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The importance of long term stable performance and durability of reverse osmosis elements

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ABSTRACT

Water scarcity is being recognized as one of the main threats that mankind is facing globally. Reverse osmosis membrane technology has developed as a promising technology to address this problem. This increase has been driven as materials are improved and costs dropped. This is especially relevant for Middle East countries (ME), where population is located in arid and semi-arid regions with limited rainfalls and a high degree of evaporation due to the high temperatures the region is exposed to. Therefore, getting a robust element that is able to offer a stable salt rejection even after multiple cleanings is of utmost importance to sustain the population and economic growth of the region. This paper aims at demonstrating the superior durability of FilmTec™ membranes compared to other manufacturers. This superior durability has been reported in a number of desalination plants where FilmTec™ membranes lifetime has exceeded more than 10 years, but a quantification and a reliable comparison of such superior durability compared to other manufacturers in a controlled environment has not been completed to date. In this paper, FilmTec™ SW30XLE elements are exposed together with equivalent commercially available membranes from other suppliers to a durability study to simulate long term operation and to determine the evolution of the membrane specifications over time. Particular focus is paid to the changes in salt rejection. Membrane durability plays a determining role in membrane replacement, which ultimately has a critical impact on the economics of any desalination plant. In this study, it was determined that after a number of cleanings, the salt passage increase over time of the membranes from other suppliers was close to 3.5 times larger than the value experienced by FilmTec™ membranes. More specifically, the salt passage increase experienced by FilmTec™ in the first study was 22%, while the membrane from another supplier showed a 73% increase; and in the second study, FilmTec™ had a salt passage increase of 43% while the membrane from the other manufacturer had a 140% salt passage increase. In a 100,000 m^3/d desalination plant, this enhanced durability showed by FilmTec™ elements might represent a 5.5% cost of water decrease in the reverse osmosis stage, and total savings of 1.34 US ¢/m^3 in the whole plant, which can be translated into savings of 488,000 USD/y.

Keywords: Reverse osmosis; Seawater; Robustness; Cleaning-in-place; Desalination

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1. Introduction

Water scarcity is being recognized as one of the main threats that mankind is facing globally [1]. Reverse osmosis (RO) membrane technology has developed as a promising technology to address this problem, holding roughly 44% market share and growing among all the desalinating technologies [2]. This increase has been driven as materials are improved and costs dropped [3]. This is especially relevant for Middle East countries (ME), where population is located in arid and semi-arid regions, with a very limited rainfall, and where due to high ambient temperatures, evaporation contributes to a higher stress degree to the naturally available water sources. Moreover, water scarcity is aggravated by the population increase this region is exposed, as well as the economic development [4]. All these factors, together with the favorable energy to product quality ratio that seawater reverse osmosis (SWRO) offers, has situated this technology as one key driver to sustain population living standards in ME countries [5].

This paper aims at demonstrating the superior durability of FilmTec™ membranes compared to other manufacturers. This superior durability has been reported in a number of desalination plants where FilmTec™ membranes life time has exceeded more than 10 years but a quantification and a reliable comparison of such superior durability compared to other manufacturers in a controlled environment has not been completed to date. In this paper, FilmTec™ SW30XLE elements are exposed together with equivalent commercially available membranes from other suppliers to a durability study to simulate long term operation and to determine the evolution of the membrane specifications over time. Particular focus is paid to the changes in salt rejection.

Finally, it is worth noticing that membrane durability plays a determining role in membrane replacement, which ultimately has a critical impact in the economics of any desalination plant.

2. Methods

In order to compare the durability of the different products, reverse osmosis elements are kept in operation for a certain period of time while being exposed to a number of chemical cleanings. To ensure a fair comparison between FilmTec™ membranes and the elements from other suppliers, a unit, which enables identical side by side operation is used. Details of the protocol used during the study is described below.

2.1. Membranes evaluated

The following low energy grade seawater reverse osmosis elements were tested in the Middle East Innovation Center at the Water Research Center that DuPont has at the King Abdullah University of Science and Technology (KAUST). Two equivalent membranes sets using the FilmTec™ SW30XLE membrane chemistry were tested against two other membrane manufacturer brands. Two different experiments were performed, one with Red Seawater, and the other with synthetic seawater. The specifications of the elements tested can be found in Table 1.

2.2. Water composition

This study was carried out using two different water sources. The first one corresponds to the natural Red Seawater that the KAUST University has natural access to. The water composition can be found in Table 2.

The second type of water used corresponds to synthetic seawater based on 32,000 mg/L of sodium chloride and

Table 2
Red Seawater composition

Compound	Concentration (mg/L)
Ammonium (NH_4)	0.1
Barium (Ba)	0.01
Bicarbonates (HCO_3)	124
Boron (B)	3.4
Calcium (Ca)	425
Carbon dioxide (CO_2)	0.29
Carbonates (CO_3)	43
Chloride (Cl)	22,515
Fluoride (F)	1.41
Magnesium (Mg)	1,329
pH	8.1
Potassium (K)	511
Silica (SiO_2)	1
Sodium (Na)	12,833
Strontium (Sr)	6.2
Sulfate (SO_4)	3,038
Total dissolved solids (TDS)	40,845

Table 1
FilmTec™ reverse osmosis element specifications[a]

Experiment	Product	Active area (ft^2)	Permeate flow (gpd)	Stabilized salt rejection
Seawater (Study 1)	FilmTec™ SW30XLE-400	400	9,000	99.8%
	Membrane A from Supplier 1	400	9,000	99.8%
Synthetic seawater (Study 2)	FilmTec™ SW30XLE-440	440	9,900	99.8%
	Membrane B from Supplier 2	440	9,900	99.85%

[a] Permeate flow and salt (NaCl) rejection is based on the following standard test conditions: 32,000 mg/L NaCl, 5 mg/L B, 55 bar, 25°C, pH 8 and 8% recovery.

5 mg/L of boron added to SWRO permeate. Specific composition of this water can be found in Table 3.

2.3. Experimental plant

Two studies are included in this durability assessment, which were performed in an 8-inch pressure vessel industrial scale unit. Pipping and pressure vessels are made of super duplex stainless steel, in order to prevent corrosion or pitting of the steel. Additionally, a high pressure pump is responsible of delivering seawater at the adequate pressure into the plant. Finally, permeate and filtrate water is collected into a tank, where it is recirculated using the high pressure pump into the membranes. The plant is fully automated through a programmable logic controller (PLC), which records all the signals into a data logger. Feed flow and permeate flow are recorded using accurate flow indicator transmitters. Also temperature, feed conductivity and permeate conductivity are recorded with their respective automatic indicator transmitter instruments. Finally, feed, concentrate and permeate pressure is also automatically monitored and recorded. A plant schematic can be found in Fig. 1. Additionally, a picture of the plant is shown in Fig. 2.

Table 3
Synthetic water composition

Compound	Concentration (mg/L)
Boron (B)	5.0
Chloride (Cl)	19,412
pH	8.0
Sodium (Na)	12,588
Total dissolved solids (TDS)	32,005

2.4. Operating conditions

Two durability studies were performed. The first one was performed using real Red Seawater and the second with synthetic seawater with the objective of validating the results obtained.

During the first study using real seawater, the membranes were operated in recirculation at a feed flow of 8 m^3/h, a water recovery of 13%, and a water flux of 28 $L/(m^2h)$. Feed pressure ranged from 55 to 56 bar. Water temperature changed from 25°C and 29°C. After 2 days of operation, a cleaning-in-place (CIP), consisting of a caustic cleaning at pH 12 at 35°C for 135 min and an acid cleaning at pH 2 and 25°C for 135 min was performed. Then this

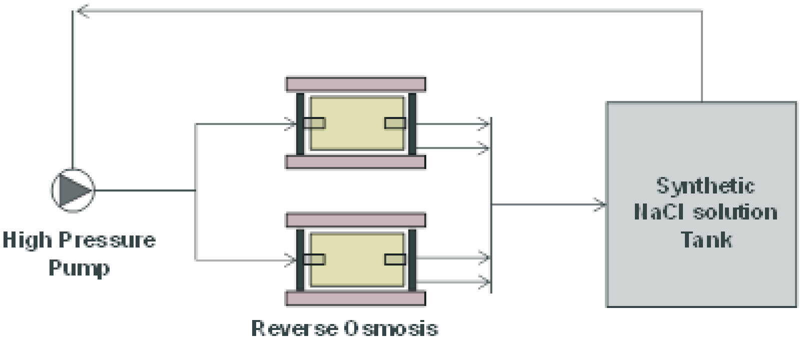

Fig. 1. Durability study pilot plant scheme.

Fig. 2. Durability study pilot plant photo.

operating cycle was repeated until 12 cleanings were completed. After this time, membranes were left in operation until they were fully stabilized.

The second study used synthetic seawater, the membranes were operated in recirculation at a feed flow of 14–19 m^3/h, a water recovery of 13%, and a water flux of 30 L/(m^2h). Feed pressure ranged from 44 to 55 bar. Water temperature changed from 25°C and 29°C. After 5 days of operation, a cleaning-in-place, consisting of a caustic cleaning at pH 12 at 35°C for 135 min and an acid cleaning at pH 2 and 25°C for 135 min was performed. Then, this operating cycle was repeated until 5 cleanings were performed. After this time, membranes were left in operation until they were fully stabilized.

2.5. Cost model

Potential cost savings are modeled using the cost model developed by Markus Busch [6]. In order to perform this simulation exercise, a seawater reverse osmosis desalination plant of 100,000 m^3/d with DuPont IntegraFlux™ SFP-2880 Ultrafiltration modules being operated at 70 L/m^2 h is modeled. In the first pass, the reverse osmosis modeled uses FilmTec™ SW30XLE-440 elements, and operates at 12 L/m^2 h at 45% recovery. The second pass uses FilmTec™ ECO PRO-400 elements, and it is operated at 17 L/(m^2h) at 70% recovery. Lifetime of the plant is assumed to be 20 years, an interest depreciation rate is considered to be 10% and electricity price is chosen to be 0.08 USD/kWh.

3. Results

3.1. Durability study with real seawater (Study 1)

FilmTec™ SW30XLE-400 has been compared against another membrane from manufacturer 1, herein depicted as Membrane A. This membrane is commercially available and has similar published specifications as the FilmTec™ product. Focusing on the trend of the normalized water permeability coefficient (A-value) over time, it can be observed that both membranes showed a similar performance and evolution. It should be noticed the A-value evolution is the same as the normalized permeate water flow. This trend is depicted in Fig. 3.

The analysis of normalized salt passage evolution over time is presented in Fig. 4. It should be noticed that this normalized salt passage evolution is herein represented and is proportional to the salt passage coefficient (B-value). In this plot, it can be observed that despite FilmTec™ SW30XLE-400 started with a 30% higher salt passage compared to Membrane A, after the second cleaning (CIP), both membranes showed the same normalized salt passage. Finally, at the end of the experiment, Membrane B showed a 10% higher salt passage compared to the SW30XLE-400 membrane. This indicated that while SW30XLE-400 experienced an increase in normalized salt passage of 22%, Membrane A experienced an increase of 73% in salt passage. The salt passage increased showed by Membrane A is almost 3.5 larger than the value of the SW30XLE membrane.

In order to help summarizing these results, the stabilized normalized B-values after each cleaning has been recorded, and converted to equivalent normalized salt rejection. Then, it has been assumed that each year, a seawater desalination plant might perform 4 cleanings (CIP) per year. All these points that represent durability impact over time have been fitted into a grade 3 polynomial. The correlation for both SW30XLE-400 and Membrane A have been rather good, obtaining R^2 values of 0.9486 and 0.9582 respectively. Fig. 5 shows this analysis, where the same conclusions as the previous plot shows can be obtained.

3.2. Durability study with synthetic water (Study 2)

FilmTec™ SW30XLE-440 has been compared against a membrane from manufacturer 2, herein depicted as Membrane B. When observing the normalized water permeability coefficient (A-value) over time, it can be observed that both membranes showed a similar performance and evolution over time, having Membrane B up to 14% higher water permeability. This trend is depicted in Fig. 6.

The analysis of normalized salt passage evolution over time is presented in Fig. 7. It should be noticed that this

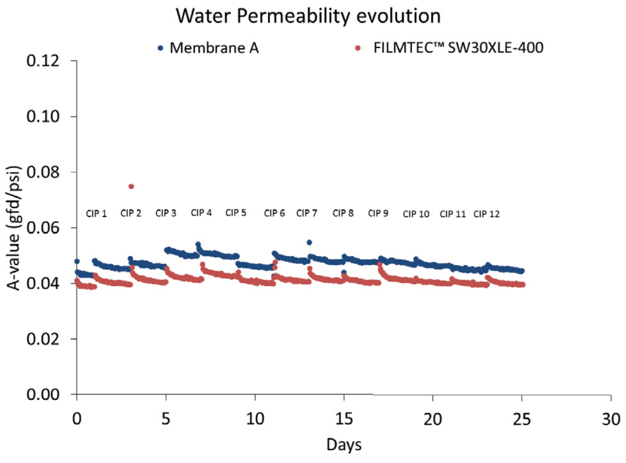

Fig. 3. Water permeability evolution of Membrane A vs. FilmTec™ SW30XLE-400.

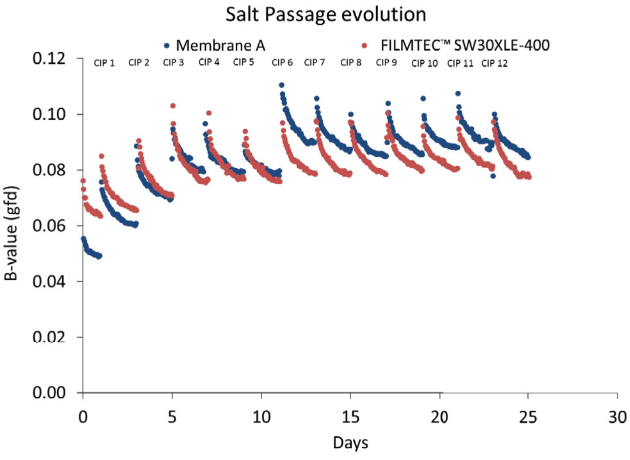

Fig. 4. Salt passage evolution of Membrane A vs. FilmTec™ SW30XLE-400.

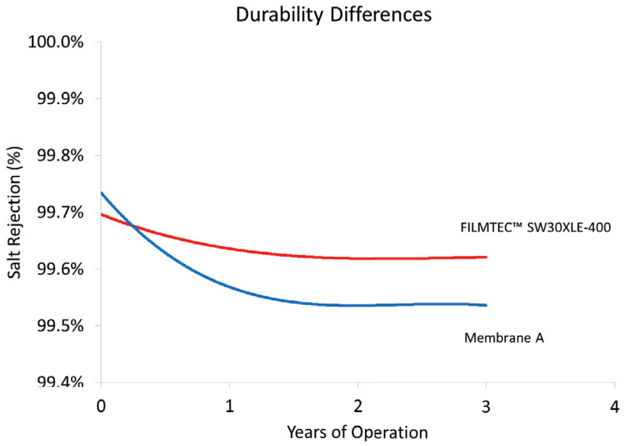

Fig. 5. Durability differences of Membrane A vs. FilmTec™ SW30XLE-400.

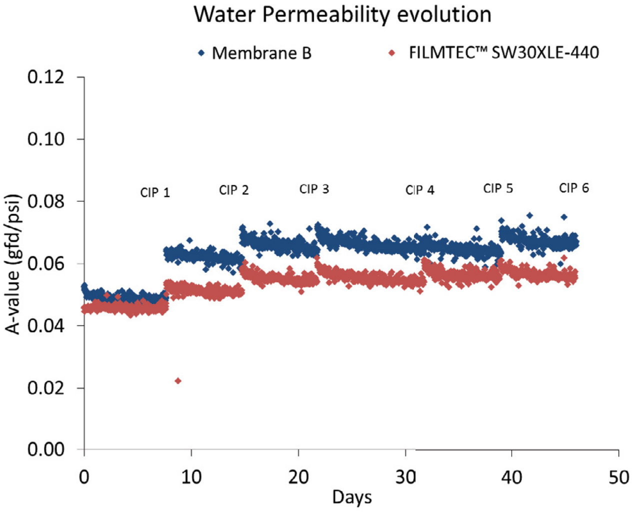

Fig. 6. Water permeability evolution of Membrane B vs. FilmTec™ SW30XLE-440.

normalized salt passage evolution is herein represented and is proportional to the salt passage coefficient (B-value). In this plot, it can be observed that despite FilmTec™ SW30XLE-440 started with a 37% higher salt passage compared to Membrane B and that after the second cleaning (CIP), both membranes showed the same normalized salt passage. Finally, at the end of the experiment, Membrane B showed a 23% higher salt passage compared to the SW30XLE-440 membrane. This indicated that while SW30XLE-440 experienced an increase in normalized salt passage of 43%, Membrane B experienced an increase of 140% in salt passage. Similar to the results of Membrane A, Membrane B experienced an increase in salt passage close to 3.5 times larger than the FilmTec™ membrane. It is worth emphasizing that despite SW30XLE-440 seemed to experience a greater increase in normalized salt passage over time, this was due to the fact that the SW30XLE-400 started with a lower rejection. However, it can be seen that both elements tend to reach a similar stabilized normalized salt rejection point.

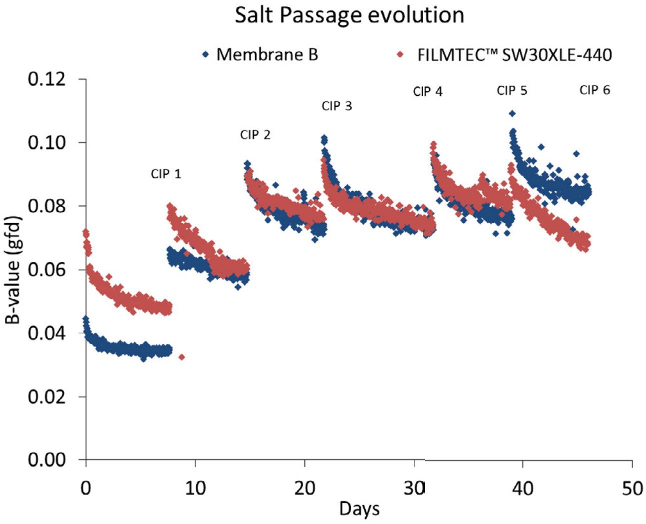

Fig. 7. Salt passage evolution of Membrane B vs. FilmTec™ SW30XLE-440.

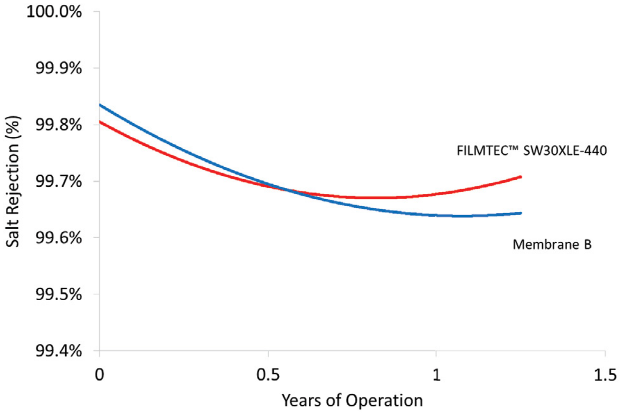

Fig. 8. Durability differences of Membrane B vs. FilmTec™ SW30XLE-440.

In order to help summarizing these results, the stabilized normalized B-values after each cleaning has been recorded, and converted to equivalent normalized salt rejection. Then, it has been assumed that each year, a seawater desalination plant might perform 4 cleanings (CIP) per year. Then, all these points that represent durability impact over time have been fitted into a grade 2 polynomial. The correlation for both SW30XLE-440 and Membrane B have been good, obtaining R^2 values of 0.9572 and 0.9493 respectively. Fig. 8 shows this analysis, where the same conclusions as the previous plot shows can be obtained.

3.3. Potential savings

Assuming that replacement rates in the first pass are set up into an hypothetical value of an annualized rate of

12%, and thanks to the more than 3 times lower salt passage increase achieved in the DuPont membranes, DuPont replacement rates can be set to 4%, while others such as Membrane A and B are set to 12% could be assumed. This would represent savings in the total cost of water of 5.5% in the whole reverse osmosis part corresponding to 1.26 US ¢/m^3, and up to 2.1% in the whole desalination plant corresponding to 1.34 US ¢/m^3. In this specific example of a 100,000 m^3/d, this will represents a savings of 488,000 USD/y to the whole seawater desalination plant. A table with each cost depicted is available in Table 4.

Table 4
Cost breakdown of potential savings in a 100,000 m^3/d seawater desalination plant in US ¢/m^3

Item	Normal replacements	Lower replacements
Intake and primary treatment - CapEx	3.41	3.41
Intake and primary treatment - OpEx	1.43	1.43
Ultrafiltration - CapEx	3.35	3.35
Ultrafiltration - OpEx	3.06	3.06
Pre RO stage - CapEx	0.21	0.21
Pre RO stage - OpEx	0.41	0.41
RO stage - CapEx	12.90	12.90
RO stage - OpEx	22.85	21.59
Brine and potabilization - CapEx	1.25	1.25
Brine and potabilization - OpEx	0.33	0.33
General cost - CapEx	6.25	6.25
General cost - OpEx	3.53	3.53
Contingency and profit - CapEx	4.25	4.25
Contingency and profit - OpEx	1.90	1.82
Total	65.14	63.81

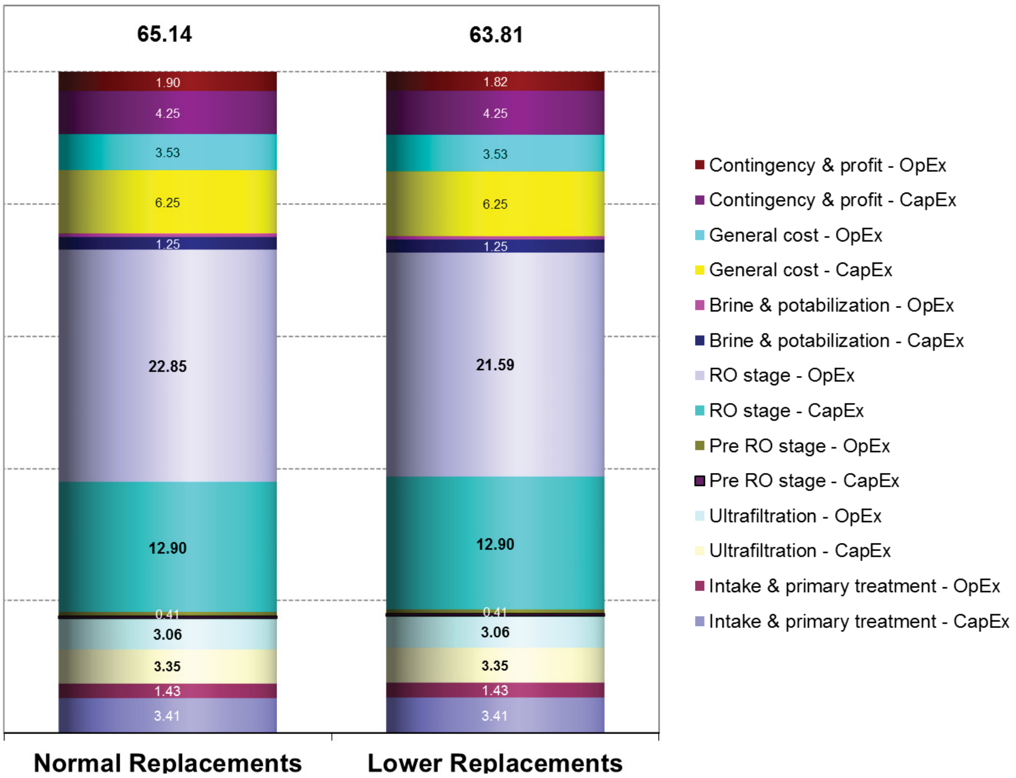

Fig. 9. Scheme of potential savings in a 100,000 m^3/d seawater desalination plant in US ¢/m^3.

A more visual cost breakdown can be seen in Fig. 9, where it can be seen the cost advantage thanks to the reduction in reverse osmosis replacement in the first stage.

4. Conclusions

Membrane durability associated to the period of time during which a membrane maintains a good performance plays a critical role in the economics of any seawater desalination installation. In this paper, the durability of FilmTec™ membranes is compared with two commercially available products with similar published specifications from two other manufacturers. In order to assess the durability of each membrane, they have been exposed to normal operation and a number of cleanings. The evolution of permeate flow and salt passage is closely monitored to assess the durability of each product. The key conclusions reached from this work are listed below:

- As a result of the chemical cleanings, all membranes experienced a decrease in salt rejection. FilmTec™ membranes observed a salt passage increase of 22% when operated with real seawater, while Membrane A experienced a salt passage increase of 73%. When operated with synthetic water, salt passage increase experienced by FilmTec™ membrane was 43% while Membrane B showed a 140% salt passage increase.
- Membranes A and B from other suppliers showed a close to 3.5 times larger salt passage increase compared to FilmTec™.
- Higher durability can be translated into lower membrane replacement rates. It is estimated that in a 100,000 m^3/d desalination plant, this enhanced durability of FilmTec™ membranes might represent savings of 5.5% in the reverse osmosis stage and 2.1% in the whole desalination plant. The total savings in the whole plant are estimated to be of 1.34 US ¢/m^3, which represents a total savings of 488,000 USD/y.

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