

COAGULATION, FLOCCULATION AND CLARIFICATION OF DRINKING WATER

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Photo by author

The intent of this paper is to provide cursory information about coagulation, flocculation and clarification. This knowledge will provide a basis for understanding the needs of the customer wishing to monitor these processes. There is no attempt to provide an exhaustive description of various coagulants, coagulant aids, flocculants, mechanical flocculation techniques, clarification designs or configurations or a comparison of relative merits of the various designs, troubleshooting or operational theories. Consult citations in the list of references if more detailed information is desired.

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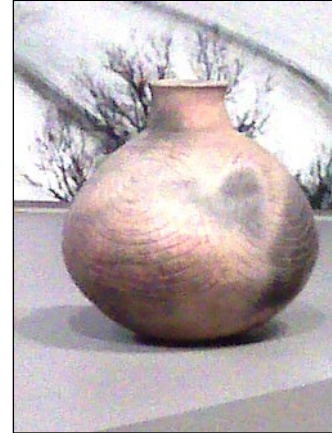
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Introduction

Most water treatment practices including coagulation, flocculation and clarification, date back hundreds and in some cases thousands of years. References as old as 2000 B.C describe what we know today as coagulation.



Figure 1: Earthen jars used to store water
 “It is good to keep water in copper vessels, to expose it to sunlight and filter through charcoal.” And, “...heat foul water by boiling and exposing to sunlight and by dipping seven times into it a piece of hot copper, then to filter and cool in an earthen vessel.” (Baker, Vol. 1). Left, a jar (‘earthen vessel’ from the Middle East from about 300 BC; right, a jar used in the SW United States in the 1860s. Photos by author.



Use of the seeds of *Strychous potatorum*, a deciduous tree, as a coagulant may date back to the 6th century B.C. The seeds contain – “a polysaccharide consisting of a 1:7 mixture of galactomannan and galactan. These findings suggest that such seed extracts may function as a particulate, colloidal and soluble polymeric coagulant as well as a coagulant aid. The presence of other constituents in these seed extracts is uncertain, and there is concern that they may contain toxicants, because the portions of the plant also are used for medicinal purposes.” (Sobsey, WHO).

Vitruvius (15 B.C.) recommended that cisterns be constructed in two or three compartments and the water transferred from one to another of them, thus allowing the mud to settle, and insuring clearness and limpidity. Otherwise, he wrote, it would be necessary to clarify the water by adding ‘salt’. Pliney (c.77 A.D. said that polenta, a kind of food, added to nitrous or bitter water would render it potable in two hours, and that a similar property is possessed by chalk of Rhodes and the argilla of Italy. This is the first mention found of lime and aluminous earth as precipitants. (Baker, Vol. 1)

But it has been only in the last 100 years or so that we’ve come to understand and thus gain some control over the mechanisms of these processes.

Today:

- The scientific principles behind water treatment are better understood.
- There is a better appreciation for the multiple barrier approach to water treatment.
- Individuals using the measurement tools and treatment processes are better educated and trained.
- Modern measurement tools permit identification of process variation whereby operators can refine and further improve water treatment operations.
- Improved measurement capability and improved operations have permitted engineers to improve treatment process designs.

More than to any other development, credit for improvement of water quality is due to the development of reliable water quality monitoring devices in the last two decades. These include instruments that measure and record pH, residual chlorine and turbidity. A variety of other quality-sensing devices is available, but the three foregoing are the most commonly used. These devices enable the operator to identify episodes of deficient treatment which in the past frequently went unnoticed. Now these deviations in quality are conspicuously apparent on the quality-sensing recorders and corrective action can be taken promptly. (Hudson, 1981)

Hudson's observation is certainly true of the processes of coagulation, flocculation and sedimentation. Measurement tools such as zeta meters, streaming current monitors, and conventional and laser nephelometers have become available in just the last 30 years. Even the modern pH and conductivity instruments have been available since only the 1950's and 1960's. Improved ability to make chemical and physical measurements of water treatment processes have allowed designs used for centuries to be refined and new designs to be created. Perhaps more important, these same measurements enable better operation once the design is implemented in steel and concrete!

Coagulation

Chemical treatment typically is applied prior to sedimentation and filtration to enhance the ability of a treatment process to remove particles. Two steps typically are employed: coagulation and flocculation. Coagulation is a process to neutralize charges and then to form a gelatinous mass to trap (or bridge) particles thus forming a mass large enough to settle or be trapped in the filter. Flocculation is gentle stirring or agitation to encourage the particles thus formed to agglomerate into masses large enough to settle or be filtered from solution.

Particles in water smaller than about 10 microns are difficult to remove by simple settling or by filtration. This is especially true for particles smaller than 1 micron – colloids.

Particle Size Vs. Settling Rate Table							
(Assuming specific gravity of 2.65)							
Particle Diameter, mm	Example	Total Surface Area		Mass, mg per particle*	Total Number of Particles	Time to Settle One Ft.**	Time to Settle One Meter**
		Metric	English				
10	Gravel	3.1419 cm ²	0.487 in. ²	1.3868E+03	1.E+00	0.3 sec	0.98 sec
1	Coarse Sand	31.4193 cm ²	4.87 in. ²	1.3868E+00	1.E+03	3.0 sec	9.84 sec
0.1	Fine Sand	314.1929 cm ²	48.7 in. ²	1.3868E-03	1.E+06	38 sec.	2.08 min
0.01	Silt	0.3140 m ²	3.38 ft. ²	1.3868E-06	1.E+09	33 min	1.80 hrs
0.001	Bacteria	3.1340 m ²	33.7 ft. ²	1.3868E-09	1.E+12	55 hrs	7.52 days
0.0001	Colloidal	31.7728 m ²	38 yd ²	1.3868E-12	1.E+15	230 days	2.07 yrs
0.00001	Colloidal	2832.7995 m ²	0.7 acres	1.3868E-15	1.E+18	6.3 yrs	20.66 yrs
0.000001	Colloidal	28327.99 m ²	7.0 acres	1.3868E-18	1.E+21	63 yrs	206.64 yrs

* Note: Total mass in the system remains constant at 1.386 grams or 1,386 mg
 **Assumes completely quiescent conditions

Figure 2: Table of particle size vs. settling rate

Adapted from Water Quality and Treatment, 3rd Ed. The left column indicates starting with a single particle 10 mm in diameter. The table then illustrates the resulting change in particle size, total surface area, number of particles and settling time as the initial particle is ground up to make smaller particles. One particle 10mm in diameter becomes 10^{12} particles by the time it is ground to a size of 0.001 mm (1 μ m). Notice also while the mass per unit particle decreases, the total mass in the system remains unchanged. Clearly, there is not necessarily any correlation between particle counts and mass, turbidity and mass or between particle counts and turbidity!

Coagulation is, “the effect produced by the addition of a chemical to a colloidal dispersion resulting in particle destabilization by the reduction of the forces tending to keep the particles apart.” (Water Quality and Treatment, 3rd, ed., p. 72)



Figure 3: Lake Tekapo

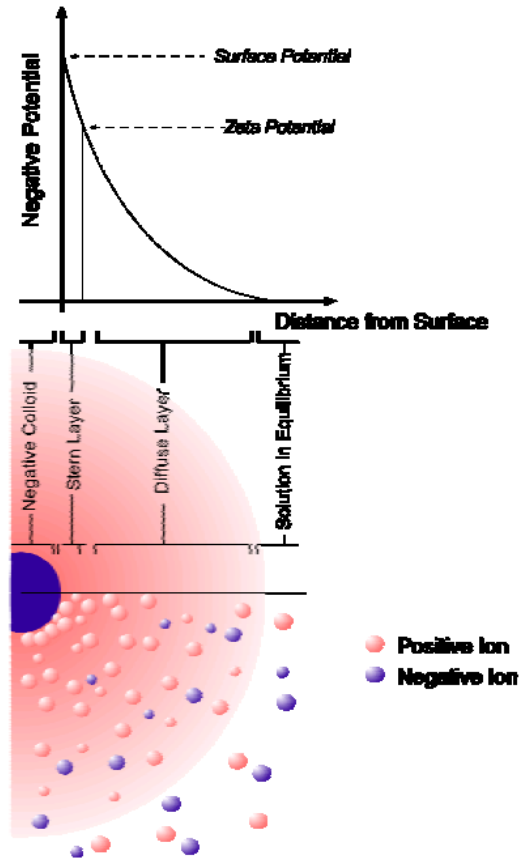
Lake Tekapo is fed by run off from glaciers and rivers near Mt Cook and Mt Tasman on the South Island of New Zealand. Colloidal glacial till (glacial flour) in suspension causes the color. “The unique, turquoise coloured lake water of Tekapo is the result of ancient glacier ice crushing mountain rock on its journey from the slopes of the Southern Alps to the rivers of the massive valleys that deliver the melted ice to the lake. The crushed rock produces a fine, flour-like powder that remains suspended in the water and, when reflecting light, produces the pale blue colour for which Lake Tekapo is renowned. The lake is 32 km long and 120 meters deep at its deepest part.” (Earth and Sky, Ltd.) Photo by author.

Colloids are stable in water because:

- Colloids have a very large surface area relative to their mass (See Figure 2).
- Colloids typically have a static electric charge. Most colloidal particles in water have a negative charge.
- Static charge is a surface effect. The greater the surface area relative to the particle mass, the greater the effect of the charge.
- The mass of the particles is small enough that even Brownian motion is sufficient to ‘stir’ the suspension.
- The particles cannot agglomerate into larger particles and settle because
 - They repel one another.
 - The force of repulsion exceeds the force of gravity that otherwise would cause them to settle!
 - The charged particles attract a cloud of other charges to surround the colloidal particle. This is often termed the ‘double-layer theory’ or double-layer model. So, colloids repel one another and they are kept apart by the double-layer effect.

Figure 4: Illustration of diffuse double layer (Edney)

“The double layer model is used to explain the distribution of ions around each colloidal particle. This is a long standing conventional approach to colloid analysis; a more detailed description is available in a number of works on this subject (e.g. Bratby, 1980).



For illustrative purposes we will assume a negatively charge colloid. Closest to the negative surface of the colloid there is a layer of strongly bound positive ions – this is known as the Stern layer. Further positive ions are still attracted to the colloid but are repelled by the Stern layer; likewise, negative ions are attracted to the positive ions but repelled by the colloid. A dynamic equilibrium of negative and positive ions forms outside the Stern layer, known as the diffuse layer. The concentration of positive ions in the diffuse layer gradually decreases as the distance from the colloid increases until beyond a certain distance the ion concentrations are the same as the equilibrium in the water.

The strongly held positive ions near the surface and the charged layer surrounding this is where the name double layer comes from. The point just outside the stern layer is often called the shear plane as motion of the particle through the water shears the diffuse layer away.

The thickness of these layers depends on the concentration of ions in solution. At any distance from the surface the charge density

is equal to the difference between the concentration of positive and negative ions at that distance. This results in an electrical potential (which is a voltage, caused by separation of charges) existing across the layers. This potential is greatest near the surface and decreases to zero as the distance from the colloid increases. A graph of this potential curve is useful because it indicates the distance at which the interaction between colloids will occur. The potential at the boundary between the Stern layer and diffuse layer is called the zeta potential. Zeta-potential is useful, as it is a direct indication of the amount of energy required to bring separate particles together.” (Edney)

The purpose of adding a coagulant is to neutralize the charge. In theory, since most particles in water are negatively charged, any positive ion (cation) can be used as a coagulant. A sodium compound (like sodium hydroxide), contributes a monovalent ion, Na^+ . A calcium compound (like calcium hydroxide) contributes a divalent ion, Ca^{2+} . Aluminum and iron coagulants contribute trivalent aluminum ions, Al^{3+} and trivalent iron ions, Fe^{3+} , respectively. Two chemists, Schultz in 1882 and Hardy in 1900, demonstrated the greater the charge of the cation, the greater the effectiveness of charge neutralization.

Schultz–Hardy Rule

The Schultz-Hardy Rule indicates the relative effectiveness for mono- vs. di- vs. trivalent ions is in the ratio of 1:100:1000 respectively. For a variety of reasons, for drinking water applications the relative effectiveness of the monovalent (Na^+) vs. divalent (Ca^{2+}) vs. trivalent (Al^{3+}) ions is 1:60:700, respectively. That is, a trivalent aluminum ion will be 700 times more effective in charge neutralization than the monovalent sodium ion. Thus aluminum and iron compounds are most often used as coagulants. Sodium or calcium salts added for pH adjustment may contribute to the coagulation process. One will occasionally find references to use of hydrated lime (calcium hydroxide) as a coagulant.

Charge neutralization occurs very rapidly. Thus, design of the rapid mix system of a water treatment plant is extremely important. After a short time, the ions form hydroxide gels. The gels then can trap particles or bridge between particles creating a floc that may settle or at least be large enough to be removed by filtration. Where the coagulation/flocculation process appears to be inefficient or ineffective it is reasonable to suspect inadequate mixing as at least part of the cause.

In the early part of the 1900's much of the emphasis in coagulation was placed on controlling coagulation to produce floc that was large, tough and dense. The clarifiers and filter designs used at that time were designed for such flocs. By the 1950's a greater appreciation of the function of charge neutralization was gained. Then, in the 1960's, a practical meter for measuring the effect of charge neutralization was developed - the zeta-meter. By the 1980's an on-line streaming current monitor had become fairly common. Returning to the quote from Hudson in the introduction – the practice of water treatment has followed improvements in measurement techniques. Today it is widely accepted and practiced that a combination of charge neutralization and floc formation is necessary to effectively and efficiently remove colloidal sized particles from water.

Coagulation with Salts of Aluminum and Iron

Powdered, granular or crystalline salts and solutions of iron and aluminum like hydrated aluminum sulfate (5.8 to 8.5% water soluble alumina, Al_2O_3), liquid alum (17% Al_2O_3 , typically equivalent to 5.33# of dry alum per gallon), ferric sulfate and ferric chloride (typically a 38-42% solution) still are still widely used. Measurement and management of pH and alkalinity are critical when these salts are used. Alkalinity is consumed when these compounds are used. There is an ideal range of pH for each of the compounds.

Coagulant	Empirical Formula	pH Range (s)	Alkalinity Consumed*
Aluminum Sulfate	$\text{Al}_2(\text{SO}_4)_3 \cdot 14 \text{H}_2\text{O}$	Theory 5.5 to 7.8	0.49 mg/l for each 1 mg/l of alum
		Typical 6.0 to 7.4	
Ferric Sulfate	$\text{Fe}_2\text{SO}_4 \cdot 9 \text{H}_2\text{O}$	4.0 to 11.0	0.53 mg/l for each mg/l of ferric sulfate
Ferric Chloride	FeCl_3	4.0 to 11.0	0.92 mg/l for each mg/l of ferric chloride
* See Alkalinity Requirement for Aluminum and Iron Coagulants in the Appendix for calculation of the alkalinity requirements for alum, ferric sulfate and ferric chloride.			

Figure 5: pH ranges and alkalinity consumed for aluminum and iron coagulants

Sodium aluminate, NaAlO_2 , has a variety of industrial uses and has been utilized as a coagulant in drinking water treatment as a supplement to alum and may be encountered in lime-soda softening processes. It has been used in wastewater treatment as a coagulant in the phosphorous removal process. While the other aluminum and iron salts act as acids consuming alkalinity, sodium aluminate acts as a base. Each mg/l of sodium aluminate contributes nearly 2 mg/l as CaCO_3 of alkalinity. Thus, sodium aluminate may be useful in soft, low alkalinity water.

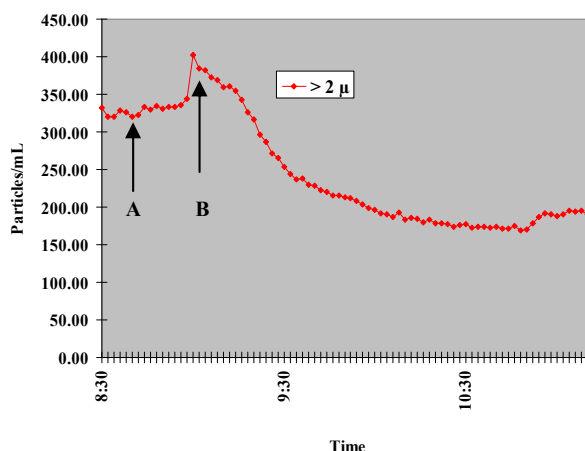


Figure 6: pH correction for alum feed

Alum was being used as a coagulant at a relatively high pH. At point A on the chart the pH was 7.8. At point B sulfuric acid addition was started and the pH lowered to 7.2, a much better pH for alum coagulation. Particle counts immediately dropped. Establishing the proper conditions of pH and alkalinity before addition of a coagulant are important to successful coagulation and flocculation.

Other Coagulants and Coagulant Aids

A number of other compounds are being used today either to replace the metal salts or to complement them. When used to complement the metal salts they are referred to generally as a coagulant aid or perhaps as flocculant aids. Interest in use of other compounds is generally driven by one or a combination of three factors: Reduced cost; reduced solids; or, less dependence on conditions of alkalinity and pH.

A compound often encountered is polyaluminum chloride. As can be seen in the equations above, alum and ferric compounds, when added to water, hydrolyze consuming alkalinity thus having a significant effect on pH. Polyaluminum chloride (PAC or PACl - more commonly today PACl is preferred to PAC as the term PAC sometimes is used to mean powdered activated carbon) is pre-reacted during manufacture and thus the pH and alkalinity of the water are not impacted as much as with alum. PFCl or Polyferric chloride is available but will seldom be encountered.

Polyelectrolytes

Polymers used in water treatment are generally low molecular weight (<500,000) and may be used as primary coagulants, coagulant aids, flocculent aids or as filter aids. Cationic, anionic and nonionic compounds are available. Polymers used for primary coagulants, coagulant aids are generally cationic compounds. Flocculant aids will typically be anionic or nonionic and slightly higher molecular weight. Those used as filter aids may be slightly cationic or nonionic.

Polymers used as primary coagulants are typically dosed at 0.1 to 2 mg/l. Polymers used as coagulant aids are typically dosed at 0.1 to 0.5 mg/l and those used as flocculant or filter aids might be dosed at less than 0.1 mg/l.

Cationic polymers most often encountered are one of two quaternary amines: polydiallyldimethyl ammonium chloride (polyDADMAC) or epichlorohydrin dimethylamine (epiDMA). There are a large number of chemical suppliers compounding an enormous variety of polymers. Each product, of course, claims to be superior to anything else. The fact is most of them will work well - somewhere! The only way to be certain a particular polymer will work in a particular treatment system is to jar test and pilot test the use of the compound.

Those desiring detailed discussion of various coagulants and the mechanisms by which they function can refer to Water Quality and Treatment, 5th ed., chapter 6 and Handbook of Public Water Systems, 2nd ed., chapter 10.

Health Effect Concerns for Use of Polymers

As one might suspect, addition of these compounds to water is not without some concern. PolyDADMAC and epiDMA have been associated with formation of nitrosamines. There are about 9 compounds in this general group that can be produced as DBP from chlorination and chloramination practices. These compounds are toxic and may be carcinogenic. N-nitrosodimethylamine (NDMA) specifically is of concern and is on USEPA's Priority Pollutant and Contaminant Candidate List 3. USEPA currently has no MCL's set for any of the nitrosamines but some states and the World Health Organization (WHO) have set guidelines. WHO guidelines for NDMA call for less than 100 ng/l. The State of California has set an action level and public health goal of 10 ng/l and 3 ng/l of NDMA, respectively.

Enhanced Coagulation

'Enhanced coagulation' is the phrase used to define the process of obtaining improved removal of disinfection byproduct (DBP) precursors by conventional treatment. (Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual).

Concern with formation of DBP resulting from reactions of chlorine with naturally occurring organic matter (NOM) led to the Disinfection and Disinfection Byproducts Rule (DDBP). Specific goals are spelled out for managing the water treatment process in order to optimize removal of NOM.

Because TOC (total organic carbon) is easily measured and monitored, the treatment technique uses a TOC removal requirement. However, basing a performance standard on a uniform TOC removal requirement is inappropriate because some waters are especially difficult to treat. If the TOC removal requirements were based solely upon the treatability of "difficult-to-treat" waters, many systems with "easier-to-treat" waters would not be required to achieve significant TOC removal. Alternatively,

a standard based upon what many systems could not readily achieve would introduce large transactional costs to States and utilities.

To address these concerns, a two-step standard for enhanced coagulation and enhanced precipitative softening was developed. Step 1 includes TOC removal performance criteria which, if achieved, define compliance. The Step 1 TOC removal percentages are dependent on alkalinity, as TOC removal is generally more difficult in higher alkalinity waters, and source water with low TOC levels. Step 2 allows systems with difficult-to-treat waters to demonstrate to the State, through a specific protocol, an alternative TOC removal level for defining compliance. The final rule also contains certain alternative compliance criteria that allow a system to demonstrate compliance. (Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual).

TABLE 2-1
Required Removal of TOC by Enhanced Coagulation
For Plants Using Conventional Treatment:
Step 1 Removal Percentages^{a, b}

SOURCE WATER TOC (mg/L)	SOURCE WATER ALKALINITY (mg/L as CaCO ₃)		
	0 to 60	>60 to 120	>120 ^c
>2.0 - 4.0	35.0%	25.0%	15.0%
>4.0 - 8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

Notes:

- Enhanced coagulation and enhanced softening plants meeting at least one of the six alternative compliance criteria in Section 2.4 are not required to meet the removal percentages in this table.
- Softening plants meeting one of the two alternative compliance criteria for softening in Section 2.4 are not required to meet the removal percentages in this table.
- Plants practicing precipitative softening must meet the TOC removal requirements in this column.

Figure 7: Required removal of TOC by enhanced coagulation
From Enhanced Coagulation and Enhanced Precipitative Softening Guidance
Manual

Achieving NOM reduction may also involve use of a preoxidant such as ozone, chlorine dioxide or permanganate (sodium or potassium permanganate). Some utilities will find measurement of TOC and/or UV absorbance (UV254) to be useful in optimizing coagulation.



Figure 8: NOM in source water

Enhanced coagulation refers to optimizing coagulation, flocculation, clarification and filtration to remove organic matter from water that may contribute to formation of disinfection byproducts. The organic matter may be from man-made sources such as industrial discharges. Mother Nature also contributes. Decaying vegetable matter in the high mountain meadow (above left) as well as decaying matter from the mangroves in the Florida Everglades (above right) can contribute significant organic matter. The brown color of the water around the mangroves is due to the tannins and humic substances from the decomposing plant material.

The contribution from the high mountain meadow may be seasonal or after a storm event while levels of organic matter in warmer climates will be more constant. In some cases the constant instance may be easier to treat. The treatment process once established needs only to be monitored and maintained. Seasonal or intermittent start/stop treatment needs may be more difficult to control. In either case, the key to successful enhanced coagulation is measurement! Photos by author.

City of Houston Study

In the late 1990's, the City of Houston, Texas planned a study to address concerns about compliance with rules for DBPs:

The City of Houston, Texas has been aware of the implications that current and pending regulatory standards would have on the operation of their four surface water treatment facilities. In particular, the City has closely monitored changes in regulations related to enhanced coagulation, total organic carbon (TOC) removal, and disinfection by-products (DBP) reduction. The City has, and continues, to conduct extensive bench, pilot, and plant scale tests to determine how these regulatory changes would impact the operation of their surface water facilities.

The TOC content of the source and finished water is the common attribute that significantly impacts each of the regulations of interest. TOC is perhaps the one water quality parameter that could impact the financial bottom line of a utility most. In most cases, a fully automated surface treatment facility still measures TOC by collecting periodic grab samples for laboratory analysis. Making treatment decisions based on periodic TOC grab samples is comparable to flying a commercial airliner without instrumentation. (Reavis)

Extensive laboratory investigations were followed by a year long pilot study with continuous on-line instrumentation. The study concluded in 2001 with the recommendation to purchase on-line TOC analyzers.

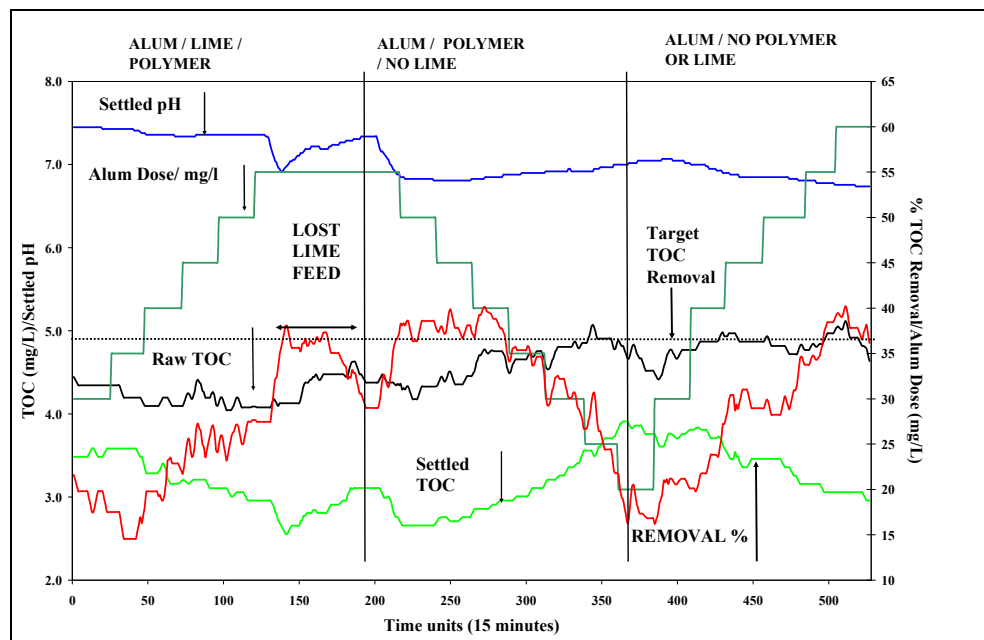


Figure 9: City of Houston DBP/TOC study

“After nearly a year of plant scale evaluation, the recommendation is being made that on-line TOC analyzers be purchased to enhance facility operations. During the trial, the instrument was used to monitor plant performance and to evaluate alternate coagulants and coagulant aids. The most interesting results of the study related to how poorly the operators responded to changing raw water parameters when given daily grab sample results and how much better they were able to respond when allowed to utilize the on-line analyzer. The on-line TOC analyzer allowed the operators to track real time water quality changes and therefore respond much quicker than would be possible if grab samples were being used.”
(*Ibid.*)

UV-254 Measurement May Be Valuable

Compounds of concern for DDBP and thus enhanced coagulation - humic substances, tannins, and lignin - are compounds containing double bonds (atoms bound by two pairs of electrons). These compounds absorb ultraviolet light and thus may be detected at a wavelength of 254 nm. All of these substances are a portion, or subset of total organic carbon. Thus in many waters measurement at a wavelength of 254 nm may be a good surrogate for TOC. Measurement at a wavelength of 254nm, as with the DR5000 or UVAS is of Specific Absorption Coefficient (SAC) in units of 1/meter or m^{-1} .

The SAC at a wavelength (λ) of 254 nm:

- Is a summing parameter measuring dissolved organic constituents
- Reports the UV absorption of the water at $\lambda = 254$ nm.
- It may be possible to directly correlate SAC to other parameters including biochemical oxygen demand (BOD), chemical oxygen demand (COD), and TOC.

- Direct correlation to any of these may not always be possible.
- In drinking water applications while it may not always be possible to correlate to TOC, the SAC may still be useful in observing the trend of the organic constituents of the water.

A relationship of SAC to TOC, BOD and COD is illustrated below.

Parameter	Measurement Variable	Measurement Method	Venn Diagram of groups/substances measured
BOD	O ₂ Consumption	Microbial oxidation	
COD	O ₂ Consumption	Wet chemical oxidation	
TOC	Carbon	UV/Persulfate digestion or high temperature or two-stage advance oxidation	
SAC	UV absorbance at $\lambda = 254$ nm	UV absorbance measurement	

Figure 10: Relationship of SAC to other parameters

SAC 254 is an independent total parameter for the dissolved organic content of water and evaluates, like all other total parameters, only a specific fraction of the water load. Despite major similarities, total parameters can only be converted from one to another within certain limits. However, if a correlation is found between UV and another total parameter, the converted measured values from UVAS probes can be displayed as TOC_{uv}, BOD_{uv}, and COD_{uv}. To determine the correlation, measure the SAC value over several days.

During periods of low and high load UV absorption:

- Take a representative sample at the UVAS probe location.
- Read the related SAC value from the probe.
- Perform a laboratory measurement of the parameter to be correlated, e.g. BOD, COD, TOC, etc. Repeat this analysis over a period of several days to weeks in order to determine the exact correlation. (Hach DOC023.54.03230 UVAS sc Sensor USER MANUAL October 2005, Edition 2)

Specific Ultraviolet Light Absorbance, SUVA may be calculated. SUVA is the ratio of SAC to DOC in units of $\text{mg/l}\cdot\text{m}^{-1}$. Dissolved organic carbon (DOC), is that fraction of total organic carbon after the sample is passed through a $0.45\mu\text{m}$ filter.

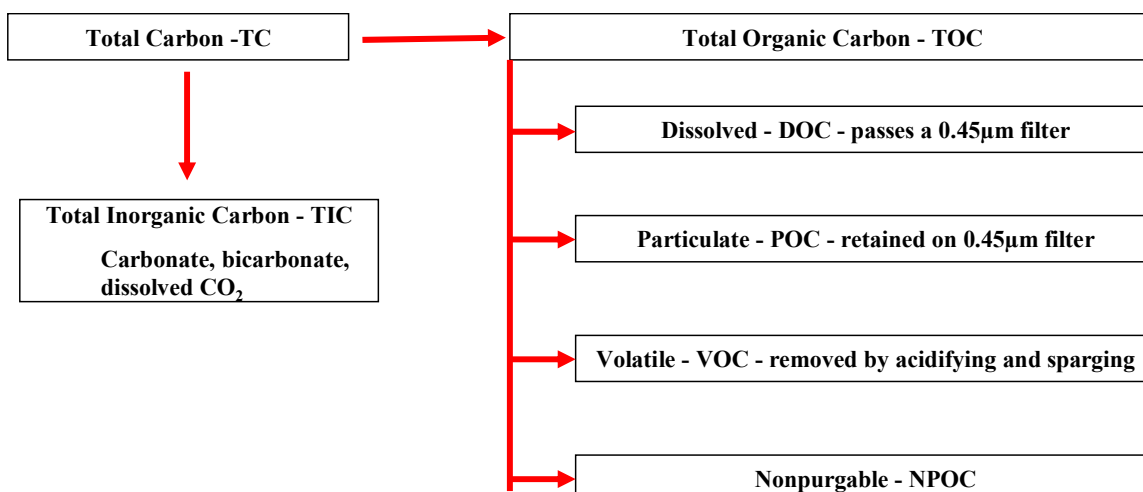


Figure 11: Total carbon fractions

UV-254 measurement thus may be valuable to provide compliance with the DDBP rule but may be independently used to control the coagulation process directly.

The higher molecular weight fraction of NOM (the fraction that tends to be removed by coagulation and that has the greater yield of disinfection byproducts) absorbs UV light and consequently, UV light absorbance (typically at a wavelength of 254 nm) can be used as a simple surrogate measure for DOC. Also, the ratio of the UV absorbance to the DOC concentration (called the specific UV absorbance or SUVA) can be used as an indicator of the molecular weight distribution of the NOM in the water... Waters with a low humic acid fraction (generally low-DOC waters) tend to have SUVA's that are less than $2 \text{ L/mg C}\cdot\text{m}^{-1}$, whereas water with a high humic acid fraction have SUVA's between 3 and $5 \text{ L/mg C}\cdot\text{m}^{-1}$. A high SUVA means that the DOC of the water will tend to control the coagulant dosage and relatively high removals of DOC can be expected... When the SUVA is less than $3 \text{ L/mg C}\cdot\text{m}^{-1}$; the effect of the DOC on the coagulant dosage may be negligible. (Water Quality and Treatment, 5th ed., pg 6.4)

Connie Schreppel, Mohawk Valley Water Authority, Utica, NY reported ([Opflow](#), January 2010):

MVWA installed on-line continuous-read UV_{254} monitors at the treatment plant and a portable UV_{254} instrument was incorporated in the laboratory... MVWA is using the UV_{254} test to supplement color and turbidity analysis... UV_{254} measures the amount of UV light absorbed or transmitted through water, indicating the amount of the water's dissolved NOM.

Relying on turbidity alone without using UV_{254} as an indicator of NOM in water can result in ineffective optimization of coagulation. Although organic levels are increasing or decreasing, turbidity can remain the same.

By monitoring UV₂₅₄ on raw water as it enters the plant, operators can determine if a sudden increase in organics occurs...

For years, the color test has been recognized as a good NOM indicator because certain humic acids can sometimes give visible color to water. However, it's possible to have water with low visible color without having correspondingly low amounts of organics. UV₂₅₄ testing can fill the gap and provide a better picture of the water's real organic content.

MVWA's first UV₂₅₄ online monitor was installed at the treatment plant to continuously monitor raw water organic content. This single monitor was programmed later to also monitor filtered water UV₂₅₄ levels. Using these two UV₂₅₄ readings MVWA began to assess the treatment process' effectiveness in removing NOM. MVWA went another step by synchronizing raw water UV₂₅₄ results to correspond with filtered water UV₂₅₄ results, resulting in real-time NOM reduction and enhanced coagulation.

Measuring Prior to Coagulation

As has been demonstrated and discussed above, certain values, especially pH and alkalinity are critical for control of the coagulation process. Adjustments to pH and/or alkalinity must be made prior to coagulant addition to be most effective. And for enhanced coagulation one may need to make other measurements as well, such as TOC and or SAC (absorbance at UV₂₅₄). Other water quality issues may dictate the need for additional monitoring. Problem parameters commonly encountered include manganese, iron, nitrate, arsenic and other less common parameters. The following table lists on-line and grab sample testing that should be considered in raw water prior to coagulation.

Parameter	Laboratory Measurement	On-line Measurement	Reason to monitor
Alkalinity	Digital Titrator	APA 6000 Alkalinity	Water quality, coagulation control
Aluminum	ECR or Aluminon methods	NA	Coagulation
Ammonia	HQd series meter and ISE probe	AISE sc probe w sc200 or sc1000 controller	Water quality, disinfection
Arsenic	Silver Diethyldithiocarbamate method	NA	Health MCL
Conductivity	HQd series meter and probe	Contacting probe w sc200 or sc1000 controller	Raw water contamination
Dissolved Oxygen	HQd series meter and LDO	LDO w SC200 or SC1000 controller	Water quality
Hardness	Digital Titrator	APA 6000 Hardness	Water quality
Iron	FerroVer Iron method	NA	Aesthetic; Coagulation
Manganese	PAN or Periodate methods	NA	Aesthetic
Nitrate	NitraVer 5; ISE	NITRATAX plus sc	Health MCL
ORP	HQd series meter and probe	ORP w sc200 or sc1000 controller	Water quality, control of preoxidant
Permanganate	PAN or Periodate methods	NA	Preoxidant for NOM
pH	HQd series meter and probe	pHD probe w sc200 or sc1000 controller	Coagulation control
Total Organic Carbon	TOC test	astroTOC, BioTector [®] B7000 or B3500C <small>BioTector is a registered trademark of BioTector Analytical Systems, Ltd.</small>	Water quality, SUVA calc., coagulation control, DDBP rule compliance
Turbidity/Solids	2100Q, 2100N or 2100AN	SS7, SOLITAX sc w sc200 or sc1000 controller	Water quality
UV254	DR5000	UVAS	NOM, SUVA, coagulation control

Figure 12: Measurements for raw water prior to coagulation

Measuring Following Coagulation

Immediately following coagulant addition (after sufficient time for the coagulant and coagulant aid to be well mixed, typically at the end of rapid mix) one may measure zeta potential, streaming current, alkalinity and pH. Where the water is well buffered (alkalinity > 100 mg/l) periodic grab sample alkalinity measurement may be sufficient. However in poorly buffered (low alkalinity) water and aluminum or iron salts are used as coagulants, an APA 6000 Alkalinity analyzer will pay dividends. pH is critical and should always be monitoring continuously following coagulant addition. Grab sample measurement of zeta potential and/or continuous on-line measurement of streaming current potential also will pay significant dividends in control of the coagulation process. See Measurement Tools for Coagulation and Flocculation, below, for more detail on measurement of these important parameters.



Figure 13: Source Water Panel and the Event Monitor® Trigger System
 The Source Water Monitoring Panel can be configured with six probes selected to meet the particular needs of the individual water source. Select from the Solitax, pH, conductivity, ORP, LDO, NH4D, NitraTax and UVAS. Combine the panel with a TOC Analyzer and the Event Monitor for the most sophisticated source water monitoring system available.
 Hach Company stock photos

Flocculation

“Flocculation is the turbulent mixing phase following the dispersion, hydrolysis, and polymerization of the coagulant in the rapid mix.” (Hudson). More simply put: flocculation is slow mixing to encourage collision of particles and the gel to form a larger mass that will be settled or filtered from solutions. Flocculation may be carried out by deliberate mixing for a half hour or more and is then followed by settling. Flocculation may also occur due to simple random motion of particles in solution – Brownian motion. Brownian motion is usually described as being caused by molecules of the fluid impacting the solid in solution. The effect is typically significant only on submicron particles.

Particles not removed by settling are removed by filtration. If direct filtration is employed, the flocculated water will proceed directly to filtration without any settling. In this case, flocculation is typically carried out for only a few minutes.

Flocculator mixing schemes vary and may include a baffled basin, maze basin, vertical or horizontal paddles, axial-flow impellers and others.



**Figure 14:
Flocculator
designs
Maze Flocculation
Basin Left,
Rotating
horizontal Pickets
(paddles) Right.
Photos by author.**

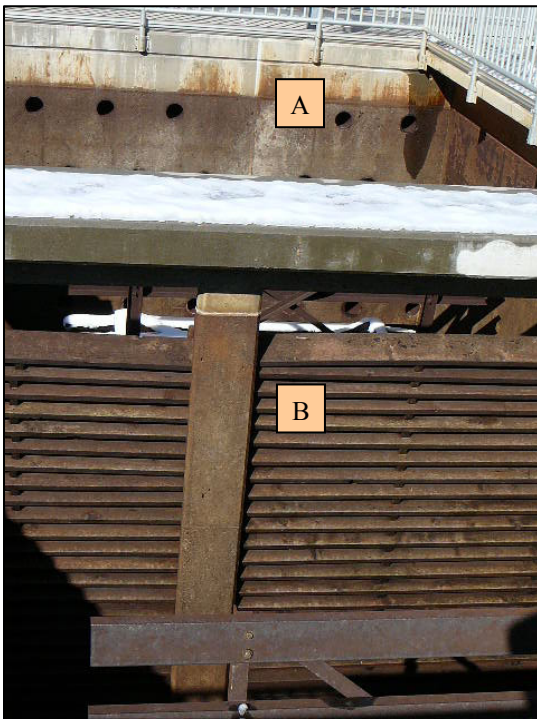


Figure 15: Two stage flocculation basin

Two stage flocculation basin with (A) a perforated inlet wall followed by horizontal flocculator paddles. Then (B), water passes from the first chamber into the second chamber through horizontal slats. Horizontal paddles are again employed in the second chamber. Ozone, chlorine or chlorine dioxide applied prior to this point for disinfection credit would certainly benefit from a baffling factor of 0.7 or higher for this basin design. See Table of Baffling Factors, in the section titled “Clarifier Design Impacts Disinfection.” Photo by author.

Ballasted Flocculation

Flocculation efficiency is affected by the ability of a floc to form and, once formed to efficiently settle. Particles in the raw water and the chemical floc formed may not be ideal for settling and filtration; thus, various agents may be added to enhance the floc formation and floc density. As mentioned above, chemicals such as polymers can be added as flocculation aids but they may or may not provide any enhancement in ability to settle or even to form a floc. They primarily improve the quality of floc. In some cases it is desirable to add a ‘target’. Just as a rain drop requires a nucleus for the drop to form on, so floc requires a nucleus. Sand, powdered activated carbon and clay have all been used to provide nuclei to enhance floc formation and to provide density to enhance

settling. A relatively modern variation of that process one frequently encounters is under the brand name Actiflo® - a trademark of I. Kruger Inc. In the Actiflo process, very fine sand is mixed in rapid mix with the coagulant.



Figure 16: Actiflo process for ballasted flocculation

Measurement Tools for Coagulation and Flocculation

Measuring Aluminum and Iron

When iron or aluminum chemicals are used as coagulants, the metal should be measured in the raw water, filter influent and filter effluent. The iron or aluminum concentration in the filter effluent should be no more than and preferably less than, the raw water and filter influent concentrations. For most water the FerroVer[®] 3 Iron Reagent (1, 10 Phenanthroline method) for total iron is appropriate for iron and the AluVer 3[®] Aluminum Reagent (Aluminon method) is appropriate for aluminum. For low level iron use the FerroZine[™] Iron Reagent and for low level aluminum the Eriochrome Cyanide R (ECR) method (ECR may not be used with DR900's). When measuring aluminum, fluoride interferes (and vice versa). All aluminum measurements must be corrected for fluoride interference. Once the fluoride is measured, use the fluoride interference correction chart in the method. The correction charts for the AluVer 3 and the ECR method are different. Care must be taken to use the correct chart.

Use the SPADNS 2 (arsenic-free) or fluoride electrode to measure fluoride. Fluoride must be measured regardless of whether or not the utility fluoridates. Fluoride exists naturally in every water source on earth – ground or surface. Natural fluoride concentration may range from 0.1 to over 10 mg/l.

Iron and Aluminum Reagents				Instrument*
Test	Reagent	Range – mg/l	Cat. No.	
Iron (total)	FerroVer PP	0.02 - 3.00	2105769	C, S, PC
	FerroVer AV	0.02 - 3.00	2507025	C, S, PC
Iron	FerroZine	0.009 - 1.400	230166	C**, S
Aluminum	AluVer 3	0.008 - 0.800	2242000	C, S, PC
Aluminum	ECR	0.002 - 0.250	2603700	S
* PC – Pocket Colorimeter C – colorimeter S – spectrophotometer				
**DR900				

Figure 17: Reagents for Iron and Aluminum Tests

The Jar Test

The jar test is the most basic test for control of coagulation/flocculation/filtration and is completed with a multiple stirrer such as the Phipps Bird. It would seem a test and an apparatus so simple would have existed for many years. Yet, at least in the water industry, the multiple place stirrers can be traced to as recently as about 1920. An early attempt to conduct the equivalent of today's jar test but using a single glass dish is recorded just a few years earlier.



Figure 18: Jar test apparatus
Phipps Bird 6-Place Programmable Multiple Stirrer with 1-liter
round glass beakers. Hach Company stock photo

The jar test can be performed with round jars, square jars, ½ L jars, 1 L jars, 2 L Wagner Jars or for that matter, mayonnaise jars.

- Features the customer should look for are a back panel, typically black to view the water in the jars and a white or lighted base.
- You may encounter Hach brand multiple stirrers that used ½ liter jars. The product was discontinued several years ago.
- The Phipps Bird has a lighted base under the jars.
- When using the lighted base, the light should be left off except when observing the floc formation or settling process. When the lights are on, the base will generate heat sufficient to create convection currents. Changing the temperature of the water during coagulation and flocculation will lead to non-representative floc formation and the convection currents will interfere with settling.



Wagner™ Jar – p/n 41170-00, 2-liter
square plastic flocc jar for the jar test.
The Wagner Jar has a tap near the
bottom of the jar to facilitate withdrawal
of a sample for further testing of pH,
turbidity, alkalinity, streaming current,
zeta potential, etc. Photo by author.

Figure 19: Wagner™ Jar

The jar test is as much art as it is science. A different coagulant dose is added to each of the 4 or 6 jars. A short period of rapid mixing (for coagulation) and then a longer period of slow mixing (flocculation) occur. Last, a no-stirring quiescent period permits settling. Chemicals for pH adjustment, coagulant aids; ballasting substances (carbon, clay, etc.) also may be added to the jars. It is important to vary only one parameter at a time!

During stirring and the quiescent periods the operator or lab tech will observe the jar for floc formation and settling rate and use this information to then make chemical dose changes to the process. Each plant operator and chemist (or university professor, engineer, chemical sales person, etc) is very sensitive about their particular technique so

one should tread carefully in suggesting any variation in their technique. Users will be adamant about use of a square vs. round jar, big jar or little jar, this rapid mix period vs. another, the slow stir speed, etc. They will be absolutely sure their combination of art and science is THE way to do it.

The jar test is an attempt to simulate in a one or two liter jar what is going on in a basin 20'X30'X15' containing 67,000 gallons. The jar test is also an attempt to simulate with little 1"x2" paddle stirrers and jars the mixing energy with a train of huge paddles extending the entire length of a 40 foot long flocculation chamber and maybe 15 feet in diameter.

It is as much an art as a science because operators have to learn to interpret "when my little jar looks this way, my big basin will look this way." The more measurements are made; the better the operator or lab person can interpret the jar test results – based more on measurement (science) and less on art. This is important because filter performance is directly affected by how well the floc forms, settles and withstands shearing effects during mixing and filtration. Apparatus to enhance the jar test include a wide array of other Hach products:

- Measure pH with the HQd series or SensIon series pH meter and probe – One must measure pH especially with aluminum or iron salts (aluminum sulfate, liquid alum, ferric chloride, ferric sulfate).
 - Coagulants have an optimal pH range in which they should be used.
 - Aluminum sulfate or liquid alum work well from a pH of about 5.5 (optimum color removal) to the low 7's.
 - Iron compounds – ferric sulfate and ferric chloride – operate well over a much wider range of pH well into the high 8's.
 - Monitor the endpoint of the alkalinity titration with pH measurement, see below.
- Measure alkalinity with the Digital Titrator® and associated reagents. Use of the metallic salts as coagulants consumes alkalinity.
 - As a rule of thumb, one must have (numerically) ½ the alkalinity of the amount of alum or ferric sulfate coagulant dose needed. If a dose of 20 mg/l of alum is needed, then the alkalinity must be at least 10 mg/l. For ferric chloride, it's nearly 1:1. That is, for a dose of 30 mg/l ferric chloride, at least 30 mg/l of alkalinity must be available.
 - Customers should be encouraged to monitor the alkalinity titration with pH measurement rather than trying to observe the color changes. Whether using methyl orange or bromcresol green/methyl red indicators, it is difficult for many if not most people to see the subtle color changes.
- Measure turbidity with a lab or portable turbidimeter (2100P, 2100Q, 2100N or 2100AN). Measure the turbidity at the beginning and the turbidity of the supernatant at the end of the settling period. Filter a portion of the supernatant through medium speed filter paper and again measure the turbidity.
- Both a large (1-10ml) and small (0.1-1.0 ml) TenSette® Pipet – Use the TenSette to:
 - Prepare standard jar test solutions such that each ml of stock solution added to a jar of sample to be tested results in a concentration of 10 mg/l. Add the number

of grams or milliliters specified to 300 ml of dilution water. Mix and dilute up to one liter (1000 ml) for the stock solution.

For dry alum or iron coagulants:			
Size of sample for jar test	Milligrams of dry alum or iron coagulants for each 1 liter of stock solution		Concentration resulting when 1 ml of stock solution is added to the water to be tested
0.5 liter jars	5,000 mg (5 g)		10 mg/l
1.0 liter jars	10,000 mg (10 g)		
2.0 liter jars	20,000 mg (20 g)		
For liquid alum or liquid ferric chloride			
Size of sample for jar test	ml of liquid alum (assuming a 48% solution) to prepare 1 liter of stock solution	ml of ferric chloride (assuming a 40% solution) to prepare 1 liter of stock solution	Concentration resulting when 1 ml of stock solution is added to the water to be tested
0.5 liter jars	7.8 ml	8.9 ml	10 mg/l
1.0 liter jars	15.6 ml	17.8 ml	
2.0 liter jars	31.2 ml	35.7 ml	

Figure 20: Preparation of stock jar test solutions

- Use the TenSette pipet to dose each of the jars with the appropriate coagulant/coagulant aid dose.
 - Use the 1-10 TenSette pipet for 10 mg/l increments or
 - Use the 0.1-1.0 TenSette pipet for 1 mg/l increments.
 - Realistically 1 mg/l increments are about all the resolution one can achieve with the jar test.
- Use to withdraw aliquot of supernatant
 - For testing turbidity and for a filtration test
 - Alkalinity measurement
- Plastic funnels and medium speed filter paper. Filtering supernatant through medium speed filter paper is a surprisingly good simulation of what can be achieved with filtration in the plant's filters. Measure turbidity before filtration to determine effectiveness of settling and then after filtration to estimate how well the sample will hold up (floc tough enough to withstand the shearing forces) during filtration.



Figure 21: Six-place assembly for filtering samples after a jar test.
Photo by author.

When a treatment plant uses liquid alum, or other liquid coagulant, coagulant aids or filter aids, the products can vary in percent of active component from manufacturer to manufacturer and in some cases from lot to lot. The percent concentration must be known before one can calculate how to make a standard solution (as above) for these liquid products.

Equipment and Apparatus for the Jar Test		
Cat. No.	Description	Use
Multiple Stirrer, choose one of the following		
2631700	Phipps Bird 6-Place Programmable Multiple Stirrer supplied with 6 1-liter round glass beakers,	Multiple stirrer for jar test
2703800	6-place nonprogrammable w/o beakers	Multiple stirrer for jar test
2704000	4-place programmable w/o beakers	Multiple stirrer for jar test
2703900	4-place nonprogrammable w/o beakers	Multiple stirrer for jar test
4117000	Wagner Jar	2-liter square plastic floc jar
50083	Glass Beaker, round, 1 liter, pk/6	Jar test w round jars
pH Meter, choose one of the following or better		
pH	SensION+ 3w/ pH Combination Electrode	Measure pH/ alkalinity end point
8505900	HQ11d pH meter w/ gel-filled combination pH electrode, buffers and probe stand	Measure pH/ alkalinity end point
Digital Titrator, cartridges and indicators		
2270900	Universal Digital Titrator Kit w/ manual, 100 ml graduated cylinder, 125 and 250 ml Erlenmeyer flasks	Alkalinity test
1438801	0.1600 N H ₂ SO ₄ Titration Cartridge	Low range alkalinity test
1438901	1.600 N H ₂ SO ₄ Titration Cartridge	High range alkalinity test
94299	Phenolphthalein PP, pk/100	Indicator for p-alkalinity test
94399	Bromcresol Green Methyl Red PP pk/100	Indicator for total alkalinity test
2271900	Reagent Set for Alkalinity – includes titration cartridges and indicators above.	
Other Instruments and Apparatus		
2100Q01 4700000 4700100	2100Q Portable Turbidimeter OR 2100N Laboratory Turbidimeter OR 2100AN Laboratory Turbidimeter	Test clarity of supernatant and filtrate from jar test
19700-01	TenSette Pipet, 0.1-1.0 in	Jar test chemical dosing
2185696	Pipet tips, 0.1-1.0	
1970010	TenSette Pipet, 1.0-10.0 in	Jar test chemical dosing, transfer supernatant for further testing
2199796	Pipet tips, 1.0-10.0	
108368	Funnel, each	Filtration testing of the supernatant
69257	Filters, pleated	Filtration testing of the supernatant

Figure 22: Equipment and apparatus for the jar test

Zeta Potential

Zeta potential is a test to quantify the charge on colloids in the water to be treated. Ideally one would like to be able to monitor the zeta potential of the raw water and use with feed-forward control to set the coagulant dosage. In practice it is nearly universally used for feed-back control. That is, after coagulant addition a sample can be immediately taken to determine the charge neutralization and then that information used to adjust the coagulant dose. Zeta potential of zero is theoretically ideal. In practice most utilities will have a slightly negative zeta potential after coagulation. A positive zeta potential indicates a likely overfeed of coagulant. There are several drawbacks to use of zeta potential.

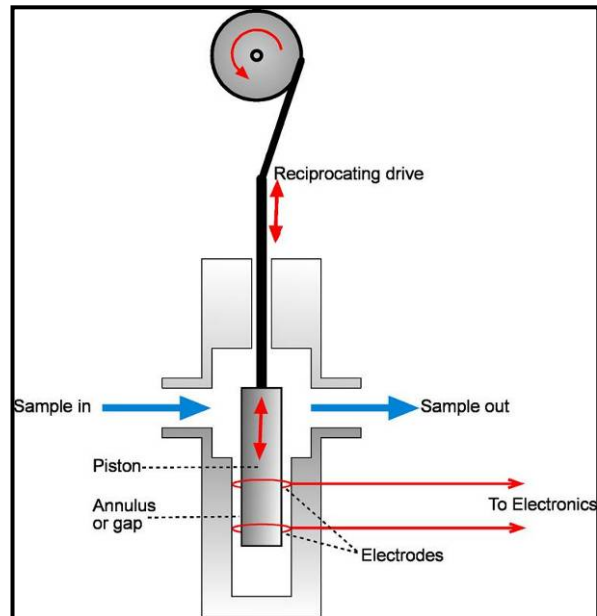
- It is a laboratory, grab sample tool.
- Instruments for measuring zeta potential are relatively expensive, typically in excess of \$15,000.
- While they are not complicated tools, learning to interpret the data from a zeta meter is often time consuming.
- There is not a clear cut procedure for how to interpret zeta potential measurements and apply them to the process. Every treatment plant is different and each water source is different.
- Learning what zeta potential is ideal for a particular treatment plant and water involves repeated testing and observation. A good place to start is with the jar test. If a treatment plant has learned to interpret the jar test, then the zeta potential of the dosage selected during the jar test can be measured. A sample is also taken from the application point of the coagulant in the process immediately after rapid mixing. If the plant sample has a different zeta potential than the jar, the coagulant feed can be adjusted to match the zeta potential of the jar test.
- After further observation of the process quality, additional minor adjustments can be tried. Again the process should be observed and measured. The results are used to refine judgments made both in the process and in interpretation of the jar test.
- This trial and error process carried out over time in a disciplined manner will result in a better optimized chemical feed. While a jar test may indicate a coagulant dose to the nearest 2-3 mg/l, using zeta potential can refine that judgment to within tenths of an mg/l of coagulant. The time invested is well spent as savings in several areas of the treatment process will result. Properly applied, the return on investment can easily be less than a year.
- The bottom line is few utilities use measurement of zeta potential. Cost, complexity, lack of understanding of the principle, and lack of the desire for disciplined study have limited the use of this very valuable tool.

Streaming Current

Streaming current is an on-line measurement of how well charge neutralization has occurred. It is not the same as zeta potential but can provide much the same level of information for process control. It has both drawbacks and advantages over zeta potential measurement.

Figure 23: Schematic diagram of a streaming current sensor (Edney)

The SCM is based on the effect where the walls of the capillaries through which the colloidal material flows quickly gain a coating of particles and take on the surface charge characteristics of these particles. The SC sensor consists of a piston and a close-ended chamber. A narrow gap, an annulus 200-500µm wide, exists between the piston and the walls of the chamber. The piston is driven up and down at a fixed frequency, typically 4-5 strokes per second, forcing sample water in and out of the chamber through the annulus.



As the piston and chamber surfaces are coated with charged particles, the water flowing rapidly up and down through the annulus results in displacement of the counter-ions.

The SC signal measured by electrodes in the annulus is proportional to the water velocity and therefore alternates in time with the piston. This signal is typically in the range of 0.05µA to 5µA depending on the particular conditions. Measurement of SC in a closed chamber has several advantages compared to measurement directly in a flowing stream:

- The closed end is electrically isolated and removes problems caused by large potentials in the process stream from other sources.
- The signal is alternating at the frequency of the piston. This allows it to be separated from external noise and offset caused by electrode drift and dissymmetry.
- Practical aspects of instrumentation, such as that the closed chamber can be shielded from electromagnetic interference and cleaned easily. (Edney)

- Streaming current is an on-line measurement providing continuous feedback
- Optimally, one would use both zeta potential and streaming current measurement.
- pH of the process must be controlled for effective coagulation and flocculation. If pH is not controlled, it will be difficult to achieve benefit of a streaming current meter.
- Streaming current is strongly influenced by salinity, conductivity and pH variations. If the pH, conductivity, or salinity of the water to be treated is highly variable, streaming current measurements may have limited value or will be problematic.
- On the other hand, if streaming current has worked well for a period of time and suddenly seems to not correlate well, that is a signal of a significant change in water quality that should be investigated and understood.
- Streaming current requires much less effort to learn to use than a zeta potential measurement.
- Streaming current meters are less expensive than zeta meters.
- One of the greatest challenges of streaming current application is locating the right point of measurement. The sample must be as close as possible to the point of application of the coagulant but after it is well mixed. Often the ideal point is not accessible.



Figure 24: Accufloc Streaming Current Monitor.

Clarification

Clarifiers (sedimentation basins) provide a quiescent, low velocity (typically <0.5 ft/sec) area where the solid/floc mixture can settle from solution. A variety of designs are in use – square, rectangular and round. Many are fitted with proprietary modifications to improve settling performance. Detention time in a clarifier is typically between 30 and 45 minutes.

Some will be described below. Characteristics common to all will be:

- A means to introduce the flocculated water uniformly to the clarifier
- A means to collect and discharge accumulated solids
- A means to collect clear effluent and transport to the filtration step
- A means to ensure complete treatment and minimize or prevent short circuiting

Perhaps the simplest designs one will encounter is a rectangular basin with sloped floor equipped with manual or automatic means of solids collection and withdrawal.

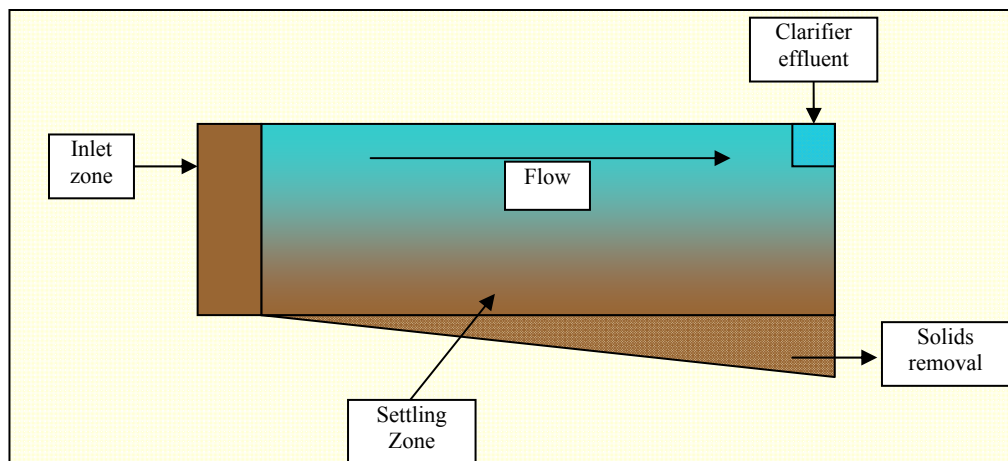


Figure 25: Rectangular clarifier



Figure 26: Rectangular clarifier sludge removal system
 Left, basin with flight and chain sludge removal system. Horizontal scrapers move settled sludge to a collection trough. Right, as water passes through a clarifier, settling progresses, one sees the floc cloud ending before the water reaches the end of the clarifier. Photos by author.



Figure 27: Clarifier w/ perforated inlet baffle wall
 The rectangular clarifier pictured has a perforated inlet baffle wall. The design is intended to uniformly distribute the flocculated water across the basin to provide uniform settling time and to minimize short circuiting. At left, the perforated inlet wall. Sludge collection pipes (white) visible at the bottom. At right one can see jet streams (red arrows) of the flocculated water entering the basin through the holes. This design would be credited with a baffling factor of 0.7 or better for purposes of calculation of CT. See discussion below under Clarifier Design Impacts Disinfection. Photos by author.

Modifications to improve performance may include some baffling to minimize short circuiting, automatic systems to remove solids including scrapers moving along the bottom, or vacuum sludge withdrawal systems. A variety of clarifiers known as solids contact clarifiers enhance floc formation and settling characteristics. To enhance settling, modifications such as closely-spaced parallel plates and tube settlers may be employed.

Solids Contact and Blanket Clarifiers

Solids contact clarifiers attempt to enhance floc formation and settling characteristics by providing an environment where newly forming and newly formed flocs collide/mix/interact with existing solids. Solids contact clarifiers combine the flocculation and settling steps into a single unit process. A blanket clarifier is similar in that the newly formed floc typically ‘rises’ through a layer or blanket of existing solids.

Several companies offer solids contact clarifiers each with a variation of the application of this concept they believe is superior to other approaches. The different designs do have sets of conditions and treatment objectives for which they are truly optimized. “One size” does not fit all. A few designs one is likely to encounter are:

- **Solids CONTACT CLARIFIER™** by WesTech Engineering, Inc. - “The recirculation impeller is the “Heart” of the Solids CONTACT CLARIFIER™. WesTech’s radial impeller is located at the top of the draft tube and is designed with swept back blades to minimize shearing of floc particles and horsepower required. WesTech’s Solids CONTACT CLARIFIER™ is available in both center pier and bridge supported configurations, circular or square basins, and concrete or steel tanks. Cylindrical or conical reaction wells are designed for specific applications.”
- **SpiraCone™** by Siemens – “The General Filter SPIRACONE™ Clarifier is an up flow sludge blanket clarifier that combines mixing, flocculation and sedimentation in a single basin. Raw water and chemicals are hydraulically mixed then pass upward through the various zones within the basin for reaction, flocculation, sludge removal and clarification. Hydraulic mixing eliminates mechanical mixers, while the conical shape eliminates scrapers.”



Figure 28: SpiraCone Solids Contact Clarifier
Photo by author.

- **Superpulsator®** by Infilco Degremont – “The Superpulsator® Clarifier combines basic chemical principles and proven clarification technology in a high-rate, solids contact clarifier that offers maximum efficiency. This unique design combines flocculation and clarification functions in one basin for optimal use of space. Vacuum generated flow pulsations create a homogeneous sludge blanket that results in excellent effluent quality at minimal operating costs.”
- **Claricone®** by CB&I, Inc. – “The ClariCone maintains a dense, suspended, rotating slurry blanket that provides excellent solids contact, accelerated floc formation and exceptional solids capture. Thus, chemical usage is reduced and O&M costs are minimized. The conically shaped concentrator maximizes the slurry discharge concentration and allows plant personnel to visually monitor slurry discharge.”

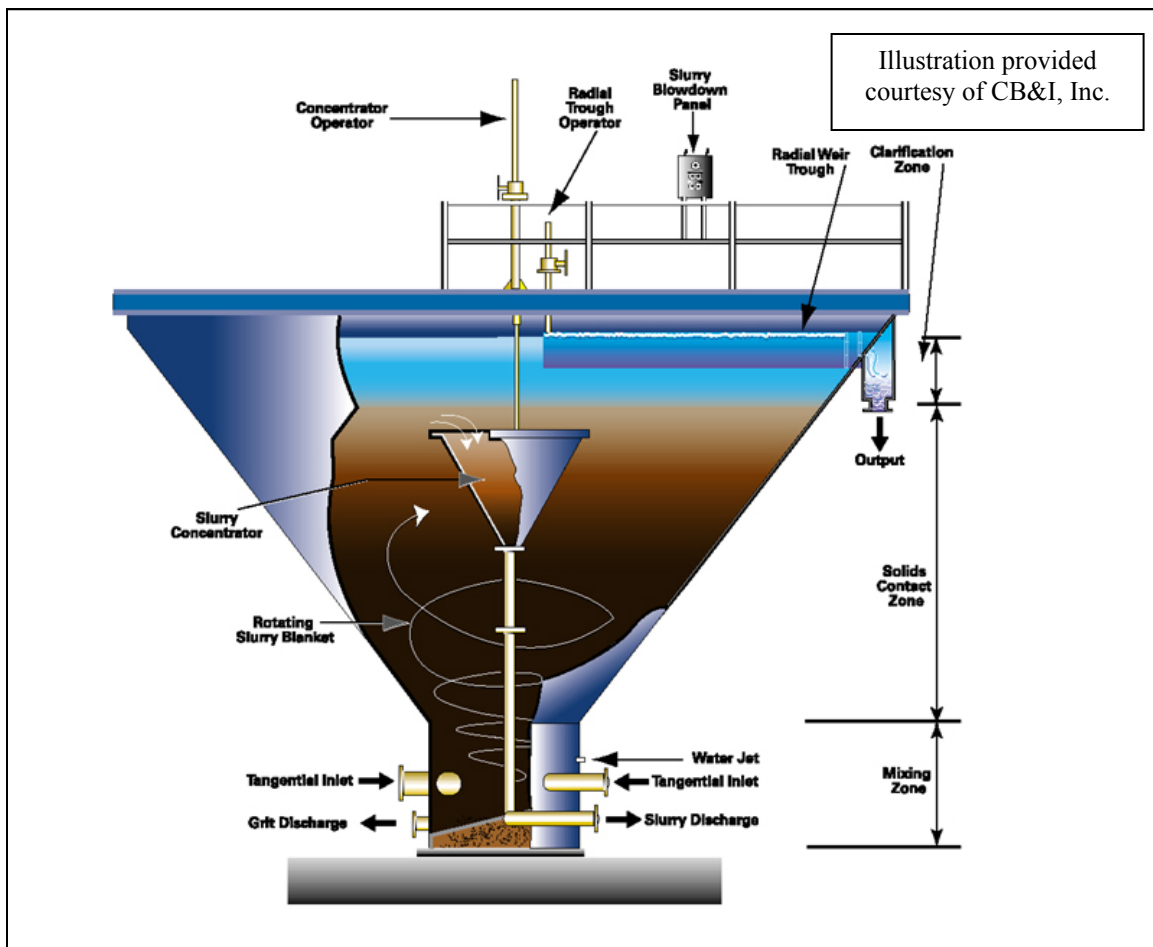


Figure 29: Claricone cross-sectional diagram.

- Clar-I-Vator® by Smith and Lovelace, Inc. – “A CLAR-I-VATOR® solids contact clarifier overcomes some of the problems exhibited in the sludge blanket clarifier. It basically controls the chemical reactions taking place, flocculation, and the sedimentation phenomena more positively than in a sludge blanket clarifier and is not as readily affected by changes and flows or by process. In the CLAR-I-VATOR® solids contact clarifier, the liquid stream enters into a central detention zone where chemicals can be added. Within this zone, there is a re-circulator paddle which is activated by a variable speed drive. This paddle creates a pressure differential within this zone and essentially pumps previously settled material from a central settling cone into the re-circulation zone and positively contacts it with the incoming waste. In so doing, the incoming waste can be flocculated with chemicals added at that point. The incoming solids create a thermodynamically favorable environment to bring a chemical reaction to completion, conserve chemicals and provide a more favorable settling characteristic to the solid.”



Figure 30: Clar-I-Vator
Used with permission of Smith and Lovelace, Inc.

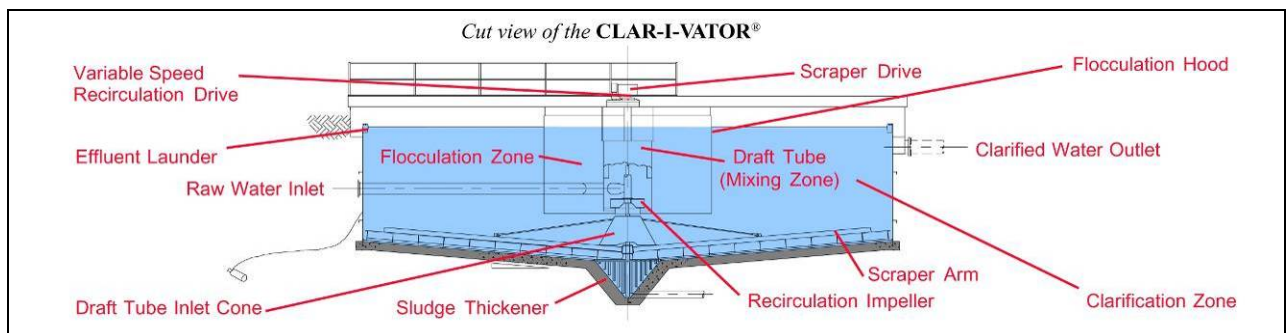


Figure 31: Cut view of the Clar-I-Vator Solids Contact Clarifier.
Used with permission of Smith and Lovelace, Inc.

Tube Settlers and Parallel Plates to Enhance Separation

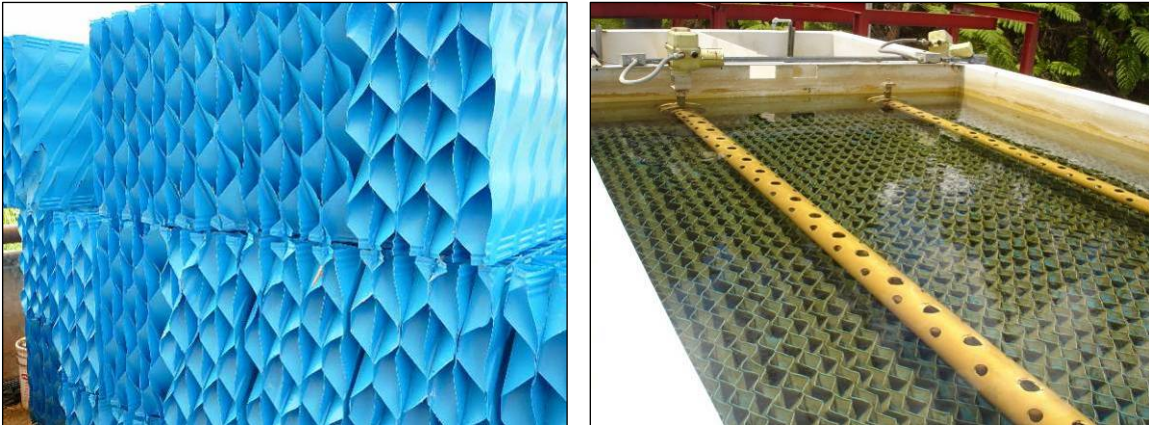


Figure 32: Tube Settlers enhance settling

Tube settlers are modules which can be incorporated into new clarifiers or retrofitted to old. The ‘tubes’ are typically about 2”X2” square assembled in modules as pictured (above left). The tubes are usually inclined at about 60°. The relatively large surface area provides friction which encourages solids/liquid separation. The steep incline of 60° encourages gravity settling of the accumulated solids. As solids move by gravity down the tubes they also interact with solids in the water rising in the tubes to trap additional solids. The system pictured above right is functioning quite well. The system pictured at left is not functioning as well as many of the tubes are nearly plugged by solids. Often all that is needed for a situation like that pictured is to stop flow temporarily, drop the water level down rather quickly to ‘flush’ the solids and then go back to normal operation. Note the clarification process at left is being monitored with a Hach Company Solitax sc ts-line suspended solids probe. Photos by author.

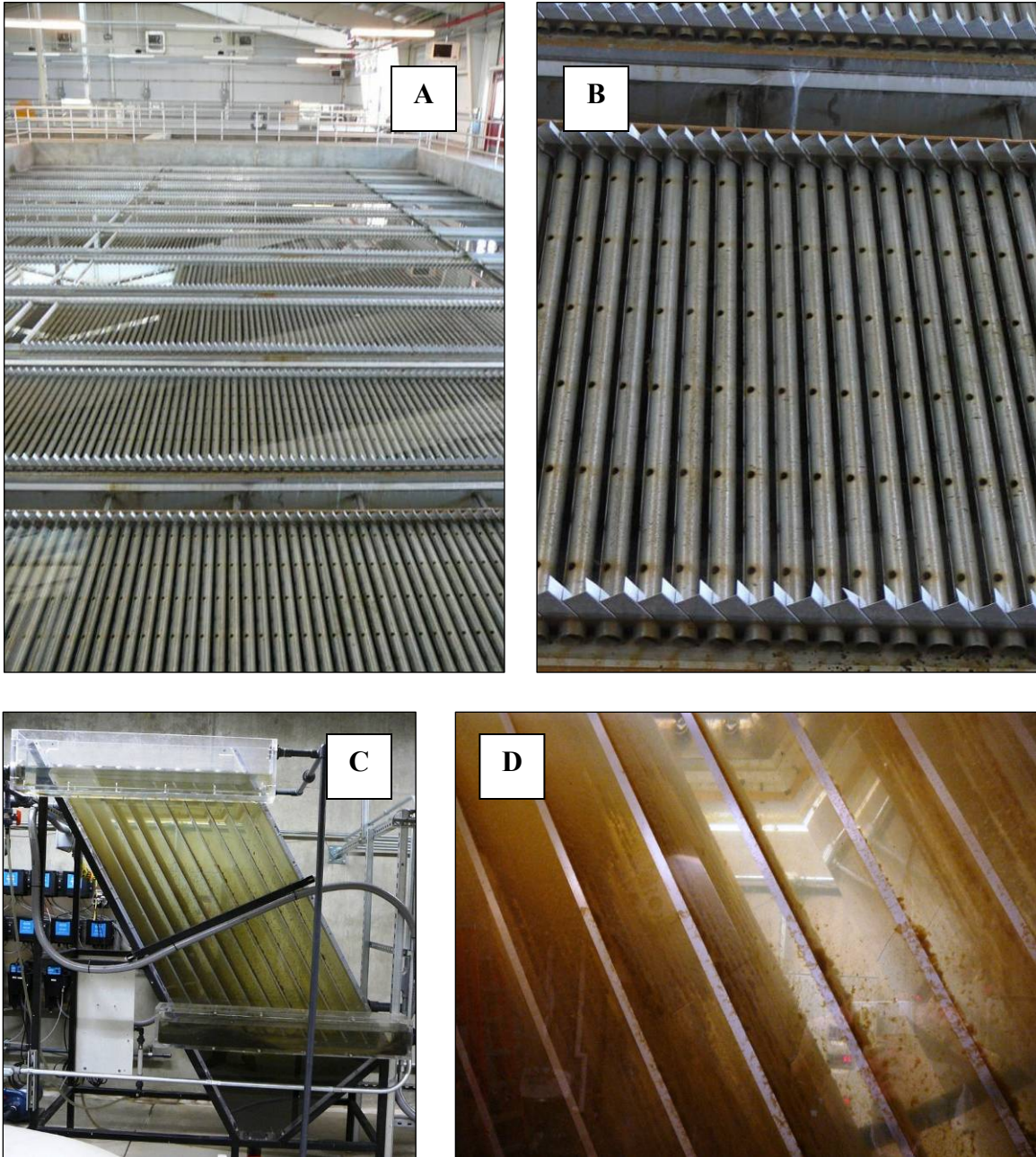


Figure 33: Inclined Plate Settlers

The most well known brand of inclined plate settlers is Lamella® (a registered trademark of Parkson Corp.). In a fashion somewhat similar to the tube settlers, the plates typically are spaced about 2" apart and are inclined at about 60° to encourage solid/liquid separation and to encourage solids to roll down the plates (D). Parallel plates can be fitted to conventional clarifiers (A and B). Plate settlers are somewhat less prone to the type of solids accumulation previously shown for tube settlers. Parallel plate settlers can be used in a complete module as illustrated in (C) as a package clarifier. Effluent from a flocculator can be fed directly to a module as pictured. Photos by author.

Effluent Collection

Clarifiers typically have a collection trough (launderers) around the outside edge or may have multiple radial collection troughs in round clarifiers. Rectangular clarifiers may have a single trough at the end of the basin or multiple parallel troughs. Regardless of configuration, the collection trough (launderer) has one purpose – to collect the effluent water uniformly and thus discourage ‘short circuiting’. A scum baffle may be provided to prevent floating scum, foam and or solids from entering the trough. The wall of the effluent trough typically will be fitted with a weir plate. It may be a simple flat plate, a v-notch plate or a plate with uniformly spaced circular orifices. The weir plate typically is thin forming a ‘sharp crest’ which provides minimal drag (frictional resistance to flow) and which minimizes collection of solids, oils or chemical films that would inhibit the free escape of the water past the weir. One can observe that the design with perforations or orifices would be more prone to plugging. Plugging results in non-uniform collection and short circuiting.



Figure 34: Circular drinking water clarifier with radial launderers and v-notch weir plates
Photo by author.

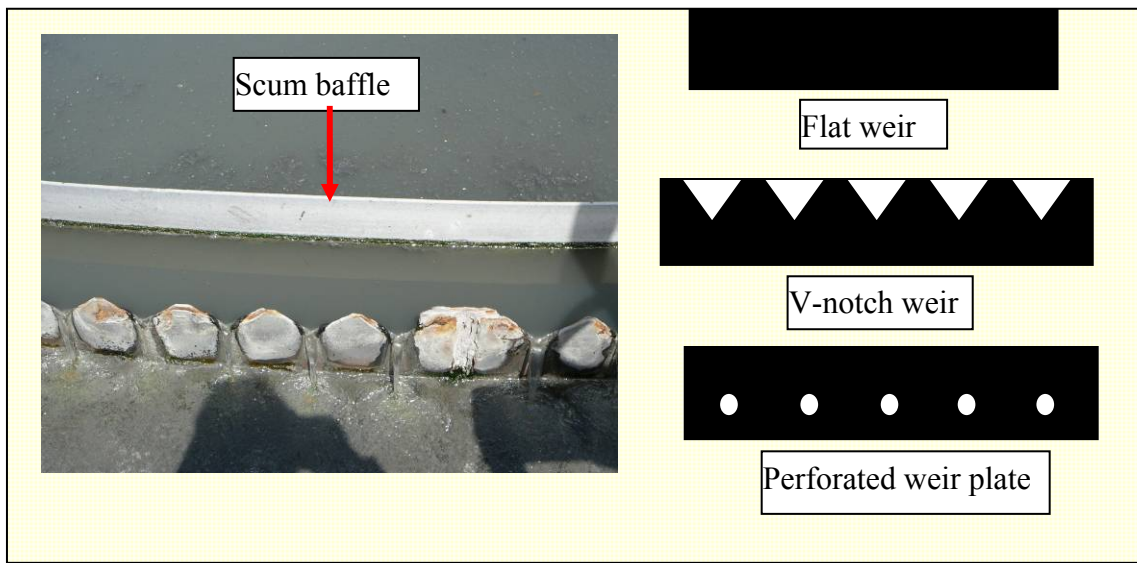


Figure 35: Clarifier effluent weir configurations

Left: Primary clarifier at a wastewater treatment plant with scum baffle and v-notch weir plate.
Right: Typical clarifier effluent weir configurations. Photo by author.

Dissolved Air Flotation (DAF) Clarifiers

Dissolved air flotation or DAF clarification, as the name indicates, relies on floating particles to the surface using air bubbles rather than the conventional approach of gravity clarifiers. DAFs are employed in drinking water where gravity clarifiers are ineffective such as where particulate contamination is low and the objective is removal of low-density materials such as microorganisms (algae, cysts), natural organic matter (NOM) and floc in low turbidity, soft water. They're also used in iron and manganese removal systems.

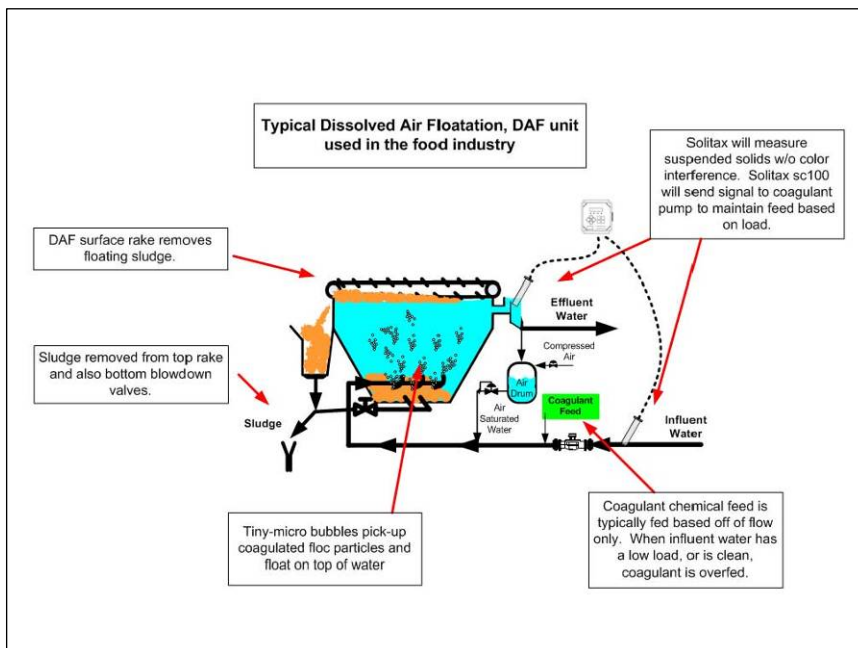


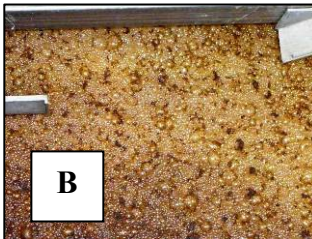
Figure 36: DAF Schematic for food processing

DAFs find use in wastewater treatment as sludge thickeners and in many industrial processes ranging from food processing to oil/water separation in oil fields and refineries. Illustration courtesy of Marc Hansen, Hach Company

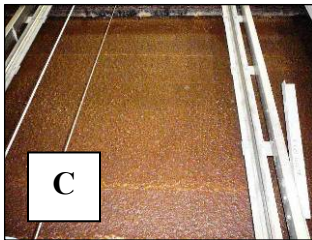


Figure 37: DAF sequence of operation

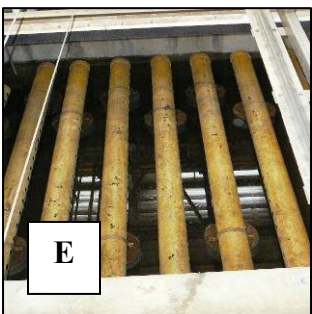
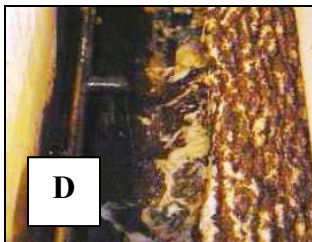
A portion of clarified or filtered water is saturated with air in the saturator tank (A).



The air-saturated water is injected into the clarifier influent stream. The air bubbles 'attach' to the flocculated particle and float them to the top (B).



A scraper arm (C) then removes the layer of 'dirt'-laden foam and deposits in a waste trough (D). Some DAFs will use hydraulic removal of the accumulated foam. In this case the foam is caused to float over the outlet weir periodically by either lowering the outlet weir or restricting the effluent clear water draw off (thus temporarily raising the surface level) and causing it to overflow the fixed weir.



The lower layer of clarified water then is drawn off of the clarifier by an effluent manifold (E).
Photos by author.

Clarifier Design Impacts Disinfection

If a disinfectant – chlorine, ozone or chlorine dioxide – is applied prior to flocculation and/or clarification; then, the design of the basin must be considered in calculation of CT for the US EPA rules established under the Safe Drinking Water Act (SDWA); Long Term 1 Enhanced Surface Water Treatment Rule, LT1ESWTR; Long Term 2 Enhanced Surface Water Treatment Rule, LT2ESWTR; and/or the Ground Water Rule. CT (or Ct, there is no difference in the two expressions) is an expression of the concentration of a chemical disinfectant, C in mg/l, multiplied by the contact time, T in minutes. The unit of measure for CT then is (mg-min)/l. See [Calculation of CT Values for Compliance with Drinking Water Regulations](#), for detailed information about CT calculations.

The contribution of the flocculation and clarification steps CT is to provide contact time, T. And, the contribution is based on how well designed (baffled) the flocculation and clarification processes are to provide plug flow. Consider: If a circular basin is 20 feet high, 60 feet in diameter with a minimum working level of 12 feet, then the detention time at a flow of 5000 gallons/min. is 50.7 minutes:

Volume in gallons = $\pi r^2 h \times 7.48 = 253,661$ gallons.

$$\text{Detention Time (contact time)} = \frac{253,661 \text{ gal.}}{5000 \text{ gal.}} \times \frac{1 \text{ min.}}{5000 \text{ gal.}} = \frac{50.7 \text{ minutes.}}{5000 \text{ gal.}}$$

How well does the basin provide plug flow? Does it really take every drop of water 50.7 minutes to transit through the basin? Does a certain volume of water travel through the device as a plug flow (first in, first out) or can the flow short circuit? The table below can help determine what actual credit for contact time should be allocated to the process.

Baffling Conditions	Baffling Factor	Baffling Description
Unbaffled (mixed flow)	0.1	None, agitate basin, very low length to width ratio, high inlet and outlet flow velocities. Can be approximately achieved in flash mix tank.
Poor	.0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles
Average	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders
Perfect (plug flow)	1.0	Very high length to width ration (pipeline flow), perforated inlet, outlet and intrabasin baffles

Figure 38: Table of baffling factors

Actual Detention Time = Calculated Detention Time X Baffling Factor

If the basin is unbaffled, then

Actual Detention Time = 50.7 minutes X 0.1 or 5.1 minutes!

It should be apparent that a poorly baffled basin also will not provide good performance for flocculation or clarification either!

Measuring Clarifier Performance

Many of the same analytical methods and instruments used to monitor the raw water can and should be repeated for clarifier effluent. Of course if iron or aluminum coagulants have been used, they should be measured. Ideally, one would like the iron and/or aluminum in clarifier effluent to be equal to or less than the amount in the raw water. Certainly, the filter effluent values must be less than for raw water.

Parameter	Laboratory Measurement	On-line Measurement	Reason to monitor
Alkalinity	Digital Titrator	APA 6000 Alkalinity	Water quality, coagulation control
Aluminum	ECR or Aluminon	NA	Coagulation
Hardness	Digital Titrator	APA 6000 Hardness	Water quality
Iron	FerroVer Iron	NA	Aesthetic; Coagulation
Manganese	PAN or Periodate Method	NA	Aesthetic
ORP	HQd series meter and probe	ORP w sc200 or sc1000 controller	Water quality, control of preoxidant
Permanganate	PAN or Periodate Method	NA	Preoxidant for NOM
Particle Counting		2200 PCX Particle Counter	Clarifier effluent/filter influent particle counts to determine log removal of particles
pH	HQd series meter and probe	pHD pH w sc200 or SC1000 controller	Coagulation control
Sludge Level	Sludge Judge sampler or TSS Portable Hand-held Turbidity, Suspended Solids and Sludge Level	Sonatax w sc200 or sc1000 controller	Manage sludge level in the clarifier
Total Organic Carbon	TOC test	1950+	Water quality, SUVA calc., coagulation control, DDBP rule compliance
Turbidity/Solids	2100Q, 2100N or 2100AN	SS7, UltraTurb, or Solitax w sc200 or sc1000 controller	Water quality
UV254	DR5000	UVAS	NOM, SUVA, coagulation control

Figure 39: Clarifier performance measurements

Figure 40: Sonatax for sludge level in clarifiers

Monitoring sludge level in a drinking water clarifier can be a challenge. The system pictured is a primary clarifier at wastewater plant. Wastewater sludge tends to be much more dense than sludge caused by drinking water flocs. Thus ultrasonic sludge level devices such as the Sonatax work well in wastewater applications but may not work as well in a drinking water application. It is prudent to pilot test a Sonatax for drinking water. If Sonatax is found to work well, the articulated arm (pictured) normally is not necessary as drinking water clarifiers typically do not have a surface rake. Photo by author.





Figure 41: pH monitoring

There should be little doubt of the importance of monitoring pH in clarifier effluent, especially if the process requires pH adjustment prior to filtration as is the case in some iron and manganese removal processes. Measurement and management of pH from raw water to final effluent is critical to a successful drinking water treatment process. It is especially important in coagulation/flocculation and clarification.

Photo by author.



Figure 42: Turbidity and suspended solids monitoring for clarifier effluent

The Solitax, UltraTurb and Surface Scatter 7 are all good choices for monitoring clarifier effluent. For in-line monitoring or expression as solids rather than NTU, the Solitax is a great choice. For the UltraTurb be sure to include the self-cleaning option. Photos by author.

Figure 43: Digital Titrator

The Digital Titrator is ideal for testing the alkalinity and hardness to monitor the raw water, coagulation process and finished water. For alkalinity the user should be encouraged to monitor the titration with a pH meter rather than by color change. The color changes are difficult for many people to adequately interpret. Using a pH meter to titrate first to a pH of 8.3 (phenolphthalein or P alkalinity) and then to a pH of 4.5 (total or T alkalinity) is much easier and more accurate than looking for color changes.

Photo by author.



Log Removal

TABLE IV.D-1.—MICROBIAL TOOLBOX: OPTIONS, CREDITS AND CRITERIA	
Toolbox option	Cryptosporidium treatment credit with design and operational criteria ¹
Source Protection and Management Toolbox Options	
Watershed control program	0.5-log credit for State-approved program comprising required elements, annual program status report to State, and regular watershed survey. Unfiltered PWSs are not eligible for credit.
Alternative source/intake management.	No prescribed credit. PWSs may conduct simultaneous monitoring for treatment bin classification at alternative intake locations or under alternative intake management strategies.
Prefiltration Toolbox Options	
Presedimentation basin with coagulation.	0.5-log credit during any month that presedimentation basins achieve a monthly mean reduction of 0.5-log or greater in turbidity or alternative State-approved performance criteria. To be eligible, basins must be operated continuously with coagulant addition and all plant flow must pass through basins.
Two-stage lime softening	0.5-log credit for two-stage softening where chemical addition and hardness precipitation occur in both stages. All plant flow must pass through both stages. Single-stage softening is credited as equivalent to conventional treatment.
Bank filtration	0.5-log credit for 25-foot setback; 1.0-log credit for 50-foot setback; horizontal and vertical wells only; aquifer must be unconsolidated sand containing at least 10 percent fines (as defined in rule); average turbidity in wells must be less than 1 NTU. PWSs using existing wells followed by filtration must monitor the well effluent to determine bin classification and are not eligible for additional credit.

Figure 44: USEPA Microbial Toolbox options for source water and clarification

As can be seen in the above figure the terms ‘log removal’ or ‘log credit’ are widely used to express performance of various treatment processes. The table indicates a 0.5 log credit for cryptosporidium removal is applicable for coagulation and sedimentation prior to filtration.

The terms can be somewhat confusing for users. Recall a logarithm is the exponent to which a number is raised for a particular number base, in the 10-base counting system it is the exponent to which 10 is raised. The log removal calculation is straight forward: $\log(\text{Influent}/\text{effluent})$ which can also be calculated as $\log(\text{influent}) - \log(\text{effluent})$. (Recall from algebra, $\log(a/b) = \log a - \log b$)

For example, if a raw water has 16,000 particles/ml $>2\mu\text{m}$

- $16,000 = 1.6 \times 10^4$, or $\log 16,000 = 4.204$, or $16,000 = 10^{4.204}$
- If after filtration the water has 16 particles/ml $>2\mu\text{m}$,
 - then there was a 3 log removal (10^3) –the decimal moved to the left 3 places.
 - Or, 99.9 % of the particles ($16,000 - 16 / 16,000 = 0.999$ or 99.9%)
- If the effluent counts were 123, then the log removal would be $\log(16,000/123)$ or $\log(16,000) - \log(123) = 2.114$.

Percent Removal	Decimal equivalent	Log Removal
90 %	0.90	1 log
99 %	0.99	2 log
99.9 %	0.999	3 log
99.99 %	0.9999	4 log

Figure 45: Percent vs. Log Removal

For some treatment processes, it is problematic to express results in terms of log removal. When monitoring membranes with a particle counter, permeate (effluent) may approach zero particle counts. As the permeate approaches zero particle counts $\log(\text{influent}/\text{effluent})$ becomes undefined – division by zero. Rearranging the expression to $\log(\text{influent}) - \log(\text{effluent})$ does not solve the problem. There is no exponent (logarithm) to which any number can be raised which will yield zero. $\log(0)$ is undefined. Hence if the effluent approaches zero, it is best to express the removal as a percent removal.

It makes sense to express quantitative measurements (particle counts, number of cysts or oocysts, mg/l of iron) in terms of log reduction or log removal. It does not make sense to express qualitative measurements, like turbidity, in terms of log removal. In spite of this, users and even some regulatory rules and documents will use ‘log removal of turbidity’ as a criteria for performance. Notice the table above makes reference to, “a monthly mean reduction of a 0.5-log or greater in turbidity or alternative State-approved performance criteria.”

“Turbidity is not a direct measure of suspended particles in water but, instead, a measure of the scattering effect such particles have on light.” (Reference: Turbidity Science, Hach Company, M Sadar. Original edition titled: Understanding Turbidity Measurement, Hach Company, Clifford Hach).

One certainly can express any number of measurements in terms of log removal or percent removal if it makes sense to the user to do so. It doesn't make any sense but one could maintain that starting at a pH of 14 and ending at a pH of 1.4 is a "one log removal." Actually pH is a logarithmic function. A change from pH 14 to 13 is a one log change. Is that one log removal?

So the raw turbidity is 2.9. If the clarifier effluent is 0.28 NTU, is that greater than 1-log removal? Many utilities and regulatory agencies will say it is. The difficulty is, since turbidity is qualitative, not quantitative, there is no way to prove it! Here lies the crux of the problem of encouraging customers to think of turbidity in terms of log removal. Sooner or later someone will ask you to prove it.

If a customer or regulatory agency thinks it is meaningful to express turbidity in terms of log removal, that's their prerogative. But Hach Company should not encourage it or condone it because it can't be proven!

Monitoring the Process is a Complex Task

It takes more than just analytical measurement to understand what is going on in the treatment process. Consider the system illustrated below:

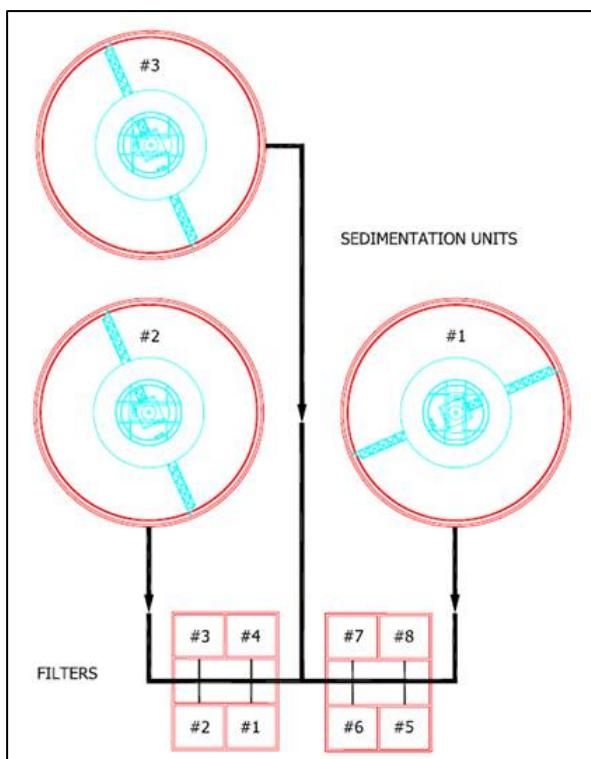


Figure 46: Treatment plant schematics

The treatment plant illustrated was built in three phases with clarifier #2 and filters 1-4, then clarifier #1 and filters 5-8 and finally clarifier #3. One can see it is very difficult to tell how the plant hydraulics actually work. There are valves to isolate each clarifier and also modulate the flows such that any filter can be fed from any clarifier. If one wants to monitor filter influent to say filter #7, which clarifier is feeding it? Is it a blend of clarifiers #1 and #3? If the influent is a blend of the clarifier effluents, what is the ratio? When working with a treatment facility on a monitoring plan it is very useful to get and use the plant piping schematics and illustrations such as these to get a feel for the complexities and not to just shoot from the hip with a guess as to the number and location of best monitoring points. Turbidity, particle counts, and pH should all be monitored continuously on each of the clarifier effluents near the filter buildings.

(Illustrations used with permission of McGoodwin, Williams and Yates, Inc., Fayetteville, AR)

Summary and Conclusion

No single unit process in drinking water treatment stands alone. The success (effectiveness) of every step in the process depends on preceding processes and steps that follow to make the entire treatment process function. And measurement is critical at every step. Perhaps monitoring of source water, coagulation and clarification are the most overlooked when instrumentation is installed in a water treatment process. Possible reasons include:

1. No mandate. With few exceptions monitoring of source water, coagulation, flocculation and clarification is for operational control - there are few regulatory requirements.
2. Budgets are always a problem and the few dollars available are allocated to the measurements that are regulatory mandates
3. There is a lack of understanding of the importance measurement plays in the successful application of these unit processes
4. Tools like streaming current and Zeta Potential are relatively new, poorly understood and expensive and thus are underutilized.

The figure below illustrates the treatment process from source to tap with suggestions for measurements at each point in the process. The illustration is by no means exhaustive but can be a guide for exploring opportunities when talking about measurement opportunities at a water treatment facility.

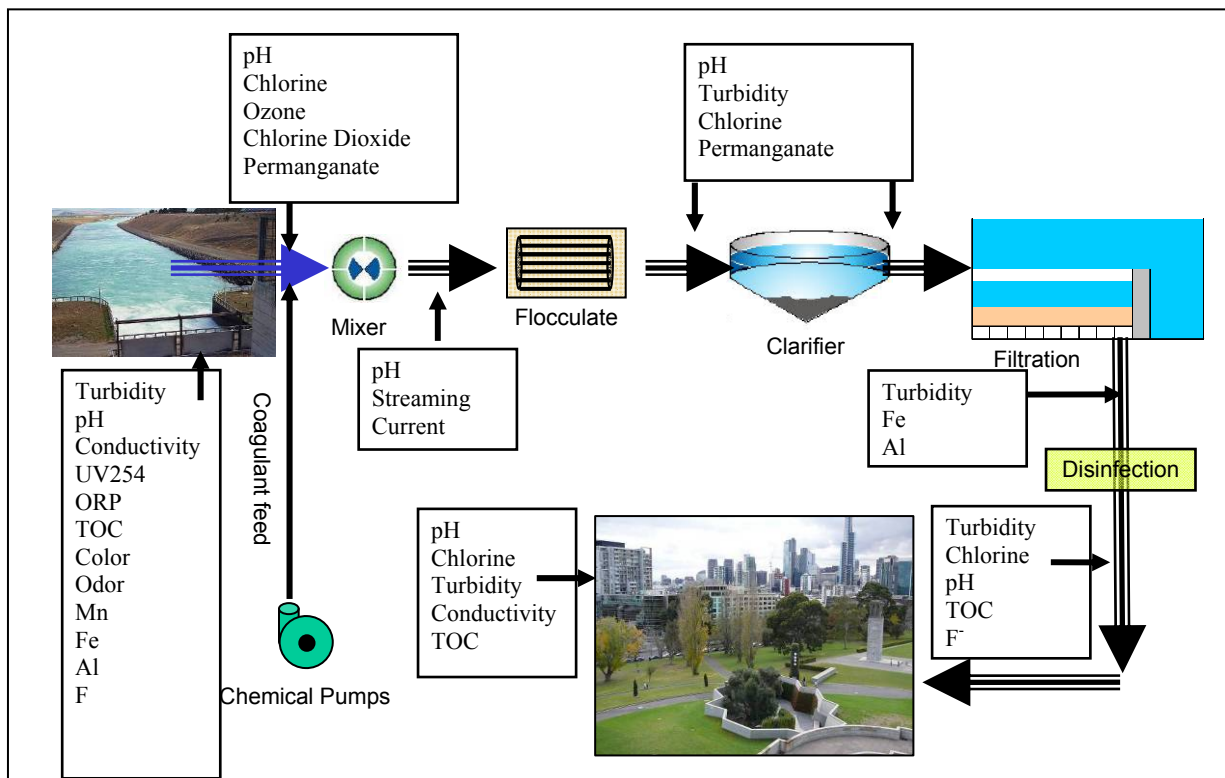


Figure 47: Typical water treatment process

The Water Treatment Continuum

Figure 48: The Water Treatment Continuum

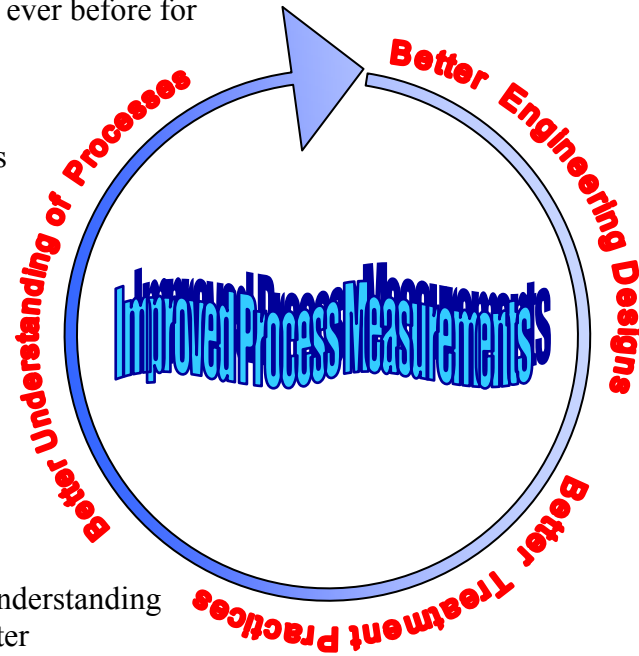
Most water treatment practices in use today have been used for centuries. Quality of the treatment plant effluent is better than ever before for four primary reasons:

The ability to measure the process – chemical, physical and biological – is better than ever before.

Improved measurement ability has led to a better understanding of the water treatment processes and functions.

Persons charged with managing and operating the systems are better trained than ever before.

Finally, better measurement, better understanding and better operations then permit better engineering designs. And so it starts again – with yet better measurement tools.



Acknowledgements

The following individuals contributed to preparation of this paper by their review, editorial critique and suggestions on technical content: Rebecca Engelhardt, Steve Cason, Vadim Malkov and Robert Geary. Their assistance is very much appreciated.

Appendix — Calculations

Rectangular Clarifier Volume

Volume of a rectangular clarifier is calculated by:

$V \text{ (ft}^3\text{)} = \text{Length (ft)} \times \text{Width (ft)} \times \text{Height (ft) or depth}$

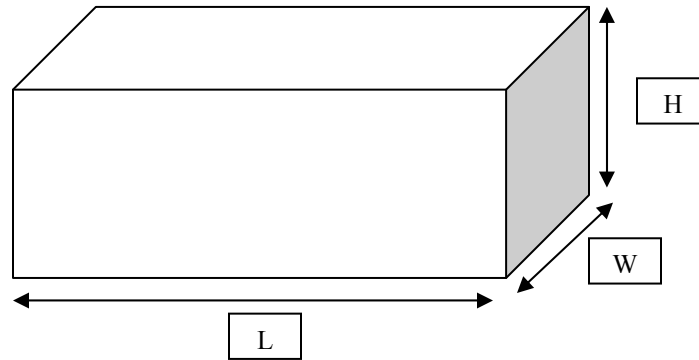


Figure 49: Rectangular clarifier

1. Calculate the volume, in gallons of a rectangular clarifier 40 ft long, 20 ft wide with a maximum water depth of 13 ft.

$$V = L \times W \times H$$

$$\underline{V \text{ (gal.)}} = \underline{40 \text{ ft}} \times \underline{20 \text{ ft}} \times \underline{13 \text{ ft}} \times \frac{7.48 \text{ gal}}{\text{ft}^3}$$

$$V = 62,233.60 \text{ gallons}$$

2. Calculate the volume in gallons of a clarifier 40 ft long and 25 feet wide. The clarifier has a sloped bottom. Water is 18 feet deep at one end, 15 ft deep at the other.

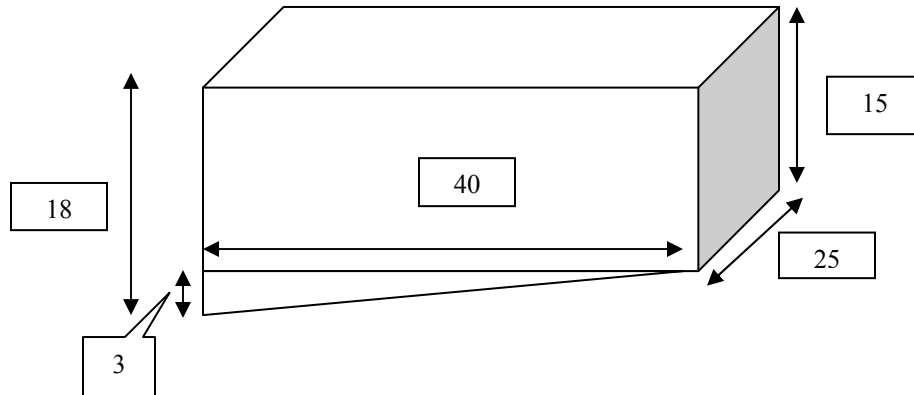


Figure 50: Rectangular clarifier with sloped bottom

The simplest way to approach this problem is to calculate the volume of the basic rectangular portion, 40 ft X 25 ft X 15 ft. Then, add the volume added by the sloped, triangular bottom. The volume of the triangular portion is: $\frac{1}{2} (L \times W \times H)$.

Where, H is just the 3 feet of additional depth.

Volume of rectangular portion gal

$$V \text{ (gal)} = \frac{40 \text{ ft}}{\text{rect.}} \times \frac{25 \text{ ft}}{\text{rect.}} \times \frac{15 \text{ ft}}{\text{rect.}} \times \frac{7.48 \text{ gal}}{\text{ft}^3}$$

$$V \text{ (MG)} = 112,200 \text{ gal}$$

Volume of the triangular portion in MG

$$V \text{ (MG)} = \frac{1}{2} \text{ triangle} \times \frac{40 \text{ ft}}{\text{triangle}} \times \frac{25 \text{ ft}}{\text{triangle}} \times \frac{3 \text{ ft}}{\text{triangle}} \times \frac{7.48 \text{ gal}}{\text{ft}^3}$$

$$V \text{ (MG)} = 11,220 \text{ gal}$$

$$\begin{aligned} \text{Total volume of clarifier} &= 112,400 \text{ gal} + 11,220 \text{ gal} \\ &= 123,620 \text{ gal.} \end{aligned}$$

Circular Clarifier Volume

3. Calculate the volume in gallons of a circular clarifier with a diameter of 60 feet and a sidewall depth of 12 feet. The clarifier has a conical bottom with center depth of 17 feet.

As with the previous problem with a rectangular clarifier with sloped bottom, the easiest solution to this problem is to calculate the volume of the cylinder and the volume of the conical bottom separately, then add the two together.

$$\text{Volume of a cylinder} = \frac{1}{2} \pi r^2 H \text{ (area of the circle X height or depth)}$$

Volume of a cone = $\frac{1}{3} \pi r^2 H$

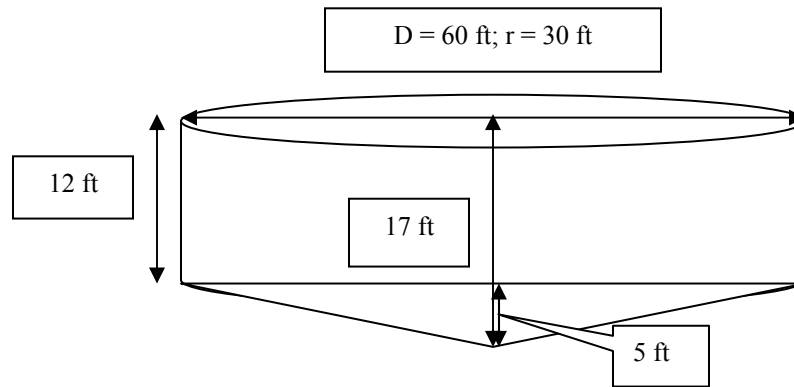


Figure 51: Circular clarifier with conical bottom

$$V \text{ (gal) cylinder} = \frac{1}{2} \times \pi \times \frac{(30 \text{ ft})^2}{2} \times \frac{12 \text{ ft}}{2} \times \frac{7.48 \text{ gal}}{\text{ft}^3}$$

$$V \text{ (gal) cylinder} = \frac{1}{2} \times \pi \times \frac{900 \text{ ft}^2}{2} \times \frac{12 \text{ ft}}{2} \times \frac{7.48 \text{ gal}}{\text{ft}^3}$$

V (gal) cylinder = 40,392 gal.

$$V \text{ (gal) cone} = \frac{1}{3} \times \pi \times \frac{(30 \text{ ft})^2}{3} \times \frac{5 \text{ ft}}{3} \times \frac{7.48 \text{ gal}}{\text{ft}^3}$$

V (gal) cone = 11,220 gal.

Total volume = 40,392 gal + 11,220 gal = 51,612 gal

Detention Time

Detention time, time to fill, and time to empty are all the same calculation

$$\text{Detention time (DT): } \frac{DT}{\text{Flow rate}} = \frac{\text{Volume}}{\text{Flow rate}}$$

Or,

$$DT = \frac{\text{Volume}}{\text{Flow rate}}$$

For the rectangular clarifier example above, calculate the detention time in minutes at a flow rate of 2500 gallons/min.

One must be certain the units of measure are the same for the volume and flow rate. That is, if volume is given in gallons, then the flow rate must be in gallons.

$$\frac{\text{DT min}}{\quad} = \frac{123,620 \text{ gal}}{\quad} \times \frac{\text{min}}{2500 \text{ gal}}$$

$$\text{DT min} = 49 \text{ min}$$

4. Calculate the detention time in minutes for the above circular clarifier if the flow rate is 2 cfs (cubic feet per second)

Make certain the units of measure agree!

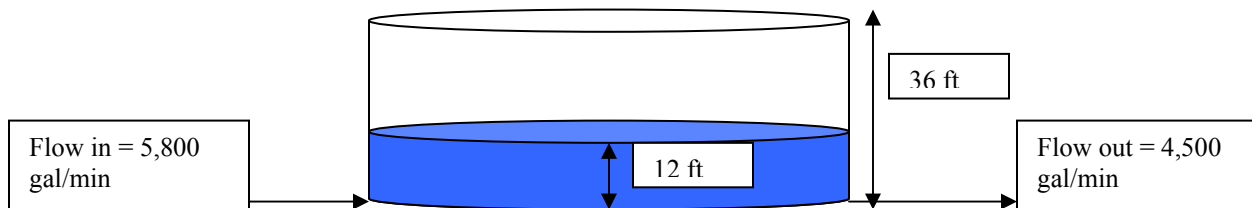
$$\frac{\text{DT min}}{\quad} = \frac{51,612 \text{ gal}}{\quad} \times \frac{1 \text{ ft}^3}{7.48 \text{ gal}} \times \frac{\text{sec}}{2 \text{ ft}^3} \times \frac{\text{min}}{60 \text{ sec}}$$

$$\text{DT min} = 58 \text{ min.}$$

A ground-level storage tank with flat bottom, 200 feet in diameter and 38 feet tall with a maximum water level of 36 feet, is 1/3 full and has an outflow of 4,500 gal/min.

Simultaneously, in flow to the tank is 5,800 gal/min. How long will the tank take to fill in minutes?

This problem is best visualized if broken into parts. It helps a great deal to make a sketch and label it.



First, calculate the total volume of the tank. If the diameter is 200 ft, then the tank radius is 100ft.

$$\text{V (gal) cylinder} = \frac{1}{2} \times \pi \times (100 \text{ ft})^2 \times 36 \text{ ft} \times \frac{7.48 \text{ gal}}{\text{ft}^3}$$

$$\text{Vol. gal} = 8,455,392 \text{ gallons}$$

But, the problem indicates the tank has only 12 feet of water so,
Vol. currently in the tank

$$\text{Vol. currently in tank, gal} = \frac{8,455,392 \text{ gal}}{\quad} \times \frac{12}{36}$$

Vol. in tank = 2,818,464 gal in tank. **That means the tank needs 5,636,928 gallons to fill.** (8,455,392 gal - 2,818,464 gal = 5,636,928 gal)

Now, the demand on the tank is 4500 gallons/min while it is filling at a rate of 5,800 gallons. Thus, the NET fill rate is 1,300 gallons/min (5,800 gal/min – 4,500 gal/min = 1,300 gal/min)

$$\text{Time to fill, min} = \frac{5,636,928 \text{ gal}}{1,300 \text{ gal/min}} \times \frac{\text{min}}{1,300 \text{ gal}}$$

Time to fill, min = 4,336 min. Or,

$$\text{Time to fill in hrs} = \frac{4,336 \text{ min}}{60 \text{ min/hr}} \times \frac{1 \text{ hr}}{60 \text{ min}}$$

Time in hours = 72.3 hrs

Surface Overflow Rate (Surface Loading Rate) and Weir Overflow Rate

Surface overflow (loading) rate is calculated by dividing the average daily flow by the surface area of the clarifier typically with final units of gallons per day per square foot. The **weir overflow (loading) rate** is the average daily flow rate divided by the number of lineal feet of weir with final units of gallons per day per foot.

5. Calculate the surface overflow and weir overflow rates for a basin 40 ft X 25 ft X 12 ft at a flow of 1000 gallons/min if the weir is 90% of the width of the clarifier.

$$\text{Surface Overflow Rate, Gal/da/ft}^2 = \frac{1000 \text{ gal}}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{1}{40 \text{ ft} \times 25 \text{ ft}}$$

Surface Overflow Rate, Gal/da/ft² = 1,400 gal/da/ft²

6. Calculate the weir overflow rate. Since the weir length is 90% of the basin width, the weir length = 25 ft X 0.90 = 22.5 ft.

$$\text{Weir Overflow Rate, Gal/da/ft}^2 = \frac{1000 \text{ gal}}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{1}{22.5}$$

Weir Overflow Rate, Gal/da/ft² = 64,000 gal/day/ft

Chemical Feed Calculations

Most chemical feed calculations can be solved with a single, easy to use equation. To find concentration in mg/l or ppm (parts per million – one part by weight to a million parts by weight):

$$\text{mg/l or ppm} = \frac{\# \text{ of chemical}}{8.34 \times \text{MGD}}$$

Where: MGD is million gallons per day and 8.34 is the weight of a gallon of water. Thus the denominator, 8.34 X MGD simply converts the denominator to units of pounds per day instead of million gallons. Most chemical feed problems are weight to weight concentration calculations.

Another way to express the calculation is:

$$\frac{\text{mg/l or ppm}}{\text{day}} = \frac{\# \text{ of chemical}}{\text{day}} \times \frac{1 \text{ gallon of water}}{8.34\#} \times \frac{1 \text{ day}}{\text{MG}}$$

Parts per million – ppm, and mg/l often are used interchangeably. They are equivalent only when working with solutions with the specific gravity (density) of water at 4°C. For most ordinary purposes when working with water within normal ambient ranges, one can assume the specific gravity of water at 4°C. (Specific gravity of water is 1 or density of 1g/1cc. And at 4°C, 1cc of water is equal to 1 ml of water. In English units the density is 8.34 #/gallon)

If a solution is being used that is not the specific gravity of water, ppm and mg/l are not interchangeable.

7. Show that for water at 4°C, 1 ppm and 1 mg/l are equivalent:

$$\frac{1 \text{ mg}}{\text{liter}} = \frac{1 \text{ mg}}{1 \text{ liter}} \times \frac{1 \text{ liter}}{1,000 \text{ ml}} \times \frac{1 \text{ ml}}{1 \text{ cc}} \times \frac{1 \text{ cc}}{1 \text{ g}} \times \frac{1 \text{ g}}{1,000 \text{ mg}}$$

$$\frac{1 \text{ mg}}{\text{liter}} = \frac{1}{1} \times \frac{1}{1,000} \times \frac{1}{1} \times \frac{1}{1} \times \frac{1}{1,000}$$

$$\frac{1 \text{ mg}}{\text{liter}} = \frac{1 \text{ parts}}{1,000,000 \text{ parts}} = \frac{1 \text{ ppm}}{1,000,000 \text{ parts}}$$

8. Calculate the chemical dosage in mg/l if 2,000 pounds of aluminum sulfate (alum) are added to 20 million gallons of water per day.

$$\frac{\text{mg/l or ppm}}{\text{day}} = \frac{\# \text{ of chemical}}{\text{day}} \times \frac{1 \text{ gallon of water}}{8.34\#} \times \frac{1 \text{ day}}{\text{MG water}}$$

$$\frac{\text{mg/l (ppm) Cl}_2}{\text{day}} = \frac{2000\# \text{ alum}}{\text{day}} \times \frac{1 \text{ gallon of water}}{8.34\#} \times \frac{1 \text{ day}}{20 \text{ MG water}}$$

$$\frac{\text{mg/l (ppm) Cl}_2}{\text{day}} = \frac{2000 \text{ alum}}{\text{day}} \times \frac{1}{8.34} \times \frac{1 \text{ day}}{20 \text{ M}}$$

$$\frac{\text{mg/l (ppm) Cl}_2}{\text{day}} = \frac{11.99 \text{ parts alum}}{1000,000} = \frac{11.99 \text{ mg alum}}{1}$$

Of course the equation can be modified to calculate the pounds of chemical necessary per day to achieve a particular concentration:

$$\frac{\# \text{ chemical}}{\text{day}} = \frac{\text{Parts}}{\text{M parts}} \times \frac{8.34 \#}{\text{gallon}} \times \frac{\text{MG}}{\text{day}}$$

9. How many pounds per day of lime, Ca(OH)_2 must be fed to maintain a concentration of 10 mg/l (ppm) at a flow rate of 4 MGD.

$$\frac{\# \text{ Ca(OH)}_2}{\text{day}} = \frac{10 \text{ parts}}{\text{M parts}} \times \frac{8.34\#}{1 \text{ gallon}} \times \frac{5 \text{ MG}}{\text{day}}$$

$$\frac{\# \text{ Ca(OH)}_2}{\text{day}} = \frac{2}{\text{day}} \times \frac{8.34\#}{1} \times \frac{4}{\text{day}}$$

$$\frac{\# \text{ Ca(OH)}_2}{\text{day}} = \frac{417 \#}{\text{day}}$$

10. How many pounds per day of ferric sulfate (ferric) should be fed to maintain a concentration of 40 mg/l at a flow of 10 MGD.

$$\frac{\# \text{ ferric}}{\text{day}} = \frac{40 \text{ parts}}{\text{M parts}} \times \frac{8.34\#}{1 \text{ gallon of water}} \times \frac{10 \text{ MG}}{\text{day}}$$

$$\frac{\# \text{ ferric}}{\text{day}} = \frac{40}{1} \times \frac{8.34\#}{1} \times \frac{10}{\text{day}}$$

$$\frac{\# \text{ ferric}}{\text{day}} = \frac{3,336 \#}{\text{day}}$$

Example: A concentration of 0.2 mg/l of a polymer coagulant aid is required for a given treatment objective. The polymer stock solution is 1%. Calculate the ml/min of the stock solution the polymer pump must deliver if the water flow rate is 5 MGD.

1% of a million parts is 10,000 parts per million parts or 10,000 mg/l
(if one assumes the solution has the density of water)

$$\frac{\text{ml polymer}}{\text{min}} = \frac{0.2 \text{ mg}}{1} \times \frac{1}{10,000 \text{ mg}} \times \frac{5 \text{ MG}}{\text{day}} \times \frac{3780 \text{ ml}}{\text{gal}} \times \frac{1 \text{ day}}{24 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}}$$

$$\frac{\text{ml polymer}}{\text{min}} = \frac{0.2 \text{ mg}}{1} \times \frac{1}{10,000 \text{ mg}} \times \frac{5 \text{ MG}}{\text{day}} \times \frac{3780 \text{ ml}}{\text{gal}} \times \frac{1 \text{ day}}{24 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}}$$

$$\frac{\text{ml polymer}}{\text{min}} = \frac{262.5 \text{ ml}}{\text{min}}$$

Alkalinity Requirement for Aluminum and Iron Coagulants

For aluminum sulfate, if one assumes the majority of the alkalinity is available as calcium bicarbonate, then:



One Mole of hydrated aluminum sulfate (alum) reacts with 3 moles of calcium hydrogen carbonate (calcium bicarbonate).

One mole of alum = 621 mg; one mole of calcium bicarbonate = 342 mg; and, one mole of calcium carbonate (CaCO_3) = 100 mg.

Since one typically expresses alkalinity as CaCO_3 :

$$\text{One mole Ca}(\text{HCO}_3)_2 \text{ as CaCO}_3 = 342 \text{ mg Ca}(\text{HCO}_3)_2 \times \frac{100 \text{ mg CaCO}_3}{342 \text{ mg Ca}(\text{HCO}_3)_2}$$

One mole $\text{Ca}(\text{HCO}_3)_2$ as $\text{CaCO}_3 = 100 \text{ mg}$

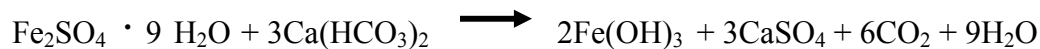
So, 621 mg (1 mole) of alum reacts with 300 mg of $\text{Ca}(\text{HCO}_3)_2$ as CaCO_3 .

Thus the alkalinity required is:

$$\frac{\text{moles of alkalinity}}{1 \text{ mole of alum}} = \frac{3 \text{ moles of } \text{Ca}(\text{HCO}_3)_2 \text{ as } \text{CaCO}_3}{\text{Al}_2(\text{SO}_4)_3 \cdot 14 \text{ H}_2\text{O}} = \frac{300 \text{ mg}}{621 \text{ mg}} = \frac{0.49 \text{ moles of alkalinity}}{1 \text{ mole of alum}}$$

Similarly:

Ferric Sulfate (1 mole = 272 mg):



$$\frac{\text{moles of alkalinity}}{1 \text{ mole of Ferric Sulfate}} = \frac{3 \text{ moles of } \text{Ca}(\text{HCO}_3)_2 \text{ as } \text{CaCO}_3}{\text{Fe}_2(\text{SO}_4)_3} = \frac{300 \text{ mg}}{562 \text{ mg}} = \frac{0.53 \text{ moles of alkalinity}}{1 \text{ mole of Ferric Sulfate}}$$

And for ferric chloride (1 mole = 325 mg):



$$\frac{\text{moles of alkalinity}}{\text{mole of Ferric Sulfate}} = \frac{3 \text{ moles of } \text{Ca}(\text{HCO}_3)_2 \text{ as } \text{CaCO}_3}{2 \text{ moles } \text{FeCl}_3} = \frac{300 \text{ mg}}{325 \text{ mg}} = \frac{0.92 \text{ moles of alkalinity}}{1 \text{ mole of Ferric chloride}}$$

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