Fundamentals of biological treatment I

Fundamentals of biological treatment I

- General overview
- Typical biological treatment processes used in wastewater treatment plants (WWTPs)
- Microbial growth kinetics

Objectives of biological treatment

- Transform dissolved and particulate biological constituents into acceptable end products
- Capture and incorporate suspended and non-settleable colloidal solids into a biological floc or biofilm
- Transform or remove nutrients (N & P)
- In some cases, remove specific trace organic constituents and compounds

Biodegradation of organic matter

- For heterotrophic, aerobic bacteria:

$$\nu_1 \ (organic\ material) + \nu_2 O_2 + \nu_3 NH_3 + \nu_4 PO_4{}^{3-}$$

$$\xrightarrow{\text{microorganisms}} \nu_5 \ (new\ cells) + \nu_6 CO_2 + \nu_7 H_2O$$

- Oxidize organic materials (reduced carbon) to obtain energy for the production of new cells

Oxidation-reduction reaction

- Or, redox reaction
- Involves the transfer of electrons from an electron donor to an electron acceptor
- **Respiratory metabolism**: generating energy by enzyme-mediated electron transport to an external e^- acceptor

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

e^- donor **e^- acceptor**

- **Fermentative metabolism**: use an internal e^- acceptor
  - Less energy efficient than respiration, lower growth rates

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Types of biological processes

- Aerobic vs. anoxic vs. anaerobic
  - **Aerobic**: presence of dissolved oxygen (O_2)
  - **Anoxic**: absence of O_2, but presence of combined oxygen (usually NO_3^- & NO_2^-)
  - **Anaerobic**: absence of both O_2 and combined oxygen

- Suspended growth vs. attached growth processes

Biological treatment processes for WWTPs

Type	Common name	Use
Aerobic processes:		
Suspended growth	Activated sludge	CBOD removal, nitrification
	Aerated lagoon	CBOD removal, nitrification
	Aerobic digestion	Stabilization, CBOD removal
	Membrane bioreactor	CBOD removal, nitrification
	Nitritation process	Nitritation
Attached growth	Biological aerated filters	CBOD removal, nitrification
	Moving bed bioreactor	CBOD removal, nitrification
	Packed-bed reactors	CBOD removal, nitrification
	Rotating biological contactors	CBOD removal, nitrification
	Trickling filters	CBOD removal, nitrification
	Trickling filter/activated sludge	CBOD removal, nitrification
	Integrated fixed film activated sludge (IFAS)	CBOD removal, nitrification

Biological treatment processes for WWTPs

Type	Common name	Use
Anoxic processes:		
Suspended growth	Suspended-growth denitrification	Denitrification
Attached growth	Attached growth denitrification filter	Denitrification
Anaerobic processes:		
Suspended growth	Anaerobic contact processes	CBOD removal
	Anaerobic digestion	Stabilization, solids destruction, pathogen kill
	Anammox process	Denitritation, ammonia removal
Attached growth	Aeaerobic packed and fluidized bed	CBOD removal, waste stabilization, denitrification
Sludge blanket	Upflow anaerobic sludge blanket	CBOD removal, especially high strength wastes
Hybrid	Upflow sludge blanket/attached growth	CBOD removal

Biological treatment processes for WWTPs

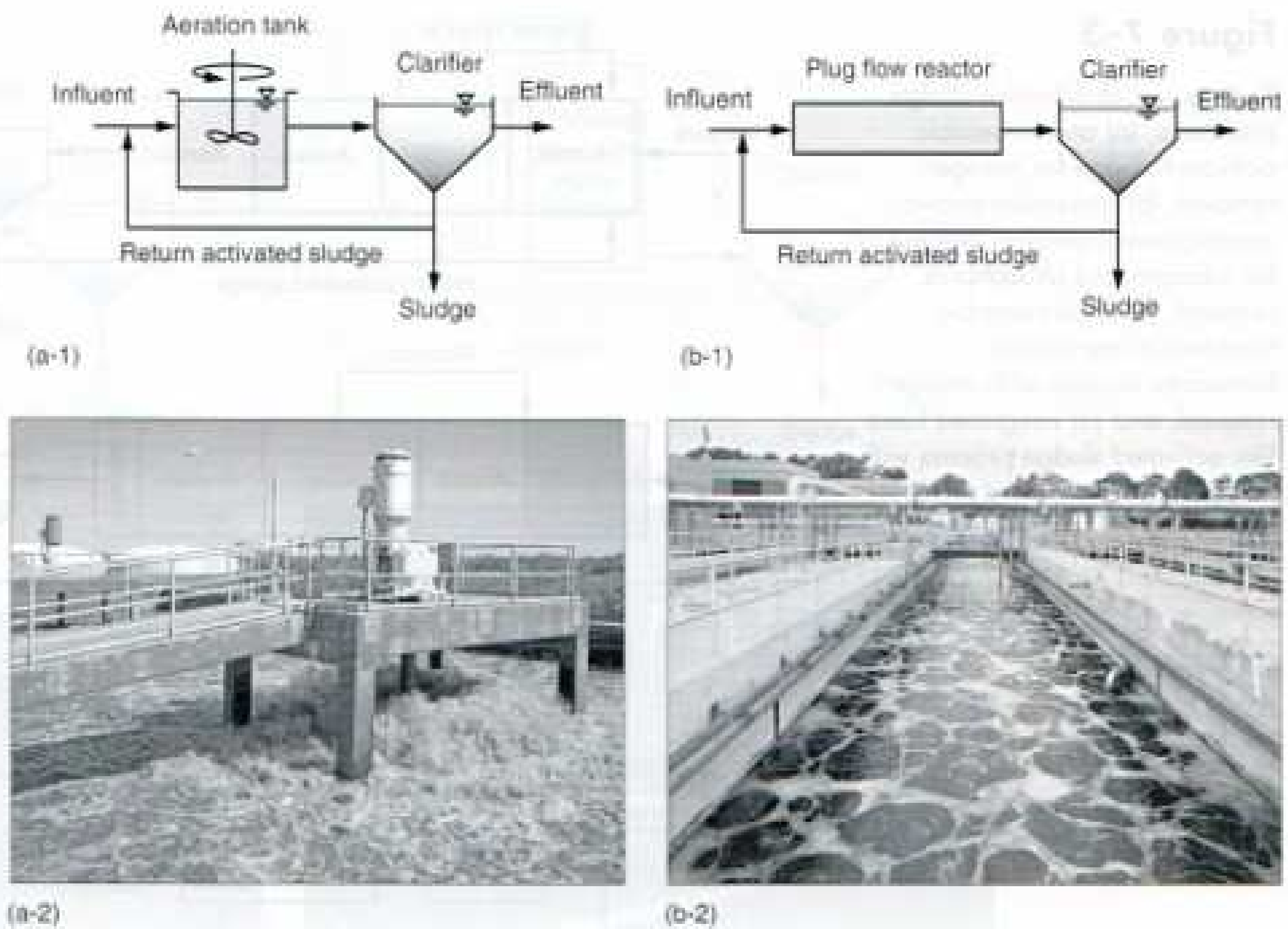
Type	Common name	Use
Combined aerobic, anoxic, and anaerobic processes:		
Suspended growth	Single- or multi-stage processes, Various proprietary processes	CBOD removal, nitrification, denitrification, and P removal
Hybrid	Single- or multi-stage suspended growth processes with fixed film media	CBOD removal, nitrification, denitrification, and P removal
Lagoon processes:		
Aerobic lagoons	Aerobic lagoons	CBOD removal, nitrification
Maturation (tertiary) lagoons	Maturation (tertiary) lagoons	CBOD removal, nitrification
Facultative lagoons	Facultative lagoons	CBOD removal, nitrification
Anaerobic lagoons	Anaerobic lagoons	CBOD removal, nitrification (waste stabilization)

Suspended growth processes

- **Microorganisms are maintained in liquid suspension by appropriate mixing methods**

- **Activated sludge process**
  - A suspended growth process
  - Most common for municipal wastewater treatment
  - First developed around 1910's
  - Named so because it involves the production of an activated mass of microorganisms capable of degrading wastes under aerobic conditions

Activated sludge - basics



#1

Activated sludge - basics

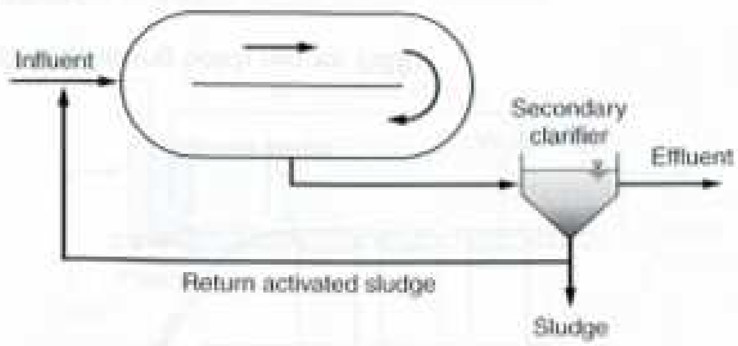
- **Aeration tank**
  - Influent wastewater with the microbial suspension is mixed and aerated
    - The mixture is called as "mixed liquor"
    - In activated sludge, conventionally total suspended solids are called as "mixed liquor suspended solids (MLSS)" and VSS as "mixed liquor volatile suspended solids (MLVSS)"
  - The mixed liquor then flows to a clarifier for settling
  - The settled biomass, called "activated sludge" is returned to the aeration tank
  - A portion of the settled biomass is removed daily or periodically

Activated sludge - modifications

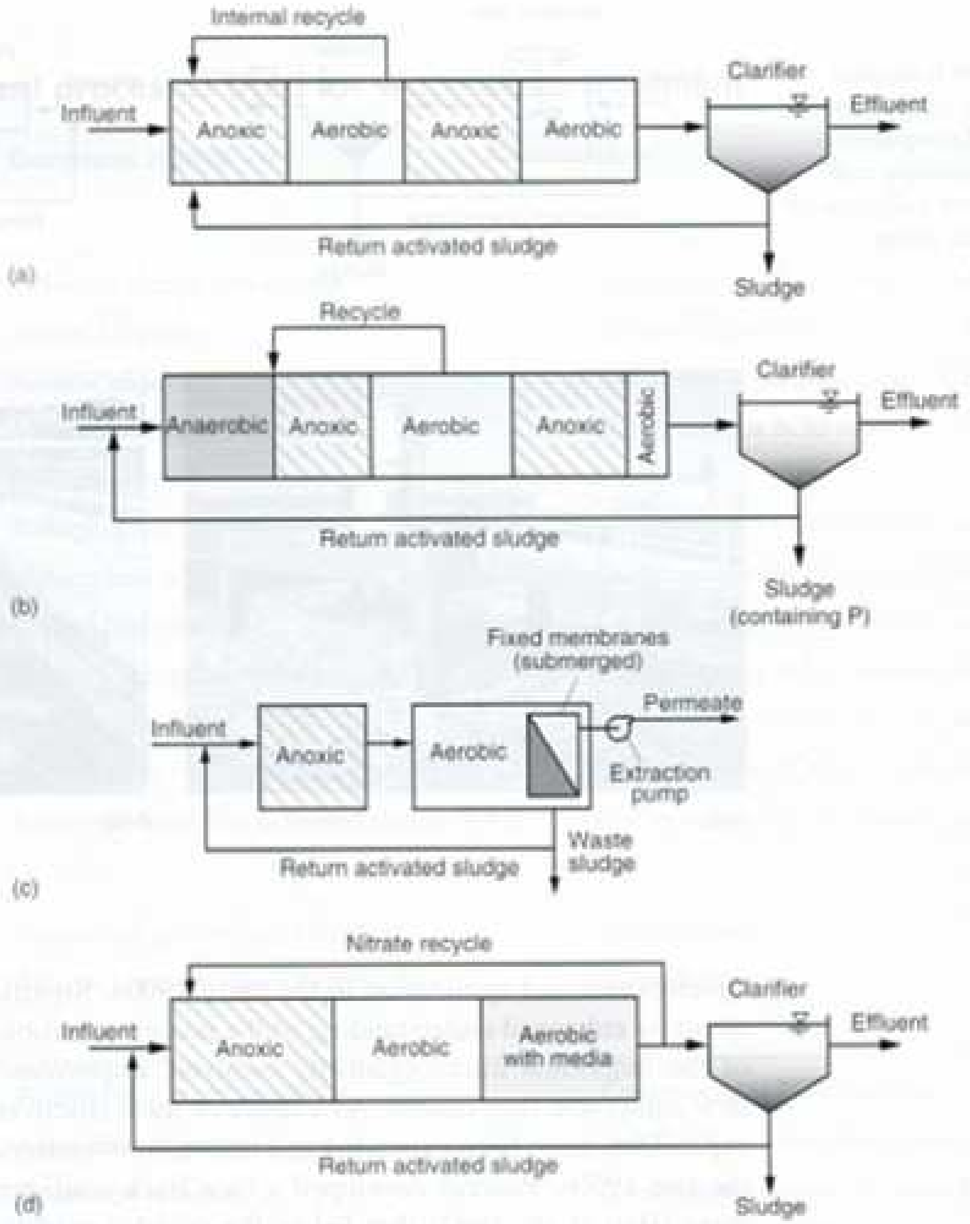
- **Lots of modifications and varieties were made to activated sludge processes due to**
  - Improvements in understanding of microorganisms, aeration technology, etc.
  - Enhanced effluent quality, nutrient removal, etc.
  - Develop most suitable processes at certain conditions
  - Resolve operational problems

- **Examples**
  - Oxidation ditch – less energy intensive
  - Biological selectors – prevent filamentous growth that causes settling problems
  - Staged reactor configurations – improve biological nutrient removal
  - Membrane bioreactor (MBR) – use of membranes for liquid-solid separation

#2



<Oxidation ditch>



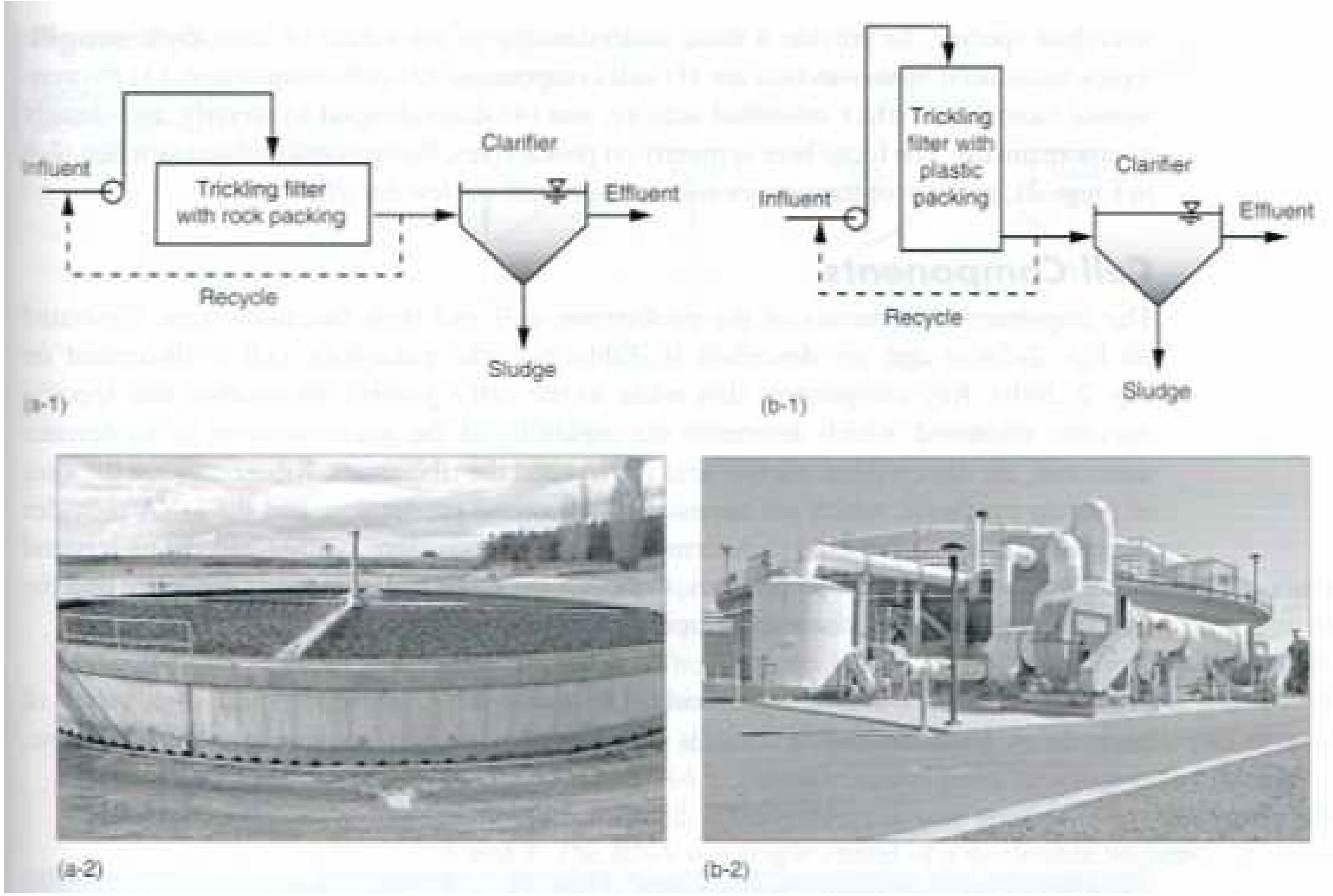
Progression of activated sludge processes: (a) anoxic-aerobic activated sludge for nitrogen removal, (b) anaerobic-anoxic-aerobic-anoxic-aerobic process for nitrogen and phosphorus removal, (c) anoxic-aerobic treatment in membrane bioreactor process with nitrogen removal, and (d) integrated fixed film activated sludge process with nitrogen removal.

#3

Attached growth processes

- Microorganisms are **attached to an inert** packing material
- The organic material and nutrients are removed from the wastewater flowing past the attached growth (**biofilm**)
- Packing materials
  - Rock, gravel, slag, sand, redwood, plastics, etc.
- Aerobic vs. anaerobic
- Completely submerged vs. partially submerged vs. non-submerged
- Most common: **trickling filter**

Trickling filters



Attached growth biological treatment process: (a-1) schematic and (a-2) view of trickling filter with rock packing; and (b-1) schematic and (b-2) view of covered tower trickling filter with plastic packing. The air injection and odor control facilities are shown on the foreground. The tower filter is 10 m high and 50 m in diameter.

#4

Biomass yield

- **The ratio of the amount of biomass produced to the amount of substrate consumed**

$$Biomass\ yield, Y = \frac{g\ \ biomass\ produced}{g\ \ substrate\ consumed}$$

Microbial growth kinetics: major variables

- **Organic matter**
  - Electron donor for biological growth of heterotrophic bacteria
  - What's in interest: the amount of organic compounds <u>that can eventually be degraded by microorganisms</u> in wastewater
  - Defined as "biodegradable COD (**bCOD**) or ultimate BOD (**UBOD**)
  - Both bCOD & UBOD are comprised of soluble, colloidal, and particulate matter
  - We will discuss mainly on the <u>**biodegradable soluble COD**</u> (**bsCOD**)
  - Particulate or colloidal COD must be first hydrolyzed to bsCOD before they are utilized by microorganisms as carbon & energy source

Microbial growth kinetics: major variables

- **Biomass & other suspended solids**
  - **Volatile suspended solids (VSS)** are often used as a surrogate for biomass concentration
  - In activated sludge systems, the TSS and VSS are often termed as "*mixed liquor suspended solids (MLSS)*" and "*mixed liquor volatile suspended solids (MLVSS)*", respectively
  - MLVSS (or MLSS) is not equal to the active biomass
    - The solids contain cell debris and other suspended particles
    - Some portion of the solids is non-biodegradable
    - **Non-biodegradable volatile suspended solids** (nbVSS): organics, non-degradable → derived from influent wastewater and also produced as cell debris
    - **Inert inorganic total suspended solids** (iTSS): inorganics → originate from influent wastewater

Rate of utilization of soluble substrates

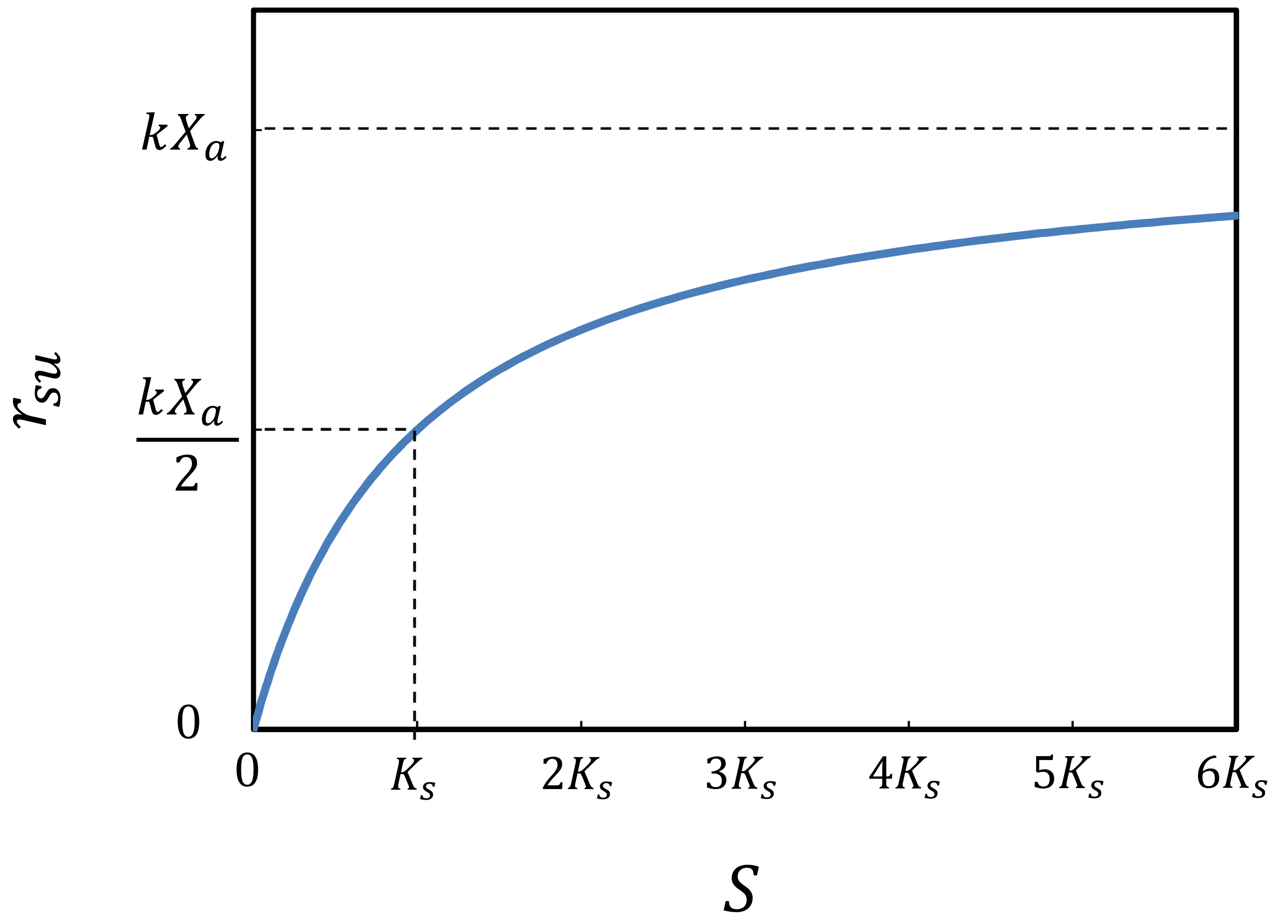
The Monod equation

$$\boxed{r_{su} = \frac{kX_aS}{K_s + S}}$$

r_{su} = substrate utilization rate (g/m³-d)
k = maximum specific substrate utilization rate (g substrate/g biomass-d)
X_a= active biomass concentration (g/m³)
S = growth-limiting substrate concentration (g/m³)
K_s = half-velocity constant, substrate concentration at one-half the maximum specific substrate utilization rate (g/m³)

– A "saturation-type" reaction kinetics: linear increase with S when $S \ll K_s$, approach maximum when $S \gg K_s$

Monod equation



Modeling bacterial growth

- As bacteria consume the substrate, some (specific) portion is used for energy and the other is used to produce new biomass

  (assumption)

  new growth of cells is directly proportional to the substrate utilized

- So, the bacteria growth rate from substrate utilization is expressed as:

$$\boxed{r_g = \left(\frac{dX_a}{dt}\right)_{growth} = \frac{\mu_m X_a S}{K_s + S}}$$

r_g = bacteria growth rate from substrate utilization (g/m^3-d)

μ_m = maximum specific bacteria growth rate (1/d)

with $\quad r_g = Y r_{su} \quad$ and $\quad \mu_m = kY$

***Y* = *<u>true yield</u>* (g biomass/g substrate utilized)**

→ This is the biomass yield we studied!

Monod equation – other forms

- The substrate utilization rate can be written as:

$$r_{su} = \frac{\mu_m X_a S}{Y(K_s + S)}$$

- Another form of Monod equation:

$$\mu = \frac{1}{X_a} \cdot \left(\frac{dX_a}{dt}\right)_{growth} = \frac{\mu_m S}{K_s + S}$$

μ = <u>specific</u> bacteria growth rate (1/d)

Biomass decay

- Microorganism concentration **decrease** when the substrate is depleted
- This is true in the presence of substrates as well!
- Decay (or endogenous decay, endogenous respiration)
  - Cell maintenance energy needs
  - Cell lysis due to death or stress from environmental factors
  - Predation (protozoa, etc.)
  - Generally assumed to be proportional to cell concentration:

$$\left(\frac{dX_a}{dt}\right)_{decay} = -bX_a$$

X_a = active biomass concentration [M/L^3]
b = decay coefficient [T^{-1}]

  - b in the range of 0.05 ~ 0.20 d^{-1}

Net biomass growth rate

- **Net biomass growth rate**

  (net biomass growth)

  = (biomass growth according to substrate utilization) – (biomass decay)

$$\boxed{\begin{aligned} r_X &= Yr_{su} - bX_a \\ &= Y\frac{kX_aS}{K_s + S} - bX_a \end{aligned}}$$

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

- **Net specific biomass growth rate**

$$\mu_{net} = \frac{r_X}{X_a} = Y\frac{kS}{K_s + S} - b$$

μ_{net} = net specific biomass growth rate (1/d)

Monod equation – generalized

- Actually, the Monod kinetics can be applied for any growth-limiting substrates
  - Substrates can be e^- donor, e^- acceptor, nutrients, etc.
  - Quite often the e^- donor is limiting while others are available in excess – for growth kinetics, the term substrate generally refers to e^- donor

- **Generalized equation**
  - If factors other than e^- donor can be limiting, include those as well!

Monod equation – generalized

ex) for aerobic, heterotrophic bacteria; if bsCOD, DO, and ammonia-N are limiting:

$$r_{su} = \left[\frac{\mu_{H,max} S_s}{Y_H (K_s + S_s)}\right]\left(\frac{S_o}{K_o + S_o}\right)\left(\frac{S_{NH}}{K_{NH} + S_{NH}}\right) X_{a,H}$$

$\mu_{H,max}$= *maximum specific growth rate of heterotrophic bacteria (1/d)*

Y_H = *heterotrophic bacteria synthesis yield coefficient (g VSS/g COD used)*

$X_{a,H}$ = *active heterotrophic bacteria concentration (g VSS/m^3)*

S_i = *concentration for variable i (i = substrate, DO, ammonia-nitrogen) (g/m^3)*

K_i = *half-velocity constant for variable i (g/m^3)*

here, the term "substrate" is used for bsCOD (the e$^-$ donor)

Typical range of parameters

Typical range/values of kinetic coefficients for activated sludge process

Coefficient	Unit	Value[a]	
		Range	Typical
k	g bsCOD/g VSS-d	4-12	6
K_s	mg/L BOD	20-60	30
	mg/L bsCOD	5-30	15
Y	mg VSS/mg BOD	0.4-0.8	0.6
	mg VSS/mg COD	0.4-0.6	0.45
b	1/d	0.06-0.15	0.10

[a]At 20^{o}C, from Metcalf & Eddy / Aecom

References

#1, #2, #3, #4) Metcalf & Eddy, Aecom (2014) Wastewater Engineering: Treatment and Resource Recovery, 5th ed. McGraw-Hill, p. 559, 789, 560, 561.

Fundamentals of biological treatment II

Fundamentals of biological treatment II

- Additional info prior to reactor analysis

- Activated sludge process analysis
  - Solutions for effluent substrate concentration (***S***) & aeration tank active biomass concentration (X_a)
  - Solids production rates
  - Oxygen supply requirement

- Exercise on activated sludge process design & analysis

- Activated sludge process: design and operational parameters

Temperature effect

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

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

θ= temperature correction factor,
range from 1.02 to 1.25

MLVSS other than 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**

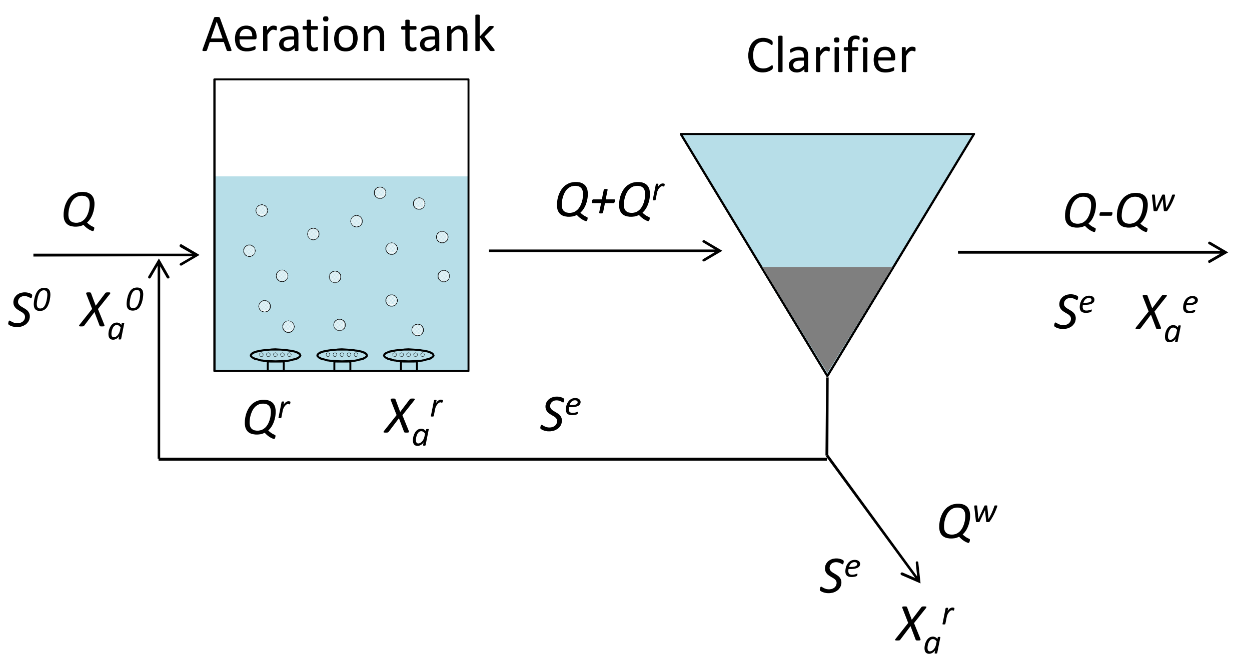
$$\boxed{r_{X,i} = f_d b X_a}$$

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

f_d = fraction of biomass that remains as cell debris,

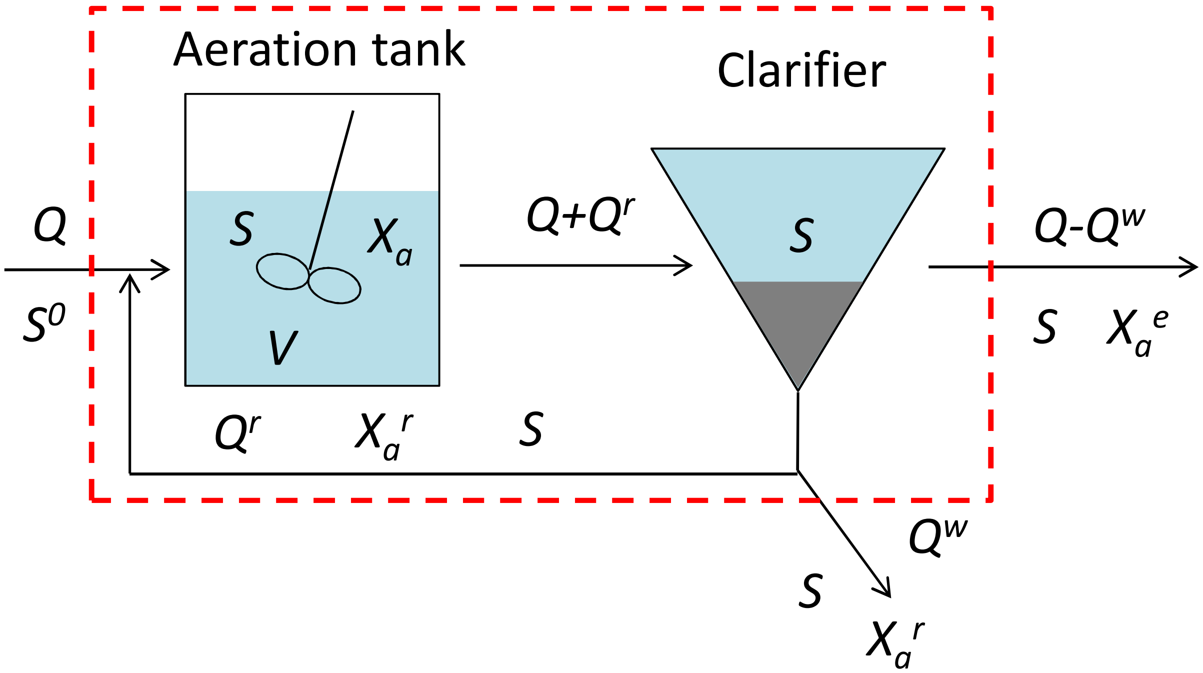
0.10-0.15 g VSS/g biomass VSS depleted by decay

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



- Assumptions for the current class:
  - Aeration tank is a CSTR
  - 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

  2) Substrate mass balance

Modeling suspended growth processes

Assume steady state

1) Biomass mass balance

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

$$\frac{(Q - Q^w)X_a{}^e + Q^w X_a{}^r}{V} = r_X \;= Y r_{su} - bX_a$$

$$\frac{1}{SRT} = \frac{(Q - Q^w)X_a{}^e + Q^w X_a{}^r}{V X_a} = \frac{r_X}{X_a} = \frac{Y r_{su} - bX_a}{X_a}$$

r_{su} = substrate utilization rate [$M_s\, L^{-3}\, T^{-1}$] $= \frac{Q(S^0 - S)}{V} = \frac{S^0 - S}{\tau}$

$$\frac{1}{SRT} = \frac{Y(S^0 - S)/\tau - bX_a}{X_a}$$

Modeling suspended growth processes

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

2) Substrate mass balance

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

$$(S^0 - S) = \underbrace{\frac{V}{Q}}_{\tau\, =}\underbrace{r_{su}}_{=\frac{kX_aS}{K_s + S}} = \tau\frac{kX_aS}{K_s + S} \quad = \tau\frac{kS}{K_s + S}\left(\frac{SRT}{\tau}\right)\left[\frac{Y(S^0 - S)}{1 + b(SRT)}\right]$$

$$1 = \left(\frac{kS}{K_s + S}\right)\left[\frac{Y(SRT)}{1 + b(SRT)}\right]$$

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

X_a & S @ steady state: final solution

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

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

- 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

- **Solids production rate** of the system
  - Assume the effluent VSS and TSS is negligible
    → production of sludge is the only way for VSS/TSS to exit the system
  - Then:

$$(VSS/TSS\ production\ rate) = \frac{(Amount\ of\ VSS/TSS\ in\ the\ system)}{(Residence\ time\ of\ VSS/TSS\ in\ the\ system)}$$

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

$P_{X,VSS}$ = 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: VSS

- **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 X_i (nbVSS)

- **nbVSS mass balance in the system**

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

- **nbVSS in aeration tank, X_i, at steady state**

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

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

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

Daily total VSS production rate

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*

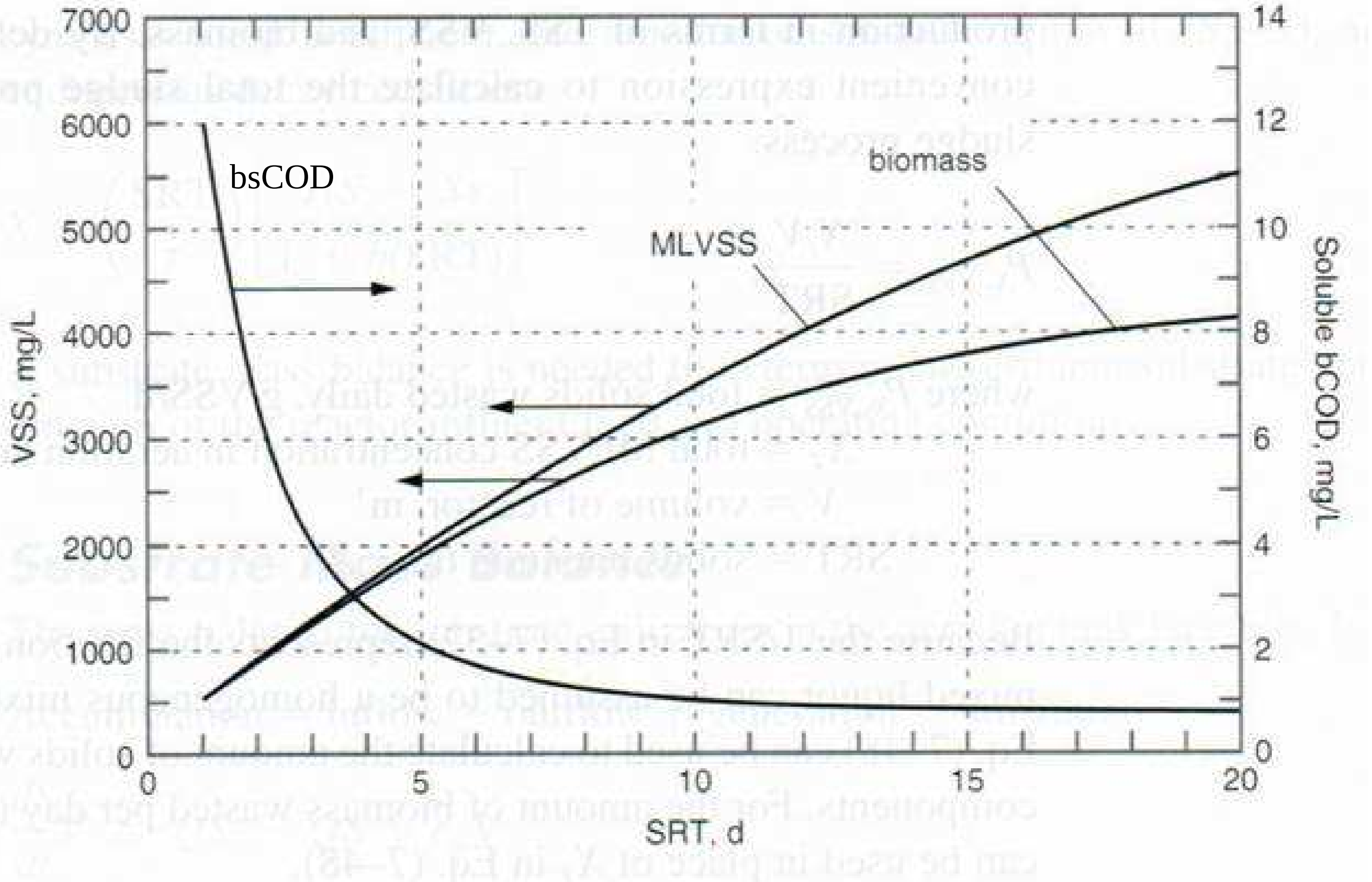
The daily total VSS production (= wasted) rate, $P_{X,VSS}$ (g VSS/d):

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

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

Effect of SRT on bsCOD, biomass, and MLVSS

#1



Daily total TSS production rate

- **The daily TSS (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 production of total sludge as TSS (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?
- This problem can be solved by the **mass balance of COD** in the system
- We assume O_2 is the only electron acceptor utilized in the system

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

4 equivalents of electrons are required to reduce 32 g of O_2

- And the electrons are provided by organic matter in the system via:
  - Utilization of substrates that originates from the influent
  - Endogenous decay of active biomass

- **Oxygen consumed in the system = COD removed from the system**

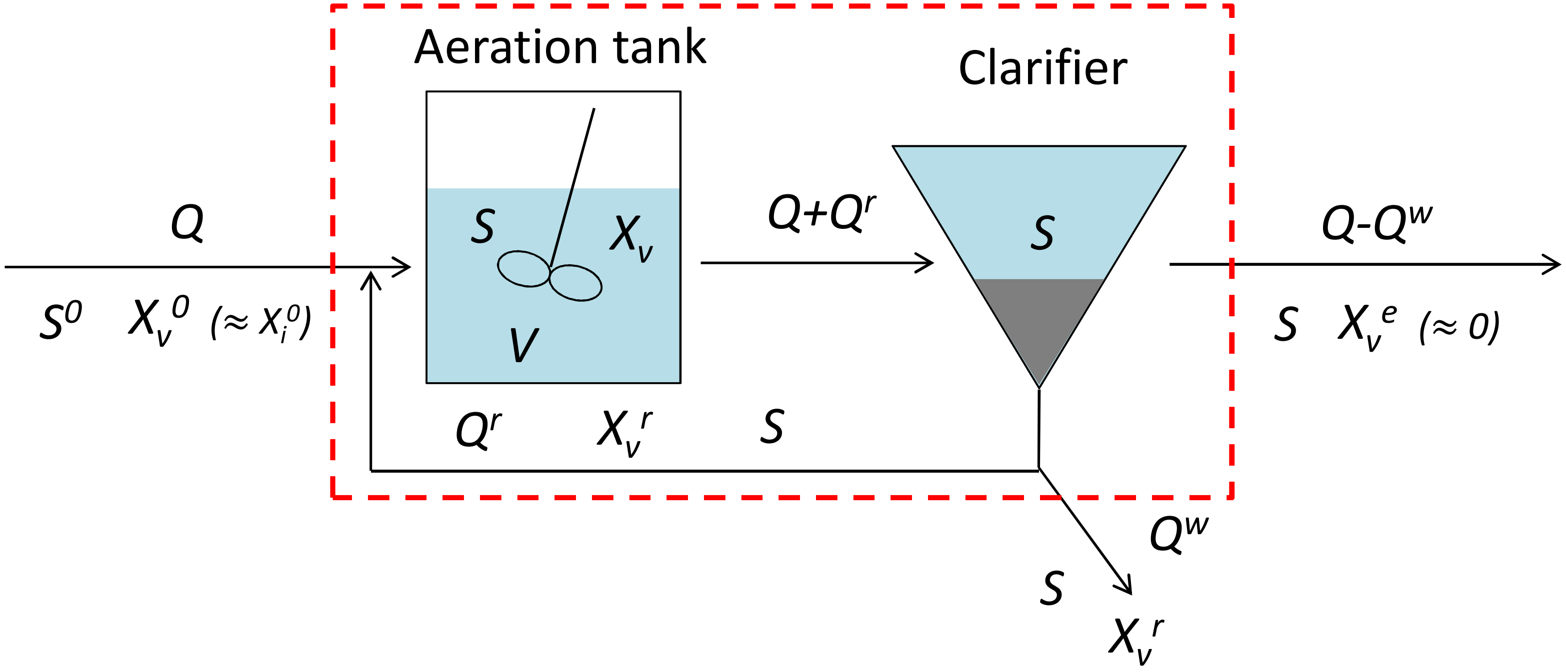
COD of biomass

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

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

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

COD mass balance



$Q(S^0+1.42X_i^0)$

(COD introduced with influent)

= (COD exits with effluent) + (COD exits as sludge) + (COD removed in aeration tank)

$(Q-Q^w)S$ $Q^wS+1.42P_{X,VSS}$

(COD removed in the aeration tank) = (Oxygen consumed in aeration tank)

Daily oxygen requirement

Therefore,

(Oxygen consumed in aeration tank) $= Q\left(S_o + 1.42X_i{}^0\right) - QS - 1.42P_{X,VSS}$

Recall

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

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

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

R_o = *daily oxygen requirement (g/d)*

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

Activated sludge process design & analysis

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)

$k = 12.5\ g\ COD/g\ VSS - d$ $\quad\quad$ $K_s = 10\ g\ COD/m^3$

$Y = 0.40\ g\ VSS/g\ COD$ $\quad\quad$ $f_d = 0.15$

$b = 0.10\ /d$ $\quad\quad$ $Biomass\ VSS/TSS = 0.85$

Activated sludge process design & analysis

1) Effluent bsCOD

$$S = \frac{K_s[1 + b(SRT)]}{SRT(Yk - b) - 1} = \frac{10 \cdot (1 + 0.10 \cdot 6)}{6 \cdot (0.40 \cdot 12.5 - 0.10) - 1} = 0.56\ g\ bsCOD/m^3$$

caution: for simplicity units are not shown – check by yourself!

2) HRT required to achieve $X_{VSS} = 2500\ g/m^3$

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

$$2500 = \left(\frac{6}{\tau}\right)\left[\frac{0.40 \cdot (192 - 0.56)}{1 + 0.10 \cdot 6}\right] + 0.15 \cdot 0.10 \cdot X_a \cdot 6 + \frac{30 \cdot 6}{\tau}$$

Note that the first term on the right hand side, $\left(\frac{SRT}{\tau}\right)\left[\frac{Y(S^0 - S)}{1+b(SRT)}\right]$, equals to X_a

$$2500 = \frac{287.2}{\tau} + 0.15 \cdot 0.10 \cdot \frac{287.2}{\tau} \cdot 6 + \frac{30 \cdot 6}{\tau}$$

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$$2500 = \frac{493.0}{\tau}$$

$$\tau = 0.197\ d$$

3) Daily sludge production

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

$$V = Q \cdot \tau = 1000\ m^3/d \cdot 0.197d = 197\ m^3$$

$$P_{X,VSS} = \frac{2500\ g/m^3 \cdot 197\ m^3}{6\ d} = 8.21 \times 10^4\ g\ VSS/d = 82.1\ kg\ VSS/d$$

$$P_{X,TSS} =$$

$$\frac{1}{0.85} \cdot \frac{QY(S^0 - S)}{1 + b(SRT)} + \frac{1}{0.85} \cdot \frac{(f_d)(b)YQ(S^0 - S)SRT}{1 + b(SRT)} + QX_i{}^0 + Q\left(X_{TSS}{}^0 - X_{VSS}{}^0\right)$$

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$$P_{X,TSS} = \frac{1}{0.85} \cdot \frac{1000 \cdot 0.40 \cdot (192 - 0.56)}{1 + 0.10 \cdot 6}$$

$$+ \frac{1}{0.85} \cdot \frac{0.15 \cdot 0.10 \cdot 0.40 \cdot 1000 \cdot (192 - 0.56) \cdot 6}{1 + 0.10 \cdot 6} + 1000 \cdot 30 + 1000 \cdot 10$$

$$= 1.01 \times 10^5 \ g\ TSS/d = 101\ kg\ TSS/d$$

4) Fraction of active biomass in MLVSS

From

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

$$= \frac{287.2}{\tau} + \frac{25.8}{\tau} + \frac{180}{\tau}$$

The first term is active biomass

Activated sludge process design & analysis

$$Active\ biomass\ fraction = \frac{287.2/\tau}{287.2/\tau + 25.8/\tau + 180/\tau} = 0.58$$

5) Oxygen requirement

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

Recall

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

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

So:

$$P_{X,bio} = P_{X,VSS} - QX_i{}^0$$

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$$P_{X,bio} = 82.1\ kg\ VSS/d - 1000\ m^3/d \cdot 30\ g/m^3 \cdot 10^{-3}\ kg/g$$

$$= 52.1\ kg\ VSS/d$$

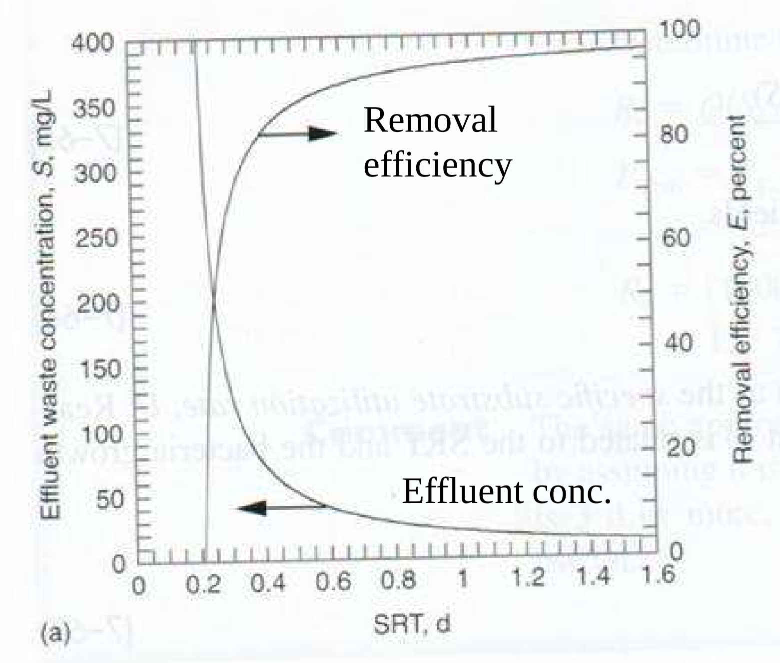
$$R_o = 1000\ m^3/d \cdot (192 - 0.56)\ g/m^3 \cdot 10^{-3}\ kg/g - 1.42 \cdot 52.1\ kg\ VSS/d$$

$$= 117\ kg\ O_2/d$$

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



#2

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)**

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

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

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

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

References

#1, #2) Metcalf & Eddy, Aecom (2014) Wastewater Engineering: Treatment and Resource Recovery, 5th ed. McGraw-Hill, p. 602, 608.