Coagulation and Rapid Mixing

Coagulation is the process by which particles become destabilized and begin to clump together. Coagulation is an essential component in water treatment operations. Evaluation and optimization of the coagulation/rapid mixing step of the water treatment process includes a variety of aspects. Optimal coagulant dosages are critical to proper floc formation and filter performance. Maintaining the proper control of these chemicals can mean the difference between an optimized surface plant and a poorly run surface plant. Inadequate mixing of chemicals or their addition at inappropriate points in the treatment plant can also limit performance.

Effect on Turbidity

Coagulation by itself does not reduce turbidity. In fact, turbidity may increase during the coagulation process due to additional insoluble compounds that are generated by chemical addition. The processes of flocculation, sedimentation, and filtration should be used with coagulation to reduce suspended solids and turbidity.

Coagulants and Polymers

The coagulation process includes using primary coagulants and may include the addition of coagulant and/or filter aids. The difference between these two categories is as follows:

1. **Primary coagulants:** Primary coagulants are used to cause particles to become destabilized and begin to clump together (California State University, 1994). Examples of primary coagulants are metallic salts, such as aluminum sulfate (referred to as alum), ferric sulfate, and ferric chloride. Cationic polymers may also be used as primary coagulants.

2. **Coagulant Aids and Enhanced Coagulants:** Coagulant aids and enhanced coagulants add density to slow-settling floc and help maintain floc formation (California State University, 1994). Organic polymers, such as polyaluminum hydroxychloride (PACl), are typically used to enhance coagulation in combination with a primary coagulant. The advantage of these organic polymers is that they have a high positive charge and are much more effective at small dosages. Even though they may be more expensive, a smaller amount may be needed, thereby saving money. Organic polymers also typically produce less sludge.

Typical coagulants and aids are discussed in further detail below:

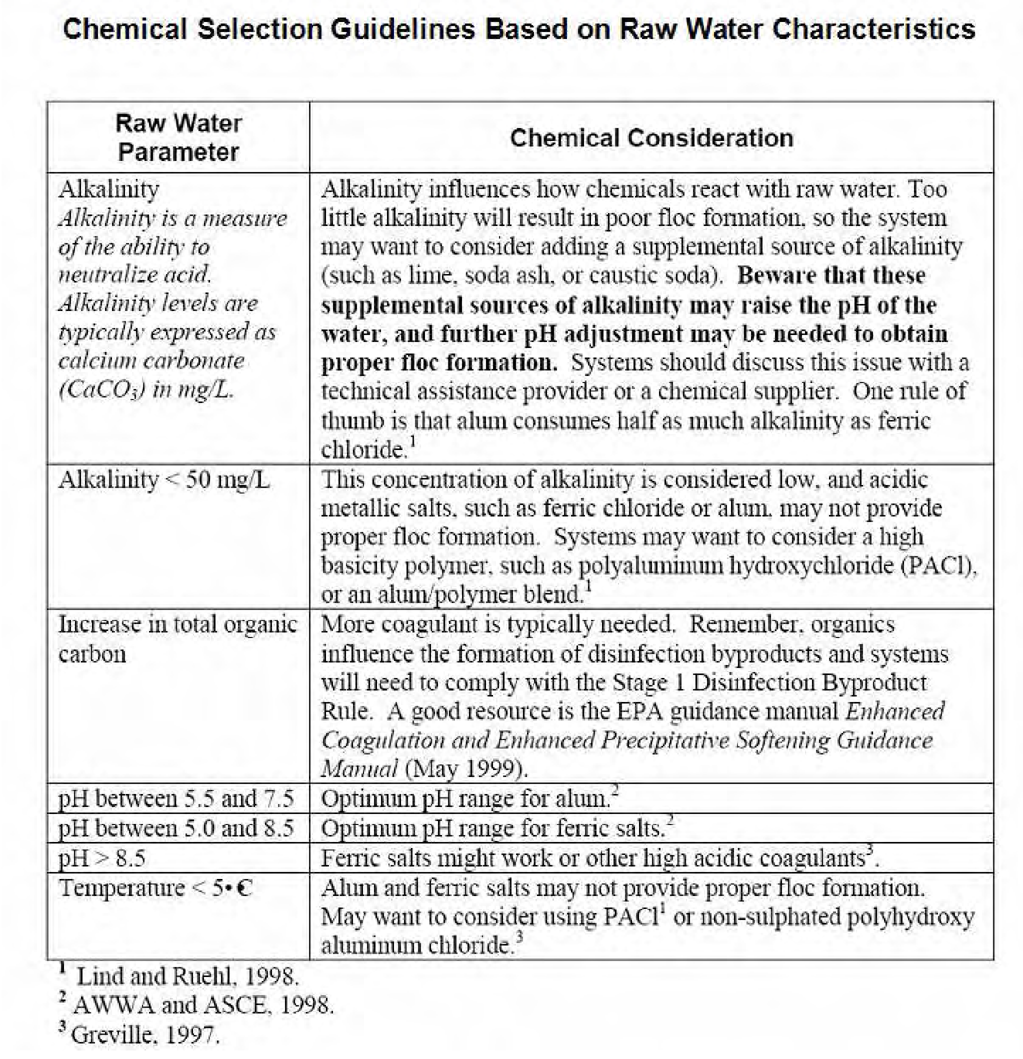
Chemicals commonly used for primary coagulants include aluminum or iron salts and organic polymers. The most common aluminum salt used for coagulation is aluminum sulfate, or alum. Alum may react in different ways to achieve coagulation. When used at relatively low doses (<5 mg/L), charge neutralization (destabilization) is believed to be the primary mechanism involved. At higher dosages, the primary coagulation mechanism tends to be entrapment. In this case, aluminum hydroxide ($Al(OH)_2$) precipitates forming a “sweepfloc” that tends to capture suspended solids as it settles out of suspension. The pH of the water plays an important role when alum is used for coagulation because the solubility of the aluminum species in water is pH dependent. If the pH of the water is between 4 and 5, alum is generally present in the form of positive ions (i.e., $Al(OH)_{2+}$, $Al_8(OH)_{4+}$, and Al_{3+}). However, optimum coagulation occurs when negatively charged forms of alum predominate, which occurs when the pH is between 6 and 8. When alum is used and charge neutralization is the primary coagulation mechanism, effective flash mixing is critical to the success of the process. When the primary mechanism is entrapment, effective flash mixing is less critical than flocculation.

Ferric chloride ($FeCl_3$) is the most common iron salt used to achieve coagulation. Its reactions in the coagulation process are similar to those of alum, but its relative solubility and pH range differ significantly from those of alum.

Both alum and ferric chloride can be used to generate inorganic polymeric coagulants. These coagulants are typically generated by partially neutralizing concentrated solutions of alum or ferric chloride with a base such as sodium hydroxide prior to their use in the coagulation process (AWWA and ASCE, 1990). The resulting inorganic polymers may have some advantages over alum or ferric chloride for turbidity removal in cold waters or in low-alkalinity waters.

Organic polymers tend to be large molecules composed of chains of smaller "monomer" groups (AWWA and ASCE, 1990). Because of their large size and charge characteristics, polymers can promote destabilization through bridging, charge neutralization, or both. Polymers are often used in conjunction with other coagulants such as alum or ferric chloride to optimize solids removal.

The table below provides some guidelines for selecting the proper chemical based on some raw water characteristics.



Chemical Selection Guidelines Based on Raw Water Characteristics

Raw Water Parameter	Chemical Consideration
Alkalinity *Alkalinity is a measure of the ability to neutralize acid. Alkalinity levels are typically expressed as calcium carbonate ($CaCO_3$) in mg/L.*	Alkalinity influences how chemicals react with raw water. Too little alkalinity will result in poor floc formation, so the system may want to consider adding a supplemental source of alkalinity (such as lime, soda ash, or caustic soda). **Beware that these supplemental sources of alkalinity may raise the pH of the water, and further pH adjustment may be needed to obtain proper floc formation.** Systems should discuss this issue with a technical assistance provider or a chemical supplier. One rule of thumb is that alum consumes half as much alkalinity as ferric chloride.[1]
Alkalinity < 50 mg/L	This concentration of alkalinity is considered low, and acidic metallic salts, such as ferric chloride or alum, may not provide proper floc formation. Systems may want to consider a high basicity polymer, such as polyaluminum hydroxychloride (PACl), or an alum/polymer blend.[1]
Increase in total organic carbon	More coagulant is typically needed. Remember, organics influence the formation of disinfection byproducts and systems will need to comply with the Stage 1 Disinfection Byproduct Rule. A good resource is the EPA guidance manual *Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual* (May 1999).
pH between 5.5 and 7.5	Optimum pH range for alum.[2]
pH between 5.0 and 8.5	Optimum pH range for ferric salts.[2]
pH > 8.5	Ferric salts might work or other high acidic coagulants[3].
Temperature < 5•€	Alum and ferric salts may not provide proper floc formation. May want to consider using PACl[1] or non-sulphated polyhydroxy aluminum chloride.[3]

[1] Lind and Ruehl, 1998.
[2] AWWA and ASCE, 1998.
[3] Greville, 1997.

Cost may be a consideration when selecting chemicals. The system should perform an economic analysis when comparing chemicals and not just compare unit cost. For instance, a polymer may cost more per unit than alum, but less polymer may be needed than alum. Therefore, the total cost for polymer may not be much different than the total cost for alum. The following issues may be evaluated as options to consider for treatment process enhancement.

Chemicals

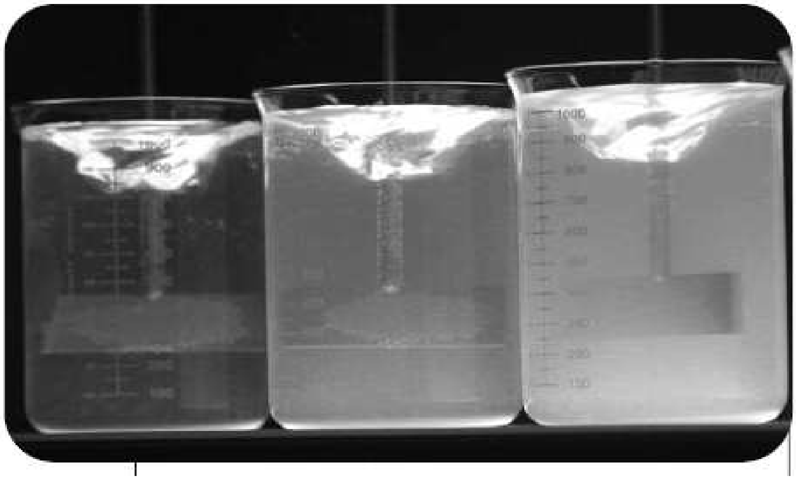
An evaluation of the chemicals used in the treatment process can identify the appropriateness of the coagulation chemicals being used. A thorough understanding of coagulation chemistry is important, and changes to coagulation chemicals should not be made without careful consideration. The following items should be considered when evaluating chemicals and coagulation:

1. What is the protocol for low-turbidity water? The primary coagulant should never be shut off, regardless of raw water turbidity.
2. Are chemicals being dosed properly with regard to pH, alkalinity, and turbidity? Is dose selection based on frequent jar testing or other testing methods such as streaming current monitoring, zeta potential, or pilot filters? Relying exclusively on past practice may not be enough. The system may want to consider doing a jar test while the plant is running well to see how floc in the jar should look (see Appendix F for jar test information).
3. Do standard operating procedures (SOPs) exist for coagulation controls? Systems should develop SOPs and establish a testing method that is suited to the plant and personnel. SOPs should be based on the consensus of all operators to ensure shared knowledge and experience. Also, all processes should be documented as they are performed so they may be reproduced in the future. An example SOP is provided in Appendix G.
4. Are the correct chemicals being used? Is the best coagulant being used for the situation? Changing coagulant chemicals or adding coagulant aids may improve the settleability of the flocculated water and in turn optimize performance. Coagulants may also be changed seasonally. The system should be carefully evaluated before full-scale plant changes of chemicals are made. If the system does change chemicals and needs an immediate response, the operator may need to purge the chemical feed line, particularly if the chemicals are far (several hundred feet or more) from the point of application.
5. Does the pH need to be increased through supplemental alkalinity? Adding a supplemental source of alkalinity, such as lime or soda ash, may be necessary for proper floc formation. However, adding lime (or other alkali supplements) and iron- or aluminum-based coagulants at the same point can degrade turbidity removal performance. The coagulant works on the high pH lime, the same as it does with naturally occurring turbidity or alkalinity. Therefore, the addition of lime typically creates the demand for more ferric- or alum based coagulant and the operator will probably add more coagulant in response to this demand. More coagulant can cause the pH to decrease, and more lime is typically added to compensate. Although finished water quality may be adequate when the raw water is stable, the plant pays a high cost in chemicals and sludge removal. This particular procedure is not foolproof and may not be effective at all when raw water characteristics change rapidly. One solution to this issue is to shift the feed line locations. Moving the coagulant line as far downstream as practicable from the lime addition point may allow the turbidity from the lime to fully dissolve. Placing the lime line well downstream of the coagulant addition point may allow for the coagulation of DBP precursors at a lower, more efficient pH before the lime addition elevates pH (Lind and Ruehl, 1998). Note that this mode of operation will not work for lime softening plants.

6. Do operators have the ability to respond to varying water quality conditions by adjusting coagulation controls? Systems should provide operators with learning opportunities so that they are able to react to unusual situations quickly and appropriately. Heavy rains or lake turnover may happen rarely, but noting indicators of these events will help with planning. For example, a sudden drop in pH may occur prior to the first heavy rain reaching the intake. Systems should use this as a trigger to change the coagulant dosage.
7. Are chemicals used before manufacturer recommended expiration or use-by dates? Does the chemical supplier operate an ISO 9000 production facility and provide quality certification? Chemical purity is important in all treatment systems.
8. Are chemicals being added in the correct order? The order of chemical addition is very important, because certain chemicals interfere with others. Jar tests should be used to develop optimal sequences. The system may also want to consider changing the location of chemical feed points. For instance, some utilities have found that optimum water quality was achieved when a coagulant was fed in raw water and a polymer was fed prior to filtration.
9. Is the chemical feed system operating properly? Operators should consider checking the accuracy of chemical feed systems at least once daily or once per shift. The system may want to install calibration columns on chemical feed lines to verify proper dosage or provide some other form of calibration. Systems should not set the chemical feed pumps to operate at maximum stroke and feed rates, which can damage the pumps.
10. Are chemicals properly mixed, particularly chemicals that are diluted? The system may want to consider an automatic mixer in the chemical tank to provide thorough mixing.

Jar Testing

The raw water characteristics will affect the type and amount of chemicals used. Changes in raw water pH, temperature, alkalinity, total organic carbon, and turbidity will affect coagulation and, subsequently, filtration and finished water quality. Jar tests are an excellent way to determine the best type and amount of chemical (or combination of chemicals) to use for varying raw water characteristics. Appendix F provides information on jar testing. Also, documenting actual plant operations on a daily basis will give operators a resource for information about past treatment for various raw water conditions.



Jar tests are a valuable tool to determine types and amounts of chemicals to use for optimum floc formation. Jar tests allow a system to experiment with different coagulants, polymers, pH controllers, and oxidants. The jar test should simulate actual plant operating conditions, such as mixing rates and detention times. The information obtained from the jar test can prove invaluable as a system considers different treatment techniques. The most important part of the jar test is to document the procedures used to enable replication in the future. The following worksheets can be used for the jar test. These worksheets are from EPA's Handbook *Optimizing Water Treatment Plant Performance Using the Composite Correction Program, 1998 Edition* (EPA

625-6-91-027). An operator who has never performed a jar test may want to seek technical assistance.

Procedures for the actual jar test are not presented due to the volume of information required. The following references are recommended for detailed instructions for performing a jar test:

1. AWWA. 1992. Operational Control of Coagulation and Filtration Processes. M37. American Water Works Association. Denver, Colorado.
2. California State University. 1994. Water Treatment Plant Operation, Volume 1. Third Edition. California State University. Sacramento, California.

JAR TEST PROCEDURE (page 1)

TEST CONDITIONS

Facility	**Date**	**Time**	**Turbidity**	**Temperature**	**pH**	**Alkalinity**	

Water Source	**Coagulant**	**Coagulant Aid**	

PREPARING STOCK SOLUTIONS

Step 1	Select desired stock concentration (see Table 1). Choose a stock solution concentration that will be practical for transferring chemicals to jars.

Table 1

Stock Solution (%)	Concentration (mg/L)	mg/L dosage per mL of stock solution added to 2 liter jar
0.01	100	0.05
0.05	500	0.25
0.1	1,000	0.5
0.2	2,000	1.0
0.5	5,000	2.5
1.0	10,000	5.0
1.5	15,000	7.5
2.0	20,000	10.0

Desired Stock Solution (%)	Coagulant	Coag. Aid	

Step 2	Determine chemical amount to add to 1-liter flask. If using dry products, see Table 2. If using liquid products, go to step 3.

Table 2

Stock Solution (%)	Conc. (mg/L)	mg of alum added to 1-liter flask
0.01	100	100
0.05	500	500
0.1	1,000	1,000
0.2	2,000	2,000
0.5	5,000	5,000
1.0	10,000	10,000
1.5	15,000	15,000
2.0	20,000	20,000

Desired Amount In 1-liter flask (mL)	Coagulant	Coag. Aid	

Step 3	Determine liquid chemical amount to add to volumetric flask. For liquid chemicals, use the equation

$$\text{mL coagulant} = \frac{(\text{stock solution \%}) \times (\text{flask volume, mL}) \times (8.34\ \text{lb/gal})}{100 \times (\text{chemical strength, lb/gal})}$$

	Coagulant	Polymer	
Chemical Strength (lb/gal)[1]			
Stock Solution Volume (mL)			
Desired Volume of Chemical to add to Flask (mL)			

[1] Note: Chemical Strength = chemical density x % strength

JAR TEST PROCEDURE (page 2)

JAR SETUP

Set up individual jar doses based on desired range of test.
Determine amount of stock solution by dividing doses by mg/L per mL (see Table 1).

Coagulant – Jar #	1	2	3	4	5	6	
Dose (mg/L)							
Stock Solution (mL)							
Coagulant Aid – Jar #	1	2	3	4	5	6	
Dose (mg/L)							
Stock Solution (mL)							
	1	2	3	4	5	6	
Dose (mg/L)							
Stock Solution (mL)							

TEST PROCEDURE

Step 1 — Set rapid mix time equal to rapid mix detention time.
To determine rapid mix time, use the following equation -

$$\text{Rapid mix time (min)} = \frac{(\text{rapid mix volume, gal}) \times (1{,}440\ \text{min / day}) \times (60\ \text{sec / min})}{(\text{plant flow rate, gal / d})}$$

Mix Volume (gal)	
Plant Flow Rate (gal/d)	
Mix Time (sec)	

Step 2 — Set total flocculation time equal to total flocculation time in plant.
To determine total flocculation time, use the following equation -

$$\text{Floc time (min)} = \frac{(\text{flocculator volume, gal}) \times (1{,}440\ \text{min / day})}{(\text{plant flow rate, gal / d})}$$

Floc Volume (gal)			
Floc Time (min)			

Step 3 — Use Figure 1* to determine the jar mixing energy values (rpm) that correspond to the approximate flocculator mixing energy values (G). Flocculator mixing energy can be estimated from the plant design information (O&M manual) or can be calculated from the equation described in Appendix F – B.1.Flocculation*.

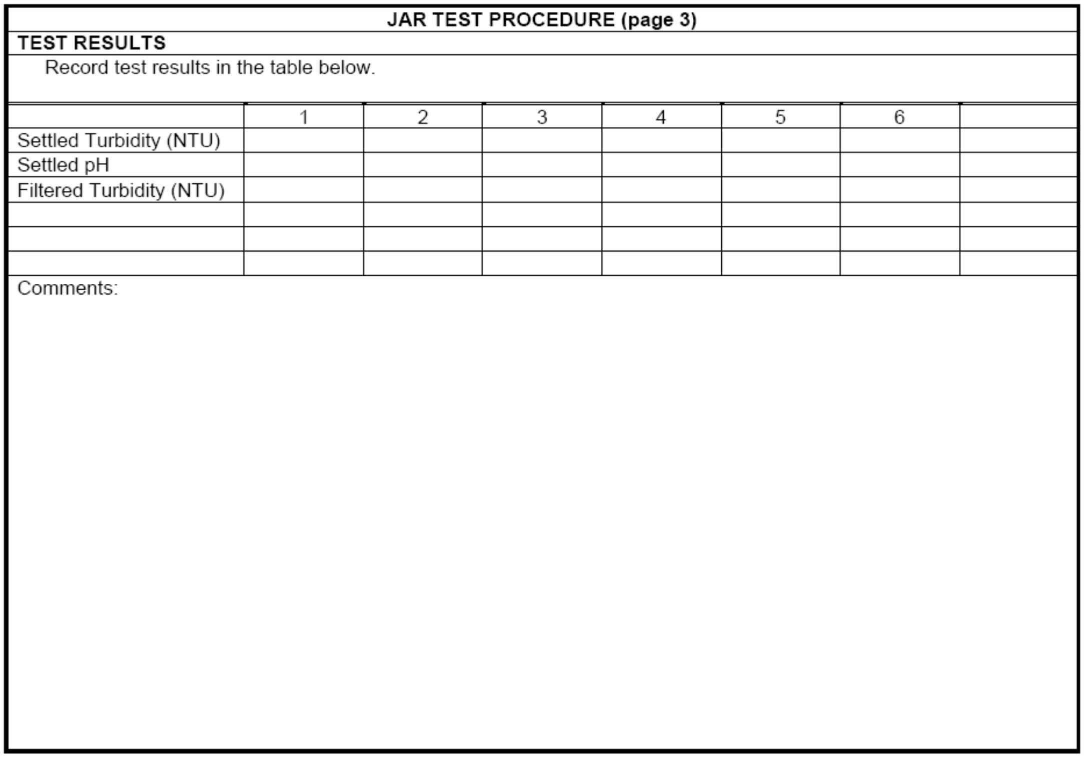
Flocculator Stage	1st	2nd	3rd	
Flocculator Mixing (G)				
Jar Mixing (rpm)				

Step 4 — Set sample time based on particle settling velocity. Use the equation below to determine sample time when using 2-liter gator jars as described in Figure 1*.

$$\text{Sample time (min)} = \frac{(10\ \text{cm}) \times (\text{surface area, ft}^2) \times (1{,}440\ \text{min / day}) \times (7.48\ \text{gal / ft}^3)}{(\text{plant flow rate, gal / d}) \times (30.48\ \text{cm / ft})}$$

Sedimentation Surface Area (ft^2)	
Plant Flow Rate (gal/day)	
Sample Time (min)	

* Figure 1 and Appendix F can be found in *Optimizing Water Treatment Plant Performance Using the Composite Correction Program, 1998 Edition* (EPA 625-6-91-027).



JAR TEST PROCEDURE (page 3)

TEST RESULTS

Record test results in the table below.

	1	2	3	4	5	6	
Settled Turbidity (NTU)							
Settled pH							
Filtered Turbidity (NTU)							

Comments:

Feed Systems

Feed systems are another important aspect of the coagulation step in typical treatment processes. The figures below show examples of chemical feed systems.

Polymer Feed Pump

Alum Feed Pump

Feed systems need to deliver coagulants into the treatment system at rates necessary for optimal performance. The following aspects of feed systems should be evaluated:

1. Is redundancy a consideration? Redundancy should be built into the feed systems so that proper feeding of chemicals can be maintained if primary systems fail or malfunction.
2. Do chemical feed pumps have sufficient dosage range? Feed systems should be sized so that chemical dosages can be changed to meet varying conditions.
3. Are chemical feed systems and solution piping checked regularly? Preventive maintenance is critical for avoiding process upsets due to equipment breakdown. Coagulant lines should be flushed out frequently to prevent buildup. Where possible, chemical feed lines should be easy to take apart for quick replacement or simpler maintenance.
4. Is a diaphragm pump used? A continuous pump allows coagulants to be added in a way that avoids pulsed flow patterns.
5. Does the plant stock repair parts for all critical equipment? Repair parts with a long lead-time for delivery should be reordered as soon as possible after removal from inventory.

The following is an example of an operating procedure for the chemical feed practices when raw water turbidity is between 10 and 20 NTU. It may be used as a standard operating procedure (SOP) and is an example that may provide valuable guidelines for systems. However, be careful when conducting any of the procedures contained in the following example operating procedure. Each system is unique and what works well for one system may not work for another. Chemical feed SOPs should be developed based on specific filtered water turbidity goals, jar testing, experience, and other site-specific conditions.

EXAMPLE OPERATING PROCEDURE

Chemical Feed Practices for Raw Water Turbidity Between 10 and 20 NTU[1]

1. Set the alum feed rate at 15 mg/L (metering pump speed at 50 percent speed; do not change the stroke setting).
2. Set the polymer feed rate at 3 mg/L (metering pump speed at 50 percent speed; do not change the stroke setting).
3. Start the plant with clean filters. If filters are not clean, backwash them using SOPs for backwashing.
4. After 20 minutes, note the effluent turbidity readings from the sedimentation basins and from individual filters.
5. The settled water turbidity should be less than 2 NTU. If turbidity exceeds 2 NTU off of a sedimentation basin, check the individual filter effluent (IFE) turbidities:
    a. If IFE turbidities are less than 0.1 NTU, do not adjust the chemical feed rates.
    b. If IFE turbidities are greater than 0.1 NTU but less than 0.25 NTU, increase the alum feed rate by 5 percent. Wait another 20 minutes to observe.
6. Repeat procedures in Step 5 as necessary.
7. If any of the IFE turbidity readings exceed 0.25 NTU, take the appropriate filter(s) off-line and reduce the flow through the plant by 200 gpm for each filter that is off-line.
8. If IFE turbidity remains between 0.10 NTU and 0.25 NTU after 4 hours of operation, or if a filter(s) is still off-line after 4 hours of operation, call the plant supervisor at 555-5050.
    a. Begin jar testing using alum doses of 10 mg/L, 20 mg/L, 30 mg/L and 40 mg/L.
    b. After results are obtained, run another jar test using alum doses that are slightly above and below the best result from the first test. For example, if the best results were obtained at 30 mg/L, run another set of tests at 26 mg/L, 28 mg/L, 30 mg/L and 32 mg/L.
    c. After the best alum dose is determined from the second jar test, reduce that alum dose by 5 mg/L, and run another set of tests using that alum dose and polymer doses of 2 mg/L, 3 mg/L, 4 mg/L and 5 mg/L. Select the best results from this jar test as the full-scale plant doses for alum and polymer.

IFE Turbidity Goals (for <u>all</u> raw water quality conditions): < 0.10 NTU within 15 minutes of start-up, < 0.10 NTU 95 percent of the time, and always < 0.3 NTU. Raw water turbidity changes should not affect finished water quality.

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[1] These procedures assume that:

- Process control decisions are based upon jar testing results and on past records and experience with similar water conditions.
- Chemical feed pumps have been calibrated recently.
- Chemicals have been mixed in accordance with standard practices and manufacturers recommendations.

Satisfactory Dispersal/Application Points

Coagulation and mixing also depends on satisfactory dispersal of coagulation chemicals and appropriate application points. Coagulants should be well-dispersed so that optimal coagulation may occur. Enough feed points should be used so chemicals are able to mix completely. The system should evaluate the following items:

1. Is dispersion taking place? Coagulation reactions occur rapidly, probably in less than 1 second. When injecting at hydraulic jumps, weirs, or flumes, the coagulant should be distributed uniformly across the width of the flow.
2. Where are coagulants being added? Generally, metal salts should be introduced at the point of maximum energy input. Low-molecular weight cationic polymers can be fed with metal salts at the rapid mix or at second stage mixing following the metal salt. High-molecular weight nonionic/anionic floc/filter aids should be introduced to the process stream at a point of gentle mixing. Most polymer feed solutions should be provided with a “cure time” or “aged” before use. Use of an inline blender with carrier water aids in further dispersal at application. Most polymers have specific preparation instructions and should not be added directly in the raw, concentrated form in which they are received.
3. Is rapid mixing equipment checked frequently? Systems should check the condition of equipment and ensure that baffling provides for adequate, even flow.

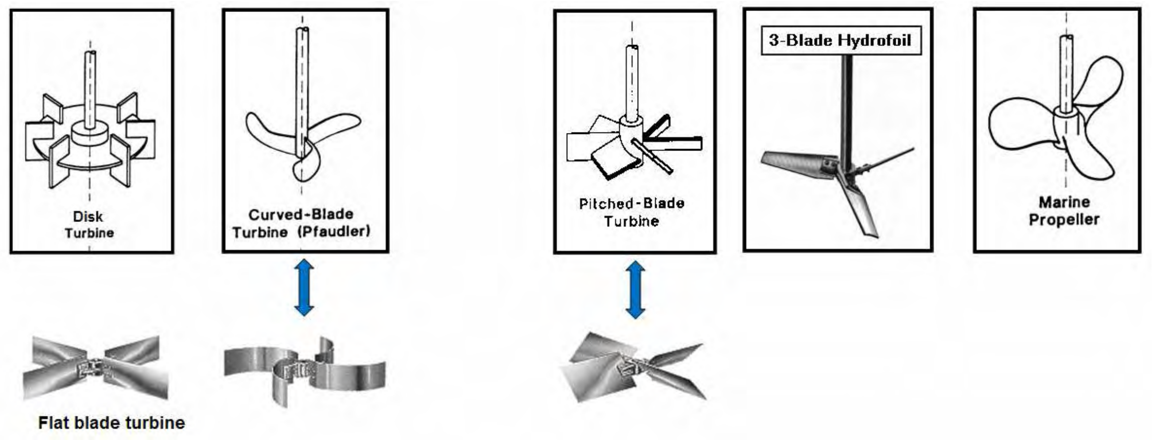
Rapid Mixing

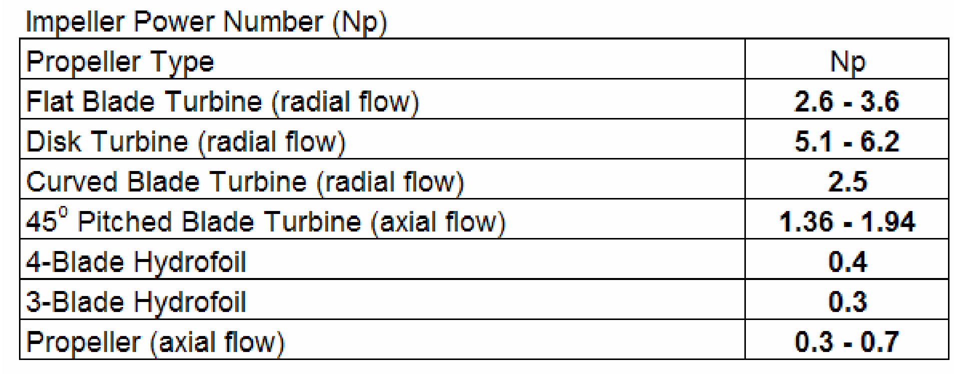
Mixing distributes the coagulant chemicals throughout the water stream. When alum or ferric chloride is used to achieve destabilization through charge neutralization, it is extremely important that the coagulant chemical be distributed quickly and efficiently because the intermediate products of the coagulant reaction are the destabilizing agents. These intermediate species are short-lived and they must contact the solids particles in the water if destabilization is to be achieved. When other mechanisms are predominant in the coagulation process, or when organic polymers are being used as the coagulant chemical, immediate distribution of the coagulant chemical is not as critical and less-intense mixing may be acceptable, or even desirable. In some cases, excessive mixing may serve to break up coagulant molecules or floc particles, thereby reducing the effectiveness of subsequent solids removal processes.

The time needed to achieve efficient coagulation varies depending on the coagulation mechanism involved. When the mechanism is charge neutralization, the detention time needed may be one second or less. When the mechanism is sweep floc or entrapment, longer detention times on the order of 1 to 30 seconds may be appropriate (Kawumara, 2000; AWWA and ASCE, 1998; Hudson, 1981).

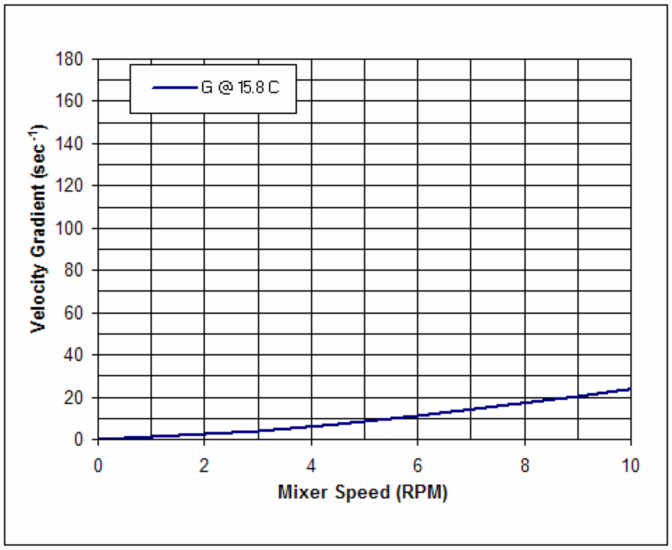
In general, the lower the coagulant dosage, the faster the mixing should occur because chemical reactions happen very quickly at low dosages. Rapid mixing disperses a coagulant through the raw water faster than the reaction takes place. When alum or ferric chloride are used in lower dosages (for charge destabilization; not sweep floc development), it is important to ensure that they mix very quickly with the raw water to be effective. Engineers have developed methods of determining appropriate mixing rates, called “mixing intensity values” or “velocity gradient” abbreviated as the letter “G.” This value is used to size various mixing mechanisms such as static mixers, impellers, and blades and depends upon the type of mechanism used.

Examples of various types of rapid mix mechanisms, impeller power numbers, and an example of a velocity gradient curve are shown below*:




Impeller Power Number (Np)

Propeller Type	Np
Flat Blade Turbine (radial flow)	**2.6 - 3.6**
Disk Turbine (radial flow)	**5.1 - 6.2**
Curved Blade Turbine (radial flow)	**2.5**
45^0 Pitched Blade Turbine (axial flow)	**1.36 - 1.94**
4-Blade Hydrofoil	**0.4**
3-Blade Hydrofoil	**0.3**
Propeller (axial flow)	**0.3 - 0.7**



*Source of information, equations, and images: Mixing in Coagulation and Flocculation, AWWARF 1991 & Water Works Engineering, Qasim & Zhu, Prentice Hall PTR 2000.

Conversion Factors and Equations for Determining Coagulant Dose

ABBREVIATIONS

ac = acre
cfs = cubic feet per second
cm = centimeter
d = diameter
ft = feet
ft^3 = cubic feet
gal = gallons
gpd = gallons per day
gpm = gallons per minute
gpg = grains per gallon
g = grams

ha = hectare
hr = hour
in = inches
in^3 = cubic inches
kg = kilogram
L = liter
lbs = pounds
mg = milligrams
MG = million gallons
MGD = million gallons per day
m^3 = cubic meters

mi = mile
min = minute
mL = milliliter
ppm = parts per million (mg/L)
r = inner radius
sec = second
Sp Gr = specific gravity
sq ft = square feet
sq in = square inches
sq m = square meters
yd = yard

CONVERSION FACTORS

AREA:

1 sq ft = 144 sq in or 144 sq in/sq ft
1 ac = 43,560 sq ft or 43,560 sq ft/ac

DOSAGE:

1 grain/gal = 17.1 mg/L or 17.1 mg/L/gpg
1 mg = 64.7 grains or 64.7 grains/mg

LENGTH:

1 ft = 12 in or 12 in/ft
1 yd = 3 ft or 3 ft/yd
1 mi = 5,280 ft or 5,280 ft/mi

UNITS:

1 million = 1,000,000 = 1×10^6

VOLUME:

1 ft^3 = 7.48 gal or 7.48 gal/ft^3
1 liter = 1,000 mL or 1,000 mL/L
1 gal = 3.785 L or 3.785 L/gal
1 gal = 231 in^3 or 231 in^3/gal

DENSITY:

1 gal = 8.34 lbs or 8.34 lbs/gal
1 ft^3 = 62.4 lbs or 62.4 lbs/ ft^3

FLOW:

1 MGD = 694 gpm or 694 gpm/MGD
1 MGD = 1.55 cfs or 1.55 cfs/MGD

TIME:

1 min = 60 sec or 60 sec/min
1 hr = 60 min or 60 min/hr
1 day = 24 hr or 24 hr/day

WEIGHT:

1 g = 1,000 mg or 1,000 mg/g
1 kg = 1,000 g or 1,000 g/kg
1 lb = 454 g or 454 g/lb
1 kg = 2.2 lbs or 2.2 lbs/kg

CONVERSION FACTORS (Metric System)

AREA:

1 ha = 2.47 ac or 2.47 ac/ha

1 ha = 10,000 sq m or 1,000 sq m/ha

DENSITY:

1 liter = 1 kg or 1 kg/L

VOLUME:

1 m^3 = 1,000 L or 1,000 L/ m^3

1 gal = 3.785 L or 3.785 L/gal

LENGTH:

1 m = 100 cm or 100 cm/m

1 m = 3.28 ft or 3.28 ft/m

FLOW:

1 MGD = 3,785 m^3 or 3,785 m^3/MGD

WEIGHT:

1 gm = 1,000 mg or 1,000 mg/gm

1 kg = 1,000 gm or 1,000 gm/kg

FORMULAS

I. FLOWS:

$$1)\ \text{Flow, gpm} = \frac{(\text{Flow, MGD})(1{,}000{,}000\ \text{gal / MG})}{(60\ \text{min / hr})(24\ \text{hr / day})}$$

or

$$2)\ \text{Flow, MGD} = \frac{(\text{Flow, GPM})(60\ \text{min / hr})(24\ \text{hr / day})}{1{,}000{,}000\ \text{gal / MG}}$$

IV. COAGULATION AND FLOCCULATION:

$$1)\ \text{Polymer, lbs} = \frac{(\text{Polymer Solution, gal})(\text{Polymer, \%})(\text{Sp Gr})(8.34\ \text{lbs / gal})}{100\%}$$

$$2)\ \text{Dose, mg/L} = \frac{\text{Chemical Feed, lbs / day}}{(\text{Flow, MGD})(8.34\ \text{lbs / gal})}$$

$$3)\ \text{Polymer, \%} = \frac{(\text{Dry Polymer, lbs})(100\%)}{(\text{Dry Polymer, lbs} + \text{Water, lbs})}$$

$$4)\ \text{Liquid Polymer, gal} = \frac{(\text{Polymer Solution, \%})(\text{Vol of Solution, gal})}{\text{Liquid Polymer, \%}}$$

II. CHEMICAL FEEDS:

A. Dry Chemicals (Weight-based)

1) Feed Rate, lb/day $= \dfrac{(\text{Feed Rate, g / min})(1440\text{ min / day})}{454\text{ g / lb}}$

2) Dosage, ppm $= \dfrac{\text{Feed Rate, lb / day}}{(\text{Flow, MGD})(8.34\text{ lb / gal})}$

B. Liquid Chemicals (Volume-based)

1) Feed Rate, gal/day $= \dfrac{(\text{Feed Rate, mL / min})(1440\text{ min / day})}{3{,}785\text{ mL / gal}}$

2) Dosage, ppm $= \dfrac{\text{Feed Rate, gal / day}}{\text{Flow, MGD}}$

C. Liquid Chemicals (Liquid Weight-based)

1) Feed Rate, lb/day $= \dfrac{(\text{Feed Rate, mL / min})(1440\text{ min / day})(\text{Sp Gr})(8.34\text{ lb / gal})}{3{,}785\text{ mL / gal}}$

2) Dosage, ppm $= \dfrac{\text{Feed Rate, lb / day}}{(\text{Flow, MGD})(8.34\text{ lb / gal})}$

D. Liquid Chemicals (Dry Weight-based)

1) Feed Rate, dry lb/day

$$= \frac{(\text{Feed Rate, mL / min})(1440\text{ min / day})(\text{Sp Gr})(\%\text{ concentration})(8.34\text{ lb / gal})}{(3{,}785\text{ mL / gal})(100\,\%)}$$

2) Dosage, ppm $= \dfrac{\text{Feed Rate, dry lb / day}}{(\text{Flow, MGD})(8.34\text{ lb / gal})}$

III. CHEMICAL DOSES:

A. Calibration of a Dry Chemical Feeder:

$$\text{Chemical Feed Rate, lb/day} = \frac{\text{Chemical Applied, lbs}}{\text{Length of Application, day}}$$

B. Calibration of a Solution Chemical Feeder:

1) Chemical Feed, lbs/day

$$= \frac{(\text{Chem Conc, mg / L})(\text{Vol Pumped, mL})(60\ \text{min / hr})(24\ \text{hr / day})}{(\text{Time Pumped, min})(1000\ \text{mL / L})(1000\ \text{mg / gm})(454\ \text{gm / lb})}$$

2) Chemical Feed, gpm $= \dfrac{\text{Chemical Used, gal}}{\text{Length of Application, min}}$

3) Chemical Solution, lbs/gal $= \dfrac{(\text{Chemical Solution, \%})(\text{Sp Gr})(8.34\ \text{lbs / gal})}{100\%}$

4) Feed Pump, gpd $= \dfrac{\text{Chemical Feed, lbs / day}}{\text{Chemical Solution, lbs / gal}}$

C. Chemical Feeder Setting :

1) Chemical Feed, lbs/day = (Flow, MGD)(Dose, mg/L)(8.34 lbs/gal)

2) Chemical Feeder Setting, mL/min

$$= \frac{(\text{Flow, MGD})(\text{Chemical Dose, mg / L})(3.785\ \text{L / gal})(1{,}000{,}000\ \text{gal / MG})}{(\text{Liquid Chemical, mg / mL})(24\ \text{hr / day})(60\ \text{min / hr})}$$

3) Chemical Feeder Setting, gal/day

$$= \frac{(\text{Flow, MGD})(\text{Chemical Dose, mg / L})(8.34\ \text{lbs / gal})}{\text{Liquid Chemical, lbs / gal}}$$

4) Chemical Feeder Setting, %

$$= \frac{(\text{Desired Feed Pump Rate, gpd})(100\%)}{\text{Maximum Feed Pump Rate, gpd}}$$

SAMPLE CALCULATIONS FOR DETERMINING FLOWS AND CHEMICAL DOSES

The following examples demonstrate how the previously presented equations can be used if a system is conducting jar tests or modifying chemical feed practices to improve filter effluent turbidity. Systems may find these examples useful for calculating flow values or determining chemical feed settings.

EXAMPLE 1: Flow Conversion

To convert a flow from gpm to MGD:

Scenario: If a system's flow is 900 gpm and the flow needs to be converted to MGD, the following equation can be used:

$$\text{Flow, MGD} = \frac{(\text{Flow, gpm})(60\ \text{min / hr})(24\ \text{hr / day})}{1{,}000{,}000\ \text{gal / MG}}$$

$$= \frac{(900\ \text{gpm})(60\ \text{min / hr})(24\ \text{hr / day})}{1{,}000{,}000\ \text{gal / MG}}$$

Flow = **1.3 MGD**

EXAMPLE 2: Chemical Doses

To calculate the liquid alum chemical feeder setting in milliliters per minute:

Scenario: The optimum liquid alum dose based on the jar tests at a particular plant is 12 mg/L. The system wants to determine the setting on the liquid alum chemical feeder in milliliters per minute when the plant flow is 5.3 MGD. The liquid alum delivered to the plant contains 439.8 milligrams of alum per milliliter of liquid solution.

Chemical Feeder Setting, mL/min

$$= \frac{(\text{Flow, MGD})(\text{Alum Dose, mg / L})(3.785\ \text{L / gal})(1{,}000{,}000\ \text{gal / MG})}{(\text{Liquid Alum, mg / mL})(24\ \text{hr / day})(60\ \text{min / hr})}$$

$$= \frac{(5.3\ \text{MGD})(12\ \text{mg / L})(3.785\ \text{L / gal})(1{,}000{,}000\ \text{gal / MG})}{(439.8\ \text{mg / mL})(24\ \text{hr / day})(60\ \text{min / hr})}$$

Chemical Feeder Setting = **380 mL/min**

EXAMPLE 3: Chemical Dose

To calculate the liquid alum chemical feeder setting in gallons per day:

Scenario: The optimum liquid alum dose based on the jar tests at a particular plant is 12 mg/L. The system wants to determine the setting on the liquid alum chemical feeder in gallons per day when the flow is 5.3 MGD. The liquid alum delivered to the plant contains 4.42 pounds of alum per gallon of liquid solution.

$$\text{Chemical Feeder Setting, gpd} = \frac{(\text{Flow, MGD})(\text{Alum Dose, mg / L})(8.34\ \text{lbs / gal})}{\text{LiquidAlum, lbs / gal}}$$

$$= \frac{(5.3\ \text{MGD})(12\ \text{mg / L})(8.34\ \text{lbs / gal})}{4.42\ \text{lbs / gal}}$$

Chemical Feeder Setting = **120 gpd**

EXAMPLE 4: Chemical Dose

To calculate the polymer fed by the chemical feed pump in pounds of polymer per day:

Scenario: A system wants to determine the chemical feed in pounds of polymer per day from a chemical feed pump. The polymer solution contains 18,000 mg polymer per liter. Assume the specific gravity of the polymer solution is 1.0. During a test run, the chemical feed pump delivered 700 mL of polymer solution during 7 minutes.

$$\text{Polymer Feed, lbs/day} = \frac{(\text{Chemical Conc, mg / L})(\text{Vol Pumped, mL})(60\ \text{min / hr})(24\ \text{hr / day})}{(\text{Time Pumped, min})(1000\ \text{mL / L})(1000\ \text{mg / gm})(454\ \text{gm / lb})}$$

$$= \frac{(18{,}000\ \text{mg / L})(700\ \text{mL})(60\ \text{min / hr})(24\ \text{hr / day})}{(7\ \text{min})(1000\ \text{mL / L})(1000\ \text{mg / gm})(454\ \text{gm / lb})}$$

Polymer Feed = **5.7 lbs polymer/day**

EXAMPLE 5: Chemical Dose

To calculate the flow delivered by the pump in gallons per minute and gallons per day:

Scenario: A small chemical feed pump lowered the chemical solution in a 4-foot diameter tank 1 foot and 3 inches during a 6-hour period.

1. Tank Drop, in feet $= 1 \text{ ft} + \dfrac{3 \text{ in}}{12 \text{ in / ft}}$

$= 1 \text{ ft} + 0.25 \text{ ft}$

Tank Drop $=$ **1.25 ft**

2. Determine the gallons of solution pumped.

Volume Pumped = (Area, sq ft)(Drop, ft)(7.48 gal/cu ft)

Area $= \pi r^2$

π = 3.1416 (constant)

r = radius, ft = (diameter / 2) = 4 ft/2 = 2 ft

Area $= (3.1416)(2 \text{ ft})^2 = 12.5664 \text{ ft}^2$

Volume Pumped $= (12.5664 \text{ ft}^2)(1.25 \text{ ft})(7.48 \text{ gal/cu ft})$

Volume Pumped = **117.5 gal**

3. Estimate the flow delivered by the pump in gallons per minute and gallons per day.

$$\text{Flow, gpm} = \frac{\text{Volume Pumped, gal}}{(\text{Time, hr})(60 \text{ min / hr})}$$

$$= \frac{117.5 \text{ gal}}{(6 \text{ hr})(60 \text{ min/hr})}$$

Flow = **0.33 gpm**

OR

$$\text{Flow, gpd} = \frac{(\text{Volume Pumped, gal})(24 \text{ hr / day})}{\text{Time, hr}}$$

$$= \frac{(117.5 \text{ gal})(24 \text{ hr / day})}{6 \text{ hr}}$$

Flow = **470 gpd**

EXAMPLE 6: Chemical Dose

To determine the settings in percent stroke on a chemical feed pump (the chemical could be chlorine, polymer, potassium permanganate or any other chemical solution fed by a pump) for various doses of a chemical in milligrams per liter:

Scenario: The raw water flow rate to which the chemicals are delivered is 315 gpm. The solution strength of the chemical being pumped is 3.8 percent. Assume the specific gravity of the chemical solution is 1.0. The chemical feed pump has a maximum capacity of 97 gallons per day at a setting of 100 percent capacity.

1. Convert the raw water flow from gallons per minute to million gallons per day.

Raw Water Flow, gpd = (Raw Water Flow, gpm)(60 min/hr)(24 hr/day)

= (315 gal/min)(60 min/hr)(24 hr/day)

= 454,000 gal/day

Raw Water Flow = **454,000 gpd = 0.454 MGD**

2. Change the chemical solution strength from a percentage to pounds of chemical per gallon of solution. A 3.8-percent solution means we have 3.8 pounds of chemical in a solution of water and chemical weighing 100 pounds.

$$\text{Chemical Solution, lbs/gal} = \frac{(\text{Chemical Solution, \%})(8.34\ \text{lbs / gal})(\text{Sp Gr})}{100\,\%}$$

$$= \frac{(3.8\,\%)(8.34\ \text{lbs / gal})(1.0)}{100\,\%}$$

Chemical Solution = **0.32 lbs chemical/gallon solution**

3. Calculate the chemical feed in pounds per day for a chemical dose of 0.5 milligrams per liter. Assume various chemical doses of 0.5, 1.0, 1.5, 2.0, 2.5 mg/L and upward so that if we know the desired chemical dose, we can easily determine the setting (percent stroke) on the chemical feed pump.

Chemical Feed, lbs/day = (Raw Water Flow, MGD)(Dose, mg/L)(8.34 lbs/gal)

= (0.454 MGD)(0.5 mg/L)(8.34 lbs/gal)

Chemical Feed = **1.9 lbs/day**

4. Determine the desired flow from the chemical feed pump in gallons per day.

$$\text{Feed Pump, gpd} = \frac{\text{Chemical Feed, lbs / day}}{\text{Chemical Solution, lbs / gal}}$$

$$= \frac{1.9 \text{ lbs / day}}{0.32 \text{ lbs / gal}}$$

Feed Pump = **5.9 gpd**

5. Determine the setting on the chemical feed pump as a percent. In this case we want to know the setting as a percent of the pump stroke.

$$\text{Setting, \%} = \frac{(\text{Desired Feed Pump, gpd})(100\%)}{\text{Maximum Feed Pump, gpd}}$$

$$= \frac{(5.9 \text{ gpd})(100\%)}{97 \text{ gpd}}$$

Setting = **6%**

6. Now change the chemical dose in Step 3 from 0.5 mg/L to 1.0 mg/L and other higher doses and repeat the remainder of the steps, to calculate the data in Table 1.

7. Plot the data in Table 1 (Chemical Dose, mg/L vs. Pump Setting, % stroke) to obtain Figure 1. For any desired chemical dose in milligrams per liter, use Figure 1 to determine the necessary chemical feed pump setting.

TABLE 1 - SETTING FOR CHEMICAL FEED PUMP

Pump Flow, GPM = 315 gpm
Solution Strength, % = 3.8%

Chemical Dose, mg/L	Chemical Feed, lbs/day	Feed Pump, gpd	Pump Setting, % stroke
0.5	1.9	5.9	6.0
1.0	3.8	11.8	12.2
1.5	5.7	17.8	18.4
2.0	7.6	23.7	24.4
2.5	9.5	29.7	30.6
3.0	11.4	35.6	36.7
3.5	13.2	41.2	42.5
4.0	15.1	47.2	48.7
4.5	17.0	53.1	54.7
5.0	18.9	59.1	60.9
5.5	20.8	65.0	67.0
6.0	22.7	70.9	73.1
6.5	24.6	76.9	79.3
7.0	26.5	82.8	85.4
7.5	28.4	88.7	91.4

FIGURE 1 - CHEMICAL FEED PUMP SETTINGS FOR VARIOUS CHEMICAL DOSES FROM TABLE 1, ABOVE