Micro & Ultra-filtration in Reverse Osmosis Pretreatment

Stephen I. Rome (Speaker)
Mechanical Equipment Company, New Orleans LA

Scott Smith
Mechanical Equipment Company, New Orleans LA

Kyaw Moe
Mechanical Equipment Company, New Orleans LA

Nathaniel Matherne
Mechanical Equipment Company, New Orleans LA

BACKGROUND

Reverse osmosis is in use around the world for not only the desalination of sea water but also for purifying tap water prior to bottling or for feed to distillation equipment for the production of ultra pure water. Impurities present in the feed water to the reverse osmosis membrane will build up on the membrane surface and will require higher feed pressures to drive the water through the membrane. RO membranes see two modes of failure that are due to water chemistry: scaling and fouling. Proper pretreament is essential to maximize the efficiency and longevity of the RO system.

Scaling occurs when soluble inorganic compounds in feed water concentrate and precipitate onto the membrane surface and form a scale. This scale can be very difficult to remove and treatment often depends on the type of scale that is on the membrane. Scale formation due to exceeding the solubility limits of these compounds is extremely detrimental to RO system effectiveness and membrane life. Common inorganics that lead to scaling are Calcium Carbonate, Calcium Sulfate, and Silica. The feed water is often treated by methods such as acid injection, softening, or addition of a scale inhibitor to reduce or eliminate these scaling compounds. Another way to control scale formation is to reduce the system recovery. Higher recoveries may cause the precipitation of these inorganics due to increasing their concentration above the solubility limits in the concentrate stream. The system recovery can be reduced to bring this concentration below the solubility levels.

Fouling occurs because of two different cases, colloids and/or biological growth. Colloidal matter such as clay, colloidal silica, and dead microorganisms often lead to non-biological fouling. Measuring and calculating the Silt Density Index can find the content of these colloids in source water. Pretreatment options that help reduce or eliminate colloidal matter in feed water are media filtration, coagulation-flocculation, cartridge filtration, microfiltration, or ultrafiltration.

Fouling due to biological growth on the membrane surface is known as biological fouling. With biological fouling, bacteria, fungi, viruses, etc. collect on the membrane surface and form a living film under the correct conditions. Biofilms are very hard to clean due to the fact that the film on the membrane surface is often thick and thus provides a layer of protection for these microorganisms. These organisms feed on the deposited organic material located on the membrane surface and can quickly multiply adversely effecting the membrane flux rates and causing a rapid build up of differential pressure across the RO membrane array. Chlorination is an effective pretreatment to combat biofouling but the chlorinated water must be dechlorinated before going into the RO membrane array to avoid oxidation of the membranes and membrane failure.

As these scalants and foulants build up on the RO membrane surface, higher and higher feed pressure is required to maintain a constant recovery level. These higher feed pressures are attributed to the build-up of materials on the membrane surface. The pressure drop across all pressure vessels in the array is measured and is known as the differential pressure. This differential pressure is a good indicator of the amount of fouling occurring in the membrane array. The differential pressure is calculated by subtracting the RO membrane reject pressure from the feed pressure. Most commercially available RO membranes have a maximum allowable differential pressure, typically 20-30 psi for a single element. Operation beyond this maximum differential pressure can result in serious mechanical damage to the membranes due to the large forces that are generated in the flow direction in the membrane. Each membrane sees a larger and larger force as the differential pressure builds towards the end of the array. The permeate tubes see the majority of this force and the last element sees the largest of all the forces created by the pressure drops of the upstream elements.

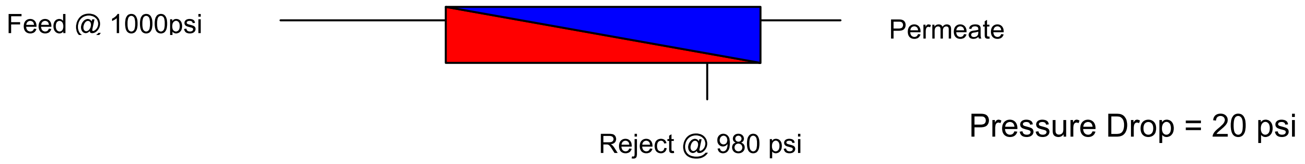


Figure 1. Differential Pressure Measurement

In order to return the membranes to their original operational levels of permeate flow and water quality, the membranes must be chemically cleaned. A low pH cleaner is used to remove mineral scale while a high pH cleaner is used to remove biofilm. Chemical cleaning a RO membrane is typically a lengthy manual procedure and at some point, the membranes become permanently fouled and the production levels of the membrane cannot be restored to acceptable levels of production. At this point the membranes must be replaced to restore the performance of the RO system.

A major source of the fouling is the suspended solids contained in the RO feed water. The typical measurement of these suspended solids is turbidity expressed in nephelometric turbidity units or NTU. This is a measure of the light scattered at a particular wavelength by a sample of the water. The higher the level of suspended solids present in the water, the higher the NTU reading.

Source Water	**Avg. Measured Turbidity**
Bentonite / Canal Water Mix – New Orleans, La	108.452 NTU
Littoral Waters - Chesapeake Bay, Md.	64.0 NTU
Littoral Waters - Pascagoula, Mississippi	16.970 NTU
Industrial Canal – New Orleans, Louisiana	11.975 NTU
Littoral Waters – Camp Lejuene, N. C.	5.123 NTU
Ocean Inlet – Port Hueneme, California	1.433 NTU

Table 1. Average Turbidity Measurements of Various Source Waters

In order to prolong the time between cleanings and the overall useful life of the RO membranes, it is necessary to pre-treat the RO feed water to remove the suspended solids. To be effective, the water produced from the RO pretreatment system must remove solids to such a degree that turbidity is no longer a viable method to measure the remaining solids present, i.e. the turbidity measurement is zero. At this point, the suspended solids are measured by observing the decrease in flow through a filter paper. The standard method for this measurement is the silt density index or SDI. The SDI of a water is calculated by the following formula;

$$\mathrm{SDI}_{15} = [\, 1 - T_0/T_{15} \,] * 100$$

where T_0 is the time required to collect a specific volume of water (typically 500 mls) flowing through a .45 micron filter paper at 30 psig inlet pressure and T_{15} is the time required to collect the same specific volume after 15 minutes. The apparatus commonly used for collecting the SDI measurement is shown in figure 2.

Based on vendor literature, RO manufacturers specify an SDI of 3 or less as acceptable for feed to their membranes. Feed water with a higher SDI will result in a significantly lower lifetime for the membranes.

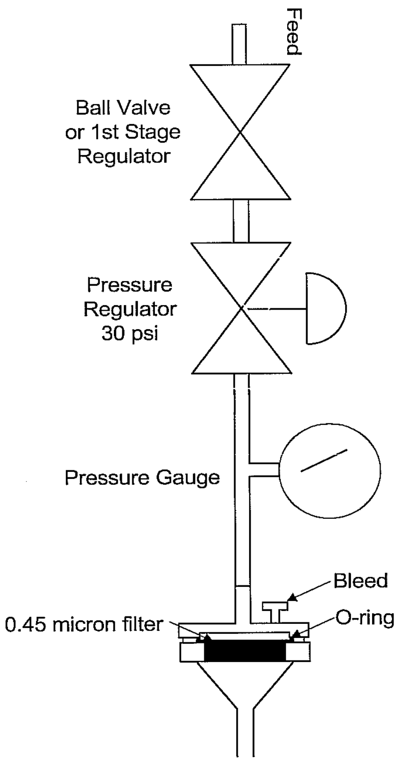


Figure 2. SDI Apparatus

TRADITIONAL PRETREATMENT OPTIONS

Multimedia Filters

The function of a media filter is to reduce the level of suspended solids present in the feed water. The unfiltered water flows downward through the filter media bed. Suspended solids become trapped in the media bed and remain trapped until the media bed is backwashed. During the backwash process, the flow through the media bed is reversed, the media bed is fluidized, and the trapped solids are released and flushed to drain. Upon completion of the backwash process, flow is redirected downward through the media bed and flows to drain thereby rinsing the media bed before the filter is returned to normal service.

If an uninterrupted flow of filtered water is required, it will be necessary to utilize multiple filter units piped in a parallel arrangement. This will allow one filter at a time to be removed from service and backwashed while maintaining operation.

The filter vessel is sized to provide the proper flow velocity through the media bed and to provide sufficient “freeboard” for bed expansion during the backwash process. The filter vessel is fitted with the appropriate connections to accommodate the required distribution system components. The vessel is free-standing and fully supports the unit piping and valves. The media bed is composed of two or more layers of media. The size and density of the media in the layers are selected to provide multi-step filtration in normal operation and proper bed stratification during backwash. The internal distribution system insures uniform water flow through the media bed. The fine openings in the distributors prevent media loss and the V-shaped design of the openings prevents clogging.

In order to provide the required modes of operation, service, backwash and rinse, a means of controlling the valves is provided. For units incorporating a multi-port valve the valve control is an integral part of the multi-port valve. For units with individual valves a separate timer / stager or programmable logic controller provides the control. A series of valves, or a single multi-port valve, divert the water as required for the service, backwash and rinse modes of operation. The face piping routes the water from the terminal points through the series of diversion valves and into and out of the vessel.

Figure 3. Typical Multi Media Installation
Source: MECO

Multi-media filter vessels must be large enough to accommodate the flux rates based on the feed water flow rate as well as the necessary internal piping and media. A filter sized for a 6 gpm flow is typically 14 to 16 inches in diameter and 65 inches tall, containing 3 to 4 cubic feet of media. Units typically weigh between 230 to 365 pounds.

Cartridge Filters

Standard disposable or cleanable filtration cartridges are available in a variety of materials and lengths. Nominal cartridge lengths of 10 inches to 40 inches are readily obtainable from a wide range of commercial sources along with vessels able to accommodate from one to six elements. Filter materials range from spiral wound cotton to various synthetics such as polypropylene and polyester. Filtration ratings down to .2 micron absolute with 99.9 % efficiency are available.

Cartridge filters operate in a dead end flow mode and have a fixed dirt handling capacity. Once exceeded, flow will cease until the element is either replaced or cleaned, if possible. In water with a high level of suspended solids, such as the Mississippi delta region of the Gulf of Mexico, this can result in multiple daily cartridge change outs. Because of this fouling, a large quantity of replacement elements must be available to keep the systems running.

The US Navy uses cartridge filter systems for pre-treatment for their RO water makers on so-called “blue water” ships. These systems have disposable cartridges of 100 microns, 20 microns and 3 microns in series. However, due to the limited dirt handling capacity of the pre-treatment system, the Navy does not use these water makers in littoral waters.

THE CHALLENGE

In 1998, the US Army issued a design specification for a Lightweight Water Purifier (LWP). Highlights of the specifications called for a production of 125 gallons per hour of potable water from surface water sources and 75 gallons per hour from seawater with salt concentrations of up to 45,000 ppm. The unit had to fit into the back of a HMMWV along with a generator and all supplies required to support 140 hours of operation. The total weight of the complete unit with all supplies had to be less than 2,000 pounds.

The space and weight requirements precluded the use of a traditional multimedia RO pretreatment system. The obligation to include 140 hours of supplies along with the hardware in the cargo space of a HMMWV likewise precluded the use of an RO pretreatment system utilizing disposable cartridge elements. An attempt to use sintered metal back-washable cartridge elements (GSII US Army Lightweight Water Purifier design) proved unsuccessful due to high organic loadings and the inability of the backwash to remove biofilm.

In researching new technologies, Mechanical Equipment Company (MECO) decided to investigate microfiltration (MF) and ultrafiltration (UF) as RO pretreatment systems. Two designs were executed using the same diesel driven high-pressure pump and RO membrane arrangement but utilizing the different pretreatment options. Both systems would satisfy the dimensional, weight, and supply requirements of the Army specification.

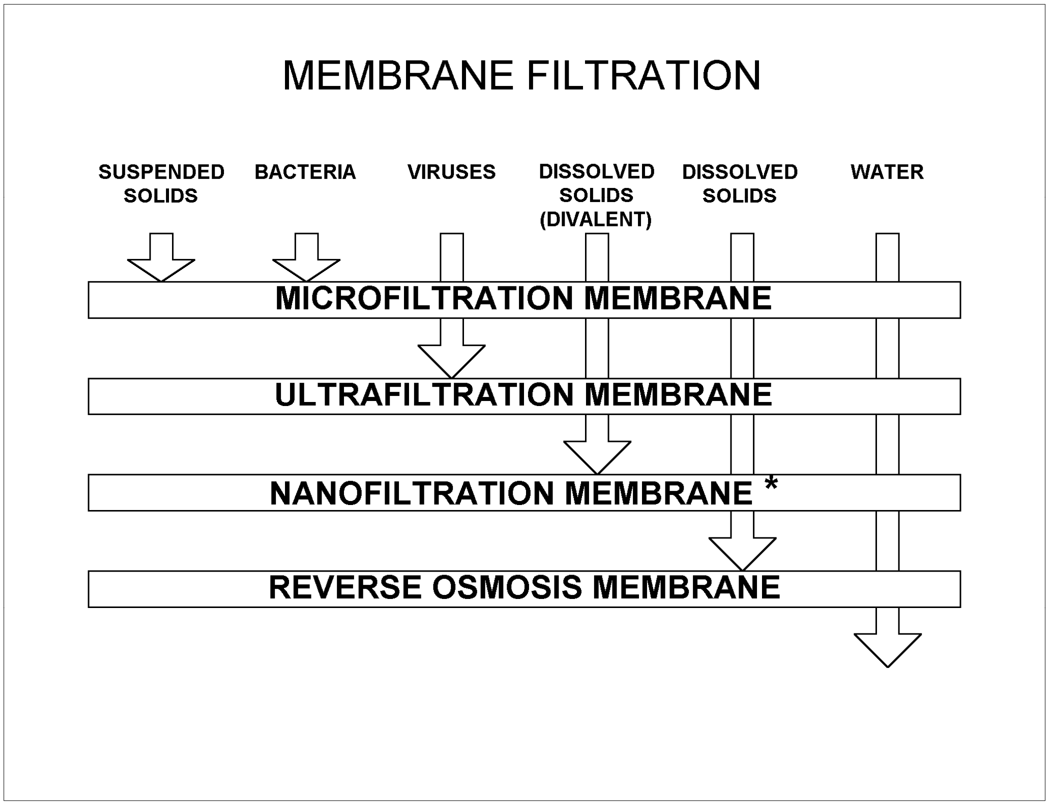


Figure 4. Filtration Range Chart

Micro filtration

Microfiltration employs the use of a porous fiber that filters out most unwanted constituents in feed water. There are several types of microfiltration membranes such as hollow fiber membranes and spiral wound membranes. As an example, a spiral-wound membrane consists of flat sheets wrapped in a spiral configuration similar to a reverse osmosis membrane. The pores in a hollow fiber membrane or spiral wound membrane should be consistently on the order of 0.1 to 0.2 μm in size. Microfiltration provides the end user with the ability to consistently and efficiently remove suspended solids, bacteria, yeast, some viruses, and harmful biological contaminants such as Giardia Lamblia and Cryptosporidium from feed water. However, reverse osmosis or nanofiltration are needed for the removal of most organic compounds and dissolved salts. Typical fiber material is dependant on the manufacturer and application but can be commonly found in PVDF (Polyvinylidenefluoride), Polyacrylonitrile, or Polyethylene. Material choice can be dictated upon also considering the Molecular Weight Cutoff of the membrane material. A membrane containing a smaller MWCO provides better overall filtration.

There are a multitude of applications for microfiltration ranging from pretreatment for the offshore industry to the pharmaceutical industry. This filtration method is commonly used at municipal drinking and wastewater treatment plants as both a pretreatment and polishing mechanism. Microfiltration can be very cost effective in comparison to multi-media and cartridge filtration systems due to having the ability to regularly clean the membrane and continue service for much longer periods of time. Media and cartridges typically must be replaced quite frequently depending on the level of suspended solids but it is important to remember that these filtration methods do not provide the level of filtration that microfiltration provides. This lack of filtration can lead to more frequent downstream equipment maintenance due to faster scale build-up and possibly more methods of purification due to the larger size of the solids present in the pre-filtered water.

A typical microfiltration system consists of a skid frame containing racks that can hold several membranes with valves and instruments to help monitor system properties such as pressure, flow, and backwash frequency. These instruments also help to control the flow to the membrane. The driving force behind this process is the pressure provided by a booster pump. Typical feed pressures for microfiltration systems are around 30 to 50 psi. Filtration can occur in one of two ways with a hollow fiber membrane like that used on the Lightweight Water Purifier, outside to in or inside to out. Filtered water is commonly known as filtrate. Microfiltration mostly operates in a cross flow pattern and so a small amount of concentrated dirty water known is left over and is known as reject.

The total amount of filtrate that the membrane makes each day per square foot of membrane surface area is know as flux. Flux is measured in gallons of filtrate per square foot of membrane surface per day. Membrane manufacturers have a ceiling value for the acceptable flux range of any certain element.

While a microfiltration unit is in operation, it is often flushed and backwashed to remove deposits from the fiber surfaces. However, the system will eventually need to be cleaned to resume its most effective level of performance by removing caked solids that flushing and backwashing can no longer remove. The main parameter used to show the effectivity and operational cleanliness of a system is transmembrane pressure, or TMP. When this pressure rises to 30 psi or higher, the suspended solids and other impurities in the water have “caked” on the membrane surface and the loss in pressure as the water moves across the membrane surface exemplifies the level of this caked material. The pores in the membrane wall are effectively clogged and filtrate flow is drastically reduced when the TMP has risen to the upper end of the allowable range. At this point the unit can be backwashed with permeate for a specified amount of time and at a particular flow rate, normally around 1.5 times the feed rate. This basically works in reverse of the normal flow path and forces filtrate at a higher flow rate back through the pores dislodging the cake on the membrane surface. The resulting freed debris is dumped to drain. To further aid in cleaning the membrane surface, a pressurized air scour can also be utilized to help dislodge additional caked-on material. Low-pressure air is injected into the feed flow at the normal flow rate. The air helps to agitate the membrane fibers further loosening any remaining cake. Filtrate is not made during this scouring. The air scour can be done on a less frequent basis depending on how severe the turbidity of the water is.

Although backwashing and air scouring cleans the membranes effectively, there comes a point when it will take a chemical cleaning to restore the membranes to their normal filtration capabilities. Here, a closed loop is formed and cleaning chemicals are circulated through the system. The filtrate is dumped to drain and the reject is recirculated back into the cleaning tank. The cleaning is stopped and the unit is put back into normal operating mode and all filtrate is dumped to drain for a set amount of time. Normal operation can then be resumed and the new TMP should read near the level of a new membrane. When backwashing, air scouring, and chemical cleaning will no longer reduce the TMP, the membrane is considered to be fouled and must be replaced.

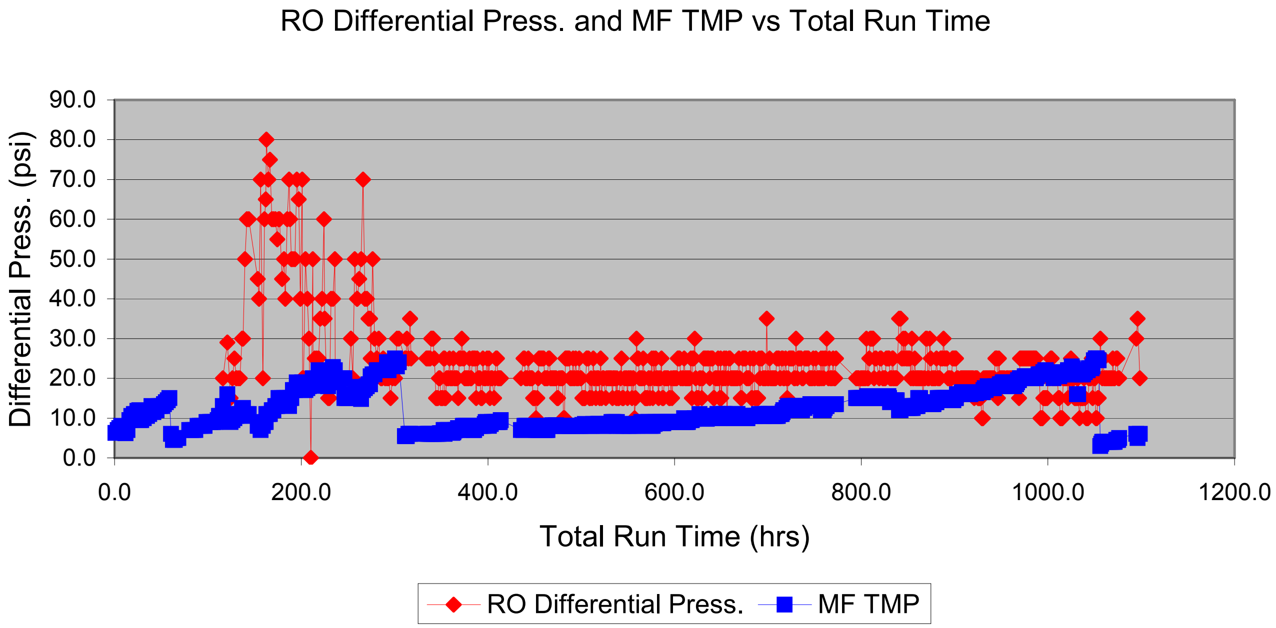
There are several factors that affect the cleaning frequency for a microfiltration, or ultrafiltration system. The main factors are operational recovery and the filtrate flux rate. These system factors are optimized to produce the maximum amount of filtrate with the smallest possible cleaning frequency per the end user's needs. As a rule of thumb, the higher the system recovery and flux rate, the shorter the productive run time will be and subsequent cleaning frequency will increase. By increasing the reject rate, one can allow more of the concentrated, rejected material to be removed via the higher flow rate. In doing so, it will take a longer time to grow a large film of reject material on the membrane surface thus improving the membrane's productive life between cleanings. Operational recovery is the ratio of filtrate made to the feed flow rate expressed as a percentage. Therefore, if the recovery is raised, permeate output increases accordingly as does the flux rate.

Microfiltration and the LWP

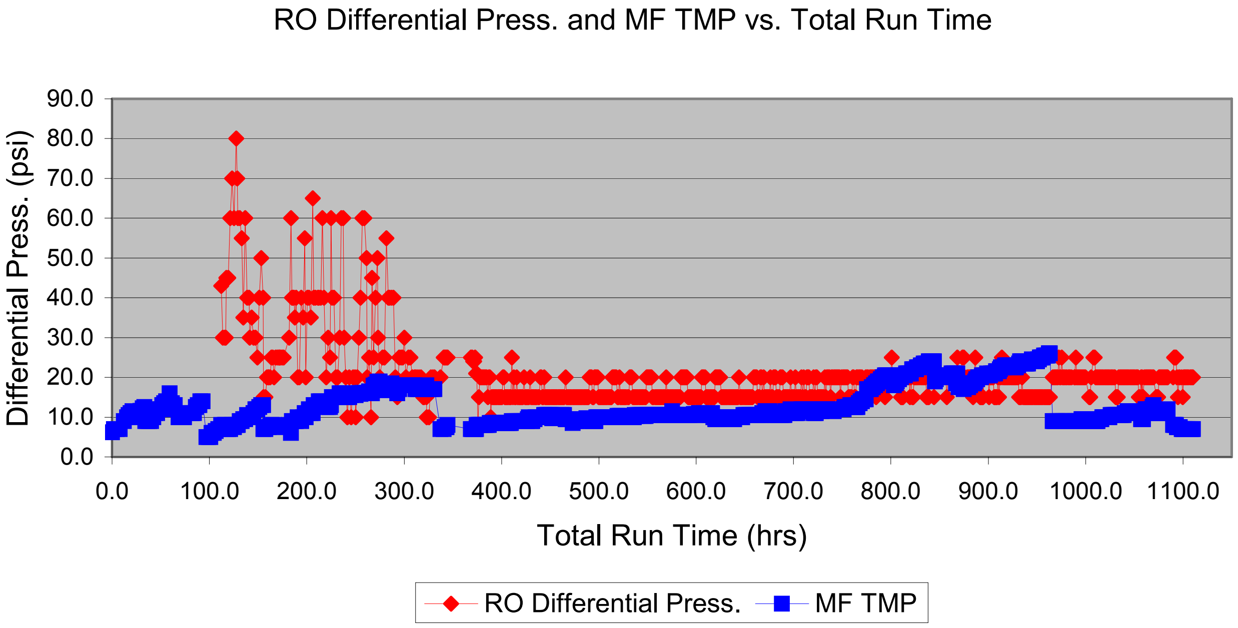
As stated previously, the military Lightweight Water Purifier design team tested microfiltration as the pre-filtering system for the reverse osmosis skid feed initially. Analysis of several hundred operational testing hours on this system yielded interesting data regarding the use of microfiltration as an upstream RO pretreatment. This data is discussed in more detail below.

The LWP went through multiple rounds of testing to optimize the system design for maximum reliability and longevity. The unit configuration during the first round of reliability testing used microfiltration as the RO pretreatment. Graphs 1, 2, and 3, seen below, show the RO differential pressure fluctuation as a function of total run time with each of the three prototype units. The raw water source, located at Port Hueneme, California, was measured at approximately 45K ppm TDS with an average turbidity of 5.12 NTU. No RO cleanings were required at any point during this testing.

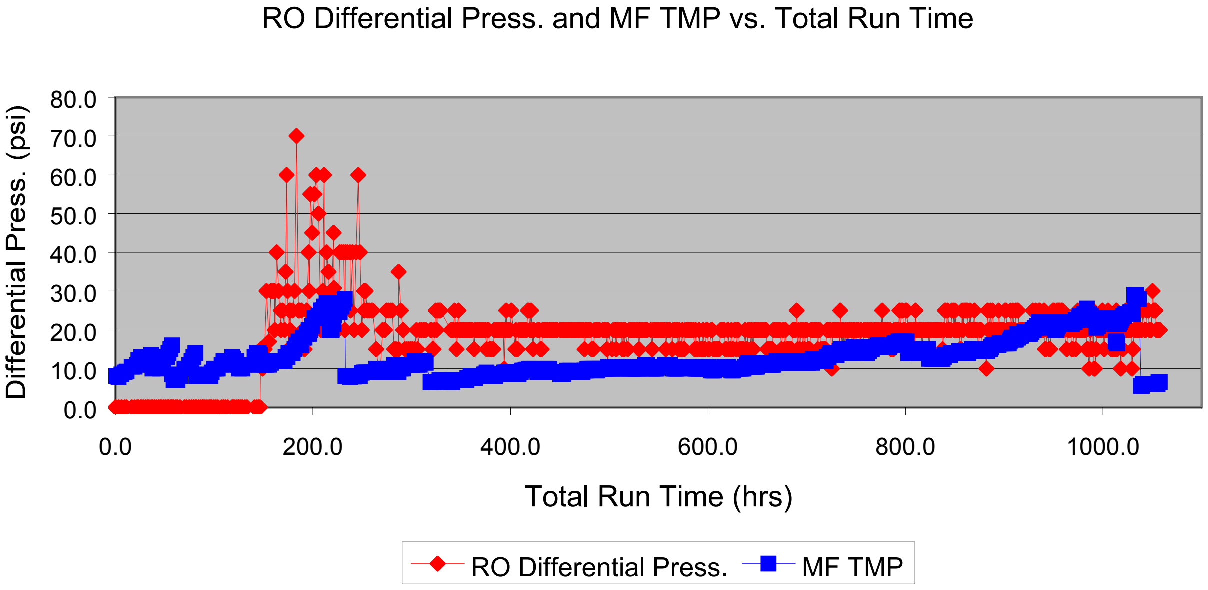
The RO differential pressure is somewhat erratic. However, during 1000 hours of accumulated operating time, not one RO cleaning was required. In addition, the MF cleaning frequency was very small.



Graph 1. MF prototype unit 1 with water source from Chesapeake Bay, Md. & Port Hueneme, Ca.



Graph 2. MF prototype unit 2 with source water from Chesapeake Bay, Md. & Port Hueneme, Ca.



Graph 3. MF prototype unit 3 with source water from Chesapeake Bay, Md. Port Hueneme, Ca.

Ultra filtration

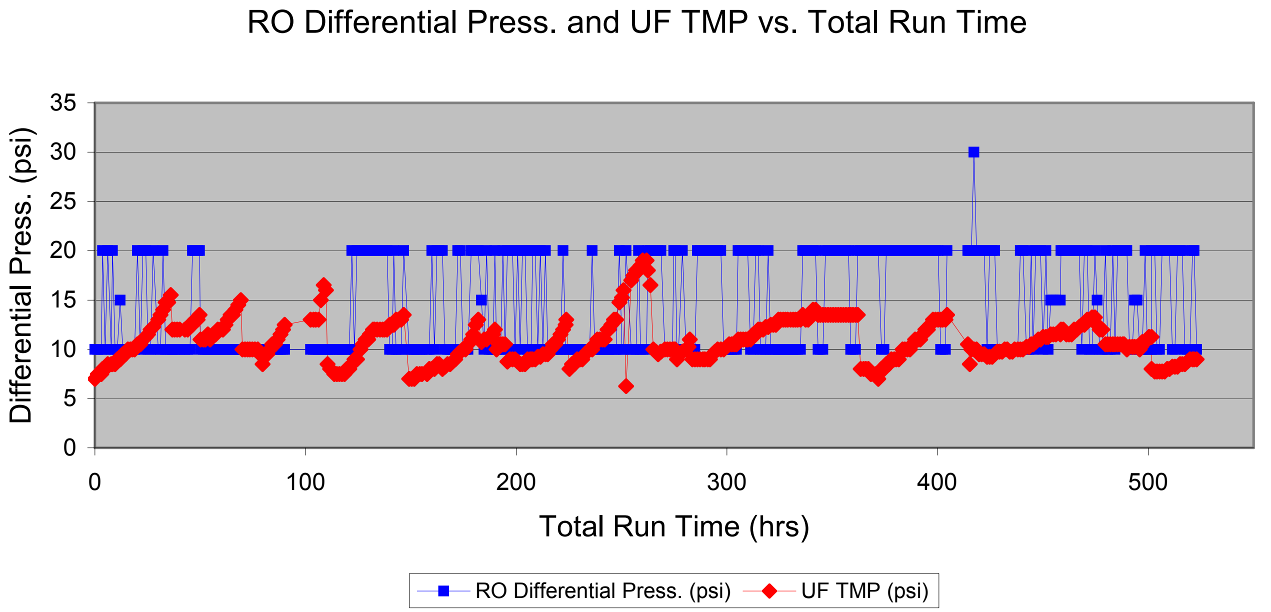
Membrane filtration is often characterized by the pore size of the membrane in use. However, other properties of membranes include Molecular Weight Cutoff, typical operating pressure, and membrane configurations, i.e. tubular, spiral wound, hollow fiber. Ultrafiltration membranes filter impurities as small as 0.01µm. Impurity rejection is based on size as shown in Figure 4. Membrane materials for ultrafiltration can vary widely from polysulfone or ceramic to polyamide or a cellulose acetate polymer. Since membrane filtration is a pressure driven process, the smaller the membrane pores are the larger the feed pressure must be to help drive the purified fluid across the membrane surface. Unwanted impurities are left deposited on the membrane surface and are carried away by the reject stream, which is highly concentrated with these impurities.

Like microfiltration, it was found through research and development that ultrafilitration upstream of a RO train significantly lengthens the time between cleanings. It was also found, and is reflected in the collected data, that ultrafiltration pretreatment allowed the RO system to operate much more consistently than before. The consistent, low TMP that was read during testing exemplifies this assertion. This is attributed to the ability of the ultrafiltration system to significantly reduce the turbidity of the feed water, hence greatly reducing the scaling potential of the feed water to the RO membranes. The graphs below show the LWP ultrafiltration differential pressures for three different units while going through reliability testing at Camp Leguene, North Carolina. Feed water was pulled directly from a bay located on the base. As shown previously, typical turbidity measurements were found to be around 5 NTU as an average value.

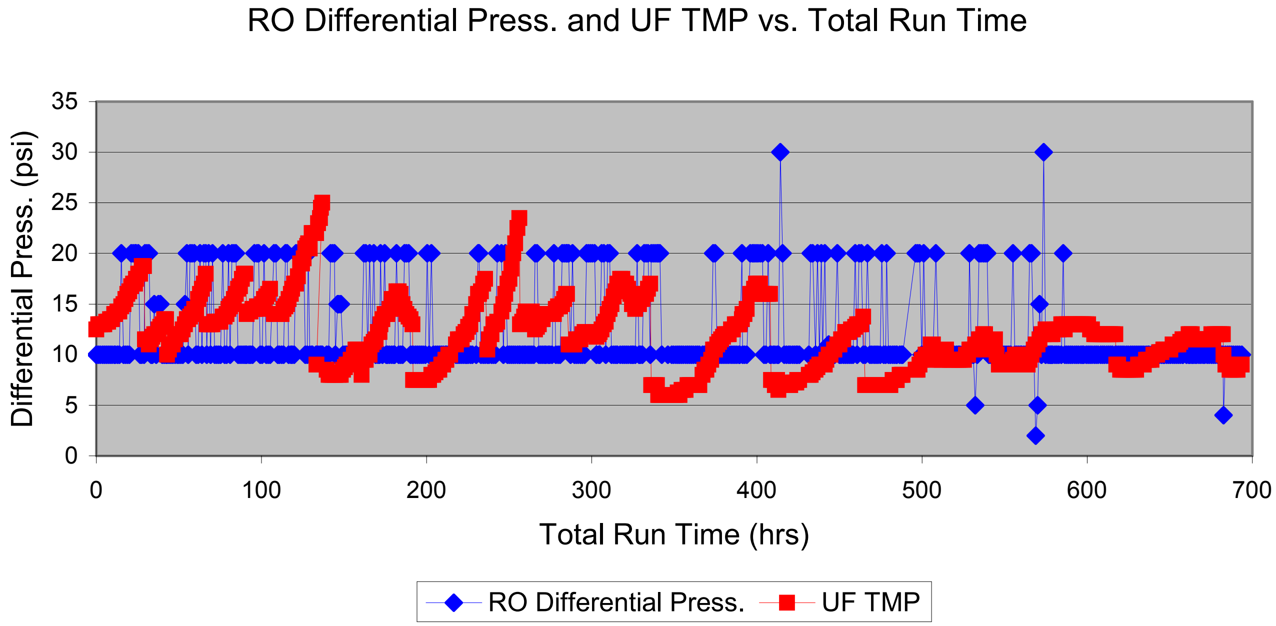
As with the microfiltration system, the ultrafiltration system performed exceptionally well. The RO system was not cleaned once and the differential pressure of the unit held very steady, as seen in the data below. With the LWP ultrafiltration system a series of automated actions is achieved using electrically actuated solenoid valves, both the feed and backwash pumps, and a Programmable Logic Controller. Using a combination of backwash and fastflush techniques, the system is able to go offline from making filtrate for a period of time while maintaining an adequate amount of filtrate to sustain the RO high-pressure pump during the cleaning episode.

Several different sets of data were taken with the system running in several different variations. These variations in parameters included the following:

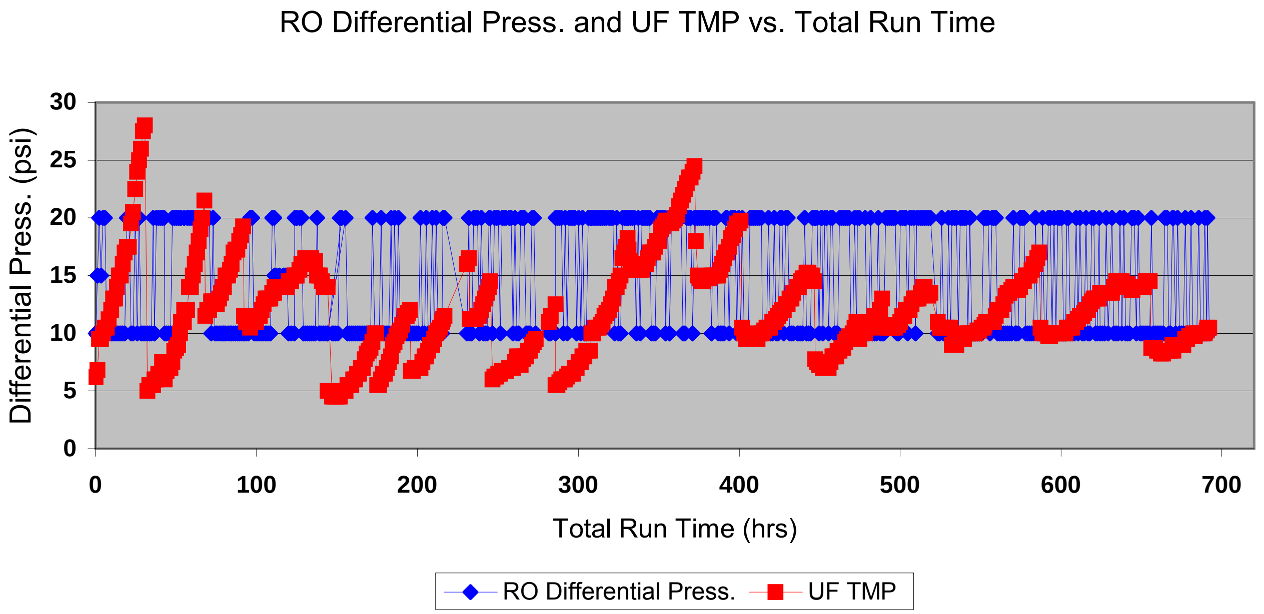
1) Manual isolation of each membrane during the backwash/fastflush phase.
2) Varying the reject while maintaining adequate filtrate flow for meeting required RO permeate capacity given a set rejection and feed rate.
3) Installing solenoid-operated valves that permit the system to be backwashed and fastflushed.



Graph 4. UF Prototype unit 1 with source water from Chesapeake Bay, Md. & Camp Lejuene, N.C.



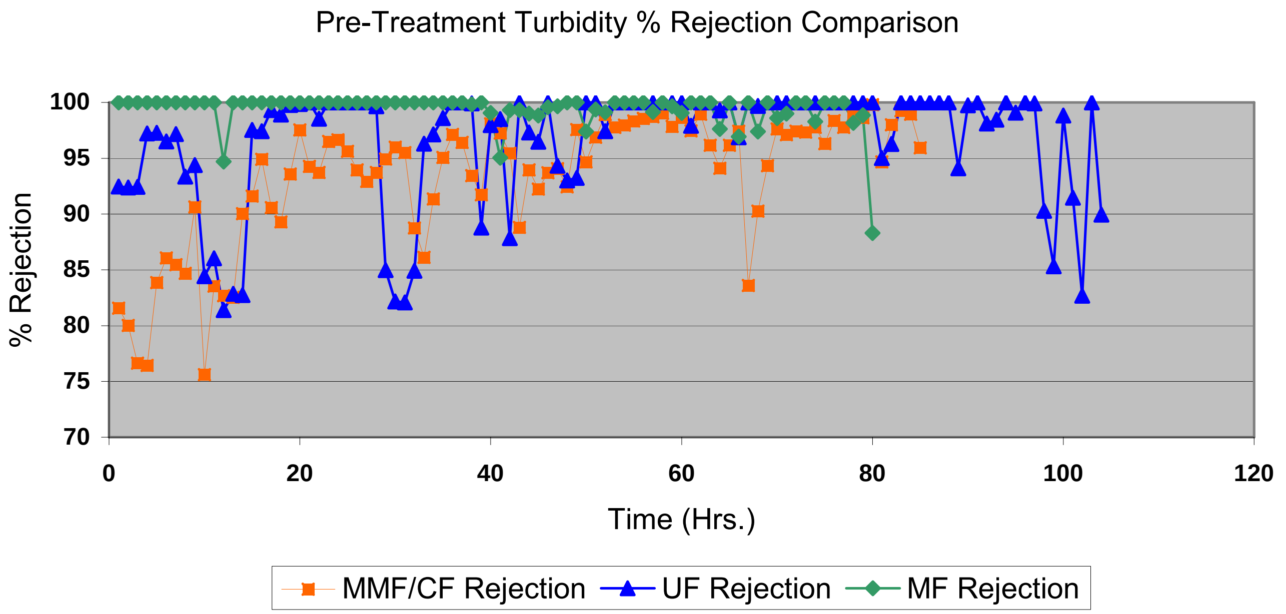
Graph 5. UF Prototype unit 2 with source water from Chesapeake Bay, Md. & Camp Lejuene, N.C.



Graph 6. UF Prototype unit 3 with source water from Chesapeake Bay, Md. & Camp Lejuene, N.C.

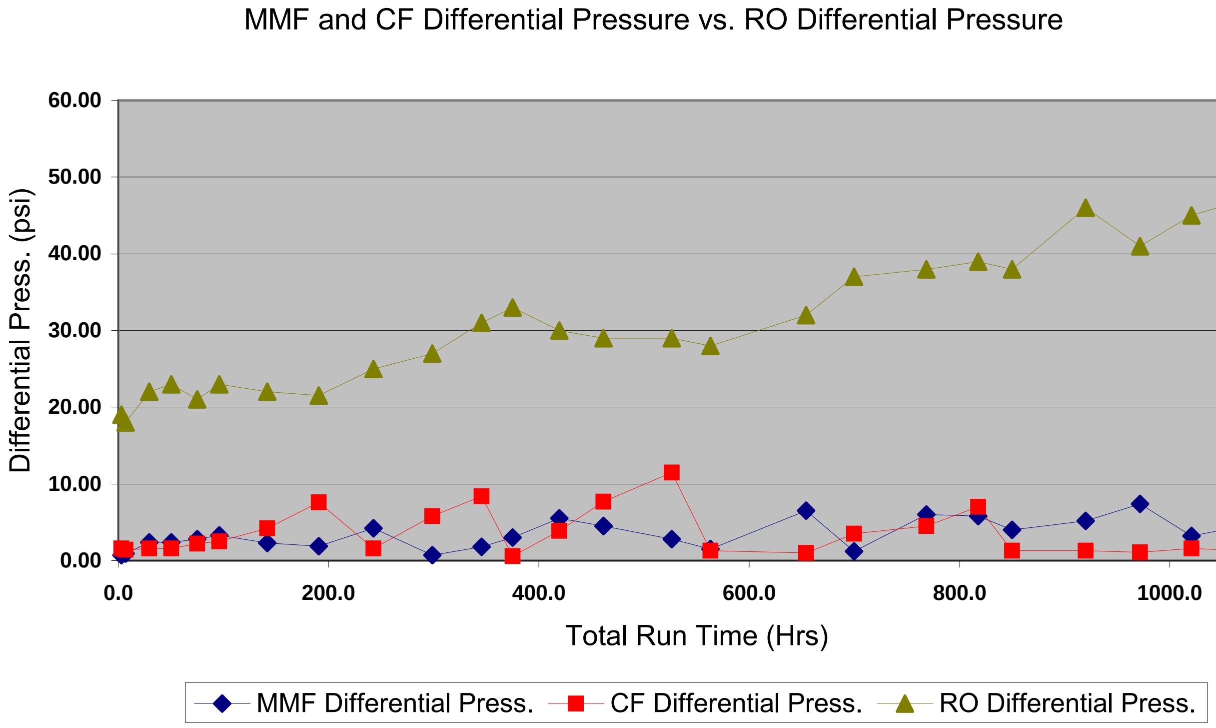
Filtration Results from Testing

The reduction of feed water turbidity was calculated for all tested forms of filtration: ultrafiltration, microfiltration, cartridge filtration, and multi media filtration. The percent reduction of the feed water turbidity is the feed turbidity divided by the filtrate turbidity. The results of these calculations for each filtration method can be seen in Graph 7 as taken during a 100 hr test period. Because the data is taken from different water sources based on unit location during military testing, the average source water turbidity for each varies greatly. MMF and CF data were taken from a MMF/CF filtration system that put the two methods in series. This data was taken at Port Hueneme, California. The average feed turbidity reading for each of these filtration methods was 2.47 NTU to the MMF and 0.244 NTU to the CF from the Port Hueneme test sight. Ultrafiltration data was taken at a marine military installation located in Camp Lejune, North Carolina. The average turbidity reading here was found to be 18.2 NTU. The microfiltration testing was also performed at Port Hueneme, California. The average turbidity value for this test was 6.15 NTU. Membrane filtration, whether UF or MF, demonstrates a higher removal of suspended solids than the more traditional multimedia and cartridge filtration in series. Cartridge filter change frequency was not available.



Graph 7. Comparison of the percent reduction of feed turbidity in various prefiltration systems
MMF and CF data courtesy of NFESC, Port Hueneme, Ca.

Further review of the data collected from a 600 gal/hr Reverse Osmosis Water Purification System (ROWPU) belonging to the U.S. Army shows the build up of the RO system's differential pressure utilizing MMF and CF in series as the prefiltration systems. Plotted in Graph 8 are the differential pressure readings for the MMF, CF, and RO systems over a period of run time. The gradual rise in RO differential pressure should be noted. In comparison to that seen from the UF system, the effectiveness of the UF system on both controlling RO differential pressure and reducing turbidity is obvious over a comparable time period considering other filtration types.



Graph 8. 600 ROWPU unit using MMF and CF prefiltration.
MMF and CF data courtesy of NFESC, Port Hueneme, Ca.

Summary

While multimedia and cartridge filtration do reduce the turbidity of feedwater to downstream reverse osmosis systems, membrane filtration is more effective and efficient at reducing turbidity and controlling RO differential pressure. Presented data has shown that microfiltration and ultafiltration each reduced the turbidity present in the feedwater more than 96% as an average. This is in comparison to a 92% reduction of turbidity in a system utilizing multimedia and cartridge filtration in series. The RO differential pressure, a sign of fouling on the membrane surface, was held down with little to no fluctuation using ultrafiltration. Microfiltration prior to an RO system yielded lower control over the RO differential pressure despite having the highest turbidity reduction. Multimedia and cartridge filtration data analysis showed steady increase in RO differential pressure over a similar run time.

There were no chemical cleanings performed on the ultrafiltration pretreatment system during over 900 hrs of cumulative operation time between three pilot systems. In addition, not one chemical cleaning of the RO skid was performed during UF/MF testing despite operating on a feedwater TDS of greater than 60K and feed turbidities as high as 53 NTU. This is attributed to the excellent performance in turbidity reduction by the ultrafiltration and microfiltration systems. The frequency of cartridge filter changing and multimedia backwashing was not provided by NFESC.

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References

Dow North America, Liquid Seperations. Filmtec Membrane Elements Technical Manual. 1995.

Koch Membrane Systems, Inc. Industrial Water Filtration Product Manual. 1999.