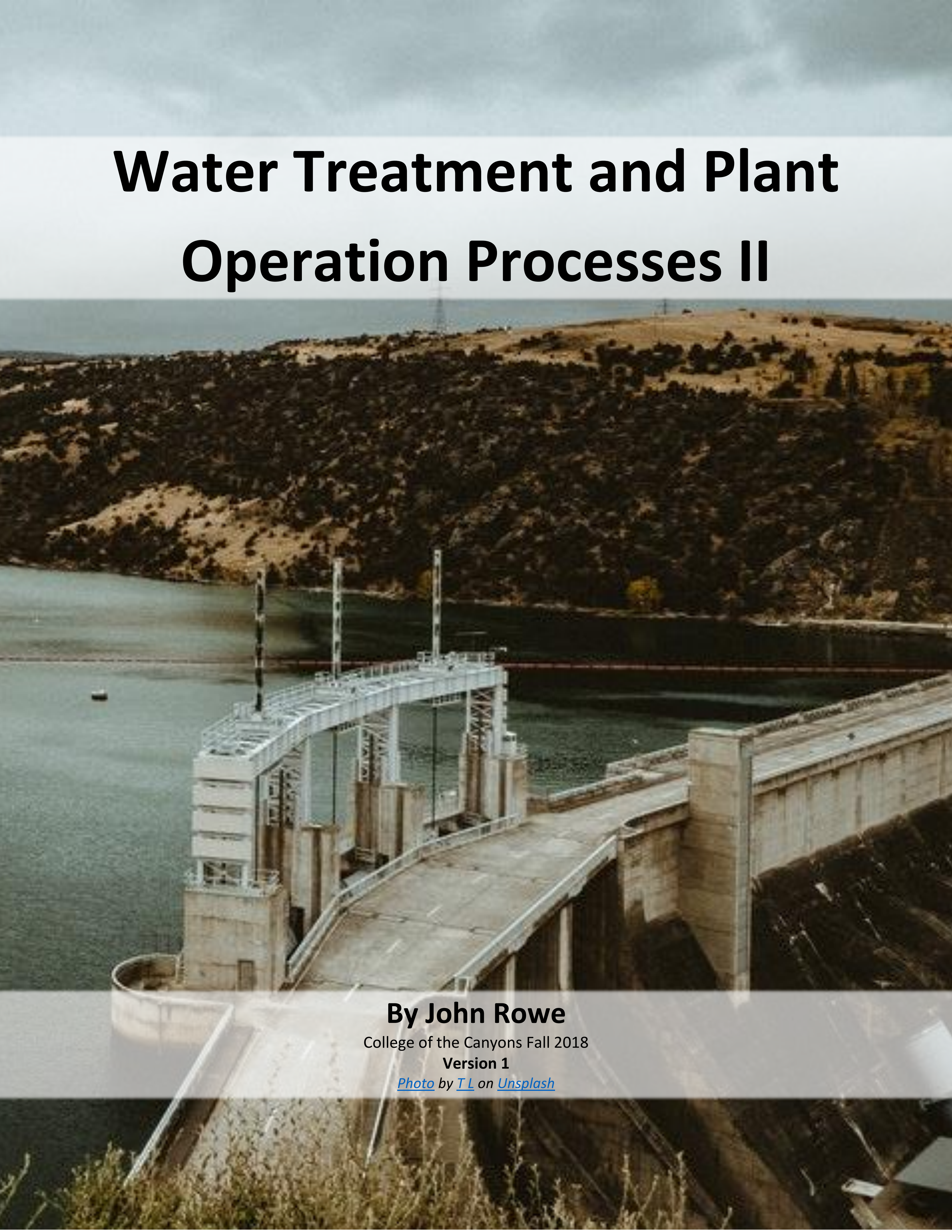

Water Treatment and Plant Operation Processes II

By John Rowe

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Photo by T L on Unsplash

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Water Treatment Objectives

The basic objective in the operation of drinking water treatment plants is to produce a drinking water that is safe and aesthetically pleasing at a reasonable cost with respect to capital as well as operation and maintenance.

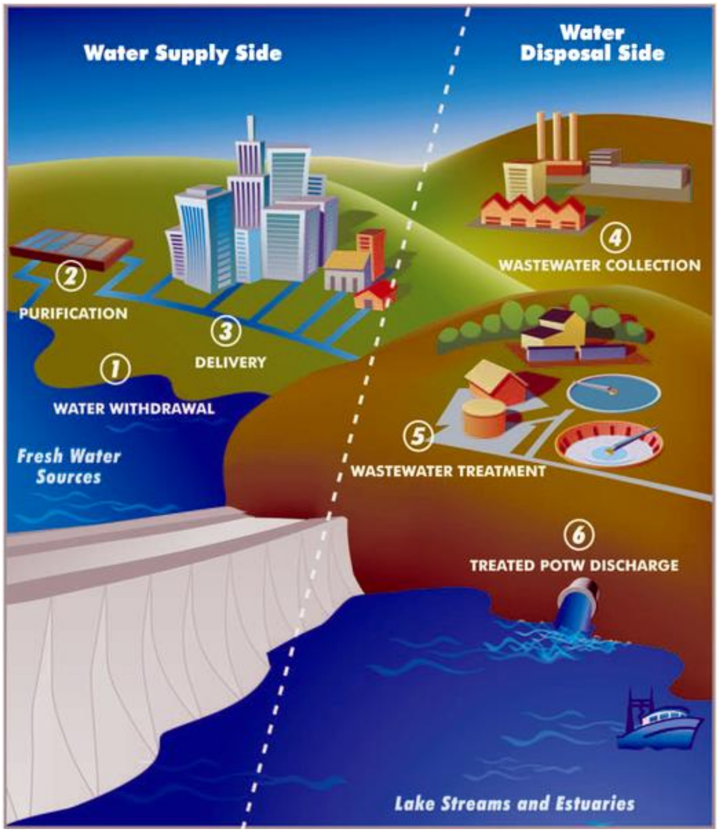

Figure 1-1 – Image by the EPA is in the public domain

From a public health perspective, production of a safe drinking water is one that is free of harmful microorganisms and toxic materials, and this object is the first priority. It is also important to produce a high-quality, water that appeals to the consumer. Generally, the water must be clear, free of turbidity, colorless, and free of objectionable tastes and odors.

Consumers also show a preference for water supplies that do not stain plumbing fixtures and clothes, do not corrode plumbing fixtures and piping, and do not leave scale deposits or spot glassware.

Consumer sensitivity to the environment has significantly increased in recent years. With regard to water quality, consumer demands have never been greater. In some instances, consumers have substituted bottled water to meet specific needs, namely, for drinking water and cooking purposes.

Design engineers select water treatment processes on the basis of the type of water source, source water quality, and the desired finished water quality which is established by drinking water regulations and consumer desires.

Water has many important uses and each requires a specific level of water quality. Delivering safe and pleasant drinking water to customers should be the operator's primary concern. Drinking water should be acceptable to domestic and commercial water users. Some industries, such as food and drug processors and the electronics industry, require high quality water. Many industries locate where the local water supply meets their specific needs, and other industries maintain a water treatment facility on-site to produce water suitable for their needs.

The Safe Drinking Water Act

Regulations concerning public water systems are focused on the production of water that is safe for people to drink. These regulations continue to change in order to address new information concerning the health effects of different substances that may be in drinking water. Operators are urged to develop close working relationships with local regulatory agencies in order to keep informed of the changes in regulations and requirements. An excellent source of up-to the-minute information concerning drinking water regulations is the US Environmental Protection Agency's toll-free Safe Drinking Water Hotline at (800)426-4791.

In 1974, the Safe Drinking Water Act was signed into law, giving the federal government, through the EPA, the authority to:

1. Set national standards regulating the levels of contaminants in drinking water
2. Require public water systems to monitor and report their levels of identified contaminates
3. Establish uniform guidelines specifying the acceptable treatment technologies for cleansing drinking water of unsafe levels of pollutants

The EPA sets two kinds of drinking water standards. Primary regulations establish maximum contaminant levels based on the health significance of the contaminants while the secondary standards are established based on aesthetic considerations and are a state option.

While the Safe Drinking Water Act (SDWA) gives the EPA responsibility for developing drinking water regulations, it gives state regulatory agencies the opportunity to assume primary responsibility for enforcing the regulations.

Implementation of the SDWA has improved basic drinking water purity across the nation. However, the EPA surveys of surface water and groundwater indicate the presence of synthetic organic chemicals in the nation's water sources, with a small percentage at the levels of concern. In addition, research studies suggest that some naturally occurring contaminants may pose even greater risks to human health than the synthetic contaminants. Further, concern is growing concerning microbial and radon contamination.

In the years following passage of the SDWA, Congress felt that the EPA was slow to regulate contaminants and states were lax in enforcing the law. Consequently, in 1986 and again in 1996, Congress enacted amendments designed to strengthen the 1974 SDWA. The amendments set deadlines for the establishment of maximum contaminant levels, placed greater emphasis on enforcement, authorized penalties for tampering with drinking water supplies, mandated the complete elimination of lead from drinking water, and placed considerable emphasis on the protection of underground drinking water sources.

In 1996, the president signed new SDWA amendments into law. These amendments changed the existing SDWA, created new programs, and included more than $12-billion in federal funds for drinking water programs and activities.

Topics covered in the amendments include:

- Arsenic research
- Assistance for water infrastructure and watersheds
- Assistance to low income communities located along the US Mexican border
- Backwash water recycling
- Bottled water
- Capacity development
- Consumer awareness
- Contaminant selection and standard setting authority
- Definitions of water systems
- Disinfectants and disinfection byproducts
- Drinking water studies and research
- Effective date of regulations
- Enforcement
- Environmental finance centers and capacity clearinghouse
- Estrogenic substances screening program
- Conditions that could qualify a water system for an exemption
- Groundwater disinfection
- Groundwater protection programs
- Lead plumbing and pipes
- Monitoring and information gathering
- Monitoring relief
- Monitoring for unregulated contaminants
- Occurrence of contaminants in drinking water database
- Operator certification
- Primacy
- Public notification

- Drinking water regulations for radon
- Review of National Primary Drinking Water Regulation (NPDWR)
- Risk assessment application to establishing NPDWRs
- Small systems technical assistance program
- Source water quality assessment and petition programs
- State revolving loan fund
- Authorization to promulgate an NPSWR for sulfate
- Surface Water Treatment Rule (SWTR) compliance
- Variance treatment technologies
- Water conservation
- Waterborne disease study and training

Because not all contaminants can be controlled through treatment processes, source protection is an important component of producing a high-quality drinking water.

Water Treatment Plants

Communities have established water treatment plants to produce safe and pleasant drinking water that meets SWDA requirements. This water must be free of disease-causing organisms and toxic substances. Also, the water should not have a disagreeable taste, odor, or appearance.

A water treatment plant takes raw water from a source, such as a stream or lake, groundwater, or reclaimed water, and passes the water through a series of interrelated treatment processes; if the quality of the raw water changes or any process fails to do its intended job, the downstream processes are affected. The raw water flows through tanks or basins where chemicals are added and mixed with it. Then the water slowly flows through larger tanks that allow the heavier suspended solids to settle out. Any remaining solids are removed by filtration and the water is disinfected. The size of a water treatment plant as well as the number and specific types of processes it uses depends on several factors:

1. Raw water impurities
2. Water quality standards
3. Water demand by population served
4. Fire protection
5. Cost considerations.

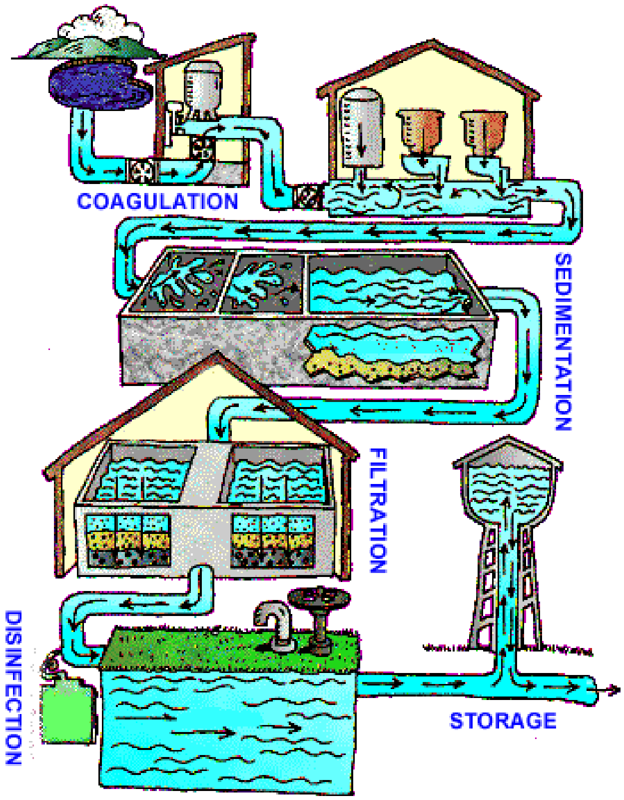

Figure 1-2 – Image by the EPA is in the public domain

Treatment Process Changes

To maintain adequate clear well and distribution system water storage levels, raw or source water flow changes may be required. Raw water flow changes should take into account the travel or detention time between the source of supply and the treatment plant.

When storage demands change and require adjustments in the flow of water through a plant, the operator may also be required to perform the following functions:

1. Adjust chemical feed rates
2. Change filtration rates
3. Perform jar tests
4. Observe floc formation and floc settling characteristics
5. Monitor process performance
6. Collect process water quality samples
7. Visually inspect overall process conditions

Some of these changes may occur automatically if the plant has flow-paced chemical feeders. However, changes in chemical feed rates are required when using manually operated chemical feeders because they are generally set to feed a specific amount of chemical, and this amount is dependent on the rate of flow.

Filters are usually operated at a constant production rate. Automatic control systems typically maintain uniform flow rates, but the number of filters in service can be changed by starting or stopping individual filter units to meet changing needs.

The unit treatment processes, such as coagulation, flocculation, and sedimentation, is designed to operate over a broad range of flow rates. However, in some instances, major flow changes may require adding or removing treatment processes from service.

Chemical Use and Handling

A wide variety of chemicals are used in water treatment plants in the production of safe and palatable drinking water. They play a crucial role in controlling process performance and producing a high-quality water. Chemicals are used in the following aspects of water treatment:

1. Clarification (turbidity reduction)
2. Disinfection
3. Taste and odor control
4. Algae control
5. Corrosion/scaling control
6. Water softening
7. Fluoridation

The American Water Works Association (AWWA) has developed standards for many of the chemicals, which help to ensure that only quality chemicals are used in water treatment. These standards should be referred to when ordering treatment chemicals (see AWWAQ Standards, Section B-Treatment, www.awwa.org).

The initial selection of specific chemicals and anticipated feed rates for a given application are frequently determined by pilot-plant testing of the specific source water. Pilot-plant test are usually performed by the water treatment plant designer by constructing a small scale treatment plant at or near the source of supply. Pilot tests provide the designer, as well as the treatment plant operator, with valuable information on the treatability of a given source of supply over a broad range of water quality conditions.

Operators should be thoroughly familiar with the types of chemicals used in water treatment, specific chemical selection and applications, evaluation methods for determining performance, and safe storage and handling techniques. All chemicals are potentially dangerous, and all necessary precautions must be taken before handling any chemical. All containers, no matter what the use, should bear precautionary labeling.

A Safety Data Sheet (SDS) is the best source of information concerning dangerous chemicals. No chemical should be received, stored, or handled until essential safety information is provided to those individuals who will come into contact with the substance. Among other informational items, the SDS will provide:

1. Identification of the product and the manufacturer or distributor
2. Identification of all hazards regarding the chemical
3. Composition/information on ingredients
4. First-aid measures including important symptoms/effects and required treatment
5. Fire-fighting measures including suitable extinguishing techniques and equipment and chemical hazards from fire
6. Accidental release measures listing emergency procedures, protective equipment, and proper methods of containment and cleanup
7. Handling and storage precautions, including incompatibilities
8. Exposure controls/personal protection including exposure and threshold limits and personal protective equipment
9. Stability and reactivity, including possible hazardous reactions
10. Toxic effects on living organisms including routes of exposure, as well as related symptoms, acute and chronic effects, and numerical measures of toxicity

Remember, do not work with a chemical unless the hazards involved with its usage are understood and unless the necessary protective equipment is available. Contact local safety regulatory agencies concerning specific chemicals if any doubt exists concerning safe procedures.

Coagulation and Flocculation

Particulate impurities in water result from land erosion, dissolved minerals, and the decay of plant material. Additional impurities are added by airborne contamination, industrial discharges, and by animal wastes. Surface water sources and reclaimed water, polluted by people and nature, are likely to contain suspended and dissolved organic and inorganic material, as well as biological forms such as bacteria and plankton. With few exceptions, this water requires treatment to remove particulate impurities and color before it is distributed to the consumer.

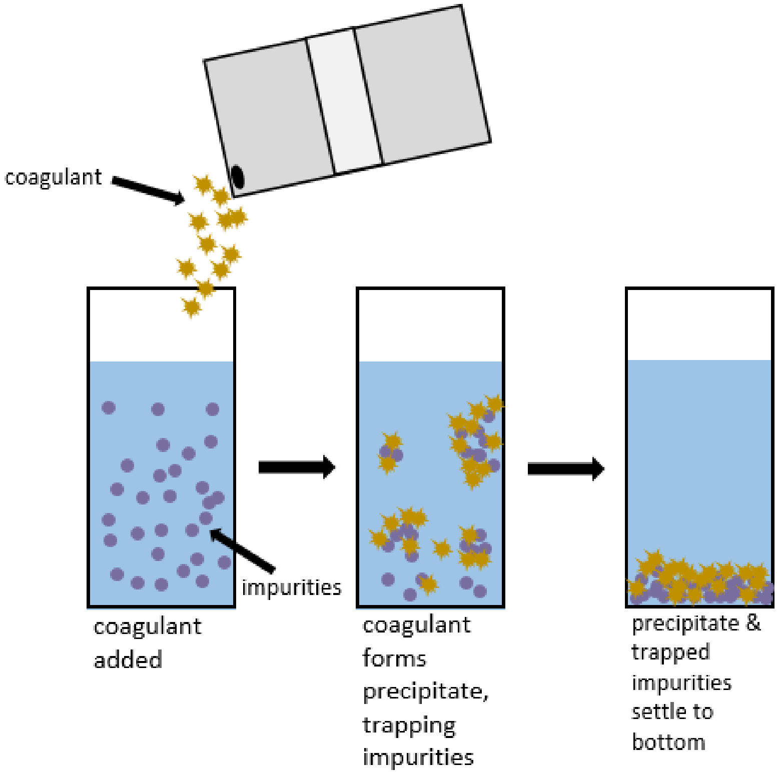

Figure 1-3 – Image by COC OER is licensed under CC BY

Coagulation

The term coagulation describes the effect produced when certain chemicals are added to raw water containing slowly settling or nonsettleable particles. The small particles begin to form larger or heavier floc, which is removed by sedimentation and filtration.

The mixing of the coagulant chemical and the raw water to be treated is commonly referred to as flash mixing. The primary purpose of the flash-mix process is to rapidly mix and equally distribute the coagulant chemical throughout the water column. The entire process occurs in a very short time (several seconds), and the first results are the formation of very small particles.

Coagulants

In practice, chemical coagulants are referred to as primary coagulants or as coagulant aids. Primary coagulants neutralize the electrical charges of the particles, which cause them to begin to clump together. The purpose of coagulant aids is to add density to slow-settling flocs and add toughness so the floc will not break up in the processes that follow.

Metallic salts like aluminum sulfate, ferric sulfate, ferrous sulfate, and synthetic organic polymers are commonly used as coagulation chemicals in water treatment, because they are effective, relatively low in cost, available, and easy to handle, store, and apply.

When metallic salts, such as aluminum sulfate or ferric sulfate, are added to water, a series of reactions occur with the water and with other ions in the water. Sufficient chemical quantities must be added to the water to exceed the solubility limit of the metal hydroxide, resulting in the formation of a precipitate (floc). The resulting floc formed will then adsorb on particles (turbidity) in the water.

The synthetic organic polymers used in water treatment consist of long chains of small subunits, called monomers (which is a molecule group). The polymer chains can be linear or branched structures, ranging in length from a fraction of a micron to 10 microns. The total number of monomers in a synthetic polymer can be varied to produce materials of different molecular weights, which vary from about 100 to 10,000,000. Cationic polymers have a positive electrical charge, anionic polymers have a negative charge, and nonionic polymers have no electrical charge.

The polymers normally used in water treatment contain ionizable groups on the monomeric units and are referred to as polyelectrolytes. Polymers with positively charged groups on the monomeric units are referred to as cationic polyelectrolytes, while polymers with negatively charged particles are called anionic polyelectrolytes. Polymers without ionizable groups are referred to as nonionic polymers.

Cationic polymers have the ability to adsorb on negatively charged particles, turbidity, and neutralize their charge. They can also form an interparticle bridge that collects the particles. Anionic and nonionic polymers also form interparticle bridges, which aid in collecting and removing particles from water.

While alum is perhaps the most commonly used coagulant chemical, cationic polymers are used in the water treatment field as a primary coagulant and as a coagulant aid. Anionic and nonionic polymers have also proven to be effective in certain applications as coagulant aids and filter aids.

One of the problems that will confront the water treatment plant operator in the selection of an appropriate polymer is that a tremendous number of polymers are available in the marketplace, and no universal evaluation method has been adopted for polymer selection. The operator should use caution in the selection and use of polymers and should take note of these considerations:

1. Polymer overdosing will adversely affect coagulation efficiency and when used as a filter aid, overdosing can result in accelerated head loss buildup.
2. Not all water supplies can be treated with equal success.
3. Some polymers lose their effectiveness when used in the presence of a chlorine residual.
4. Some polymers are dosage limited. The operator should obtain the maximum safe dosage that can be applied from the specific chemical manufacturer.

Because universal standards do not exist for the selection and use of organic polymers, the operator should be careful to select those products that have been approved by state and federal regulatory agencies for use in potable water treatment. The chemical supplier should be required to provide written evidence of this approval. Many chemical suppliers have considerable experience in dealing with many types of water and may be able to recommend the best polymer for the situation.

Basic Coagulant Chemistry

The theory of coagulation is complex. Coagulation is a physical and chemical reaction occurring between the alkalinity of the water and the coagulant added to the water, which results in the formation of insoluble flocs.

For a specific coagulant, the pH of the water determines which hydrolysis species predominates after mixing the chemical with the water to be treated. Lower pH values tend to favor positively charged species, which are desirable for reacting with negatively charged colloids and particulates, forming insoluble flocs, and removing impurities from the water.

The best pH for coagulation usually falls in the range of pH 5 to 7. The proper pH range must be maintained because coagulants generally react with the alkalinity in the water. Residual alkalinity in the water serves as a buffer to the system preventing the pH from changing, and alkalinity aids in the complete precipitation of the coagulant chemicals. The amount of alkalinity in the source water is generally not a problem unless the alkalinity is very low. Alkalinity may be increased by the addition of lime or soda ash.

Polymers are generally added in the coagulation process to stimulate or improve the formation of insoluble flocs.

Generally, the operator has no control over the pH and alkalinity of the source water. Hence, evaluation of these water quality indicators may play a major role in selecting the type of chemical coagulants to be used at a particular water treatment plant, or in changing the type of coagulant normally used if significant changes in pH and alkalinity occur in the raw water.

In some instances, the natural alkalinity in the raw water may be too low to produce complete precipitation of alum. In these cases, lime is often added to ensure complete precipitation. Care must be used to keep the pH within the desired range.

Overdosing as well as under-dosing of coagulants can lead to reduced solids removal efficiency. This condition can be corrected by carefully performing jar tests and verifying process performance after making any changes in the operation of the coagulation process.

Effective Mixing

It is desirable to complete the coagulation reaction, mixing of chemicals into the water, in as short of a time as possible. It is preferable to complete the mixing in several seconds because the reaction time is short. For complete coagulation and flocculation to take place, the coagulant must make contact with the suspended particles in the water. This process is accomplished by flash mixing.

Several methods can be used to mix the chemicals with the water to be treated.

1. Hydraulic mixing using flow energy in the system
2. Mechanical mixing
3. Diffusers and grid systems
4. Pumped blenders

Hydraulic mixing with baffles or throttling valves works well in systems that have sufficient water velocity to cause turbulence in the water being treated. The turbulence in the flowing water mixes the chemicals with the water.

Mechanical mixers like paddles, turbines, and propellers are frequently used in coagulation facilities. Mechanical mixers are versatile and reliable; however, they use the greatest amount of electric energy for mixing the coagulant with the water being treated.

Pumped blenders have also been used for mixing in coagulation facilities. In this system, the coagulant is added directly to the water being treated through a diffuser in a pipe. This system can provide rapid dispersion of the coagulant and does not create any significant head loss in the system. Electric energy consumption is considerably less than that of a comparable mechanical mixer.

Mixing of chemical coagulants can be satisfactorily accomplished in a coagulation basin, a special rectangular tank with mixing devices. Mixing may also occur in the influent channel or a pipeline to the flocculation basin if the flow velocity is high enough to produce the necessary turbulence. The shape of the basin is part of the flash-mixing system design as well.

Flocculation

Flocculation is a slow stirring process that causes the gathering together of small, coagulated particles into larger, settleable particles. The flocculation process provides contact between particles to promote their gathering together into floc for ease of removal by sedimentation and filtration. Generally, these contacts or collisions between particles result from gentile stirring created by a mechanical or hydraulic means of mixing.

An efficient flocculation process involves the selection of the right stirring time, detention time, the proper stirring intensity, a properly shaped basin for uniform mixing, and mechanical equipment or other means of creating the stirring action. Insufficient mixing will result in ineffective collisions and poor floc formation. Excessive mixing may tear apart the flocculated particles after they have clumped together.

Detention Time

Detention time is usually not a critical factor in the coagulation or flash mixing process if the chemical coagulants are satisfactorily dispersed into the water being treated and mixed for at least several seconds. Detention time is required for the necessary chemical reactions to take place. Some operators have been able to reduce coagulant dosages by increasing the amount of detention time between the point of the addition of the coagulant and the flocculation basins. In the flocculation process, however, stirring, or detention, time is quite important. The minimum detention time recommended for flocculation ranges from about 5 to 20 minutes for direct filtration systems and up to 30 minutes for conventional filtration. Also the size and shape of the flocculation facility influences the detention time needed for optimum floc development.

Types of Flocculators

Two types of mechanical flocculators are commonly installed, horizontal paddle wheels and vertical flocculators. They provide satisfactory performance; however, the vertical flocculators usually require less maintenance because they eliminate submerged bearings and packing. Vertical flocculators can be of the propeller, paddle, or turbines types.

Some flocculation can also be accomplished by the turbulence resulting from the roughness in conduits or channels, or by the dissipated energy for head losses associated with weirs, baffles, and orifices used to create turbulence, which will mix chemicals with the water. Weirs and baffles are boards or plates that water flows over while orifices are holes in walls that water flows through. Generally, these methods find only limited use because of the disadvantages attributed to a localized distribution of turbulence, inadequate detention time, and widely variable turbulence resulting from flow fluctuations.

Flocculation Basins

The shapes of flocculation basins are determined partially by the flocculator selected and for the basin’s compatibility with adjoining structure like sedimentation basins. Flocculation basins for horizontal flocculators are generally rectangular in shape, while basins for vertical flocculators are nearly square. The depth of flocculation basins is usually about the same as the sedimentation basins.

The best flocculation is usually achieved in a compartmentalized basin. The compartments are separated by baffles to prevent short-circuiting of the water being treated. The turbulence can be reduced gradually by reducing the speed of the mixers in each succeeding tank or by reducing the surface area of the paddles. This design is called tapered energy mixing. The reason for reducing the speed of the stirrers is to prevent breaking apart the large floc particles that have already formed. If the floc is broken up, then the resulting floc will not settle and will overload the filters.

The solids-contact process, upflow clarifiers, is used in some water treatment plants to improve the overall solids removal process. These units combine the coagulation, flocculation, and sedimentation processes.

Interaction with Other Treatment Processes

Coagulation and flocculation processes are required to precondition or prepare nonsettleable particles present in raw water for removal by sedimentation and filtration. Small particles, without proper coagulation and flocculation, are too light to settle out of the water column and will not be large enough to be trapped during filtration. It is convenient to consider coagulation-flocculation as one treatment process.

Because the purpose of coagulation-flocculation is to promote particulate removal, the effectiveness of the sedimentation and filtration processes, as well as overall plant performance, depends upon successful coagulation-flocculation. Disinfection of the water can also be affected by poor coagulation-flocculation performance. Bacteria and other disease-causing organisms can be bound up in suspended particles; and thereby, shielded from disinfection. If the solids removal processes are inadequate before final disinfection, especially filtration, then turbidity and disinfection will be inadequate. Effective coagulation-flocculation promotes the removal of natural organic compounds. Removal of these compounds reduces the formation of trihalomethanes following the use of chlorine for disinfection.

Process Control for Coagulation/Flocculation

The theory behind the chemical reactions and the formation of floc associated with the coagulation-flocculation process is complex. From a practical viewpoint, the operator of the water treatment plant must be able to measure and control the performance of these processes on a continuous basis.

The most important consideration in coagulation-flocculation process control is the selection of the proper type and amount of coagulant chemicals to be added to the water being treated. This determination is commonly made in the laboratory with the aid of a jar testing apparatus. When selecting a particular type of coagulant chemical, consideration must be given to the quantity and solids content of the sludge created and the means of ultimate disposal. Jar tests should be run at least daily and more often when the quality of the raw water changes. Changes in the raw water may require changes in the amount of chemical or type of chemical.

Normal Operation

Coagulation-flocculation is a pretreatment process for the sedimentation and filtration processes. The suspended solids are mostly removed in the sedimentation basin; and, filtration is the final step in the process of removing solids from the water. The coagulation-flocculation process should be operated and controlled to improve filtration and produce a filtered final water that is low in turbidity.

The measurement of filtered water turbidity periodically using grab samples or continuously using a turbidity meter will give the operator a good indication of the overall process performance. However, the operator cannot rely solely on filtered water turbidity for complete process control. The difficulty in relying on a single water quality indicator, such as turbidity, is that it takes a considerable amount of time to transport the water through the various treatment processes before it is filtered and turbidity measured. Depending on the amount of water being processed, the total transit time through the treatment plant can vary from as few as 2 hours to more than 6 hours. This amount of time means that a change in coagulant dosage at the front end of the plant will not be noticed in the final finished water quality for at least 2 hours, depending of flow conditions. Turbidity, as well as other water quality indicators, such as pH, temperature, chlorine demand, and floc quality, must be monitored throughout the water treatment process so that poor process performance can be spotted early and corrective measure can be taken.

Process control guidelines for a specific plant are often developed to assist the operator in making these determinations. These guidelines incorporate theory, operator experience, practical knowledge of the source water conditions, and known performance characteristics of the treatment facility.

Process Actions

In the normal operation of the coagulation-flocculation process, the operator performs a variety of jobs within the water treatment plant. The number and types of functions that each operator will perform vary considerably depending on the size and type of plant and the number of operators working at the plant. In some facilities operators are required to control almost all process actions as well as perform most routine maintenance activities. Regardless of the plant size, operators should be thoroughly familiar with the routine and special operations and maintenance procedures associated with plant’s treatment processes.

Jobs performed by an operator in the normal operation of the coagulation-flocculation process include:

1. Monitor process performance
2. Evaluate water quality conditions (raw and treated water)
3. Check and adjust process controls and equipment
4. Visually inspect facilities

Monitoring process performance is an ongoing activity. Filtered water turbidity levels are controlled to a great extent by the efficiency of the coagulation-flocculation process. Early detection of a failure is extremely important because considerable time elapses while the water flows through the coagulation, flocculation, sedimentation, and filtration processes.

Process performance can be monitored with the aid of continuous water quality analyzers, which automatically measure a specific water quality indicator such as turbidity. However, reliable and accurate water quality analyzers are expensive and, in certain cases, automated equipment is not readily available for measuring water quality indicators of concern to operators. A combination of techniques must be used by operators to evaluate process performance including visual observations, and periodic laboratory tests to supplement continuous water quality analyzers.

Visual observations and laboratory tests of coagulation-flocculation process performance should be performed on a routine basis. The most common laboratory tests are turbidity, alkalinity, pH, color, temperature, and chlorine demand. The frequency of these observations and tests depends on how much the quality of the source water supply can or does change. In treatment plants where the source water is stored in a large upstream lake or reservoir, the water quality is generally more stable or constant than water taken directly from rivers or streams.

In the case of direct diversions from a stream or river, water quality conditions will vary seasonally as well as daily. In extreme cases such as during heavy runoff periods, hourly changes in water quality can be expected. The appropriate frequency of performing certain tests may be as often as hourly, or perhaps once per 8-hour shift.

Visual checks of the coagulation-flocculation process generally include an observation of the turbulence of the water in the flash-mixing channel or chamber, and close observation of the size and distribution of floc in the flocculation basins. An uneven distribution of floc could be an indication of short-circuiting in the flocculation basin. Floc particles that are too small or too large may not settle properly and could cause trouble during removal in the sedimentation and filtration processes. These observations are frequently supplemented by laboratory evaluations, which are necessary to provide better data.

Floc settling characteristics require laboratory evaluation based on trial and experience methods using jar testing. The speed adjustment of flocculators take into account:

1. Volume of floc to be formed, such as if source water turbidity is low, a small pinpoint floc may be best suited for removal on the filters in direct filtration. Lower flocculator speeds are appropriate in this case. On the other hand, high turbidity source water generally requires near-maximum flocculator speed to produce a readily settleable floc.

2. Visual observations of short-circuiting may indicate flocculator mixing intensity is not sufficient, while floc breakup is an indication that the mixing turbulence is too high for the type of floc formed.
3. Water temperature affects the rate of chemical reactions. These reactions decrease with temperature so that increasing the speed of the flocculator to account for lower water temperatures because higher mixing turbulence is required.

These concepts are not easily measured. Experience and judgment are needed. One of the real limitations in process control is too much reliance on the settled turbidity value. Turbidity gives an indirect measurement of suspended solids concentration, it does not describe particle size, density, volume, or the ability of a particular filter to handle the water being applied to it.

Based on an overall evaluation of process performance, the operator may need to make minor changes in chemical feed dosages, or adjust the speed of the flash mixer or flocculators. These processes are normal actions associated with minor changes in source water quality such as turbidity or temperature fluctuations.

Flash mixers are generally less sensitive to speed adjustments than flocculators because their primary purpose is to disperse chemicals rapidly into the water being treated. This reaction is almost instantaneous.

Process equipment, such as chemical feeders, should be checked regularly to ensure that they are accurately feeding the desired amount of chemical.

The operator should routinely perform a visual inspection of the overall coagulation-flocculation physical facilities. This inspection is part of good housekeeping practices. Leaves, twigs, and other debris can easily buildup in influent channels or in flocculation basins. If ignored, this material can get into other processes where it can foul meters, water quality monitors, pumps, or other mechanical equipment. In some cases, taste and odor problems can develop from microorganisms that can grow in debris and sediment that accumulate in plant facilities.

Detention Times

To calculate the expected detention times in the flash-mix chamber, distribution channel, and flocculation basins, use the dimensions of the basin or pipe to calculate the volume in gallons and divide this volume in gallons by the flow. The calculation will be in the units of time that is used for the flow. These times are important when determining the optimum chemical dosage for the water that is being treated using jar tests. Also, these times are necessary for the desired chemical reactions to occur.

Formulas:

1. To calculate the volume (V) of a rectangular tank or basin in cubic feet,

   V, ft^3 = Length, ft x Width, ft x Depth, ft

2. To calculate the volume of a circular tank or clarifier in cubic feet,

   $V, ft^3 = \pi/4$ x $Diameter^2, ft^2$ x Depth, ft ; the term $\pi/4$ is equal to 0.785

3. Frequently, the volume is gallons, rather than cubic feet,

   V, gal = V, ft^3 x $7.48\ gal/ft^3$

4. To calculate the detention time (t) of any chamber, tank, basin, or clarifier,

   $$t, \text{min.} = \frac{\text{V,gal}}{\text{flow rate,gpd}} \times \frac{\text{d}}{\text{24h}} \times \frac{\text{h}}{\text{60 min}}$$

   or

   t, h = V, gal/flow rate, gal/d x d/24 h

Formulas

To determine the chemical feed rate or flow from a chemical feeder, the amount or volume fed during a known time period must be known. The flow from a chemical feeder can be calculated by knowing the volume pumped from a chemical storage tank and the time period.

$$\text{Flow, GPM} = \frac{\text{Volume Pumped, gal}}{\text{Pumping Time, min}}$$

or

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

Liquid polymer feed rates are often measured in pounds per day. To calculate this feed rate, the strength of the polymer solution as a percent or as milligrams per liter, the specific gravity of the solution, the volume pumped, and the time period must be known.

$$\text{Polymer Feed, lb/day} = \frac{\text{(Polymer Concentration, mg/L)(Vol Pumped, mL)(60 min/hr)(24 hr/day)}}{\text{(Time Pumped, min)(1,000 mL/L)(454 g/lb)}}$$

To determine the actual feed from a dry chemical feeder, the operator must know the pounds of chemical fed and the time period.

$$\text{Chemical Feed, lb/day} = \frac{(\text{Chemical Fed, lb})(60\ \text{min/hr})(24\ \text{hr/day})}{\text{Time, min}}$$

Detention times are calculated by dividing the volume in gallons by the flow in gallons per day. This produces the detention time in days. Multiply by 24 hours per day to obtain the detention time in hours. To convert the detention time from hours to minutes, multiply by 60 minutes per hour. To convert the detention time from hours to minutes, multiple by 60 minutes per hour and minutes to seconds multiple by 60 seconds per minute. Many operators prepare curves of flow versus detention time for the basins in their plants. These curves allow for easy selection of stirring times when performing jar tests.

Jar Testing

The purpose of jar testing is for operators to observe on a small scale how changes in chemicals, chemical doses, dosages, mixing times and other parameters affect the plant's performance. Jar testing consists of collecting a sample to be tested, adding the coagulant or other chemical with rapid mixing, followed by slow-mix flocculation, and then settling with the mixer turned off. After settling, a sample of the supernatant, the clear water on top, is taken to determine water quality parameters such as pH, turbidity, and alkalinity. Because the idea is to test variations, particularly, in chemicals or doses, multiple jars are usually run in parallel.

The goal is to simulate the full-scale plant; however, it is almost impossible to exactly duplicate in a laboratory experiment the flow-through conditions that are occurring in the treatment plant. Nevertheless, the goal is for the jar test results to accurately reflect how the plant will respond to the chemicals being tested. In the jar testing procedure, the mixing time should be the same time as the hydraulic detention time in the plant's flocculation basins. On the other hand, the settling time should not be the same as that in the plant because the particles are settling only a few inches in the jar and many feet in the plant. Choose a settling time in which the jar turbidity is approximately the same as the settling tank effluent. Similarly, the rotations per minute set on the laboratory mixer should not be the same as those settings in the plant. The intensity of the mixing should be the same in each case; however, mixing intensity depends on the amount of mixing power delivered to the water per unit volume. Different kinds of mixers have different relationships between the mixing speed and the power delivered to the water. The relationship for the jar test mixer is different from the plant mixer, so the mixing time will be different as well. Adjust the laboratory mixer speed until the jar test results approximate the plant performance. Finally, because temperature can affect floc formation, jar tests should be run at about the same temperature as the plant water temperature. If this process is inconvenient to do regularly, then try to do a one-time experiment in which the same jar tests are repeated at different temperatures to get an idea of how big an impact the temperature variable has on test results.

Checking the Plant Performance against Jar Tests

It is wise to check the effectiveness of process changes based on jar test results. A process protocol that allows an operator to check the effectiveness of jar testing results is carried out as follows:

1. When the coagulant feeders are working properly collect a sample of well-mixed water from the effluent of the flash-mix chamber to finely adjust process performance. Take the sample to the lab and perform another jar test. First, test the chemical dosage to determine whether the dosage is too high or too low.
2. Fill two jars with the flash-mixed sample. The second jar is a check on the first in case the sample is not representative. Because the chemicals have already been mixed in the sample water, floc will start to form. Be sure the sample stays mixed while pouring off the volumes into the six jars for jar testing.
3. Mix the samples at the speed and time used in the original test.
4. Stop the stirrers. Allow floc to settle for 30 minutes or the time used in the original test. When stirrers are stopped, immediately collect a sample from the flocculation basin effluent. Fill an experimental jar for comparison with other jars.
5. In all of the jars, observe how quickly the floc settles, floc appearance, and turbidity of settled water above the floc. They should be similar.
6. Evaluate the jar test results and make further process adjustments as appropriate.

Evaluation of Plant Performance

One of the best ways to evaluate the performance of the coagulation-flocculation process is to observe the process in the plant. During the walk through the treatment plant, the operator should take some clear plastic beakers. Obtain some water out of each stage of the treatment process. Hold the sample up to a light and look at the clarity of the water between the floc and study the shape and size of the floc. Study the development of the floc from one flocculation chamber to the next and into the sedimentation basin.

1. Observe the floc as it enters the flocculation basins. The floc should be small and well-dispersed throughout the flow. If not, the flash mixer may not be providing effective mixing or he chemical dose or feed rate may be too low.
2. Tiny floc may be an indication that the chemical coagulant dose is too low. A popcorn flake is a desirable floc appearance. If the water has a milky appearance or a bluish tint, the dose is probably too high.
3. As it moves through the flocculation basins, the size of the floc should be increasing. If the floc size increases and then later starts to break up, the mixing intensity of the downstream flocculators may be too high. Try reducing the speed of the flocculators, or increasing the polymer dosage.
4. Look for the floc settling out in the sedimentation basin. If a lot of floc is observed flowing over the laundering weirs, the floc is too light to settle during the detention time produced by the flow rate. By increasing the chemical coagulant dose or adding a

coagulant aid such as a polymer, a heavier, larger floc may be produced. The appearance of fine floc particles washing over the effluent weirs could be an indication of too much coagulant and the dose should be reduced. Regardless of the problem, make only one change at a time and evaluate the results.

5. Bring some beakers with samples from various locations back to the laboratory, let them sit for a while, and then observe the floc settling.
6. Evaluate the filter performance.

Calculating the Amount of Chemical Required

In calculating the amount of a chemical that should be added to the water for treatment, the operator must know the flow in gallons per day and millions of gallons per day. Then using the dosage determined through jar testing the pounds of chemical per day can be calculated.

Lbs per day, chemical = Flow Rate, MGD x dosage, jar testing mg/L x 8.34 lbs/day

Chemical Feeding

The chemical feed rate delivered by chemical feeders must be checked regularly. Jar tests will show the best dosages of chemicals in mg/L. To check on the feed rate delivered by a chemical feeder, measure the volume (in gallons for a liquid chemical feeder) or the weight (in pounds of a dry chemical feeder) delivered during a 24-hour period. The flow during this time period also needs to be known and is recorded in gallons per day or million gallons per day. In this calculation, the operator must know the flow rate in millions of gallons per day and the total amount of chemical feed in pounds.

Chemical used, lbs per day = Flow rate, MGD x chemical dosage, mg/L x 8.34 lbs per gallon

Chemical, lbs/day = (Flow rate, MGD)(chemical dosage, mg/L)(8.34 lbs/gal)

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

Preparation of Chemical Solutions

Polymers are frequently used as coagulant aids. Polymers are often supplied as dry chemicals, and operators usually need a specific solution concentration (mg/L or percent solution). The solution concentration depends on the type of polymer and the polymer’s molecular weight of the polymer. The higher the molecular weight the polymer is the more difficult it is to mix the polymer with dilution water and to feed the resulting solution to the water being treated; in higher molecular weights, the problem is that the solution becomes very viscous. Therefore, anionic and nonionic dry polymers used as coagulant aids are prepared as very dilute solutions. Cationic polymers in the dry form can be prepared at higher solution concentrations because their molecular weights are small.

High molecular weight polymers are difficult to prepare. To be effective, polymer solutions must be the same throughout (homogeneous). They must be thin enough to be accurately measured and pumped to the flash-mix chamber.

When mixing a dry polymer with water, sift or spread the polymer evenly over the surface of the water in the mixing chamber. The polymer should be sucked evenly into the hole (vortex) of the stirred water. This process will ensure that each particle of polymer is set individually. This process will also ensure an even dispersion and prevent the formation of large, sticky balls of polymer that have dry polymer in the middle.

Excessive mixing speeds, mixing time, and the buildup of heat can break down the polymer chain and reduce its effectiveness.

High concentrations of polymer result in very thick, sticky solutions. Prepare and use concentrations of polymers that can be metered and measured easily and pumped accurately to the flash mixer.

Adding dry polymer to water must be done in a closed system or under an efficient dust collector. Polymer powders on floors and walkways become extremely slippery when wet and are very difficult to remove. In the interest of safety, keep polymers off the floor. Use an inert, absorbent material, such as sand or earth, to clean up spills.

When mixing dry or liquid polymers, follow the directions of the polymer supplier. Polymer solutions are usually prepared in batches or as a batch mixture. Often they are stored after mixing in a day tank or an aging tank to allow time for all the powder to dissolve or the solution to become completely mixed.

To prepare a specific percent polymer solution, use this formula,

$$\text{Polymer, \%} = \frac{\text{Dry Polymer, lbs} \times 100\%}{\text{Dry Polymer, lbs} + \text{Water, lbs}}$$

$$\text{Dry Polymer, lbs} = \frac{\text{Water, lbs}}{\dfrac{100\%}{\text{Polymer, \%}} - 1.0}$$

$$\text{Water, lbs} = \frac{\text{Dry Polymer, lbs} \times 100\%}{\text{Polymer, \%}} - \text{Dry Polymer, lbs}$$

$$\text{Water, gal} = \text{Water, lbs} \times \frac{\text{gal}}{8.34\ \text{lb}}$$

When working with liquid polymers, usually the supplier provides the percent polymer in the liquid polymer. The problem is to determine how much of the supplier's polymer should be mixed with water to produce a tank or barrel of coagulant with a diluted or lower percent polymer.

$P_{polymer} \text{ x } V_{polymer} = P_{solution} \text{ x } V_{solution}$

Where,

$P_{polymer}$ = Percent polymer provided by the supplier
$V_{polymer}$ = Volume of the polymer from the supplier
$P_{solution}$ = Percent polymer needed
$V_{solution}$ = Volume of the polymer after adding water to the solution from the supplier

$$P_{solution} = \frac{P_{polymer} \text{ x } V_{polymer}}{V_{solution}}$$

or

$$V_{solution} = \frac{P_{polymer} \text{ x } V_{polymer}}{P_{solution}}$$

Review Questions

1. Calculate the applied feed dosage rate if 3 million gallons of water is treated with 100 pounds of chlorine gas.

2. What is the flow rate in gallons per minute if the total daily flow is 2.4 million gallons/day?

3. What is the applied dosage rate for a water treatment plant with a flow of 4.1 million gallons per day in pounds per day if the chlorine dosage is 3.8 mg/L?

Test Questions

1. Which of the following does not have an effect on the speed of flocculators in the coagulation/flocculation process?

   a. Volume of floc to be formed
   b. Visual observations of short-circuiting
   c. Water temperature
   d. Chlorine demand

2. The most important consideration in coagulation-flocculation process control is __________.

   a. selection of the proper type and amount of coagulant chemicals
   b. the flow rate
   c. water temperature
   d. chlorine demand

3. The term _________ describes the effect produced when certain chemicals are added to raw water containing slowly settling or non-settleable particles.

   a. flocculation
   b. coagulation
   c. filtration
   d. disinfection

4. __________ is a physical and chemical reaction occurring between the alkalinity of the water and the chemcial added to the water, which results in the formation of insoluble flocs.

   a. flocculation
   b. coagulation
   c. filtration
   d. disinfection

5. __________ is a slow stirring process that causes the gathering together of small, coagulated particles into larger, settleable particles.

   1. flocculation
   2. coagulation
   3. filtration
   4. disinfection

6. Calculate the amount of a chemical in pounds per day that should be added to water for treatment, when the flow is 830,000 gallons per day and the dosage determined through jar testing is 11 mg/L of alum.

CHAPTER 2: CONTACT TIME CALCULATIONS

Objectives:

- Outline disinfection process and system requirements
- Define CT concept
- Calculate flow rates and detention time
- Calculate CT value

CT Concept

Disinfection is a key component to the multi-barrier approach to provide safe drinking water. Water treatment can be broken into two phases:

1. The water treatment process
2. Disinfection

CT is defined as the disinfectant residual concentration (i.e. C) multiplied by the effective contact time (i.e. T). The corresponding unit is mg/L-min. The effective contact time T is also known as T10. T10 refers to the effective contact time, which is the time it takes 10% of the volume of a unit to pass through that unit and T is referred as theoretical detection time. In completing CT calculations, the following operating or design conditions must be applied to determine the effective contact time provided at a water treatment plant:

- The peak hourly flow rate (typically the pump peak flow)
- Minimum normal operating level of the storage reservoir, clear well or tank
- The baffling factor for the chlorine contact tank
- Minimum disinfectant residual measured at the end of each disinfection segment, or the minimum disinfectant residual allowed in the Permit to Operate
- Minimum temperature of the water undergoing disinfection
- Maximum pH of the water undergoing.

The baffling factor (BF) of a contact tank is used to adjust the theoretical detention time to a more realistic value of the T and reduces the effective storage volume to account for potential short circuiting. It is expressed as T10/T, where T10 refers to the effective contact time, which is the time it takes 10% of the volume of a unit to pass through that unit and T is referred as theoretical detection time. A reliable and accurate method to determine the BF (T10/T) of a disinfection system is through the use of a tracer study or computational fluid dynamics modeling.

For daily operation at facilities where CT calculation is an on-going operating requirement, CT may be calculated using actual values for reservoir volume, flow, temperature, pH, chlorine residual and other required factors. However, for design purpose, conservative CT calculation must be used to determine if the system will meet CT requirements at all times. For a seasonal operation system, CT calculation for winter and summer conditions may be required to cover the worst case scenario.

In case where more than one disinfectant is used, or where there are multiple disinfectant injection points, disinfection segments should be identified. In the case of multiple disinfection segments, the CT calculation is performed for each individual disinfection segment and then summed to get for the total CT value for the entire system.

CT Values are an important part of calculating disinfectant dosage for the chlorination of drinking water. The goal of disinfection is the inactivation of microorganisms. Inactivation depends on:

- The microorganism
- The disinfectant being used
- The concentration of the disinfectant
- The contact time
- The temperature
- pH of the water.

Disinfection Process

Disinfection destroys harmful organisms. Disinfection can be accomplished physically or chemically. Physical methods include:

1. Physically removing the organisms from the water
2. Introducing motion that will disrupt the cells' biological activity and kill or inactivate them.

Chemical methods alter the cell chemistry causing the microorganism to die. The most widely used disinfectant chemical is chorine. Chlorine is easily obtained, relatively inexpensive, and most importantly, leaves residual chlorine that can be measured. Other disinfectants are also used. Presently, an interest in disinfectants other than chlorine exist because of the carcinogenic compounds that chlorine can form (THMs).

Physical Means of Disinfection

- Ultraviolet rays can be used to destroy pathogenic microorganisms. To be effective, the rays must come in contact with each microorganism. The ultraviolet energy disrupts various organic components of the cell causing a biological change that is fatal to the microorganism. This system has not had widespread acceptance because of the lack of a measurable residual and the cost of operation. Currently, the use of ultraviolet rays is limited to small or local systems and industrial applications. Oceangoing ships use these systems for their water supply. Advances in UV technology and concern about disinfection byproducts produced by other disinfectants have prompted a renewed interest in UV disinfection.

- Heat has been used for centuries to disinfect water. Boiling water for about 5 minutes will destroy essentially all microorganisms. This method is energy intensive and thus expensive. However, it is the only practical treatment process for disinfection in the event of a disaster when individual local users are required to boil their water.
- Ultrasonic waves have been used to disinfect water on a limited scale. Sonic waves destroy microorganisms by vibration. This procedure is not yet practical and is expensive.

Chemical Disinfectants Other Than Chlorine

- Iodine has been used as a disinfectant in water, but its use has been limited to emergency treatment of water supplies. Although it has long been recognized as a good disinfectant, iodine's high cost and potential physiological effects on pregnant women has prevented widespread acceptance. The recommended dosage is two drops of iodine (7% available iodine) in a liter of water.
- Bromine has been used only on a very limited scale for water treatment because of its handling difficulties. Bromine causes skin burns on contact. Because bromine is a very reactive chemical, residuals are hard to obtain. This lack of a measurable residual also limits its use. Bromine can be purchased at swimming pool supply stores.
- Bases, such as sodium hydroxide and lime, can be effective disinfectants but the high pH leaves a bitter taste in the finished water. Bases can also cause skin burns when left too long in contact with the skin. Bases effectively kill all microorganism (sterilize). Although this method has not been used on a large scale, bases have been used to sterilize water pipes.
- Ozone, in the United States, has been used for taste and odor control. The limited use has been due to its high costs, lack of residual, difficulty in storing, and maintenance requirements. Although ozone is effective in disinfecting water, its use is limited by its solubility. The temperature and pressure of the water being treated regulate the amount of ozone that can be dissolved in the water. These factors tend to limit the disinfectant strength that can be made available to treat water. Many scientists claim that ozone destroys all microorganisms. Unfortunately, significant residual ozone does not guarantee that treated water is safe to drink. Organic solids may protect organisms from the disinfecting action and increase the amount of ozone needed for the disinfection process. In addition, ozone residuals cannot be maintained in metallic conduits for any period of time because of ozone's reactive nature. The inability of ozone to provide a residual in the distribution system is a major drawback to its use. However, recent information concerning the formation of THMs by chlorine compounds has resulted in a renewed interest in ozone as an alternative means of disinfection.

Chlorine

Chlorine is a greenish-yellow gas with a penetrating and distinctive odor. The gas is two- and-a-half times heavier than air. Chlorine has a high coefficient of expansion. If the temperature increases 50 F, the volume will increase 84 to 89 percent. This expansion could easily rupture a cylinder or a line full of liquid chlorine. For this reason, no chlorine containers should be filled to more than 85 percent of their capacity. One liter of liquid chlorine can evaporate and produce 450 liters of chlorine gas.

Chlorine is nonflammable and nonexplosive, but it will support combustion. When the temperature rises, so does the vapor pressure of chlorine. When the temperature increase, the chlorine gas inside a chlorine container will increase. This property of chlorine must be considered when:

1. Feeding chlorine gas from a container
2. Dealing with a leaking chlorine cylinder

Chlorine Disinfection Action

The exact mechanism of chlorine disinfection action is not fully known. One theory holds that chlorine exerts a direct action against the bacterial cell; thus destroying it. Another theory is that the toxic character of chlorine inactivates the cell's enzymes, which enable living microorganisms to use their food supply. As a result, the organisms die of starvation. From the point of view of water treatment, the exact mechanism of chlorine disinfection is less important than its demonstrated effects as a disinfectant.

When chlorine is added to water, several chemical reactions take place. Some involve the molecules of water, and some involve organic and inorganic substances suspended in the water. Water combines with inorganic and organic materials to form chlorine compounds. If chlorine is continued to be added to the water, eventually a point exists where the reactions with organic and inorganic materials stop. At this point, the chorine demand has been satisfied.

When the amount of chlorine needed to satisfy the chlorine demand and the amount of chlorine residual needed for disinfection is added, the chlorine dose is computed. The chlorine dose is the amount of chlorine that has to be added to the water to disinfect it.

Cl_{dose}, mg/L = Cl_{demand}, mg/L + $Cl_{residual}$, mg/L

where

Cl_{demand}, mg/L = Cl_{dose}, mg/L - $Cl_{residual}$, mg/L

and

$Cl_{residual}$, mg/L = Cl_{dose}, mg/L - Cl_{demand}, mg/L

Where,

$Cl_{combined}$ = Combined Chlorine forms
Cl_{free} = Free Chlorine

Chlorine Reactions with Water

Free chlorine combines with water to form hypochlorous and hydrochloric acid. In solutions that are dilute and have a pH above 4, the formation of HOCl (hypochlorous acid) is almost complete and leaves little free chlorine.

Chlorine + Water ⟷ Hypochlorous Acid + Hydrochloric Acid

Depending on the pH, some hypochlorous acid will disassociate and produce a hydrogen ion and a hypochlorite ion. Hypochlorous acid is a weak acid and is poorly dissociated at pH levels below 6. Below pH 6, the free chlorine is almost all in the hypochlorous form. Above pH 9, almost all of the free chlorine is in the hypochlorite form and almost none is in the hypochlorous form.

Hypochlorous Acid ⟷ Hydrogen ion + Hypochlorite

Normally, in water with a pH of 7.5, approximately 50 percent of the chlorine present will be in the hypochlorous form and 50 percent will be in the form of hypochlorite. This phenomenon is important since hypochlorous and hypochlorite differ in their respective disinfection ability, hypochlorous has a much greater disinfection potential than hypochlorite.

Chlorine Reactions with Impurities in Water

Most water contains some impurities. The more common impurities that react with chorine that effects the disinfection ability of chlorine are:

1. Hydrogen sulfide and ammonia are two inorganic substances that may be found in water when it reaches the disinfection stage of treatment. Their presence can complicate the use of chlorine for disinfection purposes. Hydrogen sulfide and ammonia are reducing agents, and they give up electrons easily. Chlorine reacts rapidly with these particular reducing agents producing some undesirable results. Hydrogen sulfide produces an odor that smells like rotten eggs. It reacts with chlorine to form sulfuric acid and elemental sulfur (depending on temperature, pH, and hydrogen sulfide concentration). Elemental sulfur is objectionable because it can cause odor problems and will precipitate as finely divided white particles that are sometimes colloidal in nature. The chemical reaction between hydrogen sulfide and chlorine is:

Hydrogen Sulfide + Chlorine +Oxygen Ion → Elemental Sulfur + Water + Chloride Ions

The chlorine required to oxidize hydrogen sulfide to sulfur and water is 2.08 mg/L chlorine to 1 mg/L hydrogen sulfide. The complete oxidation of hydrogen sulfide to the sulfate form is:

Hydrogen Sulfide + Chlorine + Water → Sulfuric Acid + Hydrochloric Acid

When chlorine is added to water containing ammonia, it reacts rapidly with the ammonia and forms chloramines. Therefore, less chlorine is available to act as a disinfectant. As the concentration of ammonia increases, the disinfectant power of the chorine drops off at a rapid rate.

2. When organic materials are present in water being disinfected with chlorine, the chemical reaction that takes place may produce suspected carcinogenic compounds. The formation of these compounds can be prevented by limiting the amount of prechlorination and by removing the organic materials before chlorination of the water.

Hypochlorite

The use of hypochlorite to treat potable water achieves the same result as chlorine gas. Hypochlorite may be applied in the form of calcium hypochlorite or sodium hypochlorite. The form of calcium hypochlorite most frequently used to disinfect water is known as High Test Hypochlorite.

Calcium Hypochlorite + Water → Hydrochlorous Acid + Calcium Hydroxide

Sodium Hypochlorite + Water → Hydrochlorous Acid = Sodium Hydroxide

In systems, where calcium hypochlorite is used a problem occurs when sodium fluoride is injected at the same point as the hypochlorite. A server crust forms when the calcium and fluoride ions combine.

Differences between Chlorine Gas and Hypochlorite Compound Reactions

The only difference between the reactions of hypochlorite compounds and chlorine gas is the side reactions of the end products. The reaction of chlorine gas tends to lower the pH by the formation of hydrochloric acid, which favors the formation of hypochlorous acid. The hypochlorite tends to raise the pH with the formation of the hydroxyl ions from the calcium or sodium hydroxide. At a high pH of around 8.5 or higher, the hypochlorous acid is almost completely dissociated to the ineffective hypochlorite ion. This reaction also depends on the buffer capacity of the water.

Onsite Chlorine Generation

Small water systems are generating chlorine on site for their water treatment processes. Onsite generation of chlorine is attractive due to the lower safety hazards and costs involved. Onsite generated chlorine systems produce 0.8 percent sodium hypochlorite. This solution strength is below the lower limit deemed a hazardous liquid, with obvious economic and safety advantages.

The operator's only duties with onsite generation systems are to observe the control panel daily for proper operating guidelines and to dump bags of salt every few weeks. Since the assemblies include an ion exchange water softener, mineral deposits forming with the electrolytic cell are minimal, with an acid cleaning being necessary only every few months. Cell voltage is controlled at a low value to maximize electrode life, which is about 3 years. Process brine strength and cell current determine chlorine production at the anode, while hydrogen gas is continually vented from the cathode. The units include provisions for storing the chlorine solution to deliver chlorine for several days in the event of a power failure or other problems causing equipment failure.

Breakpoint Chlorination

In determining how much chlorine the operator will need for disinfection, operators must remember a certain chlorine residual in the form of a free available chlorine residual is the goal. Chlorine in this form has the highest disinfecting ability. Breakpoint chlorination is the name of this process of adding chlorine to water until the chlorine demand has been satisfied. Further additions of chlorine will result in a chlorine residual that is directly proportional to the amount of chlorine added beyond the breakpoint. Public water supplies are normally chlorinated past the breakpoint.

Assume the water being chlorinated contains some manganese, iron, nitrite, organic matter, and ammonia. When a small amount of chlorine is added, the chlorine reacts with (oxidizes) the manganese, iron, and nitrite. No disinfection and no chlorine residual occurs. When additional chlorine is added, enough to react with the organics and ammonia, chlororganics and chloramines form. The chloramines produce a combined available chlorine residual which is chlorine combined with other substances, mainly ammonia. Combined residuals have poor disinfecting power and may cause tastes and odors.

By adding more chlorine, the chloramines and some of the chlororganics are destroyed, which results in a drop in combined chlorine residual. When all of the chloramines are gone, adding more chlorine produces free available residual chlorine which is free in the sense that it has not reacted with anything and is available in that it can and will react if needed. Free available residual chlorine is the best residual for disinfection. It disinfects faster and without the swimming pool odor of combined residual chlorine. The point at which the chlorine residual curve bottoms out is called the breakpoint, and chlorination beyond this point is called breakpoint chlorination. In water treatment plants today it is common practice to go past the breakpoint. This process means that the treated water will have a very effective disinfectant because it is in the form of free available residual chlorine.

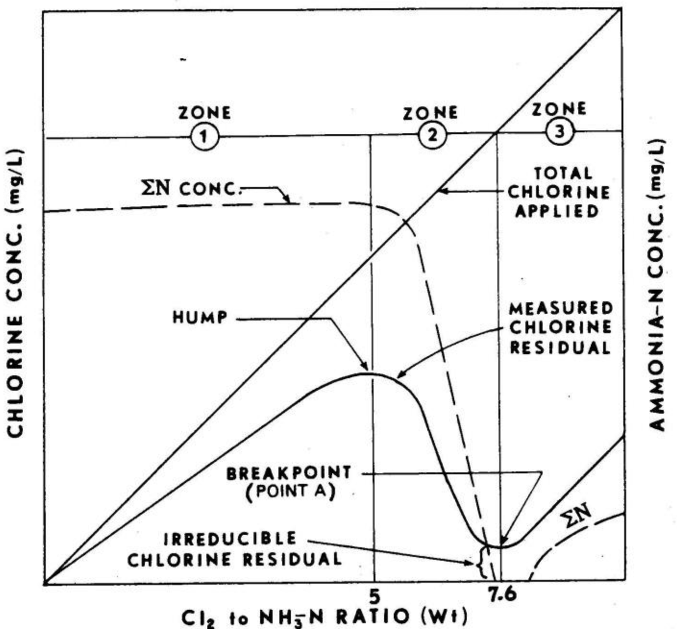

Figure 2-2 Breakpoint Chlorination Curve – Image by State of New South Wales NSW Ministry of Health is licensed under CC BY

CT Values

The purpose of the SWTR is to ensure that pathogenic organisms are removed or inactivated by the treatment process. To meet this goal, all systems are required to disinfect their water supplies. For some water systems using very clean source water and meeting the other criteria to avoid filtration, disinfection alone can achieve the 3-log (99.9-percent) *Giardia* and 4-log (99.99-percent) virus inactivation levels required by the Surface Water Treatment Rule.

Several methods of disinfection are in common use, including free chlorination, chloramination, use of chlorine dioxide, and application of ozone. The concentration of chemical needed and the length of contact time needed to ensure disinfection are different for each disinfectant. Therefore, the effectiveness of the disinfectant is measured by the time (t) in minutes of the disinfectant's contact in the water and the concentration (C) of the disinfectant residual in mg/L measured at the end of the contact time. The product of these two factors (C × t) provides a measure of the degree of pathogenic inactivation.

The required CT value to achieve pathogenic inactivation is dependent upon the organism in question, type of disinfectant, pH, and temperature of the water supply. Time or T is measured from point of application to the point where C is determined. T must be based on peak hour flow rate conditions. In pipelines, T is calculated by dividing the volume of the pipeline in gallons by the flow rate in gallons per minute (GPM). In reservoirs and basins, dye tracer tests must be used to determine T. In this case, T is the time it takes for 10 percent of the tracer to pass the measuring point.

A properly operated filtration system can achieve limited removal or inactivation of microorganisms. For this reason, systems that are required to filter their water are permitted to apply a factor that represents the microorganism removal value of filtration when calculating CT values to meet the disinfection requirements.

The factor (removal credit) varies with the type of filtration system. Its purpose is to take into account the combined effect of disinfection and filtration in meeting the SWTR microbial standards.

The effectiveness of disinfection is demonstrated through the concept of contact time (CT), which is defined as a product of a disinfectant residual concentration(C), in mg/L and the effective disinfectant contact time (T), in minutes.

CT Disinfection demonstrates that the required disinfection is being achieved.
CT Disinfection is a straightforward three step process. These steps include:

1. Determine how much CT is need.
2. Determine how much CT is achieved.
3. Ensure CT achieved is more than CT required.

The CT value is developed to relate the levels of inactivation under different operational conditions. For true groundwater systems, a CT value must be achieved that provides a minimum of a 4-log virus reduction/inactivation; while all surface water or Groundwater Under Direct Influence (GUDI) systems, a CT value must be achieved that provides a minimum of a 0.5 log *Giardia* and 2-log virus reduction/inactivation. Depending on the treatment process, additional Crypto and *Giardia* removal/inactivation may be required for a surface water source. Significant deterioration of water quality may require further removal or inactivation of viruses, *Cryptosporidium*, and *Giardia*.

CT is simply the concentration of chlorine in water times the time of contact that the chlorine has with the water before the first customer tap.

Example:

If a water system is providing water to a community, and if the well capacity is 100 gpm, the residual chlorine concentration is 0.1 mg/L free chlorine measured at the tank, the pump capacity is 250 gpm, and no baffling is provided except that the inlet to the storage tank is located at the top and the outlet is located at the bottom on the opposite wall, the pH is 7.5, the tank capacity is 50,000 gallons and the lowest operating volume is 25,000 gallons, and the water temperature is 20^{o}C, then what is the CT value?

Equations: Total Detention Time = Lowest Operating Volume/Peak Flow

The operating volume should be taken during peak hour demand.

Solution:

The well capacity is irrelevant in the example because it has no bearing on the peak flow of the water system. However, the pump's peak flow of 250 gpm does have an effect on the CT value, and the rule describes that the lowest operating volume must be used in CT calculation.

Peak Flow = 250 gpm
Baffling Factor = 0.3 (from Baffling Factor Table)
Lowest operating tank volume = 25,000 gallons
CT required from table = 3 mg/L-min

Total Detention Time = Lowest Operating Volume/Peak Flow
= 25,000 gallons/250 gpm
Total Detention Time = 100 minutes

Contact Time = Total Detention Time x Baffling Factor (from Baffling factor table)
= 100 minutes x 0.3
Contact Time = 30 minutes

CT calculation = Residual Chlorine Concentration x Contact Time
= 0.1 mg/L x 30 minutes
CT calculation = 3 mg/L / minute

Inactivation Ratio = Inactivation Ratio = CT cal /CT req
= 3 mg/L-min / 3 mg/L -min
Inactivation Ratio = 1

All surface and ground water under the influence of surface water systems should be using CT Disinfection to demonstrate that you are achieving sufficient water treatment to inactivate protozoa and viruses. Disinfection with free chlorine that inactivates protozoa will usually provide enough CT to kill viruses as well.

Practicing CT Disinfection is the safe thing to do. CT Disinfection is the disinfection standard. CT Disinfection is also the water treatment industry standard for disinfection. It is the best method to ensure that the water you are providing your customers is safe. If your water has been exposed to the surface, it has also been exposed to surface contamination, whether from livestock, wild animals or other human activity.

In water treatment practice, tables of the product C × t are used to calculate disinfection dosages. These tables express the required CT values to achieve a desired removal of microorganisms of interest in drinking water, such as *Giardia lamblia* cysts, for a given disinfectant under constant temperature and pH conditions.

The disinfection of water is crucial to ensuring that the water is safe to drink and free of harmful bacteria and other organisms. The primary methods of disinfection are chlorination, hydrogen peroxide injection, ozone, and UV light. These methods, however, require sufficient contact time between the water and the disinfectant. Proper contact time must also be complemented by the correct dosage of a disinfectant; multiplying the concentration of the disinfectant by the time of contact with the water will provide a CT value.

Review Questions

1. Describe the disinfection process using chlorine.

2. Define CT concept.

3. What is the detention time in hours for a sedimentation basin that contains 240,000 gallons with a flow into the basin being 1,700 gpm?

4. What is the flow rate if the detention time is 2 hours and the basin contains 100,000 gallons of water?

5. If a water system is providing water to a community, and if the well capacity is 200 gpm, the residual chlorine concentration is 0.5 mg/L free chlorine measured at the tank, the pump capacity is 300 gpm, and no baffling is provided, the pH is 7.5, the tank capacity is 25,000 gallons and the lowest operating volume is 20,000 gallons, and the water temperature is 20°C, then what is the Contact Time value (CT value)?

Test Questions

1. _________is the product of the concentration of a disinfectant and the contact time with the water being disinfected. It is typically expressed in units of mg-min/L. The goal of disinfection is the inactivation of microorganisms.

   a. Free chlorine residual
   b. Chlorine demand
   c. CT value
   d. Breakpoint chlorination

2. _____________ is the name of this process of adding chlorine to water until the chlorine demand has been satisfied. Further additions of chlorine will result in a chlorine residual that is directly proportional to the amount of chorine.

   a. Free chlorine residual
   b. Chlorine demand
   c. CT value
   d. Breakpoint chlorination

3. __________is a key component to the multi-barrier approach to provide safe drinking water.

   a. Free chlorine residual
   b. Chlorine demand
   c. CT value
   d. Chlorination

4. Which of the following is not a physical means of disinfection?

   a. Ultraviolet rays
   b. Heat
   c. Bases
   d. Ultrasonic waves

5. Which of the following is not a chemical disinfectant?

   a. Iodine
   b. UV light
   c. Bases
   d. Ozone

6. _________is also the water treatment industry standard for disinfection. It is the best method to ensure that the water you are providing your customers is safe.

   a. Free chlorine residual
   b. Chlorine demand
   c. CT Disinfection
   d. Breakpoint chlorination

CHAPTER 3: DISINFECTION BY-PRODUCTS AND ALTERNATIVE DISINFECTANTS

Objectives:

- Explain the nature and occurrence of disinfection by-products
- Outline the Disinfection By-Products Rule
- Describe the formation of disinfection by-products
- Describe the methods of the minimization of disinfection by-products

Disinfection By-Products

Disinfection of drinking water by the addition of chlorine has long been considered a highly effective yet relatively low-cost method of preventing widespread outbreaks of waterborne diseases. In addition to reacting with disease-causing organisms in water, however, chlorine also reacts with many other types of organic materials.

Disinfection Treatment	Disinfection Byproducts
Chlorination	Trihalomethanes Haloacetic Acids Chlorate
Chlorine Dioxide	Chlorite Chlorate
Chloramine	Chlorate
Ozonation	Bromate

Figure 3-1 – Disinfection byproducts form when disinfectants used in water treatment plants react with bromide and/or natural organic matter

Growing scientific evidence suggests that the byproducts of these chemical reactions can produce adverse health effects in humans. The highest priority health risk concern in the regulation of drinking water is the potential risk-risk tradeoff between the control of microbiological contamination (bacteria, viruses, and protozoa) on one side and DBPs on the other. This risk-risk tradeoff arises because, typically, the least expensive way for a public water system to increase microbial control is to increase disinfection (which generally increases byproduct formation) and the easiest way to reduce byproducts is to decrease disinfection (which generally increases microbial risk).

Microbiological contamination often causes flu-like symptoms; however, it can also cause serious diseases such as hepatitis, giardiasis, cryptosporidiosis, and Legionnaire’s Disease. DBPs may pose the risk of cancer and developmental effects.

THMs and HAA5s are examples of compounds formed by the reaction of chlorine with organic matter in water. THMs are suspected of being carcinogenic and have been regulated by EPA in the 1996 SDWA amendments. The MCL for TTHMs is 0.080 milligram per liter or 80 micrograms per liter, and HAA5s have an MCL of 0.060 milligrams per liter or 60 micrograms per liter.

In May 1996, EPA published the Information Collection Rule (ICR). This rule required large public water systems to undertake extensive monitoring of microbial contaminants and DBPs in their water systems. Also, some water systems conducted studies on the use of granular activated carbon and membrane processes. The data reported under the ICR were used by EPA to learn more about the occurrence of microbial contamination and DBPs, the health risks posed, appropriate analytical methods, and effective forms of treatment. The ICR data form the scientific basis for EPA's development of the Enhanced Surface Water Treatment Rule and the Disinfectants and Disinfection Byproducts Rule.

EPA issued the Stage 1 DBPR on December 16, 1998 (Federal Register 63, No. 241). This rule set new MCLGs and MCLs for TTHMs, HAA5, bromate, and chlorite. Maximum residual disinfectant level goals (MRDLGs) and maximum residual disinfectant levels (MRDLs) have also been set for chlorine, chloramine, and chlorine dioxide.

The Stage 1 DBPR attempts to further reduce potential formation of harmful DBPs by requiring the removal of THM precursors. A treatment technique of enhanced coagulation, enhanced softening, or use of granular activated carbon (GAC) applies to conventional filtration systems. In most cases, systems must reduce total organic carbon (TOC) levels based on specific source water quality factors.

For large systems (serving more than 10,000 persons) that use surface water or groundwater under the direct influence of surface water, the compliance date for the Stage 1 DBPR was January 1, 2002. Small systems (serving fewer than 10,000) that use surface water or groundwater under the direct influence of surface water and all groundwater systems must have complied by January 1, 2004.

The Stage 1 DBPR has very specific laboratory and monitoring requirements. The routine monitoring requirements include the following regulated contaminants/disinfectants:

1. TTHM/HAA5
2. Bromate
3. Chlorite
4. Chlorine/chloramines
5. Chlorine dioxide
6. DBP precursors (TOC/alkalinity/specific UV absorbance)

Also, the Stage 1 DBPR specifies the monitoring coverage in terms of surface water, groundwater, and groundwater under direct influence (GWUDI), population served, and the type of filtration system and disinfection system. Monitoring frequency depends on the type of source water, population served, and type of treatment and disinfection system. The routine monitoring requirements are based on the regulated contaminants/disinfectants and include the MCL, MRDL, analytical method, preservation/quenching agent, holding time for sample/extract, and sample container size and type.

On December 15, 2005, EPA promulgated the Stage 2 DBPR. This rule reduces potential cancer and reproductive and developmental health risks from DBPs in drinking water, which form when disinfectants are used to control microbial pathogens. This final rule strengthens public health protection for consumers by tightening compliance monitoring requirements for two groups of DBPs: TTHMs and HAA5.

The rule targets systems with the greatest risk and builds incrementally on existing rules. This regulation reduces DBP exposure and related potential health risks and provides more equitable public health protection. The Stage 2 DBPR was promulgated simultaneously with the Long Term 2 Enhanced Surface Water Treatment Rule to address concerns about risk tradeoffs between pathogens and DBPs.

Under the Stage 2 DBPR, systems will conduct an evaluation of their distribution systems, known as an Initial Distribution System Evaluation (IDSE), to identify the locations with high DBP concentrations. These locations are used by the systems as the sampling sites for Stage 2 DBPR compliance monitoring.

Compliance with the maximum contaminant levels for two groups of DBPs (TTHMs and HAA5) is calculated for each monitoring location in the distribution system. This approach, referred to as the locational running annual average (LRAA), differs from previous requirements, which determine compliance by calculating the running annual average of samples from all monitoring locations across the system.

The Stage 2 DBPR also requires each system to determine if they have exceeded an operational evaluation level, which is identified using their compliance monitoring results. The operational evaluation level provides an early warning of possible future MCL violations, which allows the system to take proactive steps to remain in compliance. A system that exceeds an operational evaluation level is required to review their operational practices and submit a report to their state that identifies actions that may be taken to mitigate future high DBP levels; particularly, those levels that may jeopardize their compliance with the DBP MCLs.

Factors Influencing Disinfection

Many factors influence successful disinfection during water treatment. These factors include pH, temperature, turbidity, reducing agents, and microorganism.

pH

The pH of water being treated can alter the efficiency of disinfectants. Chlorine disinfects water much faster at a pH around 7.0 rather than at a pH over 8.0.

Temperature

Temperature conditions also influence the effectiveness of the disinfectant. The higher the temperature of water, the more efficiently it can be treated. Water near 70 to 85F (21 to 29 C) is easier to disinfect than water at 40 to 60 F (4 to 16C). Longer contact times are required to disinfect water at lower temperatures. To speed up the process, operators often use larger amounts of chemicals. Be aware, though, that the higher the chlorine concentration, the greater the dissipation rate of chlorine into the atmosphere. This process can produce odors and wastes chlorine.

Turbidity

Under normal operating conditions, the turbidly level of water being treated is very low by the time the water reaches the disinfection process. Excessive turbidity will greatly reduce the efficiency of the disinfecting chemical or process. Studies in water treatment plants have demonstrated that when water is filtered to a turbidity of one unit or less, most of the bacteria have been removed.

The suspended matter can also change the chemical nature of the water when the disinfectant is added. Some types of suspended solids can create a continuing demand for the chemical; thus changing the effective germicidal properties of the disinfectant.

Organic Matter

Organics found in water can consume great amounts of disinfectants while forming unwanted compounds. Trihalomethanes (THMs and HAA5s) are an example of undesirable compounds formed by reactions between chlorine and certain organics. Disinfecting chemicals often react with organics and reducing agents. Then, if any of the chemical remains available after this initial reaction, it can act as an effective disinfectant. The reactions with organics and reducing agents, however, will significantly reduce the amount of chemical available for disinfection.

Inorganic Matter

Inorganic compounds, such as ammonia in water can create special problems. In the presence of ammonia, some oxidizing chemicals form side compounds causing a partial loss of disinfecting power. Silt can also create a chemical demand. It is clear, that the chemical properties of the water being treated can seriously interfere with the effectiveness of disinfecting chemicals.

Figure 3-2

Chlorine

Organic Matter

Carcinogenic Disinfection Byproducts

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Reducing Agents

Chlorine combines with a wide variety of materials, especially reducing agents. Most of the reactions are rapid, though other reactions are much slower. These side reactions complicate the use of chlorine for disinfection. The demand for chlorine by reducing agents must be satisfied before chlorine becomes available to disinfect. Examples of inorganic reducing agents present in water that will react with chlorine include hydrogen sulfide, ferrous ions, manganous ions, ammonia, and nitrite. Organic reducing agents in water will react with chlorine and form chlorinated organic materials that have a potential health significance.

Microorganisms

The concentration of microorganisms is important because the higher the number of microorganisms, the greater the demand for a disinfecting chemical. The resistance of microorganisms to specific disinfectants varies greatly. Non-spore-forming bacteria are generally less resistant than spore-forming bacteria. Cysts and viruses can be resistant to certain types of disinfectants.

Removal Process for Microorganisms

Pathogenic organisms can be removed from water, killed, or inactivated by various physical and chemical water treatment processes. These processes include:

1. Coagulation-chemical coagulation followed by sedimentation and filtration will remove 90 to 95-percent of the pathogenic organism, depending on which chemicals are used. Alum usage can increase virus removals up to 99-percent.

2. Sedimentation-properly designed sedimentation processes can effectively remove 20 to 70-percent of the pathogenic microorganisms. This removal rate is accomplished by allowing the pathogenic and non-pathogenic organisms to settle out by gravity, assisted by chemical floc.
3. Filtration-filtering water through granular filters is an effective means of removing pathogenic and other organisms form water. The removal rates vary from 20 to 99+ percent, depending on the coarseness of the filter media and the type and effectiveness of pretreatment.
4. Disinfection-disinfection chemicals, such as chlorine, are added to water to kill or inactivate pathogenic microorganisms.

Disinfection Process

Disinfection destroys harmful organisms. This can be accomplished either physically or chemically. Physical methods include:

1. Physically remove the organisms from the water
2. Introduce motion that will disrupt the cells' biological activity and kill or inactivate them.

Chemical methods alter the cell chemistry causing the microorganism to die. The most widely used disinfectant chemical is chorine. Chlorine is easily obtained, relatively inexpensive, and most importantly, leaves a residual chlorine that can be measured. Other disinfectants are also used. Presently, an interest in disinfectants other than chlorine exist because of the carcinogenic compounds that chlorine can form (THMs).

Physical Means of Disinfection

- Ultraviolet rays can be used to destroy pathogenic microorganisms. To be effective, the rays must come in contact with each microorganism. The ultraviolet energy disrupts various organic components of the cell causing a biological change that is fatal to the microorganism. This system has not had widespread acceptance because of the lack of a measurable residual and the cost of operation. Currently, the use of ultraviolet rays is limited to small or local systems and industrial applications. Oceangoing ships use these systems for their water supply. Advances in UV technology and concern about disinfection byproducts produced by other disinfectants have prompted a renewed interest in UV disinfection.
- Heat has been used for centuries to disinfect water. Boiling water for about 5 minutes will destroy essentially all microorganisms. This method is energy intensive and thus expensive. However, it is the only practical treatment process for disinfection in the event of a disaster when individual local users are required to boil their water.
- Ultrasonic waves have been used to disinfect water on a limited scale. Sonic waves destroy microorganisms by vibration. This procedure is not yet practical and is expensive.

Chemical Disinfectants Other Than Chlorine

- Iodine has been used as a disinfectant in water, but its use has been limited to emergency treatment of water supplies. Although it has long been recognized as a good disinfectant, iodine's high cost and potential physiological effects on pregnant women has prevented widespread acceptance. The recommended dosage is two drops of iodine (7% available iodine) in a liter of water.
- Bromine has been used only on a very limited scale for water treatment because of its handling difficulties. Bromine causes skin burns on contact. Because bromine is a very reactive chemical, residuals are hard to obtain. This lack of a measureable residual also limits its use. Bromine can be purchased at swimming pool supply stores.
- Bases, such as sodium hydroxide and lime, can be effective disinfectants but the high pH leaves a bitter taste in the finished water. Bases can also cause skin burns when left too long in contact with the skin. Bases effectively kill all microorganism (sterilize). Although this method has not been used on a large scale, bases have been used to sterilize water pipes.
- Ozone, in the United States, has been used for taste and odor control. The limited use has been due to its high costs, lack of residual, difficulty in storing, and maintenance requirements. Although ozone is effective in disinfecting water, its use is limited by its solubility. The temperature and pressure of the water being treated regulate the amount of ozone that can be dissolved in the water. These factors tend to limit the disinfectant strength that can be made available to treat water. Many scientists claim that ozone destroys all microorganisms. Unfortunately, significant residual ozone does not guarantee that treated water is safe to drink. Organic solids may protect organisms from the disinfecting action and increase the amount of ozone needed for the disinfection process. In addition, ozone residuals cannot be maintained in metallic conduits for any period of time because of ozone's reactive nature. The inability of ozone to provide a residual in the distribution system is a major drawback to its use. However, recent information concerning the formation of THMs by chlorine compounds has resulted in a renewed interest in ozone as an alternative means of disinfection.

Chloramination

Chloramination is used as an alternative disinfection process in place of free chlorine. An operator's decision to use chloramine in place of chlorine depends on several factors, including the quality of the raw water, the ability of the treatment plant to meet various regulations, operational practices, and distribution system characteristics. Chloramines have proven effective in accomplishing:

1. Reducing the formation of THMs and other DBPs
2. Maintaining a detectable residual throughout the distribution system
3. Penetrating the biofilm in the pipeline and reducing the potential for coliform regrowth
4. Killing or inactivating heterotrophic plate count bacteria
5. Reducing taste and odor problems

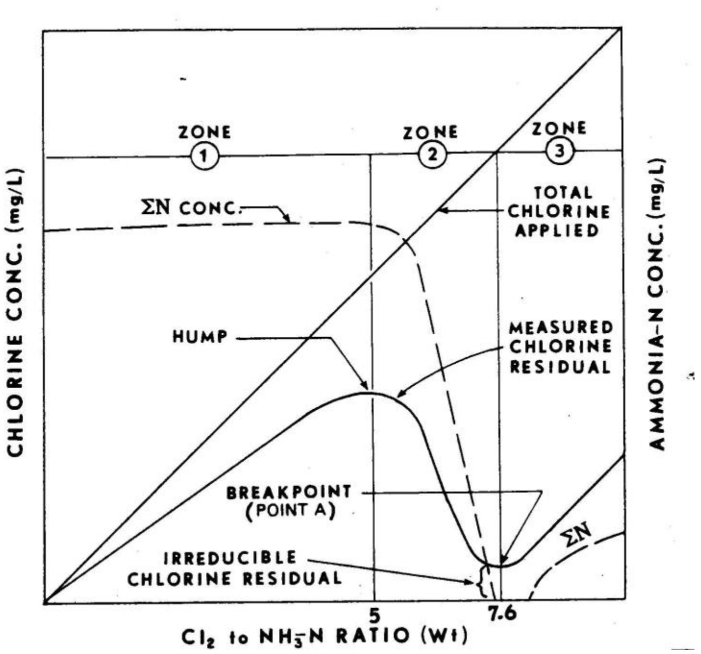

Figure 3-3 Chloramines – Image by State of New South Wales NSW Ministry of Health is licensed under CC BY

Chlorine Dioxide

Chlorine dioxide can be used as a disinfectant. Chlorine dioxide does not form carcinogenic compounds that may be formed by other chlorine compounds. Also, it is not affected by ammonia, and it is a very effective disinfectant at higher pH levels. In addition, chlorine dioxide reacts with sulfide compounds; thus, helping to remove them and eliminate their characteristic odors. Phenolic tastes and odors can be controlled by using chlorine dioxide.

Chlorine dioxide reacts with water to form chlorate and chlorite ions:

Chlorine Dioxide + Water → Chlorite Ion + Hydrogen Ion

Reactions with impurities in water:

1. Inorganic compounds-chlorine dioxide is an effective oxidizing agent with iron and manganese and does not leave objectionable tastes or odors in the finished water. Because of its oxidizing ability, chlorine dioxide usage must be monitored and the dosage will have to be increased when treating water with iron and manganese.
2. Organic compounds-chlorine dioxide does not react with organics in water. Therefore, the danger of forming potentially dangerous THMs does not exist.

Ultraviolet Systems

Ultraviolet light (UV) is found just beyond the visible light spectrum. When UV light is absorbed by cells of microorganisms, it damages the genetic material in such a way that the organisms are no longer able to grow or reproduce, and ultimately, it kills them. Today with growing concern about the safety aspects of handling chlorine and the possible health effects of chlorination byproducts, UV disinfection is gaining in popularity. UV technology can also provide inactivation of *Cryptosporidium* and *Giardia*, which are resistant to common disinfectants like chlorine or ozonation.

The combination of UV technology and chlorination allows an efficient disinfecting system by killing or inactivating a larger range of microorganisms than using only one disinfectant. The UV disinfection process is particularly adapted to water with a good quality. The efficiency of UV disinfection depends on the quality of water and on the treatment stages upstream. Raw water with low turbidity and with low levels of color favor the penetration of UV light and improves disinfection efficiency.

Corrosive water can damage UV systems, and technological advances are being made. Several manufacturers produce UV disinfection systems for water and wastewater applications. As operating experience with installed systems increases, UV disinfection may become a practical alternative to the use of chlorination at water treatment plants.

UV Lamp Types

Each UV lamp assembly consists of a UV lamp enclosed in an individual quartz sleeve with the ends appropriately sealed using an O-ring and a quartz end plug. All lamps within a UV system are identical type, length, diameter, power, ad output. Three types of electrode-type lamps are used to produce UV radiation, and these types are:

1. Low-pressure, low-intensity
2. Low-pressure, high-intensity
3. Medium-pressure, high-intensity

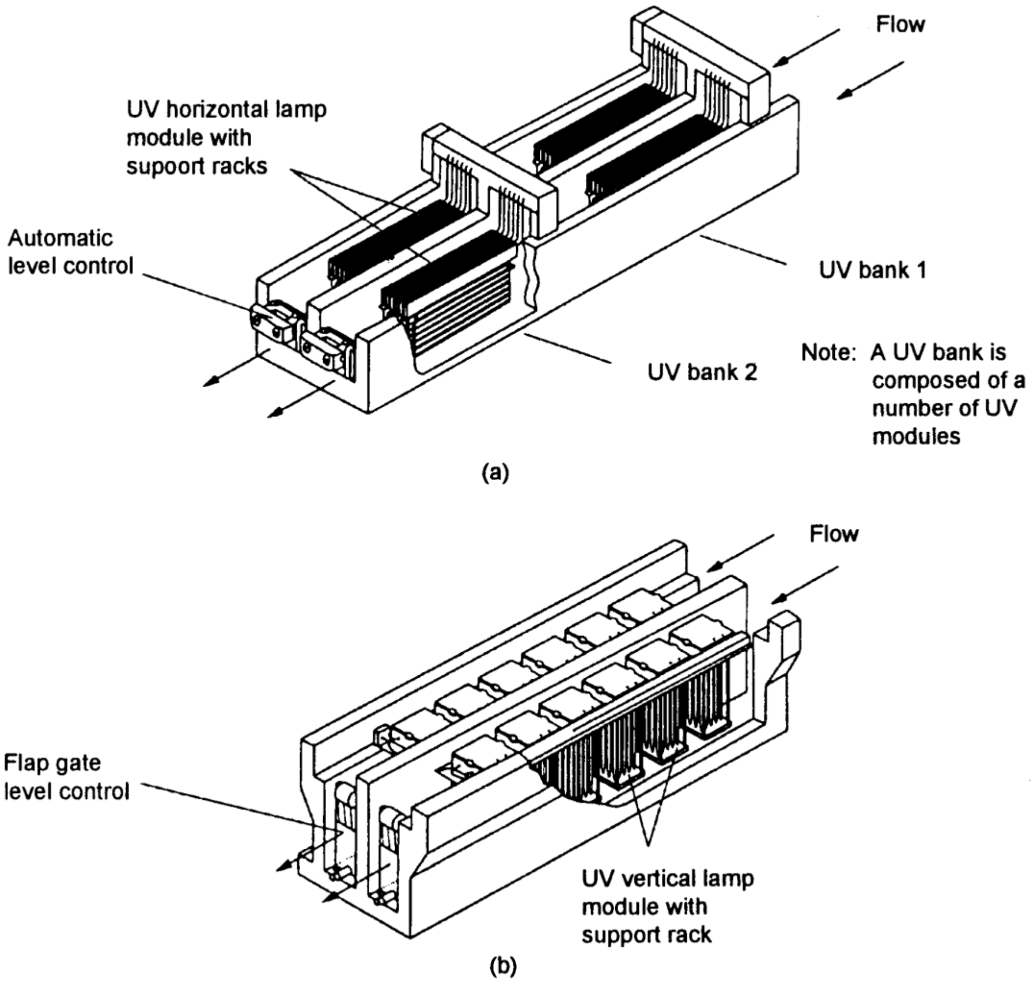

Figure 3-5 UV Disinfection Unit – Image by the EPA is in the public domain

Operation

The operation of UV disinfection systems requires little operator attention. To prevent short-circuiting and ensure that all microorganisms receive sufficient exposure to the UV radiation, the water level over the lamps must be maintained at the appropriate level. Water levels in channels can be controlled by weirs or automatic control gates.

Proper water depth must be maintained in the UV channel to ensure acceptable disinfection levels over the entire range of design flows. The UV channel water level control device must be regulated by the operator to:

- Minimize variation of the channel's water level
- Maintain the channel's water level at a defined level
- Keep the UV lamps submerged at all times
- Prevent excessive water layer thickness above the top lamp row

Monitoring Influent and Effluent Characteristics

Care must be taken not to exceed the maximum design turbidity levels and flow velocities when using these types of equipment. Suspended particles will shield microorganisms from the UV light and protect them from its destructive effects. Flows should be somewhat turbulent to ensure complete exposure of all organisms to the UV light, but flow velocity must be controlled so that the water is exposed to UV radiation long enough for the desired level of disinfection to occur.

Because ultraviolet rays leave no chemical residual like chlorine does, bacteriological tests must be made frequently to ensure that adequate disinfection is being achieved by the ultraviolet system. In addition, the lack of residual disinfectant means that no protection is provided against recontamination after the treated water has left the disinfection facility. When the treated water is exposed to visible light, the microorganism can be reactivated. Microorganisms that have not been killed have the ability to heal when exposed to sunlight. The solution to this problem is to design UV systems with a high efficiency for killing microorganisms.

Ozone Systems

Ozone (O_3) is an alternative treatment process for disinfecting water. Ozone is produced when oxygen molecules are exposed to an energy source and converted to the unstable gas, ozone, which is used for disinfection. Ozone is a very strong oxidant and virucide.

The effectiveness of ozone disinfection depends on the susceptibility of the target organism, the contact time, and the concentration of the ozone. After generation, ozone is fed into a down-flow contact chamber containing the water to be disinfected. The purpose of the contact chamber is to transfer ozone from the gas bubble to the water while providing sufficient contact time for disinfection. Because ozone is consumed quickly, it must be exposed to the water uniformly in a plug-flow-type contactor. An ozone disinfection system strives for the maximum solubility of ozone in water because disinfection depends on the transfer of ozone into the water. The amount of ozone that will dissolve in water at a constant temperature is a function of the partial pressure of the gaseous ozone above the water or in the gas feed stream. All ozone disinfection systems should be pilot tested and calibrated before installation to ensure they meet the disinfection requirements for their particular sites.

Equipment

Ozone is normally generated on site because it is very unstable and decomposes to elemental oxygen in a short time after generation. Ozonation equipment consists of four major parts:

1. Gas preparation unit
2. Electrical power unit
3. Ozone generator
4. Contactor

Gas Preparation

The gas preparation unit to produce dry air usually consists of a commercial air dryer with a dew point monitoring system. This portion of the system is the most critical part of the system.

Electrical Supply Unit

This unit is normally a very special electrical control system. The most common electrical supply unit provides low frequency, variable voltage. For large installations, medium frequency, variable voltage is used to reduce power costs and because it allows for higher outputs of ozone.

Ozone Generator

This unit consists of a pair of electrodes separated by a gas space and a layer of glass insulation. Oxygen-containing gas is passed through the empty space as a high-voltage alternating current is applied. An electrical discharge occurs across the gas space and ozone is formed when a portion of the oxygen is ionized and then becomes associated with non-ionized oxygen molecules.

Ozone Contactor

This unit is a mixing chamber for the ozone-rich material and the process water. The objective is to dissolve enough ozone in the water to achieve disinfection at the lowest possible cost. These units are available in many configurations:

1. Multi-Stage Porous Diffuser
   a. Single application of an ozone-rich stream
   b. Application of ozone to second state

2. Educator System
   a. Total flow through educator
   b. Partial plant flow through the educator

3. Turbine
   a. Positive pressure
   b. Negative pressure

4. Packed bed
   a. Concurrent ozone-rich flow
   b. Countercurrent ozone-rich flow

5. Two-level diffuser
    a. Lower chamber off gases applied to upper chamber
    b. Application of ozone-rich gas to lower chamber

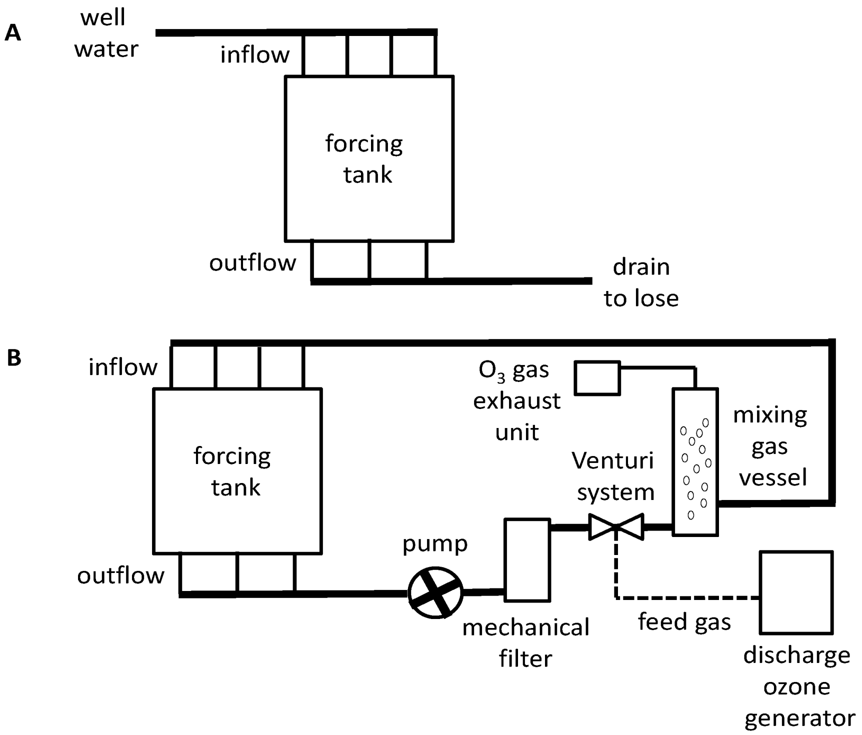

Figure 3-6 Ozone generator - Image by Carlo Nicoletto, Carmelo Maucieri, and Paolo Sambo is licensed under CC BY

For disinfection purposes, the diffuser-type ozone contactor is the most commonly used design. The off gases must be treated before release to the atmosphere. The most common method of treatment is the use of activated carbon and dilution.

Ozone Residuals

Residual ozone is measured by the iodometric method. The procedure is:

1. Collect an 800 ml sample in a 1-liter wash bottle
2. Pass pure air or nitrogen through the sample and then through an absorber containing 400 mL KI solution. Continue for 5 to 10 minutes at a rate of 1.0 liter/minute to purge all ozone from the sample.
3. Transfer KI solution to another vessel.
4. Add 20 mL 1 N sulfuric acid to reduce the pH to 2.
5. Titrate with a 0.005 N sodium thiosulfate solution.
6. Add several drops of starch.
7. The end point is reached when the purple color is discharged and solution becomes colorless.
8. Repeat this test using a blank or distilled water.

9. Calculation

O_3 , mg/L = ((A + B) x N x 24,000)/V_{sample} mL

Where,

A = mL of titrant for sample
B = mL of titrant for blank (positive if turned blue and negative if had to back titrate blank)
N = normality of sodium thiosulfate
V_{sample} = volume of the sample

Continuous inline ozone residual analyzers are available similar to the continuous inline chlorine residual analyzers.

Safety

Ozone is a toxic gas that is a hazard to plants and animals. Ozone irritates nasal passages in low concentrations. When ozone breaks down in the atmosphere as a result of photochemical reactions, the resulting atmospheric pollutants can be very harmful. However, ozone is less of a hazard than gaseous chlorine because chlorine is normally manufactured and delivered to the plant site. Ozone is produced on the site, it is used in low concentrations, and it is not stored under pressure. Problem leaks can be stopped by turning the unit off.

Ozone production equipment has various fail-safe protection devices that will automatically shut off the equipment when a potential hazard develops.

Maintenance

Electrical equipment and pressure vessels should be inspected monthly by trained operators. A yearly preventive maintenance program should be conducted by factory representative or by an operator trained by the manufacturer. Lubrication of the moving parts should be done according to the manufacturer's recommended schedule.

Applications of Ozone

In addition to using ozone after filtration for bacterial disinfection and viral inactivation, ozone may be used for several other purposes in treating drinking water. Ozone may be used before coagulation for treating iron and manganese, helping flocculation, and removing algae. When ozone is applied before filtration it may be used for oxidizing organics, removing color, or treating tastes and odors.

Advantages and Limitations of Ozone

The advantages include:

1. Ozone is more effective than chlorine in destroying viruses and bacteria.
2. The ozonation process uses a short contact time (10 to 30 minutes).
3. No harmful residuals that need to be removed after ozonation are produce or are present.
4. After ozonation, no regrowth of microorganisms occurs, except for those organisms protected by the particulates in the water stream.
5. Ozone is generated on site, and fewer safety problems associated with shipping and handling exist.
6. Removes color, odor, and tastes (phenols).
7. Oxidizes iron, manganese, sulfide, and organics.

The limitations include:

1. Low dosage may not effectively inactivate some viruses, spores, and cysts.
2. Ozonation is a more complex technology than chlorination or UV disinfection, requiring complicated equipment and efficient contacting systems.
3. Ozone is very reactive and corrosive, and requires corrosion-resistant materials such as stainless steel.
4. Ozonation is not economical for water with high levels of suspended solids, biochemical oxygen demand, chemical oxygen demand, or total organic carbon.
5. Ozone is extremely irritating and possibly toxic, so off gases from the contactor must be destroyed to prevent exposure.
6. The cost of treatment can be relatively high in capital and power costs.

Ozone can be an effective disinfectant, however, the capital costs and the O&M costs of ozone may not be competitive with available disinfection alternatives.

Review Questions

1. Describe disinfection byproducts.

2. Explain the Disinfection Byproducts Rule.

3. Describe the formation of disinfection byproducts.

Test Questions

1. The MCL for TTHMs is _________, and HAA5s have an MCL of __________.

    a. 0.080 milligram per liter, 0.060 milligrams per liter
    b. 0.10 milligrams per liter, 0.080 milligrams per liter
    c. 80 milligrams per liter, 60 milligrams per liter
    d. 60 micrograms per liter, 40 micrograms per liter

2. Compliance with the maximum contaminant levels for two groups of DBPs in the Stage II Disinfection Byproducts Rule (TTHMs and HAA5) is calculated for _________ in the distribution system. This approach, referred to as the locational running annual average (LRAA), differs from previous requirements, which determine compliance by calculating the running annual average of samples from all monitoring locations across the system.

    a. random sites
    b. each monitoring location
    c. dead ends
    d. the first tap

3. Temperature conditions influence the effectiveness of the disinfectant. The higher the temperature of water, the _______ efficiently it can be treated.

    a. less
    b. no change in how
    c. more
    d. none are correct (more factors influence the efficiency and temperature efficiency cannot be determined)

4. ___________ are an example of undesirable compounds formed by reactions between chlorine and certain organics. Disinfecting chemicals often react with organics and reducing agents.

    a. Benzene
    b. Chlorite
    c. Trihalomethanes (THMs and HAA5s)
    d. Chlorate

5. ________ does not form carcinogenic compounds that may be formed by other chlorine compounds.

   a. Gas chlorine
   b. Sodium hypochlorite
   c. Calcium hypochlorite
   d. Chlorine dioxide

6. _______ can be used to destroy pathogenic microorganisms. To be effective, the rays must come in contact with each microorganism.

   a. X-rays
   b. Radium
   c. Ultraviolet light
   d. Radon

7. The inability of ______ to provide a residual in the distribution system is a major drawback to its use.

   a. ozone
   b. chloramines
   c. chlorine dioxide
   d. calcium hypochlorite

8. _______ have proven effective in accomplishing reducing the formation of THMs and other DBPs and maintaining a detectable residual throughout the distribution system.

   a. UV light
   b. Ozone
   c. Heat
   d. Chloramines

9. ________ can be used as a disinfectant. It does not form carcinogenic compounds that may be formed by disinfectants. Also, it is not affected by ammonia, and it is a very effective disinfectant at higher pH levels.

   a. UV light
   b. Ozone
   c. Chlorine dioxide
   d. Sodium hypochlorite

10. In addition to using _____ after filtration for bacterial disinfection and viral inactivation, it may be used for several other purposes in treating drinking water. It can be used before coagulation for treating iron and manganese, helping flocculation, and removing algae, and when it is applied before filtration it may be used for oxidizing organics, removing color, or treating tastes and odors. However, it does not produce a residual that is carried into the distribution system.

    a. UV light
    b. Ozone
    c. Chlorine dioxide
    d. Chloramines

CHAPTER 4: CHLORAMINATION

Objectives:

- Describe chloramination
- Outline the uses of chloramination
- Explain the formation of chloramines

Chloramines are disinfectants used to treat drinking water and they:

1. Are most commonly formed when ammonia is added to chlorine to treat drinking water
2. Provide longer-lasting disinfection as the water moves through pipes to customers

Chloramines have been used by water utilities since the 1930s. One in five Americans use drinking water treated with chloramines for disinfection. Water that contains chloramines and meets EPA regulatory standards is safe to use for:

1. Drinking
2. Cooking
3. Bathing
4. Other household uses

Many public water systems (PWSs) in the United States use chlorine as their secondary disinfectant. However, some PWSs have changed their secondary disinfectant to chloramines in order to meet disinfection byproduct requirements.

Chloramination is the treatment of drinking water with a chloramine disinfectant. Chlorine and small amounts of ammonia are added to water one at a time. These chemicals react to form chloramine (combined chlorine), which is a long lasting disinfectant. Chloramine disinfection is sometimes used in large distribution systems.

In the United States, the maintenance of a disinfection residual that remains measureable in the water distribution system is required by the EPA.

EPA regulations provide two choices for disinfectant residual. They are chlorine or chloramine. Many major water agencies are changing to chloramine to better meet current and anticipated federal drinking water regulations and to protect public health.

Chloramine is toxic to fish and amphibians. Chloramine, like chlorine, comes in direct contact with their bloodstream through their gills, and it must be removed from water added to aquariums and fish ponds. It must also be removed from water prior to use in dialysis machines, since water comes into direct contact with a patience's bloodstream during treatment.

Chloramine is generally considered a problem in brewing beer because it can react with and change some of the natural plant flavors that make up beer. It may slow or alter the yeast activity. Because chloramine dissipates much more slowly than chlorine from water, beer-makers prefer carbon filtration to neutralize chloramines in the water.

Much of the recent discussion concerning chloramine has focused on N-nitrosodimethylamine (NDMA), and it is critical to distinguish between chloramine and NDMA. NDMA can be a byproduct of chloramination or chlorination; however, drinking water is not a major source of exposure to NDMA. The biggest sources of human exposure to NDMA is tobacco smoke, chewing tobacco, bacon and other cured meats, beer, fish, cheese, toiletries, shampoos, cleansers, interior air of cars, and household pesticides. In addition, NDMA can form in the stomach during digestion of foods or drugs that contain alkylamines, which are naturally occurring compounds.

At very high levels, NDMA may cause serious human health problems, such as liver disease. Such effects are seen at concentrations ranging from 5 to 50 parts per million in water; for comparison a study conducted by the California Department of Health Services in 1999 and 2000 found the highest level of NDMA in drinking water that had been treated with chloramine was 0.00006 parts per million. In that study, most of the concentrations of NDMA were far lower than that, and many water samples in the California Department of Health Services study did not have any detectable concentrations of NDMA.

Chloramination

Chloramination is used as an alternative disinfection process in place of free chlorine. An operator's decision to use chloramine in place of chlorine depends on several factors, including the quality of the raw water, the ability of the treatment plant to meet various regulations, operational practices, and distribution system characteristics. Chloramines have proven effective in accomplishing:

1. Reducing the formation of THMs and other DBPs
2. Maintaining a detectable residual throughout the distribution system
3. Penetrating the biofilm in the pipeline and reducing the potential for coliform regrowth
4. Killing or inactivating heterotrophic plate count bacteria
5. Killing or inactivating heterotrophic plate count bacteria
6. Reducing taste and odor problems

Methods for Producing Chloramines

Three primary methods are used to produce chloramines:

1. Preammoniation followed by later chlorination-in this method, ammonia is applied at the rapid-mix unit process and chlorine is added downstream at the entrance to the flocculation basins. This approach usually produces lower THM levels than the postammoniation method. Preammoniation is used to form chloramines that does not

produce phenolic tastes and odors, but this method may not be as effective as postammoniation for controlling tastes and odors associated with diatoms and anaerobic bacteria in source waters.

2. Concurrent addition of chlorine and ammonia-in this method, chlorine is applied to the plant influent, and at the same time or immediately thereafter, ammonia is introduced at the rapid-mix unit process. Concurrent chloramination produces the lowest THM levels for the three methods.
3. Prechlorination/Postammoniation-in this method, chlorine is applied at the head of the plant and a free chlorine residual is maintained throughout the plant processes. Ammonia is added at the plant effluent to produce chloramines. Because of the longer free chlorine contact time, this application method will result in the formation of more THMs, but it may be necessary to use this method to meet the disinfection requirements to the Surface Water Treatment Rule. A major limitation of using chloramine residuals is that chloramines are less effective as a disinfectant than free chlorine residuals. However, chloramine residuals go deeper into the distribution system and last longer than free chlorine residuals.

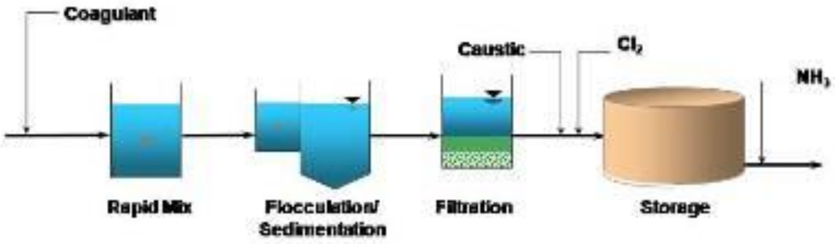

Figure 4-1 Chloramination Disinfection – Image by the EPA is in the public domain

When measuring combined chlorine residuals (chloramines) in the field, analyze for total chlorine. Total chlorine is the total concentration of chlorine in water, including the combined chlorine and the free available chlorine. No free chlorine should be present at chlorine to ammonia nitrogen ratios of 3:1 to 5:1. Care must be taken when attempting to measure free chlorine with chloraminated water because the chlorine residual will interfere with the DPD method of measuring free chlorine.

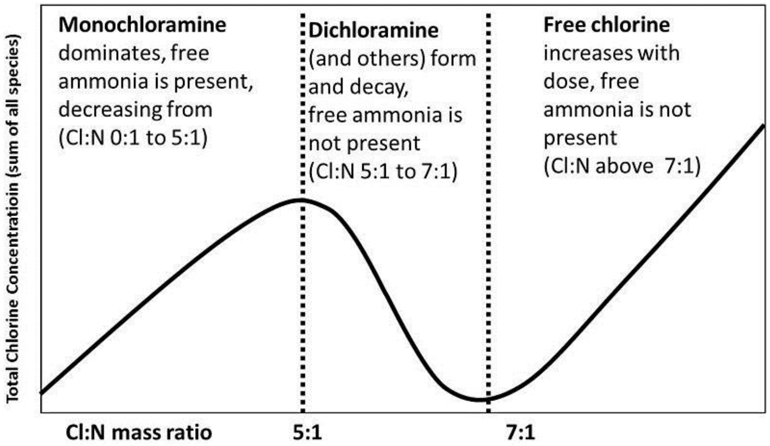

Figure 4-2 Breakpoint Curve for Chloramination – Image by Aliciacdiehl is licensed under CC BY-SA 3.0

In plants where THMs are not a problem, sufficient chlorine to get past breakpoint is added to the raw water. Chlorine residual aids coagulation and algal control, reduces odor problems, and provides sufficient chlorine contact time to effectively kill or inactivate pathogenic organisms. Therefore, the treated water will have a very low chlorine residual, but the residual will be a very effective disinfectant.

When chlorine is added to water containing ammonia, the ammonia reacts with hypochlorous acid to form monochloramine, dichloramine, and trichloramine. The formation of these chloramines depends on the pH of the solution and the initial chlorine-ammonia ratio.

At the pH levels usually found in water treatment plants (pH 6.5 to 7.5), monochloramine and dichloramine exist together. At pH levels below 5.5, only dichloramine exists. Below pH 4.0, trichloramine is the only compound found. The mono and dichloramine forms have definite disinfection powers and are of interest in the measurement of chlorine residuals. Dichloramine has a more effective disinfecting power than monochloramine. However, dichoramine is not recommended as a disinfectant because of taste and odor problems. Chlorine reacts with phenolic compounds and salicylic acid to form chlorophenol, which has an intense medicinal odor. This reaction goes much slower in the presence of monochloramine.

Nitrification

Nitrification is an important and effective microbial process in the oxidation of ammonia in land and water environments. Two groups of organisms are involved in the nitrification process:

1. Ammonia-oxidizing bacteria, *Nitrobacter*
2. Nitrite-oxidizing bacteria, *Nitrosoma*

When nitrification occurs in chloraminated drinking water, the process may lower the water quality unless the nitrification process reaches completion. Incomplete or partial nitrification causes the production of nitrite from the growth of *Nitrobacter* bacteria. This nitrite, in turn, rapidly reduces free chlorine and can interfere with the measurement of free chlorine. The end result may be a loss of total chlorine and ammonia and an increase in the concentration of heterotrophic plate count bacteria.

Factors influencing nitrification include the water temperature, the detention time in the reservoir or distribution system, excess ammonia in the water system, and the chloramine concentration used. Conditions that are most likely to lead to nitrification when using chloramines are a pH of 7.5 to 8.5, a water temperature of 77 to 86^{o}F, a free ammonia concentration in the water, and a dark environment. The danger in allowing nitrification episodes to occur is that the operator may be left with very low or no total chlorine residual. Total chlorine residual is the total concentration of chlorine in water, including the combined chlorine and the free available chlorine.

The Surface Water Treatment Rule requires disinfection of all surface water supply systems as protection against exposure to viruses, bacteria, and *Giardia*.

Drinking water regulations are constantly changing. The Interim Enhanced Surface Water Rule and the Disinfectant/Disinfection By-products Rule were passed in 1998 and further modifications of these rules have been developed. The goal of these rules was to increase the public protection form illness caused by *Cryptosporidium*, to limit the amount of certain potentially harmful disinfection byproducts that may remain in drinking water after treatment.

Review Questions

1. Describe chloramination.

2. Outline the uses of chloramination.

3. Explain the formation of chloramines.

Test Questions

1. Chloramine is toxic to fish and amphibians. Chloramine, like chlorine, comes in direct contact with their bloodstream through their gills, and it must be removed from water added to aquariums and fish ponds. It must also be removed from water prior to use in _____________

   a. boilers
   b. metal plating operations
   c. dialysis
   d. oil refining

2. Chloramine is generally considered a problem in ______ because it can react with and change some of the natural plant flavors. It may slow or alter the yeast activity.

   a. dialysis
   b. brewing beer
   c. paper manufacturing
   d. commercial baking

3. Recent discussion concerning chloramine has focused on the disinfection byproduct _______.

   a. chlorite
   b. THM
   c. bromate
   d. NDMA

4. Monochloramine and dichloramine forms of chloramines have definite disinfection powers and are of interest in the measurement of chlorine residuals. ________ has a more effective disinfecting power.

   a. Monochloramine
   b. Trichloramine
   c. Dichloramine
   d. N-nitrosodimethylamine

5. _______ ammonia-oxidizing bacteria.

   a. *Nitrobacter*
   b. *E. coli*
   c. *Cryptosporidium*
   d. *Nitrosoma*

6. _______ nitrite-oxidizing bacteria.

   a. *Nitrobacter*
   b. *E. coli*
   c. *Cryptosporidium*
   d. *Nitrosoma*

7. When nitrification occurs in chloraminated drinking water, the process may lower the water quality unless the nitrification process reaches completion. Incomplete or partial nitrification causes the production of _____ from the growth of *Nitrobacter* bacteria. This, in turn, rapidly reduces free chlorine and can interfere with the measurement of free chlorine.

   a. nitrate
   b. nitrite
   c. ammonia
   d. NDMA

8. At very high levels, NDMA may cause serious human health problems, such as _______.

   a. malformation of the brain
   b. gastrointestinal disruptions
   c. liver disease
   d. kidney disorders

9. _________ is the total concentration of chlorine in water, including the combined chlorine and the free available chlorine.

   a. Monochloramine
   b. Chlorine residual
   c. Breakpoint chlorination
   d. Total chlorine

CHAPTER 5: FLUORIDATION

Objectives:

- Describe the regulation concerning fluoride
- List the chemicals that provide fluoride ions in water supplies
- Calculate fluoride dosage for water supply

Water fluoridation is the controlled addition of fluoride to a public water supply to reduce tooth decay. Fluoridated water contains fluoride at a level that is effective for preventing caries or cavities; this process can occur naturally or by adding fluoride. Typically a fluoridated compound is added to drinking water. However, defluoridation is needed when the naturally occurring fluoride level exceeds recommended limits. In 2011 the World Health Organization (WHO) suggested a level of fluoride from 0.5 to 1.5 mg/L (milligrams per liter), depending on climate, local environment, and other sources of fluoride. Bottled water typically has unknown fluoride levels.

Dental remains a major public health concern in most industrial countries, affecting 60–90% of schoolchildren and the vast majority of adults. Water fluoridation reduces cavities in children. Efficacy in adults is less clear. A review of the prevalence of dental decay estimates a reduction in cavities when water fluoridation was used by children who had no access to other sources of fluoride. Most European countries have experienced substantial declines in tooth decay without its use, however milk and salt fluoridation is widespread.

Although fluoridation can cause dental fluorosis at levels above 2 mg/L per day, which can alter the appearance of developing teeth. Also no clear evidence exists of other adverse effects of fluoridation. Fluoride's effects depend on the total daily intake of fluoride from all sources. Drinking water is typically the largest source of fluoride, and other methods of fluoride therapy include fluoridation of toothpaste, salt, and milk. The views on the most efficient method for community prevention of tooth decay are mixed. The World Health Organization reports that water fluoridation, when feasible and culturally acceptable, has substantial advantages, especially for subgroups at high risk of dental decay. European Union (EU) finds no benefit to water fluoridation compared with topical use.

Public water fluoridation was first practiced in the U.S. As of 2012, 25 countries have artificial water fluoridation to varying degrees, 11 of them have more than 50% of their population drinking fluoridated water, and 28 countries have water that is naturally fluoridated—though in many of them the fluoride is above the recommended safe level. As of 2012, about 435 million people worldwide received water fluoridated at the recommended. About 214 million of them living in the United States.

The goal of water fluoridation is to prevent tooth decay by adjusting the concentration of fluoride in public water supplies. Tooth decay is one of the most prevalent chronic diseases worldwide. Although it is rarely life-threatening, tooth decay can cause pain and impair eating, speaking, facial appearance, and acceptance into society, and it greatly affects the quality of life of children.

The goal of water fluoridation is to prevent a chronic disease whose burdens particularly fall on children and the poor. Fluoridation does not affect the appearance, taste, or smell of drinking water. It is normally accomplished by adding one of three compounds to the water: sodium fluoride, fluorosilicic acid, or sodium fluorosilicate.

Sodium fluoride (NaF) was the first compound used, and it is the reference standard. It is a white, odorless powder or crystal; the crystalline form is preferred if manual handling is used, as it minimizes dust. It is more expensive than the other compounds, but is easily handled and is usually used by smaller utility companies. It is toxic in gram quantities by ingestion or inhalation.

Fluorosilicic acid (H_2SiF_6) is the most commonly used additive for water fluoridation in the United States. It is an inexpensive liquid by product of phosphate fertilizer manufacture. It comes in varying strengths, typically 23–25%; because it contains so much water, shipping can be expensive. It is also known as hexafluorosilicic, hexafluosilicic, hydrofluosilicic, and silicofluoric acid.

Sodium fluorosilicate (Na_2SiF_6) is the sodium salt of fluorosilicic acid. It is a powder or very fine crystal that is easier to ship than fluorosilicic acid. It is also known as sodium silicofluoride.

These compounds were chosen because of their solubility, safety, availability, and low cost. A 1992 census found that, for U.S. public water supply systems reporting the type of compound used, 63% of the population received water fluoridated with fluorosilicic acid, 28% with sodium fluorosilicate, and 9% with sodium fluoride

Figure 5-1 Feed pump application of fluoride compound into drinking water – Image by the Library of Congress is in the public domain

The Centers for Disease Control and Prevention (CDC) developed recommendations for water fluoridation that specify requirements for personnel, reporting, training, inspection, monitoring, surveillance, and actions in case of overfeed, along with technical requirements for each of compounds used. The maximum amount of fluoride from all sources (including non-dietary sources) is 0.05 mg/kg body weight per day for children and adults, including pregnant and lactating women.

In 2011, the U.S. Department of Health and Human Services (HHS) and the U.S. Environmental Protection Agency (EPA) lowered the recommended level of fluoride to 0.7 mg/L. In 2015, the U.S. Food and Drug Administration (FDA), based on the recommendation of the U.S. Public Health Service (PHS) for fluoridation of community water systems, recommended that bottled water manufacturers limit fluoride in bottled water to no more than 0.7 milligrams per liter (mg/L). Previous recommendations were based on evaluations from 1962, when the U.S. specified the optimal level of fluoride to range from 0.7 to 1.2 mg/L. These standards are not appropriate for all parts of the world, where fluoride levels might be excessive and fluoride should be removed from water. In 2011, the World Health Organization stated that 1.5 mg/L should be an absolute upper bound and that 0.5 mg/L may be an appropriate lower limit. Fluoride naturally occurring in water can be above, at, or below recommended levels. Rivers and lakes generally contain fluoride levels less than 0.5 mg/L, but groundwater, particularly in volcanic or mountainous areas, can contain as much as 50 mg/L.

In most drinking waters, over 95% of total fluoride is the F^-, with the magnesium, fluoride complex (MgF^+) being the next most common. Because fluoride levels in water are usually controlled by the solubility of fluorite (CaF_2), high natural fluoride levels are associated with calcium-deficient, alkaline, and soft water. Defluoridation is needed when the naturally occurring fluoride level exceeds recommended limits. It can be accomplished by percolating water through granular beds of activated alumina, bone meal, bone char, or tricalcium phosphate; by coagulation with alum or with precipitation with lime.

Fluoride's adverse effects depend on total fluoride dosage from all sources. At the commonly recommended dosage, the only clear adverse effect is dental fluorosis, which can alter the appearance of children's teeth during tooth development. In April 2015, recommended fluoride levels in the United States were changed to 0.7 ppm from 0.7–1.2 ppm to reduce the risk of dental fluorosis. Fluoride is the only chemical contaminate that has a primary contaminate level, 4 mg/L, and a secondary contaminate level, 2 mg/L.

Fluorosis can be prevented by monitoring all sources of fluoride, with fluoridated water directly or indirectly responsible for an estimated 40% of risk and other sources, notably toothpaste, responsible for the remaining 60%. Fluoridation has little effect on risk of bone fracture (broken bones. No clear association between fluoridation and cancer or deaths due to cancer, for cancer in general and also specifically for bone cancer (osteosarcoma).

In rare cases, improper implementation of water fluoridation can result in over fluoridation that causes outbreaks of acute fluoride poisoning, with symptoms that include nausea, vomiting, and diarrhea. Three such outbreaks were reported in the U.S. between 1991 and 1998, caused by fluoride concentrations as high as 220 mg/L; in the 1992 Alaska outbreak, 262 people became ill and one person died. In 2010, approximately 60 gallons of fluoride were released into the water supply in Asheboro, North Carolina in 90 minutes which was an amount that was intended to be released in a 24-hour period.

Like other common water additives such as chlorine, hydrofluosilicic acid and sodium silicofluoride decrease pH and cause a small increase of corrosivity; however, this problem is easily addressed by increasing the pH. Although it has been hypothesized that hydrofluosilicic acid and sodium silicofluoride might increase human lead uptake from water, a 2006 statistical analysis did not support concerns that these chemicals cause higher blood lead concentrations in children. Trace levels of arsenic and lead may be present in fluoride compounds added to water, but no credible evidence exists that their presence is of concern.

The effect of water fluoridation on the natural environment has been investigated, and no adverse effects have been established. Issues studied have included fluoride concentrations in groundwater and downstream rivers; lawns, gardens, and plants; consumption of plants grown in fluoridated water; air emissions; and equipment noise.

Fluoride exerts its major effect by interfering with the demineralization mechanism of tooth decay. Tooth decay is a disorder that features an increase within dental plaque of bacteria such as *Sreptococcus mutans* and *Lactobacillus*. These organisms produce organic acids when carbohydrates, especially sugar, are eaten. When enough acid is produced to lower the pH below 5.5, the acid dissolves tooth enamel in a process known as *demineralization*. After the sugar is gone, the mineral loss can be recovered from ions dissolved in the saliva. Cavities result when the rate of demineralization exceeds the rate of remineralization.

Sources of Fluoride
Toothpaste enhanced with fluoride
Fluoride supplements
Food processed with fluoridated water
Mouthwash enhanced with fluoride
Fluoridated water supplies

Figure 5-2

All fluoridation methods, including water fluoridation, create low levels of fluoride ions in saliva and plaque fluid that exerts a surface effect on teeth. A person living in an area with fluoridated water may experience rises of fluoride concentration in saliva to about 0.04 mg/L several times during a day. Technically, this fluoride does not prevent cavities it controls the rate at which they develop. When fluoride ions are present in plaque fluid along with dissolved hydroxyapatite, and the pH is higher than 4.5, a fluorapatite-like remineralized veneer is formed over the remaining surface of the enamel; this veneer is much more acid-resistant than the original hydroxyapatite, and is formed more quickly than ordinary remineralized enamel would be.

The MCLG for fluoride is 4.0 mg/L or 4.0 ppm. EPA has set this level of protection based on the best available science to prevent potential health problems. EPA has set an enforceable regulation for fluoride, called a maximum contaminant level (MCL), at 4.0 mg/L or 4.0 ppm. MCLs are set as close to the health goals as possible, considering cost, benefits and the ability of public water systems to detect and remove contaminants using suitable treatment technologies. In this case, the MCL equals the MCLG, because analytical methods or treatment technology do not pose any limitation.

EPA has also set a secondary standard (SMCL) for fluoride at 2.0 mg/L or 2.0 ppm. Secondary standards are non-enforceable guidelines regulating contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. EPA recommends secondary standards to water systems but does not require systems to comply. However, states may choose to adopt them as enforceable standards. Tooth discoloration and/or pitting is caused by excess fluoride exposures during the formative period prior to eruption of the teeth in children. The secondary standard of 2.0 mg/L is intended as a guideline for an upper bound level in areas which have high levels of naturally occurring fluoride. The level of the SMCL was set based upon a balancing of the beneficial effects of protection from tooth decay and the undesirable effects of excessive exposures leading to discoloration.

States may set more stringent drinking water MCLGs and MCLs for fluoride than EPA. The drinking water standards are currently under review. The Safe Drinking Water Act requires EPA to periodically review the national primary drinking water regulation for each contaminant and revise the regulation, if appropriate. In 2003 and as part of the first Six Year Review, EPA reviewed the drinking water standard for fluoride and found that new health and exposure data were available on orally ingested fluoride. EPA requested that the National Research Council (NRC) of the National Academies of Science (NAS) conduct a review of this data and in 2006, the NRC published their evaluation in a report entitled, Fluoride in Drinking Water: A Scientific Review of EPA's Standards. The NRC recommended that EPA update its fluoride risk assessment to include new data on health risks and better estimates of total exposure.

In order to calculate the fluoride dosage, or any chemical dosage, one has to know the pounds of chemical and volume of water in millions of gallons per day.

$$\text{Dosage, mg/L} = \frac{\text{Chemical, lb}}{(\text{Water, MGD})(8.34\ \text{lb/day})}$$

In order to determine the amount of feed solution in gallons or gallons per day to treated water, one must know the amount of water to be treated in gallons or gallons per day, the feed dose in mg/L, and the feed solution in mg/L.

$$\text{Feed Solution, gal} = \frac{(\text{Feed, gal})(\text{Feed dose, mg/L})}{(\text{Feed Solution, mg/L})}$$

In blending waters or mixing chemicals of different strengths, the volumes or flows of the chemicals and their strengths must be known.

$$\text{Mixture Strength, \%} = \frac{(\text{Vol I, gal})(\text{Strength I, \%}) + (\text{Vol II, gal})(\text{Strength II , \%})}{\text{Vol I, gal} + \text{Vol II, gal}}$$

Or

$$= \frac{(\text{Flow I, gpd})(\text{Strength I, \%}) + (\text{Flow II, gpd})(\text{Strength II, \%})}{(\text{Flow I, gpd}) + (\text{Flow II, gpd})}$$

When using chemicals for fluoridation, one needs to know the percentage fluoride ion purity. This information allows for the conversion of pounds of chemical dosage to pounds of fluoride ion available.

$$\text{Fluoride Ion Purity, \%} = \frac{(\text{Molecular Weight of Fluoride})(100\%)}{\text{Molecular Weight of Chemical}}$$

Review Questions

1. Describe the regulation concerning fluoride.

2. List the chemicals that provide fluoride ions in water supplies

3. Calculate fluoride dosage for water supply if 2.4 million gallons are treated each day and 14.2 pounds of fluoride is added during a 24-hour period.

Test Questions

1. EPA has set an enforceable regulation for fluoride, called a maximum contaminant level (MCL), at ______.
   a. 4.0 mg/L
   b. 2.0 mg/L
   c. 15 ppb
   d. 80 ppb

2. The goal of water fluoridation is to ______ by adjusting the concentration of fluoride in public water supplies.

   a. enhance skeletal fluorosis
   b. improve kidney function
   c. prevent tooth decay
   d. disinfect water supplies

3. Like other common water additives such as chlorine, hydrofluosilicic acid and sodium silicofluoride ______ pH and cause a small increase of corrosivity.

   a. decrease
   b. increase
   c. has no effect on
   d. helps to buffer

4. In rare cases, improper implementation of water fluoridation can result in over fluoridation that causes outbreaks of ________, with symptoms that include nausea, vomiting, and diarrhea.

   a. increased lead in drinking water
   b. acute fluoride poisoning
   c. dental fluorosis occurring
   d. over fluoridation has no side effects

5. If a water system is treating a total daily flow of 2.6 million gallons of water that has a natural fluoride level of 0.2 mg/L, how many pounds of fluoride should be added to the water each day at the water treatment plant?

   a. 12 pounds of fluoride
   b. 11.2 pounds of fluoride
   c. 10.8 pounds of fluoride
   d. 10 pounds of fluoride

CHAPTER 6: CORROSION, IRON, AND MANGANESE

Objectives:

- Describe corrosion mechanisms
- Explain scale deposition in terms of saturation
- Describe the methods of corrosion control
- Describe methods used to control iron and manganese

Corrosion Control and Water Stabilization

Corrosion is a complex topic involving numerous chemical, electrical, physical, and biological factors. A few concepts describe the major principles of corrosion. Selecting and implementing an effective corrosion-control program require and understanding of these concepts.

Corrosion is the gradual decomposition or destruction of a material by chemical action, often due to an electrochemical reaction. Corrosion may be caused by:

- Stray current electrolysis
- Galvanic corrosion caused by dissimilar metals
- Differential-concentration cells

Corrosion begins at the surface of a material and moves inward. The severity and type of corrosion depend on the chemical and physical characteristics of the water and the material.

Electrochemical Corrosion: Galvanic Cell

Metallic corrosion in potable water is always the result of an electrochemical reaction. An electrochemical reaction is a chemical reaction where the flow of electric current is an essential part of the reaction. If the electric current is stopped by breaking the circuit, the chemical reaction will stop. Also if the chemical reaction is stopped by removing one the reacting chemicals, the flow of electric current will stop. For corrosion to occur, electric current and chemical reaction must be present.

The deterioration of metal during corrosion is called an electrochemical reaction because a chemical and an electrical process are occurring. The components of the process are:

1. Anode-point from which metal is lost and electric current begins. The anode (positive pole) attracts negatively charged particles or ions (anions) in an electrolyte solution. Anions are attracted to the anode under the influence of a difference in electrical potential.

2. Cathode-point where electric current leaves the metal and flows to the anode through the electrolyte. A cathode is the negative pole or electrode of an electrolytic cell or system. It will attract positively charged particles or ions (cations) in an electrolyte solution. Cations are attracted to the cathode under the influence of a difference in electrical potential.
3. Electrolyte-conduction solution (water with dissolved salts). A substance that separates into two or more ions when it is dissolved in water.

The anode and cathode must be joined. In an iron pipe, at the anode, a molecule of iron dissolves into the water as a ferrous ion, and two electrons flow to the cathode. At the cathode the electrons leave the metal at the point of contact with the electrolyte and react with hydrogen in the water to form hydrogen gas. The hydrogen ions are always present in the water from the normal separation of water, and the electrolyte is in contact with the anode and the cathode, completing the circuit.

At the anode, the dissolved iron reacts with oxygen and the water forming a rust film composed initially ferrous hydroxide. Additional water and oxygen then react with the ferrous hydroxide to form ferric hydroxide, which becomes a second layer over the ferrous hydroxide.

This multilayered rust deposit is known as a tubercle. Tubercles can grow to the point that the carrying capacity of the pipe is significantly reduced. Also during periods of high flow rates, the tubercles may dislodge, resulting in rusty or red-colored water. The formation of a rust coating on the pipe has another important effect on the rate of corrosion. As the rust film forms, it begins to cover and protect the anode, slowing the rate of corrosion. If the rust film is flushed away, the corrosion reaction accelerates.

A more complex form of electrochemical corrosion is caused by the joining of dissimilar metals. This type of corrosion is called galvanic corrosion. Like the corrosion cell, the galvanic corrosion cell has an anode, a cathode, and electrolyte, as well as a connection between the anode and cathode. This galvanic cell, however, has two dissimilar metals at the anode and cathode. The degree to which a particular metal will become anodic (corrode) in a galvanic reaction is related to its tendency to enter into solution. In this process, the metal reverts to its natural ore state. The relative tendency of various metals to revert to an ore state is demonstrated by their position on an electromotive series or galvanic series in which the most active metals are listed at the top in table 7.1. An electromotive or galvanic series is a list of metals and alloys presented in the order of their tendency to corrode (go into solution). The size and sign of the electrode potential indicates how easily these elements will take on or give up electrons, or corrode.

The higher the level of activity, the greater the tendency for the metal to corrode. Also, the further apart the two metals are on the galvanic series, the greater the galvanic corrosion potential. The more active metal of any two in the galvanic series will always become the anode. When iron and copper water pipes are joined, the iron will corrode if water contains dissolved oxygen and the copper will be protected. Because of their active positions on the galvanic series, zinc and magnesium make excellent anodes, and they are commonly used as sacrificial anodes in water tanks or for buried pipelines to prevent corrosion. These reactive metals, called base metals, will corrode preferentially to aluminum and iron for example. A metal, such as iron, will react with dilute hydrochloric acid to form hydrogen.

On the cathodic side of the galvanic series, the least active reactive metals are called noble metals. One of the most noble metals is gold. Stainless steel is cathodic to most metals, and it is used in critical chemical industry applications where corrosion potential is great. Stainless steel is used in high-pressure reverse osmosis desalination systems due to its excellent corrosion resistance in the presence of highly conductive seawater.

As the galvanic series demonstrates, when copper and lead solder are in contact, the lead becomes the anode and will corrode in preference to the copper. The relatively high toxicity of lead and its anodic tendencies are why lead has been banned from use in potable water distribution systems by the US Government under the 1986 Safe Drinking Water Act and the Lead and Copper Rule. Other factors, such as water chemistry, biological films, and physical characteristics, like temperature and flow rate, play a role in the severity of the corrosion reaction.

An important feature of the galvanic corrosion is the relative size of the anode and cathode. The level of galvanic electric current increases as the area of the cathode increases. A large cathode will generate a high level of electrical potential. If the current is directed at a small anode, a relatively large amount of metal will dissolve from the available anode area and deep pits will form.

$Fe \rightarrow Fe^{2+} + 2e^-$
$O_2 + 4e^- + 2H_2O \rightarrow 4OH$
$Fe^{2+} + 2OH^- \rightarrow Fe(OH_2)$
$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3 + 4H_2O$

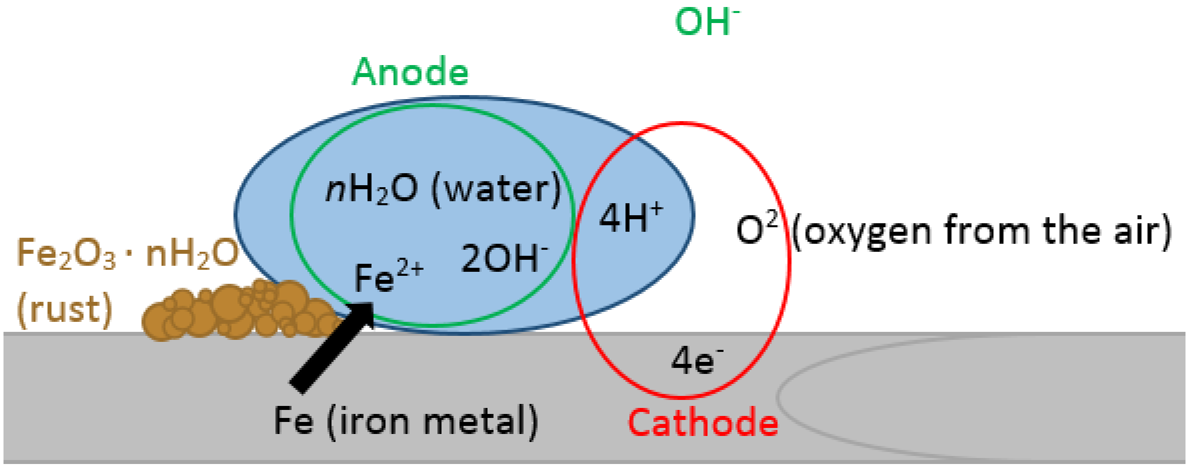

Figure 6-1 Electrochemical corrosion – Image by COC OER is licensed under CC BY

Factors influencing Corrosion

Corrosion is complex with many possible variables. The essential elements of a corrosion cell, including the specific case of a galvanic cell, are influenced by increasing or decreasing the rate of the electrochemical reaction. The electrochemical reaction rate is influenced by physical, chemical, and biological factors.

Physical Factors

Physical factors that influence corrosion include the type and arrangement of materials used in the system, system pressure, soil moisture, the presence of stray electric currents, temperature, and water flow velocity.

1. System construction - The type of materials that make up the anode and cathode influence corrosion; especially, the size of the anode and cathode

2. System pressure - High pressure increases corrosion because gases that can oxidize construction materials increase the maximum concentration of these gases in the water

3. Soil moisture - Contact with moist soil can cause external pipe corrosion because the moisture acts as the electrolyte in the corrosion cell

4. Stray electric current - Grounding of electric circuits to water pipes and can enhance corrosion. Stray current corrosion is more pronounced from direct current grounding than from alternating current grounding

5. Temperature - The rate of chemical reactions usually increases as temperature rise. Because chemical reactions are involved in corrosion, an increased temperature generally has the effect of increasing corrosion. Flow velocity has several significant influences on corrosion. Moderate flow rates are often beneficial while very high or low flow rates increase the rate of corrosion.

- Negative effects: stagnate water flow conditions increases corrosion. However, highly oxygenated water can become more corrosive under higher flow conditions as the movement of water increases the contact of oxygen with the pipe surface. In high velocities, erosion corrosion can occur, particularly in copper pipes. At rates exceeding 5ft/sec copper tubing will erode. This corrosion is more noticeable at elbows and joints and results in structural damage to the pipe. Circulating hot water systems in buildings are particularly susceptible to erosion corrosion because of flow velocities and high temperature.

- Beneficial effects: water that has protective properties, such as the tendency to deposit calcium carbonate film, or to which a corrosion inhibitor has been added, will be less corrosive under moderate flow conditions. Film formation requires deposition of calcium carbonate or the inhibitor (phosphate or silicate) on the surface of the metal. In stagnant water, deposition is limited. Under high flows, it may be scoured off the pipe as it forms or erosion corrosion may occur faster than the film deposits.

Chemical Factors

Various chemical factors influence corrosion, such as pH, alkalinity, chlorine residual, levels of dissolved solids, dissolved gases like oxygen and carbon dioxide, and the types and concentrations of various minerals present in water. These factors are:

1. Alkalinity - Alkalinity is the capacity of water to neutralize acids. This capacity is caused by the water's content of carbonate, bicarbonate, hydroxide, and occasionally borate, silicate, and phosphate. Alkalinity is expressed in milligrams per liter of equivalent calcium carbonate. Alkalinity is not the same as pH because water does not have to be strongly basic to have high alkalinity. Alkalinity is also a measure of how much acid must be added to a liquid to lower the pH to 4.5. Alkalinity is a measure of the buffering capacity, or the ability of a particular quality of water to resist a change in pH. The simples form of corrosion control is to add more alkalinity in the form of lime, soda ash, or caustic soda, or directly add calcium carbonate to the water

2. pH-measures - The amount of hydrogen ions present in the water. The hydrogen ion is extremely active (corrosive) at pH values below 4.0. Chlorine and hydrogen ions are usually present in sufficient concentrations in potable water to have a significant effect on corrosion. Low pH water tends to be corrosive, and high pH water is protective of pipe material. Very high pH water may have a tendency to deposit excessive amounts of scale, however. Certain pH levels offer less protection than would be assumed. At pH values near 8.3, the transition point between carbonate and bicarbonate, the buffering system is weak, and slightly lower pH values may be more protective

3. Dissolved solids - Solids dissolved in water are present as ions that increase the electrical conductivity of the water. Generally, the higher the dissolved solids or salt content of water, the greater the potential for corrosion to occur due to the increased conductivity. However, some solids are involved in scale formation, possibly slowing the rate of corrosion if a protective film is formed. All scale-forming components, such as iron oxide (rust) and calcium carbonate, are present first as dissolved solids in water before they deposit on the surface of pipes and fixtures

4. Hardness - The dissolved form of some of the principal scale-forming components in water is referred to as hardness. Hardness is composed primarily of calcium and magnesium ions. All hardness ions have the common property of forming a scale on the inside of pipes or fixtures under conditions of high enough concentration, and at elevated pH and temperature levels. Planned deposition of calcium carbonate film is one of the most common corrosion-control measures used in water systems. Several methods of measuring the relative level of calcium carbonate saturation in water are used. One of the simpler methods is called the Marble Test, which directly measures

whether a water sample will increase in hardness and pH when dosed with an excess of calcium carbonate. The Marble Test and a more extensive determination of the saturation level of calcium carbonate, called the Langelier Index, are used to measure the corrosivity of water and water's extent of stabilization

5. Chloride and sulfate - Chloride and sulfate ions in water inhibit the formation of protective scales by keeping hardness ions in solution. The relative amount of alkalinity compared to chloric and sulfate affects this tendency. It is recommended that the alkalinity, expressed as calcium carbonate equivalent, be five times higher than the sum of chloride and sulfate ions

6. Phosphate and silicate - These compounds have a tendency to form protective films in water systems when present in high enough concentrations and when in the correct chemical form for the particular conditions of the water. Phosphate and silicate compounds re added at the water treatment plant as a corrosion-control method

7. Trace metals - Trace metals of significance in corrosion control include copper, iron, lead, and zinc. When these elements are present in high concentrations in water, they are usually indicators of corrosion of the pipes and fittings. Copper and lead usually indicate corrosion of copper pipe and lead solder or service lines. Iron usually results from the corrosion of iron or steel pipe, and zinc results from corrosion of galvanized pipe. Iron and zinc may be involved in the formation of protective films that limit the rate of corrosion. Zinc is also a common corrosion-control additive, usually in a compound containing zinc and phosphate.

Biological Factors

Two types of organisms that can play an important role in corrosion of water distribution systems are iron bacteria and sulfate-reducing bacteria. They can increase the rate of corrosion and the formation of undesirable corrosion byproducts. Iron bacteria use dissolve iron as an energy source, and sulfate-reducing bacteria use sulfate for their energy. Each type of bacteria can grow in dense masses, and they may be relatively tolerant to disinfection by chlorine. They are particular troublesome in low-flow areas of distribution systems.

Figure 6-2 Corrosion in pipe with tubercle buildup – Image by Mr pantswearer is licensed under CC BY-SA 3.0

Oxygen Concentration Cell

Although galvanic cells are responsible for corrosion problems, by far the most common corrosion cell is the oxygen concentration cell. A dead end in the distribution system is the end of a water main that is not connected to other parts of the distribution system by means of a connection loop of pipe. An oxygen concentration cell can be started in this dead end of the water line. At this location ferrous ions and oxygen ions react to form solid ferric hydroxide and hydrogen ions. The electrons from the anode reaction flow through the metallic pipe where they react with dissolved oxygen which is replenished by flowing water. The excess hydrogen ions lower the pH and make it more corrosive.

In the dead pipe, an absence of oxygen and low pH make the conditions ideal for the growth of anaerobic bacteria. An anaerobic condition is one in which atmospheric or dissolved oxygen is not present. The action of these bacterial populations on trace organic material and on reducing the sulfate ions to sulfide are responsible for foul odors usually found in the dead ends of water mains.

As ferric hydroxide ages, it forms other minerals such as ferric oxide or iron rust. Eventually, the crust from ferric oxide becomes so thick that negative ions cannot enter the pit where corrosion is occurring, and iron ions cannot escape. The corrosion in the area stops. At this point, the pit is inactive. The reaction of dissolved oxygen with ferrous ions is very slow at low pH values. When the pH is less than 7.0, the reaction is so slow that tubercles do not form and the pits are not self-perpetuating. New pits keep starting in different places, so that corrosion appears to be uniform over the surface of the pipe.

Calcium Carbonate Saturation

Internal corrosion of pipes can be detected through rusty water complaints and by examining the insides of pipes for pitting, tubercles, and other evidence of corrosion. Corrosion from unstabilized water can be predicted by the amount of calcium carbonate saturation. The methods that are used to predict the stabilization of water are the Marble Test, Enslow Column, and the Langelier Index. Water is considered to be stable when it is just saturated with calcium carbonate. In this condition, the water will not dissolve or deposit calcium carbonate. Water treatment plant operators use two approaches to determine the calcium carbonate saturation level of their water: the Calcium Carbonate Precipitation Potential (CCPP) and the Langelier Index.

Marble Test and Enslow Column

To conduct a Marble Test for calcium carbonate saturation, first measure the pH, alkalinity, and hardness of the water sample. Add a pinch of powdered calcium carbonate and then stir the water for at least five minutes. The water should be stirred in a nearly-full stoppered flask to avoid the introduction of carbon dioxide from the air. Also, the water being stirred should be at the same temperature as the water in the distribution system. If the pH, alkalinity, or calcium carbonate increase, the water was under saturated with respect to calcium carbonate. If they decrease, the water was supersaturated. The CCPP equals the quantitative change in alkalinity (or calcium carbonate) due to the water being exposed to the powdered calcium carbonate.

The Enslow column can be conveniently used to perform the Marble Test. This tube is a column packed with calcium carbonate granules. The pH, alkalinity, and calcium carbonate are measured on a sample stream of water before and after passing through the column. The results are interpreted in the same manner as the Marble Test.

Langelier Index

Water is considered stable when it is just saturated with calcium carbonate. In stable water, the calcium carbonate is in equilibrium with the hydrogen ion concentration. If the pH is higher than the equilibrium point (positive Langelier), the water is scale forming and will deposit calcium carbonate. If the pH is lower than the equilibrium point (negative Langelier), the water is considered corrosive.

The Langelier Index (Saturation Index) is the most common index used to indicate how close water is to the equilibrium point, or the corrosiveness of water. This index is based on the equilibrium pH of water with respect calcium and alkalinity. The Langelier Index can be determined by using the equation:

$$Langelier\ Index = pH - pHs$$

- Where pH = actual pH of the water
- pH_S = pH at which water having the same alkalinity and calcium content is just saturated with calcium carbonate

In this equation, pH_S is defined as the pH value at which water of a given calcium content and alkalinity is just saturated with calcium carbonate. For some water of low calcium content and alkalinity, no pH value satisfies this definition; however, for most water, two values of pH_S exist. These difficulties can be avoided by defining pH_S as the pH where water of given calcium and bicarbonate concentrations is just saturated with calcium carbonate.

A positive Langelier Index (pH is greater than pH_S) indicates that the water is supersaturated with calcium carbonate and will tend to form scale. The water is not corrosive. A negative Langelier Index means that the water is corrosive.

The corrosive tendencies of water to particular metals, such as the ones used in distribution systems, are also significantly influenced by the amount of total dissolved solids (TDS). Water containing TDS exceeding 50 mg/L may exhibit corrosive tendencies in spite of a positive Langelier Index. The presence of various ions, such as sulfate and chloride ions in water, may interfere with the formation and maintenance of a uniform protective calcium carbonate layer on metal surfaces. In addition, the presence of these ions will accelerate the corrosion process.

Because of the various water quality indicators involved, the Langelier Index should only be used to determine the corrosive tendencies of water within a pH range of 6.5 to 9.5 provided that a sufficient amount of calcium ions and alkalinity over 40 mg/L as calcium carbonate are present in the water.

Three other indices for calcium carbonate saturation have been used:

1. Driving Force Index
2. Ryznar Index
3. Aggressive Index

Controlling Corrosion and Water Stabilization

To control corrosion, the operator must select the correct chemicals to treat the water, calculate the correct chemical dosage, and determine the proper chemical feeder settings. The water treatment operator must understand cathodic protection to control corrosion and the compounds used for cathodic protection.

Selection of Corrosion Control Chemicals

If the water is corrosive, steps should be taken to reduce the corrosivity of the water. Reducing corrosivity is almost always accomplished by treating the water with chemicals so that the water is saturated or slightly supersaturated with calcium carbonate. Chemicals should be fed after filtration. A slight excess of chemical could result in a supersaturated solution that could cement together the filer sand grains. Small amounts of turbidity could be introduced with the chemical and might produce misleading results suggesting poor filter performance. The chemical feed can take place before, after, or along with post-chlorination; however, sample should be taken only after post-chlorination because the chlorine may react with the chemicals used to reduce corrosivity.

The selection of a chemical to achieve calcium carbonate saturation will depend on the water quality characteristics of the water and the cost of the chemicals. The central idea is that all chemical characteristics and pH must be present in the right proportions to achieve calcium carbonate saturation. For water that has low hardness and low alkalinity, quicklime and hydrated lime should be added to increase the calcium content and the pH. For water with sufficient calcium but low alkalinity, soda ash may be used. For water in which the calcium and alkalinity are sufficient but the pH is too low, caustic soda would be indicated, although soda ash can also be used because it raises pH.

Zinc, Silica, and Polyphosphate Compounds

Certain zinc compounds, such a zinc phosphate, are capable of forming effective cathodic films that will control corrosion. These zinc compounds are largely proprietary. The zinc compound treatments are generally more expensive than treatment with lime or caustic, but they have the advantage that scale is less apt to be a problem. Do not use zinc phosphate compounds to control corrosion caused by water that will be stored in an open reservoir. The phosphate may cause algal blooms. Residual chlorine lasts longer in distribution systems using zinc orthophosphate. The reason for this property has been attributed to decreased chorine demand as a result of reducing iron sediments in distribution piping.

Sodium silicate has been used to treat corrosive water. A solution of sodium silicate fed at a rate of approximately 12 mg/L as silica is used for the first month, after which the rate is reduced to 8 mg/L. This method of treatment is used by individual customers, such as apartment houses and large office buildings. It I is not commonly used by water utilities.

Sodium polyphosphates, either tetrasodium pyrophosphate or sodium hexametaphosphate, have been used for corrosion control. Solutions of these compounds may form protective films but, because they react with calcium, they reduce the effective calcium concentration and thereby, increase corrosion rates. The major use of these chemicals in water treatment is to control scale formation in water that is supersaturated with calcium carbonate.

The deterioration of asbestos-cement pipe may be prevented by maintaining calcium carbonate saturation. Evidence suggests that the zinc treatment are also effective for this purpose as are treatment using traces of iron, manganese, or silica in water. Any deterioration of this type of pipe will cause an increase in pH and calcium content of water as it passes through the pipe. Tests for pH and calcium content should be performed after the pipe has been in service for two months or longer because all asbestos pipe contains at least traces of free lime, which will result in an initial increase in water pH when the pipe is placed in service.

Health Concerns

The Lead and Copper Rule describers the health concerns and regulations for water affected by lead and copper. The water treatment plant operator must understand the monitoring and treatment requirements for these contaminates, and must know the public education and reporting requirements.

Health Concerns

The health concerns concerning exposure to lead are described by the EPA:

Lead is common, natural and often useful metal found throughout the environment in lead-based paint, air, soil, household dust, food certain types of pottery, porcelain, and pewter, and water. Lead can pose a significant risk to health if too much of it enters the body. Lead builds up in the body over many years and can cause damage to the brain, red blood cells, and kidneys. The greatest risk is to young children and pregnant women where amounts of lead that will not harm adults can slow down normal mental and physical development of growing bodies. In addition, a child at play often comes into contact with sources of lead contamination, like dirt and dust, which rarely affect an adult.

Lead in drinking water, although rarely the sole cause of lead poisoning, can significantly increase a person's total lead exposure, particularly the exposure of infants who drink baby formulas and concentrated juices that are mixed with water. The EPA estimates that drinking water can make up 20 percent or more of a person's total exposure to lead.

Lead is unusual among drinking water contaminants in that it seldom occurs naturally in water supplies like rivers and lakes. Lead enters drinking water primarily as a result of the corrosion, or wearing away, of materials containing lead in the water distribution system and household plumbing. These materials include lead-based solder used to join copper pipe, brass, and chrome-plated brass faucets, and in some cases, pipes made of lead that connect the house to the water main

When water stands in lead pipes or in plumbing systems containing lead for several hours or more, the lead may dissolve into the drinking water. The water first drawn from the tap in the morning, or later in the afternoon after returning from work or school, can contain fairly high levels of lead.

The health effects of copper include stomach and intestinal distress. Prolonged doses result in liver damage. Excess intake of copper or the inability to metabolize copper is called Wilson disease.

Iron and Manganese

- Iron and manganese are frequently found together in natural waters and produce similar adverse environmental effects and color problems. Excessive amounts of iron and manganese are usually found in groundwater and in surface water contaminated by industrial waste discharges.
- Before 1962, these elements were covered by a single recommended limit.
- In 1962, the US Public Health Service recommended separate limits for iron and manganese to reflect more accurately the levels at which adverse effects occur for each.
- Each are highly objectionable in large amounts in water supplies for domestic and industrial use.
- Each element imparts color to laundered goods and plumbing fixtures.
- Taste thresholds in drinking water are considerably higher than the levels that produce staining effects.
- Each element is part of the daily nutritional requirements; however, these requirements are not met by the consumption of drinking water.

Iron

The SMCL for iron is 0.3 mg/L.

Undesirable Effects

- At levels greater than 0.05 mg/L some color may develop, staining of fixtures may occur, and precipitates may form.

- The magnitude of the staining effect is directly proportional to the concentration.
- Depending on the sensitivity of taste perception, a bitter, astringent taste can be detected from 0.1 mg/L to 1.0 mg/L.
- Precipitates that are formed create not only color problems but also lead to bacterial growth of slimes and of the iron loving bacteria, *Crenothrix*, in wells and distribution piping.

Nutritional Requirements

Daily requirement is 1 to 2 mg; however, intake of larger quantities is required as a result of poor absorption.

- The limited amount of iron permitted in water (because of objectionable taste or staining effects) constitutes only a small fraction of the amount normally consumed and does not have toxicologic (poisonous) significance.

Manganese

The SMCL for manganese is 0.05 mg/L.

Undesirable Effects

- A concentration of more than 0.02 mg/L may cause buildup of coatings in distribution piping.
- If these coatings slough off, they can cause brown blotches in laundry items and black precipitates.
- Manganese imparts a taste to water above 0.15 mg/L.
- The application of chlorine, even at low levels, increases the likelihood of precipitation of manganese at low levels.
- Unless the precipitate is removed, precipitates reaching pipelines will promote bacterial growth.

Toxic Effects

- Toxic effects are reported as a result of inhalation of manganese dust or fumes.
- Liver cirrhosis has arisen in controlled feeding of rats.
- Neurological effects have been suggested; however, these effects have not been scientifically confirmed.

Nutritional Requirements

- Daily intake of manganese from a normal diet is about 10 mg.
- Manganese is essential for proper nutrition.
- Diets deficient in manganese will interfere with growth, blood and bone formation, and reproduction.

Iron and Manganese can be controlled through aeration where iron is oxidized to ferric oxide and removed through filtration. This method works for low levels of iron in the water. Iron and manganese can be oxidized using chlorine or chlorine dioxide. Ozone also will oxidize iron. Iron and manganese can further be oxidized using potassium permanganate. Operator should use cautions in using potassium permanganate because excessive doses will cause water to become pink.

Excessive amounts of iron and manganese can also be removed using ion exchange and green sand. In ion exchange iron and manganese ions are exchanged for sodium ions.

Review Questions

1. Describe corrosion mechanisms.

2. Explain scale deposition in terms of saturation.

3. Describe the methods of corrosion control.

4. Describe methods used to control iron and manganese

Test Questions

1. _____ is the gradual decomposition or destruction of a material by chemical action, often due to an electrochemical reaction.

   a. Stabilization
   b. Oxidation
   c. Reduction
   d. Corrosion

2. Anode, cathode, and electrolyte are components that make up _______.

   a. Stabilization
   b. Oxidation
   c. Reduction
   d. Corrosion

3. In corrosion, at the______, the dissolved iron reacts with oxygen and the water forming a rust film composed initially of ferrous hydroxide. Additional water and oxygen then react with the ferrous hydroxide to form ferric hydroxide, which becomes a second layer over the ferrous hydroxide.

   a. anode
   b. cathode
   c. electrolyte
   d. junction of dissimilar metals

4. The ______ in corrosion is the point where electric current leaves the metal.

   a. anode
   b. cathode
   c. electrolyte
   d. junction of dissimilar metals

5. The ________is the conduction solution (water with dissolved salts). It is a substance that separates into two or more ions when it is dissolved in water.

   a. anode
   b. cathode
   c. electrolyte
   d. junction of dissimilar metals

6. A multilayered rust deposit is known as a _______. They can grow to the point that the carrying capacity of the pipe is significantly reduced.

   a. scale
   b. tubercle
   c. contaminate
   d. electrolyte

7. _______ is the capacity of water to neutralize acids. This capacity is caused by the water's content of carbonate, bicarbonate, hydroxide, and occasionally borate, silicate, and phosphate.

   a. Acidity
   b. Corrosion
   c. Alkalinity
   d. None of these apply

8. The _____ is the most common of the indices used to indicate how close water is to the equilibrium point, or the corrosiveness of water. This index is based on the equilibrium pH of water with respect calcium and alkalinity.

   a. Driving Force Index
   b. Ryznar Index
   c. Aggressive Index
   d. Langelier Index

9. The corrosive tendencies of water to particular metals, such as the ones used in distribution systems, are also significantly influenced by the amount of ________. Water containing 50 mg/L may exhibit corrosive tendencies in spite of a positive Langelier Index.

   a. sodium
   b. chlorine
   c. total dissolved solids
   d. oxygen

10. If the water is corrosive, steps should be taken to reduce the corrosivity of the water. Reducing corrosivity is almost always accomplished by treating the water with chemicals so that the water is saturated or slightly supersaturated with____

    a. a base
    b. calcium carbonate
    c. sodium hydroxide
    d. calcium hydroxide

11. The SMCL for iron is ____

    a. 0.05 mg/L
    b. 0.3 mg/L
    c. 1.3 mg/L
    d. 15 ppb

12. The SMCL for manganese is _____

    a. 0.05 mg/L
    b. 0.3 mg/L
    c. 1.3 mg/L
    d. 15 ppb

13. The MCL for copper is ______.

    a. 0.05 mg/L
    b. 0.3 mg/L
    c. 1.3 mg/L
    d. 15 ppb

14. The action level for lead is ______.

    a. 0.05 mg/L
    b. 0.3 mg/L
    c. 1.3 mg/L
    d. 15 ppb

CHAPTER 7: LIME SOFTENING

Objectives:

- Describe hard and soft water
- Explain hardness of water
- Explain soft water
- Describe lime softening

Water hardness is technically caused by divalent metallic cations that are capable of reacting with soap to form precipitates and with certain anions present in water to form scale. Calcium and magnesium are usually the only cations that are present in significant concentrations. Hardness is generally considered to be an expression of the total concentration of calcium and magnesium ions that are present in the water. If any of metallic ions are present in significant amounts, they should be included in the hardness determination.

Hard water is water having a high concentration of calcium and magnesium ions. Water is considered hard if it has a hardness greater than the typical hardness of water from the region. Hard water is defined as water with a hardness of more than 100 mg/L as calcium carbonate.

Hardness is a characteristic of water caused by the salts of calcium and magnesium, like bicarbonate, carbonate, sulfate, chloride, and nitrate. Excessive hardness in water is undesirable because it causes the formation of soap curds, increased use of soap, deposition of scale in boilers, damage in some industrial processes, and it causes objectionable tastes in drinking water.

Calcium hardness is caused by calcium ions (Ca^{+2}). Magnesium hardness is caused by magnesium ions (Mg^{+2}). Total hardness is the sum of the hardness caused by calcium and magnesium ions. Carbonate hardness is caused by the alkalinity present in water up to the total hardness. This value is usually less than the total hardness. Non-carbonate hardness is the portion of the total hardness in excess of the alkalinity.

Alkalinity is the capacity of water or wastewater to neutralize acids. This capacity is caused by the water's content of carbonate, bicarbonate, hydroxide, and sometimes borate, silicate, and phosphate. Alkalinity is expressed in mg/L of equivalent calcium carbonate. Alkalinity is not the same as pH because water does not have to be strongly basic to have a high alkalinity. Alkalinity is a measure of how much acid must be added to a liquid to lower the pH to 4.5.

Calcium carbonate is an expression of the concentration of specified constituents in water in terms of their equivalent value to calcium carbonate.

The dissolved minerals in water cause difficulties in doing the laundry and in dishwashing in the household. These ions cause a coating to form inside the hot water heater similar to that in a tea kettle after repeated use.

Hardness tends to shorten the life of fabrics that are washed in hard water. The scum or curds may become lodged in the fibers of the fabric and cause them to lose their softness and elasticity.

In industry, hardness can cause greater problems. Many processes are affected by the hardness content of the water used. Industrial plants using boilers for processing steam or heat must remove the hardness from their makeup water, beyond what the water treatment plants would do. The reasons is that the minerals will plate out on the boiler tubes and form a scale. This scale forms an insulation barrier that prevents proper heat transfer, causing excessive energy requirements for the boiler.

In addition to removing hardness from water, other benefits of softening include:

1. Removal of iron and manganese
2. Control of corrosion when proper stabilization of water is achieved
3. Disinfection due to high pH values when using lime
4. A reduction in taste and odors
5. Reduction of total solids content by the lime treatment process
6. Removal of radio activity

Some of the possible limitations of softening include the following:

1. Free chlorine residual is predominantly hypochlorite at pH levels above 7.5 and it is less powerful
2. Cost and benefits must be carefully weighted to justify softening
3. Ultimate disposal of process wastes
4. The pH levels associated with softening chemical precipitation of the trihalomethane fraction in the treated water can increase
5. Production of aggressive water that would tend to corrode metal ions from the distribution system piping. Hard water does not corrode pipe. Excessively hard water can cause scaling on the inside of pipes and restrict flow

The decision to soften water is up to each community because softening is done mostly as a customer service. Hard water does not have an adverse effect on health but can create several unwanted side effects:

1. Over a period of time, the detergent consuming power of hard water can be costly
2. Scale problems on fixtures will be more noticeable
3. The lifetime of several types of fabrics will be reduced with repeated washing in hard water. Also, a residue can be left in clothing, creating a dirty appearance

Two common methods are used to soften water. They are chemical precipitation (lime-soda ash) and ion exchange. Ion exchange softening is applied to water high in noncarbonated hardness and the total hardness does not exceed 350 mg/L. This method of softening can produce water of zero hardness, as opposed to lime softening where zero hardness cannot be reached.

Ion exchange softening will also remove noncarbonated hardness without the addition of soda ash, which is required with lime softening. Ion exchange is a nonselective method of softening. This method will remove total hardness which is the sum total of carbonate and non-carbonate hardness.

Limitation of ion exchange softening processes include an increase in sodium content of the softened water if the ion exchange is regenerated with sodium chloride. The sodium level should not exceed 20 mg/L in treated water because of the potentially harmful effect on persons susceptible to hypertension. The ultimate disposal of spent brine and rinse water from softeners can be a major problem for many installations.

Hardness is due to the presence of divalent metallic cations in water. Hardness is a factor commonly measured by titration. Individual divalent cations can be measured in the laboratory using an atomic absorption spectrophotometer for accurate work. Hardness is usually reported as calcium carbonate equivalent. This procedure allows operators to combine or add up the hardness caused by calcium and magnesium and reported as total hardness.

$$\text{Calcium Hardness, mg/L s CaCO}_3 = (\text{Calcium, mg/L})\frac{(\text{Equivalent Weight of CaCO}_3)}{(\text{Equivalent Weight of Calcium})}$$

$$\text{Equivalent Weight of Calcium} = \frac{\text{Atomic Weight}}{\text{Valence}}$$

To express the magnesium hardness of water as calcium carbonate equivalent:

$$\text{Magnesium Hardness, mg/L as CaCO}_3 = (\text{Magnesium, mg/L})\frac{(\text{Equivalent Weight of CaCO}_3)}{(\text{Equivalent Weight of Magnesium})}$$

When treating water the pH is important. The pH of water can be increased or decreased by the addition of certain chemicals used to treat water. In many instances, the effect on pH of adding one chemical is neutralized by the addition of another chemical. When softening water by chemical precipitation processes, like lime-soda softening, the pH must be raised to 11 for the desired chemical reaction to occur. The levels of carbon dioxide, bicarbonate ion, and carbonate ion in water is very sensitive to pH.

The stability of treated water is determined by measuring the pH and calculating the Langelier Index. This index reflects the equilibrium pH of water with respect to calcium and alkalinity.

Langelier Index (LI) = $pH - pH_s$

Where pH = actual pH of the water
pH_s = pH at which water having the same alkalinity and calcium content is just saturated with calcium carbonate

A negative Langelier Index indicates that the water is corrosive and a positive index indicates that the water is scale forming. After water has been softened, the treated water distributed to consumers must be stable which means that the water can be neither corrosive nor scale forming.

Alkalinity

Alkalinity is the capacity of water to neutralize acids. This capacity is caused by the water content of carbonate, bicarbonate, hydroxide, borate, silicate, and phosphate. Alkalinity is expressed in mg/L of equivalent calcium carbonate. Alkalinity is not the same as pH.

Alkalinity is measured in the laboratory by the addition of color indicator solutions. The alkalinity is then determined by the amount of acid required to reach a titration end point for a specific color change. The P (phenolphthalein) end point is pH 8.3. When the pH is below 8.3, no P alkalinity is present. When the pH is above 8.3, P alkalinity is present. No carbon dioxide is present when the pH is above 8.3, so no carbon dioxide is in the water when P alkalinity is present. Also hydroxide and carbonate alkalinity are not present when the pH is below 8.3.

The relationship between the various alkalinity constituents, like bicarbonate, carbonate, and hydroxide, can be based on the P (phenolphthalein) and T (total or methyl orange) alkalinity.

When the pH is less than 8.3, all alkalinity is in the bicarbonate form and is commonly referred to as natural alkalinity. When the pH is above 8.3, the alkalinity can consist of bicarbonate, carbonate, and hydroxide. As the pH increase, the alkalinity progressively shifts to carbonate and hydroxide forms.

Total alkalinity is the sum of the bicarbonate, carbonate, and hydroxide. Each of these values can be determined by measuring the P and T alkalinity in the laboratory. Alkalinity is expressed in mg/L as calcium carbonate equivalents.

Softening

Hardness is not completely removed by the chemical precipitation methods used in water treatment plants. Hardness cannot be reduced to zero using the chemical precipitation method of softening water. Water having a hardness of 150 mg/L as calcium carbonate or more is usually treated to reduce the hardness to 80 to 90 mg/L when softening is used as a water treatment option.

The minimum hardness that can be achieved by lime softening-soda ash processes is around 30 to 40 mg/L as calcium carbonate. Regardless of the method used to soften water, the consumer usually receives a blended water with a hardness of 80 to 90 mg/L as calcium carbonate when softening is utilized in water treatment facilities.

Lime-soda softening produces benefits in addition to softening water. The advantages include:

1. Removal of iron and manganese
2. Reduction of solids
3. Removal and inactivation of bacteria and viruses from the high pH involved in the treatment
4. Control of corrosion and scale formation with proper stabilization of treated water
5. Removal of excess fluoride

Limitations of the lime-soda softening process include:

1. An inability to remove all hardness
2. A high degree of operator control must be exercised for maximum efficiency in cost, hardness removal, and water stability
3. Color removal may be complicated by the softening process because of high pH levels
4. Large quantities of sludge are created that must be handled and disposed of in an acceptable manner

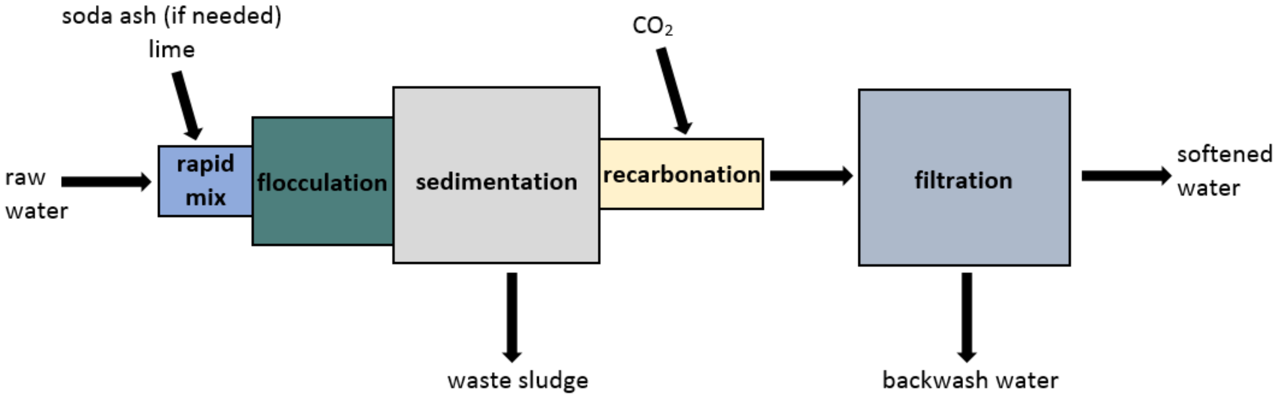

Figure 7-1 Lime Softening - Image by COC OER is licensed under CC BY

Chemical Reaction

In chemical precipitation, the hardness causing ions are converted to insoluble forms. Calcium and magnesium become less soluble as the pH increases. Calcium and magnesium can be removed from water as insoluble precipitates at high pH levels.

Addition of lime to water increases the hydroxide concentrations so that the pH increases. Addition of lime to water also converts alkalinity from the bicarbonate form to the carbonate form which causes the calcium to be precipitated as calcium carbonate. As additional lime is added to the water, the phenolphthalein alkalinity increases to a level where hydroxide becomes present allowing magnesium to precipitate as magnesium hydroxide.

Following the chemical softening process, the pH is high and the water is supersaturated with excess caustic alkalinity in the hydroxide or carbonate form. Carbon dioxide can be used to decrease causticity and scale forming tendencies of the water prior to filtration.

The chemical reactions that take place in water during the chemical precipitation process depend on whether the hardness to be removed is carbonate or non-carbonate hardness. Carbonate hardness, temporary hardness, can be removed with the use of lime only. Removal of non-carbonate hardness, permanent hardness, requires lime and soda ash.

Chemicals

The lime used in the chemical precipitation softening process can be hydrated lime, ($Ca(OH)_2$,, calcium hydroxide, or calcium oxide, CaO. Hydrated lime can be used directly. The calcium oxide or quicklime must first be slaked. This process involves adding the calcium oxide to water and heating it to cause slaking, which is the formation of calcium hydroxide ($Ca(OH)_2$) before use. Small facilities commonly use hydrated lime. Large facilities find it more economical to use quicklime (CaO) and slake it on site.

The application of lime for the removal of carbonate hardness also removes carbon dioxide. Carbon dioxide does not contribute to hardness and does not need to be removed. However, carbon dioxide will consume a portion of the lime that is used and must be considered in the dosing process.

When lime is added to water, carbon dioxide present in the water is converted to calcium carbonate if enough lime is added. Adding more lime, the calcium bicarbonate will be precipitated as calcium carbonate. To remove calcium and magnesium bicarbonate, an excess of lime must be used.

Magnesium carbonated hardness requires the addition of lime and soda ash, Na_2CO_3.

The primary chemical reactions products from the lime-soda softening process are calcium carbonate and magnesium hydroxide. The water treated has been chemically changed and is no longer stable because of pH and alkalinity changes. Lime-soda ash softened water is usually supersaturated with calcium carbonate. The degree of instability and excess calcium carbonate depends on the degree to which the water is softened. Calcium carbonate hardness is removed at a lower pH than magnesium carbonate hardness. If maximum carbonate hardness removal is practiced so that a high pH is required to remove magnesium carbonate hardness, the water will be supersaturated with calcium carbonate and magnesium hydroxide. Under these conditions, deposition of precipitates will occur in filters and pipelines.

Excess lime addition to remove magnesium carbonate hardness results in supersaturated conditions and a residual of lime, which will produce a pH of about 10.9. The excess lime is called caustic alkalinity since it raises the pH. If the pH is then lowered, better precipitation of calcium carbonate and magnesium hydroxide will occur. Alkalinity will be lowered also. This process is usually accomplished by pumping carbon dioxide gas into the water. This addition to the treated water is called re-carbonation.

Re-carbonation can be carried out in two steps. The first addition of carbon dioxide would follow excess lime addition to lower the pH to about 10.4 and encourage the precipitation of calcium carbonate and magnesium hydroxide. A second addition of carbon dioxide after treatment removes non-carbonate hardness. The pH is lowered to about 9.8 and it encourages precipitation. By carrying out re-carbonation prior to filtration, the buildup of excess lime and calcium carbonate and magnesium hydroxide precipitates in the filters will be prevented or minimized.

Care must be exercised when using re-carbonation. Feeding excess carbon dioxide can result in no lowering of the hardness by causing calcium carbonate precipitates to go back into solution and cause carbonate hardness.

An alternative method to the lime-soda ash softening process is the use of sodium hydroxide (NaOH), which is called caustic soda. The chemical reactions using caustic soda demonstrate that in removing carbon dioxide and carbonate hardness, sodium carbonate (soda ash) is formed, which will react with to remove non-carbonate hardness. Sodium hydroxide substitutes for soda ash and part of the lime to remove carbonate hardness. The use of caustic soda may have several advantages including stability in storage, less sludge formation, and ease of handling.

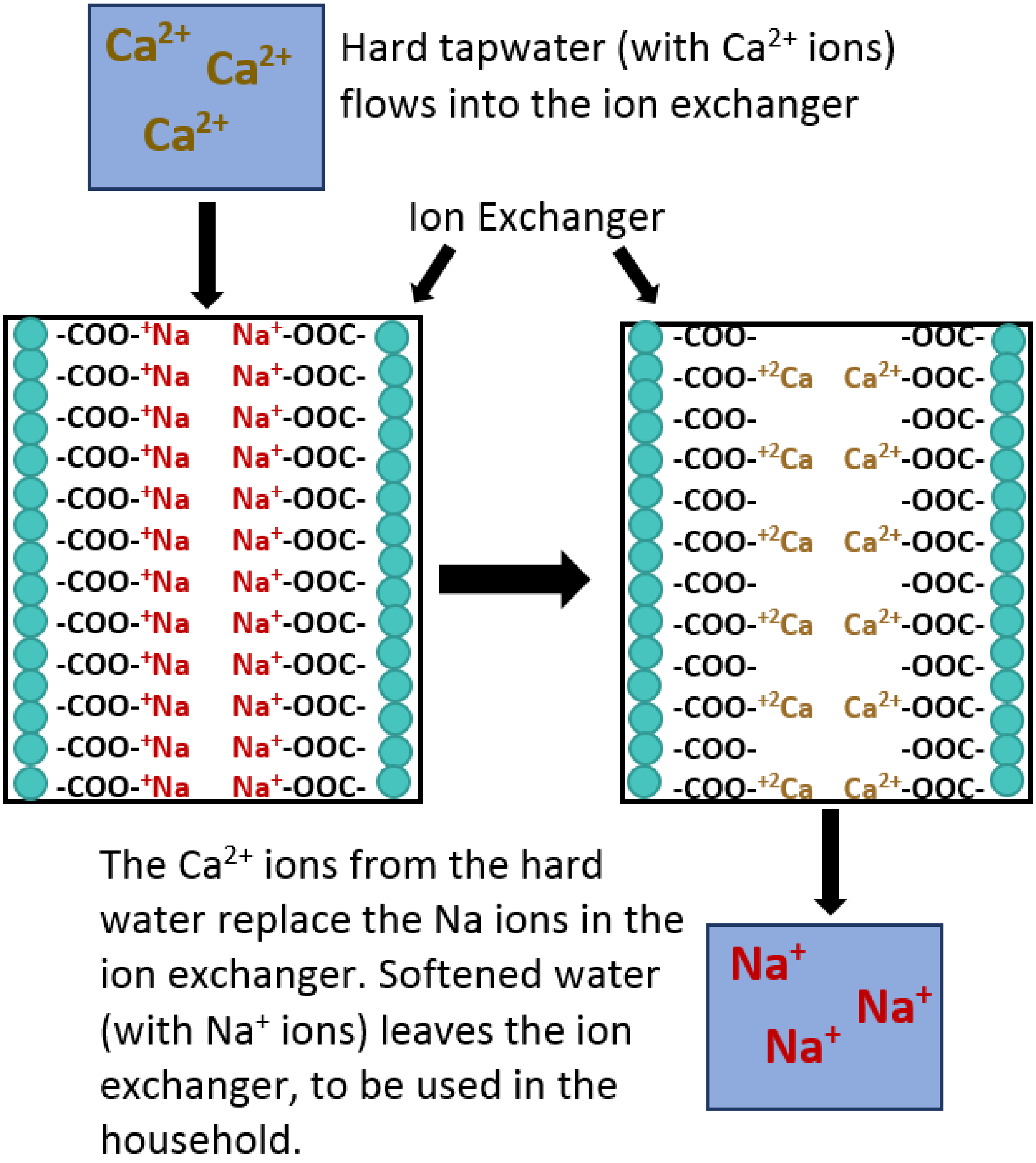

Figure 7-2 Lime Softening – Image by COC OER is licensed under CC BY

Ion Exchange Softening

Electrically charged atoms or molecules are known as ions. Ion exchange treatment processes use special resins to remove charged, inorganic contaminants like arsenic, chromium, nitrate, calcium, radium, uranium, and excess fluoride from water. When source water is passed through a series of resin beads, it exchanges its charged contaminants for the harmless charged ions stored on the resin surface. The contaminants accumulate on the resins and must be periodically cleaned with a solution that recharges the interchangeable ions.

Ion exchange resin comes in two forms: cation resins, which exchange cations like calcium, magnesium, and radium, and anion resins, which are used to remove anions like nitrate, arsenate, arsenite, or chromate. Each resin type is usually regenerated with a salt solution (sodium chloride). In the case of cation resins, the sodium ion displaces the cation from the exchange site, and in the case of anion resins, the chloride ion displaces the anion from the exchange site. As a rule, cation resins are more resistant to fouling than are anion resins. Resins can be designed to show a preference for specific ions, so that the process can be easily adapted to a wide range of different contaminants. This treatment process works best with particle-free water, because particulates can accumulate on the resin and limit its effectiveness.

Ion exchange is a common water treatment system that can be scaled to fit any size treatment facility. It may also be adapted to treat water at the point-of-use and point-of-entry levels.

Activated Alumina

Activated alumina treatment is used to attract and remove contaminant, like arsenic and fluoride, which have negatively charged ions. Activated alumina (aluminum oxide) is typically housed in canisters through which source water is passed for treatment. A series of such canisters can be linked together to match the water volume requirements of any particular system.

As alumina absorbs contaminants, it loses its capacity to treat water. Therefore, treated water quality must be carefully monitored to ensure that cartridges are replaced before they lose their treatment effectiveness. Also the capacity of the alumina is strongly influenced by the pH of the water. Lower pHs function better. Many systems use acid pretreatment to address this need.

Source water quality is an important consideration for activated alumina systems. The treatment agent will attract contaminants, as well as other negatively charged ions found in source water. This characteristic can limit the alumina’s ability to attract and remove the targeted contaminants.

Activated alumina technology can be expensive, and its costs are associated with disposal of the contaminated water that is created when alumina is purged of contaminants and recharged for future use. Large-scale activated alumina systems also require a high level of operational and maintenance expertise, and consequently are relatively rare. Small-scale systems are more common and can be tailored to accommodate specific water volume requirements.

Blending

Ion exchange softeners will produce water with zero hardness. Water with zero hardness must not be sent into the distribution system. Water with zeros hardness is corrosive and over a period of time will attack steel pipes in the system and cause red water problems.

At most softening plants, the zero hardness effluent from the softeners is mixed with filtered water having a known hardness concentration. A certain amount of water that the plant produces bypasses the softening process. This water has a known hardness concentration and is mixed in various proportions with the softener effluent to arrive at the desired level of hardness in the finished water.

The blending of water is simple and is usually controlled by a valve and meter. The operator adjusts the exact gallons per minute bypassing the softener to produce the desired hardness.

Review Questions

1. Describe hard and soft water.

2. Explain hardness of water.

3. Explain soft water.

4. Describe lime softening

Test Questions

1. ________ is generally considered to be an expression of the total concentration of calcium and magnesium ions that are present in the water.

   a. Softness
   b. Hardness
   c. Stabilization
   d. Alkalinity

2. ________ is the capacity of water or wastewater to neutralize acids. This capacity is caused by the water's content of carbonate, bicarbonate, hydroxide, and sometimes borate, silicate, and phosphate.

   a. Softness
   b. Hardness
   c. Stabilization
   d. Alkalinity

3. ______is expressed in mg/L of equivalent calcium carbonate.

   a. Softness
   b. Hardness
   c. Stabilization
   d. Alkalinity

4. In addition to removing hardness from water, which of the following is not a benefit of softening?

   a. Removal of iron and manganese
   b. Control of corrosion when proper stabilization of water is achieved
   c. Disinfection due to high pH values when using lime
   d. Production of aggressive water that would tend to corrode metal ions from the distribution system piping.

5. Which of the following is not a typical limitation of softening?

   a. Free chlorine residual is predominantly hypochlorite at pH levels above 7.5
   b. Removal of radio activity
   c. Disposal of process wastes
   d. At the pH levels associated with softening chemical precipitation of the trihalomethane
   e. fraction in the treated water can increase

6. _________ is used to soften water that is high in noncarbonated hardness and where the total hardness does not exceed 350 mg/L.

   a. Lime
   b. Lime-soda ash
   c. Calcium hydroxide
   d. Ion exchange softening

7. Limitation of ________ processes include an increase in sodium content of the softened water if the ion exchange is regenerated with sodium chloride. The sodium level should not exceed 20 mg/L in treated water because of the potentially harmful effect on persons susceptible to hypertension.

   a. Lime
   b. Lime-soda ash
   c. Calcium hydroxide
   d. Ion exchange softening

8. The primary chemical reactions products from the lime-soda softening process are _______ and __________.

   a. calcium hydroxide, magnesium hydroxide
   b. calcium carbonate, magnesium carbonate
   c. calcium carbonate, magnesium hydroxide
   d. calcium hydroxide, magnesium carbonate

9. Electrically charged atoms or molecules are known as ______.

   a. cations
   b. anions
   c. electrons
   d. ions

10. Resins are usually regenerated with _______.

   a. sodium chloride
   b. potassium chloride
   c. ferric chloride
   d. hydrochloric acid

11. Activated alumina treatment is used to attract and remove ______, which have negatively charged ions. Activated alumina (aluminum oxide) is typically housed in canisters through which source water is passed for treatment. A series of such canisters can be linked together to match the water volume requirements of any particular system.

    a. iron and magnesium
    b. magnesium and calcium
    c. nitrate and nitrite
    d. arsenic and fluoride

12. Ion exchange softeners will produce water with zero hardness. Water with zero hardness must not be sent into the distribution system. Water with zeros hardness is ___________.

    a. hard water.
    b. corrosive water
    c. scaling forming water
    d. black water

13. At most softening plants, the zero hardness effluent from the softeners is mixed with filtered water having a known hardness concentration in a process called ______.

    a. blending
    b. conservation
    c. oxidation
    d. None are correct

14. Calcium hardness is caused by calcium ions (Ca^{+2}). Magnesium hardness is caused by magnesium ions (Mg^{+2}). Total hardness is the sum of the hardness caused by calcium and magnesium ions. Carbonate hardness is caused by the _______ present in water up to the total hardness.

    a. softness
    b. hardness
    c. stability
    d. alkalinity

CHAPTER 8: ION EXCHANGE

Objectives:

- Describe ion exchange chemistry
- Define matter, ions, and compounds
- Describe the aeration process and applications

Ion Exchange Processes

Most ion exchange units in use today use sulfonated polystyrene resins as the exchange media. Ion exchange can be defined as exchanging ions found in the source water for sodium ions or chloride ions that are attached to the ion exchange resins.

Ions are atoms or molecules that have a non-zero net electrical charge. Its total number of electrons is not equal to its total number of protons. Matter occupies space and possesses rest mass, especially as distinct from energy. It comes in gas, liquid, or solid form. Ions are a form of matter. Compounds are made up of two or more atoms bonded together, and one form of bond is an ionic bond which is formed by the bonding of oppositely charged ions.

A cation is a positively charged ion, while an anion is negatively charged. Because of their opposite electric charges, cations and anions attract each other and readily form ionic compounds such as salts.
Ions can be created by chemical means, such as the dissolution of a salt into water. Ions consisting of only a single atom are atomic ions. If they consist of two or more atoms, then they are called molecular ions.

The treatment plant operator should be aware of the three types of ion exchange units:

1. An upflow unit in which the water enters from the bottom and flows up through the ion exchange bed and out the top
2. A unit that is constructed and operated like a gravity rapid sand filter. The water enters the top, flows down through the ion exchange bed, and out the bottom
3. The pressure downflow ion exchange unit is the most common. These units may be horizontal or vertical. Vertical units are preferred because of less chances of short-circuiting

The water enters the unit through an inlet distributor located in the top. It is forced (pumped) down through a bed of some type of media into an underdrain structure. From the underdrain structure, the treated water flows out of the unit and into storage or into the distribution system.

The flow pattern through a filter and ion exchange unit are similar, the difference is the action that takes place in the media or bed of each process. The filter bed may be considered an adsorption and mechanical straining device used to remove suspended solids from the water. The bed usually consists of sand, anthracite, or a combination. Once the bed becomes saturated, with the insoluble material, the filter is taken out of service, backwashed, and returned to service. This pressure filter will continue to operate until the condition reoccurs and the procedure is repeated.

The bed, media, or resin in an ion exchange unit is more complex. The resin serves as a medium in which an ion exchange takes place. As water is passed through the resin, the sodium ions on the resin are exchanged for cations in the water. The primary ions that are exchanged for sodium are calcium and magnesium. The sodium ions are released from the exchange resin and remain in the water, which flows out of the unit. The exchanged ions are retained by the resin, and is free of the exchanged ions.

Once a unit has exchanged all the sodium ions and the resin is saturated, it will no longer remove the targeted ions. The unit must be taken out of service and the targeted ions removed from the resin by exchange them with sodium ions. This process is referred to as a regeneration cycle.

In a regeneration cycle, the ions that have been retained by the resin must be removed and the sodium ions restored. For the exchange to take place, the resin must hold all ions loosely. Salt, in the form of a concentrated brine solution, is used to regenerate (recharge) the ion exchange resin. When salt is added to water it changes into or ionizes to form sodium cation and chloride anions. When the brine solution is fed into the resin, the sodium cations are exchanged. As the brine solution travels down through the resin, the sodium cations are attached to the resin. After regeneration has taken place, the bed is ready to be placed in service.

Operation

Several factors influence the procedures used to operate an ion exchange unit and the efficiency of the process. These factors include:

1. Characteristics of the ion exchange resin
2. Quality of the source water
3. Rate of flow applied to the unit
4. Salt dosage during regeneration
5. Brine concentration
6. Brine contact time

Each ion exchange unit will have at least four common stages of operation. These stages are:

1. Service
2. Backwash
3. Brine
4. Rinse

Service

The service stage of each unit is where the actual ion exchange occurs. Water is forced into the top of the unit and allowed to flow down through the exchange resin. As this process takes place the targeted ions are exchange with sodium on the resin. The sodium ions are released into the water and the exchange capacity of the unit is slowly exhausted.

The length of each service stage is dependent on source water quality. The effluent from the unit has a reduction is TDS. If the source water has high TDS levels, then some leakage may occur. If the high TDS water has high sodium levels, then the process may be hindered because a local exchange on the media for sodium may occur. The amount of leakage depends on the TDS and the salt dosage used for regeneration.

Other factors involved ae the size of the softener and the exchange capacity of the resin. The unit should produce enough water without the targeted ions so that blending of the source water and effluent from the exchange unit will produce a treated water with the desired ion content.

The exchange resin also varies in its removal capacity. The removal ability of the resin is usually expressed in grains of material removed per cubic foot of resin.

The source water characteristics, the size of the unit, and the removal capacity of the resin will determine the amount of water that can be treated before regeneration. With a few calculations, an operator can determine the capacity of the units.

Backwash

The second stage of the ion exchange process is the backwash. In this stage, the unit is taken out of service and the flow pattern through the unit is reversed. The purpose of this activity is to expand and clean the resin particles and to free any material such as iron, manganese, and particulates that might have been removed during the service stage. The backwash water entering the unit at the beginning of this stage should be applied at a slow, steady rate. If the water enters the unit too quickly, it could create a surge in the resin and wash it out of the unit with the water going to waste.

Ideal bed expansion during the backwash process should be 75 to 100 percent. When the unit is backwashed, the resin should expand to occupy a volume from 75 to 100 percent greater than when in normal service. As the bed expands, a shearing action due to the backwash water and some scrubbing action will free material that might have formed on the resin particles during the service stage.

During backwash, a small amount of resin could be lost. The amount should be minimal and the operator should check the backwash effluent at different intervals to ensure that the resin is not being lost. A glass beaker can be used to catch a sample of the effluent while the unit is backwashing. A trace amount of resin should cause no alarm; however, a steady loss of resin could indicate a problem in the unit and the cause should be located and corrected. Too much loss of resin may be caused by an improper freeboard on the tank or wash troughs. The backwash duration and flow rate will vary depending on the manufacturer, the type and size of resin used, and the water temperature.

Brine

The third stage is most often called the regeneration or brine stage. At this point, the sodium ion concentration of the resin is recharge by pumping a concentrated brine solution onto the resin. The solution is allowed to circulate through the unit and displace all water from the resin in order to provide full contact between the brine solution and the resin.

Most treatment plants use a brine solution for regeneration. The optimum brine concentration coming in contact with the ion exchange resin is around 10 to 14 percent sodium chloride solution. Concentrated brine is only used when the water within the unit serves as the dilution water. A 26 percent brine solution (saturated) cause too great of an osmotic shock on the ion exchange resin and can cause it to break up. The salt dosage used to prepare the brine solution is one of the most important factors affecting the ion exchange capacity, and it ranges from 5 to 15 pounds of salt per cubic foot of resin. Brine concentrations less than saturated require longer contact time and more solution must be applied to the resin to achieve regeneration.

The regeneration stage is very important and the operator should be certain it is properly carried out. In the regeneration stage, the sodium ions present in the brine solution are exchanged. The ions on the resin were exchanged during the service stage. The regeneration rate is usually 1 to 2 GPM per cubic foot of resin for the first 55 minutes and then 3 to 5 GPM per cubic foot for the last 5 minutes. If the regeneration process is performed correctly, then the result is a bed that is completely recharged and ready for service.

Rinse

The last stage is the rinse stage. After adequate contact time has been allowed between the brine solution and the resin, a clear rinse is applied from the top of the unit to remove the waste products and excess brine solution. The flow pattern is very similar to the service stage except that the effluent goes to waste. The waste discharge contains high concentrations of chloride. Most rinse stages will last between 20 to 40 minute, depending on the size of the unit and manufacturer.

The operator should pay close attention to the unit while it rinses. The rinse must be long enough to remove the heavy concentration of waste from the unit. If the rinse is not of sufficient time and the unit returns to service, a salty taste will be noticeable in the effluent. Taste the waste effluent near the end of the rinse stage to determine if the majority of chloride ions have been removed. The chloride ion concentration may also be measured by titration or the conductivity can be measured. If the water has a strong salty taste or excessive chloride ions are present, check the rinse rate and timer settings. The unit may need adjustment to increase the duration of the rinse stage.

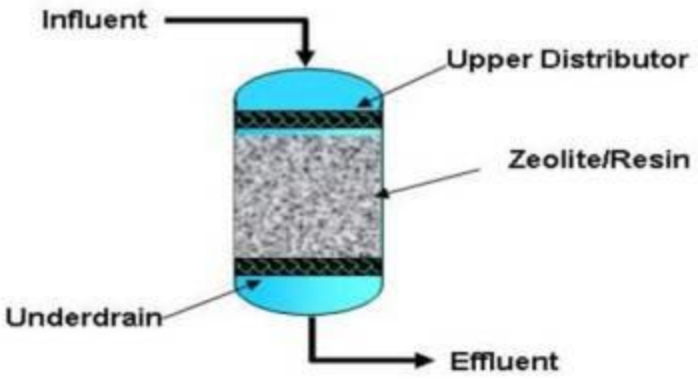

Figure 8-1 Ion Exchange – Image by the EPA is in the public domain

Treatment for Iron and Manganese

If the water contains manganese up to 0.3 mg/L and less than 0.1 mg/L of iron, an inexpensive and reasonably effective control can be achieved by feeding the water with one of the three polyphosphates. Chlorine usually must be fed along with the polyphosphate to prevent the growth of iron bacteria. The effect of the polyphosphate is to delay the precipitation of oxidized manganese for a few days so that the scale that builds up on the pipe walls is reduce.

Polyphosphate Treatment

The chlorine dose for phosphate treatment should be sufficient to produce a free chlorine residual of 0.25 mg/L after a five-minute contact time. Any of the polyphosphates can be used; however, sodium metaphosphate is effective in lower concentrations than the other polyphosphates. The proper phosphate dose is determined by laboratory bench-scale tests.

Polyphosphate treatment to control iron and manganese is most effective when the polyphosphate is added upstream from the chlorine. The chlorine should never be fed ahead of the polyphosphate because the chlorine will oxidize the iron and manganese to insoluble precipitates.

Ion Exchange

Iron and manganese ion exchange units are similar to a down flow pressure filters. The water to be treated enters the unit through an inlet distributor located in the top. The water is forced down through the ion exchange resin into an underdrain structure. From the underdrain structure, the treated water flows out of the unit to the next treatment process.

The location of the ion exchange resins with respect to other water treatment processes will depend on the raw water quality and the design engineer. If the water contains no oxygen, iron and manganese may be removed by ion exchange using the same resins that are used for water softening. If the water being treated contains any dissolved oxygen the resin becomes fouled with iron rust or insoluble manganese dioxide. The resin can be cleaned; however, this process is expensive.

The primary advantage of ion exchange for iron and manganese removal is that the plant requires little attention. The disadvantages are the danger of fouling the ion exchange resin with oxide and high initial cost.

To operate an ion exchange unit, operate as close as possible to design flows. Monitor the treated water for iron and manganese daily. When iron and manganese start to appear in the treated water, the unit must be regenerated. Regenerate with a brine solution that is treated with 0.01 pounds of sodium bisulfite per gallon (1.2 g/L) of brine to remove oxygen present. After regeneration is complete, dispose of the brine in an approved manner.

Oxidation by Aeration

Iron can be oxidized by aerating the water to form insoluble ferric hydroxide. This reaction is accelerated by an increase in pH. If the water contains organic substances, the rates will be significant lower. Reduced temperature will also lower the rates. The oxidation of manganese by aeration is so slow that this process is not used on water with high manganese concentrations.

Figure 8-2 Aeration – Image by Trlabarge is licensed under CC BY-SA 3.0

Since pH is increased by the removal of carbon dioxide, it is important that the aeration be as efficient as possible. Lime is sometimes added to the water to increase the pH along with removal of carbon dioxide. The higher the pH the shorter the time required for aeration.

Operation of the aeration process to remove iron and manganese requires careful control of the flow through the process. If the flow becomes too great, not enough time will be available for the reactions to occur. Flows are controlled by the use of variable speed pumps or the selection of the proper number or combinations of pumps. Carefully monitor the iron and manganese content of the treated water. If iron is detected, then flows may have to be reduced.

Several methods are used for delivering aeration. The water being treated can be dispersed into the air or air can be bubbled through the water. Aeration may be achieved using compressed air that passes through diffusers in the water. These diffusers produce small bubbles that allow the transfer of oxygen in the air to dissolved oxygen in the water.

Other aeration techniques include forced draft, multiple trays, cascades, and sprays. These methods may cause slime growths to develop on surfaces or coatings on media. Slime growths and coatings on media should be controlled to prevent the development of tastes and odors in the product water and the sloughing off of the slimes. Chlorination may be used to control slime growths and coatings. Regularly inspect aeration equipment for the development of anything unusual.

A reaction (detention or collection) basin follows the aeration process. The purpose of the reaction basin is to allow time for the oxidation reactions to take place. The aeration process should produce sufficient dissolved oxygen for the iron to be oxidized to insoluble ferric hydroxide. A minimum recommended detention time is 20 minutes with desirable detention times ranging from 30 to 60 minutes. The pH of the water strongly influence the time for the reaction to take place. Sometimes chlorine is added before the reaction basin.

The reaction basin is similar to a clarifier. Often the basin is baffled to prevent short-circuiting and the deposition of solids. Since no provisions for sludge removal are available, the basin must be drained and cleaned regularly. If the basins are not cleaned, slugs of deposits or sludge or mosquito and fly larvae could reach the filters in the next process and cause them to plug.

Operators must be on the alert for potential sources of contamination. Basins should have covers and protective lids to keep out rain, storm water runoff, rodents, and insects. All vents must be properly screened. The outlet to the drain must not be connected directly to a sewer or storm water drain. An air gap or some other protective device to prevent contamination from backflow must be present.

After ferric hydroxide is formed in the aeration process, it is removed by sedimentation or by filtration. If only filtration is used, water from the reaction basin is usually pumped to pressure filters. The water may also be pumped or flow by gravity to rapid sand filters.

The primary advantage of this method is that no chemicals are required; however, lime may be added to increase the pH. The major disadvantage is that small changes in raw surface water quality may affect the pH and soluble organic levels and slow the oxidation rates to a point where the capacity of the plant is reduced.

Oxidation with Chlorine

Chlorine will oxidize manganese to the insoluble manganese dioxide and will oxidize iron to insoluble ferric hydroxide, which can then be removed by filtration. The higher the chlorine residual, the faster this reaction occurs. Some compact plants have been constructed treating the water to a free chlorine residual of 5 to 10 mg/L, filtering, and dechlorinating to a residual suitable for domestic use. Do not use high doses of chlorine if the water contains a high level of organic color because excessive concentrations of total trihalomethanes could develop. The water is dechlorinated using reducing agents such as sulfur dioxide, sodium bisulfite, and sodium sulfite. Bisulfite is commonly used because it is cheaper and more stable than sulfite. When dechlorinating with reducing agents, be careful not to overdose because inadequate disinfection could result and if the dissolved oxygen level is in the water is depleted, fish kills could occur in home aquariums. Frequently, a reaction basin is installed between the chlorination and dechlorination processes to allow time for the reactions to occur.

Oxidation with Permanganate

Potassium permanganate oxidizes iron and manganese to insoluble oxides, and can be used to remove these elements in the same way that chlorine is used. The dose of potassium permanganate must be exact. Bench-scale tests are required to determine the proper dosage. Too small a dose will not oxidize all of the manganese in the water and too large a dose will allow permanganate to enter the system and produce a pink color in the water. Actual observations of the water being treated will tell if any adjustments of the chemical feeder are necessary. Most well water has relatively constant concentrations of iron and manganese. Therefore, once the chemical feeder is set, adjustments of the dosage usually are not necessary.

Experience from many water treatment plants has demonstrated that a regular filter bed (rapid sand filter or a dual media filter bed) can remove manganese as long as iron and manganese concentrations are less than 1 mg/L. These plants use chlorine or permanganate to oxidize the iron and manganese before the water being treated flows through the filter bed.

Potassium permanganate is often used with manganese zeolite or manganese greensand. Greensand is a granular material. After the greensand has been treated with potassium permanganate, it can oxidize iron and manganese to their insoluble oxides. The greensand also acts as filter and must be backwashed to remove the insoluble oxides.

Manganese greensand filters can be operated in three modes: continuous regeneration (CR), intermittent regeneration (IR), or catalytic regeneration. The method used will depend on the concentrations of iron and manganese in the water and the pH of the water.

The manganese greensand continuous regeneration process can be used for water containing iron concentrations as high as 15 mg/L; however, with concentrations so high, frequent backwashing will be necessary. Generally, water having iron concentrations in the range of 0.5

mg/L to 3.0 mg/L can be treated with more acceptable run lengths of 18 to 36 hours before backwashing.

In the continuous regeneration process, chlorine and potassium permanganate are added to the raw water ahead of the manganese greensand bed. Chlorine is added first to oxidize most of the iron and any sulfide. A slight excess of potassium permanganate is then added to oxidize the remaining iron and soluble manganese. This reaction produces insoluble oxides. When the raw water passes through the manganese greensand bed two things occur:

1. The insoluble iron oxide particles are filtered out
2. Any remaining permanganate is reduced to manganese oxides by the greensand

These manganese oxides attach to the grains of greensand; thereby, continuously regenerating the manganese greensand. As the run progresses, the filter bed becomes clogged with insoluble oxides and the differential pressure increases. When head loss reaches a predetermined point or a certain number of gallons of water have been treated, the filter must be backwashed to remove the filtered particulates.

The intermittent regeneration process is suitable for raw water containing only manganese or mostly manganese with small amounts of iron. The raw water flows through a manganese greensand bed where oxidation of manganese occurs directly on the grains or greensand. Some iron will also be oxidized directly on the grains of greensand. If the iron concentrations are high, iron oxides will quickly coat or foul the media. To prevent fouling of the media, iron is sometimes converted to its insoluble form before the water enters the greensand bed by adding chlorine ahead of the filter or aerating the water before it enters the greensand bed. After treating a certain number of gallons of water or when head loss reaches a predetermined point, the capacity of the greensand to oxidize manganese and iron is used up and the media must be backwashed and regenerated. Regeneration consists of the down flow passage of a dilute potassium permanganate solution through the bed using 1.5 ounces of potassium permanganate per cubic foot of media, followed by thorough rinsing of the media.

When well water contains low concentrations or iron and manganese and the pH is greater than 7.0, the catalytic regeneration mode of operation may be a suitable method for removing iron and manganese.

Operation of Filters

When iron and manganese are oxidized to insoluble forms by aeration, chlorination, or permanganate, the oxidation processes are usually followed by filters to remove the insoluble material.

Iron tests should be made monthly on the water entering a filter to be sure that iron is in the ferric state. Collect a sample of the water and pass the water through a filter paper. Run an iron test on the water that has passed through the filter. If the iron is still in the soluble ferrous state, iron is in the water. If aeration is being used to oxidize the iron from the soluble ferrous to the insoluble ferric state and iron is still present in the soluble state in the water entering the filter try adding chlorine or potassium permanganate. If chlorine or potassium permanganate is being used and soluble iron is in the water r entering the filter, try increasing the chemical dose. If potassium permanganate is being used, the sand may be replaced by greensand to improve the efficiency of the process.

If oxidation is being accomplished by aeration or chlorination, a free chlorine residual must be maintained in the effluent of the filter to prevent the insoluble ferric iron from returning to the soluble ferrous form and passing through the filter.

Most iron removal treatment plants are designed so that the filters are backwashed according to head loss. If iron break-through is a problem, filters should be backwashed when break-through occurs or just before break through is expected. Accurate records can reveal when break through occurs and when break thorough can be expected.

Review Questions

1. Describe ion exchange chemistry.

2. Define matter, ions, and compounds.

3. Describe the aeration process and applications

Test Questions

1. _________ can be defined as exchanging ions found in the source water for sodium ions or chloride ions that are attached to the ion exchange resins.

   a. Softening
   b. Oxidation
   c. Reduction
   d. Ion exchange

2. A _______ is a positively charged ion. An anion is negatively charged.

   a. anion
   b. cation
   c. ion
   d. electron

3. An ______ is negatively charged.

   a. anion
   b. cation
   c. ion
   d. electron

4. Once a unit has exchanged all of the sodium ions and the resin is saturated, it will no longer remove the targeted ions. The unit must be taken out of service and the targeted ions removed from the resin by exchange them with sodium ions. This process is referred to as _________.

   a. service cycle
   b. backwash cycle
   c. regeneration cycle
   d. rinse cycle

5. ________ is when the actual ion exchange occurs. Water is forced into the top of the unit and allowed to flow down through the exchange resin.

   a. service cycle
   b. backwash cycle
   c. regeneration cycle
   d. rinse cycle

6. _____ is when the unit is taken out of service and the flow pattern through the unit is reversed. The purpose of this activity is to expand and clean the resin particles and to free any material such as iron, manganese, and particulates that might have been removed

   a. service cycle
   b. backwash cycle
   c. regeneration cycle
   d. rinse cycle

7. ______ is when the sodium ion concentration of the resin is recharge by pumping a concentrated brine solution onto the resin. The solution is allowed to circulate through the unit and displace all water from the resin in order to provide full contact between the brine solution and the resin.

   a. service cycle
   b. backwash cycle
   c. regeneration cycle
   d. rinse cycle

8. After adequate contact time has been allowed during brine application, a ______ is applied to remove the waste products and excess brine solution. The flow pattern is similar to the flow through the unit except that the effluent goes to waste. The waste discharge contains high concentrations of chloride. This cycle will last between 20 to 40 minutes, depending on the size of the unit and manufacturer.

   a. service cycle
   b. backwash cycle
   c. regeneration cycle
   d. rinse cycle

9. If the water contains manganese up to 0.3 mg/L and less than 0.1 mg/L of iron, an inexpensive and reasonably effective control can be achieved by feeding the water with _______. Chlorine usually must be fed along with the polyphosphate to prevent the growth of iron bacteria.

   a. sodium chloride
   b. polyphosphate
   c. calcium carbonate
   d. magnesium hydroxide

10. Iron can be oxidized by aerating the water to form insoluble ferric hydroxide. This reaction is accelerated by __________.

    a. increasing pH
    b. increasing organic matter
    c. decreasing temperature
    d. decreasing pH

11. After the greensand has been treated with _________, it can oxidize iron and manganese to their insoluble oxides.

    a. sodium chloride
    b. calcium carbonate
    c. potassium permanganate
    d. polyphosphate

12. If oxidation of iron and manganese is being accomplished by aeration or chlorination, _______ must be maintained in the effluent of the filter to prevent the insoluble ferric iron from returning to the soluble ferrous form and passing through the filter.

    a. a pH of 8.2
    b. a permanganate residual of 0.3 mg/L
    c. a free chlorine residual
    d. None of these are required

CHAPTER 9: ACTIVATED CARBON

Objectives:

- Describe the sources and production of activated carbon
- Describe the organic chemical removal theory
- Describe the types of applications where activated carbon is used
- Outline the disposal methods and regeneration methods for activated carbon

Activated carbon is commonly used to adsorb natural organic compounds, taste and odor compounds, and synthetic organic chemicals in drinking water treatment. Adsorption is the physical and chemical process of accumulating a substance at the interface between liquid and solids phases.

Activated carbon filters are used to remove unwanted tastes, odors, radon, and some man-made volatile organic contaminants from drinking water. The efficiency of the unit depends on the type of activated carbon installed, the filter bed depth, the type of contaminants in the water and their concentration, and the contact time between the water and the carbon filter. Activated carbon filters do not adsorb every type of contaminant equally well.

The solid material used in an activated carbon filter is a specialized carbon manufactured for the purpose. Contaminants adhere to the surface of these carbon granules or become trapped in the small pores of the activated carbon. Generally, an activated carbon filter is used with a pre-treatment filter to remove sediment or iron particles that may be present and can clog the carbon filter.

Granular activated carbon is an effective filter for removing organic chemicals that may be in drinking water. Although activated carbon is efficient in removing a variety of organic chemicals, a specially formulated synthetic resin may be a better absorber for a specific contaminant.

As surface waters continue to be threatened by industrial contaminants, Ground waters are increasingly the source of potable and non-potable applications, and it is important to remove these trace organic contaminants. Treatment of such waters for the removal of organic contaminants varies based on the intended uses, however, in most cases, even trace amounts of the contaminants require some level of removal to meet drinking water requirements.

Organic substances are composed of two basic elements, carbon and hydrogen, and are often responsible for taste, odor, and color problems in ground waters. As such, treatment is used generally to improve aesthetically objectionable water.

Sources of organic compounds (VOC's, taste & odor compounds, disinfection byproducts, and free chlorine) found in ground waters may include leaking underground gasoline/storage tanks, agricultural runoff containing herbicides or pesticides, solid waste or hazardous waste landfills, and improperly disposed industrial/chemical waste.

The ability of organic compounds to cause health effects varies greatly from those that are highly toxic, to those with no known health effect. The extent and nature of the health effect will depend on many factors including level of exposure and length of time exposed. Eye and respiratory tract irritation, headaches, dizziness, visual disorders, and memory impairment are among the immediate symptoms that some people have experienced soon after exposure to some organics.

The technologies most suitable for organic contaminant removal in process waters are granular activated carbon (GAC) and aeration.

GAC has been designated by the U.S. Environmental Protection Agency (EPA) as the best available technology (BAT) for organic chemical removal. Activated carbon adsorption provides an effective and reliable treatment for removing organic contaminants and is suitable for treating a wide range of organics over a broad range of concentrations. GAC filtration will also remove chlorine.

GAC filtration is recognized by the Water Quality Association as an acceptable method to maintain certain drinking water contaminants within the limits of the EPA National Drinking Water Standards. Organics that are readily adsorbed by activated carbon include:

- Aromatic solvents (benzene, toluene, nitrobenzenes)
- Chlorinated aromatics (PCBs, chlorobenzenes, chloroaphthalene)
- Phenol and chlorophenols
- Polynuclear aromatics (acenaphthene, benzopyrenes)
- Pesticides and herbicides (DDT, aldrin, chlordane, heptachlor)
- Chlorinated aliphatics (carbon tetrachloride, chloroalkyl ethers)
- High molecular weight hydrocarbons (dyes, gasoline, amines, humics)

Various types of GAC are available for removing organics from water, however, the most frequently used carbon in the US. is coal-based carbon due to its hardness, adsorption capacity, and ease of availability.

Coagulation and Flocculation

Particulate impurities in water result from land erosion, dissolved minerals, and the decay of plant material. Additional impurities are added by airborne contamination, industrial discharges, and by animal wastes. Surface water sources and reclaimed water, polluted by people and nature, are likely to contain suspended and dissolved organic and inorganic material, as well as biological forms such as bacteria and plankton. With few exceptions, this water requires treatment to remove particulate impurities and color before it is distributed to the consumer.

Coagulation

The term coagulation describes the effect produced when certain chemicals are added to raw water containing slowly settling or nonsettleable particles. The small particles begin to form larger or heavier floc, which is removed by sedimentation and filtration.

The mixing of the coagulant chemical and the raw water to be treated is commonly referred to as flash mixing. The primary purpose of the flash-mix process is to rapidly mix and equally distribute the coagulant chemical throughout the water column. The entire process occurs in a very short time (several seconds), and the first results are the formation of very small particles.

Coagulants

In practice, chemical coagulants are referred to as primary coagulants or as coagulant aids. Primary coagulants neutralize the electrical charges of the particles, which cause them to begin to clump together. The purpose of coagulant aids is to add density to slow-settling flocs and add toughness so the floc will not break up in the processes that follow.

Metallic salts like aluminum sulfate, ferric sulfate, ferrous sulfate, and synthetic organic polymers are commonly used as coagulation chemicals in water treatment, because they are effective, relatively low in cost, available, and easy to handle, store, and apply.

When metallic salts, such as aluminum sulfate or ferric sulfate, are added to water, a series of reactions occur with the water and with other ions in the water. Sufficient chemical quantities must be added to the water to exceed the solubility limit of the metal hydroxide, resulting in the formation of a precipitate (floc). The resulting floc formed will then adsorb on particles (turbidity) in the water.

The synthetic organic polymers used in water treatment consist of long chains of small subunits, called monomers. The polymer chains can be linear or branched structures, ranging in length from a fraction of a micron to 10 microns. The total number of monomers in a synthetic polymer cn be varied to produce materials of different molecular weights, which vary from about 100 to 10,000,000. Cationic polymers have a positive electrical charge, anionic polymers have a negative charge, and nonionic polymers have no electrical charge.

The polymers normally used in water treatment contain ionizable groups on the monomeric units and are referred to as polyelectrolytes. Polymers with positively charged groups on the monomeric units are referred to as cationic polyelectrolytes, while polymers with negatively charged particles are called anionic polyelectrolytes. Polymers without ionizable groups are referred to as nonionic polymers.

Cationic polymers have the ability to adsorb on negatively charged particles, turbidity, and neutralize their charge. They can also form an interparticle bridge that collects the particles. Anionic and nonionic polymers also form interparticle bridges, which aid in collecting and removing particles from water.

While alum is perhaps the most commonly used coagulant chemical, cationic polymers are used in the water treatment field as a primary coagulant and as a coagulant aid. Anionic and nonionic polymers have also proven to be effective in certain applications as coagulant aids and filter aids.

The theory of coagulation is complex. Coagulation is a physical and chemical reaction occurring between the alkalinity of the water and the coagulant added to the water, which results in the formation of insoluble flocs.

For a specific coagulant, the pH of the water determines which hydrolysis species predominates after mixing the chemical with the water to be treated. Lower pH values tend to favor positively charged species, which are desirable for reacting with negatively charged colloids and particulates, forming insoluble flocs, and removing impurities from the water.

The best pH for coagulation usually falls in the range of pH 5 to 7. The proper pH range must be maintained because coagulants generally react with the alkalinity in the water. Residual alkalinity in the water serves as a buffer to the system preventing the pH from changing, and alkalinity aids in the complete precipitation of the coagulant chemicals. The amount of alkalinity in the source water is generally not a problem unless the alkalinity is very low. Alkalinity may be increased by the addition of lime or soda ash.

Polymers are generally added in the coagulation process to stimulate or improve the formation of insoluble flocs.

Generally, the operator has no control over the pH and alkalinity of the source water. Hence, evaluation of these water quality indicators may play a major role in selecting the type of chemical coagulants to be used at a particular water treatment plant, or in changing the type of coagulant normally used if significant changes in pH and alkalinity occur in the raw water.

In some instances, the natural alkalinity in the raw water may be too low to produce complete precipitation of alum. In these cases, lime is often added to ensure complete precipitation. Care must be used to keep the pH within the desired range.

Overdosing as well as under-dosing of coagulants can lead to reduced solids removal efficiency. This condition can be corrected by carefully performing jar tests and verifying process performance after making any changes in the operation of the coagulation process.

Flocculation

Flocculation is a slow stirring process that causes the gathering together of small, coagulated particles into larger, settleable particles. The flocculation process provides contact between particles to promote their gathering together into floc for ease of removal by sedimentation and filtration. Generally, these contacts or collisions between particles result from gentile stirring created by a mechanical or hydraulic means of mixing.

An efficient flocculation process involves the selection of the right stirring time, detention time, the proper stirring intensity, a properly shaped basin for uniform mixing, and mechanical equipment or other means of creating the stirring action. Insufficient mixing will result in ineffective collisions and poor floc formation. Excessive mixing may tear apart the flocculated particles after they have clumped together.

Adsorption

Adsorption is the gathering of a gas, liquid, or dissolved substance on the surface or interface zone of another material. This process removes taste and odor producing compounds because the compounds attach themselves to the material added to the water for that purpose. In water treatment, this material is powdered activated carbon (PAC) or granular activate carbon. PAC is added to the treatment process at the influent, and GAC is used as a filter medium. The material being removed by adsorption is known as the adsorbate, and the material responsible for the removal is known as the adsorbent.

The primary adsorbents for water treatment are the two types of activated carbon. These materials are activated by a process involving high temperature and high-pressure steam treatment. The original source of the carbon may be wood, coal, coconut shells, or bones. The purpose of the activation process is to significantly increase the surface area of the particles so that more adsorption can take place per pound of carbon.

The nature of the porous structure of the carbon compound being used will exert a significant effect on the success of the treatment process. If the pores of the carbon are too small, the compounds that are being treated will not be able to enter the structure and only a small portion of the available surface area will be used for treatment. Activation processes produce carbons with different surface areas. Because adsorption is a surface phenomenon, carbons with grater surface area generally provide greater adsorption capacity.

Activated carbon is typically rated on the basis of the phenol number or iodine number. The higher the value, the greater the adsorption capacity of the carbon for phenol or iodine. This strategy is an excellent approach for evaluating the effectiveness of a carbon for removal of phenol or iodine. However, no direct relationship between the compounds causing taste and odor problems and the removal of phenol or iodine exists. Only by testing various carbons for effective removal of objectionable tastes or odors can a good comparison be made for a particular application.

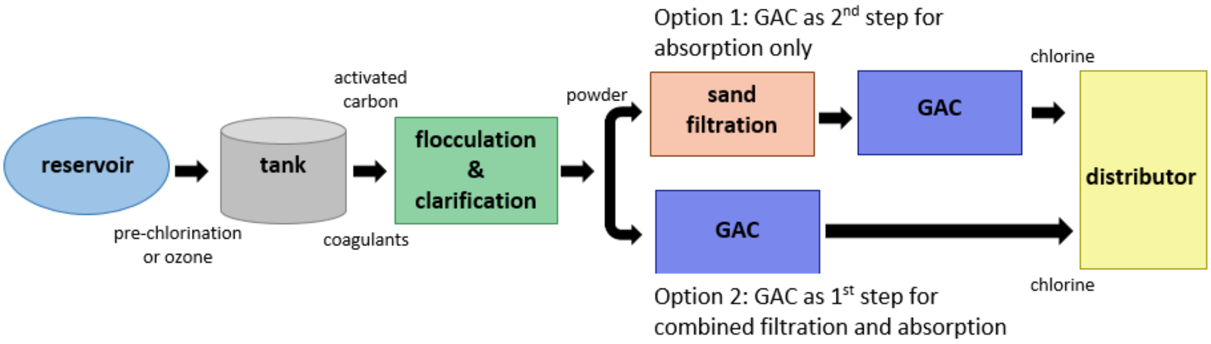

Figure 9-1 Activated Carbon – Image by COC OER is licensed under CC BY

Powdered Activated Carbon

Powdered activated carbon adsorption is the most common technique used specifically for taste and odor control at water treatment plants. This widespread use is largely because of its nonspecific action over a broad range of taste and odor causing compounds. PAC treatment does have limitations, and its effectiveness and required dose rate varies widely from plant to plant.

Powdered activated carbon can be applied to water at any point in the treatment process before filtration. Because carbon must contact the material to be removed for adsorption to occur, it is advantageous to apply PAC at the plant mixing facilities. Powdered activate carbon is often less effective at removing compounds after chlorination, so application upstream from chlorine treatment is desirable. Chlorine will react with carbon and neutralize the effects of the chlorine and the adsorption by the carbon.

Powdered activated carbon is often applied at the plant flash mixer. This location provides high-rate initial mixing and the greatest contact time through the plant. Thorough mixing and long contact time are necessary for the effectiveness of PAC. Another common location for PAC application is the filter influent. While contact time and mixing are drastically reduced compared to flash mix applications, this method ensures that the water passes through a PAC layer before release into the distribution system. This procedure is used with $KMnO_4$ treatment to prevent colored water problems in the distribution system.

When PAC is used, dosages may range from 1 to 15 mg/L. The literature indicates that as much as 100 mg/L has been required to adequately treat some serious taste and odor problems. At very high doses, treatment costs become prohibitive, and consideration of granular activated carbon treatment in the filter becomes an option.

The use of powdered activated carbon for taste and odor removal can interfere with filter performance at a water treatment plant. Caking of PAC on the surface of filters may cause substantially shorter filter runs than otherwise expected. If this occurs, adjustments to improve PAC removal in the settling process may increase the effective length of filtration. An added advantage of optimizing the settling process is the physical removal of taste and odor compounds with the settled sludge.

Granular Activated Carbon

Activated carbon is commonly used to adsorb natural organic compounds, taste and odor compounds, and synthetic organic chemicals in drinking water treatment. Adsorption is the physical and chemical process of accumulating a substance at the interface between liquid and solids phases. Activated carbon is an effective adsorbent because it is a highly porous material and provides a large surface area to which contaminants may adsorb. The two main types of activated carbon used in water treatment applications are granular activated carbon (GAC) and powdered activated carbon (PAC).

GAC is made from organic materials with high carbon contents such as wood, lignite and coal. The primary characteristic that differentiates GAC to PAC is its particle size. GAC typically has a diameter ranging between 1.2 to 1.6 mm and an apparent density ranging between 25 and 31 lb/ft^3), depending on the material used and manufacturing process. The bed density is about 10 percent less than the apparent density and is used to determine the amount of GAC required to fill a given size filter. The uniformity coefficient of GAC is quite large, typically about 1.9, to promote stratification after backwashing and minimize desorption and premature breakthrough that can result from mixing activated carbon particles with adsorbed compounds with activated carbon particles with smaller amounts of adsorbed compounds. Iodine and molasses numbers are typically used to characterize GAC. These numbers describe the quantity of small and large pore volumes in a sample of GAC. A minimum iodine number of 500 is specified for activated carbon by AWWA standards.

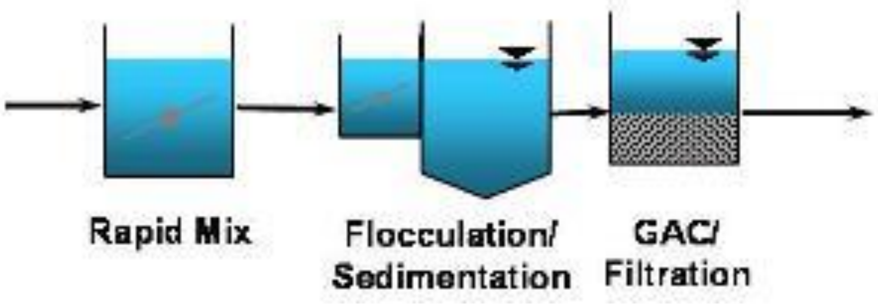

Figure 9-2 Granular Activated Carbon Filtration – Image by the EPA is in the public domain

The two most common options for locating a GAC treatment unit in water treatment plants are: (1) post-filtration adsorption, where the GAC unit is located after the conventional filtration process (post-filter contactors or adsorbers); and (2) filtration-adsorption, in which some or all of the filter media in a granular media filter is replaced with GAC.

In post-filtration applications, the GAC contactor receives the highest quality water and, thus, has as its only objective the removal of dissolved organic compounds. Backwashing of these adsorbers is usually unnecessary, unless excessive biological growth occurs. This option provides the most flexibility for handling GAC and for designing specific adsorption conditions by providing longer contact times than filter-adsorbers.

In addition to dissolved organics removal, the filter-adsorber configuration uses the GAC for turbidity and solids removal, and biological stabilization. Existing rapid sand filters can frequently be retrofitted for filtration-adsorption by replacing all or a portion of the granular media with GAC. Retrofitting existing high rate granular media filters can significantly reduce capital costs since no additional filter boxes, underdrains and backwashing systems may be required. However, filter-adsorbers have shorter filter run times and must be backwashed more frequently than post-filter adsorbers (filter-adsorber units are backwashed about as frequently as conventional high rate granular filters). In addition, filter-adsorbers may incur greater carbon losses because of increased backwashing and may cost more to operate because carbon usage is less effective.

Primary factors in determining the required GAC contactor volume are the (1) breakthrough, (2) empty bed contact time (EBCT), and (3) design flow rate. The breakthrough time is the time when the concentration of a contaminant in the effluent of the GAC unit exceeds the treatment requirement. As a rule of thumb, if the GAC effluent concentration is greater than the performance standard for over three consecutive days, the GAC is exhausted and must be replaced/regenerated. The EBCT is calculated as the empty bed volume divided by the flowrate through the carbon. Longer EBCTs can be achieved by increasing the bed volume or reducing the flow rate through the filter. The EBCT and the design flow rate define the amount of carbon to be contained in the adsorption units. A longer EBCT can delay breakthrough and reduce the GAC replacement/regeneration frequency. The carbon depth and adsorber volume can be determined once the optimum EBCT is established. Typical EBCTs for water treatment applications range between 5 to 25 minutes.

The surface loading rate for GAC filters is the flow rate through a given area of GAC filter bed and is expressed in units of gpm/ft^2. Surface loading rates for GAC filters typically range between 2 to 10 gpm/ft2. High surface loading rates can be used when highly adsorbable compounds (such as SOCs) are targeted for removal. The surface loading rate is not important when mass transfer is controlled by the rate of adsorption as is the case for less-adsorbable compounds.

The carbon usage rate (CUR) determines the rate at which carbon will be exhausted and how often carbon must be replaced/regenerated. Carbon treatment effectiveness improves with increasing contact times. Deeper beds will increase the percentage of carbon that is exhausted at breakthrough. The optimum bed depth and volume are typically selected after carefully evaluating capital and operating costs associated with reactivation frequency and contactor construction costs.

GAC contactors can be configured as either (1) downflow fixed beds, (2) upflow fixed or expanded beds, or (3) pulsed beds; with single or multiple adsorbers operated in series or in parallel. In downflow fixed beds in series, each unit is connected in series with the first adsorber receiving the highest contaminant loading and the last unit receiving the lightest contaminant load. Carbon is removed for reactivation from the first unit, with the next adsorber becoming the lead unit. For downflow fixed beds in parallel, each unit receives the same flow and contaminant load. To maximize carbon usage, multiple contactors are frequently operated in parallel-staggered mode in which each contactor is at a different stage of carbon exhaustion. Since effluent from each contactor is blended, individual contactors can be operated beyond breakthrough such that the blended flow still meets the treatment goal. Upflow expanded beds permit removal of suspended solids by periodic bed expansion and allow using smaller carbon particles without significantly increasing head loss. In pulsed bed adsorbers, removal of spent carbon occurs from the bottom of the bed while fresh carbon is added at the top without system shutdown. A pulsed bed cannot be completely exhausted, which prevents contaminant breakthrough in the effluent.

Depending on the economics, facilities may have on-site or off-site regeneration systems or may waste spent carbon and replace it with new. Spent GAC must be disposed of recognizing that contaminants can be desorbed, which can potentially result in leaching of contaminants from the spent GAC when exposed to percolating water, contaminating soils or groundwater. Due to contamination concerns, spent GAC regeneration is typically favored over disposal. The three most common GAC regeneration methods are steam, thermal and chemical; of which thermal regeneration is the most common method used. Available thermal regeneration technologies used to remove adsorbed organics from activated carbon include: (1) electric infrared ovens, (2) fluidized bed furnaces, (3) multiple hearth furnaces, and (4) rotary kilns.

Review Questions

1. Describe the sources and production of activated carbon

2. Describe the organic chemical removal theory.

3. Describe the types of applications where activated carbon is used

4. Outline the disposal methods and regeneration methods for activated carbon

Test Questions

1. _______ is the physical and chemical process of accumulating a substance at the interface between liquid and solids phases.

   a. Absorption
   b. Adsorption
   c. Oxidation
   d. Stabilization

2. The technologies most suitable for organic contaminant removal in process waters are _______ and ________.

   a. oxidation, reduction
   b. coagulation, flocculation
   c. adsorption, absorption
   d. granular activated carbon, aeration

3. ________ is the gathering of a gas, liquid, or dissolved substance on the surface or interface zone of another material.

   a. Absorption
   b. Adsorption
   c. Oxidation
   d. Stabilization

4. Activated carbon is typically rated on the basis of the __________. The higher the value, the greater the adsorption capacity of the carbon for phenol or iodine.

   a. adsorption number
   b. absorption number
   c. taste and odor number
   d. phenol number or iodine number

5. __________ is commonly used to adsorb natural organic compounds, taste and odor compounds, and synthetic organic chemicals in drinking water treatment.

   a. Oxidation
   b. Coagulation
   c. Absorption
   d. Activated carbon

6. The two primary types of activated carbon used in water treatment applications are _________ and _______.

   a. oxidation, reduction
   b. coagulation, flocculation
   c. adsorption, absorption
   d. GAC, PAC

CHAPTER 10: MEMBRANE FILTRATION

Objectives:

- Explain particle theory
- Describe the types and classification of membrane treatment processes
- List the component parts of a membrane treatment process
- Outline the applications and operation of membrane treatment processes

The kinetic theory of matter or particle theory reports that matter consists of many small particles which are constantly moving or are in a continual state of motion. The degree to which the particles move is determined by the amount of energy that they have and their relationship to other particles. The particle theory of matter is used to explain how solids, liquids, and gases are interchangeable as a result of increases or decreases in heat energy. When objects are heated, motion increases as the particles become more energetic. If the objects are cooled the motion of the particles decrease as they lose energy.

Membrane treatment technologies are advancing rapidly in the water treatment field. Membranes are being used in municipal water treatment plants, in home point-of-use applications, in reclamation facilities, and wastewater treatment plants to remove suspended and dissolved minerals from water.

Membranes contain very fine pore openings that allow water to pass through and block the passage of any contaminant larger than the pore diameter. Membranes used in water treatment are classified by their pore diameter. Classifications, from the largest pore diameter to the smallest, are microfiltration, ultrafiltration, nanofiltration, and reverse osmosis.

Microfiltration (MF) and ultrafiltration (UF) are effective in the removal of *Giardia* and *Cryptosporidium*. Reverse osmosis (RO) membranes are used for desalination/demineralization and in home drinking water units. Reverse osmosis and nanofiltration membranes are used to remove dissolved organic matter and dissolved contaminants, such as arsenic, nitrate, pesticides, and radionuclides. Also these membranes can remove ions such as calcium and magnesium and sodium and chloride. Nanofiltration can be used to reduce the concentration of natural organic matter to control the formation of disinfection byproducts.

The type of membrane used depends on the constituents to be removed from the water being treated. During water treatment, water is typically pumped against the surface of the membrane; however, water can be pulled through the membrane by a vacuum. The water pressure forces water through the membrane and the constituents that do not pass through form a waste stream that may require treatment and proper disposal.

Description of Membrane Filtration Units

Pressure Vessel or Submerged Flow

Typical water treatment membrane filtration units are installed in pressure vessels or submerged in tanks. The membranes are hollow fibers or threads with an outside diameter ranging from 0.5 to 2 mm and a wall thickness of 0.07 to 0.6 mm. In the pressure vessel installation, thousands of membrane fibers or threads are arranged in racks or skids, with each pressure vessel ranging from 4 to 12-inches in diameter and 3 to 18-feet long. Filtration flow may be from outside to inside or from inside to outside of the hollow fiber membrane.

Submerged or immersed membrane filtration systems are membrane modules suspended in basins containing the water to be treated. The treated water may then be pulled through the membrane by vacuum. Some treatment plants have removed sand from the sand filters and installed submerged membrane modules in the old filter basin.

Membrane Flow Types

Two different types of membrane filtration feed water flows exist:

1. Cross-flow filtration systems
2. Dead-end filtration systems

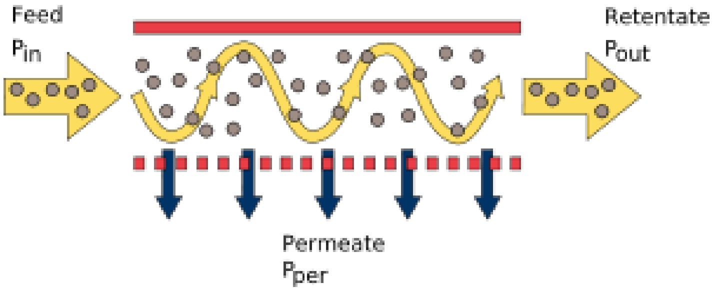

Figure 10-1 Cross-flow filtration system – Image by AD and Benutzer:Mæx is in the public domain

In cross-flow filtration systems, the flow is from the inside of the membrane, through the membrane, and the filtered water flows out of the system. The flow inside the membrane flows along the inside surface of the membrane, becomes concentrated, and flows out the end of the membrane fiber as a waste stream. In dead-end filtration systems, the water being filtered may flow from the outside into the hollow fiber or from the inside to the outside; however, in this system, no waste stream is produced. All solids accumulate on the membrane during filtration and are removed during backwash.

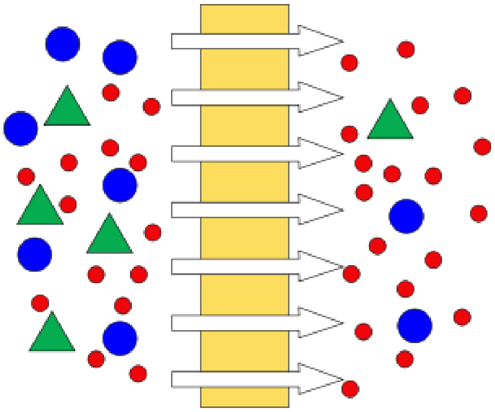

Figure 10-2 Dead-end filtration system – Image by Alexdruz and Mæx is in the public domain

Membrane Fouling

Membrane fouling can be a serious problem when operating membrane filtration processes. Membrane fouling can be described by whether the cause of the fouling can be removed (reversible or irreversible, by the material causing the fouling (biological, organic, particulate, or dissolved), and by the means of fouling (cake formation or membrane pore blockage).

Whether the cause of fouling can be removed depends on the type of membrane used and the constituents in the source water. During continued operation, the flow through the membrane may decrease; however, the flow may be recovered by backwashing and cleaning.

The constituents in the water being filtered may cause fouling. During membrane filtration, microorganisms are transported to the membrane surface where biofouling may occur. These microorganisms may not be removed by backwashing; however, they may be controlled by using chlorine. Some membrane materials such as cellulose acetate or polypropylene can be damaged using chlorine. Membrane manufacturers are tending to use materials that are not damaged by chlorine.

Dissolved organic matter may cause membrane fouling. The extent of the fouling problem depends on the characteristics of the dissolved organic matter, the membrane material, and the characteristics of the water being filtered.

During membrane filtration, particulate matter from the water being filtered collects on the membrane surface in a porous mat called a filter cake. Particulate fouling is usually reversible during periodic backwashing.

Natural organic matter can be the most common form of membrane fouling. Dissolved organic matter includes wastes and portions of aquatic plants and animals as well as organic matter washed into surface water from land. Sources of dissolved organic matter include organic chemicals found in biological systems and dissolved organic chemicals from industrial and commercial wastes. Fouling depends on the characteristics of the dissolved organic matter, the membrane material, and the source water.

Pretreatment

Experiences

Operators have learned that the interactions among coagulants, the various constituent in natural water, and the membrane materials are very complex, making the effect of coagulation on membrane performance difficult to predict. In some treatment facilities, the flow through the membrane increases with coagulation pretreatment; however, in other plants a reduction in flow can occur.

When using coagulation pretreatment before membrane filtration, operators have experienced the inconsistent outcomes regarding membrane fouling and a decline of flows through the membrane. The inconsistencies apparently result from the fact that coagulation and membrane filtration may be performed under a wide variety operational conditions. Coagulation may be performed with or without flocculation and with or without sedimentation before membrane filtration. Membrane filtration may be performed with submerged or pressurized membranes and with constant pressure or constant flow conditions. Studies conducted on a specific source water with an individual coagulant and a set coagulant dose cannot be easily compared with other source water, coagulants, and coagulant doses.

Another important consideration in the relationship between coagulation and membrane performance is that coagulation affects particulate matter and dissolved organic carbon, each can affect membrane performance. Coagulation collects particles into layer masses and, if settling is practiced, removes particles from solution, which may alter membrane fouling because of cake resistance. Coagulation also removes dissolved organic carbon from water, which may alter membrane fouling caused by adsorption.

Membrane Performance Monitoring

The operation of membranes includes monitoring and testing for membrane filtration rate and membrane integrity. This process is accomplished by pressure decay testing and sonic testing. When broken or damaged membrane fibers are discovered, they are repaired or replaced.

Reverse Osmosis Membrane Structure and Composition

The two types of semipermeable membranes that are used most often for demineralization are cellulose acetate and thin film composites. Cellulose acetate (CA), the first commercially available membrane. The cellulose acetate membrane is asymmetric meaning that one side is different from the other side. The total cellulose acetate layer is 50 to 100 microns thick; however, a thin dense layer approximately 0.2 microns thick exists at the surface. This thin, dense layer serves as the rejecting barrier of the membrane.

Researchers realized the need for a membrane with better flux and rejection characteristics than those properties of cellulose acetate. The approach to developing a better membrane was to improve the efficiencies of the thin rejecting layer and the porous substrate so the thin composite membrane was developed.

In the production of the thin composite membrane, the semipermeable membrane is separate from the support layers, and this construction enables membrane manufacturers to select polymers that will produce membranes with optimum dissolved solids rejection and water flux rates.

Membrane Performance and Properties

The basic behavior of semipermeable cellulose acetate reverse osmosis membranes can be described by two equations. The product water flow through a semipermeable membrane can be expressed:

$F_w = A(\Delta P - \Delta\pi)$

Where

F_w = Water flux (g/cm^2 sec)

A = Water permeability constant (g/cm^2 sec atm^{21})

ΔP = Pressure differential applied across the membrane (atm)

$\Delta\pi$ = Osmotic pressure differential across the membrane (atm)

Note that the water flux is the flow of water in grams per second through a membrane area of one square centimeter. Think of this flow as similar to the flow through a rapid sand filter in gallons per minute through a filter area of one square foot (GPM/ft^2).

The mineral (salt) flux (mineral passage) through the membrane can be expressed:

$F_w = B(C_1 - C_2)$

Where

F_w = Mineral flux (g/cm^2 sec)

B = Mineral permeability constant (cm/sec)

$C_1 - C_2$ = Concentration gradient across the membrane (g/cm^2)

The water permeability (A) and mineral permeability (B) constants are characteristics of the particular membrane that is used and the processing it has received.

An examination of the equations demonstrates that the water flux, which is the rate of flow through the membrane, is dependent on the applied pressure, while the mineral flux is not dependent on pressure. As the pressure of the feed water is increased, the flow of water through the membrane increases while the flow of mineral remains constant. Therefore, the quantity and the quality of the purified product (permeate) should increase with increased pressure. This result occurs because more water is present to dilute the same amount of mineral.

The water flux (F_w) decreases as the mineral content of the feed increases because the osmotic pressure contribution ($\Delta\pi$) increases with increasing mineral content. Since $\Delta\pi$ increases, the term ($\Delta P - \Delta\pi$) decreases, which results in a decrease in F_w, the water flux. As more and more feed water passes through the membrane, the mineral content of the feed water becomes higher and higher (more concentrated). The osmotic pressure contribution ($\Delta\pi$) of the concentrate increases, resulting in a lower water flux.

Since the membrane rejects a constant percentage of mineral, product water quality decreases with increased feed water concentration. Also, not that Equation 2 reveals that the greater the concentration gradient ($C_1 - C_2$) across the membrane, the greater the mineral flux (mineral flow). Therefore, the greater the feed concentration, the greater the mineral flux and mineral concentration in the product water.

Water treatment plant operators must have a basic understanding of the mathematical relationships that describes RO (reverse osmosis) membrane performance.

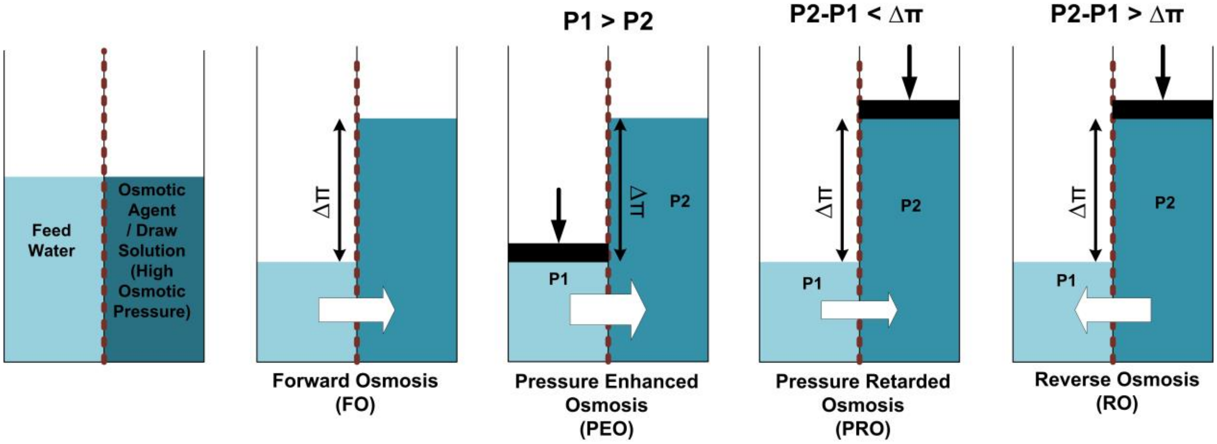

Figure 10-3 RO Filtration – Image by Starsend is licensed under CC BY-SA 3.0

Definition of Flux

The term flux is used to describe the rate of water flow through a semipermeable membrane. Flux is usually expressed in gallons per day per square foot of membrane surface or in grams per second per square centimeter.

The average membrane flux rate of a reverse osmosis system is an important operating guideline. In practice, most reverse osmosis systems will require periodic cleaning. It has been demonstrated that the cleaning frequency can be dependent on the average membrane flux rate of the system. Too high a flux rate may result in excessive fouling rates requiring frequent cleaning. Some industry guidelines for acceptable flux rates are:

Feed Water Source	**Flux Rate, GFD**
Industrial/Municipal Waste	8-12
Surface (river, lake, ocean)	8-14
Well	14-20

Mineral Rejection

The purpose of demineralization is to separate minerals from water: the ability of the membrane to reject minerals is called the mineral rejection. Mineral rejection is defined as:

$$\text{Rejection, \%} = \left(1 - \frac{\text{Product Concentration}}{\text{Feed Water Concentration}}\right) \times 100\%$$

Mineral rejections may be calculated for individual constituents in the solution by using their concentrations.

The basic equations that describe the performance of a reverse osmosis membrane indicate that rejection decreases as the feed water mineral concentration increases, because the higher mineral concentration increases the osmotic pressure. Also as the feed mineral concentration increase (TDS) rejection decreases at a given feed pressure. Rejection improves as feed pressure increases.

Typical rejection for most commonly encountered dissolved inorganics is usually between 92 and 99-percent. Divalent ions such as calcium and sulfate are better rejected than monovalent ions such as sodium or chloride.

Most demineralization applications require the use of a membrane with high rejection rates (greater than 95-percent). However, some applications can use a membrane with lower rejection rates (80-percent) and lower operating pressures (less than 150 psi). The membranes that fit this classification are commonly referred to as softening or nanofiltration membranes. These membranes produce the same quantity of water as standard RO membranes at lower operating pressures.

Softening or nanofiltration membranes are seeing widespread use for demineralization of municipal water supplies that require high rejection rates for hardness and THM formation potential, and moderate TSD rejection.

Effects of Feed Water Temperature and pH on Membrane Performance

In reverse osmosis operation, feed water temperature has a significant effect on membrane performance and must therefore be taken into account in system design and operation. Essentially, the value of the water permeation constant is only constant for a given temperature. As the temperature of the feed water increases, the flux increases. Usually, flux is reported at some standard temperature reference condition, such as 25^{o}C.

Cellulose acetate membranes are subject to long-term hydrolysis. Hydrolysis results in a lessening of mineral rejection capability. The rate of hydrolysis is accelerated by increased temperature, and is a function of feed pH. Slightly acidic pH values ensure a lower hydrolysis rate, as do cooler temperatures. Therefore, to ensure the longest possible lifetime of the cellulose acetate membrane and to slow hydrolysis, acid is added as a pretreatment step before demineralization. Thin film composite membranes are not subject to hydrolysis; however, pH adjustments of feed water may be required for scale control.

Recovery

Recovery is defined as the percentage of feed flow that is recovered as product water. Expressed mathematically, recovery can be determined by:

$$\text{Recovery, \%} = \frac{(\text{Product Flow})}{\text{Feed Flow}} \times 100\%$$

The recovery rate is usually determined or limited by two considerations. The first is the desired product water quality. Since the amount of mineral passing through the membrane is influenced by the concentration differential between the brine and product, excessive recovery can lead to exceeding product quality criteria. The second consideration concerns the solubility limits of minerals in the brine. One should not concentrate the brine to a degree that would precipitate minerals on the membrane. This effect is commonly referred to as concentration polarization.

The most common and serious problem resulting from concentration polarization is the increasing tendency for precipitation of sparingly soluble salts and the deposition of particulate matter on the membrane surface.

In any flowing hydraulic system, the fluid near a solid surface travels more slowly than the main stream of the fluid. A liquid boundary exists at the solid surface, and this phenomenon is true at the surface of the membrane in a spiral wound element or in any other membrane packaging configuration. Since water is transmitted through the membrane at a much more rapid rate than minerals, the concentration of the minerals builds up in the boundary layer (concentration polarization), and it is necessary for the minerals to diffuse back into the flowing stream. Polarization will reduce the flux and rejection of a reverse osmosis system. Since it is impractical to totally eliminate the polarization effect, it is necessary to minimize it through good design and operation.

The boundary layer effect can be minimized by increased water flow velocity and by promoting turbulence within the RO elements. Brine flow rates can be kept high as product water is removed by staging (reducing) the module pressure vessels. This design is popularly referred to as a Christmas tree arrangement. Typical flow arrangements such as 4 units- 2 units- 1unit (85-percent recovery) or 2 units -1 unit (75-percent recovery) are used most often.

These configurations consist of feeding water to a series of pressure vessels in parallel where about 50-percent of the water is separated by the membrane as product water and 50-percent of the water is rejected. The reject is fed to half as many vessels in parallel where again about 50-percent is product water and 50-percent is reject. The reject becomes the feed for the next set of vessels. By arranging the pressure vessels in the 4-2-1 arrangement, it is possible to recover over 85-percent of the feed water as product water and to maintain adequate flow rates across the membrane surface to minimize polarization.

Components of a Reverse Osmosis Unit

Pumps

Pressurization Pump

The pressures required for RO can range from 100 to 1,200 psi. Typically, the pressure ranges can be broken down as:

Application	Pressure Range (psi)
Softening	100-200
Brackish	200-500
Brackish/Seawater Mixture, Industrial Concentrating	500-800
Seawater	800-1,200

Two basic types of pumps are used for pressurizing the feed water: centrifugal and positive displacement. Important characteristics of each type of pump relating to its use in RO applications are listed:

Centrifugal Pumps

1. Typically used for applications less than 500 psi
2. Most cost effective for applications below 500 psi
3. Single impellers geared to operate higher than motor speed create excessive noise
4. Multistage centrifugal pumps are more costly to operate than single stage pumps but more efficient

Positive Displacement Pumps

1. Typically used for applications greater than 500 psi
2. Very efficient for seawater (800-1,200 psi)
3. Flow pulsations require use of pulsation dampener for velocities greater than 2FPS (feet per second)

The output of a centrifugal pump may be throttled by use of a multi-turn throttling valve. Throttling valves are used for new systems, or after a successful membrane cleaning.

The output of a positive displacement pump may not be throttled. The pump discharge line should contain a pressure relief mechanism. Optional items would be a bypass valve to control flow to the membrane section and a pulsation dampener.

Figure 10-4 RO Water Treatment – Image by Vishalsh521 is licensed under CC BY-SA 3.0

Piping

The selection of piping material depends on the water salinity and pressure. Seawater reverse osmosis requires the use of high-grade stainless steel for high-pressure lines. The most common types of materials used currently are 316L and 317L, due to their high molybdenum content. Brackish water plants typically use 304 and 316 stainless steel.

Low-pressure piping is typically made of polyvinyl chloride (PVC) or fiber-reinforced plastic/polymer (FRP). Some exotic materials such as 316SS and polyvinylidend fluoride (PVDF) are used in high-purity applications such as for semiconductor rinse water.

Pressure Vessel Housings

Several spiral-wound membrane elements are connected in series and are contained in pressure vessels. For most applications, a maximum of six 40-inch-long spiral-wound elements are contained in a single vessel. Due to improvements in the hydraulics of the spiral-wound design, seven 40-inch-long elements have been placed in one vessel. The standard material of construction is fiber-reinforced plastic/polymer (FRP). The pressure vessels are available in 200, 400, 600, 1,000, and 1,200 psi ratings. Some manufacturers can provide vessels constructed and stamped according to ASME Code-Section X.

Hollow fiber bundles are packaged in individual fiber glass housings. For seawater desalination, these housings can be rated up to 1,200 psi.

Concentrate Control Valve

A regulating valve located in the concentrate line provides a means of applying a back pressure to the membrane. Positioning this valve in conjunction with the pump discharge valve (bypass valve for positive displacement pumps) will set the concentrate and permeate flow rates.

Sample Valves

Sample valves should be located on the feed, permeate, and concentrate lines. Locations should be such that samples can be taken during all modes of operation such as servicing, flushing, cleaning, and rinsing. Sample valves should also be located in the permeate line of each permeator or pressure vessel.

Flush Connections

Provisions should be made for flushing the unit for certain applications. Examples would be seawater or brackish water with high organic content. The flush water could be acidified feed or permeate. If permeate is used, a separate inlet would be required. For all units that require flushing, a separate outlet in the concentrate line upstream of the concentrate control valve should be provided. The concentrate control valve would restrict flush flow, which is usually greater than the design concentrate flow.

Cleaning Connections

All units should have cleaning connections for each bank of permeators or pressure vessels connected in parallel. Isolation valves for each bank would allow for one bank to soak while the upstream or downstream bank is being cleaned. On large systems with many vessels or permeators connected in parallel, the cleaning system is sized for economic reasons to clean only a portion of the bank. In this case, valves are required to isolate the specific amount of vessels that can be cleaned at one time.

Permeate Rinse

It is useful to have provisions for sending permeate from one bank or unit to drain. Some processes require that the permeate achieve quality by rinsing to drain after a shutdown period. Also for certain troubleshooting procedures, poor quality permeate can be directed to drain while individual vessels are checked for poor quality.

Permeate Drawback Tank

For seawater applications, a permeate drawback tank may be provided. The purpose of the drawback tank may be provided. The purpose of the drawback tank is to provide a supply of water or an off-line unit that is subject to osmosis. Upon shutdown with removal of applied pressure, reverse osmosis ceases and osmosis begins. During osmosis, flow will occur from permeate to the feed-concentrate side of the membrane. Flushing the feed-concentrate channels with permeate after shutdown should prevent natural osmosis; however, as a precaution, drawback tanks may be provided to prevent dehydration of the membrane.

Energy Recovery Devices

Energy recovery devices installed in the high-pressure concentrate line are used in some seawater reverse osmosis plants. The basic principle of operation is the conversion of the potential energy for the high-pressure concentrate into kinetic energy. A nozzle directs the concentrate flow toward a rotor with dished vanes. The flow strikes the vanes and turns the rotor. The shaft of the rotor is connected to a pump that pressurizes the seawater feed. Due to a lack of cost-effectiveness, corrosion problems, and size restrictions, energy recovery turbines of this type have seen limited use.

Membranes

Operating plants use the RO principle in several different membrane configurations. Three types of commercially available membrane configurations are used in operating plants. They include spiral wound, hollow fine fiber, and tubular.

The spiral wound RO module was conceived as a method of obtaining a relatively high ratio of membrane area to pressure vessel volume. The membrane is supported on each side of a backing material and sealed with glue on three of the four edges of the laminate. The laminate is also sealed to a central tube that has been drilled to allow the demineralized water to enter. The membrane surfaces are separated by a screen material that acts as a brine spacer. The entire package is rolled into a spiral configuration and wrapped in a cylindrical form. The membrane modules are loaded, end to end, into a pressure vessel. Feed flow is parallel to the central tube while permeated flows through the membrane toward the central tube. Plants using this type of system include brackish water demineralizing plants.

The hollow fiber membrane type is made of aromatic polyamide fibers about the size of a human hair with an inside diameter of about 0.0016-inch. In these very small diameters, fibers can withstand high pressure. In an operating process, the fibers are placed in a pressure vessel, and one end of each fiber is sealed. The other end protrudes outside the vessel. The brackish water is under pressure on the outside of the fibers and product water flows inside of the fiber to the open end. For operating plants, the membrane modules are assembled in a configuration similar to the spiral-wound unit.

Tubular membrane processes operate on much the same principle as the hollow fine fiber except the tubes are much larger in diameter, on the order of 0.5-inch. Use of this type of membrane system is usually limited to special situation such as for wastewater with high suspended solids concentration. The tubular membrane process is not economically competitive with other available systems for treatment of most water sources.

Operation

Pretreatment

Water to be demineralized contains impurities that should be removed by pretreatment to protect the membrane and to ensure maximum efficiency of the reverse osmosis process. Depending on the water to be demineralized, it is usually necessary to treat the feed water to remove materials and conditions potentially harmful to the RO process:

1. Remove turbidity/suspended solids
2. Adjust pH and temperature
3. Remove materials to prevent scaling or fouling
4. Disinfect to prevent biological growth

Removal of Turbidity and Suspended Solids

In general, the feed water should be filtered to protect the reverse osmosis system and its accessory equipment. When the water source is a groundwater or previously treated municipal or industrial supply, this step may be accomplished by a simple screening procedure. However, such a procedure may not be adequate when the source is untreated surface water. The amount of suspended matter in surface water may vary by several orders of magnitude and may change radically in character and composition in a very short time. In such cases, in addition to the mechanical action of the filter, the operator may have to introduce chemicals for coagulation and flocculation and use filtration equipment in which the media can be washed or renewed at low cost. Pressure and gravity sand filters and diatomaceous earth filters may be required, particularly for large installations. When the particulates approach or are colloidal, chemical treatment and filtration are essential.

Cartridge filters function as a particle safeguard and not as a primary particle removal device. In general, the influent turbidity to cartridge filters should be less than 1 turbidity unit. Typical cartridge filter sizes range from 5 to 20 microns and loading rates vary from 2 to 4 GPM/ft^3.

pH and Temperature Control

An important limiting factor in the life of cellulose acetate membranes in reverse osmosis is the rate of membrane hydrolysis. Cellulose acetate will break down to cellulose and acetic acid. The rate at which this hydrolysis occurs is a function of feed water or source water, pH, and temperature. As the membrane hydrolyzes, the amount of water and the amount of solute that permeates the membrane increase and the quality of the product water deteriorates. The rate of hydrolysis is at a minimum at a pH of about 4.7, and it increases with increasing and decreasing pH. It is standard practice to inject acid, usually sulfuric acid, to adjust feed water pH to 5.5. pH adjustments minimize the effect of hydrolysis, and it is also essential in controlling precipitation of scale-forming or membrane-fouling minerals.

Calcium carbonate and calcium sulfate are probably the most common scaling salts encountered in natural water and are certainly the most common cause of scale in reverse osmosis systems. The addition of a small amount of acid can reduce the pH to a point where the alkalinity is reduced. A shift in equilibrium to the point where calcium bicarbonate, which is much more soluble, is present at all points within the reverse osmosis loop. Neutralization of 75 percent of the total alkalinity usually provides sufficient pH adjustment to achieve calcium carbonate scale control and bring the membrane into a reasonable part of the hydrolysis curve. The pH reached by 75 percent neutralization is about 5.7. Calcium carbonate precipitation is also inhibited by the control procedure used for calcium sulfate.

Calcium sulfate is relatively soluble in water in comparison to calcium carbonate. However, as pure or product water is removed from a feed solution containing calcium and sulfate, these chemicals become further concentrated in the feed water. When the limits of saturation are eventually exceeded, precipitation of calcium sulfate will occur. Since calcium sulfate solubility occurs over a wide pH range, the scale control method used to inhibit calcium sulfate precipitation is a threshold treatment with sodium hexametaphosphate. This precipitation inhibitor represses calcium carbonate and calcium sulfate by interfering with the crystal formation process. Other ploy phosphates may also be used; however, they are not as effective as sodium hexametaphosphate. Generally, 2 to 5 mg/L of this chemical is sufficient to decrease precipitation of calcium sulfate.

Other Potential Scalants

The oxides or hydroxides most commonly found in water are iron, manganese, and silica. The oxidized and precipitated forms of iron, manganese, and silica can be a serious problem to any demineralization scheme because they can coat the reverse osmosis membrane with a tenacious film, which will affect performance. The scale inhibitor most frequently used is sodium hexametaphosphate.

Microorganism

Reverse osmosis modules provide a large surface area for the attachment and growth of bacterial slimes and molds. These organisms may cause membrane fouling or module plugging. Evidence exist that occasionally the enzyme systems of some of these organisms will attack the cellulose acetate membrane. Thus a continuous application of chlorine to produce a 1 to 2 mg/L chlorine residual helps to inhibit or retard the growth of most of the organisms encountered. However, caution must be exercised since continuous exposure of the membrane to high chlorine residuals will impair membrane efficiency. Shock concentrations of up to 10 mg/L of chlorine are applied from time to time. When an oxidant-intolerant polyamide-type membrane is used, chlorination must be followed with dechlorination. One of the dechlorination agents, sodium bisulfite, is also known to be a disinfectant. Another disinfection option is the use of ultraviolet light disinfection, which leaves no oxidant residual in the water.

RO Plant Operation

Following proper pretreatment, the water to be demineralized is pressurized by high-pressure feed pumps and delivered to the RO pressure vessel membrane assemblies. The membrane assemblies consist of a series of pressure vessels arranged in a Christmas tree layout depending on the desired recovery. Typical operating pressure for brackish water demineralizing varies from 150 to 400 psi. A control valve on the influent manifold regulates the operating pressure. The volumes of feed flow and of product water are also monitored. The demineralized water is usually called permeate, and the reject water is called concentrate (brine). The recovery rate is controlled by increasing feed flow (increasing operating pressure) and by controlling the concentrate (brine) or reject with a preset brine control valve.

The operator must properly maintain and control all flows and recovery rates to avoid possible damage to the membranes from scaling.

Operators must remember that the brine flow valves are never to be fully closed. Should they be accidentally be closed during operation, 100-percent recovery will result in almost certain damage to the membranes due to the precipitation of inorganic salts. Product or permeate flow is not regulated and varies as feed water pressure and temperature change.

Most RO systems are designed to operate automatically and require a minimum of operator attention. However, continuous monitoring of system performance is an important responsibility of the operator of the operational process.

Types of Membrane Filtration Processes

Figure 10-5 – Image by Benreis is licensed under CC BY

Microfiltration (MF)

Microfiltration membranes have pores ranging from 0.1 to 2.0 microns. This process is less common with waste treatment processes because permeate from a microfilter is generally unacceptable for discharge. In some cases, this membrane process may be used in conjunction with settling agents, polymers, activated carbon, and other chemicals that assist in the retention of waste constituents. When using this membrane, care must be taken to prevent membrane pore blockage by waste streams components through the selection of the proper membrane type for the specific plant wastes.

Ultrafiltration (UF)

The process of ultrafiltration is the most common membrane-based wastewater treatment process. It uses a membrane with pore sizes ranging from 0.005 to 0.1 micron. Particles larger than the pores in the membrane, such as emulsified oils, metal hydroxides, proteins, starches, and suspended solids, are retained on the feed side of the membrane. Molecules smaller than the pores in the membrane, such as water, alcohols, salts, and sugars pass through the membrane. This filtrate, which is treated water, is often referred to as permeate.

Ultrafiltration membranes are rated on the basis of molecular weight cut-off (MWCO) and range from 1,000 to 500,000 MWCO (daltons). The use of MWCO is only an approximate indication of membrane retention capabilities and should be used with guidance of the membrane manufacturer.

Nanofiltration (NF)

Nanofiltration uses a membrane pore size between UF and RO. These membranes are effective in removing salts from a waste stream by allowing them to pass into the permeate while concentrating other components such as sugars, nitrogen components, and other waste constituents causing high BOD/COD in waste streams.

Reverse Osmosis (RO)

Reverse osmosis is the tightest membrane process in that it allows only water to pass through the membrane, retaining salts and higher molecular weight components. RO membranes are used for tertiary treatment producing water with low BOD/COD and of near-potable water quality. RO permeate may be recycled throughout the plant and reused for various plant processes. RO is normally used as a post-treatment process following coarser filtration processes such as ultrafiltration.

Review Questions

1. Explain particle theory.

2. Describe the types and classification of membrane treatment processes.

3. List the component parts of a membrane treatment process.

4. Outline the applications and operation of membrane treatment processes

Test Questions

1. In __________, the flow is from the inside of the membrane, through the membrane, and the filtered water flows out of the system.

   a. cross-flow filtration systems
   b. dead-end filtration systems
   c. counter current flow systems
   d. direct flow systems

2. In ________, the water being filtered may flow from the outside into the hollow fiber or from the inside to the outside; however, in this system, no waste stream is produced.

   a. cross-flow filtration systems
   b. dead-end filtration systems
   c. counter current flow systems
   d. direct flow systems

3. The __________ is asymmetric meaning that one side is different from the other side. The membrane is made up of one layer that is 50 to 100 microns thick and another layer that is a thin dense layer approximately 0.2 microns thick that exists at the surface. This thin, dense layer serves as the rejecting barrier of the membrane.

   a. cellulose acetate membrane
   b. thin composite membrane
   c. electrodialysis membrane
   d. distillation membrane

4. The ________, the semipermeable membrane is separate from the support layers, and this construction enables membrane manufacturers to select polymers that will produce membranes with optimum dissolved solids rejection and water flux rates.

   a. cellulose acetate membrane
   b. thin composite membrane
   c. electrodialysis membrane
   d. distillation membrane

5. _______, which is the rate of flow through the membrane, is dependent on the applied pressure.

   a. Mineral flux
   b. Water flux
   c. Mineral rejection
   d. Concentrate

6. _______, which is dependent on concentration, is not dependent on pressure.

   a. Mineral flux
   b. Water flux
   c. Mineral rejection
   d. Concentrate

7. ________ are seeing widespread use for demineralization of municipal water supplies that require high rejection rates for hardness and THM formation potential, and moderate TSD rejection.

   a. Microfiltration
   b. Ultrafiltration
   c. Nanofiltration
   d. Reverse osmosis

8. In ________, feed water temperature has a significant effect on membrane performance and must therefore be taken into account in system design and operation. Essentially, the value of the water permeation constant is only constant for a given temperature. As the temperature of the feed water increases, the flux increases. Usually, flux is reported at some standard temperature reference condition, such as $25^{o}C$.

   a. Microfiltration
   b. Ultrafiltration
   c. Nanofiltration
   d. Reverse osmosis

9. ________ processes may be used in conjunction with settling agents, polymers, activated carbon, and other chemicals that assist in the retention of waste constituents. When using this membrane, care must be taken to prevent membrane pore blockage by waste streams components through the selection of the proper membrane type for the specific plant wastes.

   a. Microfiltration
   b. Ultrafiltration
   c. Nanofiltration
   d. Reverse osmosis

10. _________ is the most common membrane-based wastewater treatment process. It uses a membrane with pore sizes ranging from 0.005 to 0.1 micron. Particles larger than the pores in the membrane, such as emulsified oils, metal hydroxides, proteins, starches, and suspended solids, are retained on the feed side of the membrane. Molecules smaller than the pores in the membrane, such as water, alcohols, salts, and sugars pass through the membrane. This filtrate, which is treated water, is often referred to as permeate.

    a. Microfiltration
    b. Ultrafiltration
    c. Nanofiltration
    d. Reverse osmosis

11. _______ is the tightest membrane process in that it allows only water to pass through the membrane, retaining salts and higher molecular weight components. These membranes are used for tertiary treatment producing water with low BOD/COD and of near-potable water quality. The permeate may be recycled throughout the plant and reused for various plant processes. This membrane type is normally used as a post-treatment process following coarser filtration processes.

    a. Microfiltration
    b. Ultrafiltration
    c. Nanofiltration
    d. Reverse osmosis

12. What is the operating pressure for nanofiltration, or softening membranes ________.

    a. 100-200 psi
    b. 200-500 psi
    c. 500-800 psi
    d. 800-1,200 psi

13. What is the operating pressure for reverse osmosis of seawater _______.

    a. 100-200 psi
    b. 200-500 psi
    c. 500-800 psi
    d. 800-1,200 psi

14. Reverse osmosis modules provide a large surface area for the attachment and growth of bacterial slimes and molds. These organisms may cause membrane fouling or module plugging. Evidence exist that occasionally the enzyme systems of some of these organisms will attack the cellulose acetate membrane. Thus a continuous application of ______ helps to inhibit or retard the growth of most of the organisms encountered.

    a. acetic acid
    b. citric acid
    c. chlorine
    d. sodium hexametaphosphate

15. The oxides or hydroxides most commonly found in water are iron, manganese, and silica. The oxidized and precipitated forms of iron, manganese, and silica can be a serious problem to any demineralization scheme because they can coat the reverse osmosis membrane with a tenacious film, which will affect performance. The scale inhibitor most frequently used is ________.

    a. acetic acid
    b. citric acid
    c. chlorine
    d. sodium hexametaphosphate

16. Cellulose acetate membranes are subject to long-term hydrolysis. Hydrolysis results in a lessening of mineral rejection capability. The rate of hydrolysis is accelerated by increased ______, and is a function of feed ______.

    a. temperature, pH
    b. organic matter, chlorine residual
    c. iron, manganese
    d. microorganisms, TDS

17. To ensure the longest possible lifetime of the cellulose acetate membrane and to slow hydrolysis, ______ is added as a pretreatment step before demineralization.

    a. base
    b. alkalinity
    c. chlorine
    d. acid

18. Thin film composite membranes are not subject to hydrolysis; however, ______ pH adjustments of feed water may be required for scale control.

    a. basic
    b. alkaline
    c. neutral
    d. acidic

19. Slightly _______ pH values ensure a lower hydrolysis rate for cellulose acetate membranes, as do cooler temperatures.

    a. basic
    b. alkaline
    c. neutral
    d. acidic

20. When an oxidant-intolerant polyamide-type membrane is used in reverse osmosis treatment, chlorination must be followed with ________.

    a. ammonia
    b. dechlorination
    c. caustic
    d. deionized water

CHAPTER 11: UV DISINFECTION AND SCADA OPERATION

Objectives:

- Explain UV disinfection theory
- Describe UV disinfection applications
- Describe supervisory control and data acquisition systems (SCADA)
- Explain the functional usage of SCADA systems

Ultraviolet Systems

Ultraviolet light (UV) is found just beyond the visible light spectrum. When UV light is absorbed by cells of microorganisms, it damages the genetic material in such a way that the organisms are no longer able to grow or reproduce, and ultimately, it kills them. Today with growing concern about the safety aspects of handling chlorine and the possible health effects of chlorination byproducts, UV disinfection is gaining in popularity. UV technology can also provide inactivation of *Cryptosporidium* and *Giardia*, which are resistant to common disinfectants like chlorine or ozonation.

The combination of UV technology and chlorination allows an efficient disinfecting system by killing or inactivating a larger range of microorganisms than using only one disinfectant. The UV disinfection process is particularly adapted to water with a good quality. The efficiency of UV disinfection depends on the quality of water and on the treatment stages upstream. Raw water with low turbidity and with low levels of color favor the penetration of UV light and improves disinfection efficiency.

Corrosive water can damage UV systems, and technological advances are being made. Several manufacturers produce UV disinfection systems for water and wastewater applications. As operating experience with installed systems increases, UV disinfection may become a practical alternative to the use of chlorination at water treatment plants.

UV Lamp Types

Each UV lamp assembly consists of a UV lamp enclosed in an individual quartz sleeve with the ends appropriately sealed using an O-ring and a quartz end plug. All lamps within a UV system are identical type, length, diameter, power, ad output. Three types of electrode-type lamps are used to produce UV radiation, and these types are:

1. Low-pressure, low-intensity
2. Low-pressure, high-intensity
3. Medium-pressure, high-intensity

UV lamp technology is currently changing as manufacturers strive to improve their products and search for potential new technologies. A ballast is a type of transformer that is used to limit the current to a UV lamp. Because UV lamps are arc-discharging devices, the more current in the arc, the lower the resistance becomes. Without a ballast to limit current, the lamp would destroy itself. Therefore, matching the lamp and ballast is very important in the design of UV disinfection systems.

UV Systems Types

The usual source of the UV radiation for disinfection systems is from low-pressure mercury vapor UV lamps that have been made into multi-lamp assemblies. Each lamp is protected by a quartz sleeve and each has watertight electrical connections. The lamp assemblies are mounted in a rack and these racks are immersed in the flowing water. The racks may be mounted within an enclosed vessel or in an open channel. Most UV installations are of the open channel configuration.

When UV lamps are installed in open channels, they are typically placed horizontal and parallel to the flow or vertical and perpendicular to the flow. In the horizontal and parallel-to-flow configuration, the lamps are arranged into horizontal modules of evenly spaced lamps. The number of lamps per module establishes the water depth in the channel. For example, 16 lamps could be stacked 3 inches apart to provide disinfection for water flowing through a 48-inch-deep open channel.

Each horizontal lamp module has a stainless-steel frame. Each module is fitted with a water proof wiring connector to the power distribution center. The connectors allow each module to be disconnected and removed from the channel separately for maintenance. The horizontal lamp modules are arranged in a support rack to form a lamp bank that covers the width of the UV channel and several such lamp banks should be placed along the channel wall. The number of UV banks per channel is determined by the required UV dosage to achieve the target effluent quality.

When it is necessary to maintain pressure within the water transmission system, UV lamps can be installed in a closed pressure vessel.

Another type of UV system, the thin film types, uses a chamber with many lamps spaced one-quarter inch apart. This system has been used in the water industry for a 9 MGD treatment plant.

Operators may also encounter a Teflon tube UV disinfection system, although this design is not in common use. Water flows in a thin-walled Teflon tube past a series of UV lamps. UV light penetrates the Teflon tube and is absorbed by the fluid. The advantage of this system is that water never comes in contact with the lamps. However, scale does eventually build up on the pipe walls and must be removed, or the Teflon tube must be replaced. This type of system has generally been replaced by the quartz sleeve.

Safety

The light from a UV lamp can cause serious burns to one's eyes and skin. Always take precautions to protect the eyes. Never look into the uncovered parts of the UV chamber without proper protective glasses. Do not plug a UV unit into an electrical outlet or switch a unit on without having the UV lamps properly secured in the UV water chamber and the box closed.

UV lamps contain mercury vapor, a hazardous substance that will be released if a lamp is broken. Handle UV lamps with care and be prepared with the proper equipment to clean up any spills.

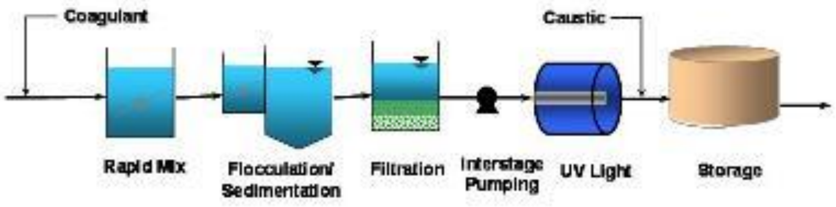

Figure 11-1 UV Disinfection in Drinking Water – Image by the EPA is in the public domain

Operation

The operation of UV disinfection systems requires little operator attention. To prevent short-circuiting and ensure that all microorganisms receive sufficient exposure to the UV radiation, the water level over the lamps must be maintained at the appropriate level. Water levels in channels can be controlled by weirs or automatic control gates.

Proper water depth must be maintained in the UV channel to ensure acceptable disinfection levels over the entire range of design flows. The UV channel water level control device must be regulated by the operator to:

1. Minimize variation of the channel's water level
2. Maintain the channel's water level at a defined level
3. Keep the UV lamps submerged at all times
4. Prevent excessive water layer thickness above the top lamp row

UV Light Intensity Effectiveness

To disinfect the water, UV light must be intense enough to penetrate the cell walls of the pathogens. The UV light intensity that reaches the pathogens is affected by the condition of the UV lamps and the quality of the water. The UV unit automatically adjusts UV dose according to the light transmission and effluent flow.

The UV lamp condition is affected by the lamp's age and the amount of slime on its surface. An old or dirty lamp has a reduced UV light intensity. The UV unit periodically cleans the lamps by mechanical means. The operator can adjust the frequency and the number of wiping cycles of the cleaning process. The UV lights can be cleaned manually in cleaning tanks that contain a chemical solution formulated for the purpose.

Upstream processes affect the quality of the water, measured as turbidity and total suspended solids (TSS). High turbidity inhibits light transmission through the water; thereby, reducing the disinfecting power of the light in proportion to its distance from the light source. High TSS, besides inhibiting light transmission, shields bacteria and protects organisms from the UV radiation. Insufficient UV light intensity can initiate a chain of events leading to ineffective disinfection and noncompliance.

Low UV light intensity will produce a low level of disinfection, and low intensity will result in high total coliform bacteria or high virus counts in the plants effluent, insufficient disinfection, and noncompliance.

The lamp must be replaced when its output at maximum power is insufficient to disinfect.

Minimum UV Dose Management

The primary control function of a programmable logic controller is to manage the minimum UV dose applied to a UV channel. The actual UV dose control (dose pacing) is controlled for each UV channel and is based on maintaining a minimum dosing level.

The maintenance of a minimum dosing level is usually done by flow pacing. The applied dose is calculated from the flow rate and the end-of-lamp-life intensity at the specified transmittance multiplied by ballast power.

The dose calculation is based on received dose, derived from flow and input from the intensity sensors.

The PLC (programmable logic controller) also controls the UV intensity in the UV channel. Each channel has a separate ballast control loop using the intensity set point as its target. The loop controls the intensity by calculating the lowest intensity of the banks in use. Then, it adjusts the ballast/lamp power to achieve the intensity set point. The action of the UV system PLC is summarized as:

1. Receives a minimum UV intensity from a preset value, which is field adjustable
2. Receives a target UV intensity form a preset value, which is field adjustable
3. Compares the target UV intensity with the actual UV intensity
4. Makes an adjustment to the output power of all of the ballast cards in operation accordingly

If the actual UV intensity goes below minimum UV intensity for more than 2 minutes, the PLC should activate a low intensity channel bank alarm and flag the bank as failed. This action will start the next assist bank, and after a preset time (10 minutes) will shut down the failed bank.

The level of ballast output power is identical for all of the ballast cards within a UV bank.

The UV system operates to maintain a minimum UV dose at all times, with a safety margin to accommodate operational changes and changeover procedures:

1. As flow increases or transmission reduces, the UV dose will be reduced and the PLC will increase ballast output to compensate. It will start up the assist bank when the duty bank is at 85-percent of full power or the dose is less than the design level plus the safety factor. Once the assist bank is at 100-percent power, output will be reduced on both banks to get the correct dose.
2. As flow decreases or transmission increases, the UV dose will be increased and the PLC will reduce ballast output to compensate. It will shut down the assist bank when ballast output is at 50-percent and the dose is greater than the design level plus the safety factor. Output on the duty bank will increased to 100 percent before shutting down the assist bank.

UV Dose Calculation

The intensity of the radiation and the contact time determine the UV dose received by the bacteria, leading to the effectiveness of the process. UV dose is the standard indicator of the UV effectiveness and is expressed as:

UV_{dose}, $mJ/cm^2 = UV_{intensity}$, $mW/cm^2 \times T$, s

Where,

T = Retention Time, s

Dosage is typically expressed as milli-joules per square centimeter (mJ/cm^2) and intensity as milliwatt seconds per square centimeter ($mW\ s/cm^2$).

In water disinfection systems, molecules are suspended solids in the water absorb UV energy. The worst-case intensity (the farthest point from the UV source) is used in the calculation.

Channel Volume Calculation

The UV channel volume refers to the irradiated volume of the UV reactor. This area is the volume in which the bacteria are exposed to UV radiation. This space is a fixed value calculated as:

UV Channel Volume per Bank, ft^3 = (UV Channel Width, ft x Top Water Level, ft x lamp Arc Length, ft) – (Volume of Quartz Sleeves, ft^3)

Retention Time Calculation

The retention time is the amount of time that the bacteria are in contact with the UV radiation. Head loss and velocity calculations ensure that an optimal hydraulic condition exists in the channel. The retention time is calculated by dividing the UV channel volume by the flow rate within the UV channel as:

$T(s) = V_{reactor}$, ft^3/Q, ft^3/s

Where,

$V_{reactor}$ = Volume of the UV Reactor

Flow Rate Calculation

The total inflow rate is supplied by the flowmeter. This value is scaled by using the maximum flow, which transforms the inflow rate to tenths of MGD, then is displayed on a screen as a flow rate. A programmable logic controller calculates the rate per channel. This flow rate is for use in the control of the UV system exclusively and should not be used for any other purpose.

Monitoring Lamp Output Intensity

Lamp output declines with use so the operator must monitor the output intensity and replace lamps that no longer meet design standards, as well as any lamps the simply burn out. Lamp intensity monitors can be installed to assist the operator in monitoring the level of light output. Lamp failure indicators connected to the main UV control panel will alert the operator when a lamp burns out and requires replacement. In addition, computerized systems are available to monitor and record the age (burn time) of each lamp.

Monitoring Influent and Effluent Characteristics

Care must be taken not to exceed the maximum design turbidity levels and flow velocities when using this types of equipment. Suspended particles will shield microorganisms from the UV light and protect them from its destructive effects. Flows should be somewhat turbulent to ensure complete exposure of all organisms to the UV light, but flow velocity must be controlled so that the water is exposed to UV radiation long enough for the desired level of disinfection to occur.

Because ultraviolet rays leave no chemical residual like chlorine does, bacteriological tests must be made frequently to ensure that adequate disinfection is being achieved by the ultraviolet system. In addition, the lack of residual disinfectant means that no protection is provided against recontamination after the treated water has left the disinfection facility. When the treated water is exposed to visible light, the microorganism can be reactivated. Microorganisms that have not been killed have the ability to heal when exposed to sunlight. The solution to this problem is to design UV systems with a high efficiency for killing microorganisms.

Emergence Alarms

UV systems require extensive alarm systems to ensure continuous complete disinfection of the water being treated. Typical emergency alarms on UV systems include:

1. Inlet level high
2. Inlet turbidity high
3. Sample flow low
4. Inlet gate motorized gate control failure
5. Inlet channel high transmittance
6. Inlet channel low transmittance
7. Diversion gate failure
8. Isolation gate failure
9. Inlet gate failure
10. System flow rates
11. Unit power failure
12. Channels inlet gates failure
13. Channel level sensor low/high
14. Channel level sensor low/low
15. Low dose

Operators need to inspect these instruments and be sure they are performing as intended.

Maintenance

A UV system is capable of continuous use if a simple maintenance routine is performed at regular intervals. By checking the following items regularly, the operator of a UV system can determine when maintenance is needed.

1. Check the UV monitor for significant reduction in lamp output.
2. Monitor the process for major changes in normal flow conditions such as incoming water quality.
3. Check for fouling of the quartz sleeves and the UV intensity monitor probes.
4. Check the indicator light display to ensure that all of the UV lamps are energized.
5. Monitor the elapsed time meter, microbiological results, and lamp log sheet to determine when UV lamps require replacement.
6. Check the quartz sleeves for discoloration. This effect of UV radiation on the quartz is called solarization. Excessive solarization is an indication that a sleeve is close to the

end of its useful service life. Solarization reduces the ability of the sleeves to transmit the necessary amount of UV radiation to the process.

Maintenance on UV systems requires two tasks: cleaning the quartz sleeves and changing the lamps.

Algae and other attached biological growths may form on the walls and floor of the UV channel. This slime can slough off, potentially hindering the disinfection process. If this condition occurs, the UV channel should be dewatered and hosed out to remove accumulated algae and slimes.

Quartz Sleeve Cleaning

Fouling of the quartz sleeves occurs when cations such as calcium, iron, or aluminum ions attach to protein and colloidal matter that crystallizes on the quartz sleeves. As this coating builds up on the sleeves, the intensity of the UV light decreases to the point where the buildup has to be removed for the system to remain effective. The rate at which fouling of the quartz sleeves occurs depends on several factors, including:

1. Types of treatment processes before UV disinfection.
2. Quality of water being treated.
3. Chemicals used in the treatment processes.
4. Length of time that the lamps are submerged.
5. Velocity of the water flowing through the UV system. Very low or stagnant flows are especially likely to permit the settling of solids and the resulting fouling problems.

How often quartz sleeves need to be cleaned depends on the quality of the water being treated and the treatment chemicals used before disinfection. Dipping the UV modules for 5 minutes in a suitable cleaning solution will remove scale that has deposited on the quartz sleeves. Cleaning is best done using an inorganic acid solution with a pH between 2 and 3. The two most suitable cleaning solutions are nitric acid in strengths to approximately 50 percent concentration and a 5 percent or 10 percent solution of phosphoric acid. To clean the system while still continuing to disinfect normal flows, single modules can be removed from the channel, cleaned, and reinstalled. The other modules remaining online while one is being cleaned should be able to provide for continuous disinfection.

In-channel cleaning of UV lamps is another option, but it has some disadvantages. A backup channel is required and a much greater volume of acid solution is needed. Also, additional equipment and storage tanks for chemicals are required. Precautions must be taken to prevent damage to concrete channels from the acid cleaning solution. Epoxy coatings normally used to protect concrete from acid attack are not used in UV disinfection systems because the epoxy tends to break down under high UV-light intensities.

The complexity of the cleaning system depends on the size of the system and the required cleaning frequency.

Lamp Maintenance

The lamps are the only components that have to be changed on a regular basis. Their service life can be from 7,500 hours to 20,000 hours. This variation can be attributed to three factors:

1. The level of suspended solids in the water to be disinfected and the fecal coliform level to be achieved affects the life of the lamp. Better-quality effluents or less-stringent fecal coliform standards require smaller UV doses. Since lamps lose intensity with age, the smaller the UV dose required, the greater the drop on lamp output that can be tolerated.
2. The frequency of ON/OFF cycles to a maximum of 4 per 24 hours can considerably prolong lamp life.
3. The operating temperature of the lamp electrodes affects lamp service life. System temperatures usually depend on system conditions. Systems with lamp electrodes operating at the same temperature operate up to three times longer than systems where the two electrodes operate at different temperatures. This operating difference can occur in systems with lamps protruding through the bulkhead where only one electrode is immersed in the water and the other electrode is surrounded by air if the air temperature is routinely higher than the water temperature.

The largest drop in lamp output occurs during the first 7,500 hours. This decrease is between 30 and 40-percent. Thereafter, the annual decrease in lamp output (5 to 10-percent) is caused by a decreased volume of gases within the lamps and by a compositional change in the quartz (solarization), which makes it more opaque to UV light.

Operators should contact the appropriate regulatory agency to determine the proper way to dispose of used UV lamps. Do not throw used lamps in a garbage can to get rid of them because of hazardous mercury in the lamps.

Troubleshooting

System Hydraulics

Erratic or reduced inactivation performance is often caused by poor system hydraulics. System short-circuiting, poor entry and exit flow conditions, and dead spaces or dead zones in the reactor can be sources of poor performance.

Biofilms on UV Channel Walls and Equipment

Biofilms are typically fungal and filamentous bacteria that develop on exposed surfaces and are especially troublesome on areas exposed to light. Biofilms can contain and shield bacteria. When biofilms break away from surfaces, they protect the bacteria in the clumps as they pass thorough the UV disinfection system. Operators should periodically remove biofilms using a hypochlorite disinfecting solution.

Particles Shielding Bacteria

Particles can shield bacteria and reduce the effectiveness of the UV disinfection process. These particles should be removed by upstream treatment processes such as improve clarifier performance or some type of filtration.

Supervisory Control and Data Acquisition System (SCADA)

A supervisory control and data acquisition system (SCADA) is a computer-monitored alarm, response, control, and data acquisition process that is used to monitor and adjust treatment processes and operate treatment facilities. SCADA systems have become essential to operating water and wastewater facilities. A SCADA system is a collection of monitoring and communication equipment with a computer interface running the SCADA software package. It is designed to help operators monitor and control treatment processes.

Primitive SCADA systems began with oversight and monitoring of a variety of industrial systems, including power companies, major utilities, building environments, manufacturing processes, and mass transportation systems. In addition to process control, SCADA systems perform automated monitoring, data logging, alarm, and diagnostic functions that allow treatment facilities to be run safely and efficiently using a relatively small staff. SCADA systems collect real-time data from the plant, make adjustments based on plant conditions, and regulate processes to prevent costly failures.

SCADA systems can be as basic as a single personal computer connected to a small laboratory or manufacturing process through simple input/output (I/O) interfaces. This simple system can be more than sufficient for a small plant, and could easily be configured with assistance from in-house staff. Improved staff efficiency and system reliability are seen even at this basic level.

Midsize plants may use one or more programmable logic controllers (PLCs) networked together with distributed I/O subsystems and multiple operator interfaces. Some configurations could be handled by in-house staff, or a SCADA system provider could work with staff to set the appropriate monitoring and alarm functions that would operate across the system. Midsize systems may monitor several thousand I/O points.

The most complex SCADA systems include networks of remote telemetry (terminal) units, or RTUs, that may cover entire plant complexes or pipeline distribution systems. Such systems use data concentrators and I/O subsystems to communicate with one another across telecommunication media. For such large, complex systems, a SCADA system override is likely to be necessary. Designing, installing, and setting up operations for these complex SCADA systems is a specialized field. O&M staff need to coordinate with the SCADA system override to ensure that alarms and monitoring functions are properly designed.

Controllers

Programmable logic controllers (PLCs) are control devices that act as replacements for hardwired relay panels that were used in the early years of process automation. PLCs are used in many industries, including manufacturing, assembly lines, and lighting applications. They originally used simple ladder logic, but programming languages and environments have evolved over the years. PLCs can be used in complex sequential relays, process controls, distributed control systems, and networking. A programming standard, produced by the International Electrotechnical Commission (IEC), has been established to program PLCs; however, a variety of logic languages can be used. The dramatic increase in processing power, networking capabilities, and program memory storage capacities has helped PLCs to become more practical and cost-effective for many process control applications, from industrial treatment plants to small facilities.

Control Functions

SCADA systems allow operators to control virtually the entire advanced water treatment facility from a computer. The operator can control tank levels, pump sequences, pump speeds, DO residuals, chemical dosing, membrane functions, advanced oxidation, UV dosing, and diverting flows from one treatment train to another. SCADA systems also allow operators to monitor and control advance water treatment plants with mobile devices such as smartphones and computing tablets.

Monitoring Functions

SCADA systems provide the operator an effective visual interface. Most SCADA systems provide animated graphic depictions of the processes combined with individual process values. Real-time data can be obtained and analyzed as a trend to observe any process changes. These tools provide the operator with the ability to monitor the treatment plant systems effectively and to catch process upsets, often before they occur.

Data Logging Functions

As the PLC receives information from the equipment and advanced water treatment processes and subsystems, the data is transferred to the SCADA system. The SCADA system electronically archives selected data to be able to recall and review it as needed. These electronic records can be exported from the SCADA system in a variety of forms, including a comma separated variable (.CSV) file. These files can be used in other applications for further analysis or formatting into reports. Hard copies of status and alarm data can be printed and retained for plant recordkeeping. These records include date, time, and changes made. Changes to the processes can be tracked through an archive of set-point changes, alarms, and equipment adjustments. This historical data assists operators with investigating process upsets and equipment failures, and it provides well-documented data for reporting purposes.

Alarm Functions

SCADA alarm functions are important tools for operators. The alarm functions are integrated into the SCADA system, alerting operators to process upsets by pinpointing the precise area where the upset occurs. Operators can respond quickly and accurately, reducing the chance that a process upset will result in a violation of state or federally issued waste discharge requirements.

Some systems include the ability to automatically contact operators who are on call. These systems can sometimes be set to communicate with mobile devices such as smartphones and computing tablets, providing operators with more flexibility.

Diagnostic Functions

SCADA systems can be set up to incorporate statistical online analyses of process data. This tool can be used to assist operators with avoiding equipment failures, process upsets, or false instrument readings. The system can detect random changes that may occur when instrument calibration drifts occur or when control components are at risk of failure. The operator is provided with the information in order to respond proactively, before failures or upsets occur.

Remote Telemetry Units

SCADA systems are capable of monitoring sprawling systems by using remote (or radio) telemetry units (RTUs). These units handle inputs, generate control outputs, and concentrate data for transmission back to the host computer. RTUs are used when monitoring devices need to be placed at isolated equipment sites, pump stations, wells or intake structures, or along a stretch of pipeline. Because RTUs usually communicate using radio waves in the same range as commercial radio frequencies, they may require Federal Communication Commission licensing. In some instances, the remote monitoring devise may use traditional electrical cabling. These units are considered remote terminal units (also RTUs).

Operator Interface

Operator interfaces (OIs) are alternately available as MMIs (man machine interfaces), HMIs (human machine interface), VDUs (video display units), VDTs (video display terminals), and probably a few more configurations as well. Operator interfaces allow the operator to view the entirety of the process on one (or several) screen(s). Operator interfaces vary in size and design, from rudimentary terminals displaying basic process information to large, full-color touchscreens with animated graphics. Often, a combination of display types is used to allow operators to interface at a number of key process points. Small displays may be mounted directly on process equipment to allow process changes to be made in the field, while large displays are better suited to a central control room or office where the entirety of the process can be overseen. All the display types are intended to inform the operator of the status of the process being monitored, including alerting the operator to any problems in the system and providing the means to make any necessary adjustments to the process.

Process Computer Control Systems

The computer control system is a computer-monitor alarm, response, control, and data acquisition system used by operators to monitor and adjust their treatment processes and facilities. Computer control systems used for process control can be classified as distributed control systems (DSC) and supervisory control and data acquisition systems (SCADA). The DCS and the SCADA systems preform the same functions in different settings. The distributed control systems (DSC) are typically used to control and monitor processes in treatment plants. The supervisory control and data acquisition systems (SCADA) are most commonly used to control and monitor distribution system facilities that are widely separated geographically. At larger water facilities DCS and SCADA system are used to provide treatment process control and distribution system controls. Smaller utilities often combine all of the controls necessary into a SCADA system. In large and small utilities, the operator interface to each system and plant processes is provided in a single control room.

The computer control system collects, stores, and analyzes information concerning all aspects of operation and maintenance, transmits alarm signals, and allows fingertip control of alarms, equipment, and processes. The computer control system provides the informant that operators need to resolve minor problems before they become major incidents. As the nerve center at the treatment plant, the system allows operators to enhance the efficiency of their facility by keeping them fully informed and fully in control.

The five components of a computer control system are:

1. Process instrumentation and control devices that sense process variables in the field and actuate equipment
2. The input/output (I/O) interface sends and receives data with the process instrumentation and control devices
3. The central processing unit (CPU) is the system component that contains the program instructions for the control system. These instructions are programmed to react based on a control strategy. The CPU gathers data from the various interfaces and sends commands to field devices to operator the plant processes
4. The communication interfaces provide the means for the computer control system to send data to and from outside computer systems, business systems, other process control systems, and equipment.
5. The human machine interface is commonly a computer workstation that is running the computer control system software that provides the plant data to the operator on the workstation screen

These components are the means by which the control system gathers and distributes information for the human operator and the process instrumentation and other equipment.

The computer control system may be used in various capacities, from data collection and storage only, to total data analysis, interpretation, and process control.

Computer control systems monitor levels, pressures, and flows and operate pumps, valves, and alarms. They monitor temperatures, speeds, motor currents, pH, turbidity, and other operating parameters. They also provide control, as necessary. Computer control systems provide a log of historical data for events, analog signal trends, and equipment operating time for maintenance purposes. The information collected may be read by an operator on computer screen readouts or analyzed and plotted by the computer as trend charts.

Computer control systems provide a picture of the plant's overall status on a computer screen. In addition, detailed pictures of specific portions of the system can be examined by the operator through the computer workstation. The graphical displays on the computer screens can include current operating information, which the operator can use to determine if the guidelines are within acceptable operating ranges or if any adjustments are necessary.

Computer control systems are capable of analyzing data and providing operating, maintenance, regulatory, and annual reports. Operation and maintenance personnel rely on a computer control system to help them prepare daily, weekly, and monthly maintenance schedules, monitor the spare parts and inventory status, order additional spare parts, print out work orders, and record completed work assignments.

Computer control systems can also be used to enhance energy conservation programs. Operators can develop energy management control strategies that allow for maximum energy savings and maximum treatment flow before peak flow periods. In this type of system, power meters are used to accurately measure and record power consumption. The information can be reviewed by operators to watch for changes that may indicate equipment problems.

Emergency response procedures can also be programmed into a computer control system. Operator responses can be provided for different operational scenarios that might be encountered as a result of adverse weather changes, fires, earthquakes, or other emergency situations.

Typical Computer Control System Functions

Computer control systems for water treatment plants and distribution systems are usually operated together, with the controls located at the treatment plant. Information that historically was recorded on paper strip charts is now being recorded and stored by computers. This information can be retrieved and reviewed easily by the operator. Therefore, computer control systems are more efficient in providing operators with the information that they need to make informed and timely decisions.

Computer control systems give the treatment plant operator the tools to optimize plant processes based on current and historical operating information. The treatment plant influent and effluent are monitored continuously for many process variables, such as flow, turbidity, pH, ammonium, chlorine, and nitrogen. If these indicators change significantly or exceed predetermined levels, the computer control system alerts the operator or changes the process based on a preprogrammed control strategy defined by the operator.

Figure 11-2 SCADA Control Monitor – Image by hhdgomez is licensed under CC BY-SA 4.0

Historical operating data stored in a computer control system is readily available at any time. The computer control system can be queried to identify, for instance, when peak plant influent flows were greater than a set normal flows. Plant performance under these conditions can be recalled using the computer control system, analyzed be the operators, and the results used to operate the plant accordingly.

Electrical energy consumption can be optimized by the use of computer control systems. Computer controls can be programmed with a control strategy to reduce energy costs by automatically operating equipment when demands for power are low. Most power companies are eager to help operators save money by structuring their rates to encourage electrical energy consumption when demands for power are low and to discourage consumption when demands for power are high. Computer controls can be programmed with a control strategy to reduce energy costs by automatically operating equipment when demands for power are low.

Computer control systems are being continually improved to help operator do a better job. Operators can create display screens the show graphics and whatever operating characteristics that are wished to be displayed. The main screen could be a flow diagram from influent to effluent showing the main treatment and auxiliary process areas. Critical operating information could be displayed for the main treatment flow path and process area, with navigation capabilities to easily access detailed screens for each piece of equipment.

Information on the screen should be color coded to indicate if a pump is running, ready, unavailable, or failed, of if a valve is open, closed, moving, unavailable, or failed. The computer uses a failed signal to inform the operator that something is wrong with the information or the signal it is receiving or is being instructed to display. The computer senses and reports information that is not consistent with the rest of the information available.

The operator can request a computer to display a summary of all alarm conditions in a plant, a particular plant area, or a process system. A blinking alarm signal indicates that the alarm condition has not yet been acknowledged by the operator. A steady alarm signal, one that is not blinking, indicates that the alarm has been acknowledged but the condition causing it has not yet been fixed. Also, the screen could be set up to automatically designate certain alarm conditions as priority alarms, requiring immediate operator attention.

With proper security implementation, computer control systems allow operators to have remote access to plant controls from anywhere using a laptop or remote workstation. This option provides the flexibility for off-duty staff to help on-duty operators solve operational problems. Computer networking systems allow operators at terminals in offices, in plants, and in the field to work together and use the same information or whatever information they need from one central computer database.

A drawback of some computer control systems is that when the system goes down due to a power failure, the numbers displayed will be the numbers that were registered immediately before the failure, not the current numbers. The operator may therefore experience a period of time where accurate, current information about the system is not immediately available.

Customer satisfaction with the performance of a water utility can be enhanced by the use of an effective computer control system. Coordination of the treatment facility control and the distribution system control is used to avoid water shortages and low pressures.

When operators decide to initiate or expand a computer control system for their plant process system, the first step is to decide what the computer control system should do to make the operators' jobs easier, more efficient, and safer, and to make their facilities' performance more reliable and cost effective. Costs savings associated with the use of a computer control system frequently include reduced labor cost for operation, maintenance, and monitoring functions that were formerly performed manually. Precise control of chemical feed rates by a computer control system eliminates wasteful overdosing. Preventive maintenance monitoring can save on equipment and repair costs, and energy saving may result from off-peak electrical power rates. Operators should visit facilities with computer control systems and talk with the operators about what they find beneficial and detrimental with regard to computer control systems and how the systems contribute to their performance as operators.

The greatest challenge for operators using computer control systems is to realize that just because a computer system says something does not mean that the computer is always correct. Also when the system fails due to a power failure or for any other reason, operators will be required to operate the plant manually and without critical information.

Operators will always be needed to question and analyze the results from computer control systems. They will be needed to see if the effluent looks as it should, to listen to a pump to be sure it sounds right, and to smell the process and the equipment to determine if unexpected or unidentified changes are occurring. Treatment plants and distribution systems will always need alert, knowledgeable, and experienced operators who have a feel for their plants and their distribution systems.

Operation

Usually, instrumentation systems are remarkably, reliable year after year, assuming proper application, setup, operation, and maintenance. Reliable measurement systems even though outdated are found in regular service at some plants up to 50 years after installation. Good design and application account for such long service. Most important is the careful operation and regular maintenance of the instruments' components. The key to proper operation and maintenance is the operator's practical understanding of the system. Operators must know how to recognize malfunctioning instruments so as to prevent prolonged damaging operations, shut down and prepare devices for seasonal or other long-term nonoperation, and perform preventive maintenance tasks to ensure proper operation in the long term. A sensitive instrumentation system can be ruined in short order with neglect in any one of these three areas.

Operators should be familiar with the technical manual of each piece of equipment and instrument encountered in a plant. Each manual will have a section devoted to the operation of a certain component of a complete measuring or control system. Detailed descriptions of the maintenance tasks and operating checks will usually be found in the manual. Depending on the general type of instrument and the suggested frequency of the operation and maintenance/checking tasks can range from none to monthly. From an operations standpoint, these tasks include learning, and constant attention to, what constitutes normal function. From a maintenance standpoint, they include ensuring proper and continuing protection and care of each component of the instrument.

Indication of Proper Function

The usual pattern of day-to-day operation of measuring and control systems in a plant should become so familiar to operators that they almost unconsciously sense any significant change. This reality is especially evident and true for systems with recorders where the pen trace is visible. An operator should watch indicators and controllers for their characteristic actions and pay close attention to trend records. Using the trend capability of the computer control system provides a method to analyze the reaction of one process variable to a change in another or other process variables.

Two of the surest indications of serious electrical problems in instruments or power circuits are smoke or a burning odor. Such signs of a problem should never be ignored. Smoke/odor means heat, and no device can operate long at unduly high temperatures. Any electrical equipment that begins to show signs of excessive heat must be shut down immediately, regardless of how critical it is to plant operation. Overheated equipment will very likely fail very soon anyway, with the damage being aggravated by continued usage. Fuses and circuit breakers do not always de-energize circuits before damage occurs, so they cannot be relied on to do so.

Operators frequently forget to reset an individual alarm. This failure is especially prevalent when an annunciator panel is allowed to operate day after day with lit-up alarm indicators and one light is not easily noticeable. Also when a plant operator must be away from the main duty station, the system may be set so the audible part of the alarm system is temporarily squelched. When the operator returns, the audible alarm system may inadvertently not be reactivated. In these instances, the consequences of inattention can be serious. Therefore, develop the habit of checking annunciator systems often.

Preventive Maintenance (PM)

Preventive maintenance (PM) means that attention is given periodically to equipment in order to prevent future malfunctions. Corrective maintenance involves actual, significant repairs. Routine operational checks are part of the preventive maintenance program in that a potential problem may be discovered and corrected before it becomes serious.

Preventive maintenance duties for instrumentation should be included in the plant's general PM program. If the plant has no formal routine PM program, it should have one. Such a program must be organized, set up, and recorded. Operators should have reminders, guides, and a record of PM tasks. Without explicit measures, experience shows that preventive maintenance is put off indefinitely. Eventually, the press of critical corrective maintenance and even equipment replacement projects eliminate preventive maintenance forever. The fact that instrumentation is usually very reliable may keep it running long after pumps and other equipment have failed. Instrumentation maintenance duties require proper attention periodically to maximize the instruments effective life. Actually, PM tasks and checks on modern instrument systems are quite minimal so no valid reason exists for failing to perform these tasks.

The technical manual for each item of instrumentation in the plant should be available so the operator can refer to it for O&M purposes. When a manual cannot be located, contact the manufacturer of the unit. Be sure to give all relevant serial/model numbers in a request for a manual. All equipment manuals should be kept in one protected location and signed out as needed. Become familiar with the sections of the manual related to O&M, and follow their procedures and recommendations closely.

A good practice is to have on-hand any supplies and spare parts that are or may be necessary for instrument operation or service. Some technical manuals contain a list of recommended spare parts.

Since PM measures can be so diverse for different types, brands, and ages of instrumentation only a few general considerations are applicable:

1. Protect all instrumentation from moisture, vibration, mechanical shock, vandalism, and unauthorized access.
2. Keep instrument components clean on the outside and closed/sealed against inside contamination
3. Do not presume to lubricate, tweak, fix calibrate, free up, or modify any component of a system arbitrarily
4. Do keep recorder pens and charts functioning as designed by frequent checking, servicing, bleed pneumatic systems regularly, ensure continuity of power for electrical devices, and do not neglect routine analytical instrument cleanings and standardizing duties as required

It is a good idea to get to know and cooperate fully with the plant instrument service person. Good communication between this person and the operating staff can result in better all-around operation. Or it may be a good idea to enter into an instrumentation service contact with an established company or with the manufacturer. Usually, general maintenance personnel are not qualified to perform extensive maintenance on modern instrumentation.

Operational Checks

Computer control systems provide the best tools for observing the operating functions of plant process systems. The operator interface provides the ability to view all areas of plant operation. Most systems provide the ability to display trends of multiple process variables on the same graphical display. These trends are tools that operators use extensively to monitor and control facility processes.

Operational checks are most efficiently made by observing each system for its continuing sign of normal operation. However, some measuring systems may be cycled within their range of action as a check on the responsiveness of components. Whenever an operator or a technician disturbs normal operation during checking or for any reason, plant process operating personnel must be informed. Ideally, it should be before the disturbance takes place. If a recorder trace is altered from its usual pattern in the process, the person causing the upset should initial the chart appropriately and note the time. Some plants require operators to mark or date each chart at midnight of each day for easy reference and filing.

Generally, any extensive operating check of instrumentation should be performed by the instrument technician during routine PM program activities.

Review Questions

1. Explain UV disinfection theory.

2. Describe UV disinfection applications.

3. Describe supervisory control and data acquisition systems (SCADA).

4. Explain the functional usage of SCADA systems.

Test Questions

1. When UV light is absorbed by cells of microorganisms, it damages the _____ in such a way that the organisms are no longer able to grow or reproduce, and ultimately, it kills them.

   a. cell wall
   b. organelles
   c. plasma membrane
   d. genetic material

2. The usual source of the UV radiation for disinfection systems is from _______ that have been made into multi-lamp assemblies. Each lamp is protected by a quartz sleeve and each has watertight electrical connections. The lamp assemblies are mounted in a rack and these racks are immersed in the flowing water.

   a. low-pressure mercury vapor UV lamps
   b. low-pressure, low-intensity lamps
   c. low-pressure, high-intensity lamps
   d. medium-pressure, high-intensity lamps

3. ________ must be maintained in the UV channel to ensure acceptable disinfection levels over the entire range of design flows.

   a. Proper chlorine residual
   b. Proper water depth
   c. Proper TDS removal
   d. None of these are correct

4. To disinfect the water, UV light must be ________ of the pathogens. The UV light intensity that reaches the pathogens is affected by the condition of the UV lamps and the quality of the water.

   a. at a very high wave length to penetrate the cell walls
   b. at a very low wave length to penetrate the cell walls
   c. intense enough to penetrate the cell walls
   d. of short duration in order to penetrate the cell walls

5. The largest drop in lamp output occurs during the first _______. This decrease is between 30 and 40-percent. Thereafter, the annual decrease in lamp output (5 to 10-percent) is caused by a decreased volume of gases within the lamps and by a compositional change in the quartz (solarization), which makes it more opaque to UV light.

   a. 5,000 hours of use
   b. 5,500 hours of use
   c. 7,000 hours of use
   d. 7,500 hours of use

6. Erratic or reduced inactivation performance of coliforms is often caused by _______.

   a. poor system hydraulics
   b. system short-circuiting
   c. poor entry and exit flow conditions
   d. All are correct

7. _______ can shield bacteria and reduce the effectiveness of the UV disinfection process. They should be removed by upstream treatment processes such as improve clarifier performance or some type of filtration.

   a. Excessive water
   b. Turbidity
   c. Excessive alkalinity
   d. Low chlorine residuals

8. ________ are most commonly used to control and monitor system facilities that are widely separated.

   a. DSC systems
   b. PLC systems
   c. SCADA systems
   d. Pneumatic systems

9. The greatest challenge for operators using computer control systems is to realize that just because a computer system says something does not mean that the computer is ______. Also when the system fails due to a power failure or for any other reason, operators are required to operate the plant manually and without critical information.

   a. wrong
   b. always correct
   c. malfunctioning
   d. failing

10. Computer control systems give the treatment plant operator the tools to ______ plant processes based on current and historical operating information.

    a. optimize
    b. diminish
    c. ignore
    d. degrade