ESTABLISHED PRACTICES, INNOVATIVE DESIGN, AND NEW PRODUCTS:
A NEW GENERATION OF ULTRA HIGH PRESSURE DESALINATION

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Abstract

In common parlance, reverse osmosis (RO) is often described as removing salt from water. In practice however, these processes squeeze water from a salt solution resulting in concentrate to be disposed or treated further in more expensive processes which pose significant challenges to the viability of a project. Disposal options may be cost-prohibitive or unavailable altogether, while conventional options for Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) bear significant capital cost and energy consumption.

The current 1200PSI (83bar) environment for membrane desalination and concentration was established at the turn of the millennium. In this time, seawater reverse osmosis (SWRO) recoveries of 40%-50% have been the norm with maximum brine salinities of 80 - 90k ppm in concentration and reuse applications. However, demand for higher RO pressures to address feed salinity and concentration requirements conflict with efforts to reduce capital cost and energy consumption, requiring advanced membrane solutions for increased recovery and concentration.

Today's generation of Ultra High Pressure (UHP) systems rated for 1740PSI (120bar) represent the convergence of established practices, innovative design, and new products. Taking a page from longstanding high recovery brackish RO practices, multistage systems optimize feed and brine velocity to limit fouling and scaling, while recent developments in proven UHP turbocharger technology and application have demonstrated that designers can distribute brine energy to each stage as needed to optimize net driving pressure and velocity for balanced, stable high recovery operation.

The successful implementation of a two-stage SWRO plant with dual turbochargers in Mexico demonstrated that 60% recovery can be reliably achieved with low energy consumption and fouling using conventional membranes. In addition, an upcoming brine concentration/ZLD project in Saudi Arabia will demonstrate that UHP can be reliably and economically achieved for brine mining of valuable minerals. These proven practices are entirely applicable to UHP, providing the framework for implementation of today's UHP membranes and turbochargers as well as supporting equipment such as pressure vessels and couplings.

These developments represent the next step in the evolution of reverse osmosis, combining established principles with advanced products and design to expand the possibilities for membrane solutions at ultra-high salt concentrations. While this combination of accepted and advanced practices addresses process and application challenges today, regulations and standards must keep pace to ensure these developments are embraced with the same confidence as conventional technologies.

From pumps and turbos to membranes, their pressure vessels and couplings, the desalination industry's best and brightest engineers are collaborating as never before to make UHP a reliable, commercially viable solution to the conflicting priorities of concentration and reuse processes. This paper will describe these challenges and how they are being addressed by the industry's best experts working independently and together to inhabit the new UHP frontier.

Description

Membrane processes for concentration and reuse in Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) applications have conflicting concerns of increasing brine salinity versus capital and energy cost. Today's generation of Ultra High Pressure (UHP) systems represent the final process evolution in reverse osmosis, a convergence of established practices, innovative design, and new products including turbochargers, membranes, pressure vessels, and couplings to make UHP a reliable, commercially viable solution. This paper will describe the challenges in this effort and how they are being addressed by the industry's best experts working independently and together to inhabit the new UHP frontier.

Introduction

From a mass balance perspective, recovery represents an inefficiency in all desalination processes. For a given quantity of saline feed, a percentage of pure freshwater is forced through a membrane, with the balance to be disposed or sent to another process as a concentrate of rejected salts and suspended matter. In this view, the most efficient process would reduce brine discharge to the maximum extent that is technically and economically feasible.

While this is an essential function of crossflow membrane processes, the percentage and resulting quantity of water concentrated as reject has significant implications for the design and operation of reverse osmosis (RO) systems. As fresh water is recovered through a membrane system, the increasing concentration of dissolved and suspended matter must be kept in solution or suspension to prevent fouling and scaling. In addition, as osmotic pressure increases with the concentration of total dissolved solids (TDS), the system must account for this increase to ensure consistent production throughout the length of the membrane array. As a result, a considerable amount of engineering experience, skill, and effort is devoted to designing and maintaining systems that manage the impacts of higher concentrations of biofoulants, colloidal matter, particulates, and dissolved solids that come with increasing recovery.

This can be considered in two broad categories. On one hand, physical and chemical pretreatment conditions water to reduce fouling load and scaling potential; on the other, membrane systems can be optimized to fully exploit the advantages of crossflow in spiral-wound membranes.

All membrane manufacturers issue design guidelines covering concentration polarization, flux, and feed/brine flow rate to promote crossflow essential to long-term operation. For this reason, brackish water reverse osmosis (BWRO) systems employ multistage arrays to increase membrane surface area while maintaining minimum brine velocities. While multistage arrays maintain flow velocity, other measures are needed to maintain sufficient net driving pressure (NDP) as osmotic pressure increases.

High recovery brackish systems operating with low brine TDS and operating pressures frequently employ measures such as membrane selection, internal staging, and permeate backpressure to manage available pressure from the first stage high pressure pump (HPP). Membrane selection, whether a single membrane type is used in a stage or different membrane types are used in a stage (internal staging), is limited by the range of membranes available for a given application. Permeate backpressure is limited by the pressure ratings of vessel permeate ports and results in throttling losses that increase specific energy consumption (SEC). From an operating perspective, the risk of membrane damage due to water hammer also increases with permeate backpressure and none of these measures minimize energy loss with pressurized brine.

The value of these measures is reduced as osmotic pressures increase with concentration in high recovery systems, requiring additional measures such as interstage boosting and UHP stages for concentrations above 80,000ppm TDS. Interstage boosting allows designers and operators greater flexibility and control for adjusting and maintaining NDP, while UHP stages increase the range of operating pressure for osmotic pressures above 800PSI (55bar).

These options to achieve higher recoveries are thus met with both increased complexity of operation and greater cost. The system designer must evaluate the impact of these advanced designs to properly balance the capital and operating costs to achieve the best value for the project.

As the heart, lungs, and rib cage are the key components of aerobic function in the human body, the turbochargers, membranes, pressure vessels, and couplings are the key components of separation in a reverse osmosis system. Increasing the capabilities and limits of these key components results in a more efficient system with increased recovery and reduced disposal or processing by other processes.

Basic Principles

Any conversation of enhanced or high recovery must begin with concentration. As high purity permeate is recovered, dissolved and suspended solids are concentrated in the remaining brine. For a 5000 ppm feedwater at 75% recovery and membrane salt rejection greater than 99%, the concentration factor would be 4 such that the brine TDS would be 20,000ppm as follows:

$$\text{Concentration factor} = 1 / (1 - \text{recovery})$$

$$\text{Concentration factor} = 1 / (1 - 0.75)$$

$$\text{Concentration factor} = 1 / 0.25$$

$$\text{Concentration factor} = 4$$

As a pressure-driven process, RO systems are directly affected by osmotic pressure. In water, osmotic pressure is approximately 10 PSI / 1000 ppm TDS; from our previous example, the osmotic pressure of a 5000ppm feedwater is ~50 PSI while the osmotic pressure of the 20,000ppm brine is ~200 PSI.

Reverse osmosis and nanofiltration systems work by applying sufficient pressure to overcome osmotic pressure and drive permeate through a semipermeable membrane. This feed pressure, P_{Feed}, is the sum of all pressures as represented by the following equations:

$$\text{Net Driving Pressure (NDP)} = (P_{Feed} - P_{Osmotic}) - (P_{Permeate} + P_{Loss})$$

$$\text{Net Driving Pressure (NDP)} \approx P_{Feed} - P_{Osmotic}$$

$$\text{Feed Pressure} \approx \text{NDP} + P_{Osmotic}$$

In the above equations, hydraulic pressure losses, P_{Loss}, are primarily due to the friction losses which arise as the water flows through the spacer on the feed side of a spiral wound element. For seawater systems, the value of this term as well as the permeate pressure, $P_{Permeate}$ are often negligible in comparison to NDP and the osmotic pressure difference, $P_{Osmotic}$. Thus, NDP will be considered the difference between feed and osmotic pressure.

When calculating feed pressure for a given membrane array, designers consider osmotic pressure and NDP for the two extremes of TDS found at the lead and tail elements. This compromise results in an imbalanced membrane array; to have sufficient feed pressure for usable NDP on the tail elements, the lead elements will have an excess of NDP with high lead element flux and concentration polarization factors. Figure 1 shows this effect for a two-stage array without interstage booster.

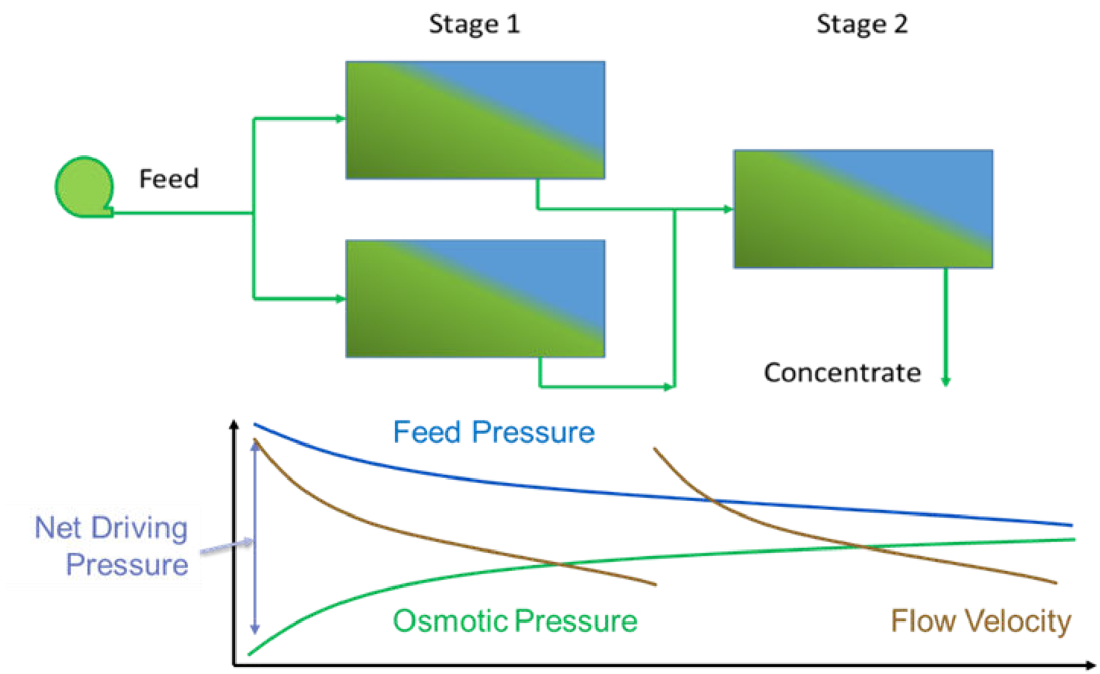


Figure 1: Pressure and Feed/Brine Flow in a Two-Stage Array

The effects of this energy imbalance can be expressed in terms of velocity, specifically membrane flux. In RO and NF, flux is defined as the volume of permeate per unit area produced by an element or group of elements in a time interval. Flux is measured in gfd (gallons/square foot/day) or lmh (liters/square meter/hour).

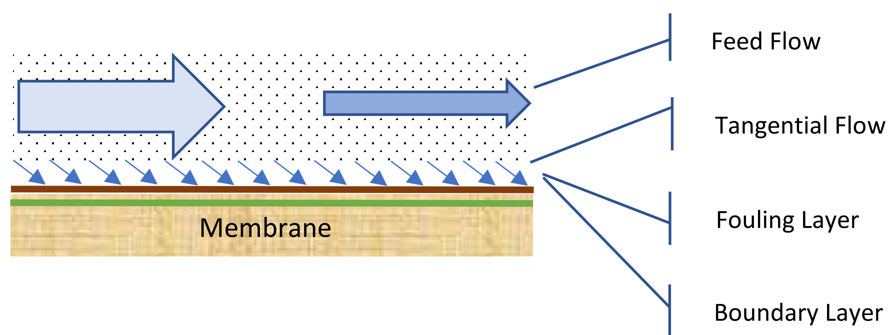


Figure 2: Flow and Flux at Membrane Surface

Figure 2 shows the effects of high membrane flux on lead elements. High flux results in convective forces that bring foulants to the membrane surface while a boundary layer of more concentrated salts forms due to concentration polarization at the membrane surface. The rapid decrease in lateral feed velocity resulting from high flux contributes to these effects as there is limited velocity to disrupt either layer, resulting in increased salt passage, increased osmotic pressure, as well as long-term fouling and scaling.

In single-stage SWRO systems, the lead element experiences high flux which places it at increased risk of fouling, while subsequent elements operate at considerably lower flux rates to achieve the desired recovery. However, as lead element fouling reduces permeate production, subsequent elements are required to operate at much higher flux rates than designed to maintain recovery, raising their risk for fouling as well.

While this effect has been largely ignored in single-stage seawater systems due to the low recoveries favored by contemporary seawater RO systems, the multi-stage arrays used to manage brine velocity in brackish RO systems allow for limited flux balancing via membrane selection and permeate backpressure.

Balancing flux and velocity in a membrane array can be accomplished in many ways, but the goal is always the same. By managing or applying pressure throughout the length of the membrane array, the goal is to reduce variations in NDP that result in high or low membrane flux. Figure 3 shows various curves for feed pressure, osmotic pressure, feed/brine flow velocity, and net driving pressure in a balanced, two-stage array:

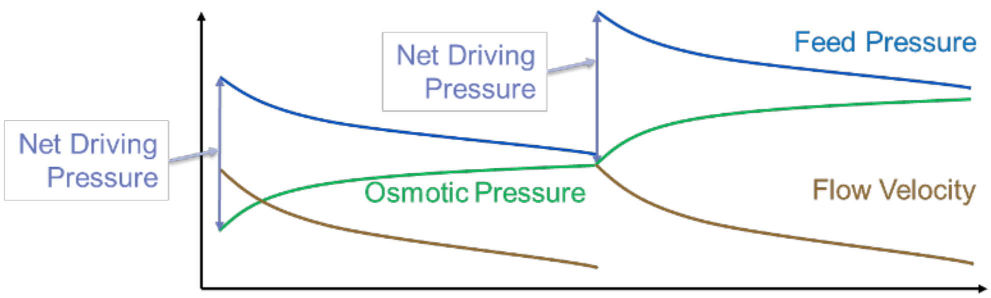


Figure 3: Pressure and Feed/Brine Flow in a Flux-Balanced, Two-Stage Array

In UHP systems, flux and velocity balancing with pumps or turbochargers offers a greater range of interstage control when combined with measures such as membrane selection and/or permeate backpressure, allowing pressure to be added as needed while reducing the need to mitigate high lead element flux and its effects on concentration polarization, salt passage, fouling, and scaling.

Turbochargers in UHP Applications

Conservation of energy in a UHP process requires boosting feed pressure from the brine of the previous high-pressure stage to restore NDP for additional recovery, but this poses challenges for implementation and energy efficiency. Few pumps can receive high inlet pressures without modifications, and additional instrumentation and controls are required to maintain and adjust operation with varying conditions. In addition, the energy conserving benefits of a balanced interstage design are reduced by the efficiencies of pumps, motors, and drives.

Turbochargers offer a compact, efficient, and effective solution for interstage boost in UHP systems. Consisting of a single-stage centrifugal pump driven by a single-stage radial inflow turbine on a common, dynamically balanced shaft, the turbocharger is entirely brine-driven without electrical requirements or adaptation for high inlet pressures. A diagram of the turbocharger is shown in Figure 4:

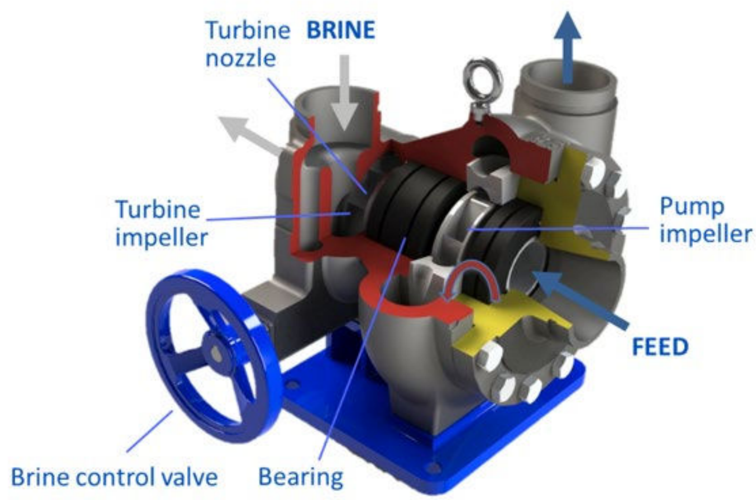


Figure 4: Hydraulic Pressure Booster – a "turbocharger device" (courtesy FEDCO)

An important, but little-discussed, aspect of turbocharger design and application is the brine ratio between feed flow through the pump and brine flow through the turbine. The brine ratio can be expressed as follows:

$$\text{Brine Ratio} = \text{Brine Flow} / \text{Feed Flow}$$

For a given centrifugal device and total developed head (TDH), efficiency generally increases with unit capacity. Likewise, for a given turbocharger, transfer efficiency increases as the brine ratio approaches 1.0. In a typical single-stage SWRO operating at 50% recovery, the brine ratio would be 0.5, but as an interstage booster in a balanced system, the ratio would be 0.6-0.7 resulting in an improvement in transfer efficiency such that an interstage booster typically requires a portion of the available brine energy. In high recovery, multistage applications where the turbocharger is used as the sole interstage booster, the brine contains sufficient energy to drive the final UHP stage without additional input.

Among energy recovery devices (ERD), turbochargers are unique in their flexibility, allowing designers to recover and apply partial or full brine energy to an equal or greater feed flow. The key to determining and controlling recovered energy is the coefficient of velocity, expressed as Cv (US standard units) or Kv (Metric units) based on the following formula:

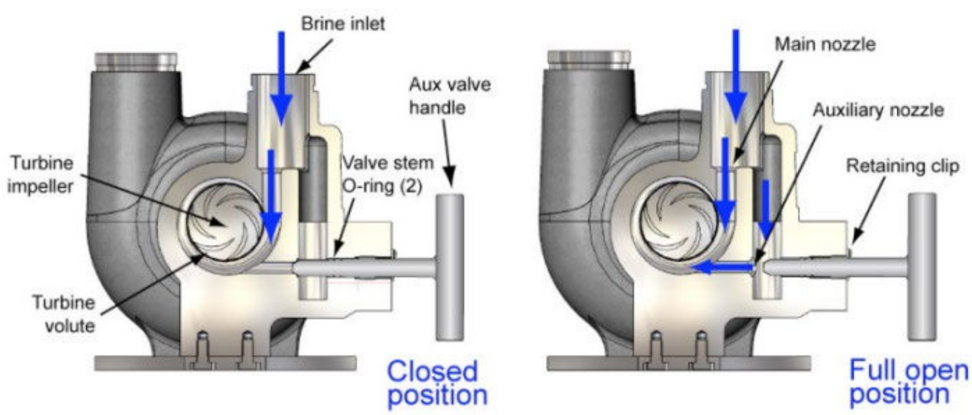
$$C_V = Q\sqrt{\frac{S.G.}{\Delta P}}$$

Imperial units
Cv → Flow coefficient
Q → Flow [gpm]
S.G. → Specific gravity []
ΔP → Differential pressure [psi]

Kv = 1.156 * Cv   for metric units

Figure 5: Coefficient of Velocity (Cv) formula

For a given flow Q and specific gravity SG, a differential pressure ΔP through the turbocharger's nozzle results in high velocity which is converted to power by impulse and reaction in the turbine rotor, which transfers that energy directly to the single-stage centrifugal pump impeller. Due to the high velocity of the incoming brine, this rotor has high rotating speeds which result in high single stage pump efficiencies of up to 90% or more. In turbochargers with an integrated auxiliary nozzle, Cv can be adjusted manually or automatically, increasing or decreasing fluid velocity and resulting boost, based on operating conditions or desired duty point.



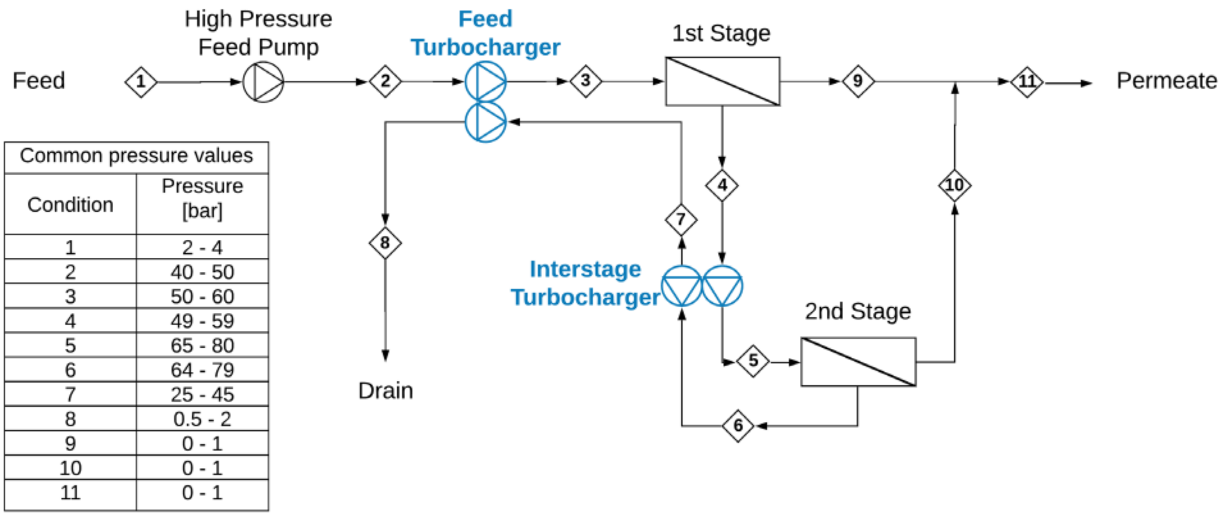
Closed position → Highest Boost
Highest fluid velocity → highest turbine RPM

Open position → Lowest Boost
Lowest fluid velocity → lowest turbine RPM

Figure 6: Effect of auxiliary valve on rotor speed and boost (courtesy FEDCO)

The flexibility of turbochargers in UHP applications is a key advantage, enabling designers to apply UHP using established design principles of multistage design with interstage boost. Where maximum boost is required for pressures at or near the limits of UHP systems, the turbocharger will apply all or most of the available brine energy, but where lower UHP pressures are required, the surplus brine energy can be used to drive feed or interstage turbochargers on the first and second stages, respectively.

This approach, called Biturbo™, applies proven advantages of vessel staging and interstage boost to manage NDP and flux at recoveries up to 60% in seawater RO (SWRO) applications; a sample Biturbo™ diagram is shown in Figure 7:



Common pressure values	
Condition	Pressure [bar]
1	2 - 4
2	40 - 50
3	50 - 60
4	49 - 59
5	65 - 80
6	64 - 79
7	25 - 45
8	0.5 - 2
9	0 - 1
10	0 - 1
11	0 - 1

Figure 7: Biturbo™ configuration for high SWRO recovery, consisting of a high pressure pump and two turbos, one located on the feed and another one installed between stages. Common pressure values during operation shown in insert.

By making each membrane contribute to total production, the hydraulic balance resulting from Biturbo™ enables designers and operators to increase recovery to the chemical and physical limits of the system rather than limiting recovery based on feed pressure and lead element flux at the first stage. In this way, a Biturbo™ system follows the same design rules of membrane velocity, concentration polarization, recovery, and flux as any conventional single or multistage RO system. Furthermore, OEMs may choose from any membrane, pressure vessel and/or components manufacturer in the market.

Compared to other approaches for conventional and UHP high recovery arrays, Biturbo™ applies brine energy as needed to increase feed pressure, such that these integrated systems operate as a cost and energy efficient whole rather than a patchwork of separate subsystems.

The efficiency, flexibility and capability of Biturbo™ for increasing recovery in conventional and UHP systems is realized by seawater RO and brine mining RO applications in Mexico and Saudi Arabia, respectively. The 2019 paper presented in Dubai at the International Desalination Association World Congress detailed the design and experience of a 60% recovery Biturbo™ SWRO that began operation in 2019[1], while the upcoming brine concentration/ZLD by the Desalination Technology Research Institute (DTRI) of the Saline Water Conversion Corporation (SWCC) includes Biturbo™ as well as advanced UHP membranes, pressure vessels, and couplings for a state-of-the-art, cost-effective solution for mining valuable minerals from the brine generated by desalination plants[2].

Figure 8: Biturbo™ skid and turbocharger arrangement
(left) Feed turbocharger at bottom; interstage turbocharger at top
(right) Full skid installed at Rancho San Lucas, Baja California, Mexico

Ultra High Pressure FRP Pressure Vessels

Essentially all Reverse Osmosis pressure vessels today are made of Fiberglass Reinforced Plastic (FRP).

This Technology has been the preferred Pressure Vessel Material since the early 1970's when Fluid Systems began using FRP vessels. Before that time, coated steel pipe was used, however difficulties with coating integrity and standard pipe dimensional tolerances created problems. The solution of composite plastic material was developed and proved to be the correct solution. FRP materials can be made to very controlled tolerances, they have high strength-to-weight ratio and selection of the plastic materials, (typically epoxy chemistry) are non-corrosive to high saltwater concentrations making them an ideal choice for reverse osmosis desalination vessels. FRP vessels were used in the first large seawater RO project, in Jeddah Saudi Arabia which was constructed by Fluid Systems in 1978 and started in January 1979. Figure 9 shows an early military RO system, a US Army ROWPU from this era (1978) with FRP vessels.

Figure 9: Military ROWPU (Reverse Osmosis Water Purification Unit)

Seawater-rated FRP Pressure Vessels have been around since the initial large seawater RO projects in the mid and late 1970's. Another early membrane pioneer, DuPont, introduced the B-9 brackish membrane module in 1969 which also had an FRP pressure vessel constructed of commercial FRP pipe. The seawater version of this product line, the B-10 module, was introduced in 1974 with an FRP vessel. These early seawater vessels were rated for 1000 PSI, while cellulose acetate brackish membranes of this era operated at maximum pressure of 600 PSI.

The high strength glass fibers provide the strength in FRP vessels while the epoxy structure locks the glass fibers in place and provides chemical corrosion protection. In current FPR vessels, glass fibers constitute approximately 75% of the mass of the vessel.

Vessel Design for Higher Pressures

The mechanical design for FRP pressure vessels operating at high pressure must consider three specific considerations. These are (1) Hoop and (2) Longitudinal Stresses in the vessel wall as well as (3) stresses imposed by the end closure design. If side ports are utilized, additional design effort is required to design side ports and winding patterns around the side ports. As side ports are usually considered the weak link in current FRP vessels, (caused by weakening of the vessel when glass fibers are cut in manufacturing the side port hole) the initial UHP vessel design utilized end ports where the high pressure feed and concentrate connections are located in the vessel end plate as shown in Figure 10.

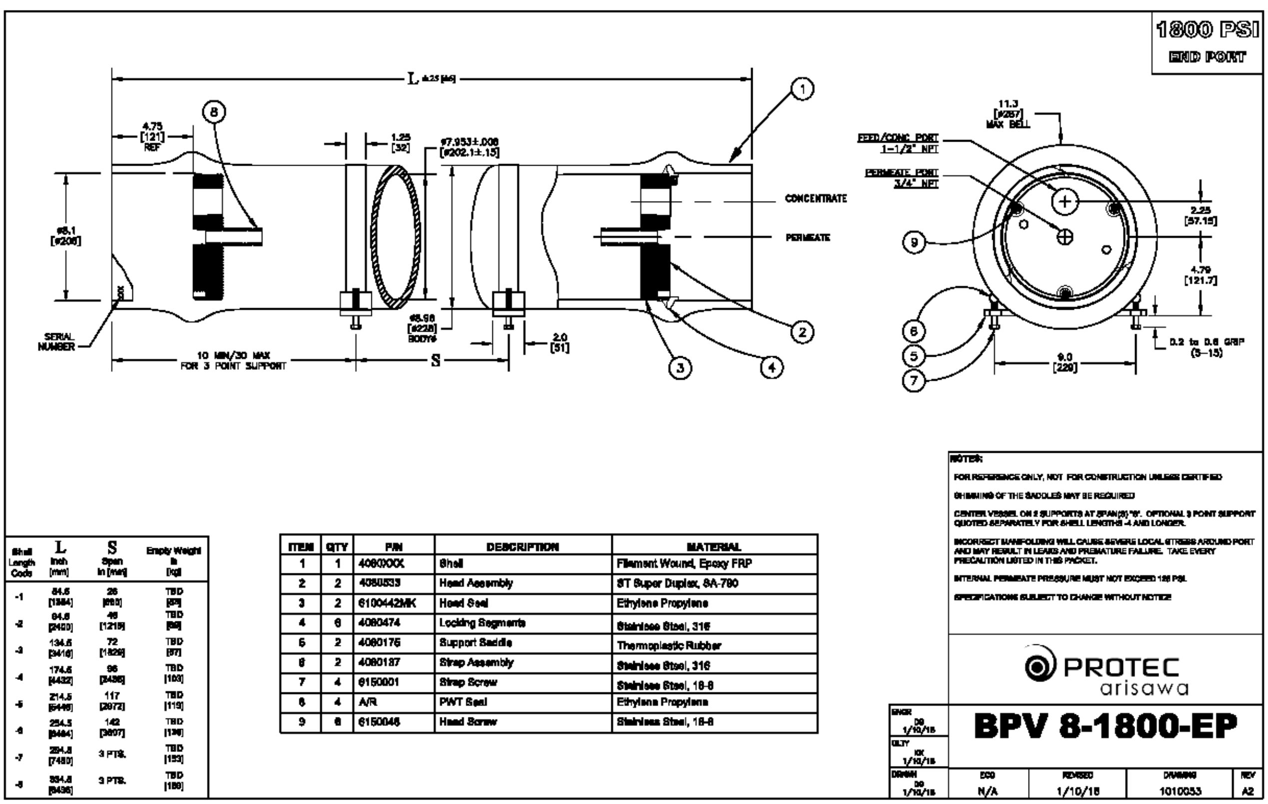


Figure 10: 1800 PSI Vessel

The Hoop and Longitudinal stresses are accommodated in the design of the FRP vessels by controlling the winding angle of the fiber strands during winding. By orienting the angle of the glass fibers to the longitudinal axis of the vessel (approximately 45 – 55 º) optimization of the vessel design can be achieved.

Hoop Stress is generated around the circumference of the vessel wall due to radial forces on the inner surface of the vessel wall.

Hoop Stress is determined by the following simple equations for thin-walled vessels.

$$S_H = (P \text{ X } D)/(2 \text{ X } WT)$$

Longitudinal stress in pressurized vessels is that stress produced parallel to the center line of the cylinder.

$$S_L = (P \text{ X } D)/(4 \text{ X } WT)$$

Where S_H and S_L are Hoop and Longitudinal Stress, P is pressure, D is inside diameter of vessel and WT is wall thickness. To maintain the same allowable stresses in the vessel, when the pressure is increased and vessel ID is constant, one builds a vessel with thicker walls.

The end closure stress calculation is based on the stress required to remove a cylinder of the vessel defined by the ID of the vessel at the bell end, the depth of the retaining ring groove and the length of the end margin (length between end of vessel and retaining ring grove). This so-called end margin "tear out stress", as shown in figure 11. This stress can be calculated as follows:

$$S_{TO} = \frac{\underline{(P \text{ x } \pi \text{ X } D^2/4)}}{\Pi \text{ x } L \text{ X } Dr}$$

Where P is pressure, D inside diameter, Dr diameter of insert ring grove and L is end margin. As seen the length of the end margin can be increased with increased pressure to maintain allowable stress.

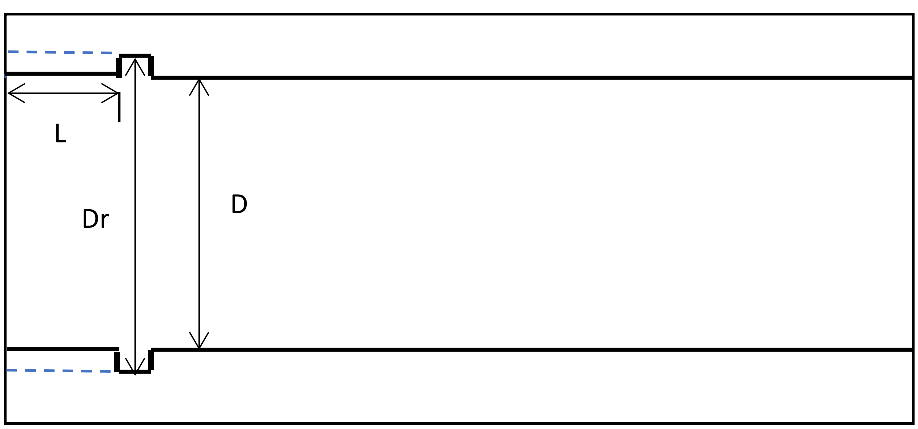


Figure 11: End Closure "Tear Out Stress" Showing Retaining Ring Groove / End Margin Length

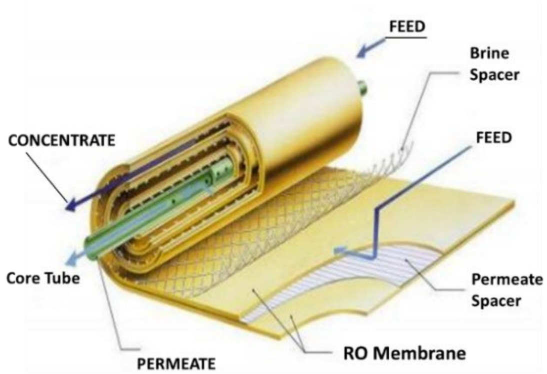
In summary, designing a FRP pressure vessel without side ports, capable of withstanding high pressure is quite straight forward requiring only thicker walls and a combination of longer end margin and retaining ring groove depth. Note that glass fibers are not cut in forming the retaining ring groove. Instead, a plastic and disposable groove former is placed on the mandrill and the vessel is wound around the groove former. However, it is important that the fibers are placed in correct location at the groove to maintain integrity of the vessel.

The current version (2019) of the ASME code Section X for FRP vessels covers vessels with design pressure up to 2,000 PSI. Protec-Arisawa has designed, manufactured, and tested the vessel according to the code requirement including burst pressure of a minimum of 6 times design pressure. The current high pressure product line includes vessels with design pressure of 1200, 1500, 1800 and 2000 PSI.

Ultra-High Pressure RO Elements

Operating a RO element at ultra-high pressures (UHP) is a major challenge for products comprised of plastic-based materials. This is due to the creep and compression that happens in plastic materials which is greatly accelerated by the elevated pressures and temperatures. In terms of the specific issues with the components of a spiral wound RO element, key considerations for operation at UHP are listed in Figure 12.

New UHP RO elements have been developed to address these issues, often implementing the use of more robust materials. Not only is it expected that these elements will run at extreme temperatures and pressures, but they will also encounter high fouling water conditions. This is because many of the applications of MLD and ZLD are for industrial wastewaters. These are often high in organic composition and scale potential, and have multiple pretreatment steps which may not also operate in an optimum manner.



Spiral Component	Nature of Issue
Membrane	Compaction
Feed Spacer	High fouling feed water
Permeate Spacer	Concern with collapse of channels, embossing of membrane
Core Tube	Collapse
Leaf Adhesive	Prevention of osmotic blisters
Outerwrap	Higher Stresses due to dP, harsh environment
ATD	Higher Stresses due to dP, harsh environment

Figure 12: Depiction of membrane embossing into the permeate support.

The new PRO XP1 element was developed to operate at pressures up to 1800 PSI (124 bar); however, there are trade-offs on allowable pressure as temperature is increased. This is shown in Figure 13. The rejection of the element is 99.8%, when measured at typical SWRO testing conditions, 32,000 ppm NaCl and 800 PSI.

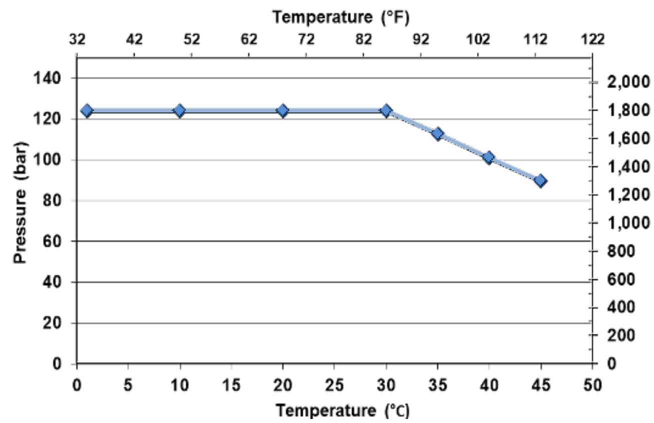


Figure 13: Pressure limitation for UHP RO element as a function of temperature

This UHP RO element was tested in the laboratory with both synthetic saline solutions and with industrial wastewater samples. The first test was with a standard sodium chloride feed using a 4" diameter PRO-XP1 4040 element operating at a fixed 1740 pai (120 bar), where the concentrate is recycled, but the permeate is removed. The results in Figure 14A show the variation of permeate flux and quality over a range of reject concentrations from 66,000 mg/l TDS to 126,000 mg/l TDS. As expected, the flux drops as the feed salinity rises. This is a result of the osmotic pressure increasing and NDP decreasing. The decreasing water flux and increasing feed salinity will cause the rejection of the membrane to drop. For the feed salinity range teste, the flux dropped from 14.8 to 1.2 gfd (25 to 2 lmh), and the permeate concentration increased in conductivity from 1 to 5 mS/cm.

The second study was carried out on a water sample from a site looking to implement UHP RO to maximize water recovery and minimize their waste (i.e. MLD). This water was primarily composed of sodium, chloride, sulfate, metals and hardness. After softening the water, the feedwater to the RO was composed of sodium, chlorides, sulfates and low levels of hardness and a variety of metals. The water was treated in two phases, one phase that concentrated the solution from 30,000 ppm TDS up to 64,000 mg/l TDS. This concentrated solution was then treated a second time by the PRO-XP1 ultra-high-pressure RO element at 1740 PSI (120 bar). The resulting performance is shown in Figure 14B. The solution was concentrated from 64,000 mg/l TDS up to 148,000 mg/l TDS. Over this range, the permeate varied from 0.1 mS/cm at the start of the trial to 1.6 mS/cm at the highest feed concentration. The flux started at 14.8 gfd (25 lmh) at the lower concentration and dropped to 3.0 gfd (5 lmh) at the highest feed concentration. Both trials demonstrated that it was possible to achieve brine concentrations well in excess of 120,000 mg/l TDS with PRO-XP1 element.

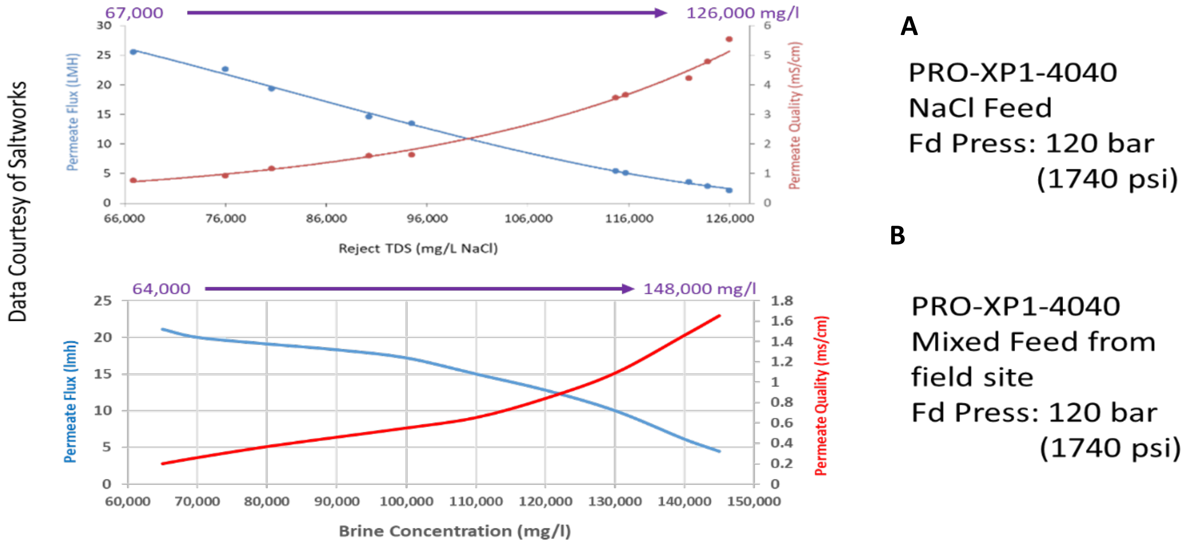


Figure 14: Flux and permeate conductivity values as a function of the increasing feed TDS. A) NaCl synthetic solution, and B) Softened Industrial Wastewater

Despite the improvements in the design and materials used in present day UHP RO elements, inevitably, they will undergo compaction and there will be embossing of membranes into the permeate spacer channels at this extreme conditions. The changes to the membrane and element have a big impact on performance. In particular, the flow from the element (at fixed pressure) will decrease over time when exposed to such conditions.

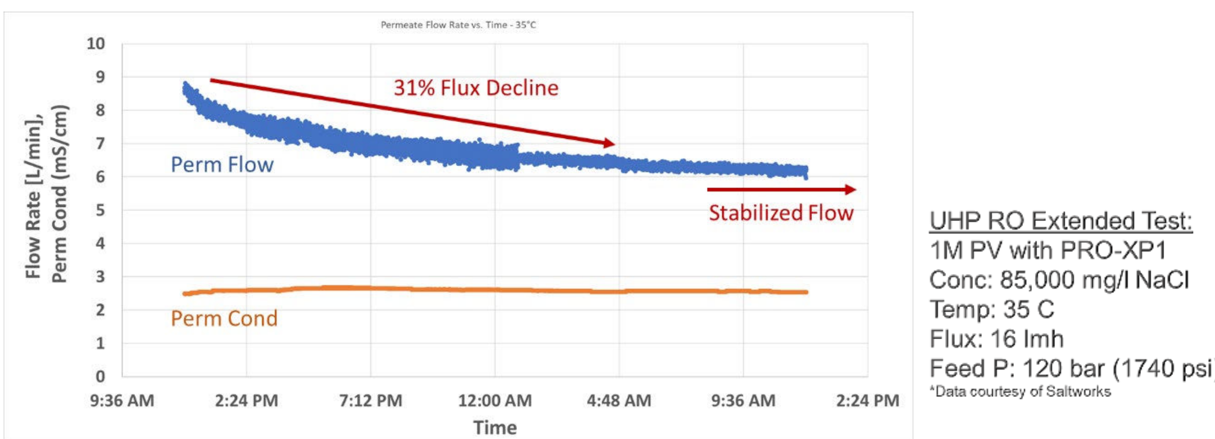


Figure 15: Permeate flow and conductivity trends as a function of operation time at UHP

An example of this is shown in Figure 15, where a PRO XP1 element is operated with a solution of 85,000 mg/l NaCl. Both the permeate and the brine were recycled back to the feed so that the feed concentration was held stable throughout the test. Temperature was controlled to 35 C. From the data in Figure 15, it can be seen that the membrane flux declined by 31% during the first 24 hrs of operation. After that "break-in" period, the flux rate stabilized. During this operation time, the permeate conductivity went up slightly, in a manner that corresponded with the flux loss. This can be attributed to the lower flux rate, or water transport rate. Lower flux rates will always result in lower rejection, due to the smaller amount of water present to dilute the salt that permeates the membrane.

Despite the complexity and added costs of UHP RO, the benefits for MLD and ZLD are significant. As explained earlier, it is common to use RO staging to treat lower salinity waste streams to increase the recovery of water and minimize the brine wastewater. A typical example of a MLD system operation is shown in Figure 16. This graph shows the feed pressure for RO stages and the requisite specific energy required for the various concentration steps of a treatment process. For a brackish wastewater with initial concentration of 1800 mg/l TDS, the blue lines depict the various concentration steps achieved in a multistage RO process and the corresponding specific energy requirement. Four stages of RO are required to increase the brine to 55,000 mg/l TDS. In the past, this brine may then be sent to an evaporator to reach ~200,000 mg/l TDS. However, the specific energy consumption for this last step is enormously high, 22 kwh/m^3. With new UHP RO elements, it is possible reach ~120,000 mg/l TDS. As can be seen, the specific energy consumption for UHP RO is less than half the energy consumed by the evaporators. In some cases, designers would also like to further concentrate seawater for recovery of valuable minerals in seawater. The violet line shows the how SWRO + UHPRO can be much more energy efficient that SWRO + Evaporation. Thus, UHP RO has great promise to increase recovery of valuable water resources more economically, while minimizing the volume of wastewater without the high cost of evaporation technologies.

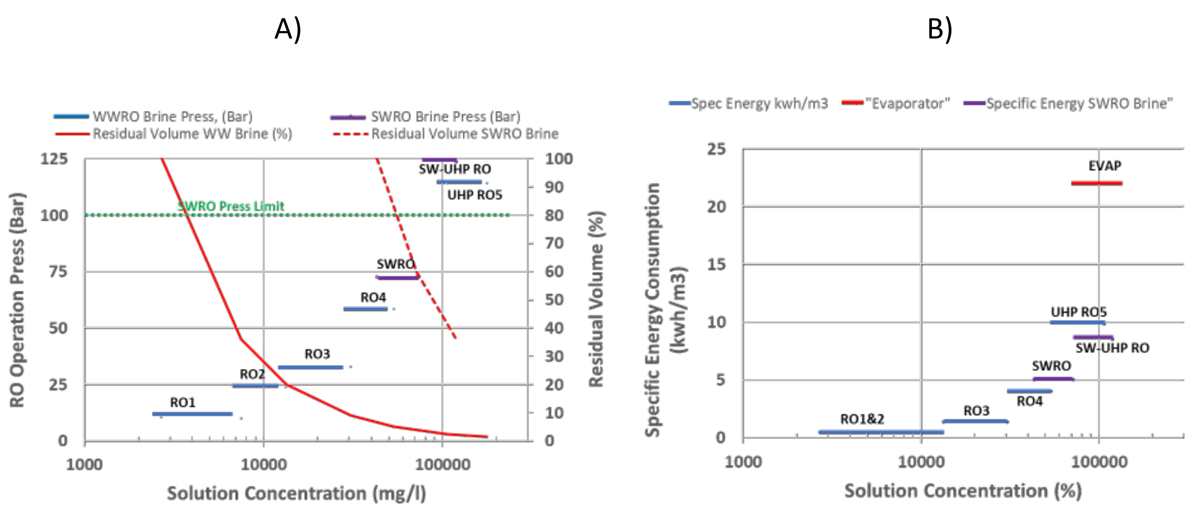


Figure 16: Pressure (A) and Specific Energy Consumption (B) for the super concentration of brackish wastewater or seawater

Ultra High Pressure Grooved Couplings

Most seawater-reverse-osmosis piping system joints comprise grooved flexible couplings in duplex or super duplex material of construction.

This joint system consists of an outer peripheral surface grooving of the ends of the two pipes to be joined and a hydraulic seal provided by a hollow ring gasket which seals at both pipe outer surfaces, distal to the coupling housing engagement grooves. Two, half-coupling housings lock the two pipes together via peripheral keys located outboard on each housing half-coupling, fully engaging the coupling groove on the adjoining pipe sections. See figure 17 below:

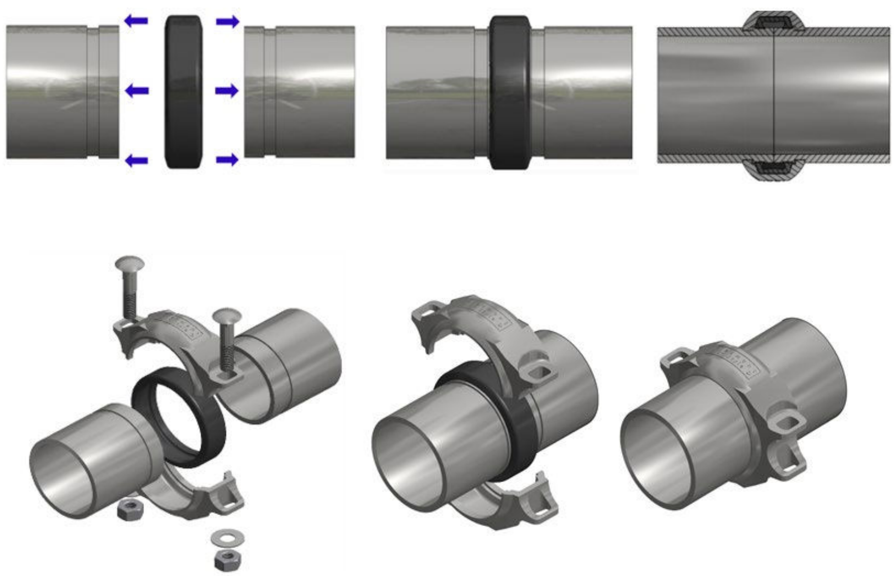


Figure 17: Breakdown of Grooved Flexible Couplings in Reverse Osmosis

Grooved flexible couplings have been the preferred type of connection for inlet and outlets of membrane pressure vessels from the beginnings of desalination by reverse osmosis in the 1970's.

As shown in Figure 18, this type of connection provides both axial and angular flexibility:

1- Axial separation between joined pipes allows expansions and contractions at the joint during normal operation of a reverse osmosis system.
2- Angular deflection tolerance between the joined pipes is also imparted by the pipe-groove width being greater compared to the coupling key width, the same provision which allows the axial compliance.

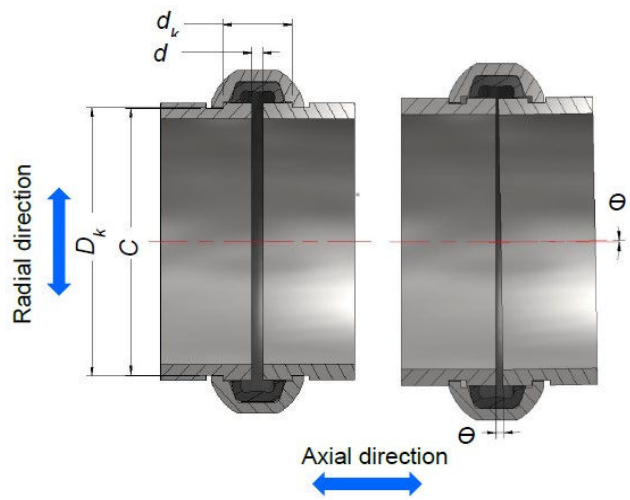


Figure 18: Pipe End Separation Gap and Angular Deflection

Grooved flexible couplings have been used for more than 100 years, traditionally, the most common application for these couplings has been fire protection systems. When reverse osmosis was developed in the 1970's, the material available for grooved flexible coupling was painted ductile iron and subsequently 316 stainless steel. Challenges faced with coating integrity and in general low resistivity to the highly corrosive environments in which these couplings operate in desalination plants, lead to the development of the first duplex grooved couplings about 20 years ago by Piedmont founder and incorporation of Piedmont Pacific as a grooved coupling manufacturer, specialized in highly corrosion resistant materials, and high pressure applications, such as sea water and brackish water reverse osmosis.

Since the first duplex and super duplex couplings were developed for 1000 PSI and 1200 PSI applications, in the early 2000's, an ever-increasing percentage of sea water reverse osmosis plants have been using these specialized couplings.

Another change that has started to happen more recently is the use of duplex and super duplex hardware (bolts, nuts and washers) together with duplex or super duplex coupling.

This is most critical in high and ultra high pressure applications, where corrosion cracking and crevice corrosion is common and very dangerous in couplings and any bolts in this environment.

Due to issues of availability, long manufacturing lead times and higher cost, duplex bolts, nuts, and washers were long considered impractical by the industry. Recently, a change is taking place and duplex/super duplex hardware has become the gold standard of hardware material for grooved couplings in this industry. Being used in an ever-increasing percentage of sea water reverse osmosis plants worldwide.

SS316 bolts   Duplex bolts

Figure 19: 316 stainless steel bolts with crevice corrosion vs corrosion free duplex bolts

Similar to what has been registered in other applications with stainless steel bolt failures, due to chloride stress corrosion cracking, such as swimming pools [3,4], oil & gas offshore plants piping and valve equipment [5,6], among others, the desalination community has realized the inadvisable risk associated with using lesser materials than duplex bolts in these critical applications.

The high risk of this type of failures in desalination plants and especially high-pressure applications is what has led to the development of a special bolt design by Piedmont, in duplex and super duplex material, following the highest design and manufacturing quality standards.

Another area commonly affected by crevice corrosion in these applications are the pipe ends, near the groove. The use of pipe materials with high crevice and pitting resistance (PREN > 40), such as super duplex 2507, as well as a machined and passivated outer surface of the pipe in the area where the gasket seats, help minimize risk of crevice corrosion in desalination plants. [7,8].

Also, less sulfur % contamination has been determined to be beneficial against gasket seating area pipe crevice corrosion [8,9]. Therefore, it is especially advisable to assure use of peroxide-cured EPDM gaskets instead of sulfur-cured EPDM gaskets in these corrosion prone joints.

Groove Coupling Design for Higher Pressures

From the outset of desalination by reverse osmosis, most systems have operated near 1,000 PSIG, with operation at more than 1,200 PSIG extremely rare.

Now along with the need to operate reverse osmosis systems at greater recovery and pressures, the need has evolved for new flexible grooved couplings, along with new membrane elements and pressure vessels, rated for those greater operating pressures.

The mechanical design of a duplex grooved flexible coupling operating at a high pressure is based on the AWWA C606 and ASTM F1476 standards for coupling specifications and ASTM A995 with respect to duplex and super duplex materials.

The rating of high pressure couplings like these is based on cut grooved Schedule 40S (or heavier) pipe for Style S (1500 PSI) couplings and Schedule 80 (or heavier) for Style H (2000 PSI), according to ANSI/AWWA C606-2011 specifications, made of special alloys as per ASME B31.1 standard.

Key factors to consider in the design:

Internal Sourced End Load:

The coupling keys and pipe groove bearing walls are subjected to pressure thrust, commonly known as end load, resulting from internal pressure in addition to external piping forces. At high working pressure, joined pipe sections of a flexible coupling joint will move apart axially to the maximum allowable pipe end separation gap because of the thrusts exerted by end loads. The bearing wall of the groove is pulled against the inside face of the coupling key preventing pipe separation (Fig.20):

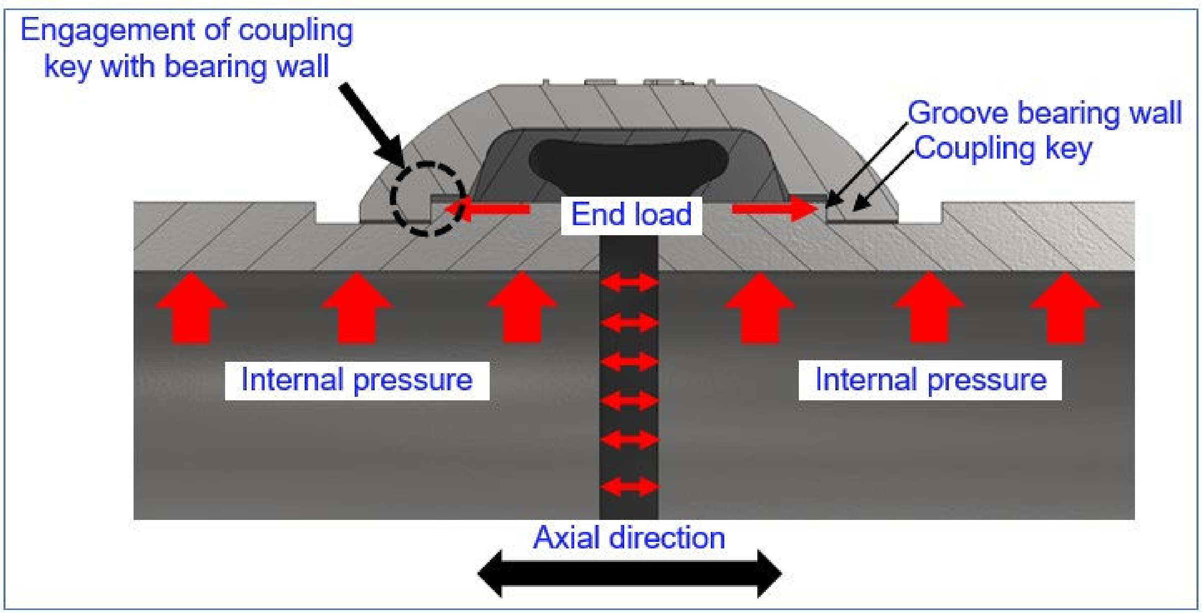


Figure 20: – Coupling key engagement

The **end loads,** so denoted, are the maximum total loads from all internal and/or external forces, to which the flexible coupling joint should be subjected under working conditions:

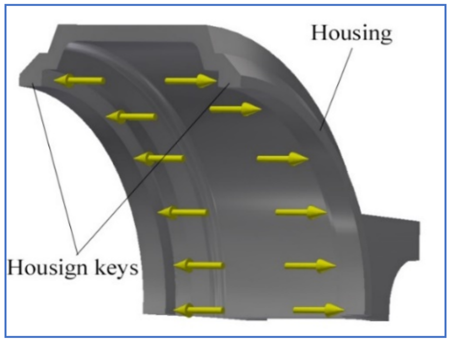


Figure 21: End load acting on coupling keys

The internal sourced end load (*F*) is a function of pipe's outer diameter and the applied hydrostatic pressure, which can be calculated as:

$$F = \frac{\pi}{4} \times OD^2 \times P$$

Where: *F* = end load (lbf); *OD* = pipe outer diameter (inch) and *P* = internal pressure (PSI).

<u>Groove bearing wall limit:</u>

The current groove system (as per AWWA C0606) strength is a limiting variable in the design of a coupling.

Too much contact pressure will deform the pipe groove bearing wall, as well as the coupling's key.

See figure 22 below with a graph of the contact pressure at the pipe groove originated by the end loads, at the rated pressure, of Style D couplings (1200PSI rating; blue dotted line), and Style H (2000 PSI rating; orange dotted line):

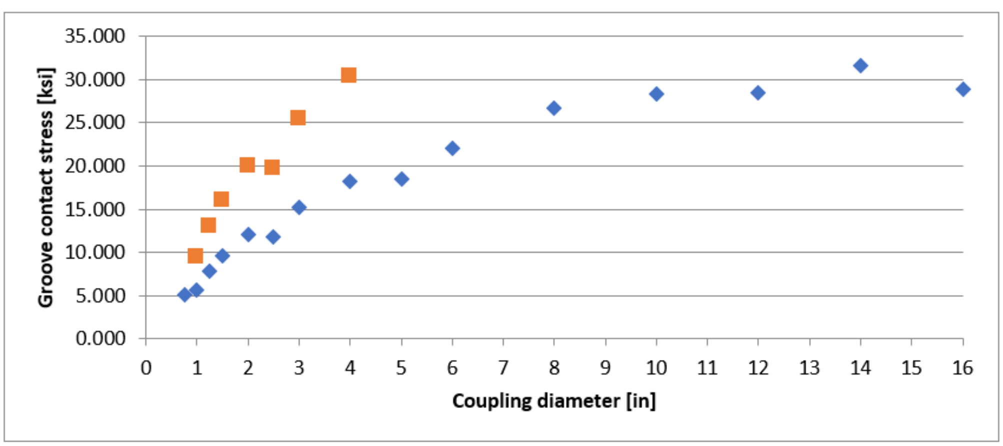


Figure 22: Contact pressure at pipe groove – 1200 psi vs 2000 psi

Note the asymptotical character of the blue data points at about 30 ksi (206 MPa). For practical reasons this can be considered the not-to-exceed threshold. Note also that 316L piping have minimum yield strength of 25 ksi (172 MPa). So, the ultra high pressure coupling (Style H, orange shown above) should therefore only be used with duplex (yield strength of 65ksi (448MPa)) pipes or stronger, of Schedule 80s or heavier.

Apart from strength limits, elastic and plastic displacement values are also a key parameter to follow, in order to prevent the coupling groove key to bend and disengage from the pipe groove once installed and pressurized.

In summary, designing a duplex grooved flexible coupling for ultra high pressure, requires a special design with thicker walls and stronger bolts, ideally in duplex material. Also, special restrictions apply to the material, thickness and surface finishing of the grooved pipes being connected, to ensure that the pipe joint as a whole can resist these ultra high pressures and corrosion risks are minimized.

Piedmont has designed, manufactured, and tested the ultra high pressure grooved couplings according to ASTM 1476 code requirements, including burst pressure of a minimum of 3 times design pressure. The current high pressure product line includes couplings with design pressure of 1,200, 1,500 and 2,000 PSIG. See figure 23 below:

Figure 23: 1500 psi couplings (Style S) and 2000

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