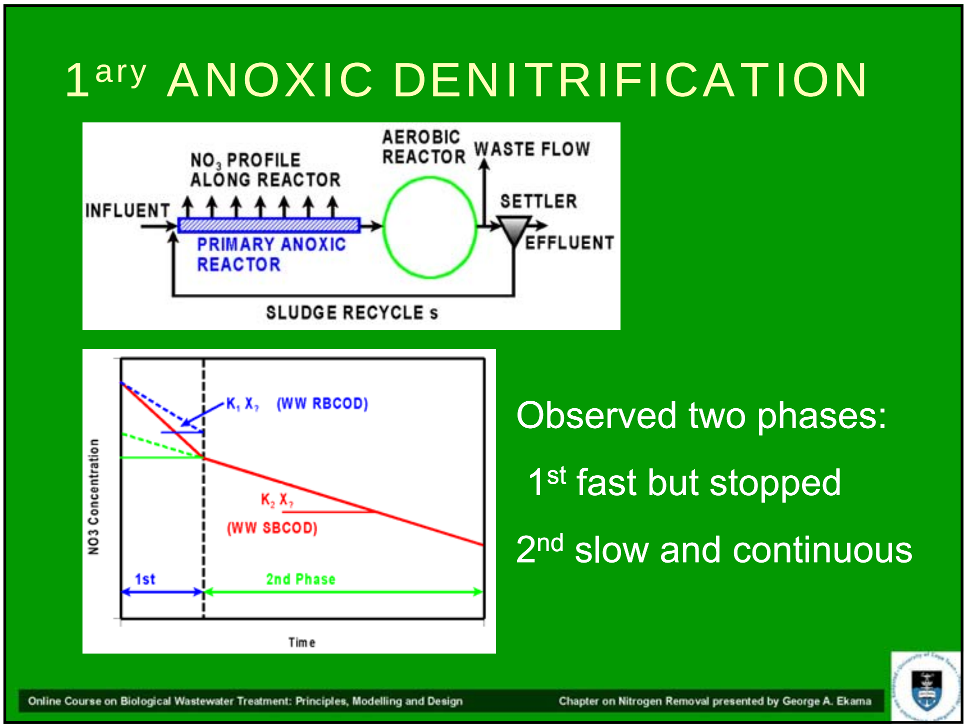
DENITRIFICATION MODEL

- Design principle – match supply rate of e^- acceptors (NO_3^-) and supply rate e^- donors (organics ≡ denit. potential)
  - Find denitrification potential (D_p) of anoxic reactor
  - Match NO_3^- load on anoxic (N_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^{ary} ANOXIC DENITRIFICATION

Observed single continuous decrease in nitrate conc



1^{ary} ANOXIC DENITRIFICATION

Observed two phases:

1st fast but stopped

2nd slow and continuous

DENITRIFICATION KINETICS (1)

- From literature and data, express denit rate

$d(NO_3\text{-}N)/dt = -K X_v$ $mgNO_3\text{-}N/(l.d)$

- K = specific denitrification rate

  $mgNO_3\text{-}N/(mgVSS.d)$
- 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…

$d(NO_3\text{-}N)/dt = -K X_{BH}$ $mgNO_3\text{-}N/(l.d)$

K = active OHO specific denitrification rate

$mgNO_3\text{-}N/(mgOHOVSS.d)$

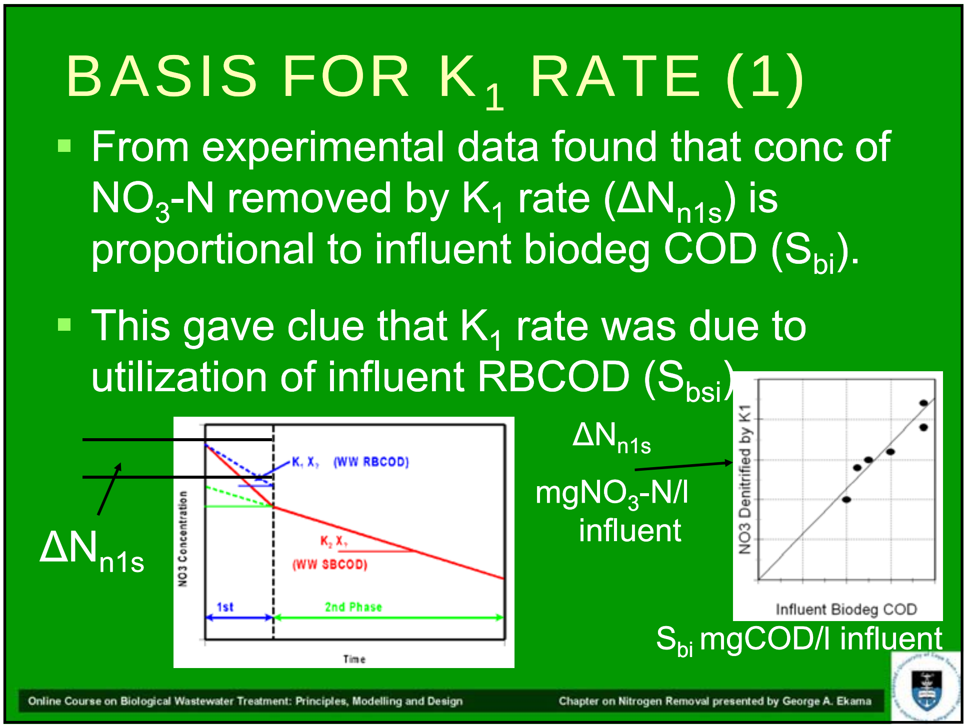
- X_{BH} obtained from steady state model.
- K rates now more consistent with sludge age (R_s).

DENITRIFICATION K RATES (1)

- Large data base of profiles at 14 and 20°C -
  $K_1 = 0.72\ (1.2)^{(T-20)}$ (halves in 4°C)
  $K_2 = 0.101\ (1.08)^{(T-20)}$ (halves in 9°C)
  $K_3 = 0.072\ (1.03)^{(T-20)}$ (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 (ΔN_{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 ΔN_{n1s} and influent biodeg COD (S_{bi}) is α, so…

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

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

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

$(1-f_{cv}Y_{Hv})/2.86$ = e^- to NO_3^- (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

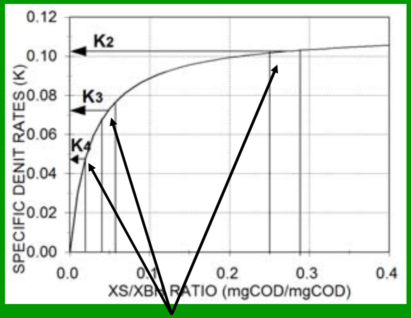
$$K_1 = \frac{(1-Y_H) f_{cv} \mu_H}{2.86 Y_H} \frac{S_S}{K_S + S_S} \quad \text{where} \quad \frac{S_S}{K_S + S_S} \approx 1$$

$mgNO_3$-$N/(mgOHOVSS.d)$

- So with $K_1 = 0.72$, $Y_H = 0.67$, $\mu_H \approx 2.8/d$.
- In range of μ_H measured in AS systems - 1 to 4 /d. μ_H varies with reactor mixing regime – high in plug flow reactors, low in completely mixed.

BASIS FOR K_2 & K_3 RATES

In simulation models utilization of SBCOD is modeled with the saturation kinetics – so K_2 and K_3 are



$$K_2 = K_3 = K_4 = \frac{(1-Y_H)}{2.86\,Y_H}\,\frac{\eta\,K_h(X_s/X_{BH})}{[K_x+(X_s/X_{BH})]}$$

$mgNO_3$-N/(mgOHOVSS.d)

where

X_S/X_{BH} is progressively lower in primary (K_2) secondary (K_3) and anoxic-aerobic digestion (K_4).

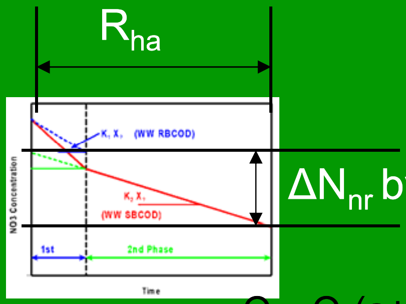
X_S/X_{BH} ratio does not change much in anoxic reactors – hence K rates approx. constant.

STEADY STATE MODEL

- From denitrification kinetics…

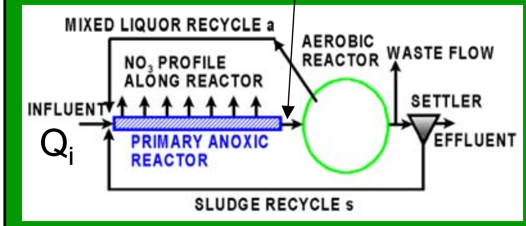
  $\Delta(NO_3\text{-}N)/\Delta t = -\,K\,X_{BH}$ $mgNO_3$-N/(l.d)
- Apply to an anoxic reactor – definitions –
  - $\Delta N_{nr} = K\,X_{BH}\,R_{ha}$ = reactor nitrate removal $mgNO_3$-N/(l flow through reactor.d)
  - R_{ha} = actual ret time of anoxic reactor
  - $\Delta N_{ns} = K\,X_{BH}\,R_{hn}$ = system nitrate removal $mgNO_3$-N/(l influent flow through system.d)
  - R_{hn} = nominal ret time of anoxic reactor.

STEADY STATE MODEL



ΔN_{nr} by K_2

$Q_r = Q_i\,(a+s+1)$



$R_{ha} = V_{ax}/\{Q_i(a+s+1)\}$

$R_{hn} = V_{ax}/Q_i$

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

ΔN_{nr} happens $(a+s+1)$ times per Q_i

So $\Delta N_{ns} = \Delta N_{nr}\,(a+s+1)$

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

DENIT. POTENTIAL OF SECONDARY ANOXIC (1)

- This is the system NO_3–N removal (/litre influent) by K_3 rate in 2^{ary} anoxic
- $D_{p3} = \Delta N_{nss} = K_3 X_{BH} R_{hns}$ mgNO$_3$-N/l influent
- But $R_{hns} = V_{axs}/Q_i$
- So $D_{p3} = K_3(X_{BH}V_{axs})/Q_i$

  where $(X_{BH}V_{axs})/Q_i$ is OHO mass in 2^{ary} anoxic per l influent flow, which is obtained from COD removal steady state model.

DENIT. POTENTIAL OF SECONDARY ANOXIC (2)

- Defining the 2^{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 $(X_{BH}V_p /Q_i)$ = 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^{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^{ary} anoxic

  $\Delta N_{n2s} = S_{bi}\ K_2\ f_{x1}\ Y_{Hv}R_s/(1+b_HR_s)$ $mgNO_3$-N/l influent

  $f_{x1} = 1^{ary}$ anoxic sludge mass fraction

DENIT. POTENTIAL OF PRIMARY ANOXIC (2)

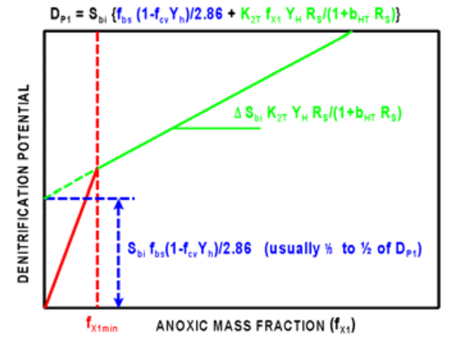
- So adding nitrate removal by K_1 (RBCOD) and K_2 (SBCOD) rates….

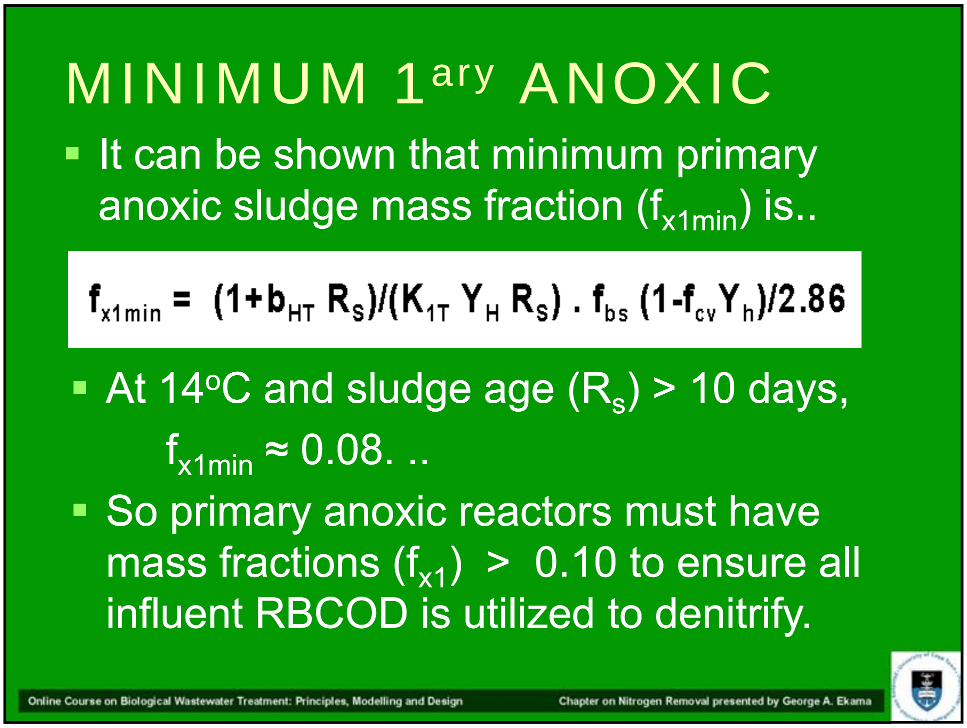
  $D_{p1} = S_{bi}\ f_{bs}\ (1-f_{cv}Y_{Hv})/2.86$
  $+ S_{bi}\ K_2\ f_{x1}\ Y_{Hv}R_s/(1+b_HR_s)$
  $mgNO_3$-N/l influent
- Note D_{p1} depends on…

  (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^{ary} anoxic mass fraction increases,
- but must be larger than minimum (f_{x1min}) to utilize all influent RBCOD.
- It is inefficient to not use all RBCOD in 1^{ary} anoxic.





MINIMUM 1^{ary} ANOXIC

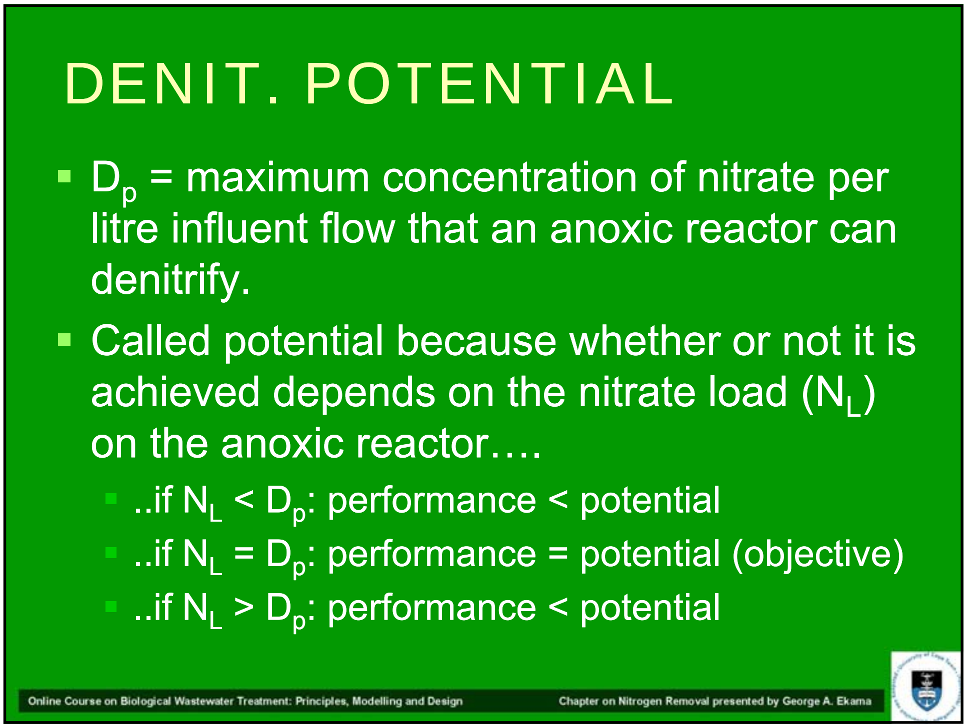
- It can be shown that minimum primary anoxic sludge mass fraction (f_{x1min}) is..

$$f_{x1min} = (1+b_{HT} R_S)/(K_{1T} Y_H R_S) \, . \, f_{bs} (1-f_{cv} Y_h)/2.86$$

- At 14^{o}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 (μ_{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.

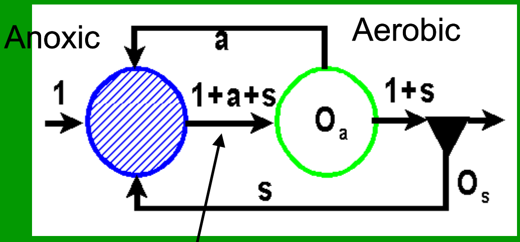
DESIGN PROCEDURE (2)

- 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°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} ≈0.25, near complete N removal can be achieved with WW organics only in 1^{ary} and 2^{ary} 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^{ary} and 2^{ary}, and dose methanol into 2^{ary}.
  - With dosing, 2^{ary} acts like a 1^{ary} so add a RBCOD term to D_{p3} Eq. Yield (Y_{Hv}) for methanol is lower than the usual 0.45 mgVSS/mgCOD AS value.
  - Adjust design parameters (R_s, f_{xm}, f_{x1}, f_{x3}, a) until economical design is obtained.
- This design procedure is demonstrated with some examples.

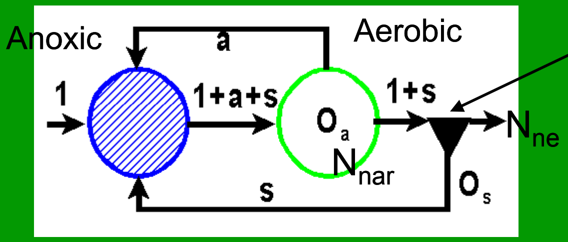
PROCEDURE DEMO: MLE (1)



- 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.

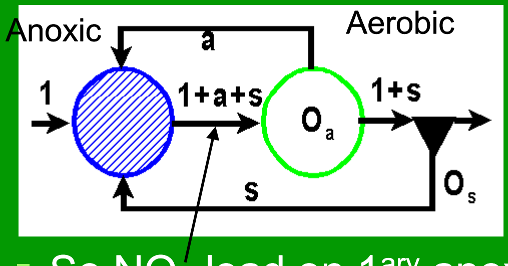
PROCEDURE DEMO: MLE (2)



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 = $N_c/(a+s+1)$.

PROCEDURE DEMO: MLE (3)

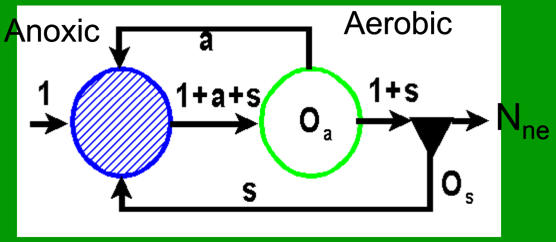


DO in recycles O_a and O_s mg/l

- So NO_3 load on 1^{ary} anoxic (N_{nlp}) = {aerobic NO_3 conc + nitrate equivalent of DO} x recycle ratios, i.e.

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

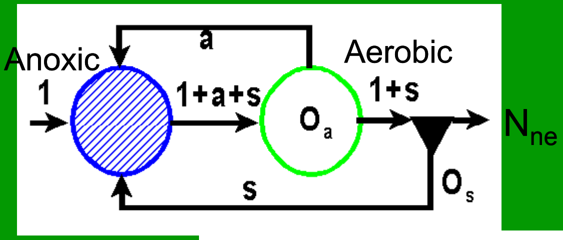
PROCEDURE DEMO: MLE (4)



- For optimum denitrification (lowest N_{ne}), set nitrate load (N_{nlp}) = to denit. potential D_{p1}. Only unknown is a recycle, so solve for a_{opt}.

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

PROCEDURE DEMO: MLE (5)



$$a_{opt} = [-B+\sqrt{B^2+4AC}]/(2A) \qquad (5.59)$$

where

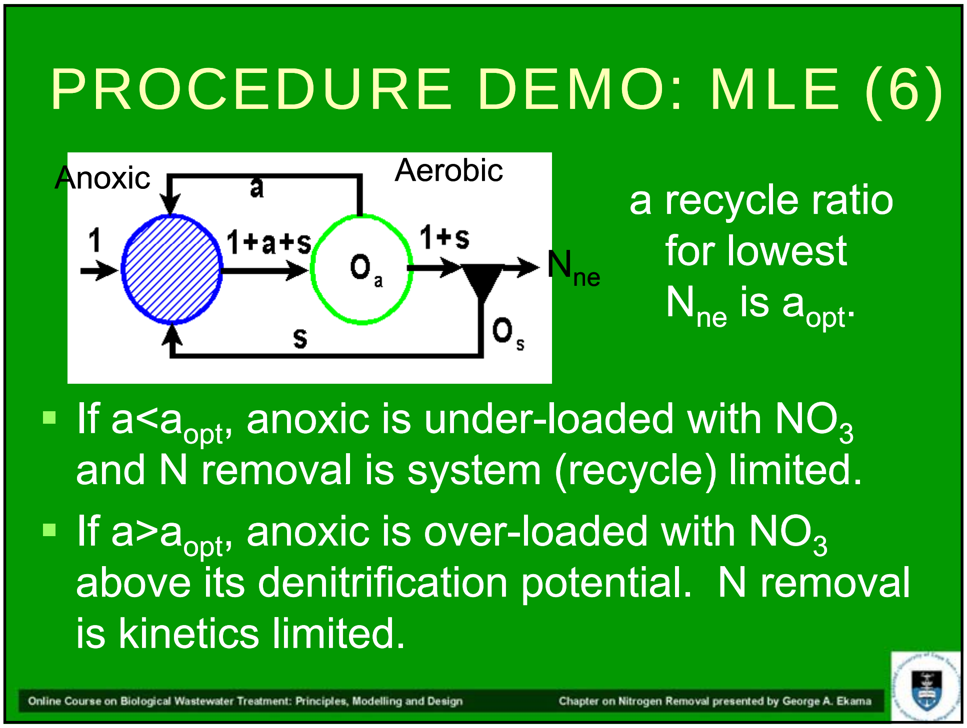
$A = O_a/2.86$

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

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

and

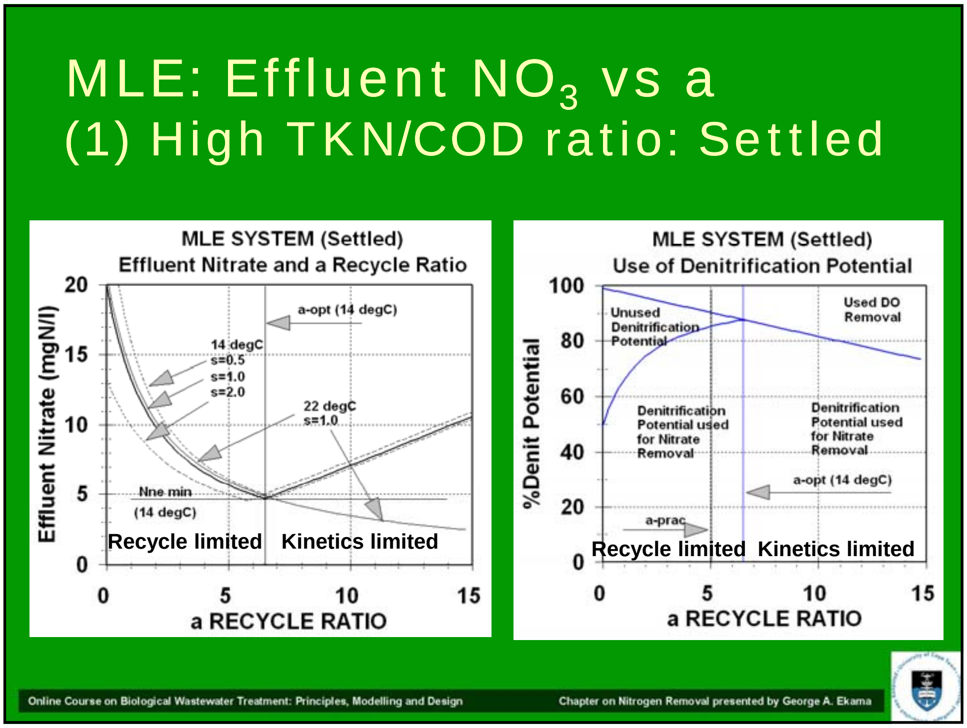
$$N_{nemin} = N_{neaopt} = N_c/(a_{opt}+s+1) \text{ (mgN/ℓ)} \qquad (5.60)$$



PROCEDURE DEMO: MLE (6)

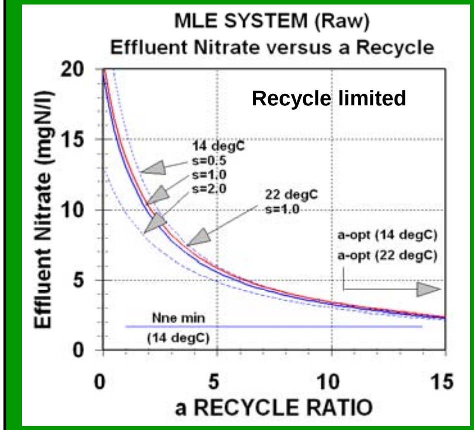
a recycle ratio for lowest N_{ne} is a_{opt}.

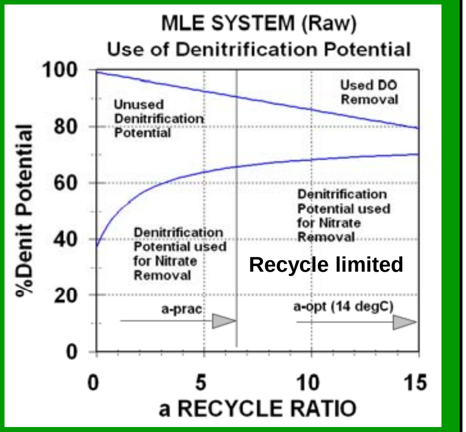
- If $a<a_{opt}$, anoxic is under-loaded with NO_3 and N removal is system (recycle) limited.
- If $a>a_{opt}$, anoxic is over-loaded with NO_3 above its denitrification potential. N removal is kinetics limited.



MLE: Effluent NO_3 vs a
(1) High TKN/COD ratio: Settled

MLE: Effluent NO_3 vs a
(2) Low TKN/COD ratio: Raw





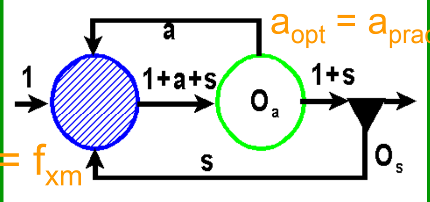
MAXIMUM PRACTICAL a

- 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).

BALANCED MLE SYSTEM



$a_{opt} = a_{prac} = 5:1$

N_{ti}

$f_{x1} = f_{xm}$

- 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.

BALANCED MLE SYSTEM

- 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}.
- Do NOT need any new equations!
- 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 = to a_{opt}

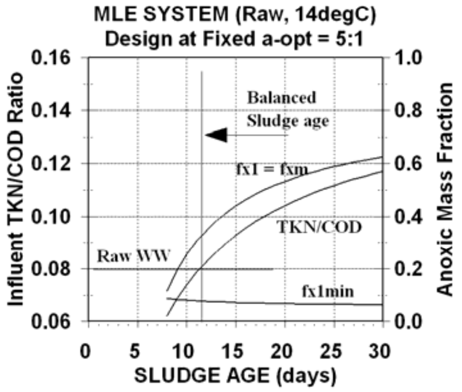
(4) Calculate nitrification capacity (N_c) from NO_3 load - denit potential Eq.….

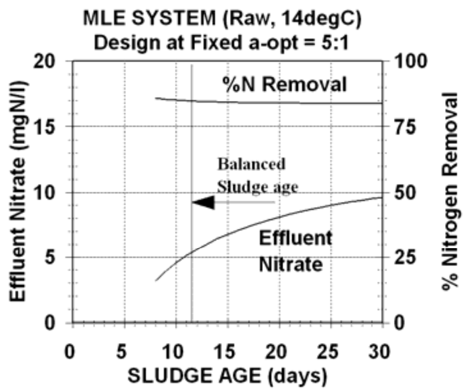
$$N_{nlp} = \left[\frac{N_c}{(a+s+1)} + \frac{O_a}{2.86}\right] a + \left[\frac{N_c}{(a+s+1)} + \frac{O_s}{2.86}\right] s = D_{p1}$$

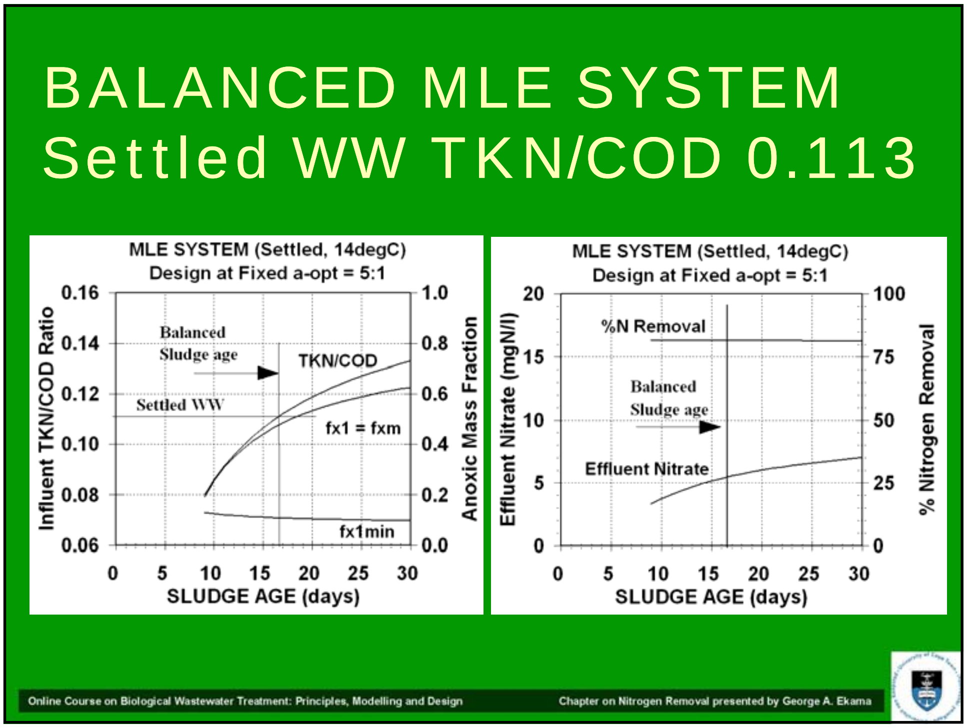
(5) Calculate N_{ti} from

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

BALANCED MLE SYSTEM Raw WW TKN/COD 0.08







BALANCED MLE SYSTEM
Settled WW TKN/COD 0.113

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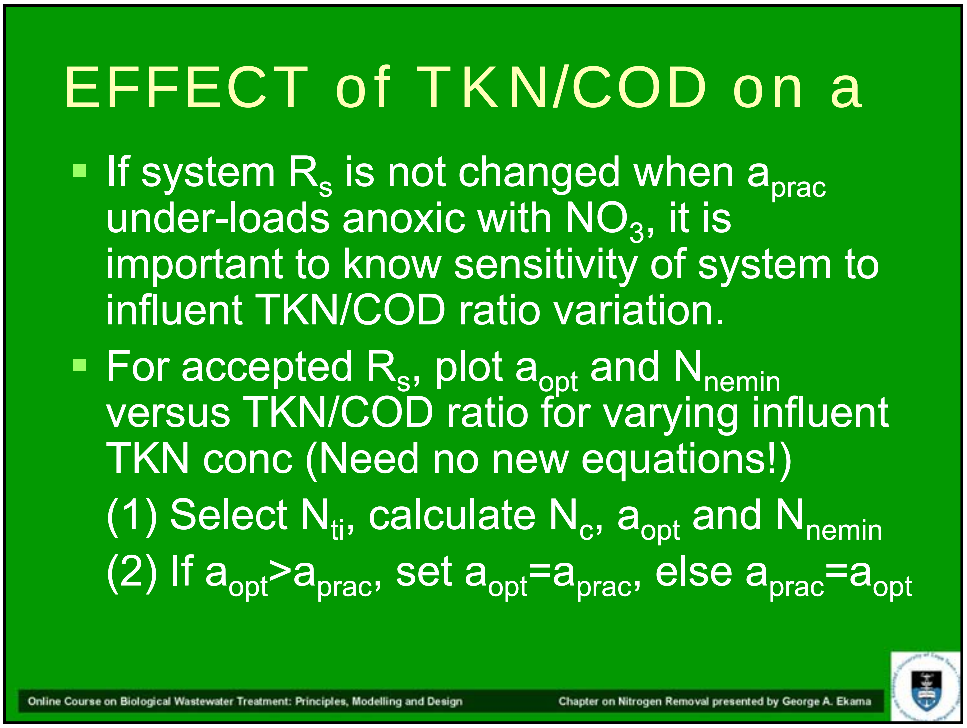
Chapter on Nitrogen Removal presented by George A. Ekama



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}

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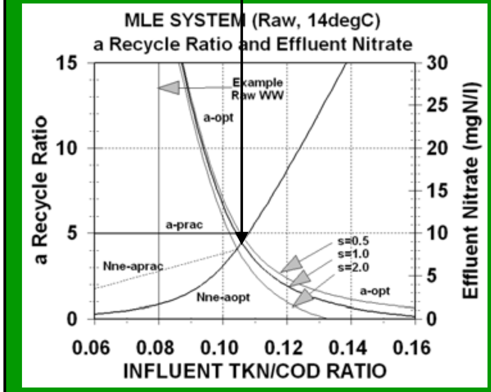
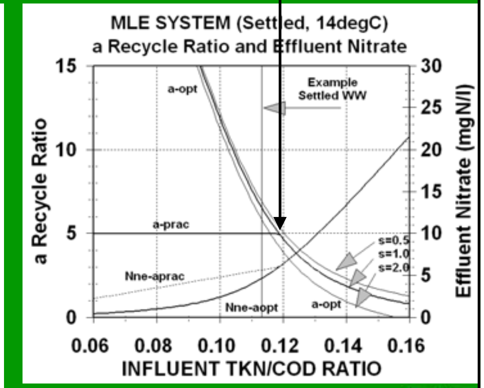
EFFECT of TKN/COD on a-recycle and Effluent NO_3

Sludge age = 20d

TKN/COD ratio that balances MLE





EFFECT of TKN/COD on a-recycle and Effluent NO_3

(1) If influent TKN/COD ratio is low (<0.10),

- a_{opt} is high and > a_{prac} (= 5:1)
- effluent NO_3 is low, but not < 4-5 mgN/l.
- If zero effluent NO_3 is required, subdivide anoxic into 1^{ary} and 2^{ary} anoxic reactors and dose methanol into 2^{ary} anoxic – details in notes.

EFFECT of TKN/COD on a-recycle and Effluent NO_3

(2) If influent TKN/COD ratio is high (>0.10),

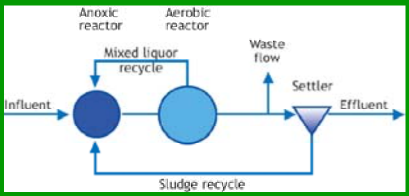
- a_{opt} is low and < a_{prac} (= 5:1)
- effluent NO_3 is high, > 5 and up to 15 $mgNO_3$-N/l depending on influent TKN/COD ratio.
- If low effluent NO_3 is required, subdivide anoxic into 1^{ary} and 2^{ary} anoxic reactors and dose methanol into 2^{ary} anoxic – details in notes.

REACTOR VOLUMES (1)

- Calculated N removal without knowing anoxic zone volume or retention time, only mass fractions (f_{xt}, f_{xm} f_{x1}, 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 – 1^{ary} anoxic sludge mass fraction $f_{x1} = (X_{tp}V_{axp})/(X_tV_p)$,

REACTOR VOLUMES (2)

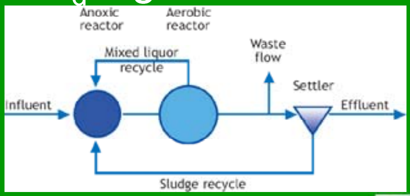
- In the MLE, anoxic reactor X_t (MLSS) conc is same as aerobic reactor X_t, so volume fractions = mass fractions.
- If f_{x1}= 0.45, then 1^{ary} anoxic volume = 0.45 (45%) of system reactor volume.



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!

ACKNOWLEDGEMENTS

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And others