APPENDIX

Calculation procedure for balanced SRT of MLE system

The balanced SRT of a MLE system is the SRT at which the equivalent nitrate load on the primary anoxic reactor is equal to its denitrification potential at a maximum economical mixed liquor a-recycle ratio (a_{prac}) of say 6:1 ($a_{opt}=a_{prac}$) and can be calculated as shown below. A list of Symols and abbreviations sorted into wastewater characteristics, system parameters and kinetic and stoichiometric constant groups is given at the end.

(1) With wastewater characteristics defined, select a sludge age (SRT, R_s).

(2) Calculate the A and B values from the wastewater characteristics. Because the A and B values relate to the wastewater characteristics and OHO biomass, they are the same for the ND and NDEBPR systems.

(3) Calculate the maximum unaerated sludge mass fraction (f_{xm}) from

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

(4) Set the primary anoxic sludge mass fraction (f_{x1}) equal to the maximum unaerated sludge mass fraction allowed (f_{xm}) and check that f_{x1} is greater than the minimum primary anoxic sludge mass fraction (f_{x1min}) required to utilize all the readily biodegradable organics (BSO),

$$f_{x1} > f_{x1min} = \frac{f_{Sb's}(1-f_{cv}Y_H)(1+b_{HT}R_s)}{2.86K_{1T}Y_H R_S}$$

If $f_{x1}<f_{x1min}$, select a longer SRT are return to step 1.
If $f_{x1} \geq f_{x1min}$, continue with step 5.

(5) Calculate the denitrification potential of the primary anoxic reactor (D_{p1}) from

$$D_{p1} = S_{bi}\left[\frac{f_{Sb's}(1-f_{cv}Y_H)}{2.86} + K_{2T}f_{x1}\frac{Y_H R_s}{(1+b_{HT}R_s)}\right] \qquad \text{mgNO}_3\text{-N/l} \qquad (3)$$

(6) Select the underflow (s) recycle ratio, the DO concentrations in the a and s recycles (O_a and O_s) and a maximum practical a-recycle ratio ($a=a_{prac}=6$ say) and calculate the nitrification capacity (N_c) from Eq 3.

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

(7) Calculate the nitrogen concentration required for sludge production (N_s) from

$$N_s = f_n\frac{S_{ti}L_{MLE,VSS}}{R_s} \qquad \text{mgN/l influent}$$

where $L_{MLE,VSS}$ is given buy Eq 10 below.

(8) Calculate the effluent TKN concentration (N_{te})

$$N_{te} = N_{ouse} + N_{ae}$$

$$N_{ae} = \frac{K_{nT}}{(S_f - 1)} \qquad \text{mgFSA-N/l provided } f_{x1}=f_{xm}$$

If the unaerated sludge mass fraction (f_{xt}), which for the MLE is he primary anoxic sludge mass fraction (f_{x1}), is less than the maximum unaerated mass fraction (f_{xm}), i.e. $f_{x1}=f_{xt}<f_{xm}$, which is not the case when calculating the balanced SRT, then,

$$N_{ae} = \frac{K_{nT}(b_{AT} + 1/R_S)}{(1-f_{xt})\,\mu_{AmT}-(b_{AT}+1/R_S)} \qquad \text{mgN/l provided } f_{xt}<f_{xm}$$

Equations 7 and 8 give the same N_{ae} concentration when $f_{xt}=f_{xm}$.

(9) Calculate the influent TKN concentration (N_{ti}) from Eq 8

$$N_{ti} = N_c + N_s + N_{te}$$

(10) If the calculated N_{ti} is lower than the actual N_{ti}, increase the SRT and repeat steps 1 to 9 or if the calculated N_{ti} is higher than the actual N_{ti}, decrease the SRT and repeat steps 1 to 9. The SRT at which the calculated N_{ti} is equal to the actual N_{ti} is the balanced MLE system SRT.

If steps 1 to 9 are coded into a spreadsheet, then the balanced SRT can be found with a “what-if” table calculation as follows: Set up a column (say A) with SRT values ranging from 1 to 30 days in steps of 0.1d in rows A3 to A304. Extract from the steps 1 to 9 calculation, the relevant answers required in B2 to say H2 including the influent TKN concentration (N_{ti}) in the last column (I). Run the “what-if”, which will fill in the results for all the columns from B3 to H304. In column J, write an if statement like @if[I(x)>Actual N_{ti}, A(x),1000] and copy it from J3 to J304. This if statement compares the calculated N_{ti} with the actual N_{ti} and enters 1000 in column J if calculated N_{ti} < actual N_{ti} and the SRT when the calculated N_{ti} > actual N_{ti}. Then at J2 at the top of column J, search for the minimum value in column J with @min(J3..J304). This minimum value is the balanced SRT of the UCT system at which the calculated N_{ti} is just greater than the actual N_{ti}.

The L factor for fully aerobic and anoxic-aerobic activated sludge systems

For fully aerobic and anoxic-aerobic nitrification-denitrification (ND) Modified Ludzack-Ettinger (MLE) and 4 stage Bardenpho systems, the L factor equation (kgTSS in reactor per kgCOD load/d), which is the inverse of the F/M in kgCOD/(kgTSS.d), is:

$$L_{MLE,TSS} = \frac{MX_{tave}}{FS_{ti}} = (1-f_{S'up}-f_{S'us})\frac{Y_H R_s}{(1+b_{HT}R_s)}(1+f_H b_{HT} R_s + f_{iOHO}) + \left[\frac{f_{S'up}}{f_{cvUPO}} + \frac{X_{Ioi}}{S_{ti}}\right] R_s \qquad (10)$$

where

MX_t = mass of TSS in reactor (kgTSS) = $V_R\ X_{tave}$

V_R = volume of reactor (m^3)

X_{tave} = average TSS concentration in reactor ($kgTSS/m^3$)

The L factor in terms of VSS, as required in Eq 5 above, is obtained by setting the f_{iOHO} and X_{IOi} that relate to the ISS in Eq 10 to zero, viz.

$$L_{MLE,VSS} = \frac{MX_{vave}}{FS_{ti}} = (1 - f_{S'up} - f_{S'us})\frac{Y_H R_s}{(1 + b_{HT}R_s)}(1 + f_H b_{HT} R_s) + \left[\frac{f_{S'up}}{f_{cvUPO}}\right] R_s \qquad (11)$$

Explicit equation for balanced SRT of the MLE system

An explicit equation for the balanced SRT of an MLE system has ben derived, viz.

$$R_{sBalMLE} = \frac{C.E_{MLE} + D - A.B + A.S_f K_{2T}\dfrac{Y_H}{\mu_{AmT}} - E_{MLE} f_n \left[A.Y_H + S_{ti}\dfrac{f_{S'up}}{f_{cvUPO}}\right]}{A(B.b_{HT} + K_{2T}Y_H) - A.S_f b_{AT} K_{2T}\dfrac{Y_H}{\mu_{AmT}} - b_{HT}(C.E_{MLE} + D) + E_{MLE} f_n b_{HT}\left[A.Y_H f_H + S_{ti}\dfrac{f_{S'up}}{f_{cvUPO}}\right]}$$

where the composite parameters

A = influent biodegradable organics (VFA+FBSO+BPO) as COD = $S_{bi}=S_{ti}(1-f_{S'us}-f_{S'up})$
VFA = volatile fatty acids
FBSO = fermentable biodegradable soluble organics
BPO = biodegradable particulate organics
B = $f_{Sb's}\,(1-f_{cv,OHO}\,Y_H)/2.86$
C = Influent minus effluent TKN concentrations = N_{ti} - N_{te} mgN/l
D = $(a_{prac}\,O_a + s\,O_s)/2.86$
E_{MLE} = $(a_{prac}+s)/(a_{prac}+s+1)$ = proportion of nitrate recycled to primary anoxic zone in MLE

Calculation procedure for ADWF capacity of MLE system

Once the SRT of a fully aerobic or ND system (MLE or 4 stage Bardenpho) has been decided or is known from the existing plant, the ADWF treatment capacity for known reactor volume (V_R, m^3) and secondary settling tank (SST) surface area (A_{ST}, m^2) can be calculated as follows:

(1) Select sludge settleability in terms of DSVI (ml/gTSS)
(2) Convert DSVI to SSVI and flux theory V_0 (m/h) and n (ml/gTSS) constants using the equations from Ekama and Marais (1896) or Ekama et al. (1997), viz.

$SSVI = 0.67 DSVI$ (12); $\quad \frac{V_0}{n} = 67.9\, e^{0.016\,SSVI}$ kgTSS/(m (13)

$n = 0.880 - 0.393\log\left[\frac{V_0}{n}\right]$ ml/gTSS (14); $\quad V_0 = n\left[\frac{V_0}{n}\right]$ m/h (15)

(3) $Q_{ADWF} = \frac{V_R X_{tave}}{L_{MLE} S_{ti}}$ ML/d (16); $\quad \frac{f_q Q_{ADWF} 1000}{A_{ST} 24} = q_i\ m/h = V_s = 0.8 V_0 e^{-nX_{tave}}$

(4) Substitute Eq (16) for Q_{ADWF} into Eq (17) yields:

$X_{tave} = H_{MLE}\, e^{-nX_{tave}}$ kgTSS/m^3 (18)

(5) Solve for X_{tave} in Eq 18 where

$$H_{MLE} = \frac{L_{MLE} S_{ti} A_{ST} 0.8\, V_0 24}{f_q V_R 1000}$$

(6) With X_{tave} known, Q_{ADWF} is given in Mℓ/d by Eq (16).

For the MLE system (and 4 stage Bardenpho), the TSS concentration in the different anoxic and aerobic zones of the reactor are all the same. Hence the average TSS concentration (X_{tave}) in the system is also the TSS concentration that enters the SST from the last reactor of the system.
List of Symbols

and sorting the rest of the variables in Eq 1 into wastewater characteristic, system parameter and kinetic and stoichiometric constant groups:

(1) Wastewater characteristics
f_{cvUPO} = COD/VSS ratio of influent unbiodegradable particulate organics (UPO) = 1.481 mgCOD/mgVSS
FS_{ti} = daily influent COD flux (kgCOD/d) = Q_{ADWF} S_{ti}
$f_{S'us}$ = unbiodegradable soluble organics (USO) COD fraction of total COD
$f_{S'up}$ = unbiodegradable particulate organics (UPO) COD fraction of total COD
Q_{ADWF} = average dry weather flow (ML/d)
S_{ti} = flow weighted average total influent COD concentration (mgCOD/l)
X_{IOi} = flow weighted average influent ISS concentration (mgISS/l)

(2) System parameters
R_s = solids retention time (SRT) or system sludge age (d)

(3) Kinetic and stoichiometric constants
Y_H = OHO VSS based yield coefficient = 0.45 mgVSS/mgCOD
f_H = unbiodegradable fraction of OHO biomass = 0.20 mgVSS/mgOHOVSS
f_{iOHO} = inorganic suspended solids (ISS) content of OHO (0.15 mgISS/mgOHOVSS)
b_{HT} = OHO endogenous respiration rate at T ºC /d
= $b_{H20}(1.029)^{(T-20)}$ where b_{H20} is the rate at 20ºC = 0.24 /d

where the composite parameters
A = influent biodegradable organics (VFA+FBSO+BPO) as COD = S_{bi}=$S_{ti}(1-f_{S'us}-f_{S'up})$
VFA = volatile fatty acids
FBSO = fermentable biodegradable soluble organics
BPO = biodegradable particulate organics
B = $f_{Sb's}\ (1-f_{cv,OHO}\ Y_H)/2.86$
C = Influent minus effluent TKN concentrations = N_{ti} - N_{te} mgN/l
D = $(a_{prac}\ O_a + s\ O_s)/2.86$
E_{MLE} = $(a_{prac}+s)/(a_{prac}+s+1)$ = proportion of nitrate recycled to primary anoxic zone in MLE

(1) Wastewater characteristics
N_{ti} = influent TKN concentration mgN/l
S_{ti} = influent flow weighted total COD organics concentration mgCOD/l
$f_{Sb's}$ = fraction of biodegradable COD that is readily biodegradable
= $[S_{bsai}$ (VFA) + S_{bsfi} (FBSO)]/[S_{bsai} (VFA) + S_{bsfi} (FBSO) +S_{bpi} (BPO)]
S_{bsai} = VFA COD concentration in influent.

S_{bsfi} = FBSO COD concentration in influent.

(2) System parameters

f_{xm} = maximum unaerated mass fraction of system

f_{xt} = total unaerated mass fraction of system ($\leq f_{xm}$)

S_f = Safety factor on nitrification

a_{prac} = maximum practical mixed liquor a-recycle ratio

O_a = dissolved oxygen concentration in the aerobic reactor mgO/l

s = underflow recycle ratio

O_s = dissolved oxygen concentration in the underflow from SST mgO/l

(3) Kinetic and stoichiometric constants

2.86 = electron accepting oxygen equivalent of nitrate (gO/gNO_3-N)

K_{nT} = Monod half saturation coefficient for ANO mgFSA-N/l
= $K_{n20}(1.123)^{(T-20)}$ where K_{n20} is the coefficient at 20ºC = 1.0 mgN/l

b_{AT} = ANO endogenous respiration rate at T ºC /d
= $b_{A20}(1.029)^{(T-20)}$ where b_{A20} = 0.04 /d

K_{2T} = 2nd denitrification rate in primary anoxic zone of MLE due to slowly biodegradable organics (BPO) at TºC
= $K_{220}(1.08)^{(T-20)}$ where K_{220} is the rate at 20ºC = 0.101 mgNO_3-N/(mgOHOVSS.d)

μ_{AmT} = ANO maximum specific growth rate at T ºC /d
= μ_{Am20} $(1.123)^{(T-20)}$ where μ_{Am20} is the rate at 20ºC

T = temperature in ºC

f_n = nitrogen content of VSS (OHO biomass, endogenous residue and unbiodegradable particulate organics from influent) = 0.10 mgN/mgVSS

(4) Effluent concentrations

N_{te} = effluent TKN concentration mgN/l
= $N_{ouse} + N_{ae}$

N_{ouse} = nitrogen concentration of the unbiodegradable soluble organics (USO) mgN/l

N_{ae} = effluent ammonia concentration mgN/l
= K_{nT} $(b_{AT}+1/R_s)/[(1-f_{xt})\mu_{AmT}-(b_{AT}+1/R_s)]$ for $f_{xt} < f_{xm}$
= $K_{nT}/(S_f -1)$ for $f_{xt} = f_{xm}$ mgFSA-N/l

Table 3: MLE, UCT and JHB system maximum capacity and effluent quality.

	MLE system		UCT system		JHB system	
Wastewater type	Raw	Settled	Raw	Settled	Raw	Settled
Influent TKN/COD ratio	0.0784	0.0936	0.0784	0.0936	0.0784	0.0936
Balanced SRT (d)	11.4	13.61	10.70	12.80		
Unaerated mass fraction	0.425	0.492	0.397	0.470		
Primary anoxic mass frac	0.425	0.492	0.277	0.350		
Effluent TKN (mgN/l)	2.66	2.66	2.66	2.66		
Effluent Nitrate (mgN/l)	7.57	6.80	7.26	6.52		
Effluent Total N (mgN/l)	10.23	9.47	9.92	9.19		
% N removal	88.6	88.6	89.0	86.9		
Aerobic TSS (kgTSS/m^3)	3.98	3.38	4.20	3.44		
Capacity Q_{ADWF} (ML/d)	21.36	33.50	19.63	24.65		
Effluent OP (mgP/l)	12.86	13.54	0.0	0.0		