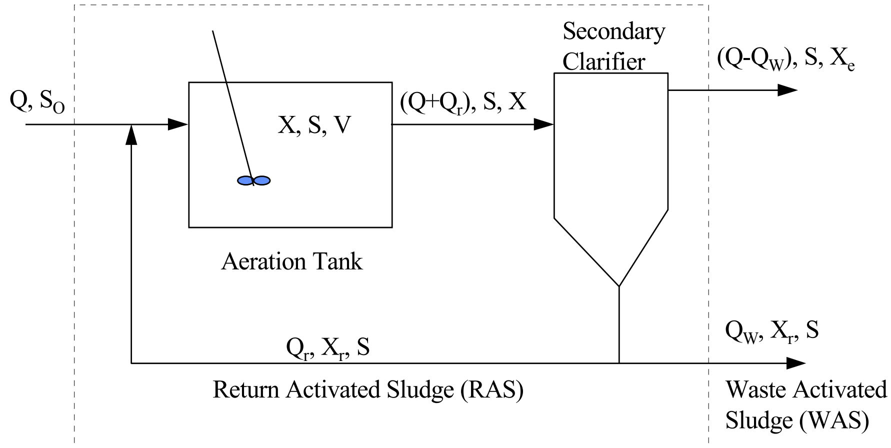
# Completely Mixed Activated Sludge (CMAS) Bioreactor Design Equations




Mass Balance:

Biomass:

$$QX_O + V\left(\frac{\mu_{max} SX}{K_S + S} - k_d X\right) = (Q - Q_w) X_e + Q_w X_w$$

Substrate:

$$QS_O - V\left(\frac{\mu_{max} SX}{Y(K_S + S)}\right) = (Q - Q_w) S_e + Q_w S_w$$

where $Q$, $Q_w$ = influent flow and waste flow, respectively, $m^3/d$

$V$ = volume of aeration basin, $m^3$

$\mu_{max}$ = maximum specific growth rate coefficient, $h^{-1}$

$K_S$ = half saturation coefficient, mg/L

$k_d$ = decay coefficient, $h^{-1}$

$X_O$, $X$, $X_e$, $X_w$ = biomass in influent, bioreactor, effluent, and waste, mg/L as MLVSS

$S$ = soluble substrate concentration in bioreactor, mg/L as BOD or COD

$S_O$ = influent substrate concentration, mg/L as BOD or COD

$Y$ = biomass yield, mg biomass formed/ mg substrate utilized (mg VSS/ mg BOD)

Assumptions:

1. Influent and effluent ____________________ concentration is negligible
2. Aeration basin is a _____________________ CSTR, $S = S_w = S_e$
3. All reactions occur in _____________________ basin

Then:

$$\frac{\mu_{max} S}{K_S + S} = \frac{Q_w X_w}{VX} + k_d \quad ; \quad \frac{\mu_{max} S}{K_S + S} = \frac{QY}{VX}(S_O - S)$$

Observe:

$$\frac{Q}{V} = \frac{1}{\theta} \qquad ; \qquad \frac{Q_w X_w}{VX} = \frac{1}{\theta_c}$$

Where $\theta$ = the hydraulic retention time, HRT, and $\theta_c$ = the solids residence time, SRT. This results in the following design equations:

$$S = \frac{K_S\,(1 + k_d\,\theta_c)}{\theta_c\,(\mu_{max} - k_d) - 1} \quad ; \quad \theta_c = \frac{K_S + S}{S\,(\mu_{max} - k_d) - K_S\,k_d} \quad ; \quad X = \frac{\theta_c\,Y(S_O - S)}{\theta\,(1 + k_d\,\theta_c)}$$

The minimum soluble BOD concentration that can be achieved as $\theta_c \rightarrow \infty$ :

$$S_{min} = \frac{K_S\,k_d}{\mu_{max} - k_d}$$

The minimum $\theta_c$ achievable as $\mu \rightarrow \mu_{max}$ :

$$\theta_{c_{min}} = \frac{K_S + S_O}{S_O\,(\mu_{max} - k_d) - K_S\,k_d}$$

**<u>Steps for Activated Sludge Design</u>**

1. Establish effluent soluble $BOD_5$ allowable to meet $BOD_5$ and SS effluent limits.

2. Determine what $\theta_c$ is required to meet the effluent soluble $BOD_5$ allowable.

3. Solve for the mixed liquor volatile suspended solids, MLVSS, concentration given a particular hydraulic residence time, $\theta$. Or solve for $\theta$ given a particular MLVSS.

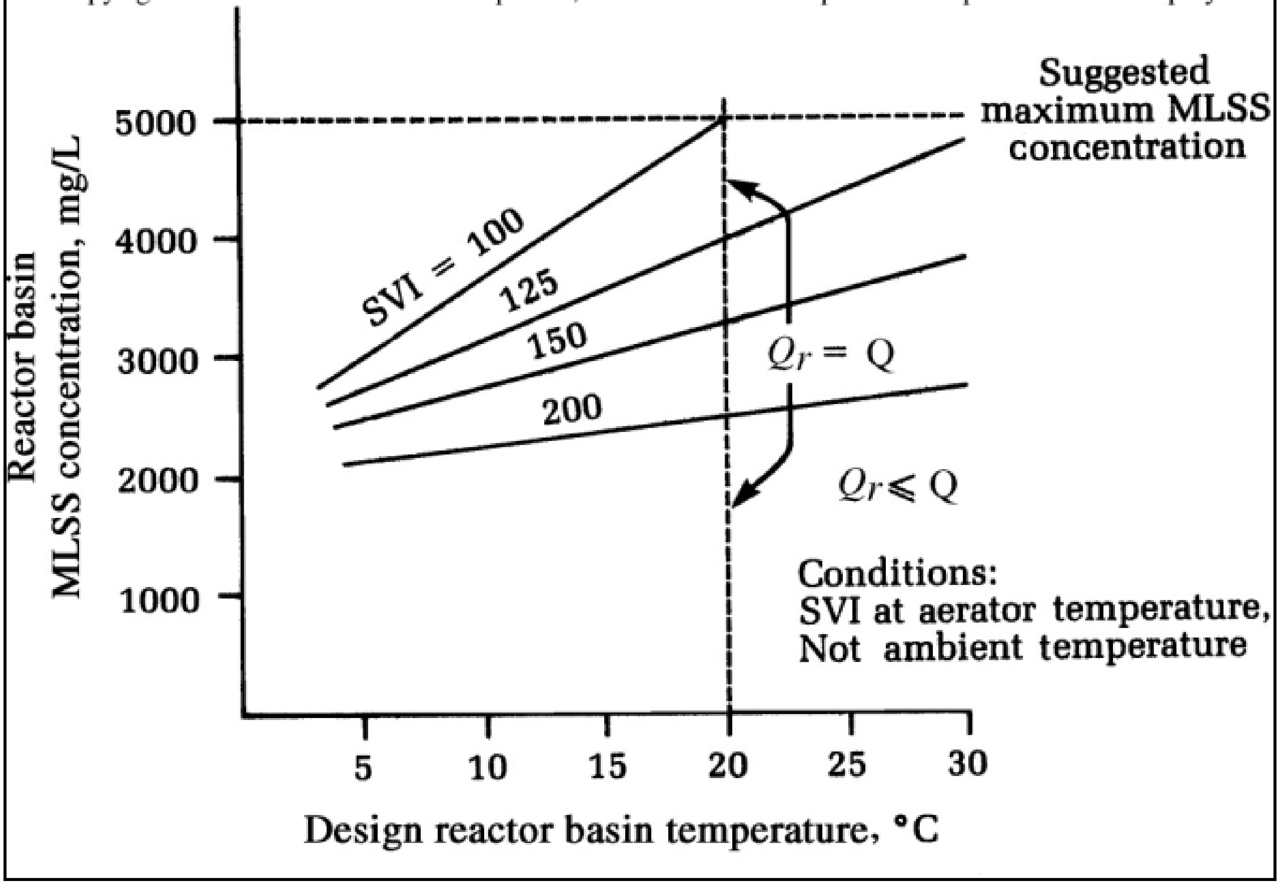
4. Calculate the return activated sludge (RAS) flow, $Q_r$, and concentration, $X_r'$.

$$X_r' Q_r = X'(Q_r + Q) \quad ; \quad X_r' = 10^6/SVI$$

where $X'$ = MLSS, mg/L ($X'$ typically is approximately $1.2 \cdot X$)
$X_r'$ = RAS concentration, mg/L
$Q_r$ = RAS flow rate, $m^3/s$

Find $X_r'$ using the sludge volume index, SVI, from the following figure:






**5. Sludge production can be estimated as follows:**

$$P_X = Y_{OBS}\, Q\, (S_O - S)\, \frac{kg}{1000\ g}$$

where:
$P_X$ = sludge production, kg/d
$Y_{OBS}$ = observed growth yield, mg biomass formed, VSS/ mg $BOD_5$ utilized
Q = influent flow, $m^3/d$
$S_O$ = influent $BOD_5$
S = effluent $BOD_5$

$Y_{OBS}$ can be estimated as :

$$Y_{OBS} = \frac{Y}{1 + k_d \cdot \theta_c}$$

**6. Oxygen requirement for carbonaceous BOD removal can be calculated as:**

$$O_2\ req = \left( \frac{Q(S_O - S)}{f} \cdot \frac{kg}{1000\ g} \right) - 1.42 \cdot P_X$$

where $f$ = the conversion from $BOD_5$ to $BOD_L$, (0.45- 0.68)

When nitrification is occurring the oxygen requirement can be calculated as:

$$O_2\ req = \left( \frac{Q(S_O - S)}{f} \cdot \frac{kg}{1000\ g} \right) - 1.42 \cdot P_X + 4.57\ Q\ (N_O - N) \cdot \frac{kg}{1000\ g}$$

where $N_O$ and N are the influent and effluent $NH_4$-N concentrations, respectively.

**7. Calculate the alkalinity consumed.**

The conversion of $NH_3$-N to nitrate not only requires oxygen but it also consumes considerable amount of alkalinity (7.1 mg/L as $CaCO_3$ for every mg/L $NH_3$-N):

$$\text{alk consumed (kg/d)} = Q\ (N_O - N) \cdot 7.1\ \text{mg/L as } CaCO_3/\text{mg } NH_4\text{-N} \cdot (\text{kg}/1000\ \text{g})$$

8. **Settling Tank Design**

The design of primary and secondary settling tanks can be done on the basis of settling tests and/or established design criteria. In general, the design of tanks must meet established overflow rate and weir loading criteria.

10 State Standards Criteria

| Criteria | Primary Settling Tanks | | Secondary Settling Tanks | |
|---|---|---|---|---|
| Overflow Rate, $m^3/m^2 \cdot d$<br>OR = Q/A | Avg | Peak | Peak | |
| | 41 | 60-120* | 49 | |
| Weir Loading, $m^3/m \cdot d$<br>WL = Q/L | < 1 mgd | > 1 mgd | < 1 mgd | > 1 mgd |
| | 250 | 375 | 250 | 375 |

* for tanks not receiving waste activated sludge, use 49 $m^3/m^2 \cdot d$ for primary clarifiers receiving WAS

## Activated Sludge Operational Considerations

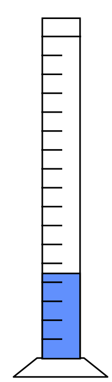
An operator of an activated sludge plant is concerned with three things:

1. E__________________ quality ($BOD_5$ and SS)
2. S____________________ characteristics of the biomass (SVI)
3. Sludge w________________________ or solids inventory ($\theta_c$, F/M)

> These three objectives/operational parameters are interrelated. A good settling sludge will produce good effluent quality. Maintaining the proper solids inventory will produce a good settling sludge. Controlling $\theta_c$ will maintain the proper solids inventory.

**SVI** - Sludge v__________________ index.

- Measure of s_________________ characteristics of biomass.
- Measured in a g________________ cylinder after 30 minutes of settling.
- Units of mL/g.
- A d____________________ SVI is in the range of 75 - 150.



**Sludge Bulking**

- Sludge bulking is the condition where the SVI is h_________ and the suspended solids are not settling in the secondary settling tank.
- It is usually an indication of **f______________________ organisms** - long string-like organisms which outcompete the flocculent organisms because of their large surface area.
- Filamentous organisms can be caused by

a) l_________ F/M ratio
b) l_________ DO
c) nutrient d__________________
d) l_________ pH
e) i_________________ or toxicity

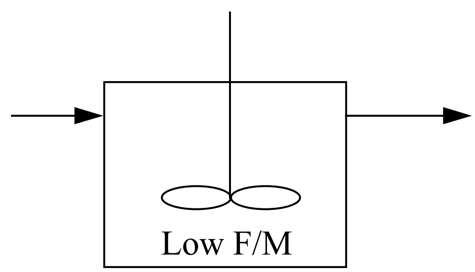
**F/M Ratio**

- The f____________ to m__________________________ (F/M) ratio is an alternative control/design parameter to $\theta_c$ for the operation of an activated sludge plant.

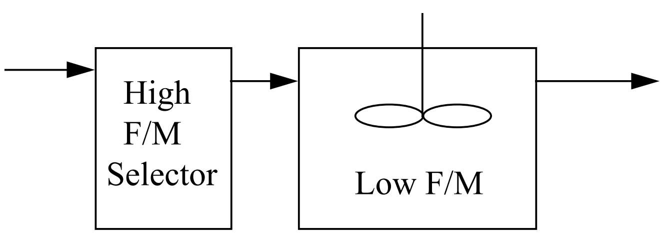
$$\frac{F}{M} = \frac{Q\ S_O}{V\ X} = \frac{mg\ \ BOD_5/dD}{mg\ \ MLVSS}$$

**Note: the F/M ratio is inversely proportional to $\theta_c$.**

- Low F/M ratios are typical in c_____________________ mixed activated sludge (CMAS) systems.
- CMAS systems, consequently, often have filamentous b_______________ problems.




Single Tank CMAS




CMAS with Selector

- By using a **s________________**, the F/M in the first compartment of an activated sludge system can be increased, giving the f___________________ microorganisms a competitive advantage.

**SUMMARY OF ACRONYMS**

| | |
|---|---|
| SRT | solids retention time (or solids residence time), also MCRT, mean cell residence time |
| MLSS | mixed liquor suspended solids |
| MLVSS | mixed liquor volatile suspended solids (used as a surrogate measurement of the biomass in an activated sludge system |
| SVI | sludge volume index - a measurement of the settling properties of activated sludge |
| F:M | food:microorganisms ratio, an alternative design parameter for A.S. system |
| RAS, WAS | return and waste activated sludge |