Updated: 26 November 2019

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CEE 370 Environmental Engineering Principles

Lecture #32

Wastewater Treatment III:

Process Modeling & Residuals

Reading M&Z: Chapter 9

Reading: Davis & Cornwall, Chapt 6-1 to 6-8

Reading: Davis & Masten, Chapter 11-11 to 11-12

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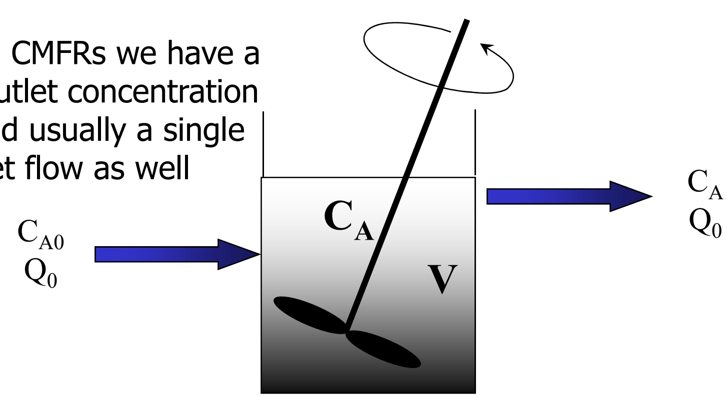
Microbial Biomass in a CMFR

General Reactor mass balance

$$\frac{dm_A}{dt} = \sum_{i=1}^{n}(C_{Ai}Q_i)_{in} - \sum_{j=1}^{n}(C_{Aj}Q_j)_{out} - r_A V$$

But with CMFRs we have a single outlet concentration (C_A) and usually a single inlet flow as well



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Batch Microbial Growth

General Reactor mass balance

$$\frac{dM_A}{dt} = \sum_{i=1}^{n} (C_{Ai} Q_i)_{in} - \sum_{j=1}^{n} (C_{Aj} Q_j)_{out} - r_A V$$

0 0

Batch reactors are usually filled, allowed to react, then emptied for the next batch

Because there isn't any flow in a batch reactor:

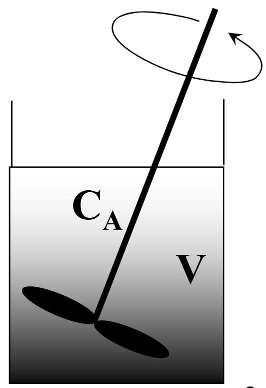
$$\frac{1}{V}\frac{dM_A}{dt} = -r_A$$

And:

$$\frac{dC_A}{dt} = -r_A$$

X kX

For 1[st] order biomass growth



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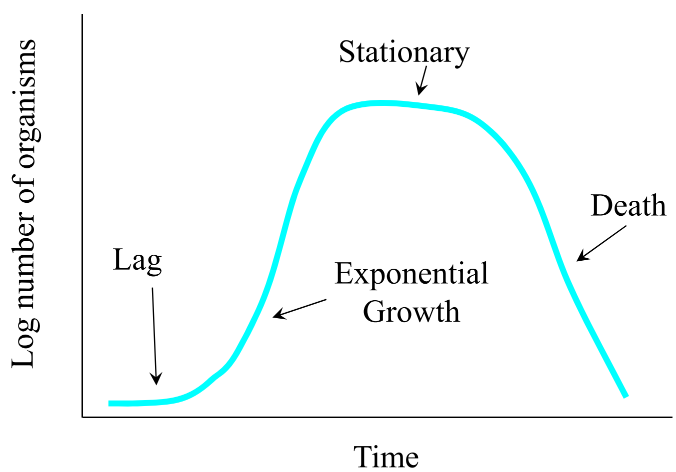
Batch Microbial Growth

- Observed behavior

Covered in lecture #17



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Exponential Growth model

Covered in lecture #17

$$\left(\frac{dX}{dt}\right)_{gr} \equiv \mu X$$

D&M Text

where,

D&M Text			
N	X	=	concentration of microorganisms at time t
t	t	=	time
r	μ	=	proportionality constant or specific growth rate, [time^{-1}]
dN/dt	dX/dt	=	microbial growth rate, [mass per volume-time]

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Exp. Growth (cont.)

Covered in lecture #17

$$\left(\frac{dX}{dt}\right)_{gr} \equiv \mu X \quad \text{or} \quad \left(\frac{dX}{X}\right)_{gr} \equiv \mu dt$$

$$\ln\left(\frac{X}{X_o}\right) = \mu t$$

$$X = X_o e^{\mu t}$$

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Substrate-limited Growth

- Also known as resource-limited growth
  - THE MONOD MODEL

$$\mu = \mu_{\max} \frac{S}{K_S + S} \quad \text{and} \quad \left(\frac{dX}{dt}\right)_{gr} \equiv \mu X = \mu_{\max} \frac{SX}{K_S + S}$$

where,

μ_{max} = maximum specific growth rate, [day^{-1}]
S = concentration of limiting substrate, [mg/L]
K_s = Monod or half-velocity constant, or half saturation coefficient, [mg/L]

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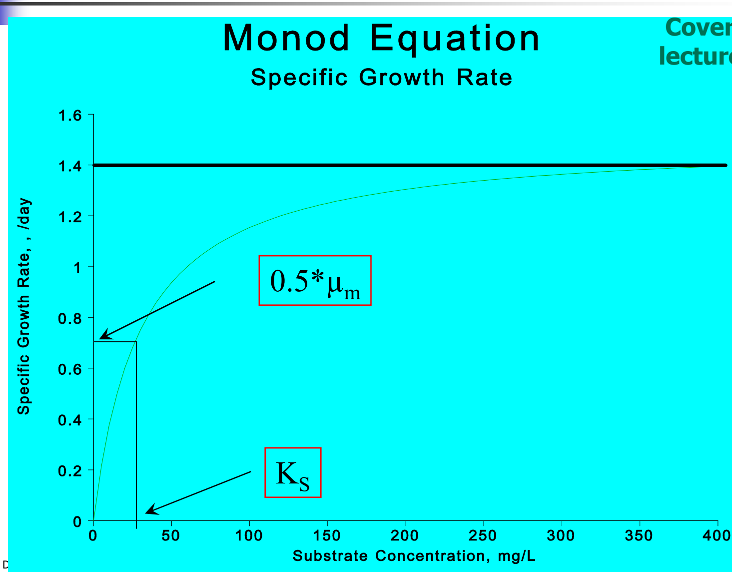
Monod Kinetics



Covered in lecture #17

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Substrate Utilization & Yield

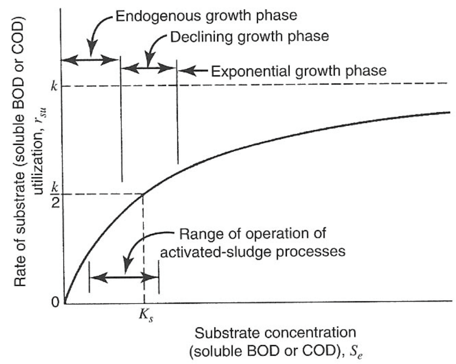
- Related to growth by Y, the yield coefficient
  - Mass of cells produced per mass of substrate utilized

H&H, Fig 11-38, pp.406

$$Y \equiv \frac{\Delta X}{\Delta S} = \frac{dX/dt}{dS/dt}$$

  - Just pertains to cell growth

$$\left(\frac{dX}{dt}\right)_{gr} = Y\frac{dS}{dt}$$



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Microbial Growth

$$\left(\frac{dX}{dt}\right)_{gr} = Y\frac{dS}{dt}$$

- Monod kinetics in a chemostat (batch reactor)

$$\left(\frac{dX}{dt}\right)_{gr} \equiv \mu X = \mu_{max}\frac{SX}{K_S + S}$$

Substitute for dS & Divide by Y →

$$\frac{dS}{dt} = \frac{\mu_{max}}{Y}\frac{XS}{K_S + S}$$

$$r_{su} = k\frac{XS_e}{K_S + S_e}$$

  - Where
    - dS/dt = r_{su} = actual substrate utilization rate
    - k = maximum substrate utilization rate = μ_{max}/Y
    - S = concentration of substrate (S_e in H&H)
    - K_S = half-saturation constant
    - Y = cell yield = dX/dS

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Death

- Bacterial cells also die at a characteristic first order rate with a rate constant, k

$$\left(\frac{dX}{dt}\right)_d = -k_d X$$

- This occurs at all times, and is independent of the substrate concentration

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Overall model: chemostat

- Combining growth and death, we have:

$$\left(\frac{dX}{dt}\right)_{net} = \left(\frac{dX}{dt}\right)_{gr} + \left(\frac{dX}{dt}\right)_d$$

$$= \mu_{\max}\frac{SX}{K_S + S} - k_d X$$

See: M&Z equ 9.3

- And in terms of substrate utilization

$$Y \equiv \left(\frac{dX}{dt}\right)_{gr} \div \frac{dS}{dt}$$

$$\left(\frac{dX}{dt}\right)_{net} = Y\left(\frac{dS}{dt}\right) - k_d X$$

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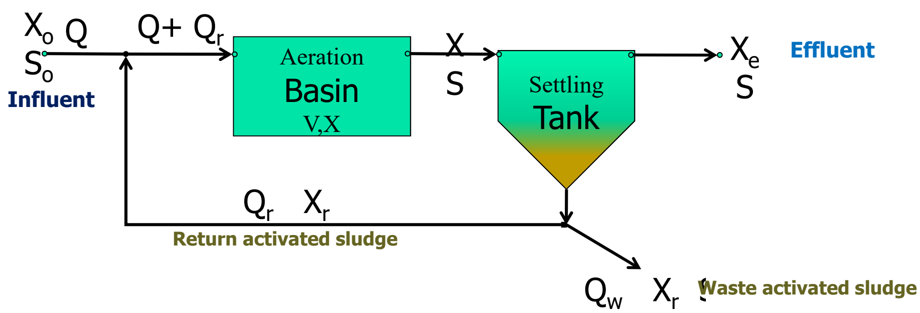
Activated Sludge Flow Schematic

- Conventional



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Efficiency & HRT

- Efficiency of BOD removal

$$E = \frac{(S_o - S)100\%}{S_o}$$

- Hydraulic Retention Time, HRT (Aeration Time)
  - Same as retention time in DWT (t_R)

$$\theta = \frac{V}{Q}$$

  - Actual HRT is a bit different
    - Isn't used as much in design

$$\theta_{act} = \frac{V}{Q + Q_R}$$

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SRT – solids retention time & R

- SRT: Primary operation and design parameter
  - How long does biomass stay in system

$$\theta_c = \frac{biomass\ in\ tank}{rate\ of\ biomass\ leaving\ system}$$

$$\theta_c = \frac{XV}{(Q - Q_w)X_e + Q_w X_r} \approx \frac{XV}{Q_w X_r}$$

See: M&Z equ 9.10

  - Typically equals 5-15 days
- Recycle Ratio $R = \frac{Q_r}{Q}$
  - Values of 0.25-1.0 are typical

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F:M Ratio and volumetric loading

- Food-to-Microorganism Ratio (F/M)

$$\frac{F}{M} = \frac{food\ supplied\ per\ day}{biomass\ in\ tank}$$

$$\frac{F}{M} = \frac{Q * BOD}{V * X}$$

$$\frac{F}{M} = \frac{QS_o}{XV}$$

M&Z equ 9.16

  - Typical values are 0.2-0.6 in complete mixed AS
- BOD volumetric Loading

$$Loading = \frac{QS_o}{V}$$

  - Typically 50-120 lb BOD/day/1000ft^3 tank volume

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Act. Sludge: Biomass Model

- Steady State mass balance on biomass

$$V\frac{dX}{dt} = 0 = QX_o - Q_eX_e - Q_wX_r + V\left(\frac{dX}{dt}\right)_{batch}$$

$$\left(\frac{dX}{dt}\right)_{net} = \left(\frac{dX}{dt}\right)_{gr} + \left(\frac{dX}{dt}\right)_{d} = \mu_{max}\frac{SX}{K_S + S} - k_dX$$

From chemostat model

  - Incorporating the chemostat model gets:

$$V\frac{dX}{dt} = 0 = QX_o - Q_eX_e - Q_wX_r + V\left(\mu_{max}\frac{SX}{K_S + S} - k_dX\right)$$

  - And simplifying

$$-QX_o + Q_eX_e + Q_wX_r = V\left(\mu_{max}\frac{SX}{K_S + S} - k_dX\right)$$

    - Finally, we recognize that the amount of solids entering with the WW (i.e., X_o) and leaving in the treated effluent (i.e., X_e) is quite small and can be neglected

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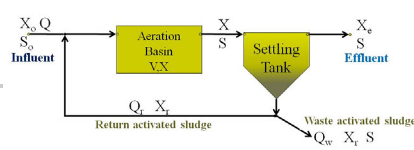
Biomass Model II



- So it becomes

$$Q_wX_r = V\left(\mu_{max}\frac{SX}{K_S + S} - k_dX\right)$$

- And rearranging

$$\frac{1}{\theta_c} \approx \quad \frac{Q_wX_r}{VX} = \mu_{max}\frac{S}{K_S + S} - k_d$$

Earlier equation for SRT

$$\theta_c = \frac{XV}{(Q - Q_w)X_e + Q_wX_r} \approx \frac{XV}{Q_wX_r}$$

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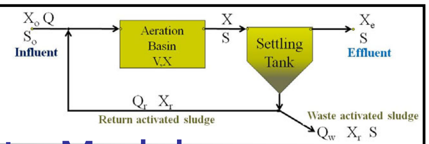

Act. Sludge: Substrate Model

- Steady state mass balance on subst

$$V\frac{dS}{dt} = 0 = QS_o - Q_eS - Q_wS + V\left(\frac{dS}{dt}\right)_{batch}$$

$$\frac{dS}{dt} = \frac{\mu_{max}}{Y}\frac{XS}{K_S + S}$$

From chemostat model

  - Substituting and noting that $Q_e = Q - Q_w$

$$QS_o = QS - Q_wS + Q_wS - V\left(\frac{\mu_{max}}{Y}\frac{XS}{K_S+S}\right)$$

  - And further simplifying

$$Q(S_o - S) = V\left(\frac{\mu_{max}}{Y}\frac{XS}{K_S+S}\right)$$

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Merging the biomass & substrate models

- If we divide the previous equation by V and X

$$\frac{Q(S_o - S)}{VX} = \frac{\mu_{max}}{Y}\frac{S}{K_S+S}$$

$$Q(S_o - S) = V\left(\frac{\mu_{max}}{Y}\frac{XS}{K_S+S}\right)$$

- Multiply both sides by Y

$$\frac{YQ(S_o - S)}{VX} = \mu_{max}\frac{S}{K_S+S}$$

M&Z equ 9.8

- Now insert the LH term into the earlier equation based on biomass

$$\frac{1}{\theta_c} = \frac{Q_wX_r}{VX} = \mu_{max}\frac{S}{K_S+S} - k_d$$

$$\frac{1}{\theta_c} = \frac{Q_wX_r}{VX} = \frac{YQ(S_o - S)}{VX} - k_d$$

M&Z equ 9.9

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Combined model II

- Now recognize that Q/V is the reciprocal of the HRT

$$\frac{1}{\theta_c} = \frac{1}{\theta}\frac{Y(S_o - S)}{X} - k_d$$

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Question

- All else being equal, as SRT goes up:
  1. Settleability goes down
  2. F/M goes down
  3. Waste sludge return ratio must go down
  4. Endogenous respiration becomes less important
  5. Sludge yield increases

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Aeration: Loadings

- Food-to-Microorganism Ratio (F/M)

$$\frac{F}{M} = \frac{Q * BOD}{V * X}$$

- Sludge Age or mean cell residence time (θ_c)

$$\theta_c = \frac{VX}{(X_e Q_e) + (X_W Q_W)} \approx \frac{VX}{X_W Q_W}$$

- Where
  - Q=WW flow
  - V=volume of aeration tank
  - X=MLVSS=mixed liquor volatile suspended solids (biomass concentration)
  - X_e=VSS_e = suspended solids in wastewater effluent
  - X_W=VSS_w = suspended solids in waste sludge
  - Q_w = flow of waste sludge
- SS is sometimes used instead of VSS

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Operating Criteria

- Loading, biomass, retention time, etc

H&H, Table11-4, pp.395

TABLE 11–4

Summary of Loadings and Operational Parameters for Aeration Processes

Process	BOD Loading (lb BOD/day per 1000 cu ft)[a]	MLSS (mg/l)	F/M Ratio (lb BOD/day per lb MLSS)[b]	Sludge Age (days)	Aeration Period (hr)	Return Sludge Rates (percent)	BOD Removal Efficiency (percent)
Conventional	20 to 40	1000 to 3000	0.2 to 0.5	5 to 15	4.0 to 7.5	20 to 40	80 to 90
Step aeration	40 to 60	1500 to 3500	0.2 to 0.5	5 to 15	4.0 to 7.0	30 to 50	80 to 90
Extended aeration	10 to 20	2000 to 8000	0.05 to 0.2	20 and up	20 to 30	50 to 100	85 to 95
High-purity oxygen	120 and up	4000 to 8000	0.6 to 1.5	3 to 10	1.0 to 3.0	30 to 50	80 to 90

[a] 1.0 lb/1000 cu ft/day = 16.0 $g/m^3 \cdot d$

[b] 1.0 lb/day/lb MLSS = 1.0 $g/d \cdot g$ MLSS

Activated Sludge

- Mixed liquor
- Return Activated sludge

Aeration!

1. Surface aerators
2. Bubble diffusers

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CEE 370 Environmental Engineering Principles

Lecture #32b

Wastewater Treatment IIIb:

Process Modeling & Residuals

Reading: M&Z Chapter 9.11

Other Reading: Davis & Cornwall, Chapt 6-1 to 6-8 and Davis & Masten, Chapter 11-11 to 11-12

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Anaerobic Digester Problem

Anaerobic digesters are commonly used in wastewater treatment. The biological process produces both carbon dioxide and methane gases. A laboratory worker plans to make a "synthetic" digester gas. There is currently 2 L of methane gas at 1.5 atm and 1 L of carbon dioxide gas at 1 atm in the lab. If these two samples are mixed in a 4 L tank, what will be the partial pressures of the individual gases? The total pressure?

Example 4.4 from Ray

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Solution to Anaerobic Digester Problem

First, we must find the partial pressures of the individual gases using the ideal gas law:

$$P_1 V_1 = nRT = P_2 V_2 \quad \text{or} \quad P_2 = P_1\left(\frac{V_1}{V_2}\right)$$

For methane gas $P_2 = 1.5 \text{ atm}\left(\frac{2 \text{ L}}{4 \text{ L}}\right) = 0.75 \text{ atm}$

For carbon dioxide gas: $P_2 = 1 \text{ atm}\left(\frac{1 \text{ L}}{4 \text{ L}}\right) = 0.25 \text{ atm}$

And the total is: $P_t = P_{CH_4} + P_{CO_2} = 1 \text{ atm}$

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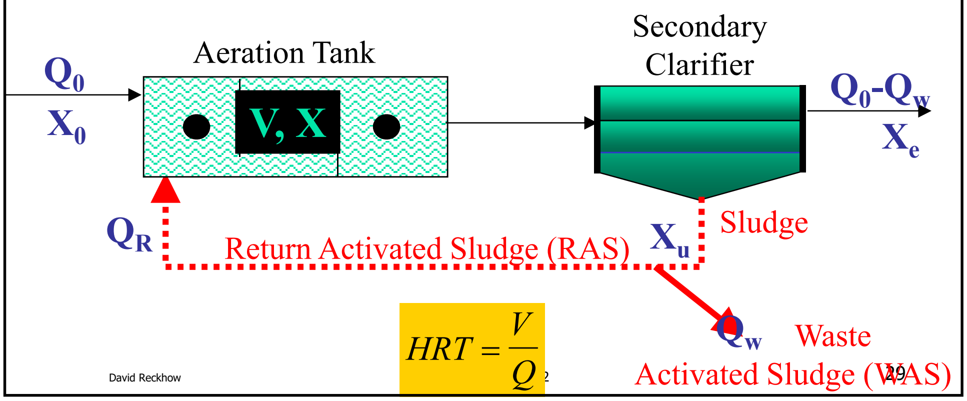
SRT=solids retention time

Solids Balance

$$SRT = \frac{XV}{Q_w X_u} = \frac{\text{mass of organisms in tank}}{\text{mass of organisms removed per day}}$$



$$HRT = \frac{V}{Q}$$

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We will cover this in CEE 471

Solids Mass Balance

- Consider aeration tank and clarifier together
  - Biomass in + biomass produced due to growth = biomass out

$$Q_0 X_0 + V\frac{dX}{dt} = (Q_0 - Q_w)X_e + Q_w X_w$$

  - Now using the combined growth equation without limitation to carrying capacity:

$$\frac{dX}{dt} = \left[\mu_{max}\left(\frac{S}{K_s + S}\right) - k_d\right]X$$

  - Combining and assuming X_0 and X_e to be negligible:

$$\frac{\mu_{max} S}{K_s + S} = \frac{Q_w X_w}{VX} + k_d$$

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We cover this in detail in CEE 471

Substrate Mass Balance

- Consider aeration tank and clarifier together
  - Substrate in + substrate consumed by biomass = substrate out

$$Q_0 S_0 + V\frac{dS}{dt} = (Q_0 - Q_w)S + Q_w S$$

Note that effluent and waste sludge substrate concentrations are considered the same

  - Now using the combined substrate utilization equation without limitation to carrying capacity:

$$\frac{dS}{dt} = -\frac{1}{Y}\left[\mu_{max}\left(\frac{S}{K_s+S}\right) - k_d\right]X$$

  - Combining and rearranging:

$$\frac{\mu_{max} S}{K_s + S} = \frac{Q_0 Y}{VX}(S_0 - S)$$

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We cover this in CEE 471

Combined Mass Balances

- In summary the solids and substrate mass balance equations are:

$$\frac{\mu_{max} S}{K_s + S} = \frac{Q_w X_w}{VX} + k_d \qquad \frac{\mu_{max} S}{K_s + S} = \frac{Q_0 Y}{VX}(S_0 - S)$$

- These can be easily combined (left hand terms are the same):

$$\frac{Q_w X_w}{VX} = \frac{Q_0 Y}{VX}(S_0 - S) - k_d$$

$$\frac{1}{\Theta_c}$$

The mean cell residence time, or sludge age

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Sludge Treatment

- Depends on type of sludge
- Typical process train
  - Thickening or dewatering
  - Conditioning
  - Stabilization (usually for wastewater)
  - Disposal
- Nonmechanical methods
  - Lagoons
  - Sand-drying beds
  - Freeze treatment
- Mechanical methods
  - Centrifugation
  - Vacuum filtration
  - Belt filter press
  - Plate filters

See also Lecture #30

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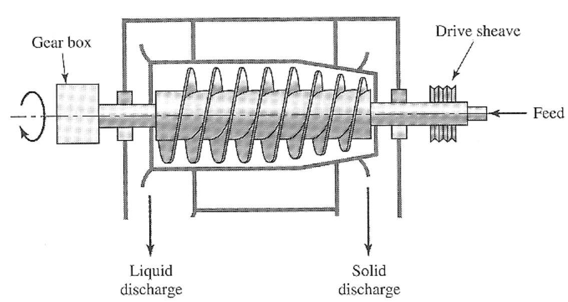
- Centrifuge

FIGURE 9–21

Solid bowl centrifuge.



From Lecture #30

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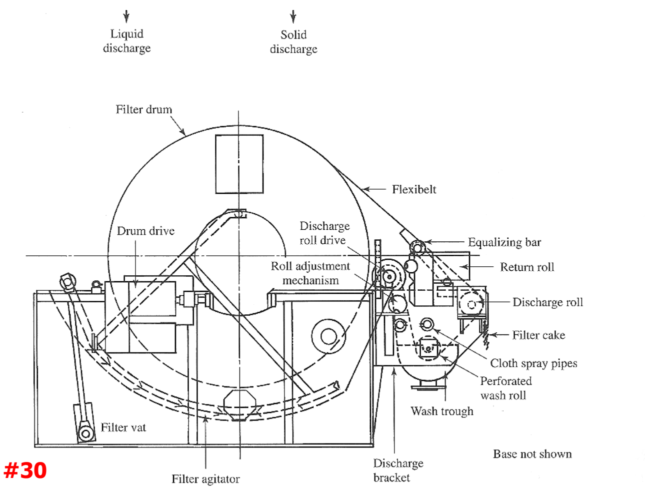
Vacuum Filter

FIGURE 9–22

Vacuum filter. (*Courtesy of Komline-Sanderson Engineering Corporation.*)



From Lecture #30

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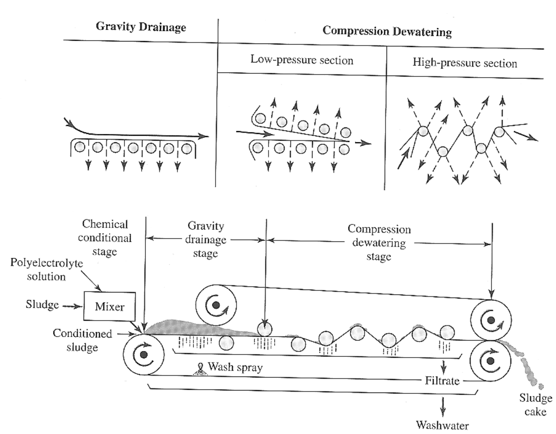
Belt Filter Press

FIGURE 9–23

Continuous belt filter press. (*Source:* U.S. Environmental Protection Agency, *Process Design Manual, Sludge Treatment and Disposal,* 1979.)



From Lecture #30

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- To next lecture