Comparison of ATV and M&E BNR Designs

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MONOD KINETICS

http://www.ohiowater.org/OTCO/downloads/Presentations/WW%2009/Albert%20Pincince.pdf

SIX ~~FIVE~~ EQUATIONS THAT CHANGED THE WORLD

$$F = \frac{GMm}{d^2}$$

Newton and the Universal Law of Gravity

$$P + \rho\frac{v^2}{2} = Constant$$

Bernoulli and the Law of Hydrodynamic Pressure

$$\nabla E = -\frac{\partial B}{\partial t}$$

Faraday and the Law of Electromagnetic Induction

$$\Delta S_{universe} > 0$$

Clausius and the Second Law of Thermodynamics

$$E = mc^2$$

Einstein and the Theory of Special Relativity

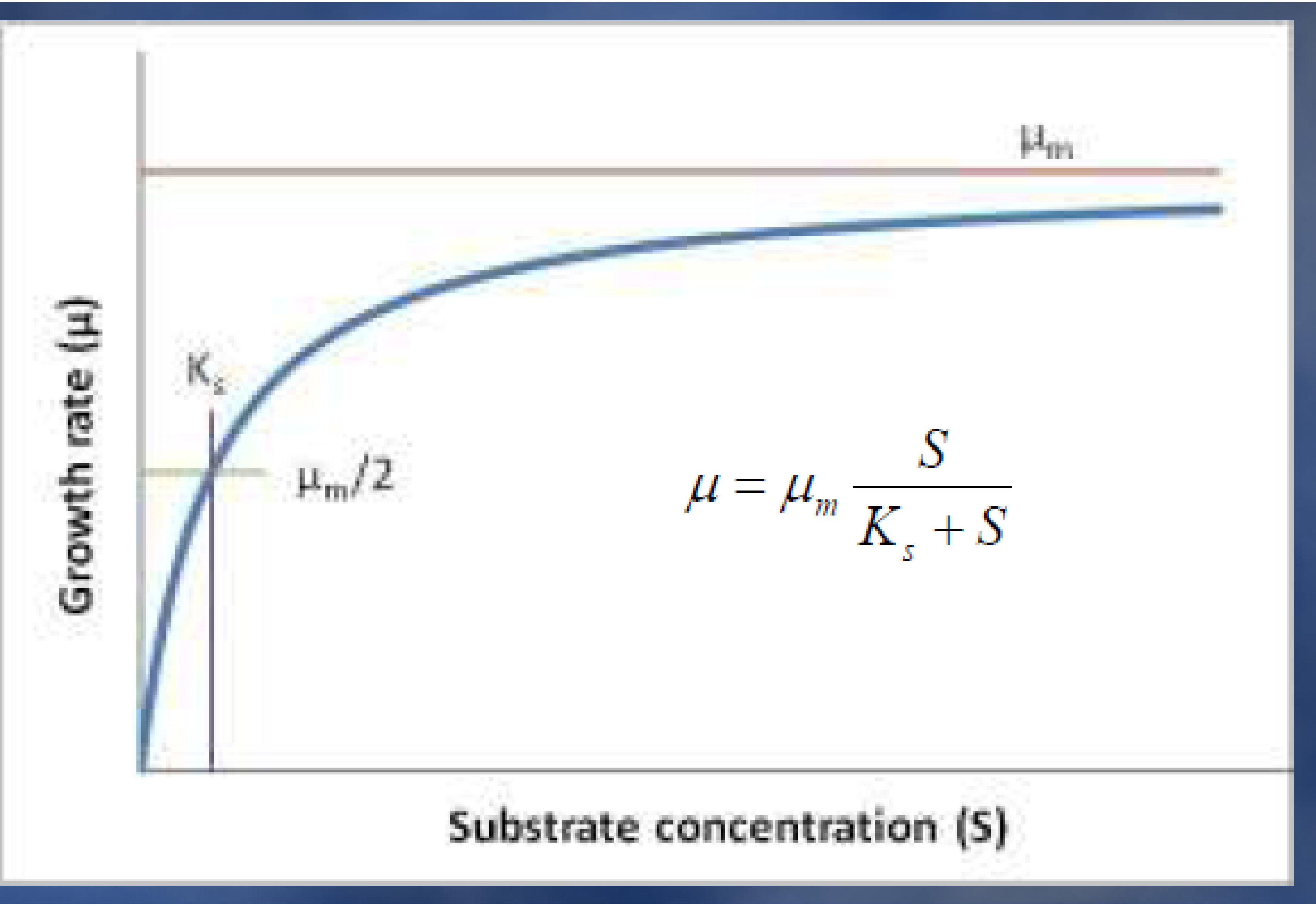
$$\boxed{\mu = \mu_m \frac{S}{K_s + S}}$$

Monod and the Equation for Bacterial Growth

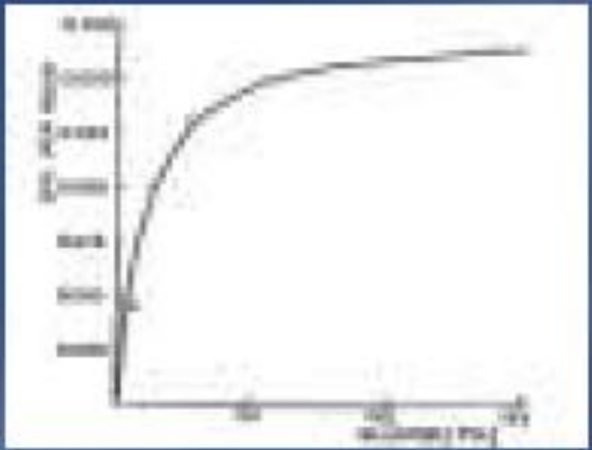
Monod's equation is

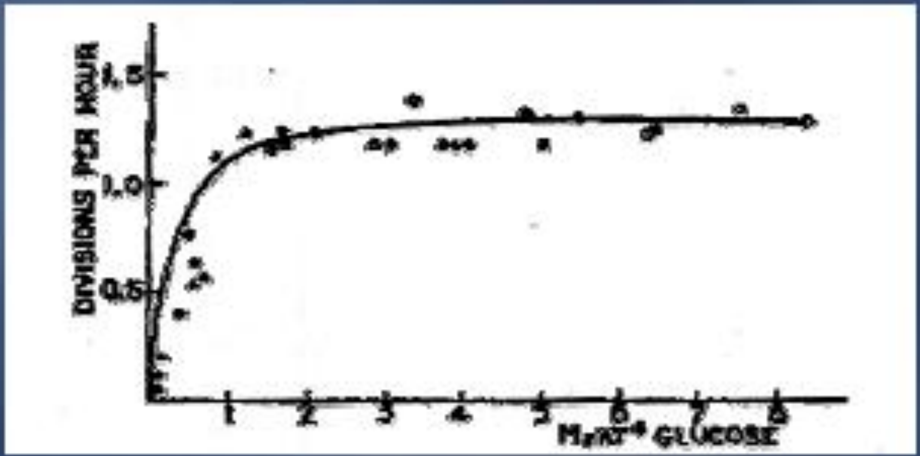
$$\mu = \mu_m \frac{S}{K_s + S}$$

μ = growth rate
μ_m = maximum growth rate
S = concentration of limiting nutrient
K_s = "half-velocity" constant


μm
Ks
μm/2
Growth rate (μ)
Substrate concentration (S)
$$\mu = \mu_m \frac{S}{K_s + S}$$

- Not derived from first principles
- Fit curves to results of batch experiments
- Equation analogous to one for saturation of hemoglobin
- Also similar to Michaelis-Menten equation for enzyme kinetics





$$r_g = -Y\, r_s$$

Herbert and coworkers

- Developed equations for concentrations of effluent product and of bacteria
- First used the term "washout"
- Explained reasons for deviations from theory
  - Lack of complete mixing
  - Endogenous respiration—added decay term to equations

$$r_X = (\mu - b)X$$

After Lawrence and McCarty, we end up with these two equations

- Equation to determine SRT

$$\frac{1}{\theta_c} = \mu - b$$

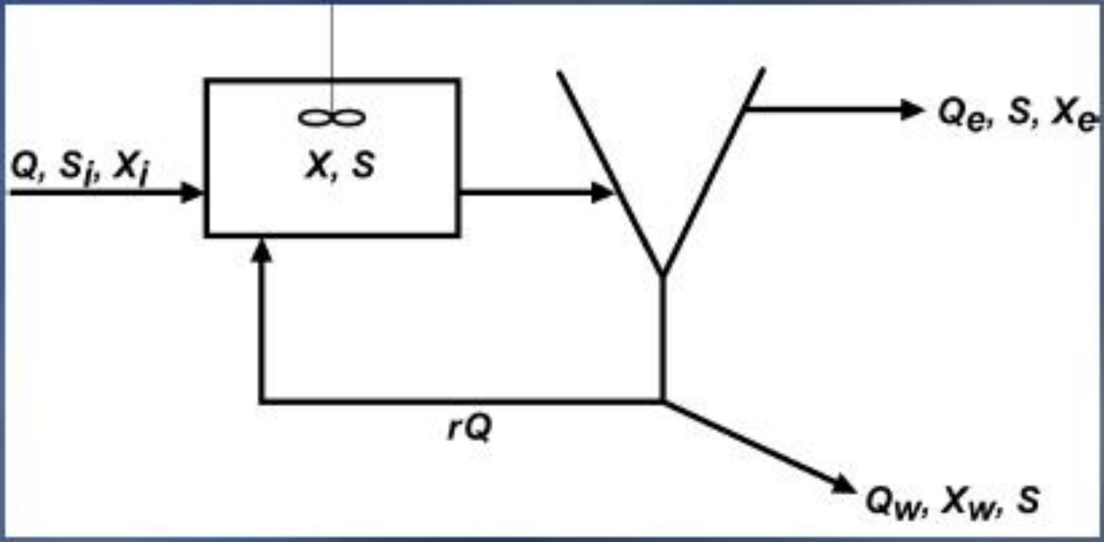
where $\mu = \mu_m \frac{S}{K_s + S}$

- Equation to determine associated biomass

$$\frac{1}{\theta_c} = Y\frac{F}{M} - b$$

F = mass of BOD ***removed***/time
M = volume times concentration

Solids produced are either:



Related to growth:

$$(\mu - b)\,XV$$

Related to removal of substrate:

$$Y(S_i - S)Q$$

Equations for Mass Balance

Solids in + Solids produced = Solids leaving

<u>Related to growth</u>:

$$QX_i + (\mu - b)\,XV = Q_eX_e + Q_wX_w$$

<u>Related to removal of substrate</u>:

$$QX_i + Y(S_i - S)Q = Q_eX_e - Q_wX_w$$

Rearranging the two equations:

$$(\mu - b)\, XV = Q_e X_e + Q_w X_w = P$$

$$Y(S_i - S)Q - bXV = Q_e X_e + Q_w X_w = P$$

Define mean cell residence time (or solids retention time or sludge age) as biomass under aeration divided by biomass leaving system.

$$\theta_c = \frac{XV}{Q_e X_e + Q_w X_w} = \frac{XV}{P} = \frac{M}{P}$$

Combine equations

$$\frac{1}{\theta_c} = \mu - b$$

and

$$\frac{1}{\theta_c} = \frac{Y(S_i - S)Q}{XV} - b$$

Introduce F/M Ratio

- Define F (food) as rate of substrate removal:

$$F = Q(S_i - S)$$

- Define M as mass in aeration tank

$$M = XV$$

- Equation based on mass becomes:

$$\frac{1}{\theta_c} = Y\frac{F}{M} - b$$

To determine effluent substrate concentration, look at based on substrate.

$$\frac{1}{\theta_c} = \mu - b$$

- and its equivalent:

$$\frac{1}{\theta_c} = \mu_{\max} \frac{S}{K_s + S} - b$$

- Rearrange, and solve for S to obtain:

$$S = \frac{K_s(1 + b\theta_c)}{\theta_c(\mu_{\max} - b) - 1}$$

To determine biomass in aeration tank, look at this equation

$$\frac{1}{\theta_c} = Y\frac{F}{M} - b$$

- and its equivalent:

$$\frac{1}{\theta_c} = \frac{Y(S_i - S)Q}{XV} - b$$

- Solve for M:

$$M = VX = \frac{QY(S_i - S)\theta_c}{1 + b\theta_c}$$

To determine biomass in aeration tank, look at this equation

$$\frac{1}{\theta_c} = Y\frac{F}{M} - b$$

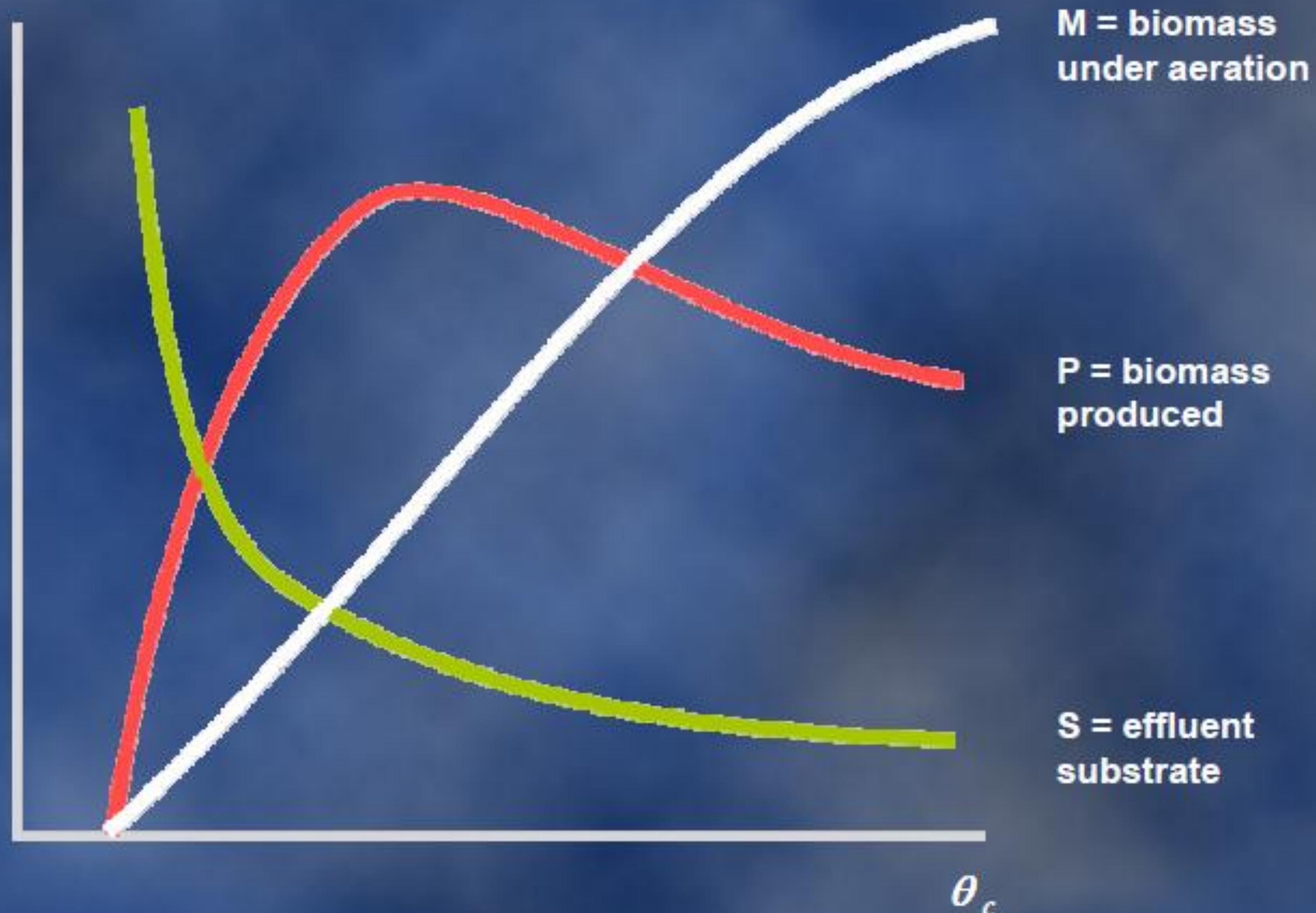
- and its equivalent:

$$\frac{1}{\theta_c} = \frac{Y(S_i - S)Q}{XV} - b$$

- Solve for M :

$$M = VX = \frac{QY(S_i - S)\,\theta_c}{1 + b\,\theta_c}$$

Plots of equations



When does washout occur?

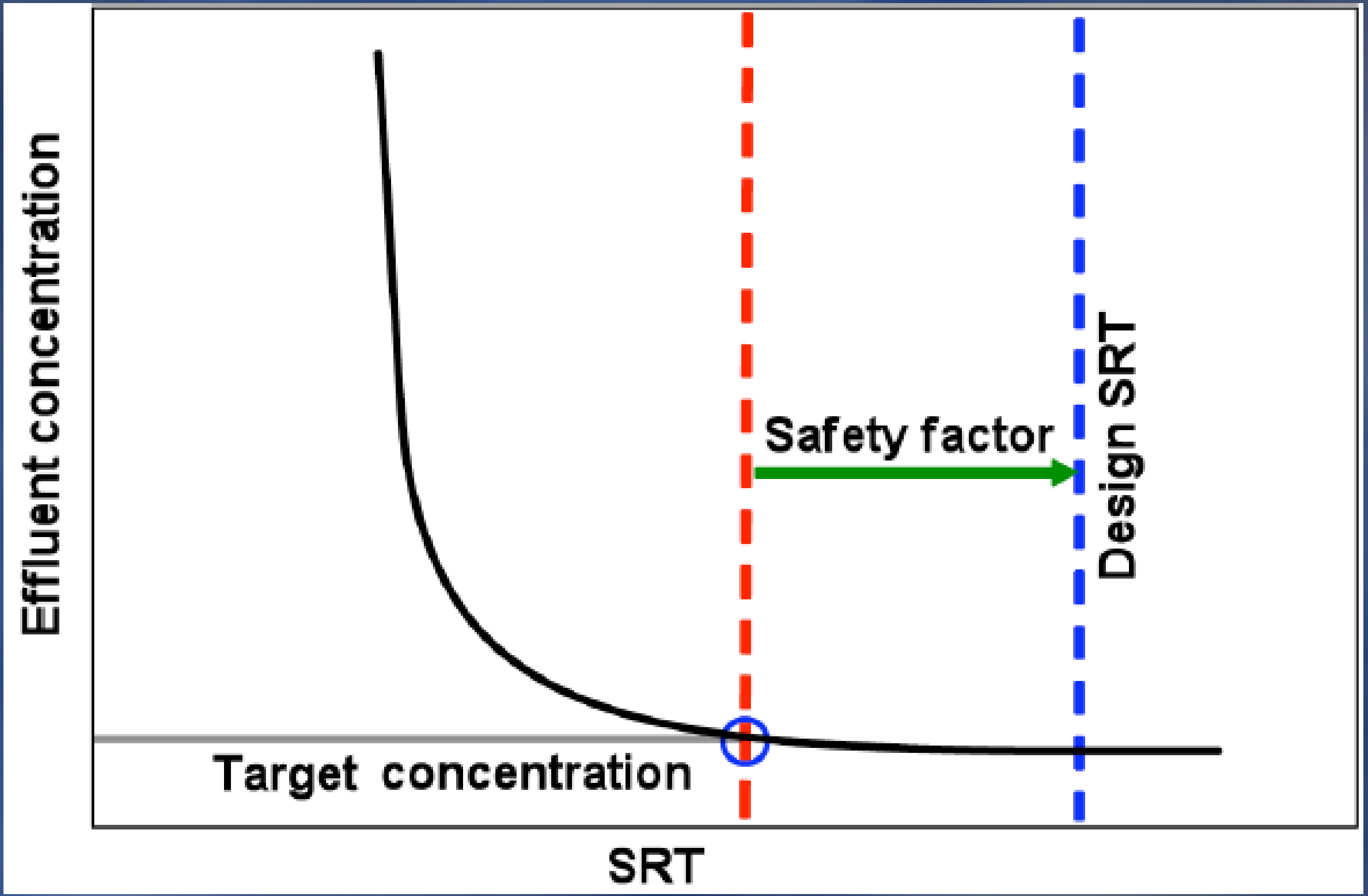
- At washout, effluent concentration is the same as influent and is much higher than K_s
- In equation

$$\frac{1}{\theta_c} = \mu_{\max} \frac{S}{K_s + S} - b$$

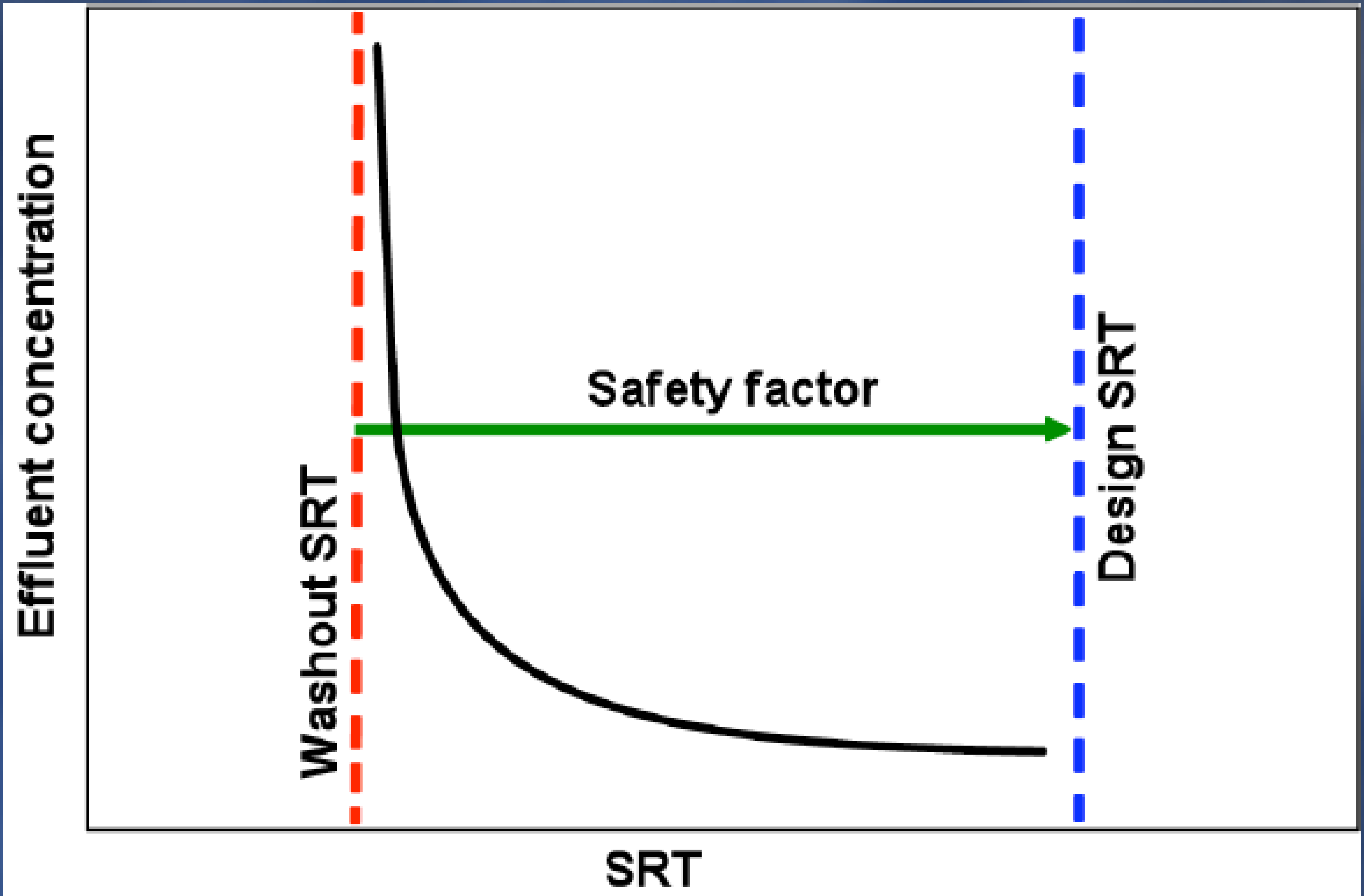
- K_s is neglected
- Equation becomes

$$\frac{1}{\theta_c{}^M} = \mu_{\max} - b$$

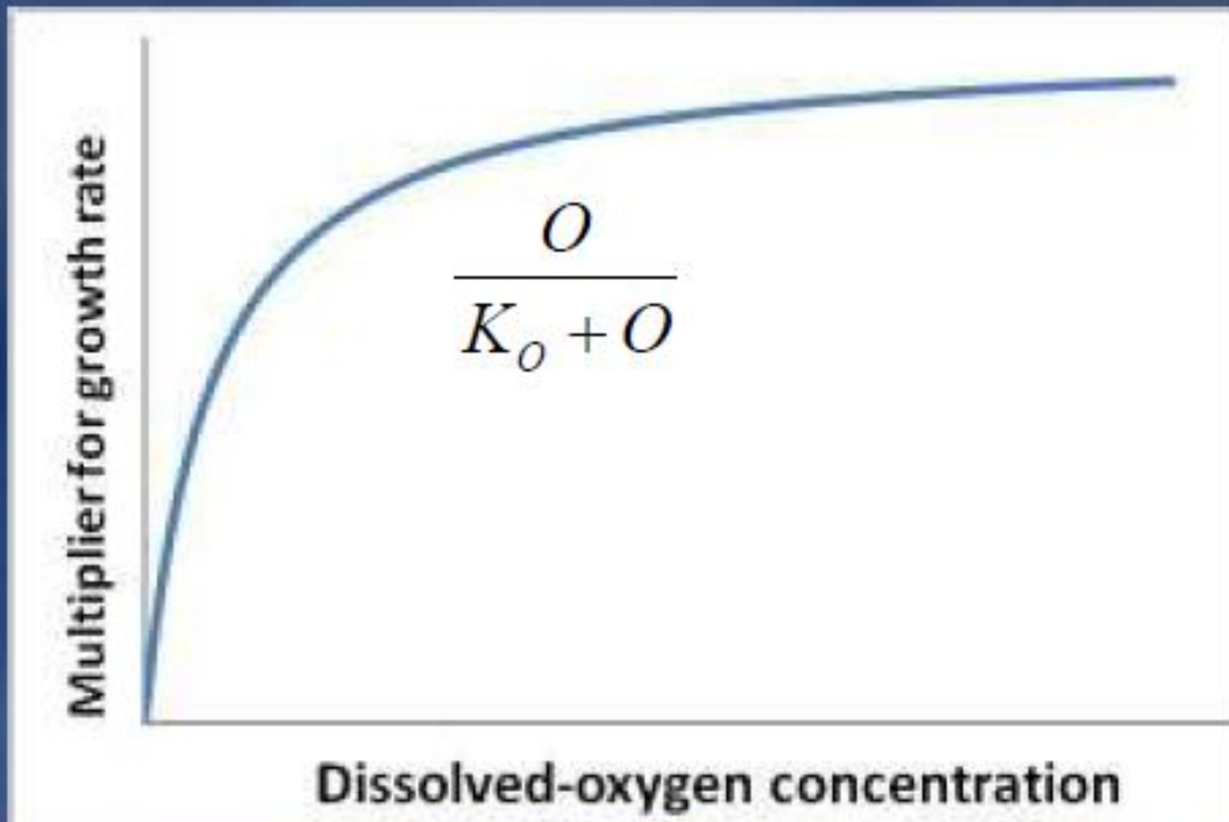
Application of safety factor to effluent concentration



Application of safety factor to washout SRT

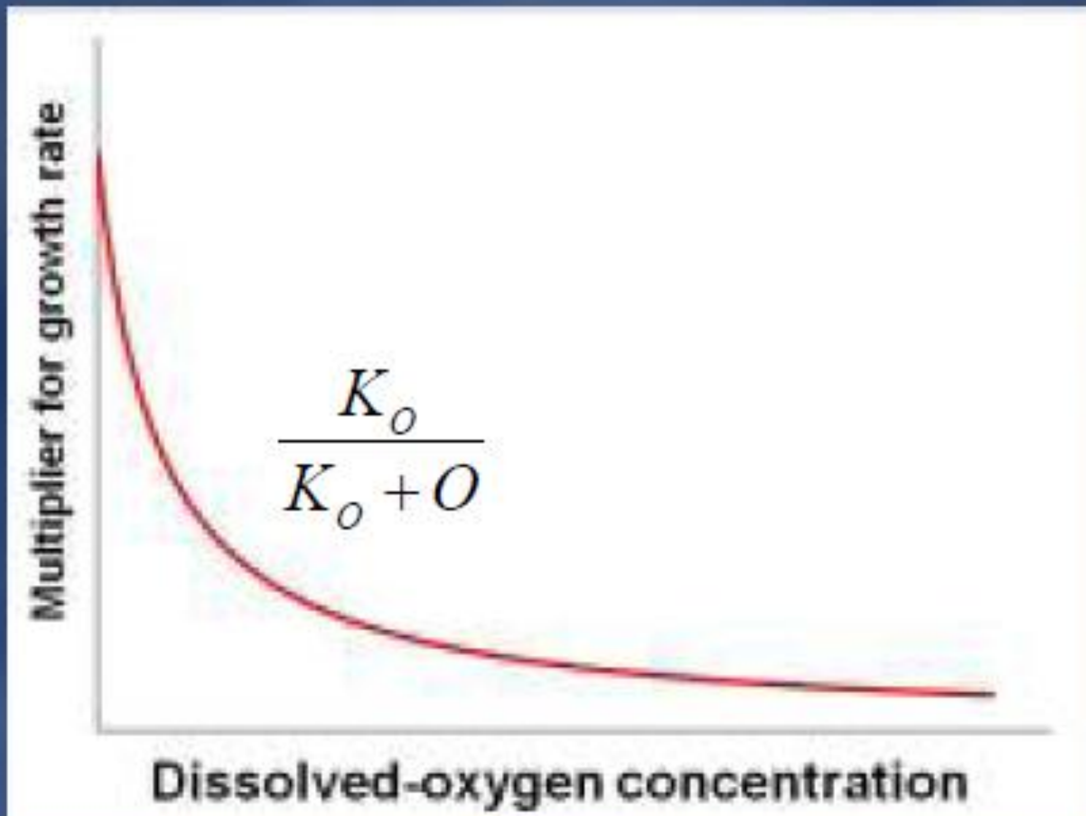


Other uses of Monod-type kinetics (I) Effect of dissolved-oxygen concentration for aerobic systems



$$\mu = \mu_m \frac{S}{K_s + S} \frac{O}{K_O + O}$$

Other uses of Monod-type kinetics (II) Effect of dissolved-oxygen concentration for anoxic systems



$$\mu = \mu_m \frac{S}{K_s + S} \frac{K_O}{K_O + O}$$

Other uses of Monod-type kinetics (V) Examining inhibition

- **Haldane/Andrews**

$$\frac{S}{S + K_S + \frac{S^2}{K_I}}$$

- **Competitive**

$$\frac{S}{S + K_S\left(1 + \frac{I}{K_I}\right)}$$

- **Noncompetitive**

$$\frac{S}{(S + K_S)\left(1 + \frac{I}{K_I}\right)}$$

Derivation of:

$$\frac{1}{F/M} = \frac{Y_H SRT}{1 + b_{H,T} SRT}$$

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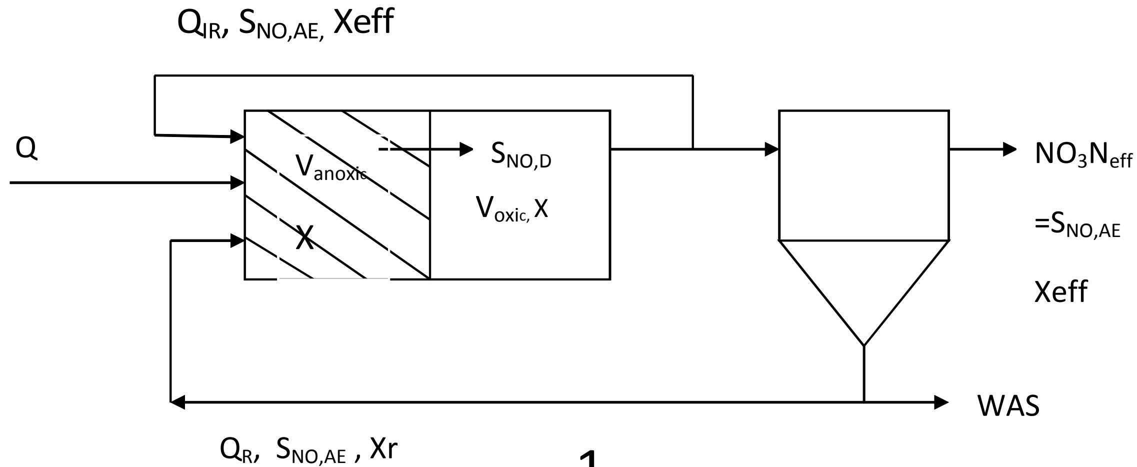
Rate of substrate utilization:



$$r_{su} = \frac{\mu_H}{Y_H} X_{BH} = -\frac{Q(S_0 - S)}{\forall_T} \quad \text{......} 1$$

$$r_g = \mu_H X_{BH} - b_{H,T} X_{BH} = Y_H r_{su} - b_{H,T} X_{BH} \quad \text{......} 2$$

Making a microorganism mass balance for a completely mixed flow reactor with recycle:

$$\cancelto{0}{\forall_T \frac{dX_{eff}}{dt}} = \cancelto{0}{Q_{in} X_{in}} - (Q_W X_{BH} + Q_{eff} X_e) - \forall_T r_g \quad \text{......} 3$$

At steady-state, and for X_{in}=0, substituting r_g from Eq 2 in Eq3;

$$\frac{Q_W X_{BH} + Q_{eff} X_e}{\forall_T X_{BH}} = Y_H \frac{r_{su}}{X_{BH}} - b_{H,T} \quad \text{.......... 4}$$

$$\frac{1}{SRT} = Y_H \frac{r_{su}}{X_{BH}} - b_{H,T} \quad \text{.......... 5}$$

Substituting r_{su} from Eq1;

$$X_{BH} = -\frac{Q(S_0 - S)}{\forall_T} * \frac{Y_H SRT}{1 + b_{H,T} SRT} \quad \text{.......... 6}$$

$$\boxed{\frac{1}{F/M} = -\frac{\forall_T X_{BH}}{Q(S_0 - S)} = \frac{Y_H SRT}{1 + b_{H,T} SRT}} \quad \text{.......... 7}$$

From definiton of SRT;

$$\boxed{P_{X,T} = \frac{\forall_T X}{SRT} = \frac{Y_H Q(S_0 - S)}{(1 + b_{H,T} SRT)}}$$

Dependence of $S_{NO3Neff}$ on Internal Recirculation (IR)

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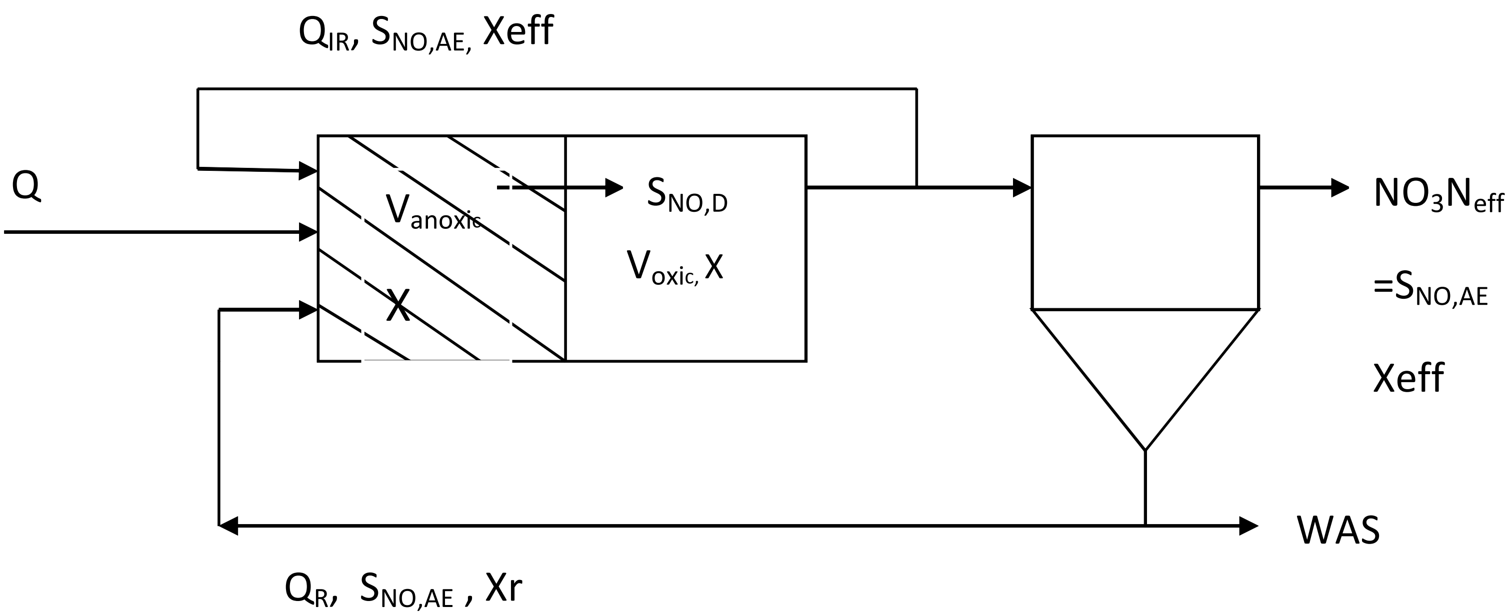
Derivation of Dependence of $S_{NO3Neff}$ on Internal Recirculation (IR)

$$TN_{in} = TKN_{in} + NO_3N_{in}$$

Assume $NO_3N_{in} = 0$

TKN nitrogen to be oxidized = $(TN_{in} - TKN_{eff}) - X_{orgN,WAS} = (1 + R + IR)(S_{NO,AE} - S_{NO,D})$



$$IR = \frac{(TKN_{in} - TKN_{eff} - X_{orgN,WAS})}{S_{NO,AE} - S_{NO,D}} - (1 + R)$$

$$IR = \frac{(TKN_{in} - TKN_{eff} - X_{orgN,WAS})}{S_{NO,AE} - S_{NO,D}} - (1 + R)$$

Assume optimized anoxic volume and $S_{NO,D}$=0

$$IR = \frac{NO_X}{NO_3N_{eff}} - (1 + R)$$

Nitrate to be denitrifed = $Q(R+IR)*NO_3N_{eff}$

Comparison of ATV 131 & M&E

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ATV in a Nutshell

$$BOD_{Load} = Q\,BOD_0 / 1000$$

$$F_T = 1.072^{T-15}$$

Choose V_D/V_T

$$SRT = (SF)\frac{3.4}{(1 - V_D/V_T)}(1.103)^{15-T}$$

SRT = 3.4 d @ 15°C
= 5.55 d @ 10°C
ensures sufficient nitrifies

$$ER = (SRT.F_T) / (1 + 0.17 F_T\,SRT)$$

$$Y_{obsH} = 0.75 + 0.60(SS_0 / BOD_0) - 0.102(ER)$$

$$P_{XT} = Y_{obsH} \cdot BOD_{Load}$$

P_{XT} calcs

Choose SVI=(50-200)
R = 0.75, t_{Th} = 2.5 h

$$X_R = 0.70\frac{10^6}{SVI}\sqrt[3]{t_{Th}}$$

$$X = X_R\left(\frac{R}{1+R}\right)$$

Calculate X from SVI

$$V_T = P_{XT} \cdot SRT / X$$

$$Req'd\ DN_{cap} = \frac{S_{NO_3,D}}{C_{BOD_0}}$$

$$OU_C = 0.56 + 0.15(ER)$$ 1

$$OUR_C = OU_C \cdot BOD_{Load}$$

$$DN_{pot} = \frac{a(0.75)OUR_C}{2.9}\left(V_D / V_T\right)$$

DN_{pot} calc's
a = 1 for Simult DN –0.235

$$a = 2.95\left(100\frac{V_D}{V_T}\right)^{-0.235}$$

$$DN_{cap} = NDN = NN + (NO_3N_0 - NO_3N_{eff})$$
$$NN = TKN_{oxidized} - WASN$$

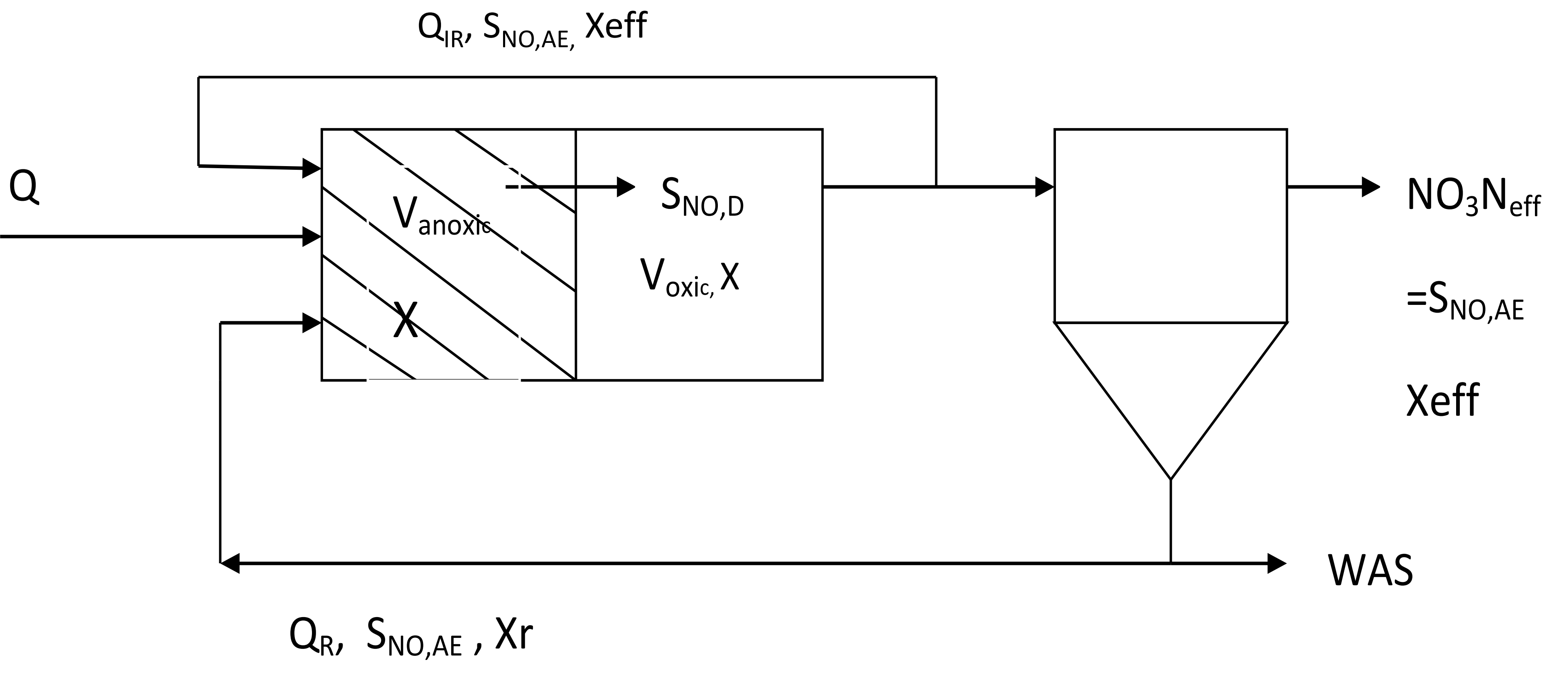
For SRT>10
WASN = 0.04 BOD_0
If SRT< 10
WASN = 0.05 BOD_0

DN_{cap} calc's

Let $DN_{cap} = DN_{pot}$

$$NO_3N_{eff} = (NN - DN_{pot}) + NO_3N_0$$

S & X Mass Balances in Pre-DN



A. Calculating Aerobic Sludge Age (SRT_a)

Writing in terms of ASM Model Notations

$$\mu_A = \hat{\mu}_A = \left(\frac{S_{NH}}{K_{NH} + S_{NH}} \right) \left(\frac{S_0}{K_{0,n} + S_0} \right) - b_A$$

$$\hat{\mu}_{A,T} = \mu_{A,20} (1.07)^{T-20}$$

$$SRT_a = \frac{1}{\mu_{A,T} * SF}$$

A. Biological Sludge Production ($P_{x,bio}$)

Effluent BOD Concentrations, S:

$$S = K_s \frac{(1 + b_{H,T} SRT_a)}{SRT_a(\mu_{H,T} - b_{H,T}) - 1}$$

$$b_{H,T} = b_{H,20}(1.04)^{T-20}$$

$$\mu_{H,T} = \mu_{H,20}(1.07)^{T-20}$$

$$P_{x,bio} = \underbrace{QY_H \frac{(S_0 - S)}{1 + b_{H,T} SRT_a}}_{P_{X,H}} + \underbrace{QY_H f_d b_{H,T} \frac{SRT_a(S_0 - S)}{1 + b_{H,T} SRT_a}}_{\text{P}_\text{X}\text{-particulates formed from decay of heterotrophs}} + \underbrace{QY_A \frac{NO_X}{(1 + b_{A,T} SRT_a)}}_{P_{X,A}}$$

$$NO_X = \text{Oxidized TKN} = \underbrace{TKN_{in} - TKN_{eff}}_{TKN_{oxid}} - \underbrace{0.12(P_{x,bio}/Q)}_{X_{orgN,WAS}}$$

A. Total Sludge Production ($P_{x,TSS}$)

$$P_{X,TSS} = \frac{P_{X,bio}}{0.85} + Q.nbVSS + Q(TSS_0 - VSS_0)$$

$$\frac{MLVSS}{MLSS} = \frac{P_{X,VSS}}{P_{X,TSS}}$$

$$nbVSS = (1 - \frac{bpCOD}{pCOD})VSS$$

$$VSS_0 = 0.65TSS_0$$

bpCOD=27%

pCOD = 40%

Choose X_T

$$\forall_a = \frac{(P_{X,TSS} + P_{X,PO_4})}{X_T} SRT_a$$

$$X_R = 2X \quad \left\{ \quad \frac{X}{X_R} = \frac{R}{1+R}, R = 1 \right.$$

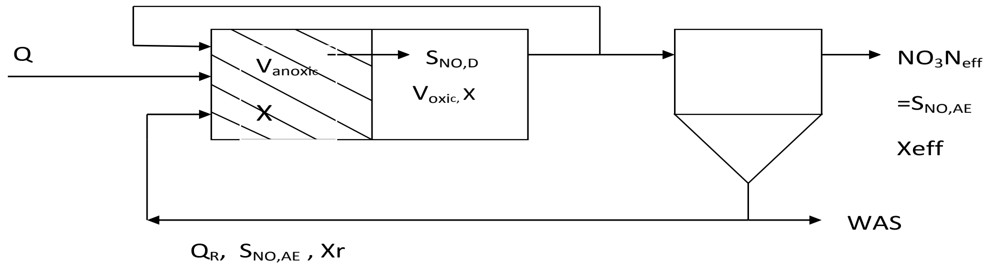
$$\boxed{IR = \frac{NO_X}{S_{NO_3N_{eff}}} - (1+R)}$$

$$\boxed{SDNR_{20} = 0.19 \frac{gNO_3N/d}{gMLVSS}}$$

$$SDNR_T = SDNR_{20}(1.026)^{T-20}$$

$$\frac{1}{(F/M)_a} = \frac{\forall_a . MLVSS_{biomass}}{Q(S_0 - S)} = Y_H \frac{SRT_a}{1 + b_{H,T} SRT_a}$$

$$\boxed{MLVSS_{biomass} = \frac{Y_H SRT_a Q(S_0 - S)}{\forall_a (1 + b_{H,T} SRT_a)}}$$



Total NO_3N recirculated is denitrified.

$$\boxed{\text{Required } NO_3N \text{ removal} = Q(R+IR).NO_3N_{eff}}$$

Assume a retention time for anoxic tank, $t_{R,DN}$

$$\forall_{DN} = \frac{Q}{24} * t_{R,DN}$$

$$\boxed{NO_3N \text{ removed} = \forall_{DN} * SNDR_T * MLVSS_{biomass}}$$

$$\forall_T = \forall_{DN} + \forall_a$$

$$SRT_T = \frac{X_T * \forall_T}{P_{X,TSS}}$$