BENEFITS OF OPERATING WITH THE NEW THIN-MEMBRANE TECHNOLOGY IN A MUNICIPAL DRINKING WATER RO

Kirk A. Lai, Hydranautics/Nitto Denko, 401 Jones Rd., Oceanside, CA, 92058
401 Jones Rd. Email : kirk.lai@nitto.com, Phone : 760-901-2500

Wayne Bates, Hydranautics/Nitto Denko, Oceanside, CA, 92058

Rich Franks, Hydranautics/Nitto Denko, Oceanside, CA, 92058

Craig R. Bartels, Hydranautics/Nitto Denko, Oceanside, CA, 92058

Allan Clum, Mount Pleasant Waterworks

Tony Hill, Mount Pleasant Waterworks

Abstract

Mount Pleasant Waterworks (MPW) is currently operating the first municipal drinking water RO system using a new, thin membrane technology. The new technology increases the amount of active membrane area that can be manufactured in the standard spiral wound element. Mount Pleasant Water District is the first municipal district to replace conventional RO spirals with new spirals utilizing the new technology and demonstrate how an existing RO system can realize the benefits of this innovative membrane while avoiding costly design modifications.

The spiral wound element was originally developed in the 1970s to package RO flat sheet membrane into a compact, efficient, and usable unit. Since its inception, incremental improvements in the spiral element design and materials of construction have led to enhanced efficiencies and productivity. However, the overall element design has remained largely unchanged. Most notably, in recent years, efforts to fit more material into the present spiral element configuration reached an optimal plateau. Advances in automated manufacturing resulted in either increasing the membrane surface area or increasing the thickness of the feed/brine spacer. Either enhancement could be selected depending on the quality of the feedwater or the efficiency of the pre-treatment. However, it was not possible for the system designer to capitalize on the benefits associated with both enhancements. For this reason, when treating high quality source water, system designers prefer to use spiral elements that contain higher surface area to realize lower capital cost or lower operating cost. But the higher area elements forfeit the benefits associated with a thicker feed/brine spacer which include reduced differential pressure losses, less fouling and improved cleaning effectiveness. In recent years, thanks to innovations in material science, a new generation of RO elements are now being manufactured. These new elements, now running in the Mount Pleasant RO, offer both a larger surface area and thicker feed/brine spacer.

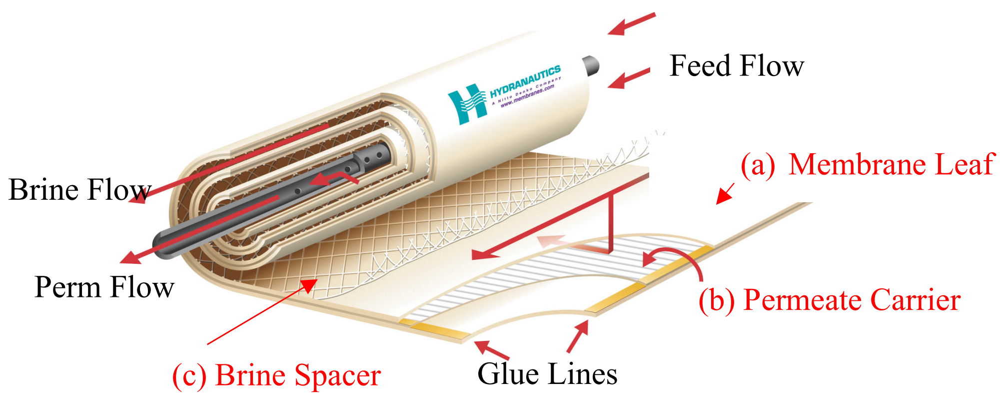
This paper will detail the innovation in the construction of the new membrane material and compare its design and performance to that of the conventional membrane. Based on the operation of these new elements at Mount Pleasant, the benefits of the new membrane will be compared to the previously installed conventional membranes. The comparison will include operating data to demonstrate a reduction in feed pressure, differential pressure, and energy consumption.

Introduction

The standard spiral wound elements used in almost all RO and NF applications for the past 30 years consists of the different polymeric components shown in Figure 1, including multiple (a) membrane leaves each sandwiched between a (b) permeate carrier on the low salinity side of the membrane and a (c) brine spacer on the high salinity side of the membrane.

Figure 1:

Cutaway of the standard spiral element showing the (a) membrane leaf, (b) permeate carrier, and (c) brine spacer.



Each of these three layers has its own thickness and therefore consumes its own proportion of volume available in the spiral. Table 1 lists the thickness of each of the three layers and their percentage of volume within the spiral.

Table 1:

Comparing the thickness of the three layers of material in the spiral element leaves and the percentage volume each layer consumes.

Layer in the Spiral Element	Thickness	% of Vol in Spiral Element
(a) Membrane Leaf	8 mil	16 %
(b) Permeate Carrier	10 mil	19 %
(c) Brine Spacer	34 mil	65 %
Total	**52 mil**	**100%**

Due to these volume limitations, the standard spiral element typically contains 400 sq ft of active membrane area. While membrane manufactures are continually seeking ways to increase the area, to do so requires reducing the thickness of one of the other two layers. Because the brine spacer consumes most of the element volume, manufactures offer higher area, 440 sq ft elements, by using a thinner, 28-mil, brine spacer. But reducing the thickness of the brine spacer has the disadvantage of increasing differential pressure losses and increasing fouling rates. The thinner spacer can also be more difficult to clean when it becomes fouled. For these reasons, many RO plants choose to sacrifice the additional membrane area to avoid the challenges associated with the thinner spacer.

Reducing the thickness of the permeate carrier would allow for more membrane to be packaged into the spiral element. However, the permeate carrier thickness is currently optimized to direct the maximum volume of permeate along the backside of the membrane leaf and into the permeate core tube. Any reduction in permeate carrier thickness would restrict that flow and reduce the element's water productivity.

In recent years, a new type of element has been developed with new materials of construction that allow for a higher area of 440 sq ft while keeping the 34-mil spacer. This was done by reducing the thickness of the membrane layer. But modifying the membrane layer without affecting water permeability or salt rejection can be challenging and requires a clear understanding of its composition and what portion can be modified. As shown in Table 2, the membrane layer in the spiral element is a composite of three layers: 1) polyamide rejecting layer 2) polysulfone support layer, and 3) polyester support layer. Based on the thickness of each layer in the standard membrane, it is evident that the separating polyamide rejecting layer would have little effect if it were reduced in thickness. The bulk of the thickness of the membrane sheet comes from the polyester support layer. This layer is designed to provide support to a thin polysulfone layer which, in turn, provides support to the very thin polyamide layer. By reducing the thickness of the polyester support from 150 microns to less than 100 microns, the overall thickness of the membrane sheet can be reduced, allowing for additional membrane leaves and, therefore, more membrane area to be packaged into the spiral element.

When manufacturing the thin membrane, only the support layer is changed. No change occurs in the polyamide rejection layer. The polyamide thickness remains the same and the polyamide chemistry remains the same. For this reason, the salt rejection of the thin membrane remains the same as the standard membrane. But reducing the thickness of the support layer raises questions about the effectiveness of the thinner support layer to adequately support the membrane at higher pressures up to the elements maximum rated brackish pressure of 600 psi. The question is addressed when considering the conventional membrane, with a 150-micron polyester backing, is actually over engineered for brackish pressures and operating conditions. The same 150-micron backing used in conventional brackish RO membranes, with a maximum rated feed pressure of 600 psi, is also used to support the seawater RO membrane, which sees pressures as high as 1200 psi. It is, therefore, reasonable to assume that the thinner membrane would provide sufficient support at pressures up to 600 psi. To provide added durability, the thin membrane is also rolled into the spiral element on top of a modified brine spacer. This new brine spacer is designed with thinner channels to ensure no embossing of the membrane into the channels at higher feed pressures.

But despite laboratory testing and simulations to demonstrate the advantages of the thin membrane over the conventional membrane, the true test comes from its performance in the field. The ability of the thin membrane to perform in the field has been demonstrated through pilot testing in Singapore (Bartels, 2015) and in Southern California (Knoell, 2017) as well as in a full-scale municipal wastewater reclamation plant in Southern California (Franks, 2021). What was missing from these field demonstrations was detailed data comparing the thin membrane performance with conventional membranes. That type of comparison data became available when the thin membrane was operated at Mt. Pleasant Waterworks. Thanks to detailed monitoring of its RO systems, the operation of the thin membrane in a full-scale municipal groundwater plant for over two years, as discussed below, confirms the new membranes' long-term stability as well as its economic benefits relative to the standard membrane.

Table 2:

Comparing the thickness of the three layers of material comprising the membrane leaf in the standard membrane and the new, thin membrane.

Layer in the membrane leaf	Standard Membrane Thickness	New Thin Membrane Thickness
1)polyamide rejecting layer	0.15 microns	0.15 microns
2)polysulfone support layer	50 microns	40 microns
3)polyester support layer	150 microns	60 microns
Total	**200.15 microns ≈ 8 mil**	**100.15 microns ≈ 4 mil**

System Design

Mount Pleasant Waterworks (MPW) is a private utility located in South Carolina and bounded by Charleston Harbor and the Atlantic Ocean and it services over 90,000 people with potable drinking water. The MPW has operated RO systems since 1992 and currently has four RO water treatment plants and six deep wells. The wells are on average 2,000 feet deep and pull water from the Charleston Aquifer. The feed water quality is good but is relatively high for potable water use at 1500-1600 mg/l (ppm) TDS (Total Dissolved Solids) and 8.4 – 8.6 pH average. Pretreatment uses only antiscalant but does not acidify to lower the feed pH. A medium pressure RO system was selected to lower RO plant finished product TDS to < 200-400 ppm using a blended stream of 88-95% RO permeate at roughly 60-120 ppm and 5-12% well water at 1500-1600 ppm TDS. Raw water temperature is warm and can vary from 90-98F. The purpose of blending RO permeate with well water is to add back fluoride for dental health and add alkalinity to control corrosion in the distribution system. Final treatment is chloramines before it leaves the plant.

MPW loaded their Plant 3 RO in October 2009 using the 1st generation ESPA2 (standard membrane) elements. These membranes were replaced after 10 years of successful operation with the 3rd generation ESPA2-LD MAX (thin membrane). Table 3 compares the evolution in design and specifications from ESPA2 to ESPA2-LD MAX with more membrane area and greater feed spacer thickness.

Table 3: Specifications for Medium Pressure RO elements over time

Medium Pressure RO	1st Generation	2nd Generation	2nd Generation	3rd Generation
Membrane thickness	200 microns	200 microns	200 microns	100 microns
Membrane Area	400 sq. ft.	400 sq. ft.	440 sq.ft	440 sq. ft.
Brine Spacer	31 mil	34 mil	28 mil	34 mil
Flow Rating @ 150 psi	9,000 gpd	10,000 gpd	12,000 gpd	12,000 gpd
% NaCl Rejection	99.6%	99.6%	99.6%	99.6%
Introduced	1995	2009	2009	2018

MPW Plant 3 uses 4 RO units, each unit is constructed with an 11:5 array x 7M vessels for a total of 112 element in each unit. Originally the plant was loaded with standard thickness, 400 sq ft membrane and each RO unit ran at 500 gpm (0.720 MGD), 16.1 gfd flux and 80% recovery. On this new set of 440 sq ft thin membrane, each RO unit is running at 530 gpm (0.763 MGD), 15.5 gfd flux and 80% recovery. Table 4 below is a summary of RO design projections for the plant based on the different elements at startup using the raw feed at 1543 ppm TDS, the maximum temperature of 98F, permeate flow of 530 gpm (0.763 MGD), 8 psi permeate back pressure, 80% recovery and 24/7 operation. The combined pump/motor/VFD efficiency was 80%. Key items to note is the improvement in energy requirement over the years and that a 10% reduction in membrane flux from 17.0 to 15.5% will result in a reduction of permeate rejection.

Table 4: Projected Design Summary with different generation elements

Medium Pressure RO	**1st Generation**	2nd Generation	2nd Generation	**3rd Generation**
Pumping Energy kwH/kgal of permeate	**1.67**	1.44	1.47	**1.33**
Annual energy cost at $0.10 per kwH	**$28,000**	$24,000	$25,000	**$22,000**
Annual energy cost savings per RO unit		14%	11%	**21%**
Feed Pressure psi	**148 psi**	128 psi	131 psi	**116 psi**
Delta P (feed to reject)	**52 psid**	31 psid	57 psid	**29psid**
Perm Flow	**530 gpm**	530 gpm	530 gpm	**530 gpm**
Flux	**17.0 gfd**	17.0 gfd	15.5 gfd	**15.5 gfd**
Permeate TDS	**65 ppm**	71 ppm	102 ppm	**97 ppm (+49%)**
% Rejection (feed-brine average)	**98.5% (1.5%)**	98.4%	97.7%	**97.8% (2.2%)**

System Operation

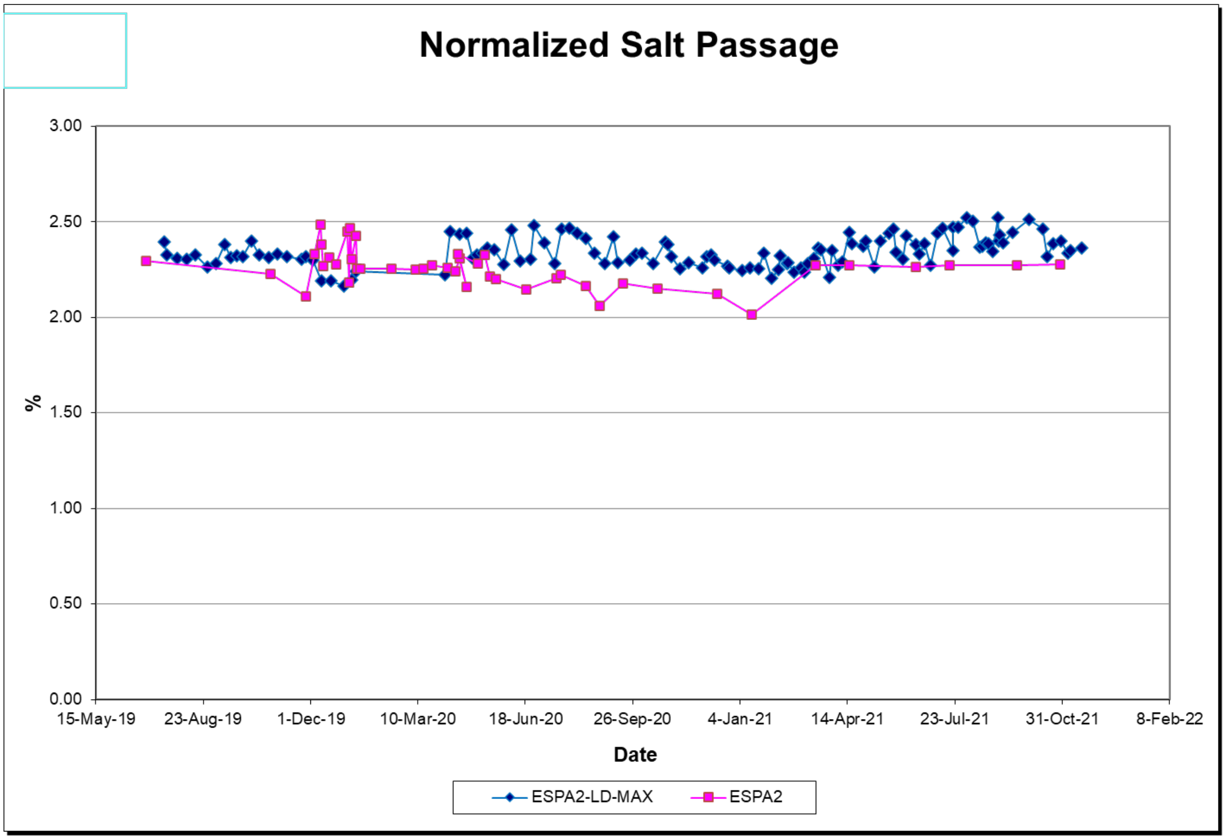
At the time of writing this paper, this current set of membranes at Plant 3 had been in service for 28 months, up to November 2021. Originally the plant was loaded with standard thickness, 400 sq ft membrane and each RO unit ran at 500 gpm (0.720 MGD), 16.1 gfd flux and 80% recovery. On this new set of 440 sq ft thin membrane, each RO unit is running at 530 gpm (0.763 MGD), 15.5 gfd flux and 80% recovery.

Table 5: RO Plant 3 of ESPA2 vs ESPA2-LD-MAX over 28 months (850 days) of run time

RO Plant 3 Actual Data	ESPA2	ESPA2-LD-MAX
Membrane area	400 sq ft	**440 sq ft**
Feed pressure (Day 1 to Day 850)	150 – 170 psi	**115 – 115 psi**
Unit average flux	16.2 gfd	**15.5 gfd**
Unit Differential Pressure - normalized	61.7 psi (both stages)	**30.8 psi** (both stages)
Total Permeate production - average	504 gpm (725,760 gpd)	**530 gpm (763,200 gpd)**
Net Driving Pressure - average	94.2 psi	**65.3 psi**
Specific Flux – temp corrected to 25°C	0.128 gfd/psi	**0.169 gfd/psi**
Normalized Permeate Flow	489 gpm	**562 gpm**
Normalized Permeate Salt Passage	2.25%	2.34 % (+4%)
Well water temperature (annually)	32 - 37°C (90 - 98°F)	32 - 37°C (90 - 98°F)

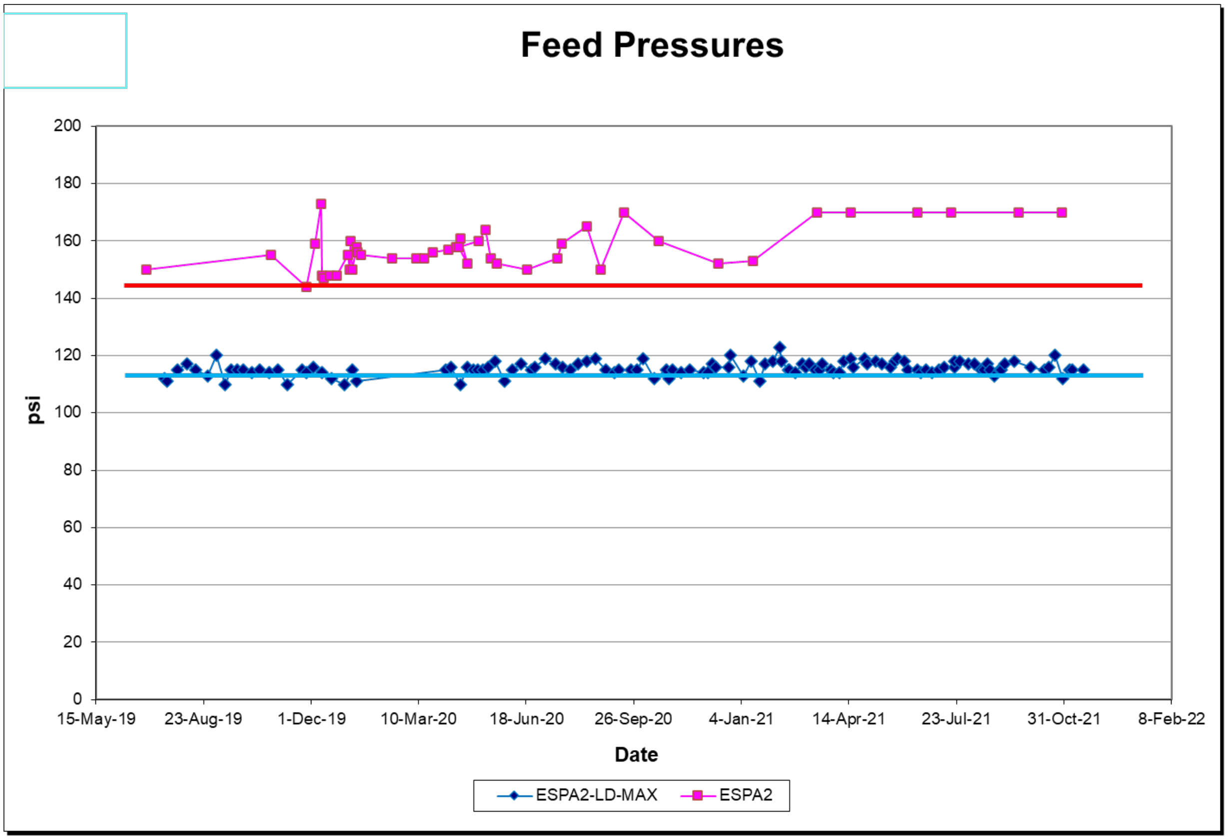
The following graphs show the performance comparison of 28 months of ESPA2-LD-MAX (blue data curves) and the first 28 months of the previous ESPA2 (pink data curves).

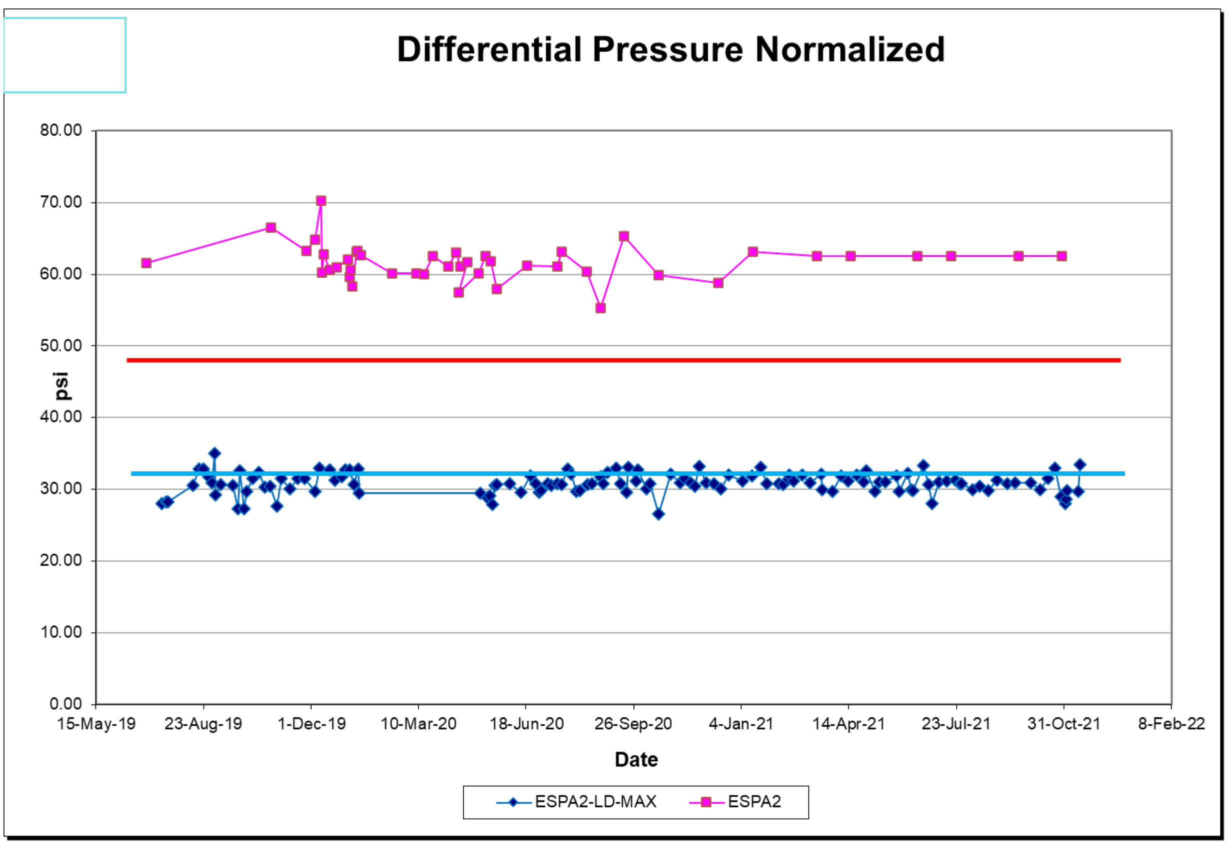
Plant 3 started up and ran steady state for 6 months from July 15, 2019 to Jan 15, 2020 and then there was a 4-month total plant shut down due to Deep Well 4 mechanical failure. The RO units were put in preservative for that time and after the pump was fixed and the well rehabbed, the RO's saw mostly stable salt passage after the restart. The normalized salt passage averaged 2.34% for the newer ESPA2-LD-MAX and 2.25% average normalized salt passage for the older ESPA2.



The Feed Pressure graph below shows the difference in actual feed pressures. The red horizontal line represents the IMS Design projected value of the older ESPA2 under these operating conditions at 143 psi and that pink data curve started out at 150 psi, but during the 28 months it eventually climbed to 170 psi.

The light blue horizontal line represents the IMS Design projected value of the ESPA2-LD-MAX under these operating conditions at 116 psi and that blue data curve started out at 115 psi and stayed there throughout the 28 months. The feed pressure has been consistent with this new membrane.

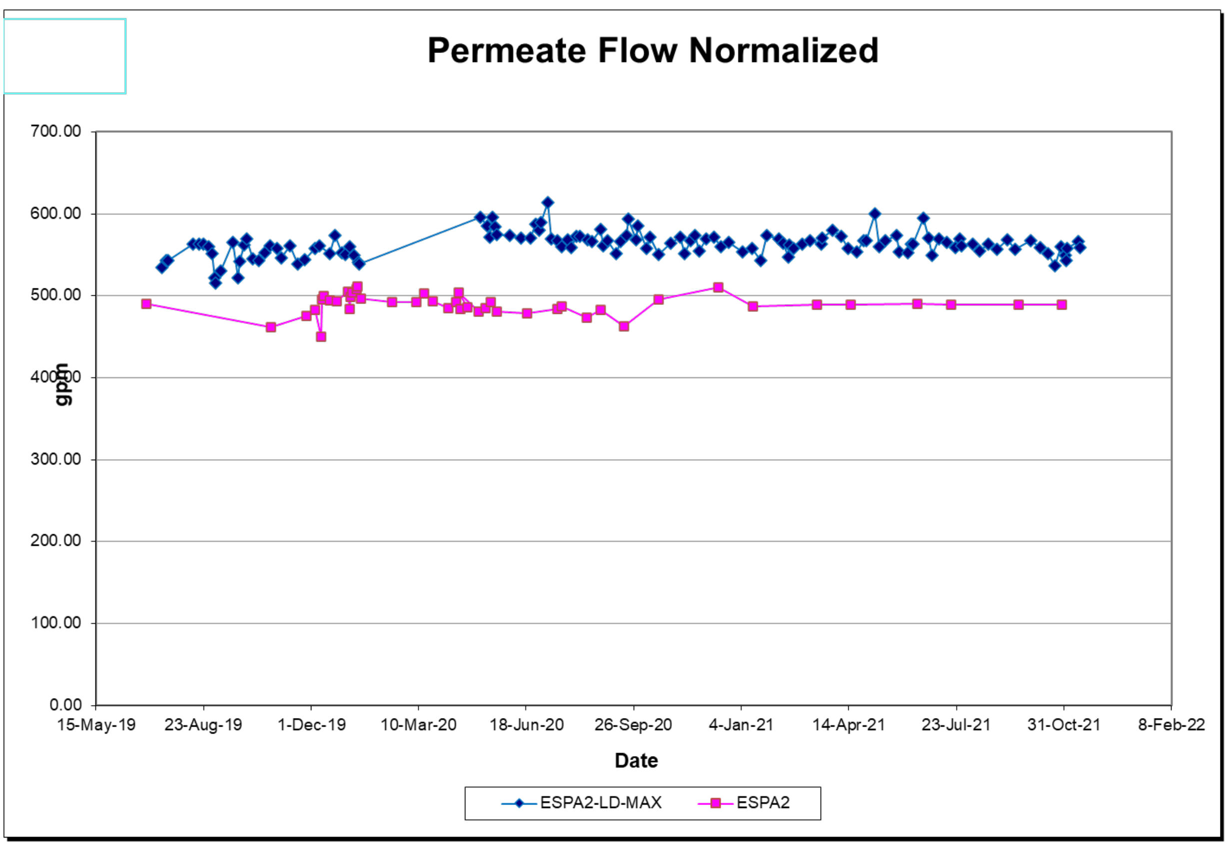

Feed Pressures
200
180
160
140
120
100
80
60
40
20
0
psi
15-May-19
23-Aug-19
1-Dec-19
10-Mar-20
18-Jun-20
26-Sep-20
4-Jan-21
14-Apr-21
23-Jul-21
31-Oct-21
8-Feb-22
Date
ESPA2-LD-MAX
ESPA2


Differential Pressure Normalized
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
psi
15-May-19
23-Aug-19
1-Dec-19
10-Mar-20
18-Jun-20
26-Sep-20
4-Jan-21
14-Apr-21
23-Jul-21
31-Oct-21
8-Feb-22
Date
ESPA2-LD-MAX
ESPA2

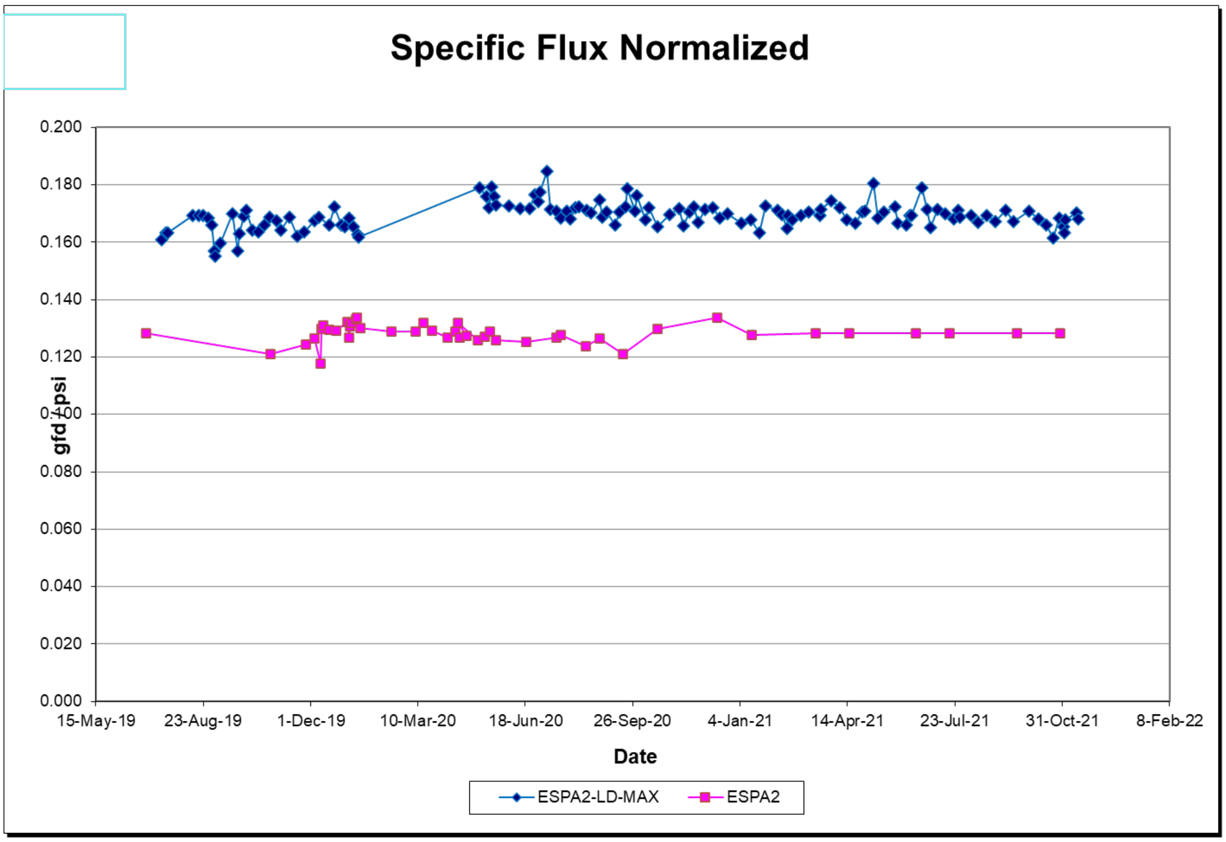
The normalized differential pressure graph above has blue and pink curves that represent the sum of both the 1st and 2nd stage DP's. The red horizontal line represents the IMS Design projected value of the older ESPA2 under these operating conditions at 48 psi and the pink data curve averaged 61.7 psi over the 28 months.

The light blue horizontal line represents the IMS Design projected value of the new ESPA2-LD-MAX under these operating conditions at 32.5 psi and the blue data curve averaged 30.8 psi over the same duration. There is a 31 psi difference in average normalized differential pressure between the older ESPA2 with 28-mil and the newer, larger 34-mil feed-brine spacer of the ESPA2-LD-MAX. This graph clearly shows how much more efficient the 34-mil spacer performs.

Below is the graph for permeate flow normalized. The older ESPA2 averaged 489 gpm throughout the 28 months and the new ESPA2-LD-MAX averaged 562 gpm. Even though there was only a 30 gpm increase in actual permeate flow, due to the lower net driving pressure, there was a 73 gpm normalized increase overall.



This graph below is for specific flux normalized. This too shows the same pattern as the normalized permeate flows, the ESPA2-LD-MAX is making more gfd / psi as it requires less net driving pressure to produce target flows. These newer membranes are also averaging 15.5 gfd flux, which is not as taxing to the flat sheet vs 16.2 gfd for the older ESPA2.



Performance on the ESPA2-LD-MAX shows a lot of improvement over the older ESPA2 in the way of lower feed pressure, lower DP, increased permeate flow, increased specific flux, at very similar permeate quality.

Discussion

Observations of 28 months of operating data comparing both the new thin membrane higher area ESPA2-LD-MAX at 440 sq ft and the older, standard ESPA2 membrane at 400 sq ft confirms that thin membrane can maintain integrity as well as the conventional, thicker membrane. Comparing operation of the two-element type also demonstrates the benefits of using elements with thinner membrane, including:

1. Lower overall feed pressure, equates to cost savings in electricity
2. Lower average flux across 112 membranes and better cross flow velocity
3. Lower differential pressure (DP) from Feed to Reject (both stages)
4. More permeate production at a higher specific flux
5. More permeate production without adding equipment and hardware
6. Slight increase in salt passage due to the reduction in flux.

Conclusion

After decades of incremental changes to the design and construction of the spiral wound RO/NF element, an improvement to the polyester support layer of the membrane has led to an increase in the amount of active surface area packaged into the element without sacrificing brine spacer thickness. The new, thin membrane leads to an increase in active surface area from 400 sq ft to 440 sq ft while maintaining the thicker, 34-mil brine spacer.

The installation of thin membrane elements at MPW Plant 3 resulted in greater membrane area and thicker brine spacer thickness without modification to the existing RO system. The existing RO, using elements with a 31-mil spacer and 400 sq ft was replaced with the new, thin membrane elements using a 34-mil spacer and 440 sq ft. Operating with the thin membrane resulted in:

1. **Reduced operating cost**. With more membrane area, the system could run at lower flux, lower feed pressure and lower energy consumption. No change to the existing system design was required to realize this benefit.

2. **Increased productivity**. The existing RO was also able to increase its output without a plant expansion. The existing feed pumps were able to handle the 5% greater flow. Therefore, no pump retrofit was required to realize this benefit.

References

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