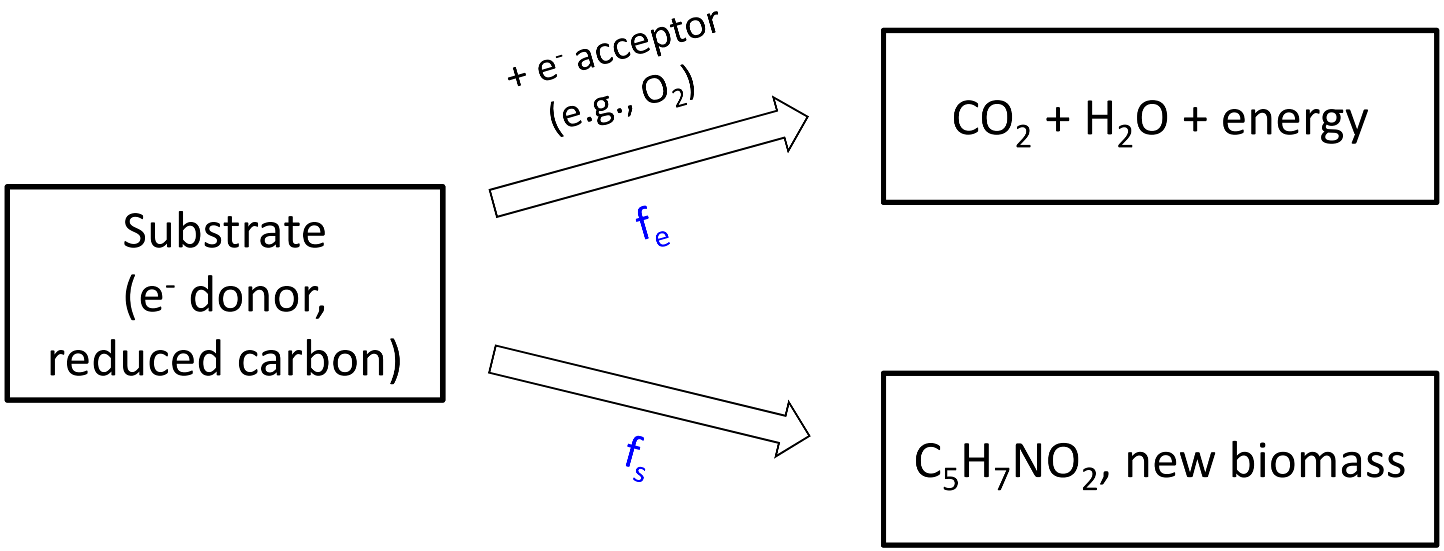
Fundamentals of biological treatment II

Oxygen uptake rate

- How much oxygen is needed for the bacterial growth?
- **Electron partitioning**



f_e: fraction of e^- donor electron used for energy generation

f_s: fraction of e^- donor electron used for cell synthesis

$f_e + f_s = 1$

Oxygen uptake rate

- COD of a substrate is directly proportional to "how much the carbon is reduced compared to its fully oxidized state (CO_2)"

$$O_2 + 4e^- \rightarrow 2O^{2-}$$

32 g O_2 per 4 moles of electrons

electrons are provided by the e^- donor

- Biomass COD ($C_5H_7NO_2$ – representative cell formula)

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O$$

$$\frac{5 \times 32\ g\ COD/mole\ C_5H_7NO_2}{113\ g\ C_5H_7NO_2/mole\ C_5H_7NO_2} = \mathbf{1.42\ g\ COD/g\ C_5H_7NO_2}$$

Oxygen uptake rate

- When substrates are utilized by microorganisms,
  - Some fraction of substrate COD is converted to biomass COD (Some fraction of electrons is transferred to biomass)
  - The other fraction of substrate COD is consumed (The other fraction of electrons is donated to e^- acceptor)

- So:

(substrate COD utilization rate)

= (biomass COD production rate) + (oxygen consumption rate)

$$r_o = r_{su} - 1.42 r_X$$

r_o = oxygen uptake rate (g O_2/m^3-d)

r_{su} = substrate utilization rate (g bsCOD/m^3-d)

r_X = net biomass growth rate (g VSS/m^3-d)

Temperature effect

- Recall the modified van't Hoff-Arrhenius relationship:

$$k_T = k_{20}\theta^{(T-20)}$$

θ= temperature correction factor, range from 1.02 to 1.25

Total VSS and active biomass

- Note that total VSS includes not only active biomass but also:
  - Cell debris resulting from endogenous decay
  - Non-biodegradable VSS (nbVSS) in the influent wastewater
- During cell death, some portion dissolves into the liquid for consumption by other bacteria, and the other portion remains as non-biodegradable material
  - 10~15% of original cell weight is converted to nbVSS
  - This is referred to as cell debris

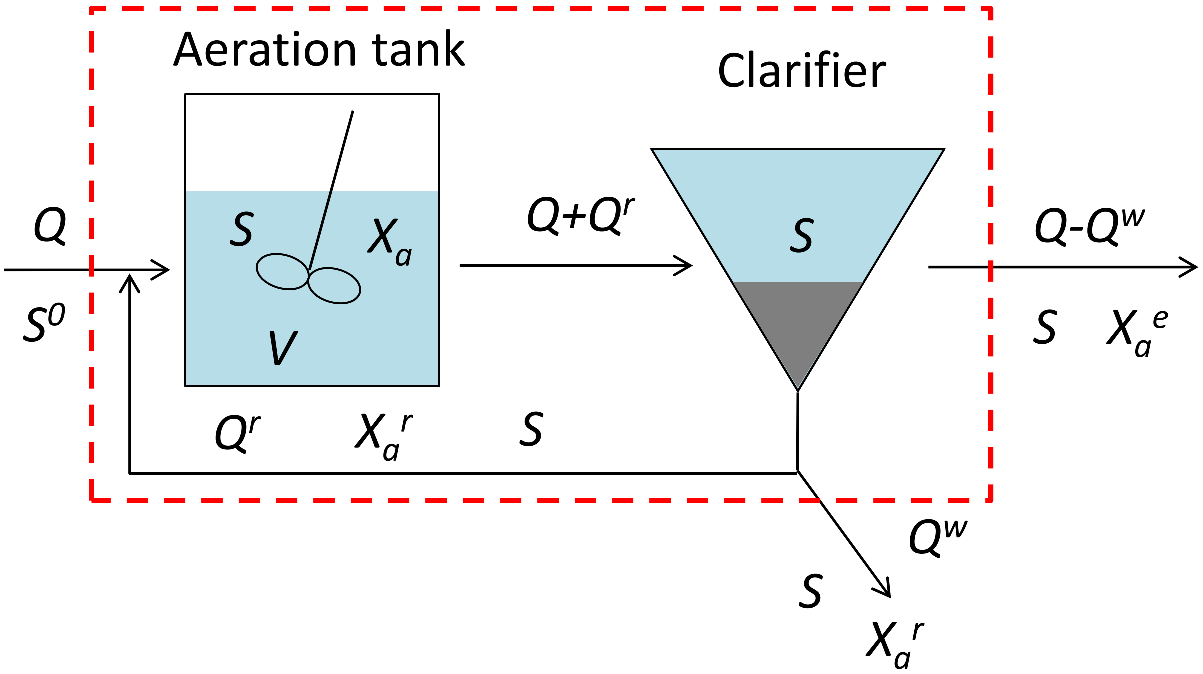
- **Rate of production of cell debris**

$$r_{X,i} = f_d bX$$

$r_{X,i}$ = rate of cell debris production (g VSS/m^3-d)

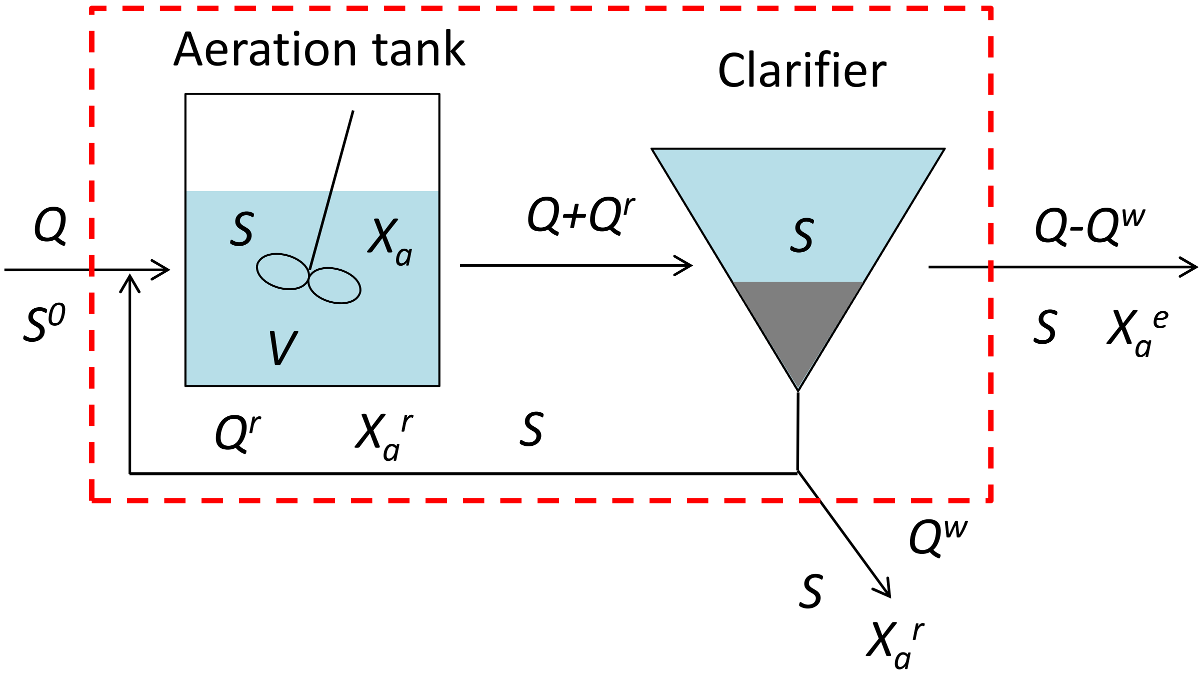
f_d = fraction of biomass that remains as cell debris,
0.10-0.15 g VSS/g biomass VSS depleted by decay

Activated sludge - schematic diagram



– The majority of the settled sludge in the secondary clarifier is returned to the aeration tank to obtain high biomass concentration
– Some portion of the settled sludge (due to net growth of biomass) is removed from the system for steady state operation

Activated sludge - schematic diagram



- General assumptions:
  - Biodegradation of substrate occurs in the aeration tank only, not in the clarifier
  - No active biomass in the influent

Key variable - SRT

- **S**olids **R**etention **T**ime (or mean cell residence time)
- The average time the activated sludge solids are in the system
- So SRT can be defined as:

  (Amount of solids in the system) / (rate of solids exiting the system)

Assuming that the amount of solids in the clarifier is negligible compared to that in the aeration tank,

$$SRT = \frac{VX_a}{(Q - Q^w){X_a}^e + Q^w {X_a}^r}$$

SRT = solids retention time (d)

V = aeration tank volume (m^3)

Q = influent flowrate (m^3/d)

X_a = active biomass concentration in the aeration tank (g VSS/m^3)

Q^w = waste sludge flowrate (m^3/d)

${X_a}^e$ = active biomass concentration in the effluent (g VSS/m^3)

${X_a}^r$ = active biomass concentration in the return activated sludge line (g VSS/m^3)

Modeling suspended growth processes

- Use the mass balance technique
- Use the kinetic expressions we have discussed

- We can set mass balance for two substances in the activated sludge system:

1) Biomass mass balance

$$V\frac{dX_a}{dt} = 0 - [(Q - Q^w)X_a{}^e] - Q^w X_a{}^r + r_X V$$

2) Substrate mass balance

$$V\frac{dS}{dt} = QS^0 - QS - r_{su}V$$

Modeling suspended growth processes

- Solving the two mass balance equations, we get:

$$X_a = \left(\frac{SRT}{\tau}\right)\left[\frac{Y(S^0 - S)}{1 + b(SRT)}\right]$$

$$S = \frac{K_s[1 + b(SRT)]}{SRT(Yk - b) - 1}$$

  – The effluent substrate (=our target!) concentration is a function of SRT and growth kinetic parameters
  – <u>SRT is the only controllable variable</u>
  – The effluent substrate concentration is **<u>NOT</u>** a function of influent concentration (but S^0 affects X)

Solids production

- Remember:
  - VSS = active biomass + α
  - TSS = active biomass + α + β
- **Daily production of total sludge** from the system
  - At steady state, the mixed liquor can be assumed as a homogeneous mixture of active biomass and other solids (→ same SRT applies to VSS and TSS!)

$$P_{X,VSS} = \frac{X_{VSS}V}{SRT}$$

$P_{X,VSS}$ = daily production of total sludge as VSS (g VSS/d)

X_{VSS} = total MLVSS concentration in aeration tank (g VSS/m^3)

$$P_{X,TSS} = \frac{X_{TSS}V}{SRT}$$

$P_{X,TSS}$ = daily production of total sludge as TSS (g TSS/d)

X_{TSS} = total MLSS concentration in aeration tank (g TSS/m^3)

Modeling solids production

- **Total MLVSS in the aeration tank, X_{VSS}**

$$X_{VSS} = X_a + X_i$$

X_i = nbVSS concentration in aeration tank (g VSS/m^3)

→ Additional mass balance needed for nbVSS

$$V\frac{dX_i}{dt} = QX_i^{\,0} - \frac{X_i V}{SRT} + r_{X,i}V$$

$X_i^{\,0}$ = nbVSS concentration in influent (g VSS/m^3)

$r_{X,i}$ = rate of nbVSS production from cell debris (g/m^3-d)

At steady state:

$$X_i = \frac{X_i^{\,0}(SRT)}{\tau} + (f_d)(b)(X_a)(SRT)$$

Modeling solids production

Therefore,

$$X_{VSS} = \left(\frac{SRT}{\tau}\right)\left[\frac{Y(S^0 - S)}{1 + b(SRT)}\right] + (f_d)(b)(X_a)(SRT) + \frac{{X_i}^0(SRT)}{\tau}$$

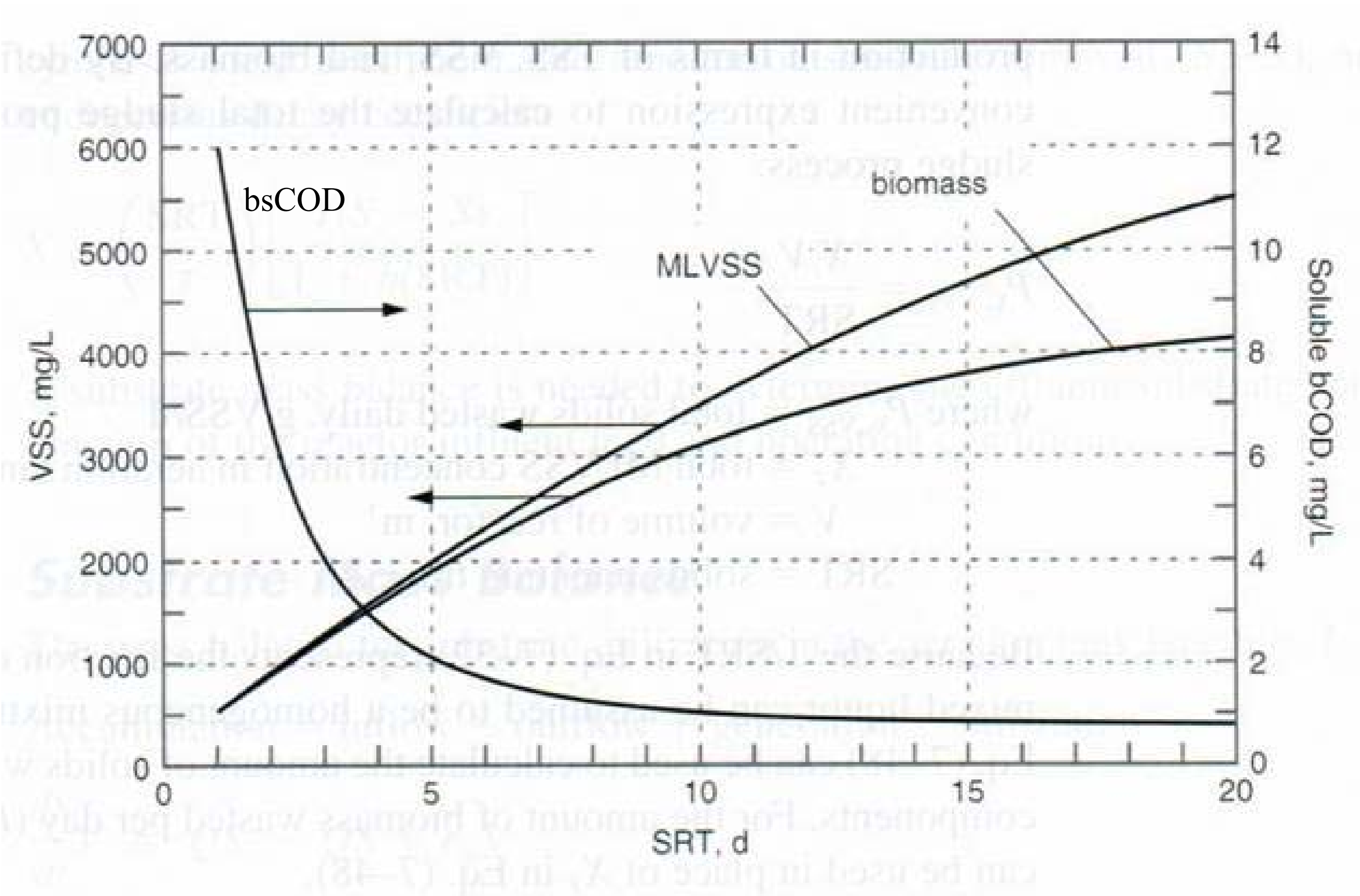
Active biomass *Cell debris* *nbVSS in influent*

The daily total VSS production (=wasted) rate, $P_{X,VSS}$ (g VSS/d):

$$P_{X,VSS} = \frac{QY(S^0 - S)}{1 + b(SRT)} + \frac{(f_d)(b)YQ(S^0 - S)SRT}{1 + b(SRT)} + Q{X_i}^0$$

(A) ***(B)*** ***(C)***

Effect of SRT on bsCOD, biomass, and MLVSS



Modeling solids production

- **The daily MLSS (total dry solids) wasted**

Note: TSS = VSS + FSS (inorganics)

  - Inorganic solids originate from influent and the biomass
  - Biomass contains 10-15% inorganic solids by dry weight
  - Use a VSS/TSS ratio of 0.85 for a typical biomass

$$P_{X,TSS} = \frac{(A)}{0.85} + \frac{(B)}{0.85} + C + Q\left(X_{TSS}{}^{0} - X_{VSS}{}^{0}\right)$$

$P_{X,TSS}$ = daily MLSSS produced per day (g TSS/d)

$X_{TSS}{}^{0}$ = influent wastewater TSS concentration (g/m^3)

$X_{VSS}{}^{0}$ = influent wastewater VSS concentration (g/m^3)

Oxygen requirements

- Additional matter of interest: **how much oxygen should be provided** to support the aerobic biodegradation?
- Recall that by degradation of substrates:
  - some portion of the biodegradable COD (bCOD) is combined with O_2 to be mineralized or converted to oxidized organic compounds
- Some O_2 is also consumed for endogenous respiration

- Consider the COD mass balance of the system:

Oxygen used = (bCOD removed) – (COD of waste sludge)

$$R_o = Q(S_o - S) - 1.42P_{X,bio}$$

R_o = daily oxygen requirement (g/d)

*$P_{X,bio}$ = biomass as VSS wasted per day, **(A) + (B)** (g/d)*

Example question

Q: A complete-mix suspended growth activated sludge process with recycle is used to treat municipal wastewater after primary sedimentation. The characteristics of the primary effluent are: flow = 1000 m^3/d, bsCOD = 192 g/m^3, nbVSS = 30 g/m^3, and inert inorganics = 10 g/m^3. The aeration tank MLVSS is 2500 g/m^3. Using these data and the kinetics coefficients given below, design a system with a 6-d SRT and determine the following:

1) The effluent bsCOD concentration
2) Hydraulic retention time required
3) Daily sludge production (in kg/d as VSS and TSS)
4) Fraction of active biomass in the MLVSS
5) Oxygen requirement (in kg/d)

$k = 12.5\ g\ COD/g\ VSS - d$

$K_s = 10\ g\ COD/m^3$

$Y = 0.40\ g\ VSS/g\ COD$

$f_d = 0.15$

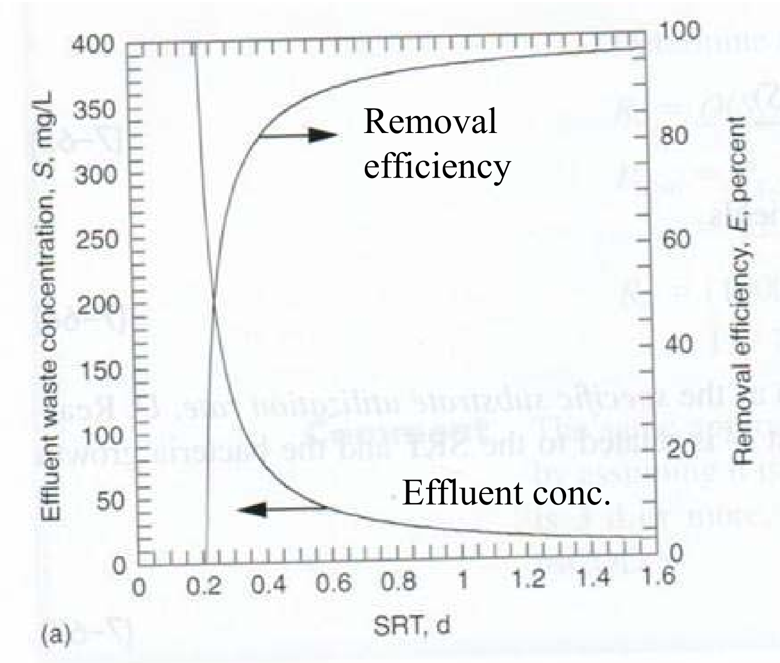
$b = 0.10\ /d$

$Biomass\ VSS/TSS = 0.85$

Design & operating parameters

- **SRT: key variable**
  - When kinetic coefficients are fixed, the effluent concentration is solely a function of SRT

- Effluent concentration as a function of SRT



For CSTR with recycle

Design & operating parameters

- **The minimum solids retention residence time, SRT_{min}**
  - The SRT at which the cells are washed out from the system faster than they can reproduce

$$\frac{1}{SRT_{min}} = \frac{YkS^0}{K_s + S^0} - b$$

  - In many situations, $K_s << S^0$, so:

$$\frac{1}{SRT_{min}} \approx Yk - b = \mu_m - b$$

  - Process safety factor, SF

$$SF = \frac{SRT_{des}}{SRT_{min}}$$

SRT_{des} = design SRT (d)

Design & operating parameters

- **F/M ratio (food to microorganism ratio)**

$$F/M = \frac{QS^0}{VX} = \frac{S^0}{\tau X}$$

F/M = food to microorganism ratio (g bsCOD/g VSS-d)

  – High F/M $\Rightarrow$ low steady-state SRT

- **Volumetric organic loading rate**
  – The amount of BOD or COD applied to the aeration tank volume per day

$$L_{org} = \frac{QS^0}{V \cdot (10^3\ g/kg)}$$

L_{org} = volumetric organic loading rate (kg bsCOD/m^3-d)