Industrial **Reverse Osmosis** System Design

By Jeff Tate

Industrial system design

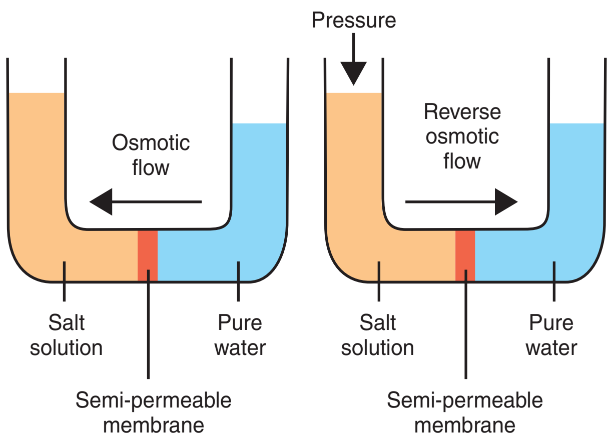
Photo courtesy of Hydranautics

Introduction

Reverse osmosis (RO) is currently used in various applications ranging from small, undersink drinking water units to large industrial systems. The technology is widely used and accepted as it removes both dissolved ionic and organic impurities. This article will focus on the reverse osmosis technology in industrial applications and will discuss factors that differentiate industrial RO from commercial-grade systems.

RO installations are sometimes unsuccessful due to the system design and application. The approach and recommendations in this article are based on 16 years of experience in system design and application, as well as design experience and operating observations of successful membrane systems. The goal of this paper is to present factors that will contribute to reliable operation for many years. Alternate designs are sometimes used.

Figure 1. Reverse osmosis process

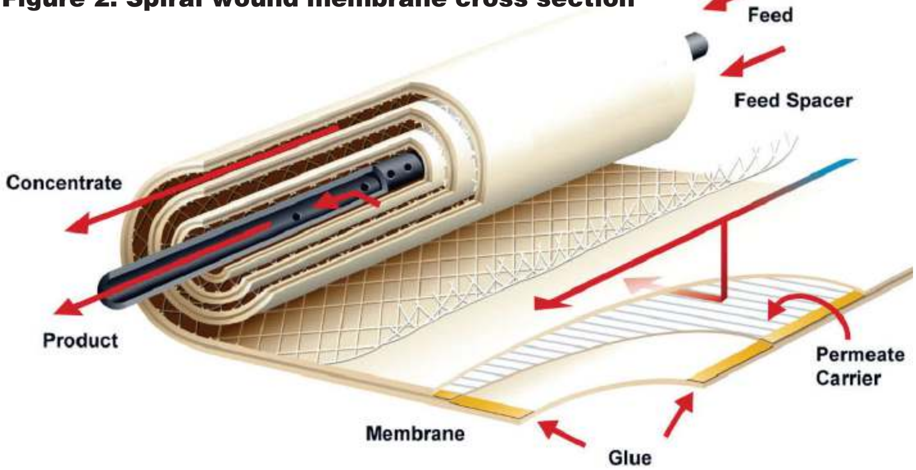


A natural process

Osmosis is the natural phenomenon that occurs as pure water flows across a semi-permeable membrane to the side that contains a higher concentration of dissolved solids. The higher the dissolved solids concentration, the more pure water (dilute) will flow to the concentrated side. The osmotic pressure that occurs results in a higher level of concentrate water than dilute water (Figure 1). An externally applied pressure, higher than the osmotic pressure, drives water in the opposite direction, producing a higher volume of pure water. This process is called reverse osmosis.

The most common RO membranes are spiral wound (Figure 2). Several layers of flat-sheet membranes, concentrate chambers (feed spacers) and dilute chambers (permeate carriers) are wound around a center permeate tube that collects the dilute water. The membrane element is sealed around the outer edges with a glue line. The design of spiral-wound membranes is such that feedwater enters on the feed side of the membrane at a high pressure. Reverse osmosis occurs and low TDS water is collected in the permeate tube, then exits the center of the membrane element. The feedwater becomes more and more concentrated as it flows across the membrane and exits as the concentrate reject at much higher TDS levels than the feed

Figure 2. Spiral wound membrane cross section



flow. Since membranes are reported to have pores as small as 0.005 microns, the majority of organics (dissolved and undissolved) and other suspended solids cannot pass through the membrane. They are therefore typically rejected with the concentrate.

Commercial system design

Small commercial systems utilize 2.5- and four-inch diameter membranes are normally housed in PVC or stainless steel single membrane housings. There may be some PVC or stainless steel piping, but hoses are typically used to connect the RO housings, reducing materials cost and assembly time to manufacture (Figure 3).

In commercial systems, instrumentation is basic. Depending on the manufacturer, there are usually permeate and concentrate flow rotameters with a concentrate pressure gauge and a motor starter

Usually, a preprogrammed microprocessor is used to start and stop the RO system based on product level in the permeate storage tank. The microprocessors also feature *pretreatment lockout* to prevent the system from running if a media filter is in backwash or softener is in regeneration. Low- and high-pressure pump protection is included for additional cost.

Commercial system pretreatment often includes a multimedia filter, softener and activated carbon filter. Backwashable filters and softener vessels are fiberglass reinforced plastic (FRP) constructed with a timer-based control valve. The systems include a plastic pre-filter rated at five microns and a multistage centrifugal pump. SS needle valves are used to control concentrate flow with no control of permeate flow. The result is a fluctuation of product water flow rate.

Depending on the manufacturer, some parts may be brass rather than stainless steel to reduce cost without concern of the life the system. If the purchaser is educated about system benefits, concentrate recirculation, pre-filter inlet and outlet pressure gauges, pump throttling valves, soft motor starters or variable frequency drive (VFD) and FRP membrane vessels, cold-water membranes and permeate pressure gauges may be included.

Figure 3. Commercial system design

Photo courtesy of Hydranautics

Commercial RO permeate flow of the system is usually rated close to the maximum allowed by the membrane manufacturer, rather than based on the application and membrane flux. *Recovery* is defined as the permeate flow rate divided by the feed flow rate, and expressed as a percentage. Recoveries can be as low as 15 percent without concentrate recirculation or as high as 75 percent with concentrate recirculation. Since the feedwater flow rate drops as permeate passes across the membrane, the feedwater becomes concentrated with high scaling and fouling containments the further across the membrane surface it flows.

In order to minimize fouling or scaling of the concentrate contaminants, a minimum flow rate is required to maintain high velocity and turbulence on the membrane surface. The concentrate recirculation option allows higher recoveries and less wastewater by mixing feedwater with rejected concentrate water.

Industrial system design

Higher end, heavy industrial RO systems should have a different design philosophy than their commercial counterparts. Some system manufacturers implement commercial features into the industrial design; however, large RO plants should provide more reliable performance and membrane life than their commercial counterparts. Although system cost is important, long-term operation, membrane life and performance are also critical as the membrane elements represent a significant investment to industrial RO users.

In commercial systems, membrane cost for 2.5- and four-inch diameter elements may range from \$100-\$350 per element. Most consider small membranes disposable due to the low-cost of membrane replacement and small number of membrane elements in a system. Industrial systems generally feature multiple eight-inch membranes, usually ranging in number from 18 to 180 per skid (see photo on page 38). Each eight-inch membrane typically costs \$600-\$700, so the membranes represent tens and even hundreds of thousands of dollars.

The recommended pressure vessel holds six elements or less per vessel. Some system providers may use vessels capable of holding up to seven or eight elements, but the concentrate flow and velocity drops as flow passes across each membrane element inside the vessel. As concentrate velocity drops, scaling increases. Therefore, a maximum of six elements per vessel is the recommended design to prevent scaling.

Reliable performance in salt rejection and flow are critical for heavy industrial users. To achieve even better purity, permeate can be further polished by electrodeionization (EDI). By combining RO and EDI, the system can produce continuous ultra-pure water without chemical regeneration.

Feedwater sources

Feedwater source is the first concern when designing an RO system. For brackish water reverse osmosis (BWRO) membranes, the water source is typically surface or well water, but can also be industrial or municipal wastewater. Even if the source is municipally treated, it is imperative to review where the municipality draws their water. This allows for optimal system design, as the characteristics of the water source will affect the RO membrane operation.

The water source is one factor in determining the potential for fouling and scaling. Fouling is the accumulation of solids on the membrane surface and/or feed spacer. Scaling is a chemical reaction where dissolved solids are precipitated out from the feedwater on the concentrate side of the membrane. The most common forms of scaling are calcium carbonate, barium sulfate, calcium sulfate, strontium sulfate, calcium fluoride and silica.

Surface water may be from lakes, rivers, reservoirs, etc. By its very nature, surface water is prone to fouling due to seasonal fluctuations in suspended solids, biological contaminants and total organic carbon (TOC). It tends to contain low total dissolved solids (TDS), heavy metals and hardness. Surface water is usually disinfected to kill bacteria, most commonly with chlorine, ultraviolet light (UV) or ozone. While this disinfection removes the living microorganisms, the remaining byproducts are organic matter and food for bacteria. Disinfection therefore can result in higher organic and/or biofouling potential on the membranes downstream. During rain, the suspended solids may increase which increases the potential for plugging of the membranes.

The two most meaningful methods of measuring suspended solids are turbidity and silt density index (SDI). Turbidity is most commonly measured in nephelometric turbidity units (NTU) and increases as the water ability to transmit light (transparency) decreases. SDI is a calculation of fouling potential according to test standard *ASTM D-4189*. It is calculated by flowing water through a 0.45-micron filter at 30 psi in a 500 mL jar before and after a standard 15-minute run time through the filter. The percentage of plugging is calculated by comparing the time to fill a 500 mL jar with the RO feedwater before the test (t_i) with the time required to fill after the test (t_f).

Turbidity should be less than 0.5 NTU for optimal performance and maximum of 1.0 NTU. Acceptable SDI levels at the RO inlet are less than 5.0 (15-minute test), but SDI should be less than 3.0 for optimal performance.

Well water (also called ground water) is taken from underground supplies. It usually contains very little suspended solids, as the earth acts as a natural filter when water drains underground. Well water typically has higher dissolved solids and frequently is high in hardness, heavy metals and possibly silica.

Pretreatment

RO pretreatment is optimized based on feedwater characteristics. Suspended solids are removed by filtration. Media filtration is limited to filtering between 10 to 20 microns, while membrane filtration (such as ultrafiltration) can filter below 0.03 microns.

Scaling potential is reduced either by ion exchange softening or chemical injection. Ion exchange (IX) softening is a reliable technology if regenerated properly; however, industrial ion exchange systems are more expensive than chemical injection. Industrial IX systems are usually dual trains. For reliability, the vessels are recommended to be ASME code carbon steel with epoxy or rubber lining and external painted surface. The valves are automatically PLC-controlled.

Acid injection and antiscalant injection are two methods for reducing scaling on membrane surfaces. For acid injection, hydrochloric acid is preferred over sulfuric acid, as the latter can increase the sulfate scaling potential. The process of acid injection will increase carbon dioxide levels that load polishing ion exchange or EDI.

Antiscalant chemical injection simply requires a small storage tank filled with RO permeate and suitable antiscalants, level switches, manual isolation valves and a chemical metering pump. The appropriate antiscalant chemical is determined by the specific scaling ions, pH and recovery. Antiscalant chemicals are generally considered safer than acid. Chemical selection and dosage are provided by the chemical supplier. However, a reliable and experienced manufacturer with a full range of antiscalant products designed for many specific feedwater and RO requirements should be used.

Scaling potential is measured in Langelier saturation index (LSI) for brackish water. LSI is calculated by subtracting the calculated pH of saturation of calcium carbonate from the actual feed pH. LSI should be less than negative 0.2 if antiscalant injection is not used. Antiscalant injection permits LSI as high as 1.8 depending on the antiscalant used.

Table 1. Average flux rates and expected percent decrease in flux

Water type	SDI	Average flux	Flux decline/year (%)
Surface water	3 - 5	8 - 12 gfd	7.3 - 9.9
Well water	< 3	14 - 16 gfd	4.4 - 7.3
RO permeate	<1	20 - 25 gfd	2.3 - 4.4

RO membranes cannot handle oxidizers, including free chlorine. If chlorine is in the feedwater, it must be removed either by activated carbon adsorption or sodium metabisulfite injection. Activated carbon filters are more capital intensive than bisulfite injection and carbon media is a known breeding ground for bacteria. Bisulfite can be manually controlled, but automatic control and proper set up will ensure chlorine is entirely scavenged without over injection of the bisulfite, which can cause sulfate-reducing bacteria (SRB) growth.

Control instrumentation can be a reliable online titration chlorine monitor or oxidation reduction potential (ORP). ORP set points will vary from site to site, so an experienced technician should run titration tests to determine the optimal set point. ORP is set 30 to 50 millivolts (mv) lower than at which zero ppm free chlorine is achieved. Manual tests for free chlorine should be performed during routine maintenance to confirm the setpoint over time.

Staging and selection of RO membranes is based on feedwater and product water requirements. As the system ages, an increase in salt passage and a decrease in flux is expected. Membranes should have a three-year warranty, so a three-year projection is typically used for design. Salt passage increases as temperature increases; the warmest temperature is used to confirm permeate quality. The pressure required to produce the same permeate flow increases as temperature decreases.

In commercial systems, a small pump is typically sized to deliver the required flow at 77°F (25°C) with 500 or 1,000 ppm TDS. When colder water enters the system, the user must settle for decreased flow. Industrial users require that the minimum permeate flow be maintained at all times. The pump must be sized based on the pressure and flow at the coldest temperature after a minimum of three years of operation with specific water analysis of the plant. The pump will be oversized at warmer temperatures, so a pump throttling valve or variable frequency drive is utilized to achieve desired flow.

Membrane flux also needs to be considered. Flux is the rate of permeate flow per membrane area, usually measured in gallons per square foot per day (gfd). Commercial systems usually rate the system around 20 gfd, which causes rapid decrease in product flow and quality. Industrial systems should be designed for no more than 16 gfd for well water, 12 gfd for surface water and 25 gfd for second pass (RO permeate feedwater). Manufacturers specify a minimum concentrate flow and maximum feed flow for each membrane model. Membrane selection, staging and system recovery are designed to meet the minimum requirements and not exceed maximum requirements (Table 1).

Salt passage design usually increases at an average of seven to 10 percent per year.

Industrial RO system components

Cartridge filters, also called RO prefilters, protect RO membranes by capturing suspended solids particles as water passes through the cartridges. Cartridge filter housings should be 316L stainless steel for industrial grade systems; the number and length of cartridge elements should be sized for 3.5 gpm per 10-inch length. Filters should have a nominal rating of no more than five microns.

High-pressure pumps increase the feedwater pressure to that which is required for RO membrane operation. Pumps should be specifically sized and selected based on the temperature range and the three-year operating conditions established for the membranes. An industrial safety factor defined by the pump performance curve should be included in determining pump size. The motor should be total enclosed fan cooled (TEFC). Pumps should be operated by a soft-start motor starter, located in the control panel or motor control center (MCC) for membrane protection.

RO pressure vessels are recommended to be FRP and should be no longer than six membranes per vessel to allow optimal concentrate flow. They should be designed to meet American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code, Section X* standards. For an additional cost, vessels can be inspected during fabrication by an ASME authorized inspector and code-stamped.

High-pressure piping in the RO system should be 316LSS for high-corrosion resistance, fully fabricated and welded by qualified welders. All stainless steel fittings should be welded with threaded connections wherever possible to prevent leaks. Low-pressure piping is usually schedule 80 PVC. Piping should be hydrostatically tested with deionized water, with quality level and pressure set by a quality control engineer. In all cases, tests must be done hydrostatically.

Automatic valves should be installed at RO inlets, permeate, permeate divert, flush inlets and flush outlets. Butterfly or diaphragm valves are common for low pressure; 316SS ball valves are used for high pressure. Pneumatic actuators are either spring-return fail-closed (product) or fail-open (divert), with two-position limit switches and 80-psi spring set-up. Pneumatic tubing should also be 316SS.

Instrumentation and controls

Instrumentation is a critical component to the system's successful operation, so only reliable manufacturers and instruments that can be calibrated should be considered. All instrumentation should be monitored by the PLC. Instrumentation requirements include many elements.

Flow sensors are installed in permeate and concentrate lines. Stainless steel, liquid-filled pressure gauges are installed in the combined permeate outlet, the concentrate outlet and at each stage. Pressure gauges at the inlet and outlet of each stage allow the user to trend the pressure drop across each stage, which assists with troubleshooting and determining cleaning requirements. Pressure switches are installed at the pump suction, pump outlet and across the cartridge filter. Conductivity probes are installed at the system inlet and permeate. ORP or free chlorine and pH probes are installed at system inlet, after chemical injection. An SDI test kit should also be included with the system.

The control system is comprised of a programmable logic controller (PLC) with a recommended local 10-inch minimum color touch screen HMI and an optional remote Windows®-based operator station with remote monitoring capability. In automatic mode, the system is designed to operate based on a call for water and various other system parameters, such as the quality of water, water flow rate, etc. RO units usually start and stop based on storage tank levels. Controllers display inlet and permeate conductivity, water temperature, ORP, pH, flows and operating status of RO and EDI pretreatment. Controllers have an input option to automatically start/stop, based on product water tank levels or other relay input.

Upon shutdown and after 24-hours of idle operation, the controller automatically flushes the membranes for several minutes using permeate water. This requires automatic valves that are dedicated for membrane flushing. The fast-flush feature common with commercial systems is not recommended in the industrial design, as the inlet water contains the scaling and fouling contaminants that are removed with permeate autoflush.

In the semi-automatic mode, PLCs control and monitor all automatic train functions, while manual adjustment and monitoring is necessary for manual system devices, such as valves and indicators. Bisulfite injection rate is controlled via bisulfite pump speed, which in turn is controlled by a PID with ORP signal as the process variable; set point for the ORP signal is determined in the field by titration.

A membrane clean-in-place (CIP) system is necessary for on-site chemical cleaning and sanitization and to prepare the RO membranes for long-term storage. RO CIP is a manual process of connecting the selected stage to the CIP system, mixing the proper chemicals in the CIP tank and allowing the solution to recirculate through the selected stage. Manual valves are provided at each stage inlet and outlet and to isolate the previous and following stages in order to clean each stage individually.

Hoses usually connect CIP systems to the RO skid, but hard piping provides for convenient cleaning. CIP systems include conical-bottom gallon, high-density polyethylene tanks designed to hold the necessary chemicals. Tanks should have a low-level switch for pump and heater protection. Some manufacturers do not include a heater with the CIP system, but a heater provides much more effective cleaning, especially for biological, organic and silica fouling. The heater is sized to heat the tank water to 120°F (48.8°C) in four hours.

Industrial RO systems are designed to clean each stage individually. CIP pumps should be 316SS with TEFC motor starters designed to deliver chemicals to the selected RO stage. Flow meters measure the cleaning solution flow rate. A one-micron cartridge filter on the outlet piping from the feed pump protects RO membranes from any debris that may have been collected during the clean up process. A pH probe and transmitter monitors the pH of the cleaning solution. The necessary manual valves and PVC pipe and fittings are pre-mounted, wired and installed on a chemical-resistant, epoxy-coated steel skid.

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About the author

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About the company

♦ *Agape Water Solutions, Inc. manufactures custom-engineered, membrane-based systems for water treatment companies and provides OEMs, dealers and distributors with components, systems and technical support. The firm is the Master Service Provider in North America for Ionpure Technologies, a leading manufacturer of EDI modules.*