Fundamentals of Water Purification

By Brian Hagopian, CIPE

Pure water is becoming more important to an increasing number of businesses. More and more contaminants are being found in water supplies, making water purification more difficult and complex. Many industries, particularly the semiconductor, power generation and pharmaceutical industries, are demanding water with greater levels of purity than ever before.

As a result, there is an increasing need for plumbing engineers to be able to properly design water purification systems. Prior to doing this, we all need to understand the nature of the contaminants, or undesirable materials, found in water. We will also learn that the source of the water and the treatment done on a municipal level will determine how difficult a given water source is to purify.

This article is divided into five sections: 1) the contaminants found in water supplies, 2) contaminant variations based on water source, 3) water purification, or contaminant removal processes, 4) how to properly sequence water purification processes into an effective water purification system, and 5) the importance of controls in making the components of a water purification system operate as a synchronized whole. This article will focus primarily on the first three sections, touching only briefly on the final two. The article will conclude by discussing methods of monitoring water purity in order to determine if a system is working properly.

About the Author

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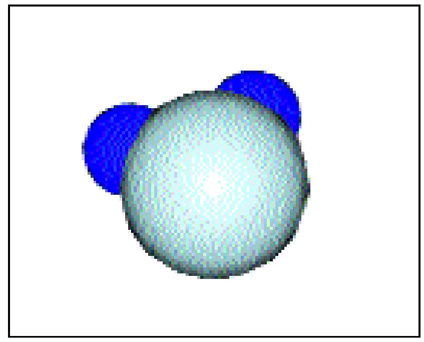
A brief introduction to common terms, technologies and equipment used in the water purification industry.

Water as a chemical

First we must understand the water molecule, which means we have to understand a bit of chemistry. Water is considered the universal solvent. It is a molecule that contains a positive and a negative end. Molecules such as water are called "polar" molecules. This polarity allows water to easily dissolve materials that are also polar. Nonpolar molecules, such as oils, hydrocarbons, etc., are much more difficult to dissolve in water. It is important to remember this when considering water purification processes.

Water also possesses unique properties because of its molecular structure. The polarity of water allows it to line up with itself (positive end to negative end, a chemical property called hydrogen bonding) as well as with other polar molecules. When water freezes, hydrogen bonding effects force water molecules to form a stable structure where its molecules are further apart than when it was in a liquid state. For this reason, ice is lighter than water, which causes it to float. Water is the only molecule that behaves this way. Hydrogen bonding plays an important role in many water purification processes.



In this three-dimensional view of a water moelcule, the end with two hydrogen atoms has a slight positive charge while the end with the oxygen atom has a slight negative charge. That makes this a polar molecule, giving it many of its unique properties.

Contaminants in water supplies

Five basic groups of contaminants are present in water: particles, dissolved salts, organics, colloids, and bacteria.

Particles are suspended solid materials that do not dissolve in water. These materials are silt, dirt, rust, and other suspended matter. If particles are large enough and/or dense enough, they may remove themselves from water by settling out naturally in areas of low flow. If they are smaller and light enough, they will stay suspended in water and must be removed by some mechanical means.

Dissolved salts are compounds that dissolve in water and separate into equal but oppositely charged “ions.” Table salt, or sodium chloride, is an example of a dissolved salt. Because charged ions conduct electricity, the dissolved salt content can be determined by measuring the conductivity of the solution.

Organics are materials that contain carbon. Many of these materials carry little, if any electrical charge, so their presence may be more difficult to detect. Sugar is an example of an organic molecule. Man-made organic chemicals are mostly small molecules that can dissolve in water. As the size of organics increases, they become more difficult to dissolve.

Colloids refer to organics which are much larger in size. These materials are typically the products of natural decomposition processes. Colloids tend to carry a slight negative charge, which causes them to repel each other like two south poles of a magnet. Although they do not readily dissolve in the water, they repel each other and form a stable suspension in water. Colloids represent one of the most difficult group of contaminants to remove from water.

Bacteria are living organisms present in water supplies. Although most are benign, some are harmful. Bacteria can grow and proliferate in pure water systems because the chemicals used to hold them in check are usually removed early in the water purification process. The presence of living bacteria also means there will be dead bacteria, along their decomposition products, in water systems.

The importance of water sources

Water sources determine the amount and type of contaminants that a water purification system will have to be designed to handle. Water travels through several states in its cycle through our environment. Water exists as water vapor, in the form of clouds, condenses to rain, flows through the ground, travels to us for use, flows through municipal treatment plants, flows into the ocean and evaporates into water vapor to complete the cycle. Water is in its purest state when it exists as water vapor. Once it condenses into rain, it begins to pick up contaminants, dissolving small bits of everything it comes into contact with.

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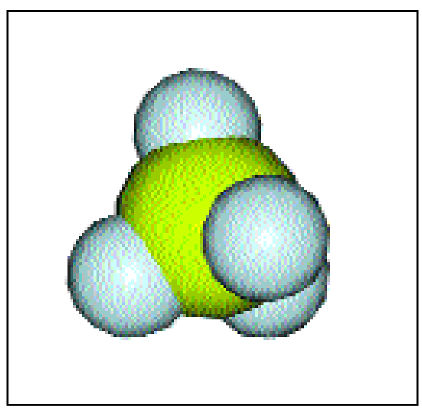
Surface water supplies. If water becomes part of a surface reservoir or river water supply, the water will come into contact with topsoil and naturally occurring vegetation. Consequently, waters from surface supplies typically contain low levels of dissolved minerals and higher levels of particulate, organic and colloidal contaminants. Surface waters may contain higher levels of a particular contaminant based on local conditions (i.e., nitrates from fertilizer runoff).

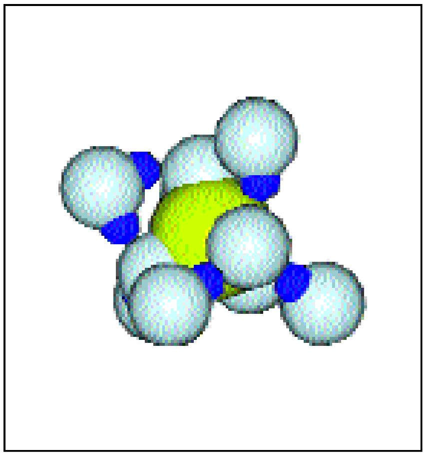
Well water supplies. If water has to travel 500 feet into the ground to become part of a municipal well water supply, it will dissolve a lot of the minerals that it encounters on the way. Waters from deep well supplies have been in contact with the ground for a longer period of time and typically contain higher levels of the dissolved minerals. Calcium and magnesium salts, which represent the hardness minerals, can be found in high concentrations in deep well waters. Hardness minerals can be easily converted to less soluble compounds with the addition of heat, leading to precipitation and scale formation.

Water is in its purest state when it exists as water vapor.

Hardness represents a major problem where water temperature needs to be raised, or where some water purification processes are employed. Deep well waters may also contain high levels of dissolved iron salts. Iron is particularly troublesome because it exists in two different states. Ferrous iron (Fe^{+2}) is found in some well waters and imparts a metallic taste to the water, but does not discolor it. After exposure to air, or another oxidant, it is converted to ferric (Fe^{+3}) iron, or rust, which is insoluble and precipitates from the water. Deep well waters are more highly filtered, containing lower levels of particles when compared to surface water supplies. Deep well waters spend little time at the surface of the earth, and contain



The sulfate (SO4-2) ion represented here consists of four oxygen atoms arranged at the points of a tetrahedron around a sulfur atom. Logic would indicate that, with a molecular weight of 96, such a molecule might be too small to be removed by reverse osmosis.



Here the same sulfate ion is shown as it would appear in a water solution. The positive ends of the water molecule surround the sulfate ion, increasing its size and making it much easier for reverse osmosis to remove. In fact, sulfate ions are removed very effectively by reverse osmosis.

lower levels of organics and colloidal materials than surface waters. All of these factors play an important role in determining the optimum water purification system for a particular need.

A responsible water system designer will begin with a water analysis, which will indicate the types and abundance of various contaminants. In addition to the standard laboratory tests, a test for colloids (such as a silt density index test) and total organic carbon is highly recommended.

Contaminant removal technologies

Many contaminants found in water can be described based on their size. Beginning at the periodic table, every element has an atomic weight, which is based on its number of protons and electrons. When combined with other elements to form molecules, each is described by its molecular weight. As molecules increase in size, their molecular weight increases and they become harder to dissolve in water. When they become large enough, they are described by their "micron" size (25 microns = 1/1000 in.). Materials this large are usually insoluble in water and exist as "suspended" solids.

Particle filters remove particles larger than the pore size of a filter. In other words, if a particle is larger than the pore size of the filter, it will not be able to pass through the filter. There are many different types of particle filters, some of which use disposable filter media, while others use permanent media. As water flow increases, or when particle loading is high, the use of a backwashing sand, multimedia or other permanent filter media is recommended over disposable particle filters.

A simple way to classify particle filters is by the size of the particles they remove. It is important to understand that filtering smaller particles usually requires more driving force (pressure). It is also important to note that filters remove a certain percentage of particles at a given particle size, and the percentage removed is usually related to the price of the filter.

Beginning at the coarse end of the particle spectrum are *coarse particle filters*, which remove suspended solids that are visible to the naked eye. Visible particles are roughly 25 microns and larger in size. Filters used for this purpose include disposable cartridge filters, bag filters, permanent backwashing media filters and a host of other filters beyond the scope of this article.

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Absolute membrane filters represent the next step down the particle filtration spectrum. These filters can remove particles down to 0.1 micron in size, including bacteria. Absolute membrane filters are widely used in water purification and also are used to filter sterile pharmaceutical solutions.

Ultrafiltration (UF) represents the next step in the particle filtration spectrum. The particle removal ratings of ultrafilters can be described by a particle size expressed in microns, or a molecular weight cutoff (MWCO), which describes the size of molecules that are removed. From the perspective of water purification, UF membranes are capable of removing colloids along with bacterial decomposition products and are used primarily for these purposes. UF membranes also represent the first filtration process in this spectrum capable of removing materials that are dissolved in water.

Reverse osmosis (RO) represents the finest step in the particle filtration spectrum. RO membranes have particle removal ratings ranging from 100-500 MWCO. These filter membranes are capable of removing nearly all organics and most of the dissolved salts from water. RO represents one of the most powerful water purification technologies available. Residential RO systems operate on incoming city water pressure, whereas industrial units use high pressure pumps to operate at pressures ranging from 150 to 1,000 psi.

As an example, those familiar with RO membranes know that they are capable of removing 90-99 percent of all dissolved sodium from the water supply. Sodium has an atomic weight of 23, which is much smaller than the pore size of RO membranes. There are a number of theories that describe the removal mechanisms for sodium and other molecules, but one of the easiest to understand is to consider the hydrogen bonding properties of water. Sodium, containing a single positive charge, and when in solution, attracts a number of water molecules, which align themselves around the sodium molecule. During any given instant, the number of water molecules aligned around the sodium molecule can change because water is a liquid and its molecules are in constant motion. Increasing the number of water molecules aligned around the sodium molecule increases the "apparent size" of the sodium molecule when it comes into contact with a RO membrane, thereby decreasing its probability of passing through the RO membrane. But, because the number of water molecules surrounding the sodium is constantly changing, some sodium molecules will pass through the RO membrane.

As it turns out, the size of the molecule, coupled with its charge, determine the "apparent size" of the molecule to a RO membrane. Molecules with a higher atomic weight and a greater charge when dissolved in water will be removed with great efficiency.

Hydrogen bonding also explains the penetration of RO membranes by small, nonpolar organic molecules. These molecules do not hydrogen bond with water, so their size does not increase, and their removal efficiency can be much more easily predicted based on molecular weight.

Other purification processes

Many other water purification processes exist, which do not completely rely on size as the primary method removing contaminants. Other properties such as charge, polarity, and molecular structure play roles in their removal from water. Some of the more common processes are described below.

The contaminants present in the water and the desired level of water purity determine the overall system design.

Carbon filters use the fine pore structure of activated carbon to remove small dissolved organic and other contaminants. Carbon filters also remove the disinfectants added to drinking water supplies to control bacteria, so careful placement of carbon filters is essential to the water purification process. Carbon filters work very well to complement RO because they remove the small organic contaminants that can pass through RO membranes.

Ultraviolet disinfection processes are used to control bacteria without using disinfecting chemicals. UV units are typically used after disinfectants are removed to control bacterial activity in a pure water system. UV radiation penetrates the cell walls of bacteria and prevents them from replicating.

TOC reducing ultraviolet disinfection processes are similar to the UV units covered above, but also emit a smaller wavelength (higher energy) of light which can be used to control organic and colloidal levels in a water purification system.

Deionization (DI) processes use inert and insoluble materials, called ion exchange resins, to remove dissolved salts from water based on their electrical charge. Two different types of resins — cation and anion resins — are used to achieve high purity water. The two most commonly used DI processes are dual bed and mixed bed deionizers. Dual bed DI uses two separate vessels, one for each of the two different DI resins. Mixed bed deionizers use a single vessel containing a mixture of cation and anion resins in order to achieve higher purity levels. DI is typically used after reverse osmosis (RO) to remove the trace dissolved salts that pass through the RO membranes.

Water softeners are commonly used in water treatment. Softeners are actually the cation portion of a deionizer, in a different (sodium) form, used to remove hardness minerals, such as calcium and magnesium, and replace them with sodium, a more readily dissolved and less scale producing mineral. This information is summarized in Table 1.

Putting it all together

There are general guidelines which are employed to put water purification processes into their correct sequence. The contaminants present in the water and the desired level of water purity determine the overall system design. Some contaminants interfere with the removal of other contaminants, so these need to be removed first.

Generally speaking, suspended materials are considered the most undesirable and are usually removed in the first steps of a water purification system. Particle filters are usually the first treatment process in a water purification system. The particles removed at this stage protect the downstream equipment. Water softeners and carbon filters typically appear next. Processes used for removing colloids should be employed here, if required, including UF or RO systems. If either of these processes are used, a storage tank is usually used to store the purified water, and pumps are added to circulate the water.

Once suspended solids are removed, the remaining contaminants may be removed with greater ease. DI processes are used next in order to remove any remaining dissolved salts. UV units, TOC reducing units, and absolute membrane filters typically follow in sequence to destroy and remove bacteria and fine particles from the water.

Control systems

While a detailed discussion of control systems is beyond the scope of this article, plumbing engineers must understand their importance. Control systems allow the various functions of a number of different devices to be integrated in a way that permits the entire system to operate as a coordinated whole. As examples, controls are needed to turn pumps on and off to fill storage tanks, to alert operators if the system is producing low quality, to report information to a central control center, and various other reasons.

The design of control systems typically is left up to the water system vendor, and the plumbing engineer has had very little say in how the controls actually operate. The net result is a vast array of widely varying control systems. At one end of the spectrum, they perform minimal control functions. At the other end, they appear so comprehensive they are too complicated to understand. Many control systems are user friendly only to the water system vendor technicians

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and not to the end user, who ultimately has to operate the system.

Because many water system vendors use similar components, it is often the control systems that separate one vendor from another. Vendors have different concepts of what is a necessary control function, and control functions will vary from one industry to the next. With a written specification that focuses on equipment with little emphasis on controls, vendors can provide minimum controls to become the successful (low) bidder on a project. The plumbing engineer, typically involved in the project only until construction is completed, may never know a substandard control system has been installed. These deficiencies typically manifest themselves after the plumbing engineer is gone, leaving the end user dissatisfied.

Testing the waters

Water testing is an important part of the picture. Testing is important before the system is designed, to alert the plumbing engineer to any unique local conditions which must be treated. After the system is installed, a comprehensive testing program should be implemented to verify the system is operating properly.

Most testing is performed at the use points in the system, after all steps of water purification, to determine if the water quality meets a certain specification, which varies from industry to industry and client to client. This type of testing is a pass/fail program, intended to determine if the water quality is good enough to use for operations. There is a flaw with this type of testing, which is explained in the example which follows. When a failed test occurs, the end user is usually at a loss as to where to look for the problem. As panic sets in, the water system vendor may receive several threatening phone calls requesting immediate action. Without information, everyone has to make assumptions. At that point, everything that can be changed usually is changed, and the problem may go away. The biggest problem with these events is that nobody really understands why the water failed its test and the end user may have spent much more money than necessary.

It is entirely possible these events could have been prevented by testing the performance of unit processes throughout the system. This helps in developing a profile on the system. End users may use this information to understand where the various contaminants are removed in their system, and can track results and watch for trends. Typically, trends indicate when contaminant levels are increasing, and allow for preventive actions to occur prior to the water going out of specification.

Some contaminants interfere with the removal of other contaminants, so these need to be removed first.

Summary

This article provides a brief introduction to common terms, technologies and equipment used in the water purification industry. It is important to understand that these explanations are generalized and are not intended to cover all technologies or conditions that may be present in a given application. □

Table 1 - Removal Capabilities of Various Water Purification Processes

	Coarse Particle Filters	Absolute Membrane Filters	Ultrafilters	Reverse Osmosis	Carbon Filtration	Ultraviolet Disinfection	Deionization
Particles	F	G-E	E	E	N	N	N
Dissolved Ions	N	N	N	G-E	N	N	E
Small Organics	N	N	N	F-G	G-E	N	P
Colloids	N	F-P	G-E	E	P-F	N	P
Bacteria	P	E	E	E	A	G	A-P

N = None P = Poor F = Fair G = Good E = Excellent A = Adds contaminants to systems