BENEFITS OF USING ULTRA HIGH PRESSURES TO TREAT INDUSTRIAL WASTEWATER

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Abstract

Due to rising costs and scarcity of water, there has been an increase in demand to reclaim water. Additionally, with the introduction of new waste regulations and increased environmental awareness, various industrial applications are beginning to find unique ways to reduce the volume and impact of their contaminated discharge.

Reverse Osmosis (RO) manufactures have found that sites that replace traditional waste treatment strategies with Ultra High Pressure RO elements and systems, can significantly reduce both power consumption and waste discharge. An industrial manufacturing plant that produced waste high in Dimethylformamide (DMF) originally utilized a bioreactor waste treatment before discharging their waste. Due to tightening discharge concentration restriction from the city and the difficulties in maintain an aging system, the site deemed it necessary to replace their bioreactor system. An ultra high pressure reverse osmosis (UHPRO) system designed by Saltworks and equipped with Hydranautics PRO-XP1 membranes was deemed a suitable replacement. After 8 months of operation, the industrial manufacturing site saw a 72% decrease in electrical cost of their DMF treatment system and were able to reach a 83% total system recovery.

Introduction

Demand for water continues to surge even while the world experiences rising water scarcity. According to the United Nations Department of Economic and Social Affairs, it is estimated that by 2025 more than 1.8 billion people will live in areas plagued by water scarcity and an addition two thirds of the world's total population will live in water-stressed areas. While climate change does influence the world's growing water scarcity, it proliferated by inadequate treatment and reuse of wastewater. Globally, it is estimated that 359 billion m^3 of wastewater is produced per year, however only 11% of that is reused.

Singapore is a country with few natural freshwater resources (Singapore National Water Agency, 2022). In the past, Singapore relied heavily on importing freshwater from Malaysia. In the early 2000s, Singapore unveiled their NEWater wastewater treatment process whereby membrane technology would be used to reclaim fresh drinking water from wastewater streams. According to Singapore's national water agency (2022), reused wastewater now meets 40% of Singapore's water demands. By 2060, 55% of the country's water demand will be met using reclaimed wastewater. In Southern California, Orange County's Groundwater Replenishment System (GWRS) further treats the city's municipal waste stream before re-injecting the treated water into the groundwater basin (Orange County Water District, 2022). This system has allowed the city to reclaim up to 380 thousand m^3 per day of fresh water. In the past, water reclamation from highly contaminated industrial effluents has been limited or unimplemented due to multiple factors, some of which include: the price of water reclamation vs price of city water, limitations in available treatment technology, and less restrictive effluent treatment mandates. The present has forced a shift in the balance of the previously mentioned factors affecting industrial wastewater reclamation: rising water costs prompted by scarcity and stricter disposal requirements of certain industrial contaminants. New innovations in Reverse Osmosis (RO) membrane technology, allowing operation at previously inoperable ultra-high pressures, offer a solution.

Surpassing the Limits of Standard RO

Limits of Existing High-Pressure RO

The maximum recovery rate of a reverse osmosis system is dictated by two entities: the scaling tendency of the water being treated or the maximum operating pressure of the RO elements. The percent recovery of an RO system is calculated by dividing the recovered permeate water flow rate by the flowrate of the wastewater fed to the system multiplied by one hundred (**Figure 1**). As recovery of a system increases, the flow rate of the feed being treated decreases and the Total Dissolved Solids (TDS) of the brine increases. The higher the TDS of the brine stream, the greater the applied pressure required to overcome the average osmotic pressure between the feed and brine stream.

$$Permeate\ Recovery\ \% = \frac{Permeate\ Flow\ Rate}{Feed\ Flow\ Rate} \times 100\%$$

Figure 1. Calculation to determine the percent recovery of a RO system.

The maximum operating feed pressure of a standard high-pressure Sea Water Reverse Osmosis (SWRO) membrane element is approximately 83 bar (1,200 psi) at a temperature of 35°C or below. When treating a high TDS feed water like seawater or certain industrial waste streams, the maximum process recovery will be primarily gated by the standard SWRO element's maximum operation pressure.

Design Considerations for Ultra High Pressure (UHP) RO

A conventional spiral wound RO element is constructed with the following parts: a core tube, feed spacer webbing, RO membrane, permeate carrier, Anti-Telescoping Devise (ATD), and a Fiberglass Reinforced Plastic (FRP) shell (**Figure 2**). When a standard element operates at pressures outside of its maximum specifications, the structural integrity of one or multiple parts of the element may be compromised, resulting in irreversible damage, loss in performance, and a possible plant safety issue if it is not removed from the system. When designing an element that can exceed maximum sea water operation pressures, membrane manufacturers utilize appropriate materials and manufacturing techniques to improve the sturdiness of each component of the would be UHPRO element. Without this extra durability, the permeate carrier could collapse (**Figure 3**), the core tube could collapse (**Figure 4**), damage could be sustained to the external casing (**Figure 5**), and the thin membrane layer could compact to such a degree that operational permeate flux would be negligible.

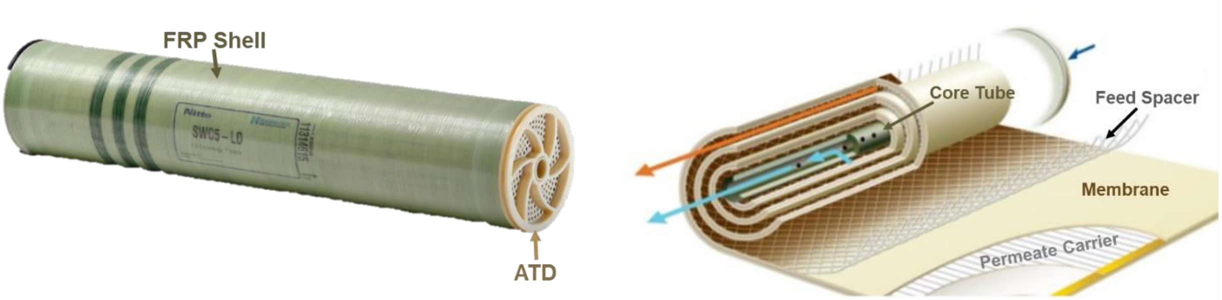

Figure 2. Anatomy of a conventional Spiral wound RO element.

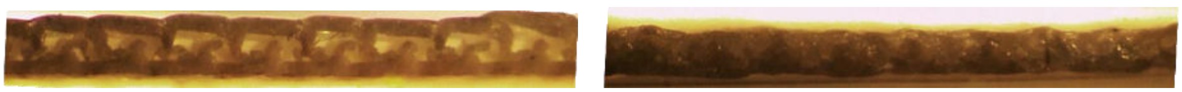

Figure 3. Cross section of the permeate carrier of a standard RO element (left). Cross section of the permeate carrier of a standard RO element after testing at higher than the standard maximum operation parameters (right). Notably, the channels of the permeate carrier of the tested element (right) have collapsed.

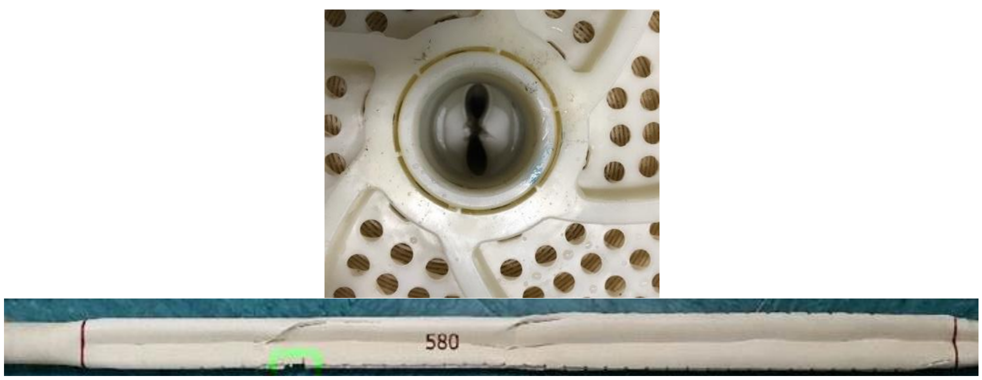

Figure 4. Core tube failure when exposed to higher than the standard maximum operation parameters as viewed in the complete element (top) and when removed from the element (bottom).

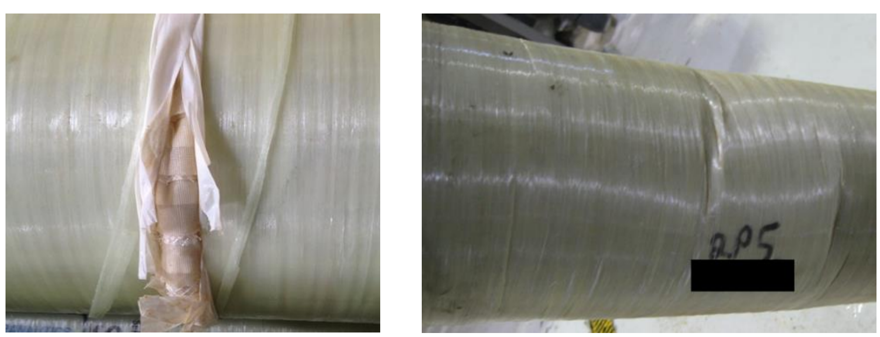

Figure 5. External element damage when exposed to higher than the standard maximum operation parameters.

Performance of the UHPRO element PRO-XP1

The Hydranautics PRO-XP1 is an ultra-high pressure capable spiral wound RO element that is designed to operate up to a max pressure of 124 bar (1,800 psi). Element performance is portrayed with two pilot tests: Pilot Test #1 and Pilot Test #2. Both tests utilized single 4" diameter PRO-XP1 elements that operated in a closed loop system held constant at 120 bar.

Pilot Test #1 treated an initial solution of 66,000 mg/L TDS NaCl. The concentrate was recirculated (**Figure 6**) until the brine reached a final concentration of approximately 126,000 mg/L TDS NaCl. Performance data from the 4" PRO-XP1 element was collected periodically during the length of the test. The change in the element's flux and permeate quality as the feed TDS increased can be seen in **Figure 7**. As is explained earlier in this paper, as the TDS of the feed water increases, the osmotic pressure increases and the applied pressure required to produce permeate increases. Because the pressure was held constant while TDS increased, permeate flux decreased. The permeate salinity also increased as feed salinity increased which is to be expected as membrane rejection is a function of total salinity.

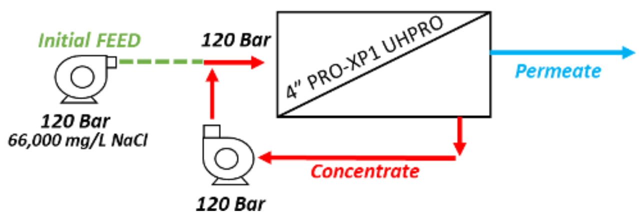

Figure 6. Process diagram of Pilot Test #1.

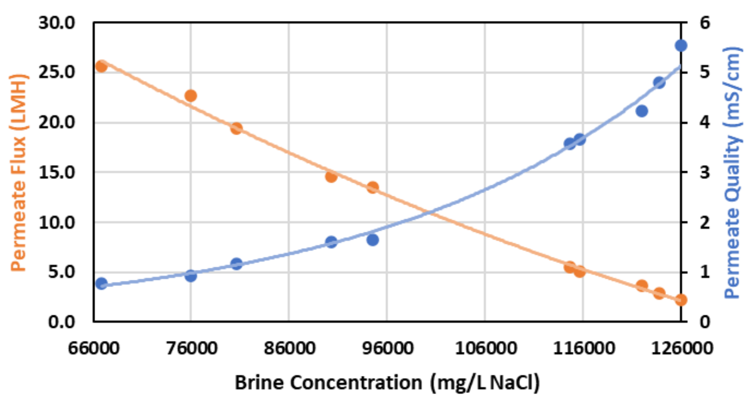

Figure 7. Change in permeate flux and permeate quality of a 4" PRO-XP1 element when treating multiple salinities of a NaCl feed solution. Summarizes results of Pilot Test #1.

Pilot Test #2 treated a collected field site water sample that was approximately 65,000 mg/L TDS. The concentrate was recirculated (**Figure 8**) until the brine reached a final concentration of approximately 145,000 mg/L TDS. Performance data from the 4" PRO-XP1 element was collected periodically during the length of the test. The change in the element's flux and permeate quality as the feed TDS increased can be seen in **Figure 9**. The ending flux in Pilot Test #2 was higher than what was observed in Pilot test #1, even though Pilot Test #2 ended with a higher TDS brine. This was due to the mix of ions in the water sample collected from the field which contained an appreciable amount of sulfates resulting in a lower osmotic pressure at 145,000 TDS than the NaCl solution's osmotic pressure at 126,000 TDS.

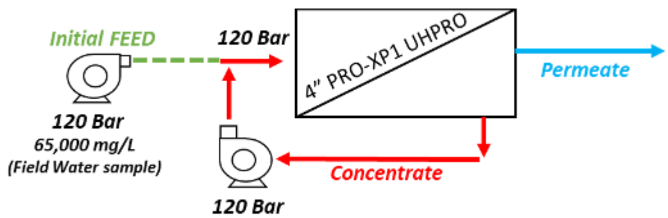

Figure 8. Process diagram of Pilot Test #2.

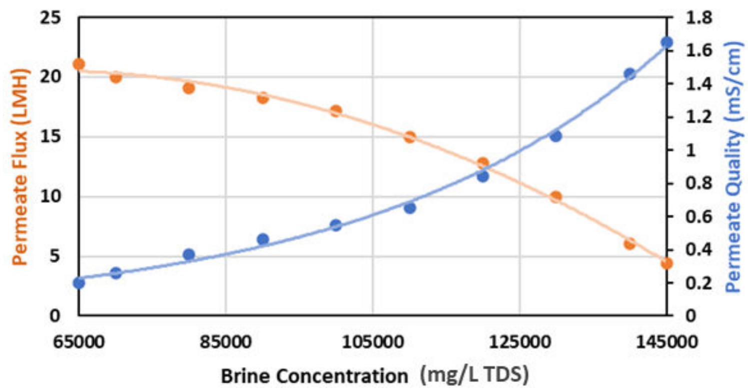

Figure 9. Change in permeate flux and permeate quality of a 4" PRO-XP1 element when treating multiple salinities of a water sample collected from the field. Summarizes results of Pilot Test #2

If membrane scaling and fouling are controlled, systems utilizing 8" diameter PRO-XP1 UHPRO elements are able to concentrate sodium chloride up to 130,000 mg/L TDS NaCl. This is a significant increase to the roughly 80,000 mg/L TDS NaCl achieved by standard SWRO elements.

Reliability and Stability of UHPRO PRO-XP1

Due to the variability of stressors that exist when treating unique, high salinity influent at ultra-high pressures, the performance of PRO-XP1 elements cannot be generalized. However, due to the stability of the PRO-XP1 element construction, a compaction factor has been developed that allows a designer to calculate the pressures, permeate quality, and expected fluxes based on: influent ion composition, permeate recovery, and maximum system temperature. This compaction factor is integrated into the membrane manufacture's projection software. The compaction factor is most heavily influenced by the system's maximum temperature, so it is recommended that UHPRO systems employ reliable temperature controls.

When PRO-XP1 elements are first loaded into a new system they will start with a high flux that will decrease until stabilizing near the projected flux after one to three days (**Figure 10**). It is not uncommon for the initial flux rate of PRO-XP1 elements to start 25% to 45% higher than their stabilized flux.

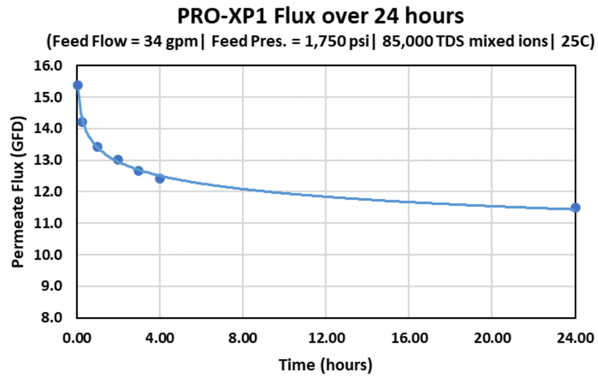

Figure 10. Flux stabilization of PRO-XP1 elements after 24 hours of operation.

PRO-XP1 has demonstrated stable performance even in the face of extreme conditions. A PRO-XP1 pilot that treated high TDS, high COD industrial waste showed consistent permeate quality (**Figure 11, left**) over an 8-month span even with harsh CIP cleanings performed on the system every two weeks. As is custom for systems treating an influent high in organics, the pilot experienced an increase in feed pressure during the first month of operation before stabilizing (**Figure 12**).

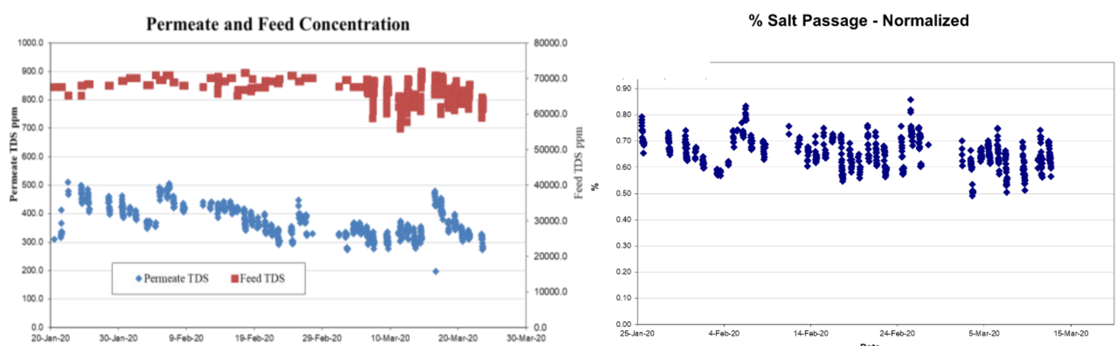

Figure 11. Permeate and feed concentrations (left) and normalized salt passage % (right) during the first 3 months of pilot operation.

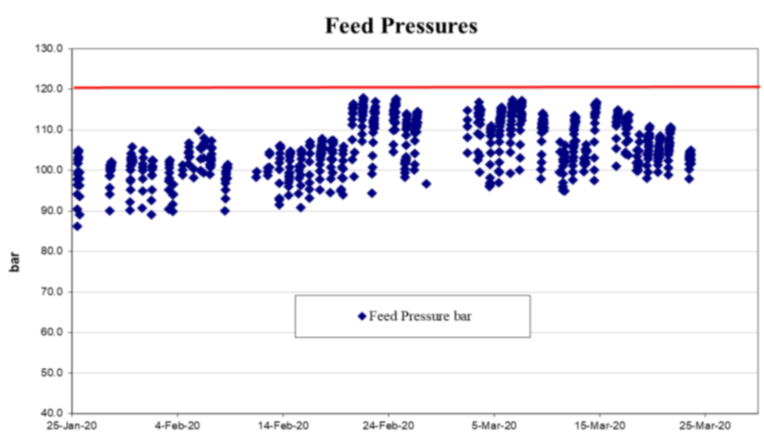

Figure 12. Feed pressure during the first 3 months of pilot operation.

Limitations of UHPRO PRO-XP1

As alluded to in the previous subsection, the performance of PRO-XP1 elements is dictated by the variation of compaction the membrane layer experiences from the system's unique operation parameters. When operating at pressures above seawater RO limitations, the PRO-XP1 will be more sensitive to any increase in temperature. Membrane compaction is not a reversable process. Once PRO-XP1 elements operate at a higher temperature than their previous maximum temperature, their performance will change.

Due to this temperature sensitivity, if the maximum operating temperature of a PRO-XP1 system exceeds 30°C, the maximum operational pressure will decrease. The rate at which the maximum operational feed pressure decreases with temperature can be seen in **Figure 13** and **Table 1**.

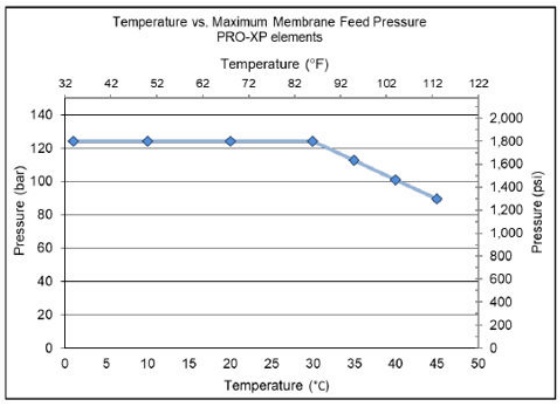

Figure 13. Maximum Temperature per Maximum Feed Pressure for PRO-XP1 elements

Table 1. Maximum Temperature per Maximum Feed Pressure limits for PRO-XP1 elements

°F	°C	psi	bar
33.8	1	1,800	124.1
50	10	1,800	124.1
68	20	1,800	124.1
86	30	1,800	124.1
95	35	1,635	112.7
104	40	1,465	101.0
113	45	1,300	89.6

While operating pressure limits for PRO-XP1 are lower at elevated temperatures, they still outperform conventional element pressure limits at all temperature ranges (**Figure 14**).

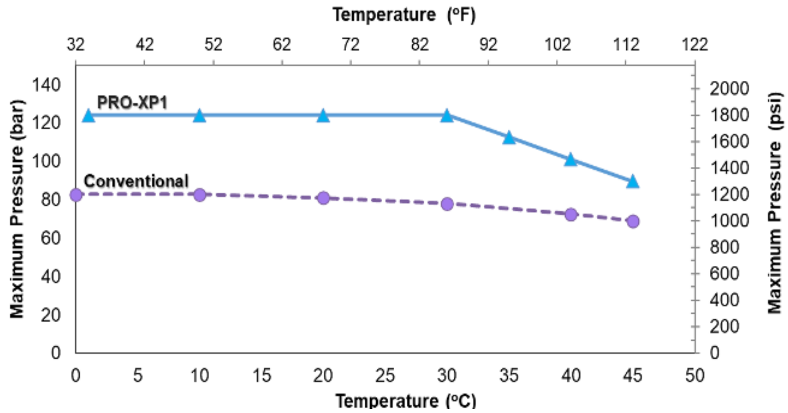

Figure 14. Comparison of Maximum Operation Pressures of PRO-XP1 and Conventional RO Elements Across a Range of Operation Temperatures.

Benefits of Replacement of Industrial Bioreactor with UHPRO

An industrial manufacturing plant (Plant A) produces wastewater containing an organic solvent, Dimethylformamide (DMF). In 2019 Plant A prepared to increase their manufacturing output, but were limited by their waste discharge. During the expansion planning phase, Plant A determined that their current bioreactor would not be able to produce a discharge that would meet current city discharge limits. Additionally, the existing bioreactor system was aging and in need of replacement. Therefore, Plant A considered a variant of treatment alternatives to replace the bioreactor. The two main options were a new bioreactor or a high recovery RO system. Ultimately, Plant A chose the multi-step RO process to super concentrate the organic waste stream.

The critical part of the process utilized a novel RO concentrator system designed jointly by Saltworks and Hydranautics, which was based on Hydranautics SWC5-LD and PRO-XP1 membranes. The proposed concentrator system (**Figure 15**) was a two stage RO: the first stage operates at 62 bar and was loaded with six SWC5-LD seawater RO elements, the second stage operated at 110 bar and is loaded with six PRO-XP1 UHPRO elements (**Figure 16**). The project's capital cost for installing the entire treatment system, including the UHPRO system, was 24% lower than that of a new bioreactor system (**Table 2**).

Table 2. Comparison of the approximate Capital Costs and Annual Operating Costs for a New Bioreactor system vs a New UHPRO system.

	New Bioreactor	New UHPRO
Total Estimated Capital Cost	X	76% × X
Estimated Annual Operating Cost	~ $ 800,000 / year	~ $675,000 / year

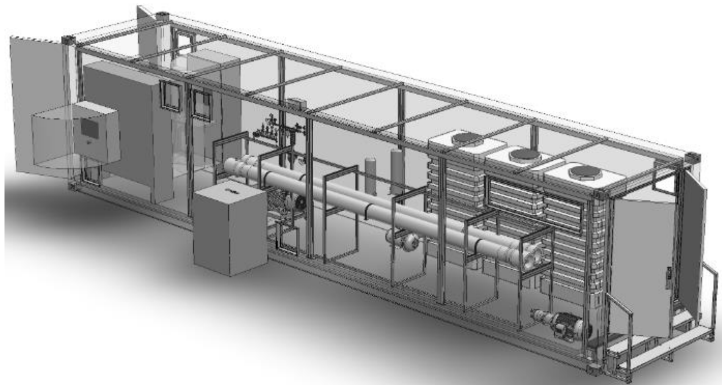

Figure 15. 3D Representation of Plant A's Waste Concentrator RO System.

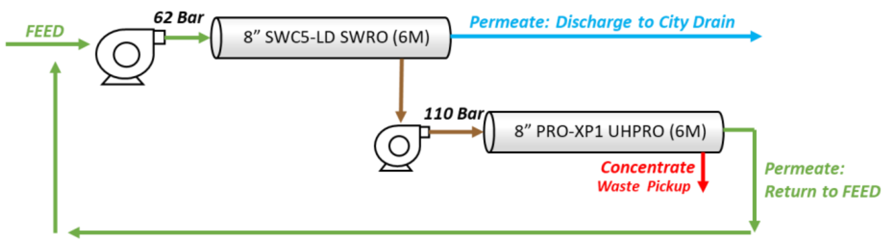

Figure 16. Process Diagram of the Waste Concentrator RO System for Plant A.

Construction of Plant A's waste concentrator RO system began in October 2020 and became fully operational in March 2021. The waste concentrator was projected to only achieve 60% recovery when operating at target pressures; however on startup and after a year of operation the total system recovery reached 83%. The overall recovery was greater than 95%. The small amount of concentrated waste of the system is stored and hauled away by qualified waste disposal service. This waste contains 11.9 times the concentration of DMF that was present in the influent. DMF is absent or exists at undetectable levels in the permeate that is discharged to the city drain.

The following benefits were identified when Plant A reviewed the costs of utilizing the waste concentrator RO after a year of operation: the actual annual operating cost for the system was 14% lower than initially estimated (**Table 3**) and Plant A reduced its power consumption by approximately 154,000 kWh per month.

Table 3. Estimated vs Actual Annual Operating costs of Plant A's Waste Concentrator RO system

	Annual Operating Cost
Estimated	~ $ 675,000
Actual	~ $ 583,000

Summary

Membrane manufacturers are beginning to implement innovative RO element designs to allow specialized products to operate at ultra-high pressures. Hydranautics' UHPRO PRO-XP1 element has been shown to concentrate a sodium chloride solution 1.6 times further than what conventional sea water elements are able to. Rigorous lab and field testing has shown that PRO-XP1 elements can hold up to the demanding conditions industrial and high salinity treatment requires and perform reliably. The energy requirement for an UHPRO is significantly less than other thermal dependent waste treatment processes like a bioreactor waste treatment system. After replacing their old Bioreactor waste management system with UHPRO, the Southern California Industrial Manufacturing Plant (Plant A) experienced a reduction in operating cost which totaled to an approximate savings of $597,000 annually. With the current experienced savings plus the growth in revenue from increased production, it is expected that Plant A will have achieved ROI within one year.

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