Lecture 6 Sedimentation and flocculation - Part 2

Coagulation mechanisms (continued)

2. Charge neutralization

   Adding positively charged ions that adsorb to particle surface can reduce surface charge and repulsion

3. Entrapment in precipitate

   Al and Fe salts added at right pH will precipitate as flocs with colloids as nuclei

4. Particle bridging

   Large organic molecules (both anionic and cationic) attach to multiple particles "bridging" them (often used in addition to metal salts)

Once particles are coagulated, they can be flocculated

Flocculation occurs by:

1. Brownian motion - important for small particles ($< 0.5\ \mu m$)
2. Stirring - mechanical stirring strong enough to cause particle collisions but not so strong as to break up particles
3. Differential settlement - larger, faster particles catch up with smaller, slower particles

Flocculated settling is sometimes called Type II settling

Since particles become larger as they fall, settling velocity keeps increasing (see Figure pg 2)

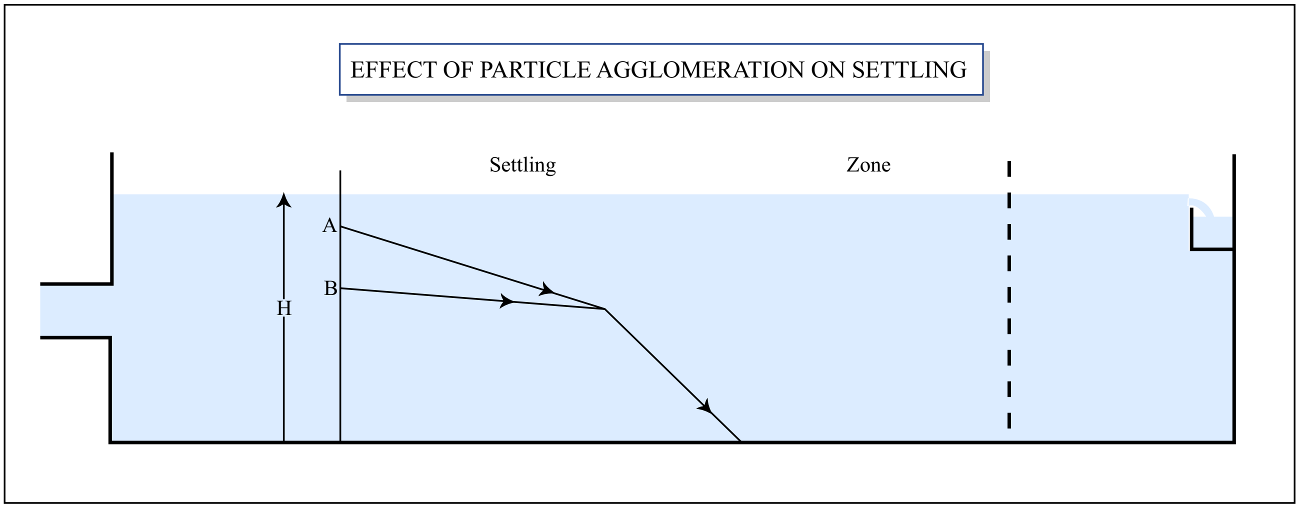


Figure by MIT OCW.

Adapted from: Camp, T. R. "Studies of Sedimentation Basin Design." *Sewage and Industrial Wastes* 25, no. 1 (1953): 1-12.

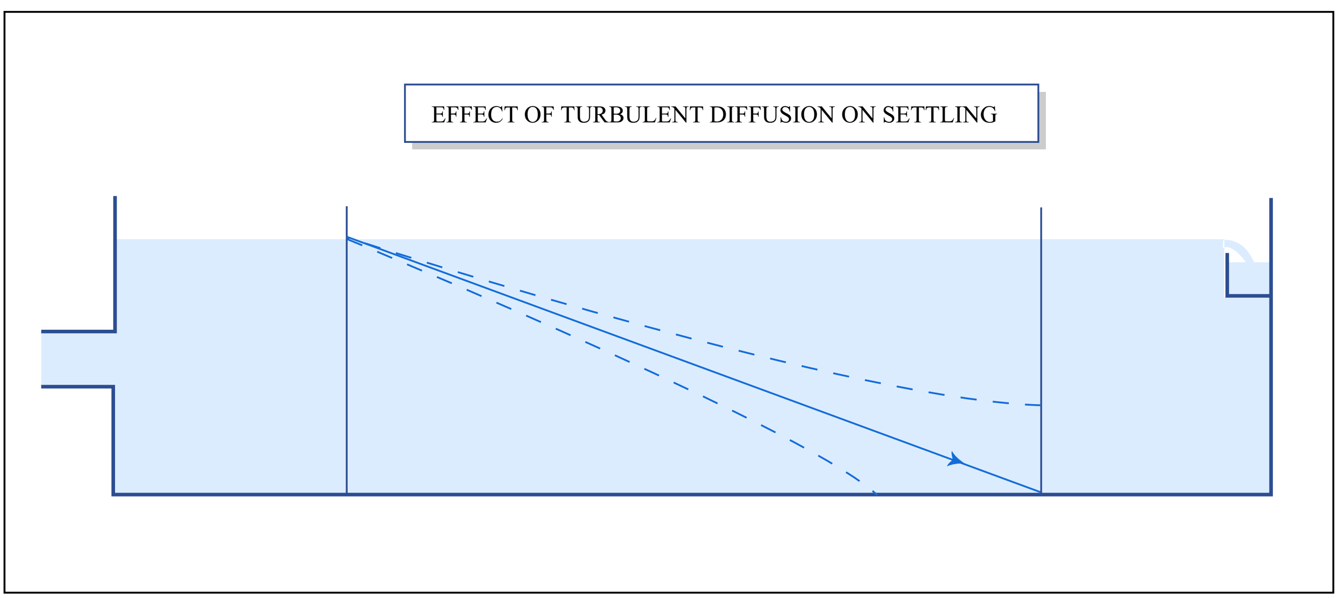
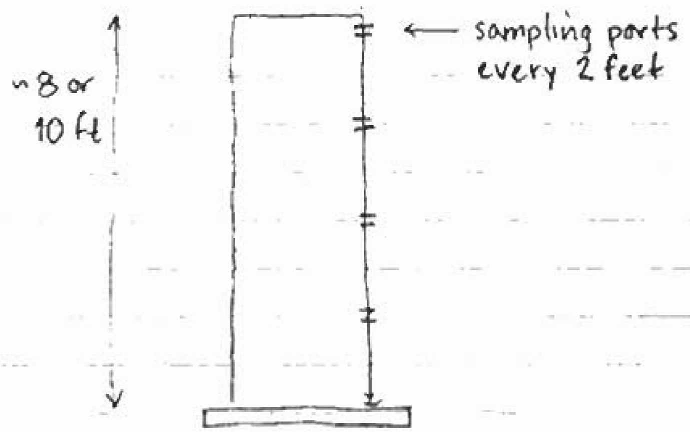


Figure by MIT OCW.

Adapted from: Camp, T. R. "Studies of Sedimentation Basin Design." *Sewage and Industrial Wastes* 25, no. 1 (1953): 1-12.

Design of clarifier for Type II (flocculant) Sedimentation requires knowledge of settling velocity distribution

Lab apparatus is column of depth similar to prototype tank and with diameter ≥ 5 in to reduce wall effects



see illustration pg 4

Initially, suspended sediment is well mixed, then allowed to settle

Samples are taken at each port at selected time intervals e.g. 5, 10, 20, 40, 60, 120 minutes and c/c_0 determined

Removals are then charted on depth vs. time plot (see pg 5) and removal isolines determined

The fraction removed at detention time t (e.g. t_2 on pg 5) comes from chart by reading Δdepth between removal isolines reading vertically from x-axis

$$\% \text{ removed} = \underbrace{\frac{\Delta h_1}{h_5} \times \frac{R_1 + R_2}{2}}_{\text{percent removed from } \Delta h_1 \text{ interval}} + \frac{\Delta h_2}{h_5} \times \frac{R_2 + R_3}{2} + \frac{\Delta h_3}{h_5} \times \frac{R_3 + R_4}{2} + \frac{\Delta h_4}{h_5} \times \frac{R_4 + R_5}{2}$$

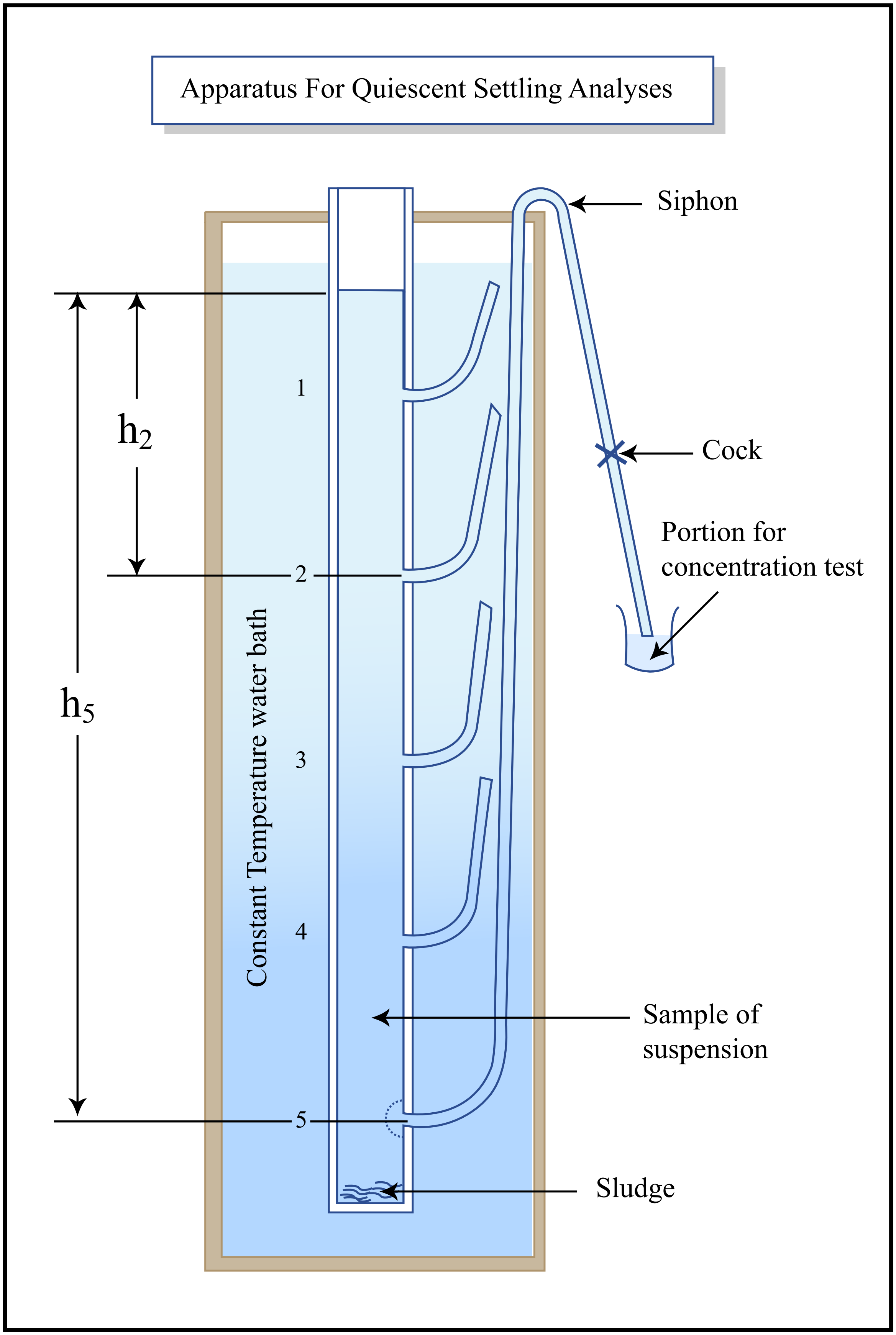


Figure by MIT OCW. Adapted from Camp, T. R., 1946. Sedimentation and the design of settling tanks. *Transactions ASCE*. Vol. 111, Pg. 895-936.

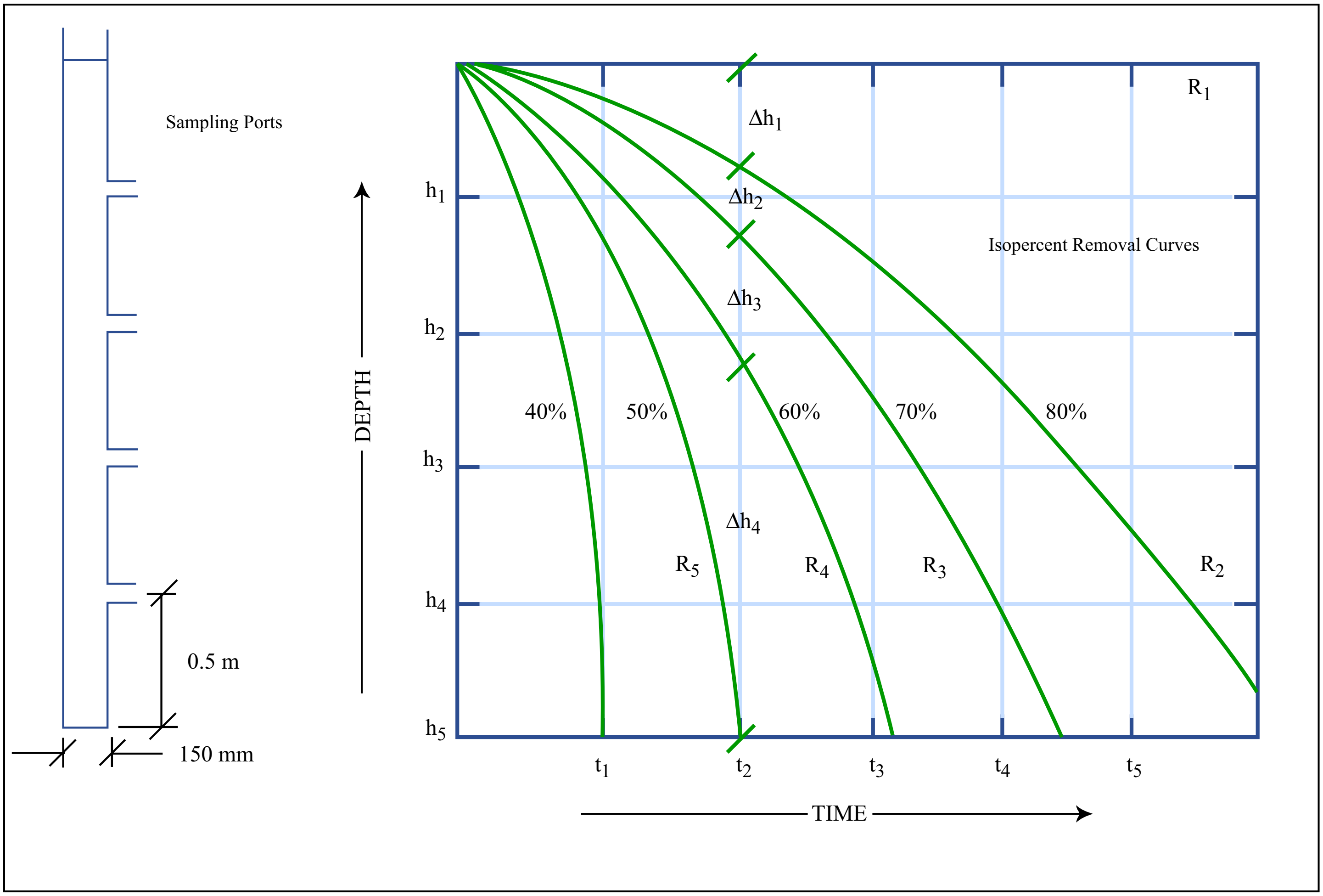


Figure by MIT OCW.

Adapted from: G. Tchobanoglous, F. L. Burton, and H. D. Stensel. *Wastewater Engineering: Treatment and Reuse*. 4th ed. Metcalf & Eddy Inc., New York, NY: McGraw-Hill, 2003, p. 369.

% removed at time t_2 =

$$\frac{\Delta h_1}{h_5} \times \frac{R_1+R_2}{2} + \frac{\Delta h_2}{h_5} \times \frac{R_2+R_3}{2} + \frac{\Delta h_3}{h_5} \times \frac{R_3+R_4}{2}$$

$$+ \quad \frac{\Delta h_4}{h_5} \quad \frac{R_4+R_5}{2}$$

Questions to consider:

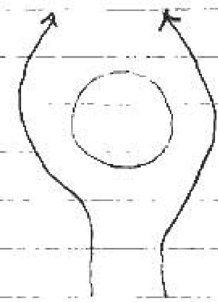
Why do removal isolines curve downwards?

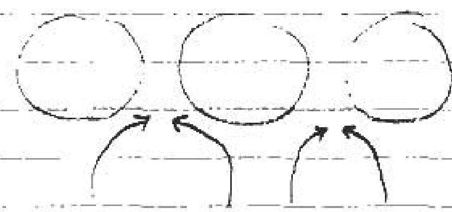
How would isoline curves look with discrete particle settling?

Note that calculation procedure above is not needed for discrete particle settling - can develop curve of fraction removed vs. V as shown in Lecture 5, pg. 10

Type III settling is called hindered or zone settling

At high particle concentrations, inter-particle repulsion interferes with settling. Also, there is less room for flow to go around particles, creating hydrodynamic forces keeping particles from settling:


unhindered

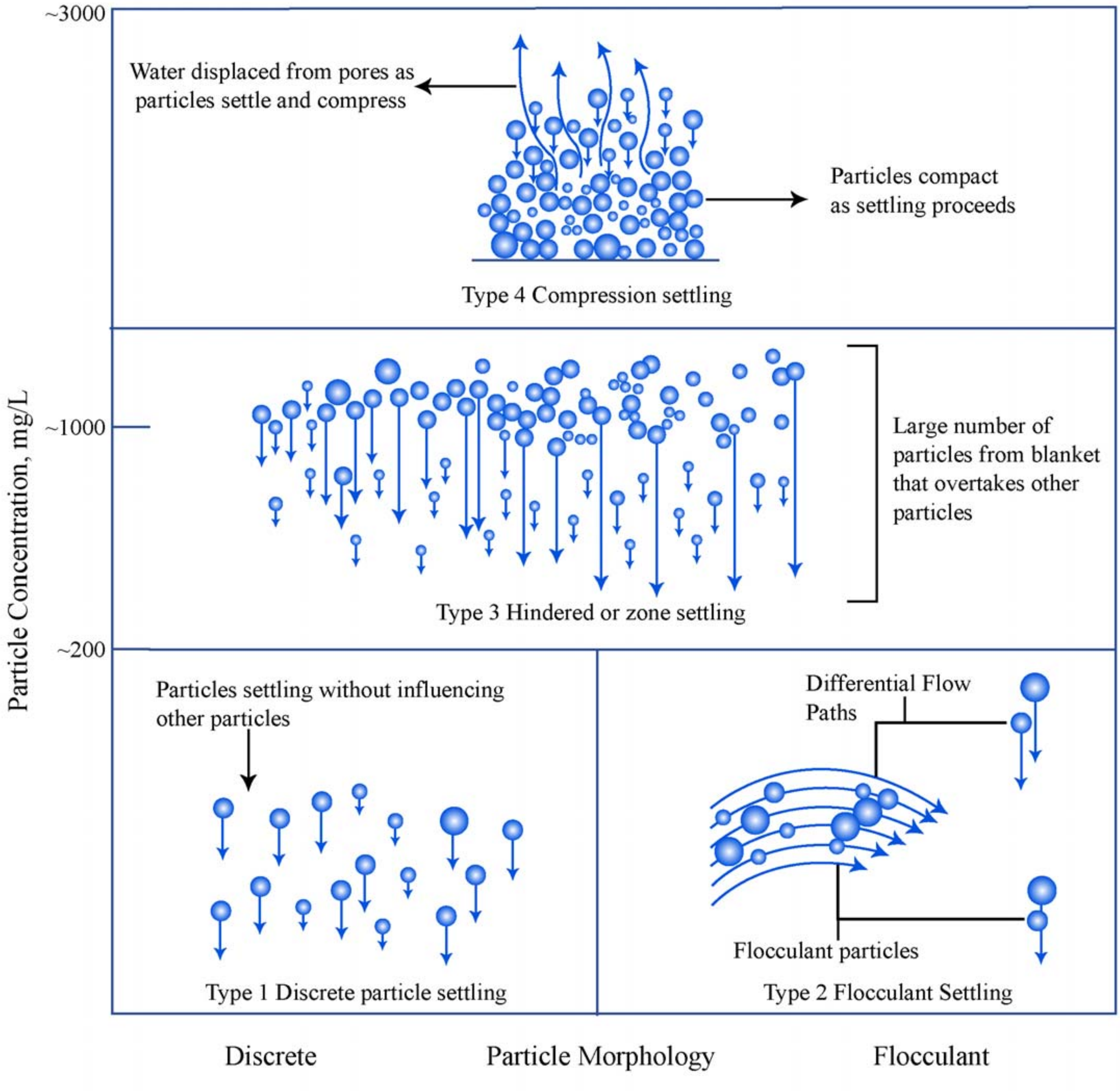

hindered

Called compression settling or Type IV settling

Type IV settling is called compression settling

Water gets squeezed out of sludge

See summary of types of settling in figure on pg 8



Relationship between settling type, concentration, and flocculent nature of particles.

Figure by MIT OCW.

Adapted from: MWH, J. C. Crittenden, R. R. Trussell, D. W. Hand, K. J. Howe, and G. Tchobanoglous. *Water Treatment: Principles and Design*. 2nd ed. Hoboken, NJ: John Wiley & Sons, 2005, p. 781.

Choice of coagulants is typically site specific and determined by jar tests with different additives

Possible additives:

- Aluminum sulfate (alum) forms $Al(OH)_3$ flocs
- Ferrous sulfate
- Ferric salts eg ferric chloride
- Polymers - many proprietary products

Choice depends on local cost and efficacy

Some metal salts may be inexpensively available as industrial by-product

Typical designs

	t_R	overflow rate
Water treatment (VH, p.374)	2 - 4 hr	20-40 $m^3/m^2 \cdot d$
Wastewater (M+E)		
Grit chamber (p. 385)	0.75 - 1.5	~ 60
Primary clarifiers (p. 398)	1.5 - 2.5	30 - 50
Primary with AS return (p 398)	1.5 - 2.5	24 - 32
Secondary clarifiers (p. 687) (+ VH 378)	2 - 3	16 - 28

Rectangular tanks - usually have chain-drive scrapers to bring sludge to withdrawal trough in tank bottom
Typically 3 m deep for water treatment
See illustration pg 11
(from Reynolds + Richard, pg 249)

Circular tanks - inflow at center, outflow along perimeter weir or radial collection troughs
circular rake arm to rake sludge to center (water treatment) or with suction pipes (wastewater)
See illustrations, pg. 12-14
Depths usually 3 m or more

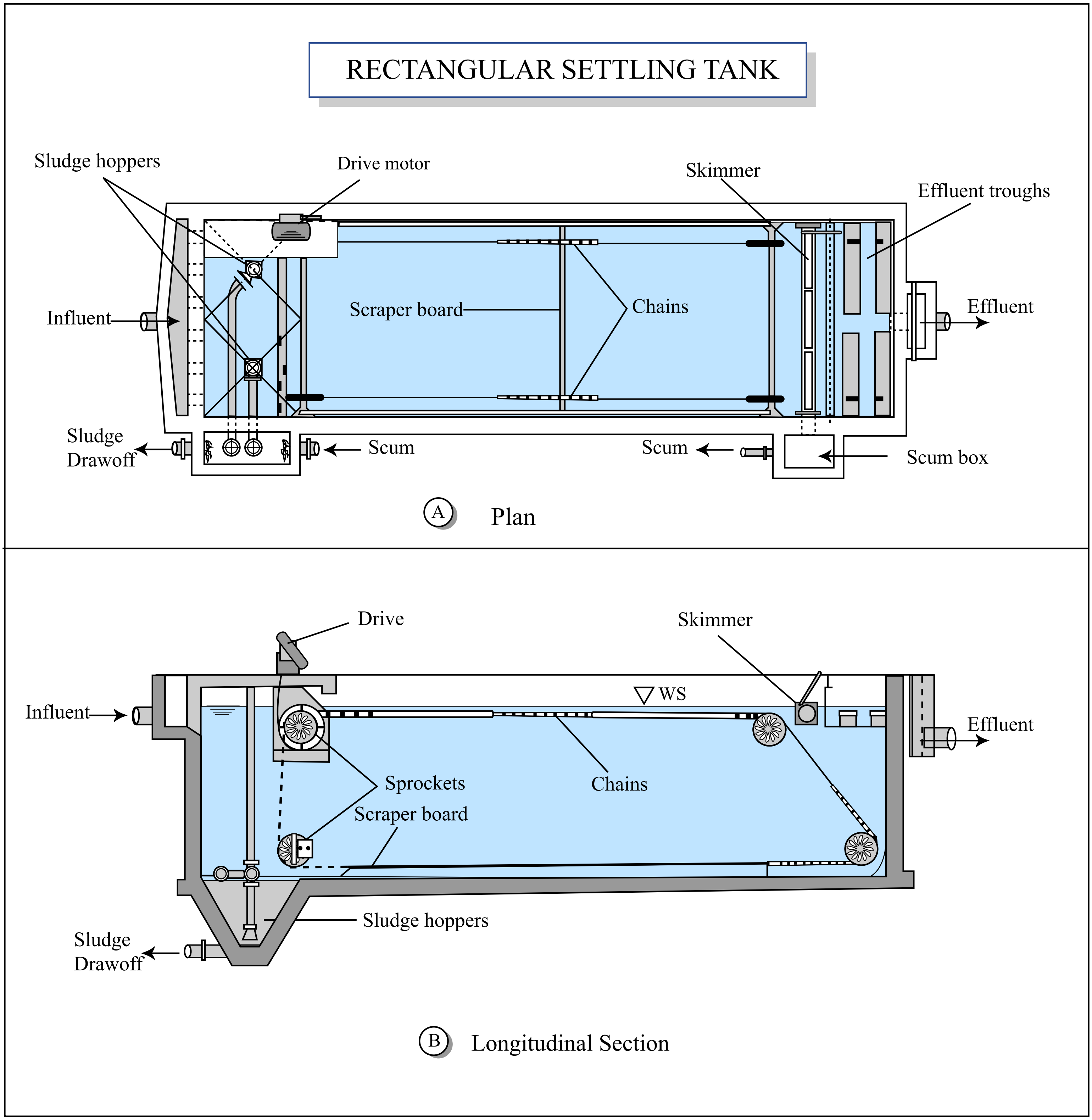
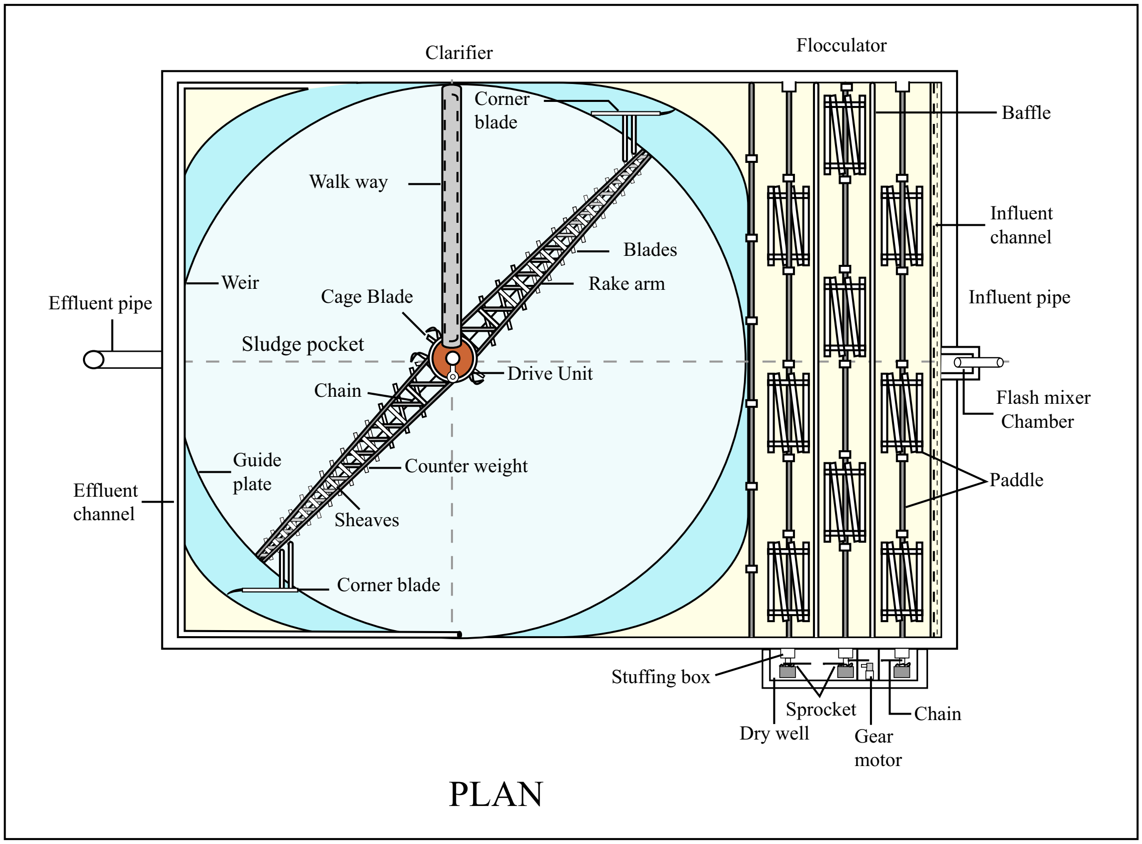


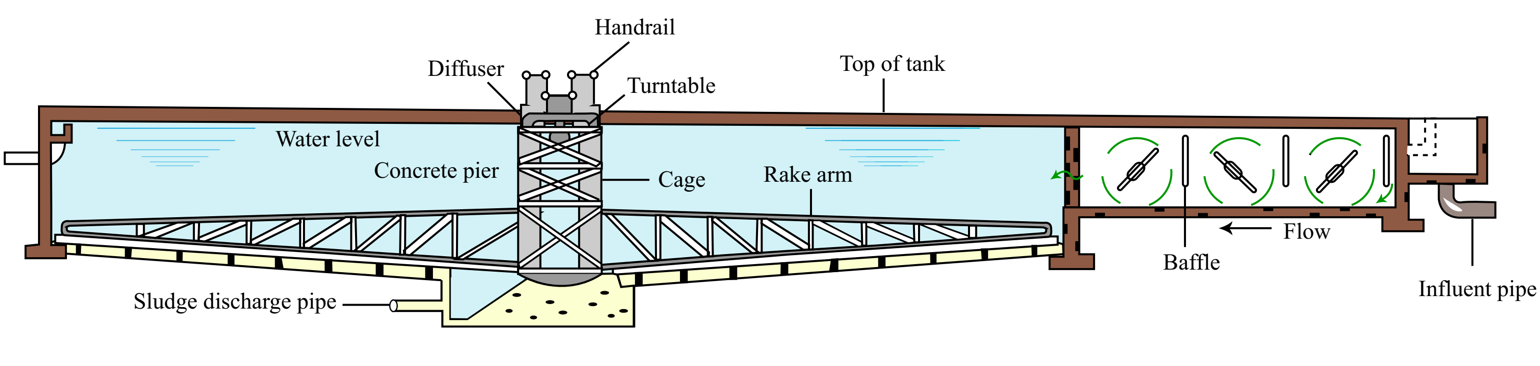
Figure by MIT OCW.

Adapted from: Reynolds, T. D., and P. A. Richards. *Unit Operations and Processes in Environmental Engineering*. 2nd ed. Boston, MA: PWS Publishing Company, 1996, p. 249. ISBN: 0534948847.

Better hydraulic characteristics in long, narrow settling tank

Less short circuiting





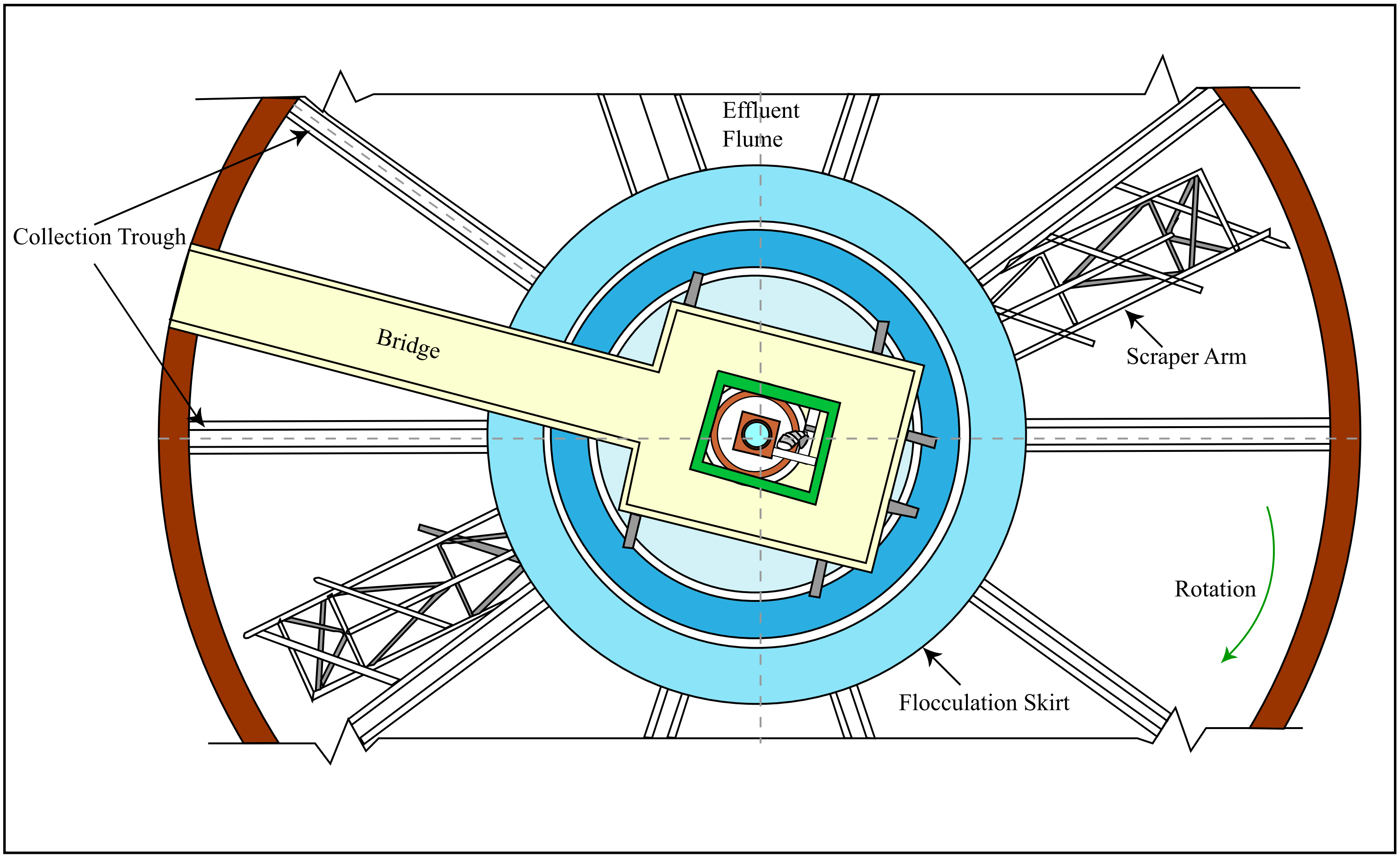
Flocculator & square sedimentation tank for water clarification, illustrating ceoss-flowoperation.

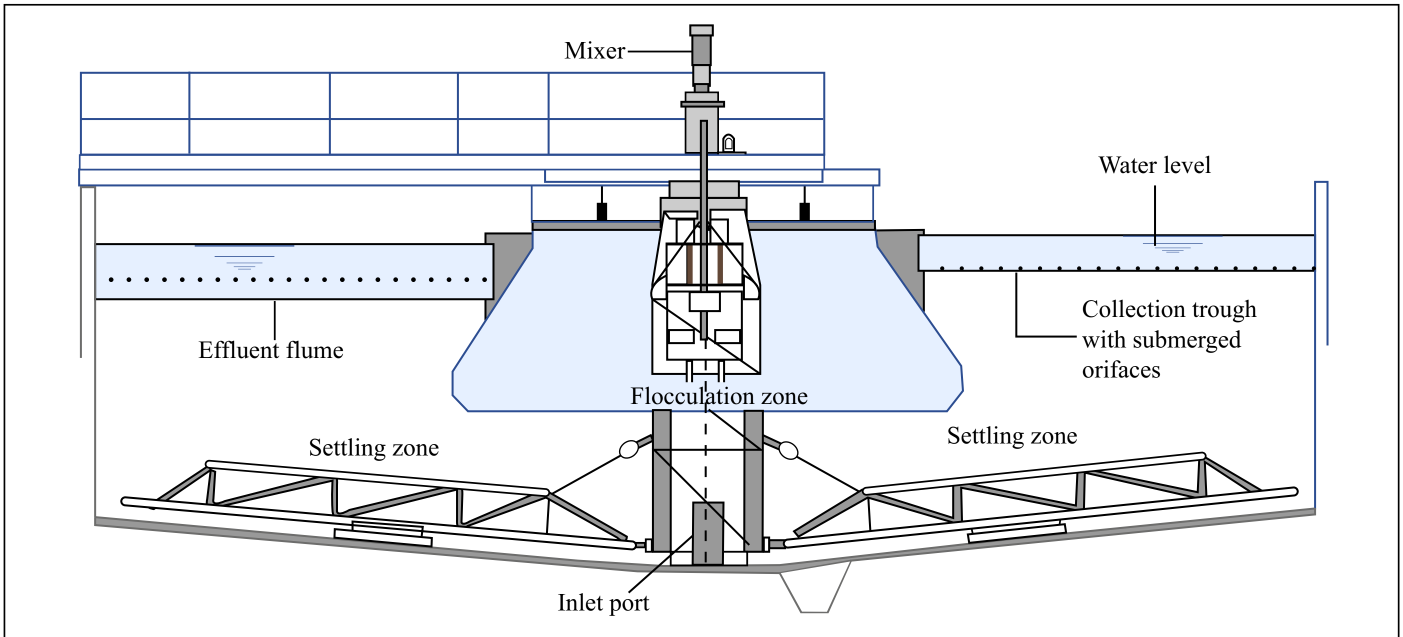
Figure by MIT OCW.

Adapted from: Droste, R. L. *Theory and Practice of Water and Wastewater Treatment*. Hoboken, NJ: John Wiley & Sons, 1997.

Less expensive since side walls can be shared
Circular sludge collectors are relative trouble free
but corner sweeps are problematic
More weir length in corners leads to non-uniform
radial flow - sludge collects in corners

MWH 817





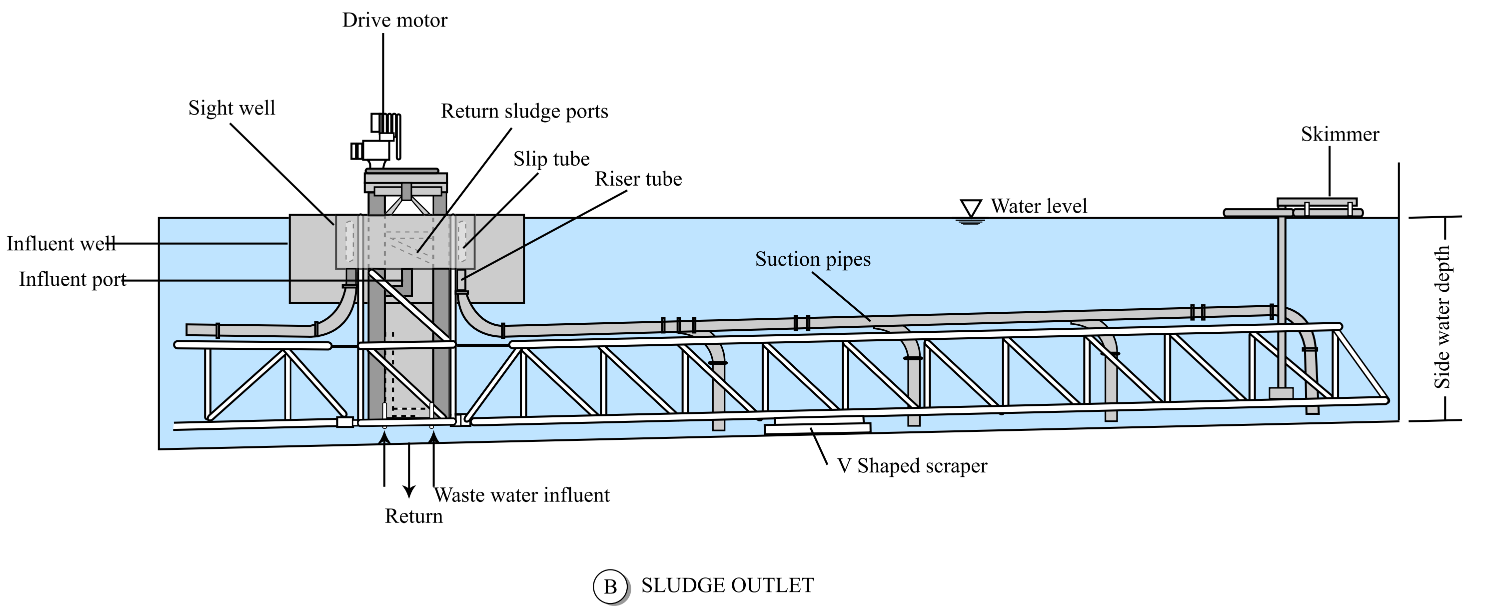
Flocculator-clarifier provides mixing, flocculation, & sedimentation in a compartmented concentric circular tank.

Figure by MIT OCW.

Adapted from: Droste, R. L. *Theory and Practice of Water and Wastewater Treatment.* Hoboken, NJ: John Wiley & Sons, 1997.

lower capital cost than rectangular tank
Circular sludge sweep is relatively trouble free

MWH 817



Final clarifier designed for use with activated-sludge processes. Return sludge is withdrawn through suction (uptake) pipes located along the collector arm for rapid return to the aeration tank. Sludge flowing from each pipe can be observed in the sight well.

Figure by MIT OCW.

Adapted from: Droste, R. L. *Theory and Practice of Water and Wastewater Treatment*. Hoboken, NJ: John Wiley & Sons, 1997.

Rakes sludge to suction pipes

Earlier analysis of discrete particle settling shows that a shallow tank would be more efficient in settling particles

But usually, sedimentation tanks are about 3 m deep or more - why?

Answers: to take advantage of floc formation
shallow tanks can be more easily disrupted by turbulence
need space to accumulate sludge

A "shallow" depth design is the inclined plate separator - see illustration pg 16
(from Droste, pg 306)

Analysis of reactors showed a long rectangular tank is better than a circular tank - so why so many circular tanks?

Answers: less expensive construction
sludge collection is easier

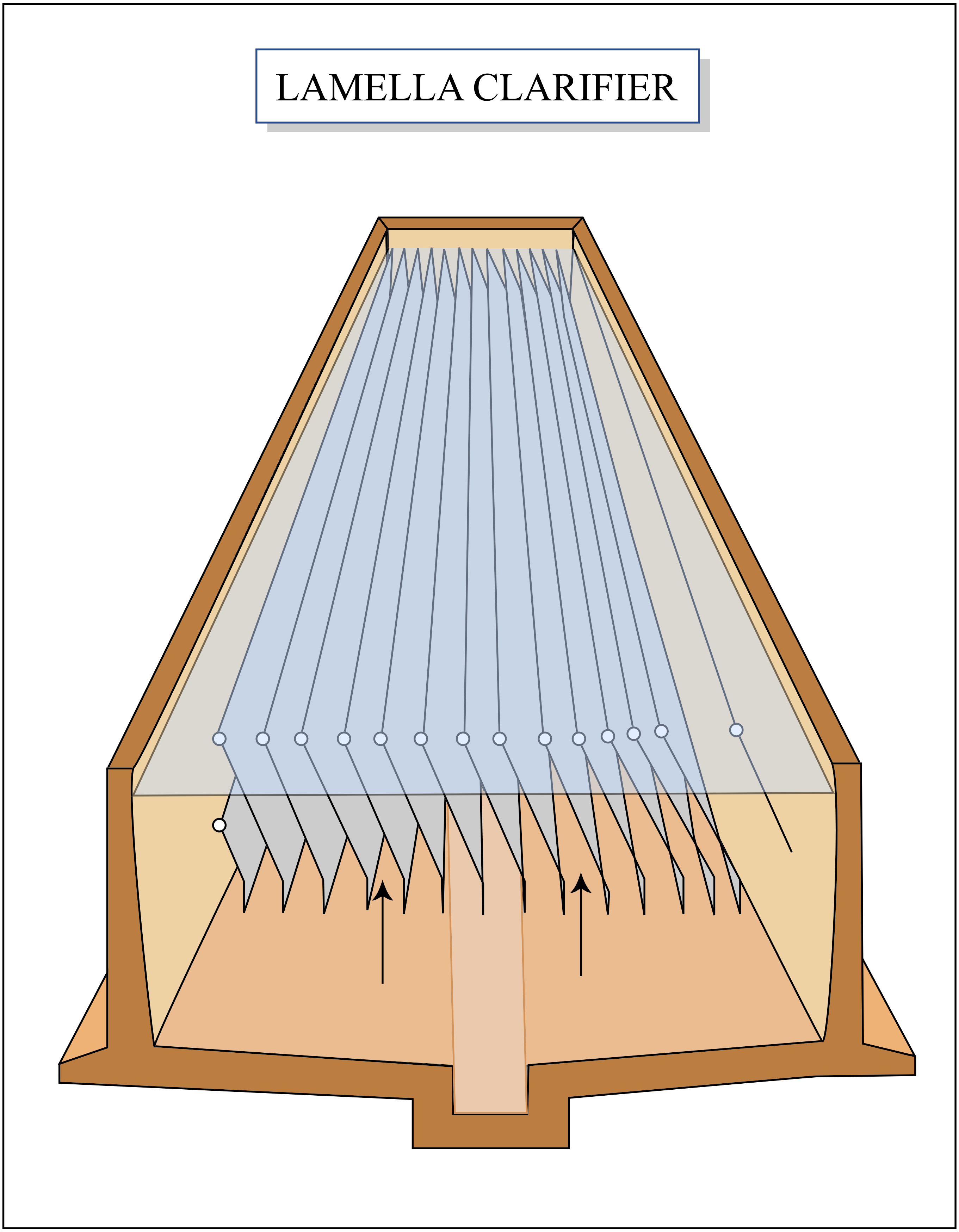


Figure by MIT OCW.

Adapted from: Binnie, C., M. Kimber, and G. Smethurst. *Basic Water Treatment*. 3rd ed. Cambridge, UK: Royal Society of Chemistry, 2002.

Mixing

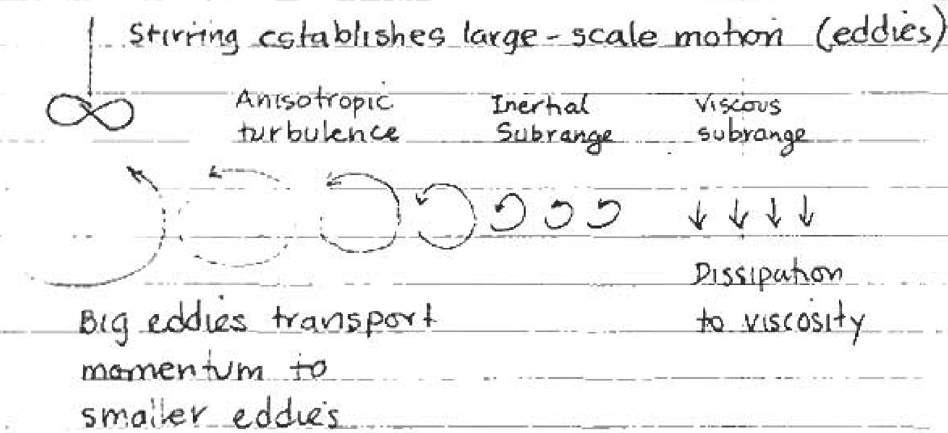
Mixing causes particles to collide so they can stick together (coagulate) and form and grow flocs

Mixing for coagulation is vigorous → causes lots of collisions to get particles to coalesce

Mixing for flocculation is gentle: Strong enough to cause collisions but not so strong to break up large flocs

Mixing in water & wastewater treatment is turbulent

Turbulence goes through turbulence cascade:

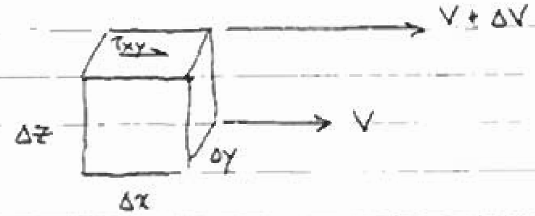


Summary by L.F. Richardson

"Big whorls have little whorls
Which feed on their velocity
Little whorls have smaller whorls
And so on to viscosity"

Rate of energy dissipation dictates velocity gradient $\left(\frac{dV}{dz} = G\right)$
In turn, number of collisions is proportional to velocity gradient

Consider fluid element subject to shear force τ_{xy} which causes velocity gradient



$$\text{Force} = \tau_{xy}\,\Delta x\,\Delta y = \mu\frac{dV}{dz}\,\Delta x\,\Delta y$$

(τ_{xy}: force per unit area; $\mu\frac{dV}{dz}$: by definition of Newtonian fluid)

μ = dynamic viscosity of water $\left[\frac{N\cdot s}{m^2}\right]$

Power = Force × Velocity

Power per unit volume is

$$\frac{P}{\forall} = \frac{P}{\Delta x\,\Delta y\,\Delta z} = \frac{\overbrace{\left[\mu\frac{dV}{dz}\,\Delta x\,\Delta y\right]}^{\text{Force}}\overbrace{\left[\frac{dV}{dz}\,\Delta z\right]}^{\text{Velocity}}}{\Delta x\,\Delta y\,\Delta z}$$

$$= \mu\left(\frac{dV}{dz}\right)^2 = \mu G^2$$

$$\therefore\quad G = \sqrt{\frac{P}{\mu\forall}}\qquad \text{Camp-Stein}$$

G = Root-mean-square velocity gradient caused by mixing $[1/s]$

P = Power of mixing input to reactor $\left[\frac{N\text{-}m}{s}\right]$

$\forall$ = Volume of vessel $[m^3]$

Number of particle collisions is proportional to GT_R

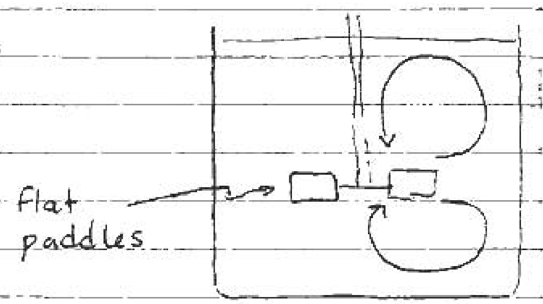
T_R = hydraulic residence time

→ Design parameters for mixing: G and T_R

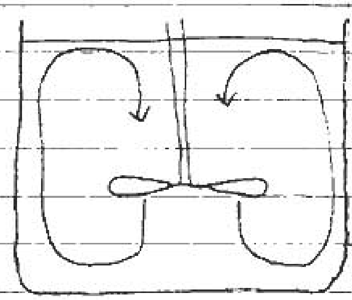
Jar tests determine optimum G and T_R for specific coagulants in specific water or wastewater

Different types of mixers impart energy in different ways, power is captured by different empirical or semi-empirical formulas (see text)

Radial-flow mixers:



Axial-flow mixers



Some impellers cause vortices which can break up floc

Baffles are sometimes added to tanks to reduce vortices and rotational flow (see page 20)

Page 21 shows paddles at Chattahoochee Water Treatment Plant, Atlanta

Tapered Horizontal-Flow Flocculator at a plant in Cochabamba, Bolivia.

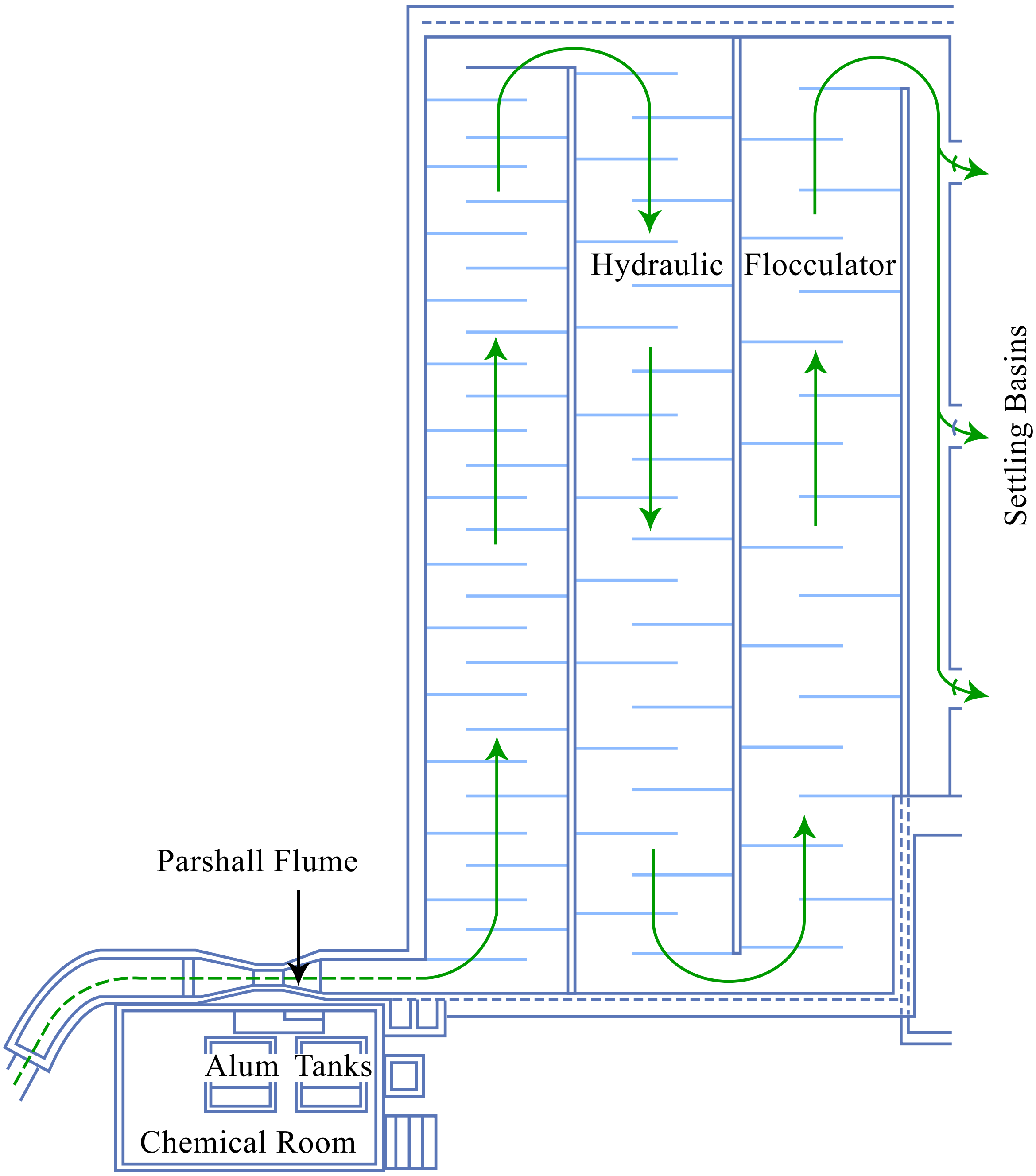


Figure by MIT OCW.

Adapted from : Schulz, C. R., and D. A. Okun. *Surface Water Treatement for Communities in Developing Countries*. Intermediate Technology Publications, London, UK.

Example of power equation:

Paddle flocculators (pg. 34)

$$P = \frac{C_D A_p \rho V_R^3}{2}$$

C_D drag coeff for paddle
A_p area of paddle projected in direction of movement
ρ density of water
V_R velocity of paddle relative to water
~ 70 to 80% of paddle speed

C_D = 1.2 to 1.9 for length : width of 1 to 20

Other mixing devices

Chemical injection into center of flowing pipe
(pumped flash mixing)

Static mixers (in-line vanes in pipe to cause mixing)

Baffling in tank

Pneumatic agitators (bubblers)