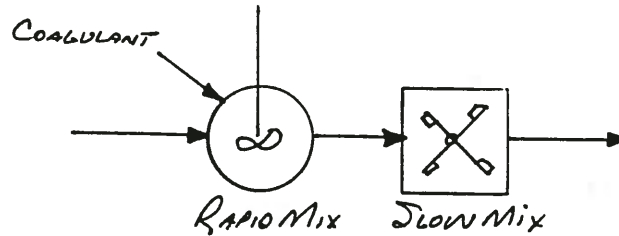


IV. COAGULATION/FLOCCULATION

- Process Objective: Destabilization and aggregation of colloidal inorganic and organic particulates. ↑ clays
↑ color
- Schematic ...



Coagulation Flocculation

∴ Coagulation ≡ destabilization of particulates

Flocculation ≡ aggregation of destabilized particulates into flocs.

Table 1. Overview of Coagulation - Flocculation Process Aggregation of Particulates

Phenomenon	Action	Terminology	Facility Involved
Formation of active coagulant species	Preparation of coagulant (dilution, dissolution) Treatment dispersion of coagulant chemical reactions with ligands (OH ⁻ , SO ₄ ⁻) e.g., hydrolysis, polymerization, complex formation	Chemical handling (coagulant preparation) Rapid mixing, Flash mixing, Initial mixing	Chemical handling and feeding equipment Mixing device for rapid and thorough dispersion of chemical; high turbulence, high-shear environment
Particulate destabilization	Compression of double layer by in-different electrolytes Charge neutralization by specifically adsorbed charged species Surface precipitation and formation of interparticle "bridges" Coagulant precipitation and entrapment (sweep floc) of particulates	Aggregation 1. Coagulation	
Particulate transport	Random collisions due to thermal motion of water molecules (Brownian motion) Ordered collisions due to differential relative particulate velocities achieved by mixing and differential settling	2. Flocculation a. Perikinetic flocculation b. Orthokinetic flocculation	Flocculation basins and mixing devices for low-shear turbulence

- Particulate suspensions are thermodynamically unstable and given sufficient time will eventually settle. However, this process is not economically feasible. Coagulation-flocculation facilities must eliminate particulate

stability and thereby increase the rate of subsequent particulate removal by solids-liquid separation processes.

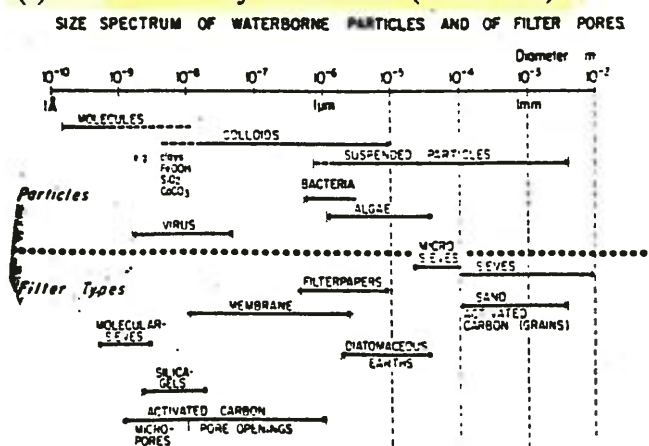
A. Stability of Particulates

- A review of the causes of particulate stability will provide an understanding of the techniques that can be used to destabilize particulars.
- General Particulates Characteristics ...
 - Hydrophobic Particulates^{les}:
 - Well-defined interface.
 - Low affinity for H₂O molecules.
 - Aggregate irreversibly over time.
 - Primarily inorganic origin, e.g. clay particles non-hydrated metal oxides.
 - Hydrophilic Particulates:
 - Lack of clear phase boundary.
 - Generally macromolecular organic compounds.
 - Reversibly preconstituted after aggregation.
 - Primarily of organic origin, e.g. humic matter, viruses, bacteria, algae (living and dead).

Note:

Because biocolloids adsorb on the surface of inorganic particulates, *most particles generally exhibit heterogeneous surface properties in natural water systems.*

- Stability Mechanisms ...
 - Colloidal dispersions in water are needed in suspension by:
 - (i) Extremely small size (1-200 nm)



(ii) State of Hydration (chemical combination with water), e.g. many inorganic particulates in natural waters show some hydrophilic properties because water molecules will bind to the surface which provide a liquid barrier to successful particulate collisions.

(iii) Surface Electric Charge

- Principal mechanism controlling the stability of particulate is electrostatic repulsion.
- Electrical charges at particulate surfaces arise in 3 principal ways:
 1. *Crystal imperfections.* Under geologic conditions, silicon atoms in crystalline materials can be replaced by atoms with lower valence, such as an aluminum ion, giving an excess negative charge to the crystal material. This process, known as *isomorphous substitution*, produces negative charges on the surface of clay particles (Olphen, 1963).
 2. *Preferential adsorption of specific ions.* When some particulates are dispersed in water, soluble polyelectrolytes of natural

origin may *adsorb on their surfaces*.

Typically, a negatively charged polymer, such as a fulvic acid molecule, may adsorb on the surface of a positively charged particulate (e.g., CaCO₃).

3. *Specific chemical reactions of ionogenic groups on particulate surfaces.* Many particulate surfaces contain ionogenic groups, *such as hydroxyl or carboxyl functional groups, which dissociate in water, producing a surface electrical charge that depends on the solution pH.* Typical examples include hydrolyzable metal oxides (e.g., iron oxides) and bacteria (carboxyl groups on bacterial surface).

B. Properties of Selected Particulates

1. Clay Colloids

(a) Structure of Clay - Reference Handout

- Crystalline, Al or Mg silicates with stacked layered structure.
- Alternating layers of ...
 - (i) Silica or Tetrahedral Sheet (T)
[Si & O]
 - (ii) Gibbsite/Brucite Layer or Octahedral (O)
[Mg or Al & O]
- Two or three layer unit ...
 - T-O
 - T-O-T

(b) Charge Density

- pH_{ZPC} = zero point charge = isoelectric point = $\text{F}(\text{pH})$
 - $\text{pH} > \text{pH}_{\text{ZPC}} \rightarrow$ negative charge
 - $\text{pH} < \text{pH}_{\text{ZPC}} \rightarrow$ positive charge.

- In theory, may destabilize particulates by adjusting pH to pH_{ZPC} in order to reduce repulsion forces.

Table 2. Surface Characteristics of Particulates Commonly Found in Natural Waters and Wastewaters

	Zero Point of Charge, pH_{ZPC}
INORGANIC (hydrophobic)	
"Al(OH) ₃ " (amorph)	7.5-8.5
Al ₂ O ₃	9.1
CuO ₃	9.5
"Fe(OH) ₃ " (amorph)	8.5
MgO	12.4
MnO ₂	2-4.5
SiO ₂	2-3.5
Clays	
Kaolinite	3.3-4.6
Montmorillonite	2.5
Asbestos	
Chrysotile	10-12
Crocidolite	5-6
CaCO ₃	8-9
Ca ₄ (PO ₄) ₃ OH	6-7
FePO ₄	3
AlPO ₄	4
ORGANIC (hydrophilic)	
Algae	3-5
Bacteria	2-4
Humic acid	3
Oil droplets	2-5

Examples ...

At natural water pHs...

- Kaolinite → 3-8 meq/100 gm of clay
- Montmorillonite → 80 meq/100 gm of clay

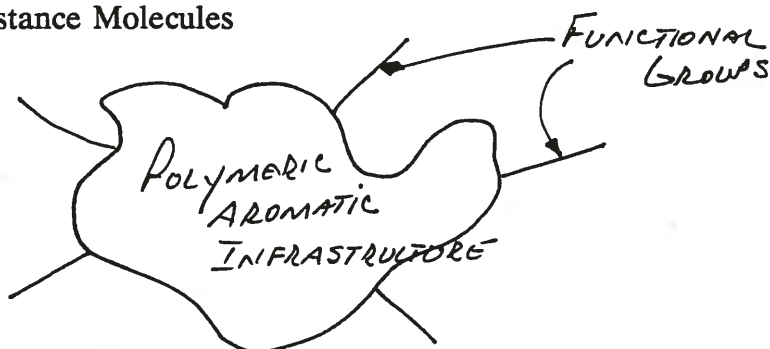
∴ More difficult to remove!

2. Organic Acids (Humic Substances = H.A. + F.A.)

<u>Characteristics*</u>	<u>F.A.</u>	<u>H.A.</u>
Occurrence	Most Prevalent (83%)	Least (17%)
AMW*	< 10,000	10,000-200,000
Charge Density THMFP	Higher Less Reactive	Lower More Reactive

*Operation Definition → @pH = 1, H.A. settles out and F.A. remains in solution.

- Humic Substance Molecules

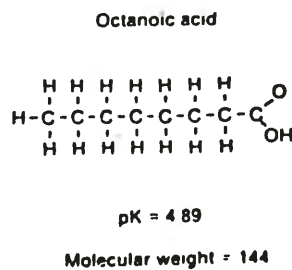
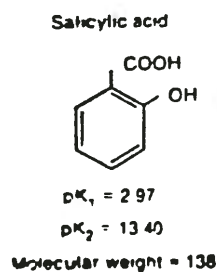
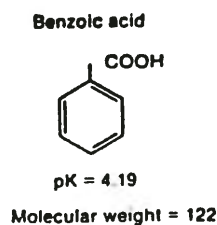
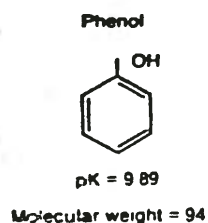


- Functional Groups ...

- Carboxylic M-COOH pKa ≈ 5
∴ pH < pKa → M-OH
pH > pKa → M-O⁻ + H⁺

- Phenolic M-OH pKa ≈ 9
∴ pH < pKa → M-OH
pH > pKa → M-O⁻ + H⁺

- Model Compounds ...

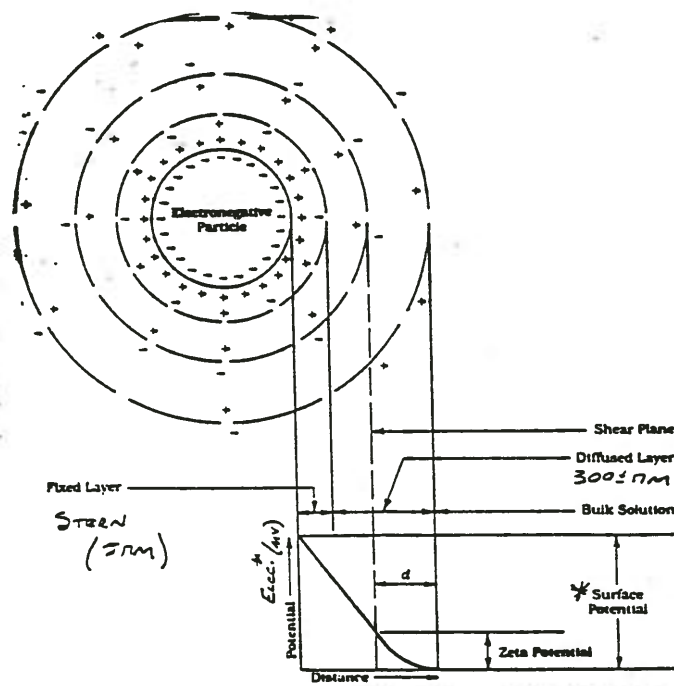


• $SUVA = \text{SPECIFIC UV ABSORBANCE} = \frac{UV(254nm) \times 100}{ODC} = \frac{L}{mg \cdot m}$

Figure 1. Structural configuration of the four model organic compounds

C. Evaluation of Particulate Surface Chemistry

1. Diffuse Double Layer (DDL)



*Total Potential Cannot Measure ...

- Two opposing forces ...
 - Electrostatic attraction and diffusion (tendency of ions to diffuse in the direction of decreasing conc. = Fick's Law) produce a diffuse cloud of ions surrounding the particulate which can extend up to 300 nm into the solution. This is known as the electrical or diffuse double layer (DDL).
- Zeta potential = the electrical potential between the shear plane and bulk solution. Determine by electrophoresis measurements.

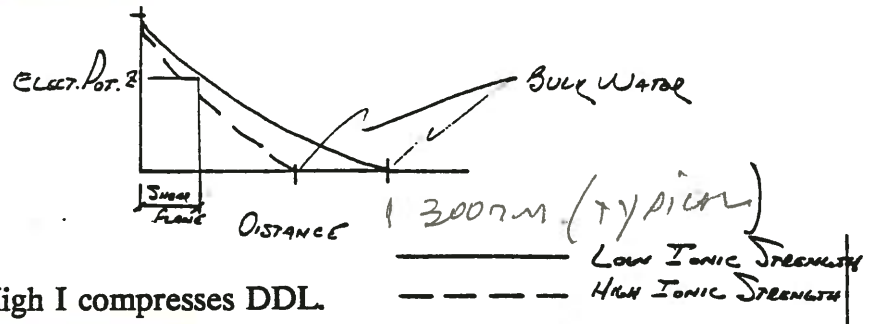
$$Z = \frac{4\pi qd}{D}$$

q = charge per unit area

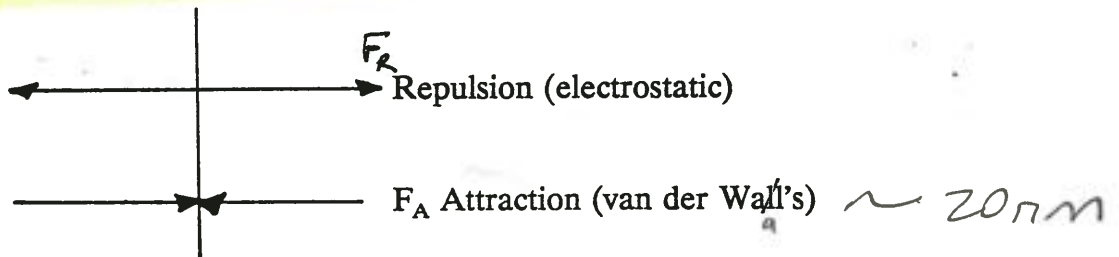
d = thickness of diffused layer

D = liquid dielectric constant (water ~ 80).

2. Effect of Ionic Strength

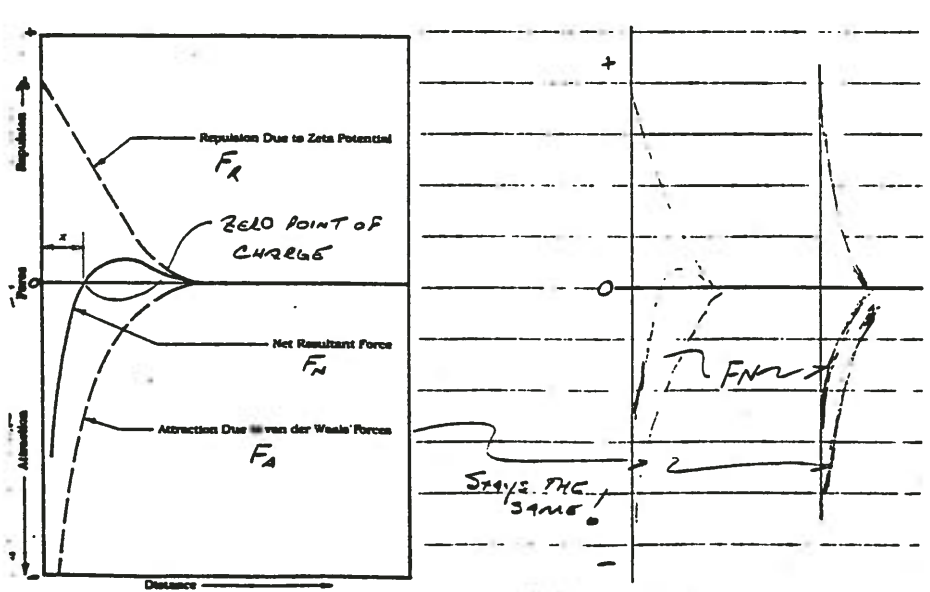


3. Interaction Between Colloids



$$\begin{aligned} \text{Net force} &= F_N = F_R - F_A \\ &= + \rightarrow \text{Repulsion} \\ &= - \rightarrow \text{Attraction} \end{aligned}$$

Figure 2.2 Colloidal interparticulate forces versus distance



@ low ionic strength

@ high ionic strength

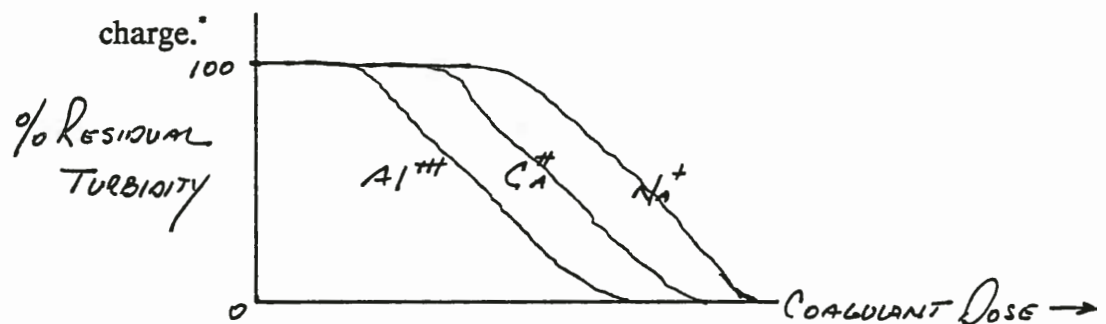
The higher the ionic strength (salinity), the greater the tendency for attraction forces to predominate by compressing the DDL and reducing Zeta potential.

D. Mechanisms for Destabilization

- To induce colloidal particles to **aggregate**, two distinct steps must occur:
 - coagulation** (i) repulsion forces must be reduced, i.e., the particle must be destabilised, and
 - flocculation** (ii) particle transport must be achieved to provide contacts between destabilised particles.
- Particle destabilization can be achieved by four mechanisms (chemical coagulant):

1. Compression of DDL

- Empirically, van der Waal's attractive forces will predominate when the zeta potential is reduced below $20 \pm \text{mV}$.
- Theoretically, can reduce the zeta potential (reduce repulsion forces) by decreasing the thickness of the DDL caused by increasing the ionic strength.
- Consequently, when fresh water enters the ocean the turbidity drops out (reason for details!)
- The relative coagulating power of metal ions is a function of charge.*

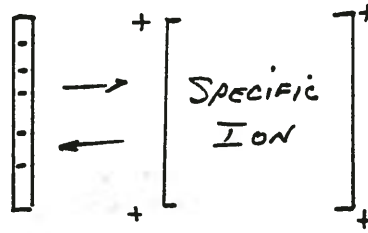


*Note... All metal cations are hydrated in water and do not exist as simple ions!

- Theoretical models predict that the coagulation concentration for counter-ions with 1, 2 and 3 valences should be in the ratio $\frac{1}{1^6} : \frac{1}{2^6} : \frac{1}{3^6}$ or equivalent ratios of 1000 : 16 : 1.37 which is in good agreement with empirical Schulze-Hardy Rule.
- Not normally cost-effective in water treatment!

2. Charge Neutralization/Electrostatic Attraction

- Occurs when surfaces are oppositely charged.



- Can be promoted by:
 - * (a) The adsorption of specific ions (coagulant) on the particulate surface, or
 - (b) Alteration of pH
 - Particle surface charges depend on solution pH and can exhibit both (+) and (-) surface charges.

Table 6-2. Surface characteristics of particulates commonly found in natural waters and wastewaters

	Zero Point of Charge, pH zpc
INORGANIC (hydrophobic)	
"Al(OH) ₃ " (amorph)	7.5-8.5
Al ₂ O ₃	9.1
CaO	9.3
"Fe(OH) ₃ " (amorph)	8.5
MgO	12.4
MnO ₂	2-4.5
SiO ₂	2-3.5
Clays	
Kaolinite	3.3-4.6
Montmorillonite	2.5
Asbestos	
Chrysotile	10-12
Crocidolite	5-6
CaCO ₃	8-9
Ca ₃ (PO ₄) ₂ ·OH	6-7
FePO ₄	3
AlPO ₄	4
ORGANIC (hydrophilic)	
Algae	3-5
Bacteria	2-4
Humic acid	3
Oil droplets	2-5

SURFACE CHARGE
 ↑ (-)
 pH = pH_{ZPC} = 0
 ↓ (+)

3. Inter-Particle Bridging

- Electrostatic removal model does not predict the destabilization of biocolloids.
- Evidence indicates that long-chain polymers carrying negative charges can form bridges between particulates, thus destabilizing the suspension.
- *This mechanism has been shown to be the major mechanism controlling the aggregation of bacterial and algal suspensions.*

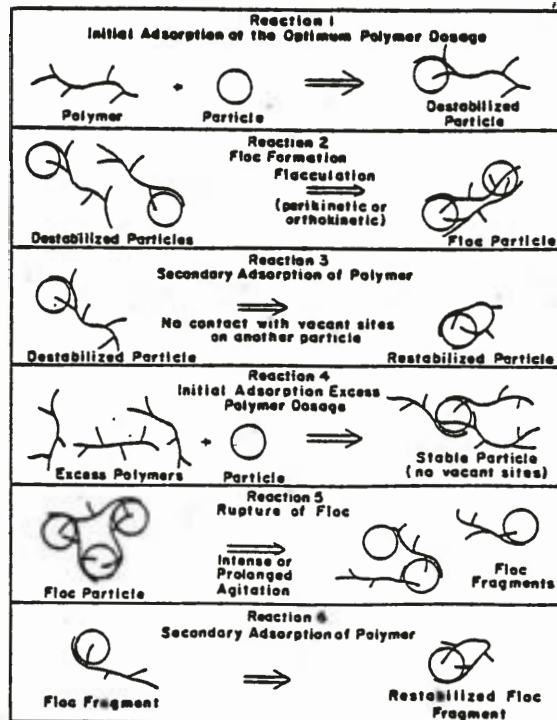


Figure 2-3 Schematic representation of the bridging model for the destabilization of colloids by polymers.

4. Enmeshment Within a Precipitate (Sweep Flocc)

- Finely divided particulates are entrapped in the amorphous precipitate formed, e.g. $Al(OH)_3(s)$, $Fe(OH)_3(s)$
- This mechanism predominates in water treatment applications where pH values are generally maintained between pH 6 and 8 and aluminum or iron salts are used at concentrations exceeding saturation with respect to the amorphous metal hydroxide solid that is formed.

Summary ...

- | | | |
|--|----------------|---------------------|
| <ul style="list-style-type: none"> • DDL Compression • Charge Neutralization | } Coagulation | } Function of Dose! |
| <ul style="list-style-type: none"> • Bridging • Enmeshment | } Flocculation | |

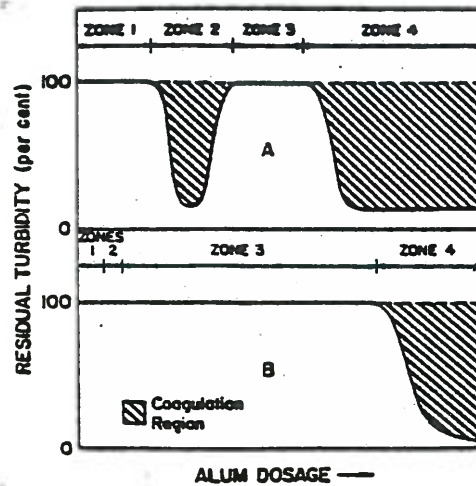


Figure 4. Coagulation of waters with high (A) and low (B) turbidities using alum

Zone I - Insufficient Dose

Zone II - Destabilization (charge neutralization)

Zone III - Restabilization (overdose)

Zone IV - Sweep Floc

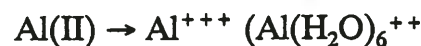
E. Factors Influencing Coagulation (BESIDES TEMPERATURE)

1. Type of Coagulant

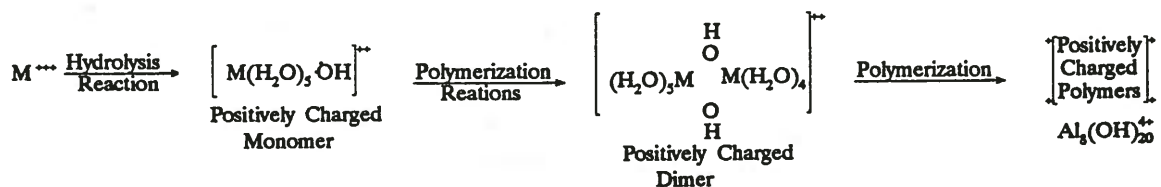
(a) Inorganic

(i) Aluminum

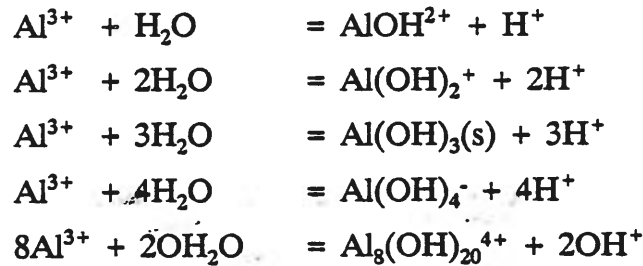
- Alum $\text{Al}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$ $n = 18$ reagent
 $= 14$ commercial



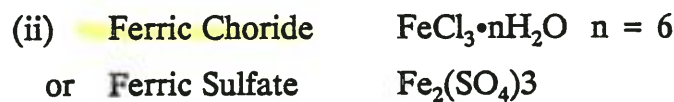
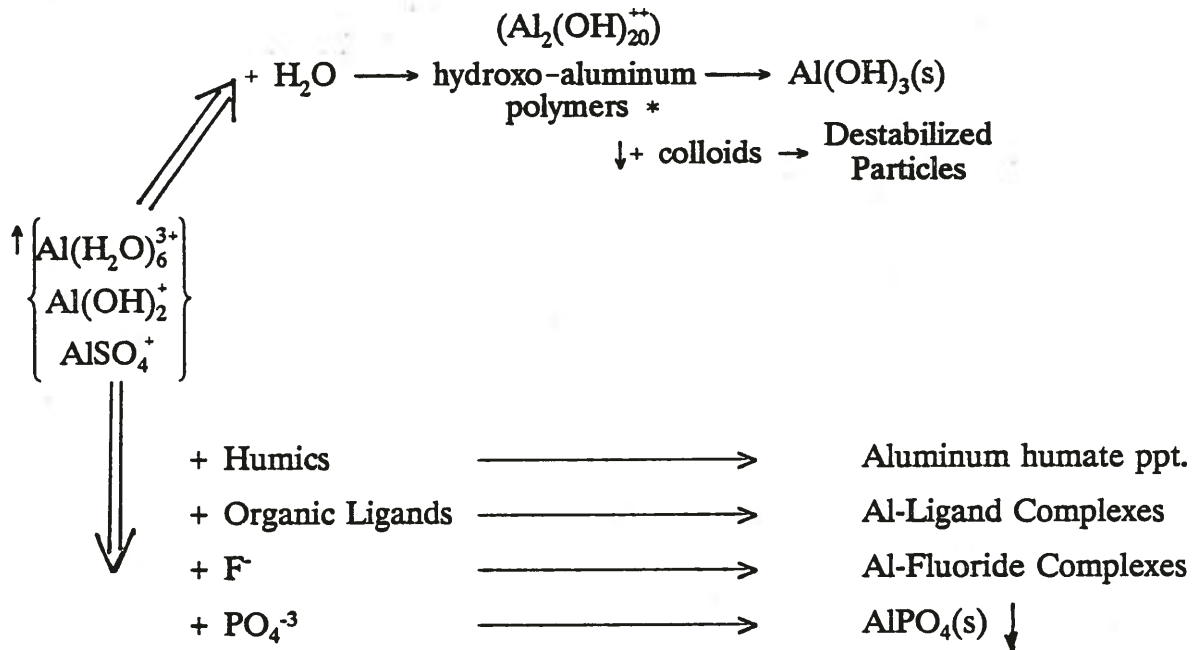
Aquatic Chemistry of Metal Salts Al^{+++} and Fe^{+++}



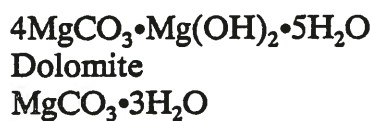
Alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14 \text{H}_2\text{O}$) dissolves readily in water releasing SO_4 ions to solution. The Al^{3+} (actually a shorthand since it exists as $\text{Al}(\text{H}_2\text{O})_6^{3+}$) undergoes hydrolysis reactions, some of which follow:



Protons are liberated making alum an acid; thus alkalinity is consumed.



(iii) Magnesium

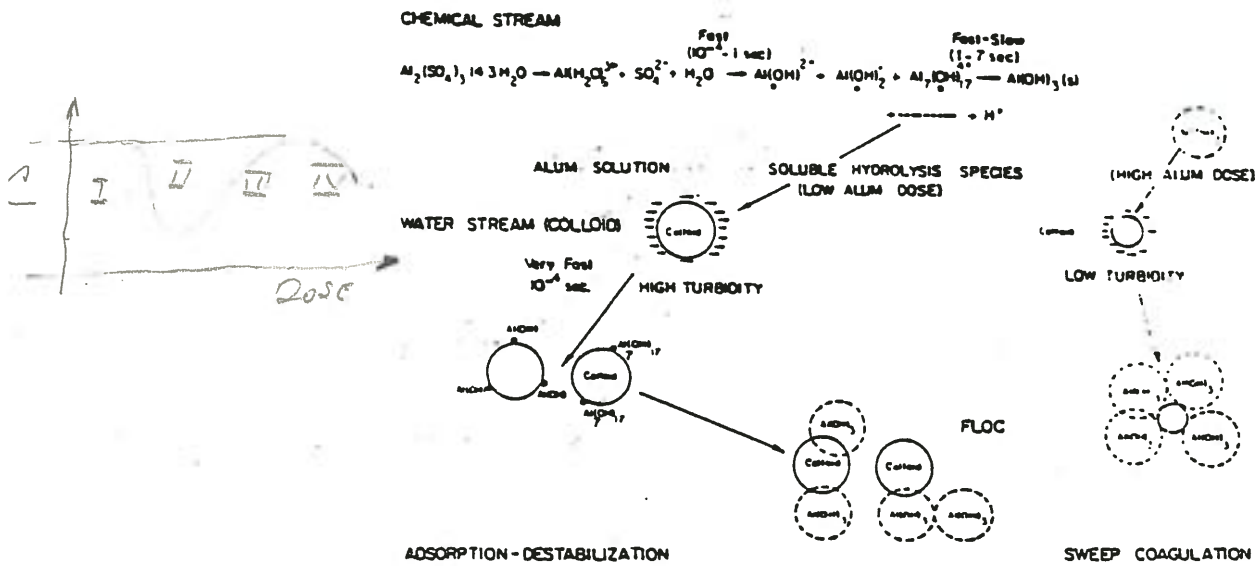


- Mg(OH)_2 can be an effective coagulant for removal of color and turbidity.
- Mg^{2+} - naturally or added to sufficient concentrations.
- Coagulation can be achieved by simply adding a sufficient amount of lime to precipitate $\text{Mg(OH)}_2(\text{s})$.
- Both Mg and lime can be recovered from the sludge and recycled.
- Reactions are as follows:

(iv) Polyaluminum Chloride (PACl)

2. Coagulant Dose

- Zone II or IV → charge neutralization vs "sweep floc".



Reaction Schematics of Coagulation

3. pH Effects on Metal Coagulants

High pH - won't accomplish much $M(OH)_4^-$

Low pH - inhibits hydrolysis reaction - metal coagulant won't go.

pH reduced by hydrolysis and sweep floc. (need high alkalinity for sweep floc).

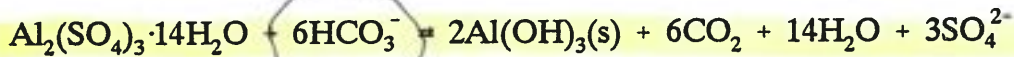
Optimum conditions will make use of both charge neutralization and interparticle bridging.

All species = (dose, pH)

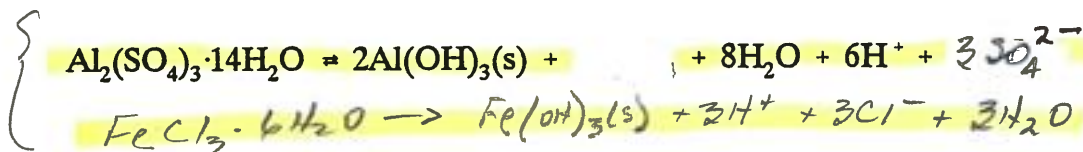
@ low pH and low dose → hydroxo-metal polymers

@ high pH and high dose → precipitate $Al(OH)_3$ ↓ sweep floc!

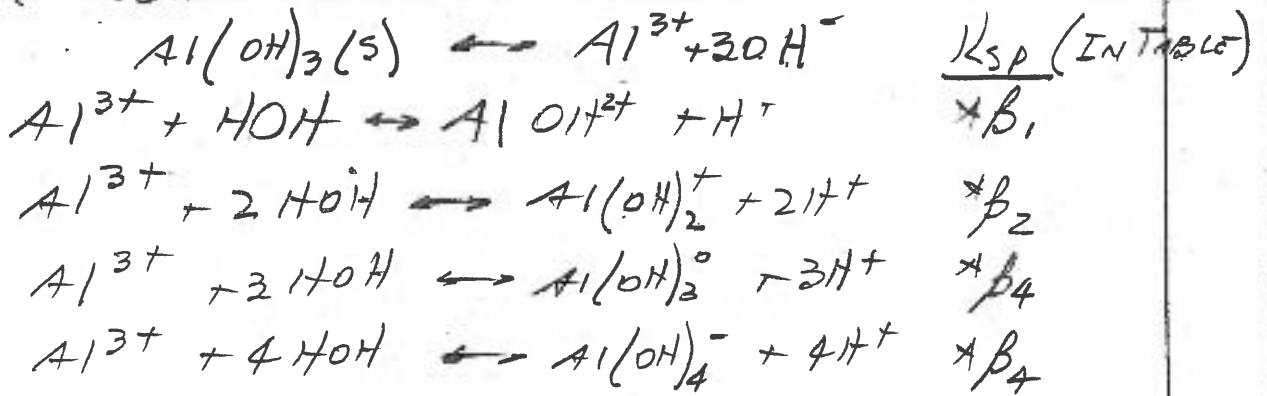
4. Alkalinity



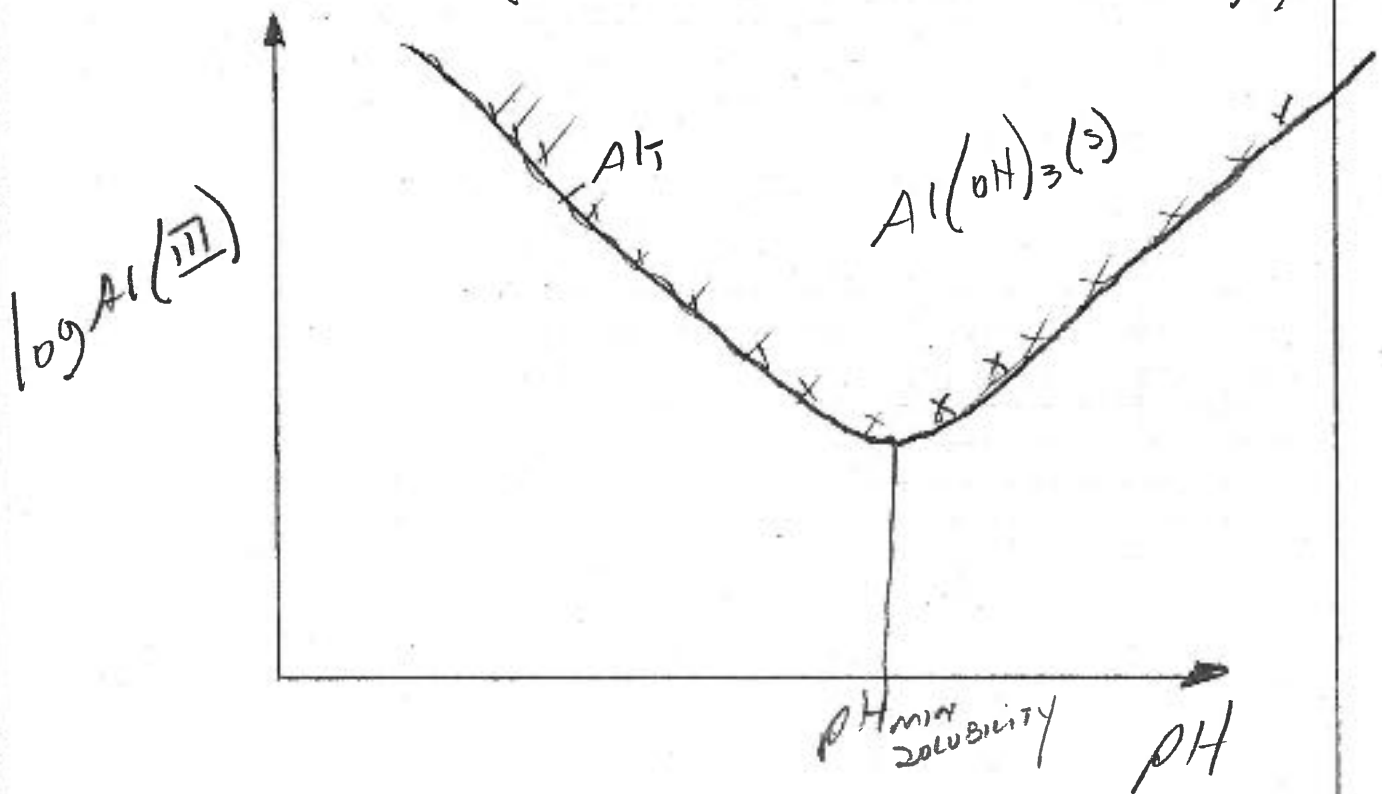
or



Al(OH)₃(s) FORMATION



$$\begin{aligned}
 \text{Al}_T &= \text{Al}^{3+} + \text{AlOH}^{2+} + \text{Al(OH)}_2^+ + \text{Al(OH)}_3^0 + \text{Al(OH)}_4^- \\
 &= (\text{Al}^{3+}) \left(1 + \frac{\text{AlOH}^{2+}}{\text{Al}^{3+}} + \frac{\text{Al(OH)}_2^+}{\text{Al}^{3+}} + \frac{\text{Al(OH)}_3^0}{\text{Al}^{3+}} + \frac{\text{Al(OH)}_4^-}{\text{Al}^{3+}} \right) \\
 &= \frac{K_{\text{sp}} (\text{H}^+)^3}{K_{\text{vw}}^3} \left(1 + \frac{* \beta_1}{(\text{H}^+)} + \frac{* \beta_2}{(\text{H}^+)^2} + \dots + \frac{* \beta_4}{(\text{H}^+)^4} \right)
 \end{aligned}$$



$$\text{Al}_T = \frac{K_{\text{sp}} (\text{H}^+)^3}{K_{\text{vw}}^3} \left(1 + \sum_{i=1}^4 \frac{* \beta_i}{(\text{H}^+)^i} \right)$$



CONVERTING COAGULANT DOSE TO METAL DOSE

A. ALUM

$$\bullet \text{ Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O} \rightarrow \text{M.W.} = 594 \left(\begin{array}{l} 666 \text{ mg} \\ \text{mm} \end{array} \right)$$

$$\text{E.W.} = \frac{666}{6} = 111 \frac{\text{mg}}{\text{meq}}$$

$$\bullet \text{ Al} \rightarrow \text{A.W.} = 27$$

$$\text{E.W.} = \frac{27}{3} = 9 \frac{\text{mg}}{\text{meq}}$$

$$\begin{array}{l} \text{60} \\ \text{60} \end{array} \frac{60 \text{ mg AS ALUM (REMB. GARD)} }{2}$$

$$111 \text{ mg/meq} \times 9 \frac{\text{mg}}{\text{meq}} = 4.86 \frac{\text{mg}}{\text{L}}$$

B. FeCl₃ - FERRIC CHLORIDE

$$\bullet \text{ FeCl}_3 \rightarrow \text{M.W.} = 162.4 \frac{\text{mg}}{\text{mm}}$$

$$\bullet \text{ Fe} = \frac{55.85}{2} = 27.925 \frac{\text{mg}}{\text{meq}}$$

$$\begin{array}{l} \text{60} \\ \text{60} \end{array} \frac{60 \text{ mg AS FeCl}_3}{2}$$

$$54.1 \text{ mg/meq} \times 27.925 \frac{\text{mg}}{\text{meq}} = 20.6 \frac{\text{mg}}{\text{L}}$$

$$\frac{\text{mg/L Conc.}_1}{\text{E.W.}_{\text{Conc.}_1}} \times \text{E.W.}_{\text{CoAl}_2} = \text{mg/L CoAl}_2$$

$$\text{E.W.} = \frac{\text{M.W.}}{Z}$$

TABLE 3-1

Coagulant Dosage Equivalents ¹

Regular Grade Alum (Aluminum Sulfate) Al ₂ (SO ₄) ₃ *14 H ₂ O (mg/L)	Reagent Grade Alum (Aluminum Sulfate) Al ₂ (SO ₄) ₃ *18 H ₂ O (mg/L)	Ferric Chloride FeCl ₃ * 6H ₂ O (mg/L)	Ferric Chloride FeCl ₃ (mg/L)	Ferric Sulfate Fe ₂ (SO ₄) ₃ * 9H ₂ O (mg/L)	Ferrous Sulfate FeSO ₄ * 7H ₂ O (mg/L)
10	11.2	9.1	5.5	9.5	9.4
20	22	18	11	19	19
30	34	27	16	28	28
40	45	36	22	38	37
50	56	46	27	47	47
60	67	55	33	57	56
70	78	64	38	66	66
80	90	73	44	76	75
90	101	82	49	85	84
100	112	91	55	95	94

Notes:

1. All dosages reported as "active" chemicals, prior to dilution

- Freshly prepared (no more than seven days old) stock solution of alum or other coagulant. (See step 2 of Section 3.2.2.2 for an example of preparation of a stock solution.)
- Sample bottles compatible with analysis of coagulated water for alkalinity and pH measurement.
- Sample bottles suitable for TOC analysis.
- 25 and 50 mL pipettes, with 10 mL graduated pipette bulbs. Pipettes are used to accurately measure volumes during preparation of stock solutions. Pipette bulbs are available with start/stop buttons for very accurate measurement. Volumetric pipettes may be used for more precise dosages. Plastic disposable syringes (without needles) may be used to measure coagulant doses to be applied during the jar tests.
- 1 L graduated cylinders.
- Miscellaneous beakers and other glassware.

(b) Organic

Table 6-3 Synthetic Organic Coagulations Used in Water Treatment

Type	Examples	Molecular Weight Range	Uses	Observations
Nonionic	Polyacrylamide $\left[\begin{array}{c} \text{CH}_2-\text{CH} \\ \\ \text{C}=\text{O} \\ \\ \text{NH}_2 \end{array} \right]_n$	10^5-10^7	Coagulant aid, filter aid	Used to increase floc strength, available as powder or emulsion, used mostly as filter aid
Anionic	Hydrolyzed polyacrylamide $\left[\begin{array}{c} \text{CH}_2-\text{CH}-\text{CH}_2-\text{CH} \\ \qquad \qquad \\ \text{C}=\text{O} \qquad \qquad \text{C}=\text{O} \\ \qquad \qquad \qquad \\ \text{NH}_2 \qquad \qquad \text{ONa} \end{array} \right]_n$	10^4-10^7	Coagulant aid, filter aid, sludge conditioning	Produced by controlled hydrolysis of polyacrylamide; range of MW, charge density available, charge depends on pH
Cationic	Poly(DADMAC) or poly(DMDAAC) polymers $\left[\begin{array}{c} \text{CH}_2-\text{CH}-\text{CH}-\text{CH}_2 \\ \qquad \\ \text{CH}_2 \quad \text{CH}_2 \\ \qquad \\ \text{N}^+ \\ \qquad \\ \text{CH}_3 \quad \text{CH}_3 \end{array} \right]_n \text{Cl}^-$	10^4-10^6	Primary coagulant, turbidity/color removal, sludge conditioning	Most widely used primary coagulant; may be used in conjunction with inorganic coagulant; chlorine resistant; charge density not pH sensitive; available in liquid form
Cationic	Quaternized polyamines $\left[\begin{array}{c} \text{CH}_2-\text{CH}-\text{CH}_2-\text{N}^+ \\ \qquad \qquad \\ \text{OH} \qquad \qquad \text{CH}_3 \end{array} \right]_n \text{Cl}^-$	10^4-10^5	Primary coagulant, color/turbidity removal	Mostly widely used primary coagulant for color removal; properties similar to poly(DADMAC)
Cationic	Polyamines $\left[\text{CH}_2-\text{CH}_2-\text{NH}_2 \right]_n$	10^4-10^7	Primary coagulant, also coagulant aid (high MW)	Includes several types of polymers; less widely used as primary coagulant, reacts with chlorine; charge density depends on pH

- Polyelectrolyte = Polymer whose monomers contain ionizable groups.
- Size & Shape of a polymer is important to its effectiveness = f (I, ionic valences, pH).
- Dosages ~ 0.5 to 1.5 mg/L of cationic polymer are often effective for coagulation which compares to 10-20 times that amount for alum to achieve the same results.

Note ...

Dosage control is more difficult with polymers because of their narrow range of effectiveness.

- Advantages ...
 - (i) Polymers do not lower pH and is appropriate for treating low alkalinity waters.
 - (ii) Reduced sludge volumes.
 - (iii) Better dewatering sludge.
 - (iv) Reduced aluminum residues in D.W.

Table 9-7

Application guidance for Al(III) and Fe(III) as coagulants and prehydrolyzed metal coagulants used in water treatment

Water Quality Parameter	Coagulant		
	Alum(III)	Fe(III)	PACI
Turbidity	For low turbidity waters (i.e., low particle concentration), sweep floc will be required.	For low turbidity waters (i.e., low particle concentration), sweep floc will be required.	For low turbidity waters (i.e., low particle concentration), sweep floc will be required. Medium-basicity PACIs (40–50 percent) are suitable for cold waters with low turbidity.
Alkalinity	High alkalinity values make pH adjustment for optimum coagulation more difficult. If sufficient alkalinity is not present, soluble aluminum is formed, which can result in postflocculation in downstream processes. Supplemental alkalinity should be added before coagulant.	Although high alkalinity values make pH adjustment for optimum coagulation more difficult, its impact on coagulation using Fe is less than Al.	
pH	The optimum pH range is between 5.5 and 7.7 but will fluctuate seasonally (see Fig. 9-16). Typically, the optimum pH will be nearer 6 in the summer and 7 in the colder winter months. Higher pH levels often correspond to periods of algal growth, which in turn will affect the coagulant dose.	The optimum pH range is from 5 to 8.5 or more (see Fig. 9-16). Floc formed in colder water tends to be weaker.	PACIs are less sensitive to pH. Can be used over the pH range of 4.5–9.5.
NOM	The removal of NOM will normally control the coagulant dose. Removal of NOM tends to increase as pH is reduced. Removal of up to 70 percent has been achieved.	The removal of NOM will normally control the coagulant dose. Removal of NOM tends to increase as pH is reduced. Removal of up to 80 percent has been achieved.	The removal of NOM will normally control the coagulant dose. Removal of NOM tends to increase as the pH is reduced. Removals of up to 70 percent have been achieved. Low-basicity PACIs (up to 20 percent) are suitable for waters high in color and total organic carbon.
Temperature	Temperature affects solubility products. Floc formed in colder water tends to be weaker.	Floc formed in colder water tends to be weaker.	
Mixing	Hydrolysis reactions are very fast. Mixing times should be less than 1 s and preferably less than 0.5 s.	Hydrolysis reactions are very fast. Mixing times should be less than 1 s and preferably less than 0.5 s.	Because the PACI is prehydrolyzed the initial mixing time is somewhat less critical.

- Need alkalinity for coagulant reactions to go.
- Buffering prevents restabilization
- Rule of Thumb -

REVIEW
COAGULATION
AIDS

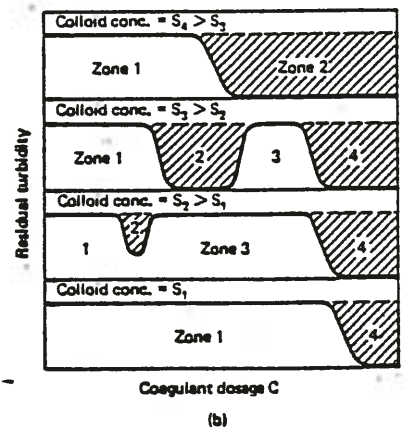
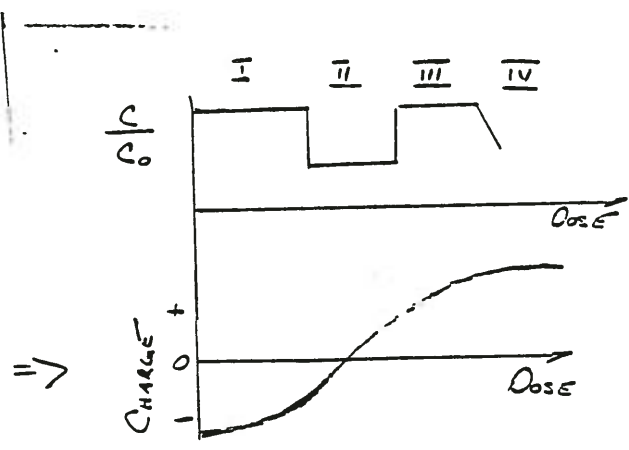
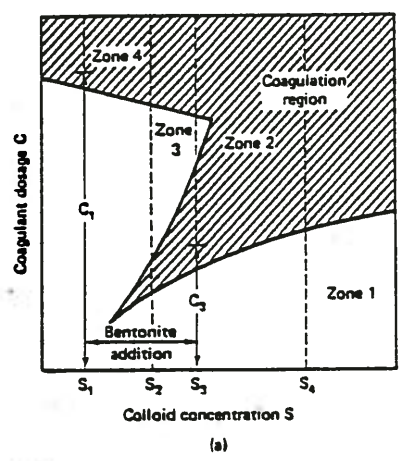
1 mg of alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$) may produce approximately 0.26 mg of $\text{Al}(\text{OH})_3(\text{s})$ and may consume approximately 0.5 mg of alkalinity as CaCO_3 .

1:1 FOR FeCl_3

5. Nature and Concentration of Turbidity $\&$ NOM

- a.) TURBIDITY
- Low suspensions \rightarrow sweep floc removal
 - Wide range \rightarrow better floc

1.0 mg of ALK.
AD CaCO_3
CONSUMED
 $\&$ 0.66 mg/L $\text{Fe}(\text{OH})_3$
PRODUCED.



BEST REMOVALS NEAR (SLIGHTLY+) POINT OF ZERO CHARGE.

Figure 7-6 Schematic coagulation curves at constant pH. Shaded areas represent regions in which coagulation occurs (after Stumm and O'Melia, 1968).

Coagulation of Turbidity

Turbidity in water is caused by the presence of suspended matter such as clay, silt, nonliving organic particulates, plankton and other microscopic organisms. Turbid waters are classified into four types:

Group 1: High turbidity-low alkalinity. With relatively small dosages of coagulant, water of this type should be easily coagulated by adsorption and charge neutralization. Depression of pH makes this method more effective, since the aquometallic ions are more effective at lower pH values. However, care should be used to prevent excessively low pH.

Group 2: High turbidity-high alkalinity. The pH will be relatively unaffected by coagulant addition. Because of the high alkalinity, adsorption and charge neutralization will be less effective than in waters of low alkalinity. Higher coagulant dosage should be used to ensure sweep coagulation.

Group 3: Low turbidity-high alkalinity. The small number of colloids make coagulation difficult, even if the particle charge has been neutralized. The principal coagulation mechanism is sweep coagulation with moderate coagulant dosage. Addition of some turbidity may decrease the amount of coagulant needed.

Group 4: Low turbidity-low alkalinity. Again, the small number of colloids make coagulation difficult, and low alkalinity prevents effective $\text{Al}(\text{OH})_3$ formation. Additional turbidity can be added to convert this water to that of group 1, or additional alkalinity can be added to convert it to a Group 3 type. It may be advantageous to add both turbidity and alkalinity.

It should be recognized that the above cases are generalizations. Optimum treatment of any water can only be determined by careful analysis using the jar test or other pilot-plant procedures.

→ b.) ADD EDWARDS' LECTURE FOR NOM INFLUENCE

WATER CHARACTERISTICS

- ◆ **What Controls the Coagulant Dose ?**

Particles or Dissolved NOM

- ◆ **Answer**

Depends on the Concentration and Especially the Composition of the NOM. NOM Controls When Composed Largely of Aquatic Humics

PARTICLES VS. NOM

Clay Particle Negative Charge: 0.1 to 1 $\mu\text{eq}/\text{mg}$

Say 0.2 $\mu\text{eq}/\text{mg}$

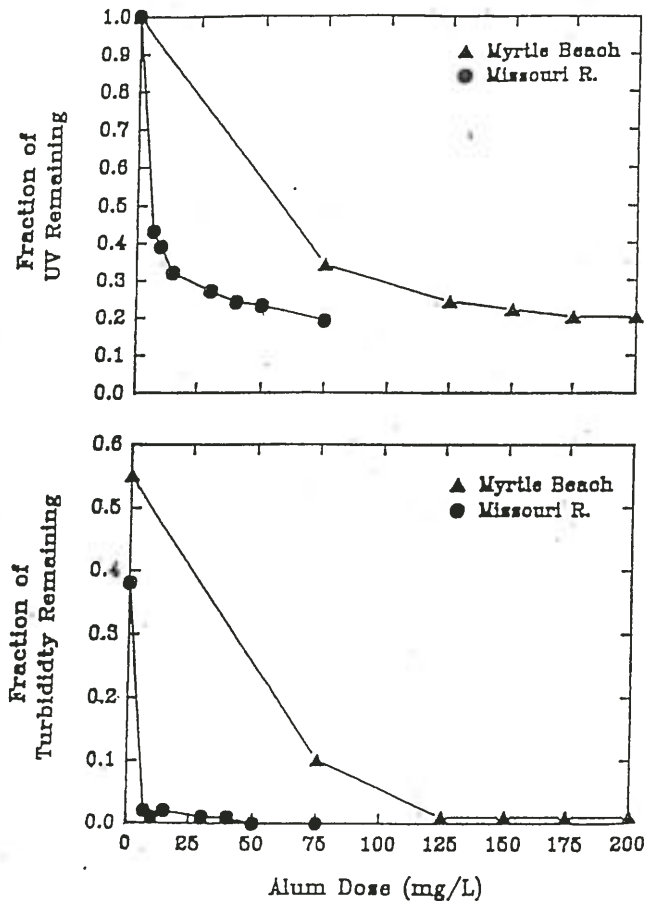
NOM Negative Charge: 5 to 15 $\mu\text{eq}/\text{mg}$ DOC (Aquatic Fulvic Acid)

PARTICLES

Turb. ntu	C mg/L	Φ ppm	N #/mL	Neg. Charge $\mu\text{eq}/\text{L}$
~1	2-4	2	3.8×10^6	0.4
~10	20-40	20	3.8×10^7	4

For 1 μm diameter particles; 0.2 $\mu\text{eq}/\text{mg}$

Edzwald (*Wat. Sci. & Tech.*, Vol. 27, 1993)



GUIDELINES: DOES DISSOLVED NOM CONTROL COAGULATION?

◆ Operational Determination:

Specific UV Absorbance (SUVA)

UV Absorbance at 254 nm per mg/L of DOC

Expressed as m^{-1} per mg/L DOC

GUIDELINES: COAGULATION CONTROL

- ◆ **SUVA < 2: NOM is non-humic; does not control coagulation.**
- ◆ **SUVA 2-4: NOM Is a mixture of non-humics and humics; influences coagulation.**
- ◆ **SUVA of 4 or higher: NOM is high in aquatic humics; controls coagulation.**

SUVA USES

- ESTIMATE THE DOC OF A WATER
- CHARACTERIZATION OF THE DOC
- ROUGH ESTIMATES OF DOC REMOVALS BY METAL COAGULANTS (Al & Fe Salts)

- Example of Estimating DOC

→ Myrtle Beach, SC

* Measure the raw water UV at 0.87 cm^{-1}

* SUVA known at $4.2 \text{ m}^{-1}/\text{mg/L DOC}$

* Calculation of DOC

$$\text{DOC} = \frac{\text{UV}}{\text{SUVA}} = \frac{87}{4.2} \approx 21 \text{ mg/L}$$

PROBLEMS DUE TO TOC

- **Natural Color** Aquatic Humics
 - **Health Effects** DBP Precursors
- 1 mg/L TOC**
- THMFP** 50 to 100 µg/L (pH 7 - 8)
- HAAFP** 50 to 100 µg/L (pH 6 -7)

- **Enhanced Coagulation Rule**

Minimize TOC: Cause of DBPs

- **Control Coagulant Dosages**

For Many Waters it is DOC not Turbidity

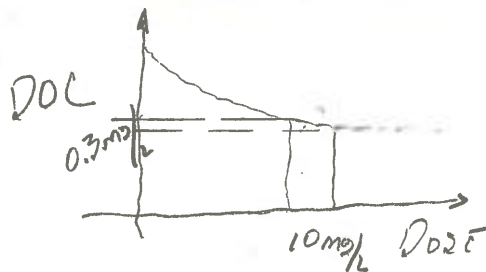
ENHANCED COAGULATION

Required Percent Removals of TOC

Raw Water TOC (mg/L)	Raw Water Alkalinity (mg/L CaCO ₃)		
	< 60	60 - 120	> 120
< 2	No Action	No Action	No Action
2 - 4	40	30	20
4 - 8	45	35	25
> 8	50	40	30

ENHANCED COAGULATION

- **STEP 1: TOC Removal Based on Raw Water TOC & Alkalinity**
 - ➔ **If Requirement is Not Met, Utility Must Perform Enhanced Coagulation Tests in Step 2**
- **STEP 2: Bench or Pilot Testing Required**
 - ➔ **Addition of Alum in 10 mg/L Increments or Equivalent Amounts for Ferric Salts (See Table). Dose Based on Point When an Additional 10 mg/L Alum Does Not Decrease the Residual TOC by 0.3 mg/L**
 - ➔ **Testing on a Quarterly Basis and Must be Conducted at pH Levels No Greater than Indicated -- See Maximum pH Table**



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PROBLEMS WITH EPA'S ENHANCED COAGULATION

- **Based on Alkalinity of Source Water**
 - ⇒ **Should be Based on Nature of NOM!**
 - ⇒ **Should base on SUVA -- Waters with high SUVA are conducive to DOC removal by coagulation**
- **Does Not Recognize that Coagulants Convert Soluble NOM (DOC) into Particles -- i.e., Phase Change**
 - ⇒ **DOC Measurements vs. TOC**

For Most Surface Waters DOC is 90 to 99% of the TOC.

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⇒ EPA requires TOC measurements to evaluate coagulants. Makes sense for plant measurements of raw and final waters to meet requirement, but should measure DOC in evaluating coagulants and impact of coagulation

- **Maximum pH Conditions**

⇒ pH 5.5 for Alum -- Several Concerns

- **PACls are as Effective as Alum**

- **Organic Cationic Polymers Have a Role**

**ENHANCED COAGULATION LEVEL
MAXIMUM pH***

Alk mg/L CaCO ₃	Maximum pH
0 - 60	5.5
60 - 120	6.3
120 - 240	7.0
> 240	7.5

*Enhanced Coagulation Requirement,
Federal Register, Vol. 59, No. 145
(July 29, 1994)

- OPTIMUM OPERATING COAGULATION CONDITIONS

- ⇒ DOC Removal
- ⇒ Particle Flocculation and Separation
- ⇒ Filter Performance
- ⇒ Residual Coagulant
- ⇒ Sludge Production

GUIDELINES: COAGULANT DOSAGES FOR WATER SUPPLIES WHERE NOM CONTROLS

◆ Aluminum Coagulants

pH 6 to 6.5: 0.7 mg as Al/mg DOC

pH 7 to 7.5: 1 mg as Al/mg DOC

Recommended pH for Alum

Water Temp: 10 °C or Above;

Use pH 6.1 - 6.5

Water Temp: Less than 10 °C

Use pH 6.5 - 6.8

GUIDELINES: COAGULANT DOSAGES (CONT'D)

◆ **Ferric Coagulants**

pH 5.5: 2 mg as Fe per mg/DOC

**pH 7 - 7.5: 4 mg as Fe per
mg/DOC**

◆ **Organic Cationic Polymers**

**0.65 - 1 mg *Active Polymer*/ mg
DOC**

DOC REMOVALS

- **DEPENDS ON:**
 - **Nature of the NOM**
 - **Concentration of DOC**
 - **Coagulant Type and Dose**
 - **pH**

GUIDELINES: ESTIMATES OF DOC REMOVAL

◆ SUVA < 2

Aluminum and Ferric Coagulants

~ 20 %

Organic Cationic Polymers

~ 10 %

◆ SUVA 2 - 3

Aluminum and Ferric Coagulants

~ 20 to 50 %

Organic Cationic Polymers

~ 10 to 30 %

GUIDELINES: ESTIMATES OF DOC REMOVAL (CONT'D)

◆ SUVA 3 -4 and Higher

Aluminum and Ferric Coagulants

~ 50 to 70 %

Organic Cationic Polymers

~ 30 to 40 %

6. Coagulant Aids

(a) Bentonite Clay

- Provide nuclei for particle aggregation
- Helps "weight" the aggregated floc
- Primarily used for high color, low turbidity waters

(b) Powdered Activated Carbon

- Ditto as before but is a little more expensive
- Can also remove organics and taste and odor compounds

(c) Polyelectrolytes

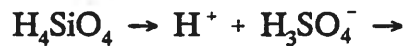
- Increase floc size and strength by bridging
- M.W. range - 1000 to 10^6
- Typical doses vary from 0.1 mg/L to 2 mg/L
- Manufacturers ...

Dow
Calgon
Atlas

Betz
Nalco
Hercules

*(d) Activated Silica - 7-11% of the alum dose

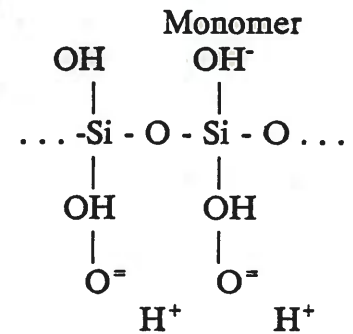
Generally considered to be obsolete by advanced polymers.



↑ Ortho-Silic Acid

Polymerization

→



∴ Acts as an anionic polyelectrolytes

7. Mixing Intensity

- f (dissipation of power in water)
- Parameter of mixing intensity, G
- G = temporal mean velocity gradient, τ^{-1}

\bar{G} = RELATIVE MEAN VELOCITY



$$G = \left\langle \frac{du}{dz} \right\rangle = \frac{1 \text{ ft/s}}{0.1 \text{ ft}} = 10 \text{ sec}^{-1}$$

↑ special mean value over time

$$G = \frac{\text{Relative Velocity}}{\text{Distance}} = \left(\frac{P}{\mu V} \right)^{1/2} = \left(\frac{F_D v}{\mu V} \right)^{1/2} = \left(\frac{\rho \gamma h_L}{\mu V} \right)^{1/2}$$

where P = net powder dissipated in water.

(1) Evaluation of relative velocity, v

$$v_p = \text{velocity of paddle} = \frac{2\pi r n}{60} \quad n = \text{rpm}$$

$$v_w = \text{velocity of "swirling" water mass} = 20-30\% v_p$$

$$v = \text{velocity of paddle relative to water} = v_p - v_w = k v_p$$

(2) Evaluation of drag force

WHERE
k = 0.70 - 0.80

(i) For Flat Blade Paddles

$$F_D = C_D \rho A \frac{v^2}{2}$$

$$\therefore \text{Power} = F_D v = C_D \rho A \frac{v^3}{2}$$

Summary $G = \left(\frac{P}{\mu V} \right)^{1/2} = \left(\frac{C_D \rho A v^3}{\mu V 2} \right)^{1/2} = f(\text{Power input, volume, paddle configuration and density of water})$

$C_D = f(\text{paddle geometry})$	L/W	C_D
	1	1.16
	5	1.20
	20	1.50
	∞	1.90

→ 1.8 typically

Note ...

$$\rho = \frac{\gamma}{g} \quad v = \frac{\mu}{\rho} = \frac{\mu g}{\gamma}$$

$$\gamma = \frac{62.4 \text{ lbs}}{\text{ft}^3}$$

μ = absolute viscosity

v = kinematic viscosity

MEAN VELOCITY GRADIENT DETERMINATIONS FOR
ONE LITER RECTANGULAR MIXING JAR

$$G = \left(\frac{P}{V\mu}\right)^{\frac{1}{2}} = \left(\frac{F_D v}{V\mu}\right)^{\frac{1}{2}} = \left(\frac{C_D \rho A v^3}{V\mu^2}\right)^{\frac{1}{2}}$$

where

- G = velocity gradient, sec⁻¹
 P = power utilized, ft-lb/sec
 V = volume of fluid, ft³
 μ = absolute viscosity of fluid, lb-sec/ft²
 F_D = drag force on the paddle, lb.
 C_D = coefficient of drag, dimensionless
 A = area of paddle, ft²
 ρ = fluid density, lb sec²/ft⁴
 v = relative velocity of fluid with respect to paddle, ft/sec

Let $v = kv_p$

where

- v_p = paddle velocity, ft/sec
 k = ratio of fluid velocity to paddle velocity

and

$$v_p = \frac{2\pi rN}{60}$$

where

- r = paddle radius, ft
 N = revolutions per minute (rpm)

Therefore

$$G = \left(\frac{C_D \rho A k^3 \pi^3 r^3 N^3}{5.4 \times 10^4 V \mu}\right)^{\frac{1}{2}}$$

3.75" x 3.75" Jar

For the jar test equipment used herein:

Temperature = 23°C = 73.4°F

K = 0.70

C_D = 1.8 for rectangular paddles

A = paddle area equals 1-inch x 3-inch

V = one liter sample volume

Thus

$$G = 0.2113 N^{3/2}$$

See attached figure (B-1)

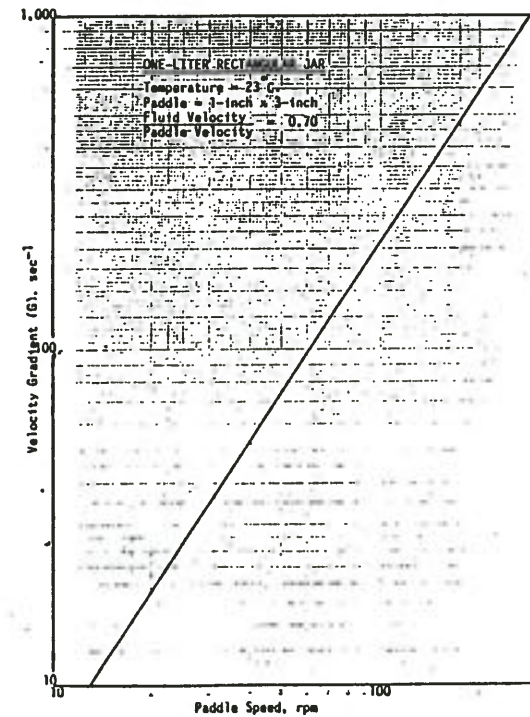


Figure B-1. Relationship between paddle speed and velocity gradient.

(ii) For Impellers

$$R = \frac{D_i^2 n \rho}{\mu} = \frac{D_i^2 n}{\nu}$$

(a) For turbulent flow ($R > 10,000$) ...
RAPID MIX

$$P = \frac{K_T n^3 D_i^5 \gamma}{g} = K_T n^3 D_i^5 \rho$$

where P = power, ft-lb/sec

K_T = impeller constant for turbulent flow (Table)

n = rps

D_i = impeller diameter, ft.

(b) For laminar flow ($R < 10-20$) ... *Slow Mix*

$$P = \frac{K_L n^2 D_i^3 \mu}{g}$$


Table 2.2 Values of Constants K_L and K_T for Baffled Tanks Having Four Baffles at Tank Wall, with Width Equal to 10 Percent of the Tank

Type of Impeller	Diameter	
	K_L	K_T
Propeller, pitch of 1, 3 blades	41.0	0.32
Propeller, pitch of 2, 3 blades	43.5	1.00
Turbine, 4 flat blades, vaned disc	71.0	6.30
Turbine, 6 flat blades, vaned disc	71.0	6.30
Turbine, 6 curved blades	70.0	4.80
Fan turbine, 6 blades at 45°	70.0	1.65
Shrouded turbine, 6 curved blades	97.5	1.08
Shrouded turbine, with stator, no baffles	172.5	1.12
Flat paddles, 2 blades (single paddle), $D/W_1 = 4$	43.0	2.25
Flat paddles, 2 blades, $D/W_1 = 6$	36.5	1.60
Flat paddles, 2 blades, $D/W_1 = 8$	33.0	1.15
Flat paddles, 4 blades, $D/W_1 = 6$	49.0	2.75
Flat paddles, 6 blades, $D/W_1 = 6$	71.0	3.82

$$* G = \left(\frac{P_{net}}{M V} \right)^{1/2} *$$

(iii) For Diffused Aeration

$$P = 81.5 G_a \log \left(\frac{h+34}{34} \right)$$

$$(81.5 = 14.7 \frac{lb}{IN^2} \times \frac{12^2 IN^2}{1 FT^2} \times \frac{1 min}{60 SEC} \times 2.3)$$

where G_a = air flow rate, CFM and h = diffuser depth, ft.

$$P = P_a Q_a \ln \left(\frac{33.9+h}{33.9} \right) = P_a V_a \ln \frac{P_c}{P_a} = f$$

$$* G = \left(\frac{P_{net}}{M V} \right)^{1/2} *$$

Air Pressure

Air Pressure $\frac{KN}{m^2}$
 Point of discharge, $\frac{KN}{m^2}$
 Air Pressure $\frac{KN}{m^2}$
 Air Pressure $\frac{KN}{m^2}$

Power number
 $P = n^3 \rho n D^3$ m³E

(iv) For Hydraulic Pipes Baffles ...

$$G = \left(\frac{\rho g h_L}{\mu T} \right)^{1/2} \quad G = \left(\frac{\rho h_L}{t} \right)^{1/2} \Rightarrow P = Q \rho g h_L = Q \delta h_L \quad \therefore G = \left(\frac{Q \delta h_L}{\mu T} \right)^{1/2} = \left(\frac{\delta h_L}{\mu T} \right)^{1/2}$$
 where h_L = headloss and t = detention time.

$$\text{PIPES} \rightarrow \bar{h}_L = \frac{f L v^2}{0.2g}$$

$$\text{BAFFLED MIXING CHANNEL} \rightarrow = \frac{L v^2}{C^2 R_h}$$

$$h_L = \frac{K v^2}{2g}$$

$$h_L \text{ FROM } 180^\circ \text{ TURN}$$

$$K = 2.5 - 4$$

$R_h = \text{HYDRAULIC RADIUS}$
 $C = \text{CHEZY COEFF}$

Table 9-18
Design criteria for hydraulic flocculation

Parameter	Unit	Value
Average G	s ⁻¹	30-40
Channel velocities	m/s	0.15-0.45
Minimum residence time	min	20
Head loss at 180° turn	VH	3.2-3.5
Head loss through slit or port	VH	1.5
Minimum distance between baffles ^b	m	0.75
Minimum water depth	m	1

^a VH = velocity head.
^b To facilitate cleaning.

(iv) HYDRAULIC & PIPES

BAFFLED CHANNELS

Baffled channels are the most common form of hydraulic flocculators. In these flocculators energy dissipation is achieved by changing THE DIRECTION OF FLOW.

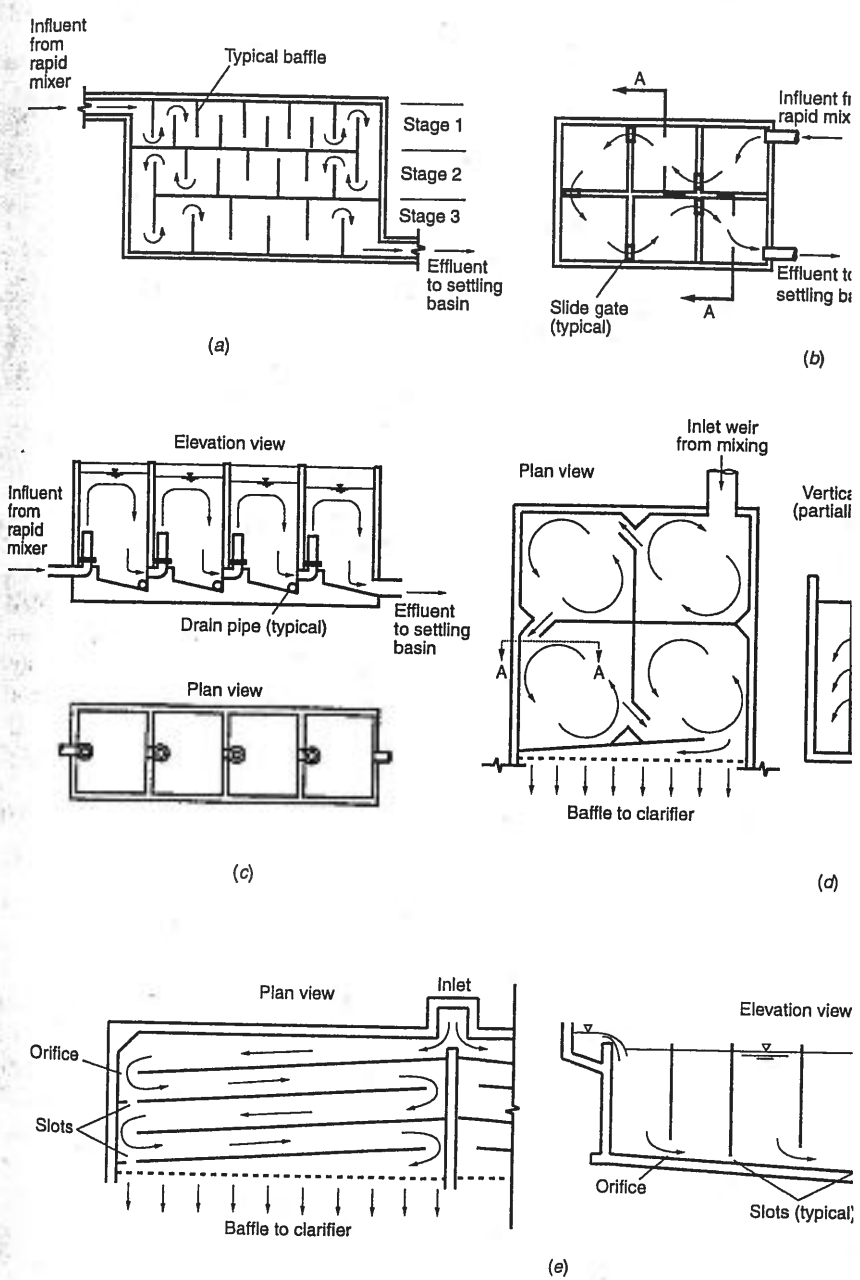


Figure 9-40 Examples of some alternative designs of hydraulic flocculators: (a) tapered horizontal baffled hydraulic flocculator, (b) helicoidal flow flocculator, (c) Alabama-type hydraulic flocculator, (d) variable-gate hydraulic flocculator, and (e) orifice and channel over and under flocculator.

(V.)

COARSE-MEDIA FLOCCULATORS

$$\bar{G} = \left(\frac{\rho g \Delta H}{\mu t} \right)^{1/2}$$

$$(9-90) \quad \frac{\Delta H}{\Delta L} = a \left(\frac{\mu}{\rho g} \right) \left[\frac{(1-\epsilon)^2}{\epsilon^3} \right] \left(\frac{1}{d} \right)^2 v_{\infty} + b \left(\frac{1}{g} \right) \left(\frac{1-\epsilon}{\epsilon^3} \right) \left(\frac{1}{d} \right) v_{\infty}^2 \quad (9-91)$$

where a, b = empirical coefficients

d = characteristic size of media (e.g., d_{10} determined by sieve analysis), m

ϵ = bulk porosity of media bed, m^3/m^3

v_{∞} = superficial velocity through media bed (flow rate divided by media bed cross-sectional area), m/s

Table 9-19

Summary of parameters for head loss through granular media

Medium	Coefficients		Typical Porosity $\epsilon, \%$
	a	b	
Crushed anthracite	210-245	3.5-5.3	47-52
Crushed sand	110-145	2.0-2.5	40-43
Glass beads	130-150	1.3-1.8	38-40

Source: From Trussell and Chang (1999).

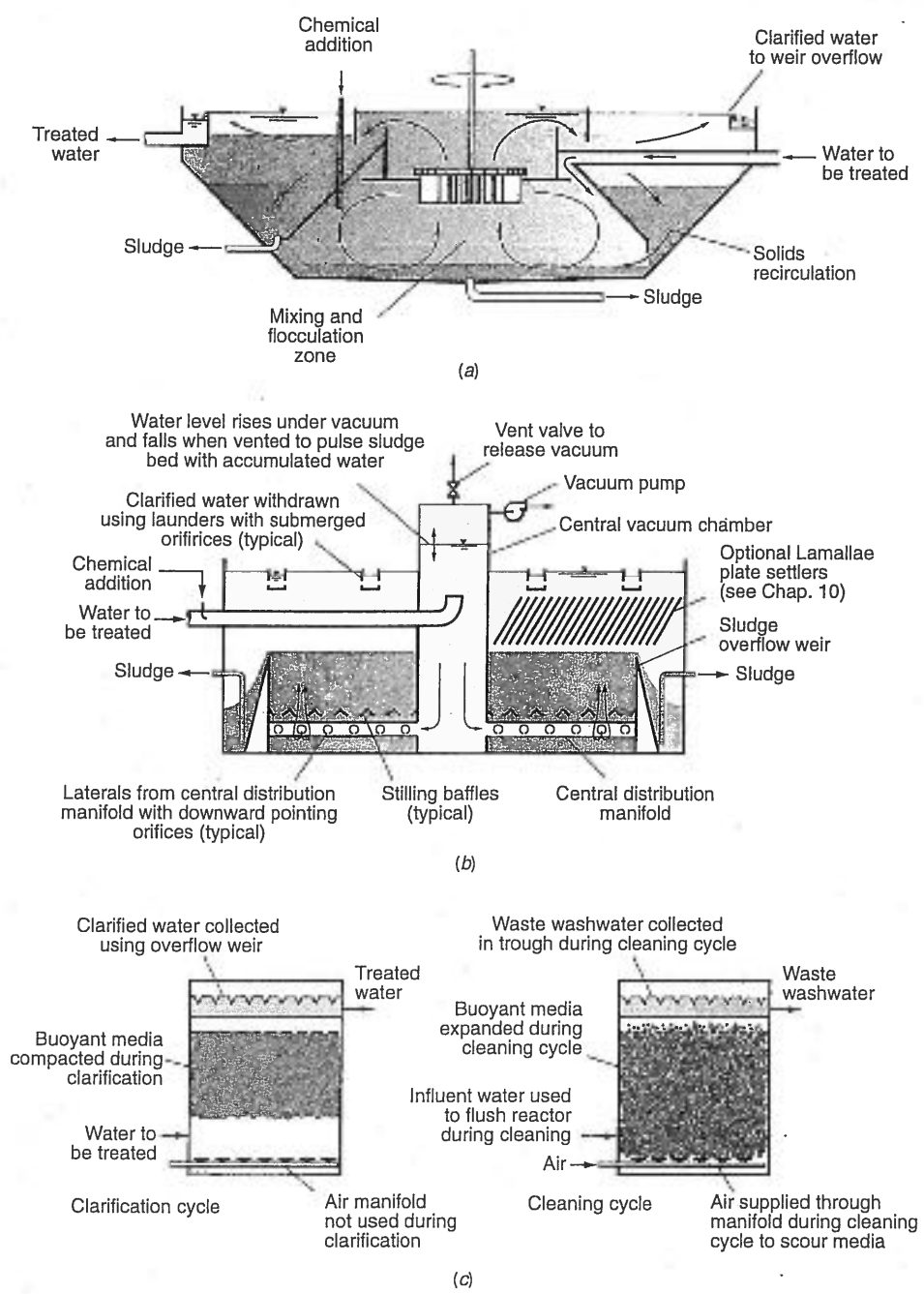


Figure 9-44 Three common types of proprietary reactor clarifiers: (a) reactor clarifier (IDI Accelerator), (b) sludge blanket clarifier (Pulsator, when optional lamella plates are added, the unit is known as the Super Pulsator), and (c) IDI absorption clarifier (Courtesy of Inflico Degrémont, Inc.).

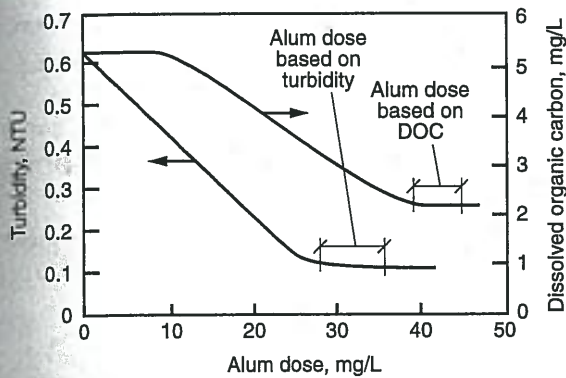


Figure 9-19
Residual turbidity and dissolved organic matter as function of alum dose.

• MODELING DOC REMOVAL BY METAL COAGULATION

sources for coagulation with alum (608 jar tests). In the model development, it was assumed that DOC is composed of adsorbable and nonadsorbable fractions. Accordingly, the effluent DOC after the coagulation process is the sum of the nonadsorbable DOC and the DOC that is adsorbable but not adsorbed and is given by the expression

$$\begin{aligned} \text{DOC remaining after coagulation (mg/L)} \\ = \text{adsorbable DOC remaining after coagulation (mg/L)} \quad (9-21) \\ + \text{nonadsorbable DOC remaining after coagulation (mg/L)} \end{aligned}$$

The adsorbable DOC that is not adsorbed during the coagulation process is the DOC fraction that is in equilibrium with the DOC that is adsorbed to the floc. The nonadsorbable DOC (mg/L) is determined using the expression

$$\text{DOC} = \left[\underset{\text{NON ADSORB}}{K_1} (\text{SUVA})_{\text{raw water}} + K_2 \right] \times \text{DOC}_{\text{initial}} \quad (9-22)$$

$$(\text{SUVA})_{\text{raw water}} = (10^2 \text{ cm}^2/\text{m}) \left(\frac{\text{UV}_{254}/\text{cm}}{\text{DOC}} \right)_{\text{raw water}} \quad (9-23)$$

where $(\text{SUVA})_{\text{raw water}}$ = specific UV absorbance of raw water, $\text{L}/\text{mg} \cdot \text{m}$
 $\text{DOC}_{\text{initial}}$ = initial concentration of dissolved organic carbon, mg/L

K_1, K_2 = empirical fitting constants

A Langmuir isotherm is used to determine the amount of DOC that is adsorbed:

$$q = \frac{Q_M b [C]_{\text{eq}}}{1 + b [C]_{\text{eq}}} \quad (9-24)$$

where q = equilibrium amount of DOC adsorbed, $\text{mg DOC}/\text{g adsorbent}$ (adsorbent is floc that is formed)

Q_M = monolayer coverage, which is a function of pH = (x_3 pH³ + x_2 pH² + x_1 pH), mg DOC/g adsorbent
 x_1, x_2, x_3 = empirical fitting constants (see Table 9-2), unitless
 b = Langmuir equilibrium constant, L/mg DOC

$[C]_{eq}$ = equilibrium aqueous-phase concentration of DOC, mg/L (ADSORBABLE FRACTION REMAINING)

In the final form of the model, the mass of DOC (mg) adsorbed per meq of coagulant to the amount adsorbed is equated to the Langmuir isotherm as follows: ADSORBABLE DOC REMAINING

$$\frac{[1 - (SUVA)_{raw\ water} K_1 - K_2] DOC_{initial} - [C]_{eq}}{M} = \frac{(x_3 pH^3 + x_2 pH^2 + x_1 pH) b [C]_{eq}}{1 + b [C]_{eq}} \quad (9-25)$$

where M = Fe³⁺ or Al³⁺ coagulant added and metal hydroxide solid formed, mM
 pH = coagulation pH
 b = Langmuir equilibrium constant for adsorbable DOC to hydroxide surface, L/mg DOC

The DOC model can be used to plan jar tests for a water supply and assess how much DOC may be removed using coagulation. The DOC removal may be correlated with the trihalomethane formation potential (THMFP) reductions, which has to be determined from testing, although Eq. 9-25 can be used for a crude assessment of the benefit. The model parameters and associated statistics shown in Table 9-9 were determined for iron and aluminum coagulation.

Table 9-9
 Summary of best-fit model coefficients for DOC removal with iron and aluminum

Parameter	DOC Model Coefficients	
	Iron	Aluminum
Standard error, mg/L	0.47	0.4
Standard error, %	9.3	9.5
90% confidence, %	±21	±21
x_3	4.96	4.91
x_2	-73.9	-74.2
x_1	280	284
K_1	-0.028	-0.075
K_2	0.23	0.56
b	0.068	0.147

Source: Adapted from Edwards (1997).

Example 9-4 Removal of DOC

Predict the DOC removal using alum for the following conditions: initial DOC = 4 mg/L, pH 7, and $(\text{SUVA})_{\text{raw water}} = 2.5 \text{ L/mg} \cdot \text{m}$ using the general model. Assume the molar concentration of alum is 0.1 mM.

Solution

1. Rearrange Eq. 9-25 to determine $[C]_{\text{eq}}$:

$$\frac{[1 - (\text{SUVA})_{\text{raw water}} K_1 - K_2] \text{DOC}_{\text{initial}} - [C]_{\text{eq}}}{M} = \frac{(x_3 \text{pH}^3 + x_2 \text{pH}^2 + x_1 \text{pH}) b [C]_{\text{eq}}}{1 + b [C]_{\text{eq}}}$$

- a. Substitute variables in for terms in Eq. 9-25 to simplify:

$$A = [1 - (\text{SUVA})_{\text{raw water}} K_1 - K_2] \text{DOC}_{\text{initial}}$$

$$B = (x_3 \text{pH}^3 + x_2 \text{pH}^2 + x_1 \text{pH}) b$$

- b. Rearrange Eq. 9-25 with substituted variable and develop an expression for $[C]_{\text{eq}}$:

$$\frac{A - [C]_{\text{eq}}}{M} = \frac{B [C]_{\text{eq}}}{1 + b [C]_{\text{eq}}}$$

$$b [C]_{\text{eq}}^2 + (MB + 1 - Ab) [C]_{\text{eq}} - A = 0$$

- c. Solve the quadratic equation and use the positive expression:

$$[C]_{\text{eq}} = \frac{-(MB + 1 - Ab) + \sqrt{(MB + 1 - Ab)^2 + 4bA}}{2b}$$

ADSORBABLE FRACTION STILL IN SOLUTION.

2. Substitute known quantities into the quadratic expression and solve for $[C]_{\text{eq}}$ using alum.

- a. From Table 9-9, the required constants for alum are $K_1 = -0.075$, $K_2 = 0.56$, $b = 0.147$, $x_1 = 284$, $x_2 = -74.2$, and $x_3 = 4.91$.

- b. Substitute the constant values and solve for A and B:

$$A = [1 - (\text{SUVA})_{\text{raw water}} K_1 - K_2] \text{DOC}_{\text{initial}} = 2.51$$

$$B = (x_3 \text{pH}^3 + x_2 \text{pH}^2 + x_1 \text{pH}) b = 5.34$$

- c. Substitute the values of A and B into the equation developed in step 1 and solve for the adsorbable fraction of the DOC, $[C]_{eq}$:

$$[C]_{eq} = \frac{-(5.34 M + 1 - 0.369) + \sqrt{(5.34 M + 1 - 0.369)^2 + 1.476}}{0.294}$$

$$= 1.76 \text{ mg/L}$$

ADSORBABLE FRACTION
STILL IN SOLUTION

3. Determine the DOC remaining.

- a. Determine the nonadsorbable DOC using Eq. 9-22:

$$\begin{aligned} \text{nonadsorbable DOC} &= [K_1(\text{SUVA})_{\text{raw water}} + K_2] \times \text{DOC}_{\text{initial}} \\ &= [(-0.075 \times 2.5) + 0.56] \times 4 \text{ mg/L} \\ &= 1.49 \text{ mg/L} \end{aligned}$$

- b. Determine the DOC remaining using Eq. 9-21:

$$\begin{aligned} \text{DOC remaining} &= [C]_{eq} + \text{nonadsorbable DOC} \\ &= 1.76 + 1.49 = 3.25 \text{ mg/L} \end{aligned}$$

Of the 3.25 mg/L DOC remaining, 1.49 mg/L is nonadsorbable, and 1.76 mg/L is adsorbable but not adsorbed.

4. Determine the DOC removal:

$$\begin{aligned} \text{DOC removal} &= \text{DOC initial} - \text{DOC remaining} \\ &= 4 - 3.25 = 0.75 \text{ mg/L} \end{aligned}$$

Alternative Techniques to Reduce Coagulant Dose

A number of alternative techniques have been evaluated to reduce the coagulant dose, including (1) preozonation and (2) the use of selective ion exchange resins. These techniques are discussed briefly below.

COAGULANT REDUCTION THROUGH USE OF OZONATION

It has been reported that preozonation can be used to improve NOM removal in some instances; however, the results have proven to be quite variable.

For high DOC concentrations, the optimum coagulant dosage is dictated by the required DOC removal, and ozone dosages in the range of 0.1 to 2.0

AGGREGATION MODELLING

8. Particle Collision/Aggregation - General Model

- Fundamental problem in modelling coagulation - flocculation process -
 - Predicting the change in particle size distribution with time for a given chemical and hydrodynamic condition.
- In general ...

→ Particle of size d_i collide with particle d_j forming particles of size d_k ; at the same time ...

Aggregates of size d_k may break-up into smaller aggregates due to hydrodynamic shearing forces.

Thus, mathematically:

$$N_{ij} = \beta (d_i, d_j) n_i n_j \quad [1]$$

of collisions per unit time per unit volume = collisions frequency function x particle concentrations

$$\beta = f \left(\begin{array}{l} \text{size of particles,} \\ \text{flocculation transport} \\ \text{mechanism} \end{array} , \begin{array}{l} \text{efficiency} \\ \text{of particle} \\ \text{collisions for} \\ \text{attachment} \end{array} \right)$$

The general model for aggregation;

$$\text{Friedlander, 1917} \Rightarrow \frac{dn_k}{dt} = \frac{1}{2} \sum \beta (d_i, d_j) n_i n_j - n_k \sum \beta (d_i, d_k) n_i \quad [2]$$

formation rate of aggregates of size d_k = sum of all collisions between i & j particles - disappearance of d_k aggregates due to collisions between k particles and all others.

Note: Assumes no particle break-up.

- However, more simplified models are required for design purposes.
- Particle collisions in water can occur by 3 different processes:

(a) **Brownian Diffusion** (Thermal Effects) = perikinetic flocculation.

- Minor influence on particles $> 1 \mu\text{m}$.

- $\beta_{BD} = \frac{8}{3} \alpha \frac{\bar{k}T}{\mu}$ = collision frequency function

\bar{k} = Boltzmann's constant

T = absolute temp. ($^{\circ}\text{K}$)

μ = dynamic viscosity

$$\alpha = \frac{\text{collision freq. factor}}{\text{attachment rate}} = \frac{\text{collision rate}}{\text{collision rate}}$$

(sticking factor)

$$= 0 - 1$$

↑ every collision results in an attachment

- Combining with the general model for formation rate of aggregates, Eqn [2]:

$$\boxed{\frac{dN_T}{dt} = \frac{4}{3} \alpha \frac{\bar{k}T}{\mu} N_T^2} \leftarrow \text{2nd order Rxn.} \quad [3]$$

where $N_T = \sum n_k$.

Rate constant = $5.4 \times 10^{-15} \frac{\text{L}}{\text{sec}}$ @ 20°C assumed $\alpha = 1$.

- ∴ Conclude aggregation by Brownian diffusion/flocculation is relatively slow process.

Example:

Assuming $\alpha = 1$

20°C

$N_T = 10^8$ particles/L.

- ∴ To reduce conc. of particles by $1/2$ using Brownian flocculation will require 20 days!

(b) **Fluid Shear Flocculation** (flow effects = orthokinetic flocculation)

- Mechanical mixing employed to accelerate aggregation of coarse-size particles ($> 1\mu\text{m}$):

$$\beta_{SH} = \frac{8}{\pi} G V_i$$

where V_i = volume of i particles of size d_i .

- Substituting in general model neglecting break up ...

$$\frac{dN_T}{dt} = - \frac{K_A}{\pi} \alpha \phi G N_T \quad [4]$$

where

$$\phi = \frac{\text{volume of particles}}{\text{unit volume of solution}} = \sum n_i \frac{\pi d_i^3}{6}$$

or

$$\ln \frac{N}{N_0} = - \left(\frac{4\alpha\phi G}{\pi} \right) t \rightarrow \text{a good way to determine } \alpha$$

Handwritten note: $\ln \frac{N}{N_0} = -K_A G t$

Notes ...

- (i) G can be engineered
- (ii) Floc break-up cannot be neglected
- (iii) Heterogenous (wide size dist.) particles will result in higher rates of aggregation.

(c) Differential Sedimentation

$$\beta_{DS}(d_i, d_j) = \frac{\pi(\rho_p - \rho)g\alpha}{72\mu} (d_i + d_j)^3 |d_i - d_j| \quad [5]$$

- For suspensions containing a wide range of particle sizes, diff. sed. can be a significant transport mechanism.

Example: Problem

Consider a *particulate suspension of spherical particles with only two sizes, 100 and 1 μm . Compare the collision frequency factor for transport by Brownian motion, fluid shear, and differential sedimentation in a low fluid-shear environment, using the following data:*

$$G = 1 \text{ sec}^{-1}$$

$$\Delta\rho = 10 \text{ kg/m}^3$$

$$\mu = 0.001 \text{ kg/m-sec } (T = 20^\circ\text{C})$$

$$\alpha = 1.0$$

Solution

for $d = 1 \mu\text{m}$, we have

$$\beta_{Br} = 1.08 \times 10^{-17} \text{ m}^3/\text{sec}$$

$$\beta_{sh} = \frac{8Gv_i}{\pi}$$

Since $v_{100 \mu\text{m}} > v_{1 \mu\text{m}}$ the 100- μm particle dominates β due to shear. Thus,

$$\beta_{sh} = 1/33 \times 10^{-12} \text{ m}^3/\text{sec}$$

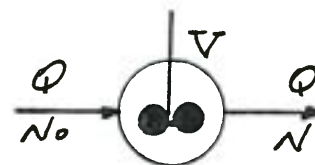
For the collision frequency of differential sedimentation, we obtain

$$\beta_{sed} = 4.36 \times 10^{-13} \text{ m}^3/\text{sec}$$

which is roughly 30 percent of the shear collision frequency factor. Thus, in low-shear systems such as sedimentation basins, differential sedimentation can become an important transport mechanism.

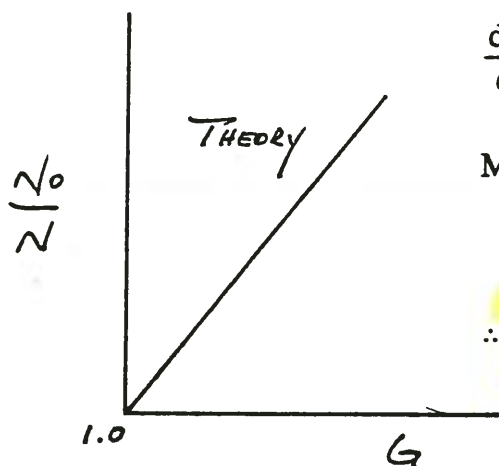
Applications to Process Design:

9. Kinetics of Flocculation (Fluid Shear)



$$-\frac{dN}{dt} = K_A GN \quad \text{where } N = \text{remaining turbidity and } K_A = \text{empirical aggregation constant} = \frac{4\alpha\phi}{\pi}$$

1. Assuming no shear

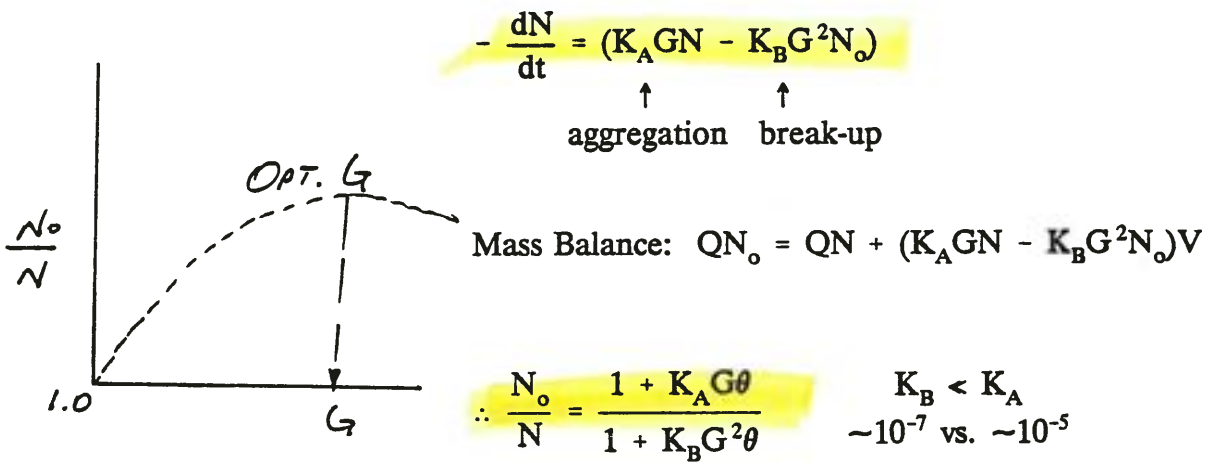


$$\frac{dN}{dt} = -K_A GN$$

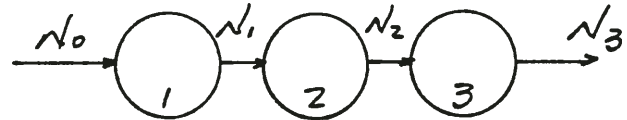
$$\text{Mass Balance: } QN_0 = QN - \frac{dN}{dt} V = QN + K_A GNV$$

$$\therefore \frac{N_0}{N} = 1 + K_A G\theta \quad \text{or} \quad \frac{N}{N_0} = \frac{1}{1 + K_A G\theta}$$

2. Assuming shear (Kaufman)



3. Cascade of flocculators



$$\text{1st} \quad \frac{N_1}{N_0} = \frac{1}{1 + KG_1\theta}$$

$$\text{2nd} \quad \frac{N_2}{N_1} = \frac{1}{1 + KG_2\theta}$$

$$\text{3rd} \quad \frac{N_3}{N_2} = \frac{1}{1 + KG_3\theta}$$

$$\frac{N_3}{N_0} = \frac{N_3}{N_2} \cdot \frac{N_2}{N_1} \cdot \frac{N_1}{N_0} = \frac{1}{1 + KG_3\theta} \cdot \frac{1}{1 + KG_2\theta} \cdot \frac{1}{1 + KG_1\theta}$$

Table 6-4 Reported Kinetic Parameters: Flocculation Kinetics

System	Kinetic Parameters		Reference
	Aggregation, K_A	Breakup, K_B (sec)	
Kaolin-alum	4.5×10^{-5}	1×10^{-7}	Argaman (1970)
Kaolin-alum	2.5×10^{-4}	4.5×10^{-7}	Bratby (1977)
Natural particulates-alum	1.8×10^{-5}	0.8×10^{-7}	Argaman (1971)
Alum-phosphate precipitate	2.8×10^{-4}	3.4×10^{-7}	
Alum-phosphate plus polymer	2.7×10^{-4}	1×10^{-7}	Odegaard (1979)
Lime-phosphate, pH 11	5.6×10^{-4}	2.4×10^{-7}	

11 13. Jar Tests

- Permits laboratory studies on chemical coagulation and flocculation.
- Determines the
 - Effectiveness of various coagulants
 - Optimum dosage for coagulation
 - Optimum pH for coagulation
 - Concentration of coagulant aid
 - Most effective order in which to add various chemicals.
- The general for conducting a jar test may be outlined as follows:
 - (a) Fill six 1- or 2-liter beakers with a measured amount of water to be treated.
 - (b) Add the coagulant and/or other chemicals to each sample.
 - (c) Flash-mix the samples by agitating at maximum speed (100 rpm) for 1 min.
 - (d) Flocculate the samples at a stirring rate of 20-70 rpm for 10-30 min. Record the time of floc appearance for each beaker.
- (3) Stop the agitation and record the nature of the floc, clarity of supernatant, and settling characteristics of the floc.

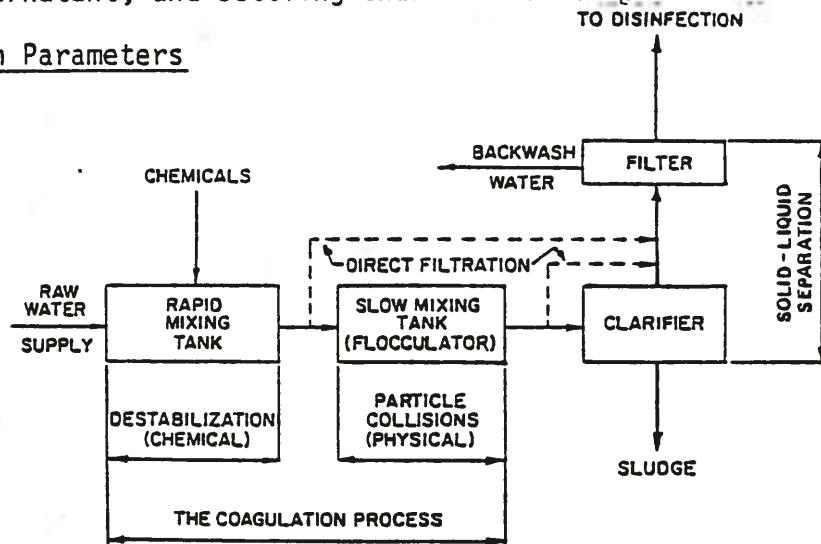
12 14. Summary of Design Parameters

Figure 1. Schematic diagram of a coagulation process in a water treatment plant.

a) Rapid Mixer

- Mechanical vs. baffled system vs. combination
- θ = detention time = 10-60 sec. with 30 sec. as average
- $G > 300 \text{ sec}^{-1}$ with 500 sec^{-1} average $> 1000 \text{ s}^{-1}$
- Power requirements = 0.25 - 1 hp/MG

b) Slow Mixer

- θ = detention time = 10-45 minutes
- $G = 20-80 \text{ sec}^{-1}$ $GT = 10^4 \text{ to } 10^5$
- Inlet and outlet design should prevent short-circuiting and destruction of floc
- Velocity of flocculated water through pipes or conduits to settling basins should not be less than 0.5 or greater than 1.5 fps.
- Agitators should be driven by variable-speed drives with the peripheral speed of paddles ranging from 0.5 to 2.0 fps.

TEN STATES STANDARDS

TREATMENT (GENERAL AND CLARIFICATION)

PART 4

4.1.2 Rapid mix

Rapid mix shall mean the rapid dispersion of chemicals throughout the water to be treated, usually by violent agitation. The engineer shall submit the design basis for the velocity gradient (G value) selected, considering the chemicals to be added and water temperature, color and other related water quality parameters.

- a. Equipment - Basins should be equipped with mechanical mixing devices.
- b. Mixing - The detention period should be not more than thirty seconds.
- c. Location - The rapid mix and flocculation basin shall be as close together as possible.

4.1.3 Flocculation

Flocculation shall mean the agitation of water at low velocities for long periods of time.

- a. Basin Design - Inlet and outlet design shall prevent short-circuiting and destruction of floc. A drain and/or pumps shall be provided to handle dewatering and sludge removal.
- b. Detention - The flow-through velocity shall be not less than 0.5 nor greater than 1.5 feet per minute with a detention time for floc formation of at least 30 minutes.
- c. Equipment - Agitators shall be driven by variable speed drives with the peripheral speed of paddles ranging from 0.5 to 3.0 feet per second.
- d. Piping - Flocculation and sedimentation basins shall be as close together as possible. The velocity of flocculated water through pipes or conduits to settling basins shall be not less than 0.5 nor greater than 1.5 feet per second. Allowances must be made to minimize turbulence at bends and changes in direction.
- e. Other designs - Baffling may be used to provide for flocculation in small plants only after consultation with the reviewing authority. The design should be such that the velocities and flows noted above will be maintained.
- f. Superstructure - A superstructure over the flocculation basins may be required.

4.1.4 Sedimentation

Sedimentation shall follow flocculation. The detention time for

DESIGN OF COAGULATION UNITS AND CHEMICAL APPLICATION

By Shamim Hasan

I. Chemical application and the flash mixing system are main factors in effective water treatment.

A. Chemical application involves the coagulant and other chemicals pertinent for the process water to achieve treatment goals.

B. A suitably chosen coagulant destabilizes the charge on colloids and SS (including bacteria and viruses) and flash mixing quickly and uniformly disperses the coagulant throughout the water process. This process is called coagulation.

C. Important design considerations

1. Type of coagulant to be employed
2. Number of chemicals to be fed into the system and the characteristics of each
3. Alternatives in flash mixing systems
4. Types of chemical diffusers
5. Subsequent processes
6. Available headloss for the flash mixer; raw water conditions
7. Local conditions for cost and efficiency reasons
8. Variations in the plant flow rate

D. Design choices are based on effectiveness, reliability, minimal maintenance and cost.

E. General design criterion for flash mixing is the velocity gradient G (in sec^{-1}).

F. Flash mixing system should be 0.3% of total construction cost.

II. Type of coagulant to use

A. The type sets the design criteria for the flash mixing system and for effective flocculation and clarification.

B. Most common coagulants

1. Metal salt coagulants (aluminum sulfate, ferric chloride, ferric sulfate)
 - hydrolysis occurs within 1 second and readily adsorbs to colloid particles which causes destabilization of their electrical charge; the hydrolytic products are quickly polymerized through hydrolytic reactions.
 - dispersion of metal coagulants should be complete within 1-2 seconds.
2. Synthetic polymers (e.g. polydiallyl dimethyl ammonium, cationic polymers)
 - all polymers do not undergo hydrolysis when fed to the process water. For example: hydrolytic reactions do not occur when cationic polymers are fed to the process water, therefore flash mixing is not critical; the rate of colloid adsorption is much slower because of their large physical size.
 - dispersion of polymers should be complete within 2-5 seconds.

C. Importance of flash or instantaneous mixing

1. Hydrolysis and polymerization are very fast reactions.
2. A uniform supply of coagulant and a uniform process water pH are essential for the production of hydrolytic products.
3. Adsorption of these species to colloidal particles occurs quickly.

III. Number of chemicals to add and their characteristics

A. Typically 2 or 3 chemicals are fed into the flash mixer. Most common coagulants are alum and ionic and non-ionic polymers. Most common chemicals are potassium permanganate, chlorine, PAC, ammonia, lime and caustic soda.

proportion to this plant flow rate.

B. If seasonal plant flow fluctuation is too great to satisfy this product, the design must provide two parallel hydraulic flash mixing systems where one system is used during low flow season.

C. Mixing energy must be adjusted to satisfy the proper $G \times t$ range due to variations in mixing time.

XI. Design Criteria

A. The effect of coagulation is affected by the shape of the reactor tank, the degree of flow short-circuiting, the type of mixing element, the degree of energy input and the effective mixing time.

B. Appropriate design parameters should be based on: 1) chemical diffusion rates 2) the degree of turbulence associate with the inertial forces (use power number), and 3) Reynolds number. BUT THE WIDELY ACCEPTED GENERAL DESIGN CRITERION FOR FLASH MIXING IS THE VELOCITY GRADIENT (G):

$$G = (P/uV)^{0.5}$$

where, P= power input

u = absolute viscosity of water

V = volume of the mixing zone

C. Effective design criteria

1. The product of the mixing energy ($G \text{ sec}^{-1}$) and mixing time (sec) should range between 300 to 1600 for effective flash mixing.

2. Pump diffusion: $Gxt = 400-1600$; mixing velocity = 20-25 fps at orifice

3. In-line static mixers: $Gxt = 350-1700$; $t=1-5\text{sec}$

D. See Integrated Design of Water Treatment Facilities(pp80-93) for examples on flash mixing and chemical application design.

E. Jar test should be performed to optimize coagulant, chemical application sequence, mixing energy and time and to evaluate the clarifier and filtration performance and corrosive characteristics of settled water.

XII. Operation and Maintenance

A. Most important factor is the selection of proper chemicals and the application of the correct quantities to an ever changing raw water quality and plant flow rate.

B. Constant monitoring of the chemical feed and flash mixing systems.

C. Adjustment of the mixing energy due to changes in plant flow.

D. Plants equipped with mechanical flash mixers should have the motor and speed reducer, mixer shaft run-out, vibrations, and noises checked on a regular basis.

B. Standard criteria for the evaluation of utilized chemicals

1. Necessity of instantaneous mixing.
2. Potential chemical reactions that prevent the process chemicals from acting individually.
3. The proper chemical application sequence (to raw water) to yield most effective results.
 - This is very important because 1) it produces good quality results and reduces the total chemical cost, 2) it is vital for low alkaline raw water so proper addition of alkaline chemicals along with alum are possible.

IV. Alternatives in the flash mixing process

A. Most conventional treatment plants produce quality water without the use of a flash mixer provided that coagulant used is in excess of 30-40% of the required dosage when using the flash mixer.

B. Diffusion mixing by pressured water jets

1. This is the first choice of flash mixing systems because there is essentially no additional head loss by the mixer, it is effective, it has a controllable degree of mixing, it has low power consumption (half of mechanical mixer), it is cost effective and all parts are "off the shelf".
2. Disadvantages- there is potential of the coagulant to clog the nozzles and it difficult to apply it to a system with extra large pipes or channels (> 100 in. diam).

C. In-line static mixers

1. Advantages- lack of moving parts, no requirement of external energy to be put into the system, fewer clogging problems than the pump diffusion type of mixers.
2. Disadvantages- degree of mixing and mixing time are a function of low rate, units are proprietary items and design engineer must rely on performance claims of manufacturer.

D. Hydraulic Mixing

1. Types of mixing devices are parshall flumes, venturi type meters and weirs.

E. Mechanical flash mixing

1. Most frequently used type of flash mixing unit
2. Design parameters: $G = 300 \text{ s}^{-1}$, time = 10-30 sec, hp = 0.25-1.0 hp/mgd
3. Not preferred for continuous flow process due to 1) lack of instantaneous mixing characteristics 2) production of significant flow short-circuiting 3) a mixing period that is too long for metal salt coagulant 4) backmixing

F. Diffusion by pipe grid

1. This depends on the wake turbulence created by the pipe grids
2. Clogging of orifices is a problem after several months
3. This method should only be included on pilot scale installations

V. Chemical Diffusers (see Figure 1 for illustrations- p. 70) - The type of diffuser depends on whether chemicals fed to the flash mixing system are in solution or slurry.

A. Diffusers for slurry

1. Pipe application uses the open end of the diffuser pipe as the diffuser.
2. Channel flow uses a trough with notches or holes at the bottom.

B. Diffusers for solutions are most often a pipe with multiple orifices for pipe and channel flow application.

C. Clogging of diffuser orifices is a major concern. Provisions for a periodic cleaning should be included in the design of the feed system (extra diffuser).

D. Figure 2 illustrates basic design criteria for multi-orifice diffusers (p. 71).

VI. Subsequent Processes

A. The coagulant dosage and the degree of pretreatment can be quite different depending on the type of treatment processes that will be after the flash mixing.

B. The four basic process trains used in modern water treatment are in-line filtration, direct filtration, two-stage filtration and complete conventional treatment.

1. In-line, direct and two-stage filtration have no sedimentation process thus requiring low levels of coagulant (2-6 mg/L) and when inadequate flash mixing of coagulant occurs this results in higher filtered water turbidity because the small amount of coagulant fails to disperse uniformly.

2. Modified complete conventional treatments include lime softening and high-level complete treatment processes, such as ozonation and GAC adsorption. These processes have sedimentation and thereby allow the formation of good settleable floc provided an adequate dose of alum is applied (15-30 mg/L). An effective flash mixing system requires 30-40% less alum.

C. Sludge conditioning and wash waste clarification is treated differently from ordinary water treatment because of the high concentration of solids. The coagulant used in alum sludge conditioning is a polymer. Polymers do not require instant mixing therefore the optimum is: $G=100-150 \text{ s}^{-1}$ and $t \leq 1 \text{ min}$.

VII. Available head loss for the flash mixer

A. A headloss of 2 ft is generally required to ensure good mixing for the flash mixer. A pressure valve or electric power generator could be used to reduce pressure in the raw water line of the treatment plant.

B. When headloss is not allowable pump diffusion should be used.

C. When instantaneous mixing is not necessary, a pipe diffuser system should be used.

VIII. Important Raw Water Characteristics

A. Hardness of process water and dissolved and suspended solids are directly related to clogging of chemical diffuser orifices and feed lines. Easy cleaning processes should be used on diffusers and feed lines.

B. pH and alkalinity

C. Temperature effects are minimal

IX. Local conditions for cost and efficiency reasons - this will affect the plant in a practical and aesthetic viewpoint

A. Availability of equipment and parts.

B. Availability of services within the area.

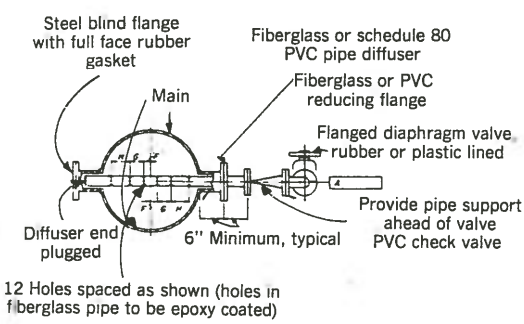
C. Reliability of the power supply.

D. Winter temperatures/ wind storms

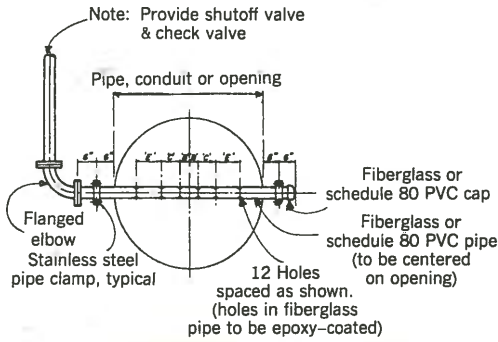
E. Vandalism

X. Variation in plant flow rate

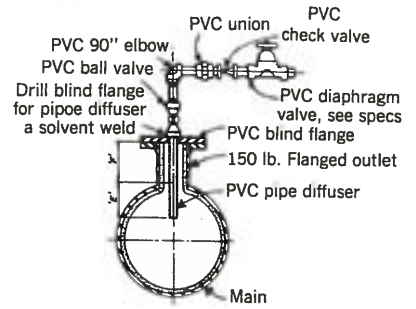
A. Variations in water demand causes fluctuations in the plant flow rate on daily and seasonal bases. The mixing energy of the hydraulic flash mixing system must change in



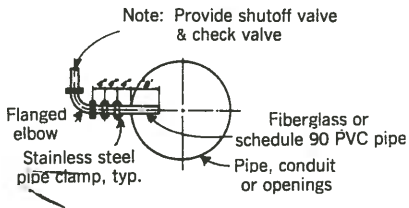
Type A: In-line Diffuser



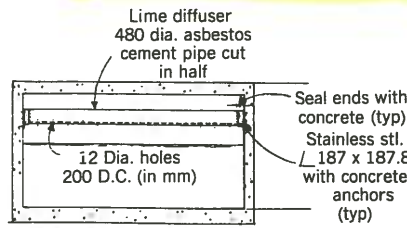
Type B: In a Tank Inlet or in a Channel



Type C: In-line (Removable)



Type D: In a Tank Inlet or in a Structure



Type E: Gravity Feed from a Trough Above Water Surface



Type F: Fine-bubble Gas Diffusers

Figure 3.2.3-3 Chemical diffusers.

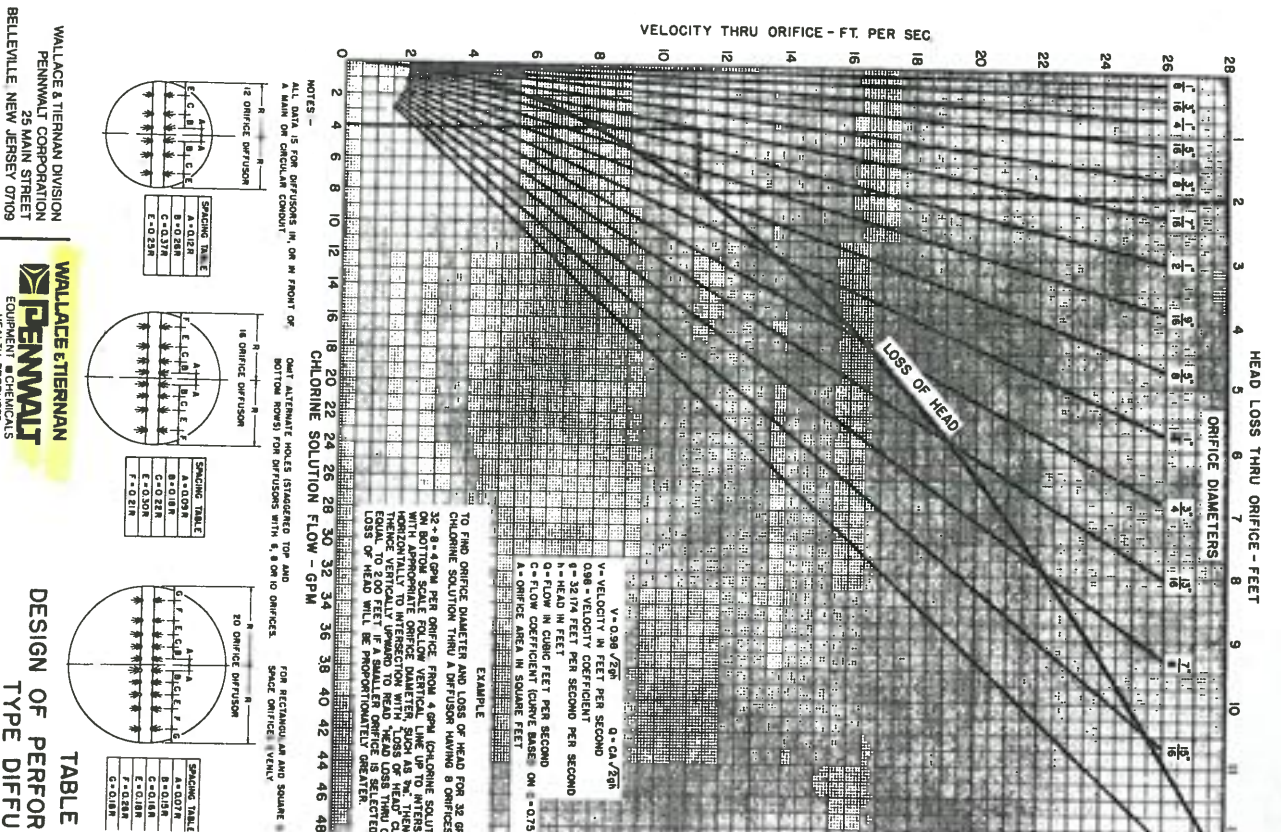


Figure 3.2.3-4 Diffuser pipe design guide.

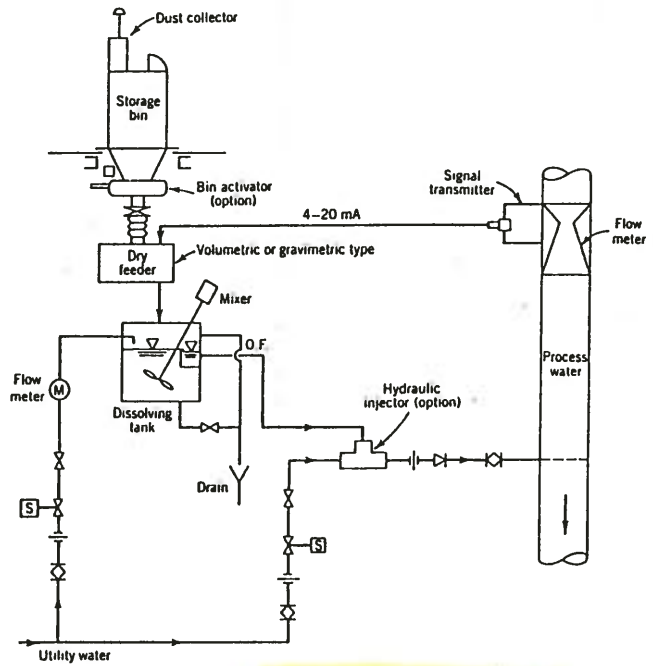


FIGURE 21-5. Dry chemical feeding system (typical).

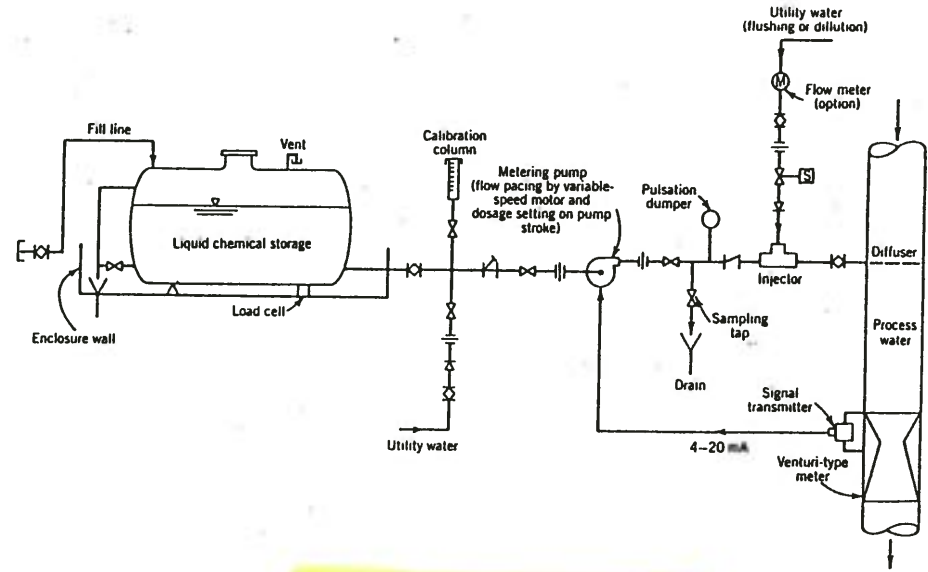


FIGURE 21-2. Typical metering pump feeding system.

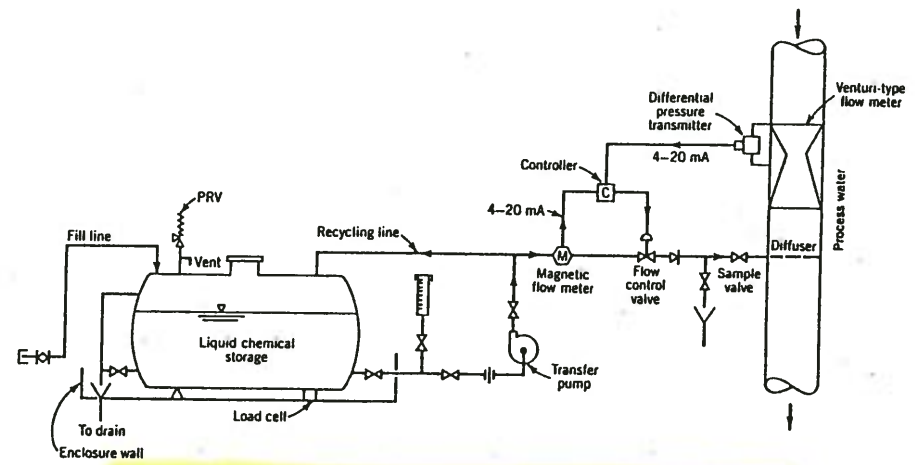
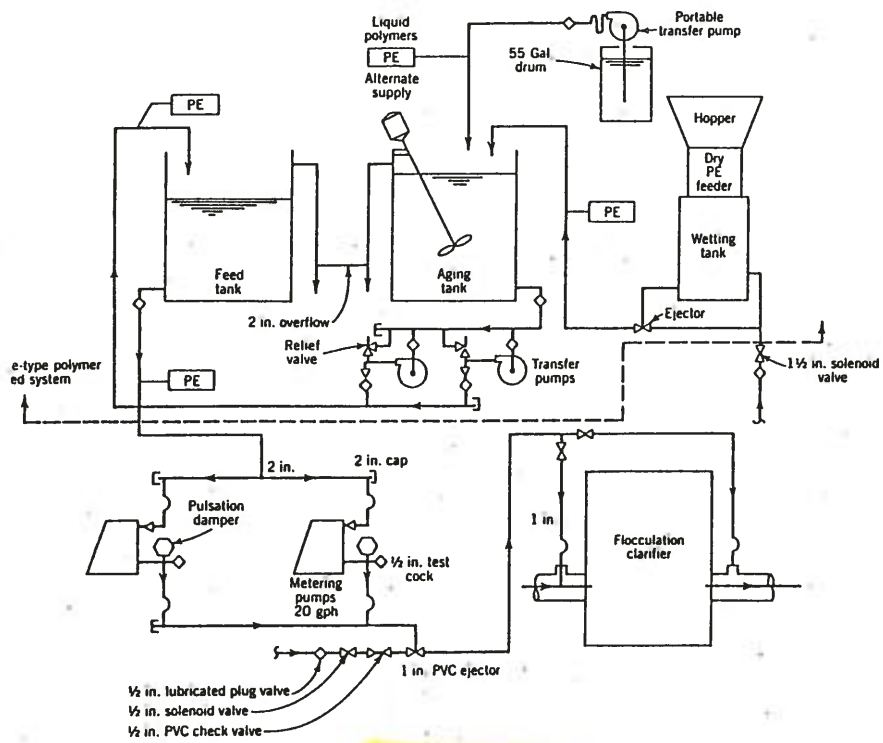


FIGURE 21-3. Flow-placing solution feed system (closed-loop control with magnetic flow meter).

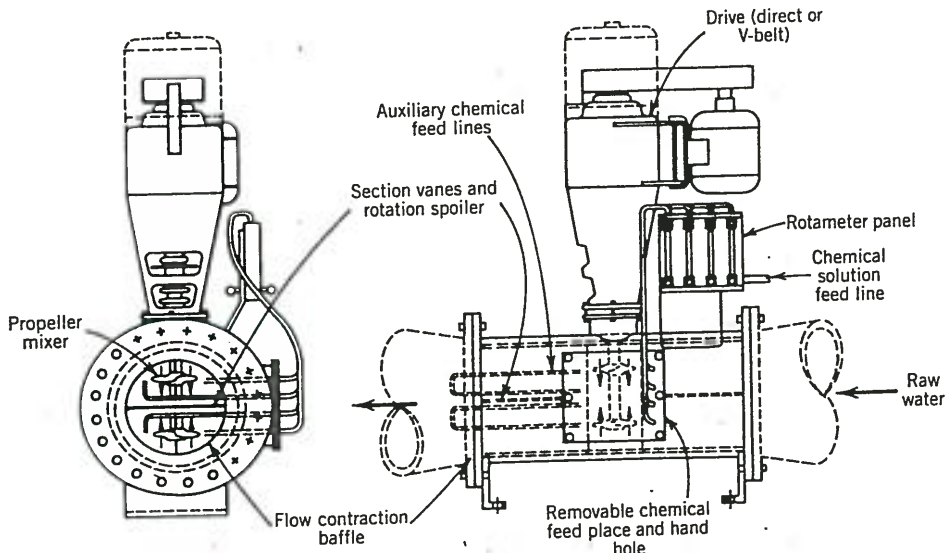


FIGURE 21-9. In-line blender flash mixer. (Courtesy of Walker Process.)

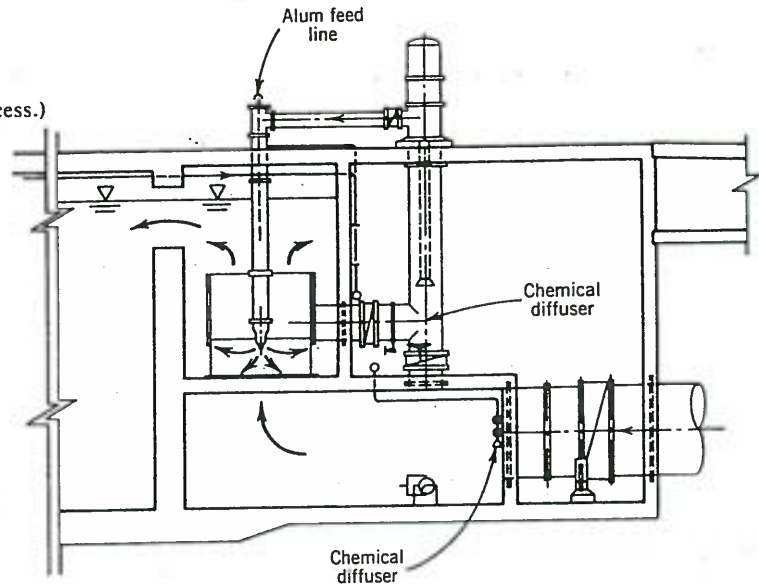


FIGURE 21-10. Pump injection-diffusion flash mixer.

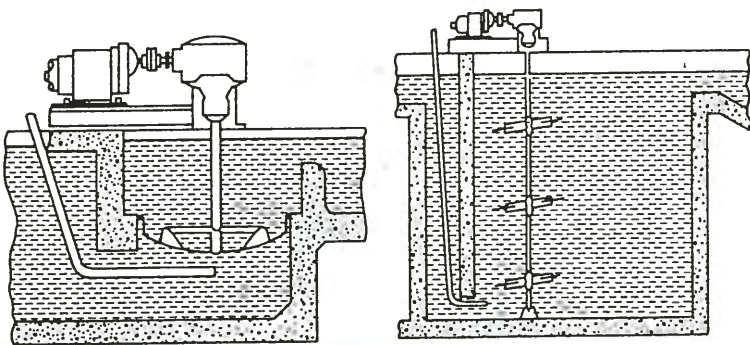


FIGURE 21-11. Mechanical flash mixing system. (Reprinted with permission from *Water Quality and Treatment*, American Water Works Association. Copyright 1971, McGraw-Hill Book Company.)

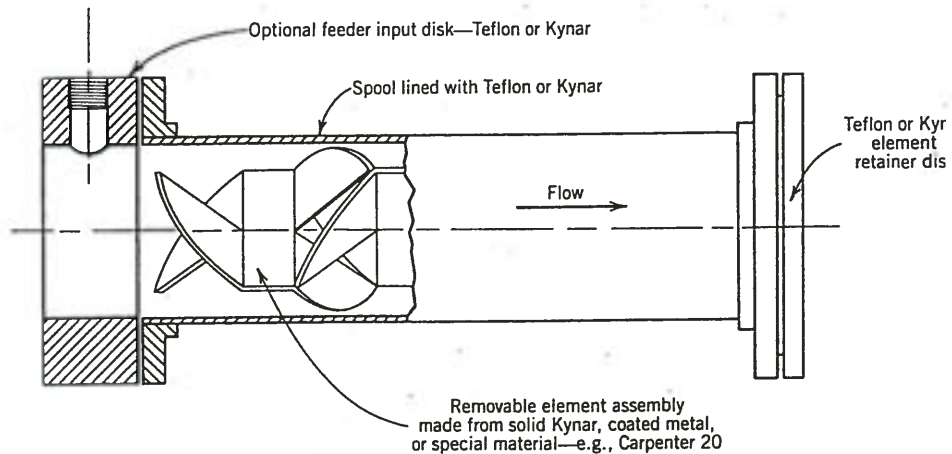


FIGURE 21-8. Motionless (static) mixer. (Courtesy of KOMAX.)

FLOCCULATION

Doug Crimi

Purpose - To accelerate the rate of particle collisions, causing the agglomeration of electrolytically destabilized colloidal particles (via molecular motion and physical mixing of the fluid) into settleable and filterable sizes.

I. Flocculation Process Design Considerations

A) Raw water quality and flocculation characteristics

- 1) raw water quality: turbidity, TOC, pH, alkalinity, color, algae counts, temperature
- 2) water quality data for wet and dry seasons, pref. 1 year
- 3) jar tests determine floc characteristics (size, cohesiveness, settleability, etc.)

B) Design requirements are based on treatment process and finished water quality goals

- 1) modify flocculation process to better enable rest of treatment train to accomplish goals (maximum removal of contaminant in most cost effective way)
- 2) improve flocculation and sedimentation steps of the process train and effectively remove: color as a THM precursor, algae as a source of taste and odor, asbestos fibers (limitations), and certain toxic metals and compounds
- 3) eg. direct filtration process, flocculation tanks should not produce large settleable flocs since a sedimentation process is not involved

C) Available hydraulic headloss and plant flow variations

- 1) if limited allowable headloss is approx. < 2-3 ft., hydraulic flocculation methods ruled out and forced to use mechanical methods
- 2) if year round flow rate fluctuation is +/- 50 % from daily average flow rate, hydraulic flocculation is applicable and will perform effectively

D) Local conditions (site topography, climate conditions, availability of services, capability of the operational personnel, and level of the local technology)

E) Cost (evaluate both initial or capital costs as well as operation and maintenance costs)

F) Relation to existing treatment facilities

- 1) rule of thumb: make all the flocculation units identical so that uniform performance and operation and maintenance procedures can be maintained

G) Miscellaneous

- 1) hydraulic characteristics of the flocculation tank
 - a) prevention of flow short-circuiting
 - b) creation of effective eddies and turbulence
 - c) minimization of high shear forces created by the mixing blades
- 2) scum and sludge removal

II. Flocculation process selection guidelines and alternatives (mechanical mixers and baffles)

A) Selection guidelines

1) flocculation process

- a) type of treatment process (eg. conventional, direct filtration, softening, or sludge conditioning)

- b) raw water quality (eg. turbidity color, temp.)
- c) flocculation characteristics in response to changes in mixing intensity and mixing times

2) mixing

- a) local conditions (eg. wind, ice buildup, viscosity of gear oil in cold cond's)
- b) available head loss across the plant
- c) shape and depth of the basin
- d) capital and O & M costs

B) Alternatives

1) mechanical mixing systems

a) advantages

- 1) minimal maintenance
- 2) operational flexibility
- 3) very little headloss across tank
- 4) easy control of mixing intensity
- 5) effectiveness
- 6) minimal impact to the overall performance if one unit malfunctions

EX good raw water quality and direct filtration feasible, filter bed will usually be reverse graded high-rate filter bed such as a dual media type, therefore floc should be small but strong in order to resist the high shearing forces within the bed --- VERTICAL SHAFT HIGH-ENERGY FLOCCULATORS - See Figures 3.2.4-3 and 3.2.4-4

EX poor raw water quality (polluted or med.- high turbidity) - produce good floc and effective sedimentation (cold water regions) ---PADDLE FLOCCULATORS better floc due to large number of blades, larger total blade perimeter and larger blade surface area - See Figures 3.2.4-3 and 3.2.4-4

2) baffled channel system

- a) need moderate amt. of allowable head loss
- b) advantages: no mechanical parts, good for developing countries
- c) horizontally and/or vertically baffled
- d) two disadvantages: signif. headloss (1-2 ft.) and mixing intensity is function of flow rate

3) contact flocculation

- a) minimal maintenance
- b) similar to in-line filtration process
- c) advantages: -compact size and lack of moving parts
-hydraulic loadings of 10 - 15 gpm/ft²
-empty bed contact time 3 - 5 min
- d) disadvantages: system depends on minimal variations of plant flow rate

- 4) diffused air or water jet agitation
 - a) auxiliary or temporary measure due to high energy consumption and inefficient flocculation process

III. Design Criteria

A) General design criteria - See Tables 3.2.4-1 and 3.2.4-2

- 1) energy input: $G \times t = 1 \times 10^4$ to 1×10^5
 t is in seconds (5×10^4 s-1 avg.)
 or $G = 10 - 70$ s-1 (30s-1 avg.)
- 2) detention times: 20 - 30 min at maximum daily flow rate
- 3) water depth: 10 - 15 ft. (3-4.5 m)
- 4) flocculation stages: 2 - 6 stages (usually 3 - 4)
 - a) factors determining the number of flocculation stages
 - 1) type of subsequent treatment unit (sedimentation, filter, or sludge drying bed) and the type of overall process (direct filtration or complete process)
 - 2) quality and treatability of the raw water: Turbidity levels, the nature of the turbidity, and water temperature during the cold months
 - 3) degree of flow short-circuiting across the flocculation basin (with or without baffles) and the type of baffles
 - 4) local conditions: regulatory requirements and the operation and maintenance of the flocculation process

B) Vertical shaft flocculators

- 1) diameter of mixing blade (D) / tank diameter (T) < 0.35
- 2) max. flow velocity induced by the mixing blade: < 8 fps in first stage
 < 2 fps in last stage

C) Horizontal shaft flocculators

- 1) total paddle area = 10 - 25 % of the tank cross-sectional area
- 2) each arm should have a minimum of three paddles
- 3) peripheral speed of the paddles should be between 0.5 and 3.3 fps
- 4) $G = 50$ s-1 initially
 $= 5 - 10$ s-1 in last stage
- 5) direct filtration, design flocculation tanks with "around the end" channels
 flocculation tank part of rect. clarifier, flow direction for both processes should be the same

D) Baffled walls

- 1) compartmentalize each stage of the mechanical mixer flocculation process w/ proper baffled walls
- 2) each baffle should have orifices 4 - 6 in. in diameter uniformly distributed across its vertical surface
- 3) baffle velocity = 1.2 - 1.8 fps
- 4) submerge baffle 0.5 in. beneath water surface
- 5) if flocculation tank is designed as part of the sedimentation tank, baffle flow rate velocity < 0.8 fps

- 6) baffles produce additional mixing energy
- E) Baffled channel (hydraulic) flocculators
 - 1) approx. 6 channels
 - 2) headloss across flocculation tank must be approximately 1 - 2 ft
 - 3) avg. G value of 30 - 40 sec⁻¹
 - 4) minimum residence time of 20 min. at max. plant flow

IV. Order of Preference

- A) Vertical shaft flocculators, with hydrofoil type long blades, in horizontal flow tanks with proper compartmentalization in each flocculation stage
- B) Paddle flocculators in horizontal flow tanks with proper compartmentalization in each stage
- C) Baffled channel flocculation tanks for plants with fairly constant flow rates

V. Operation and Maintenance

- A) Three basic operational procedures
 - 1) check floc size by visual observation (submerged spotlight preferred at night, 12-18 in. below water surface)
 - 2) scum removal from surface (unsightly)
 - 3) control algae growth in tanks (unsightly, gives water objectionable taste and odor) - maintain +0.3 mg/l residual Cl to prevent algal growth
 - 4) if mechanical mixing is provided, inspect mixer speed control regularly (one speed will not work for all conditions)
 - 5) baffled channels require much less maintenance than mechanical mixers (less moving parts)

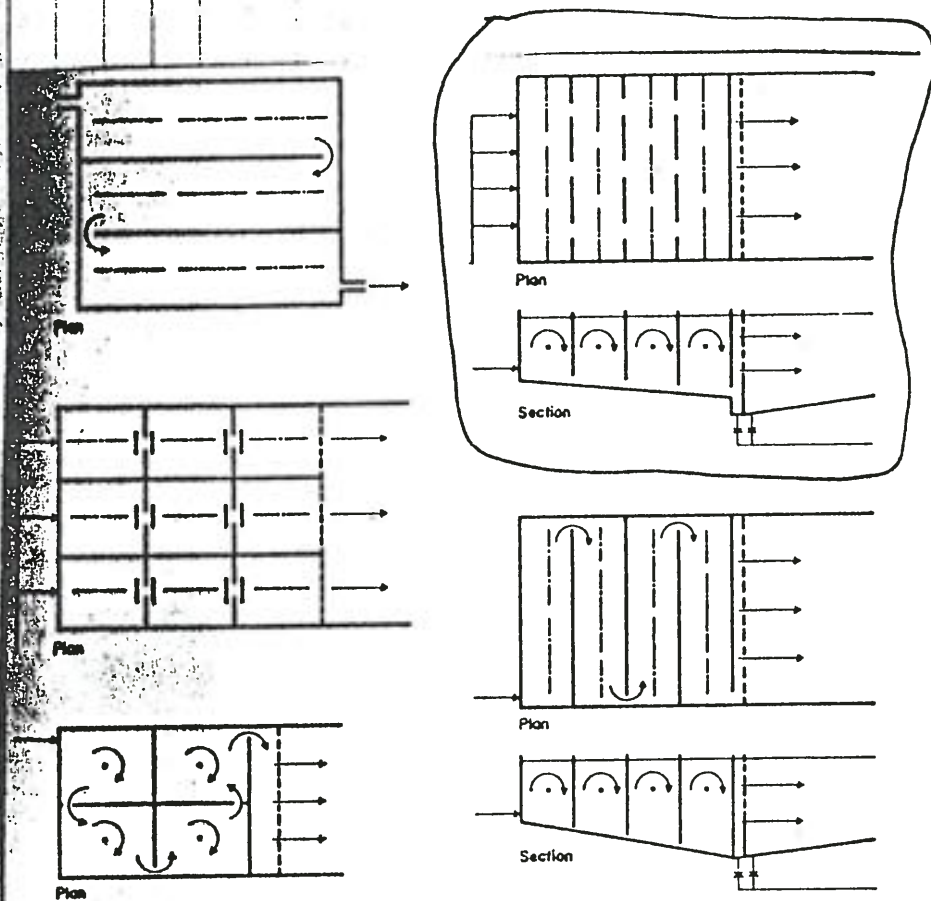


Fig. 8. Flocculator Layouts

Arrows represent the path of water flow. The easiest way to manage flocculated water is to build the flocculator and settling basin integrally, with a permeable baffle discharging the flocculated water into the basin to assure uniform horizontal and vertical distribution of settling basin inlet flow.

FLOCCULATORS

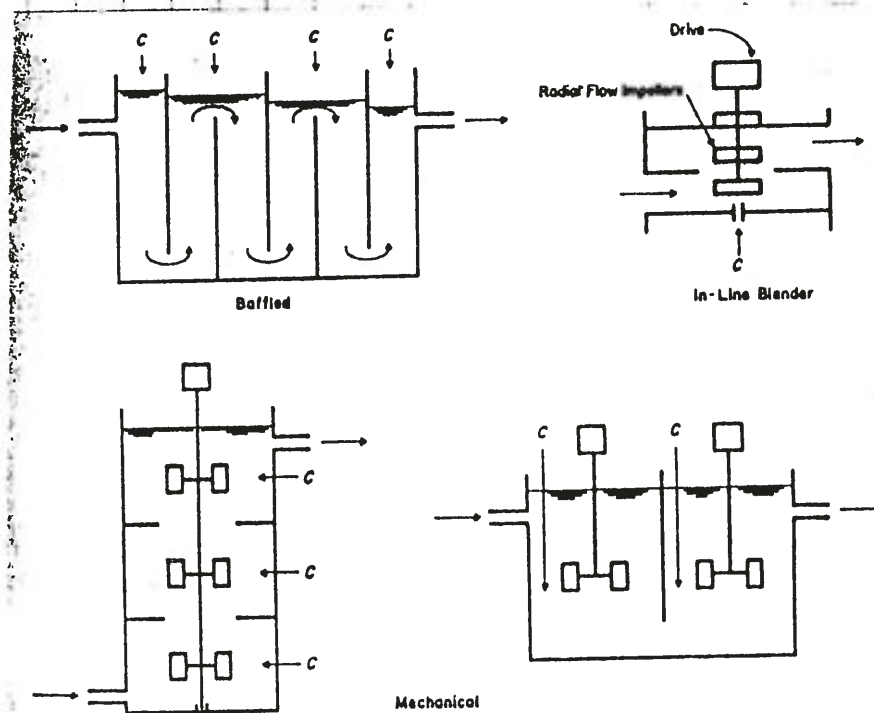
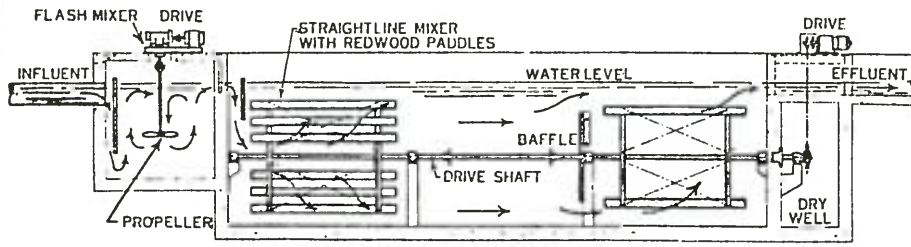


Fig. 4. Types of Rapid Mixers

O designates the point of chemical injection. Practice in design of rapid mixing units has been to provide 10-30-sec detention time with relatively high powered mixing devices, sized to yield velocity gradients in the order of 300 fps, or more.

RAPID MIXERS



(a)

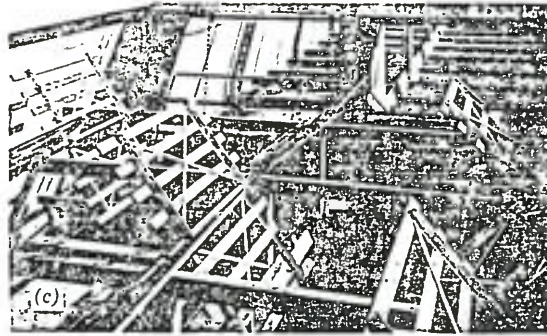
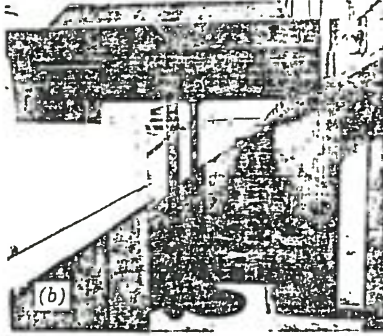


Figure 7-5 Straightline rapid mix and flocculation basin used in chemical treatment of water. (a) Longitudinal section of flash and horizontal slow mixers. (b) Propeller mixer provides rapid blending of chemicals into water. (c) Slow, horizontal-paddle mixer allows flocculation. (LINK-BELT Product, Courtesy of Environmental Equipment Division, FMC Corporation)

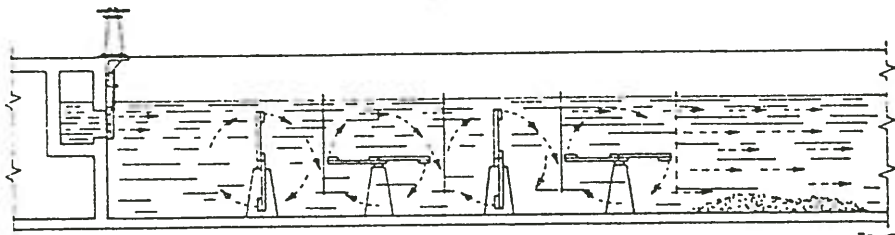


Fig. 8a Flocculating equipment. A series of paddles placed transversely across the tank width are arranged to impart a barrel-roll motion to the water.

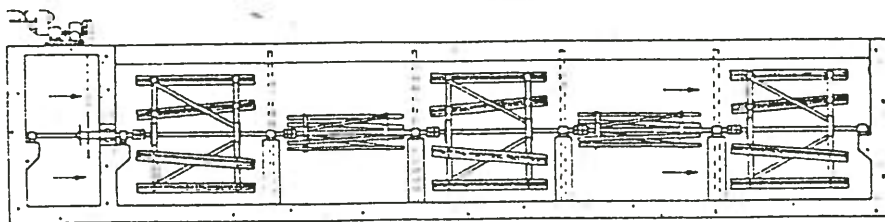


Fig. 8b Paddle reel flocculator. The intensity of mixing depends on the area of the paddle blades and the rotational speed of the shaft. The water flows in the direction of the drive shaft.

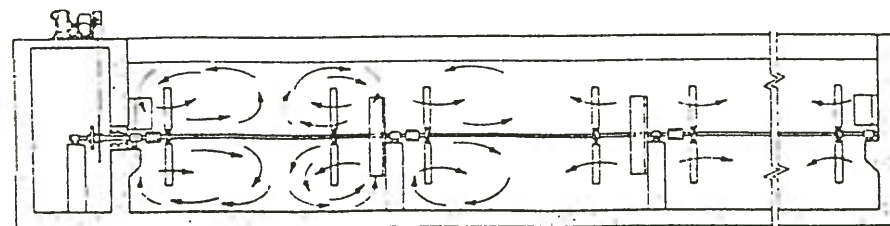
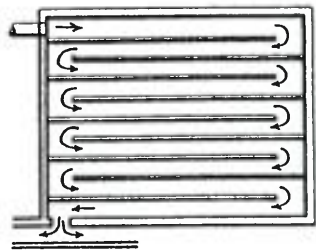
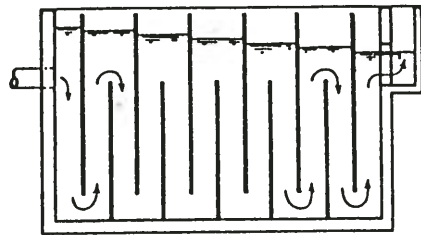


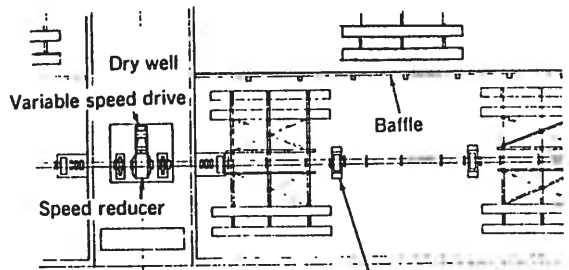
Fig. 8c Axial-flow propeller flocculator. This mixing unit is similar to the paddle reel flocculator.



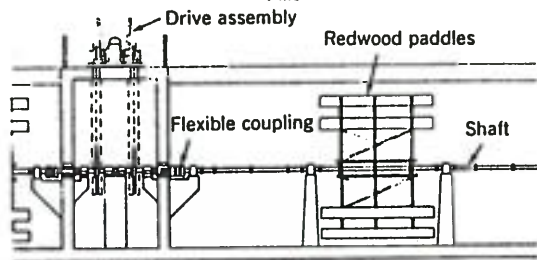
Plan of round-the-end baffled mixing basin.



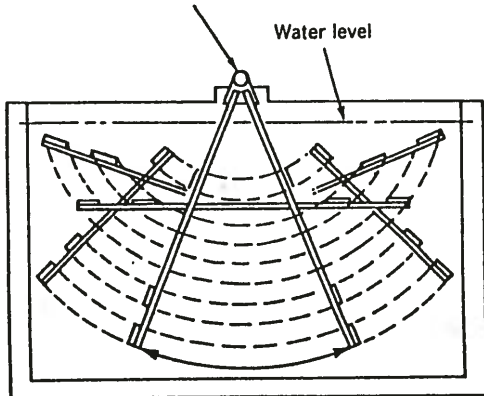
Section through over-and-under baffled mixing chamber.



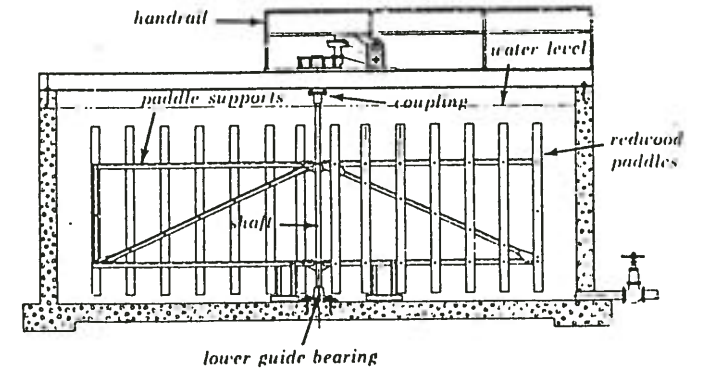
Flocculator of horizontal shaft with mixing paddles



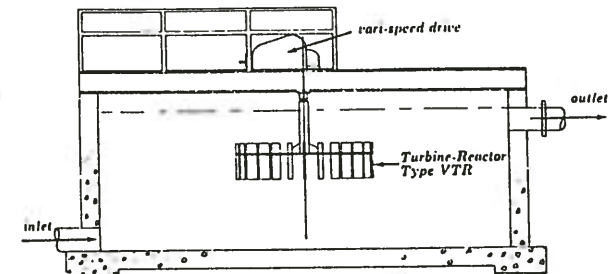
Shaft and bearings above water



Swinging paddle type flocculator

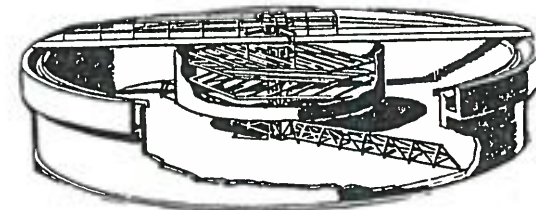


(a)



ILLUSTRATIVE SECTION

(b)



(c)

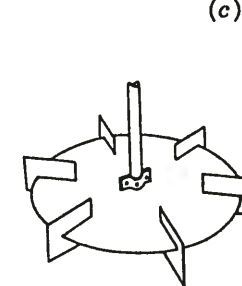
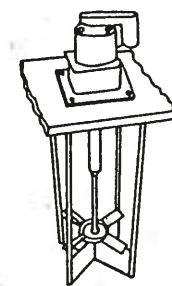


Plate turbine type.

(d)



Axial flow propeller type with straightening vanes.

(e)

Figure 3.2.4-4 Mechanical flocculators. (a) Paddle wheel on vertical shaft. (b) Turbine mixer. (c) Moving lattice type. (d) Plate turbine type. (e) Small size vertical shaft

TABLE 21-7. Flocculator Design Guidelines^a

Type of Flocculator	Basic Design Criteria	Advantages and Disadvantages
Vertical shaft	G value up to 100 sec^{-1} , maximum tip speed of 2 m/sec, approximately 5–10 m ² basin surface area per unit, downward flow pattern preferable for propeller unit, stator baffles should be provided for turbine units	Easy maintenance and few breakdowns. Suitable for high-energy input. Suitable for direct filtration and conventional treatment. Many units required for a large plant. High capital cost for variable-speed reducers and support slabs.
Horizontal-shaft paddle	G value up to 50 sec^{-1} , maximum tip speed of 1 m/sec, number of paddles adjusted for tapered mixing, paddle area should not exceed 20 percent of tank section area	Generally produces a large-size floc. Simple mixing unit. Suitable for conventional treatment. Need for precise installation and maintenance. Difficult to increase energy input. Problems with leakage and shaft alignment.
Baffled channel	Tapered mixing by adjusting baffles, maximum flow velocity of approximately 0.75 m/sec, end-around baffle used when total head loss across tank is limited	Performs well if the plant flowrate is reasonably constant. Little maintenance. A lack of flexibility for mixing intensity. High head loss for the over-and-under baffle.
Diffused air and water jets	$G = 95\text{--}20 \text{ sec}^{-1}$ or $Gt = 10^5\text{--}10^6$, may be used for auxiliary mixing when plant is overloaded	Simple installation and less capital cost. Limited amount of operational data available. High local velocities for water jet flocculators. High operational cost for air diffuser flocculators.

^a Mechanical flocculator units have more flexible mixing conditions. Proper compartmentalization and stator baffles improve the efficiency of mechanical flocculators. Thus, changing the unit or the blades may not always be necessary to achieve better flocculation.

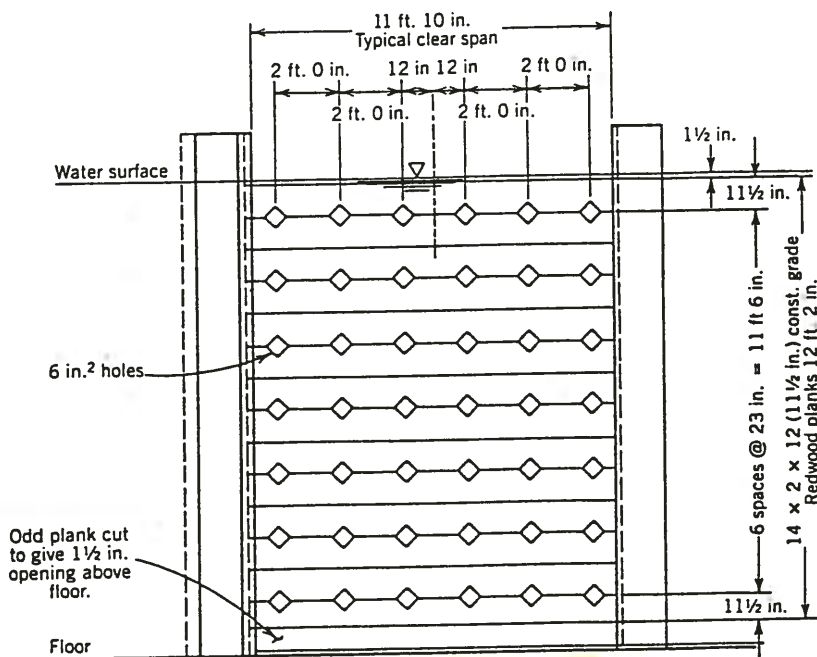


FIGURE 21-16. Baffle wall.

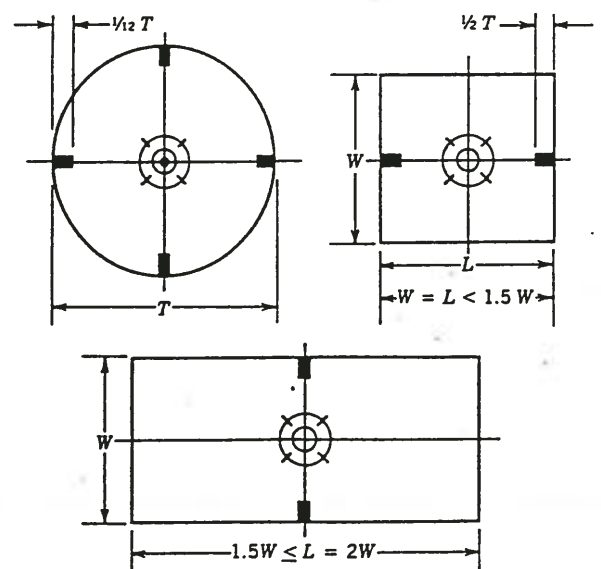


FIGURE 21-17. Schematic illustration of tank baffles. (Courtesy of Lightnin Mixing Equipment Co.)