

APPENDIX K

GENERAL PROCESS SELECTION CRITERIA

General Process Selection Criteria

This appendix discusses criteria used in the selection of chemicals and equipment for coagulation, mixing, flocculation, clarification, and disinfection.

1. Coagulant Feed, Dosage Monitoring, and Control

1.1 Coagulant Feed Pumps and Systems

Problems associated with chemical feed pumps include:

- drifting out of calibration, which fails to deliver the desired chemical dosage
- pump failure with no chemical fed

Pump calibration can be checked by methods described later. Loss of coagulant feed is likely to be characterized by absence of floc. In a direct filtration plant, failure of a coagulant feed pump or exhaustion of the coagulant supply would probably be indicated by a sharp rise in turbidity less than one hour after the failure. At a conventional treatment plant, loss of coagulant feed could result in filling a sedimentation basin with uncoagulated water before filtered water turbidity began to rise. At conventional plants, the absence of floc in flocculator effluent would provide an earlier warning of feed pump failure than a filtered water turbidity increase.

Chemical feed flexibility and proper handling of coagulant chemicals contribute to effective pretreatment. Ability to feed either ferric or alum coagulant gives plant staff the flexibility to use either chemical as appropriate. In small water treatment plants and in package plants, diaphragm pumps are commonly used to feed chemicals. Diaphragm pumps function in a manner similar to how a human heart pumps. Liquid being pumped enters a chamber, a valve closes to prevent backflow, and the chamber is squeezed, forcing liquid to move forward. Like human hearts, diaphragm pumps move liquid in pulses. The pumping rate for a diaphragm pump can be modified by varying the stroke length (which varies the volume change that occurs with each stroke) and by changing the number of strokes per minute. If the number of strokes per minute is reduced in an effort to feed chemical at the low end of the pump's range, then a diaphragm pump is feeding chemical into the pipeline and into the rapid mixer on an intermittent basis. When a diaphragm pump is used in conjunction with an in-line mixer, where residence time is maybe only one or two seconds, the on-off pumping action of a diaphragm pump could result in some raw water being overdosed with coagulant and other raw water receiving no coagulant until all water was blended together in a flocculator. This does not make the most effective use of coagulant chemicals.

The pulsing action of a diaphragm pump can be dampened by installing a vertical, capped piece of pipe one or two feet in length at a location downstream of the

pump (between the pump and the rapid mixer). This device is called an accumulator and may be available commercially. To work properly, the capped vertical pipe must contain air. During the pumping phase, chemical is forced into the pipeline and some goes into the vertical pipe, compressing the air. During the resting phase, the compressed air forces chemical out of the pipe causing it to flow down the pipeline. This provides a flow of chemical that is more uniform, ensuring that all raw water is exposed to coagulant chemical. Installation of an accumulator pipe to dampen flow pulsations is a task that can easily be performed by most water treatment plant operators if such a device is lacking on chemical feed lines supplied by a diaphragm pump.

1.1.1 Order of Chemical Addition.

When pH adjustment is used in conjunction with coagulation, the order of chemical addition should be evaluated in jar tests. Sometimes, adjusting pH before addition of coagulant may yield better results. In other instances however, adding the coagulant first may produce better water quality. After jar test results are known, if bench-scale testing has indicated that the order of chemical addition in the full-scale plant ought to be changed, this should first be done in a temporary manner until the preferred order of chemical addition can be verified.

1.1.2 Monitoring Coagulant Dosage

Volumetric monitoring. Coagulant dosage can be tracked by measuring the volume of coagulant feed over a period of time and relating that to the volume of water treated. Volume use changes in day tank over a period of time, or changes in total volume of liquid fed as measured by a positive displacement fluid flow meter, are needed for calculation.

A quick way to monitor chemical feed rate is to have piping arranged so the chemical feed pump can be supplied from a graduated cylinder that holds about 1 minute's worth of chemical at the maximum pumping rate.

Streaming current instrument. For waters having low to moderate TDS concentrations, and at plants where coagulation is practiced for removal of particulate matter rather than for removal of natural organic matter, streaming current instrumentation can be very useful as a guide for operators to monitor coagulant dosage. When a streaming current instrument is used for coagulant dosage monitoring, a sudden, large change in the streaming current can signal loss of coagulant chemical feed, and as such may serve as an indirect indication of coagulant feed.

1.1.3 Control of Coagulant Feed

Chemical dosages have to be changed in response to changes in source water quality.

Streaming current instrument output. This technique is not useful for water softening, and may not work at water treatment plants where enhanced

coagulation must be practiced to attain the required extent of removal of TOC. This technique is most appropriate where particle destabilization is the purpose of coagulation. At some treatment plants, chemical feeders are directly linked to streaming current readout, whereas at other plants, plant operators check the streaming current readout and then make chemical dosage decisions based on this, other information, and their experience and training.

Coagulant dosage paced to raw water flow. To improve operations efficiency and reduce the amount of “busy work” for operators whenever a change in plant flow occurs, pacing coagulant dosage to raw water flow is very helpful. This is especially valuable for maintaining proper coagulation dosage when raw water flow needs to be changed frequently, such as one or more times per day. Use of flow-paced chemical feed simplifies the operator’s job, enabling him or her to focus on other matters at the plant when flow has to be changed frequently.

1.2 Polymer selection, feed, dosage determination, and dosage control

Polymers are important for water treatment in the United States. They are used in many plants. Reasons for polymer use include strengthening weak floc, decreasing usage of metal coagulants as a means of reducing sludge production, and improving the turbidity and particle count in water at the beginning of a filter run after backwashing. Symptoms of problems caused by polymer use can include mudball formation in the media, high rates of head loss build-up with little penetration of floc down into the filter media, and inability to filter out turbidity if a cationic polymer is seriously overdosed.

1.2.1 Cationic Polymers

Cationic polymers can be used to aid or supplement positively charged metal coagulants. When used in this way they are often added simultaneously with the metal coagulant. Sometimes cationic polymers are used as the only coagulant chemical. Cationic polymers may be used in conjunction with iron or aluminum coagulants to reduce the dosage of the metal coagulants. Polymer sludge is less voluminous than metal coagulant sludge, so cationics are sometimes used in conjunction with metal coagulants when an important goal in treatment is reduction of the volume of sludge produced. The positive charge on these polymers is used to neutralize the negative surface charge found on most kinds of particles encountered in raw water, just as the positively charged alum or iron coagulant can be used to neutralize the negative charges on particles in water. Cationic polymers tend to have molecular weights of 500,000 or lower. This is about one tenth of the molecular weight typical for anionic and nonionic polymers.

When cationic polymers are used as the primary coagulant or as a coagulant aid, polymer dosage must be carefully controlled. Typical dosages range from 0.1 to 5 mg/L (Montgomery, 1985). When cationic polymer is added to water, the positively charged polymer at low dosages neutralizes some or all of the negative charge on particles in the water. If more cationic polymer is added, though, the

charge on the particles can become positive. A particle with a high positive charge resists joining with other positively charged particles in flocculation, and may not be removed by filtration. Overdosing with cationic polymer can lead to treatment results that are as bad as results of underdosing. With polymers, it is not true that “If a little is good, a lot is even better.”

Cationic polymers can be quite effective for turbidity removal, but they are not as effective as metal coagulants for removal of natural organic matter. Typically the dosage of metal coagulant required for removing natural organic matter is proportional to the amount of organic matter present in water. Metal coagulants are used in dosages large enough to form somewhat voluminous floc for removal of organic matter, as in enhanced coagulation. Cationic polymers do not compete well when the goal of treatment is removal of natural organic matter.

1.2.2 Flocculant aid (anionic and nonionic) polymers

Polymers used to aid flocculation tend to be nonionic or anionic, with molecular weights of one million or more. Dosages used are lower than dosages of cationic polymers. The very high molecular weight enables these polymers to “bridge” between tiny coagulated particles and helps to hold them together. This bridging forms stronger floc, but excessive dosages of flocculant aid polymers can form a floc so tough and large that it cannot penetrate into a granular media filter bed more than a few inches. This causes rapid increases in head loss and short filter runs.

Another potential problem with high dosages of anionic or nonionic polymers is the difficulty encountered when filters are backwashed. Observations of filter washing in clear plastic filter columns revealed that polymer use could cause filter media to become somewhat cemented together, and when the media broke up during backwash, it first broke into chunks with angular shapes, similar to the shape of broken concrete. With extensive and vigorous surface washing, these chunks of polymer-cemented filter media could be broken up and the media freed from the floc-media matrix.

One consideration in the use of flocculant aid polymers is the possible need for delay time between addition of the metal coagulant (alum or iron) and adding polymer. Some plants are designed for addition of alum or iron coagulant with a very turbulent rapid mix. Adding a flocculant aid polymer at a second, gentler stage of mixing is common.

1.2.3 Filter aid polymers

Filter aid polymers are typically high molecular weight nonionic polymers, and they are generally used in dosages of 0.005 to 0.05 mg/L. Filter aid polymers are used to strengthen floc or to improve attachment of particles within the filter. Filter aid increases the floc’s resistance to shear forces within the filter bed so that turbidity increases associated with filter rate increases can be minimized or

eliminated. Filter aid polymers may also be added to backwash water to reduce the initial turbidity spike.

Location of dosing point for adding filter aid can influence efficacy of the polymer because of the amount of mixing that may be attained after polymer addition and because of residence time between polymer addition and filtration. If differences in filter performance are noted, with higher filtered turbidity from filters closest to the filter aid addition point and lower filtered turbidity from filters farthest from the filter aid addition point, this may indicate insufficient time for the filter aid to be in the water and interact with particles before they are filtered. Generally, pretreated water flowing to filters is not stirred or mixed, but a small amount of hydraulic mixing or gentle mechanical stirring may help distribute the filter aid more uniformly through the water so it can do a better job. Determining the appropriate location for adding filter aid polymer has to be done in a pilot plant or full-scale facility.

2. Rapid Mixing

Mixing of treatment chemicals into water is a key process for treatment plants employing either coagulation or lime softening. Rapid mixing is an essential and important unit operation in chemical pretreatment. The various types of rapid mixing techniques used include back-mix reactors (a propeller mixer stirring a tank), hydraulic jump, baffled tanks, static in-line mixers, motorized in-line mixers, hydraulic injectors, pump-injected mixers, and injection of chemical into the impeller of a pump.

2.1 Mixing for Coagulation

Rapid mixing needs to be very fast and thorough when inorganic coagulants are added to water, as the rate of chemical reaction is very swift. When the less complex hydrolysis (dissolution) products of aluminum or ferric coagulants contact particles in water, the particles can be destabilized and prepared for flocculation. This is why very rapid dispersion of coagulant chemical is recommended for coagulation plants where direct filtration is practiced. On the other hand, if the less complex hydrolysis (dissolution) products of aluminum or ferric coagulants have time to contact each other, aluminum hydroxide or ferric hydroxide flocs will form. Use of high dosages of coagulant is common in plants that employ the sweep floc mechanism of coagulation, relying on large flocs to aid clarification. Some plants have attained greater efficiency in coagulant usage by converting from a situation of ineffective mixing to effective mixing.

Treatment problems can result from inadequate mixing or from discharge of coagulated water from more than one point in a single mixing chamber.

Flocculation is employed at most treatment plants following coagulant addition and rapid mixing to promote particle-to-particle collisions and to build floc size. When coagulated particles collide, they have a greater tendency to stick together

because of the coagulation process. Without flocculation, the rate of collision would be very slow. Flocculation is a crucial process if sedimentation is employed, as the very small colloidal particles present in raw water would not settle in a reasonable length of time, even if coagulated. The combination of coagulation plus flocculation properly applied brings about the formation of settleable floc particles.

Flocculation is an engineered process designed to increase the rate of particle-particle collisions and floc formation. Collisions between particles are promoted by imparting energy into the water. The energy input is expressed as Gt . The factor G in flocculation energy input is the velocity gradient. A velocity gradient could be thought of in terms of (feet per second) per foot or $\text{ft} \times \text{sec}^{-1} \times \text{ft}^{-1}$. The ft units cancel out, and we are left with sec^{-1} for units of G . The second factor in total energy input during flocculation is the time of flocculation, t , measured in seconds. The Gt product is used to express energy input in flocculation, and because the seconds units cancel out, Gt is a dimensionless number.

Literature suggests that G values need to be in the range of $300 - 5000 \text{ s}^{-1}$ for rapid mixing depending on mixer type and coagulant type. G values less than 100 s^{-1} are used for flocculation but the Gt values should be in the region of $10^4 - 10^5$. It appears therefore that recommended G and Gt values vary widely in the literature, and the correct value for any plant should be determined through jar testing, both at the design stage and when necessary to assist routine operation.

3. Types of Flocculation

The formation of gentle eddy currents or mild turbulence in water brings about the particle-particle collisions needed to form flocs. The currents or turbulence can be induced in the water by mechanical stirring, by bubbling air into a basin, or by creating multiple changes in flow direction in a long channel (hydraulic flocculation).

3.1 Hydraulic

Hydraulic flocculation was the type of flocculation typically employed in water treatment plants designed in the first couple of decades in the 20th century. An example of an early design still in existence is the Chain of Rocks Plant in St. Louis, which was brought online around 1905 for the St. Louis Exposition. Energy input in hydraulic flocculation is measured as head loss. The presence of many baffles in a flocculation channel or basin causes the water flow to twist and turn, causing turbulence. Energy input increases as head loss through the basin increases.

Both flocculation energy input and flocculation time can vary with rate of flow unless special provisions are made to vary energy input. Hydraulic flocculation basins can be designed with movable baffles, allowing plant operators to change the energy input by changing the baffle position and therefore changing head loss

incurred as water flows past the baffles. This approach has been used in some recently constructed plants such as one operated by the Contra Costa Water District in California.

3.2 Mechanical

Mechanical flocculation processes use a variety of stirring devices to gently agitate water and form flocs. In contrast to hydraulic flocculation, energy input is independent of the rate of flow. One advantage of mechanical flocculation is that operators may be able to vary energy input by changing the speed of the stirring device. Mechanical flocculation has largely supplanted hydraulic flocculation in plants designed and built in the last half of the 20th century. The types used include paddle wheel, turbine, and walking beam flocculators.

Vertical shaft, multi-speed, pitched-blade turbine flocculators were designed and installed in treatment plants more recently. This type of mechanical flocculator was well suited for direct filtration plants operating at low dosages of coagulant chemical. For dissolved air flotation, flocculation equipment that produces small flocs is desirable, as small floc particles are readily floated. On the other hand, the paddle wheel flocculator was considered more appropriate for conventional treatment plants employing sedimentation because this type of flocculator can be used to build settleable flocs.

3.3 Importance of Baffling

The effectiveness of the flocculation process is highest when the flocculation basins have been designed to avoid short-circuiting. When short-circuiting occurs in a basin, water flows through in a time that is shorter than the theoretical detention time. Although short-circuiting in flocculation basins cannot be totally eliminated, minimizing this problem is important because attaining a uniform floc retention time yields a more uniform floc size. When floc sizes range from very small to very large, the larger flocs may settle well while the smallest do not and are carried over to the filters. Attaining a fairly uniform floc size can improve sedimentation performance, particularly when plate settlers are employed.

Floc size is related to the flocculation time and energy dissipated into the water. Floc particles subjected to constant mixing intensity tend to grow larger with the passage of time. Flocs passing through the flocculation basin quickly have less time to grow and are likely to be smaller. Formation of uniform-sized flocs is promoted by use of multiple floc basins in series, or by placing multiple sets of baffles in a single floc basin to subdivide it. This causes the flow pattern to be closer to plug flow and gives a greater uniformity of detention times.

The function of baffles is to promote plug flow and prevent water from being discharged from a flocculation zone prematurely. In a basin with transverse flow, baffles are set up across the width of the basin. Influent flow is distributed across the width of the basin and water flows down the length of the basin, perpendicular to the baffles, from the entry end to the discharge end. In a basin set up for

serpentine flow, coagulated water enters at one corner of the flocculation basin and flows from across the influent end from one side to the other, then turns a corner and flows back. The flow of water moves progressively closer to the outlet of the basin only at the corners, but otherwise flow is perpendicular to a line running from the entry to the exit of the basin.

A successful conversion of a flocculation basin from transverse flow to serpentine flow was carried out at Fort Collins, Colorado (Bryant et al. 1990). In this plant, horizontal shaft paddle flocculators were being used. The shafts of the flocculators were parallel to the baffle walls. The flow pattern was changed so the water entered a flocculation chamber at one end and flowed through the chamber parallel to the flocculator shafts in a series of stages, exiting at the opposite end. This conversion produced floc particles having a much smaller size distribution and resulted in a substantial improvement in performance of a lamella plate settler. Turbidity produced by the serpentine flocculator pattern averaged 0.7 NTU versus 1.5 NTU for average turbidity from the transverse flow flocculation pattern.

3.4 Optimizing GT

Some flocculation basins are designed to have the highest energy input at the beginning of flocculation and the lowest energy input in the final stage of flocculation. This is referred to as tapered flocculation. When very small, coagulated particles are present in the water, as immediately after rapid mixing, substantial energy input is needed to stir the water and cause particle-to-particle collisions. Later, after flocs have formed, if the stirring energy is too high the floc may break up, so lower energy input is attained by decreasing the area of the flocculator paddles or by operating the paddles at a lower rotational speed.

The rate of floc formation decreases as water becomes colder. At locations where water temperature varies by 20° to 30° C throughout the year, operators ought to consider evaluating flocculator energy input seasonally and changing flocculation energy input as appropriate.

3.5 Floc Size Determination

Determination of floc size has been a technically difficult procedure. Usually this has been done as part of a research effort. Light microscopes have been used although this is tedious. Particle counters are likely to break up floc during the process of measuring floc particle size, making those results questionable. Some processes, such as plate settling, seem to be sensitive to floc size. Plate settlers work best when the flocs are uniform in size.

As a rule, larger flocs are required for sedimentation, and smaller “pin point” flocs for DAF and direct filtration. When charge neutralization is the filtration mechanism, for example in contact and direct filtration, the production of visible flocs is not expected. Contact filtration experiments at Thames Water’s pilot

plant in the early 1990s showed severe breakthrough of turbidity and iron when using coagulant doses large enough to form flocs.

4. Gravity Sedimentation Clarifiers

4.1 Gravity Sedimentation Concepts

Particles with a density greater than water have a downward settling velocity in quiescent water. When such particles flow through a tank of nearly quiescent water, they move toward the bottom of the tank as they flow from the entry towards the discharge end of the tank. If the particle has a downward, or settling, velocity great enough to enable the particle to settle to bottom of the basin before water exits the clarifier at the far end, then the particle can be removed through settling. The settling velocity theoretically needed to remove a particle in a basin can be calculated on the basis of the basin's dimensions and the rate of flow through the basin. If the distance a particle has to settle can be decreased while maintaining a constant horizontal velocity, then the residence time needed for settling can also be decreased.

Some factors affecting settling velocity are evident in Stokes Law. Stokes Law indicates that settling velocity increases as the difference between the specific gravity of the particle and the specific gravity of water increases. Settling velocity also increases as the square of the diameter of the particle. Denser flocs and larger flocs settle faster. Settling velocity decreases as the viscosity of water increases, so the resistance to settling is greater in cold water and settling occurs more slowly.

4.2 Causes of Problems in Settling Basins

Short-circuiting in sedimentation basins has been the cause of many sedimentation problems. Short-circuiting reduces detention time in the basin, decreasing the opportunity for suspended solids to settle to the bottom where they can be removed. It also causes floc carryover when strong currents cause basin velocities to be excessive.

Causes of short-circuiting include poorly designed clarifier inlets, poorly designed clarifier outlets, currents within the basin caused by sustained strong winds, and differences in the specific gravity of water. Poor inlet baffling is often a cause of short-circuiting in sedimentation basins. Thermal differences within a basin can also cause short-circuiting. Water is denser at colder temperatures, so cold water can go to the bottom after it enters a clarifier containing warmer water. Water is less dense at warmer temperatures, so if the influent water is warmer than the water in the tank, it can flow to the top of a clarifier, and "float" across the denser, colder water already in the clarifier. Water also is denser at very high turbidity (higher suspended solids concentrations); such water can flow to the bottom of a clarifier containing water lower in turbidity. Strong sustained crosswinds can cause water to roll over in a clarifier, creating a different form of short-circuiting.

When sustained winds occur and cause short-circuiting, barriers can be built to serve as windbreaks.

In regions that have hot days and cool nights, some source waters may be subject to diurnal water temperature variations. Temperature changes of this type can present serious problems to clarifiers by causing inversion of the water and sludge layers. A consequence of an inversion in a clarifier could be severe carry-over of floc with high settled water turbidity and short filter runs.

Settling basin performance can be deteriorated by build-up of sludge in weirs and in the basin. Build-up of deposits on weirs and in collector troughs can interfere with flow patterns for withdrawing settled water from the basin. Excessive deposits of sludge reduce the effective volume of the basin, reducing detention time, and promoting the resuspension of sludge by water flowing through the basin. Effective sludge removal and keeping weirs clean are necessary for optimum settling basin performance.

4.3 High Rate Sedimentation Processes

4.3.1 Sludge Blanket Clarifiers and Reactor-Clarifiers

Sludge blanket clarifiers and reactor-clarifiers are designed to have a mixing zone, a flocculation zone, and a sedimentation zone all within one basin. Treatment chemicals are added and mixed, floc forms, and then water rises through the sedimentation zone. The upward flow of water through the sedimentation zone causes the floc to rise. A variety of designs have been developed so that the upward velocity decreases as the water moves toward the top of the clarifier. They include the original hopper-bottomed tanks and subsequent designs of flat-bottomed tanks with multiple hoppers, a circular wedge, or other design concepts intended to allow the upward velocity to decrease as water flows up to effluent weirs. In basins employing this design concept, the floc blanket rises to a point where the upward velocity is not sufficient to carry floc higher. As other flocs pass through the blanket, they can combine with floc in the blanket and are removed in this manner. This allows floc blanket clarifiers to be operated at higher rates than conventional settling basins.

One factor that is important in sludge blanket clarifier and reactor-clarifier operation is the need to maintain equilibrium in the clarifier. The height of the blanket in the clarifier is a function of the floc particle size and density as well as the upward velocity of the water. A floc blanket that is subject to decreasing water velocity will fall to a lower level in the clarifier and could perhaps drop to the bottom of the basin, out of suspension. A higher water velocity will cause the blanket to move up toward the basin outlet. If the velocity is excessive, the floc blanket will be washed out. For these reasons, floc blanket processes perform best when they are operated at a constant rate, as in a base-loaded plant. The worst mode of operation for sludge blanket clarifiers and reactor-clarifiers is an on-off operation with daily start-up and shutdown. When flow stops, the

suspended solids settle to the bottom of the basin, so that no blanket is functioning when the units are restarted.

Sludge blanket clarifiers and reactor-clarifiers are designed to operate at overflow rates higher than the rates for conventional sedimentation basins. Like conventional sedimentation basins, sludge blanket clarifiers and reactor-clarifiers are vulnerable to short circuiting caused by density differences resulting from sudden changes in water temperature. When such events occur, operators may have few options other than reducing flow through the plant to downrate the clarifiers sufficiently such that floc does not wash out and go onto the filters.

4.3.2 Sludge recirculation clarifiers

In this system, a portion of the sludge is withdrawn and recirculated together with polymer and coagulated water. The purpose of sludge recirculation is to provide a greater contact opportunity for flocculation and to form a floc that will settle better by incorporating some existing suspended solids into the newly-forming floc. This objective is different from the purpose of sludge recirculation in the lime softening process, in which the presence of calcium carbonate crystals promotes more rapid precipitation of additional calcium carbonate. In reactor (solids-contact) clarifiers, sludge is recirculated in the mixing/flocculation zone to facilitate particle growth and sedimentation performance.

4.3.3 Inclined Tube Settlers

Inclined tube settlers were developed to provide very short travel distances to reach the bottom-collecting surface. Whereas a floc particle might have to travel down 12 to 16 feet from the top of the water to the floor of a conventional sedimentation basin where it would be removed from flowing water, in a tube settler a particle needs to travel down only a few inches to contact the bottom of the tube. Therefore, the detention time needed for effective settling in tube settlers is much shorter than the time needed in conventional sedimentation basins. Tube settler modules are fabricated with many tubes stacked together. Tube shapes include square, rectangular, hexagonal, and others. Inclined tube settling modules have been retrofitted into numerous settling basins to improve their performance.

Because of the way they are placed into sedimentation basins and supported, tube settler modules need to be fabricated from lightweight, non-corroding materials. Some are made of plastic. Treatment plant staff and their contractors must be very careful to avoid welding or other activities that could generate intense heat near the tube settler modules, as some tube settler modules have caught fire as a result of careless maintenance and repair activities.

4.3.4 Inclined Plate Settlers

Inclined plate settlers, like tube settlers, accomplish settling in a short time by reducing to inches the distance a particle must settle in order to contact the "bottom" of the basin. Installing inclined plate assemblies in existing basins is

often difficult, so this equipment is frequently used in new facilities rather than in retrofits of older settling basins. Basins equipped with inclined plate settlers are better able to cope with changing rates of flow than conventional sedimentation basins.

Like conventional settling basins and inclined tube settlers, performance of inclined plate settlers is optimized when the size of the floc is uniform. A change from cross-flow flocculation to serpentine flocculation resulted in improved performance for an inclined plate settler in Colorado.

4.3.5 Weighted or Ballasted Floc Clarifiers

Use of weighted or ballasted floc to accelerate settling is a relatively new concept in the United States although it has been used for a number of years in Europe. Floc resulting from coagulation often has a low settling velocity, necessitating design of settling basins with detention times as long as four hours. By weighting floc with a dense particle, it can be made to settle much more rapidly so sedimentation can be accomplished in less than one-half hour.

In this process, very fine sand and coagulant chemical are added to raw water in a flash mixing tank where coagulation occurs. Then polymer is added to make the sand adhere to the floc, and gentle stirring builds floc sizes up so the floc settles very rapidly. Settled floc and sand are continuously removed by sedimentation, and are pumped to a cyclone separator where the floc is separated from the sand. Clean sand is then reused to weight floc.

Some operational aspects of this process are different from other sedimentation processes. The key to the very rapid settling attained in this process is the attachment of floc to very fine sand. Addition of fine sand to flocculated water would be futile if the two kinds of particles did not attach. Without attachment the sand would settle very rapidly and floc would remain suspended in the water. Therefore control of polymer addition to attain effective sand-floc attachment is essential for successful operation of the process. Another aspect not encountered in other sedimentation processes is that a very small amount of sand is lost in the process so make-up sand is needed and would be added on a periodic basis.

5. Dissolved Air Flotation (DAF) Clarifiers

5.1 Concepts of Dissolved Air Flotation

Dissolved air flotation is an especially effective clarification process for removal of particulate matter that has poor settling characteristics. Low turbidity (< 100 and preferably < 30 NTU) waters with high loadings of low-density particles such as algae or flocculated colored organic material are the major DAF applications. Raw waters from reservoirs with heavy clay, silt, and sand settled out, but with algal loads or upland colored, are low turbidity sources commonly treated now by DAF rather than the gravity sedimentation used in the UK, Scandinavia, and Australia. DAF plants have recently been built for such applications in some US communities.

In the DAF process, a side stream of treated water (about 6 to 10 percent of the process flow) from the DAF clarifier is pumped through a pressurized vessel where it contacts air under pressure, typically ranging from 60 to 80 psi (420 to 560 kPa). With respect to normal atmospheric conditions, the water leaving the saturator is supersaturated. It passes through one or more pressure reducing nozzles or needle valves into the inlet zone, close to the bottom of the DAF clarifier, where flocculated water is introduced. When the pressure on the supersaturated water reverts to atmospheric pressure, the supersaturated air leaves the water, forming a cloud of microscopic bubbles. If the DAF clarifier is properly designed and operated, this cloud of tiny bubbles rises to the top of the water in the clarifier. Floc particles attach to the rising bubbles and are carried to the water surface. Over a period of time, ranging from a fraction of an hour to several hours, the floc builds up on the water surface forming a floating scum. Periodically, the floated floc is scraped or floated off the water surface before it can become so compact and heavy that it settles to the bottom of the DAF clarifier.

In-filter DAF, a process in which the DAF clarification zone is in the water above filters, is increasing in popularity for shaving the peaks of algal blooms and preventing short filter runs in otherwise low turbidity raw water treatment systems. This type of equipment is generally proprietary, being produced by a number of manufacturers. When the area of the filter bed is the same as the area of the DAF clarifier, the clarifier-operating rate for DAF and the filtration rate are the same. DAF clarification must be interrupted for filter backwashing, but because DAF clarification can be restarted very rapidly, this is not a serious problem.

DAF should be used where the suspended solids concentration in the raw water is relatively low or the density of particles is low (e.g. color and algae). As compared to conventional gravity sedimentation basins, DAF has the advantage of start-up times that are only a matter of minutes, so it is a process that can be operated effectively on a start and stop basis. This is in contrast to blanket clarifier processes, which should be operated continuously to maintain the blanket in suspension. As with any process involving coagulation, DAF cannot perform properly without proper control of chemical dosing. Proper hydraulic design is required for DAF to work correctly. DAF also requires proper management of saturated water recycling.

5.2 Role of Pretreatment for Effective DAF Clarification

As with coagulation and sedimentation, effective coagulation is necessary for successful operation of DAF clarifiers. Floc particles and particulate matter in the raw water are carried to the water surface by attaching to the rising bubbles. Suspended particles that have not been properly coagulated will not be as likely to stick to the bubbles and float to the top.

Flocculation for the DAF process can have a shorter detention time than flocculation for a conventional settling basin because the objective is to have small flocs of destabilized particles that readily attach to rising bubbles. Edzwald et al. (1999) successfully operated DAF pilot plants having flocculation detention times as short as 5 minutes and DAF hydraulic loading rates as high as 12 to 16 gpm/sf (29 to 39 m/hr). Flocculation for a DAF clarifier would bear a stronger resemblance to flocculation for a direct filtration plant than for a conventional plant with a settling basin.

5.3 The DAF Clarifier

Recycle water percentage and operating pressure for saturator are two factors governing the quantity of air bubbles introduced into the DAF clarifier. If the particle concentration in raw water is high, a higher volume of bubbles may be needed for successful flotation of the floc and particles. More bubbles can be introduced into the clarifier by raising the air pressure in the saturator, or by increasing the recycle water percentage. Additional operating costs are caused by either action, so to minimize operating costs, higher recycle percentages or higher saturator pressures would not be used unless necessary. Depending on the nature of the pump performance curve for the recycle pump, raising the saturator pressure may decrease the recycle flow percentage. In such a situation, adjusting both saturator pressure and pump flow may be necessary to obtain a higher volume of bubbles in the clarifier.

Removal of floated sludge, called float, from the clarifier surface is required periodically, before the float begins to break up and settle to the bottom of the clarifier. If the float remains on top of the clarified water for a long period of time, the float at the edge of the clarifier may adhere to the clarifier wall during removal. This tendency can be mitigated by spraying water on the clarifier wall and in the floc sludge channel for a short time before and during removal of the float. Floated solids from a DAF clarifier can have solids content ranging from 1% to 3%, sometimes exceeding 3%. Collected solids should be transported to a site for treatment or disposal with a minimum use of water to avoid diluting the solids with more water and thus increasing the amount of water to be removed later. If the water level of the clarifier is raised to remove the float by flooding, the solids content of the sludge can be less than 0.2 percent.

DAF clarifiers are usually covered to prevent disturbance of the floated solids by natural phenomena including rain, hail, and high wind. If the floated solids were to be broken up and sank, their removal would be very difficult, probably accomplished only by shutting down the process and draining and cleaning the basin. Disruption of the floated solids could cause high loadings of particulate matter onto filters if the solids found their way to the discharge ports in the DAF clarifier.

6. Disinfection

Disinfection is the inactivation, or killing, of pathogens in drinking water. This process is a necessary barrier to transmission of waterborne disease by microorganisms. Disinfection provides a large measure of public health protection at a relatively low cost, compared to many other water treatment processes. Chemical disinfection is the accepted practice within the drinking water industry in the United States. The vast majority of U.S. water utilities use chemical disinfection, employing free chlorine, chloramine, ozone, chlorine dioxide, UV, or combinations thereof.

The USEPA has set forth requirements for disinfection of unfiltered surface waters in the Surface Water Treatment Rule (SWTR) and has given recommendations for disinfection of filtered waters in the Guidance Manual. The degree of chemical disinfection is assessed in terms of CT, in which C is the residual concentration of the disinfectant in mg/L, and T is the time in minutes for which the water and disinfectant chemical were in contact. The product of these parameters is compared to required standards to determine compliance. CT values for inactivation of *Giardia lamblia* cysts and enteric viruses are listed in the Guidance Manual for free chlorine, chloramine, chlorine dioxide, and ozone. The relative effectiveness of these chemical disinfectants for inactivating *Giardia* and viruses can be inferred from the published CT values.

The Interim Enhanced Surface Water Treatment Rule (IESWTR) was promulgated in December 1998, and requires public water systems serving more than 10,000 people to achieve compliance with new, more rigorous disinfection and turbidity requirements by January 2002. This regulation sets a removal requirement of 2 log for *Cryptosporidium* for surface water systems that filter. No specific inactivation requirements were included in this regulation for *Cryptosporidium*, but inactivation requirements (possibly in conjunction with removal requirements) will likely be included in future regulations. Table 1 lists the disinfecting advantages and disadvantages of chlorine, chlorine dioxide, chloramine, ozone, and UV.

Table 1. Advantages And Disadvantages Of Alternative Disinfectants

	ADVANTAGES	DISADVANTAGES
Chlorine	<ul style="list-style-type: none"> • Can be applied at various points along treatment • Strong disinfectant • Additional iron, manganese oxidation (coated media) • Prevents algal growth • Operator familiarity, simple to operate • Low cost 	<ul style="list-style-type: none"> • Requires scrubber system (costly) in gaseous form • RMP requirements • High THM formation • pH and temperature dependent • Longer detention times required for pathogen inactivation

	ADVANTAGES	DISADVANTAGES
Chlorine Dioxide	<ul style="list-style-type: none"> • Low THM formation • Potential 0.5 log <i>Crypto</i> inactivation based on proper design and implementation • Can be used as a preoxidant • Low equipment costs • Additional taste and odor control for phenolics • Oxidation of iron and manganese 	<ul style="list-style-type: none"> • Gas can volatize easily • Chlorite formation can be problematic • High operating costs • Odor complaints from off-gassing in free chlorine systems in some houses with new carpet.
Chloramine	<ul style="list-style-type: none"> • Low THM formation • Taste and odor control (reduces chlorine smell) • Persistent disinfectant residual in distribution system • Optimal use in sequence with another disinfectant • Low capital / operating costs 	<ul style="list-style-type: none"> • No oxidation of iron, manganese, or color • Potential for nitrification. • Not recommended as primary disinfectant by USEPA
Ozone	<ul style="list-style-type: none"> • Low operating costs • Potential 0.5 – 2.0 log <i>Crypto</i> inactivation based on proper design and implementation • Can improve effectiveness of coagulation and filtration • Additional taste and odor control • Additional oxidation of iron and manganese and other reduced inorganics 	<ul style="list-style-type: none"> • Generation equipment requires maintenance • High capital costs • Residual cannot be maintained in distribution system • Bromate formation can be problematic
UV	<ul style="list-style-type: none"> • Strong disinfection occurs in low turbidity water • Could be used as primary disinfectant if additional disinfectant is added to maintain residual • Effective inactivation of bacteria, pathogens and viruses • Low capital and operating costs 	<ul style="list-style-type: none"> • System headloss can be problematic • Treatment of high mineral content water may require frequent cleaning • USEPA guidelines still being developed • No residual in distribution system
Sodium Hypochlorite	<ul style="list-style-type: none"> • Will not require scrubber system • Can be applied at various points along treatment • Strong disinfectant • Additional iron, manganese oxidation (coated media) • Prevents algal growth 	<ul style="list-style-type: none"> • Costly; requires significant electrical system • Storage an issue for long term • High THM formation • pH and temperature dependent • Longer detention times required for pathogen inactivation

6.1 Chlorine Disinfection

For years, chlorination has been used by water utilities for disinfection, as well as for iron and manganese oxidation, taste and odor control, prevention of algal growth, and treatment to address various other water quality problems. After the discovery of trihalomethanes (THMs) in drinking water, water utilities examined

treatment alternatives to reduce the use of chlorine, especially during pretreatment. Today, chlorine is still the primary chemical used for disinfection; however, many water treatment facilities convert free chlorine to chloramines prior to distribution to reduce THM formation and to maintain a sustainable disinfectant residual in the distribution system.

Sources of chlorine include: chlorine gas, sodium hypochlorite, and calcium hypochlorite. Free chlorine is a relatively inexpensive disinfectant, and has been very effective for the inactivation of many kinds of microorganisms. Chlorine can be applied at various points within the treatment train. This has contributed to its widespread usage. However, free chlorine use has several disadvantages. Its effectiveness is pH and temperature-dependent. At pH values above 7, hypochlorous acid (HOCl), the more powerful form of free chlorine, disassociates to form hypochlorite ion, OCl⁻, a weaker disinfectant. Thus, as the pH increases above pH 7, free chlorine disinfection is less effective. This has implications for distribution system disinfection in the present era of concern about corrosion control and Lead and Copper Rule compliance. Free chlorine has not been found to be as effective as chloramine for controlling biofilms in the distribution system. Another drawback to using free chlorine as a disinfectant is the formation of disinfection by-products (DBPs). At higher pH values, the reaction of chlorine with DBP precursors to form THMs is accelerated, and higher yields of THMs are realized. At lower pH values, THM formation is lessened, however the formation of some HAAs and other DBPs is enhanced.

6.2 Chloramine Disinfection

Chloramines have become more widely used due to their ability to provide a degree of disinfection without substantial THM formation. Taste and odor control and maintenance of a more stable residual in distribution systems are other benefits of chloramine usage. If improperly managed, however, the application of chloramines can support bacterial growth (nitrification) in the distribution system. Nitrification is a microbial process in which residual ammonia is oxidized to nitrite and nitrate. Nitrification results in rapid depletion of the chloramine residual and typically an increase in positive coliform samples and enhanced growth of heterotrophic bacteria. Increasing chloramine residuals will not prevent or control nitrification episodes, as nitrite in the distribution system rapidly degrades the chloramine residual before it can inactivate the nitrifying bacteria. Breakpoint chlorination (i.e., reversion to a free chlorine residual within the distribution system) is considered the most effective control measure for nitrification.

Chloramination is accomplished by combining free chlorine with ammonia or an ammonium salt, to form chloramine. Chloramine is not as strong as chlorine for disinfection, and it is not recommended as a primary disinfectant by the USEPA. Chloramines are also too weak to oxidize iron and manganese and natural organic color. Chloramine does, however, form a persistent disinfectant residual, and is used by numerous water utilities for maintenance of a residual in the distribution

system. Chloramine is slower to react with substances on the walls of water mains, thus it has a better opportunity to penetrate tubercles and biofilms and kill resident bacteria.

Even though chloramines are not considered strong disinfectants for primary disinfection, their use in sequential disinfection for inactivation of *Cryptosporidium*, in which a strong disinfectant such as free chlorine, chlorine dioxide, or ozone is followed by an extended period of contact with chloramine, has shown promise.

6.3 Chlorine Dioxide (ClO₂)

Chlorine dioxide (ClO₂) is a very effective disinfectant. More than 500 water utilities use chlorine dioxide either full-time or seasonally to control taste and odors, oxidize iron and manganese, and reduce the levels of DBPs in the finished water. Most often, it is used as a substitute for chlorine as a preoxidant and is applied to the raw water.

The practical ClO₂ dosage applied during water treatment is restricted by the Maximum Residual Disinfectant Level (MRDL) imposed in the D/DBP Rule on ClO₂ (0.8 mg/L) and Maximum Contaminant Levels (MCL) of its major by-product, chlorite ion (ClO₂⁻, 1.0 mg/L). One major change in the Stage I D/DBP Rule is the increase in the chlorite MCL (from 0.08 mg/L as originally proposed by the USEPA). This has allowed many utilities to continue to use or to initiate the use of ClO₂ to meet at least part of the overall oxidant demand of the water supply without forming DBPs. Many have selected ClO₂ rather than ozone because ozone use is often impractical (i.e., high bromide levels in the raw water leading to bromate ion formation) or economically prohibitive due to its high capital cost. Unlike chlorine, chlorine dioxide does not hydrolyze in water to forms that reduce its disinfection properties.

Typically, sodium chlorite and chlorine are reacted in a generator to form chlorine dioxide. The resulting product is added to the raw water either as a gas or as a concentrated solution. Chlorine dioxide generation equipment is usually quite simple and relatively inexpensive, but sodium chlorite can be an expensive reagent. Achieving production of high-purity ClO₂ with certain types of generators is difficult. A problem especially for use in pilot plants is that most generators cannot operate efficiently at low production levels. In addition, creating and maintaining reliable flow from a side stream from a larger generator is often extremely difficult. The result is that dosages to the raw water vary considerably, making interpretation of the data quite difficult.

One type of generator currently on the market produces ClO₂ by reacting humidified chlorine gas with solid sodium chlorite and can be operated reliably at very low production levels. One pound of chlorine produces 1.9 pounds of ClO₂, and the operational control for these units is the flow of chlorine through the solid canisters of sodium chlorite.

A major problem associated with ClO_2 use in full-scale operation is that the oxidant is a gas at temperatures greater than 11 °C and is easily volatilized if the generator effluent is added to the rapid mixer and is exposed to the atmosphere during the contact period. Furthermore, ClO_2 is oxidized to chlorate ions by photolysis in sunlight (and even under fluorescent lighting), and therefore, maximum benefit from ClO_2 treatment is achieved only if the contact basin is covered or if the reactions take place in a pipeline.

Monitoring the ClO_2 residual in water immediately after dosing is difficult because reliable aqueous ClO_2 detectors are not available. Therefore, dose control is mandatory, and few, if any, of the ClO_2 generators can be paced to flow. As a result, operators must constantly adjust the generators to maintain the desired level of flow. Removing scale in the reaction column and chemical feed lines is essential when 25 percent solutions of sodium chlorite are used. Ensuring that the rotameters used to regulate reactant feed rates are properly sized and maintained is also another essential component of a reliable operation.

The chemical analyses of ClO_2 and ClO_2^- pose other problems at the treatment plant. The D/DBP Rule specifies that operators must be trained in the use of the amperometric titrator because daily analyses of ClO_2 in finished water leaving the plant by amperometric titration is mandated. While many operators are versed in chlorine residual analyses by amperometric titration, accurate analysis of ClO_2 is considerably more difficult. If ClO_2^- levels are to be monitored, the plant laboratory must be equipped with an ion chromatograph, which is quite expensive and difficult to operate. Generally, the method is too expensive and complicated for routine use, and utilities find it better to control the distribution-system ClO_2^- levels by maintaining the applied ClO_2 dose below 1.0 to 1.2 mg/L.

In many localities, the major impacts on ClO_2 treatment caused by seasonal and annual water quality variations are those associated with increased levels of reducing agents in the water supply. During low-flow situations, impounded water supplies can become anaerobic and develop high concentrations of iron and manganese near the bottom. Runoff following rain events can add increased levels of organic matter to the raw water and can cause dilution of natural organic matter concentrations. All these factors influence the ClO_2 demand of the water supply, and as it varies, operators must be aware of the changes and adjust the ClO_2 feed rate accordingly.

Because ClO_2 solubility decreases with increased temperature, a utility can expect that losses of the gas from uncovered basins at the treatment plant will be greater during warmer weather. Odor complaints from plant personnel and neighboring customers usually increase when the water temperature is warm because the ClO_2 solubility decreases markedly with increased temperature. Another disadvantage is the potential odor problems associated with ClO_2 regeneration and off-gassing upon the late addition of chlorine for residual maintenance. Customer complaints

have indicated “cat urine” odors. These odors, however, are typically not a problem when chloramine is used for residual maintenance.

Similar to ozone, chlorine dioxide residuals degrade rapidly; therefore, chlorine or chloramines are generally used to maintain a disinfectant residual within the distribution system.

6.4 Ozone Disinfection

Ozone is the most powerful disinfectant available to the water industry. It has been repeatedly demonstrated to be more effective than any other chemical disinfectant against *Cryptosporidium*. When used as a pre-oxidant before coagulation and filtration, ozone has been shown to improve the effectiveness of filtration in many waters, and at lower coagulant dosages. Preoxidation can facilitate improved filtered water quality in terms of lower turbidity and lower particle counts. Other advantages of ozone are its ability to combat tastes and odors, to break down organic matter so it can be removed from water by biological filtration, and to oxidize iron, manganese, and other reduced inorganics. The ability to breakdown large organic molecules can be a disadvantage if ozone is used and excessive amounts of biodegradable matter are formed but not removed before water enters the distribution system. This situation can result in the formation of biofilms in pipelines. Ozone is the most capital expensive disinfectant to install, but its many advantages can help offset the cost.

Advanced oxidation processes (AOPs) convert dissolved ozone to hydroxyl radicals. The formation of hydroxyl radicals also occurs rapidly as pH is elevated (e.g., varying from a slow reaction at pH 6 and below, to an instantaneous reaction at pH 9 and above). The ability of hydroxyl radicals to inactivate microbes is not well defined, and specific CT values for AOPs have not been developed because (a) the half-life of hydroxyl free radicals is on the order of microseconds and (b) the highest concentration of hydroxyl free radicals that can be developed in an aqueous solution is on the order of 10^{-12} Molar. Available data for microbial inactivation by AOPs is limited.

Bromate is an inorganic by-product of ozonation of waters containing bromide. The D/DBP Rule has established an MCL of 0.010 mg/L for bromate. Bromate formation is a function of the bromide concentration, molecular ozone, hydroxyl radicals, and organic and inorganic precursors. Ozone oxidizes bromide to hypobromous acid (HOBr), which, at pH levels typical of water treatment plants, is in equilibrium with hypobromite (HOBr^-). The reaction between ozone and HOBr^- forms bromate.

An important requirement of the SWTR is that a disinfectant residual must be maintained in distribution systems of water utilities that treat surface water. Ozone dissipates so rapidly that a residual cannot be maintained. Therefore, to maintain a distribution system residual, free chlorine or chloramine must be used.

6.5 UV Disinfection

Currently, there are over 1,000 UV systems for potable water disinfection in the United States, and over 2,000 installations in Europe. Ultraviolet light wavelengths range from 200 to 400 nm, but the germicidal range is only between 230 and 260 nm. The dosage of UV is reported as mW-sec/cm² (milliwatt-second per square centimeter).

The following factors are used to design a UV disinfection system and can pose both advantages and disadvantages to utilities:

- Dose response curve
- Disinfection requirements
- System headloss (for retrofit applications)
- Transmittance
- Water quality

The applied UV dose is a critical factor that must be determined before the design of a UV system can be completed. The dose may be as specified by the regulatory agency or determined experimentally. Disinfection requirements (i.e., to achieve regulatory compliance) are equally important. System headloss needs to be examined when UV is being considered for incorporation into existing facilities. The headloss through a UV system is usually low, however additional pumping may be required, based on the hydraulics of the water treatment plant.

Major components of UV systems include a chamber, UV lamps, quartz sleeves, cleaning system, ballasts, and a control system. The UV lamps are housed in quartz sleeves for protection from encrustation and breakage. There are three types of UV lamps used for disinfection: low pressure, low pressure/high intensity, and medium pressure. Low pressure lamps (both low pressure and low pressure/high intensity) produce a monochromatic wave that is primarily in the germicidal range. Medium pressure systems are polychromatic, producing wavelengths over the entire UV range.

Water quality impacts the frequency of cleaning UV fixtures. Waters with high concentrations of hardness, manganese, and iron typically require more frequent and rigorous cleaning due to staining and encrustation of the quartz sleeves. UV system performance is generally not impacted in a pH range of 6 to 9. Temperature can have an impact on design and performance of the UV system. Colder water temperatures may require more equipment while warmer water temperatures may result in less equipment.

Research indicates that protozoa, virus, and bacteria inactivation are capable with UV. Unfortunately, most states do not yet have guidelines for UV disinfection and are therefore waiting for guidance from USEPA. (The Agency is currently

preparing several guidance documents to familiarize state primacy agencies and utilities with UV system design and operational issues.) UV could potentially be used as a primary disinfectant; however, an additional disinfectant would need to be added to maintain a residual in the distribution system.