Introduction to Water Treatment

What Is In This Chapter?

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Key Words

- Acute
- Adsorption
- Aeration
- Aesthetics
- Agglomerate
- Aggressive Water
- Air Scour
- Alkalinity
- Alternative Filtration
- Alum
- Anionic
- Arsenate
- Arsenite
- Backwash
- Bag Filter
- Biofilms
- Breakpoint Chlorination
- Calcium Carbonate
- Cartridge Filter
- Cationic
- Chloramines
- Chlorine Demand
- Chronic
- Coagulation
- Coliform Bacteria
- Color
- Combined Chlorine Residual
- Complexed
- Contact Time
- Conventional Treatment
- Coprecipitation
- Cryptosporidium
- Demand
- Diatomaceous Earth Filter
- Differential Pressure
- Direct Filtration
- Disinfection
- Disinfection Byproducts
- Dosage
- Effective Size Turbidity Breakthrough
- Filtration
- Floc
- Flocculation
- Free Chlorine Residual
- Giardia
- Greensand
- HAA5
- Hardness
- Headloss
- Health Related
- Hydraulic Loading
- Hydrogen Sulfide Gas
- Hydrophilic
- Hydrophobic
- Hypochlorite
- Hypochlorite Ion
- Hypochlorous Acid
- Ion Exchange
- Launder
- Log Inactivation
- Membrane Cartridge Filtration
- mg/L
- Microfiltration
- Nanofiltration
- Nonionic
- Odor
- Organic Carbon
- Oxidation
- pH
- Polymeric
- Polymers
- Precipitates
- Residual
- Reverse Osmosis
- Schmutzdecke
- Sedimentation
- Septum
- Sequestering Agent
- Slow Sand Filtration
- Soda Ash
- Softening
- Soluble
- Stratify
- Total Chlorine Residual
- TTHMs
- Turbidity
- Ultrafiltration
- Zeolite

Introduction

Lesson Content

This lesson on water treatment focuses on the reasons for treatment, the basic processes associated with treatment, and the application of these processes to surface water, groundwater, and some specialized water treatment applications.

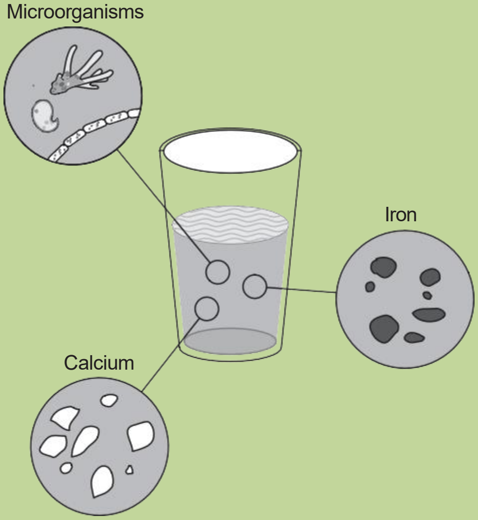
Water Treatment Overview

Treatment systems are installed for two reasons: to remove those things that can cause disease and those things that create nuisances. The basic goal is to protect public health. However, the broader goal is to provide potable water that is safe to drink, pleasant in appearance, pleasant in taste and odor, and cost-effective to produce.

While most of the concepts, processes, and systems discussed in this lesson are used in both small and large communities, the focus of this lesson will be on small systems, primarily those systems serving a population of fewer than 500 and located in rural Alaska.

Reasons for Water Treatment

The two main reasons for treating water are 1) to remove those contaminants that are harmful to health and 2) to remove contaminants that make the water look, taste, or smell bad. Since many contaminants harmful to health cannot be seen, smelled, or tasted, early water treatment efforts focused on making the water more appealing to the consumer or improving the **aesthetic**[1] qualities of the water. However, with advances in modern science, our ability to detect microorganisms and very low levels of harmful chemicals has led to advanced treatment technologies to remove **health-related**[2] contaminants that may be present in very small amounts.



Contaminants that must be removed

Aesthetic Contaminants

Aesthetic contaminants affect the appearance, taste, or **odor**[3] of the water. Most are not directly harmful to human health, but their presence may lead to problems that can indirectly result in health concerns. Aesthetic contaminants include cloudiness or **turbidity**[4], iron and manganese, **color**[5], the rotten egg odor caused by **hydrogen sulfide gas**[6], and **hardness**[7], to name a few.

Health-related Contaminants

Contaminants that can affect human health can be naturally occurring, man-made, or a result of the treatment process itself. Health-related contaminants can be further subdivided into those contaminants that can cause sickness or illness at very low levels or low exposures, the so-called **acute**[8] contaminants, or those that can cause sickness or illness only after prolonged exposure to the contaminant in drinking water, called **chronic**[9] contaminants. Health-related contaminants include pathogenic microorganisms; inorganic materials such as lead, arsenic, nitrate and nitrite; and **disinfection byproducts**[10] that can be formed during chlorination.

[1] Aesthetics - With water, the term means pleasant in appearance, odor, and taste.

[2] Health-related - Capable of influencing health.

[3] Odor - A quality that affects the sense of smell.

[4] Turbidity - A condition in water caused by the presence of suspended matter, resulting in the scattering and absorption of light rays.

[5] Color - Primarily organic colloidal particles in water.

[6] Hydrogen Sulfide Gas - A gas that results from bacterial anaerobic decay. It produces a strong rotten egg odor that can be detected at levels as low as 0.1 µg/L.

[7] Hardness - A characteristic of water caused primarily by calcium and magnesium ions. Hardness causes deposits and scale to form on pipes and fixtures.

[8] Acute - A rapid onset with low levels of exposure.

[9] Chronic - A slow onset with repeated exposures over long periods of time.

[10] Disinfection Byproducts - A chemical compound formed by the reaction of a disinfectant with contaminants in water.

Some of the more common contaminants encountered in water treatment

Contaminant	Affects	Source	Common Treatment Options
Giardia[11]	Health	Organism	Filtration/Disinfection
Cryptosporidium[12]	Health	Organism	Filtration
Viruses	Health	Organism	Filtration/Disinfection
TTHM[13]	Health	Disinfection Byproduct	Filtration/Adsorption/Disinfectant Selection
HAA5[14]	Health	Disinfection Byproduct	Filtration/Adsorption/Disinfectant Selection
Arsenic	Health	Mineral	Co-precipitation/Adsorption
Lead	Health	Mineral/Corrosion	Corrosion Control
Copper	Health	Mineral/Corrosion	Corrosion Control
Nitrate	Health	Nitrogen	Ion Exchange/Reverse Osmosis
Manganese	Health/Aesthetic	Mineral	Oxidation/Filtration/Adsorption
Iron	Health/Aesthetic	Mineral	Oxidation/Filtration
Turbidity	Health/Aesthetic	Particle Matter	Filtration
Color	Aesthetic	Minerals or Organics	Oxidation/Filtration/Adsorption
Odor	Aesthetic	Hydrogen Sulfide	Oxidation/Aeration
Hardness	Aesthetic	Minerals	Ion Exchange/Reverse Osmosis

Basic Water Treatment Unit Processes

Water treatment requires chemical, physical, and sometimes biological processes to remove contaminants. The more common processes used in potable water treatment are the chemical and physical processes. Biological processes are primarily used for treatment of wastewater. However, the slow sand filtration process is a biological process that has been historically used to remove pathogens from potable water. The biological activated carbon (BAC) process is also a biological process that is used to remove organic contaminants from potable water.

The chemical processes involved in potable water treatment include **oxidation**[15], **coagulation**[16] and **disinfection**[17]. The physical processes include **flocculation**[18], **sedimentation**[19], **filtration**[20], **adsorption**[21], and disinfection using ultraviolet light. The types of processes that are required and the order in which they are used depend on the types and concentrations of contaminants that must be removed. Examples of this include oxidation, followed by filtration or sedimentation, followed by filtration. In the first example, the oxidation process causes the dissolved contaminants to form a **precipitate**[22], which is then removed by filtration. In the second example, sedimentation removes most of the solids by gravity and reduces the solids loading on the down stream filtration process.

[11] Giardia - A pathogenic microorganism excreted by some animals that is 6-18 micrometers in size.

[12] Cryptosporidium - A pathogenic microorganism excreted by some animals that is 4-6 micrometers in size.

[13] TTHMs (Trihalomethanes, also referred to as TTHMs or Total Trihalomethanes) - (1) Regulations - The sum of the concentrations of bromodichloromethane, dibromochloromethane, tribromomethane, and trichloromethane. (2) Compounds formed when natural organic substances from decaying vegetation and soil (such as humic and fulvic acids) react with chlorine.

[14] HAA5 - Five Haloacetic Acids including monochloroacetic acid, dichloroacetic acid, trochloroacetic acid, monobromoacetic acid, and dibromoacetic acid. Compounds formed when natural organic substances from decaying vegetation and soil (such as humic and fulvic acids) react with chlorine.

[15] Oxidation - The addition of oxygen, removal of hydrogen, or removal of electrons.

[16] Coagulation - In water treatment, the destabilization and initial aggregation of colloidal and finely divided suspended matter by the addition of a floc-forming chemical.

[17] Disinfection - The process used to control pathogenic organisms.

[18] Flocculation - The agglomeration of colloidal and finely divided suspended matter after coagulation by gentle stirring by either mechanical or hydraulic means.

[19] Sedimentation - The removal of solid particles from water by settling induced by gravity.

[20] Filtration - The process of passing liquid through a filtering medium -which may consist of granular material such as sand, magnetite, or diatomaceous earth, finely woven cloth, unglazed porcelain, or specially prepared paper-to remove suspended colloidal matter.

[21] Adsorption - The gathering of a gas or dissolved substance onto the surface of a solid.

[22] Precipitate - The material that results from precipitation - A phenomenon that occurs when a substance held in solution in a liquid passes out of solution into a solid form.

The following section provides a brief introduction to each of these basic water treatment processes. Each process will be presented in the order that they are normally used in a treatment train.

Oxidation

Chemical oxidation is used in water treatment to aid in the removal of inorganic contaminants such as iron (Fe^{2+}), manganese (Mn^{2+}), and arsenic (As^{3+}) to improve removals of particles by coagulation or to destroy taste- and odor-causing compounds. Oxidation can also be used prior to coagulation, filtration, adsorption, or sedimentation to improve the removal of inorganics, particulates, taste, or odor.

Oxidants

The most commonly used oxidants in small systems include chlorine (Cl_2) and potassium permanganate ($KMnO_4$). To a lesser extent, ozone and chlorine dioxide are also used for this purpose. Chlorine is supplied in gas, solid, and liquid forms; and potassium permanganate is usually supplied as a fine granular solid material that is dissolved in water. Ozone is a gas that is generated onsite using pure oxygen or air. The selection of the most desirable oxidant is dependent upon a number of factors, including process requirements, operational cost, chemical safety, and operational complexity.

Mixing

Oxidants are injected as a gas or a liquid. Mixing or diffusion of the gas or liquid into the water stream occurs very quickly; and therefore, mixing energy is rarely a significant issue for small systems. As a result, static or mechanical mixers are typically not required, although diffusers or injector assemblies are often used to enhance the diffusion of the oxidant into the water.

Reaction Time

Reaction time is a critical parameter when oxidants are used in the treatment process. The speed or reaction rate is dependent on the type of oxidant, type of contaminant, **pH**[23], and water temperature. As a general rule, lower pH or water temperature tends to slow the rate of oxidation.

The oxidation rate can be slowed or the oxidant demand can be increased by the presence of other contaminants, such as organic carbon, ammonia, manganese, or iron. Organic carbon can become attached to the iron or manganese, resulting in a **complexed**[24] form of the iron or manganese. This problem can be encountered when ammonia, hydrogen sulfide, and organic carbon in excess of 2 mg/L are present in water containing ferrous iron or manganous manganese. The use of chlorine as an oxidant in water containing these types of complexes can result in the formation of disinfection byproducts such as trihalomethanes (TTHM) and/or haloacetic acids (HAA5). The presence of these complexed materials may also make the removal of iron or manganese difficult unless coagulation or an appropriate membrane filtration process is used.

Ammonia will cause competing demands for chlorine and will result in the formation of chloramines unless breakpoint chlorination is used to obtain a free chlorine residual. Chloramines are a much weaker oxidant than free chlorine and significantly slow the oxidation of iron and manganese.

[23] pH - An expression of the intensity of the basic or acidic strength of water. pH may range from 0 to 14, where 0 is most acid, 14 most alkaline, and 7 neutral. Natural waters usually have a pH between 6.5 and 8.5. Mathematically, $pH = -\log_{10}[H^+]$.

[24] Complexed - A bound form of two or more substances.

Typical oxidant demands for chlorine and potassium permanganate

Oxidant	Contaminant	Demand
Chlorine	Fe^{2+}	0.64 mg Cl_2/mg Fe^{2+}
	Mn^{2+}	1.29 mg Cl_2/mg Mn^{2+}
	As^{3+}	0.95 mg Cl_2/mg As^{3+}
Potassium Permanganate	Fe^{2+}	0.94 mg $KMnO_4$/mg Fe^{2+}
	Mn^{2+}	1.92 mg $KMnO_4$/mg Mn^{2+}
	As^{3+}	1.26 mg $KMnO_4$/mg As^{3+}

Operational Considerations

The control of the oxidation process is usually a manual operation for small systems. When chlorine is used, the proper dosage can be determined using a free chlorine test kit. The presence of free chlorine after a prescribed amount of time indicates that enough oxidant has been added to satisfy the oxidant demand. A visual test for oxidant demand is often used for potassium permanganate. The proper dosage will result in a slight pink color remaining after a period of time. When the water contains large amounts of iron, the proper dosage of permanganate is often indicated by a salmon color or a slight pink color, depending on levels of iron in the oxidized water. Similar tests for chlorine or potassium permanganate demand can be used for arsenic oxidation as well.

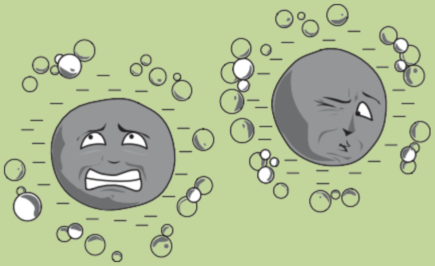
Coagulation

Most organic and inorganic material suspended in water and not dissolved will settle out if given enough time. However, the main materials that contribute to color and turbidity are either dissolved or too small to settle. The basic problem comes from material that is less than one micrometer (0.001 mm) in size, called colloidal material.

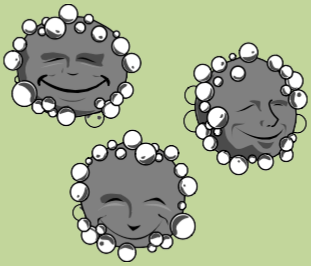
Particle Diameter mm	Representative Particle	Time Required to Settle in 1 ft. (0.3 m) Depth
		Settleable
10	Gravel	0.03 sec
1	Coarse Sand	3 sec
0.1	Fine Sand	38 sec
0.01	Silt	33 min
		Considered Nonsettleable
0.001 (1 µ)	Bacteria	55 hours
0.0001	Color	230 days
0.00001	Colloidal Particles	6.3 years
0.000001	Colloidal Particles	63 year minimum

Colloids do not settle in a reasonable length of time due to electrical charges on their surface. At one micrometer (also stated as 1 µm) in size, the influence of the surface charges offsets gravity, and the particles stay suspended. For instance, a particle 0.01 mm in diameter will settle one foot in 33 minutes, but a particle 0.0001 mm in diameter (a colloid) will settle only one foot in 230 days.

There are two types of colloidal material:



- **Hydrophobic**[25] – Hydrophobic means water-fearing. Hydrophobic colloidal material is mostly inorganic material that contributes to turbidity and carries a negative electrical surface charge.



- **Hydrophllic**[26] – Hydrophilic means water-loving. Hydrophilic colloidal material is mostly composed of organic material that is the common source of color in water. Hydrophilic compounds are surrounded by water molecules that tend to make these particles negatively charged as well.

Organic material that will pass through a 0.45 micrometer membrane filter is considered to be dissolved. These materials include humic and fulvic acids that can cause color in water and are measured as **organic carbon**[27]. Total organic carbon (TOC) includes the materials that are both larger and smaller than 0.45 micrometers in size. Dissolved organic carbon (DOC) is the fraction of organic material that is smaller than 0.45 micrometers. These acids carry a negative charge.

Coagulants

There are two opposing forces that impact the removal of colloidal material:

- Stability factors – Stability factors are those factors that help to keep colloids dispersed.
- Instability factors – Instability factors are those factors that contribute to the natural removal of colloids.

The process of decreasing the stability of the colloids in water is called coagulation. Coagulation results from adding salts of iron, aluminum, or cationic **polymer**[28] to the water. Some common coagulants include the following:

- Aluminum Sulfate (**Alum**[29]) $Al_2(SO_4)_3 \cdot 18H_20$
- Sodium Aluminate – $NaAlO_2$
- Ferric Sulfate – $Fe_2(SO_4)_3 \cdot 9H_20$
- Ferrous Sulfate – $FeSO_4 \cdot 7H_20$
- Ferric Chloride – $FeCl_3$
- Polyaluminum Chloride (PAC)
- Cationic Polymers

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[25] Hydrophobic - Water-fearing. In water, hydrophobic refers to inorganic colloidal particles that contribute to turbidity.

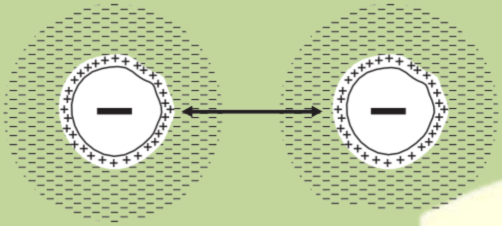
[26] Hydrophilic - Water-loving. In water, hydrophilic refers to organic colloidal particles that contribute to color.

[27] Organic Carbon - A carbon substance that comes from plant or animal sources.

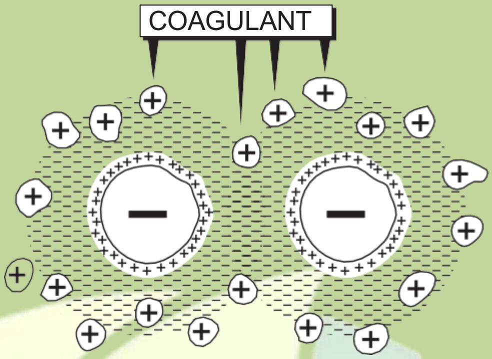
[28] Polymer - High-molecular-weight synthetic organic compound that forms ions when dissolved in water. Also called polyelectrolytes.

[29] Alum - Trade name for the common coagulant aluminum sulfate: $Al_2(SO_4)_3 \cdot 18H_20$.

The addition of metal salts or polymers to water containing negatively charged contaminants may result in a process called coagulation. The simplest coagulation process to explain occurs between alum and water. When alum is placed in water, a chemical reaction occurs that produces positive charged aluminum ions. The positively charged aluminum ions then become attached to the surface of the negatively charged colloid. The overall result is the reduction of the negative surface charges and the subsequent formation of **agglomerate**[30] (floc). This destabilizing factor is the major contribution that coagulation makes to the removal of turbidity, color, and microorganisms.



Hydrophobic particles

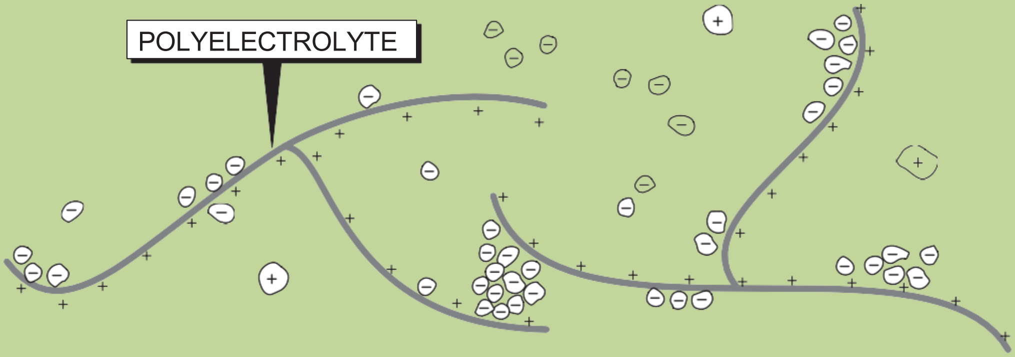


Hydrophobic particles after coagulation

There are a number of factors that influence the coagulation process. Four of the most important are pH, turbidity, temperature, and **alkalinity**[31]. The degree to which these factors influence coagulation depends upon the type of coagulant used. When metal salts are used as the primary coagulant, these factors can have a significant affect on the performance of the chemical in removing contaminants. The performance of cationic polymers, however, is less influenced by these factors.

Polyelectrolytes, or polymers, as they are commonly called, can be used as a primary coagulant or as an aid to coagulation when metal salts are used. Polymers are long string-like (chain) molecules with charges placed along the string. There are three common types of polymers:

- Positively charged **polymeric**[32] substances called **cationic**[33] polymers,
- Negatively charged polymeric substances called **anionic**[34] polymers
- Polymeric substances with no charge called **nonionic**[35] polymers



Polyelectrolyte molecule

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[30] Agglomerate - Gathered into a mass.

[31] Alkalinity - A measure of waters ability to neutralize an acid.

[32] Polymeric - A material constructed of small molecules.

[33] Cationic - An ion or group of ions with a positive charge.

[34] Anionic - An ion or group of ions with a negative charge.

[35] Nonionic - An ion or group of ions with no charge.

Flash Mixing/Rapid Mixing

Effective dispersion of the coagulant into the raw water stream ensures efficient and effective treatment. Flash mixing is very important when metal salts are used. Metal salts must be thoroughly dispersed into the stream within 1-2 seconds for effective treatment. The performance of polymers, on the other hand, is less influenced by flash mixing energy and is minimally affected by dispersion times as long as several seconds.

Pump diffusion and inline static mixers are the most common types of flash mixers:

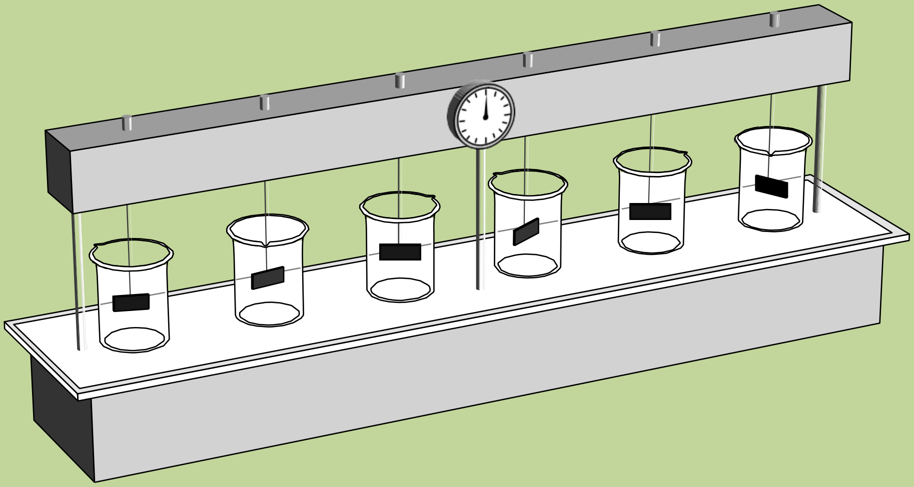
- The pump diffusion system uses jets to inject the coagulant into the raw water stream. The advantage of a pump diffusion flash mixer is that it produces no additional **headloss**[36]. The disadvantages are the additional electrical power consumption and added maintenance.
- Inline static mixers are very simple devices that can be used to provide effective mixing as well. The advantages of the inline static mixer are that it requires no electrical power and very little maintenance. The disadvantages are that mixing efficiency varies with flow rate and that headloss can be on the order of two feet or more.

Detention Time

Appropriate detention times are required for the coagulation process to proceed to completion before the water is filtered or additional chemicals are added. The mixing energy that should be used during the reaction period depends of the type of water treatment process that is being used and the type of coagulant. Detention times on the order of 10-20 minutes are common. Detention occurs in the piping, in reaction vessels, and in the head space in the filter located above the media.

Operational Considerations

To determine the correct chemical dosage, a device called a gang mixer or jar test apparatus is used. The most common is composed of six mixers connected together and six one-liter beakers. Samples of the water, along with various dosages of the coagulant, are added to the jars. The jars are stirred in an attempt to duplicate the flash mix of the plant and then slowly stirred to duplicate the mixing time and mixing energy of the plant. The proper dosage is determined by observing the best forming **floc**[37], and the pH and turbidity of a settled or filtered sample.



Gang stirrer used for jar tests

[36] Headloss - As it applies to a water filter, the difference between the pressure or head between two points.

[37] Floc - Small gelatinous masses formed in a liquid by the reaction of a coagulant added thereto.

Other types of devices are also available to indicate optimum coagulation and to control the coagulation process automatically. A coagulant charge analyzer can be used for bench testing, or a streaming current detector can be used for online measurement and control. Both devices use the net charge density of the water to indicate when optimum coagulation has been achieved. In other words, these instruments are used to measure when enough positively charged coagulant has been added to neutralize the negative surface charges of the contaminants.

Flocculation

Flocculation is a physical process of slowly mixing the coagulated water to increase the probability of particle collision. This process forms the floc. Floc is a snowflake-looking material that is made up of the colloidal particles, microorganisms, and precipitate.

Flocculants

Flocculation can occur with the addition of only the primary coagulant. However, additional chemicals can be added to improve the settling or filtering characteristics of the coagulated materials (floc). Anionic polymers are often used to aid in the formation of good floc for settling. These polymers can increase the speed of floc formation, the strength of the floc, and the weight of the floc. These polymers work through inter-particle bridging and rely on the presence of positive surface charges on the coagulated floc to create bonds with the negatively charged polymer chains. The optimum dosage of the anionic polymer is directly related to the amount of coagulated material that is present in the water.

Mixing Energy

The two most common types of mixers that are used for flocculation include baffled channels or paddles. In some cases, pipelines are also used to provide flocculation.

- Baffled channel mixers rely on hydraulics to provide the necessary flocculation (mixing) energy. Flocculation energy in baffled channel mixers varies with changes in water flow rate or temperature.
- Paddle mixers provide the greatest level of operational control. The speed of the paddles can be changed to compensate for changes in water temperature, turbidity, or flow rate.

Tapered energy is critical in preparing the flocculated material for efficient filtration or sedimentation. The type of floc that is formed depends on the type of chemicals that are used and the mixing energy that is provided. Higher mixing energies form smaller denser floc that is ideal for filtering. In contrast, lower mixing energies form larger heavier floc that is ideal for settling.

Detention Time

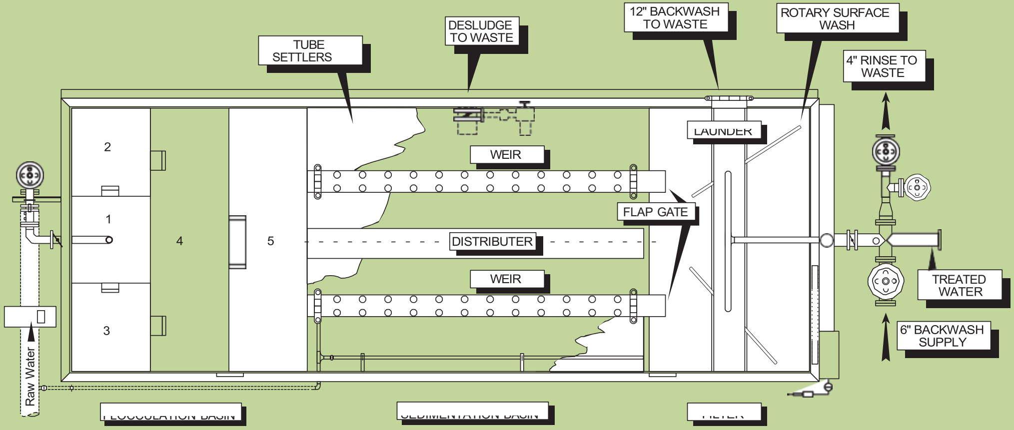
The flocculation process requires 15 to 45 minutes of mixing. The time is based on the chemistry of the water, the water temperature, and the mixing intensity. The temperature is the key component in determining the amount of time required for good floc formation.

Operational Considerations

The jar test apparatus is also used to determine the proper dosage of flocculant (anionic polymer). Proper timing between the addition of the coagulant and flocculant is very important when anionic polymers are used. Adding the flocculant at the point when a pin floc is formed can produce remarkable results. Adding the flocculant too early or too late will reduce its effectiveness. Determining the proper dosage and timing is mainly a visual test, but instruments such as a turbidimeter can be used to aid the process. The addition of too little polymer will not adequately remove the turbidity from the settled water. The addition of too much polymer will result in flocculated material settling in the jars, even as the jar stirrer paddles continue to rotate. Flocculated material will also settle in the flocculation tanks of a full-scale system if too much anionic polymer is added.

Clarification and Sedimentation

Clarification of water involves removing contaminants through simple gravity sedimentation or through solids contact processes that operate in either a down-flow or up-flow configuration. The three most common types of clarifiers used in small systems include gravity sedimentation, up-flow sludge blanket clarification, or down-flow contact clarification. The down-flow contact clarification process uses large-diameter media, and the up-flow contact process may use floating media or simply the sludge blanket itself. In small systems, gravity sedimentation and sludge blanket clarification are generally proprietary systems designed and constructed as part of a conventional packaged water treatment system. Presently, contact clarifiers are more commonly custom-designed and resemble a roughing filter or prefilter in a two-stage filtration process.



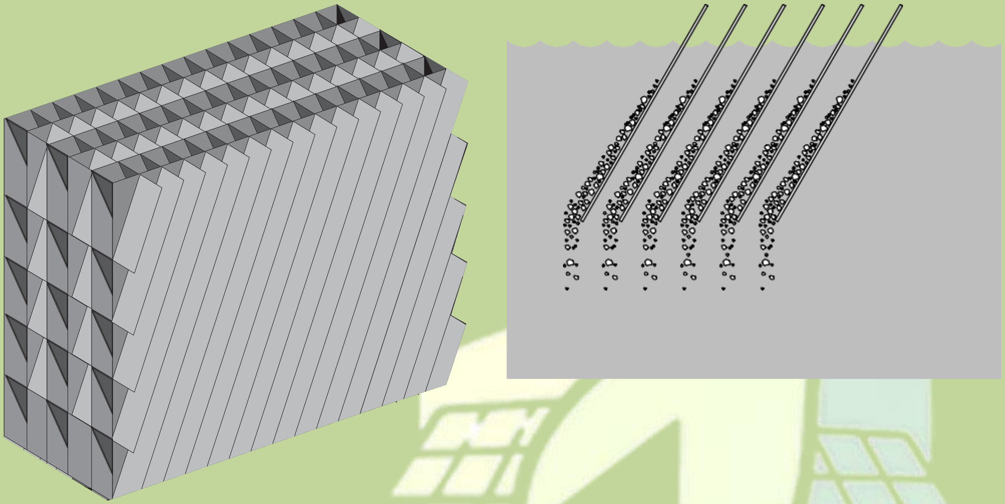
Top view of conventional filtration package treatment plant

Types of Clarifiers

Today, gravity sedimentation units generally incorporate tube settlers to improve removal efficiencies. Tube settlers are typically two-inch-square or oval-shaped tubes placed on a 7.5° to 60° angle in the top two feet of the gravity sedimentation basin. The flow direction is up through the tubes. The angled tubes increase efficiency because a particle has to fall only a short distance in order to be intercepted by the sludge blanket. As water flows up through the tubes, the settled sludge moves down the tubes into the bottom of the basin.

One method of improving the efficiency of the sedimentation process is to use the sludge blanket itself as a solids contact media. In this type of clarification process, a sludge blanket is maintained in the bottom one third of the sedimentation basin. The flow of water is up through the sludge blanket. The sludge in the blanket increases the frequency of collision of the coagulated particles, and thus increases flocculation and improves solids removals. The sludge blanket works very much like a big net and is used to improve solids removals.

Down-flow contact clarifiers use large diameter media placed in a filter vessel ahead of the final filter in a two-stage configuration. The term roughing filter is often used to describe a down-flow contact clarifier. The media used in a down-flow contact clarifier is generally 2 mm - 3 mm in diameter and can consist of sand, anthracite or some proprietary media. This size media provides ample storage volume for flocculated material while being fine enough to remove or filter the flocculated particles. The allowable hydraulic loading rate of the down-flow contact clarifier depends on the relative strength of the flocculated particles and the temperature of the water.



Tube settlers

Operational Considerations

The up-flow velocity in the sedimentation basin depends on the settling characteristics of the flocculated particles and the temperature of the water. The term used to describe the up-flow velocity is surface loading. The surface loading rate for a sedimentation basin that incorporates inclined tube settlers is expressed as gallons per minute per square foot of water surface area and usually ranges between 2 - 3.5 gpm/ft^2.

When gravity sedimentation is used, the settled particles form sludge that must be removed from the basin and discharged to waste. The rate of removal depends on the rate of solids accumulation. Sludge must be removed to prevent solids from rising to the surface of the clarifier, either because it is entering the tube settlers or because gas is forming on the settled floc and buoying it to the surface. Drains are provided on the bottom of the settling basin, and settled sludge is discharged from the clarifier at specified intervals. Automatic valves with timed actuators optimize the clarification process and ensure consistent performance.

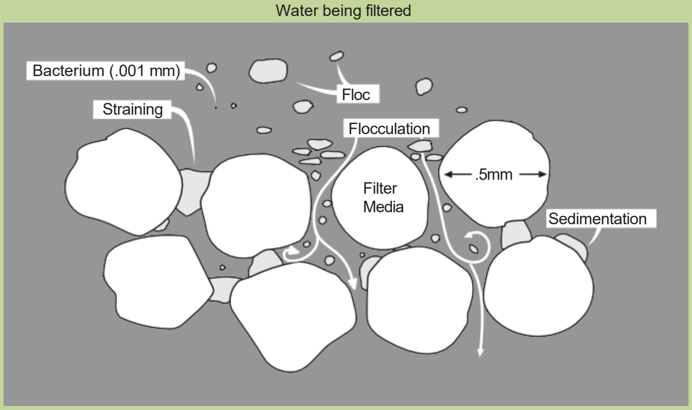
Down-flow contact clarifiers are designed based on the flow rate of the water through the unit. The loading rate on the unit is referred to as the hydraulic loading and is expressed in gallons per minute per square foot of media/bed area. The hydraulic loading rate for contact clarifiers can vary from less than 1 gpm/ft^2 to over 8 gpm/ft^2. The optimum loading rate is based on the amount and strength of flocculated material being applied to the unit. The application of contact clarifiers is limited to coagulated waters with a low solids loading. Finally, the down-flow contact clarification process has the advantage of being less complicated and less costly to operate than a gravity sedimentation unit.

Like the gravity sedimentation or up-flow sludge blanket clarification processes, the accumulated solids must be removed from the down-flow contact clarifier. This removal process is accomplished by backwashing at set intervals or when the turbidity of the effluent from the contact clarifier begins to rise. Backwashing rates are significantly higher than what is required for typical sand and anthracite (dual media) filters. Air scour followed by an up-flow **backwash**[38] of 25 - 35 gpm/ft^2 is required to dislodge and remove accumulated solids.

The objective of clarification is to reduce the solids loading on the down stream processes (filters) and thus increase the length of the filter cycle. The performance of the clarifier can be measured by the turbidity of the clarifier effluent or visual observation of the clarified water. The process control variables include the use of flocculant aids, the type of flocculant aid used, the location where the flocculant aid is added, the timing between coagulant injection and flocculant aid addition, the mixing energy provided during flocculation, and the **hydraulic loading**[39] being applied to the clarifier.

Granular Media Filtration

Filtration is a physical process of separating suspended and colloidal particles from water by passing the water through a filter media. Filtration involves a number of physical processes. Among these are straining, settling, and adsorption. As particle contaminants pass into the filter, the spaces between the filter grains become clogged, which reduces the openings. Some contaminants are removed merely because they settle onto a media grain. Others are adsorbed onto the surface of individual filter grains. This adsorption process helps to collect the contaminants (floc) and thus reduces the size of the openings between the media grains.



Adsorption of floc onto individual filter grains

As water and particles (floc) enter the filter, they begin to settle, adsorb, and collect in the upper portion of the filter media. This increases the pressure above the particles, driving them down into the media. As the floc penetrates into the filter bed, the openings get smaller, and the bed becomes clogged. This increases the friction between the water and the filter bed. As a result, there is an increase in the difference between the pressure at the top of the filter and the pressure at the bottom of the filter. This difference in pressure is called **differential pressure**[40].

Types of Filters

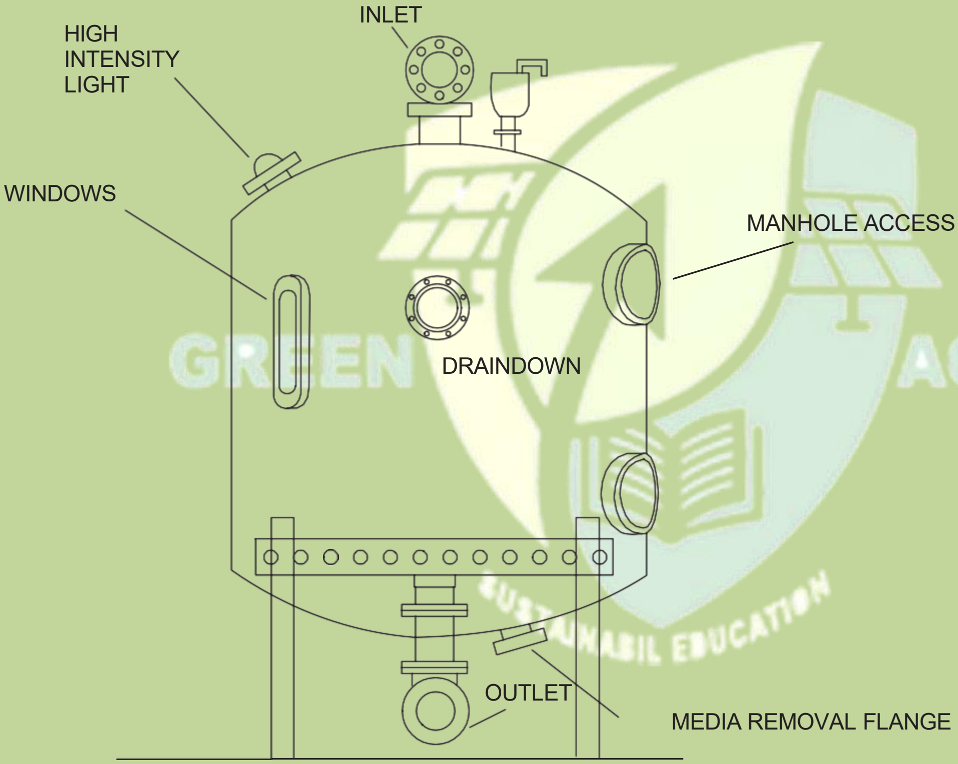
The two main types of filters used in small systems include gravity filters and pressure filters.

[38] Backwash - The reversal of flow through a filter in order to clean the filter by removing material trapped by the media in the filtration process.

[39] Hydraulic Loading - The flow rate per surface or cross-sectional area.

[40] Differential Pressure - The difference in water pressure between two points.

- **Gravity filters** rely on the depth of water above the filter media to provide the driving force to pass water through the media as it clogs. The amount of available driving force or water depth (head) is limited by the sidewall height of the filter tank above the surface of the filter media. The sidewall height is thus limited by the ceiling height in the building.
- **Pressure filters** are enclosed in pressure vessels and can operate with much higher driving forces. In general, most gravity filters operate with 4 - 6 feet of available head, and pressure filters operate with 10 - 20 feet of head. A major advantage of the pressure filter is that water can be treated under pressure and pumped to a water storage tank at a higher elevation without the need to pump the water after filtration. One disadvantage of the pressure filtration system is the inability to visually observe the condition of the filter media and the backwash process. However, new pressure filters now incorporate windows for visual inspection and light to illuminate the tank interior and filter bed.



Pressure filter

Filter Media

Filter media can consist of silica sand, greensand, anthracite coal, activated carbon, and many other types of media. These media can be used by themselves as a single media filter or mixed to provide improved filtration characteristics. The two most common types of granular media filters include dual-media filters and tri-media (mixed media) filters. Dual-media filters consist of anthracite coal and silica sand; and tri-media filters have anthracite coal, silica sand and fine garnet. The general goal in the filtration process is to provide coarse-to-fine filtration. Water passes through the larger anthracite media at the top of the filter first and finally through the finer grained sand located at the bottom of the filter. This design provides increased solids removals as the water progresses through the filter. The densities of the filter media are selected to allow the media to **stratify**[41] during the up-flow backwash cycle, thus

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[41] Stratify - To place into layers.

placing the larger anthracite coal media on the top of the filter bed. The filter then operates in a down-flow configuration.

Greensand media is typically used in conjunction with anthracite coal in a dual-media configuration. This type of media is used to remove inorganic contaminants such as manganese and iron. The principle of course to fine filtration also applies to the greensand filter. These filters will be discussed in greater detail in the sections on inorganic adsorption and groundwater treatment.

Activated carbon can be used as a topping for silica sand as well but is more commonly used as a single media. The main purpose of activated carbon is not to remove solids but to adsorb organic contaminants. These types of filters are called contactors. These will be discussed in more detail in the sections dealing with organic adsorption and surface water treatment.

Hydraulic Loading

Filter design is based on hydraulic loading and the treatment capacity of the filters. Slow sand filtration utilizes a single fine-grained sand bed. The hydraulic loading for this process varies from as little as 0.04 gpm/ft^2 to as much as 0.08 gpm/ft^2. Although higher loading rates up to 0.20 gpm/ft^2 have been used. This process is essentially a biological process, and the type of water that can be successfully treated is limited by the turbidity of the source water.

Rapid sand filters use higher loading rates and can successfully treat a wide range of raw water conditions. These filters can be used as a post treatment after clarification or without clarification in what is referred to as **direct filtration**[42]. The recommended hydraulic loading rates for rapid sand filters range from 1 gpm/ft^2 to 5 gpm/ft^2 (typical for packaged plants). These filters use medium-sized sand with an **effective size**[43] of approximately 0.5 mm. Filters using larger diameter media can operate at loading rates up to 10 gpm/ft^2. The use of high hydraulic loading rates in the filtration process is analogous to driving a car fast. The filtration process, like the car, becomes more difficult to control at higher velocities (hydraulic loading rates). However, the use of higher hydraulic loading rates allows the life of older facilities to be extended or smaller treatment system footprints to produce larger amounts of water.

Operational Considerations

One of the major keys to proper water treatment plant operation is to clean the filter before the floc penetrates completely through the filter bed resulting in **turbidity breakthrough**[44]. For most filters, this cleaning point is when effluent turbidity begins to rise and approaches the maximum value allowed by regulations. In the past, headloss through the filter governed the filtration cycle or filter run. However, turbidity limits are usually reached in most systems before terminal headloss is reached. This effluent turbidity value is typically reached after 12 to 72 hours of filter operation. The cleaning process is accomplished by allowing water to flow up through the filter bed at an appropriate velocity to expand the bed and remove the contaminants (floc) trapped by the media. This process is called “backwashing the filter.” An auxiliary wash process is used to agitate the media and breakup the accumulated floc prior to the backwash process. The auxiliary wash process can be accomplished by injecting air up through the media or agitating the surface of the media with jets of water. Injecting air is the most beneficial auxiliary wash system because it thoroughly agitates the entire media bed throughout its depth. Injecting air up through the media in this manner is referred to as **air scour**[45].

[42] Direct Filtration - A gravity or pressure filter system involving coagulation, flocculation, filtration, and disinfection.

[43] Effective Size - The diameter of particles for which 10 percent of the total grains are smaller and 90 percent are larger.

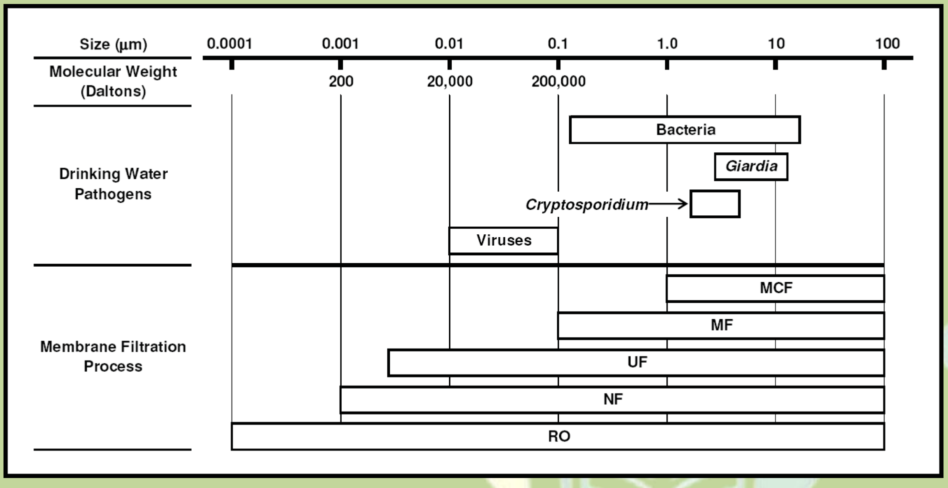
[44] Turbidity Breakthrough - A rapid rise of turbidity in the effluent from a filter.

[45] Air Scour - The agitation of filter media by the injection of compressed air.

Membrane Filtration

Membrane processes commonly used in water treatment include **membrane cartridge filtration**[46] (MCF), **microfiltration**[47] (MF), **ultrafiltration**[48] (UF), **nanofiltration**[49] (NF), and **reverse osmosis**[50] (RO). The MCF process includes using **Bag Filters**[51] and **Cartridge Filters**[52] and is used to remove larger pathogens such as Giardia and Cryptosporidium. The MF and UF processes are effective at removing turbidity, particles, and pathogens from water. The NF process provides a higher level of treatment than the MF/UF processes and has the added capability of removing dissolved organic contaminants. The RO process provides the highest level of treatment of the membrane processes and is also effective in removing salts from brackish water or seawater. Membrane processes are classified based on effective size range.

The figure below, taken from the *EPA Membrane Filtration Guidance Manual*, illustrates the ability of each type of membrane process to remove various drinking water pathogens and provides the filtration size range of each process.



As noted earlier, the MCF process includes bag filters and cartridge filters. These filters are essentially a course membrane filter designed specifically to remove Giardia and Cryptosporidium. They are marginally effective at reducing turbidity and minimally effective at removing organic contaminants. Therefore, the application of these types of filters is limited to low turbidity water with minimal levels of organic contaminants. These types of membrane filters are rated for removal of Giardia and Cryptosporidium based on a maximum filtration flow rate and differential pressure. They are also certified for use in a specific filter housing. Bag or cartridge filters are considered to be **Alternative Filtration**[53] devices and must be approved by the Alaska Department of Environmental Conservation (ADEC).

Operational Considerations

The amount of pressure required to force water through membrane filters can vary significantly based on the type of membrane used. In general, the pressure required to pass water through the membrane starts at some lower value and increases as the membrane becomes clogged. Required pressures can be as low as 20 psi for bag or cartridge filters to more than 1,000 psi for reverse osmosis.

When a bag or cartridge filter becomes clogged, it is discarded. For the other types of membranes listed above, the filter is either backwashed when the cutoff pressure has been reached or chemically cleaned. Backwashing membranes may also require

[46] Membrane Cartridge Filtration - Bag or cartridge filters capable of removing giardia and cryptosporidium.

[47] Microfiltration - Membrane filters capable of removing pathogenic organisms larger than 0.1 micrometers in size.

[48] Ultrafiltration - Membrane filters capable of removing pathogenic organisms larger than 0.005 micrometers in size.

[49] Nanofiltration - Membrane filters capable of removing pathogenic organisms and dissolved organic contaminants larger than 0.001 micrometers in size.

[50] Reverse Osmosis - Membrane filters capable of removing pathogenic organisms, dissolved organic, and salts contaminants larger than 0.0001 micrometers in size.

[51] Bag Filter - A membrane filter shaped like a bag.

[52] Cartridge Filter - A membrane filter in the form of a cartridge.

[53] Alternative Filtration - A filtration technology other than diatomaceous earth filtration, conventional or direct filtration, or slow sand filtration that is used to meet the requirements of the Surface Water Treatment Rule.

using chemicals to extend the time between cleanings. Chemical cleaning is used to control membrane fouling. Chemical cleaning is the primary means of restoring the membranes because they cannot be effectively cleaned by backwash alone. Over time, however, even chemical cleaning of the membranes cannot restore the required capacity, and the membranes must then be replaced.

In some cases, pretreatment to remove or reduce contaminant loading on the membranes may be required. Careful consideration must be given when selecting a membrane process for a specific application. Pilot testing may be required for unusual membrane applications.

Adsorption

Organic and inorganic contaminants can be removed from water through the adsorption process. Adsorption of a substance involves its accumulation onto the surface of a solid called the adsorbent. Adsorbents can include stationary media, such as activated carbon, ion exchange resins, or metal oxides. Adsorbents can also include aluminum or ferric chloride floc that forms during coagulation. This floc can adsorb organics such as organic carbon and inorganics such as arsenic.

Organic Adsorption

Activated carbon can be used to remove hundreds of different types of organic contaminants. It can be injected into the water as a powder, or it can be placed in a vessel in granular form for the water to flow through it. The powdered form is known as powdered activated carbon (PAC) and the granular form is known as granular activated carbon (GAC). Greater process control and adsorptive capacities can be achieved with the GAC.

GAC is placed in a vessel that resembles a filter. Two vessels are normally used and are typically operated in series. Series operation is used to ensure nearly 100 percent of the adsorption capacity of the GAC is used. The media is replaced only in the lead vessel each time, and the lead vessel is then switched to become the lag vessel. In other words, the contactor with the oldest media operates as the lead contactor, and the following contactor contains the new media and operates as a polishing contactor.

Contactors are design based on contact time. Generally, 10 minutes to 20 minutes of contact is required to obtain the desired removals and to optimize the adsorption capacity of the media.

The useful life of GAC media is a function of its ability to adsorb the target contaminant. When the media is new, nearly 100 percent of the target contaminant can be removed. As the use of the contactor progresses, less and less contaminant is removed until a maximum acceptable effluent contaminant concentration is reached. The adsorption capacity of the media at the top of the contactor can be nearly 100 percent utilized while the adsorption capacity of the media at the bottom of the contactor is only partially consumed. As a result, contactors are operated in series to fully exhaust the media in the lead contactor. The exhausted media is then removed and discarded or sent back to a facility to be regenerated.

Inorganic Adsorption

Some inorganic contaminants can be removed through the adsorption process as well. Adsorption can be on to the surface of a filter media or on to the surface of floc. Common adsorption media includes ferric oxide or activated alumina. Inorganic contaminants that can be removed by adsorption include arsenic, manganese, fluoride, as well as many others.

Arsenic is almost always a contaminant that is associated with groundwater. Arsenic can exist as either **arsenite**[54] (As^{3+}) or **arsenate**[55] (As^{5+}). Arsenite is difficult to remove using the adsorption process without first converting it to arsenate. Converting arsenite to arsenate can be accomplished through oxidation using chlorine or potassium permanganate. Once the arsenic is oxidized, it can then be removed by adsorption onto the surface of an iron floc or onto the surface of an iron oxide-coated filter media.

Arsenite can be removed from groundwater supplies in conjunction with the iron and manganese removal process. The concentration of iron must be at least 50 times greater than the concentration of the arsenic to obtain acceptable removals of the arsenic. This process is called **coprecipitation**[56]. The iron and the arsenic are oxidized simultaneously by chlorine or potassium permanganate. The natural iron forms a ferric (iron) floc when it is oxidized, and the arsenic is then adsorbed onto the surface of the floc.

Operational Considerations

Operation of an adsorption process using fixed media such as activated carbon or an iron-based granular media is based on breakthrough of the contaminant into the finished water. As noted earlier, the amount of water that can be treated through the process is a function of the concentration of the target contaminant and any other interfering agents. Pilot tests must be completed to determine the amount of water that can be effectively treated through the process. Change out frequency of the media is then a function of the quantity of water that can be treated.

Operation of a process using coprecipitation can be based on either breakthrough of the contaminant or clogging of the filter media. When the filter clogs or contaminant levels in the filter effluent begin to rise, the filter is then backwashed, and the process is started over.

Disinfection

Disinfection is defined as the process used to control waterborne pathogenic organisms and thus prevent waterborne disease. The goal of proper disinfection in a water system is to inactivate all disease-causing organisms. Disinfection should not be confused with sterilization, which is the complete killing of all living organisms. An example of the difference between disinfection and sterilization is the difference between placing alcohol on the skin before a shot (disinfection) and boiling surgical instruments (sterilization).

The effectiveness of disinfection in a drinking water system is measured by testing for the presence or absence of **coliform bacteria**[57]. Coliform bacteria that are found in water are generally not pathogenic, but they are a good indicator of contamination. Their absence indicates the possibility that the water is potable. Their presence indicates the possibility of contamination.

[54] Aresnite - Arsenic (III), the dissolved form of arsenic.

[55] Arsenate - Arsenic (V), the oxidized form of arsenic.

[56] Coprecipitation - Simultaneous precipitation of more than one substance containing impurities within its mass.

[57] Coliform Bacteria - The coliform group of bacteria is a bacterial indicator of contamination. This group has the intestinal tract of human beings as one of its primary habitats. Coliforms may also be found in the intestinal tract of warm-blooded animals and in plants, soil, air, and the aquatic environment.

Coliform bacteria have been selected as the indicator of bacteriological water quality for several reasons:

- They survive longer than most pathogenic organisms in the water environment.
- They are easy to test for. That is, the testing process has been perfected, and it is not excessively expensive or difficult.
- They are less sensitive to disinfection than many of the pathogens.

The requirements for testing the effectiveness of disinfection are to sample and test the distribution system. In order for the water to be potable, there should be a chlorine residual in all parts of the system and a complete absence of coliform in each and every sample. The presence of a single organism is cause to resample and retest.

The most commonly used disinfection alternatives in small systems today include chlorine, chloramines, ultraviolet light, and ozone. Disinfectants can be described as primary disinfectants or secondary disinfectants:

- Primary disinfectants are used to inactivate pathogenic organisms.
- Secondary disinfectants are used to maintain a disinfectant residual in the distribution system. Generally, secondary disinfectants include free chlorine or monochloramine because they can provide a persistent and detectable residual.

Chlorine

Chlorine is the most common method of disinfection used in the United States today. Despite problems, it remains our standard method of disinfection because 1) it costs less than most of the other methods, and 2) we have more knowledge about chlorine than any other disinfectant.

One of the major advantages of using chlorine is the effective residual that it produces. A residual indicates that disinfection is completed, and the system has an acceptable bacteriological quality. Maintaining a residual in the distribution system provides another line of defense against pathogenic organisms that can enter the distribution system. A residual in the distribution system helps to prevent regrowth of microorganisms injured but not inactivated during the initial (primary) disinfection stage.

Chemical Alternatives

There are two chlorine products used to disinfect drinking water: gas and **hypochlorites**[58]. Hypochlorites can be in either a liquid or powder form. The liquid is sodium hypochlorite. Household bleach is sodium hypochlorite. Powdered hypochlorite is calcium hypochlorite. HTH™ is a brand name for one of the common calcium hypochlorite products.

Gas chlorine is provided in 100 lb, 150 lb, or 1-ton containers. Chlorine is placed in the container as a liquid. The liquid boils at room temperature, producing a gas and pressure in the cylinder. At a temperature of 70° F, a chlorine cylinder will have a pressure of 85 psi. Chlorine gas is 100 percent chlorine.

Combining chlorine with either calcium or sodium produces hypochlorites. Calcium hypochlorites are available in either powder or tablet form and can contain chlorine concentrations up to 67 percent. Chlorine concentrations of household bleach range

[58] Hypochlorites - Compounds containing chlorine that are used for disinfection. They are available as liquids or solids and in barrels, drums, and cans.

from 4.75 percent to 5.25 percent. Sodium hypochlorite is a liquid such as bleach. Sodium hypochlorite is found in concentrations up to 15 percent.

There are differences between the reactions of chlorine gas and hypochlorite compounds in water that must be considered. When chlorine gas is added to water, it tends to consume alkalinity and lower the pH through the formation of hydrochloric acid. On the other hand, the addition of hypochlorite to water tends to raise the pH from the addition of calcium or sodium hydroxide.

Chlorine Disinfection

There are several things that can interfere with or have a negative impact on the ability of chlorine to disinfect. Among these are pH, temperature, type of organisms, type of residual, quantity of interfering agents, and **contact time**[59].

Hypochlorous acid (HOCl) is the best of the disinfection products. Hypochlorous acid is 100 to 300 times better than the hypochlorite ion (OCl^-) as a disinfectant. It requires five to 20 times more combined residual to do the same job as free residuals.

As the temperature of the water rises, chlorine compounds will evaporate or dissipate faster from the surface of the water. Thus at higher water temperatures, a higher dosage is required to maintain the same level of disinfection.

Not all organisms are affected in the same way by chlorine. For instance, viruses are much harder to kill than bacteria and require higher chlorine dosages. Also, some protozoa form cysts, or hard shells, that are difficult for chlorine to penetrate. Examples include the protozoan Cryptosporidium, which is extremely resistant to chlorine, and the cysts of Giardia, which are difficult but not impossible to inactivate with chlorine.

As we described previously, free chlorine residual is the best of the disinfectants. To maintain an effective line of defense against pathogenic organisms, State regulations require a residual of 0.2 mg/L of disinfectant at the point where the water enters the distribution system and a trace of disinfectant residual at all points in the distribution system. Due to limitations in contact time, higher residuals may be necessary to achieve proper disinfection.

Chlorination Practice

One of the major difficulties new operators have with the chlorination process is to understand the terms used to describe the various reactions and processes used in chlorination. The following table provides a brief description of the common terms used in chlorination.

[59] Contact Time - The amount of time in minutes that the disinfectant, measured as a free residual, is in contact with the water before the water is delivered to the first customer.

Definition of Chlorination Terms

Term	Description
Dosage	Dosage[60] is the amount of chlorine added to the system. The units used to describe dosage can be either milligrams per liter (mg/L) or pounds per day. The most common is mg/L.
Demand	Demand[61] is the amount of chlorine that is used by iron, manganese, turbidity, algae, organics, and microorganisms in the water. Because the reaction between chlorine and organic contaminants is not instantaneous, the measurable demand increases with time. For instance, the measurable demand five minutes after applying chlorine will be less than the demand after 20 minutes. Demand, like dosage, is expressed in mg/L.
Residual	Residual[62] is the amount of chlorine remaining after the demand is satisfied. Residual, like demand, is based on time. The longer the time after dosage, the lower the residual will be until all of the demand has been satisfied. Residual, like dosage and demand, is expressed in mg/L. There are three types of residual: free, combined, and total.
Free Residual	Free chlorine residual[63] is the number obtained when testing for the presence in water of chlorine gas, hypochlorous acid[64] (HOCl), and the hypochlorite ion[65] (OCl^-). Free chlorine is a stronger disinfectant than combined chlorine.
Combined Residual	Combined chlorine residuals[66] is the result of combining free chlorine with nitrogen compounds. Combined residuals are also called chloramines. There are three common chloramines: monochloramines, dichloramines, and trichloramines.
Total Chlorine Residual	Total chlorine residual[67] is the mathematical combination of free and combined residuals. Total residual can be determined directly with standard chlorine residual test kits. Total residual is the normal test required at wastewater treatment facilities.
Pre-Chlorination	Pre-Chlorination is the addition of chlorine prior to a unit process. In water treatment, pre-chlorination usually means the application of chlorine prior to any other treatment.
Post-Chlorination	Post-Chlorination is the addition of chlorine after a unit process. In water treatment, this is considered to be the chlorination of the water after treatment. The addition of chlorine to a treatment plant clearwell is post-chlorination.
Super-Chlorination	Super-Chlorination is the addition of a chlorine dosage so large that the water must be dechlorinated prior to use. There is no set value that is accepted as indicating super chlorination.
Dechlorination	Dechlorination is the reduction of the residual to an acceptable level. Dechlorination can be accomplished with the use of chemicals such as sulfur dioxide and sodium bisulfite.
Chloramines	If there are nitrogen compounds in the water, the hypochlorous acid will combine with them to form chloramines. Nitrogen compounds include inorganic nitrogen such as ammonia and organic nitrogen like protein and amino acids.

[60] Dosage - When related to chlorine, the amount of chlorine added to the system.

[61] Demand - When related to chlorine, the amount of chlorine utilized by iron, manganese, algae, and microorganisms in a specified period of time.

[62] Residual - What is remaining in the water after a set period of time.

[63] Free Chlorine Residual - The amount of chlorine available as dissolved gas, hypochlorous acid, or hypochlorite ion that is not combined with an ammonia or other organic compounds. It is 25 times more powerful than the combined chlorine residual.

[64] Hypochlorous Acid - An usable strongly oxidizing but weak acid (HOCl) obtained in solution along with hydrochloric acid by reaction of chlorine with water.

[65] Hypochlorite Ion - An ion that results from the reaction of chlorine gas and water. Hypochlorite ion (OCl^-), along with hypochlorous acid, are called free chlorine residual. However, the hypochlorite ion is not as powerful a disinfectant as hypochlorous acid.

[66] Combined Chlorine Residual - The amount of chlorine available as a combination of chlorine and nitrogen.

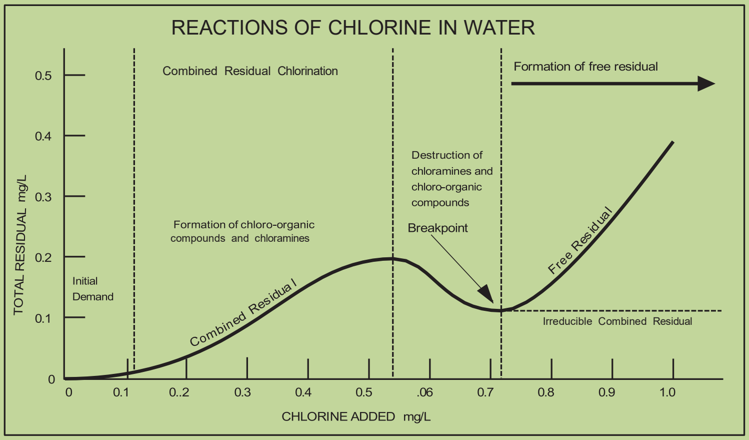
[67] Total Chlorine Residual - The sum of the combined and free chlorine residuals.

Breakpoint Chlorination

The concept of **break point chlorination**[68] is extremely important for the operator to understand. The chlorine breakpoint can be determined only by experimentation. This experiment is not difficult to perform. It requires twenty 1000 mL beakers and a solution of chlorine. The water is placed in the beakers and dosed with progressively larger amounts of chlorine. For instance, you might start with zero in the first beaker, then 0.5 mg/L, and 1.0 mg/L, and so on. After a period of time, say 20 minutes, each beaker is tested for total chlorine residual and the results plotted.

Components of the Breakpoint Curve

Curve Component	Explanation
Initial Demand	When the curve starts, there is no residual, even though there was a dosage. This is called the initial demand and is the result of the chlorine being used by microorganisms and interfering agents.
First Rising Leg	After the initial demand, the curve slopes upward. This part of the curve is produced by chlorine combining to form chloramines. All of the residual measured on this part of the curve is combined residual (monochloramine).
Dropping Curve	At some point, the curve will begin to drop back toward zero. This portion of the curve results from a reduction in combined residuals. This occurs because enough chlorine has been added to destroy (oxidize) the nitrogen compounds that were being used to form combined residuals (chloramines).
Breakpoint	The breakpoint is the point where the downward slope of the curve breaks upward. At this point, all of the nitrogen compounds that could be destroyed have been destroyed.
Second Rising Leg	After breakpoint, the curve starts upward again, usually at a 45° angle. It is only on this part of the curve that free residuals can be found.
Irreducible Combined Residual	The distance that the breakpoint is above zero is a measure of the remaining combined residual that will be in the water. This combined residual exists because some of the nitrogen compounds cannot be oxidized by chlorine. If irreducible combined residual is more than 15 percent of the total residual, chlorine odor and taste complaints will be high.



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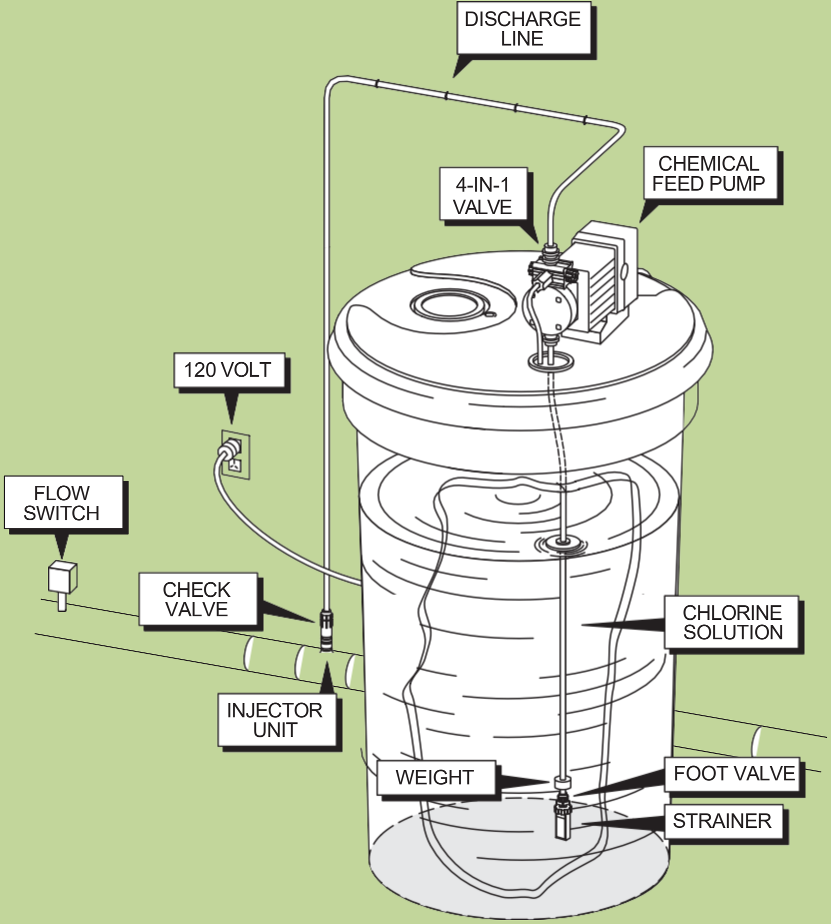
[68] Breakpoint Chlorination - The point at which near-complete oxidation of nitrogen compounds is reached. Any residual beyond breakpoint is mostly free chlorine.

Chlorination Equipment

The gas chlorine feed equipment used in a water system is rated in pounds per day (the maximum amount of chlorine that the system can feed in a day). All of the units sold today are vacuum-operated. This is a safety feature. If there is a break in one of the components in the chlorinator, the vacuum will be lost and the chlorinator will shut down without allowing gas to escape.

The most common hypochlorinator system is composed of a 20 to 50 gallon corrosion-proof tank (usually plastic) in which a hypochlorite solution is mixed. This solution is pumped into the system using a chemical feed pump. To protect the pump, a strainer is placed on the end of the suction line. Also on the suction line is a weight and foot valve. The weight keeps the line in the solution, and the foot valve helps to maintain the prime on the pump. On the end of the discharge line is a check valve. This valve prevents the water in the system from flowing back through the pump into the mixing tank.



Typical hypochlorination feed equipment

Sodium hypochlorite can be generated onsite using high-grade, high-quality salt, water, and electricity. The strength of the sodium hypochlorite solution produced using this equipment is around 0.8 percent. The process water must have less than 17 mg/L hardness, and in many cases in Alaska, the water must be heated. The sodium hypochlorite solution at 0.8 percent is very stable. However, because of the low chlorine concentration of the solution, a relatively large injection pump is required to deliver the needed dosage. Lastly, a by-product of onsite sodium hypochlorite generation includes the production of hydrogen gas H_2. Safe disposal of this gas must be considered for this application.

Chloramines

Chloramines[69] have been used as a disinfectant in drinking water treatment since the beginning of the 20th century. Chloramines are produced when chlorine is added to water containing nitrogen compounds such as ammonia nitrogen. This reaction is detailed above in the breakpoint chlorination example. There are three types of chloramines that are produced, including monochloramines, dichloramines, and trichloramines. From the water treatment perspective, the desired form of chloramine is monochloramine because of its biocidal properties and minimal taste and odor production. Dichloramines and trichloramines are less desirable because of the chlorinous tastes and odors that they produce.

The major benefits of monochloramines include their tendency to produce fewer disinfection by-products such as TTHMs and HAA5s, minimal chlorinous tastes and odors, persistence to reach distant areas of the distribution system, and effectiveness as a secondary disinfectant in penetrating **biofilms**[70] in distribution systems.

Chloramines are less effective as a biocide than free chlorine for inactivating pathogenic microorganisms. For this reason, chloramines are generally not used as a primary disinfectant. Chloramines are, however, an excellent secondary or final disinfectant because they form a very stable and persistent residual.

Chloramination Equipment

The equipment required to produce chloramines is essentially the same equipment required for chlorination systems. Chlorine can be injected as a gas or a liquid, and ammonia can also be injected as a gas or a liquid. In addition, both chlorine and ammonia are also available in liquid form or in granular form that can be dissolved in water. Great care must also be taken to ensure that concentrated chlorine and ammonia are never mixed because they will form nitrogen trichloride, a potentially explosive compound.

Ultraviolet Light (UV)

One of the numerous forms of energy is electromagnetic. UV light is in the electromagnetic spectrum between X-rays and visible light. Practical UV disinfection in water treatment occurs primarily at a wavelength between 200 nanometers (nm) and 300 nm. A mercury-based UV lamp will produce ultraviolet light at 253.7 nm.

Ultraviolet Disinfection

Disinfection by UV light is very different from the mechanisms of chemical disinfection using chlorine, chloramines, or ozone. Chemical disinfectants inactivate microorganisms by damaging cellular structures, interfering with metabolism, and hindering growth. UV light inactivates microorganisms by damaging their nucleic acid and preventing them from replicating, thus making it impossible for the organisms to infect the host.

The UV dosages required to inactivate viruses are substantially higher than those required to inactive Cryptospordium and Giardia. UV leaves no residual and thus requires the addition of chlorine or some other secondary disinfectant to maintain a residual in the system.

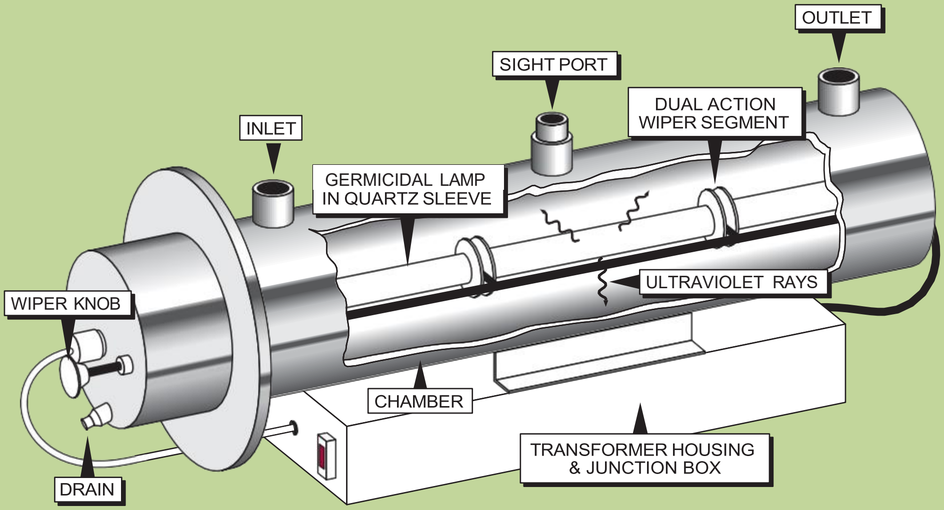
Ultraviolet Disinfection Equipment

UV reactors must consistently deliver the dosage of UV radiation necessary to inactivate the target pathogens. Factors that interfere in the delivery of the proper dosage

[69] Chloramines - Compounds produced when chlorine and ammonia react. A weak oxidant or disinfectant.

[70] Biofilms - A colony of tiny microorganisms.

include poor water quality such as high turbidity, absorbance of the light by organics, low bulb light output (caused by slime buildup or bulb degradation), or an increase in the water flow rate past the light source. To ensure proper treatment, commercial UV reactors are equipped with UV sensors, temperature sensors, flow meters, and cleaning mechanisms for the bulbs.



UV disinfection system

Ozone

Ozone (O_3) is a colorless gas with a characteristic odor reminiscent of a lightning storm. Ozone has been used in drinking water treatment for many years in France, Germany, and Canada. Its use in the United Stares has been increasing as concerns about chlorinated by-products have increased. Because of the reactivity of ozone, residuals cannot be maintained for more than a few minutes. As a result, ozone is considered to be a primary disinfectant and requires the use of chlorine or chloramines as a secondary disinfectant.

Ozone Disinfection

Ozone is a very powerful disinfectant. The concentration and reaction times are substantially lower than those required for free chlorine. Required CT values for inactivation of Giardia by ozone are on the order of 1/10th of those required for free chlorine.

Ozone Disinfection Equipment

Because of its extreme reactivity, ozone gas must be produced onsite. It is a product of the action of electrical fields on oxygen. The oxygen can be derived from air or shipped to the site as pure oxygen in compressed gas cylinders. After the ozone is generated, it is piped to a contactor. Ozone is then injected at the bottom of the contactor tank into a diffuser, and the fine bubbles rise through the water as the water flows downward into the tank. Ozone is transferred from the gas phase into the water through this process, where it is free to react with the contaminants.

The CT Concept

One of the keys in predicting the effectiveness of a chemical disinfectant on microorganisms is CT. The disinfectant residual concentration is the “C,” and the contact time is the “T.” CT is calculated based on a specified disinfectant residual being maintained prior to the first customer: Concentration (mg/L) x Contact time (minutes).

Experimentation has shown that specific CT values are necessary for the inactivation of viruses and Giardia. The required CT value will vary depending on the disinfectant, pH, temperature, and the organisms that must be inactivated. Charts and formulas are available to make this determination.

Tables in the EPA's *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* list the required CT values for various types of disinfectants.

CT Values for Various Disinfectants

Disinfectant	Disinfectant Concentration	Log Inactivation*	Microorganism	pH	Water Temperature	Required CT
Free Chlorine	0.6 mg/L	1	Giardia	7.0	<34° F	67
	Varies	3	Viruses	6-9	<34° F	9
Chloramines	Varies	1	Giardia	6-9	<34° F	1,270
	Varies	3	Viruses	N/A	<34° F	2,063
Ozone	Varies	1	Giardia	---	<34° F	0.97
	Varies	3	Viruses	---	<34° F	1.4

*Log inactivation[71] is related to the percentage of organisms inactivated. One log is equal to 90 percent; two logs equal 99 percent; and three logs equal 99.9 percent inactivation.

Surface Water Treatment Systems

The control of turbidity, color, microorganisms, and, to some extent, taste and odor is commonly accomplished through some type of filtration system. The Surface Water Treatment Rule describes five different types of filtration systems: **conventional treatment**[72], direct filtration, **slow sand filtration**[73], **diatomaceous earth filtration**[74], and alternate filtration technologies such as bag filters and cartridge filters.

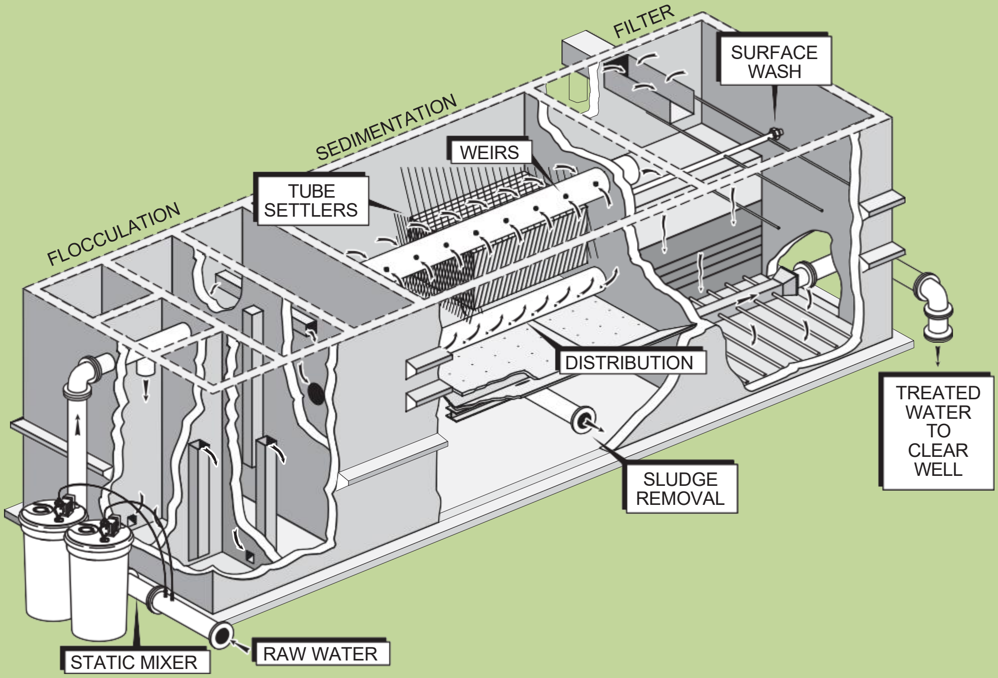
Conventional treatment includes rapid gravity filters, either built on-site or provided as a skid-mounted packaged system with flocculation and sedimentation units. Direct filtration is similar to conventional treatment with the exception that there is no sedimentation unit. The third type of filtration is called slow sand filtration and the fourth is diatomaceous earth filtration. In addition, the regulations allow the use of "alternate filtration technologies." Alternate filtration includes cartridge filters or bag filters. Membranes have also been identified as a technology to address the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). Membranes are an option that can meet not only the requirements of the SWTR, but also the cryptosporidium removal requirements of the LT2ESWTR.

[71] Log Inactivation - A mathematical relationship relating percent inactivation to logarithmic inactivation. Common inactivations are three log or 99.9 percent and four log or 99.99 percent.

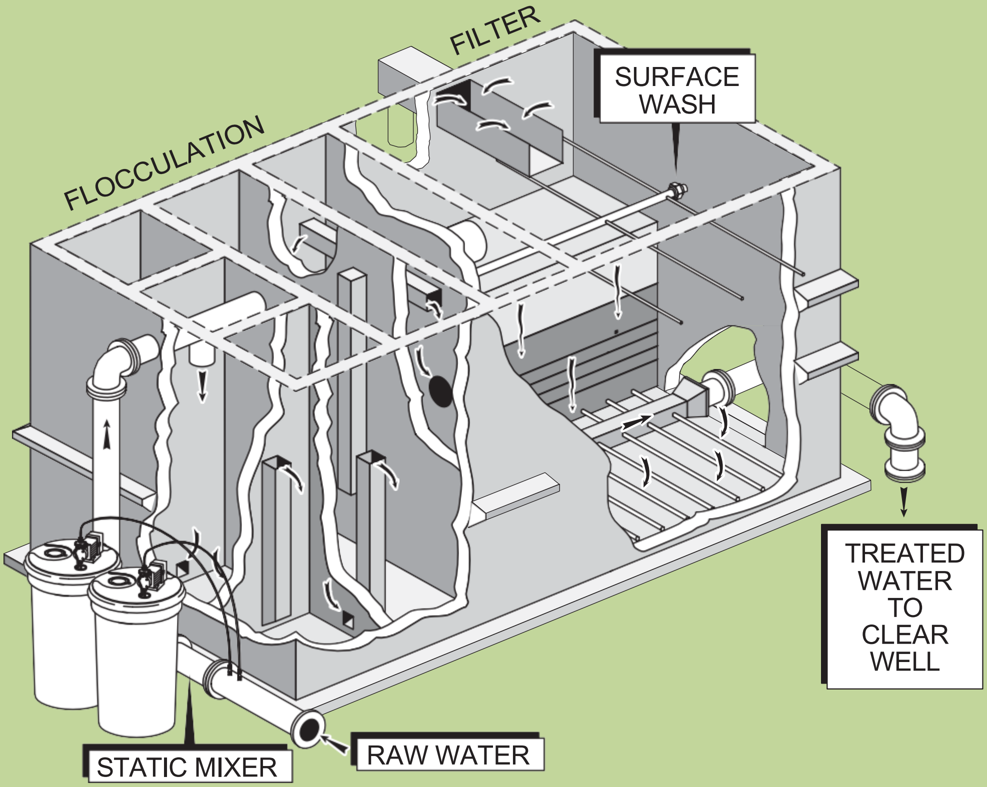
[72] Conventional Treatment - A standard treatment process involving coagulation, flocculation, sedimentation, filtration, and disinfection.

[73] Slow Sand Filtration - A method of filtration that uses a layer of microorganisms and sand media to remove contaminants.

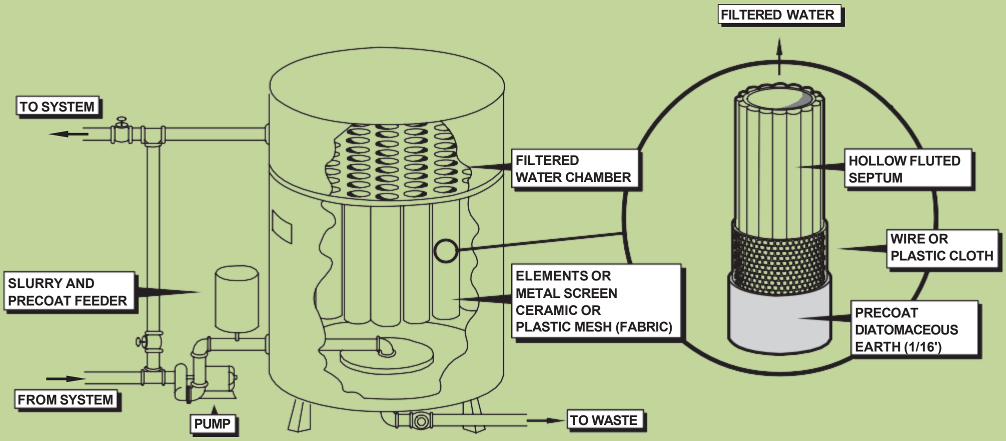
[74] Diatomaceous Earth Filter - A pressure filter utilizing a media made from diatoms.



Typical conventional package treatment plant



Direct Filtration - gravity filter system



Diatomaceous earth filter

There are common variations of the conventional treatment and direct filtration processes that can be used to meet regulatory water treatment goals, to improve process efficiency, and to reduce the operational complexity of surface water treatment processes. These include two-stage filtration and pressure filtration.

One of the main goals in operating a surface water treatment system is to achieve efficient filter runs. The more water a filter produces before a backwash is required, the lower the percentage of treated water lost to backwash. In other words, backwashing a properly designed filter requires about the same amount of water each time it is cleaned. The water that is used for backwash must be potable water from the water storage tank. Potable water is used to avoid injecting contaminants or debris into the filter underdrains. Generally, filtration efficiencies greater than 95 percent are considered acceptable. Efficiencies substantially less than 95 percent are cause for further investigation. Filtration efficiency is calculated as follows:

Filter efficiency (%) = 100 – (Backwash water volume/Water produced during the filter run)

It should be noted that a water source may be treated using direct filtration if backwash water waste can be limited to an acceptable level. High contaminant concentrations can substantially shorten filter runs and thus reduce efficiencies below an acceptable level. The addition of pretreatment such as a clarifier must be provided to reduce solids loading on the filters if this occurs. In this situation, conventional treatment is the preferred process. However, conventional treatment should not be used when a clarifier is not required.

Applied Water Quality

The quality of water from the source should determine the most appropriate type of treatment. Water quality issues that must be considered include the amount of turbidity, organics, algae, and total dissolved solids (TDS).

As a general rule of thumb, the higher the levels of contaminants in the raw water, the greater the level of treatment that is required prior to filtration. The filtration process is usually the final removal process in a water treatment system. Pretreatment processes such as flocculation, sedimentation, contact clarification, roughing filters, etc. are simply used to reduce the solids load on the final filters.

The table below provides general guidelines of applicable raw water quality for some of the basic water treatment processes:

	Conventional Treatment	Two-Stage Filtration	Direct Filtration	Alternative Filtration
Turbidity (NTU)	<5000	<50	<15	<1.5
App. Color (CU)	<3000	<50	<20	<15
Algae (ASU/mL)	<10000	<5000	<500	<100
TTHMF (mg/L)	<0.20	<0.16	<0.13	<0.08
HAA_5F (mg/L)	<0.15	<0.12	<0.10	<0.06

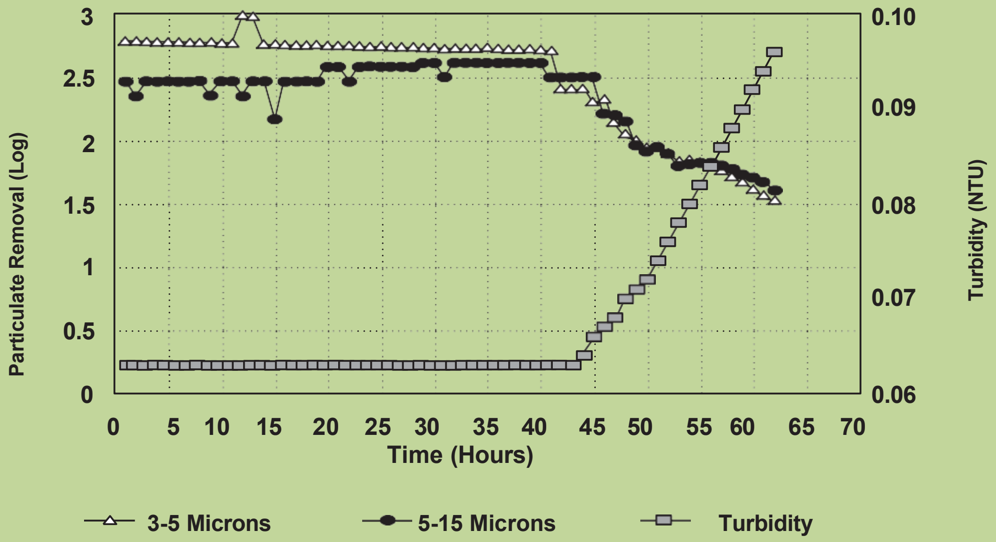
Note

1. The above criteria are general recommendations. Exceptions may be possible under certain conditions.
2. The criteria presented for direct filtration is also applicable to pressure filtration and slow sand filtration.
3. Alternative Filtration is also referred to as a membrane process specifically defined as Membrane Cartridge Filtration (MCF) in the US EPA Membrane Filtration Guidance Manual. Both cartridge filters and bag filters are used in this process.
4. Total Trihalomethane Formation (TTHMF) and Five Haloacetic Acid Formation (HAA_5F) are the levels of disinfection by-products that would be produced under typical chlorination and distribution system operating conditions.
5. ASU stands for Areal Standard Unit.
6. Presedimentation may be required for turbidities over 1000 NTU.

Operational Control

The issue of operational control of surface water treatment systems has become increasingly important as water treatment regulations have become more stringent. Water treatment systems must consistently produce water compliant with the required removals of microorganisms and disinfection inactivations. To do this, turbidities must be maintained within very narrow tolerances, and disinfection must be consistently applied. Instrumentation has become mandatory equipment to ensure proper operation of the water treatment system and to allow accurate reporting of performance.

At a minimum, online turbidimeters and recorders are now required to consistently monitor process turbidities and to allow reporting of turbidities at the required intervals. Turbidimeters can also be configured to shut the system down in order to prevent high turbidity water from entering the system and thus prevent a violation of regulatory requirements. Particle counters are also available for online monitoring of process performance; however, these units are expensive, and there are no regulatory requirements or standards for their use.



Filter run

Automated control of the coagulation process is also available through the use of a Streaming Current Detector (SCD). A SCD measures the net charge density in the water and can be used to determine when the optimum amount of coagulant has been added. The contaminants in raw water have a highly negative net charge. Optimum coagulation occurs when the net charge nears a value of zero as measured by the SCD. Most SCDs are equipped with a signal output capability that can be used to provide online control of a coagulant feed pump. This automated control can ensure consistent optimization of the coagulation process.

Online chlorine analyzers are also available for monitoring disinfectant residuals. The devices can be configured to provide automated control of the chlorine injection pump. This type of instrument can ensure that proper disinfection is consistently maintained.

Conventional Treatment

The basic unit processes employed in a conventional treatment system include coagulation, flocculation, sedimentation, and filtration. Typically, conventional treatment systems are capable of producing a final effluent turbidity of less than 0.1 NTU. Filtration rates for conventional treatment ranges from 2 to 6 gpm/ft^2, with 4 gpm/ft^2 as the most common.

The conventional treatment system starts with the chemical feed system. This system can include dry or liquid feeders for alum, ferric salts, lime, **soda ash**[75], potassium permanganate, and/or polymers. The chemical is fed into the raw water just prior to or directly into some type of flash mixing unit. The flash mixer quickly mixes the chemical with the water. Flash mix systems include static or mechanical mixers. Static mixers are more common on small package plants, and mechanical mixers are more common on the larger facilities.

Flocculation systems vary from simple hydraulic systems using baffled chambers to mechanical mixers that resemble a paddle wheel that slowly rotates through the water. Small package plants commonly use hydraulic systems, and mechanical mixers are used for the larger facilities.

[75] Soda Ash - A common name for commercial sodium carbonate. A salt used in water treatment to increase the alkalinity of pH value of water or to neutralize acidity.

The sedimentation basins come in a wide variety of shapes: round, square, and rectangular. The most common are rectangular. Most basins used in small facilities have an inlet distributor or area designed to allow for a smooth entry of the water into the basin. The water travels up through the basin, possibly into the tube settlers, and then into collection devices called weirs or effluent **launders**[76].

Sludge is removed from the clarifier by gravity in the smaller facilities and by mechanical means in larger facilities. The large facilities may use scraper arms that move the sludge to a collection point or vacuum devices that lift the sludge from the bottom of the clarifier and deposit it into a channel. The sludge is then piped to a pond or settling facility and then to land disposal.

Water passes from the sedimentation basin into the filters. The filter is composed of a box, with an underdrain system, support gravel, and filter media. The underdrain system is designed to collect the water as it passes through the filter and to distribute backwash water evenly through the filter.

Most filter systems have a surface wash system or an air scour system to provide agitation of the media prior to backwash. The surface wash system consists of a series of nozzles attached to an arm or grid. The nozzles are pointed down, so they will break up the accumulation of flocculated material on the filter bed surface and thus increase the life of the media by preventing mudballs from forming and sinking into to the bed.

The air scour system is also used to agitate the media through the injection of air up through the entire depth of the bed. Air scour provides a more thorough cleaning than the surface wash because it agitates all of the media aggressively.

Two-stage Filtration

A two-stage filtration system can be housed in open tanks and operate as gravity filters or enclosed in vessels and operated as pressure filters. Two-stage filtration systems consist of two filters operated in series. The first filter contains large-diameter media and functions as either a clarifier or a flocculator, depending on the size of the media and flow rate. In general, media smaller than about 2 mm is required for clarification, and media larger than 4 mm is required for flocculation. Water treatment objectives and the nature of the contaminants determine the most appropriate media configuration. A more thorough discussion regarding two-stage filtration is given earlier in the section covering basic water treatment unit processes.

In a two-stage system, both clarification and, to some extent, flocculation are carried out in the first stage filter. The size of the media, as noted earlier, determines which process is predominantly performed by the first stage filter. The hydraulic loading on the first stage filter is a function of the process that it is to perform. Lower loadings are used if it is to function primarily as a clarifier, and higher loadings are used if it is to function primarily as a flocculator. The second stage filter is designed as a standard dual media or mixed media filter. The function of the second stage, or final filter, is similar to that in a conventional treatment system.

The chemical amendments used in a two-stage system can include either or both metal salts and polymers. In general, cationic polymers are used either in conjunction with metal salts or alone to improve the shear strength of the floc. Metal salts alone produce a very weak floc, which can be broken up by the **hydraulic shear**[77] in these

[76] Launder - Sedimentation tank effluent troughs.

[77] Hydraulic Shear - The shear force of water flowing past an object.

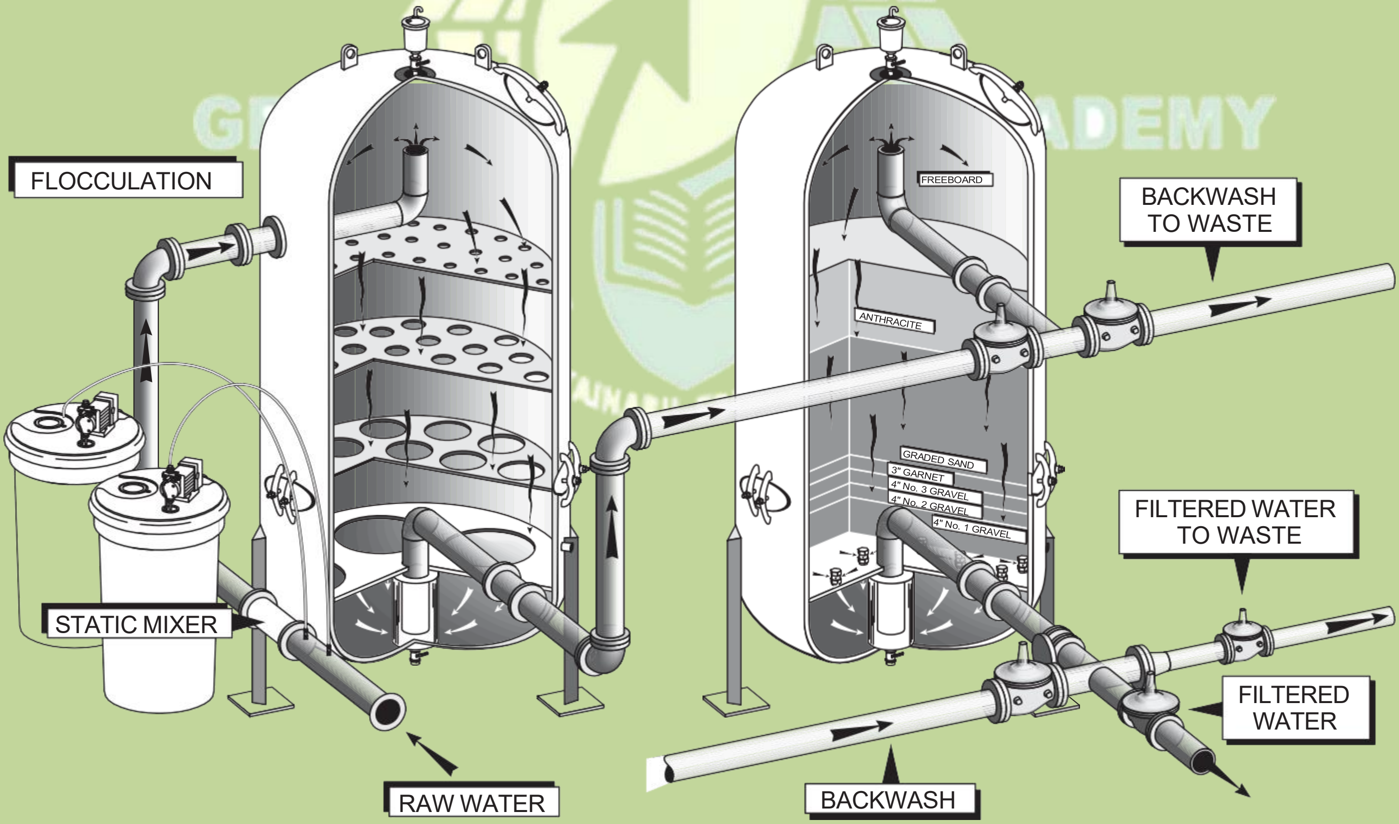
types of treatment units. Anionic polymers can also be used as chemical amendments; however, the amount of chemical that is injected must be minimized in order to reduce clogging of the media in the first stage filter.

The first stage filter must be cleaned periodically during the filtration cycle. The requirement for cleaning can be based on differential pressure across the filter (how much the filter is clogged) or on the turbidity of the effluent. The cleaning process is accomplished by first air scouring the media followed by an up-flow backwash. Because of the large media size, air scour is mandatory. Additionally, the backwash water flow rate per square foot of media area is also substantially higher than the flow rate required for the second stage filter.

Direct Filtration

A direct filtration system is simply a conventional treatment system without the clarifier. Direct filtration plants can also operate with either gravity or pressure filters.

Direct filtration is used for treating high-quality source waters with low levels of turbidity and organic contaminants. The upfront processes such as clarification are simply not required because of the low contaminant loading on the filters. Efficient filter runs can be attained because of the pristine source water and minimal solids loading on the filter. These systems are less complicated to operate because fewer unit processes are involved.



Direct filtration - pressure filter system

When raw water is pumped or piped from the source to a gravity filter, the head (pressure) is lost as the water exits the filter. Depending on the location of the water treatment plant, it is usually necessary to pump water from the plant to an elevated or pressurized water storage tank. One way to reduce pumping is to enclose the filter in a pressure vessel and thus maintain the head (pressure) of the pump or source. This type of arrangement is called pressure filtration.

Pressure filtration systems have been designed and installed in many communities throughout Alaska. The systems include a minimum of two filters, a static mixer and piping designed to provide flocculation. Hydraulic flocculation is also provided in the head space in the filter vessel above the media.

The preferred chemical amendments for direct filtration are cationic polymers. These coagulants provide a very strong floc that can withstand the hydraulic shear encountered in the filter media. In direct filtration, the filter media must remove all of the floc. Metal salts, such as aluminum sulfate or ferric sulfate, produce a weak floc that will break up in the media and result in high turbidities in the filter effluent within a relatively short period of time after the filter run begins. Cationic polymers, on the other hand, can produce long, efficient filter runs. Polymers are more expensive than metal salts, and the amount that can be injected is limited by the EPA. However, because the water that can be applied to a direct filtration system has lower levels of contaminants, it also has a lower coagulant demand, thus making the use of polymers cost-effective.

Slow Sand Filtration

Both small and large communities use slow sand filters to remove turbidity and microorganisms. They are effective when the color and turbidity of the source are low. Their operational cost is much lower than conventional treatment. However, they require large areas of ground and, in most locations in Alaska, must be enclosed in a heated building. Moreover, slow sand filters are difficult to operate when the raw water quality deteriorates.

A slow sand filter is composed of a filter bed of sand that is 24 to 42 inches deep. This bed is placed over an underdrain system. Water passes through the filter bed, and contaminants are removed from the water by a biological process. The filter bed contains microorganisms that enable the filters to remove bacteria, reduce organic matter, and reduce turbidity. The active biological layer on top of the filter media is referred to as the **Schmutzdecke**[78]. Periodically, the top one or two inches of the media must be removed in order to maintain satisfactory water production.

Diatomaceous Earth Filtration

Diatomaceous earth (DE) filters are not commonly used in Alaska in drinking water systems. They are, however, often used to filter swimming pool water. Diatomaceous earth is a white material made from the skeletal remains of diatoms. The skeletons are microscopic and, in most cases, porous. There are different grades of diatomaceous earth, and the grade is selected based on the filtration requirements.

The DE is mixed in a water slurry and fed onto a fine screen called a **septum**[79]. This septum is usually made of stainless steel, nylon, or plastic. Coating the septum with diatoms gives the filter the ability to remove very small microscopic material. A slurry of diatoms is fed with the raw water during filtration in a process called body feed. The body feed prevents premature clogging of the septum cake. These diatoms are caught on the septum, which increases the headloss and prevents the cake from clogging too rapidly by the particles being filtered. While the body feed does increase

[78] Schmutzdecke - A thin organic mat that grows on a sand filter.

[79] Septum - Filter media on which diatoms are collected during filtration with a diatomaceous earth filter. Usually made of nylon, plastic, stainless steel, or brass.

headloss, it is more gradual than if body feed were not used. When the diatoms have built-up to a depth of approximately 1/16 of an inch, they are removed by backwashing the filter.

In the past, operating costs, the inability to consistently produce low turbidity water, difficulty in maintaining a proper cake, and cake disposal problems have limited the diatomaceous filters popularity. However, recent technological improvements have led to a resurgence in the use of this process.

Membrane Filtration

Membrane filtration systems can treat a wide array of contaminants, depending on the process that is selected. The processes defined in the *EPA Membrane Filtration Guidance Manual* include membrane cartridge filtration (MCF), microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). The capabilities of each process to remove selected contaminants are detailed in the previous discussion on membrane filtration.

Membrane systems are subject to fouling and may require pretreatment for certain troublesome contaminants. For the MCF process, pretreatment may include only a roughing filter to reduce the solids loading on the down stream MCF (bag or cartridge) filter/pathogen barrier. In the more sophisticated systems, an entire conventional treatment system may precede an RO system for reduction of TDS. Other problematic contaminants are detailed in the previous discussion on membranes.

Alternative filtration is the term used by ADEC to describe the use of bag or cartridge filters for the removal of Giardia and Cryptosporidium. The application of alternative filtration is limited to pristine water containing very low levels of turbidity, organics, and algae. In these systems, cartridge or bag filters are made of a synthetic media that is contained in a housing. These systems are normally installed in a series of three or four filters. Each housing contains media successively smaller than the previous media. The filters are arranged in series so that the more expensive Giardia and Cryptosporidium barriers are protected by the less expensive prefilters. The filters are rated at a certain flow rate and maximum differential pressure. The filters are discarded when they become clogged.

All membrane filters, regardless of the type, must be replaced in time as they become fouled beyond the point where output can be recovered through backwashing and chemical cleaning. In general, bag and cartridge filters must be replaced on a monthly basis or even more frequently, depending on raw water quality. Well-maintained MF, UF, NF, and RO membrane filters can last 3-5 years on the average. Replacement of the membranes can be very expensive costing thousands of dollars every few years.

Granular Activated Carbon (GAC) Contactors

Granular activated carbon (GAC) contactors are used as a polishing step in the removal of organic contaminants. They are typically used to reduce DBPs or to control taste and odor. Contactors are usually installed in series in order to obtain the maximum utilization of the activated carbon media.

The type of process used ahead of GAC treatment can have a significant affect on the performance of the GAC and the amount of water that can be effectively treated before the media requires replacement. The use of coagulation and filtration ahead of a GAC adsorption process can serve both to reduce the amount of organic contaminants that must be removed by the GAC and to condition the organic contaminants, allowing greater removal efficiencies by adsorption.

The type of contaminant that must be removed determines the selection of the most appropriate GAC media. Manufacturers are available to help with the selection process. GAC media is typically supplied in bags. The media is then loaded into the contactor vessels, usually by hand.

The use of GAC in Alaska is limited by the high cost of shipping and large volumes of the media that must be supplied. Many communities are remote, and shipping large quantities of materials is expensive. In other areas of the country, the media can be returned to the manufacturer for regeneration, although in Alaska the media must be discarded because it is not cost-effective to return the media for regeneration. However, in some cases, the use of GAC is cost-effective in fill and draw type systems because of the low quantities of water that is used.

Operation of a GAC contactor is based on the amount of water that can be filtered before contaminants begin to break through the filter. The replacement of the media is governed by the amount of contaminant that can be tolerated in the filtered water. This target is typically set as a percentage of the contaminant entering the contactor. Pilot testing must be conducted to determine the performance of the GAC in removing the target contaminants as well as the GAC usage rate with respect to the volume of water that can be treated before media replacement is required.

Groundwater Treatment Systems

Iron, manganese, arsenic, carbon dioxide, and hydrogen sulfide are contaminants that commonly occur in groundwater and require some level of treatment for removal. Iron and manganese are found as naturally occurring **soluble**[80] minerals in the soil. By means not totally understood, bacteria and other natural conditions convert the insoluble iron and manganese into soluble forms and release them into the water. The primary problem with iron and manganese is that they stain fixtures and clothing. While they do not directly cause odor and taste problems, when there is an excess of soluble iron in the water, bacteria, referred to as "iron-reducing bacteria," will utilize the soluble iron and produce by-products that give the water a metallic taste.

Carbon dioxide and hydrogen sulfide are gases that can cause treatment problems or odor production respectively. Carbon dioxide gas tends to reduce pH and can cause gas binding in gravity filters. Hydrogen sulfide gas produces a strong rotten egg odor that can be detected at levels as low as 0.1 μg/L.

The Safe Drinking Water Act lists iron and manganese as secondary contaminants. The MCL is 0.3 mg/L for iron and 0.05 mg/L for manganese. In 2006, the US EPA lowered the MCL for arsenic from 0.05 mg/L to 0.01 mg/L. Carbon dioxide and hydrogen sulfide gas are not regulated contaminants; however, they can affect pH or odor, which are considered by ADEC to be secondary contaminants.

Applied Water Quality

The level of iron and manganese can have a major affect on the type of treatment process that is selected. In general, similar options exist for groundwater treatment also

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[80] Soluble - A substance that is easily dissolved.

used for surface water treatment. The conventional treatment process is used when high concentrations of iron and manganese must be removed prior to filtration. The direct filtration process is appropriate when lower concentrations of these contaminants are present in the source water. As a rule of thumb, when iron concentrations exceed about 10 mg/L, conventional treatment should be considered.

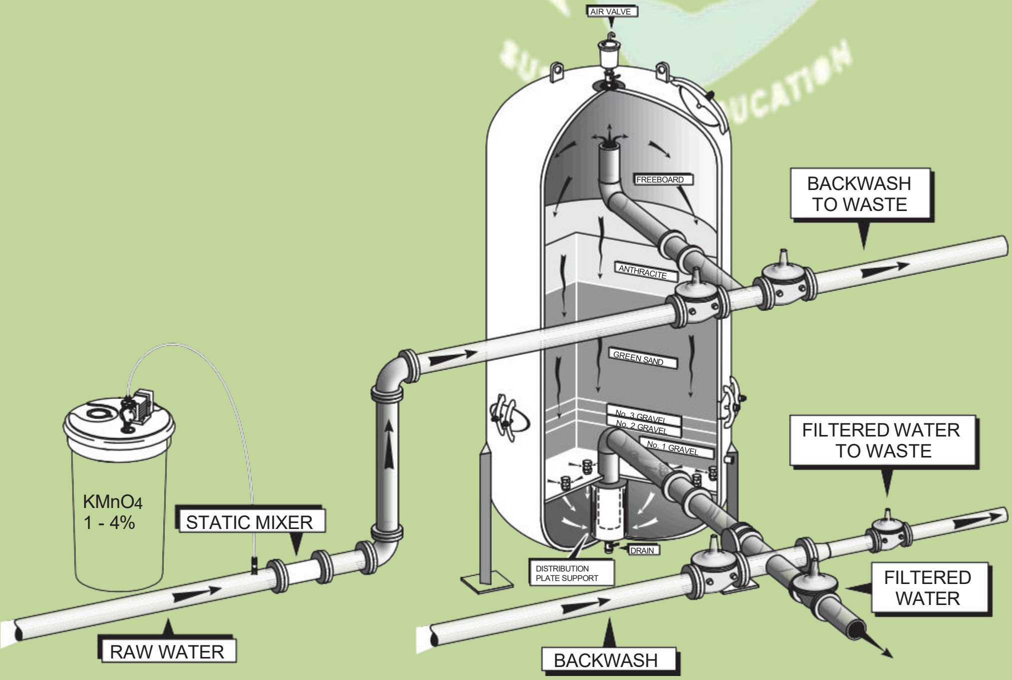
When the water contains very low concentrations of iron, the addition of a **sequestering agent**[81], such as hexametaphosphate, can be successful in keeping the iron in solution. Sequestering agents do not remove the iron, but bind it chemically so that it is not easily oxidized.

Air can also be used to oxidize iron and manganese. The air is either pumped into the water, or the water is allowed to fall over an **aeration**[82] device. The air oxidizes the iron and manganese, which are then removed by a filter. Lime is often added to raise the pH in order to speed the oxidation process.

Treatment for arsenic has been previously discussed. The most common and successful options include coprecipitation with natural iron, iron hydroxide adsorption using ferric sulfate or ferric chloride, and fixed bed adsorption using an iron-based media. Carbon dioxide can be particularly troublesome in the gravity filtration process. When conventional treatment is being considered, the presence of carbon dioxide must be carefully evaluated in the equipment selection process. Gas binding can occur in gravity filters, resulting in very short and inefficient filter runs. The use of pressure filtration after clarification can be employed in conventional treatment to overcome this problem.

Conventional Greensand Treatment

The conventional greensand treatment system that is used in groundwater treatment is designed very similar to a surface water treatment system. The major difference is the use of a natural **zeolite**[83] media called manganese **greensand**[84] in place of the silica sand in the filter.



Greensand filter system

[81] Sequestering Agent - A chemical compound or polymer that chemically ties up (sequesters) other compounds or ions so that they cannot be involved in chemical reactions.

[82] Aeration - A treatment process bringing air and water into close contact in order to remove or modify constituents in the water.

[83] Zeolite - Natural or man-made minerals that collect from a solution certain ions (sodium or $KMnO_4$) and either exchange these ions, in the case of water softening, or use the ions to oxidize a substance, as in the case of iron or manganese removal.

[84] Greensand - Naturally occurring silicates of sodium and aluminum that respond as a natural ion exchange medium. Commonly used as the primary filter medium in a potassium permanganate, greensand, iron, and manganese removal process.

When conventional greensand treatment is used, the continuous regeneration process is employed. In this process, an oxidant is continuously fed into the raw water as it enters the plant. Chemical amendments for conventional greensand treatment include chlorine or potassium permanganate for oxidation of iron and manganese to form precipitates. If organically complexed iron or manganese is present, the use of a cationic polymer or a metal salt may be required. Lastly, an anionic polymer is usually added to improve the settling characteristics of the iron floc and thus improve the efficiency of the sedimentation process.

A conventional greensand treatment system is operated in much the same way as a conventional surface water treatment system. The accumulated solids (iron and manganese) in the sedimentation basin must be periodically removed, and the filter must be backwashed to flush out accumulated contaminants. In conventional greensand treatment, the length of the filter run is usually determined by differential pressure (clogging of the media with precipitate).

Arsenic removal through the conventional greensand process is accomplished by coprecipitation. Coprecipitation occurs with iron that is naturally available or with iron that is supplemented through the addition of ferric sulfate or ferric chloride. The ratio of iron to arsenic must be at least 50:1 to provide enough sites (precipitated iron) for the arsenic to adsorb. Lastly, the arsenic must be oxidized completely before it can be adsorbed onto the surface of the iron floc.

Direct Greensand Filtration

The most common method of iron and manganese removal in Alaska is a process called the continuous regeneration manganese greensand process. This process consists of a filter filled with greensand and is typically used when concentrations of iron are less than about 10 mg/L. The filter can be configured as a pressure filter or a gravity filter. Pressure filters are the most common.

The direct filtration greensand process can also be operated in an intermittent regeneration mode. In the intermittent regeneration mode, the greensand is soaked (regenerated) using either chlorine or potassium permanganate after the filter is backwashed. The filter is then started, and contaminants are adsorbed onto the surface of the media. This process is used to treat relatively low levels of iron below about 2 mg/L.

With continuous regeneration, oxidation is carried out using either chlorine or potassium permanganate. The chlorine or potassium permanganate oxidizes the iron and manganese, turning it from a soluble to an insoluble precipitate that is filtered out by the greensand media. Besides filtering the precipitate, when using potassium permanganate, any excess potassium permanganate is adsorbed onto the greensand and acts to regenerate the media. This allows the greensand to act like a “sponge,” soaking up any excess potassium permanganate and providing oxidation in times when the dosage of potassium permanganate is insufficient to oxidize all of the iron and manganese. In this process, issues involving organic complexes of iron and manganese are addressed through the addition of a cationic polymer. However, when chlorine is used as an oxidant, a free chlorine residual must be maintained in the influent to the filter. The use of chlorine as an oxidant should be carefully considered due to the potential to form DBPs. In addition, the slower reaction times of chlorine, when compared to potassium permanganate, can result in inadequate removals of the contaminants.

In the continuous regeneration process, the filter is backwashed after a differential pressure of 6 psi is reached or when levels of iron or manganese begin to increase in the filter effluent. Differential pressures greater than 6 psi should be avoided due to the potential to fracture the surface coating of manganese dioxide on the individual media grains. Other media are available such as GreensandPlus™ or pyrolusite that can be used to withstand much higher differential pressures.

Air scour should be used for auxiliary agitation of the greensand media prior to backwash. The use of air scour enhances the removal of contaminants as well as improves the length of filter runs and the useful life of the media. Surface wash is another method of providing auxiliary agitation of the media. However, it should be noted that surface wash only agitates the surface of the media, whereas air scour agitates the entire bed throughout its depth.

In direct filtration, arsenic removal can be accomplished using coprecipitation as well. This process is limited to lower concentrations of arsenic because of the lack of a sedimentation process prior to filtration. Large amounts of precipitated materials will clog a filter quickly. The ability of the floc to withstand the hydraulic shear is also an important parameter because precipitated iron can breakup in the filter and pass through carrying the attached arsenic with it. As a result, ferric chloride is used if supplemental iron is needed for arsenic adsorption because it can form a strong filterable floc.

Fixed Bed Adsorption

In a fixed bed adsorption process, the media is used to remove the contaminants. Adsorbents include hydrous metal oxides such as activated alumina, iron, or manganese. The removal of a number of contaminants is possible with these processes. However, the following discussion will focus on the removal of the more common contaminants such as iron, manganese, and arsenic.

Iron and Manganese Removal

Greensand is coated with manganese dioxide. Greensand can be used as a fixed bed adsorption media when operated in an intermittent regeneration mode. The intermittent regeneration greensand process is limited to water containing relatively low levels of iron and when manganese removal is the primary objective. In this process, the filter is backwashed to remove accumulated contaminants and then soaked in 100 mg/L of chlorine or 60 grams of potassium permanganate per cubic foot of media for a prescribed period of time. The filter is then rinsed and placed back into operation. The length of the filter run is based on a set volume of water, which is determined based on the concentrations of contaminants present in the source water.

Arsenic Removal

Iron oxide media can be used to remove arsenic from water in a fixed bed adsorption mode. Unlike greensand, though, the media is typically not regenerated. The spent media is simply discarded, and fresh media is loaded into the vessel. Other media-like activated alumina can be used as well; however, the iron-based medias have removal capacities greater than activated alumina and also have a wider range of optimum pH levels. The adsorptive capacity of the iron-based media is affected by pH, although it is not as sensitive to pH as activated alumina. The optimum pH level for activated alumina is 5.5, compared to iron-based media that has an optimum pH range of 5.5 to 8.5. Other required water quality parameters are detailed by the manufacturers of the media. The amount of water that can be treated before the media is replaced depends on the concentration of contaminants in the source water and the amount of other competing contaminants that are present. Estimates of the volume of water that can be treated per bed change out may be provided by the media supplier. Actual performance should be determined in the field through pilot testing before a commitment is made to select this process for full-scale implementation.

Specialized Water Treatment Processes

Specialized treatment systems include those that can apply to either groundwater or surface water. They address areas such as hardness, taste and odor, fluoridation, corrosion control, and processes specific to cold regions such as heating the raw water to improve treatment.

Hardness Treatment

Hardness is most often associated with groundwater supplies. However, it can also be a problem in some surface water sources. Hardness results from calcium (Ca) and magnesium (Mg) ions. The amount of hardness in water is expressed as an equivalent amount of **calcium carbonate**[85] ($CaCO_3$). This means that regardless of the amount of the various components that make up hardness, they can be related to a specific amount of calcium carbonate.

The objection of customers to hardness is often dependent on the amount of hardness that they are used to. A person who routinely uses water with a hardness of 20 mg/L might think that a hardness of 100 mg/L is too much. On the other hand, a person who uses water with a hardness of 200 mg/L might think that 100 mg/L is very soft.

The following table provides common classifications of hardness:

Classification	mg/L CaCO3
Soft	0 - 75
Moderately Hard	75 - 150
Hard	150 - 300
Very Hard	Over 300

There are two common methods used to reduce hardness: the lime-soda ash process and **ion exchange**[86]. Because the lime-soda process is applicable only to larger facilities, it will not be discussed here.

Ion exchange is accomplished by charging a resin with sodium ions and allowing the resin to exchange the sodium ions for calcium and/or magnesium ions. Common resins include synthetic zeolite and polystyrene resins. These resins are placed in a pressure vessel. A salt brine (NaCl) is flushed through the resins. The sodium ions in the salt brine attach to the resin. The resin is then said to be charged. Water is passed through the charged resin; and the resin exchanges the sodium ions attached to the resin for calcium and magnesium ions, thus removing them from the water. After a specified period of time, the resin is regenerated using a brine solution, and the calcium and magnesium ions are flushed out of the system.

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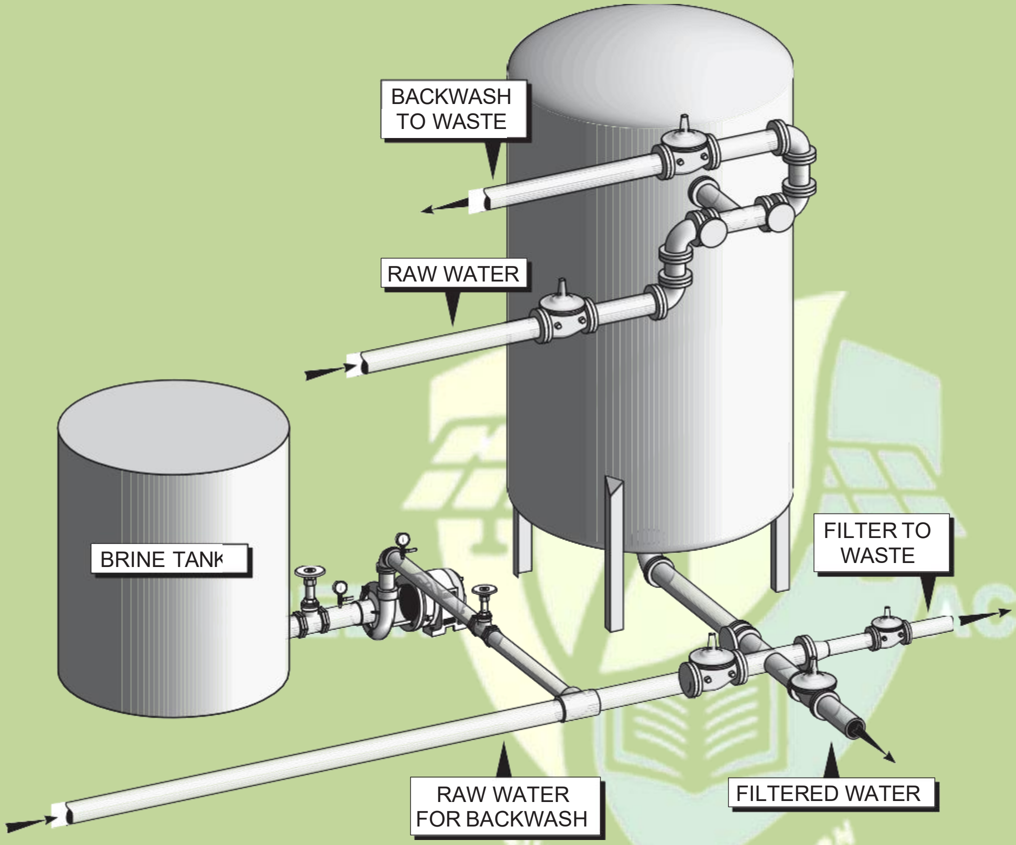
[85] Calcium Carbonate - The principle compound of hardness.The term used as an equivalent for hardness and alkalinity. Symbolically represented as $CaCO_3$.

[86] Ion Exchange - A reversible chemical reaction between an insoluble solid and a solution during which ions may be interchanged.

The ion exchange process of **softening**[87] water removes all or nearly all of the hardness and adds sodium ions to the water. One of the results is the water may become more corrosive than before. Another concern is that addition of sodium ions to the water may increase the health risk of those with high blood pressure.

The ion exchange process is used in small systems where lime soda ash systems are not practical. This process is also used to produce soft water for making calcium hypochlorite solutions and for package saturators.



Ion exchange system

Taste and Odor Treatment

Taste and odor can be caused by a wide variety of constituents. Among them are biological slimes on the inside of pipes and well screens, algae, diatoms, chemicals, and minerals in the water. Taste and odor do not directly represent a health hazard, but they can cause the customer to seek water that tastes and smells good, but may not be safe to drink. Therefore, taste and odor has a secondary MCL of 3 TON (Threshold of Odor Number).

One of the common methods used to remove taste and odor is to oxidize the materials that cause the problem. Oxidants such as chlorine, ozone, or potassium permanganate are commonly used. The main problem with using chlorine for this task is that disinfection by-products can be formed if organic contaminants are present.

Another common treatment method is to use an adsorption process such as granular activated carbon (GAC). The use of these types of systems is discussed the section on Organic Adsorption and Granular Activated Carbon Contactors. Pilot testing should be conducted before this method of treatment is selected.

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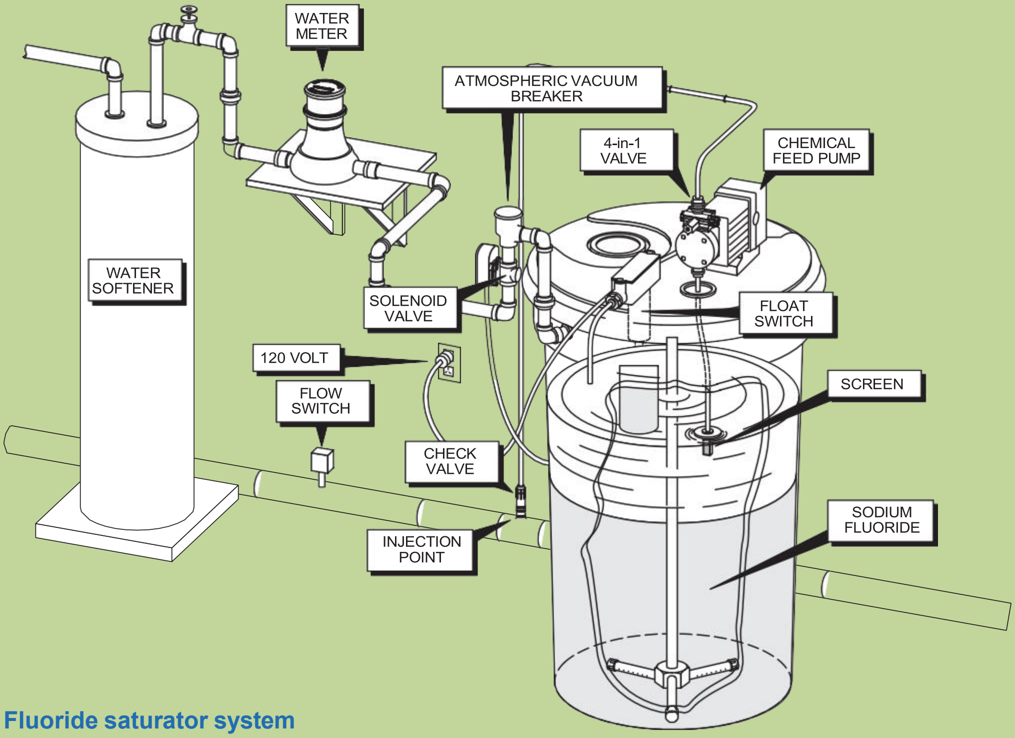
[87] Softening - The process of control or destruction of hardness.

Fluoridation

In certain populations in the Midwestern portion of the United States, it was discovered that those that drank water with natural levels of fluoride above 1 mg/L had drastically reduced occurrence of tooth decay from what was normal. As a result of this research, many communities have decided to artificially control the fluoride level in their drinking water by adding fluoride. However, increased levels of fluoride can cause a disease called fluorosis. The most common symptom is spotting of the teeth (brown spots). Therefore, a secondary limit of 2.0 mg/L has been established to prevent this problem from occurring. A primary MCL of 4.0 mg/L has also be established for fluoride. Exceeding this level can cause skeletal fluorosis, which is a deterioration of the bones. Fluoride is the only chemical that has both a secondary MCL (SMCL) and a primary MCL.

Fluoride is added to drinking water systems to reduce tooth decay. Fluoridation is effective for children up to the age of eight to 10 years of age. The process used in most of Alaska is to mix a four percent solution of sodium fluoride and feed it into the water system. The amount that is fed depends on the air temperature and on the natural fluoride levels in the raw water. The goal is to feed enough fluoride to maintain a residual of 0.8 to 1.2 mg/L.



Fluoride saturator system

There are numerous methods available to feed fluoride into a system. In rural Alaska, the most common fluoride feed system is the upflow saturator. The system uses a 50-gallon plastic tank. Sodium fluoride is placed in the tank, and the tank is filled with clean water. The solution above the fluoride crystals will become saturated with sodium fluoride at four percent (40,000 mg/L). The fluoride solution is then injected into the water system using a chemical feed pump.

The water level in the tank is maintained by a float and solenoid valve control system. The amount of water used is determined by a water meter on the water supply. Backsiphonage into the water system is prevented by a vacuum breaker on the water supply line to the saturator. A screen, float, and foot valve are placed on the suction line to the pump. To prevent water from flooding the feed tank, a check valve is installed on the discharge line where the pump discharge tubing connects to the water system.

Safety Equipment

To prevent the accidental overdose of fluoride, special safety features are built into the fluoride system:

- Wiring the fluoride feeder so that it can obtain power only when the system pump is operating.
- Placing a special plug on the fluoride feed pump electrical cord so that it cannot be plugged into any outlet other than the one that is controlled by the pumping system or flow switch.
- Placing a flow indicator in the system flow line and wiring this flow indicator so that flow must pass through the line before the fluoride feed pump can be energized.
- Installing a special valve, called a four-function valve, on the feed pump to prevent a sudden drop in system pressure from siphoning the contents of the saturator into the system.

Corrosion Control

The causes of corrosion are very complicated and not well understood. Corrosion in potable water systems can cause health-related problems, piping failures, staining and taste issues, and operational problems. Many natural waters can be corrosive. Ironically, very soft, clean water with high dissolved oxygen is desirable as a drinking water. However, this same water is said to be very aggressive. That is, minerals can be easily dissolved into the water. Two contaminants of special concern are lead and copper. Both of these are found in the piping in homes. Aggressive water can cause the levels of lead and copper to increase, representing a potential health hazard. In addition, corrosive water deteriorates the metal components of a water system and thus reduces its useful life. Surface water, such as that found in Southeast and South central Alaska, is known to be **aggressive**[88] and contributes to the blue copper stains often found on white fixtures. This aggressiveness or corrosivity of the water is the basis for the Lead and Copper rule.

Iron bacteria, which are found in most waters, can attach themselves to the walls of pipe and fittings. They form colonies that seal over in little bumps called incrustations. These colonies produce hydrogen sulfide gas that dissolves into the water and forms sulfuric acid. The acid attacks the pipe and fittings causing pits or pinholes to form.

Corrosive waters can cause the cement lining of iron pipe to dissolve into the water, leaving the pipe wall rough and increasing headloss. They can also cause asbestos to leach into the water from asbestos cement (AC) pipe. Aggressive and corrosive waters increase the cost to the customer both directly and indirectly. The customers' water heaters and faucets deteriorate faster than normal. Ultimately, the cost resulting from the deterioration of the water distribution system is shared by all.

The most common means of determining whether water is corrosive is through the use of a corrosivity index such as the Langlier Saturation Index (LSI). The LSI is a means of evaluating water quality data such as pH, total dissolved solids, tempera-

[88] Aggressive - Aggressive waters are those that are high in dissolved oxygen, are neutral to low pH, and have low (below 80 mg/L) alkalinity. These conditions allow water to easily dissolve metals such as iron, copper, and lead.

ture, hardness, and alkalinity to determine whether the water is corrosive. If the LSI is greater than 0, the water is supersaturated and tends to deposit a calcium carbonate scale layer; if the LSI is equal to 0, the water is considered to be in equilibrium and will not precipitate nor dissolve calcium carbonate; and if the LSI is less than 0, the water is undersaturated and tends to dissolve calcium carbonate. An LSI of less than 0 indicates that the water may be corrosive and that corrective action should be considered.

One method used to reduce the corrosive nature of water is to add lime or soda ash to raise the pH to 8.5. In most cases, corrosion control chemicals are fed after other treatment is completed. Most waters are not corrosive once the pH is raised to above 8.5. However, this high pH reduces the disinfection capability of chlorine.

A second method that is available to address corrosion is the use of zinc orthophosphate or polyphosphate. These chemicals coat the inside of the pipelines and protect the pipe materials from the corrosive water. The use of these chemicals involves a balancing act by the operator to not add too much or too little. If too little is added, the corrosion will continue, and if too much is added, the piping can become clogged.

Water Heating Systems

Water systems in the arctic heat their water directly or indirectly to prevent it from freezing and to enhance treatment. Heat may be applied to the water at one or more points in the system. Typical heat addition points include the following:

- Raw water prior to the treatment plant
- Directly after treatment
- In the distribution system loop as water is circulated through the distribution system
- To a heat line that is placed next to a water line in a utilidor

From a treatment perspective, heating the raw water can speed the rate of oxidation or other chemical reactions and can thus ensure that treatment is completed thoroughly within the time that is available prior to the next unit process. The physical aspects of treatment are also impacted by water temperature because of the changes in the density of the water. A change in density affects mixing energy, settling characteristics, and filtration characteristics. Thus treatment processes can be optimized by controlling water temperature. In addition, the rate of disinfection is also impacted by water temperature. In general, increasing water temperature reduces the time required to disinfect the water.

Testing and Reporting

At a properly operated water treatment plant, the following minimum records and data need to be collected:

Water Filtration Systems

1. Turbidity – raw and finished water
2. pH – raw and finished water
3. Alkalinity – raw and finished water
4. Temperature – raw and finished water
5. Amount of chemicals used

6. Chemical dosage
7. Gallons of water produced
8. Length of filter runs
9. Quantity of backwash used
10. Power consumption
11. Hours required for operation and maintenance
12. Cost per 1000 gallons produced

Water Disinfection Systems

1. Disinfectant residual
2. Quantity of disinfectant used
3. Disinfectant dosage
4. Check pump and appurtenances

Water Fluoridation Systems

1. Fluoride residual
2. Quantity of fluoride used
3. Fluoride dosage
4. Check fluoride tank, fill valve, check valve, and anti-siphon protection
5. Check pump and appurtenances

Water Heating Systems

1. Boiler temperature
2. Circulation pump pressure
3. Circulation loop temperature
4. Water temperatures

Additional information on testing your drinking water can be found in Chapter 10.