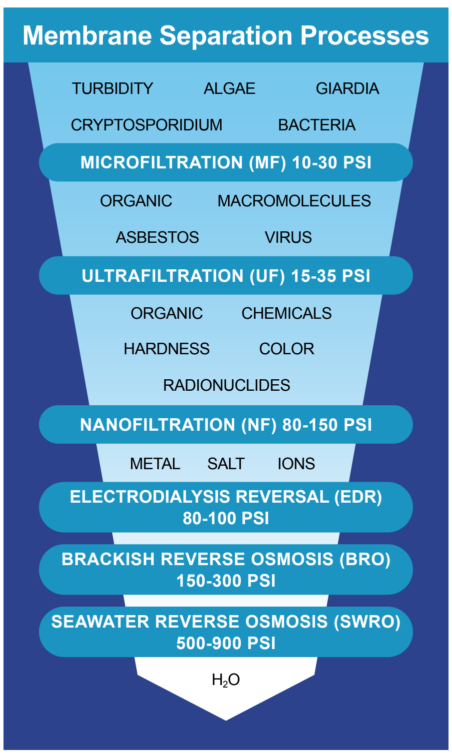
# APPLICATION of Membrane Technologies

Membrane technologies have seen a significant growth and increase in application in the last two decades. Membrane systems are now available in several different forms and sizes, each uniquely fitting a particular need and application. This fact sheet provides a brief overview of membrane technologies with their general use and application.




**Reverse osmosis** (RO) membrane technology has been successfully used since the 1970s for brackish and seawater desalination. A lower pressure RO technology called **nanofiltration** (NF), also known as “membrane softening,” has also been widely used for treatment of hard, high color, and high organic content water.

In addition, RO systems are utilized for removal of inorganic contaminants such as radionuclides, nitrates, arsenic, and other contaminants such as pesticides.

A non-pressure, electric potential driven membrane called **Electrodialysis Reversal** (EDR) has also been widely used for removal of dissolved substances and contaminants.

RO is a physical separation process in which properly pretreated source water is delivered at moderate pressures against a semi-permeable membrane. The membrane rejects most dissolved ions and molecules, while allowing water of very low dissolved ion content to pass through. This process also works as an absolute barrier for cysts and most viruses. The process produces a concentrated reject stream in addition to the clean permeate product. By-product water—or the “concentrate”—may range from 10% to 60% of the raw water pumped to the reverse osmosis unit. For most brackish waters and ionic contaminant removal applications, the concentrate is in the 10 to 25% range, while for seawater, it could be as high as 60%.

**Figure 1:** Reverse Osmosis/Nanofiltration

**Figure 2:** Electrodialysis Reversal (EDR)

In the EDR process, electrical energy pulls ions through a membrane, with separate passes required for the positive and negative ions, leaving behind feed water with only the ions without a charge. Typically, RO/NF elements are in spiral wound element configuration **(Figure 1)**, while EDR is in stacks containing membrane sheets **(Figure 2)**.

During the last two decades, utilities nationwide have turned to low pressure membrane filtration to meet more stringent water quality requirements. Low pressure **microfiltration** (MF) and **ultrafiltration** (UF) membrane filtration technologies have emerged as viable options for addressing current and future drinking water regulations related to the treatment of surface water, groundwater under the influence, and water reuse applications for microbial and turbidity removal.

MF membranes remove only particulate matter and are capable of removing particles with sizes down to 0.1- 0.2 microns. Some UF processes have a lower cutoff rating of 0.005-0.01 microns. Pressure or vacuum may be used as the driving force to transport water across the membrane surface. Most MF/UF systems operate with high recoveries of 90 to 98%. Full-scale facilities have demonstrated the efficient performance of both MF and UF as feasible treatment alternatives to conventional granular media processes. Both systems have been shown to exceed the removal efficiencies required by the Surface Water Treatment Rule such as those for *Cryptosporidium* oocyst, *Giardia* cyst, and turbidity. MF and UF membrane systems generally use hollow fibers that can be operated in the outside-in or inside-out direction of flow. Pressure (5 to 35 psi) or vacuum (-3 to -12 psi for outside-in membranes only) can be used as the driving force across the membrane.

MF and UF membranes are most commonly made from various organic polymers such as different polysulfones and polyvinylidene fluoride (PVDF). Physical configurations include hollow fiber, spiral wound, cartridge, flat plate/sheet and tubular **(Figure 3)**.

**Figure 3:** Microfiltration/Ultrafiltration

**Membrane bioreactor** (MBR) and tertiary treatment systems are the best available technologies for treating wastewater for communities that are concerned about protecting the environment and preserving potable water supplies. Whether a community needs to improve the effluent quality from its existing conventional wastewater treatment plant or construct a new compact and highly efficient wastewater treatment system, MBRs provide cost-effective solutions that will meet or exceed discharge standards for years to come. Effluent from these systems is of such high quality that it can be safely discharged into the most sensitive aquatic environments or reused in irrigation, industrial processes, or groundwater recharge **(Figure 4)**.

**Figure 4:** Membrane Bioreactor (MBR)

With so many utilities facing the threat of contamination from an increasing number of sources, the need for new and better ways of treating and protecting our water supplies is paramount. Although there is no guarantee of complete protection against an attack, spill, or infiltration of natural or international contaminants, the multi-barrier approach, along with the other benefits of membrane technology, can reduce the potential for disasters substantially. Together, with all other safety and security measures recommended by national and federal guidelines, the installation of membrane systems in a facility provides water agencies with an effective multi-barrier system.

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Membrane technologies provide high quality treatment solutions for a wide range of situations, with multiple full-scale global applications in:

- Drinking Water
- Municipal Wastewater
- Industrial Wastewater
- Ultrapure Water
- Recovery/Reuse
- Agriculture
- Landfill Leachate
- Pharmaceutical
- Power Generation
- Pulp and Paper
- Semiconductor
- Specialty Chemicals
- and even Floating Plants!

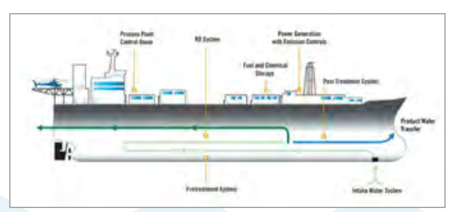

**Figure 5:** Seawater Desalination Vessel

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# Nanofiltration and Reverse Osmosis (NF/RO)

## OVERVIEW

Reverse osmosis (RO) is a physical separation process in which properly pretreated source water is delivered at moderate pressures against a semi-permeable membrane. The membrane rejects most solute ions and molecules, while allowing water of very low mineral content to pass through (**Figure 1**). This process also works as a barrier for cysts and viruses. The process produces a concentrated reject stream in addition to the clean permeate product. Reverse osmosis systems have been successfully applied to saline groundwaters, brackish waters, and seawater, as well as for removal of inorganic contaminants such as radionuclides, nitrates, arsenic, and other contaminants such as pesticides, trace organics, and per- and polyfluoroalkyl substances (PFAS).

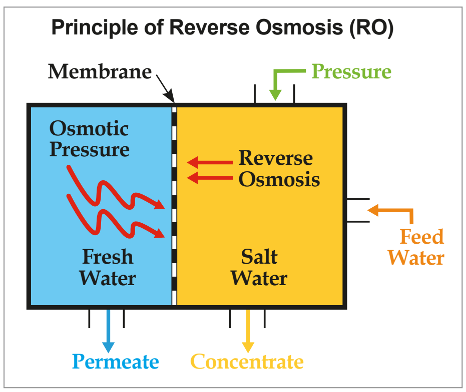


**Figure 1:** Principle of Reverse Osmosis

In an RO system, a higher concentration solution on one side of a semi-permeable, thin film composite membrane is subjected to pressure, causing low salinity permeate to diffuse through the membrane and leaving behind a more concentrated solution containing a majority of the dissolved minerals and other contaminants. The major energy requirement for reverse osmosis is to pressurize the source, or "feed" water. Depending on the characteristics of the feedwater, different types of membranes may be used. Because membranes are used for molecular level rejection, suspended solids and debris must be removed during the initial treatment phase (pretreatment) before entering the membrane elements.

A lower pressure RO technology called nanofiltration (NF), also known as membrane softening, has been successfully used to treat hard, high color, and high organic content feedwater. The NF membrane has lower monovalent ion rejection properties, making it more suitable to treat waters with low salinity and thereby reducing post-treatment and conditioning as compared with RO. The NF membrane also works as a barrier for cysts and most viruses. NF plants typically operate at 85 to 95 percent recovery. Brackish water RO plants typically recover 70 to 85 percent of the source water into permeate, and seawater RO recovery rates range from 40 to 60 percent.

Membrane elements are the building blocks of any NF/RO facilities. Elements are placed in pressure vessels in series, typically five to seven. Pressure vessels are then configured on skids, depending on the number of stages required. Multiple skids then make up the typical NF/RO facility (**Figure 2**).

## SELECTING NF/RO MEMBRANE SYSTEMS

When selecting RO/NF systems, the following should be considered:

1. ***Membrane Selection:*** The majority of NF/RO membranes are polyamide composites in a spiral wound configuration. Materials are generally cellulose acetate (CA) based and polyamide thin film composites (TFC), with TFC more commonly used. Objectives for fluid separation will determine whether to use NF/RO in either CA or TFC and will also depend on the application, feedwater, pH range, operating conditions, and permeate quality and quantity desired. Operational conditions and useful life vary depending on the type of membrane selected, quality of feedwater, and process operating parameters.
2. ***Useful Life of the Membrane:*** Membrane replacement and power consumption represent major components in the overall water production costs. Feed water salinity is important; however, other constituents that foul and scale membranes need to be controlled to maximize useful life versus replacement. Well-designed and operated RO systems can yield a membrane service life of five to 10 years with proper maintenance. Many facilities have membrane elements over 12 years. Some facilities replace elements to take advantage of improvements in energy demand and improved rejection properties even though the original membranes still perform well.

**Figure 2:** A Plant With Multiple RO Skids

3. ***Pretreatment Requirements:*** Acceptable feedwater characteristics depend on the type of membrane chosen and operational parameters of the system. Without suitable pretreatment or acceptable feedwater quality, the membrane may become fouled or scaled, and consequently its useful life is shortened. Pretreatment is essential and pretreatment processes should be tested for Silt Density Index (SDI), turbidity reduction, iron or manganese removal, stabilization of the water to prevent scale formation, microbial control, chlorine removal (for certain membrane types), and pH adjustment. As a minimum pretreatment, one-to-five-micron cartridge filters (**Figure 3**) are used to protect membranes against particulate matter or source water upsets.

**Figure 3:** Cartridge Filter Housings for Pretreatment

4. ***Treatment Efficiency:*** Reverse osmosis is highly efficient in removing metallic salts and ions from feedwater. However, efficiencies vary depending on the ion being removed and the membrane utilized. For most commonly found ions, removal efficiencies will range from 85 percent to more than 99 percent. Organics removal is dependent on the molecular weight, shape and charge of the organic molecule, and the characteristics of the membrane utilized. Organic removal efficiencies may range from as high as 99 percent to less than 50 percent, depending on the membrane type and treatment objective.

For more information on pretreatment, post treatment and piloting, visit AMTA's Membrane Technology Fact Sheet Library.

5. ***Bypass Water:*** Reverse osmosis permeate will be virtually demineralized. The extent of demineralization depends on the type of membrane used. If the raw water does not contain pathogens, viruses and unacceptable contaminants, the design may provide for a portion of the raw water to bypass the unit and blend with RO permeate. Bypass/blend can maintain stable water within the distribution system, reduce equipment size and power requirements, and improve process economics.

6. ***Post-Treatment:*** Post-treatment typically includes degasification for carbon dioxide (if excessive) and hydrogen sulfide removal (if present); pH and hardness adjustment for corrosion control; and disinfection as a secondary pathogen control and for distribution system protection.

7. ***Desalting By-Product:*** By-product water—the concentrate—may range from 10 to 60 percent of the feedwater pumped to the RO unit. For most brackish waters and ionic contaminant removal applications, the by-product is in the 10 to 25 percent range, while for seawater, it could be as high as 60 percent. The by-product volume should be evaluated in terms of availability of source water and cost of disposal. Acceptable methods of by-product disposal typically include discharge to a municipal sewer system or waste treatment facility, to sea, deep well injection, or other environmentally acceptable methods, depending on the by-product concentration, available options, and regulatory requirements.

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8. ***Pilot Plant Study:*** Prior to initiating the design of an RO treatment facility, contact the regulatory agency to determine if a pilot plant study is required. In many cases, a pilot plant study is recommended to determine the best membrane to use, pretreatment and post-treatment requirements, bypass ratio, volume of reject water, system recovery, process efficiency, and other design and operational parameters.

9. ***Skid Design:*** Depending on the size of skid, they can be pre-fabricated, factory tested and shipped to the site (**Figure 4**), or fabricated on site, which is typical of larger facilities (**Figure 5**).

**Figure 4:** Example of Prefabricated Skids

**Figure 5:** Larger RO Facility Example

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# Management of Desalination Concentrate

*A Boardwalk in a created marsh*

To date, the drinking water industry has primarily focused on the use and management of freshwater supplies to meet demands. However, in several regions of the U.S., these supplies have been utilized and managed to their full capacity. Purveyors of potable water have turned to supplies of lesser quality. These include brackish groundwater, brackish surface water, waste water recycle and seawater. Treatment of these waters for potable use requires membrane desalting technologies such as reverse osmosis (RO, nanofiltration (NF) and electrodialysis reversal (EDR).

RO, NF and EDR are used worldwide and across the US and more heavily in the states of California, Florida, and Texas. One hurdle to the growing demand for membrane desalting technologies is the disposal of resulting by-products or concentrate.

Desalination water treatment plants (DWTPs) produce concentrate as they separate salts, minerals, and other dissolved constituents from the water. The separation of these constituents' results in two flow streams: 1) a purified potable stream (permeate), and 2) a stream containing the separated dissolved constituents. The latter by-product stream is typically referred to by regulators as "concentrate" and sometimes inappropriately referred to as "brine"[1]. A mass balance will show that the total dissolved solids in the permeate and concentrate streams equals the total in the feed. No materials are added during the process

*Reverse Osmosis and Nanofiltration trains generate permeate and concentrate*

### By-Product Disposal Alternatives

Concentrate is commonly disposed of through one of six practices: 1) waste water treatment plant discharge, 2) surface water discharge, 3) irrigation, 4) deep well injection 5) evaporation ponds, 6) zero liquid discharge thermal processes. Each of these methods varies in complexity of permitting and costs, with waste water discharge commonly being the least complex and least costly and zero liquid discharge being the most complex and most costly.

Waste Water Treatment Discharge is dependent on the ability of the wastewater treatment plant to accept high salinity discharge both in terms of capacity as well as water quality. The biological process may also be impacted by the dissolved solids and salinity in the concentrate. The treatment plant outfall location may be affected by total dissolved solids restrictions or other limiting water quality concerns. A national pollution discharge elimination system (NPDES) permit is required and maintained by the WWTP owner. In some instances, a desalination plant is operated at a lower recovery so that the concentrate will not exceed the acceptable levels of salt for the WWTP.

Surface Water Discharge involves discharge to a point of outfall such as a bay, tidal lake, brackish canal, or ocean. The location and potential required by-product treatment prior to discharge are determined by state and regulatory agency water quality standards and bioassay toxicity testing. An NPDES

*Mangroves can assist in removal of dissolved nutrients*

permit is required and maintained by the DWTP owner. In a few cases a marsh has been created to take the concentrate at the head of the marsh. Water from the nearby water body is added to the marsh. As the blended water moves through the marsh, the dissolved nutrients are removed and the water quality improved. Such marshes serve a multitude of purposes including a recreational area, a robust ecosystem, nutrient filtration and removal system. Indian River County, Florida created a marsh from an abandoned citrus grove and pumps nanofiltration plant effluent into the head of the marsh. Wildlife has flourished and the quality of the discharge from the marsh is better than the river water that is blended with the concentrate at the front of the marsh.

Irrigation is sometimes used for concentrate streams relatively lower in salinity. Saline tolerant vegetation and habitat are required. This is usually determined by site-specific soil and drainage characteristics. An NPDES permit is required and maintained by the DWTP owner if run-off from irrigation is possible. With the increase

*Irrigation of golf courses*

of water reuse projects, RO and NF concentrate has been blended with treated waste water for irrigation and even stream augmentation. In one plant, the recovery rate of the NF system is kept lower than optimum to minimize the total level of salts in the concentrate and make it more compatible with the reuse water for distribution. In cases such as this the WWTP owner would hold the NPDES permit.

Deep Well Injection is very common, especially with inland DWTPs. This method injects the concentrate deep below ground under at least one

*Injection wells can be used for disposal of concentrate*

overlaying, confining geologic layer. Concentrate is confined in the injection zone. The ability to use an injection well does depend on local geology and can be an expensive alternative. The disposal wells must be double-walled, Monitoring wells are required and a redundant well is needed. Several states don't permit deep well injection.

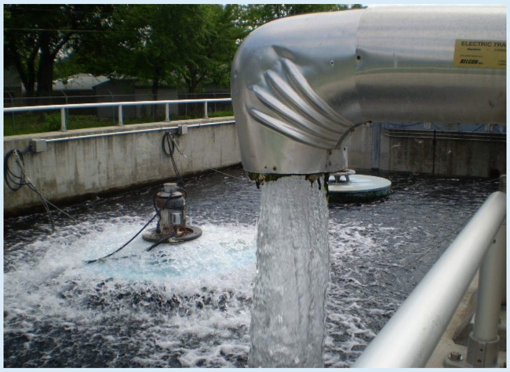
Evaporation Ponds may be used to reduce or eliminate by-product flows. This method of disposal is land-intensive and requires relatively dry climates with high net evaporation rates. Solid salt mixtures are the waste product which must be characterized and disposed of accordingly as solid waste.

Zero Liquid Discharge Thermal Processes greatly reduce or eliminate the by-product liquid stream through several unit operations including evaporation, crystallization and drying. These processes are energy intensive and are very costly. Solid wastes must be characterized and disposed of accordingly.

Another promising option for use of concentrate is being investigated in El Paso Texas. The concentrate from the Kay Bailey Hutchinson Brackish water treatment plant is being piped to an adjacent facility where the minerals are recovered for additional use. Hydrochloric acid, caustic soda, magnesium sulfate and other compounds are being produced from these minerals. The recovered water is piped back to the RO plant to augment their supply and production.

### Is Desalting By-Product from Drinking Water Production An Industrial Waste?

The answer to this question involves the synergy between the applications for membrane desalting and federal and state agencies responsible for developing laws and issuing National



*Discharge of concentrate to a mixing tank*

Pollution Discharge Elimination System (NPDES) permits.

At present, the Clean Water Act does not specifically address DWTP by-products. As a result, DWTP by-products are addressed through a default classification: industrial waste. This results in a stringent and cumbersome set of regulations applied to an often-benign by-product primarily composed of constituents from a natural water body, albeit in a form that is more concentrated. Furthermore, the term “industrial waste” is alarming to the public. Often, purveyors of potable water are required to spend excessive amounts of finance and efforts educating the public about the benign nature of this by-product. This expense transfers into higher water costs for the treatment process.

The absence of science-based regulations to address DWTP by-products has resulted in an uncertain regulatory environment. The latitude available to regulatory agencies when addressing the default classification of “industrial waste” greatly limits the ability to predict the outcome of any permitting effort and further limits the ability to accurately forecast costs, suitability, environmental compatibility, and other key planning level tasks. Of particular concern are the use of surface water discharge and the issuance of an NPDES permit. Because desalting by-product is inadequately addressed in NPDES law, surface water discharge is often the most problematic yet most applicable method of discharge for larger DWTPs, which are necessary to meet water deficits.

At present, state regulatory agencies have no choice but to address DWTP by-products through industrial waste regulations. These agencies would benefit from more specific regulatory guidance regarding desalting by-product.

*Surface water discharge is sometimes an option*

**Florida Case Study**

The State of Florida recently passed legislation to streamline the permitting process for desalting by-product waters. Though incapable of amending the Clean Water Act to reclassify the by-product out of the industrial waste program, the state was able to change the name and create permitting forms that are better suited for by-product applications.

Florida now refers to “RO concentrate” as a “potable water treatment by-product,” which is still regulated under the industrial program as required by the Clean Water Act. However, the law’s objective is to improve the economics of permitting desalting by-product discharge to surface waters by improving public perception and creating permit applications and permits that are best suited for this type of by-product. Nevertheless, a strong case can and should be made to amend the Clean Water Act to provide for a new, separate classification for DWTP streams and how to deal with them.

AMTA is actively involved in the legislation front and has made the change in regulations of concentrate disposal a top priority for the organization. If you are interested in this topic and want to help AMTA, please contact us.

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[1] Brine is water with twice the concentration of dissolved solids as seawater. Most desalting by-products do not fit this definition. The word “brine” carries a negative connotation since it is also used to refer to some wastes from the petroleum industry.

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# Public Safety and Security

Water supply vulnerability and the potential for contamination by intentional as well as natural and other unintentional means have gained attention in recent years by federal and state agencies. USEPA, the Department of Homeland Security, and the American Waterworks Association (AWWA) have provided tools and training guides for reducing national vulnerability to attacks and minimizing damages.

The purpose of this short information bulletin is not to replace any of these important documents. Instead, it should be reviewed as another tool in the toolbox. Membrane filtration is the finest filtration, capable of removing a wide range of contaminants. While microfiltration (MF) and ultrafiltration (UF) are capable of removing bacteria, Giardia, and Cryptosporidium, reverse osmosis (RO), electrodialysis reversal (EDR), and nanofiltration (NF) can remove small ions and molecules such as pesticides, radionuclides, and arsenic.

Because of health concerns, over the past several years the EPA has reduced the maximum contaminant level (MCL) for many contaminants. The resulting number of utilities with levels of contaminants such as radionuclides, arsenic, and pesticides exceeding the EPA's MCL has increased with thousands in violation.

These contaminants can be either manmade or naturally occurring, and can enter the drinking water supply through runoff (surface water) or infiltration (groundwater). When ingested, these contaminants can have negative short and long-term effects, including birth defects, nervous system damage, and cancers of the skin, lungs, bone, bladder, and kidneys. Membrane plants, as a positive barrier to microbial contamination, are more resistant to source water contamination attacks since the microbes just can't fit through the pores.

In addition, membrane filtration offers other benefits relating to enhanced security and minimizing exposure. Membrane filtration, unlike conventional filtration, is a process that can be fully enclosed in a building. This allows for all treatment processes to have restricted access.

Membrane plants generally have much more sensitive and extensive instrumentation than older conventional plants and can detect any contamination or tampering much quicker and allow the operators to take corrective action much more quickly. The programming that typically accompanies membrane filtration also allows for remote operation of the plant enabling the system to shut itself down on its own or an operator to shut the plant down even if they are not on site.

Finally, Membrane plants generally use less chemicals in the treatment process, thus depriving potential terrorists of potential targets at the plant.

With so many utilities facing the threat of contamination from an increasing number of sources, the need for new and better ways of treating and protecting our water supplies is paramount. Although there is no guarantee of 100% protection against an attack, spill, or infiltration of natural or intentional contaminants, the multi-barrier approach, along with the other benefits of membrane technology, can reduce the potential for disasters substantially. Together with all other safety and security measures recommended by national and federal guidelines, the installation of membrane systems in a facility provides water agencies with an effective multi-barrier system.

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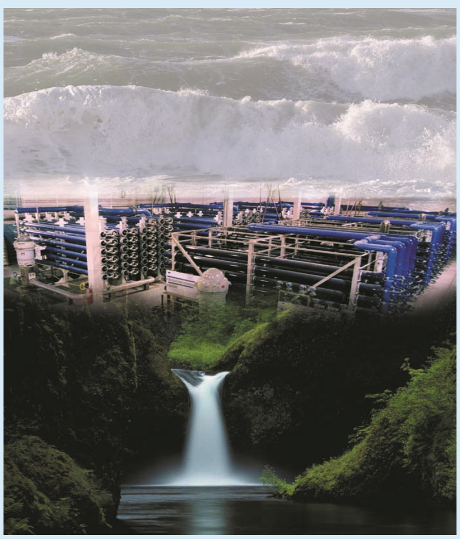
# Membrane Desalination Costs

The growing demand for fresh water in many areas of the world, due to drought, water shortages, population increases and the desire for high quality drinking water, has spurred unprecedented interest in the process of desalting seawater or brackish water (less salty than seawater, but not fresh) to increase the reliability and quantity of water supplies. Long used on ships, island resorts and in water-short countries, the practice of employing desalting technology to produce large-scale domestic supplies is only a few decades old in the United States.



Currently, more than 1,300 desalting plants are operating in the United States, producing over 400 million gallons per day of high quality water, mostly for drinking, with an anticipated investment for the next 5 years of almost $3 billion. Worldwide membrane and thermal desalination capacity is over 11 billion gallons per day from over 12 thousand plants, worth $9.2 billion per year, growing at a rate of 12% per year. Desalinated water has found many uses throughout the world. As shown in Figure 1, the largest of which is the production of acceptable quality drinking water. This water, in general, meets the US health and safety standards of the Environmental Protection Agency (EPA) and Food and Drug Administration (FDA) as well as standards established by other global Agencies, such as the World Health Organization (WHO).

Figure 2 shows the general cost reduction trend in the last few decades, in producing water using brackish and sea water sources.

Over the last 3 decades, pricing for desalting elements has been reduced substantially. As shown in Figure 3, due to technological improvements by suppliers, automation in the manufacturing process and competition, there have been significant reductions in seawater membrane costs. Similar trends have been present in brackish water modules.

Most US plants in coastal areas, desalt brackish waters, as local sources of fresh and brackish water are depleted. However there will be more large-scale seawater desalting plants built, most likely in California, Texas and Florida. Many growth opportunities exist in commercial, industrial and municipal applications for furthering the supply of good quality, low salinity water.

The most common objection to using desalted water to help meet the nation's growing water needs is that. "The process is too expensive." This is no longer valid since recent developments in both technology and processes have dramatically decreased the cost of desalting water using membrane technologies.

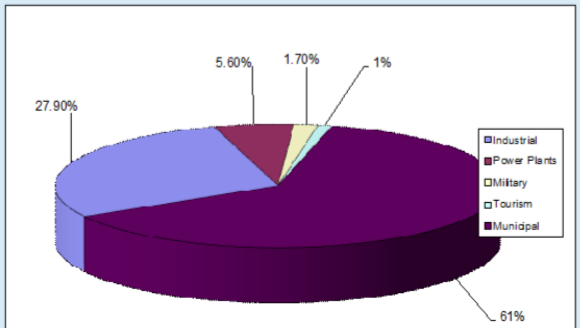


*Figure 1: Worldwide Distribution of Desalination Market Users*

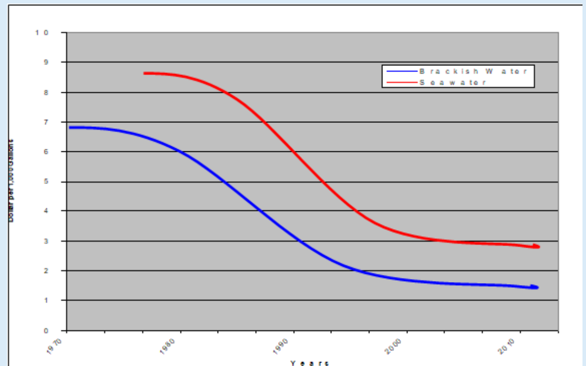


*Figure 2: Cost Reduction in Membrane Desalination*

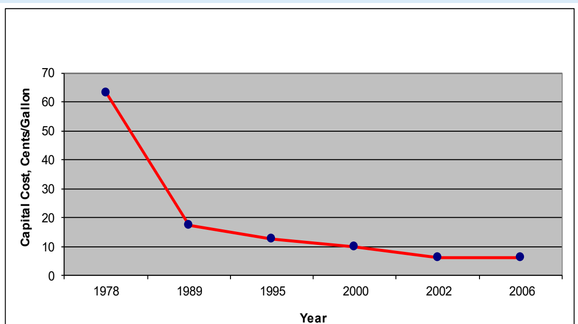


*Figure 3: Seawater Element Price Reduction*

**Desalting Cost as a Portion of Total Supply**

In most cases, desalted water is not the sole source of a community's supply. It is usually combined with water from less expensive sources. For instance, as shown in Table 1, if a community paying $2.50/1,000 gallons for its existing water decides to double its supply with desalted brackish water, in a worse case scenario, a typical family's monthly water bill would increase by about $3 per month. Similarly, if the augmented supply is 10% from desalted seawater, the monthly increase would be less than $6.60.

| TABLE 1: TOTAL WATER COSTS | | |
|---|---|---|
| **SUPPLY TYPE** | To Consumer(1) **$ per 1000 gallons** | Total Family Cost(2) **$ per month** |
| Existing Traditional supply | $0.90-2.50 | $10.80-$30.00 |
| New Desalted Water: | | |
| Brackish(3) | $1.50-3.00 | $18.00-$36.00 |
| Seawater(4, 5) | $3.00-8.00 | $36.00-$96.00 |
| Combined supply(6) | | |
| Traditional + brackish | $1.20-$2.75 | $14.40-$33.00 |
| Traditional + seawater | $1.11-$3.05 | $13.32-$36.60 |

1. *Price includes all costs to consumers for treatment and delivery.*
2. *Cost is based on a family of four using 100 gallons per day per person, for a totally monthly use of 12,000 gallons. Cost is based on the average of the "To Consumer" cost shown.*
3. *Brackish is moderately salty 1,000-5,000mg/L total dissolved solids (TDS).*
4. *Seawater contains 30,000-35,000 mg/L TDS.*
5. *Cost is for typical urban coastal community in the USA. Costs for inland communities may be higher.*
6. *Combined supply costs are for the traditional supply augmented with 50% of desalted brackish water, or 10% of desalted seawater.*

## Desalting Versus Traditional Water Development

In the US, most inexpensive traditional water resources have already been developed. New sources of supply will be more expensive than the existing ones. Of the potential new treatment options, in many cases, desalting a local resource is financially and environmentally competitive with the traditional methods such as building dams, aqueducts, canals and waste treatment plants. Cost comparisons are often made to existing water supplies. Actually, since desalted water represents a new source of supply, comparisons should be made to the cost of developing other new sources, such as surface water impoundments, remote deep well fields, dams and long distance pipelines.

In the last decade, desalting technology has improved significantly and costs have decreased by over 50 percent. At the same time, the cost of developing traditional water sources has escalated, as drinking water quality and environ- mental standards have become more stringent. Inflation affected prices and the distances from source to consumer have also increased. In many water- short areas, the costs for desalted water are already competitive with the tapping of new traditional supplies. As alternative energy sources and improved processes and equipment are developed, additional desalting cost reductions can be expected.

## Cost Factors and Graphs

The cost factors of desalting include capital costs and operating and maintenance costs. Costs can vary considerably from one locality to another based on a number of issues. In general, the amount of salt to be removed greatly affects the cost of desalting plant operation. The more salts to be removed, the more expensive the desalting process. The capacity of the facility also impacts costs, with larger plants generally being more economical. As shown in Figure 4, the larger the facility, the more cost efficient will be the utilization of equipment, labor and funds.

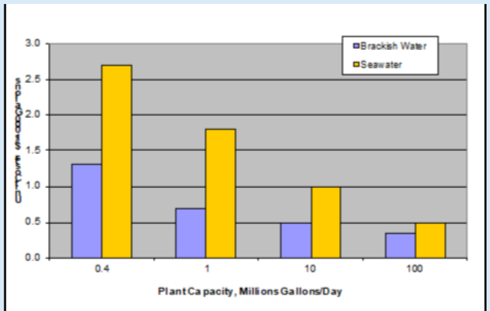



*Figure 4: Typical Operation and Maintenance Costs for Brackish and*

Energy and recovery of capital are the main ingredients of the total cost of water, amounting to about 75% of the total, as shown in Figure 5. To these values, 10-15% can be added for profit, if the desalting project is contracted as a sale of water. The energy cost portion of the total cost greatly depends on the power/fuel pricing.

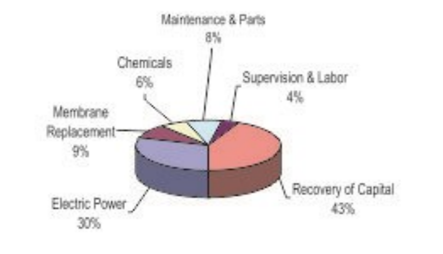



*Figure 5: Breakdown of Total Cost of Desalinated Water*

Other factors include the amount and type of pre and post treatment required, ancillary equipment selected, reliability, disposal of salt (concentrate), regulatory issues, land costs and conveyance of the water to and from the plant. Installing and operating a desalting plant involves a number of individual cost items, all of which are affected by local conditions. Figure 6 depicts typical breakdowns of these costs.

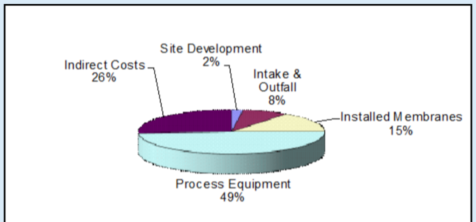



***Figure 6: Breakdown of Desalination Plant Capital Costs***

1. *Indirect Costs Include: working capital, taxes, insurance, land, engineering and project management.*
2. *Outfall cost does not include concentrate discharge treatment which sometimes could be a significant portion of the cost.*

*This material has been prepared as an educational tool by the American Membrane Technology Association (AMTA). It is designed for dissemination to the public to further the understanding of the contribution that membrane water treatment technologies can make toward improving the quality of water supplies in the US and throughout the world.*

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# Water Desalination Processes

Water desalting, or desalination, has long been utilized by water-short nations world- wide to produce or augment drinking water supplies. The process dates back to the 4th century BC when Greek sailors used an evaporative process to desalinate seawater. Today, desalination plants worldwide have the capacity to produce over 11 billion gallons a day – enough water to provide over 36 gallons a day for every person in the United States. About 1,200 desalting plants are in operation in USA.

In the United States, water is relatively inexpensive compared to many other parts of the world. However, the vagaries of weather, population growth and subsequent increases in demand for water in arid, semi- arid and coastal areas are contributing to a heightened interest in water desalination as means to augment existing supplies. In addition, many communities are turning to desalting technologies as a cost-effective method of meeting increasingly stringent water quality regulations. Most potable water desalination plants in the United States utilize membrane processes for desalting brackish (moderately saline) water and for softening and organics removal in ground water (low saline) supplies. However there are several large seawater plants in the planning phase. Desalination is generally divided into two primary categories: Distillation Processes and Membrane Processes.

**Thermal (Distillation) Processes**
Nature, through the hydrologic cycle, provides our planet with a continuous supply of fresh, distilled water. Water evaporates from the ocean (seawater) and other water bodies, accumulates in clouds as vapor, and then condenses and falls to the Earth's surface as rain or snow (fresh water). Distillation desalting processes work in the same way. Over 60 percent of the world's desalted ocean water is produced by boiling seawater to produce water vapor that is then condensed to form fresh water.

Since thermal energy represents a large portion of the overall desalting costs, distillation processes often recover and reuse waste heat from electrical power generating plants to decrease overall energy requirements. Boiling in successive stages each operated at a lower temperature and pressure can also significantly reduce the amount of energy needed.

Vapor phase, or evaporative processes are used primarily for seawater conversion, and consist of the following well established methods:

- Multistage flash evaporation (MSF)
- Multieffect distillation (MED)
- Vapor compression (VC)

MSF and MED require thermal input in addition to electric power, and because they handle hot seawater, materials selection becomes a critical factor in design. VC uses only electric power, with the thermal input coming from heat of compression. VC is generally the most economical evaporative process, but the fan compressors that are used limit the output capacity of the equipment.

*Professor Sidney Loeb and engineer Ed Selover remove newly manufactured reverse osmosis membrane from plate-and-frame production unit circa 1960.*

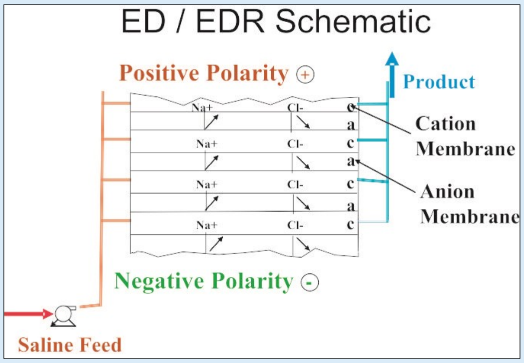
Depending on the plant design, distilled water produced from a thermal desalination plant typically has salt concentrations of between 5 to 50 parts per million (ppm) of Total Dissolved Solids (TDS). Between 25 and 50 percent of the source water is recovered by most distillation methods.

**Membrane Processes**
In the late 1940s, researchers began examining ways in which pure water could be extracted from salt water. Significant research was done in the 1950's at the University of Florida to demonstrate semi-permeable (desalination properties) of cellulose acetate (CA) membranes. During the John F. Kennedy administration, saline water conversion to fresh water was a high priority technology goal, "go to the moon and make the desert bloom", was the slogan. Supported by federal and state funding, a number of researchers advanced the science and technology of saline water conversion, but UCLA made a significant breakthrough in 1959 and became the

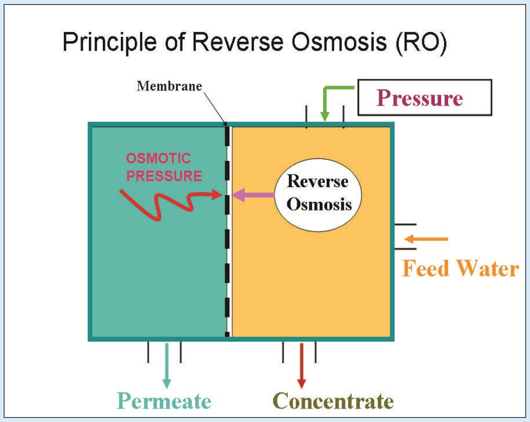
first to demonstrate to be practical a process known as reverse osmosis (RO).

About the same time, some researchers were investigating a non-permeable membrane technology known as electrodialysis. Boththe electrodialysis (ED) and Reverse Osmosis (RO) processes use membranes to separate dissolved salts from water.

**Electrodialysis**
Electrodialysis is an electrochemical process in which the salts pass through the cation and anion membranes, leaving the water behind. It is a process typically used for brackish water. Because most dissolved salts are ionic (either positively or negatively charged) and the ions are attracted to electrodes with an opposite electric charge, membranes that allow selective passage of either positively or negatively charged ions accomplish the desalting. Freshwater recovery rates for this type of process range from 75 to 95 percent of the source water.




**Reverse Osmosis**
When two solutions with different concentrations of a solute are mixed, the total amount of solutes (i.e. salts) in the two solutions will be equally distributed in the total amount of solvent (i.e. water) from the two solutions. In the natural occurring phenomenon of osmosis this is achieved by diffusion, in which solutes will move from areas of higher concentration to areas of lower concentrations until the concentration on both sides of a membrane and the resulting mixture are the same, a state called equilibrium. Equilibrium occurs when the hydrostatic pressure sifferential resulting from the concentration changes on both sides of the semi-permeable membrane is equal to the osmotic pressure of the solute.




In Reverse Osmosis, salt water on one side of a semi-permeable plastic membrane is subjected to pressure, causing fresh water to diffuse through the membrane and leaving behind a more concentrated solution than the source supply containing the majority of the dissolved minerals and other contaminants. The major energy requirement for reverse osmosis is for pressurizing the source, or "feed" water.

Depending on the characteristics of the feed water, different types of membranes may be used. Because the feed water must pass through very narrow passages as a result of the way the membrane packaged, fine particulates or suspended solids must be removed during an initial treatment phase (pretreatment). Brackish water RO plants typically recover 50 to 80 percent of the source water and seawater RO recovery rates range from 30 to 60 percent.

A "loose" version of RO nanofiltration (NF) plants typically operate at 85 to 95 percent recovery, which is typically used for organic removal and softening (reducing calcium and magnesium hardness).

**Applying the Technology**
No one desalting process is necessarily "the best." A variety of factors come into play in choosing the appropriate process for a particular situation. These factors include the quality of the source water, the desired quantity and quality of the water produced, pretreatment, energy and chemical requirements, and methods of concentrate disposal.

**Uses of Desalting**
The conversion of seawater to drinking water is the most publicly recognized use of desalination. Desalination is also used for improving the quality of drinking water from marginal or brackish sources. Membrane desalting technologies are also used in home or tap water treatment systems, in industrial wastewater treatment to reclaim and recycle, to produce high-quality water for the semi-conductor and pharmaceutical industries and for the treatment and recycling of domestic wastewater.

Membrane desalting technologies are not only used to remove salt and other dissolved minerals from water but in addition contaminants, such as dissolved heavy metals, radionuclides, pathogens, arsenic, bacterial and dissolved organic matter may also be removed in a variety of methods.

In the last twenty years, there has been a significant reduction in power requirements of membrane desalination technologies, with improvements in membrane salt rejection and flux properties. As an example Island Water Association's 5 MGD Brackish RO WTP originally installed in 1980 with CA membrane elements operating at 550 psi and 75% recovery with 10% salt passage currently operates non-CA membrane thin film composite polyamide (TFCPA) at 170 psi with only 5% passage. In fact this plant was a pioneer initially converting to TFCPA membrane elements in 1984. In charted performance from December

1986 to October 1998, this plant experienced a decrease from 3.9 KWH / Kgal to 2.7 KWH / Kgal.

**Desalination Future**

Water from desalination is not bound by many of the conditions that plague traditional fresh water development. The increase in the public awareness of the environmental problems associated with fresh water sources coupled with the new, more stringent drinking water quality regulations make development of new traditional water resources more difficult and costly. Unlike traditional water supplies, alternative desalted water supplies are not vulnerable to weather (droughts).

Membrane desalting technologies also allow plants to be built in stages to meet demand, unlike traditional water development with its high initial capital outlay. Finally, membrane desalted water is in many cases comparable in cost to water from traditional water supplies, especially if utilized to augment current supplies.

From initial experiments conducted in the 1950's which produced a few drops per hour, the reverse osmosis membrane industry has today resulted in combined worldwide production in excess of 6.8 billion gallons per day. With demand for pure water ever-increasing, and water shortages world-wide, the growth of the reverse osmosis industry is poised well into the next century.

In the early 1980's, research in US Govern- ment Labs resulted in the first Composite PolyAmide membrane. This membrane had significantly higher permeate flow and better salt rejection than CA membranes. Today, with the advancement of non-CA thin-film composite polyamide membrane elements, the industry has attained a 20 -times increase in energy efficiency over the original CA membrane elements, with a similar order of magnitude decrease in salt passage.

Experts around the world continue to research better membranes for desalination, as well as membranes for contaminant removal, water reclamation, re-use, and industrial applications. The primary focus of the research is on reduction in energy requirements and making elements with higher and selective rejection properties, while minimizing fouling tendencies.

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# Membrane Desalination Water Quality

In the United States, we now regard safe drinking water as a Constitutional right. This was not always the case. Less than a century ago, our nation was periodically beset by epidemics caused by water-borne diseases, such as cholera and typhoid, which took thousands of lives.

Today, conventional as well as advanced water treatment technologies, combined with medical advances, have made these diseases virtually nonexistent in our country. Our drinking water supplies must comply with stringent federal, state and local drinking water standards. These standards are designed to keep contaminant concentrations below the levels, which might be considered a public health threat.

Only about 20 percent of the water withdrawn from surface and ground- water supplies is actually consumed. The remaining 80 percent is generally discharged into rivers, lakes and estuaries as wastewater or irrigation return flows, and can be subsequently reused at downstream locations. Each time water is reused the concentration of pollutants (including salt) in the discharge water increases.

Water desalting, or desalination, is a treatment process used to remove salt and other dissolved minerals from brackish water and seawater. Other contaminants such as heavy metals such as mercury, bacteria, viruses, and other pathogens, organic matter and known carcinogens may also be removed by some desalting methods.

Some compounds known to have adverse health effects, such as arsenic and boron, can also be removed by desalting processes. Pressure driven membrane-based desalting processes can also used to improve the quality of hard waters (high in concentrations of magnesium and calcium), waters contaminated with nitrates, radionuclides, herbicides and pesticides, natural and synthetic organics, and pathogens.

Water Quality Standards
The history of formal water quality standards goes back less than a century. In the 1890's, what was then known as the American Public Health Association began the first push for quality criteria as well as standard methods of analysis. It was not until 1914 that the United States government (strangely enough through the Treasury Department) issued even the most basic quality standards. By 1925, the US Public Health Service was given the lead role, which it retained until the Environmental Protection Agency (EPA) was formed in 1970.

The recent history of standards in the United States revolves largely around the Safe Drinking Water Acts of 1986 and its subsequent amendments. The standards are assigned and regulated at several levels:

- The Federal government, through the EPA, sets the standards, carries out appropriate studies and re- search, coordinates the work of oth- er federal agencies and supports the states in enforcing the standards.
- The states, supported as necessary by EPA, develop their own standards, which must be at least as strict as federal standards. The states enforce the standards and develop their own certification and training programs.
- Local governments and utilities then work within the federal and state guidelines to build and operate facilities, implement land use plans and local regulations to protect water supplies, and carry out other relevant activities.
- Concerned individuals and groups propose additional standards through the initiative process. Such standards usually rely on public referenda, often at the state level, for adoption.

Uses of the Technology
In the United States, population growth and subsequent increases in demand for water in arid, semi-arid and coastal areas are contributing to a heightened interest in desalting membrane processes as a means to augment

existing supplies by treating alternative sources of water previously ignored in favor of traditional freshwater supplies. In addition, many communities are turning to membrane technology and desalting as a cost-effective method of meeting increasingly stringent water quality regulations. Desalting technology can treat non-potable water supplies that are difficult to treat with traditional technology. Desalting technology has become a reliable method of producing high quality water to help meet the nation's growing freshwater needs, and is rapidly gaining credibility as a competitive treatment technology.

Over 1,300 desalting plants are in operation nationwide. Most of these plants, located on the eastern seaboard, the Gulf coast, the southwest, and California, are used to treat brackish, or moderately salty, groundwater for municipal drinking water supplies. The next most frequent use of desalting is to produce highly purified water for industrial use. Seawater desalting is now being considered for municipal water supply in Florida, Texas, California, and Massachusetts. Desalting processes also provide clean water for a variety of other uses:

- To meet more stringent federal drinking water regulations, water suppliers nationwide are turning to desalting to remove contaminants, such as heavy metals, dissolved organics, pathogens and known carcinogens, from both ground water and surface water supplies.

- Desalting is used for water softening and to treat taste, odor and color problems, and the precursors of disinfection byproducts.
- Desalting is used to convert seawater to drinking water. Many water-short areas of the world rely solely on desalted water for their drinking water supplies.
- Desalting is used to treat wastewater from municipal sewage plants for direct or indirect reuse. Such "reclaimed" or "recycled" water may be used for irrigation, fire protection, toilet flushing, industrial processing and cooling, wetlands enhancement and groundwater recharge, among other uses.
- Reverse osmosis is used in point-of-use, home water treatment systems, by individuals concerned about water quality.
- Desalting technologies are used to remove potentially toxic contaminants from industrial wastewater prior to discharge to the environment to meet ever more stringent water quality requirements of the Federal Clean Water Act.

Post-Treatment

The permeate from desalting processes, particularly that from seawater, is primarily a dilute solution of sodium chloride. To provide stability to the water, to prevent corrosion of piping systems and domestic plumbing, post-treatment to return some calcium hardness and bicarbonate alkalinity to the water is necessary. In many locations, post-treatment also includes the removal of carbon dioxide to raise the pH, Hydrogen Sulfide removal, and the addition of fluoride which is removed during the desalting process. Very often, corrosion inhibitors are added to further reduce the corrosion potential of the finished water. As in conventional treatment, disinfection is required, but the chlorine demand is greatly reduced by the desalting process, resulting in minimal formation of disinfection byproducts.

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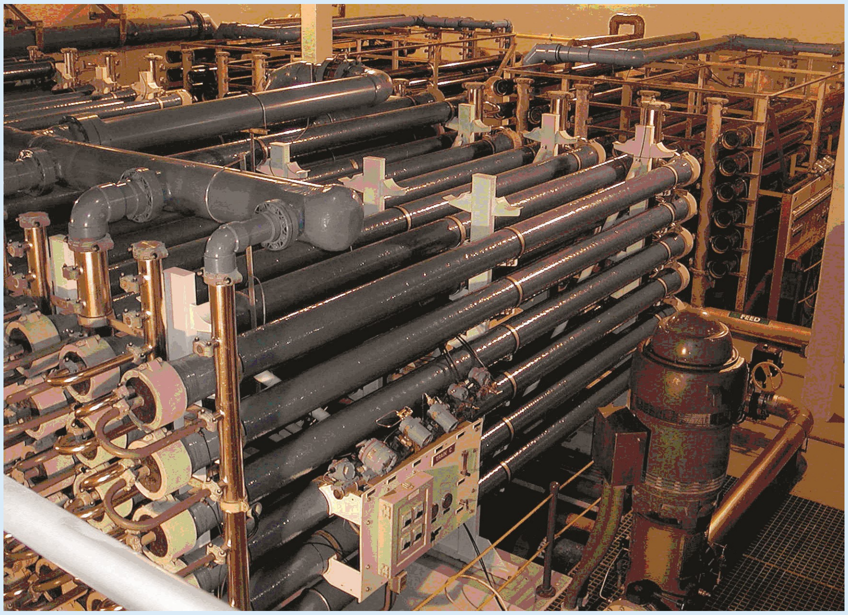
# Operation & Maintenance of Membrane Facilities

With the nation's thirst for greater volumes of high quality water, the number of membrane water treatment facilities continues to grow dramatically. The cost of desalination once thought of as financially prohibitive, now is very competitive with conventional treatment. The growing cost effectiveness of membrane treatment is directly attributable to the expanded use of the technology coupled with the growing professional knowledge base of those experienced and trained in the proper operation of these facilities. As a result, membrane treated water can now be obtained in a safe, reliable manner at a competitive cost.

Design for Efficiency

Effective and efficient operations of a membrane treatment facility begins in the project planning phases. Long term benefits will be achieved if an early understanding is obtained regarding critical plant operating parameters such as raw water quality, membrane performance when treating the actual raw water supply, membrane fouling potential and by-product (concentrate) water quality. This highly valuable information is normally obtained through on site pilot testing unless the proposed facility is duplicating an existing facility using the same raw water. Whenever possible, design and pilot testing should be performed with the involvement of future operational staff in order to gain their input on operational issues and provide them with greater familiarity with the process. Pilot Testing provides instills confidence in design allowing it to |progress efficiently while giving operators worthwhile training and experience. Long term value can now be incorporated in the plans and specifications for a facility. The product of this practice will be an optimized combination of minimized capital cost with the lowest possible recurring expense for operations and maintenance.



Staff Training & Support

It is important to note that the best designed and built facility will fail if those operating and maintaining the plant are not provided the training and support needed. The use of high quality equipment and computer-based operation and control does not guarantee the continuous production of safe water; the plant must be operated by qualified and well-trained personnel. Undoubtedly, the staff is the most valuable asset of any utility.

There now exists many training opportunities for future membrane plant operators. Many consider membrane operations training as provided by AMTA and its regional affiliates as a cost effective means to address this need. Facility start up services through the design engineer and system supplier are also critical to familiarize operators with the actual facility with the support of those already knowledgeable in the process until such time they are ready to take it over.

An enormous amount of operational experience presently exists throughout the United States. One common means of sharing this information is through technology transfer workshops and conferences offered routinely by AMTA. Sharing of case histories and other membrane process knowledge while networking with industry peers can prove very useful. Cooperative training exchanges between utilities during normal operations are also beneficial to utilities looking to train staff in advance of start up of a new

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treatment plant or to simply share day to day operating means and methods employed.

System Monitoring & Maintenance
Membrane water treatment facilities can prove to operate in rather a steady state condition if the input parameters such as raw water quality remains constant and the plant is maintained properly. This is one reason the technology has been widely accepted and many facilities are routinely operated with only minimal human oversight. However, the importance of monitoring the operation can not be overstated. Raw water quality must be reviewed frequently and operational parameters of the membrane treatment train should be continually trended and compared to original start up conditions. Pretreatment efficiencies and post treatment works should also be monitored closely. These tasks can alert operators of pending problems in time for corrective action to occur before production capabilities are impacted. While some changes in the treatment process may not significantly impact plant productivity or finished water quality, they may result in membrane degradation, more frequent cleaning, and generally higher operating costs over time if not properly addressed.

When treatment upsets or equipment failures become apparent, it is critical that adequate Maintenance resources are made available. As with any industrial facility, routine preventive maintenance activities should be performed prudently as scheduled, while responsiveness to unforeseen repairs also needs to be timely.

Unlike other treatment technologies, which produce lower quality product as the raw water quality degrades, membrane systems produce consistent water quality while sacrificing themselves.

Therefore, early detection of raw water changes making adjustments to the operational parameters to accommodate the changes, and are the key to successful plant operation. A well designed plant should include the necessary “tools” and have proper and adequate provisions for conducting routine tests and inspections. A well equipped laboratory, tools and provisions for probing, sample points for profiling are just a few examples of such provisions.

Widespread Acceptance and Application
Relative to other water treatment processes, membrane technologies are often thought of as the most widely accepted means to improve and expand water supplies. The operation and maintenance of state of the art membrane treatment plants are typically easy to operate and maintain. As a result, the world is racing to implement this reliable and cost effective technology to improve water quality and/or increase supplies.

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# Future of Desalination in the United States

As the nation's population grows and industrial development expands, our domestic need for reliable water supplies continues to become increasingly critical. As municipal, industrial, and agricultural demand for fresh water increases, the quality and availability of traditional water sources continues to decline, while the cost of developing new supplies continues to rise.

*San Diego Water Authority Claude "Bud" Lewis Carlsbad Desalination Plant, Carlsbad, CA*

*Seawater desalination facilities in California are employing beach wells to reduce pretreatment requirements and improve plant efficiency.*

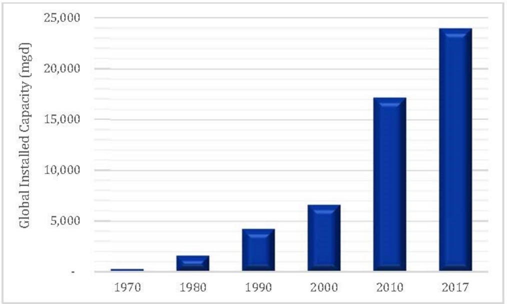
The United Nations World Water Development Report has projected that 75 percent of the world's population could face a water scarcity crisis by 2050, including many parts of the United States. Traditional surface water development sites, such as dams, reservoirs and aqueducts, are being exhausted and many proposed projects are no longer feasible due to significant environmental concerns or the high capital investments required. While conservation has been effective at reducing demands in many areas, there are limitations in the amount of water that can be conserved, and sources of new water supplies will continue to be needed in the foreseeable future.

Desalination technologies provide an opportunity to tap what would otherwise be unsuitable water supplies, such as ocean water, brackish groundwater, and wastewater effluent, to augment diminishing freshwater supplies and provide a sustainable water source to meet water needs. Ocean water desalination offers a vast water source in seemingly unlimited quantities in the United States. Over three-quarters of the earth's surface is covered by water that is too salty to sustain human life or farming. Many water stressed areas also have access to moderately salty, brackish water or wastewater supplies with elevated levels of dissolved solids. Membrane desalting, or desalination, creates new freshwater supplies by separating water from salt and other dissolved minerals in sea water, brackish water or wastewater. Other contaminants, such as dissolved metals, pathogens, organic matter (including trace organic compounds), dissolved inorganics (such as arsenic, nitrate, selenium), and radionuclides, are also removed by membrane desalination methods.

The United States currently has over 1,400 installed desalination plants with the majority being used to desalt brackish groundwater. In the future, membrane desalting will continue expanding, utilizing alternative water supplies to meet growing freshwater needs.

### Desalination Across the Globe

In 2017, desalting plants worldwide had the capacity to produce over 24 billion gallons of freshwater per day, with 59 percent of these plants using seawater or ocean water as their feedwater source. In many arid areas of the world, desalted water provides the only reliable source of fresh water. Improvements in membrane technology over the last several decades have resulted in membrane technologies surpassing thermal processes in worldwide desalting capacity. This trend will continue as membrane efficiencies further improve and as desalination membranes are applied in an increasing array of water supply and treatment applications.




*The use of Desalination has grown dramatically since the 1970 invention of the thin film composite RO Membrane.*

### Past Research Funding and Technological Advances

The desalination process dates back to the 4th century BC when Greek sailors developed an evaporative process to desalinate readily available seawater into safe drinking water. Desalting increased dramatically in the last half of the 20th century, enabling regions with limited or no freshwater supplies to grow and flourish.

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*Innovations in membrane design, such as this 16-inch configuration at a potable reuse facility, are creating more efficient designs and lower treatment costs.*

Many of the advances in desalination technologies in the past several decades were made possible by generous US government research funding. One of the most concentrated efforts was the creation of the Office of Saline Water (OSW) in the early 1950's and its successor organizations like the Office of Water Research and Technology (OWRT). From its inception in the early 1950's through its termination in 1982, when most federal desalting research was discontinued, the US government actively funded research, |development, and demonstration projects, allocating about $900 million (in 1985 dollars) in the process.

This funding supported much of the fundamental investigation and research of a variety of innovative technologies for desalting seawater and brackish water. Most importantly, these programs were primarily responsible for the development of reverse osmosis by US researchers, resulting in a groundbreaking technological advancement that was exported around the world and revolutionized saline water treatment on a global scale. Many advances in distillation technologies were developed, as well.

### Future Prospects for Desalting in the US

- Membrane technology will be increasingly employed in ocean water, brackish groundwater, and recycled wastewater treatment facilities as membrane technologies continue to improve and water supply needs become increasingly critical.
- Nanofiltration membranes will be increasingly used to remove taste, odor, and dissolved organic material in drinking water and for water softening.
- Industries will increase the use of membrane technology to remove impurities in the water used in their operations, to remove potentially toxic contaminants in their effluent, and for production of ultrapure water. Novel desalination technologies, such as forward osmosis and membrane distillation, will expand their role in addressing industrial desalination needs.
- Large scale potable reuse facilities will move forward over the next 10-20 years, employing desalination technologies to produce safe drinking water from wastewater supplies. Currently only 7% of wastewater in the United States is reused and only a small portion of this is for potable uses.
- Desalination will be increasingly employed at inland locations with advancements in high recovery RO and zero liquid discharge allowing improved concentrate management alternatives.
- The number of seawater desalination facilities will expand in the United States as improvements in energy efficiency, energy recovery, and renewable energy supplies continue.

*Inland desalination is becoming common in the US, with an increasing focus on concentrate management and disposal alternatives.*

### Implementation Challenges

While membrane desalination technologies are in use across the nation, key implementation challenges remain. As plant capacities increase, concentrate management is becoming increasingly important, particularly for inland locations where cost-effective concentrate reduction and disposal alternatives are needed. Regulations and permitting strategies for potable reuse are under development in numerous states, and these will ultimately enable the validation of significant pathogen removal with integrity testing techniques applied to desalination membranes. As planning and permitting continues for new seawater desalination facilities in California, Texas, and Florida, intake and discharge strategies are being explored to minimize the plant's impact on the marine environment.

### Need for Additional Research

Continued advancements in membrane technology will help ensure that desalination reaches its full potential in helping the nation meet its growing water needs in the face of increasing water scarcity. To meet these challenges, there is a need to continue direct federal support of desalination and other membrane research, development, and demonstration projects. Federal funding in support of research and development will not only benefit all users of desalting technology in the US, but will also improve the competitiveness of US firms overseas. While membrane-based desalination originated in the US, and major advancements continue to be made by US companies, a continued national focus is critical to maintaining our leadership within this growing and essential industry.

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(FS-11) Sept. 2018

# Pretreatment for Membrane Processes

Reverse osmosis (RO) and Nanofiltration (NF) have long been utilized for desalination, softening and contaminant removal. As the available ground water, fresh water and "clean" water sources are depleting globally, RO/NF technologies are being applied to surface waters, wastewater and ground waters. These types of source waters have substantially more particulate matters, organic substances and other solids which may not be compatible with RO/NF membrane processes. Both technologies are manufactured, designed and built for "salt" and dissolved ion removal and not particulate matter. Therefore, proper pretreatment plays a critical role in the performance, life expectancy and the overall operating costs of these systems.

Although the salt rejection characteristics of RO/NF membranes are well known to the industry since the 1980's, compatibility of feed water particulate matter, fouling/scaling rates, impact on membrane life and membrane degradation due to "poor" source waters are still being analyzed by engineers, manufacturers and end users. Unfortunately some of these problems are found after facilities are built and put in service. This is a crime, since multi-million dollar investments are at stake and improper application gives membranes a bad name. In fact, those of us involved in the membrane industry strongly believe that it is not the membranes that fail, it is improper application or inadequate pretreatment which causes failures.

Since the manufacturing process, element properties and to some degree behavior of NF spiral wound elements are the same as RO, most of the discussion in this article applies to NF systems as well as RO systems.

**Source Water Assessment**

The first and most important step in RO system planning and design is to assess the source water quantity and quality. For the water quality, which is our focus here, it is crucial to get adequate information, not just a snapshot, but a historical view of the source water quality. Table 1 is the minimum extent of water quality analysis required. For some of the parameters such as TOC, TSS, temperature, pH etc, historical data is required to establish the minimum, average and maximum expected values to be able to properly plan and design the system. For some of the parameters as noted, measurement should be done on site since the property will change with time and method of sample handling.

**Table 1: Minimum Required Water Quality Analysis**

| | |
|---|---|
| Aluminum* | Ortho Phosphate |
| Ammonia | Potassium |
| Arsenic | Selenium |
| Bacteriological (coliform) | Silica Colloidal (as Sio2) |
| Bacteriological (Total) | Silica Soluble (as Sio2) |
| Barium * | Silver |
| Bicarbonate | Sodium |
| Cadmium | Strontium* |
| Calcium | Sulfate |
| Carbonate | Total Alkalinity (m value) |
| Carbonate Alkalinity (p value) | Total Dissolved Solids |
| Chloride | Total Hardness |
| Chlorine | Total Iron* |
| Chromium | Total Organic Carbon |
| Color | Total Phosphate |
| Conductivity | Total Suspended Solids |
| Copper | Turbidity (NTU) |
| Dissolved Iron* | Zinc |
| Fluoride | |
| Free Chlorine | PRIMARY & SECONDARY MCL's |
| Lead | |
| Magnesium | **On Site Measurements** |
| Manganese | Temperature |
| Nickel | PH |
| Nitrate | Carbon dioxide |
| | Hydrogen Sulfide |

*** Recommended to be measured in ug/L.**

**Pretreatment Objectives**

The primary objective of pretreatment is to make the feed water to the RO compatible with the membrane. Pretreatment is required to increase the efficiency and life expectancy of the membrane elements by minimizing fouling, scaling and degradation of the membrane.

Fouling refers to entrapment of particulates, such as silt, clay, suspended solids, biological slime, algae, silica, iron flocs and other matter on the surface, or even worst, within the membrane pores. Typically fouling occurs in the lead elements of the first stage initially and then it works itself through the following elements. Depending on the operating conditions and water chemistry some metals, such as soluble iron and manganese, oxidize once they are within the membrane system and can precipitate anywhere throughout the RO system. Similarly, microbes can grow and spread throughout an entire RO system. Microbiological and organic fouling are perhaps the most common types of foulants and more difficult to control in surface water and wastewater applications.

Scaling refers to precipitation and deposition of sparingly soluble salts such as Calcium Sulfate, Barium Sulfate, Calcium Carbonates, Silica, Calcium Fluoride and any other super saturated salt on the immediate surface of the membrane. Typically scaling starts on the tail elements of the last stage (on the reject side), since they are treating water with the highest concentrations of ions. Once a crystal of scale forms within the membrane element, it acts as a nucleation site for additional scales to form and the rate of scale formation increases exponentially.

Inadequate pretreatment often necessitates frequent cleaning to restore product flux and salt rejection. This results in excessive chemical cleaning costs, increases system downtime, and in severe cases will result in permanent loss of performance, membrane degradation and therefore shorter membrane life.

**Table 2: Guidelines for Acceptable RO / NF Feed Water**

| Parameter | Recommended Maximum Value |
|---|---|
| Turbidity | 0.5 NTU |
| TOC | 2 mg/L |
| Iron 1 | 0.1 mg/L |
| Manganese | 0.05 mg/L |
| Oil & grease | 0.1 mg/L |
| SDI 15 | 3 |
| VOC's 2 | In ug/L range |

**1- If absolutely no chance of air entry / oxidation and pH< 7, values as high as 1-2 mg/L may be acceptable.**
**2- Higher concentrations may damage the element glue line.**

**Pretreatment Guideline**

The proper pretreatment of raw water to make it compatible as a feed water to RO must involve a total system approach for continuous, consistent and reliable operation.

The type and extent of a pretreatment system will depend on the type of source (i.e. well water, beach wells, open sea, surface water or partially treated wastewater). The major difference is not only the feed water composition, but also water quality variability by seasonal factors, climate conditions and/or activities on the surface waters.

Table 2 is a general "loose" guideline for acceptable feed water to an RO/ NF system. It should be noted that there is not a set standard among the industry for such a criteria. One of the reasons is that system design and operational parameters do play a role on potential fouling/scaling of an RO system. For example systems with higher recovery tend to foul quicker and may have a higher potential for scaling due to the fact that membrane actually sees a higher concentration of ions and impurities.

Most element manufacturers have similar guidelines but may not be as stringent since their recommendations are an absolute maximum, meaning if they are exceeded the warranty will be void. In general terms, the lower these values are the more reliable the performance, coupled with less frequent cleaning and longer membrane life. The recent generation of "low fouling" elements is believed to have more tolerance to some of the parameters listed in Table 2. Please refer to the element manufacturers for their guidelines.

Silt Density Index (SDI) test is generally viewed as an indicator for potential colloidal fouling. The standard SDI test (ASTM D-4189) is inexpensive, quick and simple to perform. However, there is significant disagreement in the RO industry on its usefulness and scientific validity. Moreover, although it is not the most scientific test, it is a good indicator of changes in the feed water and visual inspection of the membrane pad may reveal potential upstream problems early.

**Pretreatment Options**

RO pretreatment typically consists of "none" to a complex, comprehensive system for poor raw waters. The pretreatment systems can be chemical, mechanical or a combination. Tables 3 and 4 present a list of potential pretreatment options which are routinely utilized for RO systems.

Pretreatment is generally considered to be sufficient when membrane cleaning is limited to 3-4 times per year or less,

**Table 3: Potential RO/NF Chemical Pretreatment Options**

| Technique | Purpose |
|---|---|
| Coagulants / polymers | Added as a part of coagulation / flocculation process to improve solid removal |
| Scale Inhibitors | Allow new compounds to be formed which have a better solubility properties and some absorb to the surface of the micro-crystals thereby reducing further crystal formation |
| Antifoulants | Help keep some compounds such as Iron in suspension |
| Acids | To lower pH and therefore reduce scaling potential of some compounds such as Carbonates |
| Bisulfites | Dechlorination |

**Table 4: Potential RO/NF Mechanical Pretreatment Options**

| Technique | Purpose |
|---|---|
| Pre-Screens | Large objects and sand removal |
| Cartridge Filter | Protection of membrane elements |
| Clarifier | Suspended Solids reduction |
| Media filtration | Suspended Solids removal |
| Activated carbon | Organic removal and dechlorination |
| Greensand Filters | Iron / Manganese reduction |
| Ozone | Organic removal and reducing biological activities |
| UV | Reducing biological activities |
| Full conventional plant (coagulation, flocculation, sedimentation and media filtration) | Particulate, organic and biological activity removal |
| Microfiltration / Ultrafiltration | Particulate and bacteria removal and organic reduction |

**1- If absolutely no chance of air entry or oxidation and pH<6.5 (reduced state), values as high as 1-2 mg/L may be acceptable.**
**2- Higher concentrations may damage the element glue line.**

membrane elements last over 5 years and the productivity and salt rejection are maintained within the expected ranges.

The more comprehensive and complex the pretreatment becomes, the more it should be viewed as a separate system and not a side process component.

*Seawater RO Pretreatment*
Pretreatment for Seawater RO is often more critical than groundwater, because most large seawater plants use open intakes that supply raw water possessing more pollutants (oil & grease, algae, phytoplankton), fluctuations in turbidity, organic content and biological activities (Red Tide for example).

Raw water variations can significantly impact the SDI measured from the pretreatment system. Fluctuating and often high turbidities combined with frequently high levels of organic, microbial and colloidal constituents are the root cause of the ailments of open-intake based SWRO pretreatment systems. Recent studies have found that inadequate pretreatment, including coagulant addition and biofouling mitigation, may account for over 60% of SWRO system failures as shown in Figure 1. The impact of inadequate or ineffective pretreatment can be any or a combination of the following:

- Accelerated increase in net driving pressure
- Accelerated reduction in normalized permeate flow
- Accelerated increase in pressure drop across the vessel
- Increase in the RO cleaning frequency
- Reduced RO membrane life as a result of increased RO cleaning
- Reduced plant availability as a result of increased RO cleaning.

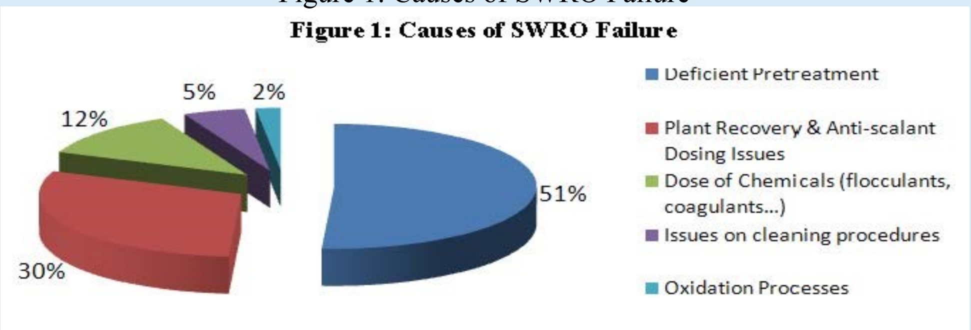
The result of these operation impacts is a direct increase in the operational costs of the seawater RO (SWRO) facility.

In the past two decades there have been many large seawater RO plants constructed, with various types of pretreatment, ranging from direct filtration to Integrated Membrane Systems (IMS) which utilizes MF or UF as a pretreatment to SWRO.

The degree of pretreatment and unit processes depends on the source water variability and quality as discussed. Three major unit processes currently utilized in SWRO pretreatment are as follows:

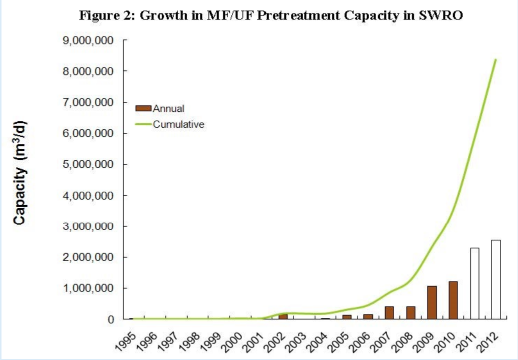
*Direct Filtration:* The most common method of providing pretreatment for SWRO is the use of coagulation, inline flocculation and dual-media filtration. This method generally is very effective at treating good quality seawater to SDIs of less than 4. When treating degraded seawater, the addition of sedimentation basins may be required for reliable |performance of the filters. Increasingly, treatment of pretreatment residuals prior to liquid discharge is required, particularly in North America and Australia. The cost associated with adding thickening and dewatering in seawater resistant materials is substantial (5%-10% of facility cost) and can often be avoided or minimized if coagulant is not required.

Figure 1: Causes of SWRO Failure




*Dissolved Air Flotation (DAF):* Various studies and full scale plants on seawater indicate that DAF can enhance the performance of downstream unit processes. The use of DAF as pre- treatment in seawater desalination may possess additional advantages over conventional coagulation/flocculation/filtration by preferentially removing oil & grease, plankton, algae and Red Tide organisms from the raw water.

Figure 2: Growth in MF/UF Pretreatment Capacity in SWRO




*Integrated Membrane Systems (IMS):* Although the application of low pressure membrane technology has been documented to provide superior pretreatment to RO seawater desalination systems, the increased capital and sometimes operating costs and limited full-scale experience (on seawater) associated with these technologies have constrained their application in full-scale facilities in the past. In recent years, continued reduction in costs have resulted in MF/UF technologies being cost competitive with conventional treatment processes. As a result, the total installed capacity has grown significantly as shown in Figure 2. As a result, more installations are enjoying the advantages of MF/UF pretreatment, which include filtrate with very low and consistent turbidity and SDI, in most cases superior to that of conventional filtration.

It is important to conduct pilot studies when deciding on the optimum pretreatment to evaluate the ability to reliably clean the MF/UF membrane over its projected life. Much of the early literature published on the use of MF/UF as pretreatment for SWRO focuses on MF/UF system filtrate turbidity and SDI. It is critical to ensure that the fouling problem has not just been transferred from the SWRO to the pretreatment process.

Various MF/UF pretreatment technologies are being applied in SWRO applications, with ten different suppliers of either spiral-wound or hollow-fiber technologies. This number is anticipated to grow as ceramic membranes and new technologies from developing markets are implemented.

The following are just a few examples on how pretreatment impacts the RO and post treatment.

Example A: Overdosing of coagulants in a coagulation/filtration pretreatment may in fact cause RO element fouling by the iron flocs carried over from the pretreatment to the RO system.

Example B: If chlorination is used to control microbiological growth in the pretreatment, overfeeding will cause degradation of Thin-Film Composite RO elements.

Example C: An activated carbon pretreatment used for organic removal or dechlorination may actually encourage biological growth due to the tendency of carbon beds to incubate microbes.

Example D: Frequently, metals such as Iron, Aluminum, Cobalt, and sometimes Arsenic are found as impurities in pretreatment chemicals. Care should be taken to specify proper chemicals with strict limitations on impurities.

Example E: Microfiltration / Ultrafiltration as a part of an Integrated Membrane System have been shown in pilot studies and full scale applications to provide the most suitable feed water to downstream RO systems. However, care should be taken to view, design and operate the MF/UF pretreatment as a separate system with its own consideration for fouling, and not "solve" the RO fouling problem by transferring it upstream to the MF/UF system.

Example F: Selection of pretreatment may impact post treatment. A good example would be if acid is used to lower the pH of the feed water (for reducing scaling potential), the carbonate will convert to the CO2 which may need to be removed with a degasifier process in the post treatment.

Example G: Some cationic polymers used in the pretreatment process may actually co-precipitate with negatively charged scale inhibitors and increase fouling potential.

Example H: If a substantial amount of sulfuric acid is added to reduce feed water pH, it may increase sulfate scaling potential due to additional sulfate from the acid.

**Conclusion**

There is not a single solution for an acceptable RO/NF pretreatment system. The solution depends on raw water composition, seasonal and historical water quality changes and the RO/NF system operational parameters. The "loose" guidelines given in this article are suggestions only and are subject to debate, as has been common in the membrane industry for over 20 years!

However, the importance of a system approach and adequate pretreatment needs cannot be over emphasized. It has also been proven that relying on frequent cleaning to "wash away" the pretreatment inadequacy is not the optimum solution and is definitely not an industry acceptable practice.

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# Membrane Bio-Reactors (MBR)

The use of Membrane Bio-Reactors (MBRs) in municipal wastewater treatment has grown widely in the past decade. This trend is primarily due to more stringent effluent water quality requirements, decreasing system costs and improved energy efficiency. Moreover, in response to a changing economic climate, MBR is commonly viewed as an option for the retrofit, expansion and upgrade of aging infrastructure to meet new nutrient limits or increase plant capacity.

Wastewater treatment plants have historically required a significant amount of land to construct the necessary tanks and infrastructure for the required levels of treatment. MBR provides a cost effective viable alternative to conventional treatment within a considerably reduced footprint. Additionally, there is ever increasing regulation related to pathogens, viruses and other constituents of concern which are not typically reduced to desirable levels by conventional treatment processes.

New water is not easily created, but some communities are doing just that, by turning to more advanced processes, such as MBR systems, which make water recovery and reuse possible. MBR technology combines conventional activated sludge treatment with low-pressure membrane filtration, thus eliminating the need for a clarifier or polishing filter. The membrane separation process provides a physical barrier to contain microorganisms to assure consistent high quality reuse water. The ability to cost effectively treat raw sewage for reuse provides a new reliable, drought proof supply of water that can benefit communities by reducing reliance on over stressed existing supplies, increase availability of potable water and improve our environment by decreasing discharges of partially treated wastewater to oceans, lakes, rivers, streams and creeks.

MBR technology is also ideally suited for an array of municipal and industrial wastewater applications such as irrigation, aquifer replenishment, wetlands development, industrial process water, boilers and cooling systems. The scalability and portability of MBR technology has also created new opportunities for satellite and scalping treatment plants. Also referred to as point-of-use or decentralized plants, satellite facilities allow communities to remotely treat wastewater, thereby alleviating the need for expanding centralized sewage systems and long distance pipelines which can be disruptive and costly. In a related application, scalping plants treat raw sewage from existing regional sewer lines, producing recycled water for local use and before sending residuals back into the sewer system.

**MBR systems offer a wide range of benefits, such as:**

- MBR is capable of meeting the most stringent effluent water quality standards. More importantly, the effluent quality is highly consistent with the membrane barrier and a more stable biomass.
- Combining space efficient membrane systems and operation at increased mixed liquor concentrations (commonly 8,000 – 18,000 mg/l); MBR systems are highly space efficient. Commonly, MBR designs will require only 30 – 50% of the space required for conventional systems designed to meet the same treatment goals. This improved space efficiency benefits not only new facilities, but allows expansion and upgrade of existing facilities up to 3-5 times existing capacity without additional treatment volume or site footprint.
- MBR systems provide this high effluent quality in a greatly simplified process, requiring only headworks, biological process, membrane filtration, and disinfection to meet the most stringent water quality standards. In comparison, conventional process requires

additional primary treatment, secondary clarifiers, Enhanced Nutrient Removal and media filtration in order to obtain the same effluent characteristics.

- MBR systems are simpler with fewer process components and maintenance requirements. Common maintenance is still required on mechanical components, but operators can now avoid difficulties in operation tied to sludge settling and clarifier sludge blankets. MBR systems are also easily automated and instrumented to measure performance, allowing systems to be remotely operated and monitored, thus significantly reducing operator attendance.
- The modular nature of the membrane system allows more efficient phasing of facilities. Membrane modules can be delivered on a "just in time" basis, reducing the need for large and costly initial construction to meet long-term projections.
- The cumulative advantages of MBR are increasingly translating into lower total installed costs as compared to conventional activated sludge and SBR technologies. Cited cost savings often include reduced concrete, space and building sizes among other factors.
- The ability of MBR systems, Microfiltration or Ultrafiltration, to produce effluent with very low solids (SDI < 2) makes them well suited as RO pre-treatment.

**MBR Wastewater Influent Limitation and Pretreatment**

The membranes in a MBR system are made from polymeric organics (PVDF, PE or PES) and assembled into units (modules, cassettes, stacks) with high packing density. Raw wastewater pretreatment is important to sustain stable MBR performance and fine screening is an essential operation of any pretreatment system. MBRs have a limited tolerance for abrasive and stringy materials, such as grit, hair and fibrous material. This material, if accumulated in the mixed liquor to a sufficient extent, can cause membrane damage and accumulation of solids and sludge between membrane fibers and plates, or clog membrane tube openings. Depending on the type of membrane technology selected and specific project drivers, some combination of coarse screening, grinders, grit removal, primary clarification and fine screening is generally recommended as pre-treatment for MBRs. However, pre-treatment requirements can vary widely between technologies and treatment objectives. In fact, recent innovations in membrane equipment design are geared toward reducing pre-treatment requirements and equipment sensitivity to damaging debris.

MBR suppliers normally specify a fine screening requirement of <3 mm mesh or hole opening (with <2 mm preferred), while side stream MBRs will typically have a tighter requirement for fine screening. Fine screens are sized for peak flow with one screen out of service to prevent overflow or bypass of unscreened wastewater. Washing and compaction of screening solids are recommended where practical to reduce the water and organic content of the screenings. Fine screens in many different configurations are available, each uniquely fitting a particular need and application. Typical fine screen configurations include

rotating brush screens, internally-fed rotary drum screens, in-channel rotary drum screens and traveling band screens.

Oil and grease in the concentrations typically found in municipal sewage have little or no impact on the operation of an MBR, however free oil and grease must be removed as this can prematurely foul membranes.

Pretreatment of industrial wastewater varies from case to case because some industrial wastewater may have high COD (>10,000 mg/L), high temperature (> 40°C), high TDS (>20,000 mg/L) or high content of inorganic solids. Without proper pretreatment, these wastewaters may jeopardize MBR applicability or economic feasibility. Most industrial wastewaters do not require fine screening and some may need physical-chemical pretreatment, such as flocculation/ coagulation and/or dissolved air flotation (DAF).

**MBR Effluent Water Quality Capability**

One of the most important advantages of MBR over conventional biological technologies is the superior quality and consistency of the produced effluent. Historically, MBR operations have proven that the effluent quality can exceed the world's most stringent wastewater treatment standards, including: California's Title 22 reuse standards, European bathing water standards, US Coast Guard, United Nation's International convention for prevention of pollution from ships and Alaskan marine discharge standards.

Not only do MBRs ensure an effluent free of solids due to the positive barrier for suspended solids and colloidal materials, but also overcome the operational problems associated with poor sludge settling in conventional activated sludge processes while maintaining a considerably higher MLSS concentration and sludge retention time. Consequently, both soluble and particulate organics in waste streams are effectively oxidized, and nutrient removal can be readily accomplished through biological nitrification, denitrification and chemical or biological phosphorus removal.

MBRs have the capability to consistently achieve the following effluent quality:

| | | |
|---|---|---|
| $BOD_5$: | < 3 | mg/L |
| TSS: | < 1 | mg/L |
| $NH_3$-N: | < 0.5 | mg/L |
| Total Nitrogen: | < 3 | mg/L |
| Total Phosphorus: | < 0.05 | mg/L |
| Turbidity: | < 0.2 | NTU |

The consistent high quality effluent produced by MBRs is suitable for a variety of municipal, industrial and commercial reuse purposes and can be applied in environmentally sensitive areas. MBR effluent is also an excellent water source for reverse osmosis applications to produce higher quality water for ground water recharge or industrial pure water reuse.

**MBR Capital/O&M Ranges**
As a result of widely varying conditions, costs for MBR systems can vary greatly. For both capital and operating costs, numerous factors will impact any particular project including:

- Membrane technology selected
- Local construction costs
- Redundancy requirements
- Hydraulic peaking factors
- Local power costs
- Project specific needs for the site, including plant buildings and enclosure
- Project size
- Materials of construction

However, to provide general guidelines we have made some general assumptions. For smaller facilities, not including package plants and less than 1 MGD, expected equipment costs should be $1.00 - $6.00 per gallon of plant capacity, with complete plant construction costs ranging between $5.00 and $22.00 per gallon of plant capacity (depending on design). Operating expenses for the combined biological and membrane systems, including power, chemicals, and membrane replacement should range from $350 - $550 per million gallons treated.

Facilities greater than 1 MGD typically see some efficiencies and economies of scale, with equipment costs of $0.75 - $1.50 per gallon of plant capacity and complete plant construction from $3.00 - $12.00 per gallon of plant capacity. Operational costs for these plants generally range from $300 - $500 per million gallons treated. Through improved products and more efficient design and construction, these costs continue to decline globally.

**Other Considerations**
For owners and utilities, there are a number of key factors to consider when contemplating selection of an MBR system. Capital costs for a typical MBR system have become more competitive and in many cases less than conventional tertiary or re- use, but still remain marginally more expensive depending on evaluation criteria and comparison methodology. However, MBR can compete economically with secondary treatment technology when nutrient limits are specified, space is limited, concrete is expensive or capacity is phased in over time. Regarding operating costs, although it is well documented that MBR systems are more energy intensive than their conventional treatment equivalents, significant gains in energy efficiency have been achieved in the last decade.

The hydraulic capacity of membranes in an MBR process is based on design flow rate criteria and temperature. Typically maximum day or peak hour flows at the expected coldest temperature will dictate the membrane surface area required for a treatment plant. The design flux (unit flow per membrane surface) is the single most important design parameter as it will dictate the surface area of membrane installed, impact membrane air scour requirements, chemical cleaning requirements, membrane replacement and warranty costs. Design flux is very site dependent and needless to say, requires careful consideration. In the past, MBR peak factors were limited to roughly twice the rated (nominal) capacity of the plant but suppliers are now employing novel approaches to storm flow management that can, in some cases, allow for much higher peaking factors.

A number of membrane configurations are commercially available and include hollow fiber (both reinforced and non-reinforced), flat plate or tubular. The differences between each of these types of membranes are significant and include materials of construction, chemical cleaning, pore size (ultrafilter vs. micofilter), air scour requirements, hydraulic configuration and membrane tank volume. Selecting the appropriate membrane configuration also requires careful consideration of robustness, operating flexibility, influent wastewater characteristics and operating costs for a given application.

Like all membrane facilities, periodic cleaning must be performed to remove biological and inorganic foulants. Initially, many MBR systems were submerged in the aeration basin requiring removal of the membrane elements or units for cleaning – this was very labor intensive, particularly as plant capacities expanded. The current trend is toward fully automated, in-situ cleanings and even chemical free technologies that minimize or eliminate the need for routine cleaning.

Membrane systems are highly automated processes and as such redundancy and reliability need to be evaluated through the design process. There are many approaches to build redundancy into an MBR process including specification of redundant trains, influent equalization (relevant for smaller facilities), stand-by power and, in some cases, hot back-up PLCs. The level of redundancy required is site specific and should properly account for available storage, overall number of process trains, reliability of power, and type of plant (end of pipe vs. water reuse facility) among other factors.

Years ago, when MBR was first introduced to the market, a perceived advantage was the decoupling of the biological process from solids removal. However, after more than two decades and based on nearly 6,000 installations worldwide, it is clear that mixed liquor characteristics can significantly impact membrane performance. Significant flexibility exists with the biological design associated with MBRs. Sound biological design such as maintaining adequate DO concentrations in aerobic reactors and proper selection of SRT is critical for overall good membrane performance. Biological process configurations options are extensive and systems can be designed for very low total nitrogen applications as well as biological phosphorus removal in addition to more conventional nitrification/denitrification systems.

**Future of MBR**

Market trends indicate MBR technologies will be increasingly utilized as part of wastewater treatment, water reuse programs to conserve our natural water resources and to provide new water sources. There are roughly 600 operating plants in the U.S. and 6,000 worldwide. From small, point-of-use plants to large 40 MGD municipal plants, MBR systems are now considered mainstream and widely accepted as best available treatment. Building on numerous system innovations, the technology is considered by many industry professionals to be “the treatment technology of choice” regardless of the size or application.

This type of support, coupled with industry improvements in the technology, will take MBR to the next level to become “not just an alternative” but “the treatment of choice” in the next few decades.

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American Membrane Technology Association

**America's Authority in Membrane Treatment**

# Membrane Separation Process

Water utilities across the world are turning to advanced treatment to meet more stringent drinking water regulations.

Membrane systems, available in variety of separation capabilities have become the technology of choice for these regulations. From the removal of turbidity, precursors and disinfectant tolerant micro-organisms relating to both groundwater and surface water supplies, as well as tapping into new water supplies, such as brackish and seawater.

Low pressure membrane filtration, such as microfiltration (MF) and ultrafiltration (UF), have emerged as viable options for addressing the current and future drinking water regulations. Full-scale facilities have demonstrated the efficient performance of both MF and UF as feasible treatment alternatives to conventional granular media processes. Both MF and UF have been shown to exceed the removal efficiencies identified in the Surface Water Treatment Rule and related rules, such as Cryptosporidium oocyst, Giardia cyst, and turbidity. MF and UF membrane systems generally use hollow fibers that can be operated in the outside-in or inside-out direction of flow. Pressure (5 to 35 psi) or vacuum (-3 to -12 psi for outside-in membranes only) can be used as the driving force across the membrane. Typical flux (rate of finished water permeate per unit membrane surface area) at 20 degrees C for MF and UF ranges between 50 and 100 gallons per square foot per day (gfd).


In desalination, salt water on one side of a semi-permeable Reverse Osmosis membrane is subjected to high pressure. This causes fresh water to diffuse through the membrane and leaves behind a more concentrated solution than the source supply, containing the majority of the dissolved minerals and other contaminants. Because the feed water must pass through very narrow passages, fine particulates or suspended solids must be removed during an initial treatment phase (pretreatment). Brackish water RO plants typically recover 60 to 85 percent of the source water, with 100-300 psi applied pressures. Seawater RO recovery rates range from 40 to 60 percent, with pressures ranging from 500-1000 psi.

A "loose" version of RO called Nanofiltration (NF) typically operates at 85 to 95 percent recovery, with lower pressures. It is typically used for organic, color and contaminant removal, as well as for softening.

Electrodialysis Reversal (EDR) is an electrochemical process in which membranes that allow selective passage of either positively or negatively charged ions can accomplish the desalting. Because most dissolved salts are ionic (either positively or negatively charged), the ions are attracted to electrodes with an opposite electric charge and are washed away in the reversal mode of operation. It is a process typically used for brackish water and contaminant removal applications. Recovery rates for EDR range from 75 to 95 percent of the source water.

*This material has been prepared as an educational tool by the American Membrane Technology Association (AMTA). It is designed for dissemination to the public to further the understanding of the contribution that membrane water treatment technologies can make toward improving the quality of water supplies in the US and throughout the world.*

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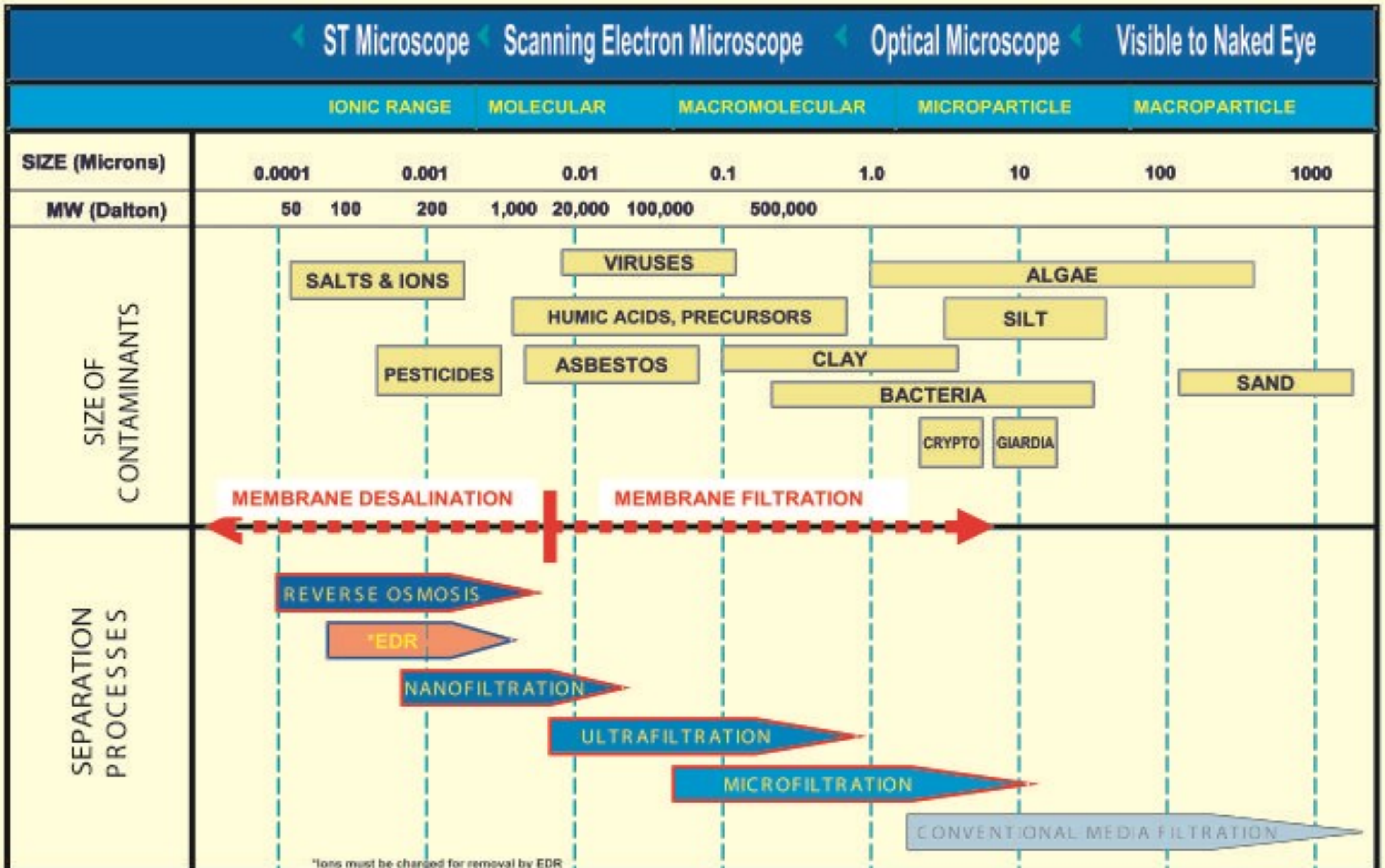
*(FS-14) Nov. 2007*

American Membrane Technology Association

**America's Authority in Membrane Treatment**

*Improving America's Waters Through Membrane Filtration and Desalting*

# Membrane Separation Processes Relative to Contaminant Size





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American Membrane Technology Association

America's Authority in Membrane Treatment

# Planning and Procurement for Membrane Plants

**Overview**

This fact sheet will cover the basic planning, piloting, procurement and construction of various membrane systems such as: Seawater and brackish water Reverse Osmosis, EDR, Nanofiltration, Ultrafiltration, Microfiltration as well as Integrated Membrane Systems (IMS).

Critical and major decision factors, including capital costs, operation and maintenance costs as well as life cycle cost approaches are discussed. Feed water quality assessments, piloting needs, project phasing, project schedule allocations, permitting needs and challenges, and other planning tools and needs are also discussed. The advantages and disadvantages of various procurement methods of delivery, such as design/bid, design/ build, and pre-purchase are highlighted.

**Project Implementation Phases**

Membrane system implementation is similar to any other water treatment project in terms of phases, however it is unique in terms of the degree of detail and the procurement steps.

A typical project implementation will have the following phases:

Phase 1: Feasibility Study
Phase 2: Conceptual Design
Phase 3: Detailed Design
Phase 4: Bidding Period
Phase 5: Construction
Phase 6: Functional Testing and Commissioning
Phase 7: Startup Phase
Phase 8: Project Closeout

**During Phase 1**, the project water quality goals and plant capacity is set. Then, with assistance from membrane manufacturers and/or specialty consultants, a critique of various technologies is conducted to assess feasibility and cost effectiveness of membrane options. Many utilities can complete this phase with their own staff. It is crucial to give a yes or no to membranes in this phase. Remember, membranes may not be the best option for all types of waters and in every application.

**For Phase 2**, advice from a specialized consultant is a must. This is when layouts and conceptual design are done to evaluate membrane options. This is also the last practical and cost effective phase to go back to feasibility study if membrane is not found to be the best alternative. Following this phase, it would be very costly to change the treatment technology and it will have a significant impact on the project schedule. A detailed water quality investigation and if required, piloting is done in this phase to verify membrane applicability, type of systems to use, as well as setting design parameters for the next phase. Depending on the piloting requirements and periods, this phase could take as little as 2-3 months to over a year, if seasonal water quality changes are substantial. If a pilot study is required, a detailed test protocol should be prepared to not only evaluate various manufacturers, but also use it as a basis for O&M cost evaluation. It is highly recommended to prepare this test protocol with guidance from the permitting agencies and make them a part of the decision process as stakeholders. The conclusion of this phase should be what type of membrane to use and who the manufacturers are. If manufacturers were invited to pilot test, you must ensure that they are being evaluated in a fair and open environment.
Test protocol is the key evaluation tool. It is also recommended to get manufacturers involved early in the draft test protocol so there are no surprises and they won't take exceptions later. Remember if you are doing this for the first time, they have done pilots side-by-side for a couple of decades!

**Before starting Phase 3**, all design parameters, plant capacity, reliability and redundancy factors, stand-by provisions, temperature and water quality considerations must be established. These will then become the design basis for the specialty consultant. Phase 3 is essentially local engineers working with specialty consultants to perform detail designs to prepare the bidding documents while the local engineer is focusing on the site work, building, incoming power, etc. The specialty consultant is doing detail design and layout for the process equipment and setting the bidding requirements for the membrane system. Depending on the project schedule and local requirements, typically three major submittals are prepared; 20%-30%, 60%-70% and 100% design. It is critical to establish the type of procurement, short list manufacturers and identify all key process needs during the 20%-30% phase. Even with the same membrane technology, the system layout, process needs and power/ chemical requirements are very different.

**Phase 4** is the most complex phase in membrane system implementation. There are many different methods of bidding membrane systems, each with its own advantages/disadvantages. Please refer to the procurement section of this paper.

**The success of Phase 5** depends on Phase 3 and 4. The single most important factor becomes how detailed the bid document is and who is responsible for what material/ equipment, as well as testing and guarantees.

**For Phases 6 and 7**, typically each entity focuses on their scope, except the overall controls, which should be one entity taking charge.

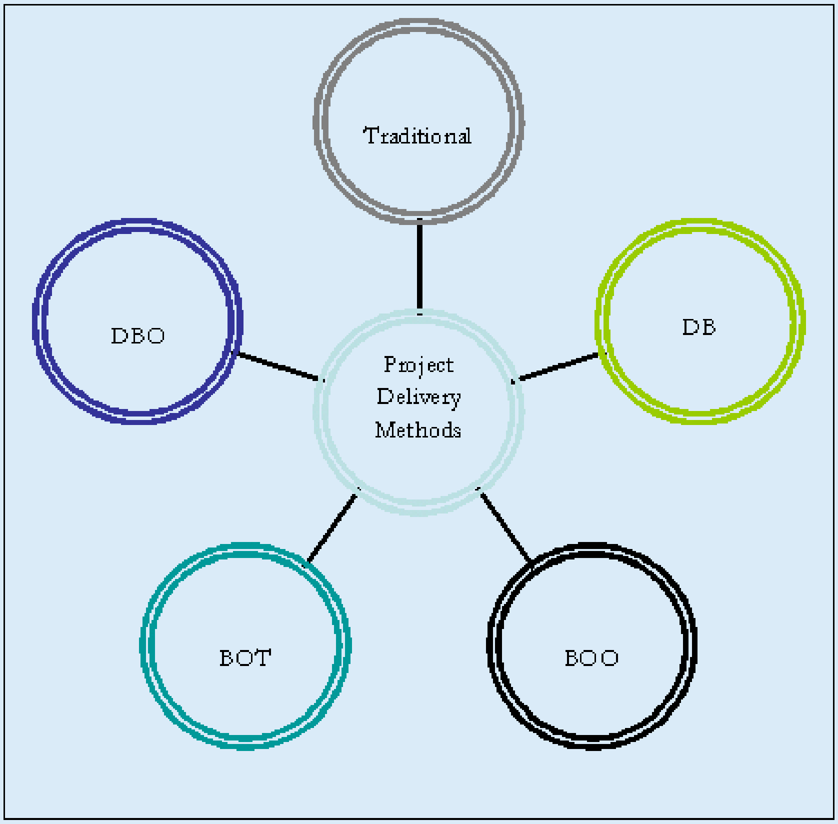
**Phase 8** is preparing as builts, final O&M manuals and each entity completing their punch lists. The specialty consultant can be of great assistance to compile all O&M and shop drawings and provide comprehensive operator training on the overall plant process, while each supplier provides detailed training of individual components.

**Bidding Documents**
The bid documents, regardless of whether it is one, two or sometimes three package, should follow the following guidelines:

- Be very detailed as far as requirement, but have flexibility for design improvements and specifics of each manufacturer. Design creativity will produce a better final product and in many cases, reduced cost.
- Stay away from generic, ambiguous and meaningless language.
- Avoid forcing factors over which the parties do not have any control.
- Do not try to force unrealistic contract periods.
- Define payment structure, payment terms and invoicing requirements. Remember most OEM's can not afford to pay for all the components and wait until project completion to get paid. There is nothing wrong with paying for pre-purchased and stored material if well documented and liability and insurances are defined.
- Avoid risk-shifting in contract languages and do not put unreasonable and uninsurable risks on any of the entities. Remember any risk must be shared and you and your consultants are part of the team with your own share.

**Procurement Options**
There are many ways of procuring membrane systems, each with its unique advantages/disadvantages. Compared to conventional treatment facilities or membrane filtration, large seawater desalination plants are better suited to take advantage of the alternative project delivery methods. Their size, permitting, construction schedule and private financing needs makes them well suited for DBB, BOO and BOT delivery methods. During the last ten years, over 50% of large seawater desalination plants have utilized private financing with alternative project delivery methods. The following is a list of popular project delivery methods, although sometimes combinations of methods are used.

**<u>Type I: Conventional Design/Bid/ Build (DBB)</u>**
IA: Parallel general or prime contractors, where one entity is controlling the site work, infrastructure, building tanking, etc. Another is installing the membrane system and process/control components. This method only works if the process prime contractor is required to hire a qualified OEM and has direct contact with the owner.



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Advantages:

- Owner deals with one entity for warranty issues
- Each contractor is directly accountable for their own contracts and to the owner

Disadvantages:

- Administration of two contracts
- Careful division of scope is required
- Some finer-pointing could arise
- Some mark-up is added by the process prime contractor

IB: Single prime contractor with assigned OEM or Manufacturer. This type works well with NF/RO projects and not so well with MF/ UF projects, especially larger projects. Regardless of the technology, the qualifications of the OEM and/or manufacturer needs to be well defined with no exceptions allowed. Do not allow post-bid shopping. Any alterations need to be defined with bid price obtained to do a fair comparison. For MF/UF life cycle, cost must be included as well as a guaranteed price for membrane replacement. Remember 70%-80% of the total water cost is O&M.

Advantages:

- Administer only one contract
- Less division of work is required

Disadvantages:

- All communication and warranties are through GC, which means a layer is added for warranty claims
- GC typically adds a mark-up
- Some responsibility questions may arise

IC: Single contractor with "Black Box" spec for equipment. This is the worst type of membrane system procurement and should be avoided. This may work well for a pump or belt press, but it has been proven over and over that it does not work for membrane systems.

**Type II: Design/Build (DB)**

This is a popular procurement method for large projects, especially overseas. Some utilities and/or states in the US may not allow this method. It works well if the documents define the minimum standards, but leave the innovation and creativity to the DB team. If you want to specify everything down to the nuts/bolts, and even color choices, then Type II is not for you, you should use Type I method.

Advantages:

- Involves the OEM and manufacturers in the early stages of design
- Selection is narrowed down to pre-qualified teams
- Owner may get quality and cost benefits from innovations

Disadvantages:

- Owners may feel they are left out
- If documents don't define the minimum standards, you may end up with less than the minimum quality product

**Type III: Design/Build/Operator/ Transfer (BOOT)**

This is not common in the US, except for very large projects. This works well for private utilities or entities who are not interested in the process, just the end product (water).

Advantages:

- One entity for everything
- BOOT team may assist in financing

Disadvantages:

- Owner has no control over design and shape of the final plant

**Type IV: Construction Management (CM at Risk)**

This is typical for some large projects in the US. Unfortunately, most of the CM companies are not true contractors; they don't have shovels and backhoes!

Advantages:

- One point of contact with one warranty
- CM acts as GC (typically more professional)

Disadvantages:

- Another layer of markup
- Owner essentially has no control over design

**Summary**

In summary, the optimum choice of contracting method depends on the project budget allocation, type of contracts allowed in your jurisdiction, size and type of membrane system and several other factors, as discussed. The list of advantages/disadvantages may help decision makers to find the most optimum method for their customized needs.

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# Membrane Post Treatment

Post treatment for low pressure membranes (MF and UF) is typically minimal consisting of disinfection (as a secondary barrier) and sometimes pH adjustment and corrosion control, depending on raw water chemistry. Since these low pressure membranes do not remove dissolved substances and water chemistry remains unchanged, the post treatment approach is similar to conventional sand filtration and therefore not discussed in this fact sheet. Instead, this fact sheet focuses on membrane desalination.

Desalination is intended for the removal of total dissolved salts (TDS) that generally cannot be removed by conventional treatment processes alone. Reverse Osmosis (RO), Nanofiltration (NF) and Electro-Dialysis Reversal (EDR) synthetic membrane processes produce treated water that requires post treatment before delivery to the distribution system as finished water. These membrane processes produce permeate water depleted in minerals which often is found to be aggressive towards distribution system components. Different RO and NF membranes have different mass transfer characteristics; using a membrane with a lower molecular weight cutoff will decrease the permeate concentration. EDR processes are impacted by the amount of electrical current and electrical requirements and less effected by the type of membrane. Regardless of specific membrane formulations, the water produced by RO, NF and EDR membrane processes is incompatible with many components and appurtenances that comprise water distribution system infrastructure. This fact sheet discusses the post-treatment of RO and NF membrane processes used for desalting drinking water supplies.

## MEMBRANE DESALINATION PROCESSES

Many municipal plants have multiple process trains installed in parallel, allowing flexibility in permeate (product water) production and ease of expansion. In some instances it is possible to bypass a portion of the raw or pretreated water around the membrane system and blend that flow with the permeate stream to reduce the size of the membrane system, improve finished water stability, and minimize capital and operating costs. The maximum allowable blend ratio is determined from an analysis of bypass and permeate water qualities.

Post-treatment processes typically include stabilization, disinfection and corrosion control, and can include degasification and/or air stripping processes if carbon dioxide and hydrogen sulfide gases are present in the permeate water. Post- treatment is needed for municipal water treatment before the membrane-treated water is delivered to the distribution system as finished water.

## POST-TREATMENT PROCESS OVERVIEW

The choice and sequence of post- treatment operations are typically determined by regulatory requirements, the design of the system, finished water quality criteria and water chemistry. The need for post-treatment generally depends on a number of factors, which can be grouped into several categories, all of which are related to water quality:

- Chemical stability
- Microbiological Stability
- Palatability and Customer Acceptability
- Secondary Impacts on Wastewater Influent Quality

A recent overview of the current state of 62 full-scale RO/NF plants, 9 greater than one-million gallons per day of capacity, used for either seawater desalination, brackish water desalination (including ground water, surface water and agricultural runoff), or wastewater reclamation provides an insight into post-treatment practices. All of the surveyed facilities reported using at least one post-treatment method for permeate conditioning and corrosion control. These included such methods as caustic addition (31%), blending with raw, semi-treated or finished water (29%), degasification/decarbonation (25%), and addition of corrosion inhibitor (14%). Most of the brackish water RO plants responding to the survey reported using degasification/decarbonation and caustic addition, with the majority blending permeate with groundwater. Permeate disinfection was reported to be used by 85% of the surveyed facilities that responded, most of which used chlorine. Other reported disinfection methods included the use of chloramine (24%) and ultraviolet irradiation (4%).

Table 1 presents the typical categorization of permeate post-treatment depending on source water type. There are four primary issues concerning the post-treatment water. These relate to blending, remineralization, disinfection and the materials used for storage and transport of the water to the tap.

Desalinated water is often blended with other sources that contribute minerals to the final blended water. Seawater as a source for blending is limited due to issues related to corrosivity and taste if the blending levels exceed about 1%. Blending of permeate water with seawater results in the addition of sodium, potassium, calcium, and magnesium to the drinking-water but also will contribute bromide and iodide which are DBP precursors, and is limited in quantity due to the significant concentrations of these constituents. Consideration should be given to the natural minerals present and whether these will result in the finished water having unacceptable water qualities in addition to unacceptable taste and odor.

**PERMEATE WATER QUALITY CONSIDERATIONS**

The chemical composition of permeate water produced by RO or NF when blended with other source water can cause water quality and infrastructure problems when distributed. Many facilities pump desalinated water directly into the distribution system without being mixed or blended with other finished water supplies that cause concern with regards to distribution system water quality. Consequently, evaluation of water quality parameters for use in determining appropriate post-treatment actions is required for desalination membrane treatment applications. Factors that should be included when referring to the quality of desalinated waters include the chemical and biological stability of water and its interaction with the distribution system. Permeate streams from sea- water and brackish water desalting processes are primarily a dilute solution of sodium chloride. Untreated permeate from sea or brackish water reverse osmosis plants does not conform to the drinking water standards of such organizations as WHO or the EPA. Due to the low TDS values RO permeate water can be unpalatable, corrosive, and suspected as unhealthy.

To stabilize the water, and to prevent corrosion (metal release) of piping systems and domestic plumbing, post-treatment is necessary to return some calcium hardness and bicarbonate alkalinity to the water. In many situations, post-treatment also includes the removal of carbon dioxide to raise the pH, hydrogen sulfide removal when required, and the addition of fluoride which is removed during the desalting process. Corrosion control is a priority when either directly pumping desalted finished waters into the distribution system or when blending different water sources from membrane process. The constituents of concern when establishing a post treatment process include the pH which will be dependent upon the buffering capacity and bicarbonate alkalinity, calcium, sulfate and chloride, dissolved oxygen, boron, total dissolved solids concentration and corrosion indices. These parameters are interrelated in the final treatment process selected for post- treatment, depending on application and source water (i.e. ocean surface versus brackish ground water supplies).

***<u>Alkalinity, Scale and Red Water</u>***

Alkalinity in water is a measure of the general buffering capacity or stability of the water. Increasing the alkalinity generally leads to lower and corrosion rate and results in less changes in the pH of distributed water; however, excess alkalinity can cause excessive scale deposition where calcium may be present. Alkalinity is thus directly related to the buffering capacity of water and is considered an important parameter affecting the pH. Alkalinity depends on the concentration of bicarbonate, carbonate, and hydroxide ions in water. For a given pH value, the higher the alkalinity value, the higher the ability of the water to withstand a change in pH due to release of H+ and OH- ions to the water. A higher alkalinity at a given pH translates into a higher dissolved inorganic carbon (DIC) concentration of the carbonate species (CO2- ). However, too high of an alkalinity at higher pH levels may accelerate lead and copper metal release. It is also known that red water prevention can be accomplished by maintaining the alkalinity in the system when considering a subsequent pH shift if treatment was to be employed. A non-stabilized finished water can experience fluctuations in pH in the distribution system as scale is deposited (scale) or dissolved (corrosion). It is desirable to maintain the alkalinity concentration in distributed water above one mill-equivalent of alkalinity, or 60 mg/L (as calcium carbonate).

**Table 1: Examples of Post Treatment Processes Based on Supply Type**

| Supply Type | Process | Examples of Applicable Post-Treatment Processes |
|---|---|---|
| Seawater | RO | 1. Recarbonation<br>2. Lime addition<br>3. Calcite bed filtration<br>4. pH and/or alkalinity adjustment<br>5. Addition of corrosion inhibitors<br>6. Primary and secondary disinfection<br>7. Blending with fresh water supplies |
| Brackish Water (Surface) | RO, NF, EDR | 1. pH and/or alkalinity adjustment<br>2. Addition of corrosion inhibitors<br>3. Primary and secondary disinfection<br>4. Blending with fresh water supplies |
| Brackish Water (Ground) | RO, NF, EDR | 1. Decarbonation (degasification)<br>2. Hydrogen sulfide stripping<br>3. pH and/or alkalinity adjustment<br>4. Addition of corrosion inhibitors<br>5. Primary and secondary disinfection<br>6. Blending with fresh water supplies<br>7. Bypass blending with raw water supply |
| Fresh Water (Ground) | NF, EDR | 1. Decarbonation<br>2. Hydrogen sulfide stripping<br>3. pH and/or alkalinity adjustment<br>4. Addition of corrosion inhibitors<br>5. Primary and secondary disinfection<br>6. Blending with fresh water supplies<br>7. Bypass blending with raw water supply |

***Dissolved Oxygen***

The oxygen concentration can have varying effects on iron corrosion. The corrosion rate increases with increasing dissolved oxygen. Dissolved oxygen is also responsible for the ability of buffering ions, including phosphates, to inhibit corrosion.

***pH***

Various studies have been done to correlate the effect of pH on corrosion in pipes. The pH in a system is directly related to the alkalinity, Ca2+ and CCPP in the system. The pH determines the buffer capacity of the water sources. When different water sources are blended the chemical stability of the blend is significantly determined by the buffering capacity of the original waters. A higher pH will usually result in a lower buffer capacity, which also can be noted to be associated with low corrosion rates and prevention of red water episodes, however most studies have shown pH to be a isolated single parameter.

***Boron***

Boron removal is more costly and difficult to process than other ions, especially when dealing with seawater. This is due to the fact that seawater is not drinkable or useable for irrigation. Treatment must be taken into consideration in order to decrease boron, and correct any other corrosive minerals that may be in the water. Boron rejections depend on temperature, pH and salt rejections. Due to low boron levels required for irrigation, several stages of reverse osmosis treatment are used. The first stage will use antiscalants on both passes to avoid risk of salt precipitation. The second stage will use caustic soda to transform boric acid to borate, which is much easier to remove. Residual boron is related to the pH levels in this stage. The degree of boron removal depends on the finished water quality goals, some countries and municipalities having more strict standards than others. WHO has recently published guidelines for boron value of 2.4 mg/L for human health perspective.

**BRACKISH GROUND WATER POST-TREATMENT CONSIDERATIONS**

The primary desalination water plant post-treatment unit operations for potable water supplies reliant upon brackish ground waters are the following:

1. Carbon dioxide removal (degasification or decarbonation)
2. Hydrogen sulfide removal (stripping) and odor control treatment (scrubbing)
3. Alkalinity recovery, pH adjustment, stabilization and corrosion control
4. Disinfection

Carbon dioxide is easily removed from brackish permeate water with the use of aeration (degasification or decarbonation). Carbon dioxide exists in equilibrium with other carbonate species as defined by equations (1), (2) and (3). The pH of the permeate water will determine the amount of carbon dioxide available to be removed from the water.

$$CO2\ (gas) + H_2O = H_2CO_3\ (gas)\ pK = 2.8 \quad (1)$$
$$H_2CO_3\ (gas) = H^+ + HCO_3\ (aq)\ pK_1 = 6.3 \quad (2)$$
$$HCO_3\ (aq) = H + CO_3\ (aq)\ pK_2 = 10.3 \quad (3)$$

Many of the brackish ground waters used as feed streams to RO or NF plants contain hydrogen sulfide. Conventional pretreatment (acid addition, scale inhibitors, cartridge filtration) will not remove hydrogen sulfide nor will the membrane process, as hydrogen sulfide will permeate the membrane as a gas. Aeration and oxidation are the two primary means for removing hydrogen sulfide. Incomplete chemical reactions in the process are often responsible for formation of polysulfide complexes and elemental sulfur, which manifest themselves as turbidity in the finished water. Hydrogen sulfide dissociates in water according to equations (4) and (5).

$$H_2S\ (gas) = H^+ + HS^-\ (aq)\ pK_1 = 7 \quad (4)$$
$$HS^{1-} = H^+ + S^{2-}\ (aq)\quad pK_2 = 14 \quad (5)$$

As shown in equation (4), since at pH of 7 only 50 percent of hydrogen sulfide exists in the gas form and is available for stripping pH adjustment is typically used to improve removal efficiency. Since the pK for hydrogen sulfide is 7, half of the sulfide speciation is present as a gas and strippable. Hence, hydrogen sulfide gas can be effectively removed at pH levels of 6.0 or less without the formation of turbidity (elemental sulfur). However, all of the carbon dioxide in the permeate water will also be removed. If stripping of sulfide occurs at pH 6.3 (bicarbonate pKa1) some buffering capacity will remain. Unless carbonate is added or a significant amount of alkalinity passes the membrane, there will be no carbonate (alkalinity) buffering in the permeate, a possible problem with respect to stabilization and corrosion control even if pH adjustment with sodium hydroxide is practiced. Better methods are required to resolve this common post-treatment issue; an increase in the pH entering the tower prior to air stripping to recover 1 to 2 meq/L of alkalinity would be beneficial. The use of carbonic acid pH adjustment prior to air stripping of hydrogen sulfide has proven to be beneficial with regards to buffering loss of finished water. The alkalinity of water is a measure of its capacity to neutralize acids. Bicarbonates represent the major form of alkalinity in water, since they are formed in considerable amounts from the action of carbon dioxide upon basic materials in the soil. Temperature, pH and the concentration of bicarbonate are important in the formation of CaCO3 feed water (equation 6).

$$Ca^{2+}\ (dissolved) + 2(HCO)\ (dissolved)\ 3/4$$
$$CaCO_3\ (solid) + H_2O + CO_2\ (gas) \quad (6)$$

TREATMENT METHODS FOR CORROSION CONTROL

The primary options for stabilization and post-treatment of membrane permeate and EDR product water include:

- pH adjustment
- Alkalinity adjustment
- Calcium adjustment
- Corrosion inhibitors
- Blending

***pH Adjustment***

Adjustment of pH is used to induce the formation of insoluble compounds on the exposed pipe walls. Passivation is the operating mechanisms for this corrosion control strategy. pH adjustment is accomplished with the addition of chemicals, such as lime, soda ash, sodium hydroxide, potassium hydroxide and carbon dioxide. pH adjustment is most suitable for source waters with low to moderate hardness and alkalinity levels (between 80 and 150 mg/L as $CaCO_3$). Frequently, this treatment technique is used in lieu of calcium carbonate precipitation. Some concerns with pH adjustment include increased formation of disinfection by-products at pH levels above 7.8, decreasing chloramines disinfection efficiency with pH values below 7.8, and a higher potential for calcium carbonate scaling in the distribution system pipe at pHs above 7.9.

***Alkalinity Adjustment***

Alkalinity adjustment frequently is used to induce the formation of insoluble compounds on the pipe walls of the distribution system. Passivation is the operating mechanism for this corrosion control strategy; carbonate passivation is achieved by incorporation of pipe materials into a metal hydroxide/carbonate protective film. This corrosion control strategy is most suitable for source waters with minimum alkalinity, and is frequently used in lieu of calcium carbonate precipitation. Alkalinity adjustment alters the concentration of dissolved inorganic carbonate (DIC) in the source water. Alkalinity adjustment can be accomplished with lime, soda ash, sodium bicarbonate, sodium hydroxide, potassium hydroxide and carbon dioxide. Sodium bicarbonate addition is preferable for alkalinity adjustment. Sodium hydroxide contributes little alkalinity to the water, but can cause dramatic increases in pH. The primary disadvantages of alkalinity adjustment include capital, operation and maintenance cost and increased carbonate scaling on pipe walls. The primary benefit of alkalinity adjustment is increasing the buffering capacity for the source water. This helps to prevent wide fluctuations in pH throughout the distribution system.

***Calcium Adjustment***

The mechanism for this corrosion control strategy is the adjustment of the equilibrium for the calcium carbonate system for the source water. The objective for this treatment technique is the precipitation of a protective film of calcium carbonate onto the pipe walls. Calcium addition or removal is not necessary for the precipitation of calcium carbonate and is accomplished with pH and alkalinity adjustment of the source water. The key to this treatment technique is to provide the conditions necessary for achieving calcium carbonate saturation. Adjustment of the pH/alkalinity is done to create conditions necessary for the calcium and carbonate ions to exceed their solubility limits in water. The concerns with using calcium carbonate adjustment include precipitating a uniform protective film throughout the distribution system, reduction in the hydraulic capacity of the water lines, and scaling in mechanical systems (boilers and hot water heaters). Scaling is of particular concern for those water systems with high levels of non-carbonate hardness and sulfate. Adjustment of the pH is necessary for the precipitation of calcium carbonate and iron stability. For lower alkalinity waters, sulfate can also precipitate calcium and cause scale.

***Odor Control***

Some ground waters may have high concentration of $H_2S$, which being a gas, will not be removed by membrane processes. Post treatment consisting of a single or sometimes two stage odor control system may be required to remove $H_2S$ and other produced gases such as $CO_2$ (if excessive pretreatment acids are added).

***Corrosion Inhibitors***

Inhibitors have found wide spread use as a method of corrosion control. The most prominent forms of inhibitors used are polyphosphates, zinc phosphates, and silicates. The inhibitors control corrosion by several mechanisms, including sequestering of the corrosion by-products, specifically lead and copper, scale inhibition, development of a coating film on the pipe walls and buffering the water at the desired pH. Operating data indicate that the choice of inhibitor depends upon pH, alkalinity, calcium and total hardness, chloride, sulfide, iron concentrations, and dissolved oxygen levels of the source water.

***Blending***

Adding or blending pre treated source water into the (permeate) product water can help in stabilizing the product water thereby reducing the impact of the before mentioned issues. However, blending introduces the need for disinfection of the pre treated water prior to or after blending. Unfortunately, blending will not stabilize the product water completely hence permeate will still need to have some level of calcium and alkalinity (alkalinity being the more important parameter) present. This can be accomplished by employing either lime or limestone treatment. If the source of the water to be blended with the product water from the reverse osmosis system is from a ground source from a limestone or chalk geological formation, the amount of lime treatment will be substantially reduced. Blending of variable and differing water supplies where desalted water serves as one of the supplies is becoming more frequent. Concern has also been expressed about the impact of extremes of major ion composition or ratios for human health. There is limited evidence to describe the health risk associated with long-term consumption of such water, although mineral content may be augmented by stabilization processes typically used by utilities practicing desalination (WHO, 2003). Desalinated waters are commonly blended with small volumes of more mineral-rich waters to improve their acceptability and particularly to reduce their aggressive attack on materials. Blending water should be fully potable; where seawater is used for this purpose, the major ions added are sodium and chloride. This does not contribute to improving hardness or ion balance, and only a small amount (typically no more than one to two percent) can be added without leading to problems of acceptability.

*Bypass Blending of Source Water*

Blending can improve the stability of the product water by increasing the alkalinity and calcium in permeate to reduce the corrosiveness of the water. The water to be used for blending may be the source water used for the reverse osmosis process or from another source, but is limited to brackish waters having moderate to low TDS with no significant DBP precursor content. Use of bypass blending or reliance on multiple source waters for blending will reduce the stress on the membrane system as it reduces the amount of water that needs to be treated and thereby reduce the operating costs of the system. When integrating into an existing system, control over corrosion inhibitors and pH adjustment should be optimized for maximum efficiency.

*Blending Multiple Source Waters*

Blended waters from coastal and estuarine areas may be more susceptible to contamination with petroleum hydrocarbons or algal toxins, which could give rise to taste and odor problems. Some ground waters or surface waters, after suitable treatment, may be employed for blending and may improve hardness and ion balance. It is necessary to model the affects of different blends to prevent the release of red water in the distribution system. Should multiple sources be used, the utility should consider the need to develop a unidirectional flushing program or distribution system rehabilitation (including replacement) prior to the incorporation of a desalting process into existing infrastructure. In addition, the water purveyor may also need to increase storage reservoir size to be able to control the blending location of multiple source waters. In most cases, the water purveyor (water utility) should expect to see an increase in its operational and maintenance expenses.

## SUMMARY

The need to stabilize water in order to prevent metal corrosion and concrete dissociation has been recognized for decades. Permeate typically is adjusted chemically in order to prevent corrosion of pipes in the distribution network and control, pH value and carbon dioxide content for scaling prevention. A buffer intensity greater than 0.5 milli equivalents per pH unit is indicative of a balanced, stabilized source water. The purveyor should focus on producing finished water having an adequate alkalinity and buffer intensity with a target that falls between one and three meq/L of bicarbonate alkalinity. Alkalinity recovery needs to be considered when selecting scaling control options, and is dependent on how much carbon dioxide and bicarbonate is in the raw water. Regardless, permeate water will require chemical disinfection. Selection of post-treatment processes may not completely consider the impacts on the distribution system, particularly when blending multiple varying supplies. Although pilot studies are often conducted for RO and NF process design considerations related to pretreatment, process optimization and operation considerations, these pilot studies often do not include adequate consideration of post treatment processes focused on specific distribution system related issues that are specific to that system. It has been recommended by researchers that water purveyors mandate studies to evaluate the secondary impact of permeate post treatment (or lack thereof) on water quality and subsequent compliance related topics: disinfection and residual maintenance, the formation of disinfection by-products, maintenance of lead and copper corrosion control, bacteriological re-growth and coliform impacts.

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American Membrane Technology Association
America's Authority in Membrane Treatment

# Pilot Testing for Membrane Plants

Overview

Although each application and justification is unique, typical goals for conducting a membrane plant pilot study are:

- To address mandates by the state or local primacy regulatory agencies
- To obtain and collect baseline raw-water-quality profiles that can be used to establish a basis of design for the full scale plant
- To obtain adequate operational data to estimate operational and maintenance costs of a full scale plant
- To optimize chemical feed, membrane flux and plant recovery rates and membrane cleaning regimes
- To familiarize the operations staff with membrane technologies and provide hands-on training
- To show compliance with regulatory requirements and confirm that the permeate water quality meets the contractual, regulatory, and site specific needs of the owner and the engineer
- To conduct research for new technology applications or optimize current technologies
- To demonstrate operational protocols and procedures

Two of the most critical needs for designing a membrane plant are delineating the quality of the feed water and predicting the desired quality of the water being produced. Different membranes can produce different permeate water qualities depending on the feed water quality and the type of membrane being used. Additional considerations for design include pretreatment, pumping requirements, process monitoring and flow control, backwash and cleaning cycles, chemical feed equipment, post treatment, and residuals disposal. These components are necessary to provide an estimate of the cost and allow a cost-benefit evaluation to be conducted.

Pilot plant testing offers the best method for evaluating the feasibility of a membrane application for a specific water supply, especially since fouling and scaling sometimes cannot be quantitatively predicted from water quality measurements alone. Fouling indices provide only an estimate of the potential for fouling, but unlike pilot-scale testing, are not predictive of long-term performance. Since most applications are unique, a site-specific understanding is necessary for the proper design of the membrane system, especially for complex raw water qualities. However, the behavior, operation and system designs of membrane filtration technologies - Microfiltration (MF) and Ultrafiltration (UF) - are different from desalting membranes - Reverse Osmosis (RO), Nanofiltration (NF) and Electro Dialysis Reversal (EDR) - requiring system-specific testing for different manufacturers' membranes.

In addition, in many states, pilot testing is required for membrane processes prior to receiving regulatory approvals and applicable permits.

**MF and UF Piloting**

Important considerations for low pressure MF and UF membrane plants include specific flux, water temperature and associated Trans-Membrane Pressure (TMP), backwash and bleed interval impact on productivity and run time, cleaning frequency and interval, and other system-specific operation, such as Chemically-Enhanced Backwashes (CEB).

Instrument verification and calibration are required for flow meters, pressure and temperature transmitters, online particle counters, and turbidimeters. Test duration is also critical for obtaining pertinent and applicable information from the pilot operation regarding cost and performance of the projected full-scale facility.

For MF and UF plants utilizing ground waters or ground waters under the direct influence of surface waters (GUDI), the design parameters are typically well known and there is not much concern with fouling and cleaning. These membranes are designed for high particulates, turbidity and microorganisms. These systems can be (and have been) designed with success utilizing conservative, but reasonable process design parameters, without the benefit of pilot studies.

For surface waters, including flashy rivers, high organic content reservoirs and lakes as well as tidal waters and seawater, it is a different case. These sources tend to vary in temperature, chemical composition and organic/metal/ solids loading seasonally and during storm events. In most of these situations, but not all, pilot testing will result in a focused and tailored design, minimizing surprises and resulting in a more reliable and efficient facility. During testing, typically a minimum of 30 days of run time should be allowed prior to altering the test conditions or pilot operation set points for any given feed water. If multiple feed waters are to be blended or varied during full scale operating conditions, then worst-case blending scenarios with regard to temperature and water-quality impacts (particularly those related to fouling) must be considered and studied at the pilot scale.

Additional consideration should be given to specific study components of a pilot program, such as challenge tests, integrity testing, and module repair procedures. A side benefit of piloting in these cases could be to obtain guaranteed life cycle costs (power, chemicals, cleaning regime and membrane replacement) from the manufacturers. The bid documents can then be prepared based on a life cycle cost and not just the capital cost. This approach typically requires longer term pilot studies (4 to 6 months) to capture seasonal changes. This approach is typically limited to very large plants due to piloting costs. To capture the peak events and seasonal impacts and decide on optimum piloting periods, the following guidelines could be used.

*Spring* may result in higher turbidity due to snow melts and late spring rainfalls in some areas and can cause reservoir turnover. Depending on the membrane type and conservatism factor used in design, as well as budget limitations, in most cases spring is not the best time to run a pilot-study.

*Summer* typically results in a better understanding of taste/odor and algae control for MF/UF systems.

*Autumn* presents challenges in areas with hardwood cover in the watershed. These areas experience more organics by the decay of leaves. Autumn's cooler air temperatures and wind on the reservoirs will typically produce more organics as well as iron/manganese issues and therefore autumn would be a better piloting period for these locations. Cleaning regimes, coagulation optimization and fouling impacts, as well as taste and odor controls become a major part of the pilot study.

*Winter* yields the coldest water temperatures for surface water sources and therefore reduction in membrane flux due to the lower viscosity of the water. All membrane manufacturers have accurate membrane specific temperature correction factors which can be used. As long as the extreme cold temperatures are utilized during design and plant sizing, winter is not typically a mandatory season to pilot.

Fouling impacts on process productivity are also best assessed by pilot testing. Evaluation of chemical cleaning is a significant component of MF and UF piloting. Longer run times may be required in order to fully evaluate clean- in-place (CIP) procedures. Also, if CEB is incorporated into the process operation, then the impact on backwash recycle operations with regard to disinfection by-product (DBP) formation potential must be evaluated. If recirculation is to be practiced in the full scale plant then the pilot testing program should incorporate the recirculation. Should citric acid be incorporated into the cleaning regime, then resultant residuals should be disposed of in an acceptable fashion and not recycled back to the front of the process stream, particularly if coagulant is used as part of the pretreatment process train.

Citric acid will interfere with coagulant pretreatment, especially when an iron base is used. Citric acid should not be allowed to come into contact with coagulant upstream of the membrane.

It is important that any problems related to scalability, such as membrane packing density, and analogous pretreatment, be incorporated into the pilot testing program. The MF and UF modules pilot tested must be comparable to anticipated full-scale module configurations. If packing density differences exist between pilot-scale and full-scale systems then inaccuracies in operation evaluations will occur. For MF and UF, the owner and the engineer are thus reliant on the manufacturer to provide a pilot system that mimics the full-scale operation, and therefore must be involved in the technical aspects of the pilot test. Typically 1000-2000 hours of pilot operation is believed to be adequate to obtain the required information for MF and UF systems. Longer periods may be required if the MF/UF system is a pretreatment to seawater RO applications.

**NF, RO and EDR Piloting**

For most clean ground water sources, such as deep confined aquifers, where dissolved solids such as salts and contaminants (arsenic, radionuclides, nitrate, etc.) are to be removed, the design parameters for RO, NF and EDR membrane systems are well known with significant data from decades of operating these plants. Utilizing these resources, coupled with laboratory testing and computer model projections, typically results in very accurate design parameter estimates. This is especially true if data from other plants using the same aquifer is available. Pilot testing in these situations may not be necessary unless required by local regulatory agencies. However, pilot testing should be done if silica is present in the water at a different level than anticipated as it greatly impacts recovery and scaling.

However, for surface water supplies, such as seawater and tidal brackish sources, problems related to long-term fouling still remain with NF, RO, and EDR, and should be assessed with pilot testing. In these cases longer intervals should be considered to capture seasonal variations and allow for the development of long term fouling assessments, particularly if biological and organic fouling is anticipated. Pretreatment and chemical conditioning of membrane feed systems should be one of the primary targets for such pilot studies.

As of now, most RO and NF elements in use are 20.3 cm (8 in.) in diameter, and it is common that piloting be performed using 10.2 cm (4 in.) diameter elements as they tend to mimic full-scale operating conditions (e.g., feed channel hydraulics). 6.35 cm (2.5 in.) diameter elements, although available for testing, are not recommended to evaluate RO full scale operating conditions, as these elements do not mimic larger-element manufacture. For NF pilot studies requiring a third stage, 6.35 cm (2.5 in.) diameter elements are often used because the need to control velocity in the third stage, despite the inherent limitations of the smaller-diameter element. With the advent of 406.4 mm (16 in.) diameter elements entering the market, the use of 10.2 cm (4 in.) membranes for analogous testing conditions may be questionable for this application. Demonstration-scale testing (on the order of 1900 m3/d (0.5 MGD)) using the large-diameter membrane would be recommended for these cases as these larger diameter elements can be mounted on pilot-scale skids. Instrument calibration of flow meters, pressure and temperature transmitters, online pH and conductivity meters and others is required for NF, RO, and EDR pilot facilities.

**Other Considerations**

There are no national standards for membrane piloting. Regulations are specific to each state and local jurisdiction. In a few states piloting of membrane plants employing “new technologies” is mandatory. Contact your local regulatory agency early in project planning to get an understanding of their pilot testing requirements. Remember, all leading MF and UF manufacturers have gone through comprehensive national testing protocols such as challenge tests (by EPA/NSF/ Dept. of Health, etc.) multiple times and there is no need to repeat these tests if also inexpensive bench tests are sufficient in establishing rejection properties of membranes for specific contaminants. Share this information and the results of previous studies with your regulatory agency.

If pilot testing is required, it should be a meaningful program tailored for the site conditions. Such comprehensive programs could cost $50,000 to $200,000 for smaller systems with limited pilot program scope to over a million dollars for large mini-plant scale facilities with an extended long term study.

Finally, there will be extensive involvement from the consultant, manufacturers, and facility operators as well as significant laboratory costs, coordination and installation of temporary housing, water, sewer, power, internet and phone for pilot units. If multiple manufacturers are being pilot tested to prequalify manufacturers that will be allowed to bid a project, these requirements are multiple requirements. Remember pilot units are not like vacuum cleaners that you plug in and start collecting data!

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# Membranes Technologies and Contaminants of Emerging Concern

## OVERVIEW

With increasing frequency, research is documenting that many inorganic, organic, and microbial constituents—not historically considered as contaminants—are present in the environment at low quantities on a global scale. These "contaminants of emerging concern" are commonly derived from municipal, agricultural, and industrial sources, yet are often dispersed to the environment via domestic and commercial pathways. Chemicals of emerging concern are influencing the selection of current and future treatment technologies utilized by the drinking water community, and membrane processes represent a tool for dealing with these contaminant challenges.

## WHAT ARE CHEMICALS OR CONTAMINANTS OF EMERGING CONCERN?

Advanced analytical capabilities have allowed scientists to identify chemicals in the environment at extremely low concentrations. Contaminants of emerging concern (CECs) are those chemicals that, recently, have been shown to occur widely in water resources and are identified as having the potential for adverse risk to public health or the environment. CECs are used daily in homes and gardens as well as in agriculture and other industries and include products such as detergents, fragrances, personal care products, prescription and non-prescription drugs, disinfectants and disinfection by-products (DBPs), pesticides, herbicides and nanomaterials.

One study conducted by the U.S. Geological Survey as part of the Toxic Substances Hydrology Program reported detections of 82 chemicals in 80 percent of 139 streams and waterways tested between 1999 and 2000. The most common chemical groups observed were steroids, antibiotics, nonprescription drugs, caffeine, and insect repellent. Potential sources of these contaminants are wastewater discharges, agricultural and industrial run-off, industrial air emissions, and discharge from individual septic systems. **Table 1** presents a partial listing of CECs found in wastewater effluent and the aquatic environment.

The U.S. Environmental Protection Agency's (EPA) 2016 Contaminant Candidate List (CCL4) included 97 chemicals or chemical groups and 12 microbial candidates, among which are chemicals used in commerce, pesticides, biological toxins, DBPs, pharmaceuticals, and waterborne pathogens. *[Note: As of 2021, EPA is working on a draft version of CCL5].* While the occurrence of CECs correlates with a variety of ecological impacts, links between CECs and the environment and a cause-and-effect relationship have not been directly established. However, these emerging chemical contaminants—industrial solvent stabilizers (1,4-dioxane), fuel oxygenates, disinfection byproducts, pharmaceuticals, personal care products, pesticides and herbicides (1,2,3-trichloropropane), algal toxins, emerging pathogens, phthalates, and other persistent compounds used in common products such as flame retardants, food packaging and water-resistant fabrics (e.g., per- and polyfluoroalkyl substances)—illustrate many technical and institutional challenges.

**TABLE 1: Emerging Contaminants in Wastewater Effluent and the Aquatic Environment**

| EMERGING CONTAMINANT CLASS | Examples |
|---|---|
| Pharmaceuticals (antibiotics/drugs) | Ibuprofen, Codeine, Caffeine, Diazepam, Acetylsalicylic acid, Carbamazepine, Diclofenac, Fenoprofen |
| Veterinary and Human Antibiotics | Trimethoprim<br>Erythromycin<br>Lincomycin<br>Sulfamethoxazole |
| Hormones | 17-b-estradiol<br>17-a-ethynylestradiol<br>Estriol<br>Estrone<br>4-nonylphenol |
| Flame Retardants | Polybromodiphenylethers<br>Tri(2-chloroethyl)phosphate |
| Per- and Polyfluoroalkyl Substances (PFAS) | Perfluorooctanesulfonic Acid (PFOS)<br>Perfluorooctanoic Acid (PFOA) |
| Personal Care Products (polycyclic musks) | Galaxolide<br>Parabens<br>Siloxanes |
| Industrial Solvents | 1,4-dioxane |

## MEMBRANE PROCESSES CAN ADDRESS CONTAMINANTS OF EMERGING CONCERN

Both regulatory requirements and public concern are driving the need to improve contaminant removal for both wastewater discharges and drinking water systems. Conventional wastewater treatment varies greatly in its ability to eliminate drug or personal care product residues and additional treatment may be required at the effluent discharge location. Likewise, drinking water providers are under increased pressure to better address contaminants, especially for industrial chemicals with limited available research data, prior to sending to customers in the distribution system. Membranes are effective for the treatment of organic precursor matter, and pilot studies show that they are also effective for meeting removal targets greater than 90 percent for many contaminants of emerging concern.

Although there are several mechanisms controlling contaminant removal by membranes, size exclusion is significant and can be used to describe membrane capability. If the contaminant is too large to pass through the membrane pore, then it is removed from permeate or filtrate streams. Contaminants can be categorized simply as microbiological (i.e., pathogens), organic solutes, and inorganic solutes. Pathogens can be further categorized as protozoa, bacteria, and viruses. Organics can be subdivided into DBPs and their total organic carbon (TOC) natural precursors, synthetic organic compounds (SOCs) and volatile organic chemicals (VOCs). Inorganic solutes include such contaminants as total dissolved solids, total hardness, metals, and other inorganic contaminants.

Reverse osmosis (RO) and nanofiltration (NF) are both diffusion and size exclusion-controlled membrane processes. RO and NF processes have the broadest span of treatment capability but require the greatest degree of pretreatment. Ultrafiltration (UF) membranes can achieve greater than six-log removal of all pathogens from drinking water and microfiltration (MF) can achieve greater than six-log removal of protozoa and bacteria. Consequently, membrane processes are ideal for removing turbidity and microbiological contaminants, and they are well suited for treating the majority of drinking water sources in the United States.

Log rejection will increase as flux increases and decrease as recovery increases in diffusion-controlled membrane processes (primarily NF and RO). No change will occur in size exclusion-controlled processes (primarily MF and UF). Pathogen removal by NF or RO is controlled by a size exclusion mechanism, whereas ion removal is diffusion controlled. Removal of organic compounds is achieved through both mechanisms. Diffusion controlled processes have the flexibility of decreasing recovery to produce a higher water quality if more feed water is drawn to meet production needs.

**Table 2** presents examples of treatment effectiveness for several specific endocrine disruptors using NF and RO. Membranes have distinct treatment advantages relative to these and other contaminants of emerging concern. RO or NF membranes can remove TOC or other DBP precursors such that free chlorine may be used for disinfection without exceeding the EPA regulated levels within the distribution system. Pressure driven membrane processes can reject five to six logs of viruses, bacteria or cysts, exceeding most—if not all—treatment capabilities of any other single process.

RO or NF membranes can reject small molecular weight pesticides and are used to meet stringent European water quality standards and will likely reject higher molecular weight pharmaceuticals, endocrine disruptors, and algal toxins.

While there are typically no water quality disadvantages to membrane separation, the significant disadvantages are cost and concentrate disposal. Fortunately, costs continue to decrease due to technological innovation, and concentrate disposal is typically a regulatory requirement rather than a technical challenge. Membranes can meet or exceed current and pending water quality regulations. Moreover, some drinking water lifecycle analyses show that the use of membranes for the removal of industrial contaminants in fresh (low chloride levels), raw water sources can be more cost-effective than other advanced treatment processes, especially at higher target removal rates.

**TABLE 2: NF and RO Treatment Effectiveness for Specific CECs**

| CHEMICAL | TYPE | REMOVAL (%) NF | REMOVAL (%) RO |
|---|---|---|---|
| Acetaminophen | Analgesics | 30 | >90 |
| Ibuprofen | | 98 | >98 |
| Naproxen | | 23 | >95 |
| Trimethoprim | AntibioticMuscle Relaxant Steroid Steroid | 22 | 90 |
| Diazepam | | 55 | >95 |
| 17β – Estradiol (Estrogen) | | 20 | 90 |
| Testosterone (Androgen) | | 60 | 95 |
| Triclosan | Antimicrobial Insecticide Surfactant | 45 | >96 |
| DEET | | 75 | >90 |
| Nonylphenol | | >99 | >99 |
| PFOA and PFOS | Industrial / Manufacturing / Aqueous Film-Forming Foam | >94 | >98 |

## EMERGING CONTAMINANT ISSUES WILL CONTINUE TO EVOLVE

Unregulated and emerging chemical contaminants present technical and institutional challenges to environmental and public health professionals and utility systems. Increasingly advanced analytical techniques identify newly detected inorganic, organic, and microbial chemicals in actual or potential sources of drinking water.

As the ability to detect these agents improves, the number of contaminants that need to be evaluated for potential health risks will continue to expand. The discovery of CECs in the environment has outpaced the research community and its ability to study the effects of these contaminants on people and the environment. Consequently, environmental professionals and utility providers must make difficult risk management decisions regarding water resource and water supply management in the face of considerable regulatory uncertainty. The significant cost to build any advanced treatment technology, combined with the uncertain effects and future discovery of additional CECs, often drives the selection of technologies that provide a more comprehensive and higher removal rate of these CECs.

While some technologies do not effectively remove many of these contaminants from water, membrane technologies are effective in removing the broadest range of CECs as either stand-alone processes or when integrated with other advanced technologies. Risk management decisions are now requiring both complex assessments of the vulnerability of a water supply source to unregulated contaminants and also an analysis of the appropriate combination of treatment processes required to meet both current and future water quality concerns arising due to CECs. The lifecycle cost must always be considered in the final analysis.

## SOURCES


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# Membrane Facility Instrumentation and Controls

**Overview**

Membrane facilities by nature tend to be automated, typically requiring more instruments and control features than conventional water treatment technologies. Depending on the type of membrane and unit processes, the level of instrumentation and control devices varies significantly among membrane plants. This fact sheet will give a general description and discuss controls that are often common to many membrane facilities.

**Reasons for controls in membrane plants**

Typically membrane plants are too complex to be operated "In Hand" and require automated controls for:

- Process optimization
- Membrane system and process equipment protection
- Safety of operation
- Quick response time. Some critical controls require fraction of a second response time!
- Regulatory compliance, such as water quality reports, pressure decay tests and Log removal calculation

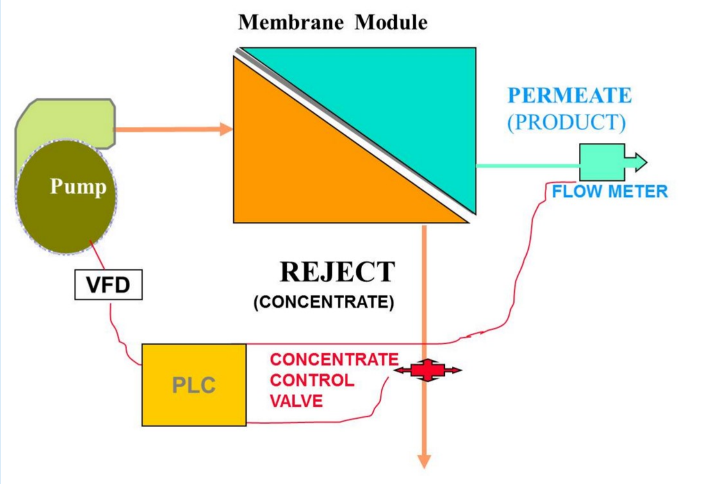


**Figure 1: Example of a simplified RO skid control**

Figure 1 shows a simplified single stage Reverse Osmosis (RO) skid control. The recovery and permeate flow are constant and set by the process design. The PLC will modulate the concentrate control valve to maintain the recovery. The PLC will ramp the feed pump VFD to maintain the permeate flow set point.

As facilities become more complex with multiple stages, passes and skids, the control systems become more complex.

**Major components of plant control**

Typical membrane plant control components are:

- Human Machine Interface (HMI): Desktop computers, printers and monitors
- HMI software
- Programmable Logic Controller (PLC)
- Wires, fiber optic, data cables, Ethernet cables
- Instruments
- Analyzers
- Remote I/O panels and communication cards
- Remote control panels: Other equipment PLCs
- Remote control devices: Variable Frequency Drives (VFDs), "smart chemical pump" and remote sub system PLCs or "mini-brains'
- Remote Telemetry Unit (RTU) and Supervisory Control Data Acquisition (SCADA) for remote sites and remote communication

**Instruments**

The quantity and type of instruments varies widely among membrane plants. They vary by type of membrane system as well as system complexity and designer/operator preferences. For example, in low pressure membrane applications (MF/ UF/MBR) there may be more flow meters, while in high pressure membrane systems (RO/NF) there may be more pressure transmitters.

Generally these instruments can be divided in three categories:

1) *Hydraulic monitoring and controls:*
   - Pressure transmitters
   - Differential pressure transmitters
   - Flow meters
   - Level transmitters
   - Level floats
2) *Water quality monitoring and controls:*
   - Conductivity meters
   - Turbidity analyzers
   - Chlorine analyzers
   - Temperature sensors
   - pH monitors
   - Particle Counters
   - Specific chemistry analyzers such as Nitrate, Fluoride, etc.
3) *Safety devices and equipment protection:*
   - Low pressure switches
   - High pressure switches
   - Vibration sensors
   - Over-heat sensors
   - Oil monitors
   - Battery backed-up safe position valves
   - High/low level floats and switches
   - Emergency Stops

**Overall Process Controls**

The membrane process engineer will closely coordinate the type, location, material and ranges of all instruments as a function of water quality and process control needs. The process engineer will also be responsible for preparing the control description, establishing alarms and plant control response to the alarms. Then the process control engineer will prepare the Piping and Instrumentation Diagrams (P&ID). A combination of all the above will be used by the programmer to program the PLC.

**Testing, Startup, and Commissioning**

Although the entire control system and programming can be completed before plant start-up, many set points and programming functions such as reaction time and delays, have to be fine-tuned during testing. It is critical that plant process components be tested in sub-systems before trying to test the entire plant. Detailed testing protocols and procedures are often needed to ensure all features are tested in a safe manner and are well documented.

**Security and Authorization**

Generally 3-5 levels of permissions and authorizations are provided in the PLC program so only authorized staff who are very familiar with the process can change major parameters or set points. Parameters such as flux rate, recovery and alarm shutdowns will have a significant impact on the membrane and plant performance and should only be changed by staff who understand the impact of such changes. Certain safety features, such as high pressure shut downs, fall in the same category.

**Performance Monitoring and Data Management**

In addition to operational controls, membrane plants require data management and performance monitoring. These requirements can be met by utilizing the membrane manufacturer's tracking/normalization software, with customized Excel sheets with graphs and with XL-reporter and other custom databases. This detailed monitoring is required for:

- Regulatory compliance reporting
- Monitoring plant performance
- Knowing when feed water quality is changing
- Being proactive to prevent fouling and scaling
- Knowing when to clean the membrane
- Estimating the membrane life to plan for replacement
- Determining the effectiveness and understanding the performance of various plant chemical additions: (Coagulants, Scale Inhibitors)

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# Industrial Applications of Membranes

**Overview**
Membrane products are well known for producing potable water in municipal plants and seawater desalination. However what is not appreciated is how much membrane technology is used in industrial applications around the world. Membranes achieve separations without a phase change and the absence of applying heat can be advantageous to some applications. The ability to remove water from a process stream or effluent has shown to be an effective way of concentrating valuable components of an aqueous stream. At times the membrane facility may not be large compared to a municipal plant but the value to the system and process may be critical for overall economic viability. Sometimes, the water available to an industrial facility may not meet the requirements of the application and membranes can be used to improve the quality so that the process can be run. Or perhaps the discharge from the processes is too great and a reduction step is needed that can be facilitated by membranes. At times, the concentration of the solution may not be desirable and an easy, efficient means of adjusting the concentration may be in order by using membranes. Finally, membranes are used in Membrane Bioreactors (MBR) for waste treatment in food and dairy, pharmaceutical and other facilities.

**Applications Include:**
Food and Beverage:

- Bottled Water
- Beer, wine, and alcoholic beverages
- Fruit juices and maple syrup
- Milk and cheese

Industrial Processes

- Clarification of biochemical processes
- Petroleum refining
- Paint, adhesive, and solvent recovery
- High purity applications such as semiconductor, boiler feed and power industry needs

Mining and Metal Processes

- Plating processes and waste reduction
- Gold and uranium recovery
- Recovery of precious metals
- Landfill leachate reduction

**Reasons for Using Membrane Technology**
Membrane processes employ a barrier layer that allows water to permeate or pass through it but rejects or retards other components from going along with that filtrate. In the case of microfiltration and ultrafiltration, distinct pores in the polymer allow for water to flow through the barrier but retard/reject the passage of species larger than the pores. Reverse osmosis barrier layers do not have distinct pores but do allow water to diffuse through the barrier layer and reject most of the dissolved ions in the mixture. Since heat is not used to effect the separations, the components in the mixture are less likely to suffer thermal degradation. Membranes are replacing diatomaceous earth filtration (DE), multimedia filtration, centrifugation, extraction, rotary vacuum filters, evaporation and distillation and other unit operations that have been used to make products. Cold sterilization of beverages, pharmaceuticals and milk take advantage of the membrane systems. Most of the membrane products commercially available have a polymeric barrier layer however ceramic membranes with distinct pores have been used in demanding conditions and are finding use in new applications. Ceramic membranes have pore sizes that classify them as microfiltration and ultrafiltration filters.

**Membrane Applications**
The range of applications that currently take advantage of membranes is impressive and continues to grow. Some of these are discussed below:

**Food and Beverage**
*Bottled water:* Since the feed water may vary from site to site, the bottled water industry has embraced membrane technology. Some purified bottled water manufacturers want to produce a reproducible product no matter what the feed source and as such they treat the local water to remove almost all of the constituents and then add back a package of ingredients to give a recognizable taste and feel to that particular brand of bottled water.

Similarly, bottled water producers utilize membranes for their barrier properties to exclude bacteria and microorganisms. Soft drink manufacturers need safe clean water free of microorganisms and make up water is treated with membranes at a number of soft drink facilities.

*Beer production:* During the production of beer, brew masters around the world are particularly specific about the consistency and quality of the water that they use for the manufacture of beer. Membrane facilities are able to take locally available water sources and treat them to acceptable ionic content including hardness and alkalinity for use. In addition, membranes are used for continuous beer stabilization to improve operating efficiency of the brewery and continuous clarification and final filtration of the beer.

*Wine:* Membranes have been used for wine clarification and the avoidance of filter aids such as diatomaceous earth (DE) eliminates a disposal issue and loss of wine that would have been associated with the spent aid. Removal of suspended solids, yeast and bacteria and automation of the filtration process reduces losses, improve economics and minimizes labor when producing wine.

*Fruit juice:* Fruit juice manufacturers take advantage of membrane technology in a number of ways. Concentration of natural juices can be achieved in which water is removed as permeate and the concentrated juice is left behind. Since no heat is applied there is no degradation of the many complex juice sugars and flavor components. Color can be controlled and even enhanced during the concentration step. Produced juice can be purified and clarified by removal of fine particles from juice which clarifies the mixture and gives it a haze-free property that allows for longer shelf life.

Since bacteria and microorganisms are excluded in membrane processes, the juice is less likely to spoil and will remain safe to drink for longer periods of time. Fruit solids can be recovered in some cases and bitterness components removed by appropriate use of membranes. Removal of limonin and polyphenols has been done in a number of fruit juices including orange, grapefruit, tangerine and many more. Apple juice clarification and concentration as well as removal of biological species that are thermal resistant have been accomplished with membrane systems.

*Maple Sap:* The sugar concentration of natural maple sap from a maple tree is very low and traditional methods of making maple syrup involved boiling off the water. Membranes have become the means for the initial removal of water to concentrate the sugar content by 75 - 90%. Not only does this conserve energy but it avoids early application of heat to the syrup components to avoid early decomposition and change of the mixture.

*Vinegar:* Production of vinegar utilizes membranes to clarify the vinegar to give high quality product with low haze potential.

*Dairy applications:* The dairy industry has embraced membranes for many years. An obvious use is the concentration of milk and whey to reduce shipping costs, produce condensed milk or provide concentrated milk for cheese production. Membranes are being used on sweet/acid whey concentration before evaporation or spray-drying. Removal of bacteria and spores from milk aids shelf life and product stability. Acids and caustic are used to clean the equipment at dairies and membranes are being used to clarify the cleaning solutions by removing suspended and dissolved solids to allow reuse of the solutions.

Cheese manufacturing produced whey that was a troublesome by-product however membrane technology has allowed for use of this material via partial demineralization and concentration. Separation of casein from whey products allow for cheese production and whey protein concentration.

**Industrial Processes**

Clarification and purification of cell broths take advantage of the barrier layer of membranes. Extraction of amino acids and lipids can be accomplished and reused in blood and other cell cultures.

Enzymes are important to industrial processes and they improve the speed or efficiency of biochemical reactions. Advancements in enzyme production have been facilitated by the use of microfiltration. The cells that generated the enzymes are rejected by the barrier layer of membranes but the enzymes can pass though the pores. Prior methods of centrifugation and filtration were hard on the enzymes and limited productivity.

Separation of sugars such as dextrose and maltose from fibrous and undesirable proteins while purifying the mixture can be done with membranes. Clarification of the process stream after saccharification has been done in different facilities. Gelatin, egg whites, soy protein and other natural products can be improved using microfiltration and ultrafiltration.

Wet corn milling grinds the corn and then membranes have been used for removal of the mud for dextrose clarification, cell and biomass removal, protein, peptide and enzyme recovery, purification of dextrose, and maltose clarification.

Methanol removal from organic mixtures has been achieved by taking advantage of the hydrophilic nature and low molecular weight of that alcohol. Extraction of valuable volatiles, dehydration of organic solvents, aroma extraction can be done. Natural essential oils and flavors can be enriched and improved via membrane fractionation and recovery.

Nutraceuticals is a growing market in which nutrition and pharmaceutical are combined. Membranes are being used for the extraction, separation, concentrate and purifications of materials that fill this demand.

Animal processing facilities generate significant volumes of blood that traditionally has been a costly waste stream. However, by concentrating the blood plasma, a valuable additive for biochemical processes or pet food can be produced, and a potential cost item becomes a revenue generating product.

Waste stream effluent reduction with membrane systems is wide spread. Pulp and paper mills utilize membrane systems to filter the effluent prior to discharge and minimize the actual amount of liquid that will be discharged from the facility.

Production of paint and adhesives may use membranes and in the automotive and appliance industry that use water soluble paints, membranes are being used to recover the paint while improving batch conductivity by removing salts and process metals. Improvements in maintenance of the solids level in the process and reuse of the paint reduce the waste load from the plant and make the overall process economics more favorable. RO for the recycle of rinse water for pre-paint rinse system and recovery of paint solids from treatment waste streams has been used to improve painting economics.

Fine chemicals and pharmaceutical production employ membranes for recovery and are used within the processes.

Aquarium salinity control – large outdoor aquariums are subject to rain water that actually dilutes the sea water concentration from the optimum levels needed to sustain the oceanic sea life. In these cases, a small RO system will remove fresh water as permeate and the concentrate can be added back the tank to maintain an acceptable salinity. Permeate can be discarded or perhaps used in some other water application on the site.

Petroleum refining uses membranes for removal of particulates and tar products from the process streams. Biofuels are increasing in production and membranes are used in the process to remove by-products and raw materials from the final product.

There are some applications that demand very high purity or ultrapure water such as semiconductor chip rinsing and processing, high pressure boiler water make-up and assorted power plant needs. Membranes play an important part in producing this very low tds water. In these uses, the presence of a salt ion or impurity could be detrimental to the final product or the equipment in use and membrane technology coupled with other separation processes allow their success.

There is a technique for washing windows that employs highly purified water to accomplish the task rather than use detergents and membranes are used to produce this water in an environmentally friendly way that reduces the organic load in the wash water.

**Metal Removal and Treatment**

Mining applications can range from reuse of mine water, treatment of secondary effluent for use in the mining operation, treating waste water to allow discharge from the plant, recycling mine drainage. Potable water can be recovered from acid mine drainage for use at the mine or in neighboring communities.

Recovery of high value metals such as gold and uranium from bleed and waste streams in mining plants can be done. Likewise, valuable metals like copper, zinc, cobalt, molybdenum and tungsten can be separated from process and effluent streams. Pre-separation of copper and gold in a mining operation has been reported.

Industrial plants utilizing homogeneous catalysts employ membrane technology to recover the valuable catalytic materials. Reusing these expensive materials impacts the economics of the process and minimizes potentially hazardous waste streams that are costly to dispose of at these facilities.

Metal recovery – electroplating baths become contaminated with metals from the process and membrane technology has been used to clean up the baths and allow reuse of the solution thereby reducing the plating waste stream. A rechargeable nickel cadmium battery plant used a membrane system to remove dissolved metals such as mercury, lead, cadmium, silver, copper and chromium.

Landfill leachate contains a variety of components and membrane treatment has been used to remove water from the stream for safe disposal and then recycle of the concentrated leachate back to the pile. Radioactive species are rejected well by membranes and contaminated water can be treated to remove and concentrate the radioactive contaminants.

**Other Applications**

Nanofiltration has been used in organic solvents to separate larger molecules from the organic solvent so that it can be reused. Non-thermal solvent recovery, decolorization of solvents, solvent exchange at room temperature, in-situ recovery of organic solvent, monomer removal are all uses that allow reuse and deliver product upgrades. Non-thermal recovery of solvents and room temperature solvent extraction are accomplished with membranes.

Some membranes can be operated in pure solvents or mixtures. They can be used for recovery of antibiotics and peptides, dissolved chemicals, polymeric binders and pigments, dissolved catalyzed and even recycling of hydrocarbons in cleaning processes.

Some other applications include:

- Pigments and paints
- Latex suspensions
- Inks and dyes
- Emulsified oils
- Color removal for alcoholic beverages

**Summary**

Membrane processes have found a great variety of applications in which their use has improved products, recovered valuable components, added stability to the mixture, enhanced the aesthetics of the solutions and contributed to the economics of the processes. Microfiltration, ultrafiltration, reverse osmosis and nanofiltration each offer different separation options for industrial applications that will continue to grow in their use.

*This material has been prepared as an educational tool by the American Membrane Technology Association (AMTA). It is designed for dissemination to the public to further the understanding of the contribution that membrane water treatment technologies can make toward improving the quality of water supplies in the US and throughout the world.*

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# Ceramic Membranes

**Membrane Filtration**

Membrane filtration is becoming the technology of choice in liquid separations around the world for applications including desalination pretreatment, removal of suspended solids from water and wastewater, membrane bioreactors (MBR), as well as food and beverage processing. Most of the membranes produced today have a polymeric barrier layer but ceramic membranes are now available for many applications.

**Ceramic Membranes**

Ceramic membranes bring the porosity expected for microfiltration/ ultrafiltration (MF/UF) separation along with the added features of a durable material with high chemical, temperature and pressure tolerance. Ceramic membranes offer proven lifecycles up to 20 years or more and are used in potable water treatment, food and dairy industry, chemical industry and waste water treatment applications. In addition, there are a number of liquid separations that have very demanding conditions, and within those realms, ceramic membranes are being used extensively.

**Membrane Material**

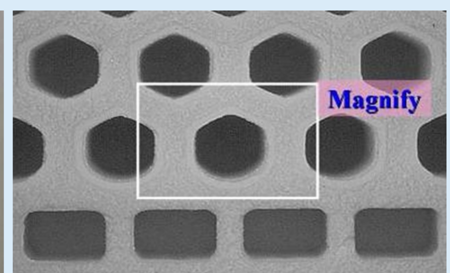
Ceramic membranes utilize a porous support such as alpha alumina or silicon carbide covered with a porous inorganic membrane layer of aluminum oxide, titanium oxide, zirconium oxide or silicon carbide rather than a polymeric barrier layer. The tubular, flat sheet, monolithic or hollow fiber support is made by extrusion, and then multiple layers of the ceramic membrane material are applied. Flat sheet membrane elements typically have the membrane coating on the outside and tubular membrane elements typically have several flow channels in the structure with the membrane coatings on the inside. Nitrides and carbides of similar metals may also be used as the barrier layer. The combined support structure and membrane layer is often referred to as a "membrane element" or ceramic element.

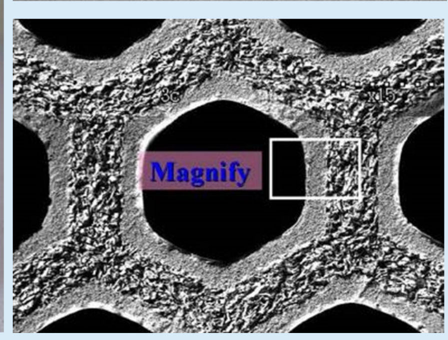
**Pore Sizes, Channel Diameters and Active Area**

The porous membrane layer will have distinct pores ranging from open microfiltration (1,4µm) to tight UF (1kD) and even nanofiltration (250D). Ceramic monolithic elements have multiple passageways or channels for the feed fluid to flow through the element or pass through the hollow fiber. Flat sheet ceramic membranes are submerged in the fluid and clean water is drawn through the membrane.

Ceramic elements come in different dimensions that can be beneficial for different applications. Some tubular types may be as long as 1,500 mm (5 feet) long. Diameters vary also and typically range from 20 to 200 mm. Filter channels can range from one very wide channel in an element to 100s of very narrow channels with inside diameters ranging from 1.0 - 25 mm (0.6 – 1.0 inches). Flat membranes can have up to 6 ft2 of surface area per sheet.

The diameter of the feed channels, its shape, the channel length and the number of channels per element will impact the membrane surface area of a ceramic element. Ceramic membrane elements of various shapes, diameters and lengths can have surface areas typically ranging from several ft 2 to nearly 300 ft 2. There can be one or up

to several thousand ceramic membrane elements in a membrane module.

### Membrane & Process Variations

Ceramic membranes are available in flat sheet, monolithic, hollow fiber and multichannel tubular elements. Flat sheet ceramic membranes are typically outside-in flow; monolithic, hollow fiber and multichannel elements are typically inside-out in dead end or cross flow configuration. The filtrate is collected as it exits the exterior surface of the porous material (element). There are some models of ceramic membranes elements with slots built into the monolith that collect filtrate and direct it to the outside of the element. The channel diameter chosen is adapted to the viscosity or TSS of the liquid to be treated. A pressurized feed stream can run from the inlet end to an outlet face in a cross-flow arrangement. Ceramic membranes used for drinking water applications are both flat sheet, outside in, as well as multichannel inside-out running in either dead end and cross flow modes of operation. Flat sheet ceramic membranes have also been used for drinking water, MBR and sludge dewatering applications.

### Flow Patterns

In some dead end flow configurations, the membrane is run in an inside-out mode with the feed flowing inside the passageway and filtrate recovered on the outside of the membrane. As the solids accumulate at the membrane surface, the flow rate will drop off at constant pressure, or the transmembrane pressure will increase at constant flow, until a backwash with water or compressed air is required. A backwash drives the filter cake off the membrane surface and produces a concentrated stream of solids for disposal or recycling to the front of the process. Chemically enhanced backwash and even clean-in place efforts with acids, alkalis and bleach restore the membrane filter for repeated reuse. There are other ceramic systems that do not use backwash and have been in operation for over twenty years, employing alternatives like back pulse, air sparging and dynamic shock.

Flux rates of tens to thousands of gfd are being realized in operating systems. One manufacturer reports Marker based Direct Integrity Test (DIT) challenge tests for ceramic membranes used for surface water to potable and have run challenge tests at 2,000 gfd. Another has NSF419 approval for DIT Challenge similar to polymeric membranes. Ceramics are very hydrophilic and therefore have high water permeability.

### Pretreatment

Some ceramic membrane systems may need some degree of pretreatment to reduce the load on the membrane plant or remove excess oil from the feed stream. High concentrations of small particulates, fibers and other items can block the feed channels and were found to erode the matrix when the wrong type or configuration of ceramic element was used. Some synthetic oils and grease may be difficult to remove from the matrix. Pretreatment methods might include centrifugation or coagulation/flocculation settlement to remove large particles or skim off free oil. Submerged flat-sheet ceramic membranes and tubular membranes tend to be usable with higher solids and oil concentrations. Similar to polymeric membranes, ceramic flat-sheet membranes used for MBR applications typically require a 2mm pre-screen.

### Equipment and Skids

Additional equipment for a ceramic membrane process might include an air compressor to assist air scours (for submerged ceramic flat sheets) and backwashing, as well as chemical make-up tanks. Air scour for ceramic flat plates is not required in all cases and there are municipal systems in operation without air scour. Some ceramic membrane manufacturers have developed process designs so that they can operate like most other pressurized polymeric membranes and can fit into the open platform design concepts utilized by several equipment OEM's. There are now cases of a ceramic membrane module retrofitting into an existing polymeric membrane system and for the most part, utilizing the existing infrastructure of piping, controls, and backwash pumps.

The ability to position more membrane elements in a module and more modules in a system can reduce the CAPEX required for a given system. There are modularized, skidded systems for ceramic membranes which provide a significant reduction in installed costs. Some of the manufacturers of ceramic membrane systems sell or rent pilot equipment.

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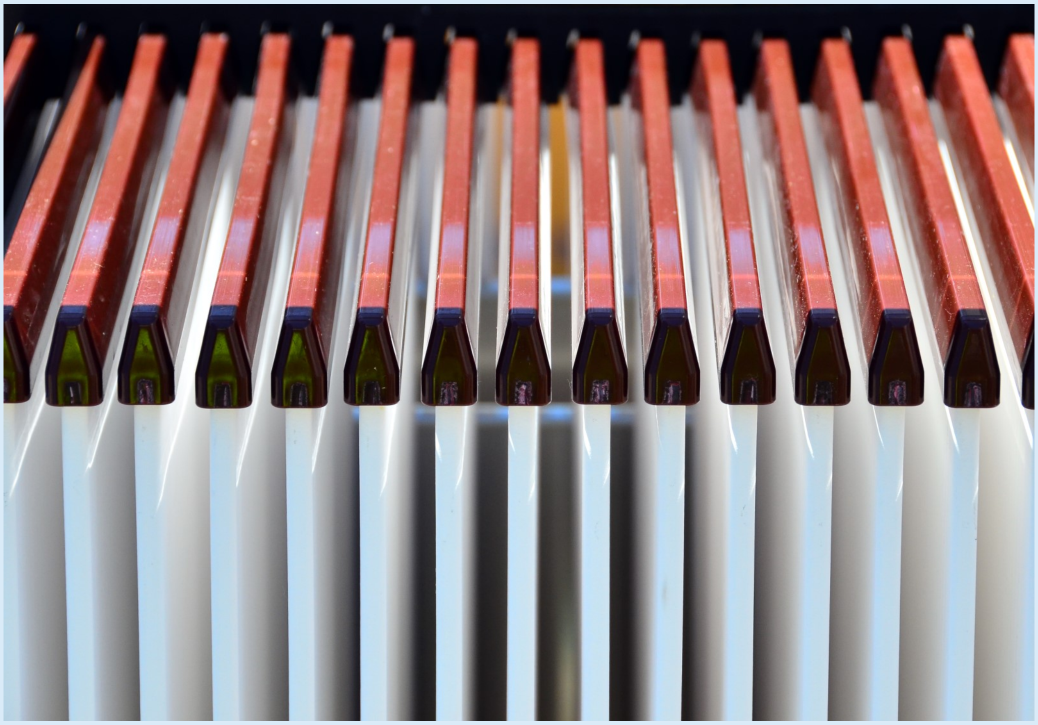
**Ceramic Membranes, Advantages, Disadvantages and Applications**

**Advantages**

Like other ultrafiltration and microfiltration membrane products, ceramic membranes offer reliable operation with a positive barrier against water quality upsets. They are mechanically strong and can be used in applications where there is increased oil and suspended solids in the feed. They are also abrasion resistant. Ceramic membranes are durable with a resistance to degradation by a wide range of chemicals and chemical concentrations, which allows more aggressive chemical cleaning procedures to be used over a pH range of 0-14. Ceramic membranes have a high resistance to ozone and chlorine, which allows for their use for disinfecting raw water prior to membranes These membranes are thermally stable and can withstand temperatures up to several hundred ºF. Some of the limitations for ceramic membranes apply only to the gaskets and other module materials, and not necessarily to the ceramics. In all cases consideration should be given to the type of ceramic material used.



High flux rates can be achieved with ceramic membranes since they can tolerate higher cross flow, which allows for extended process runs, resulting in a lower TMP for a given flux. Ceramic membranes have very high thermal stability and pressure tolerances, with working conditions mostly limited by the sealing materials and vessel/module structures.

Ceramic membranes can have a high packing density like a hollow fiber module.

As with microfiltration and ultrafiltration operations, ceramic membranes will remove disinfection by-product (DBP) precursors from surface water supply sources with proper coagulation, and with or without flocculation. They can also remove suspended solids at a ≥ 98% filtrate water recovery rate. Ceramic membranes provide an absolute barrier against upsets or surges in fluctuating raw water quality, which is characterized by a rapid increase of suspended solids and oils. Reduction or elimination of filtrate losses is made possible by minimizing or eliminating some of the separation steps needed in conventional processes. Ceramic membranes do not need to stay wet like polymeric membranes; they can be drained, removed from use and then restarted after being out of service.

A feature mentioned for ceramic membranes is the possibility of reusing the membrane material itself. Due to the materials of construction, in some cases, used ceramic membranes could be recycled as raw ceramic material to make other products. This could reduce disposal costs and eliminate landfill issues

Energy requirements of ceramic membranes may be less than other membrane separations. Lifecycle costs and capital costs can be competitive, or better than, polymeric membranes. Advances in ceramic membrane technology and processes offer greater energy efficiency, reduction in cleaning requirements, minimization of chemical usage and elimination of filtrate losses, which contributes to lifecycle costs in favor of ceramic membranes.

There have been reports of ceramic membranes with 18 years of operation, with little loss in permeability. In some cases, manufacturers may offer a 20-year warranty.

In rare cases, if chemical cleaning does not work effectively, the ceramic elements can be heated in an external oven by the membrane manufacturer to burn off the contaminants.

**Disadvantages**

Ceramic membranes have many useful properties, but the economics due to historically higher capital costs for the membranes and their system type must be considered and compared against recent advancements in cost reduction. There are a limited number of full-scale installations for potable water treatment and municipal MBR. Ceramic systems that can operate at half the CAPEX and OPEX of polymeric membrane processes are being promoted in the industry and deserve attention.

Claims of extended life cycles are inviting, but there are some possible methods for ceramic membrane degradation, including the possibility of chemical attack (very limited and mainly by fluoric acid), and thermal shock of the matrix. An advantage of ceramic membranes is the ability to heat the matrix to restore flow. However, too rapid a change in temperature, such as the introduction of a cold liquid, can result in thermal shattering of some of the ceramic materials and destruction of the element. Limits of no more than a 30ºC temperature differential and controlled heating or cooling rates are to be followed as recommended by certain manufacturers. Careful operating controls can minimize this risk. Generally, ceramic membranes are not to be frozen, although there are some exceptions with some specific designs.

Certain ceramic membranes can be subject to erosion from particulates in the feed stream, colliding with the membrane surface due to their materials of construction and manufacturing method. Fortunately, more durable ceramic membranes with abrasion resistance exist as seen in other applications, where ceramics are specifically used for their abrasion resistance quality in applications like powdered activated carbon and ceramic bearings.

## Applications

### Potable Water Applications

The use of ceramic membranes to produce potable water in the United States is limited to a half dozen installations as of 2017. In Japan, there are over 130 potable water facilities using ceramic membranes dating back to 1998, where the facility is still using the original membranes. A drinking water plant in Japan rated at 46 MGD, treating surface water was commissioned in April 2014. Several 1 MGD drinking water plants have been installed in Delaware, Texas and Mississippi and have been in operation in the USA since 2014. A 10 MGD plant treating reclaimed secondary effluent and surface water from a reservoir for indirect potable reuse stated up in January 2015 in Parker, Colorado

### Food and Dairy Industry

The food and dairy industry has embraced ceramic membranes for their unique properties. There are a number of installations around the world using these products for their sanitization properties and durability. The majority of ceramic membrane applications in the dairy industry are for Extended Shelf Life (ESL) milk where polymeric membranes simply will not work. In addition, there are systems operating that are used to defat whey, curd cheese and other dairy products. Another application that has been using ceramic membranes is the fractionation of whey proteins in the cheese making process.

Additional applications of ceramic membranes in food industry is in for beverage applications, such as juice clarification, s and beer production that require daily cleanings and, in many cases, thermal and chemical sanitization. Other applications include cell separation in amino acid production, lactic acid production, fermentation broth treatment, oil/water separations and sugar syrup production.

### Chemical Industry Applications

Ceramic membranes are used in industrial applications that include oil/ water separations, catalyst recovery, textile needs, waste water and even alkaline cleaning solution recovery. Applications to treat produced water that might be high in oil and grease, which are problematic for polymeric membranes are using ceramic membranes. Facilities in Colorado, Texas and Alberta have been installed to treat oil laden waters. Additionally, there are gas phase separations that use ceramic membranes, including separation of hydrogen from the waste steam of refinery and gasification plants, as well as separation of carbon dioxide from natural gas to a concentration of less than 2% for pipelines of natural gas.

### Sanitary Waste Water Treatment

Ceramic MBRs are now being considered in the United State but may find market share in industrial MBR and smaller municipal MBR applications. Ceramic membranes can be an effective integrity barrier for pathogens and this will be a key consideration for log removal credits in potable reuse applications including their use in MBRs

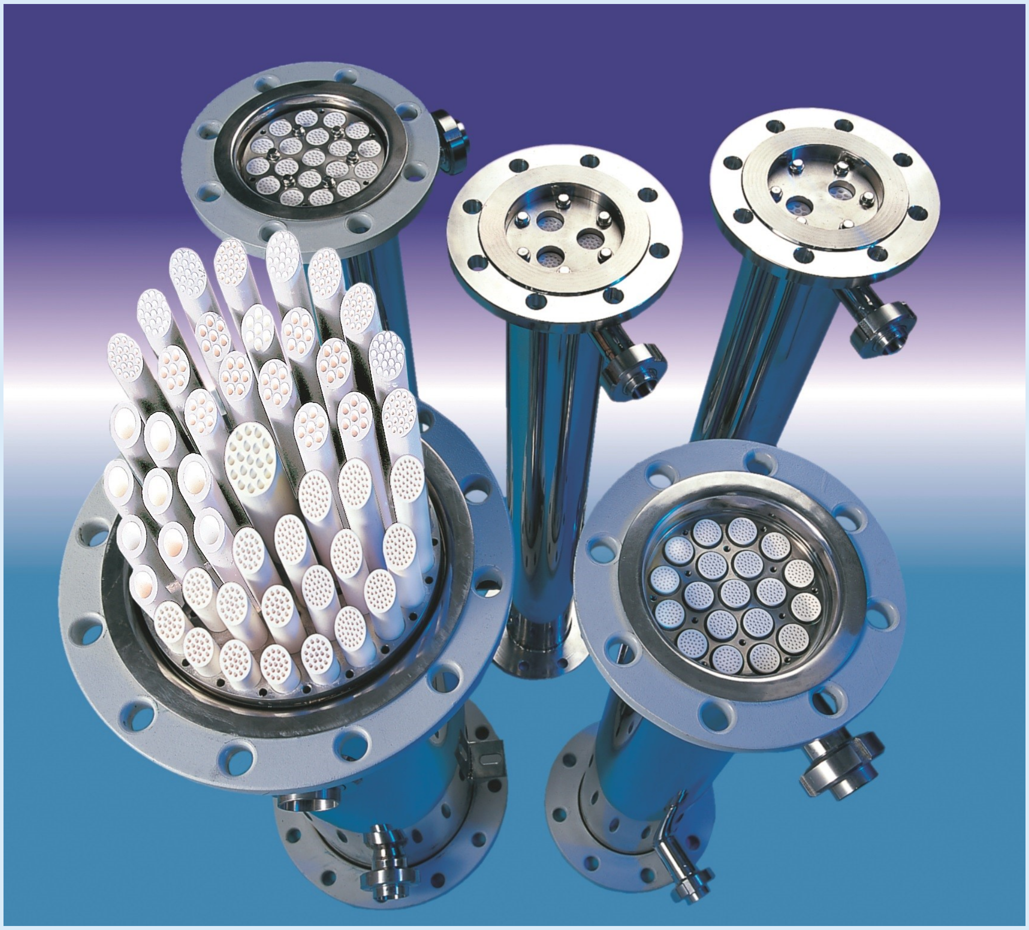
## Other Applications and Considerations

Ceramic membrane's durability, wide range of thermal and chemical stability and long lifecycles make them ideal candidates for difficult applications that would otherwise foul polymeric membranes and limit their useful life. Although ceramic membranes have traditionally been more costly than polymeric membranes, recent innovations such as; increasing surface area, reducing cleaning complexity and reducing manufacturing costs have made them more competitive. As their volume grows, especially where lifecycle costs and value are considered, ceramics will find increased use in water treatment and other applications due to these advantages.

Ceramic membranes do not remove dissolved components like reverse osmosis membrane, but do a very effective job of removing very fine solids and larger molecules and coagulated dissolved organic carbon (DOC) from solution. However, some ceramic membranes entering the market are in the nanofiltration range and may exhibit some salt rejection. Ceramic membrane systems have also been used as a pretreatment prior to ion exchange and reverse osmosis systems.

## Conclusion

Ceramic membranes have many desirable properties and are being used extensively in water purification, food and dairy applications as well as for industrial needs. These market uses of ceramics will continue to increase. As ceramic membrane production volume grows and product innovations reduce the capital cost, use of ceramic membranes will increase. They will be more prominent as they are better understood for use in potable water, waste water recycling, reuse, and even produced water in the oil field.



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# Membrane Applications in Water Reuse Projects

**Overview of Water Reuse**

Water Reuse is receiving increased national and international attention as an approach to effectively address sustainable water management mandates and proactive water supply planning. Effective reuse allows the implementation of safe, fit for purpose, and cost-effective water solutions that reduce or eliminate the unnecessary waste of limited water supplies. In parts of the world challenged by population growth, increased urbanization, ageing infrastructure, or climate change, water reuse has become an integral component of strategic water management planning. Water reuse can be implemented in either centralized or decentralized treatment facilities. Centralized water reuse refers to the use of a central wastewater treatment plant effluent for various agricultural, industrial, commercial, environmental, or drinking water supply applications. At facilities utilizing Indirect Potable Reuse (IPR) or Direct Potable Reuse (DPR), additional advanced water treatment processes beyond traditional wastewater treatment are often employed. In contrast, decentralized water reuse includes the collection of various combinations of localized wastewater or graywater sources for non-potable uses. Decentralized reuse systems provide water for subsurface and spray irrigation, toilet flushing, vehicle washing, industrial cooling applications, zoo animal washing, construction, and other non-potable applications.

**Types of Membrane Based Reuse**

The efficacy of membrane technologies in wastewater treatment has resulted in a variety of water reuse alternatives, including both non-potable and potable reuse. Wastewater has been intentionally reused for non-potable purposes in the United States since the 1800's; however, it was not until the 1960's that reuse was first intentionally applied to replenish drinking water supplies. Advanced treatment of wastewater using Reverse Osmosis (RO) membranes for indirect potable reuse began in Orange County, California in the mid-1970's. Today membranes are used in hundreds of reuse applications around the United States and the world, allowing utilities and industries to target the removal of specific contaminants, including pathogenic organisms, dissolved salts, or trace organic compounds (TrOCs). Four primary membrane types account for the majority of the membrane based reuse applications. These include:

- Membrane filtration for turbidity and pathogen reduction, including Microfiltration (MF) and Ultrafiltration (UF)
- High pressure membranes for salinity and TrOC reduction, including RO and nanofiltration (NF)

This indirect potable reuse facility in California includes two microfiltration stages and three reverse osmosis stages to operate at an overall plant recovery of 92.5%.

- Electrical potential based desalination for salinity reduction, including Electro-Dialysis (ED) and Electro-Dialysis Reversal (EDR)
- Membrane bioreactors (MBR) for a combined process that provides both secondary wastewater treatment and filtration

Each of these applications is discussed briefly below.

**Membrane Filtration**

The use of MF and UF in tertiary filtration continues to increase as membranes prove their reliability. Membrane filters provide almost complete removal of bacterial and protozoan pathogens while consistently providing high quality filtrate with turbidity values of under 0.1 NTU. Because membrane filters do not rely on coagulants for suspended solid and pathogen removal, they offer reliable alternatives for remotely operated or minimally staffed facilities. More compact plant foot-prints often allow significant increases in plant capacity when membranes are installed within existing media filter bays. Membrane filtration has also become the standard pretreatment technique for wastewater RO facilities used in either potable or non-potable reuse applications.

**Reverse Osmosis and Nanofiltration**

RO and NF are being used for the removal of TDS and TrOC in potable reuse applications, industrial reuse, and irrigation reuse, where low TDS supplies are required. RO and NF systems typically require membrane filtration as pretreatment to reduce the rate of biofouling, organic fouling, and particulate fouling. Lower fluxes are typically applied with wastewater supplies and a continuous chloramine residual is often employed to prevent biogrowth on the membranes. RO membranes have proven effective at greater than 99 percent removal of emerging contaminants such as endocrine disruptors, pharmaceuticals, personal care products and other trace organic compounds with the exception of some low molecular weight, neutrally charged compounds such as nitrosamines, trihalomethanes, and 1,4-dioxane. They have also been granted 2-log (99 percent) pathogen reduction credits for viruses, Giardia, and Cryptosporidium at several locations. Further acceptance will be a function of adequate integrity testing through online monitoring of conductivity, total organic carbon (TOC), or other applicable testing methods. There is ongoing research to identify methods for RO integrity testing that would be more widely accepted.

**Electrodialysis and Electrodialysis Reversal**

ED and EDR are being used in select reuse applications where TDS reduction is required but the removal of organics and pathogens are not essential. While Electrodialysis technologies are not as commonly used as RO for wastewater treatment, they can provide a cost effective alternative for the removal of dissolved salts and do not require membrane filtration as pretreatment. Because electrodialysis technologies employ electrical potential to attract positively and negatively charged ions, they are not effective at removing pathogens or weakly charged organic molecules, and are therefore not currently used in potable reuse applications.

**Membrane Bioreactors**

MBR has seen a rapid increase in usage over the last decade, allowing secondary and tertiary treatment to be accomplished in a single process. MBR is considerably more compact than traditional wastewater processes, can be operated at higher mixed liquor suspended solids concentrations, and provides product water with turbidity values that are consistently less than 0.1 NTU. Because of the consistent quality of the permeate, MBR systems can also be used upstream of RO membranes, where TDS and near complete TOC reduction are required. To date, MBR has mainly been used in non-potable reuse applications; however, it provides a potential treatment step for potable reuse if membrane integrity testing is incorporated into the process. MBR can also provide a unique opportunity for scalping plants and decentralized reuse facilities due to the small footprint and high level of automation.

This non-potable reuse facility in California employs Electrodialysis Reversal for the reduction of dissolved solids, supplying a new source of water for irrigation and industrial uses.

This food processing facility uses MBR and RO to recover process water and minimize the water footprint at a highly water stressed location in Arizona.

**Membranes offer a wide range of benefits for reuse**

- Near complete pathogen and suspended solids reduction
- Direct and indirect integrity monitoring to ensure the effectiveness of the treatment process
- Full automation, often allowing unstaffed facilities
- Alternatives for reducing salinity and dissolved inorganic constituents
- Near complete removal of TrOCs and other constituents of emerging concern (CECs)

**Future of Membranes in Water Reuse Applications**

Membranes (including MF, UF, NF, RO, ED, EDR and MBR) have already been successfully used for a wide range of centralized and decentralized water reuse applications. The reliability and consistency in providing predictable water quality will ensure that membrane treatment processes will continue to make significant contributions in producing "fit for purpose" water quality and provide a clear advantage for many water reuse applications. The future advances in membrane technology will no doubt result in even more creative applications and possibilities for water reuse.

Areas for potential advancement that are currently under development include backwashable NF membranes that will allow the removal of organic material with limited pretreatment, chlorine tolerant RO and NF membranes, and methods for more widely accepted RO and NF integrity testing to demonstrate effective reduction of pathogens.

*This material has been prepared as an educational tool by the American Membrane Technology Association (AMTA). It is designed for dissemination to the public to further the understanding of the contribution that membrane water treatment technologies can make toward improving the quality of water supplies in the US and throughout the world.*

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# Forward Osmosis (FO)

**Overview**

In recent years, significant advances in membrane technology, improved processes, and the need to treat more difficult waters has expanded the market potential of Forward Osmosis (FO). Initial uses of FO included the treatment of difficult waste streams, small-scale water reuse, and emergency/disaster recovery. These applications were well suited for the technology, given the main benefits of FO:

- Low propensity for fouling/scaling
- Potential to apply waste energy (i.e. salt/heat) om the effective separation/ concentration of solutions
- Ability to achieve very high concentrations of feed solutions
- Potential to convert stored chemical energy into hydrostatic pressure (e.g., pressure retarded osmosis)

FO is an osmotic membrane process, which takes advantage of osmotic pressure to drive water across a semi-permeable membrane, where two solutions of varying salinity are present. Unlike Reverse Osmosis (RO) where hydraulic pressure is required to overcome osmotic pressure, FO is not hydraulically pressurized. Water flows naturally and spontaneously from a lower salinity feed solution on one side of the membrane to dilute a higher salinity draw solution on the other side. Like RO, the semi-permeable membrane allows water to pass through it, but rejects nearly all suspended and dissolved solids.

During the FO process, the lower salinity feed solution is concentrated and the more concentrated draw solution is diluted. If fresh water is the goal of the process, a separate draw solute separation process must be included in the treatment scheme. Figure 1 illustrates Forward Osmosis and Reverse Osmosis Processes. Figures 2 and 3 show treatment scheme examples in which FO is used.

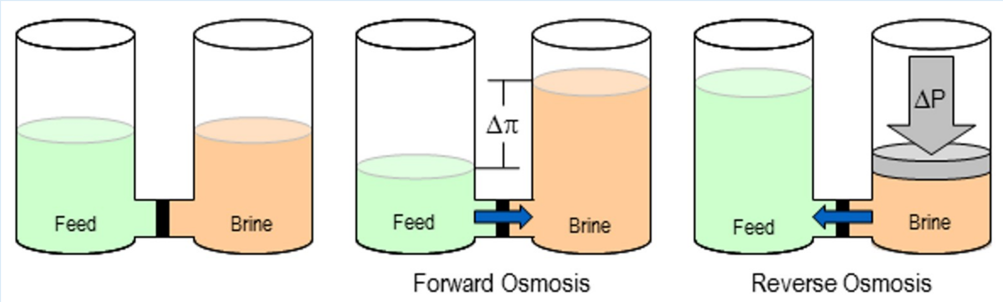


**Figure 1: Osmotic Membrane Processes**

Forward osmosis is used in the municipal, mining, oil and gas, and food and beverage industries in several ways:

- Clean water recovery
- Product concentration
- Waste concentration

FO is ideally suited to recover clean water from an impaired source. It can be used most efficiently where a high salinity draw solution is already being used to supply a desalination process, or where waste heat is available to increase the osmotic pressure driving the process. Clean water recovery treatment schemes that utilize FO require the downstream separation of the solute from the solution to produce fresh water, since it is the high concentration of the solute that is inducing the FO process. Technologies used for this downstream separation may include RO, membrane distillation (MD), thermal evaporation, thermal distillation, or the use of a specific draw solute that is removable by some other means. Alternative draw solutes that have been used include thermolytic salts (which volatilize when heat is applied) or magnetic nanoparticles. In some schemes, the FO process acts as a high-quality pre-treatment before the solute separation process. Because the FO membrane rejects nearly all foulants and other contaminants, the downstream desalination process can be designed more aggressively, targeting only the removal of the specific salt used to induce the FO process.

In other applications, FO is used for clean water recovery, but the draw solute is not separated from the diluting water. In one such process, a bag constructed of FO membrane contains a beverage concentrate (primarily sugar and flavoring). When the bag is placed in a potentially contaminated or saline water source, the beverage concentrate acts as a draw solution, pulling water across the membrane, creating a more diluted beverage. In this way, a safe, potable drink can be made using a contaminated feed water source, without applying outside energy. There are commercial products available using this scheme, marketed to back country hikers or for use as emergency hydration packs. Another use is "fertigation", in which a fertilizer is used as a draw solution to recover clean water from seawater or brackish water. The fertilizer is then diluted to the desired strength and applied to crops.

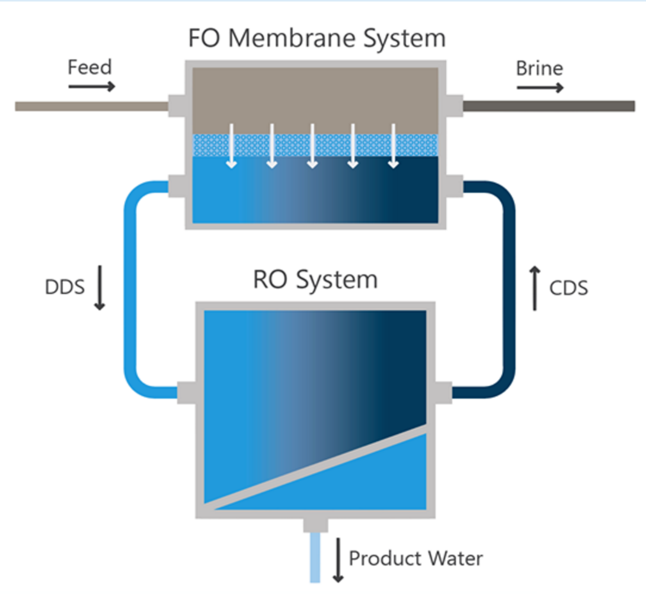


**Figure 2:** Typical FO system design with draw solution and product water separation by RO (ionic salt as osmotic agent)

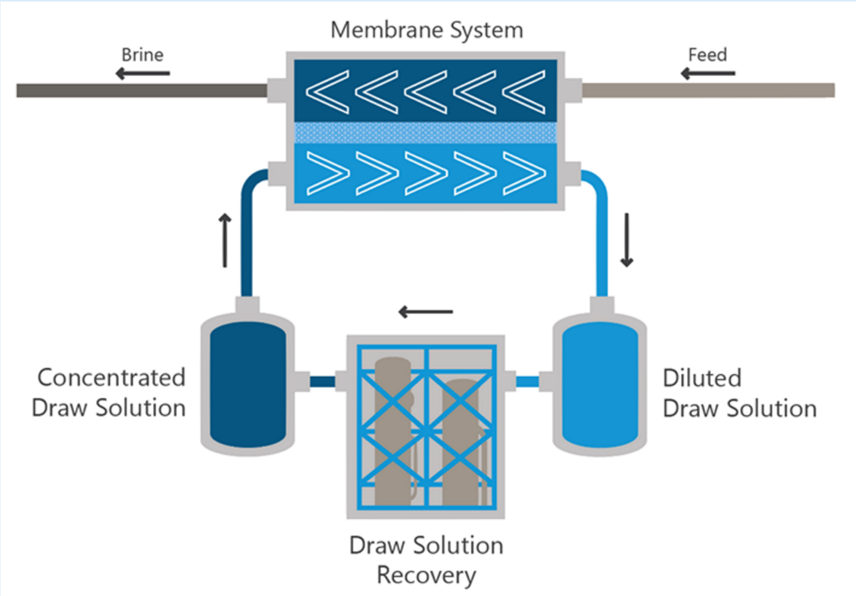


**Figure 3**: Typical FO system design with thermal draw solution and product water separation (thermolytic salt as osmotic agent)

The food and beverage industry uses FO for food product concentration. Saltwater or sugar water are used as a draw to remove excess water and subsequently concentrate juices, soups, and other food products. One significant benefit of using FO in this process is that the flavor and appearance of the food are not altered by the high heat or pressure required in other concentration methods.

In the mining, power, chemical, and oil and gas industries, FO is usually used to minimize and concentrate waste streams. In these industries, waste streams are often very difficult to concentrate due to their high salinities or high fouling or scaling potential. FO is able to highly concentrate these streams and effectively reduce the volume of waste and the associated disposal costs. Concentration factor is directly related to the osmotic potential of the draw solution being used in the system.

A sub-technology to FO, Pressure Retarded Osmosis (PRO), makes renew- able energy production possible by mixing freshwater and saltwater. In PRO, the saltwater is pressurized to some fraction of the osmotic pressure by the flux of water across the membrane. A portion of this high-pressure salt water is then relieved though a turbine, generating electricity. This technology makes it possible to generate energy from waste streams of freshwater, while reducing the volume of the waste stream.

The first FO membranes were cellulose acetate (CA) based, and contemporary CA membranes have been optimized and are still widely available for FO. The latest FO membranes, however, have adopted the thin-film composite structure of current RO membranes. FO membrane elements are commercially available in a variety of configurations, including flat sheet, spiral wound, and hollow fiber. Water fluxes in the FO process are a function of the salinities of the source water and the draw solution, but tend to be lower than other membrane technologies, including RO (on the order of 1 to 5 gallons per day per square foot). Because FO does not require high pressure, higher packing densities can be achieved in spiral wound and flat sheet FO membrane element configurations.

**The Future of Forward Osmosis**

Continued scarcity of pristine water sources, increased waste disposal costs, and continued improvements in FO technology will significantly expand the FO market in coming years. As water reuse becomes increasingly necessary, FO will be a viable technology in the water treatment arsenal to obtain high-quality pre-treatment for other separation processes. In situations where zero liquid discharge (ZLD) is mandated, for wastewater treatment, FO can reduce the cost of the energy intensive brine concentration step prior to crystallization, FO will also fill a critical void for mining and oil and gas companies that are looking for methods that minimize the volume and cost of waste disposal and increase the recovery and reuse of water and process fluids. Food and beverage companies will also look to FO as a desirable method of product concentration that protects the flavor and nutritional content of their products.

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# Energy Recovery Devices

**Overview**

The use of Energy Recovery Devices (ERDs) continues to become more commonplace as the cost of power continues to increase throughout the world. System designers are more frequently being asked to minimize the Specific Energy Consumption (SEC) even in areas where the cost of power is relatively low. By far the largest contributor to the decrease in SEC over the past three decades has been the advancements made in energy recovery technologies. All ERDs used in the water treatment industry reduce power by harnessing the energy in the concentrate (or brine) waste stream and transferring it to the feed side via various methods.

**History**

Historically, the Achilles heel of seawater reverse osmosis (SWRO) systems, brackish water reverse osmosis (BWRO) systems, and industrial water systems has been the energy intensive nature of the membrane separation process. Over the past 30 years, the industry has seen a decrease in SEC from SWRO installations without energy recovery devices operating close to 8kWh/m3 (for the RO portion of the process only) down to 2.5kWh/m3 in today's state-of-the art facilities (Chart 1). Today, all medium to large-scale SWRO facilities have adopted ERDs into their process designs and have benefited from the reduction in SEC.

**Photo 1** – Turbocharger

**Types**

Energy Recovery Devices can be broken up into two major sub-categories: centrifugal and positive displacement isobaric type.

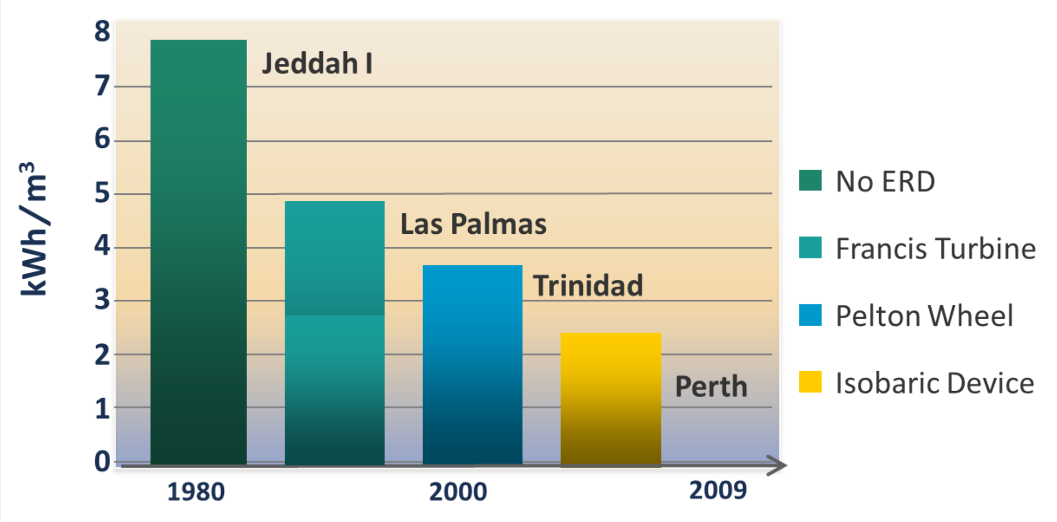


**Chart 1** – Specific Energy Consumption Trend (RO portion only)

Centrifugal ERDs include reverse running pumps, impulse type turbines and turbochargers. The turbocharger device consists of a pump section and a turbine section. Both pump and turbine sections each contain a single stage impeller. The turbine impeller extracts hydraulic energy from the brine stream and converts it to mechanical energy. The pump impeller converts the mechanical energy produced by the turbine impeller back to pressure energy in the feed stream. Thus, the turbocharger is entirely energized by the brine stream. It has no electrical requirements, external lubrication, or pneumatic requirements.

Isobaric ERDs include rotary type pressure exchangers and piston type work exchangers. The pressure exchanger device consists of a rotor, moving between the high-pressure and low low-pressure stream, which displaces the brine and typically replaces it with an equal volume of seawater. Pressure transfers directly from the high pressure membrane reject stream to a low-pressure seawater feed stream without a physical piston in the flow path. The rotor spins freely, driven by the flow at a rotation rate proportional to the flow rate.

**Photo 2**— Pressure Exchanger

Desalination Energy Reductions

**Seawater**

SWRO systems typically work at recovery rates ranging from 30% up to 55%. This means that reject brine flow accounts for the 45% up to 70% of the total membranes feed flow. Additionally and due to the high salinity of the treated water, operating pressures can be as high as 1200 psi (82.7 bar) in some cases with lower values at around 725 psi (50 bar). Therefore, the highest reductions in energy consumption are obtained in SWRO systems because there is a high flow of residual brine at a high pressure. Energy reductions can be as high as 67% depending on the operating conditions and ERD technology used.

**Brackish Water**

On the other hand, brackish water systems (BWRO) have a lot more variability on the raw water characteristics. High brackish applications require low recovery rates and high operating pressures similar to those SWRO systems where seawater is in the lower limit of salinity. Low brackish water applications can have recovery rates as high as 95% and operating pressures as low as a 50 psig (3 bar). The variability is so high that BWRO systems are typically designed to perform in a wide range of flows, pressures and recovery rates and the selection of the appropriate equipment for pumping and recovering energy can be very challenging. In some cases, technologies that were developed to save large amounts of energy in SWRO systems can become too expensive to be applied in brackish water, even when offering the highest energy savings. The selection of the proper ERD system for a BWRO must be analyzed in depth and on a case-by-case basis.

**Photo 3**—Small Turbocharger on RO Skid

**Photo 4**—Large Turbocharger

**Photo 5**—Motorized Turbocharger on RO Skid

The possible reductions range from 40% to 0% of the total energy spent in the osmosis process. Zero percent meaning that, for very low salinity BWRO systems, the best selection could be not including an ERD.

Additionally, the application of interstage ERD's have long been recognized as a way to improve membrane performance to achieve flux balance among multi-staged arrays. Interstage boosting helps to improve the production of the first and second stage to be more balanced, reducing the risk of fouling from poor hydraulic conditions within the membranes. It also helps to reduce 1st stage feed pressure hence reducing the required feed pump energy consumption. Also, when replacing an interstage booster pump an ERD can reduce or eliminate the energy consumption associated with the booster pump.

**Other Considerations**

The question is no longer whether we should use an energy recovery device, but what is the most economical ERD for a specific project. A comprehensive technical and commercial evaluation of ERDs needs to be considered to determine the most suitable ERD for a specific set of project conditions. Many times the initial capital expenditure is the only factor that is considered in deciding which ERD to select for a given project. This is a fairly common practice but can result in significant economic losses over the useful design life of the facility. The economics of ERD selection can be broken down into two primary categories of capital and operational expenditures. Both, capital expenditure (CAPEX) and operational expenses (OPEX) have many subsets that can be quantified and carefully analyzed to ensure maximum return on investment.

<u>CAPEX considerations include:</u>
Equipment Cost: Initial cost of equipment.

Installation Cost: ERD technologies vary tremendously on the amount of installation cost required to meet the manufacturers' specifications. Piston type ERDs require additional civil works, have independent PLC and hydraulic systems, and consume varying degrees of floor space (i.e., footprint). ERD racks and manifolds also add costs to each ERD offering. Centrifugal type ERDs tend to have the smallest footprint and minimal installation requirements.

Auxiliary Equipment Cost: Isobaric type ERDs require an additional circulation booster pump while centrifugal type ERDs do not. Connection types, number and size of connections, and instrumentation all need to be taken into account during the CAPEX analysis.

Other Costs: Depending on the type of ERD, there may be specific costs associated with a specific manufacturer or technology. Pelton-turbine ERDs may require an additional pump and sump system to displace the exhaust brine. Acoustical enclosures could be needed for ERDs that produce noise above 85 dB. Filtration and flushing requirements add other costs that are predominately ERD manufacturer-specific but can quickly add expenses to a proposed solution.

**Photo 6**—Pressure Exchange Skid

<u>OPEX considerations include:</u>
Maintenance: Fewer moving components will reduce the amount of maintenance required. Consider the device spare parts costs to maintain the ERD over its life span. Some ERDs may require specialized tools or shop equipment for routine maintenance, as well as downtime for repairs.

Durability: To ensure the long-term and trouble-free lifetime of the seawater reverse osmosis (SWRO) process and its enabling technology, it is essential to utilize the most advanced and reliable materials of construction. One of the more advanced and unique materials currently in use in SWRO desalination applications is high purity (>99%) aluminum oxide (alumina) ceramics.

Availability: Availability can be defined as the probability that a system or piece of equipment used under the specified conditions operates satisfactorily at any given time.

**Future of ERDs**

ERDs have become standard equipment for the reverse osmosis desalination process, both in seawater and brackish water applications. The future of these devices relate to improving performance across a variety of areas. For pressure exchanger devices, this would include decreased mixing of fluids, greater energy transfer efficiency, lower back pressure, higher turndown and higher per unit capacities. To improve the widespread adoption of ERD technologies, different purchasing strategies are being rolled out, such as a performance contract that would remove the CAPEX requirements for ERDs and instead require users to pay for the devices based on a portion of the energy saved. The economic justification or return on investment for ERDs can vary considerably based on a large variety of site-specific conditions and type of considered.

All manufacturers continue to push the envelope in developing the next generation of ERDs. Improvements in material science, hydraulic design, and reliability will continue to be the primary focus. The largest driver of innovation will be the lifecycle cost consideration of ERDs. System designers and end users will need to study the advantages and disadvantages of commercially available technologies. This evaluation typically has technical and commercial components to it.

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# Applications of Membrane Technologies in Food and Beverage

Membrane technology is probably best known for its use in water treatment and many in the public sector link membranes primarily to seawater desalination. In the United States membranes are used to desalinate brackish water, remove color, particulates and hardness from surficial wells and treat surface waters to remove turbidity, bacteria and viruses. There is, however, a large variety of additional applications in the food, dairy and beverage industry using membranes every day.

The most obvious use of membranes is to treat water to a higher quality for bottled water applications. Some manufacturers use membranes to improve the color, taste and salinity of ground water, surface water and even municipal city water. In many instances, the minerals removed from the local source via membrane treatment are blended back in under prescribed recipes to ensure a consistent feel and taste in the finished product no matter where its produced around the globe.

Likewise, treated water is a key ingredient in beverages such as Gatorade where a mixture of sweeteners, minerals and other compounds are added to low Total Dissolved Solids (TDS) water treated by a membrane system to achieve the required taste and nutrition composition and, again, ensure a consistent global taste.  Many of the major soft drink companies employ membrane systems for this same reason, treating locally sourced waters to produce a stable,

*"Membranes can be used for fruit processing"*

consistent product with good shelf stability, low turbidity and great taste. High levels of calcium and magnesium in source water can precipitate, leading to cloudiness in the finished product during storage. Many of the soft drink bottling facilities use membranes to treat the locally available water to a higher standard before blending in the syrups and carbonation.

Similarly, beer brewing relies on a consistent water quality to make sure the final taste and quality remain the same day to day. Brewmasters carefully monitor water quality and many large breweries rely on membrane technology for that purpose. Anheuser Busch in Jacksonville, FL has been using membranes to treat well water since the early 1990's.

*"Ceramic membrane system for beer processing, photograph courtesy GEA Processing Engineering, Inc."*

*"Ceramic Microfiltration and Reverse Osmosis system for skim milk processing, photograph courtesy GEA Processing Engineering, Inc."*

In addition to using membranes for high quality process water, some breweries use membrane technology for their wastewater treatment. Brewery wastewaters are typically high in Biochemical Oxygen Demand (BOD), byproducts of sugars, proteins, carbohydrates and yeasts. Some breweries like the Stone Brewing Company in Escondido, CA employ a Membrane Bioreactor (MBR) and Reverse Osmosis (RO) system to reduce the wastewater discharge from the facility and reuse some of the process water.

The dairy industry found that membranes are valuable in a large variety of treatment processes. Ultrafiltration (UF) and Microfiltration (MF) membranes separate compounds based on size and can be used for the removal of bacteria, separation and fractionation of components and more. Milk can be “disinfected” by removing bacteria and viruses using MF and UF and boxed aseptic milk products are now possible using membranes. Milk and whey protein concentrates and isolates are achieved using MF and UF membranes. A distinct advantage of membrane use in these applications is that the treated products are no longer subjected to heat separation, so thermal degradation is completely avoided.

Dairy equipment requires constant cleaning and sanitization. Membrane systems are used here as well to remove suspended and dissolved solids from spent cleaning solutions and recover the reusable acid and caustic.

Cheese processing uses membranes for the treatment of whey to produce various whey protein products. Such membrane processes have turned a discarded by-product into a valuable new revenue stream. Whey and milk concentration is achieved with membranes as is the demineralization of whey for protein recovery. Other common membrane applications in a dairy plant include the use of MF to make skim milk, and the use of Nanofiltration (NF) to separate and concentrate lactose. Enzymes play a major role in food processing and are typically produced through industrial fermentation, where microorganisms, such as yeast and bacteria are used to produce different kinds of enzymes. Microfiltration is widely used to remove the microbial cells from the fermentation broth. The broth can then be treated with Ultrafiltration membranes to harvest, concentrate, and purify the enzymes.

Maple sap collected from trees typically contains about 2% sugar (sucrose) in solution and was traditionally converted into syrup by boiling out the water. Maple farmers embraced RO and NF to concentrate sap up to 17-20 degrees brix prior to boiling.

Recently, new maple sap concentrator units have been introduced, allowing concentrations up to 35 degrees brix and a significant reduction in energy demand related to the final evaporator boiling necessary to develop the full maple flavor. Manufacturers enjoy significant process savings and improved syrup quality.

Membranes are finding their way into the tail end of food processing plants in the form of recovery systems and membrane bioreactor wastewater treatment systems. A facility in Japan installed an MBR system to treat high BOD wastewater from the facility that processed vegetables for peeling, washing and packaging. The quality of the MBR effluent is high enough to feed a downstream RO system and further reduce the TDS. The RO permeate is then reused in the plant as process water and to spray on metal roofs to effectively cool the buildings during summer. MBR systems allow facilities to reduce BOD, Total Suspended Solids (TSS) and nutrient levels below the limits of municipal sewer and environmental discharge and require smaller footprints at costs comparable to those of conventional wastewater treatment.

Facilities processing a variety of fruit and vegetable produce such as potatoes, carrots, apples, onions, lettuce, beets and bananas use membranes for wastewater treatment. These wastewaters are characterized as having

*“Wine Processing System, photograph courtesy of KOCH Membrane Systems”*

relatively higher amounts of BOD, TSS and nutrients such as nitrogen and phosphorus, when compared to municipal wastewaters.

Significantly increased yields of higher quality juice can be achieved using various membrane technologies. Apple, citrus, cranberry, cherry, grape, pomegranate, carrots and other juices are effectively clarified using UF and MF membranes, resulting in clear juices with a longer shelf life. RO is successfully used to remove water and concentrate juices, reducing transportation costs. Membrane systems typically require less labor and maintenance than conventional treatment methods and can be easily adjusted to accommodate different feed juices.

A combination resin-membrane process can reduce the bitterness of some citrus juices such as orange, grapefruit, tangerine, lemon and lime, enhancing the juice quality, consistency, and yield.

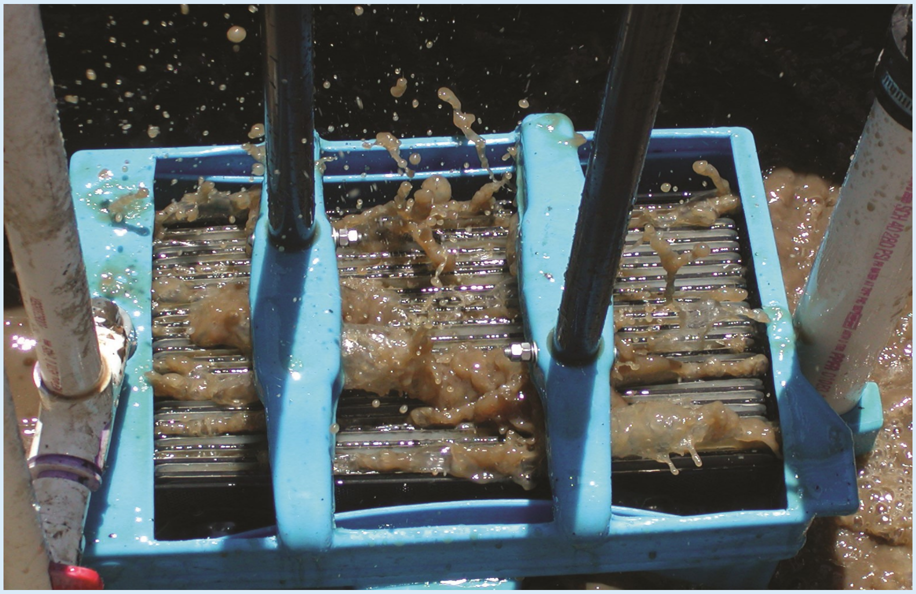
In wine production, membrane filtration is commonly used to remove suspended solids and turbidity to produce clear wine, while allowing the passage of color, ethanol, flavor and aroma components. Tubular membranes have been used for treatment of juice lees, the solids that remain after grape crushing, and wine lees, the insoluble sediments in wine processing, for the recovery of juice and wine that would otherwise be lost. Membranes deliver a higher quality product with less oxidation, no heavy metal residual and reduced waste as compared to conventional diatomaceous earth clarification, in addition to cost savings and lower labor and maintenance requirements. Alcohol adjustment in wine is achieved using membranes and one can reduce the alcohol without affecting the natural flavors in the wine. Other membrane applications for wine and juice include sugar concentration, color |concentration, volatile acidity (VA) reduction and more.

Removing TDS and undesirable heavy metals in the brew water improves the taste and aroma of coffee and minimizes scale in the brewing equipment. Membrane treatment is extremely useful to ensuring a predictable and consistent brew of coffee regardless of the water source.

*"Collecting tree sap for syrup production, photo courtesy of the Chippewa Nature Center"*

Concentrating juices and milk using membrane treatment reduces transport volumes and subsequent freight costs, requires less energy and results in fewer adverse side reactions. High value food components recovered from dairy processes can be used to fortify other products and food safety and shelf life can all be improved using membranes.

Membranes have been adopted for a variety of reasons including process flexibility, increased yield compared to alternative methods, reduced manpower for system operation, smaller footprints and overall cost saving. Eliminating diatomaceous earth filtration and its related waste and negative impacts on product taste makes membranes an attractive alternative. The comparative ease of cleaning membrane systems is also advantageous.



*"Partially-submerged MBR treating a winery waste stream, photograph courtesy of Bio-Microbics"*

Some examples of applications and the membrane process are:

MF – bacteria spore removal from skim milk, whey and WPC

MF and UF – protein fractionation

MF – delipidization of whey

MF – chemical recovery

UF – concentration and fractionation of proteins in milk

UF – brine clarification

NF – demineralization of UF permeate

NF – demineralization of whey

NF – milk electrolytes

RO – water removal from whey and other streams

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# CLEANING IN PLACE (CIP)

## Procedures For Membrane Systems

### INTRODUCTION

During normal operation of a membrane system, the membranes will eventually exhibit a loss of performance from fouling or scaling. When the normalized permeate flow has declined 10%-15%, a Clean-in-Place (CIP) should be scheduled. Review of the operating data and feed water quality will aid in determining the most effective CIP procedure. In certain situations a membrane autopsy/ cleaning analysis may be considered to help define the best CIP procedure. The manufacturer of the membrane model that is to be cleaned is a valuable resource. They generally have recommended guidelines for cleaning and their specific membrane model cutsheets provide pH and temperature limits that should not be exceeded. Suppliers of specialty membrane cleaning chemicals can also provide a wealth of knowledge. In addition, the engineer or system supplier for the membrane treatment equipment can assist with site-specific knowledge. CIPs for spiral wound membrane systems – reverse osmosis (RO) and membrane softening (NF) – are usually much more infrequent and, therefore, more of a manual process compared to CIPs for low pressure membrane systems such as micro and ultrafiltration, referred to as Membrane Filtration (MF).

### SAFETY CONSIDERATIONS

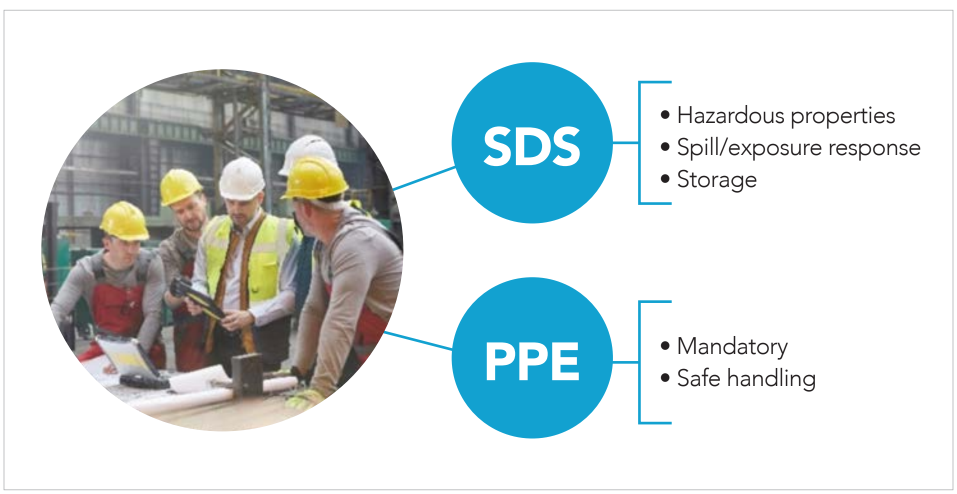
Safety is the number one concern when handling cleaning chemicals. Cleaning-in-Place chemicals should always be treated with caution. Avoid storing high and low pH cleaners next to each other as a strong reaction can occur if there is a spill. When adding the CIP chemicals, proper Personal Protective Equipment (PPE) should always be worn. This will vary depending on the chemical and the steps required to introduce them into the system. Consult the Safety Data Sheet (SDS) before first use. Special care should be taken if adding powders in an enclosed space. A well-ventilated area is optimal for handling powders.

### PRE-CIP CONSIDERATIONS

There are standard CIP guidelines that are shared for cleaning either RO/NF or MF systems. A high pH clean is usually recommended before a low pH clean because salts may precipitate or re-disperse during the high pH clean. Those salts can then be removed by the subsequent low pH clean. The opposite order has a higher propensity for foulant or scale to remain in the system after the conclusion of the CIP. Finishing with a low pH cleaning can also help restore the salt rejection of the membranes, which may be negatively impacted by the high pH cleaning. The pH of the solution should be taken prior to cleaning and compared to the target pH from the CIP procedure or manufacturer. The calculation for volume of chemicals needed should include the tank volume and piping factor to get a good estimate of the required amount. The volume calculation coupled with pH measurement should guarantee that the proper amount of chemicals has been added.

It should be noted that the solution temperature tends to increase during recirculation; hence start recirculating the CIP make-up solution with the heating element on before the final temperature is achieved. Ideally, the CIP system piping is designed with a recirculation line between the discharge of the CIP pump and the CIP tank so the solution can be mixed and heated within the CIP system prior to introduction to the membrane skid to be cleaned. A final temperature of 35-40°C for cleaning is commonly recommended. Consult the membrane manufacturer temperature guidelines for cleaning. Cleanings that can be performed at an elevated temperature are typically more effective and are essential when cleaning for biofouling.

**RO/NF:** The initial measurements for RO/NF should include a conductivity reading of the feed, permeate and concentrate water to compare after the CIP. The CIP process begins with a flush to remove any lose particles and displace process water



in the RO system with the CIP solution. Next, configure the system to be a closed circuit to recirculate the CIP chemicals or single pass if an extreme buildup of foulant or scale has occurred. Care should be taken to ensure that the valves are in the correct positions to avoid pressure build up and to control permeation of CIP chemicals. Ensure there is a path for any permeate produced to discharge back to the CIP tank so the permeate side of the membrane does not experience back pressure. Also, ensure that spool pieces are removed, block and bleed valves are in the correct position, or any other cross-connection controls are in place.

The ideal system configuration should maximize the cross flow of the CIP solution across the membrane. If possible, the CIP loop should include cartridge filters to prevent redeposition of particulates on the membrane surface. The goals for effective cleanings are to achieve high crossflow (approximately 40-50 gpm per 8" pressure vessel) at a low pressure (<60 psi). It is important to clean each stage individually so that foulant from one stage is not introduced to another stage and so that proper hydraulics and crossflow are maintained. Also, try to orient skid cleaning connections so that the cleaning solution does not have to flow through restrictions such as control valves or booster pumps. Hard-piped cleaning connections are recommended to minimize loss of cleaning solution or exposing operators to cleaning fluid, which is possible when cleaning with mobile hoses.

**MF:** Foulant buildup on MF membranes can cause a significant decrease in the membrane permeability and increase in normalized trans-membrane pressure (TMP). To test the effectiveness of a CIP cycle, it is best to note the permeability before cleaning, which is commonly measured as GFD/psi. The CIP process for MF differs from RO with respect to use of halogen-based chemical oxidizers and the ability to perform a backwash (with air-scour, if available). Conduct a regular backwash with an air-scour if available to loosen particulates deposited on the outside of the membrane surface. Air-scour is only available for outside-in flow MF membranes in a vertical assembly wherein air is introduced across the outside of the fibers. Drain the module to remove the dislodged particulates and to prevent any dilution of the CIP chemical make-up solution. The MF modules are now ready for a chemical CIP.

## CIP CONSIDERATIONS

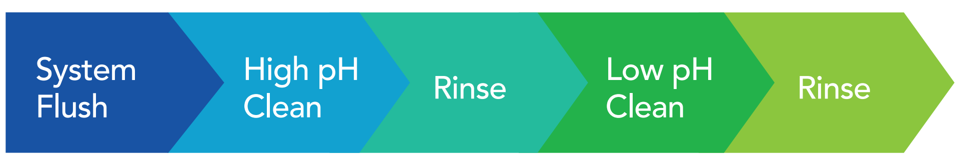
RO permeate or deionized water is preferred for the CIP make-up solution. The cleaning chemicals, especially powders, should be dissolved into the CIP solution completely before circulating through the membrane elements. This can be accomplished with a static mixer or more commonly by recirculation through the CIP pump to the tank to mix. A powdered chemical can also be premixed manually into a liquid slurry in a drum prior to introduction into the CIP system. This is especially important with powder cleaners as improper mixing could cause abrasion to the membrane surface or it may result in powder "cottage cheese" buildup that blocks the feed channels and prevents an effective cleaning.

The changes in the turbidity of a cleaning solution are good indicators of an effective CIP. Should the cleaning solution become rapidly turbid, send at least 20% of the solution to the drain and refill the tank with the CIP cleaning make-up solution. It is critical to monitor the pH and temperature of the CIP solution during the cleaning process to ensure both parameters remain at the desired levels. Strongly buffered specialty cleaning chemicals should resist pH drift whereas generic acids and caustics used for cleaning will need to be closely monitored. As a rule of thumb, pH changes of more than 1 pH unit require acid or alkali mediation.

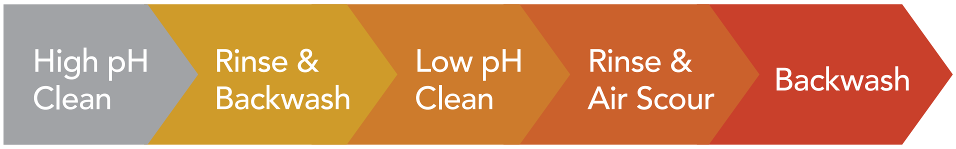
**RO/NF:** The CIP solution is recycled through the RO/NF elements for 30-60 minutes. During recycle, if the system pressure is high, permeation of the CIP solution could harm the membrane. As the system is cleaned, the flows may fluctuate. It is important to prevent spikes in crossflow rates and maintain it around 40 GPM without exceeding differential pressure (ΔP) limits specified by the membrane manufacturer.

A recycle step is often followed by a soak period. Membrane soaking is important because some chemical cleaners work best in static conditions to remove foulants. A final recycle is performed followed by a drain and system flush before the RO skid is returned to service. In cases of heavier fouling, the circulation and soak steps may have to be repeated multiple times.

**MF:** The cleaning solution is recycled through the module using a low flow pump. Depending on the flow direction of the water through the fibers, the chemical




Photos show typical packaged CIP systems for NF/RO




solution can be recycled either outside or inside of the fibers. Cleaning solution is often recycled for 30-60 minutes.

The first recycle is often followed by a soak cycle for 60 minutes or longer depending on the extent of the fouling. If extended soak times are necessary, refresh the soak solution every 20-30 minutes at a slow recirculation rate. This will also help maintain the temperature of the soak solution inside the MF module/bank.

A final recycle step is performed for 30-60 minutes followed by an air-scour and draining the CIP solution from the modules. A backwash is performed to remove any concentrated CIP chemicals before the skid is brought online. A backwash is recommended between high pH and low pH chemical cleans.

**NEUTRALIZATION:** Often the spent cleaning solution cannot be directly discharged to the sewer system due to chemical contents and high/low pH. Typically, a neutralization system is installed to adjust the pH and dechlorinate (CIP) prior to sewer system discharge.

The neutralization system can be fully automated using pH, oxidation-reduction potential and /or residual chlorine analyzers.

## POST-CIP CONSIDERATIONS

Before returning the system to service, a post-CIP rinse is performed. An RO system should be rinsed until the concentrate conductivity is similar to that of the feed, and no foaming is visible. This indicates that the chemicals used for the CIP have been completely flushed out of the system.

When the RO system is returned to service, compare the normalized operation data trends to assess CIP effectiveness. The pressure drop across each stage of the membrane system should also be recorded to check for removal of scale or biofilm. Comparing the pre- and post-CIP differential pressure data can illustrate the effectiveness of the cleaning. **Figure 1** shows how the normalized data helped the operator to make a decision to perform a CIP on time, and obtain an excellent result after the CIP, where differential pressures dropped significantly.

Permeability of the MF module is measured to check cleaning efficiency. Normalized TMPs should drop and an increase in flow through the MF membrane would indicate an effective CIP cycle.

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Photo shows a fully automated neutralization system

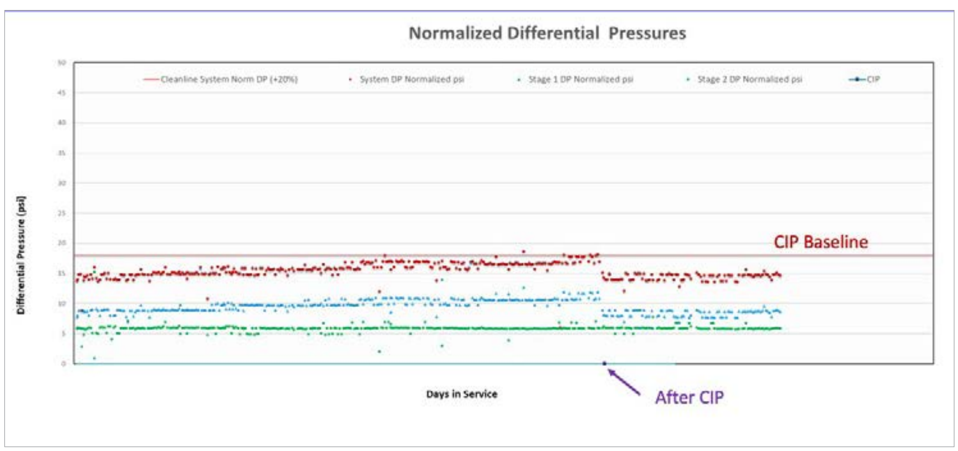


**Figure 1:** Graph shows normalized data and CIP event

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# MEMBRANE APPLICATIONS
## for Removal of PFAS and “Forever Chemicals”

### OVERVIEW

Perhaps one of the most challenging chemical groups of our era is per- and polyfluoroalkyl substances, collectively referred to as PFAS. This anthropogenic (originating in human activity) group of chemicals refers to highly fluorinated aliphatic synthetic chemicals, which have been demonstrated to be harmful in both the environment and humans. These chemicals are very persistent and can accumulate in the human body for many years, causing a variety of non-cancerous and cancerous health effects (EPA 2017). The United States Environmental Protection Agency (EPA) has set PFAS effects on water quality as a national research priority (EPA 2020).

This AMTA Fact Sheet provides useful PFAS resources for membrane practitioners, including: Background Information; Summary of Upcoming and Pending Regulations; Removal of PFAS in Drinking Water Treatment; Pilot and Full Scale PFAS Removal Efficiencies; and Summary and the Future of Membranes in Addressing PFAS/PFOS Contaminants.

### BACKGROUND INFORMATION

The PFAS family of fluorinated synthetic organic compounds are informally referred to as “forever chemicals” because of their resistance to breaking down in the environment.

Perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) are the two specific PFAS that have been produced in the largest quantities in the US (EPA 2017). An important characteristic of these chemicals, that has resulted in their versatility, is their ability to repel both oil and water, conferring hydrophobic, hydrophilic, and lipophilic properties. This has resulted in their use in a large number of industrial and consumer-based products dating back to the 1940s, including food packaging, stain-resistant carpet, waterproof clothing, paper, cardboard, nonstick cookware, microwave popcorn bags, leather products, industrial surfactants, emulsifiers, wetting agents, additives, electrical wires, fire and chemical resistant tubing, plumbing materials, and several kinds of firefighting foams (EPA 2017). While PFOS and PFOA are the most studied of the PFAS group, other replacement chemicals have emerged, including PFBS for PFOS and GenX for PFOA. Refer to **Figure 1** for a sample of materials potentially containing PFAS.

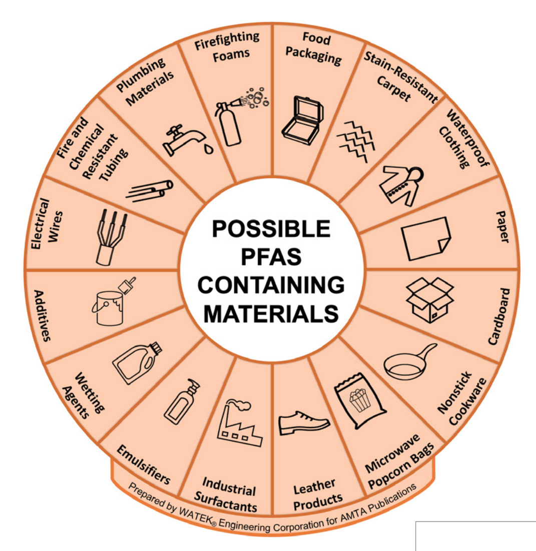
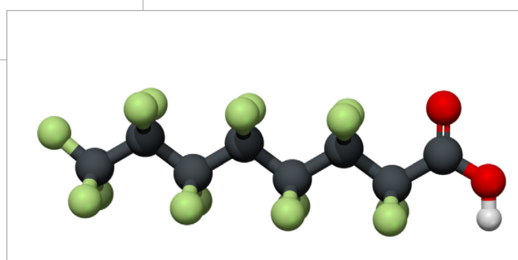



**Figure 1:** Sample of Materials Potentially Containing PFAS

**Figure 2:** Example of PFAS Chain (wikimedia.org)



In addition, the most recalcitrant PFAS—perfluoralkyl acids (PFAAs)—can be formed via microbially-facilitated environmental degradation of precursor compounds (EPA 2017). Due to their strong chemical bonds, they are highly stable and persistent in the environment (WRF 2016).

These chemicals have been extensively released to the soil, air, and water. They have been detected in solid waste, landfills and surrounding environmental media (i.e., soil, groundwater), leachates, landfill gas, wastewater effluents, biosolids, and drinking water supplies. There is clear evidence of their bioaccumulation and bioconcentration in fish and other wildlife, as well as humans (AWWA 2019, EPA 2017). Direct associations between their presence and non-cancerous and cancerous health impacts, including serious effects on the reproductive, developmental, and immune systems, have been reported (EPA 2017).

## SUMMARY OF UPCOMING AND PENDING REGULATIONS

Due to the high potency and long-lasting potential health impacts, the EPA has issued Lifetime Health Advisories at 70 nanogram per liter (ng/L) for short term exposure to PFOA and PFOS in drinking water, either individually or combined. EPA announced in February 2019 that the agency was embarking on a large-scale program for water sampling, monitoring, remediation, and health effect studies, serving as a foundation for the potential development of a federal maximum contaminant level (MCL). In February 2020, the EPA announced a preliminary regulatory determination, the first step in proposing a regulation for eight contaminants in the fourth Contaminant Candidate List (CCL4), which includes PFOA and PFOS. In addition to the federal action, several states—including California, Michigan, Massachusetts, Vermont, New Jersey, and Rhode Island, among many others—have issued primary standards, response thresholds, or guidance benchmarks for PFAS in drinking water at levels lower than the federal Health Advisory. For example, Massachusetts established a limit of 20 ng/L for the sum of six specific PFAS; Vermont set an MCL at 20 ng/L for PFOA + PFOS; Rhode Island set a limit of 10 ng/L for the sum of six PFAS; and California established Notification Levels of 5.1 and 6.5 ng/L for PFOA and PFOS, respectively. Many states have ongoing efforts for developing or revising guidance and regulations on various PFAS, causing the diffuse regulatory landscape to rapidly evolve.

Perfluorobutanesulfonic acid (PFBS), a replacement for PFOS, has been in military firefighting foam, carpeting, and food packaging, but independent scientists say it may not be much safer than the toxin it replaced. It has been linked with thyroid, kidney, and reproductive problems at very low levels of exposure. While the new assessment is a science document—not a regulatory one—it is expected to impact state and federal regulations.

## REMOVAL OF PFAS IN DRINKING WATER TREATMENT

Unfortunately, data collected from full-scale drinking water facilities indicate that conventional water treatment processes do not remove PFAS from drinking water supplies. A detailed survey of 15 full-scale drinking water treatment plants, including two potable reuse facilities, determined that conventional treatment methods (including coagulation, flocculation, sedimentation, granular media filtration, ozonation, and/or chlorination) do not lower concentrations of PFAS (Dickenson 2016). Chlorination, ozonation, and advanced oxidation processes are all ineffective for PFAS removal. Granular activated carbon (GAC) will remove PFAS, but may need periodic reactivation or replacement. Likewise, anion exchange (AIX) is effective for PFAS removal but may require periodic regeneration or change-out of spent resin. Nanofiltration (NF) and reverse osmosis (RO) membrane processes will achieve high rejections for most PFAS species; however, their use may create challenges with disposal of the concentrate, which will contain elevated levels of the compounds. Therefore, concentrate management has to be carefully planned. Although NF/RO processes remove long-chain compounds, such as PFOA and PFOS, more efficiently than their short-chain counterparts, both technologies have been demonstrated to be highly effective for the majority of the PFAS family of contaminants, with removals often exceeding 99%.

## PILOT AND FULL SCALE PFAS REMOVAL EFFICIENCIES

Many pilot studies demonstrating PFAS removal with NF/RO membranes have been and continue to be conducted, and full-scale systems are currently under construction. The EPA Treatability Database rates membrane removal by RO as "quite effective," the highest rating given any process. Pilot results in 2018 from a large, municipal surface water trial in Alabama confirmed this fact. In this trial, a three-month test was conducted to determine the optimum treatment for PFBS, a short-chain, 4-carbon PFAS of concern. The municipality was already reducing other PFAS in the feed with GAC; however, it is known that GAC is less effective for the short-chain PFAS compounds. Working with the GAC supplier, it was determined that the on-site contactors would have to be substantially expanded to provide at least 40 minutes of contact time for the 11 MGD flow to remove a substantial percentage of PFBS. Thus, both a conventional RO system and a high-recovery, proprietary Closed-Circuit Reverse Osmosis (CCRO) system operating at 90% recovery were piloted.

Final disposal of the PFBS residual stream was a concern, as the RO concentrate would contain high levels of the rejected PFAS. Although current Alabama laws do not regulate the discharge of PFAS, the municipality chose a strategy to repurpose existing activated carbon contactors rather than discharging the PFAS to the environment. Removal results for the CCRO pilot are summarized in **TABLE 1**.

PFAS removal was estimated by comparing incoming PFAS concentrations with those of the concentrate stream. With a 90% RO recovery, the concentrate would be expected to have PFAS levels ten times higher than the feed if all the PFAS were rejected. Variability in data caused by averaging and sampling lag times resulted in some removals calculated above 100%, with others slightly lower; however, the

**TABLE 1. Removal Efficiencies in Pilot Study**

| COMPOUND | FEED (NG/L) | PERMEATE (NG/L) | CONCENTRATE (NG/L) | % REMOVAL |
|---|---|---|---|---|
| PFOA | 13 | <2 | 130 | 100% |
| PFOS | 25 | <2 | 200 | >92% |
| PFBS | 7.6 | <2 | 96 | 100% |
| PFHxA | 7.3 | <2 | 68 | >93% |
| PFHxS | 3.0 | <2 | 33 | 100% |
| PFHpA | 3.6 | <2 | 37 | 100% |

overall removal for the sum of PFAS remained close to 100%. Similar removals have been demonstrated at other pilots, including an extended pilot in North Carolina, where a 41 MGD RO facility is being built **(Figure 3)** for removal of PFAS and other trace organic compounds. Similarly, full-scale wastewater RO facilities used for potable reuse in California have demonstrated complete removal of PFAS from their supplies.

**Figure 3:** PFAS Removal Facility Under Construction in Brunswick County, NC

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## SUMMARY AND THE FUTURE OF MEMBRANES IN ADDRESSING PFAS/PFOS CONTAMINANTS

Considering the widespread presence of PFAS, their persistence, and their toxicity, EPA has indicated their plans for taking concrete actions to address them as one of their highest priorities. In fact, on September 17, 2019, EPA announced allocation of $6 million to fund research for identification of both short-term solutions and long-term strategies for managing PFAS. This includes the need for cleaning PFAS contaminated sites as well as providing clean, safe, drinking water to impacted members of the public. Along these lines, many water plants are now voluntarily collecting samples to determine PFAS levels in their source water. With an increasing number of utilities finding potentially unsafe levels of PFAS in their supplies, cost effective treatment solutions are needed. For many of these utilities, membranes will provide those solutions, producing safe, reliable drinking water from their existing supplies.

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# MEMBRANE FILTRATION (MF/UF)

## OVERVIEW

Water utilities nationwide are turning to advanced filtration to meet more stringent federal drinking water regulations in order to remove turbidity, precursors, metals, and disinfectant-tolerant microorganisms from both groundwater and surface water supplies.

Low-pressure microfiltration (MF) and ultrafiltration (UF) membrane filtration technology has emerged as a viable option for addressing the current and future drinking water regulations related to the treatment of surface water, groundwater under the influence, and water reuse applications for microbial, organic, and inorganic contaminants and turbidity removal. For more than 20 years, full-scale facilities have demonstrated the efficient performance of both MF and UF as feasible treatment alternatives to conventional granular media processes. Both MF and UF have been shown to exceed the removal efficiencies identified in the US Environmental Protection Agency's (EPA) Surface Water Treatment Rule and related rules, such as those for Cryptosporidium oocyst, Giardia cyst, and turbidity.

MF and UF membrane systems generally use hollow fibers that can be operated in the outside-in or inside-out direction of flow. Pressure (5 to 35 psi) or vacuum (-3 to -12 psi for outside-in membranes only) can be used as the driving force to transport water through the membrane surface.

**Figure 1** shows some examples of MF/UF membrane modules and cassettes. At 20 degrees Celsius, typical flux rate for MF and UF ranges between 20 and 80 gallons per square foot per day (gfd). Flux rate is defined as the permeate flow per day per unit membrane surface area. In MF/UF, "permeate" is often referred to as "filtrate".

**Figure 1:** Examples of MF/UF membrane modules and cassettes

Since both processes have relatively small membrane pore sizes, membrane fouling—caused by the deposition of organic and inorganic compounds on the membrane—may occur at unacceptable levels if the system is not properly selected, designed, and/or operated. Automated periodic backwashing and chemical washing processes are used to maintain the rate of membrane fouling within acceptable limits. Chemical cleaning is employed once a maximum transmembrane pressure differential has been reached. Some systems utilize air/ liquid backwash. Typical cleaning agents utilized include acids, caustic, surfactants, enzymes, and certain oxidants, depending upon membrane material and foulants encountered. Chemicals used for cleaning and the method used in the cleaning process must be acceptable to the membrane manufacturer.

Overall treatment requirements and disinfection credits must be discussed with and approved by the reviewing authority. Disinfection is recommended after membrane filtration as a secondary pathogen control barrier and for distribution system protection.

MF and UF membranes are most commonly made from various organic polymers such as different polysulfones and polyvinylidene fluoride (PVDF). Physical configurations include hollow fiber, spiral wound, cartridge, flat plate/sheet, and tubular. MF membranes are capable of removing particles with sizes down to 0.1-0.2 microns. Some UF processes have a lower cutoff rating of 0.005-0.01 microns. Encased MF/UF modules are manifolded with all valves and instruments on a rack/skid as shown in **Figure 2**. Several racks can then be manifolded together in parallel to construct a large membrane facility, as shown in **Figure 3**.

Ceramic membranes are available for MF/UF separations and are beginning to be used in the United States for potable water applications. They have been used extensively for food and dairy and industrial applications where their robust nature and temperature tolerances are invaluable.

MF/UF membranes can be either encased (pressure) or immersed (submerged), as shown in **Figures 4** and **5**, respectively.

Membrane filtration is also becoming popular for conventional plant retrofits, replacing sand media with submerged membranes, for enhanced water quality and increased capacity. An example is shown in **Figure 6**. Typically, the net water production of the plant can be doubled without major structural modifications.

**Figure 2:** Example of skid mounted UF modules

**Figure 3:** Example of skid mounted MF racks manifolded in a plant

**Figure 4:** Example of encased (pressure) membranes

**Figure 5:** Example of immersed (submerged) membranes

**Figure 6:** Example of conventional media to submerged membrane plant

## SELECTING MF/UF MEMBRANE SYSTEMS

When selecting MF/UF systems, the following should be considered:

1. **Water Quality:** A review of historical source raw water quality and variability data, including turbidity, algae, particle counts, seasonal changes, organic contents, microbial activity, and temperature as well as other inorganic and physical parameters is critical to determine the overall cost of the system and operation. The degree of pretreatment, if any, should also be ascertained. Design considerations and membrane selection at this phase must also address target removal efficiencies and system recovery versus acceptable membrane fouling rate. At a minimum for surface water supplies, pre-screening is required.

2. **Life Expectancy:** The life expectancy of a particular membrane under consideration should be evaluated (typically 7-10 years). Membrane replacement frequency is a significant factor in operation and maintenance cost comparisons in the selection of the process. Warranties offered by manufacturers vary significantly and should be considered closely.

3. **Water Temperature:** The source water temperature can significantly impact the flux of the membrane under consideration, especially the tighter UF membranes. At low water temperatures, the flux can be reduced appreciably (due to higher water viscosity and resistance of membrane to permeate), possibly impacting process economics by the number of membrane units required for a full-scale facility. System capacity must be selected for the expected demand under seasonal (cold and warm water temperature) conditions.

4. **Operational Parameters:** Backwashing waste volumes can range from 4 to 15 percent of the permeate flow, depending upon the source water quality, membrane flux, frequency of backwashing, and the type of potential fouling. Membrane cleaning frequency is directly a function of flux rate and feed water characteristics.

5. **Monitoring:** Membrane systems used for drinking water production should be provided with an appropriate level of finished water monitoring and a direct integrity test feature. Monitoring options may include laser turbidimeters, particle counters, and manual and/or automated integrity testing using pressure decay or air diffusion tests. The EPA has published a membrane filtration guidance manual (EPA 815-R-06-009).

6. **Disinfection By-Product:** Other contaminants of concern, such as color and disinfection by-product (DBP) precursors, should also be addressed. DBPs can be removed to varying degrees by coagulation in front of the membrane system, either with settling or directly removing the coagulated contaminants with the membranes.

7. **Pilot Plant Study:** Prior to initiating the design of a MF or UF treatment facility, contact the state reviewing authority to determine the disinfection credits available for the membrane process, and whether a pilot plant study is required. In most cases, a pilot plant study is necessary to determine the best membrane to use, particulate/ organism removal efficiencies, cold and warm water flux, the need for pre-treatment, fouling potential, operating and transmembrane pressure, as well as other design considerations. Contact the state reviewing authority prior to conducting the pilot study to establish the protocol to be followed.

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8. **System Design:** Redundancy of critical components and control features should be considered in the final design. Other post-membrane treatment requirements, such as corrosion control and secondary disinfection, must be evaluated in the final design. Cross-connection control considerations must be incorporated into the system design, particularly with regard to the introduction and discharge of chemicals and waste piping. Membrane systems that use chemical washing processes with harsh chemicals require additional consideration.

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# MEMBRANE DESALINATION

## Power Usage in Perspective

### OVERVIEW

Scientists have known that the Earth's natural hydrologic cycle continuously desalinates water using solar energy and evaporates water from oceans and lakes, leaving behind salt and mineral content. The resulting freshwater vapors form clouds, which produce rain and snow. This natural hydrological cycle continuously moves salt from land to the oceans and is the main reason why the oceans are salty.

Since the 4th century humans have tried to mimic this natural cycle and have learned that, with an energy input, "desalting" or "desalination" machines can be built to produce fresh water from brackish and seawater sources. In the Middle East, people have long evaporated brackish groundwater or seawater, then condensed the vapor to produce salt-free water. Over time the process has become more sophisticated.

Today, about 300 million people get drinking water from more than 17,000 desalination plants in 150 countries worldwide. The Middle East has dominated that market out of necessity and energy availability, but with climate change and freshwater shortages around the globe, many other countries are considering desalination.

*Seventy percent of desalination plants in the world are located in the Middle East.*

Although there are many different types of desalination techniques, the least energy intensive method currently in use is through a semi-permeable membrane process, referred to as reverse osmosis (RO). Since typical brackish water RO desalination uses just a fraction (10-30%) of the energy required for seawater desalination, this fact sheet focuses on seawater desalination utilizing RO technology.

### ENERGY USAGE

Energy is the largest variable cost for seawater RO (SWRO) plant operation at approximately 60 to 70% of the cost of produced water, while all other operation and maintenance costs are less than 30 to 40% (**Figure 1**).

Energy costs for each plant depend on power pricing, type and degree of pretreatment, type of energy recovery devices, ocean salinity, concentrate disposal, regulatory requirements, land cost, and conveyance of seawater to and product water from the desalination plant.

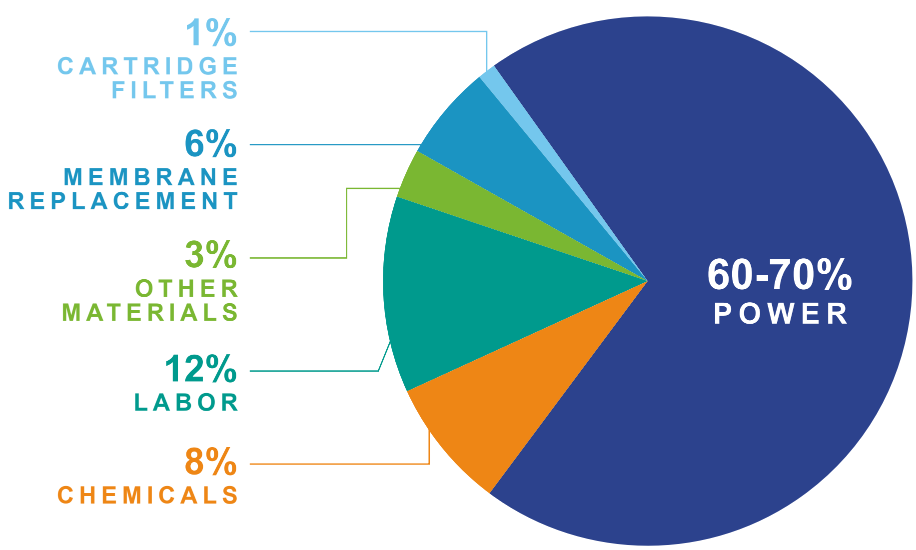



**Figure 1:** Typical Distribution of Costs for a Seawater RO Plant

## SWRO ENERGY REQUIREMENTS EXPLAINED

The required energy to force water through SWRO membranes is a function of the salinity and temperature, due to natural osmotic pressure. The required driving pressure mandates the energy requirement. Colder ocean temperatures (such as Pacific Ocean) require more pressure, while higher salinity waters (such as the Persian Gulf) also require more pressure. A general "rule of thumb" is that the net driving pressure needed to produce an equivalent amount of desalinated permeate will increase (or decrease) by about 11 psi (0.76 bar) for each 1000 mg/L incremental change in feed water salinity (Total Dissolved Solids).

The theoretical absolute minimum amount of energy required by natural osmosis to desalinate average seawater is approximately 1.0 kilowatt-hour per cubic meter (kWh/m3) of water produced, or 3.8 kilowatt-hours per thousand gallons (kWh/kgal). The actual SWRO energy requirement in the 1970s was 7.0 to 9.0 kWh/m3 (26-34 kWh/kgal). With recent technological advancements and innovations in high efficiency pumps, energy recovery systems and overall higher efficiency plants, the actual expected consumed energy has decreased significantly to 3.0 to 4.0 kWh/m3 (11-15 kWh/kgal).

As an example, the Perth Seawater Desalination Plant in Australia, which utilizes wind power and advanced energy recovery systems, uses an average of 3.5 kWh/m3 (13 kWh/kgal) of produced water. This includes the total energy required from ocean intake to customer.

## SWRO ENERGY IN PERSPECTIVE

No one will argue that seawater RO desalination consumes much higher energy than conventional freshwater treatment plants or water conservation. Desalination facilities should not be a primary option in locations where reliable fresh water sources are available and considerable cost-effective water conservation, efficiency improvements, and recycle and reuse are still possible.

**But let's put seawater RO desalination power requirements into perspective:**

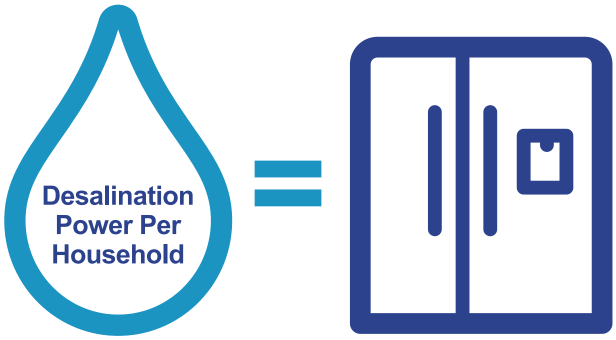
- In 2019, the U.S. Environmental Protection Agency estimated that a typical household in the U.S. uses 300 gallons of water per day (0.3 kgal/day). Using the Perth desalination plant numbers referenced above, energy consumption utilizing desalinated water per household can be calculated:

13 kWh/kgal x 0.3 kgal/day x 365 days = 1,423 kWh/year, or 1.423 megawatts/year (MW/year)

- Based on the 2019 report from the Energy Information Administration, the average U.S. household power consumption was 10.65 MW/year.

This means, if a community was served solely by desalinated seawater, energy consumption would increase by 13% (1.423/10.65).

- If we assume this same community was previously served by fresh water, which also consumes energy (approximately 3% of total power), one can estimate that a typical U.S. household served entirely by desalinated seawater will have a 10% increase in energy consumption.
- In most cases, desalinated water is used to augment existing traditional fresh water sources. If we assume 40% from fresh water and 60% from desalinated seawater, the percent increase in power consumption is between 5 and 7%.
- Based on nationwide data from the Energy Information Administration, the average annual energy usage of a typical refrigerator is about 7% of total energy used by a household. Therefore, the energy requirement for supplying a U.S. household with desalinated water (to augment existing traditional supplies) is the same as the power use of a refrigerator.



## ADVANCES TO REDUCE SWRO ENERGY REQUIREMENTS

There is considerable focus on the energy consumption of seawater desalination and the climate impacts associated with increased power generation. However, this important technology is helping many areas throughout the world that are facing freshwater shortages or where supplies are limited. The desalination industry and these communities are actively innovating and seeking solutions to increase efficiency and reduce environmental impacts, including:

- Improving desalination technology design and methods of operation to further reduce power requirements.
- Recapturing energy from RO systems by utilizing Energy Recovery Devices (ERDs), which have reduced typical SWRO energy consumption by as much as 40%. ERDs are now an integral part of most modern desalination plants. The leading ERD manufacturers are continuing to develop more efficient devices.
- Utilizing graphene membranes, which are extremely durable, incredibly thin and, unlike polyamide, are not sensitive to chlorine. Chlorination upstream of SWRO can reduce pretreatment and fouling concerns. Some of these innovative membranes are only one atom thick with holes small enough to trap salt and other minerals, but that allow water to pass.
- Incorporating other popular nanomaterial solutions such as carbon nanotubes, which are attractive for the same reasons as graphene (strong, durable material packed in a tiny package) and can absorb more than 400 percent of their weight in salt.
- Looking beyond RO to another process known as forward osmosis (FO). In FO, seawater is drawn into the system by a solution that includes salts and gases, which creates a high osmotic pressure difference between the solutions. The solutions pass through a membrane together, leaving the salts behind. As a pretreatment, FO can extend the lifespan of RO membranes by reducing the needed disinfectants and other pretreatment options.
- Reducing the energy cost of desalination through reverse osmosis pressure retarded osmosis (RO-PRO). RO-PRO works by passing an impaired freshwater source, such as wastewater, through a membrane into the highly saline solution leftover from RO, which would normally be discharged to the ocean. The mixing of the two produces pressure and energy that is used to power an RO pump.
- Incorporating renewables (wind and solar) into the energy input side of SWRO, which is a particularly promising approach to enhancing the sustainability of desalination. Currently, only 1 to 2% percent of desalinated water comes from renewable sources of energy and mainly in small-scale facilities, although larger plants are starting to add renewables to their energy portfolio. The United Arab Emirates energy company, for example, is working on the world's largest solar powered desalination plant.

*Incorporating renewables is a promising approach to enhancing the sustainability of desalination.*

- Co-locating desalination and power plants to reuse and recycle thermal energy, reduce burdens on the power grid, and make use of lower off-peak power costs.

Water agencies can also incorporate the value of the reliability and water quality advantages of membrane desalination when comparing traditional supplies (if available) to desalination. With recent concerns over the discovery of pharmaceuticals and personal care products in drinking water supplies, it makes sense to include values and advantages of membrane technologies in such comparisons.

Additionally, the value of seawater desalination should be carefully considered when comparing desalination to other alternatives. When traditional supply sources are not feasible or available, seawater desalination can be achieved in an environmentally friendly manner, without aggravating climate change or land use concerns, while being 100% drought-proof.

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# MEMBRANE Technology Applications in Power Plants

## OVERVIEW

Membrane processes for water treatment applications in the world's power plants are relatively new when compared to conventional treatment processes, such as granular media filtration and ion exchange demineralization.  Membrane processes commonly used in power plants include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), electrodialysis (ED)/electrodialysis reversal (EDR), and electrodeionization (EDI). Newer developments include forward osmosis (FO), membrane distillation, and electrodialysis metathesis (EDM). These membrane processes are used to remove solids (suspended, colloidal, and dissolved) from water while membrane contactor (MC) is a membrane process used to separate gases from water.

The power industry recognized the value of membrane technologies in water treatment more than 30 years ago and embraced the unique technological and economic benefits of RO. Those initial applications have continued to evolve. At present, there are five key areas in power plants that benefit from membrane technology use. These include:

- Boiler feed and NOx injection water treatment
- Removal of dissolved gases in water for boiler feed
- Recycled water treatment (municipal and industrial)
- Cooling tower blowdown recovery
- Concentration of solids for zero liquid discharge (ZLD)

## BOILER FEED AND $NO_X$ INJECTION WATER TREATMENT

Power plants typically require highly purified (demineralized) water for use as makeup water to steam generators (boilers) and/or for injection into the turbine combustors to control the formation of environmentally undesirable nitrogen oxides (NOx) in the turbine exhaustion gas. As the boiler pressure increases, the requirement for enhanced water quality also increases, especially as it relates to silica and total dissolved solids (TDS) concentrations. Conventional power plant water treatment processes using surface water sources include coagulation, flocculation, sedimentation, granular media filtration (GMF), granular activated carbon (GAC), cation exchange, degasification, anion exchange, and mixed bed ion exchange (MBIX). The product water is basically ultrapure water. A modern power plant may use coagulation, MF/UF, RO, and EDI to achieve similar water quality objectives as conventional treatment processes. However, the advantages of using membrane processes include higher water quality, more reliable performance and reduced handling and storage of hazardous chemicals.

**MF/UF.** MF/UF are low pressure membrane filtration processes that remove fine particles physically by size exclusion. The MF/UF membrane pore size is highly uniform and, therefore, capable of very high, or "absolute," removal of a targeted particle size or microorganism. The nominal pore sizes of MF and UF are 0.1 and 0.01 micron, respectively. However, MF and UF are considered equivalent in most water treatment applications, including the power industry. Since the early 1990s, there has been rapid growth in the use of MF/UF for the treatment of drinking water. In wastewater reclamation and power industry uses, MF and UF have enjoyed a similar level of growth, where they have essentially replaced lime softening and GMF as the preferred methods of pretreatment prior to RO for advanced reclamation projects. The use of MF/UF as pretreatment for RO has also been applied in power plant water treatment for more than 20 years.

**RO.** The use of RO as pretreatment for downstream ion exchange (IX) to reduce chemical regeneration costs has also been practiced for many years, especially since 1987 when polyamide membranes were introduced to the marketplace. RO elements made with polyamide membranes lowered the cost of producing water from a RO/IX system. This is because there is a breakeven point in TDS above which it is more economical to use IX or RO/IX. The breakeven point depends on a number of factors, including costs of chemicals, resins, membranes, energy, operating labor, maintenance, and capital-related items. In 1994, the TDS breakeven point was 130 mg/L as $CaCO_3$ (Beardsley et al., 1994). As most feedwaters supplying the deionized (DI) system are above this TDS level, RO/IX offered clear economic benefits, and installations became quite common in power plants.

**EDI.** RO-EDI has replaced RO-Mixed Bed IX (MBIX) in many power plants worldwide (Hernon et al., 1994). EDI is continuous in nature and sometimes referred to as Continuous Electrodeionization (CEDI) or Continuous Deionization (CDI). There are several different commercially available EDI products with varying design, but

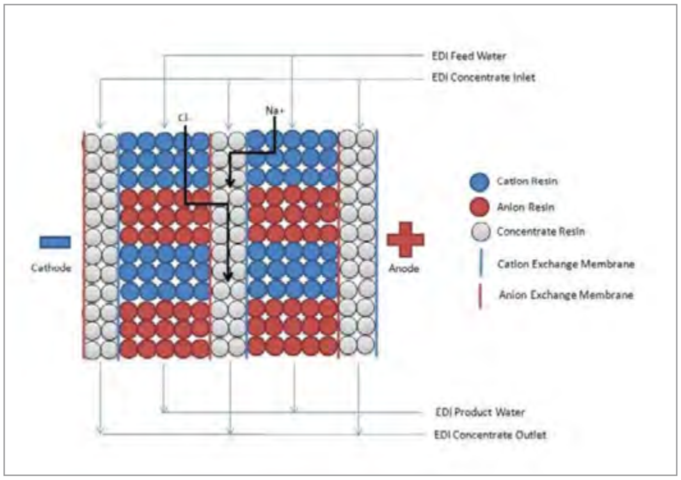


**Figure 1:** Schematic of Internal Process of One Type of EDI Device

all operate using the same principles of chemistry. EDI modules are electrochemical devices, driven by electrical energy from an external direct current (DC) power supply. Each EDI module consists of five primary components: ion exchange resin, two ion exchange membranes (cation and anion exchange), and two electrodes (cathode and anode). **Figure 1** shows a schematic diagram of the internal process of one type of EDI device.

As water flows through the EDI module and power is applied, three processes occur simultaneously: 1) the DI process where the water is purified by IX; 2) ion migration where the ions are removed from the resin; and 3) continuous regeneration of the resin. The regeneration of the cation and anion resins is by the H+ and OH- ions, respectively, which are split from $H_2O$ by the electric current, and hence acid and caustic are not needed for regeneration. EDI standard systems can produce water of 17 megohm-cm. All EDI manufacturers market a product water of up to 18 megohm-cm, but a product quality at that level will greatly depend on the EDI feed water quality. For certain raw waters, two pass RO may be needed before EDI to produce the necessary product water quality.

EDI has several advantages over IX. These include:

- No storage or handling of hazardous chemicals (acid and caustic)
- No regeneration waste neutralization needed
- Continuous operation without interruption for regeneration
- Simpler operation and maintenance

## BOILER FEED WATER DEGASSING USING MEMBRANE CONTACTORS

Membrane contactors have been used to remove dissolved oxygen (DO) in boiler feed water systems for years. More recently, they have been installed in power plant water treatment systems to remove carbon dioxide ($CO_2$) to extend MBIX resin life or to reduce capital cost and energy use by eliminating an RO pass in a RO-RO-EDI system. MCs are devices that utilize microporous, hydrophobic hollow fiber membranes that contain a large surface area, which promotes ideal mass transfer. In a typical design, water flows on one side of the microporous hollow fiber membrane, and gas flows on the other side of the membrane. Since the membrane is hydrophobic and the pores are very small, liquid will not pass through the pores. Pores in the membrane fiber provide a very stable gas/liquid interface. Manipulation of partial pressures at the interface allows gases to be added to or removed from the bulk water flow. In the MC design as shown in **Figure 2**, water enters the assembly via the distribution tube (Miller et al., 2005).

At the distribution tube midpoint is a liquid-side baffle that forces the water to flow through perforations in the distribution tube and across the fibers in a flow path that is 90 degrees from its original flow direction. The water then takes a tortuous path across the fibers until reaching an annular space between the fiber cartridge and the housing wall. Traveling along this annular space the water will reach the baffle and make a 180-degree turn around the baffle, continue back across the fibers and enter the collection tube, and then exit the MC assembly.

In addition to application for boiler makeup water treatment, MCs can also be used in the boiler system to remove DO from boiler water. With the proper configuration and system design MCs can remove essentially all DO present in the water stream. MCs can be used as a standalone deoxygenation system, or they can be used with existing technology as a hybrid system. Traditional deaerators may only remove gasses to 7-10 parts per billion (ppb), and this small amount of oxygen is still corrosive to the system. Installing a MC system in conjunction with the traditional vacuum deaerator will allow the lowest possible levels of dissolved gasses to the boiler. It is also possible to replace the traditional steam deaerator with the MC system in new installations. There are several advantages of this configuration:

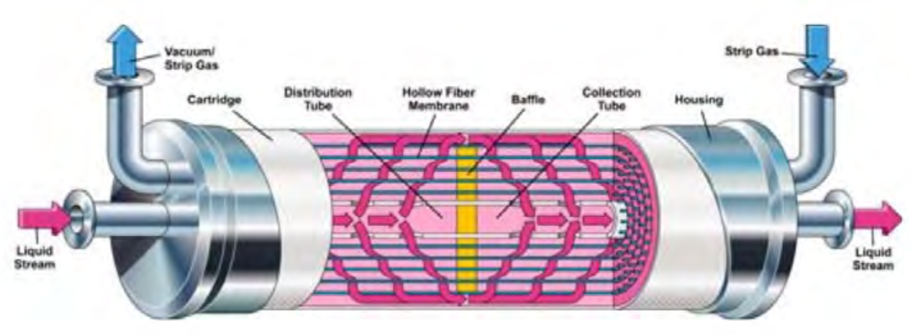


**Figure 2:** The Inside of a Membrane Contactor *(courtesy of Membrana)*

- Smaller space requirement because MC systems are modular and easily adaptable to a given footprint
- MC systems are more easily controlled. No special controls are required
- Lower energy consumption
- The MC system has a lower cost than a steam deaerator.

## MEMBRANES FOR USE IN TREATING RECYCLED WATER USED AS BOILER FEED WATER

MF/UF and RO processes have been used for treating municipal wastewater effluent for reuse as boiler feed water in refineries and power plants for more than 20 years. The El Segundo, CA, Chevron refinery has been receiving 4.3 million gallons per day (mgd) of reclaimed water to feed its boilers since 2000 (Wong and Hng, 2004). MF and RO is used to treat secondary effluent from the Hyperion Wastewater Treatment Plant and provides low-pressure boiler feedwater while a two pass RO is used to produce high-pressure boiler feedwater. The Richmond, CA, Chevron refinery has a similar arrangement with the East Bay Municipal Utilities District (EBMUD) using MF/RO to produce boiler feed water from secondary effluent. The refinery provides the two pass RO to polish RO permeate from the EBMUD MF/RO system for boiler feed. The Delta Energy Center in Pittsburg, CA, uses UF/RO to treat filtered secondary effluent from the Delta Diablo Sanitation District to supply purified water to the power plant's DI system for boiler feed makeup. There are many other similar applications in power plants worldwide, according to a membrane vendor supplying some of those UF/RO systems (Shin, 2017).

A large steel complex in the Far East installed an advanced treatment system to reclaim its industrial wastewater effluent as boiler feed water for the power/steam plants onsite (Wong, 2014). The treatment processes include coagulation, flocculation, sedimentation, UF, RO, two bed IX, and MBIX. The product water has near ultrapure water quality and is supplied to the steam plant to produce steam for power generation and for sale to other industrial plants near the steel complex.

## MEMBRANES USED IN POWER PLANT COOLING TOWER BLOWDOWN RECOVERY

Power plants use high volumes of water in cooling towers to dissipate waste heat that results from power generation. In some arid areas, power plants are trying to implement zero liquid discharge (ZLD) for environmental sustainability. Cooling tower blowdown (CTBD) recovery/reuse is one of the important elements of ZLD. A typical CTBD recovery treatment schematic includes a pretreatment process followed by RO for TDS removal. The RO system is designed to remove 90 to 95% of the TDS. Operating the RO at maximum water recovery minimizes the expense of the brine concentration process, which usually involves evaporation/crystallization for further water recovery and solids disposal. The RO permeate and evaporator/crystallizer condensate generated from the treatment processes can be reused as cooling tower/boiler makeup. Effective pretreatment for RO is critical in CTBD recovery as CTBD contains many potential membrane foulants including suspended solids, calcium precipitates, silica and various organics.

A coal-fired power plant in Southern California installed a CTBD recovery system in 2004. The average CTBD flowrate is 300 gallons per minute (gpm). The treatment process starts with chemical softening (no clarifier) and MF followed by RO. The RO permeate is returned to the cooling tower, and the reject stream is fed to a two-stage thermal system that evaporates the RO reject into crystalline solids. The solids are disposed of in landfills, the distillate is used as makeup water for the heat recovery steam generators, and the balance is returned to the cooling tower with an evaporation rate of more than 3,000 gpm.

**Figure 3** shows a process flow diagram of the CTBD and ZLD system for this power plant (Lander and Chan, 2010).

The MF system used in this project is a tubular MF system that can handle high influent solids concentration (as high as 5,000 mg/L TSS). The membranes are made of PVDF and cast on the surface of porous polymeric tubes to produce nominal pore size of 0.1 micron. Bleach (5% NaOCl) and hydrochloric acid (10% HCl) are typically used for membrane cleaning in the CTBD application. The chemically pre-treated CTBD is processed through the MF membrane modules designed for separation of the precipitates from water. The wastewater is pumped at a velocity of 12-15 ft/sec through the membrane modules connected in series. The turbulent flow, parallel to the membrane surface, produces a high-shear scrubbing action, which minimizes deposition of solids on the membrane surface. During operation, filtrate permeates through the membrane while the suspended solids retained in the recirculation loop are periodically purged for further dewatering. An automatic back-pulse mechanism is an integral part of the operational design, providing physical surface cleaning by periodically reversing the filtrate flow direction. The CTBD recovery system has been operating successfully since 2004.

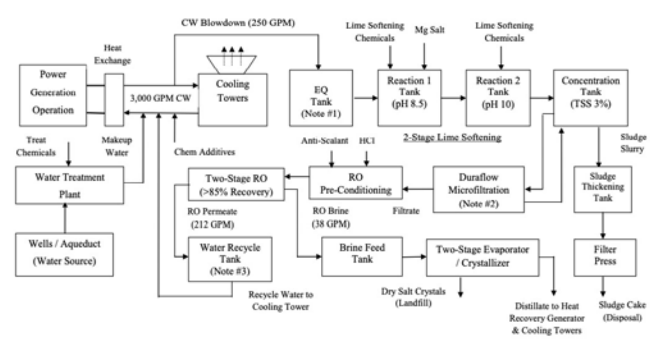


**Figure 3:** Power Plant – Cooling Tower Blowdown Water Recycle Flow Diagram Example

## USE OF FORWARD OSMOSIS IN POWER PLANT ZERO LIQUID DISCHARGE

A newer development in membrane application for power plants is the use of Forward Osmosis (FO) as a brine concentrator to replace thermal evaporator in a ZLD system. Unlike hydraulic pressure-driven RO, FO relies on osmotic pressure differences to drive water permeation across a semi-permeable membrane. In FO, water flows from the feedwater to a concentrated draw solution with an osmotic pressure that is higher than the feedwater. The produced brine can be sent to a brine crystallizer or an evaporation pond, whereas the draw solutes are separated from the desalinated water to regenerate the concentrated draw solution. Since the driving force in FO is osmotic pressure, FO can treat waters with much higher salinity than RO. In addition, FO operates at low pressure, resulting in foulant layers that are less compact and more reversible than hydraulic pressure-driven RO systems. Accordingly, FO has a much lower fouling propensity than RO, which not only reduces the operational costs related to fouling prevention and cleaning but also extends the applicability of ZLD to wastewaters with high fouling potential.

The development of thermolytic draw solutes, such as $NH_3$ and $CO_2$, paved the way for ZLD systems. The $NH_3/CO_2$ draw solution generates very high osmotic pressure driving forces and can be regenerated by low-temperature distillation. Because the thermolytic $NH_3/CO_2$ draw solution decomposes at moderate temperature (approximately 60°C at atmospheric pressure), low-grade thermal energy, such as waste heat from power plants, can be utilized to regenerate the concentrated draw solution. A recent study estimated that U.S. power plants produced 803 million gigajoules of waste heat at temperatures greater than 194°F or 90°C in 2012 (Gingerich and Mauter, 2015). The available waste heat in power plants makes it ideal for FO technology use in power plants to treat water and wastewater necessary for boiler feed makeup. The thermolytic FO process can be used as a brine concentrator after the RO stage. Compared to thermal brine concentrators, the $NH_3/CO_2$ FO can be cost competitive because a small volume of the more volatile draw solutes, as opposed to water, is vaporized to regenerate the concentrate draw solution. Furthermore, the modularity of FO results in a smaller area footprint and also renders ZLD systems more adaptable to fluctuations in the flow rate and quality of feedwater.

A power plant in Changxing in China treats a mixture of flue gas desulfurization (FGD) wastewater and CTBD at an average flow of 116 gpm. The softened feedwater is first concentrated by RO to a TDS concentration of approximately 60,000 mg/L. The $NH_3/CO_2$ FO process is then used as a brine concentrator to further concentrate the RO brine to above 220,000 mg/L TDS, while a high-quality product water (TDS < 100 mg/L after polishing by a secondary RO) is produced for reuse as boiler makeup. The FO reject is treated by the crystallizer. The overall water recovery is between 93 to 97 percent. **Figure 4** shows a process flow diagram of this plant.

## SUMMARY AND CONCLUSIONS

Membrane technologies have been used for water treatment in power generating plants for several decades. Effective applications include boiler feed makeup water treatment using MF/UF, RO, and EDI, and boiler feed water degassing using MCs. As water quality and scarcity becomes a worldwide problem, wastewater reclamation and reuse have become more commonplace, and ZLD has been applied to address these issues in power plants worldwide. The relative newcomer in membrane applications is FO, used as a brine concentrator and, potentially, a more economical alternative to traditional thermal brine concentrators such as mechanical vapor compression and multi-flash distillation systems. The abundant availability of low-grade waste heat generated by power plants offers reduced operating costs for the thermolytic FO process. More installations like these are expected to be prevalent in power plants located in arid regions. Other developing membrane technologies such as membrane distillation also make use of low-grade waste heat for operation and may one day find their niche application in the power generating industry.

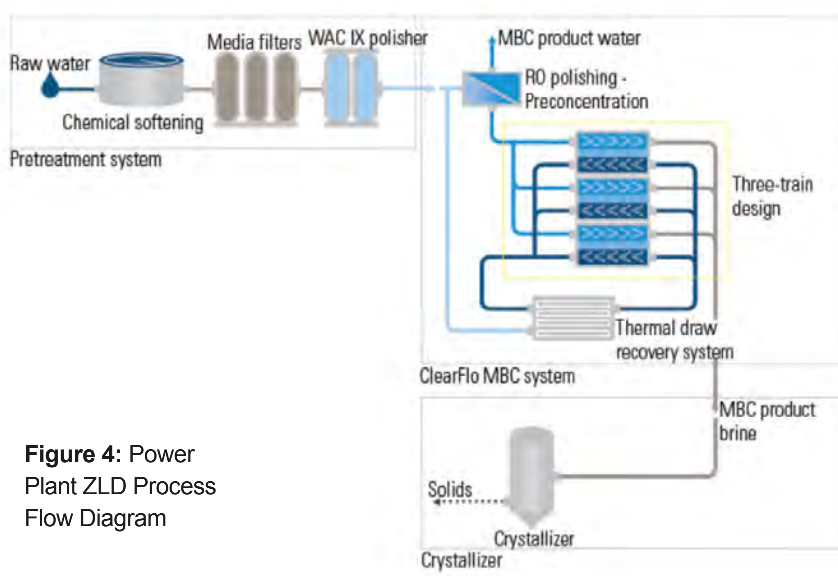


**Figure 4:** Power Plant ZLD Process Flow Diagram

**Figure 5:** Power Plant MBC System

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