The Basics – Reverse Osmosis

What is Reverse Osmosis?

Reverse Osmosis is a technology used to remove most contaminants from water by pushing the water, under pressure, through a semi-permeable membrane. This paper explains the basics in simple terms to provide a general understanding of Reverse Osmosis (RO) technology and its applications.

This paper covers the following topics:

Understanding Osmosis and Reverse Osmosis

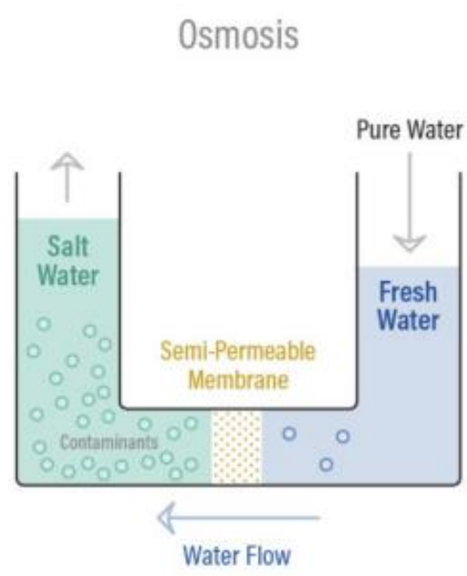
Reverse osmosis, commonly referred to as RO, is a process where a large portion of dissolved solids and other contaminants are removed from water by forcing the water through a semi-permeable reverse osmosis membrane.

Osmosis

To understand RO's purpose and process, first you must understand the naturally occurring process of Osmosis.

Osmosis is a naturally occurring phenomenon, and one of the most important processes in nature, where a weaker saline solution will tend to migrate to a strong saline solution. For example, when plant roots absorb water from the soil, or our kidneys absorb water from our blood.

The diagram to the right shows how osmosis works.



A less concentrated solution has a natural tendency to migrate to a solution with a higher concentration.

For example, if you had a container full of water with a low salt concentration and another container full of water with a high salt concentration, and they were separated by a semi-permeable membrane, then the water with the lower salt concentration would begin to migrate towards the water container with the higher salt concentration.

A semi-permeable membrane allows some atoms or molecules to pass but not others. A simple example is a screen door which allows air molecules to pass through but not pests or anything larger than the screen holes. Another example is Gore-Tex clothing which has an extremely thin plastic film with billions of small pores just big enough to let water vapor through, but small enough to prevent liquid water from passing.

Reverse Osmosis

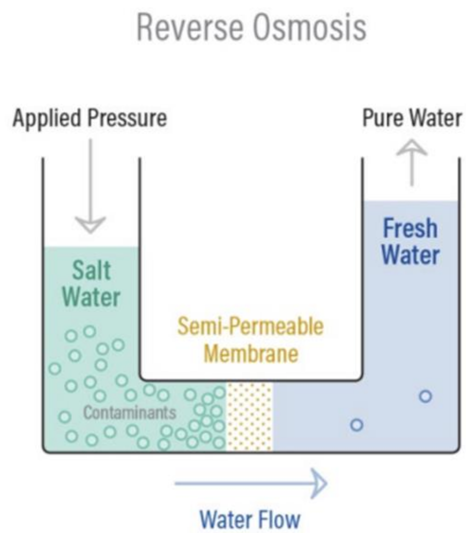
RO is the process of Osmosis in reverse. Osmosis occurs naturally without an external energy source, but reversing the osmosis process requires applying energy to the more saline solution to reverse the natural flow.

A reverse osmosis membrane is a semi-permeable membrane that allows the passage of water molecules but not most of the dissolved salts, organics, bacteria, and pyrogens. However, the water must be "pushed" through the RO membrane by applying pressure greater than the naturally occurring osmotic pressure.

The diagram on the next page outlines the RO process.

When pressure is applied to the concentrated solution, the water molecules are forced through the semi-permeable membrane while the contaminants are not allowed through.

How does Reverse Osmosis work?



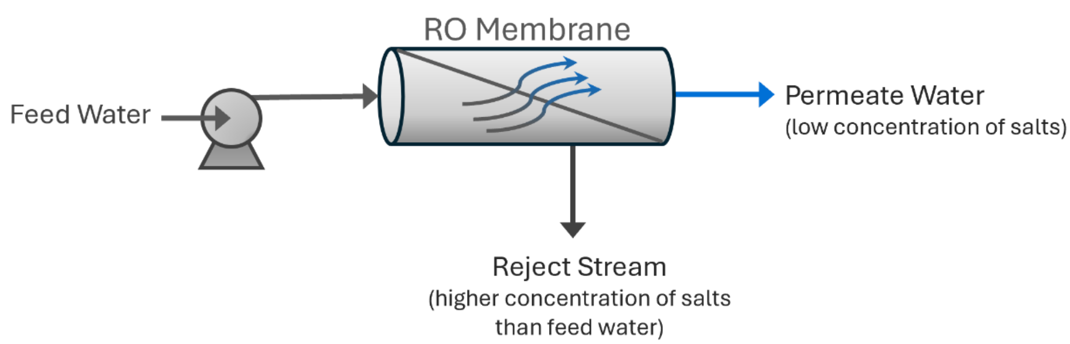
RO works using a high-pressure pump to apply pressure on the salt side of the RO system and to force the water across the semi-permeable RO membrane, leaving almost all (95% to 99%) of dissolved salts behind in the reject stream.

The amount of pressure required depends on the salt concentration of the feed water. The more concentrated the feed water, the more pressure is required to overcome the osmotic pressure.

In very simple terms, feed water is pumped into an RO system and two types of water come out: good water and bad water.

The "good" water has most contaminants removed and is called permeate. Another term for permeate is product water. Permeate is the water that was pushed through the RO membrane to remove nearly all contaminants. RO system sizes are based on permeate flow. For example, a 100 gallon per minute (gpm) RO system will produce 100 gpm of permeate water.

The "bad" water, called the concentrate, reject, or brine, is the leftover liquid will all the contaminants unable to pass through the RO membrane. All three terms are used interchangeably and mean the same thing. The simple schematic below shows how water flows through an RO system.



As the feed water enters the RO membrane under pressure (enough to overcome osmotic pressure) the water molecules pass through the semi-permeable membrane and the salts and other contaminants remain on the other side and are discharged from the system through the concentrate stream.

The concentrate either goes to a drain or, in some circumstances, is fed back into the feed water supply and recycled through the RO system to save water. The water that makes it through the RO membrane usually has approximately 95% to 99% of dissolved salts removed.

It is important to understand that RO systems employ cross filtration rather than standard dead-end filtration in which contaminants are collected within the filter media. With cross filtration, the solution passes through, or crosses, the filter with two outlets routing the filtered water one way while the contaminated water goes a different route. Cross flow filtration allows water to sweep away contaminant build up and allow enough turbulence to keep membrane surfaces clean.

What will Reverse Osmosis remove from water?

RO can remove 95-99% of dissolved salts (ions), particles, colloids, organics, bacteria, and pyrogens from feed water. An RO membrane rejects contaminants based on their size and charge. Any contaminant with a molecular weight greater than 200 will likely be rejected by a properly running RO system.

The greater the ionic charge of the contaminant, the more likely it will be unable to pass through the RO membrane. For example, a sodium ion has only one charge (monovalent) and is not rejected by the RO membrane as well as calcium, which has two charges.

RO systems cannot remove dissolved gases, such as carbon dioxide (CO_2), very well because they are not highly ionized (charged) while in solution and have a very low molecular weight. Because RO systems do not remove gases, permeate water can have a slightly lower than normal pH level, depending on dissolved CO_2 in the feed water since CO_2 is converted to carbonic acid.

RO is very effective in treating brackish, surface and ground water for both large and small flow applications. Industries that use RO water include pharmaceutical, boiler feed water, food and beverage, metal finishing, and semiconductor manufacturing to name a few.

RO System Performance and Design Calculations

There are a handful of calculations that are used to judge the performance of an RO system and for design considerations. An RO system has instrumentation that displays quality, flow, pressure and sometimes other data like temperature or hours of operation. To accurately measure the performance of an RO system you need the following operation parameters at a minimum:

1. Feed pressure
2. Permeate pressure
3. Concentrate pressure
4. Feed conductivity
5. Permeate conductivity
6. Concentrate flow
7. Permeate flow
8. Temperature

Salt Rejection %

This equation tells you how effectively the RO membranes are removing contaminants. It does not tell you how each individual membrane is performing, but rather how the system overall is performing on average.

A well-designed RO system with properly functioning RO membranes will reject 95% to 99% of most feed water contaminants (of a certain size and charge).

The following equation can be used to determine how effective the RO membranes are at removing contaminants:

$$\text{Salt Rejection \%} = \frac{\text{Feed Water Conductivity} - \text{Permeate Water Conductivity}}{\text{Feed Water Conductivity}} \times 100$$

Salt Passage %

This is simply the inverse of salt rejection described in the previous equation. This is the amount of salts, expressed as a percentage, passing through the RO system.

The lower the salt passage, the better the system is performing. A high salt passage can mean the membranes require cleaning or replacement.

$$\text{Salt Passage \%} = (1 - \text{Salt Rejection \%})$$

Recovery %

Recovery is the amount of feed water emerging from the system as good, permeate water.

Another way to think of recovery is the amount of water not being sent to drain as concentrate, but collected as permeate or product water. Higher recovery percents mean you are sending less water to drain as concentrate and saving more permeate water. However, if recovery percents are too high for the RO design, it can lead to larger problems from membrane scaling and fouling.

RO system recovery rates are established with the help of design software that considers numerous factors, such as feed water chemistry and pre-treatment before the RO system. Therefore, proper RO system recovery depends on the design. Calculating the recovery facilitates rapid determination that the system is operating outside of the intended design.

The calculation below expresses the recovery rate as a percentage.

$$\text{\% Recovery} = \frac{\text{Permeate Flow Rate (gpm)}}{\text{Feed Flow Rate (gpm)}} \times 100$$

For example, if the recovery rate is 75% then for every 100 gallons of feed water entering the RO system, you are recovering 75 gallons as usable permeate water while 25 gallons go to the drain as concentrate. Industrial RO systems typically run between 50% to 85% recovery depending on feed water characteristics and other design considerations.

Concentration Factor

The concentration factor is related to RO system recovery and is important for RO system design. The more water you recover as permeate (higher recovery %), the more concentrated salts and contaminants you collect in the concentrate stream. When the concentration factor is too high for the system design and feed water composition, the system may experience increased scaling on RO membrane surfaces.

Concentration Factor = (1 / (1 – Recovery %)

The concept is no different than that of a boiler or cooling tower with purified water exiting the system as steam leaving a concentrated solution behind. As the concentration increases, solubility limits may be exceeded and precipitate on equipment surfaces as scale.

For example, if your feed flow is 100 gpm and the permeate flow is 75 gpm, then the recovery is (75/100) x 100 = 75%. To find the concentration factor, the formula would be 1 ÷ (1 – 75%) = 4.

A concentration factor of 4 means the water going to the concentrate stream will be 4 times more concentrated than the feed water. If the feed water in this example was 500 ppm, then the concentrate stream would be 500 x 4 = 2,000 ppm.

Flux

Flux is used to express the amount of water passing (permeates) through a reverse osmosis membrane during a given time expressed as gallons per square foot per day (GFD) or liters per square meter per hour (l/m2 /hr).

A higher flux means more water is permeating through the RO membrane.

RO systems are designed to operate within a certain flux range to ensure the water flowing through the RO membrane is not too fast or slow.

$$\text{Gfd} = \frac{\text{gpm of permeate X 1,440 min/day}}{\text{\# of RO elements in system X square footage of each RO element}}$$

For example, you have the following:

- The RO system is producing 75 gpm of permeate.
- The system has 3 RO vessels each holding 6 RO membranes for a total of 3 x 6 = 18 membranes.
- The RO system membranes are Dow Filmtec BW30-365 which has 365 square feet of surface area.

To find the flux (Gfd):

$$Gfd = \frac{75\text{ gpm X }1{,}440\text{ min/day}}{18\text{ elements X }365\text{ sq ft}}$$

$$= \frac{108{,}000}{6{,}570}$$

The flux = 16 Gfd

This means 16 gallons of water passed through each square foot of each RO membrane per day.

This number could be good or bad depending on the feed water chemistry and system design. Below is a general rule of thumb for flux ranges for different source waters. This can be better determined with the help of RO design software.

If Dow Filmtec LE-440i RO membranes were used in the above example, then the flux would have been 14 Gfd. So, it is important to factor in the type of membrane used and to use consistent membrane types throughout the system.

Feed Water Source	Gfd
Sewage Effluent	5 – 10
Sea Water	8 – 12
Brackish Surface Water	10 – 14
Brackish Well Water	14 – 18
RO Permeate Water	20 – 30

Mass Balance

A Mass Balance equation is used to help determine if your flow and quality instrumentation is reading properly or requires calibration. If your instrumentation is not reading correctly, then the collected trending performance data is useless.

You will need to collect the following data from an RO system to perform a Mass Balance calculation:

1. Feed Flow (gpm)
2. Permeate Flow (gpm)
3. Concentrate Flow (gpm)
4. Feed Conductivity (µS)
5. Permeate Conductivity (µS)
6. Concentrate Conductivity (µS)

The mass balance equation is:

(Feed flow[1] X Feed Conductivity) =

(Permeate Flow X Permeate Conductivity) + (Concentrate Flow X Concentrate Conductivity)

[1]*Feed Flow equals Permeate Flow + Concentrate Flow*

For example, if you collected the following data from an RO system:

Permeate Flow	5 gpm
Feed Conductivity	500 µS
Permeate Conductivity	10 µS
Concentrate Flow	2 gpm
Concentrate Conductivity	1200 µS

Then the Mass Balance Equation would be:

(7x500) = (5 x 10) + (2x1200)

3,500 ≠ 2,450

Then find the difference:

(Difference / Sum) x 100 =

= 18%

- A difference of +/- 5% is okay.
- A difference of +/- 5% to 10% is generally adequate.
- A difference of > +/- 10% is unacceptable, and RO instrumentation calibration is required to ensure useful data is collected.

In the example above, the RO mass balance equation falls out of range and requires attention.

Understanding passes and stages in a Reverse Osmosis (RO) system

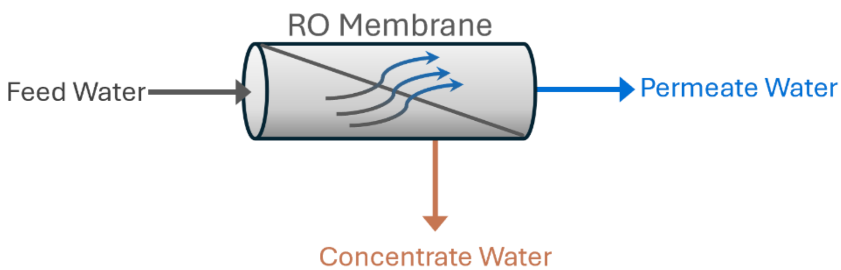
The term 'stage' and 'pass' are often mistaken for the same thing in an RO system, and the terminology can be confusing for an RO operator. It is important to understand the difference between a one- and two-stage RO and a one- and two-pass RO.

Difference between a One and Two Stage RO System

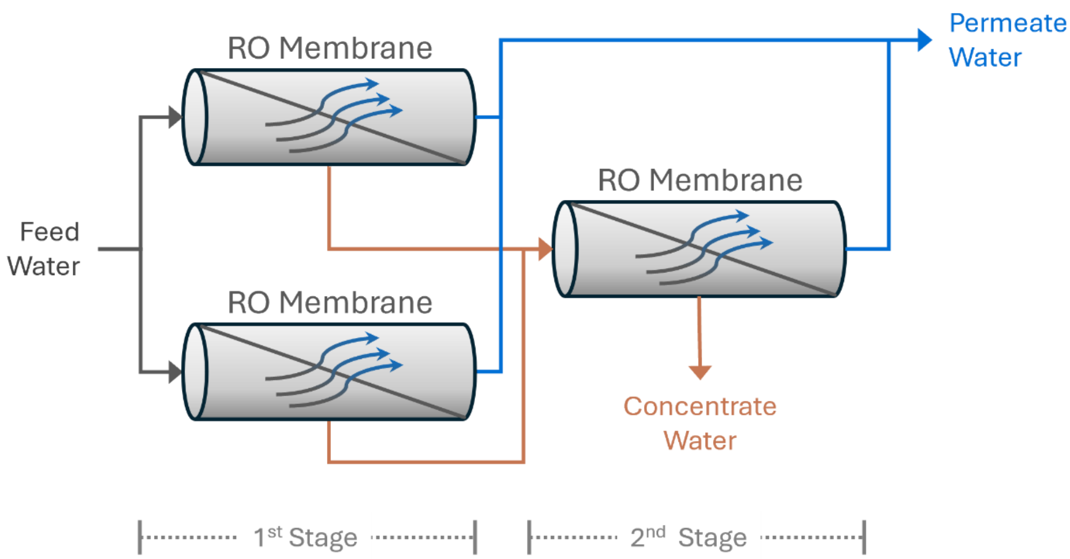
In a one-stage RO system, the feed water enters as one stream and exits the RO as either concentrate or permeate water.

In a two-stage system, the concentrate (or reject) from the first stage then becomes feed water for the second stage. The permeate water collected from the first stage is combined with permeate water from the second stage. Additional stages increase the RO system's recovery.

One-Stage RO System



Two-Stage RO System



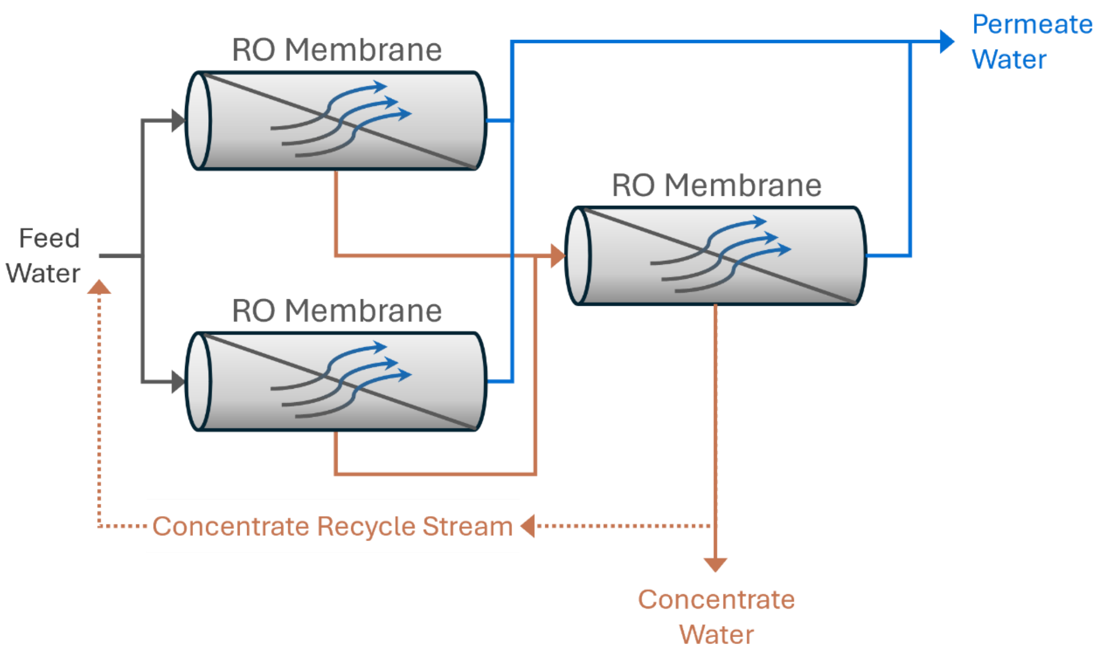
Array

In a reverse osmosis system, an array describes the physical arrangement of the pressure vessels in a two-stage system. Pressure vessels contain RO membranes (usually from 1 to 6 RO membranes are in a pressure vessel), and each stage can have a certain amount of pressure vessels with RO membranes.

The reject of each stage then becomes the feed stream for the next successive stage. The two-stage RO system above is a 2:1 array, which means the concentrate (or reject) of the first two RO vessels is fed to the next single vessel.

RO System with Concentrate Recycle

With an RO system that cannot be properly staged, and if the feed water chemistry allows, a concentrate recycle setup can be used where a portion of the concentrate stream is fed back into the feed water to the first stage to increase system recovery.



Single Pass RO vs Double Pass RO

Think of a 'pass' as a standalone RO system. The difference between a single-pass RO system and a double-pass RO system is how many RO systems the water passes through.

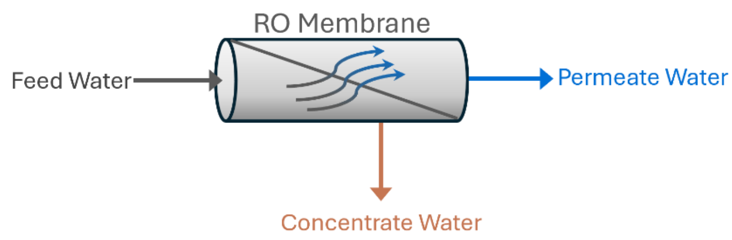
In a double-pass RO, the permeate from the first RO (the first pass) becomes the feed water to the second pass (or second RO). A double-pass RO system produces a much higher quality permeate because it has essentially gone through two RO systems.

In addition to producing a much higher quality permeate, a double-pass system also provides the opportunity to remove carbon dioxide gas from the permeate by injecting caustic between the first and second pass. $C0_2$ is undesirable when using mixed bed ion exchange resin beds after the RO system.

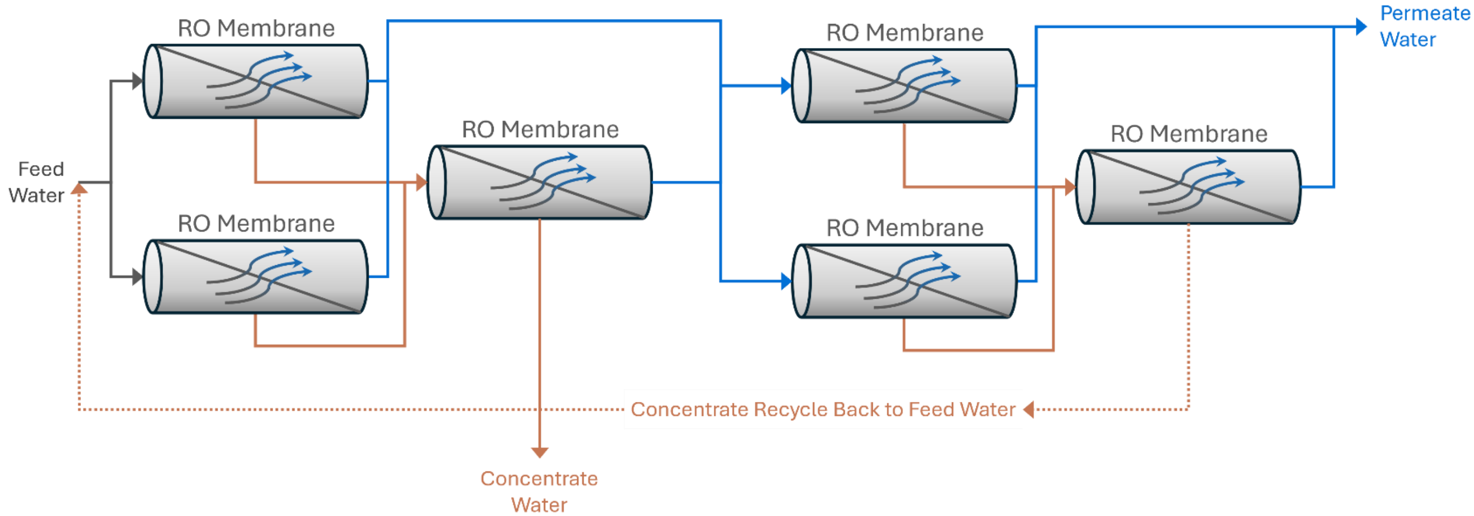
Adding caustic after the first pass increases the pH of the first pass permeate water and converts the $C0_2$ to bicarbonate (HCO_3) and carbonate (CO_{3}-$_2$) which will be rejected better by the RO membranes in the second pass.

This process can't be done with a single pass RO because injecting caustic and forming carbonate ($CO_{3\text{-}2}$) in the presence of cations such as calcium will cause RO membrane scaling.

Single-Pass RO



Double Pass RO



RO Pretreatment

Proper pretreatment using both mechanical and chemical treatments is critical for an RO system to

prevent fouling, scaling and costly premature RO membrane failure and frequent cleaning requirements. Below is a summary of common problems an RO system experiences due to lack of proper pretreatment.

Fouling

Fouling occurs when contaminants accumulate on the membrane surface effectively plugging the membrane. Many contaminants in municipal feed water are naked to the human eye and harmless for human consumption, but large enough to quickly foul (or plug) an RO system.

Fouling typically occurs in the front end of an RO system and results in a pressure drop across the RO system and a lower permeate flow. This translates into higher operating costs and eventually the need to clean or replace the RO membranes.

Fouling will take place eventually due to an RO membrane's extremely fine pore size no matter how effective the pretreatment protocols or cleaning schedule. However, proper pretreatment will minimize the need to address fouling related problems.

Fouling can be caused by:

1. Particulate or colloidal matter (dirt, silt, clay, etc.)
2. Organics (humic/fulvic acids, etc.)
3. Microorganisms (bacteria, etc.)
4. Breakthrough filter media upstream of the RO unit

Bacteria are one of the most common fouling problems since today's RO membranes cannot tolerate disinfectants such as chlorine and microorganisms are often able to thrive and multiply on the membrane surface. Microorganisms may produce biofilms that cover the membrane surface and result in heavy fouling.

Filter media upstream of the RO unit breakthrough may involve GAC carbon beds and softener beds developing an under-drain leak. Without adequate post filtration, the media can foul the RO system.

Analytical tests determine if the feed water to your RO has a high potential for fouling. mechanical filtration helps prevent RO system fouling. The most popular methods to prevent fouling are the use of multi-media filters (MMF) or microfiltration (MF). In some cases, cartridge filtration will suffice.

Scaling

As certain dissolved (inorganic) compounds become more concentrated (remember discussion on concentration factor) scaling can occur. If these compounds exceed their solubility limits, they can precipitate on the membrane surface as scale. Scaling causes higher pressure drops across the system, higher salt passage (less salt rejection), and low permeate flow.

Common scale that tends to form on RO membranes is calcium carbonate ($CaCO_3$).

Chemical Attack

Modern thin film composite membranes are not tolerant to chlorine or chloramines. Oxidizers, such as chlorine, will 'burn' holes in the membrane pores and can cause irreparable damage. The result of chemical attack on an RO membrane is higher permeate flow and higher salt passage (less salt rejection).

Increased microorganism growth on RO membranes tends to easily foul membranes since there is no biocide present to prevent growth.

Mechanical Damage

Part of the pretreatment scheme should involve pre and post RO system plumbing and controls. If 'hard starts' occur, the system may experience mechanical damage to the membranes. Likewise, too much backpressure on the RO system can cause mechanical damage to the RO membranes.

These can be addressed by using variable frequency drive motors to start high pressure pumps for RO systems along with installing check valve(s) and/or pressure relief valves to prevent excessive back pressure on the RO unit that can cause permanent membrane damage.

Pretreatment Solutions

The pretreatment solutions for RO systems listed below can help minimize fouling, scaling and chemical attack.

Multi-Media Filter (MMF)

A Multi-Media Filter is used to help prevent RO system fouling. An MMF typically contains three layers of media consisting of anthracite coal, sand, and garnet, with a supporting gravel layer at the bottom. These are the medias of choice because of the differences in size and density. The larger (but lighter) anthracite coal will be on top, and the heavier (but smaller) garnet will remain on the bottom.

The filter media arrangement allows the largest dirt particles to be removed near the top of the media bed while smaller dirt particles are retained deeper in the media. The entire bed acts as a filter allowing much longer filter run times between backwashes and more efficient particulate removal.

A well-operated MMF can remove particulates down to 15 – 20 microns. An MMF with an incorporated coagulant (which induces tiny particles to join and form particles large enough to be filtered) can remove particulates down to 5 – 10 microns. To put this in perspective, the width of a human hair is around 50 microns.

A multi-media filter is suggested when the feed water Silt Density Index (SDI) value is greater than 3 or when the turbidity is greater than 0.2 NTU. There is no exact rule, but the above guidelines should be followed to prevent premature RO membrane fourling.

It is important to have a 5-micron cartridge filter placed directly after the MMF unit to prevent the MMF media from damaging downstream pumps and fouling the RO sustem if the MMF under drains fail.

Microfiltration (MF)

Microfiltration (MF) is effective in removing colloidal and bacteria matter with a 0.1-10μm pore size and is helpful in reducing RO unit fouling potential. Membrane configuration can vary between manufacturers, but the "hollow fiber" type is the most common.

Typically, water is pumped from the outside of the fibers and clean water is collected from the inside of the fibers. Microfiltration membranes used in potable water applications usually operate in "dead-end" flow in which all the water fed to the membrane is filtered through the membrane. The installed filter cake must be periodically backwashed from the membrane surface forms.

Recovery rates are normally greater than 90 percent on feed water sources with high quality and low turbidity feeds.

Antiscalants/Scale Inhibitors

Antiscalants and scale inhibitors, as their name suggests, are chemicals added to feed water before an RO unit to help reduce the scaling potential. Antiscalants and scale inhibitors increase the solubility limits of troublesome inorganic compounds.

By increasing the solubility limits, you can concentrate the salts further than otherwise would be possible, achieving a higher recovery rate and operating at a higher concentration factor.

Antiscalants and scale inhibitors work by interfering with scale formation and crystal growth. The choice of antiscalant or scale inhibitor and correct dosage depends on feed water chemistry and RO system design.

Water Softening

A water softener can be used to help prevent RO system scaling by exchanging scale forming ions with non-scale forming ions. As with MMF units, it is important to have a 5-micron cartridge filter placed directly after the water softener if the under drains fail.

Sodium Bisulfite

Sodium bisulfite (SBS or SMBS), a reducer, added to the water stream before an RO at the proper dose can remove residual chlorine and chloramines.

Granular Activated Carbon (GAC)

GAC is used for both removing organic constituents and residual disinfectants (such as chlorine and chloramines) from water. GAC media is made from coal, nutshells, or wood. Activated carbon removes residual chlorine and chloramines by a chemical reaction involving a transfer of electrons from the surface of the GAC to the residual chlorine or chloramines. The chlorine or chloramines ends up as a chloride ion that is no longer an oxidizer.

The disadvantage of using a GAC before the RO unit is that the GAC will remove chlorine quickly at the very top of the GAC bed. This will leave the remainder of the GAC bed without any biocide to kill microorganisms. A GAC bed will absorb organics throughout the bed, which is potential food for bacteria, and eventually the GAC bed can become a breeding ground which can pass easily to the RO membranes.

Also, a GAC bed can produce very small carbon fines under some circumstances that have the potential to foul an RO. A cartridge filter should be placed after a GAC and before an RO to protect membranes from carbon fines.

RO Data Trending and Normalization

The RO membranes are the heart of the RO system and certain data points should be collected to determine RO membrane health. These data points include system pressures, flows, quality, and temperature.

Water temperature is directly proportional to pressure. As the water temperature decreases it becomes more viscous and the RO permeate flow will drop as more pressure is required to push the water through the membrane. Likewise, when the water temperature increases, the RO permeate flow will increase. As a result, RO system performance data must be normalized so flow variations are not interpreted as abnormal when no problem exists.

Normalized flows, pressures and salt rejection should be calculated, graphed and compared to baseline data (when the RO was commissioned or after the membranes were cleaned or replaced) to help troubleshoot any problems and determine when to clean or inspect the membranes for damage.

Data normalization helps show the RO membranes' true performance. As general rule, when the normalized change is +/- 15% from baseline data, the cause should be investigated, and membranes cleaned. Otherwise, RO membrane cleanings may not be effective at bringing the membranes back to near new performance.

RO Cleaning

RO membranes will inevitably require periodic cleaning – usually between 1 to 4 times a year depending on feed water quality. Generally, if the normalized pressure drops or the normalized salt passage has increased by 15%, it is time to clean the RO membranes. Or if the normalized permeate flow has decreased by 15% then it is also time to clean the RO membranes.

RO membranes can be cleaned in place (if equipped) or removed from the RO system and cleaned off site by a specialized service company. It has been proven that offsite membrane cleaning delivers a more effective cleaning than onsite cleaning skids.

RO membrane cleaning involves low and high pH cleaners to remove contaminants from the membrane. Scaling is addressed with low pH cleaners while organics, colloidal and biofouling are treated with high pH cleaners.

Cleaning RO membranes is not only about using the appropriate chemicals. Many other factors, such as flows, water temperature, water quality, properly designed and sized cleaning skids, are involved and an experienced service provider should be involved to properly clean RO membranes and prevent any damage requiring replacement.

Summary

Reverse Osmosis is an effective and proven technology to reduce water contaminants.

Further post treatment after the RO system, such as mixed bed deionization, can increase RO permeate quality and make it suitable for the most demanding applications. Proper pretreatment and RO system monitoring are crucial to preventing costly repairs and unscheduled maintenance.

With the correct system design, maintenance program, and experienced service support, your RO system should provide high purity water for many years.

For more information give us a call or visit our site