Coagulation and Flocculation in Water Treatment

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Introduction

The need to clarify water

- Aesthetics and health
- Colloids – impart color and turbidity to water – aesthetical acceptability
- Microbes are colloids too

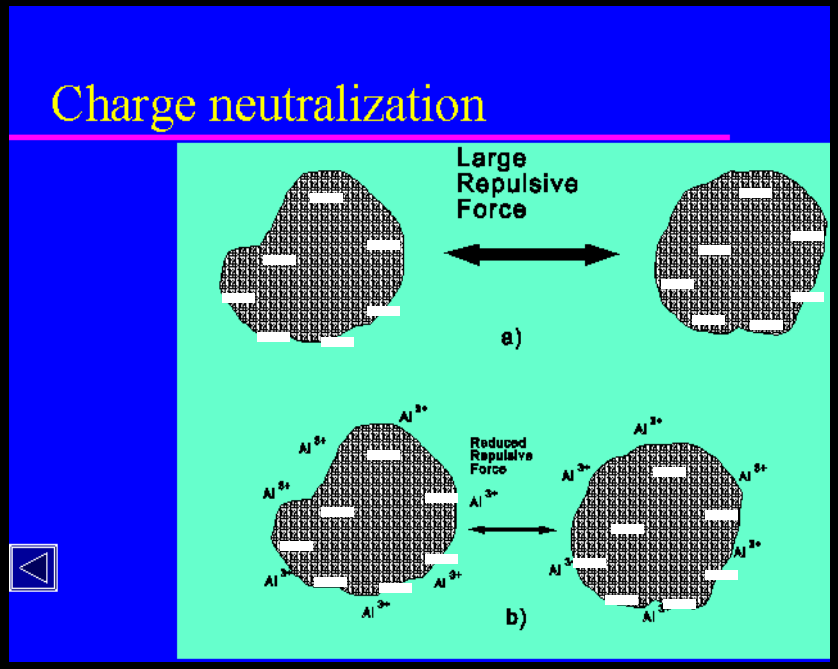
COAGULATION & FLOCCULATION

- Removal of colloidal substances from water

- Potable water requirements
- health, aesthetics, economic
- Colloids
- Size of colloids - light waves
- Brownian motion
- Stability of colloids

What is Coagulation?

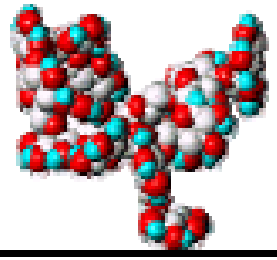
- **Coagulation** is the destabilization of colloids by addition of chemicals that neutralize the negative charges
- The chemicals are known as coagulants, usually higher valence cationic salts (Al^{3+}, Fe^{3+} etc.)
- Coagulation is essentially a chemical process



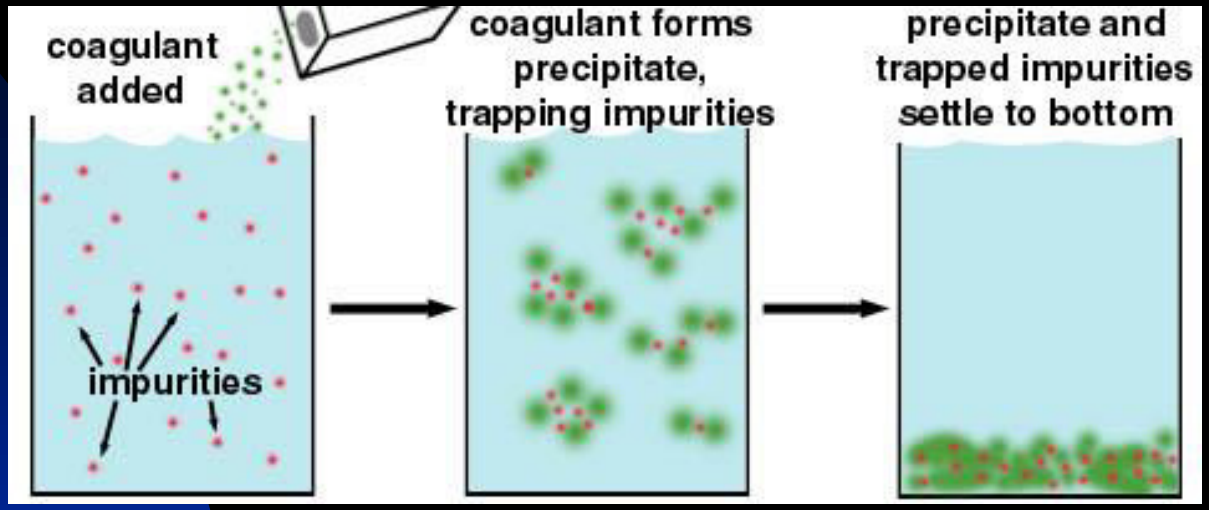
What is Flocculation?

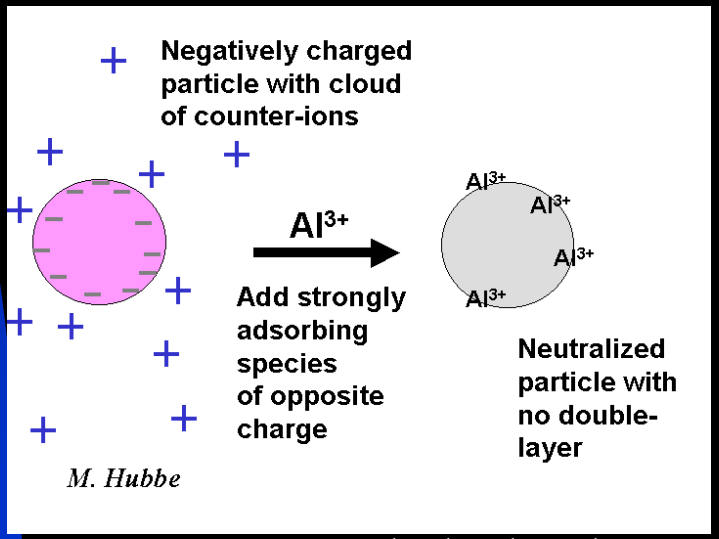
Flocculation is the agglomeration of destabilized particles into a large size particles known as flocs which can be effectively removed by sedimentation or flotation.

- Gentle mixing or ***flocculation***, then causes the destabilized (reduced charge) colloids to cluster.
- Another method of enhancing agglomeration is to add organic polymers.
- These compounds consist of a long carbon chain with active groups such as amine, nitrogen, or sulfate groups along the chain.



Coagulation aim





Why coagulation and flocculation?

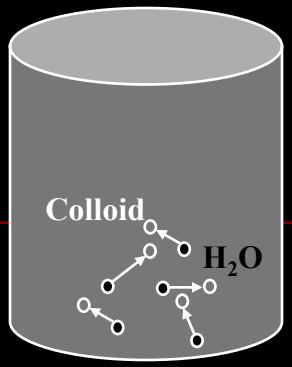
Various sizes of particles in raw water

Particle diameter (mm)	Type	Settling velocity
10	Pebble	0.73 m/s
1	Course sand	0.23 m/s
0.1	Fine sand	0.6 m/min
0.01	Silt	8.6 m/d
0.0001 (10 micron)	Large colloids	0.3 m/y
0.000001 (1 nano)	Small colloids	3 m/million y

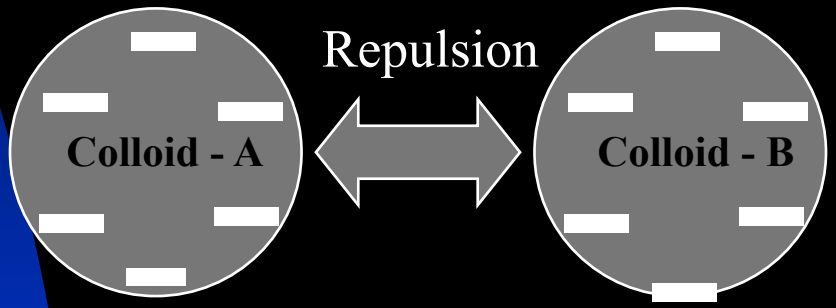
Gravity settling

Colloids – so small: gravity settling not possible

Colloid Stability



- ✓ Colloids have a net negative surface charge
- ✓ Electrostatic force prevents them from agglomeration



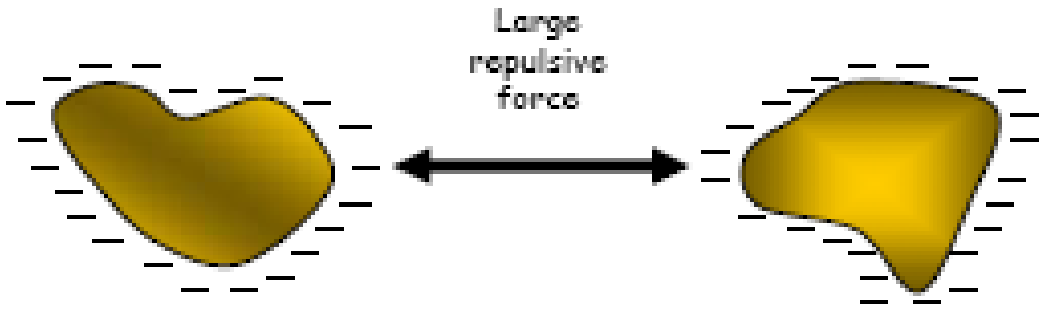
- ✓ Brownian motion keeps the colloids in suspension
- ✓ Impossible to remove colloids by gravity settling

Colloidal interaction

- There are two major forces acting on colloids:

1) electrostatic repulsion

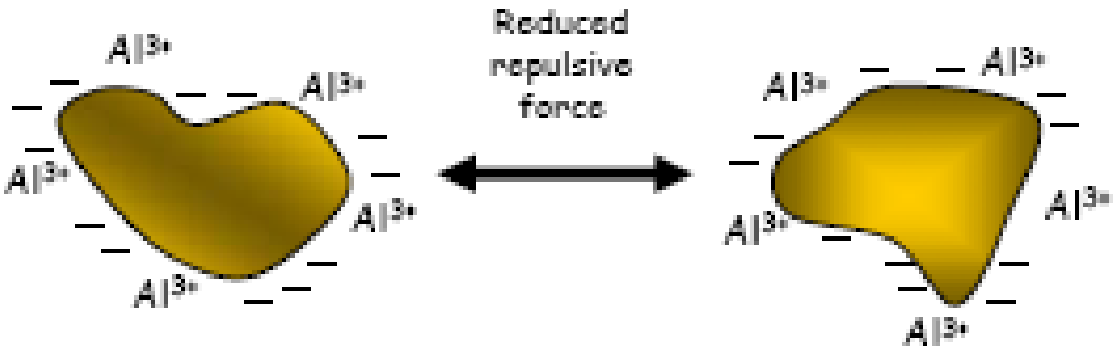
(simply, negative colloids repel other negatively charged colloids)



2) intermolecular, or van der Waals, attraction.

Charge reduction

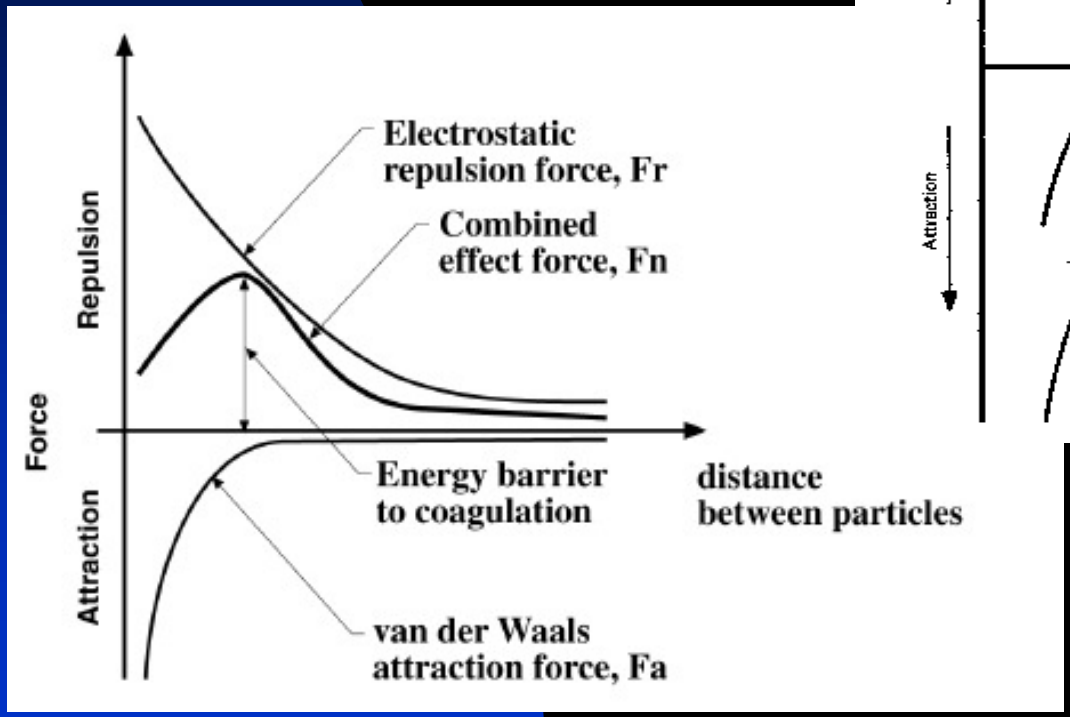
- Coagulants can be used to reduce the electrostatic repulsive forces
- The electrostatic repulsion reduced by the addition of countercharged ions [Al^{3+}]

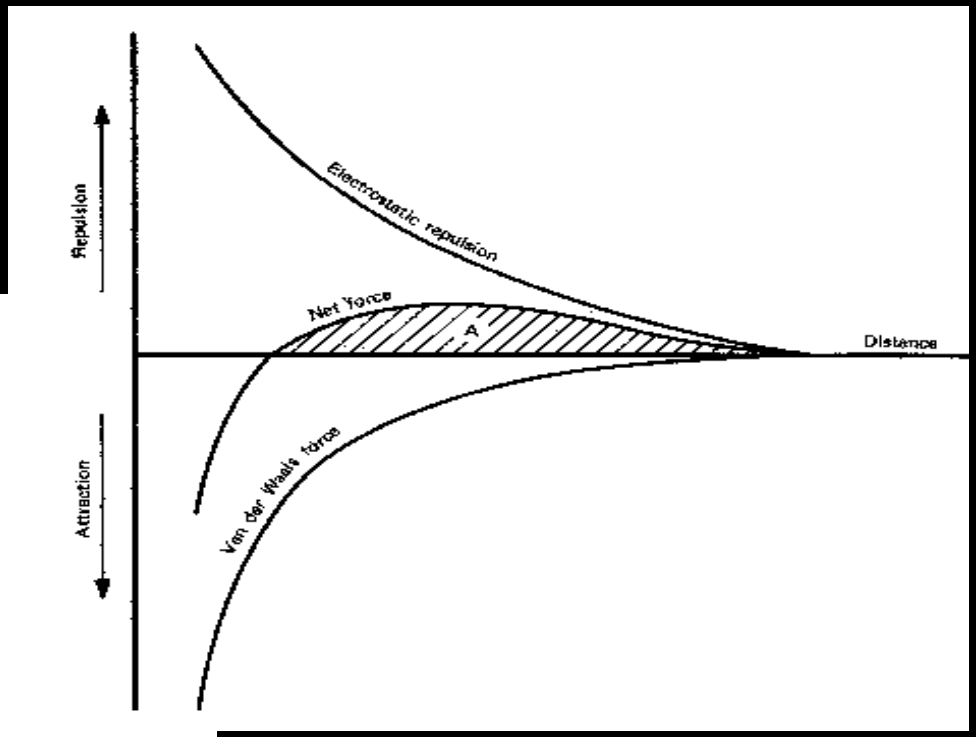


Colloid Destabilization

- Colloids can be destabilized by charge neutralization
- Positively charges ions (Na+, Mg2+, Al3+, Fe3+ etc.) neutralize the colloidal negative charges and thus destabilize them.
- With destabilization, colloids aggregate in size and start to settle

Force analysis on colloids

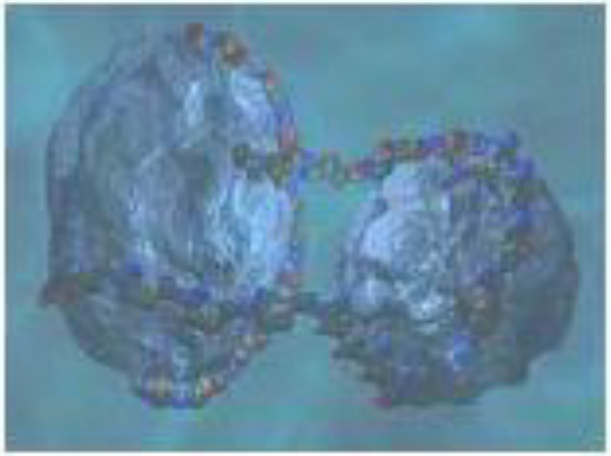


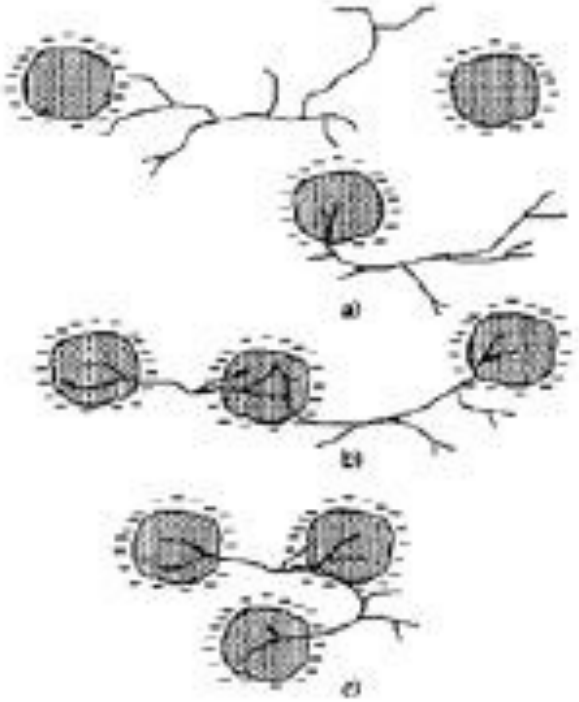


The integral of the combined forces is the energy barrier

Flocculation aids

- The chain is long enough to allow active groups to bond to multiple colloids





Floc formation with polymers

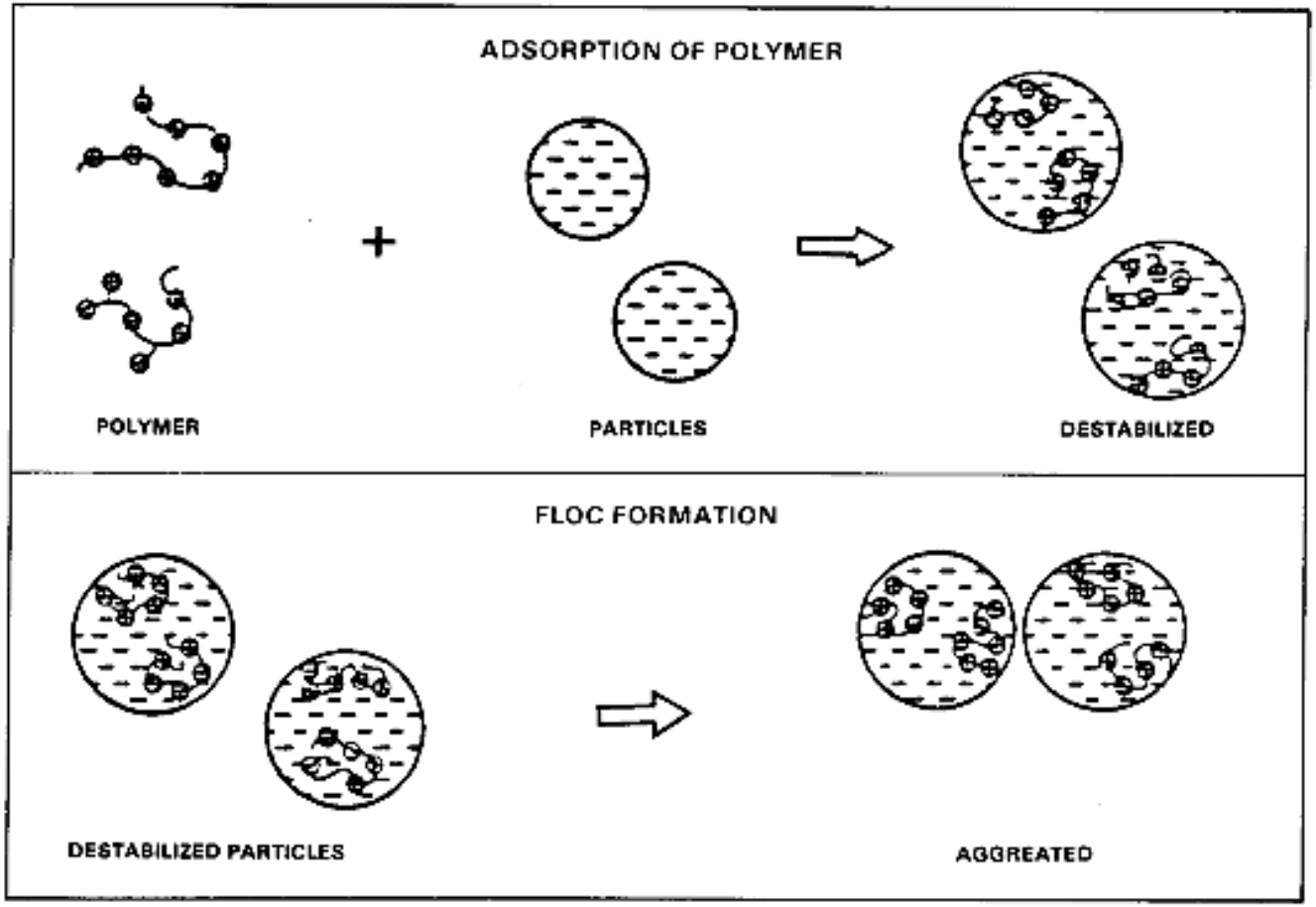


Figure 1-2. Floc formation process

Jar Tests

- The jar test – a laboratory procedure to determine the optimum pH and the optimum coagulant dose
- A jar test simulates the coagulation and flocculation processes

Determination of optimum pH

- Fill the jars with raw water sample (500 or 1000 mL) – usually 6 jars
- Adjust pH of the jars while mixing using H_2SO_4 or NaOH/lime (pH: 5.0; 5.5; 6.0; 6.5; 7.0; 7.5)
- Add same dose of the selected coagulant (alum or iron) to each jar (Coagulant dose: 5 or 10 mg/L)

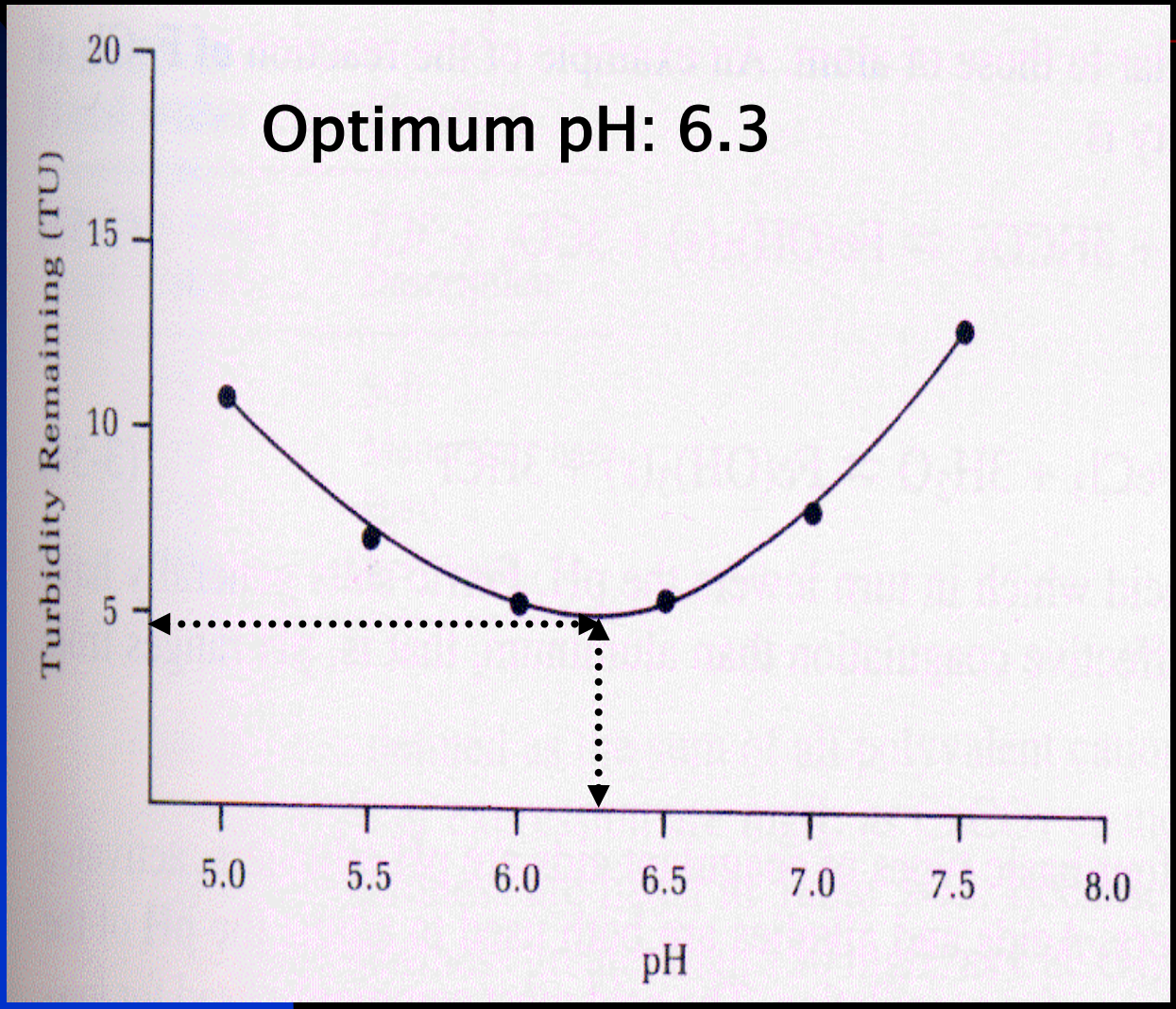
Jar Test

Jar Tests – determining optimum pH

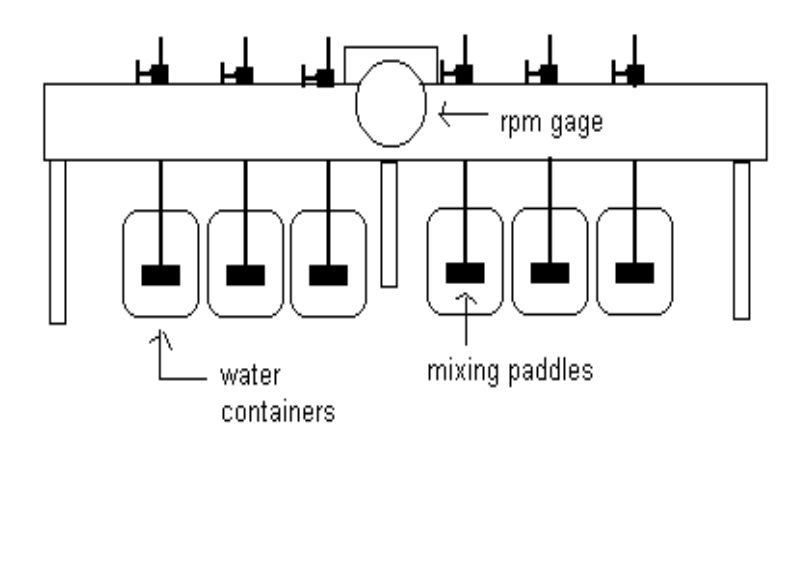
- Rapid mix each jar at 100 to 150 rpm for 1 minute. The rapid mix helps to disperse the coagulant throughout each container
- Reduce the stirring speed to 25 to 30 rpm and continue mixing for 15 to 20 mins This slower mixing speed helps promote floc formation by enhancing particle collisions, which lead to larger flocs
- Turn off the mixers and allow flocs to settle for 30 to 45 mins
- Measure the final residual turbidity in each jar
- Plot residual turbidity against pH

Jar Test set-up

Jar Tests – optimum pH



Optimum coagulant dose

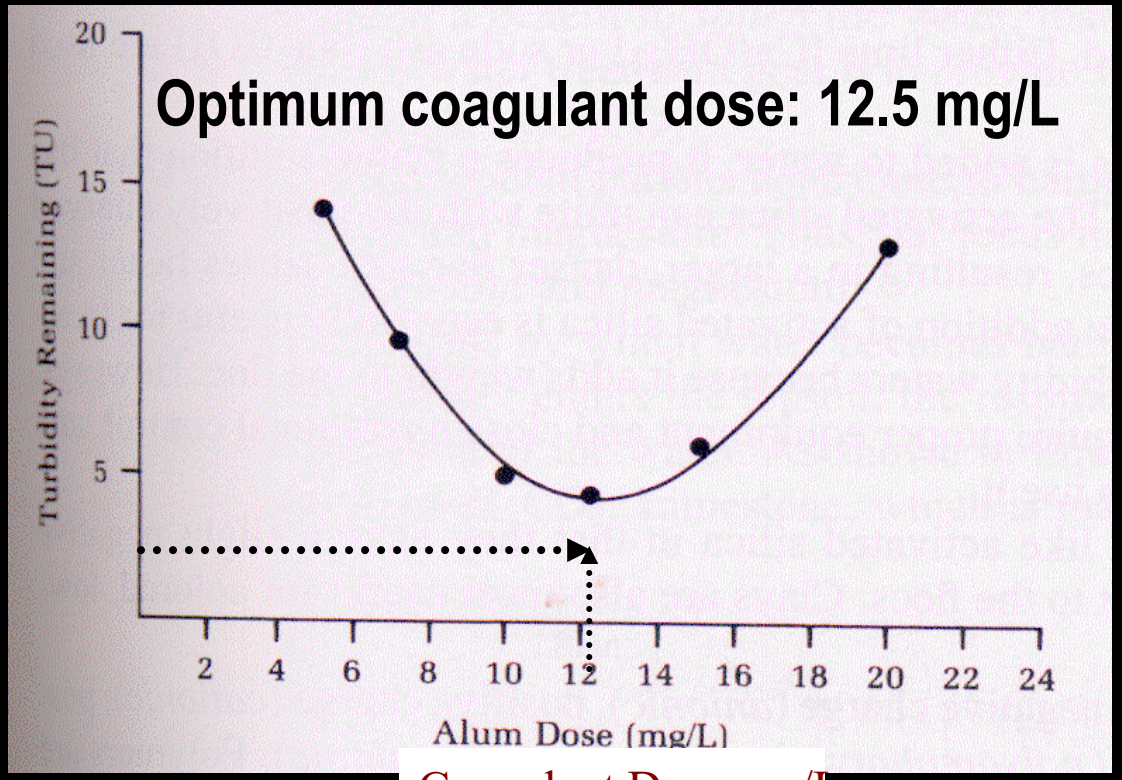


- Repeat all the previous steps
- This time adjust pH of all jars at optimum (6.3 found from first test) while mixing using H_2SO_4 or NaOH/lime
- Add different doses of the selected coagulant (alum or iron) to each jar (Coagulant dose: 5; 7; 10; 12; 15; 20 mg/L)
- Rapid mix each jar at 100 to 150 rpm for 1 minute. The rapid mix helps to disperse the coagulant throughout each container
- Reduce the stirring speed to 25 to 30 rpm for 15 to 20 mins

Optimum coagulant dose

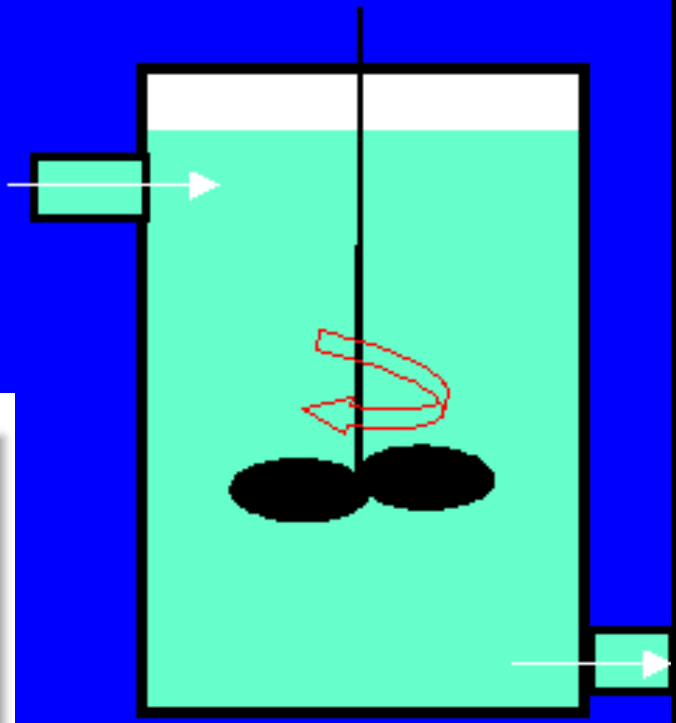
- Turn off the mixers and allow flocs to settle for 30 to 45 mins
- Then measure the final residual turbidity in each jar
- Plot residual turbidity against coagulant dose

The coagulant dose with the lowest residual turbidity will be the optimum coagulant dose

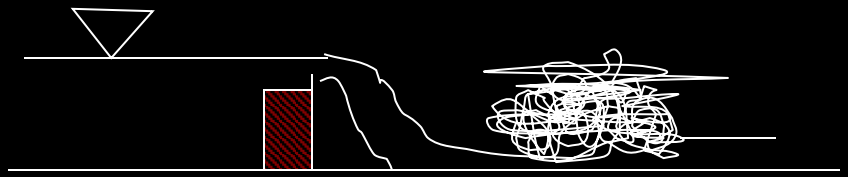


Coagulant Addition: Rapid Mix

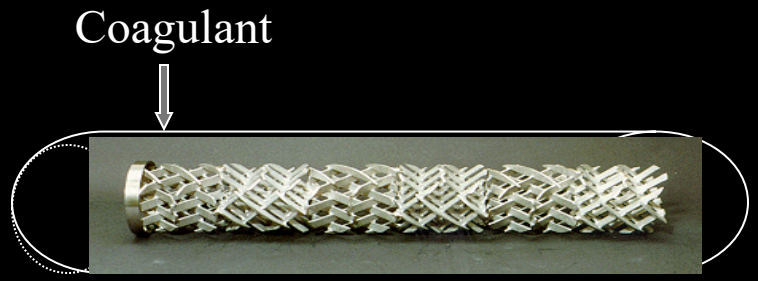
- Mixer
  - vertical shaft turbine impeller
- Tank
  - 3 to 10 ft diameter
  - flow through, top to bottom
  - 30 to 60 second detention time



- *Hydraulic Jump*: Hydraulic Jump creates turbulence and thus help better mixing.

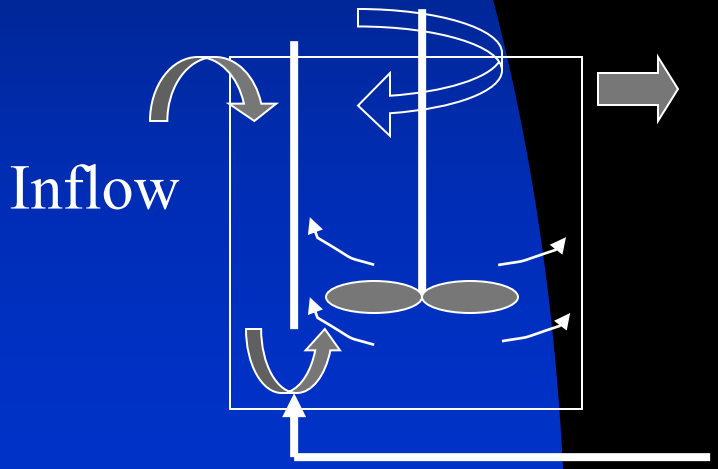


- *In-line flash mixing*

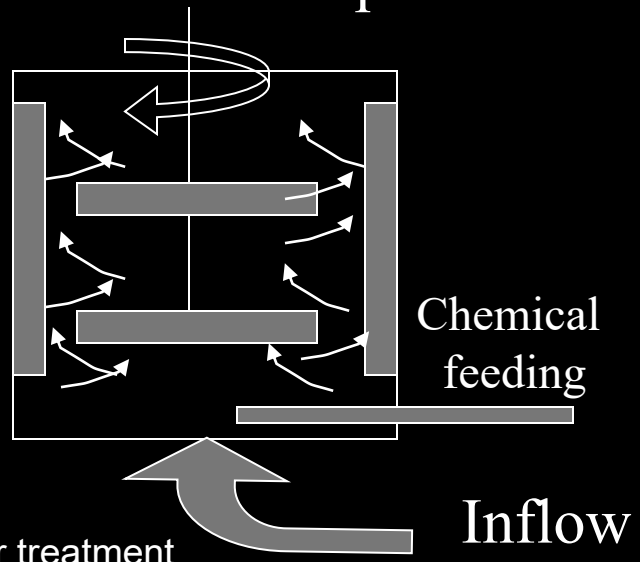


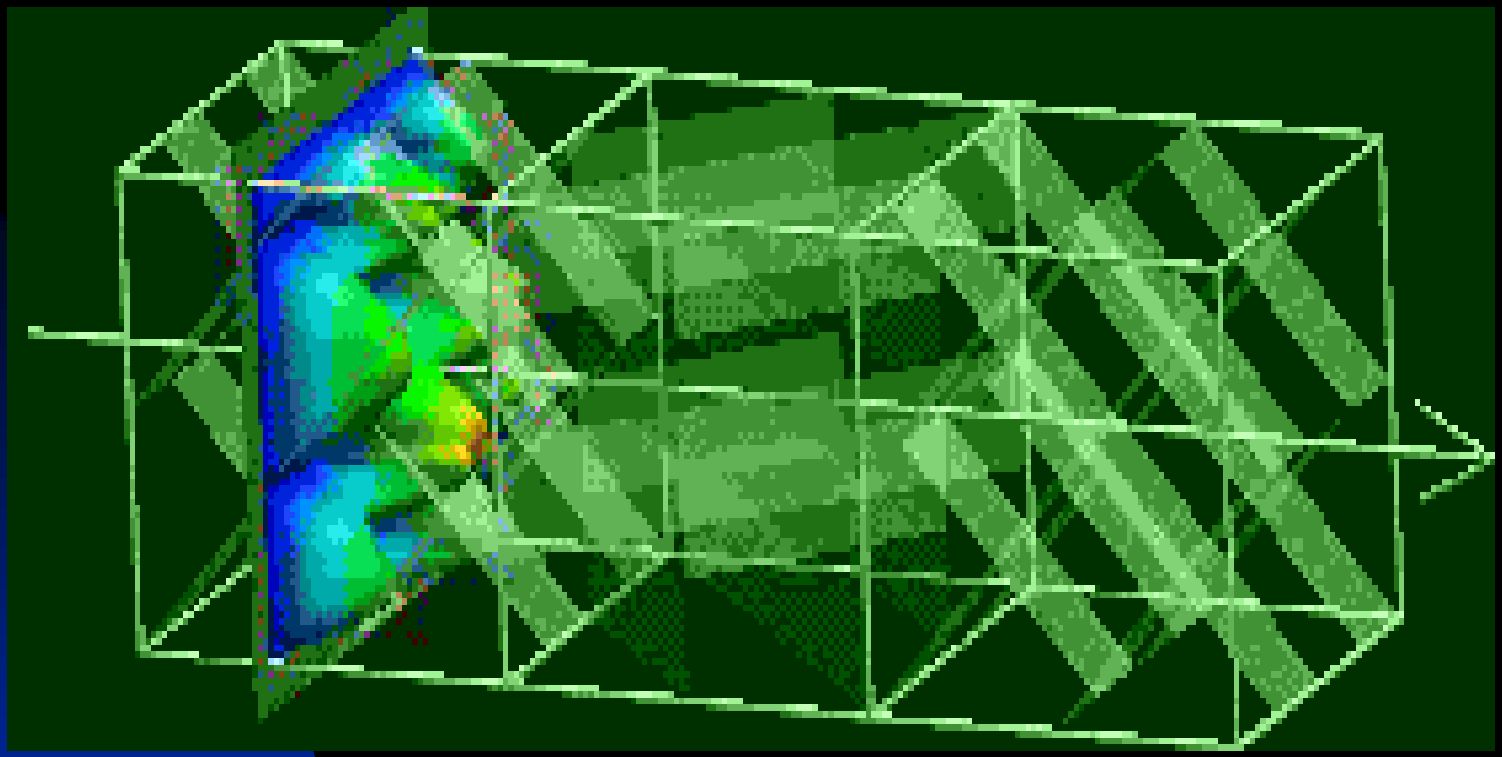
- *Mechanical mixing*

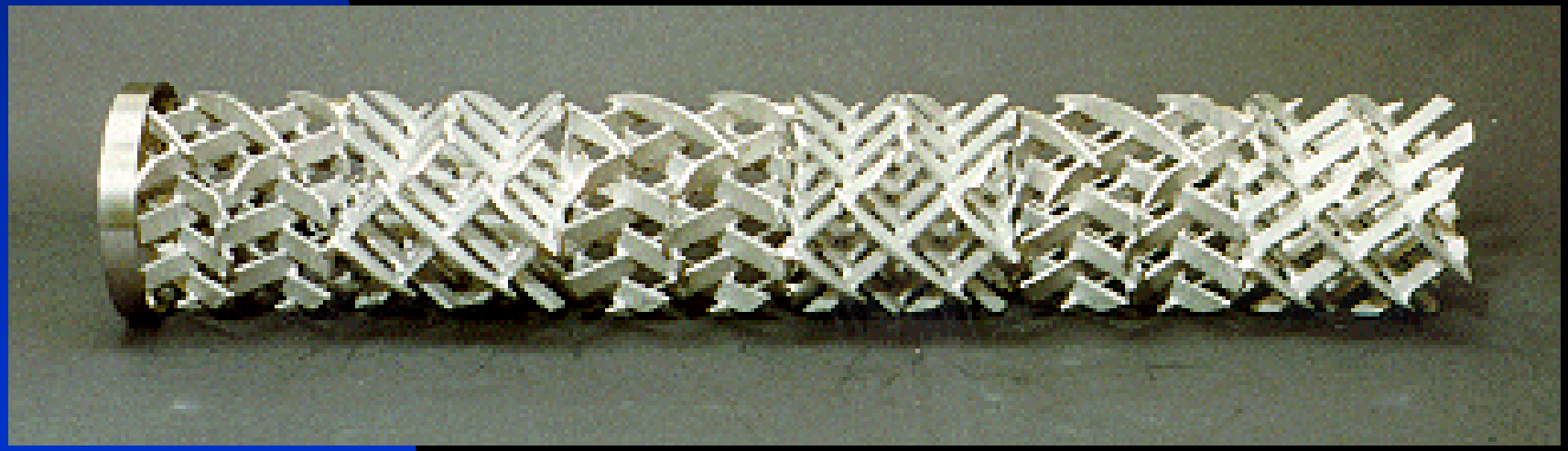
Back mix impeller



flat-blade impeller








Chemical
feeding
Inflow

❑ Relative coagulating power

Na^{+} = 1; Mg^{2+} = 30

Al^{3+} > 1000; Fe^{3+} > 1000

❑ Typical coagulants

Aluminum sulfate: $Al_2(SO4)_3.14\ H_2O$

Iron salt- Ferric sulfate: $Fe_2(SO4)_3$

Iron salt- Ferric chloride: Fe_2Cl_3

Polyaluminum chloride (PAC): $Al_2(OH)_3Cl_3$

Aluminum Chemistry

With alum addition, what happens to water pH?

$Al_2(SO4)_3.14\ H_2O \Leftrightarrow 2Al(OH)_3\downarrow + 8H_2O + 3H_2SO_4^{-2}$

1 mole of alum consumes 6 moles of bicarbonate (HCO_3^-)

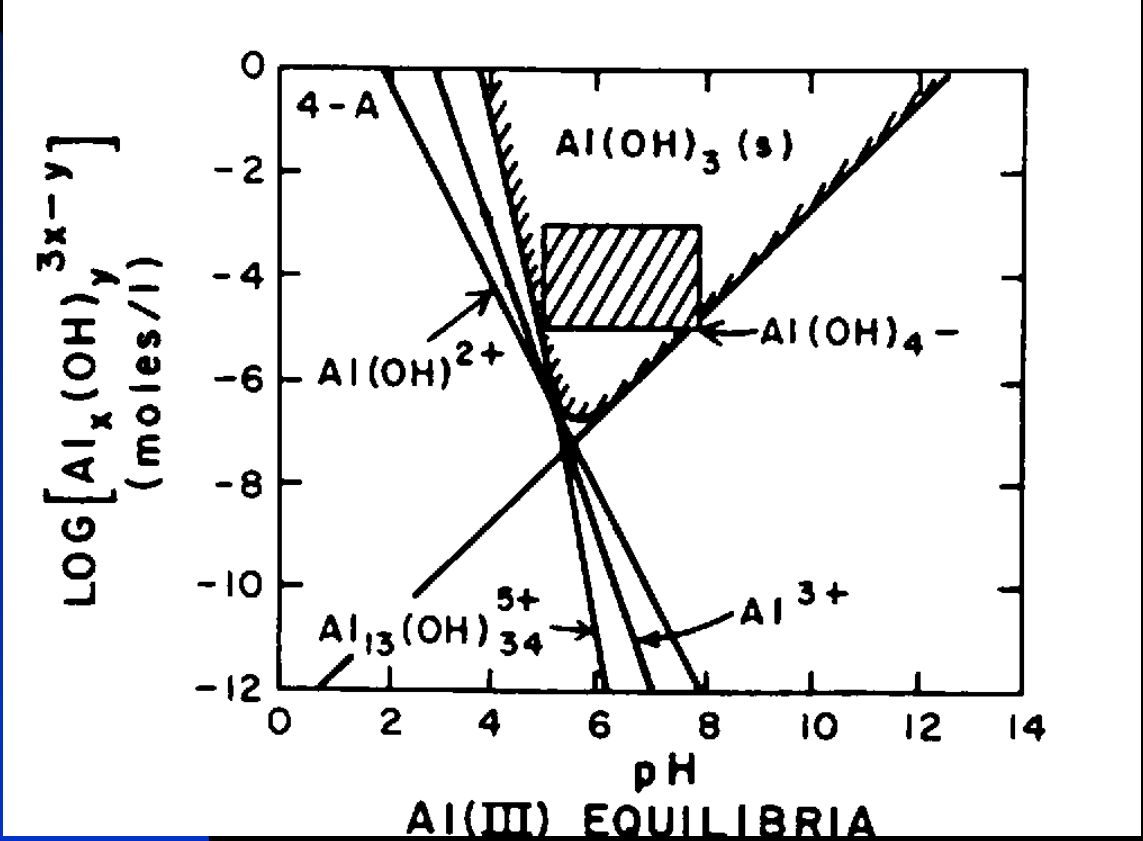
$Al_2(SO4)_3.14\ H_2O + 6HCO_3^- \Leftrightarrow 2Al(OH)_3\downarrow + 6CO_2 + 14H_2O + 3SO_4^{-2}$

If alkalinity is not enough, pH will reduce greatly

Lime or sodium carbonate may be needed to neutralize the acid.

(Optimum pH: 5.5 – 6.5)

Al^{3+} species as a function of pH



Alkalinity calculation

If 200 mg/L of alum to be added to achieve complete coagulation. How much alkalinity is consumed in mg/L as $CaCO_3$?

$$\underbrace{Al_2(SO_4)_3.14\,H_2O}_{\textbf{594 mg}} + \underbrace{6HCO_3^-}_{\textbf{366 mg}} \Leftrightarrow 2Al(OH)_3\downarrow + 6CO_2 + 14H_2O + 3SO_4^{-2}$$

594 mg alum consumes 366 mg HCO_3^-

200 mg alum will consume (366/594) x 200 mg HCO_3^-

= 123 mg HCO_3^-

Alkalinity in mg/L as $CaCO_3$ = 123 x (50/61)

= 101 mg/L as $CaCO_3$

Iron Chemistry

$FeCl_3 + 3HCO_3^- \Leftrightarrow Fe(OH)_3\downarrow + 3CO_2 + 3Cl^-$

With iron salt addition, what happens to water pH?
(Wider pH range of: 4 – 9; Best pH range of 4.5 – 5.5)

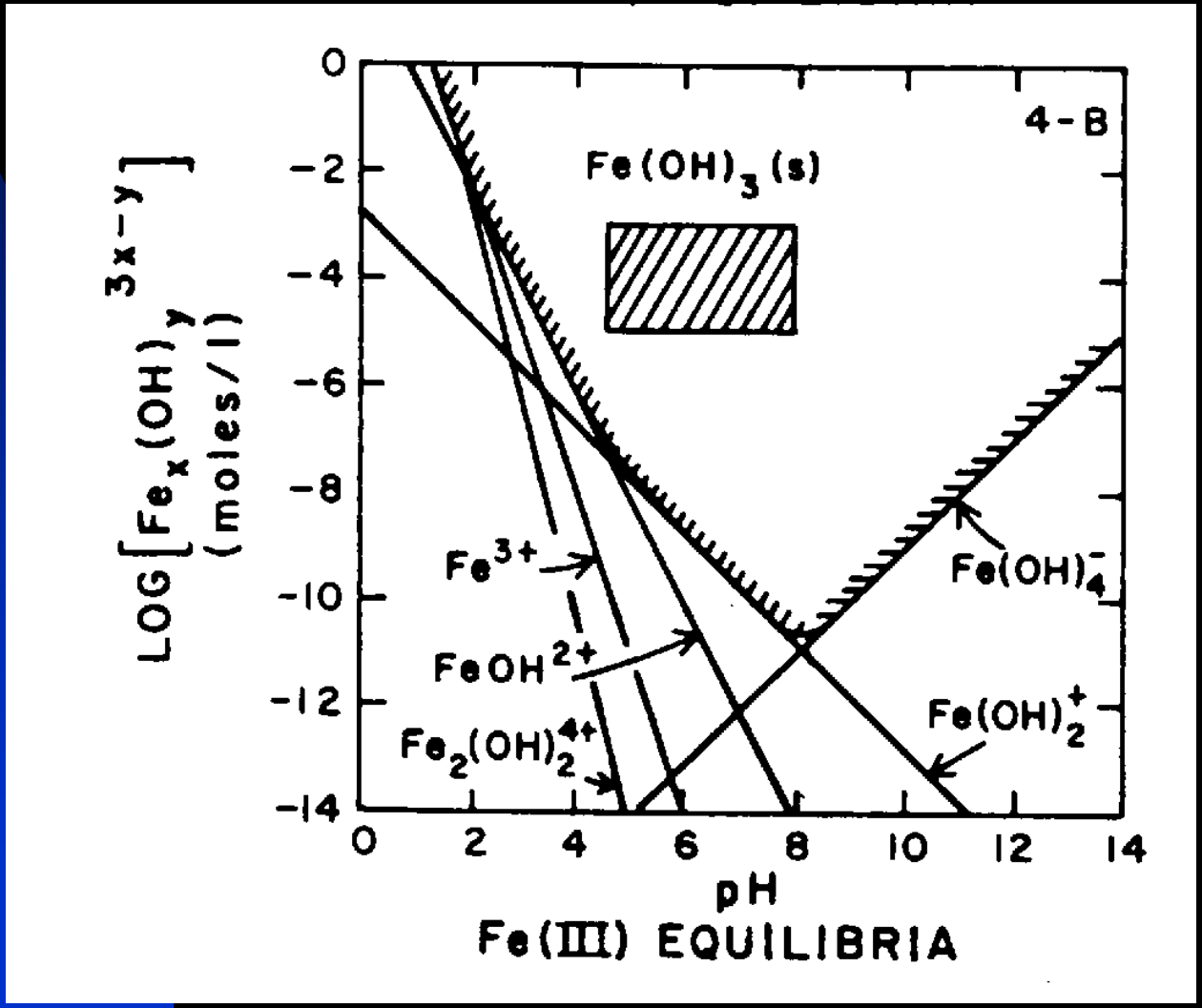
1 mole of $FeCl_3$ consumes 3 moles of bicarbonate (HCO_3^-)

If alkalinity is not enough, pH will reduce greatly due to hydrochloric acid formation. Lime or sodium carbonate may be needed to neutralize the acid. Lime is the cheapest.

Exercise: Alkalinity calculation

If 200 mg/L of ferric chloride is added for coagulation, how much alkalinity is consumed in mg/L as $CaCO_3$?

Fe species as a function of pH

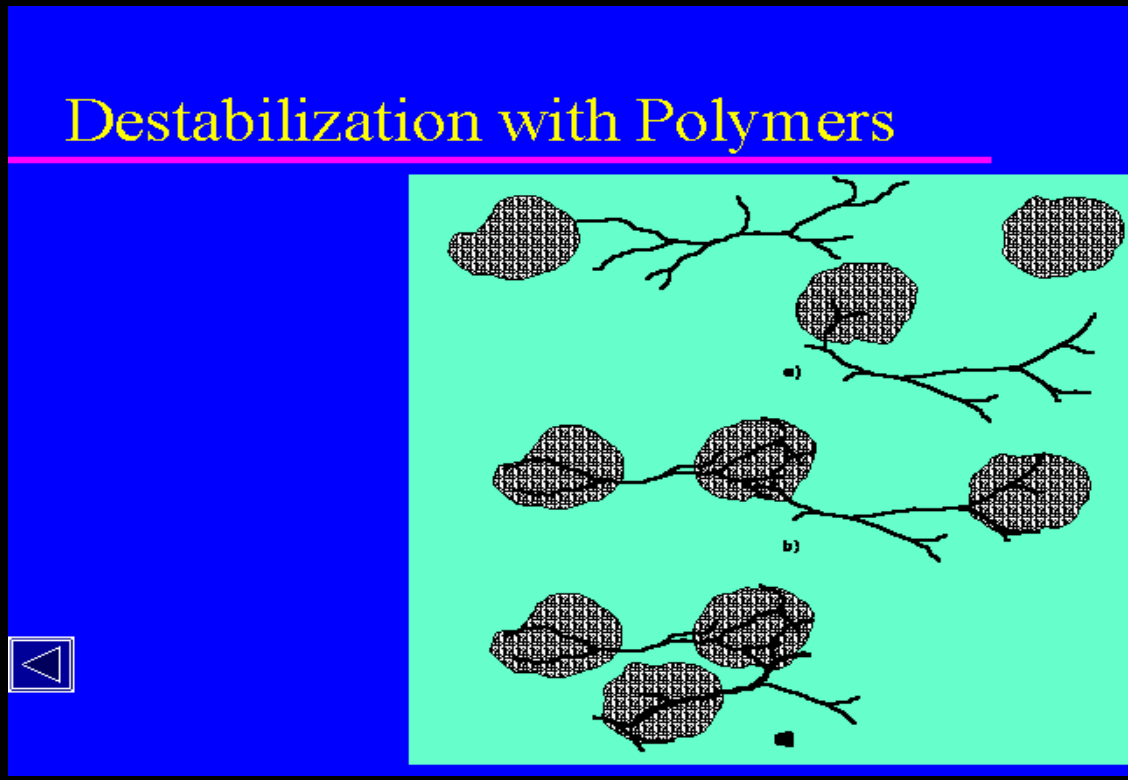


COAGULANT AIDS

Other substances than coagulants used:

- Clay minerals
- Silicates
- Polymers

Polymers are often either anionic or cationic to aid coagulation. Polymers also reinforce flocs



FLOCCULATION

Flocculation - agglomeration of colloids by collisions to form separable flocs

Examples - milk, blood, seawater

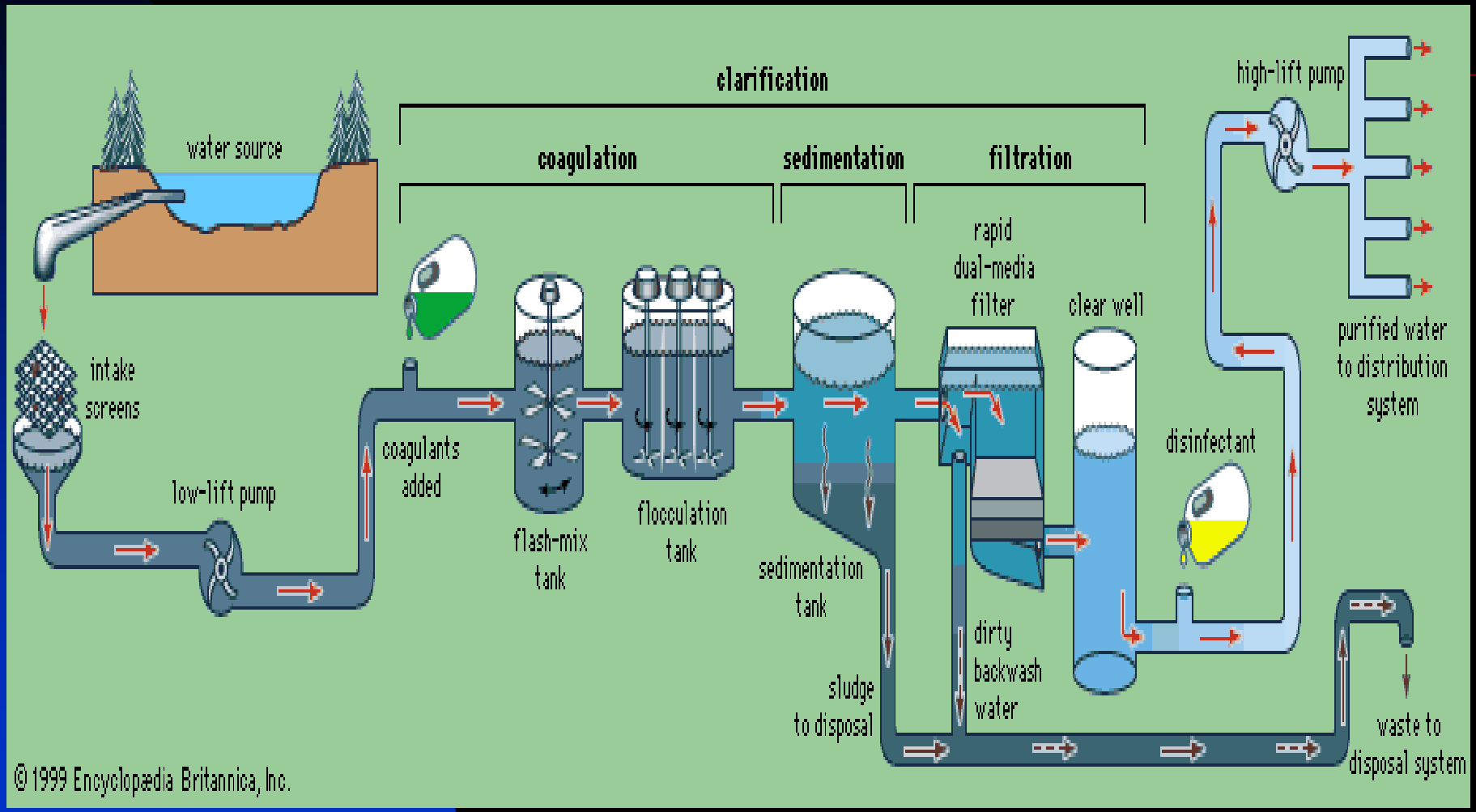
Mechanisms - perikinetic, collisions from Brownian motion
- orthokinetic, induced collisions through stirring

Orthokinetic flocculation

Velocity gradient, relative movement between colloids in a fluid body
RMS velocity gradient

Camp No. Gt Typical 2x 10^4 - 10^5

Typical layout of a water treatment plant

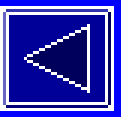


Topics of Discussion

- The place of flocculation within a water treatment process
- The use of coagulation and flocculation in the water industry
- Softening
- Separation of flocs by settling and flotation

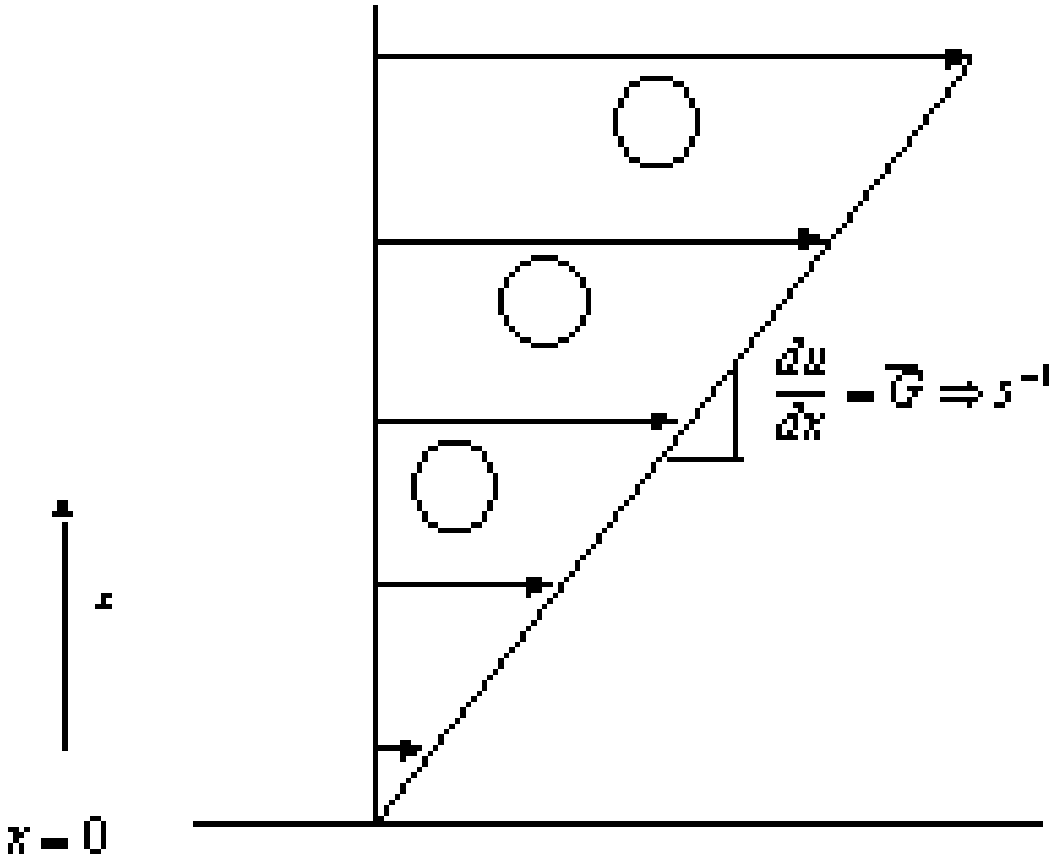
Flocculation: Purpose

- Promote agglomeration of particles into larger floc
- Units often designed on the basis of mixing intensity as described by the velocity gradient, G
  - some mixing is needed to keep particles in contact with other particles
  - too much mixing can cause floc break-up



Orthokinetic Flocculation

- Fluid Shear



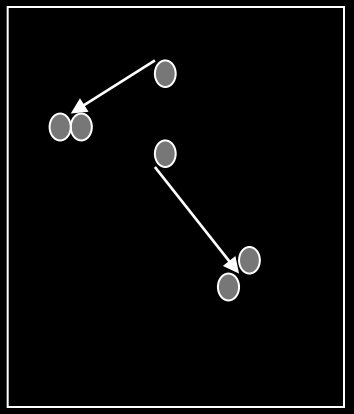
note : $u(x) = x\frac{du}{dx}$

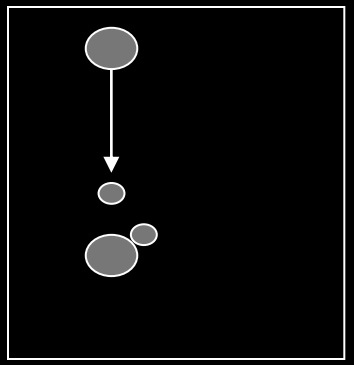
Design of Flocculator (Slow & Gentle mixing)

Flocculators are designed mainly to provide enough interparticle contacts to achieve particles agglomeration so that they can be effectively removed by sedimentation or flotation

Transport Mechanisms

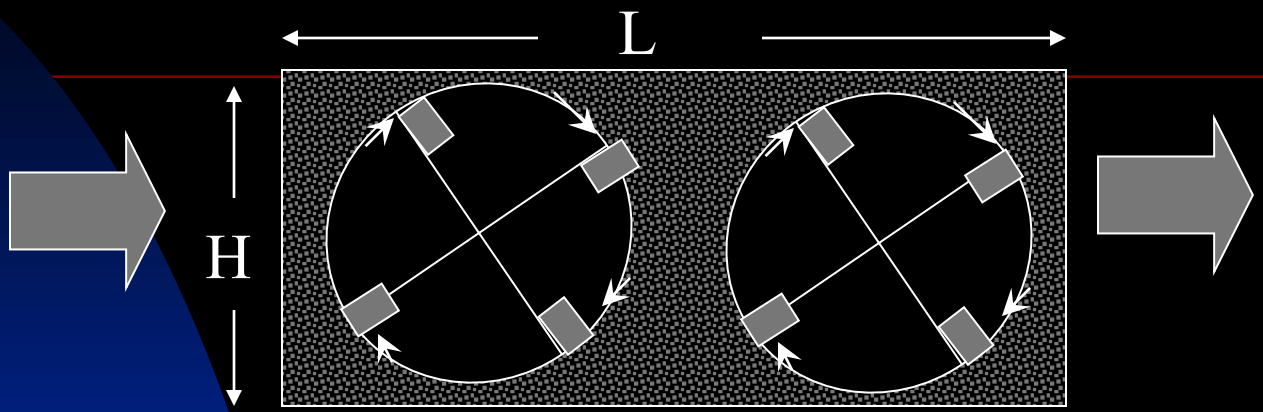
- *Brownian motion*: for relatively small particles which follow random motion and collide with other particles (perikinetic motion)
- *Differential settling*: Particles with different settling velocities in the vertical alignment collide when one overtakes the other (orthokinetic motion)



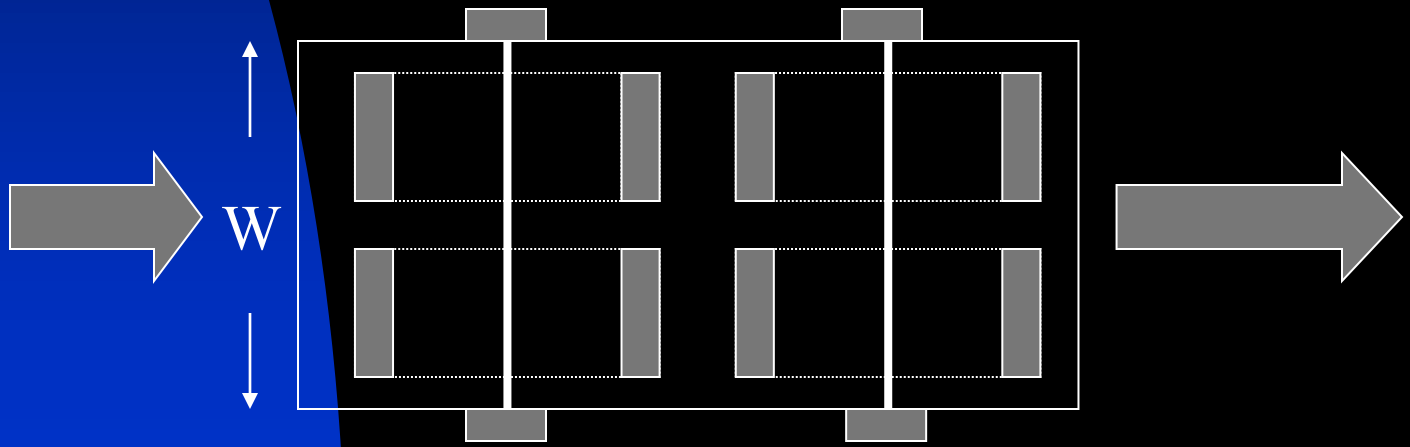


Mechanical Flocculator

Transverse paddle



Cross flow Flocculator (sectional view)

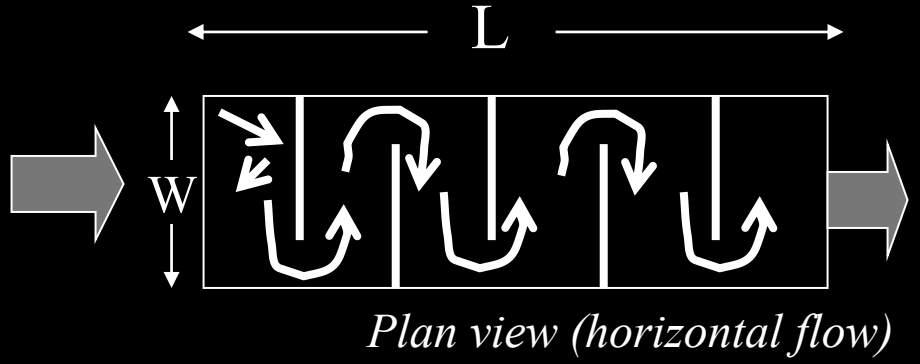


Plan (top view)

Hydraulic Flocculation

- *Horizontally baffled tank*

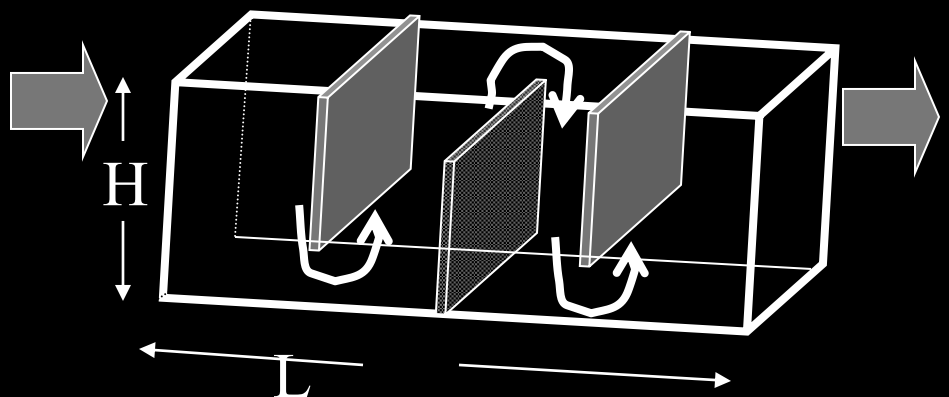
The water flows horizontally. The baffle walls help to create turbulence and thus facilitate mixing



Plan view (horizontal flow)

- *Vertically baffled tank*

The water flows vertically. The baffle walls help to create turbulence and thus facilitate mixing



Isometric View (vertical flow)

Hydraulic Flocculation

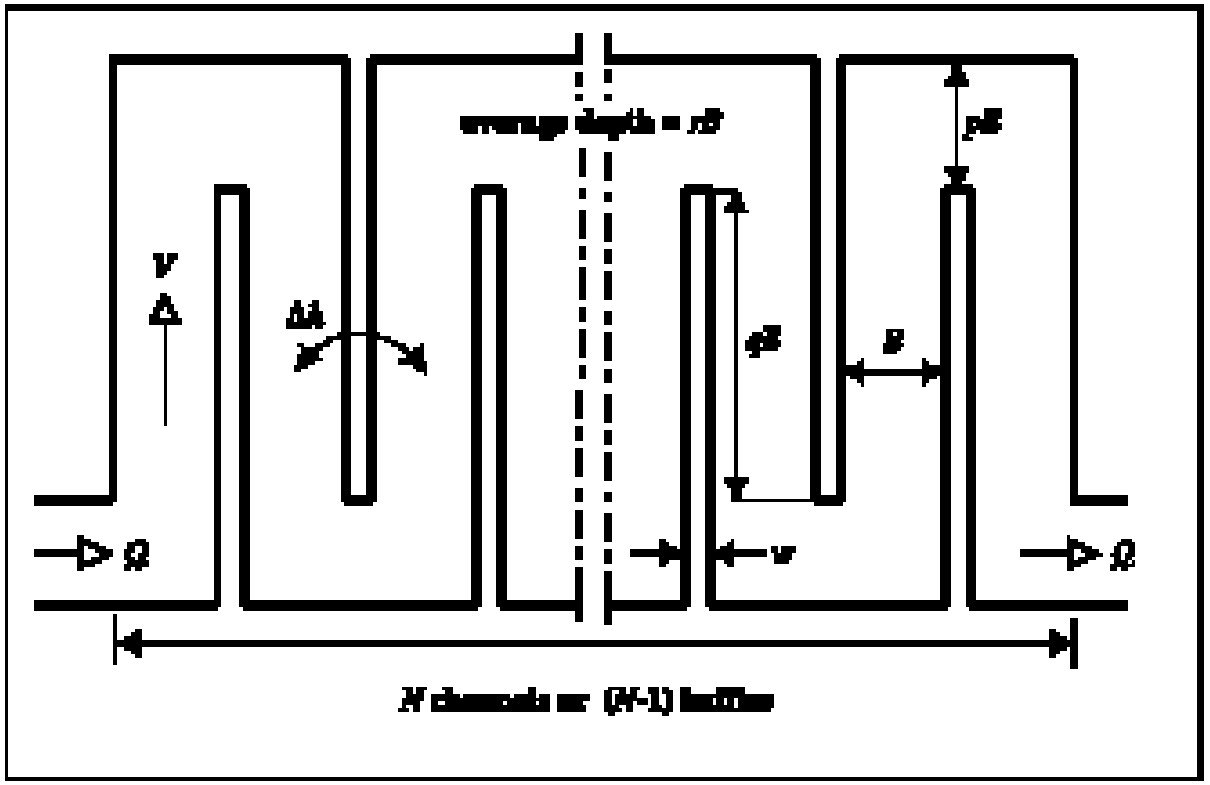
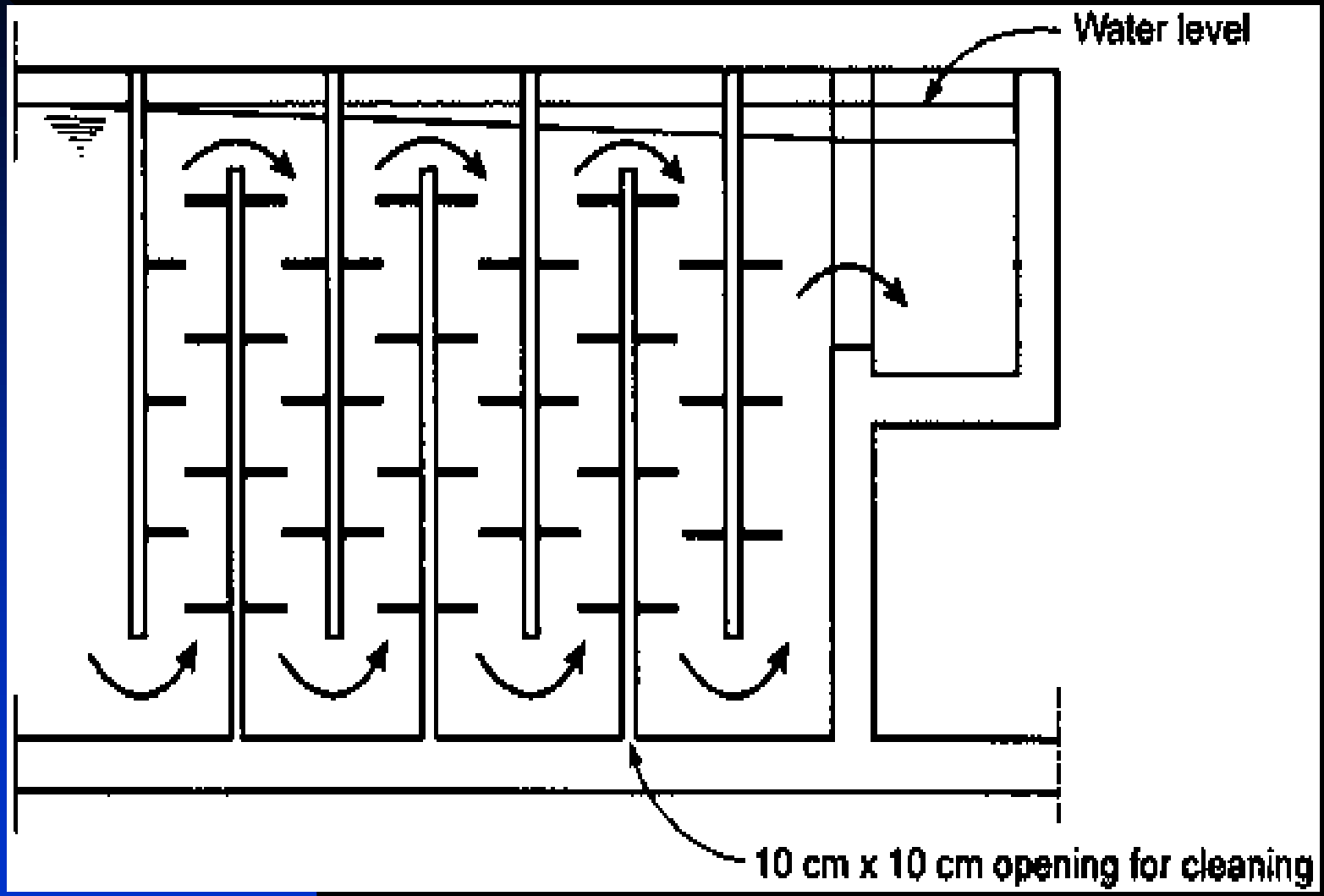


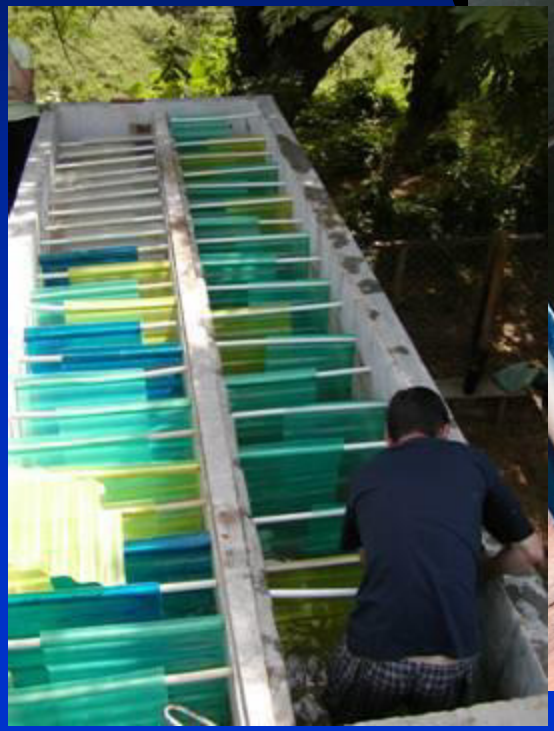
Figure 1 | Schematic layout of an around-the-end hydraulic flocculator, showing the notation used in this paper.

http://www.environmental-center.com/magazine/iwa/jws/art4.pdf

Hydraulic flocculators



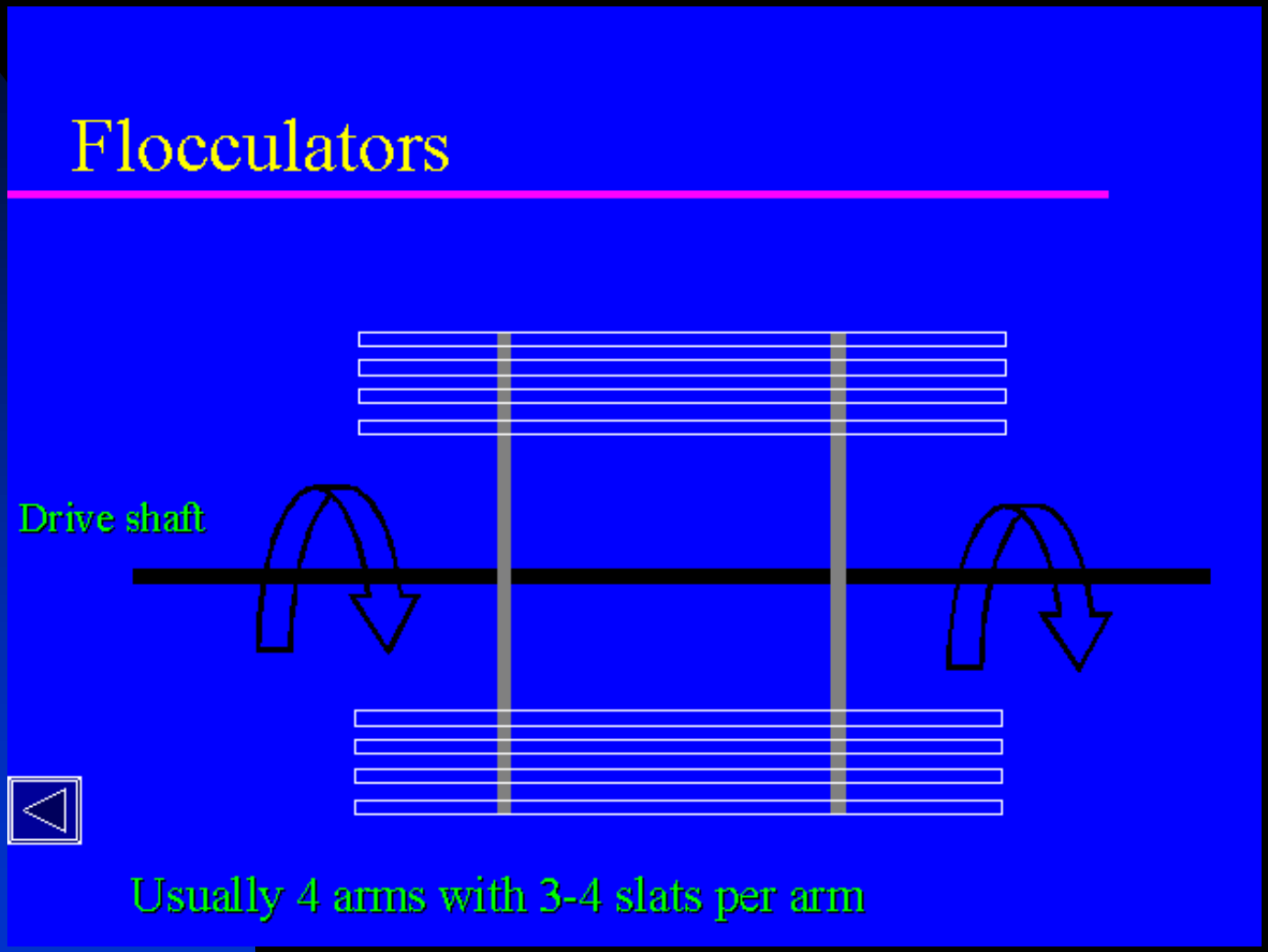
Hydraulic flocculators: simple technology



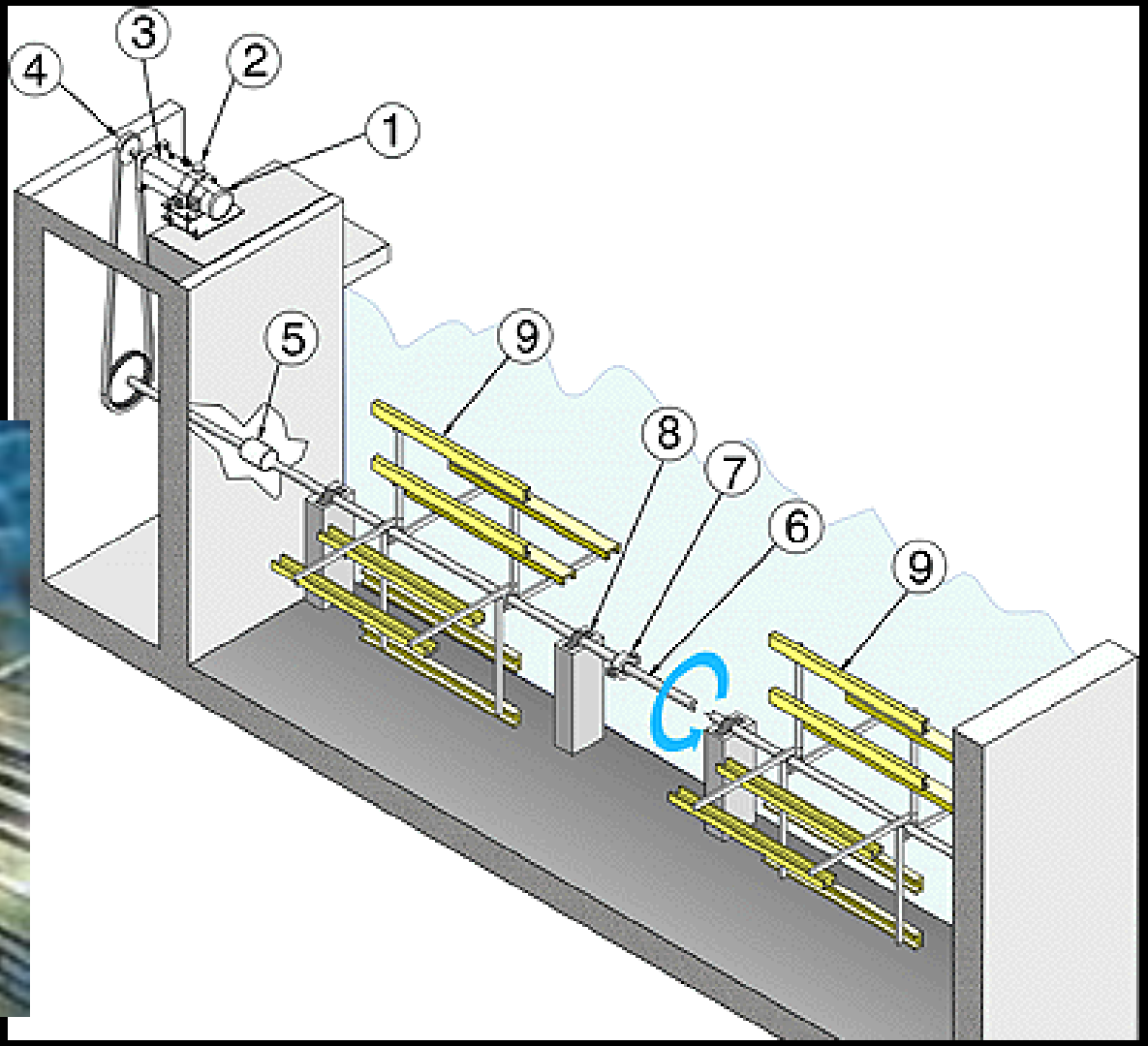
Hydraulic Flocculation: Pipe

Hydraulic Flocculation: Pipe

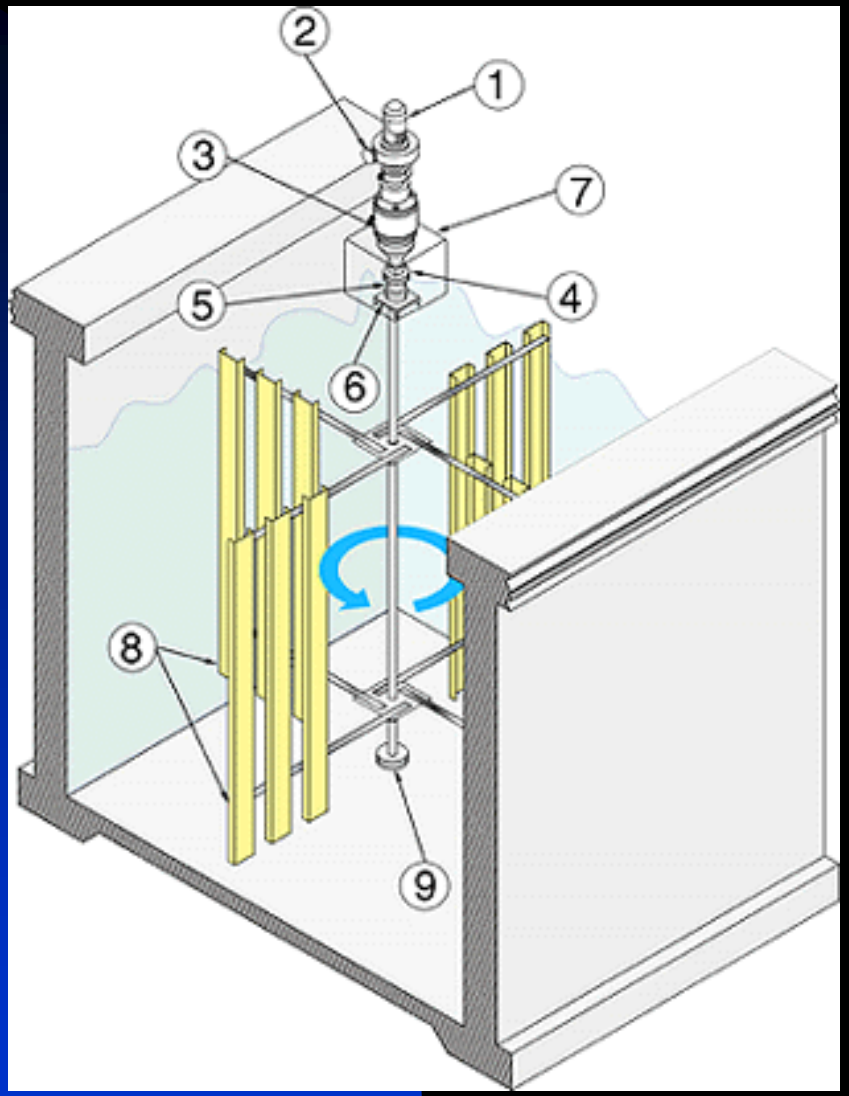
Hydraulic Flocculation:Large stirrers



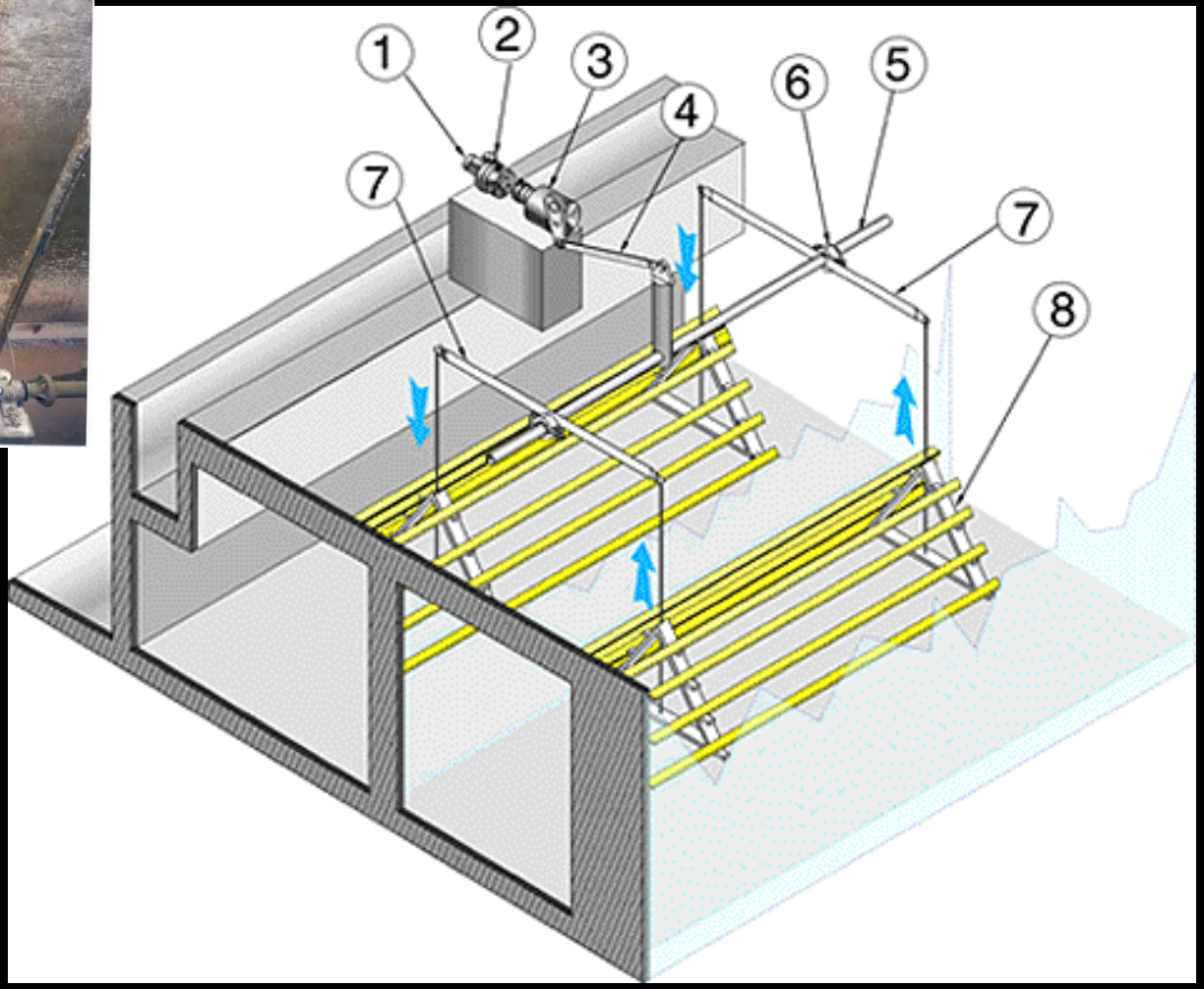
Mechanical flocculators



Mecahnical flocculators



Mechanical flocculators



Another mechanical flocculator

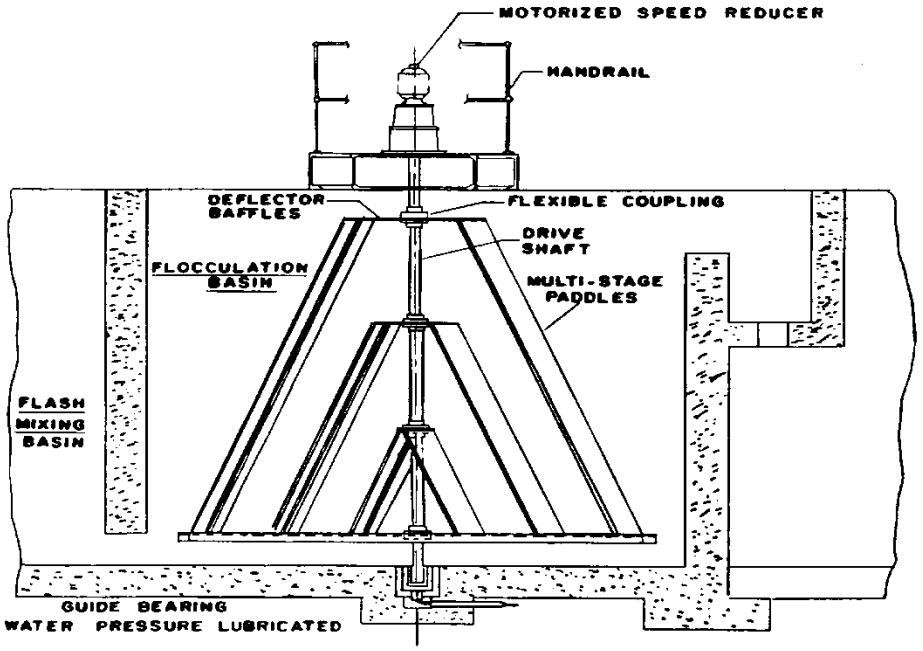
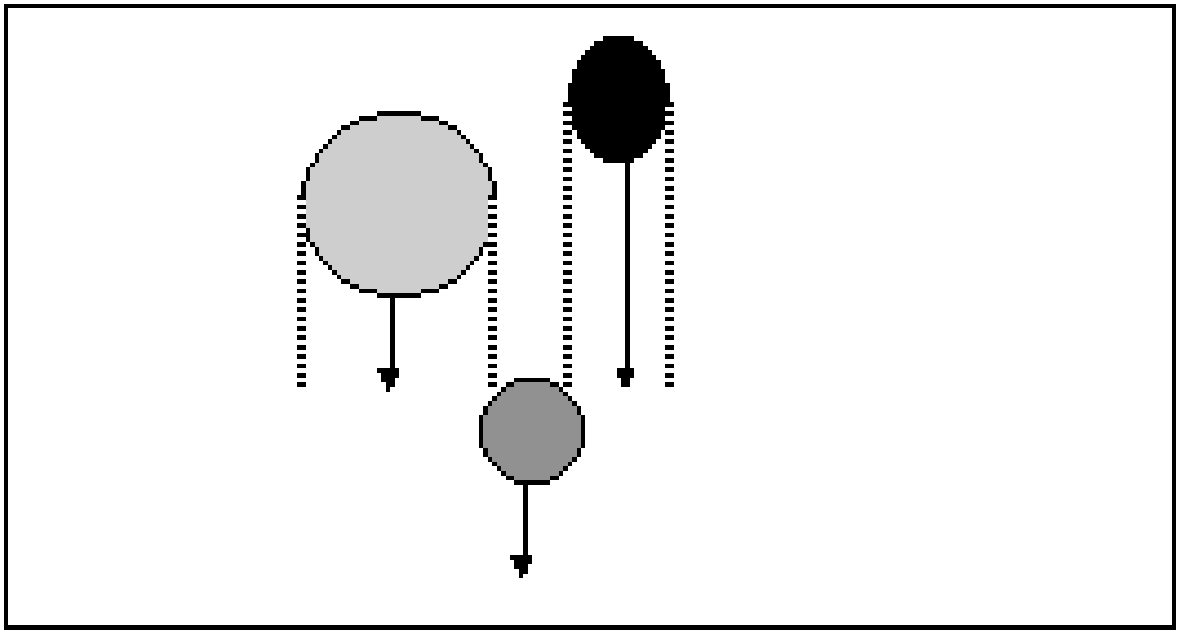


FIGURE 6-3
MECHANICAL FLOCCULATOR
VERTICAL SHAFT—PADDLE TYPE
(Courtesy of Ecodyne Corp.)

Differential settling flocculation



$$\sigma(d_1,d_2)=\binom{n_B}{72\mu}(\sigma_2-\sigma_1)(d_1+d_2)^3(d_1-d_2)$$

Dr. Andrew Ernest | Environmental Engineering | Texas A&M University - Kingsville

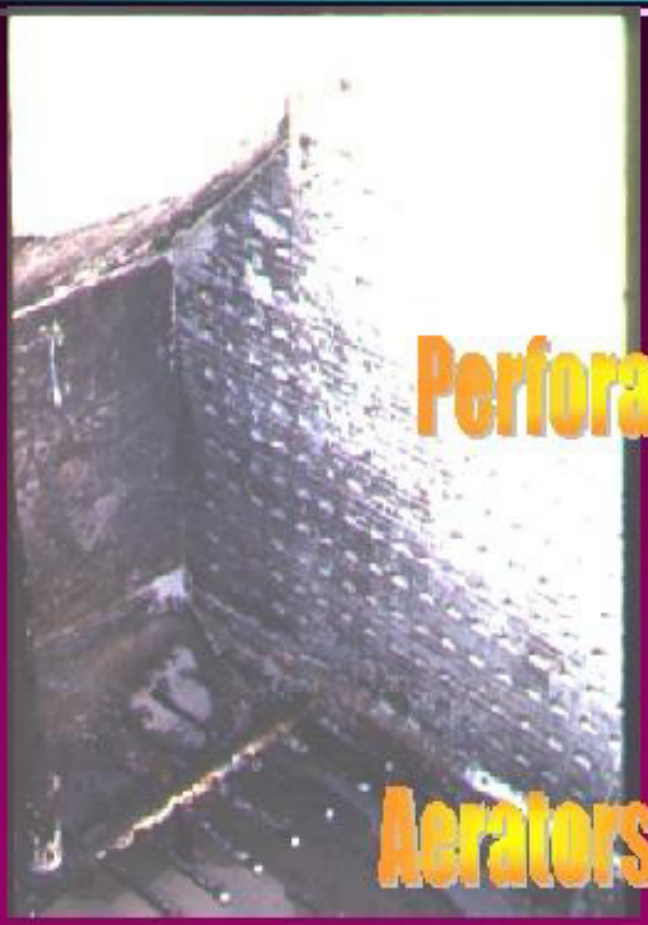
Flocculators integrated with settling

Flocculators integrated with settling

Flocculators both sides of settling

Flocculator perforated wall (in background)

Aeration to aid flocculation



Flocculation: Design

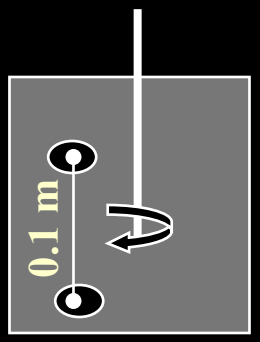
- Flow through velocity: 0.5 to 1.5 ft/min
- variable speed paddle flocculators
  - peripheral velocities of 0.5-2.0 ft/sec
  - horizontal shaft: slower, best for conventional
  - vertical shaft: faster, best for direct filtration
- typical dimensions
  - 12 ft deep
  - length/width = 4
  - 30 min detention time

Mixing and Power

- *The degree of mixing is measured by* **Velocity Gradient (G)**
- **Higher G value, intenser mixing**

Velocity Gradient: relative velocity of the two fluid particles/distance

$$G = dv/dy = 1.0/0.1 = 10\ s^{-1}$$



In mixer design, the following equation is useful

$$G = \left[\frac{P}{V\mu}\right]^{1/2}$$

G= velocity gradient, s^{-1};
P = Power input, W
V = Tank volume, m^3;
μ = Dynamic viscosity, (Pa.s)

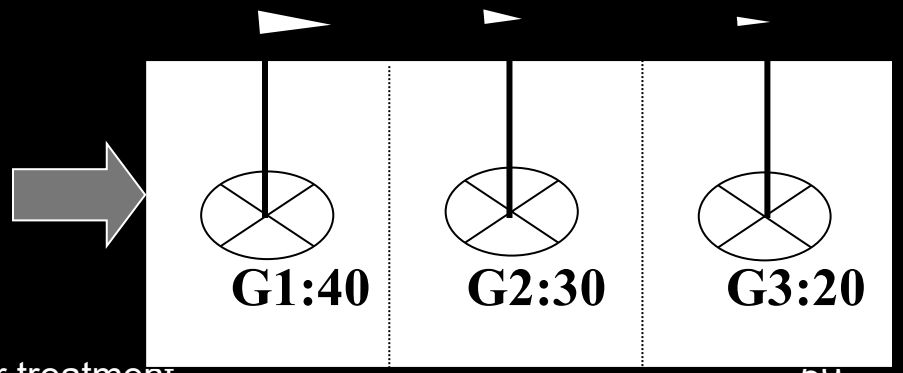
- **G value for coagulation: 700 to 1000 S^{-1}; 3000 to 5000 S^{-1} for in-line blender; 1-2 sec**
  Mixing time: 30 to 60 S
- **G value for flocculation: 20 to 80 S^{-1};**
  Mixing time: 20 to 60 min

In the flocculator design, Gt (also known Camp No.); a product of G and t is commonly used as a design parameter

Typical Gt for flocculation is $2 \times 10^4 - 10^5$

Large G and small T gives small but dense floc
Small G and large T gives big but light flocs

We need big as well as dense flocs which can be obtained by designing flocculator with different G values



Power Calculation

What horsepower level do we need to supply to a flocculation basin to provide a G value of $100 s^{-1}$ and a Gt of 100,000 for 10 MGD flow? **(Given:** $\mu = 0.89 \times 10^{-3}$ Pa.s; 1 hp = 745.7 watts)

Solution:

Retention time, t = Gt/G = 100,000/100 = 1000 secs

Volume of Flocculation basin, V = (0.438 m^3/sec) x (1000 sec)
= 438 m^3

$$G = \left[\frac{P}{V\pi}\right]^{1/2}$$

P = G^2 V x μ
= 100^2 x 438 x 0.89 x10^{-3} = 3900 W
= 3900/746 = 5.2 hp

WATER TREATMENT ENERGY CALCULATIONS

F = ma. In a gravity field, F = mg

Force in N, where a N is the force to accelerate 1kg @1m/s^2

Force to move h, Potential energy = Fh = mgh

Dimensions MLT^{-2}L, kgm^{2}s^{-2} = Nm or J

Force moving at a certain speed, introduces time dimension

Dimensions here are MT^{-1}, L/s (1L=1kg)

Rate of energy usage, or power, P = mgh/t

Dimensions are now ML^{2}T^{-3}, or kgm^{2}s^{-3} = J/s or W.

Power (W) to pump water to h, flow rate in L/s (or kg/s)

W = kg/s x h x 9.8 m/s^2

kW, divide by 1000 HP, divide by 746

VISCOSITY MEASUREMENT

Viscosity of water is a measure of its resistance to flow

The cgs unit is the Poise, 1 $gcm^{-1}s^{-1}$.
Water viscosity is c. 1cP = 0.01P = 0.001 Pa.s

Pa = N/m^2 or $kgms^{-2}m^{-2}$, so Pa.s = $kgms^{-2}m^{-2}s$ = $kgm^{-1}s^{-1}$

This could also have been derived from going from $gcm^{-1}s^{-1}$, multiplying by 100/1000.

Therefore 1cP = 0.001$kgm^{-1}s^{-1}$

Calculation of Velocity Gradient

Calculate the velocity gradient in a flocculator, where the required energy is 1 J/L. Flow rate is 4ML/d, retention time = 20 min

$$\text{Volume, } V = 4000/(24 \times 60/20) = 55.5\ m^3$$

$$\text{Flow rate} = \frac{4000 \times 1000}{24 \times 60 \times 60} = 46.3\ L/s$$

$$G = \sqrt{P/V\mu} = \sqrt{1 \times 46.3/0.001 \times 55.5}$$

$$= 28\ s^{-1}$$

Calculate height required for hydraulic flocculator

Calculate the head difference in water through a hydraulic flocculator, where the required energy input is 1 J/L and the flow rate is 4 ML/d.

Power = energy/time

1 J x L/s = kg/s x 9.8 x h

Therefore, h = 1/9.8 m

= 0.102m

Calculate Camp No

Calculate the Camp No for the hydraulic flocculator in the previous example

$$\text{Camp No} = G.t$$

$$= 28 \times 20 \times 60$$

$$= 33{,}000$$

(within the boundaries of 20,000 – 200,000)

PADDLE FLOCCULATORS

$$F = C_D A \rho v^2/2$$

$\frac{C_D A \rho \upsilon^2}{2}$ Where F = drag force, N

C_D = dimensionless drag coefficient for plates moving faces normal to direction of motion

A = cross-sectional area of the paddles, m^2

υ = relative velocity between paddles and fluid, m/s

ρ = density, 1000 kg/m^3

The power input can be computed as the product of drag force and velocity:

$$P = F\upsilon = C_D A \rho v^3/2$$

If this is substituted in the equation for G, the mean velocity gradient G becomes

$$G^2 = P/\mu V = C_D A \rho v^3/ 2\mu V$$

What you need to know

- How to determine the velocity gradient and volume, chemical and energy requirements for flocculation
- Be able to size settling tanks on the basis of particle settling rates and identify important zones in the settling tank
- Softening calculations

Disinfection Byproducts: A Reference Resource

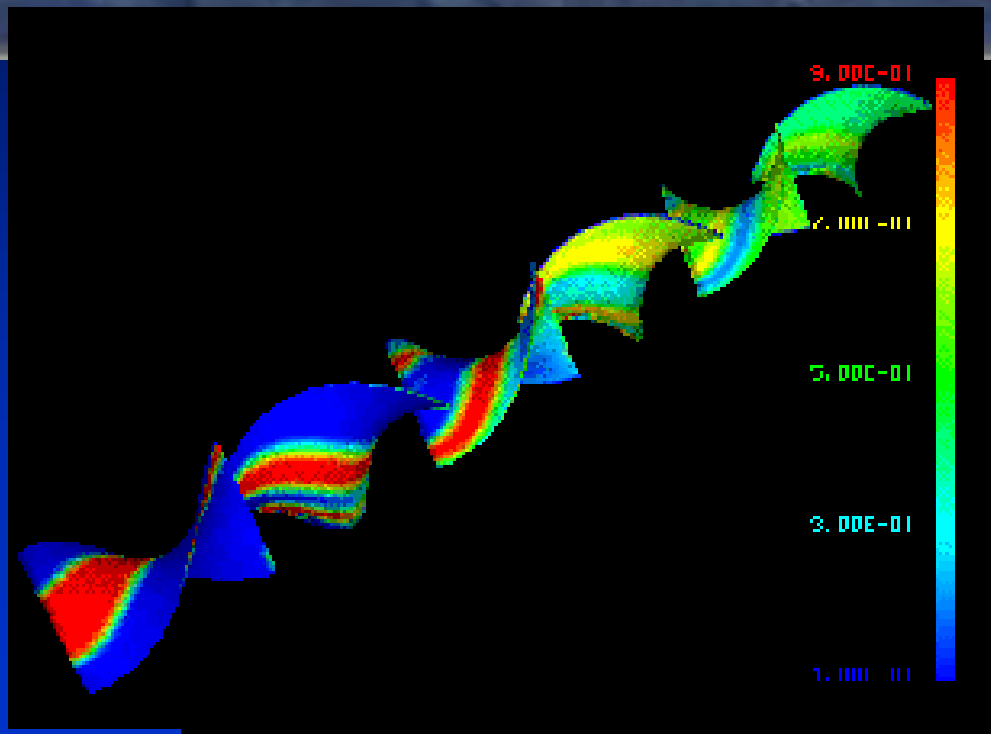
Disinfection byproducts are formed when disinfectants used in water treatment plants react with bromide and/or natural organic matter (i.e., decaying vegetation) present in the source water. Different disinfectants produce different types or amounts of disinfection byproducts. Disinfection byproducts for which regulations have been established have been identified in drinking water, including trihalomethanes, haloacetic acids, bromate, and chlorite. ----------

Trihalomethanes (THM) are a group of four chemicals that are formed along with other disinfection byproducts when chlorine or other disinfectants used to control microbial contaminants in drinking water react with naturally occurring organic and inorganic matter in water. The trihalomethanes are chloroform, bromodichloromethane, dibromochloromethane, and bromoform. EPA has published the Stage 1 Disinfectants/Disinfection Byproducts Rule to regulate total trihalomethanes (TTHM) at a maximum allowable annual average level of 80 parts per billion. This standard replaced the current standard of a maximum allowable annual average level of 100 parts per billion in December 2001 for large surface water public water systems. The standard became effective for the first time in December 2003 for small surface water and all ground water systems. ----------

Haloacetic Acids (HAA5) are a group of chemicals that are formed along with other disinfection byproducts when chlorine or other disinfectants used to control microbial contaminants in drinking water react with naturally occurring organic and inorganic matter in water. The regulated haloacetic acids, known as HAA5, are: monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid. EPA has published the Stage 1 Disinfectants/Disinfection Byproducts Rule to regulate HAA5 at 60 parts per billion annual average. This standard became effective for large surface water public water systems in December 2001 and for small surface water and all ground water public water systems in December 2003. ----------

Bromate is a chemical that is formed when ozone used to disinfect drinking water reacts with naturally occurring bromide found in source water. EPA has established the Stage 1 Disinfectants/Disinfection Byproducts Rule to regulate bromate at annual average of 10 parts per billion in drinking water. This standard will become effective for large public water systems by December 2001 and for small surface water and all ground public water systems in December 2003. ----------

Chlorite is a byproduct formed when chlorine dioxide is used to disinfect water. EPA has published the Stage1 Disinfectants/Disinfection Byproducts Rule to regulate chlorite at a monthly average level of 1 part per million in drinking water. This standard became effective for large surface water public water systems in December 2001 and for small surface water and all ground water public water systems in December 2003


9.000E-01
5.000E-01
3.000E-01

Flocculation: cont.