1.10: Membrane Filtration

Learning Objectives

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

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

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

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

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

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

Description of Membrane Filtration Units

Pressure Vessel or Submerged Flow

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

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

Membrane Flow Types

Two different types of membrane filtration feed water flows exist:

- Cross-flow filtration systems
- Dead-end filtration systems

![Cross-flow filtration system](https://workforce.libretexts.org/Bookshelves/Water_Systems_Technology/Water_151%3A_Water_Treatment_Plant_and_Ope…) Figure 1: Cross-flow filtration system – Image by AD and Benutzer:Mæx is in the public domain

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

![Image of dead-end filtration system](https://workforce.libretexts.org/Bookshelves/Water_Systems_Technology/Water_151%3A_Water_Treatment_Plan...)

**Figure \(\PageIndex{2}\): Dead-end filtration system – Image by Alexdruz and Mæx is in the public domain**

### Membrane Fouling

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

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

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

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

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

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

**Experiences**

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

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

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

**Membrane Performance Monitoring**

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

**Reverse Osmosis Membrane Structure and Composition**

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

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

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

Membrane Performance and Properties

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

- \( F_w = A(ΔP – Δπ) \) where...
  - \( F_w \) = Water flux (g/cm\(^2\) sec)
  - \( A \) = Water permeability constant (g/cm\(^2\) sec atm\(^{-1}\))
  - \( ΔP \) = Pressure differential applied across the membrane (atm)
  - \( Δπ \) = Osmotic pressure differential across the membrane (atm)

Note that the water flux is the flow of water in grams per second through a membrane area of one square centimeter. Think of this flow as similar to the flow through a rapid sand filter in gallons per minute through a filter area of one square foot (GPM/ft\(^2\)).

The mineral (salt) flux (mineral passage) through the membrane can be expressed:

- \( F_w = B(C_1 – C_2) \) where...
  - \( F_w \) = Mineral flux (g/cm\(^2\) sec)
  - \( B \) = Mineral permeability constant (cm/sec)
  - \( C_1 – C_2 \) = Concentration gradient across the membrane (g/cm\(^2\))

The water permeability (A) and mineral permeability (B) constants are characteristics of the particular membrane that is used and the processing it has received.

An examination of the equations demonstrates that the water flux, which is the rate of flow through the membrane, is dependent on the applied pressure, while the mineral flux is not dependent on pressure. As the pressure of the feed water is increased, the flow of water through the membrane increases while the flow of mineral remains constant. Therefore, the quantity and the quality of the purified product (permeate) should increase with increased pressure. This result occurs because more water is present to dilute the same amount of mineral.

The water flux \((F_w)\) decreases as the mineral content of the feed increases because the osmotic pressure contribution \((Δπ)\) increases with increasing mineral content. Since \(Δπ\) increases, the term \((ΔP – Δπ)\) decreases, which results in a decrease in \(F_w\), the water flux. As more and more feed water passes through the membrane, the mineral content of the feed water becomes higher and higher (more concentrated). The osmotic pressure contribution \((Δπ)\) of the concentrate increases, resulting in a lower water flux.

Since the membrane rejects a constant percentage of mineral, product water quality decreases with increased feed water concentration. Also, note that Equation 2 reveals that the greater the concentration gradient \((C_1 – C_2)\) across the membrane, the greater the mineral flux (mineral flow). Therefore, the greater the feed concentration, the greater the mineral flux and mineral concentration in the product water.
Water treatment plant operators must have a basic understanding of the mathematical relationships that describes RO (reverse osmosis) membrane performance.

**Definition of Flux**

The term flux is used to describe the rate of water flow through a semipermeable membrane. Flux is usually expressed in gallons per day per square foot of membrane surface or in grams per second per square centimeter.

The average membrane flux rate of a reverse osmosis system is an important operating guideline. In practice, most reverse osmosis systems will require periodic cleaning. It has been demonstrated that the cleaning frequency can be dependent on the average membrane flux rate of the system. Too high a flux rate may result in excessive fouling rates requiring frequent cleaning. Some industry guidelines for acceptable flux rates are:

<table>
<thead>
<tr>
<th>Feed Water Source</th>
<th>Flux Rate, GFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial/Municipal Waste</td>
<td>8-12</td>
</tr>
<tr>
<td>Surface (river, lake, ocean)</td>
<td>8-14</td>
</tr>
<tr>
<td>Well</td>
<td>14-20</td>
</tr>
</tbody>
</table>

**Mineral Rejection**

The purpose of demineralization is to separate minerals from water: the ability of the membrane to reject minerals is called the mineral rejection. Mineral rejection is defined as:

- Rejection, % = (1 - (Product Concentration/Feed Water Concentration)) x 100%

Mineral rejections may be calculated for individual constituents in the solution by using their concentrations.

The basic equations that describe the performance of a reverse osmosis membrane indicate that rejection decreases as the feed water mineral concentration increases, because the higher mineral concentration increases the osmotic...
pressure. Also as the feed mineral concentration increase (TDS) rejection decreases at a given feed pressure. Rejection improves as feed pressure increases.

Typical rejection for most commonly encountered dissolved inorganics is usually between 92 and 99-percent. Divalent ions such as calcium and sulfate are better rejected than monovalent ions such as sodium or chloride.

Most demineralization applications require the use of a membrane with high rejection rates (greater than 95-percent). However, some applications can use a membrane with lower rejection rates (80-percent) and lower operating pressures (less than 150 psi). The membranes that fit this classification are commonly referred to as softening or nanofiltration membranes. These membranes produce the same quantity of water as standard RO membranes at lower operating pressures.

Softening or nanofiltration membranes are seeing widespread use for demineralization of municipal water supplies that require high rejection rates for hardness and THM formation potential, and moderate TSD rejection.

**Effects of Feed Water Temperature and pH on Membrane Performance**

In reverse osmosis operation, feed water temperature has a significant effect on membrane performance and must therefore be taken into account in system design and operation. Essentially, the value of the water permeation constant is only constant for a given temperature. As the temperature of the feed water increases, the flux increases. Usually, flux is reported at some standard temperature reference condition, such as 25°C.

Cellulose acetate membranes are subject to long-term hydrolysis. Hydrolysis results in a lessening of mineral rejection capability. The rate of hydrolysis is accelerated by increased temperature, and is a function of feed pH. Slightly acidic pH values ensure a lower hydrolysis rate, as do cooler temperatures. Therefore, to ensure the longest possible lifetime of the cellulose acetate membrane and to slow hydrolysis, acid is added as a pretreatment step before demineralization. Thin film composite membranes are not subject to hydrolysis; however, pH adjustments of feed water may be required for scale control.

**Recovery**

Recovery is defined as the percentage of feed flow that is recovered as product water. Expressed mathematically, recovery can be determined by:

- \[ \text{Recovery, } \% = \left( \frac{\text{Product Flow}}{\text{Feed Flow}} \right) \times 100\% \]

The recovery rate is usually determined or limited by two considerations. The first is the desired product water quality. Since the amount of mineral passing through the membrane is influenced by the concentration differential between the brine and product, excessive recovery can lead to exceeding product quality criteria. The second consideration concerns the solubility limits of minerals in the brine. One should not concentrate the brine to a degree that would precipitate minerals on the membrane. This effect is commonly referred to as concentration polarization.

The most common and serious problem resulting from concentration polarization is the increasing tendency for precipitation of sparingly soluble salts and the deposition of particulate matter on the membrane surface.
In any flowing hydraulic system, the fluid near a solid surface travels more slowly than the main stream of the fluid. A liquid boundary exists at the solid surface, and this phenomenon is true at the surface of the membrane in a spiral wound element or in any other membrane packaging configuration. Since water is transmitted through the membrane at a much more rapid rate than minerals, the concentration of the minerals builds up in the boundary layer (concentration polarization), and it is necessary for the minerals to diffuse back into the flowing stream. Polarization will reduce the flux and rejection of a reverse osmosis system. Since it is impractical to totally eliminate the polarization effect, it is necessary to minimize it through good design and operation.

The boundary layer effect can be minimized by increased water flow velocity and by promoting turbulence within the RO elements. Brine flow rates can be kept high as product water is removed by staging (reducing) the module pressure vessels. This design is popularly referred to as a Christmas tree arrangement. Typical flow arrangements such as 4 units- 2 units- 1 unit (85-percent recovery) or 2 units -1 unit (75-percent recovery) are used most often.

These configurations consist of feeding water to a series of pressure vessels in parallel where about 50-percent of the water is separated by the membrane as product water and 50-percent of the water is rejected. The reject is fed to half as many vessels in parallel where again about 50-percent is product water and 50-percent is reject. The reject becomes the feed for the next set of vessels. By arranging the pressure vessels in the 4-2-1 arrangement, it is possible to recover over 85-percent of the feed water as product water and to maintain adequate flow rates across the membrane surface to minimize polarization.

Components of a Reverse Osmosis Unit

Pumps

Pressurization Pump

The pressures required for RO can range from 100 to 1,200 psi. Typically, the pressure ranges can be broken down as:

<table>
<thead>
<tr>
<th>Application</th>
<th>Pressure Range (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softening</td>
<td>100-200</td>
</tr>
<tr>
<td>Brackish</td>
<td>200-500</td>
</tr>
<tr>
<td>Brackish/Seawater Mixture, Industrial Concentrating</td>
<td>500-800</td>
</tr>
<tr>
<td>Seawater</td>
<td>800-1,200</td>
</tr>
</tbody>
</table>

https://workforce.libretexts.org/Bookshelves/Water_Systems_Technology/Water_151%3A_Water_Treatment_Plan...
Two basic types of pumps are used for pressurizing the feed water: centrifugal and positive displacement. Important characteristics of each type of pump relating to its use in RO applications are listed:

### Centrifugal Pumps

1. Typically used for applications less than 500 psi
2. Most cost-effective for applications below 500 psi
3. Single impellers geared to operate higher than motor speed create excessive noise
4. Multistage centrifugal pumps are more costly to operate than single-stage pumps but more efficient

### Positive Displacement Pumps

1. Typically used for applications greater than 500 psi
2. Very efficient for seawater (800-1,200 psi)
3. Flow pulsations require use of pulsation dampener for velocities greater than 2FPS (feet per second)

The output of a centrifugal pump may be throttled by use of a multi-turn throttling valve. Throttling valves are used for new systems, or after a successful membrane cleaning.

The output of a positive displacement pump may not be throttled. The pump discharge line should contain a pressure relief mechanism. Optional items would be a bypass valve to control flow to the membrane section and a pulsation dampener.

Figure 4: RO Water Treatment – Image by Vishalsh521 is licensed under CC BY-SA 3.0

### Piping

The selection of piping material depends on the water salinity and pressure. Seawater reverse osmosis requires the use of high-grade stainless steel for high-pressure lines. The most common types of materials used currently are 316L and 317L, due to their high molybdenum content. Brackish water plants typically use 304 and 316 stainless steel.
Low-pressure piping is typically made of polyvinyl chloride (PVC) or fiber-reinforced plastic/polymer (FRP). Some exotic materials such as 316SS and polyvinylidend fluoride (PVDF) are used in high-purity applications such as for semiconductor rinse water.

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**Pressure Vessel Housings**

Several spiral-wound membrane elements are connected in series and are contained in pressure vessels. For most applications, a maximum of six 40-inch-long spiral-wound elements are contained in a single vessel. Due to improvements in the hydraulics of the spiral-wound design, seven 40-inch-long elements have been placed in one vessel. The standard material of construction is fiber-reinforced plastic/polymer (FRP). The pressure vessels are available in 200, 400, 600, 1,000, and 1,200 psi ratings. Some manufacturers can provide vessels constructed and stamped according to ASME Code-Section X.

Hollow fiber bundles are packaged in individual fiber glass housings. For seawater desalination, these housings can be rated up to 1,200 psi.

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**Concentrate Control Valve**

A regulating valve located in the concentrate line provides a means of applying a back pressure to the membrane. Positioning this valve in conjunction with the pump discharge valve (bypass valve for positive displacement pumps) will set the concentrate and permeate flow rates.

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**Sample Valves**

Sample valves should be located on the feed, permeate, and concentrate lines. Locations should be such that samples can be taken during all modes of operation such as servicing, flushing, cleaning, and rinsing. Sample valves should also be located in the permeate line of each permeator or pressure vessel.

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**Flush Connections**

Provisions should be made for flushing the unit for certain applications. Examples would be seawater or brackish water with high organic content. The flush water could be acidified feed or permeate. If permeate is used, a separate inlet would be required. For all units that require flushing, a separate outlet in the concentrate line upstream of the concentrate control valve should be provided. The concentrate control valve would restrict flush flow, which is usually greater than the design concentrate flow.

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**Cleaning Connections**

All units should have cleaning connections for each bank of permeators or pressure vessels connected in parallel. Isolation valves for each bank would allow for one bank to soak while the upstream or downstream bank is being cleaned. On large systems with many vessels or permeators connected in parallel, the cleaning system is sized for...
economic reasons to clean only a portion of the bank. In this case, valves are required to isolate the specific amount of vessels that can be cleaned at one time.

**Permeate Rinse**

It is useful to have provisions for sending permeate from one bank or unit to drain. Some processes require that the permeate achieve quality by rinsing to drain after a shutdown period. Also for certain troubleshooting procedures, poor quality permeate can be directed to drain while individual vessels are checked for poor quality.

**Permeate Drawback Tank**

For seawater applications, a permeate drawback tank may be provided. The purpose of the drawback tank may be provided. The purpose of the drawback tank is to provide a supply of water or an off-line unit that is subject to osmosis. Upon shutdown with removal of applied pressure, reverse osmosis ceases and osmosis begins. During osmosis, flow will occur from permeate to the feed-concentrate side of the membrane. Flushing the feed-concentrate channels with permeate after shutdown should prevent natural osmosis; however, as a precaution, drawback tanks may be provided to prevent dehydration of the membrane.

**Energy Recovery Devices**

Energy recovery devices installed in the high-pressure concentrate line are used in some seawater reverse osmosis plants. The basic principle of operation is the conversion of the potential energy for the high-pressure concentrate into kinetic energy. A nozzle directs the concentrate flow toward a rotor with dished vanes. The flow strikes the vanes and turns the rotor. The shaft of the rotor is connected to a pump that pressurizes the seawater feed. Due to a lack of cost-effectiveness, corrosion problems, and size restrictions, energy recovery turbines of this type have seen limited use.

**Membranes**

Operating plants use the RO principle in several different membrane configurations. Three types of commercially available membrane configurations are used in operating plants. They include spiral wound, hollow fine fiber, and tubular.

The spiral wound RO module was conceived as a method of obtaining a relatively high ratio of membrane area to pressure vessel volume. The membrane is supported on each side of a backing material and sealed with glue on three of the four edges of the laminate. The laminate is also sealed to a central tube that has been drilled to allow the demineralized water to enter. The membrane surfaces are separated by a screen material that acts as a brine spacer. The entire package is rolled into a spiral configuration and wrapped in a cylindrical form. The membrane modules are loaded, end to end, into a pressure vessel. Feed flow is parallel to the central tube while permeated flows through the membrane toward the central tube. Plants using this type of system include brackish water demineralizing plants.

The hollow fiber membrane type is made of aromatic polyamide fibers about the size of a human hair with an inside diameter of about 0.0016-inch. In these very small diameters, fibers can withstand high pressure. In an operating
process, the fibers are placed in a pressure vessel, and one end of each fiber is sealed. The other end protrudes outside
the vessel. The brackish water is under pressure on the outside of the fibers and product water flows inside of the fiber
to the open end. For operating plants, the membrane modules are assembled in a configuration similar to the spiral-
ound unit.

Tubular membrane processes operate on much the same principle as the hollow fine fiber except the tubes are much
larger in diameter, on the order of 0.5-inch. Use of this type of membrane system is usually limited to special situation
such as for wastewater with high suspended solids concentration. The tubular membrane process is not economically
competitive with other available systems for treatment of most water sources.

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**Operation**

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**Pretreatment**

Water to be demineralized contains impurities that should be removed by pretreatment to protect the membrane and to
ensure maximum efficiency of the reverse osmosis process. Depending on the water to be demineralized, it is usually
necessary to treat the feed water to remove materials and conditions potentially harmful to the RO process:

- Remove turbidity/suspended solids
- Adjust pH and temperature
- Remove materials to prevent scaling or fouling
- Disinfect to prevent biological growth

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**Removal of Turbidity and Suspended Solids**

In general, the feed water should be filtered to protect the reverse osmosis system and its accessory equipment. When
the water source is a groundwater or previously treated municipal or industrial supply, this step may be accomplished by
a simple screening procedure. However, such a procedure may not be adequate when the source is untreated surface
water. The amount of suspended matter in surface water may vary by several orders of magnitude and may change
radically in character and composition in a very short time. In such cases, in addition to the mechanical action of the
filter, the operator may have to introduce chemicals for coagulation and flocculation and use filtration equipment in which
the media can be washed or renewed at low cost. Pressure and gravity sand filters and diatomaceous earth filters may
be required, particularly for large installations. When the particulates approach or are colloidal, chemical treatment and
filtration are essential.

Cartridge filters function as a particle safeguard and not as a primary particle removal device. In general, the influent
turbidity to cartridge filters should be less than 1 turbidity unit. Typical cartridge filter sizes range from 5 to 20 microns
and loading rates vary from 2 to 4 GPM/ft3.

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**pH and Temperature Control**

An important limiting factor in the life of cellulose acetate membranes in reverse osmosis is the rate of membrane
hydrolysis. Cellulose acetate will break down to cellulose and acetic acid. The rate at which this hydrolysis occurs is a function of feed water or source water, pH, and temperature. As the membrane hydrolyzes, the amount of water and the amount of solute that permeates the membrane increase and the quality of the product water deteriorates. The rate of hydrolysis is at a minimum at a pH of about 4.7, and it increases with increasing and decreasing pH. It is standard practice to inject acid, usually sulfuric acid, to adjust feed water pH to 5.5. pH adjustments minimize the effect of hydrolysis, and it is also essential in controlling precipitation of scale-forming or membrane-fouling minerals.

Calcium carbonate and calcium sulfate are probably the most common scaling salts encountered in natural water and are certainly the most common cause of scale in reverse osmosis systems. The addition of a small amount of acid can reduce the pH to a point where the alkalinity is reduced. A shift in equilibrium to the point where calcium bicarbonate, which is much more soluble, is present at all points within the reverse osmosis loop. Neutralization of 75 percent of the total alkalinity usually provides sufficient pH adjustment to achieve calcium carbonate scale control and bring the membrane into a reasonable part of the hydrolysis curve. The pH reached by 75 percent neutralization is about 5.7. Calcium carbonate precipitation is also inhibited by the control procedure used for calcium sulfate.

Calcium sulfate is relatively soluble in water in comparison to calcium carbonate. However, as pure or product water is removed from a feed solution containing calcium and sulfate, these chemicals become further concentrated in the feed water. When the limits of saturation are eventually exceeded, precipitation of calcium sulfate will occur. Since calcium sulfate solubility occurs over a wide pH range, the scale control method used to inhibit calcium sulfate precipitation is a threshold treatment with sodium hexametaphosphate. This precipitation inhibitor represses calcium carbonate and calcium sulfate by interfering with the crystal formation process. Other ploy phosphates may also be used; however, they are not as effective as sodium hexametaphosphate. Generally, 2 to 5 mg/L of this chemical is sufficient to decrease precipitation of calcium sulfate.

Other Potential Scalants

The oxides or hydroxides most commonly found in water are iron, manganese, and silica. The oxidized and precipitated forms of iron, manganese, and silica can be a serious problem to any demineralization scheme because they can coat the reverse osmosis membrane with a tenacious film, which will affect performance. The scale inhibitor most frequently used is sodium hexametaphosphate.

Microorganism

Reverse osmosis modules provide a large surface area for the attachment and growth of bacterial slimes and molds. These organisms may cause membrane fouling or module plugging. Evidence exist that occasionally the enzyme systems of some of these organisms will attack the cellulose acetate membrane. Thus a continuous application of chlorine to produce a 1 to 2 mg/L chlorine residual helps to inhibit or retard the growth of most of the organisms encountered. However, caution must be exercised since continuous exposure of the membrane to high chlorine residuals will impair membrane efficiency. Shock concentrations of up to 10 mg/L of chlorine are applied from time to time. When an oxidant-intolerant polyamide-type membrane is used, chlorination must be followed with dechlorination. One of the dechlorination agents, sodium bisulfite, is also known to be a disinfectant. Another disinfection option is the use of ultraviolet light disinfection, which leaves no oxidant residual in the water.
**RO Plant Operation**

Following proper pretreatment, the water to be demineralized is pressurized by high-pressure feed pumps and delivered to the RO pressure vessel membrane assemblies. The membrane assemblies consist of a series of pressure vessels arranged in a Christmas tree layout depending on the desired recovery. Typical operating pressure for brackish water demineralizing varies from 150 to 400 psi. A control valve on the influent manifold regulates the operating pressure. The volumes of feed flow and of product water are also monitored. The demineralized water is usually called permeate, and the reject water is called concentrate (brine). The recovery rate is controlled by increasing feed flow (increasing operating pressure) and by controlling the concentrate (brine) or reject with a preset brine control valve.

The operator must properly maintain and control all flows and recovery rates to avoid possible damage to the membranes from scaling.

Operators must remember that the brine flow valves are never to be fully closed. Should they be accidentally be closed during operation, 100-percent recovery will result in almost certain damage to the membranes due to the precipitation of inorganic salts. Product or permeate flow is not regulated and varies as feed water pressure and temperature change.

Most RO systems are designed to operate automatically and require a minimum of operator attention. However, continuous monitoring of system performance is an important responsibility of the operator of the operational process.

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**Types of Membrane Filtration Processes**

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**Microfiltration (MF)**

Microfiltration membranes have pores ranging from 0.1 to 2.0 microns. This process is less common with waste treatment processes because permeate from a microfilter is generally unacceptable for discharge. In some cases, this membrane process may be used in conjunction with settling agents, polymers, activated carbon, and other chemicals that assist in the retention of waste constituents. When using this membrane, care must be taken to prevent membrane pore blockage by waste streams components through the selection of the proper membrane type for the specific plant.
wastes.

**Ultrafiltration (UF)**

The process of ultrafiltration is the most common membrane-based wastewater treatment process. It uses a membrane with pore sizes ranging from 0.005 to 0.1 micron. Particles larger than the pores in the membrane, such as emulsified oils, metal hydroxides, proteins, starches, and suspended solids, are retained on the feed side of the membrane. Molecules smaller than the pores in the membrane, such as water, alcohols, salts, and sugars pass through the membrane. This filtrate, which is treated water, is often referred to as permeate.

Ultrafiltration membranes are rated on the basis of molecular weight cut-off (MWCO) and range from 1,000 to 500,000 MWCO (daltons). The use of MWCO is only an approximate indication of membrane retention capabilities and should be used with guidance of the membrane manufacturer.

**Nanofiltration (NF)**

Nanofiltration uses a membrane pore size between UF and RO. These membranes are effective in removing salts from a waste stream by allowing them to pass into the permeate while concentrating other components such as sugars, nitrogen components, and other waste constituents causing high BOD/COD in waste streams.

**Reverse Osmosis (RO)**

Reverse osmosis is the tightest membrane process in that it allows only water to pass through the membrane, retaining salts and higher molecular weight components. RO membranes are used for tertiary treatment producing water with low BOD/COD and of near-potable water quality. RO permeate may be recycled throughout the plant and reused for various plant processes. RO is normally used as a post-treatment process following coarser filtration processes such as ultrafiltration.

**Review Questions**

1. Explain particle theory.
2. Describe the types and classification of membrane treatment processes.
3. List the component parts of a membrane treatment process.
4. Outline the applications and operation of membrane treatment processes.

**Test Questions**

1. In __________, the flow is from the inside of the membrane, through the membrane, and the filtered water flows out of the system.
   1. Cross-flow filtration systems
   2. Dead-end filtration systems
   3. Countercurrent flow systems
4. Direct flow systems

2. In ________, the water being filtered may flow from the outside into the hollow fiber or from the inside to the outside; however, in this system, no waste stream is produced.
   1. Cross-flow filtration systems
   2. Dead-end filtration systems
   3. Countercurrent flow systems
   4. Direct flow systems

3. The __________ is asymmetric meaning that one side is different from the other side. The membrane is made up of one layer that is 50 to 100 microns thick and another layer that is a thin dense layer approximately 0.2 microns thick that exists at the surface. This thin, dense layer serves as the rejecting barrier of the membrane.
   1. Cellulose acetate membrane
   2. Thin composite membrane
   3. Electrodialysis membrane
   4. Distillation membrane

4. The __________, the semipermeable membrane is separate from the support layers, and this construction enables membrane manufacturers to select polymers that will produce membranes with optimum dissolved solids rejection and water flux rates.
   1. Cellulose acetate membrane
   2. Thin composite membrane
   3. Electrodialysis membrane
   4. Distillation membrane

5. ________, which is the rate of flow through the membrane, is dependent on the applied pressure.
   1. Mineral flux
   2. Water flux
   3. Mineral rejection
   4. Concentrate

6. ________, which is dependent on concentration, is not dependent on pressure.
   1. Mineral flux
   2. Water flux
   3. Mineral rejection
   4. Concentrate

7. ________ are seeing widespread use for demineralization of municipal water supplies that require high rejection rates for hardness and THM formation potential, and moderate TSD rejection.
   1. Microfiltration
   2. Ultrafiltration
   3. Nanofiltration
   4. Reverse osmosis

8. In ________, feed water temperature has a significant effect on membrane performance and must, therefore, be taken into account in system design and operation. Essentially, the value of the water permeation constant is only constant for a given temperature. As the temperature of the feed water increases, the flux increases. Usually, flux is reported at some standard temperature reference condition, such as 25oC.
1. Microfiltration
2. Ultrafiltration
3. Nanofiltration
4. Reverse osmosis

9. ________ processes may be used in conjunction with settling agents, polymers, activated carbon, and other chemicals that assist in the retention of waste constituents. When using this membrane, care must be taken to prevent membrane pore blockage by waste streams components through the selection of the proper membrane type for the specific plant wastes.

   1. Microfiltration
   2. Ultrafiltration
   3. Nanofiltration
   4. Reverse osmosis

10. ________ is the most common membrane-based wastewater treatment process. It uses a membrane with pore sizes ranging from 0.005 to 0.1 micron. Particles larger than the pores in the membrane, such as emulsified oils, metal hydroxides, proteins, starches, and suspended solids, are retained on the feed side of the membrane. Molecules smaller than the pores in the membrane, such as water, alcohols, salts, and sugars pass through the membrane. This filtrate, which is treated water, is often referred to as permeate.

   1. Microfiltration
   2. Ultrafiltration
   3. Nanofiltration
   4. Reverse osmosis

11. ________ is the tightest membrane process in that it allows only water to pass through the membrane, retaining salts and higher molecular weight components. These membranes are used for tertiary treatment producing water with low BOD/COD and of near-potable water quality. The permeate may be recycled throughout the plant and reused for various plant processes. This membrane type is normally used as a post-treatment process following coarser filtration processes.

   1. Microfiltration
   2. Ultrafiltration
   3. Nanofiltration
   4. Reverse osmosis

12. What is the operating pressure for nanofiltration, or softening membranes ________.

   1. 100-200 psi
   2. 200-500 psi
   3. 500-800 psi
   4. 800-1,200 psi

13. What is the operating pressure for reverse osmosis of seawater ________.

   1. 100-200 psi
   2. 200-500 psi
   3. 500-800 psi
   4. 800-1,200 psi

14. Reverse osmosis modules provide a large surface area for the attachment and growth of bacterial slimes and
molds. These organisms may cause membrane fouling or module plugging. Evidence exists that occasionally the enzyme systems of some of these organisms will attack the cellulose acetate membrane. Thus a continuous application of ______ helps to inhibit or retard the growth of most of the organisms encountered.

1. Acetic acid
2. Citric acid
3. Chlorine
4. Sodium hexametaphosphate

15. The oxides or hydroxides most commonly found in water are iron, manganese, and silica. The oxidized and precipitated forms of iron, manganese, and silica can be a serious problem to any demineralization scheme because they can coat the reverse osmosis membrane with a tenacious film, which will affect performance. The scale inhibitor most frequently used is _______.

1. Acetic acid
2. Citric acid
3. Chlorine
4. Sodium hexametaphosphate

16. Cellulose acetate membranes are subject to long-term hydrolysis. Hydrolysis results in a lessening of mineral rejection capability. The rate of hydrolysis is accelerated by increased ______, and is a function of feed _______.

1. Temperature, pH
2. Organic matter, chlorine residual
3. Iron, manganese
4. Microorganisms, TDS

17. To ensure the longest possible lifetime of the cellulose acetate membrane and to slow hydrolysis, _______ is added as a pretreatment step before demineralization.

1. Base
2. Alkalinity
3. Chlorine
4. Acid

18. Thin film composite membranes are not subject to hydrolysis; however, ______ pH adjustments of feed water may be required for scale control.

1. Basic
2. Alkaline
3. Neutral
4. Acidic

19. Slightly _______ pH values ensure a lower hydrolysis rate for cellulose acetate membranes, as do cooler temperatures.

1. Basic
2. Alkaline
3. Neutral
4. Acidic

20. When an oxidant-intolerant polyamide-type membrane is used in reverse osmosis treatment, chlorination must be followed with _______.
1. Ammonia
2. Dechlorination
3. Caustic
4. Deionized water