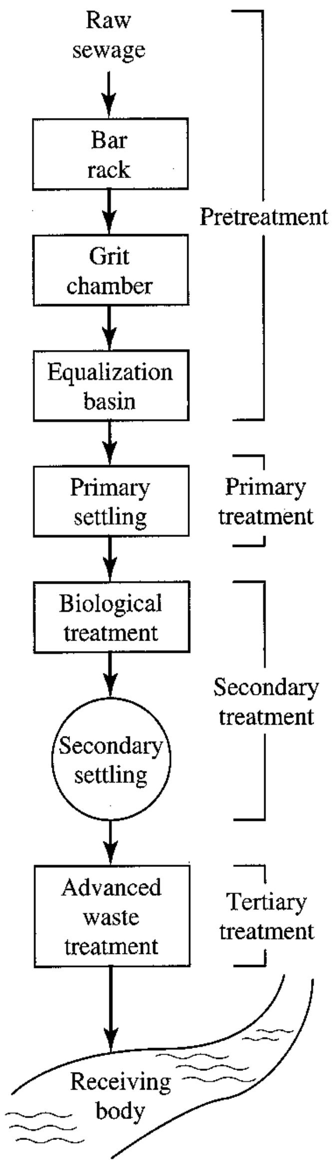
Physical unit processes I

Overview of wastewater treatment



- **Preliminary**: Removal of wastewater constituents such as rags, sticks, floatables, grit, and grease that may cause maintenance or operational problems with the subsequent processes

- **Primary**: Removal of a portion of the suspended solids and organic matter from the wastewater by gravity

- **Secondary**: Removal of biodegradable organic matter and suspended solids by biological treatment. The conventional secondary treatment process may be modified to enhance nutrient removal (biological nutrient removal, BNR)

- **Tertiary** (≈advanced): Polishing secondary effluent by i) enhanced removal of suspended solids, ii) nutrient removal, iii) removal of dissolved species, iv) removal of refractory organics, etc. Disinfection is also often classified as tertiary treatment.

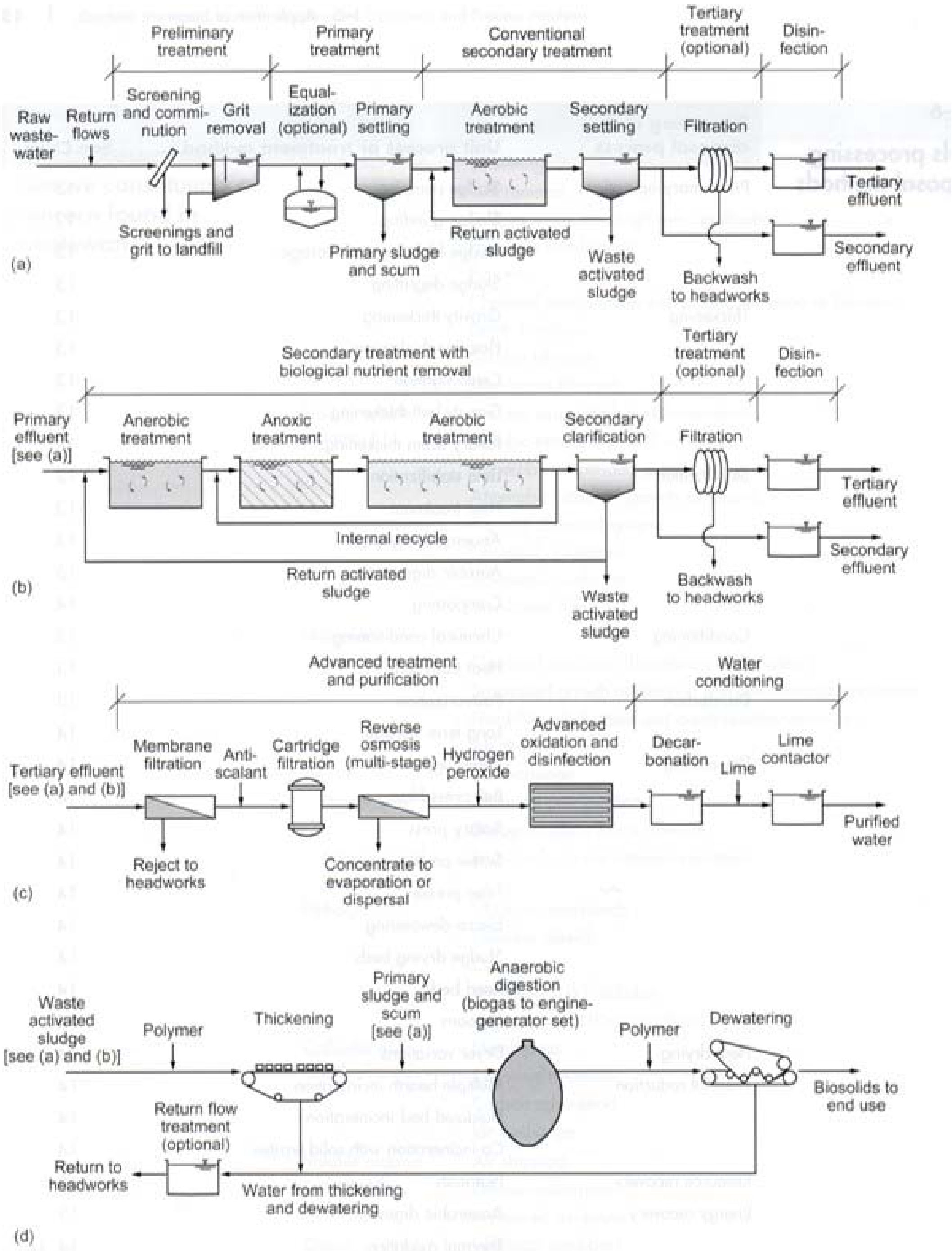
Typical flow diagrams

(a) Conventional secondary treatment

(b) Applying biological nutrient removal

(c) Advanced treatment following secondary treatment (e.g., for water reuse)

(d) Anaerobic treatment of primary and secondary sludge



Overview of wastewater treatment

- **Unit processes**
  - Wastewater treatment system is a combination of different unit processes
  - Physical, chemical, and biological unit processes
  - Unit processes for the treatment of **wastewater** and **residuals**

Unit processes

[Unit processes to remove constituents of concern from wastewater]

Target constituent	Unit process
Suspended solids	Screening; Grit removal; Sedimentation; High-rate clarification; Flotation; Chemical precipitation with settling, flotation, or filtration; Depth filtration; Surface filtration; Membrane filtration
Biodegradable organics	Aerobic suspended growth processes; Aerobic attached growth processes; Anaerobic suspended growth processes; Anaerobic attached growth processes; Physical-chemical systems; Chemical oxidation; Advanced oxidation; Membrane filtration
Nitrogen	Chemical oxidation (breakpoint chlorination); Suspended-growth nitrification and denitrification processes; Fixed film nitrification and denitrification processes; Air stripping; ion exchange
Phosphorus	Chemical precipitation; Biological P removal
Nitrogen and phosphorus	Biological nutrient removal processes

Unit processes

[Unit processes to remove constituents of concern from wastewater (cont'd)]

Target constituent	Unit process
Pathogens	Chemical disinfection (chlorine, chlorine dioxide, ozone, etc.); UV radiation; Heat treatment (pasteurization)
Colloidal and dissolved solids	Membrane filtration; Chemical treatment; Carbon adsorption; Ion exchange
Volatile organic compounds	Air stripping; Carbon adsorption; Advanced oxidation
Odors	Chemical scrubbers; Carbon adsorption; Bio-trickling filters; Compost filters

Unit processes

[Residuals processing and disposal methods]

Processing or disposal process	**Unit process or treatment method**
Preliminary operations	Sludge pumping; Sludge grinding; Sludge blending and storage; Sludge degritting
Thickening	Gravity thickening; Flotation thickening; Centrifugation; Gravity belt thickening; Rotary drum thickening
Stabilization	Lime stabilization; Heat treatment; Anaerobic digestion; Aerobic digestion; Composting
Conditioning	Chemical conditioning; Heat treatment
Disinfection	Pasteurization; Long term storage

Unit processes

[Residuals processing and disposal methods (cont'd)]

Processing or disposal process	Unit process or treatment method
Dewatering	Centrifuge; Belt press filter; Rotary press; Screw press; Filter press; Electro-dewatering; Sludge drying beds; Reed beds; Lagoons
Heat drying	Dryer variations
Thermal reduction	Multiple hearth incineration; Fluidized bed incineration; Co-incineration with solid wastes
Resource recovery	Nutrient recovery processes
Energy recovery	Anaerobic digestion; Thermal oxidation; Production of oil and liquid fuels
Ultimate disposal	Land application; Landfill; Lagooning

Physical unit processes

- Physical unit processes used in wastewater treatment
  - Screening
  - Coarse solids reduction
  - Flow equalization
  - Mixing and flocculation
  - Grit removal
  - Sedimentation (primary/secondary)
  - Flotation
  - Aeration
  - Filtration
  - VOC removal
  - Air stripping

Screening

- A device with openings, generally of uniform size, used to retain solids found in the wastewater treatment plant influent or in the combined sewer overflows

- Goal: to remove coarse materials that could i) damage subsequent process equipment, ii) reduce overall treatment process reliability and effectiveness, or iii) contaminate waterway

- Classification (by opening size)
  - Coarse screens: >6 mm
  - Fine screens: 0.5-6 mm
  - Microscreens: <0.5 mm

Coarse screens (bar racks)

- Used to protect pumps, valves, pipelines, and other apparatus from damage or clogging by rags and large objects
- Manually-cleaned (old and/or small plants) vs. mechanically cleaned screens

Top: Manually-cleaned bar screen
http://techalive.mtu.edu
Bottom: Mechanically-cleaned bar screen
http://www.degremont-technologies.com

Coarse screens - headloss

- Should be maintained low (typically <150 mm)
- Accumulation of materials on the screen → headloss buildup → need for cleaning

$$h_L = \frac{1}{C}\left(\frac{{v_s}^2 - v^2}{2g}\right)$$

h_L = headloss (m)

C = empirical discharge coefficient

(typically 0.7 for a clean screen and 0.6 for a clogged screen)

v_s= velocity of flow through the bar screen openings (m/s)

v = approach velocity in upstream channel (m/s)

Coarse screens - headloss

Q: Determine the buildup of headloss through a bar screen when 50% of the flow area is blocked off due to the accumulation of solids. Assume the following conditions apply:

Approach velocity = 0.6 m/s

Velocity through clean bar screen = 0.9 m/s

Headloss coefficient for a clean bar screen = 0.7

Headloss coefficient for a clogged bar screen = 0.6

Coarse screens - headloss

Answer)

1. The clean screen headloss

$$h_L = \frac{1}{0.7} \cdot \frac{(0.9\,m/s)^2 - (0.6\,m/s)^2}{2 \cdot 9.81\,m/s^2} = 0.033\,m$$

2. Clogged screen headloss: v_s doubles as the screen area is reduced by 50%

$$h_L = \frac{1}{0.7} \cdot \frac{(1.8\,m/s)^2 - (0.6\,m/s)^2}{2 \cdot 9.81\,m/s^2} = 0.24\,m$$

Fine screens

- Uses: i) additional preliminary treatment following coarse bar screens

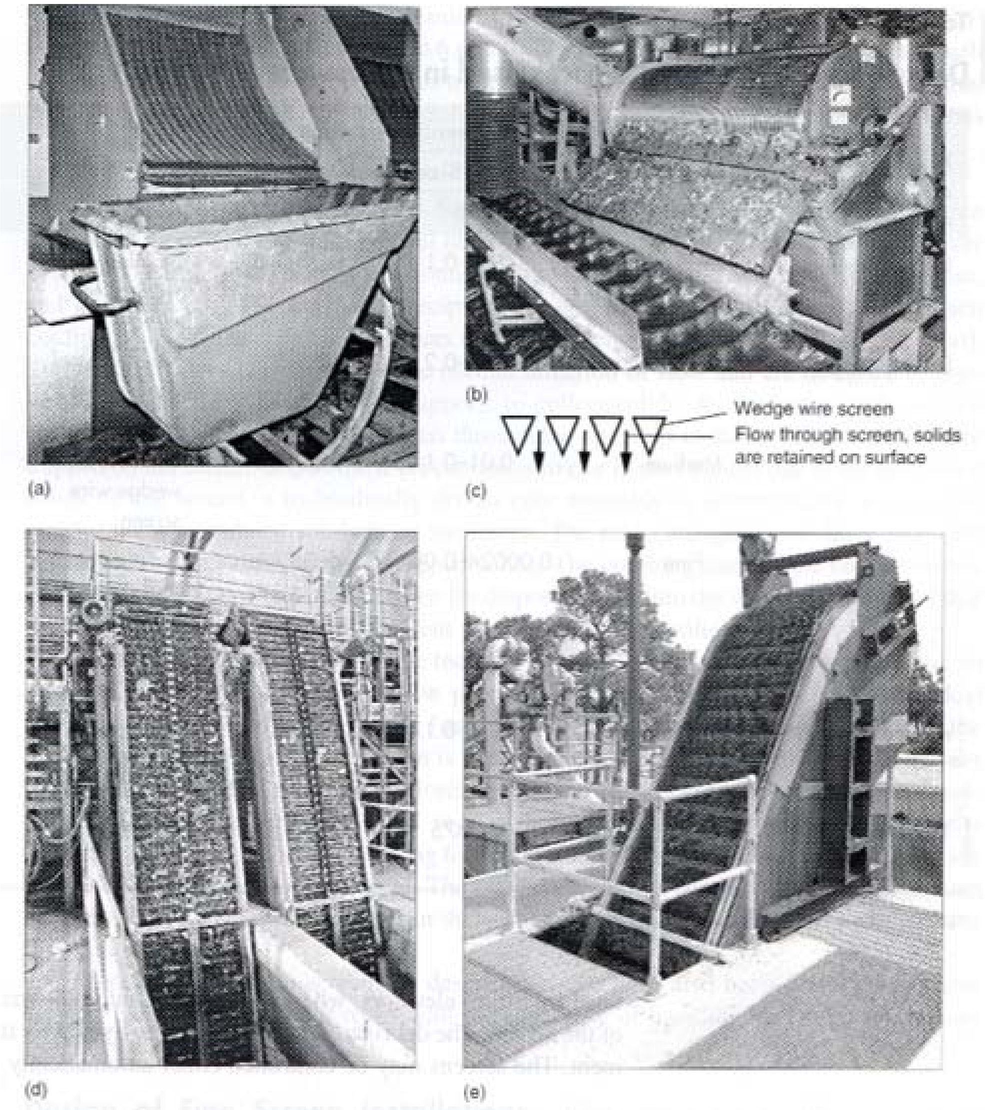
  ii) primary treatment as a substitute for primary clarifiers

  iii) CSO treatment

- Fine screens for preliminary & primary treatment
  - Significant headloss may occur - limited to plants where headloss through the screens is not a problem
  - Fine screens to replace primary treatment – for small treatment plants
  - Types: static (fixed), rotary drum, step type

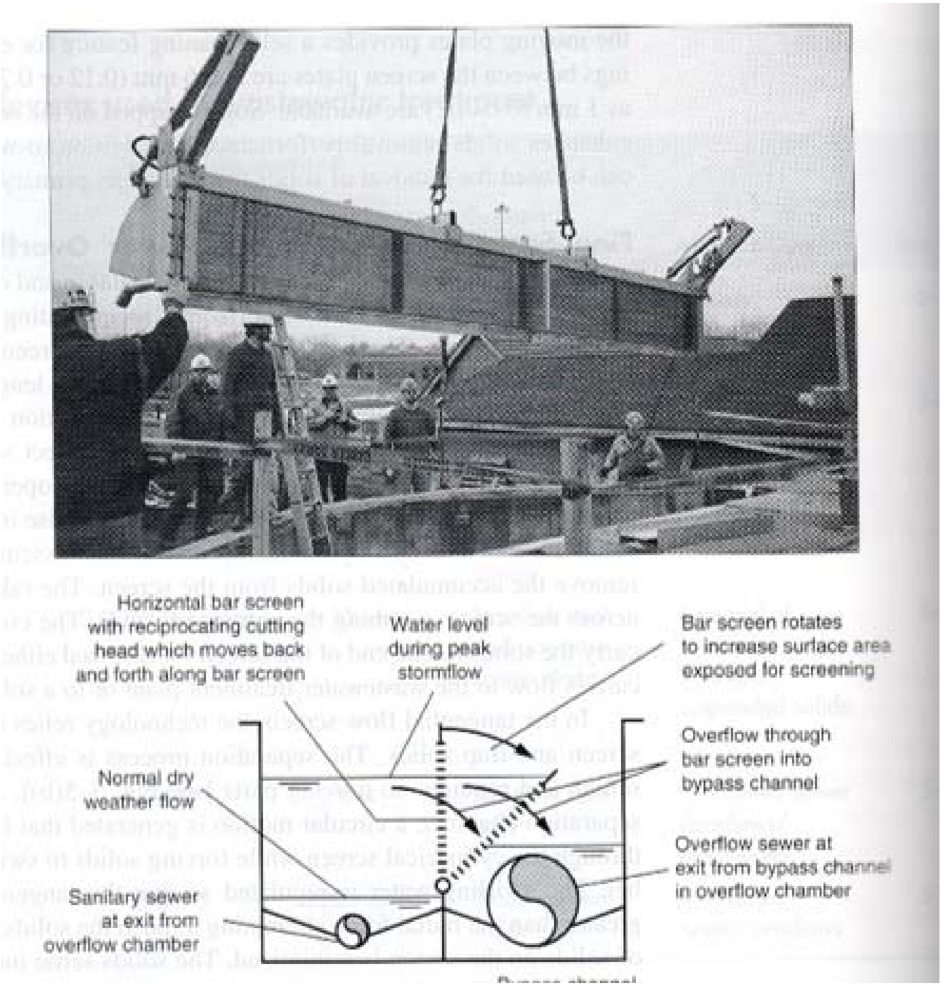
- Fine screens for CSOs
  - Relatively simple unit to reduce contaminant loadings to receiving water bodies
  - Types: horizontal reciprocating screens, tangential flow screens

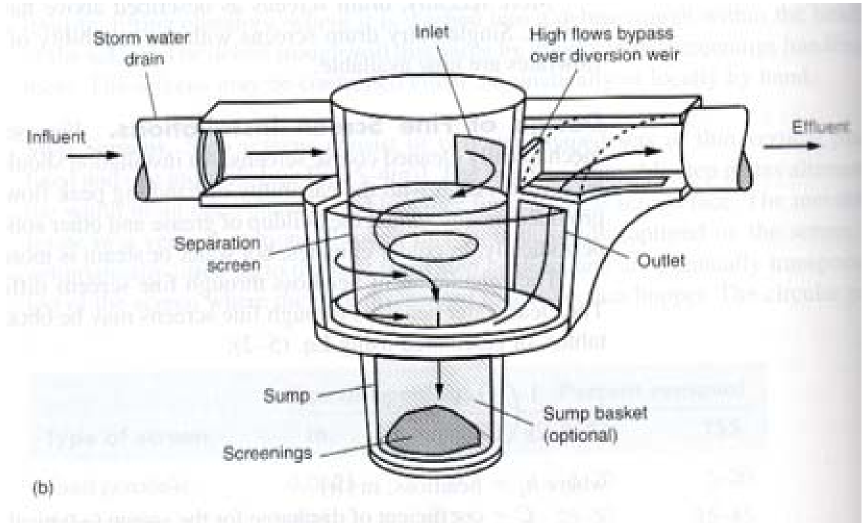
Fine screens



Typical fine screens for preliminary & primary treatment: (a) Static wedge wire; (b) wedge-wire drum screen; (c) section through wedge wire screen; (d) traveling band screen; and (e) step screen

Fine screens





Devices used for the screening of CSOs:
(a) view of horizontal screen during installation and its operating mechanism;
(b) tangential flow device with separation screen

Fine & micro screens

- Headloss through fine screens

$$h_L = \frac{1}{2g}\left(\frac{Q}{CA}\right)^2$$

Q = discharge through screen (m^3/s)

C = coefficient of discharge (typical value = 0.6 for a clean screen)

A = effective open area of submerged screen (m^2)

- **Microscreens**
  - Major uses: to remove SS from secondary effluent (as a means of advanced treatment)
  - Not frequently used

Screening

- **Materials retained on screens**
- **Characteristics**
  - Screenings retained on coarse screens
    - Mainly inert materials (rocks, branches, pieces of lumber, leaves, paper, tree roots, plastics, rags, …)
    - Some accumulation of oil and grease and organic matter may occur
  - Screenings retained on fine screens
    - Small rags, paper, plastic materials, razor blades, grit, undecomposed food waste, feces, …
    - Slightly lower specific weight, higher moisture content, and high organic matter content than screenings on coarse screens
    - Biodegradable organic matter putrefies to generate odor, so additional care is required

Screening

- Screening handling, processing, and disposal
  - Screening handling and processing
    - Major goal: volume reduction
    - Dewatering and compaction
  - Screening disposal

    1) Removal by moving to disposal areas (landfill) – most common
    2) Burial on the plant site (only for small plants)
    3) Incineration
    4) Discharge to grinders or macerators and return to the wastewater

Mixing

- Application of mixing in wastewater treatment
  - Continuous rapid mixing
    - Blending of chemicals with wastewater
    - Blending of miscible liquids
    - Addition of chemicals to sludge and biosolids
  - (Slower) Continuous mixing
    - Keeping the contents of a reactor or storage tanks in suspension (e.g., for biological treatment)
    - Flocculation (more common in water treatment!)

Mixing

- Velocity gradients and power requirement
  - Mixing can be viewed as a development of velocity gradients among fluid
  - “G value”: average velocity gradient, a measure of mixing intensity

Camp and Stein (1943)

$$\boxed{G = \sqrt{\frac{P}{\mu V}}}$$

G = average velocity gradient (1/s)
P = power requirement (W)
μ = dynamic viscosity (N-s/m^2)
V = reactor volume (m^3)

⇨ The effectiveness of mixing is a function of power input per volume

⇨ Greater power requirement to achieve greater G with the same reactor volume;

Greater power requirement to achieve the same G with the larger reactor volume

Mixing

- rapid mixing: G↑ with small τ
- gentle mixing (flocculation): G↓ with large τ

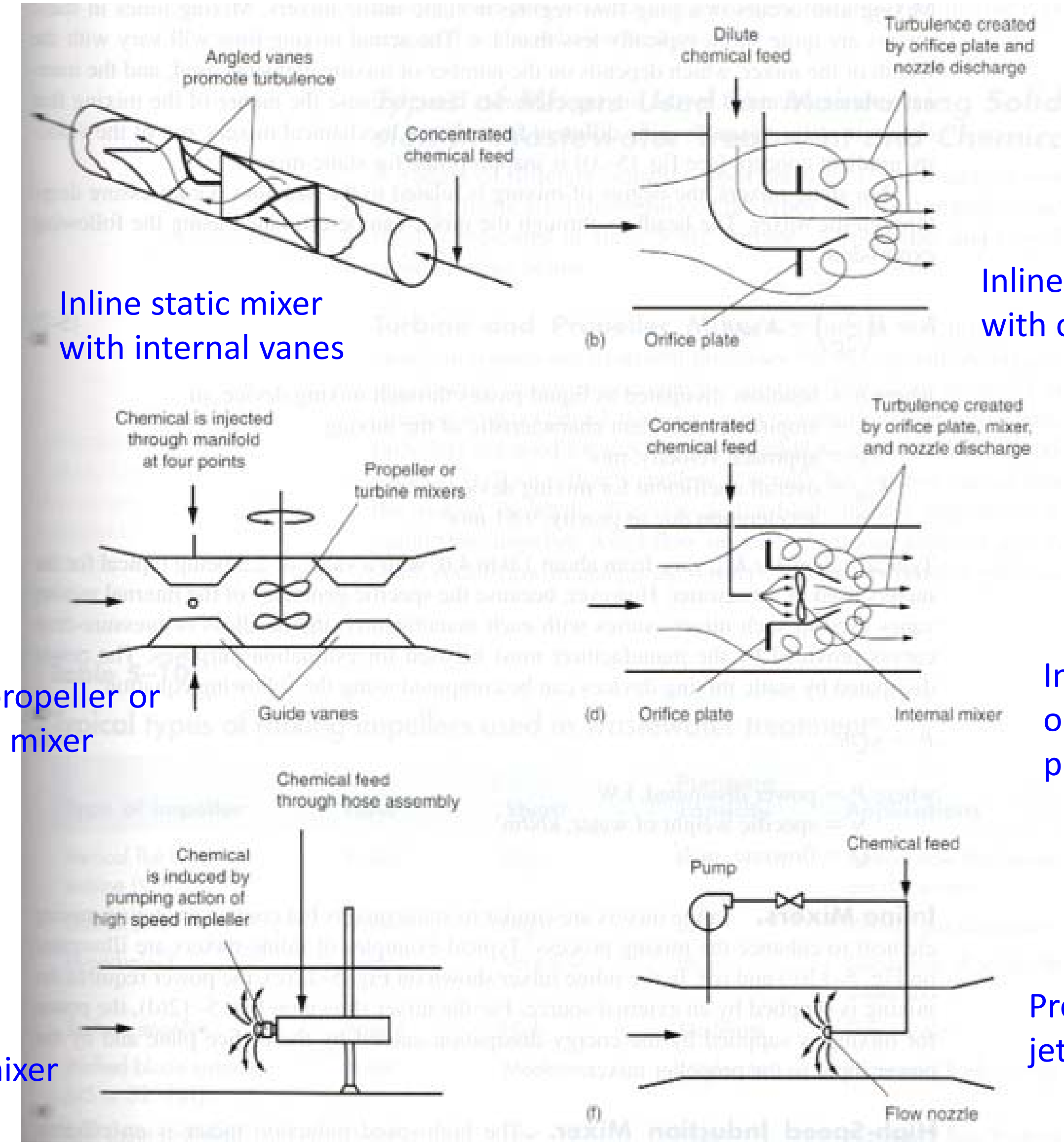
Process	Range of values	
	Retention time	G value, s^{-1}
Mixing		
Typical rapid mixing operations in wastewater treatment	5-30 s	500-1500
Rapid mixing for effective initial contact and dispersion of chemicals	<1 s	1500-6000
Rapid mixing of chemicals in contact filtrations processes	<1 s	2500-7500
Flocculation		
Typical flocculation processes used in wastewater treatment	30-60 min	50-100
Flocculation in direct filtration processes	2-10 min	25-150
Flocculation in contact filtration processes	2-5 min	25-200

Mixing

Q: Determine the theoretical power requirement to achieve a G value of 100/s in a tank with a volume of 2800 m^3. Assume that the water temperature is 15°C. What is the corresponding value when the water temperature is 5°C?

Types of mixers

Typical mixers used for rapid mixing of chemicals



Inline static mixer with internal vanes

Inline static mixer with orifice

Inline propeller or turbine mixer

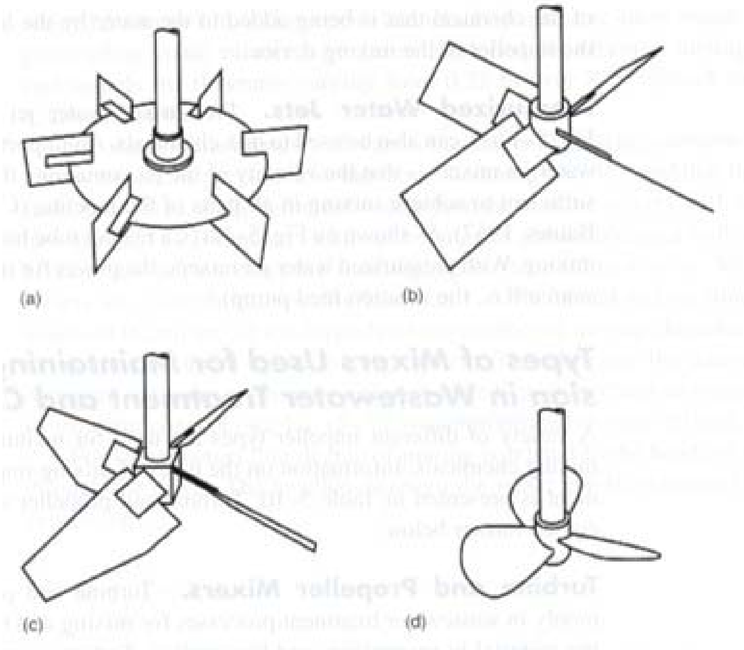
Inline mixer with orifice and internal propeller mixer

High-speed induction mixer

Pressurized water jet mixer

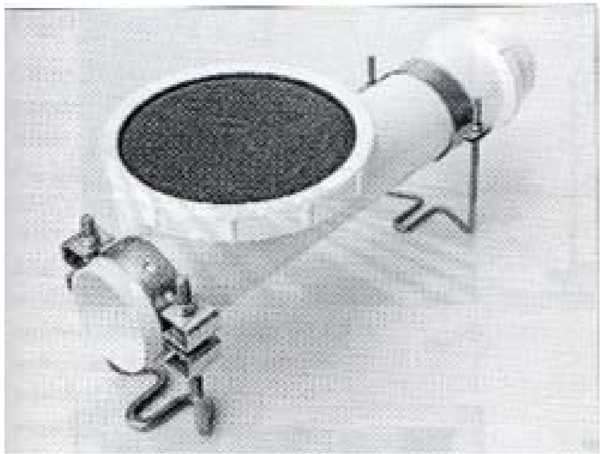
Types of mixers

Mixers for maintaining solids in suspension and chemical blending in reactors: turbine and propeller mixers most common

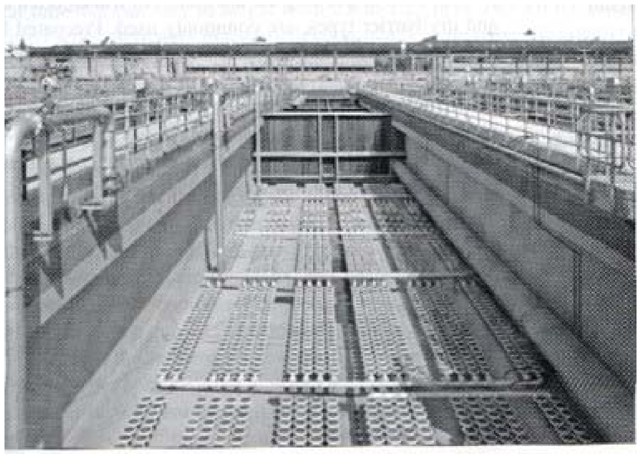


Types of mixers

- Type of mixers used for biological treatment
  - Pneumatic mixing
    - mixing is provided by injecting gas into the bottom of tanks
    - both mixing effect & oxygen supply
    - used for aeration tank of an activated sludge process



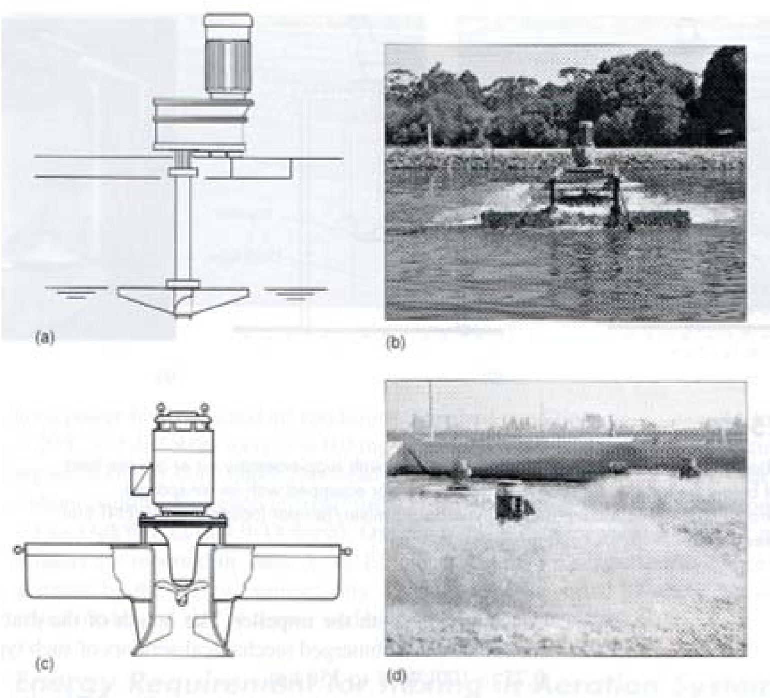
Ceramic disk diffuser



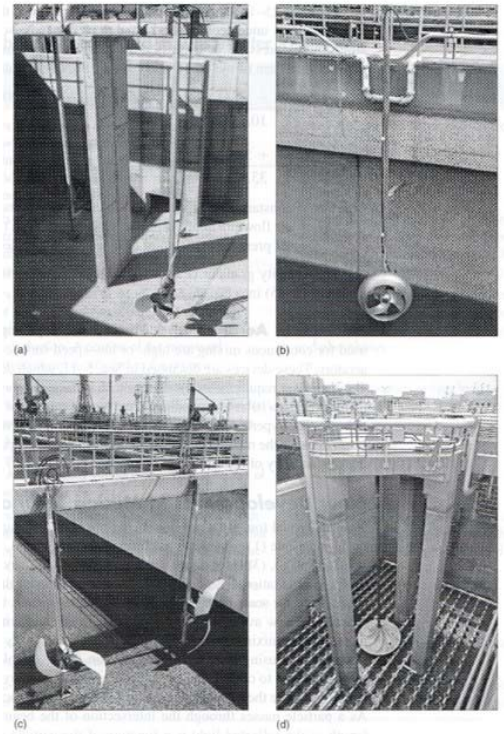
Aeration tank equipped with ceramic disk aeration devices

Types of mixers

- Type of mixers used for biological treatment (cont'd)
  - Mechanical aerators and mixers
    - for anoxic/anaerobic reactors and oxidation ditches



Surface mechanical aerators: (a), (b) – low-speed; (c), (d) – high-speed



Mixers for anoxic reactors: (a), (b) - propeller; (c) - airfoil mixer; (d) - hyperbolic mixer

Types of settling

- Class I settling – **Discrete particle settling**
  - At low solids concentration
  - Particles settle as individual entities, no significant interaction with neighboring particles
  - ex) removal of grit and sand particles

- Class II settling – **Flocculent settling**
  - Particles grow as they settle
  - Settling velocity increases as particles grow in size
  - ex) primary settling & upper part of secondary clarifier

Types of settling

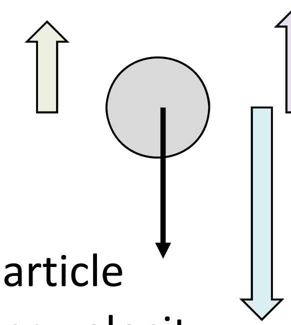
- Class III settling – **<u>zone (or hindered) settling</u>**
  - At higher solids concentration than Class I or II – interparticle forces are sufficient to hinder the settling of neighboring particles
  - Mass of particles settles as a unit; a solid-liquid interface develops at the top
  - ex) major part of secondary clarifier

- Class IV settling – **<u>compression settling</u>**
  - When solids concentration is sufficiently high – a structure is formed
  - Settling occurs only by compression of the structure by the weight of particles
  - Observed phenomenon is more like squeezing of water out of the structure
  - ex) bottom of deep secondary clarifier, sludge-thickening facilities

Particle settling theory – discrete particles

- Force applied to a settling particle

  (Assumption: spherical particle)



ρ_w = water density (kg/m^3)
g = gravity acceleration (9.81 m/s^2)
V_p = particle volume (m^3)

ρ_p = particle density (kg/m^3)

C_d = drag coefficient (unitless)
A_p = cross-sectional area of particles in the direction of flow (m^2)

Particle settling theory – discrete particles

- The terminal velocity of particle is achieved when the three forces are balanced:

$$F_M = F_B + F_D$$

$$\boxed{v_{p(t)} = \sqrt{\frac{4g}{3C_D}\left(\frac{\rho_p - \rho_w}{\rho_w}\right)d_p}}$$

$v_{p(t)}$= particle terminal velocity (m/s)
d_p= particle diameter (m)

Particle settling theory – discrete particles

- Drag coefficient, C_D
  - Divide the flow regime into three regions – laminar, transitional and turbulent – based on Reynolds number
  - **Reynolds number, N_R**
    - A dimensionless number to describe the relative amount of impelling force to viscous force
    - High N_R → more turbulence

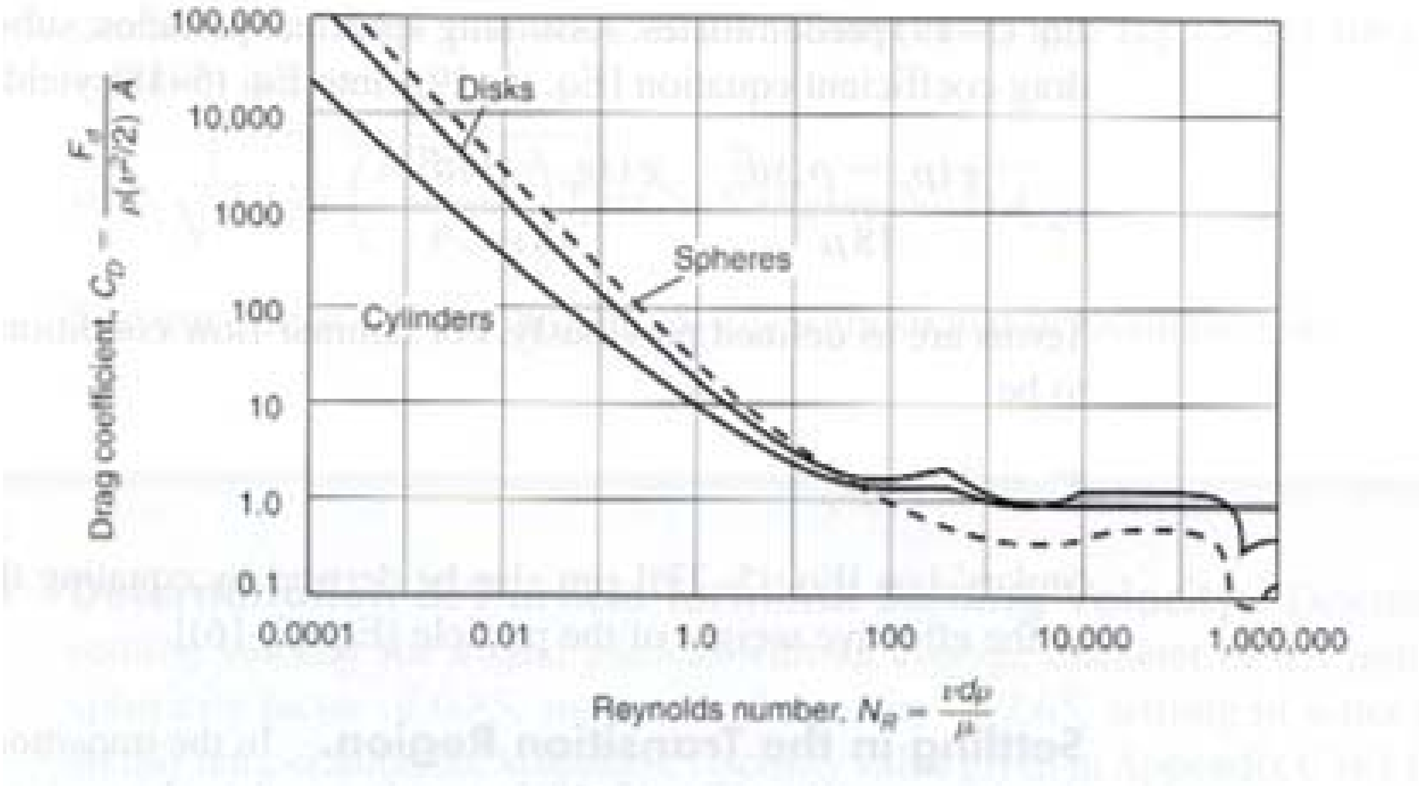
$$N_R = \frac{v_p d_p \rho_w}{\mu} = \frac{v_p d_p}{\upsilon}$$

μ = dynamic viscosity of water [N-s/m^2]

υ = kinematic viscosity of water [m^2/s]

Particle settling theory – discrete particles

- Correlation between N_R and C_D



Particle settling theory – discrete particles

1) Laminar region: $N_R < 1$

$$C_D = \frac{24}{N_R}$$

2) Transitional region: $1 < N_R < 2000$

Use following eq. for approximation of C_D:

$$C_D = \frac{24}{N_R} + \frac{24}{\sqrt{N_R}} + 0.34$$

3) Turbulent region: $N_R > 2000$

Assume $C_D \approx 0.4$

Particle settling theory – discrete particles

- For non-spherical particles
  - Use "sphericity" to account for shape variation

$$\Psi = \frac{(A/V)_{sphere}}{(A/V)_{particle}}$$

Ψ = sphericity

$\Psi \approx 0.8$ for sharp, angular sand

$\Psi \approx 0.94$ for worn sand

  - Apply "effective spherical diameter" in the equations

$$d_p{}' = \Psi \cdot d_p$$

d_p'= effective spherical diameter

d_p = characteristic length

[Typical sphericity for different shapes]

Particle	Sphericity	Characteristic length
Sphere	1.00	Diameter
Cube	0.806	Height
Cylinder (h=10r)	0.691	Length
Disc (h=r/10)	0.323	Diameter

Particle settling velocity

Q: Determine the terminal settling velocity of a spherical bacterial floc having a density of 1.050×10^3 kg/m^3 when the floc size is i) 10^{-4} m and ii) 10^{-3} m, respectively. Assume the flocs are spherical. Assume the temperature is 20°C. ($\rho_w = 0.998 \times 10^3$ kg/m^3 and $\mu = 1.002 \times 10^{-3}$ N-s/m^2)