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Reverse Osmosis Technology: Fundamentals and Water Applications*

Zahid Amjad, John F. Zibrida, and Robert W. Zuhl**
Lubrizol Advanced Materials, Inc.*
9911 Brecksville Road, Cleveland, OH 44141

Lubrizol

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** Now with ZIBEX, Inc.

*** Formerly BFGoodrich Performance Materials.

Introduction

Technology. The membrane-based separation process, which began as a scientific curiosity in the 1960s, is now a commercial reality. During the last two decades significant advances have been made in the development and application of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) processes. These processes have now become major players in the field of solid-liquid separation technology.[1, 2]

This paper provides the reader with a general understanding of principles involved in the purification of aqueous streams by a membrane separation process. Included herein are basic descriptions of membrane separation systems and overviews of commonly encountered RO system operating issues. The level of detail is intended to alert the water technologist to the methods of preventing and restoring the performance of membrane systems. This paper also includes a discussion of RO applications of interest to water technologists

Figure 1 details the characteristics of various membrane separation processes in removing various species from the feed water. Figure 1 illustrates how membranes act as barriers to mass movement but allow restricted or regulated passage of one or more species. Depending upon the feed water quality and from a cost effectiveness perspective, any combination of the membrane separation processes can be applied to achieve the desired product water quality. Among the membrane separation processes, RO is now widely applied in a number of industrial applications.

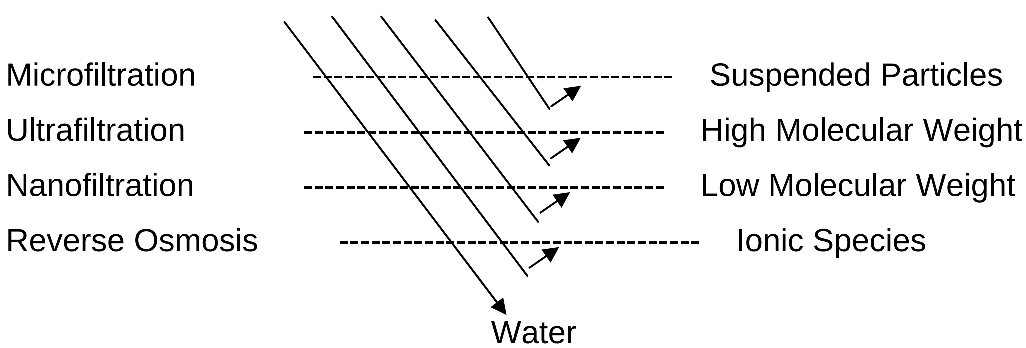


Figure 1. Membrane Separation Processes

Water purification by the RO process involves the separation of dissolved solids from the feed water by means of a semi-permeable membrane. Semi-permeable membranes allow water to pass through (permeate) readily, but are fairly impermeable to other constituents present in the feed stream. Figure 2 illustrates feed water passing over the membrane at a transmembrane pressure exceeding the osmotic pressure of the feed water with the result that the permeate (product stream) is selectively passed through the membrane. This product stream (on the low-pressure side of the membrane) is depleted of dissolved ions while the reject steam (brine or waste stream) is enriched in the dissolved material. Table 1 summarizes the osmotic pressure of various feed streams. To treat these feed streams, applied transmembrane pressure must be higher than the osmotic pressure for permeation of the solvent. Table 1 shows that the osmotic pressure strongly depends on charge, number of ions, and molecular weight.

Table 1. Osmotic Pressure (pounds per square inch) for Various Feed Streams

Feed Stream	Molecular Weight	2%	5%	10%
NaCl	58.5	250	650	--
KCl	74.6	170	455	965
K_2SO_4	174.3	92	235	470
$MgSO_4$	120.4	65	168	352
Sea water	--	220	550	1,250
Sucrose	342	24	63	134
Milk	--	--	--	90
Orange juice	--	--	--	210

Applications. RO systems are widely used for the desalination of sea and brackish waters for potable water production. The RO separation process plays a useful role in cleaning various industrial effluents including pulp and paper; recovery of metals from electroplating wastes; recovery of valuable products from acid mine drainage; municipal wastewater reclamation; and the production of ultrapure water for boiler, semiconductor, and pharmaceutical industries.[1]

Applications in the food processing industry are developing broadly and include the processing of milk, sugar, fruit and vegetable juices, and fats and meat by-products. RO technology is also used in the production of alcoholic beverages and carbonated soft drinks.

Uses of RO are also found in a variety of purifying operations. In pharmaceutical applications, the large quantities of ultrapure water required for hemodialysis is of particular significance. Other uses include process water for the production of prescription medication and over-the-counter items such as contact lenses cleaning solutions or eye drops. Medical laboratories also use a large quantity of ultrapure water in research and testing procedures.

In semiconductor manufacturing, control of particles in rinse water is crucial. The presence of even the smallest of particles could result in device failure by lithographic blocking or chemical contamination. In a plating operation, high purity water is used to rinse off any excess plating solution before drying. Improper rinsing or rinsing with poor quality water may reduce the luster of the plate, cause spotting, or inhibit the plating process completely.

Terminology

As a prerequisite to discussing RO technology and applications, this section presents definitions for several key terms.[3]

Rejection. The term rejection is used to quantify the removal of dissolved solute from the feed stream. Rejection means the amount of solute that does not pass through the membrane relative to the feed concentration and this is mathematically expressed as

$$R = (C_f - C_p) / C_f \quad \text{or } R = 1 - C_p/C_f \qquad (1)$$

Where R, C_f, and C_p are rejection, concentration of solute in the feed and permeate, respectively.

Rejection (%). The % rejection of a particular ion is defined as

$$\% R = 100 \times (1 - [\text{permeate}]_i - [\text{reject}]_i) \quad (2)$$

Rejection Rate. The degree to which dissolved solutes are repelled from an RO membrane under pressure.

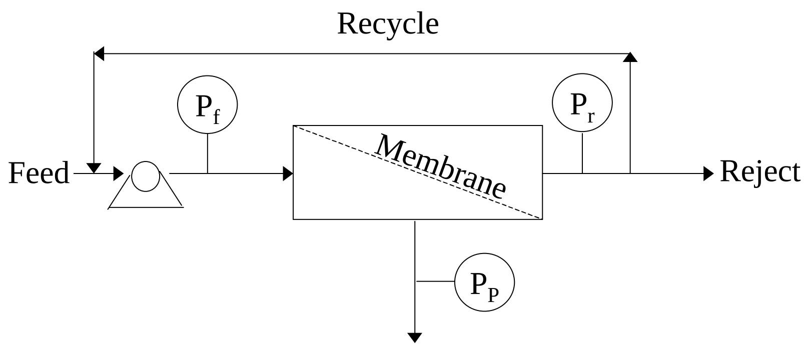


Figure 2. Fluid Streams in RO Operation

Transmembrane Pressure. The transmembrane pressure (TMP) is defined as follows:

$$TMP = [(P_f - P_r)] / 2 - P_p \quad (3)$$

Where P_f , P_p, and P_r are the pressures for the feed, permeate, and reject streams, respectively.

Pressure Drop. Pressure differential between feed and reject streams.

Flux. Flow through the membrane per unit time per membrane surface area.

Recovery (%). The ratio of the RO product water to the feed water is called recovery (Y) expressed as a percentage.

$$Y = (\text{product flow rate}) / (\text{feed flow rate}) \times 100 \quad (4)$$

Concentration Factor. Assuming that the amount of any ion passing through the membrane is close to zero, then the concentration factor (CF) for any ion is given by:

$$CF = 1 / (1 - Y) \quad (5)$$

Membrane Configurations and Materials

RO membranes typically remove greater than 99% of the dissolved salts, microorganisms, and colloids and in some cases more than 90% of the soluble silica and TOC (total organic carbon) from the feed stream. Table 2 lists the rejection levels for ions commonly present in the feed water.

Table 2. Rejection (%) of Various Ions by a Typical RO Membrane

Solute	Formula	Molecular Weight	Rejection (%)
Sodium Fluoride	NaF	42	98
Sodium Cyanide	$NaCN$*	49	97
Sodium Chloride	$NaCl$	58.5	98
Silica**	SiO_2	60	98
Sodium Bicarbonate	$NaHCO_3$	84	98
Sodium Nitrate	$NaNO_3$	85	93
Magnesium Chloride	$MgCl_2$	95	98
Calcium Chloride	$CaCl_2$	111	99
Copper Sulfate	$CuSO_4$	160	99
Urea	--	60	70
Glucose	--	180	98
Sucrose	--	342	99
Chlorinated pesticides (traces)	--	--	99

Solute rejection (approximate) 2,000 ppm solute, 225 psi, 77°F, pH 7, Dow FILMTEC® FT30 thin film composite polyamide membrane, * pH 11, ** 50 ppm

Hollow fiber and flat sheet are the most commonly used RO membrane configurations. Hollow fiber membrane is extruded like fishing line with a hole in the center to create a tiny (100 to 200 micron) hollow fiber strand. Flat sheet membrane is manufactured by applying the semi-permeable material to a woven or non-woven cloth. It is manufactured as a continuous sheet and rolled up like a large paper towel roll. Flat sheet membrane is used in "spiral wound" (SW) and "plate and frame" RO elements. Hollow fiber membrane is used in "hollow fine fiber" (HFF) and "hollow fiber" (HF) RO elements. Although HF RO elements provide more surface area, they are more prone to fouling. Table 3 summarizes advantages and disadvantages of HF and SW membrane configurations.

Table 3. Advantages and Disadvantages of Hollow Fibers and Spiral Wound Membranes

Membrane	Advantages	Disadvantages
Hollow Fiber	• High membrane surface area to volume ratio • High recovery in individual permeator • Easy to troubleshoot • Easy to change bundles in the field	• Sensitive to fouling by colloidal materials • Limited number of membrane materials and manufacturers
Spiral Wound	• Good resistance to fouling • Easy to clean • Variety of membrane materials and manufacturers	• Moderate membrane surface area • Difficult to achieve high recovery

Over 100 different materials are used to make RO membranes. However, the two most commonly used membranes are made from cellulose acetate (CA) and thin film composite (TFC). The characteristics and performance of these membranes differ significantly. Table 4 summarizes the comparative data on these membranes.

Table 4. Comparison of Cellulose Acetate and Thin Film Composite Membranes

Parameter	**Cellulose Acetate (CA)**	**Thin Film Composite (TFC)**
Operating pressure (psi)	410 to 600	200 to 500
Operating temperature (^oC)	0 to 30	0 to 45
Operating pH	4 to 6.5	2 to 11
Membrane degradation potential	Hydrolyzes at low & high pHs	Stable over broad pH range
Permeate flux (gfd)	5 to18	10 to 205
Salt rejection (%)	70 to 95	97 to 99
Stability to free chlorine	Stable to low (< 1 ppm) levels	Attacked by low levels (>0.1ppm)
Resistance to biofouling	Relatively high resistance	Low resistance
Manufacturer	Several	Several
Cost	Lower	50 to 100% more

Operating Challenges and Solutions

Fouling resulting from the foulant accumulation on the membrane surface is the major cause of RO system failure. RO membrane fouling is a complex phenomenon involving the deposition of several different but related types of foulants on the membrane surface. RO system fouling problems are becoming more prevalent as the use of low quality feed water increases. In addition, surface water treated with cationic organic flocculants poses very serious and challenging fouling problems. Operating costs increase when performance problems arise. These costs are associated with membrane cleanup, replacement, and system downtime. The success of an RO system depends largely on three factors: system design, pretreatment (e.g., chemical conditioning), and system maintenance.

RO system designs typically include a number of unit operations placed in a series. Figure 3 illustrates a typical RO system consisting of several unit operations: pretreatment, membrane unit, and post treatment. The pretreatment system adjusts the water quality of the feed water chemistry to optimize the post treatment. The primary considerations are the quality and quantity of both water entering the system (feed) and the finished water leaving the treatment process (product).

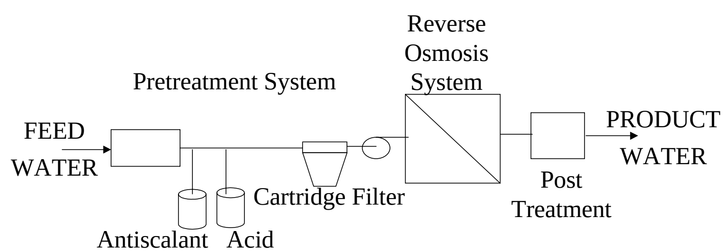


Figure 3. Typical Reverse Osmosis System

Feed Water and Pretreatment

The performance of an RO system is largely controlled by the composition of the feed water. Feed water quality will determine the amount and the type of pretreatment necessary to make RO an economical process. This balance is the primary limiting factor of most RO systems in operation today. The close relationship between water chemistry and membrane performance is why membrane manufacturers require periodic water analysis in order to maintain membrane warranties. Water sources vary widely around the world, across the country, and even within local areas. All natural waters contain organic and inorganic, dissolved and suspended contaminants. The water composition dictates the types of pretreatment process(es) that are used.

Designers and operators of the system benefit greatly from having current, accurate water analyses for all aspects of an RO system, from actual design of arrays and membrane area to the tracking of the performance and identification of trends. Periodic analyses can alert operators to changes in the feed water composition and its possible impact on the RO system and facilitate pretreatment adjustments. In addition to feed water characterization, analyses such as cartridge filter, SDI (silt density index) pad digestions, and membrane autopsies provide valuable information in troubleshooting existing systems.

Pretreatment is an essential design consideration and a key to the successful long-term performance of an RO system. Membrane surfaces are prone to fouling by particulate matter, inorganic scales (i.e., carbonate and sulfate salts of alkaline earth metals), oxides and hydroxides of aluminum and iron, organic material (i.e., humic, tannic, fulvic acids, etc.), and biological materials (e.g., bacteria, fungi). The pretreatment techniques used to alleviate these problems are nearly as varied as the problems themselves. This section provides a short description of some of the more common means of pretreating a given water to make it suitable for use as an RO feed water. It is often necessary to pilot test pretreatment unit operations to verify the efficacy of the process for a particular application.

Media Filters. The most common (and oldest) means of removing solids from the feed stream is media filtration and includes: slow sand filtration; rapid downflow or upflow sand filtration; single media anthracite, garnet, or green sand filtration; or more recently multimedia filtration. Multimedia filters often feature-layered beds of anthracite coal, various sands, finely crushed garnet, pumice, walnut shell, or many other types of media. Each type of media has distinct advantages and disadvantages that are important system design considerations, a summary of which appears in Table 5.

Table 5. Commonly Used Filtration Media

Filtration Media	Advantages	Disadvantages
Sand	Inexpensive	May not remove small colloids
Anthracite	May remove oxidants	Provides site for biological growth
Garnet	May adsorb organic material	Heavy or difficult to use
Green sand	Oxidizing media	Expensive

Media filters alone may not provide sufficient RO system pretreatment because colloidal suspended matter is often too small to be removed efficiently and particles may be charged such that they are repelled by the media itself. In these instances, a flocculant/coagulant may be added as a filter aid or coagulant that functions by adsorbing onto the surface of a colloid and to neutralizing the surface charge and allowing small particles to agglomerate or coagulate. A flocculant will bridge between small particles to form large particles that settle faster or may be retained by the filter. Popular coagulants and flocculants include alum, other aluminum and iron salts, and synthetic cationic polymers (e.g., diallyldimethyl ammonium chloride, DADMAC).

Cartridge Filters. Nearly every RO system is equipped with cartridge filters before the high-pressure pumps to prevent suspended matter from entering the system. Cartridge filters are available in a variety of sizes, configurations, and materials of construction. Most membrane manufacturers suggest 5-micron or smaller filter to provide adequate protection. In some cases it is beneficial to use cascade filtration, i.e., the use of larger filters followed by small ones to reduce individual filter loading by better depth filtration.

Microfilters and Ultrafilters. Microfiltration (MF) and ultrafiltration (UF) membranes have been introduced in recent years. These membranes are not as tolerant as media filters to suspended solids. They are also more expensive and require additional equipment for their operation. However, MF and UF membranes provide consistent, good quality low SDI water which in many cases may be fed directly to an RO system with little or no additional pretreatment. Additionally, they are fairly rugged (compared to RO). It is often beneficial if the fouling problem can be transferred from the RO to MF or UF membranes. These membranes can also usually tolerate a wide range of harsher cleaning chemicals. Some MF and UF membranes can be back flushed with air or permeate water.

Membrane Fouling

The success of an RO system depends upon membrane life and performance, the repeatability and the reproducibility of the process that the membranes are designed to perform, and periodic cleaning of the membranes to restore capacity. Membranes lose performance and are replaced due to the deposition of unwanted materials on the surface. In addition, a decrease in membrane performance may be due to other factors, i.e., degradation by chemical (oxidation, hydrolysis, etc.) and/or mechanical (compaction, telescoping) processes. For an RO process to be successful, the life of the membrane must be extended as much as possible to minimize replacement costs.

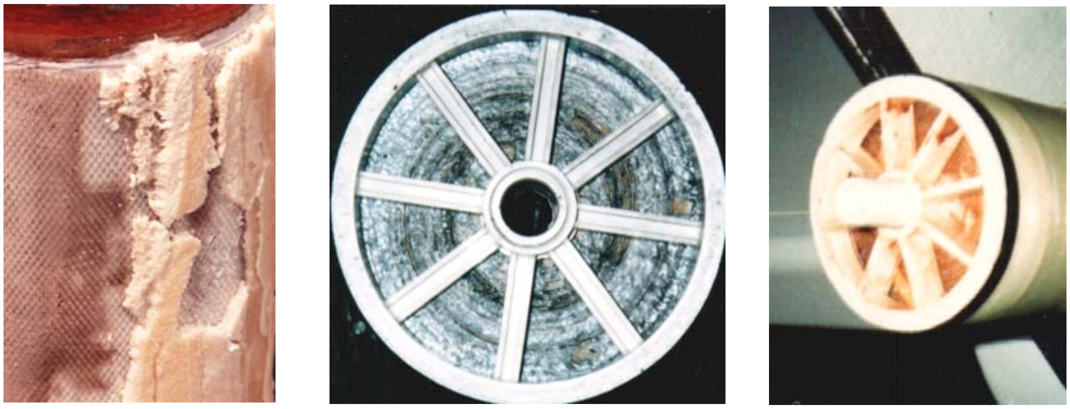
The types of foulants most commonly encountered in RO systems include:

- Inorganic fouling (scaling)
- Colloidal fouling
- Biological fouling
- Organic fouling

Scaling of RO membrane surfaces is caused by the precipitation of sparingly soluble salts from the concentrated brine. The presence of suspended solids in the water, such as mud and silt, tends to cause gross plugging of the device rather than fouling of the membrane surface.

Biofouling can be a serious problem. Biofouling is a special case of particulate fouling that involves living organisms. The biological material growing on membrane surfaces not only causes loss of flux but may physically degrade certain types of membranes.

Hydrocarbon oils (naturally occurring or as a result of pollution) have also been known to cause performance deterioration. Synthetic cationic polymers (e.g., DADMAC), have been known to carry over to the membrane system due to clarifier upset or media filters channeling. Cationic polymers are known to be incompatible with many of the acrylic acid-based antiscalants in use today and may influence membrane performance. In addition, it has also been reported that, in high hardness water, polyacrylate based antiscalant can form an insoluble salt with calcium, thus leading to membrane fouling. Detailed descriptions of fouling phenomena and their effects on membrane performance has been described elsewhere.[4, 5, 6] Figure 4 (a, b, and c) shows photographs of RO membrane fouled with (a) mineral scale, (b) bacteria, and (c) iron.



(a) (b) (c)

Figure 4. Fouled Membranes (Mineral Scale, Bacteria, and Iron)

SCALING-FOULANT CONTROL ALTERNATIVES

Several methods (discussed below) exist for reducing or preventing membrane fouling caused by the deposition of mineral scales and include softening, system recovery, acid, and antiscalant/dispersant.

Softening. Hot and cold process lime softening and sodium cycle cation exchange are commonly applied methods to remove hardness ions from feed water. Sodium (which replaces the hardness ions) salts are rarely scale forming and, therefore, can be tolerated.

Adjusting System Recovery. In RO systems, membrane fouling by mineral scale can be controlled by operating the system under conditions where solubility of scale forming salts is not exceeded, i.e., operating the RO system at lower recovery. This technique is not always effective due to concentration gradients within the membrane not controlled by the bulk flow.

Acid Feed. Acids are among the oldest treatments used to control calcium carbonate scale formation. Acid is injected into feed water to reduce alkalinity to prevent calcium carbonate precipitation. Normally, sulfuric acid is used and is relatively inexpensive. The use of sulfuric acid for alkalinity reduction increases the potential for sulfate scale (e.g., calcium sulfate, barium sulfate) formation. Though calcium sulfate is relatively soluble, strontium sulfate is becoming a problem in certain areas of the world and barium sulfate is extremely difficult to remove once it is formed. When acid is used to control pH, the product water is often degassed to remove the resultant carbon dioxide. Gasses are not rejected by RO membranes and will pass directly into the permeate stream which decreases permeate quality.

Antiscalant/Dispersant Addition. Nearly every RO water treatment program used today can benefit from the use of suitable pretreatment chemicals (e.g., antiscalants, dispersants, etc.). Depending on the system and treatment program, the pretreatment chemicals can be hexametaphosphate, homopolymer based, or copolymer based (consisting of several monomers of varying functional groups, i.e., multifunctional). In some cases, blends of polymers and other scale control agents may be used to provide well-balanced treatment technology. Chemical suppliers have researched these proprietary blends which typically have both membrane manufacturer compatibility and National Sanitation Foundation International (NSF) potable water approvals. The mechanisms by which these antiscalants/dispersants function and associated performance data were discussed in earlier publications.[7, 8, 9] Specially formulated products (e.g., Lubrizol's Aquafeed® Antiscalants) can provide excellent performance in controlling scaling (calcium carbonate, calcium sulfate), stabilizing metal ions (i.e., Fe, Mn, Zn, etc.), and dispersing particulate matter.

Silica (SiO_2) commonly found in ground water deserves a special comment. Silica usually exists in the weakly ionized soluble form. As soluble silica is concentrated in the RO process, it polymerizes to form an insoluble colloidal silica or silica gel that will foul membranes. The easiest method for preventing silica fouling is to reduce the conversion rate. The solubility of silica increases with increasing temperature and at high pH values. Operating at warmer temperatures may lessen the chance of silica fouling. Silica can be removed from the feed by lime softening, but it is very expensive and usually not practical unless other pretreatment requirements dictate lime softening.[10]

Certain polymers have been shown to be capable of dispersing fine particles of amorphous silica once they have formed. These polymeric dispersants are often used when the potential for particulate silica fouling exists. Although these dispersants may minimize the impact of the fouling, they do not address the root problem of silica polymerization. A new antifoulant was recently introduced which can effectively inhibit the silica polymerization and also disperse particulate matter. Development of this new antifoulant is a major technological breakthrough as it can facilitate the operation of RO systems with concentrate (reject) streams containing greater than 500 mg/L soluble silica.[11]

Antisclant Selection Based on Water Chemistry

The prediction of reject (brine) and permeate chemistry based on feed water is integral to the design and optimization of RO technology. The dissolved salts that concentrate in the brine develop a scaling potential dependent on make-up water chemistry, pH, and recovery. Several predictive tools have been developed to predict the scaling potential of water. While scaling indices such as Langelier, Ryznar, or Stiff and Davis are a good indication of calcium carbonate scaling, they do not include other potential scales such as calcium sulfate, barium sulfate, etc. Recent developments in system simulation can facilitate prediction of scale potentials for a number of scale forming salts in RO systems.[12, 13, 14] A scale inhibitor dosage model can be correlated to predict the required product (i.e., antiscalant, dispersant, etc.) level to reduce the potential of scaling using predictive modeling computer technology. The following example (presented in the text, Table 6, Figure 5, and Figure 6) demonstrates the use of a predictive model for selecting a product to achieve desired performance from an RO system.

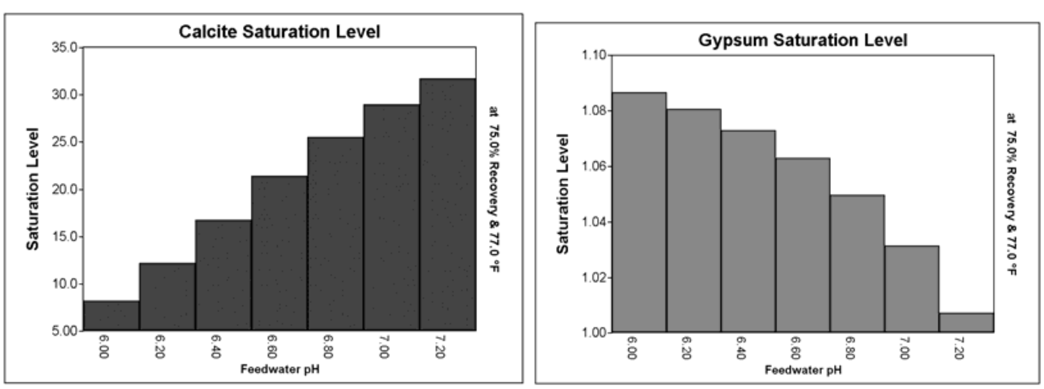
Table 6 shows analyses of an RO system raw water, feed water (pH adjusted with sulfuric acid to depress alkalinity), product water, and brine (@ 75% recovery).

Table 6. Analyses of Raw, Feed, Product, and Brine Water Streams

Parameter *	Raw	Feed	Product	Brine
Calcium	152.0	152.0	10.13	577.60
Magnesium	65	65	4.33	247.0
Barium	0.40	0.40	0.03	1.52
Strontium	2.20	2.20	0.15	8.36
Sodium	381.0	381.0	25.40	1447.8
Iron	0.05	0.05	0.00	0.19
Chloride	675.0	675.0	45.0	2565.0
Sulfate	401.0	444.0	29.60	1687.20
Bicarbonate	96.9	86.4	5.8	353.80
Carbonate	0.9	0.30	0.0	35.7
Dissolved CO_2	5.9	17.1	1.1	4.3
pH	7.50	7.00	5.32	8.25
Calculated TDS (ppm)	1819	1862	124	7075

* ppm as ion except for pH and calculated TDS

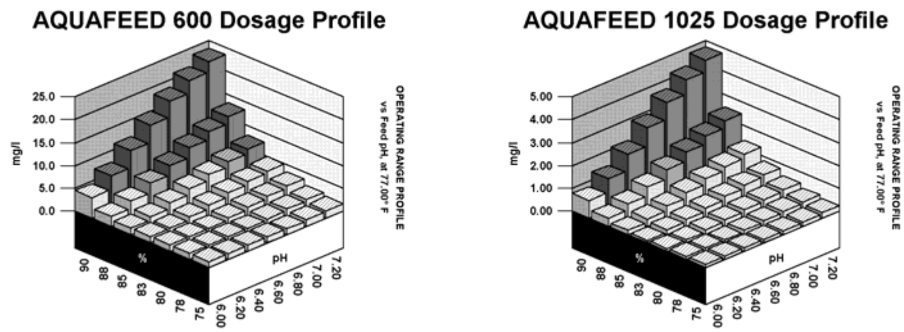
Figure 5 relates to the RO system described above and the associated brine stream data shown in Table 6 above. Figure 5(a) shows that calcite saturation varies as a function of pH. Figure 5(b) shows that gypsum saturation increases only with the increased sulfate ion from the sulfuric acid injection for pH suppression. The use of an antiscalant is important in this case in order to control the precipitation of calcite and gypsum



(a) (b)

Figure 5. Effect of pH on Calcite (a) and Gypsum (b) Saturation Levels

Figure 6 relates to the RO system described above and the associated brine stream data shown in Table 6 and Figure 5. Figure 6 portrays dosage projections for two proprietary RO antiscalants. Figure 6(a) is a dosage projection for AQUAFEED 600 Antiscalant (AF600) and Figure 6(b) is a dosage projection for AQUAFEED 1025 Antiscalant (AF1025). If an RO system feed water contains trivalent cations such as iron or aluminum in concentrations above 0.05 ppm, it is likely that a high performance multifunctional antiscalant like AF1025 will be required, especially for higher LSI conditions.



(a) (b)

Figure 6. Antiscalant Dosage as a Function of Feed Water pH and System Recovery

Cleaning

If the product flux decreases to unacceptable values (typically >10% decrease), the membrane must be cleaned. The cleaning method and frequency depend on the type of foulant and the membrane's chemical resistance. Generally, it is easier to clean a membrane that is slightly fouled (check manufacturer flux decrease guideline for cleaning).

The cleaning method typically includes (a) mechanical cleaning (i.e., direct osmosis, flushing with high-velocity water, ultrasonic, sponge ball or brush cleaning, air sparging, etc.), (b) chemical cleaning (use of chemical agents), and (c) a combination of mechanical and chemical cleanings. The most prevalent method is chemical cleaning that frequently incorporates specially formulated membrane cleaners.

A large number of chemical agents are available for removing deposits. Chemical cleaning essentially involves the use of chemicals to react with deposits, scales, corrosion products, and other foulants that affect flux rate and product water quality. These chemical agents can be classified into four categories as follows:

- Acids
- Alkalis
- Chelants
- Formulated Products

Acid cleaning has a limited effect on sand, clay, and biological matter. Alkaline cleaners can do little to dissolve and disperse hardness scale. Chelating agents are effective in dissolving calcium and barium based scales and iron oxides, but exhibit poor performance in removing oily substances and biological foulants.

Limitations of commodity chemicals have led membrane manufacturers and others to publish non-proprietary formulations for use as membrane cleaning agents. Several companies are offering proprietary formulated cleaners specially developed for removing foulants from membrane surfaces.

Clean membranes are critical for maintaining the efficient operation of RO systems. Membrane cleaning is a complex subject due to the variety of potential foulants. Characterizing deposits on fouled membranes is essential to the selection of the most economical and effective cleaner. Analyses of feed waters and spent cartridge filters, as well as evaluation of chemical changes (if any) resulting from pretreatment, provide valuable insight into foulant characteristics.

Once the magnitude and types of deposits are identified, membrane cleaning is required to restore system performance. If a deposit analysis reveals a variety of foulants (e.g., calcium carbonate scale, silica/silicate, and metal oxides/hydroxides), single-function commodity-type cleaners such as citric acid and laundry detergents may not suffice. In such instances, the use of proprietary formulated cleaners (e.g., Lubrizol's MT® 3100 Cleaner) should be considered. Prepackaged proprietary membrane cleaners typically have membrane manufacturer's compatibility approvals and proven field performance.[15]

The following factors should be considered when selecting an RO system cleaning program:

- Cleaning equipment requirement
- Membrane type and cleaner compatibility
- Foulant identification
- Ease of application
- Economics
- Environmental impacts (requirements for discharging spent cleaning solutions)

CONCENTRATE DISCHARGE

The concentrate stream of an RO system must be disposed of in accordance with local and state regulations. The following typical means of concentrate disposal has been suggested:[16]

- Surface water discharge
- Deep well injection
- Spray irrigation
- Waste water treatment facilities
- Thermal evaporation
- Solar evaporation ponds
- Drain field and bore holes

Reverse osmosis concentrate, like cycled cooling water, contains a higher amount of dissolved solids than the feed water. Typical disposal scenarios described above are selected on a case by

case basis. A large municipality treating 5 MGD (million gallon per day) near the ocean would certainly consider surface discharge while a smaller RO unit used to prepare 200 GPD (gallon per day) of finished water would probably discharge to a wastewater treatment facility. Federal, state, and local regulations are of an increasing concern for concentrate disposal.

RO vs. Other Desalination Processes

Currently, commercially available desalination technologies include distillation, ion exchange (IX), electrodialysis (ED), freezing, and reverse osmosis. From both technical and economic perspectives, RO is the most versatile desalination process as it can be used over a wide range of feed water salinities. Table 7 shows the comparison of RO, IX, and EDR. A brief description of these technologies is presented below.

Ion Exchange. At low salinities, ion exchange is more economically attractive than RO to produce high purity water for industrial, pharmaceutical, and health care applications. It has become a standard practice to use RO as a "roughing" demineralizer prior to IX for high purity water applications.

Electrodialysis. Electrodialysis (ED) involves the removal of ions from water by transport through an ion permeable membrane in which the driving force for desalting water is an electric field across alternating cation and anion exchange membranes. The applicable salinity range for ED is generally less than 5,000 mg/L because higher concentrations increase the electricity cost for ion removal.

Table 7. Comparison of Ion-Exchange, Electrodialysis, and Reverse Osmosis

Parameter	Ion Exchange (IX)	Electrodialysis (ED)	Reverse Osmosis (RO)
Rejection/exchange material	Polymeric resin	Alternating cation/anion exchange membranes	Semipermeable membranes
Mechanism	Cation/anion exchange	Electrical potential	Pressure in excess of osmotic pressure
Feed , TDS (mg/L)	<2,000	1,000 to 5,000	200 to 50,000
Product, TDS (mg/L)	0 to 550	350 to 500	20 to 50

Water Applications for RO

This section provides discussions of the use of RO and RO in combination with IX for several applications of interest to water treatment technologists.

High Purity Water. Recently, there has been an increasing interest in the application of RO in producing high purity water for the electronics industry. Several studies have been reported comparing economic aspects of different desalination technologies.

Beardsley, et al.[17] in a recent study compared the costs for RO/IX, three bed IX, and two pass RO (RO/RO). Figure 7 represents the data, which indicate that RO systems are the cost-effective solution for feed water at or above 130 mg/L TDS (as calcium carbonate). It is important to note that 130 mg/L TDS is lower than the TDS typically present in many water supplies. Figure 7 also shows the break-even point for the two-pass RO is slightly higher at about 120 mg/L TDS. Earlier studies reported a break-even at 230 mg/L and 320 mg/L.[18, 19] While the cost of membranes and resins have decreased significantly in the past five years by as much as 25 to 40%, the cost of capital has decreased even more.. Therefore, the economics of producing pure water have thus improved.

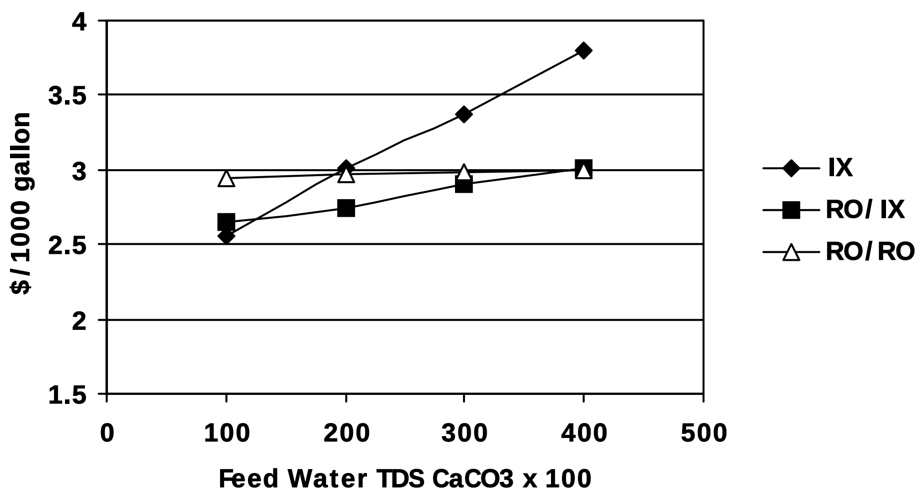


Figure 7. Comparison of RO, RO/IX, and RO/RO for Different TDS Waters

Boiler Feed Water. Simple cationic exchange for removal of calcium and magnesium hardness is commonly used in low to medium pressure boiler feed water pretreatment. Cationic exchange does not remove alkalinity and this alkalinity remains in the boiler. The use of mixed beds is required to remove both hardness and alkalinity. RO removes all dissolved solids (efficiency depends on membrane, ionic species, and number of passes through the membrane). Waters treated with RO which are fed to boilers contain a lower TDS vs. simple cationic exchange. The impact of RO feed water on boiler feed is experienced in higher cycles of concentrations and a lower carbonate alkalinity. The resultant higher cycles may result in longer residence time and boiler treatments may be challenged by higher cycle time and the possibility of increased iron content as a result. Steam condensate treatments could also be affected as carbonate alkalinity and carbon dioxide evolution may be reduced. Use of RO for boiler feed water is now a commercial reality.

Industrial Wastes. The application of membrane separation technology for treating industrial wastes has recently gained momentum as a result of the new systems installations for challenging industrial applications. RO applications for industrial waste treatment fall into four broad process categories determined by the economic and technical aspects of each situation.[20]

- Total recycle of reject and permeate
- RO as a component of chemical recovery process
- RO as a concentration step before disposal
- RO as a pretreatment before disposal

Currently, several RO systems are treating a variety of industrial wastes. Figure 8 shows an ideal application of the RO process for the total recycle of both permeate and concentrate streams. Details of process design and operational experience with different industrial wastes can be found elsewhere.

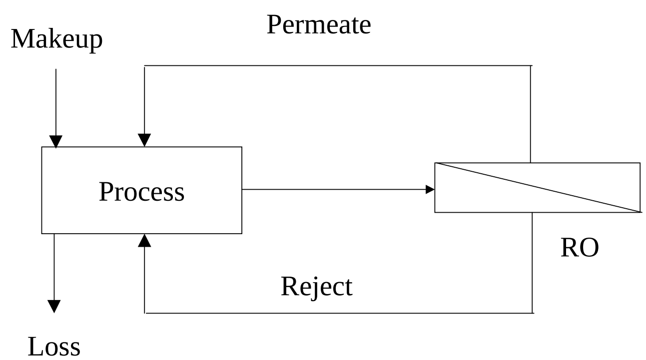


Figure 8. Total Recycle of Reject and Permeate Streams

Food Industry. RO applications in the food processing industry are rapidly developing and include processing of fats and oils, meat by-products, milk, beverages, sugar, as well as fruit and vegetable juices. RO technology is applied alone or in combination with MF and UF for concentration, purification, or recovery of the valuable components from the feed streams. RO system designs for various streams can be found in previous publications.[21]

Potable Water. Many populous coastal areas rely on highly brackish water in excess of the 500 mg/L TDS maximum imposed by the World Health Organization. In many parts of the world, reverse osmosis technology is the method of choice for desalting brackish and seawater for potable water production. Membrane separation processes require lower energy input than the equivalent distillation process. In the United States, the U.S. Environmental Protection Agency's 'Surface Water Treatment' rule and 'Disinfection By-Products' regulations have given impetus to increased use of RO technology. At the end of 1997, the worldwide capacity for more than 12,000 water desalting units was 22.7 million m^3/day (6 billion gal/day).[22]

Summary

Reverse osmosis is a useful technology applicable to a number of industrial systems of interest to water technologists. However, the efficacy of the RO process is greatly influenced by how the technology is applied. RO systems frequently experience operational problems due to membrane fouling (the most common cause of lost production), reduced membrane life, and thus, higher operating costs. Proper pretreatment selection, system design, and operation can minimize membrane fouling. In treating challenging water streams, the incorporation of a multifunctional antiscalant/dispersant into the treatment program should be considered for ensuring optimum performance from an RO system.

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Lubrizol Advanced Materials, Inc.
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