EXTENDING THE LIMITATIONS OF REVERSE OSMOSIS MEMBRANES FOR RECLAIMING CHALLENGING WASTE WATERS

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ABSTRACT

As RO membranes are increasingly used to treat more challenging and unconventional industrial waters, there is a need for new RO membranes that can handle more extreme conditions. Specifically, new applications require RO membranes that can operate beyond normal limits of temperature, pressure, and salinity. In response to these challenges, RO membrane manufacturers have developed new materials of construction and employed new element designs that allow operation at these relatively extreme conditions. These new membranes can treat waters above the typical limit of 45 C, all the way up to 90 C. They can also be used to push past the typical pressure limit of 1200 psi to as high as 1800 psi. These membranes are being used in a range of applications from high temperature industrial laundry waste to high salinity zero liquid discharge. This presentation will show the evolution of the new membranes and their limits relative to the existing membranes widely used in many standard water treatment applications. The presentation will analyze design and operating data from pilots and systems using these membranes. The analysis will help users understand the unique challenges associated with operating at extreme conditions and provide examples of actual applications where these membranes are piloted or used in full scale operations.

1. INTRODUCTION

1.1. Background

Reverse osmosis (RO) is a pressure driven process that is commonly used, and is the leading standard, for desalination when it comes to applications such as process and potable use or reuse. With a growing demand for freshwater around the world, stricter regulations, and environmental factors, treating and reusing wastewater has gained more attention. It is estimated that 18.5 trillion US gallons of wastewater is generated in North America of which only 3.8% is treated and used.[1] Thus more recently, RO has been used in various other applications including selective separation, purification, and concentration.[2] Still, conventional membranes came with pressure and temperature limitations that restricted their ability to treat a broader range of applications. Typical operating limits for commonly used membranes are temperatures around 113°F (45°C) and pressures up to 1200 psig (8.27 MPa) for seawater applications.

Some of the main challenges for membrane manufacturers to consider when treating challenging industrial streams include overcoming higher osmotic pressures or driving pressures when TDS exceeds 60,000 mg/l, membrane deformation or degradation when operating at extreme temperatures and pressures, fouling and scaling potential limiting the recovery, and brine management to reduce overall processing costs. However, further advancements and improvements in RO technology including membrane material, module and process design, and energy recovery has opened doors to treat more challenging wastewaters and address the challenges associated with the treatment of these unique streams. Specifically, new, more robust element construction allow designers to push beyond the normal limits of temperature and pressure. One such element allows for operation at temperatures up to 194°F (90°C); while a second ultra high-pressure RO (UHPRO), can concentrate the total dissolved salts (TDS) up to 120,000 ppm (12%) while operating at pressures up to 1,800 psi (124 bar).[3] These unique elements can be used to increase the overall efficiency of the treatment facility by reducing the cost of brine disposal and maximizing water recovery. This paper will review the evolution of membranes to meet these challenges as well as review a few case studies from operating pilots and full-scale systems showing performance and best practices of these new technologies.

2. APPROACH

2.1 Research and Development

The construction of an RO element consists of a permeate core tube, membrane leaves, glue, permeate carrier, and feed/brine spacer. The membrane leaves further consists of a composite of three layers: a semipermeable polyamide membrane skin layer formed on top of a polysulfone substrate that is further cast onto a non-woven polyester fabric, see Figure 1.

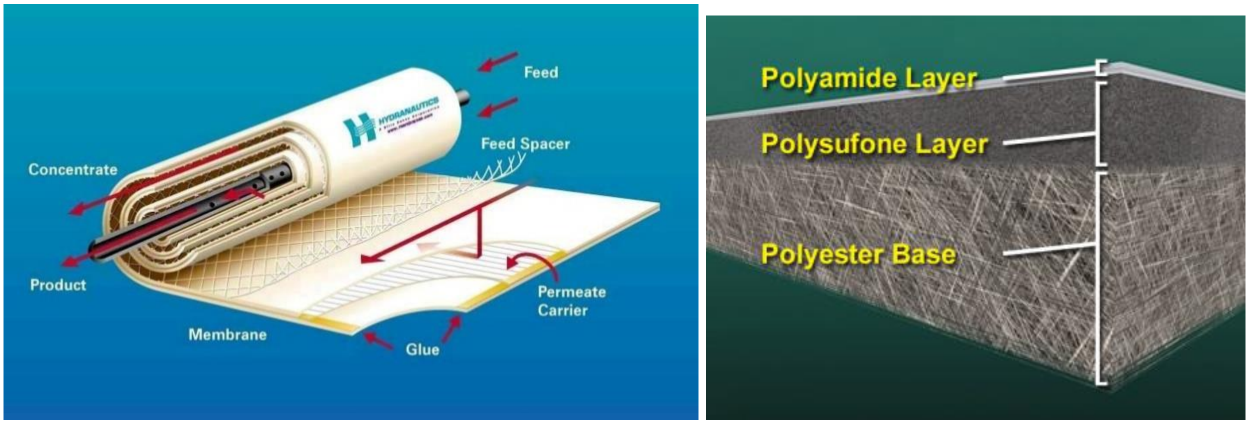


Figure 1: RO element and membrane construction.

As noted earlier, different materials of construction (MOC) within the standard RO element configuration limit the maximum temperature and pressure to 113°F (45 °C) and 1200 psi respectively. Exceeding these limits can create the potential for sudden mechanical failure or a gradual flux loss due to compaction (physical compression) of the membrane and its support layers. Unlike typical fouling, compaction is an irreversible phenomenon and is a function of both maximum operating pressure and temperature. In other words, the higher the pressure and temperature, the greater the compaction.[3] Studies in the lab evaluated different MOC to ensure the RO element would be able to effectively operate beyond typical limits as well as verify and optimize performance.

For the high temperature RO, it was noted that the maximum pressure limitation as a function of temperature drastically changed as temperatures exceeded beyond 113°F (45°C), see Figure 2. Additional testing further indicated that compaction occurred within the first 100 hours of operation when operating at higher temperatures before membrane performance stabilized, otherwise known as a break-in period. Being able to operate elements at higher temperatures would allow treatment of high temperature feed sources without the need for cooling through heat exchanger-ultimately saving in overall energy costs.

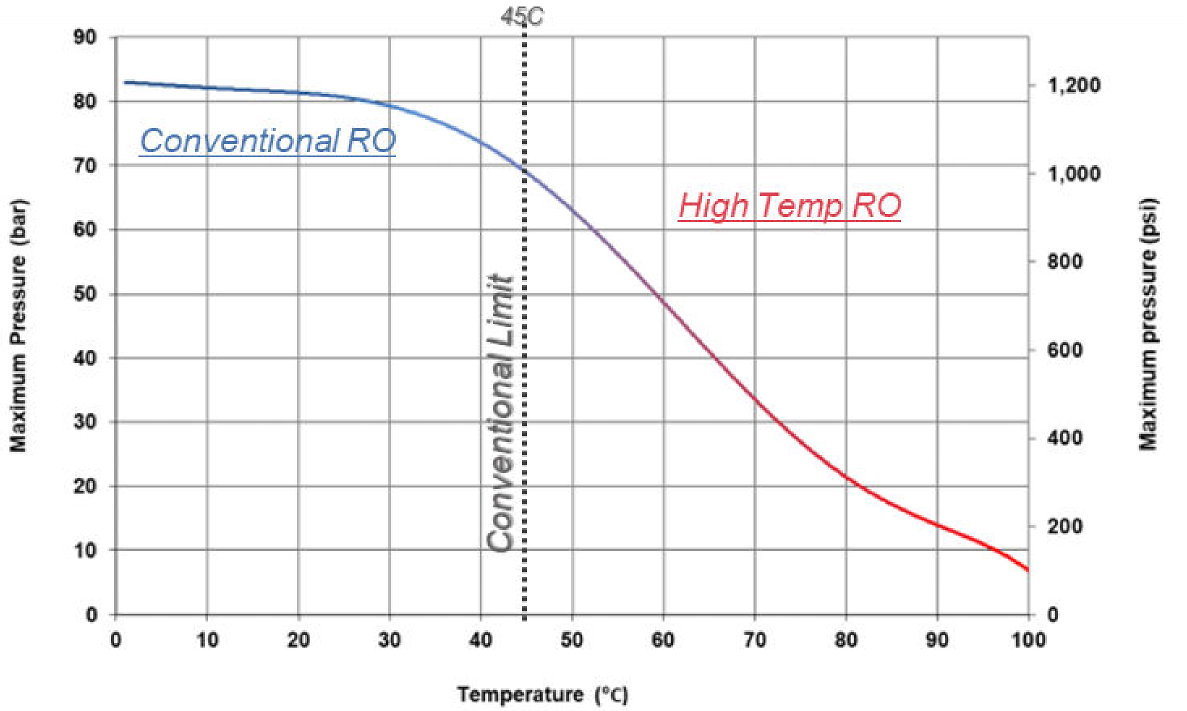


Figure 2: High temperature RO showing maximum applied pressure with increasing temperature.

For UHPRO, the elements could operate at much higher pressures when compared to conventional RO elements without damaging the membrane or compromising performance. Similar to the high temperature RO, testing a range of temperature vs. pressure revealed the maximum pressure of the elements in the UHPRO is also a function of temperature. In Figure 3, as operational temperatures increased past 86°F (30°C), the maximum applied pressure decreased; however, it remained higher than conventional elements even at 113°F (45°C). There was also immediate compaction observed with the first 24 hours of operation before flux stabilized. Being able to effectively increase the maximum applied pressure allows for more osmotic pressure to be overcome, especially in the last element, which can increase the permeate recovered as well as concentrate up solutions to higher percentages. The results shown in Figure 4 replicate the increasing feed salinity along the length of a pressure vessel from the lead element to the tail element. At the beginning of the test, when replicating the lead position, the element produced the highest flux of 25 LMH (14.7 gfd) and the best permeate quality of less than 500 us/cm. By the end of the test, the reject stream approached 126,000 mg/l of sodium chloride to simulate the osmotic pressure at the tail position, where the permeate flux decreased to 2 LMH (1.2 gfd) while the permeate quality increased to 5500 us/cm.[3]

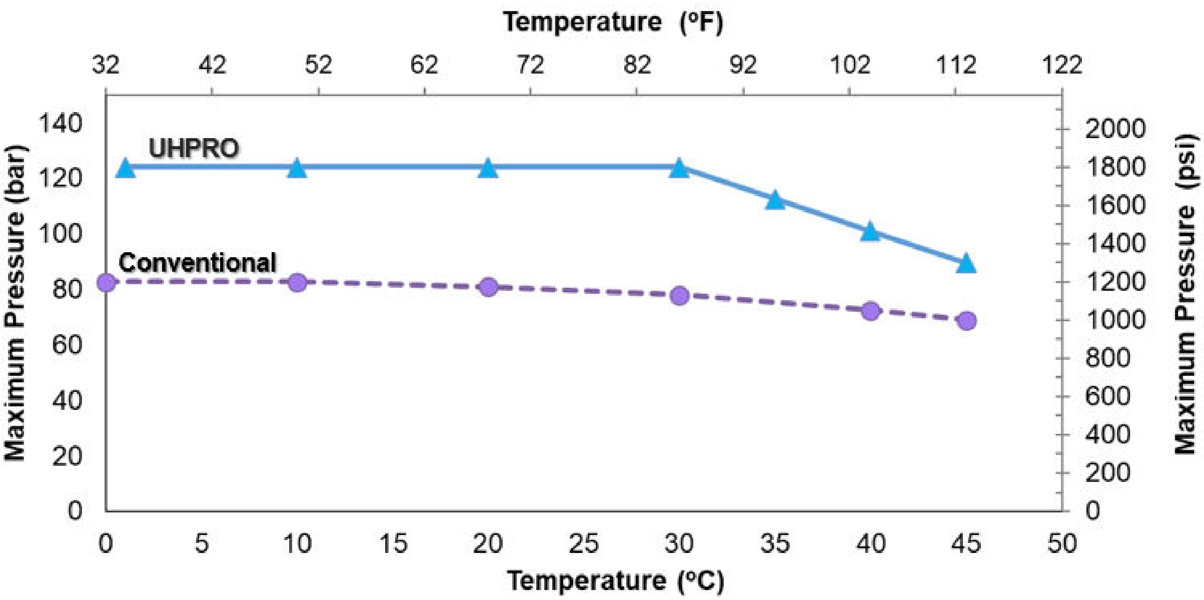


Figure 3: UHPRO showing higher maximum pressure capability than conventional RO elements.

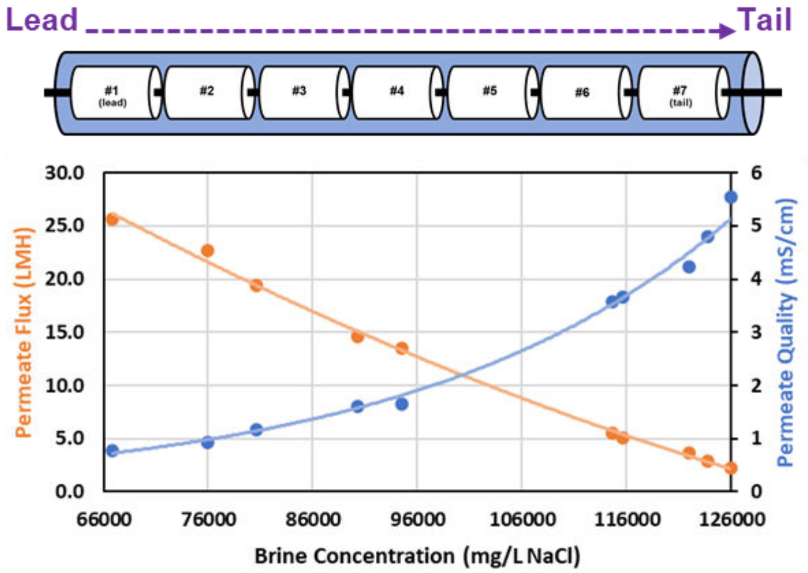


Figure 4: This graph shows the change in permeate flux and permeate quality as a function of reject concentration to understand how performance would change between the lead position and tail position within a 6 or 7 element pressure vessel.

2.2 Applications

With the improvements in RO elements to operate at more extreme conditions, this has opened doors to using spiral wound elements in a wider range of applications. Some applications where high temperature RO has been found to be a feasible and practical solution include:

- Laundry Wastewater
- Vapor Condensate Recycle
- Pulp and Paper Industry
- Mining Wastewater
- Produced Water for Oil Extraction
- Sugar Processing
- Waters in Hot Climates
- Annealing Baths

The UHPRO has been considered in other applications such as:

- Zero Liquid Discharge (ZLD) or Minimal Liquid Discharge (MLD)
- Cooling Tower Blowdown
- Textile Industry
- Tannery Wastewater
- Chemical Wastewater
- Flue Gas Desulfurization
- Coal to Chemical
- Brine Mining

The next section below will go through a couple of case studies where the high temperature RO and UHPRO have been used in various industries.

2.3 High Temperature RO Case Study

A laundry wastewater from a hospital setting typically sees temperatures of around 131°F (55°C). Additionally, typical treatment of laundry requires up to 6 Therms (175.8 kWh) per 100 pounds of laundry and 3 gallons of water per pound of laundry. A conventional RO system implemented to reclaim some of the wastewater required the laundry waste to be cooled by heat exchangers to 35C before being fed to RO system (Figure 7, left). By utilizing a high temperature RO, approximately 75 – 80% of the wastewater can be effectively recycled and reused without using a heat exchanger to reduce the temperature of feedwater to the RO (Figure 7, right). Review of the data shown in Figure 6 indicates the system performance to be very stable with normalized permeate flow remaining at an average of 70 gpm, differential pressure remaining unchanged at 10 psi, and TDS being reduced from 4000 mg/l to less than 50 mg/L (99.5% salt rejection at 55°C).

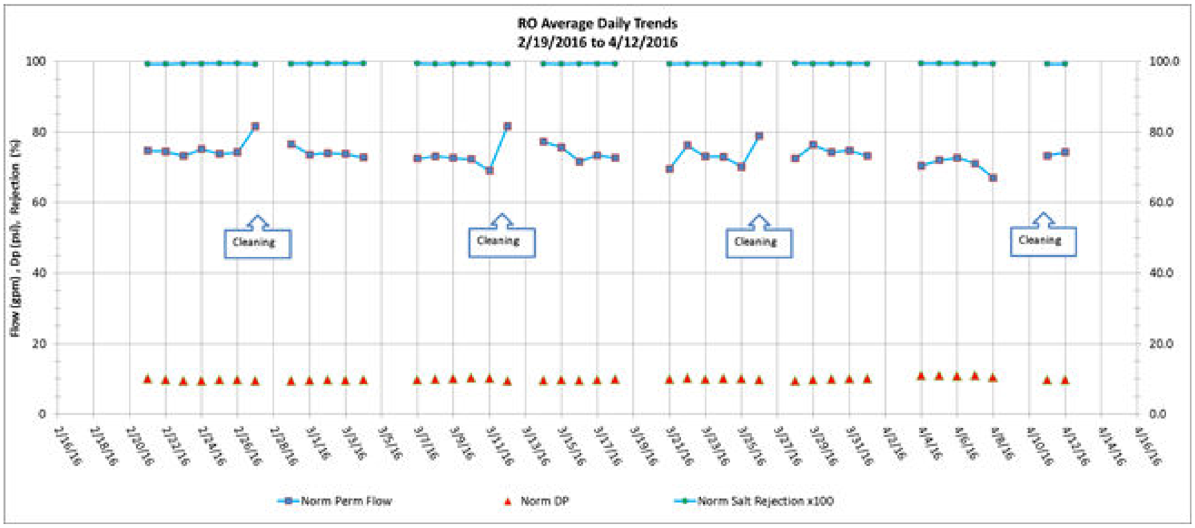


Figure 6: Normalized operating data from laundry RO system using high temperature RO.[4]

This treatment capability improved operating efficiency twofold: 1) natural gas and water could be conserved and reduce energy usage by as much as 70%[4] and 2) recycling the water further reduced the need for fresh water consumption down to 20 – 25%. Two general process diagrams utilizing a conventional RO versus a high temperature RO system can be seen in Figure 7. Reviewing the economics, utilizing the high temperature RO system provided an annual savings of $217,000 at this facility and provided a return on investment after just 2.4 years.

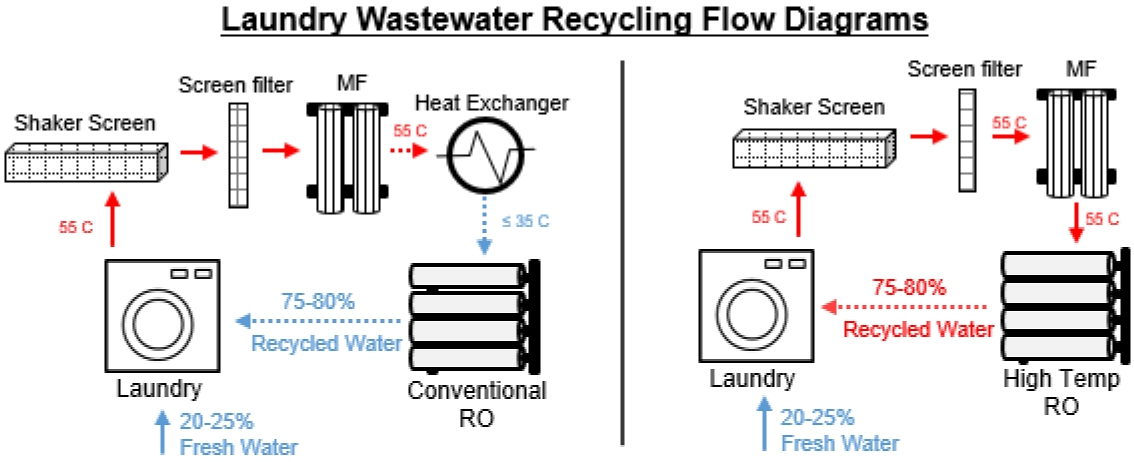


Figure 7: Process flow diagrams of treating a laundry wastewater with a conventional RO system (left) vs a high temperature RO system (right).

2.4 Ultra High Pressure RO Case Study

One of the major challenges for zero liquid discharge (ZLD) or minimal liquid discharge (MLD) processes is due to the high treatment cost of desalination. A simple, traditional ZLD system with conventional RO elements can be seen in Figure 8, which begins with a UF system to remove particulates followed by a 3-stage RO system before being sent to the evaporator. The 3-stage RO system can consist of a loose brackish RO element to concentrate up to 1%, followed by a tighter brackish element to concentrate to 4%, before finally entering a tighter RO element such as seawater to concentrate up to 8%. This would be the maximum concentration the elements could achieve due to the pressure limitations. This meant that more volume of water would need to be treated by the downstream thermal evaporator and crystallizer.

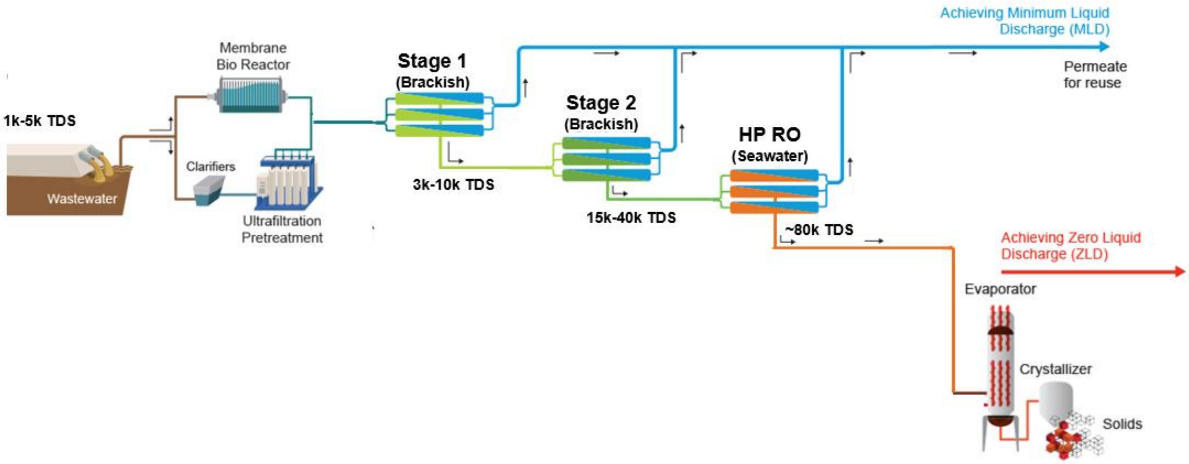
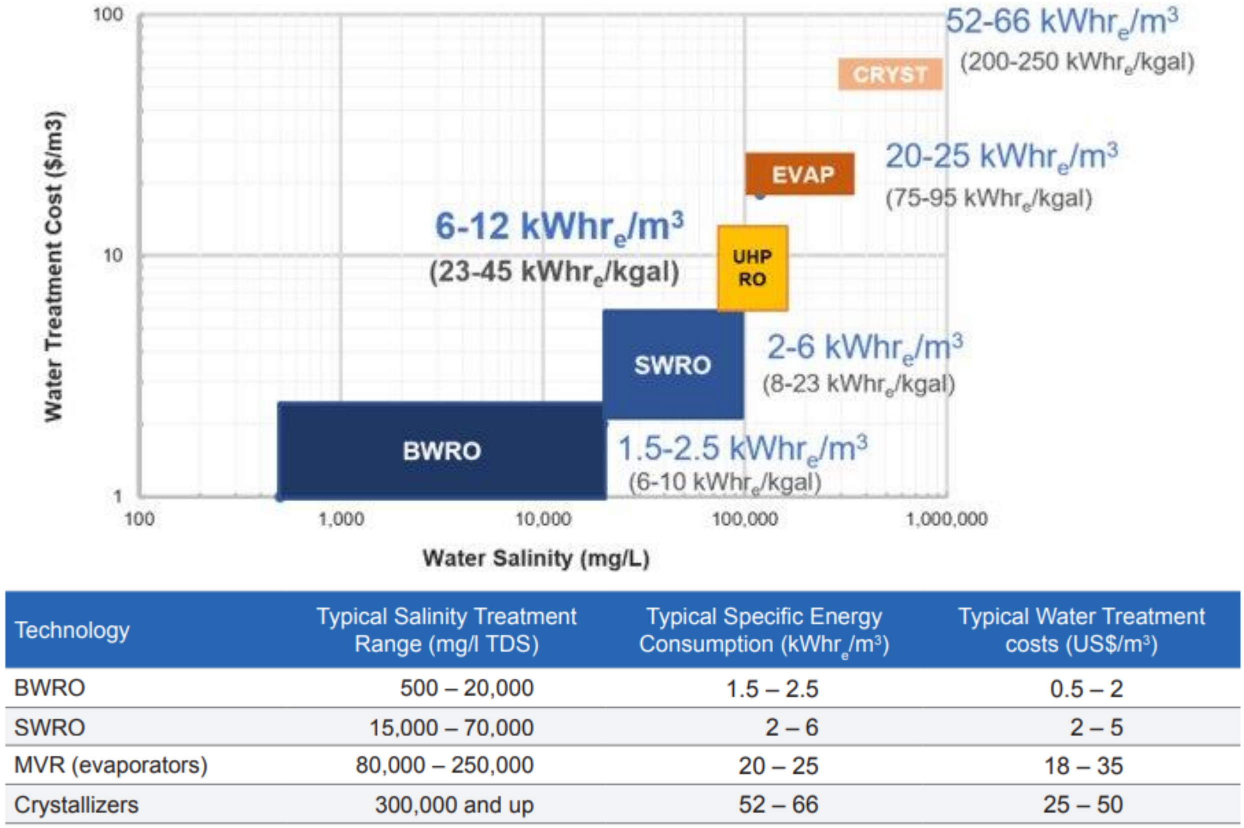


Figure 8: Conventional RO scheme for ZLD process showing maximum TDS concentration up to 8%

It is well understood that the evaporator and crystallizer's are very expensive processes and thus, there has been a growing application of ultra-high pressure RO (UHP RO) which can operate above the 1200 psi (83 bar) limit of conventional SWRO membranes.[5] Figure 9 shows the difference in treatment costs for the various desalination technologies with the highest costs found downstream in the thermal processes.



Technology	Typical Salinity Treatment Range (mg/l TDS)	Typical Specific Energy Consumption (kWhr$_e$/m^3)	Typical Water Treatment costs (US$/m^3)
BWRO	500 – 20,000	1.5 – 2.5	0.5 – 2
SWRO	15,000 – 70,000	2 – 6	2 – 5
MVR (evaporators)	80,000 – 250,000	20 – 25	18 – 35
Crystallizers	300,000 and up	52 – 66	25 – 50

Figure 9: Cost of various desalination technologies relative the UHPRO.[5]

In one feasibility study, it was found that the evaporator accounted for 31% of the total power consumption and 39% of the total daily operational costs(Figure 8). By adding an UHPRO system as shown in Figure 10, the TDS could now be concentrated to 12%, which reduced the total water volume fed into the evaporator. This resulted in a 17% decrease in power consumption and 22% decrease in daily operational costs, see Figure 11.

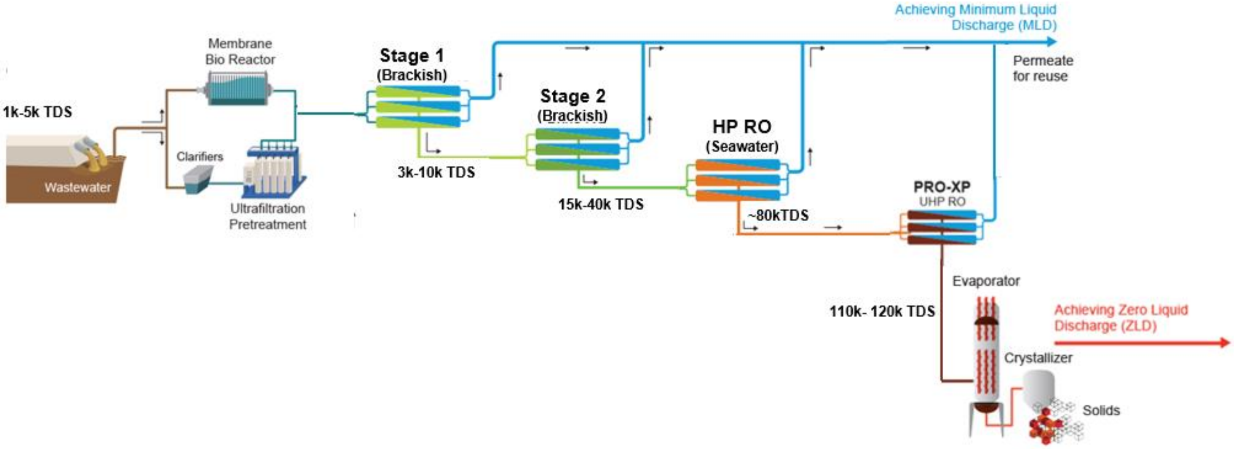


Figure 10: ZLD process with UHPRO showing TDS concentration up to 12%.

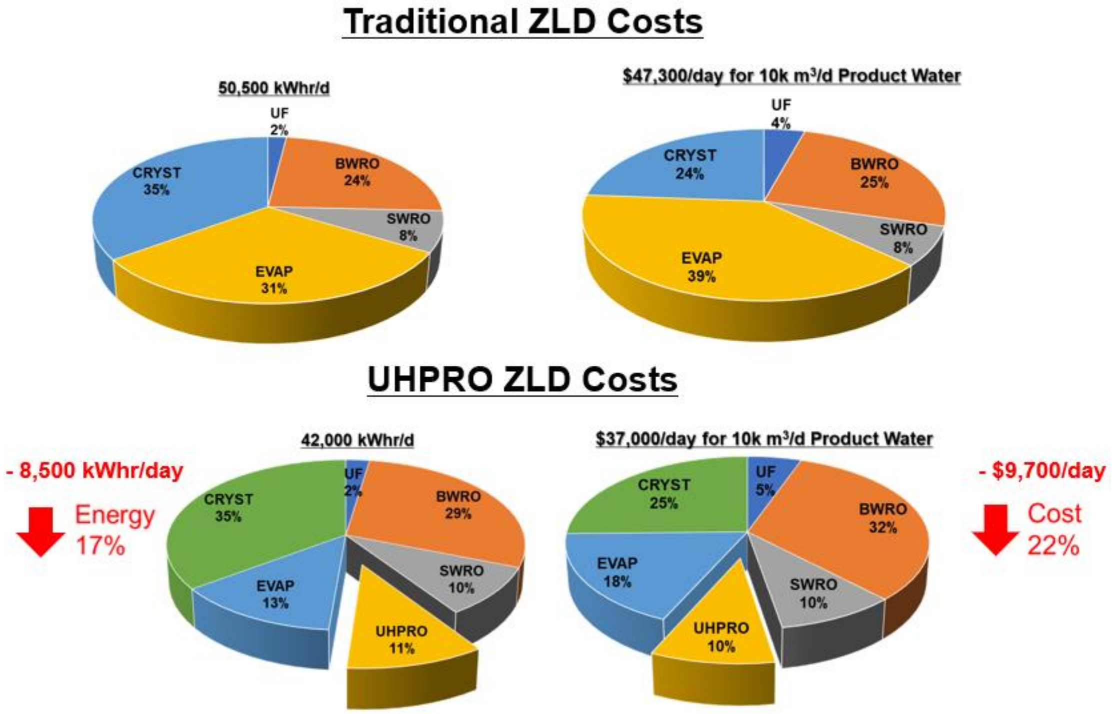


Figure 11: Operational cost savings of typical ZLD process without UHPRO vs. with a ZLD system with a UHPRO .

Looking at this more closely in a tannery wastewater application where feedwater TDS ranged between 53,700 – 60,000 ppm and COD around 3,100 mg/l, a conventional RO system recovered 65 -70% of the wastewater before being further treated by evaporator and crystallizer to produce solids. The challenges with using membranes to treat these highly contaminated effluents and achieve ZLD includes heavy fouling, frequent cleanings, solids disposal, and high operating and maintenance costs associated with the final thermal steps.[6] A pilot study was conducted with six UHPRO elements installed in two pressure vessels in series. The system operated at the maximum allowable pressure of 95 to 105 bar at 35 – 40°C for 8 months. The recovery targeted was close to 40% with fluxes around 11 LMH while consistently achieving TDS at 300 mg/l and COD's less than 30 mg/l. The overall impact reduced the flow to the evaporator and crystallizer by 40%. This eventually led to a full-scale tannery system being built that had an ROI of 3.6 months.

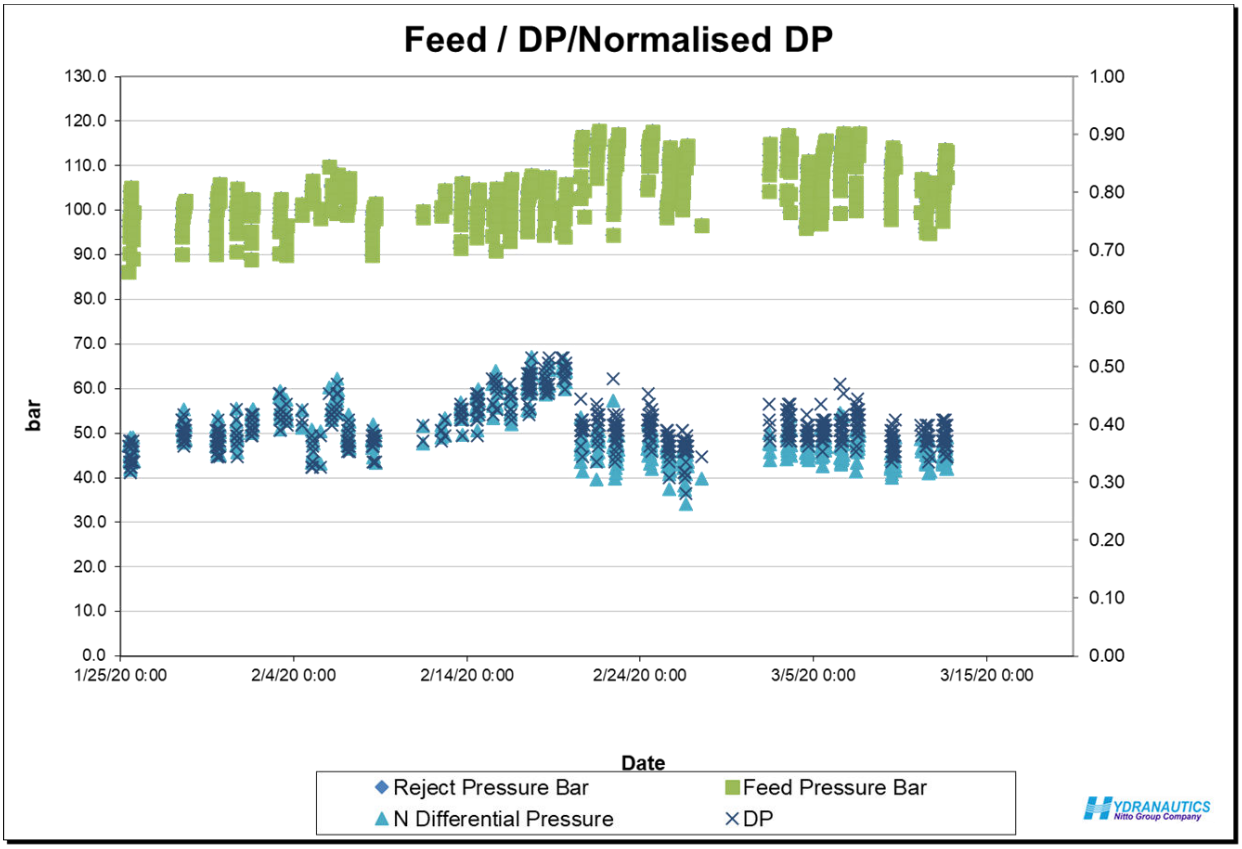


Figure 12: Normalized operating data using UHPRO to treat Tannery WW.

3. CONCLUSIONS

In recent years, water scarcity and stricter discharge regulations have become more demanding, which has increased the need to find novel solutions to lessen the environmental impact by numerous industrial users. With the development of the higher temperature and Ultra High-Pressure RO elements and systems, RO manufacturers have discovered a way to have a major environmental impact and lower operating costs when compared to other technologies. These RO technologies have shown to reduce overall energy usage from anywhere between 30% – 70% depending on the application and reduce water consumption by 25% from typical usage. Being able to treat these challenging wastewaters more economically and efficiently will allow cities and countries to conserve scarce water resources and further protect the environment.

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