Benefits of Operating the First Membrane Systems Utilizing New Thin-Membrane Technology

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ABSTRACT

In the past year, several membrane systems were started using new, Thin-Membrane Technology which allows the highest active membrane area to be manufactured into the standard spiral wound element. These new membrane systems, which include RO for municipal wastewater reclamation and NF operating on offshore oil platforms, are the first of their kind to utilize the new technology and demonstrate how a wide range of applications can benefit from this innovation.

The spiral wound element was developed in the 1970s to package RO and NF membrane material into a compact, efficient, and usable unit. Since that time, incremental improvements in 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. When treating high fouling source water such as municipal wastewater, RO designers use the thicker feed/brine spacer to reduce differential pressure losses, minimize fouling and improve cleaning effectiveness. Designers selecting elements with thicker spacer forfeit the benefits associated with higher area elements. But in recent years, thanks to innovations in material science, a new generation of RO elements are now being manufactured and operated in full scale plants. These elements offer both a larger surface area and thicker feed/brine spacer.

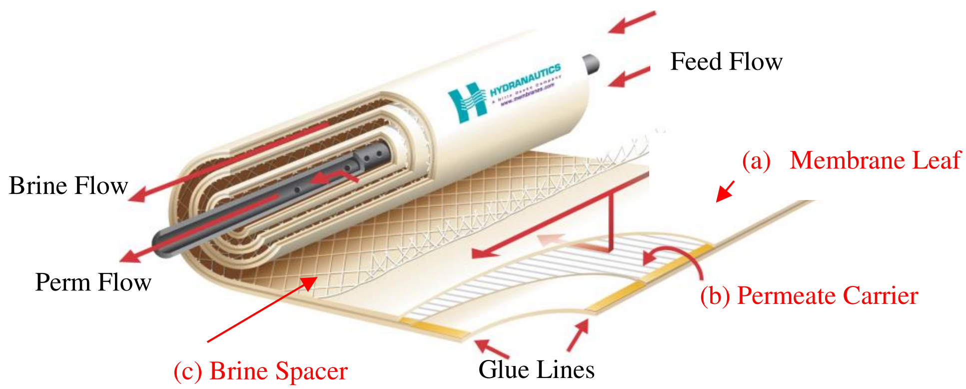
This paper will detail the innovation in the construction of the new membrane material and compare its effects on element performance with previous generation membranes. The paper will analyze the operation of these new elements in a municipal wastewater reclamation plant. Based on the operation of these new elements, this paper will discuss the durability and cost benefits of the new membrane relative to current membranes.

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, 26-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, most high fouling 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 water along the length 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.

THIN-MEMBRANE IN THE SPIRAL WOUND ELEMENT

In recent years, a new type of element was developed with new materials of construction that allow for 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: polyester support layer, polysulfone support layer, and polyamide rejecting 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 is taken up by 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 area to be packaged into the spiral element. Reducing the thickness of the support layer raises questions about the effectiveness of the thinner support layer to maintain its integrity at the elements maximum rated brackish pressure of 600 psi. However, the conventional membrane, with a 150-micron polyester backing, is over engineered for brackish pressures and operating conditions. Consider that 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 membranes, which sees pressures as high as 1200 psi. It is, therefore, reasonable to assume that the new, thinner membrane, could maintain integrity at pressures up to 600 psi. The long-term operation in a pilot and in a full scale plant, as discussed in the remainder of this paper, would be required to demonstrate that assumption.

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	New Thin Membrane
polyamide rejecting layer	0.15 microns	0.15 microns
polysulfone support layer	50 microns	40 microns

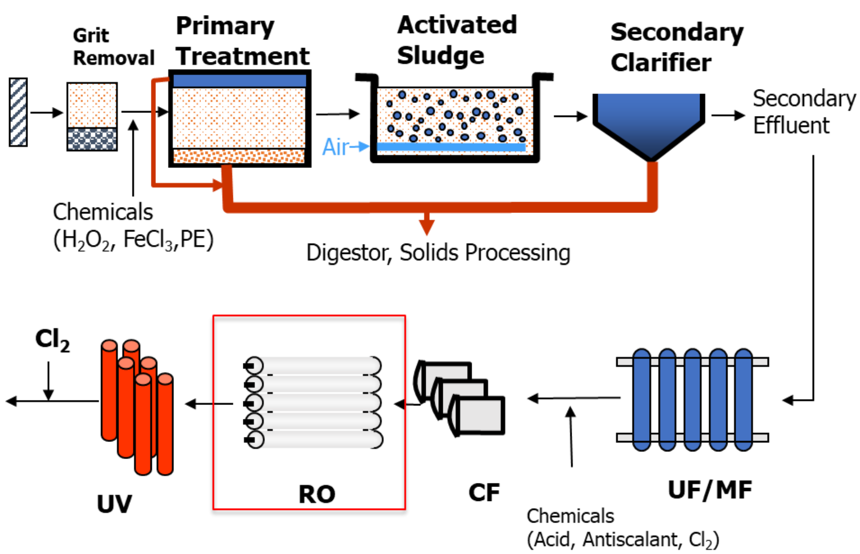
polyester support layer	150 microns	60 microns
Total	**200.15 microns ≈ 8 mil**	**100.15 microns ≈ 4 mil**

THIN MEMBRANE PILOT TESTING

In 2016, the new, thin membrane began field testing at multiple locations, including on municipal wastewater in a single, seven element, pilot vessel in Southern California (Knoell, 2017). The elements ran for over 300 days at 55% recovery and 13-15 gfd flux to replicate operating conditions in the first of three stages of standard membranes in the existing, full scale plant. As illustrated in Figure 2 below, the secondary effluent from the wastewater treatment plant was sent to low pressure MF pretreatment before going to the RO. The RO feed TDS of 1100 mg/l was concentrated to 2600 mg/l. Feed TOC of 7 mg/l was concentrated to 15 mg/l. As seen in Figure 3a, pilot feed pressure started at 120 psi and then increased to 130 psi after 40 days due to the deposition of organics on the membrane surface. Feed pressure was stable during the pilot period, showing a marked decrease or increase only on the days when flow was intentionally adjusted to test at different fluxes. The feed pressure increased a total of 40 psi from 120 psi to 160 psi by the end of 300 days of operation and one cleaning.

Figure 2:

Secondary effluent from the municipal wastewater treatment plant is sent to low pressure MF pretreatment before going to the RO membranes.

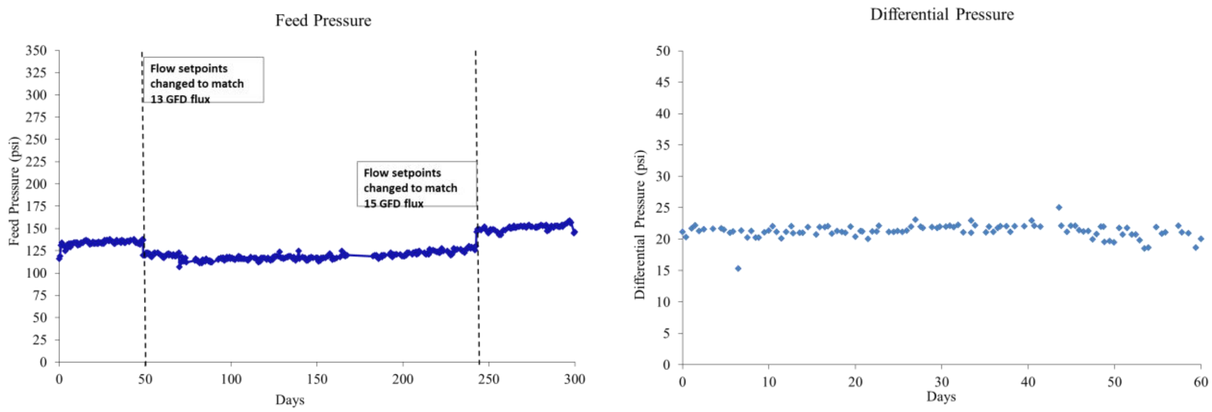


Differential pressure also remained stable around 23 psi across seven elements during the full 300 days of operation. This stability was due to the removal of particulates by MF pretreatment and control of biofouling by the presence of 3 mg/l of chloramines in the feedwater. Figure 3b shows the first 60 days of stable differential pressure which was typical of the whole pilot period.

Permeate quality remained stable during the 300-day test as well. Permeate TDS and TOC levels were consistent with the permeate produced by standard membranes in the main plant. Permeate TDS levels were around 13 mg/l. Permeate TOC levels remained below 70 ppb, well below the 500-ppb spec.

Figure 3:

Testing the thin membrane in a pilot vessel. a) Feed pressure in stage 1 during 300 days of operation. b) Differential pressure in stage 1 during the first 60 days.



a b

This pilot was the first to demonstrate the long-term stability of the new membrane. However, the membranes were operated under relatively mild, low-fouling conditions. Feed pressures never exceeded 160 psi and there was virtually no increase in differential pressure. The thin membrane remained to be challenged with more aggressive conditions, including higher fouling, higher feed pressures, higher differential pressures and higher salinities associated with higher recoveries. The opportunity for such a challenge would soon come with the debut of the membrane in its first full-scale system.

THIN MEMBRANE IN FULL SCALE SYSTEM

In Feb 2020, elements manufactured with the new thin membrane were installed in their first full-scale system, another municipal RO reclamation plant in Southern California, by replacing standard membrane which had been operating in that system for six years. Unlike the pilot system, the full-scale system regularly experienced high fouling rates and rising pressures that offered unique challenges for the new membrane.

RO FOR RECLAIMING MUNICIPAL WASTEWATER – The municipal wastewater plant located in San Pedro, California, operates four RO trains treating municipal wastewater. Each train has a capacity of 3 MGD, for a total potential plant production of 12 MGD. Each of the trains consists of two stages (Trains A and B 68:30 x 7M; Trains C and D 69:30 x 7M) with a booster pump between each stage. Each train operates at a flux of 9.6 gfd and a recovery of 85% while treating feedwater with a TDS of 2800 mg/l concentrated to a TDS of 18,600 mg/l.

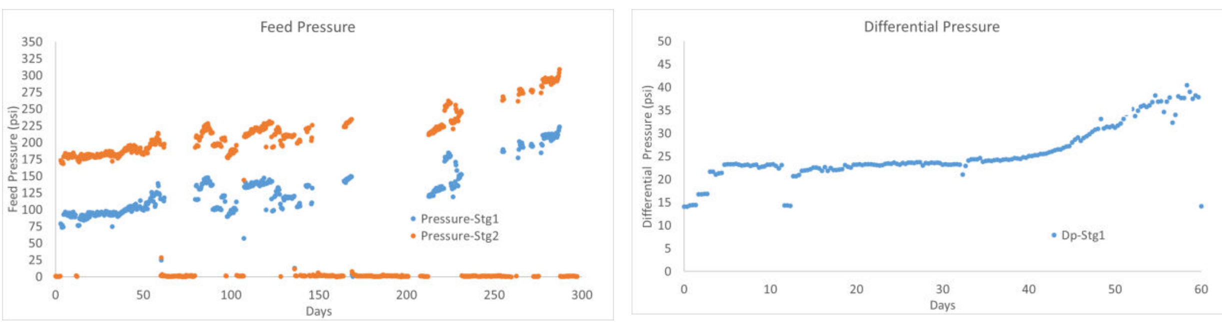
Trains A and B, operating with standard membrane elements since 2012, were experiencing high feed pressures, high differential pressures, increased salt passage, and minimal cleaning recovery. In 2020, the plant replaced the standard membrane elements with the new thin membrane elements containing 440 sq ft of active membrane area with a 34-mil feed spacer.

Over the first 300 days of operation, the thin membrane was subjected to high rates of fouling which led to high differential pressures. Figure 4a shows the feed pressure to stage 1 and stage 2. Because the system uses an interstage booster pump, stage 2 feed pressures are higher than stage 1. Nonetheless, stage 1 and stage 2 experienced a dramatic 200 psi and 132 psi feed pressure increase due to fouling, respectively. Because of the booster pump, elements in stage 2 saw the highest feed pressure of 309 psi.

The same fouling that caused an increase in feed pressure also caused an increase in differential pressures. Figure 4b shows the stage 1 differential pressure during the first 60 days of operation. Differential pressures in the first stage increased 60% from 23 psi to 37 psi due to biofouling. Membrane manufacturers recommend cleaning when differential pressure increases by 20%. This increasing differential pressure was typical throughout the first year of operation. Cleanings were only partially effective at reducing feed pressure and differential pressures. Despite the high fouling, permeate quality remained good. Permeate TDS remained below 200 mg/l and permeate TOC remained below 150 ppb.

Figure 4:

Full-scale system a) feed pressure in stage 1 and stage 2 during 300 days of operation b) differential pressure in stage 1 during first 60 days.



a b

After being in operation for 1.5 years, two thin membrane elements were extracted from Train A for retest and analysis. One element was extracted from the lead position of Stage 1 and the second element was extracted from the tail position of Stage 2. A retest of the two elements revealed a flow loss of 41% in the lead and 31% in the tail (Table 3). Such flow loss is typical of any membrane running on municipal wastewater with a TOC concentration > 5 mg/l. Retest also suggested heavy biofouling in the lead element which had increased in differential pressure from a typical 4 psi at standard test conditions to 14 psi when retested. Membrane manufacturers set the differential pressure limit for a single element at 15 psi so this element had been pushed to its limit. Despite the challenging operating conditions and heavy fouling, both lead and tail elements retested with excellent salt rejection. Before leaving the factory, the lead and tail rejected 99.7% and 99.6% of the test salt respectively. After retesting and adjusting for the lost flow, the membranes were found to have maintained their original 99.7% and 99.6% rejections.

Table 3:

Original performance and retest performance at standard test conditions after thin membrane elements were operated for 1.5 years in the full-scale system in Southern California.

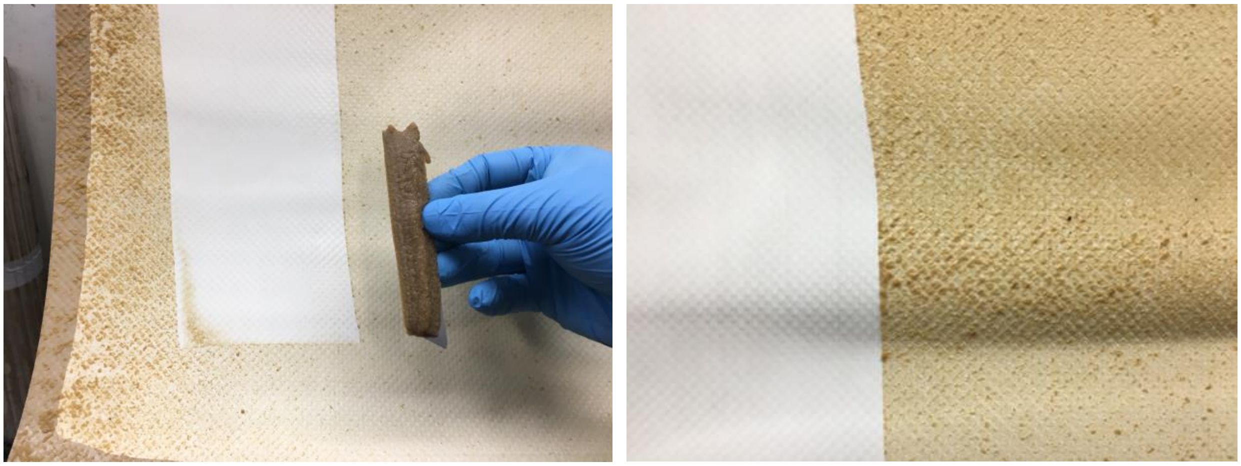
Standard Retest Performance Data							
Element Position	**Original Wet-Test Data**		**Retest**			**% Change From Original Wet-Test**	
	NaCl Rejection (%)	**Flow (GPD)**	**NaCl Rejection (%)***	**Flow (GPD)**	**dP (psi)**	**Salt Passage (%)**	**Flow (GPD)**
Lead Position	99.7%	12,328	99.7%	7,299	14.0	0%	-41%
Tail Position	99.6%	12,967	99.6%	8,984	3.8	0%	-31%

*Retest rejection is normalized based on original Wet-Test Flow

In addition to the positive retest results, the elements were autopsied to visually inspect the integrity of the membrane. The autopsy of the lead element confirmed heavy biofouling on the membrane surface. As seen in Figure 5a, scrapping the biofouling away revealed membrane with good mechanical integrity an no visual signs of failure. A closeup of this same membrane area (Figure 5b) confirmed that the thin backing prevented embossing of the membrane into the permeate carrier. A scanning electron microscope (SEM) photo confirmed the good mechanical integrity of the membrane surface at the microscopic level (Figure 5c).

Figure 4 a and b:

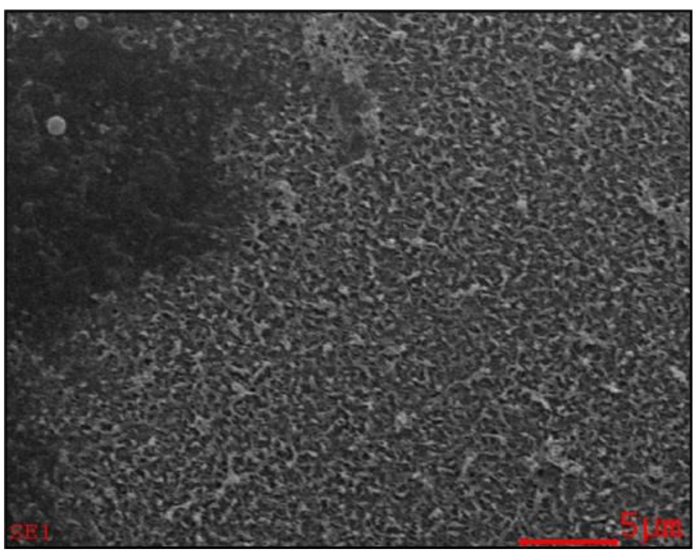
Autopsied lead element revealed a) heavy biofouling scrapped from the surface and b) an imprint of the brine spacer on the membrane surface but no embossing of the membrane into the permeate carrier.



a b

Figure 4 c:

Scanning Electron Microscope (SEM) photo confirmed good mechanical integrity of thin membrane. A darker patch of foulant can be seen in the upper left region of the photo.



C

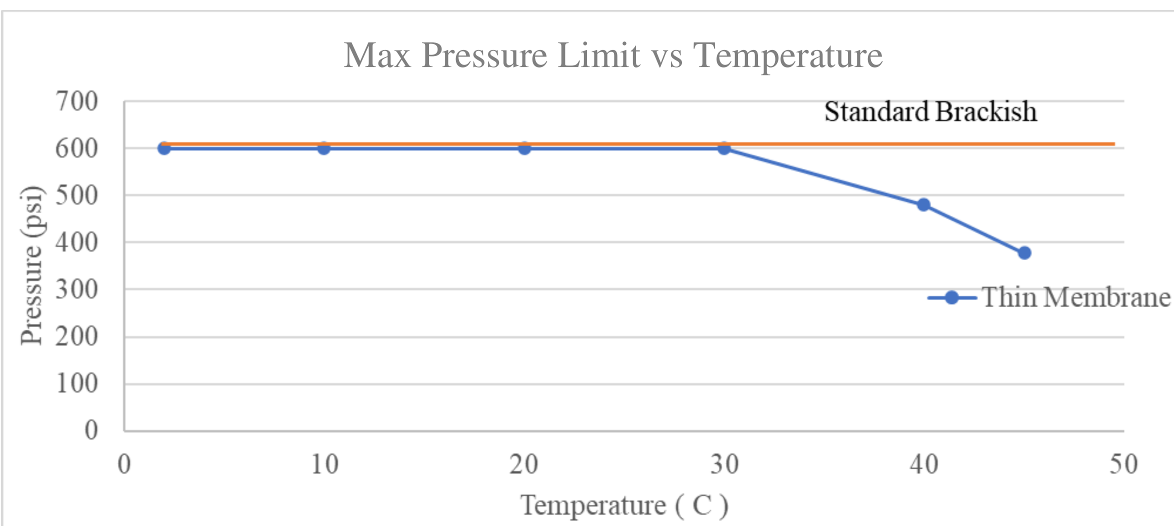
DISCUSSION

Although modification to the thin membrane has no impact on the polyamide rejecting layer, there is the question of how changing the thickness of the support layer might impact the integrity and durability of the membrane as well as the hydraulics in the feed/brine channel of the element.

INTEGRITY AND DURABILITY OF THE MEMBRANE - The extended periods of piloting and full-scale operation, at mild and more challenging conditions, confirms that thin membrane can maintain integrity as well as the conventional, thicker membrane. This is true even under high fouling, high pressure, high differential pressure, and high salinity conditions. Recalling the earlier assumption that the membrane could handle pressure up to 600 psi, it was not surprising to observe the new, thinner membrane running stably at pressures less than 300 psi. Laboratory testing confirms that the thin membrane can withstand the same 600 psi max pressures as the conventional, thicker membrane…with one caveat. Whereas the conventional membrane, with 150-micron thickness, allows for a maximum pressure of 600 psi across the whole temperature range from 1°C to 45°C, the thin membrane allows for a maximum pressure of 600 psi only up to 25°C. After 25°C, the maximum allowable pressure begins to decline as shown in Figure 5. A similar adjustment in the max pressure limit is found at higher pressures on seawater RO membranes as well. The adjustment for seawater and thin membrane accommodates for the softening of the plastics at higher temperatures and avoids embossing of the membrane into the permeate channels.

Figure 5:

Maximum feed pressure limit of the standard brackish membrane and thin membrane as a function of temperature.



HYDRAULICS IN THE ELEMENT - Another question concerns the difference in hydraulics between an element containing thin membrane and an element containing the conventional membrane. To understand the difference in flow dynamics between the two element types, one must consider what is occurring in the feed channel where there is a decrease in crossflow velocity in the higher area, 440 sq ft element. This is because the area within the element is increased by adding more leaves, which increases the feed channel cross sectional area while maintaining the same channel height. With additional channel cross sectional area, flow in each channel is reduced and therefore the crossflow velocity is reduced. Proportionally, the reduction in flow and velocity is very small. Specifically, the 10% increase in area results in 10% more channel cross sectional area which leads to a 10% reduction velocity through each channel.

To illustrate this flow difference, consider a single pressure vessel operating with 52.4 gpm feed flow into the vessel and therefore 52.4 gpm feed flow into the lead element, regardless of which element type is installed in that vessel. If the lead element is the conventional element, with 400 sq ft and 34-mil brine spacer, the element would have a channel cross section area of 164 cm^2 which would result in an average velocity of 0.202 m/s through the channel. If the lead element were constructed with 440 sq ft of the new, thinner membrane, as well as the same 34 mil spacer, then the channel total cross section area would increase to 180 cm^2, which would reduce the velocity into the channel by 10% to 0.183 m/s. How this reduction in velocity would affect performance and fouling in each element can be understood by considering the differences in both concentration polarization and Reynolds numbers.

As water flows through the membrane and salts are rejected by the membrane, a boundary layer is formed near the membrane surface in which the salt concentration at the surface exceeds the salt concentration in the bulk solution. This increase of salt concentration is called concentration polarization. The effect of concentration polarization is to reduce permeate flow rate and salt rejection. The Concentration Polarization Factor (CPF) can be defined as a ratio of salt concentration at the membrane surface (Cs) to bulk concentration (Cb).

$$CPF = Cs/Cb$$

This ratio is directly proportional to the average feed/brine flow and the permeate flow. But, as stated previously, these flows are identical in the two element types. Only the velocities within the channel, and at the membrane surface, are different. For this reason, the ratio of the channel velocity and the permeate velocity must be considered. A decrease in velocity through the channel will decrease the mixing and increase the salt concentration layer at the membrane surface. But a decrease in permeate velocity through the membrane will have the opposite effect. A decrease in permeate velocity will decrease the delivery rate of ions to the membrane surface and decrease the concentration at the surface. Table 4 below compares the ratio of these two velocities within the two elements showing their ratios to be the same. If these two ratios are the same, then the concentration polarization factor at the membrane surface is the same.

Table 4:

Comparing flow velocity ratios (concentration polarization) in single elements wound with conventional membrane and new, thin membrane.

Element	Conventional	New
Feed Flow (gpm)	52.4	52.4
Brine Spacer Thickness (mil)	34	34
Channel Cross Sectional Area (cm^2)	164	180
Flow Velocity in Channel (m/s)	0.202	0.183
Permeate Flow (gpm)	3.3	3.3
Element's Membrane Area (sq ft)	400	440
Permeate Velocity (m/d)	0.48	0.44
Velocity Ratio (Channel to Permeate)	0.42	0.42

Because the velocity of water within the feed/brine channel is different in the two different elements, the difference in Reynolds (Re) number can also be used to consider the difference in fouling potential. Considering the standard formula for Reynolds number:

$$Re = \frac{Dynamic\ Pressure}{Shearing\ Stress} = \frac{\rho v L}{\mu}$$

Where:

ρ = density of water (997 kg/m3)
$\boldsymbol{v}$ = velocity in channel (m/s)
$\boldsymbol{L}$ = characteristic channel length (0.001123 m)
$\boldsymbol{\mu}$ = dynamic viscosity of water (0.001002 kg/m/s)

The two velocities in the same channel, with a 34-mil height, would result in a Reynolds number of 225.2 for the standard element vs 204.8 for the new element. Both Reynolds numbers are well within the laminar flow range. Their difference is negligible relative to a Reynolds number of 10^5 for turbulent flow. This very small difference in Reynolds number would, therefore, make a negligible difference in the rate of fouling for each of the two elements.

BENEFICIAL USE - The use of thin membrane in a spiral wound element means that more active membrane area can be packaged into a spiral wound element without sacrificing brine spacer thickness. Use of the higher area elements with thin membrane can achieve one of the following three benefits in a full-scale system:

1. **Reduce capital cost in a new system**. A newly designed system requiring thicker, 34-mil spacer elements can be designed with 10% less piping and pressure vessels when designing with the higher area 440 sq ft rather than the standard 400 sq ft.

2. **Reduce operating cost in an existing system**. An existing system, using elements with a 34-mil spacer and 400 sq ft, can be replaced with the new elements using a 34-mil spacer and 440 sq ft. With 10% more membrane area and the same permeate flow, the

system will run at lower flux, lower feed pressure and lower energy consumption. In addition to energy savings, the lower flux will reduce the rate of fouling and cost associated with frequent chemical cleanings. No change in the existing system design is required to realize this benefit.

3. **Increase productivity from an existing system**. An existing system can increase its productivity by 10%, without a plant expansion and without reducing the 34-mil brine spacer thickness, by simply replacing old 400 sq ft elements with the new 440 sq ft elements. Because it will operate at a higher flow but the same flux, there will be no change to the feed pressure or energy consumption. If the existing feed pumps can accommodate 10% more flow, then no change in the existing system design is required to realize this benefit.

CONCLUSION

After decades of minor 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 new, thin membrane has been pilot tested on municipal wastewater for almost one year and then operated in a full-scale system treating municipal wastewaters under high fouling, high pressure, and high differential pressure conditions for over one year. During both piloting and full-scale operation, the thin membrane demonstrated its ability to maintain consistent, high rejection of salts and organics. The thin membrane element, with higher active membrane area and thicker brine spacer, has implications for reducing system capital cost, operating cost, or productivity and is especially beneficial for systems with size and weight restrictions.

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