THIN-FILM NANOCOMPOSITE MEMBRANES YIELD HIGH REJECTION AND REDUCE THE NEED FOR A SECOND PASS

Authors: Mike B. Dixon, Christopher Kurth, Warren Casey, Robert L. Burk, Randy Truby.

Presenter: Mike B. Dixon, Ph.D.
Senior Applications Engineer – NanoH_2O, Inc. – United States
mdixon@nanoh2o.com

Summary:

Since the first reverse osmosis (RO) membranes were commercialized in the 1960s, the desalination industry has undertaken extensive research to improve membrane salt rejection without sacrificing flux. Beginning in 1978, when industry-standard salt rejection was at 98.60%, membrane manufacturers steadily improved the formulation of thin-film composite membranes to achieve the present day standard of 99.70% to 99.80%. In early 2012, NanoH_2O introduced a high-rejection thin-film nanocomposite (TFN) seawater reverse osmosis (SWRO) membrane capable of 99.75% to 99.85% salt rejection and yielding 93% boron rejection at pH 8.

This paper provides a history of membrane salt rejection and improvements to SWRO industry-best practices between 1978 and 2012. Details of specific applications are provided in which the TFN high-rejection membranes deliver improved first-pass permeate quality over traditional SWRO membranes available on the market. The paper also cites two hypothetical membrane scenarios at two actual desalination plants (Barcelona, Spain and Shuwaikh, Kuwait) to illustrate different methods of reducing second-pass size. Additionally, data from the Palmachim desalination plant illustrates how high-rejection TFN membranes have been successfully used to potentially reduce the load on the second pass.

I. INTRODUCTION:

Reverse osmosis elements are routinely designed, manufactured and sold against a published performance "specification sheet" that describes the individual membrane element performance on reference seawater at defined conditions. These performance specifications are then integrated into projection software that allows engineers to predict the performance of a group of membranes using a specific feed water type at the anticipated temperature, recovery, operating pressure and other variables. Over the years, changes in published performance specifications testify to the improvements made in the performance of SWRO membrane elements.

Table 1 details SWRO membrane performance improvements between 1978 and 2012. The published specifications have been normalized over time against Fluid Systems' TFC 1501 elements used in the original 1978 Jeddah RO plant. Each Fluid Systems element contained 14 m^2 (150 ft^2) of membrane area. The published data sheets indicate the elements produced 5.7 m^3/day (1,500 GPD) at 55 bar (800 psi), 10% recovery and NaCl rejection of 98.60% [1]. Over time, there have been incremental improvements in both membrane rejection and flux. However, with the introduction of NanoH$_2$O's Qfx SW 400 SR high-rejection SWRO membrane in early 2012, a new industry standard has been set with 99.85% rejection at 24.6 m^3/day (6,500 GPD).

Table 1: Normalizing Salt Passage and Membrane Life

Year	Salt Passage %	Norm. Salt Passage	Membrane Life Years	Norm. Membrane Life
1978	1.4	1	3	1
1989	1	0.71	3	1
1995	0.8	0.57	5	1.7
2000	0.5	0.36	5	1.7
2002	0.4	0.29	5	1.7
2006	0.2	0.14	7	2.3
2008	0.2	0.14	7	2.3
2010	0.2	0.14	7	2.3
2012	0.15	0.11	7	2.3

This paper demonstrates how to avoid the need for a second pass using high rejection membranes featuring 99.85% NaCl rejection. This reduced dependence on a second pass has the potential to decrease capital expenditure by minimizing membrane and equipment needs, and lower operating expenditures through energy and maintenance savings. This has been illustrated below by: 1) undertaking projections using the element performance outlined in Table 1 to show how the percentage of water that needs treatment by a second pass has reduced; and, 2) an example of how the need for a second pass can be completely avoided by using a 99.85% rejection membrane in the first pass. This simulation uses parameters from a well-known full-scale plant, El Prat de Llobregat, in Barcelona, Spain. A second simulation shows how second-pass size can be reduced in a plant with a more challenging water quality (Shuwaik Desalination Plant in Kuwait). Additionally, a pilot study and full-scale plant results from the Palmachim

Desalination Plant illustrate how this strategy has been employed, and how the Qfx SW 400 SR performed to a reliably high standard.

II. REDUCED DEPENDENCY ON SECOND PASS THROUGH IMPROVED ELEMENT REJECTION

Projections using NanoH$_2$O's Q+ software were undertaken to demonstrate that as membrane technology has progressed, the dependence on a second pass has decreased. In these scenarios, a specifically challenging water profile was created [40,000 mg/L total dissolved solids (TDS), 30^o C, 45% recovery] along with a system production capacity of 12,500 m^3/day (3,302,150 GPD) and a target permeate TDS of 200 mg/L. Hypothetical elements were profiled based on each year of normalized performance as outlined in Table 1. Then, a mock system was created for each hypothetical element using a seven-element pressure vessel (PV) design. The number of elements used in each first pass design was determined based on an average system flux requirement of 8.8 gfd (15 LMH). The second-pass projections used a 37 m^2 (400 ft^2), 39.7 m^3/day (10,500 gpd) brackish water membrane with 99.5% rejection in a two-stage (Stage 1 = 60x7; Stage 2 = 30x7) design with 80% recovery. As first-pass element performance improved, the size of the second pass also needed to be reduced to meet minimum concentrate flows. Figure 1 indicates that as the performance of elements improved from 1978 to 2012, the percent of water required to be sent to a second pass was reduced from 100% to 0%, while at the same time the number of elements in the first pass was reduced by over three-fold.

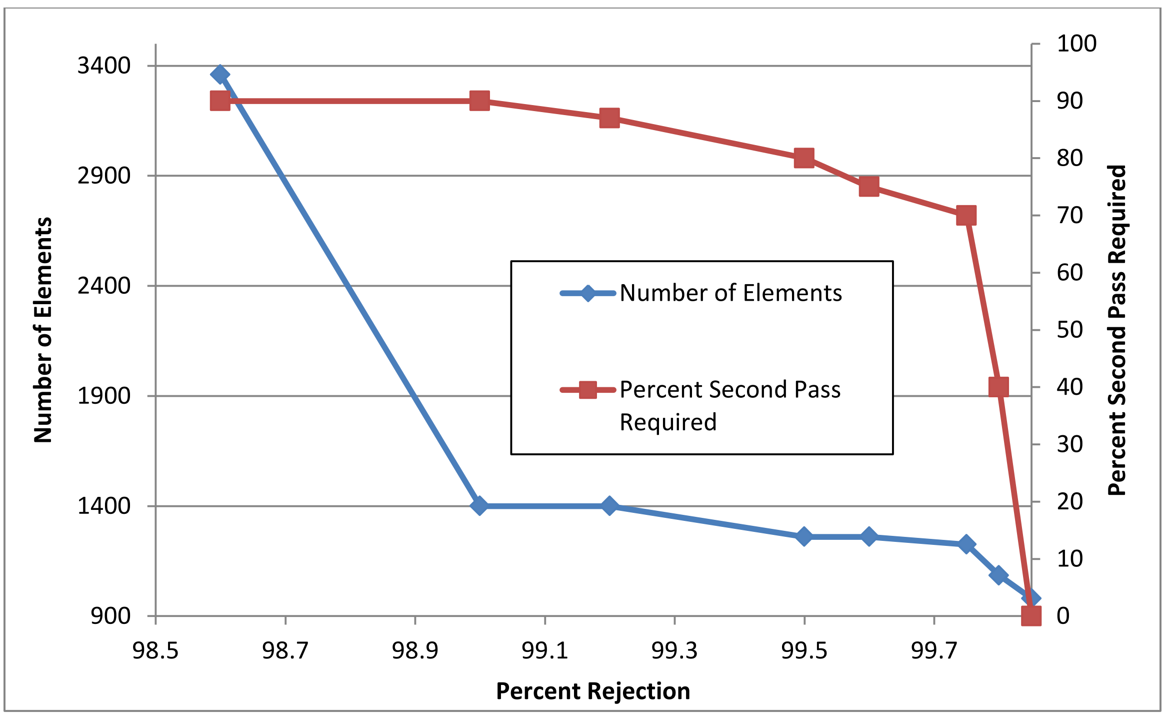

Figure 1. Number of first-pass elements required and percent of second-pass treatment needed as rejection increased over time from 1978 (98.5%) to 2012 (99.85%)

III. THEORETICAL CASE STUDY - BARCELONA

The desalination plant at El Prat de Llobregat is a 200,000 m^3/day (52,834,410 GPD) municipal plant located in Barcelona, Spain. The plant runs at 45% recovery with 10 first-pass RO trains of 20,000 m^3/day (5,283,441 GPD) with 230 pressure vessels, each of which are seven elements long, totaling 1,610 elements provided by Competitor A. The plant utilizes a small second pass of 546 elements during times of higher water temperature to maintain a Boron target of 1.0mg/L in the product water [2].

A theoretical alternate design was considered using NanoH$_2$O's Q+ Projection Software. In order to calculate adequate projections, parameters from [2] were used, but some assumptions were made, including the use of a typical seawater elemental analysis and operation of the energy recovery device at 5% volumetric mixing. A high seawater temperature for this plant was selected to provide a worst-case scenario example. In Table 2, cases 1 and 2 are projections for the mean feed water TDS, while cases 3 and 4 are projections involving a high TDS scenario based on two standard deviations from the mean.

Table 2: Projected first-pass operational parameters for the El Prat de Llobregat Desalination Plant using NanoH$_2$O's Qfx SW 400 SR high-rejection elements

Input					
Water Type	Units	Case 1	Case 2	Case 3	Case 4
Feed TDS	mg/L	37,206	37,206	38,681	38,681
Temp	°C	30	30	30	30
Yr of operation		0	5	0	5
Output					
TDS	mg/L	170.1	213.4	179.2	224.7
Boron	mg/L	0.78	0.94	0.83	0.99
Average Flux	LMH	14.0	14.0	14.0	14.0
Max. Element Recovery	%	12.5%	11.1%	12.7%	11.3%

Table 2 shows that by using Qfx SW 400 SR elements, permeate TDS concentration is low even during periods of higher feed water TDS. Permeate Boron concentration is also below the target of 1.0 mg/L despite the higher feed water TDS concentrations. Over the aging period of five years, the permeate Boron approaches 0.99 mg/L. If a rolling element replacement schedule were to be implemented, in which a small percentage of elements are replaced per year to avoid a major membrane replacement at end-of-life, the permeate Boron concentration could be controlled without the need for further treatment by a second pass. The capital cost required for the second pass at the Barcelona plant could have been saved given the higher rejection capability of the Qfx SW 400 SR membrane.

III. THEORETICAL CASE STUDY - KUWAIT

Desalination has a long history in Kuwait, where the world's first multi-stage flash (MSF) desalination plants were installed in 1953. However, RO desalination in Kuwait is a relatively new process and presents an interesting challenge, given that the country is located at the head of the Arabian Gulf. The feed water quality in Kuwait is poor, with TDS concentration as high as 45,000mg/L. Kuwait's first RO plant, Shuwaikh Desalination Plant, was commissioned in 2011 and has a capacity of 136,000 m^3/day (35.9 MGD). The plant runs at 40% overall recovery with 10 (plus one) first pass RO trains of 15,120 m^3/day (4.0 MGD).Each train has 154 pressure vessels, seven elements long, totaling 1,078 elements per train provided by Competitor B [99.75% rejection and 28.4 m^3/d (7,500 GPD) flux membranes]. Shuwaikh has a second-pass bypass design, and at times of maximum temperature, this bypass diverts 21% (1,300 m^3/h) to product water storage. The plant has a design range of 18^o to 35^o C. It utilizes a second pass of four (plus one) trains, each with 112 pressure vessels that are seven elements long, totaling 784 elements per train. The second pass pH can be adjusted to maximize Boron removal if required. The Boron target is < 1.0mg/L, and the product water TDS requirement is < 300 mg/L [3].

NanoH_2O's Q+ Projection Software was used to calculate a theoretical alternative design (Table 3). The alternate design used all SR elements in the first pass and assumed a membrane age of three years. As a result, the SR design's first-pass permeate TDS concentration was approximately half of what was produced by Competitor B. This meant that more water could be sent to the bypass and mixed with second-pass permeate in the product water tank. As less water requires treatment by a second pass, a smaller number of vessels are thus needed. Whereas Competitor B's design utilizes a total of 448 second-pass vessels for the entire plant, the alternate SR design requires only 152 vessels, approximately two-thirds fewer vessels, to maintain similar flux rates and combined permeate TDS. These 152 vessels could easily be housed in a single train, eliminating the need for three of the four second-pass trains. As this design would also require less instrumentation, controls and hardware, capital costs could be considerably reduced.

Table 3. Projected operational parameters for Shuwaikh Desalination Plant using NanoH$_2$O's Qfx SW 400 SR high-rejection elements in the first pass.

		Case 1	Case 2	Case 3	Case 4
Inputs					
Temperature	°C	18	18	35	35
Year of Operation		0	3	0	3
Bypass Flow	m^3/h	4725	4725	4725	4725
First-Pass Average Flux	LMH	15.8	15.8	15.8	15.8
Outputs					
First-Pass TDS	mg/L	110.4	126.9	290.3	332.8
First-Pass Boron	mg/L	0.58	0.65	1.14	1.27
Second-Pass Flow	m^3/h	1,418	1,418	1,418	1,418
Second-Pass TDS	mg/L	1.6	2.1	10.4	13.3
Second-Pass Boron	mg/L	0.2	0.25	0.69	0.81
Totals					
Combined TDS	mg/L	85.3	98.1	225.7	259.1
Combined Boron	mg/L	0.49	0.56	1.04	1.16
Combined Boron with pH 11.0	mg/L			0.90	1.00

IV. PALMACHIM STUDY

During a plant expansion phase, the Palmachim Desalination Plant adopted a conventional first-pass design using all Qfx SW 400 SR elements in order to limit the size of the additional second pass required to meet permeate specifications. Pilot testing was first undertaken to assure the contractors of the Qfx SR membrane's performance, followed by the installation of a single rack onsite. In 2012, additional NanoH$_2$O racks were brought online until 8,000 elements were producing 110,000 m^3/day (29 MGD) of permeate onsite. The full-scale plant has operated since 21 June, 2012 and produced the system rejection data seen in Figure 2 below.

In preparation for the upgrade, TFN elements were piloted onsite at the plant. NanoH$_2$O conducted projections for the required first-pass scenario and proposed an array of eight Qfx SW 400 SR elements in a single pressure vessel. A trial period of 56 days yielded an average normalized system rejection of 99.83% (Figure 2). During this period, average TDS was 40,682 mg/L, average temperature was 28.6° C, and the average pH was 8.0. Feed flow of 45.4 m^3/hr (287,832 GPD) and a feed pressure of 70 bar (1,015 psi) at 50% recovery produced a permeate flow of 22.7 m^3/day (5,997 GPD). As system rejection is usually lower than an individual element's NaCl rejection at industry standard testing conditions (32,000 mg/L, 25°C, 8% recovery), 99.83% average salt rejection is an excellent result.

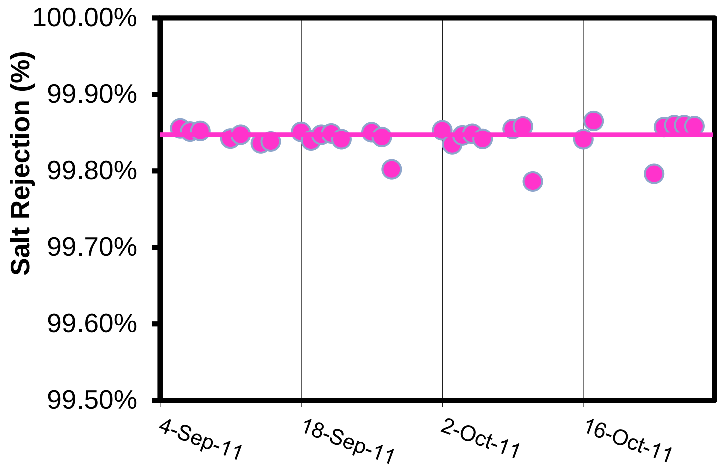

Figure 2: Salt rejection at Palmachim pilot study using Qfx SW 400 SR

After the successful pilot, a single train of NanoH$_2$O elements was installed. This full-scale trial was put into operation on 21 June, 2012.

Initial start-up conditions for Train 6 were as follows:

- Permeate Flow: 1,033 m^3/hr (6.5 MGD)
- Membrane Flux: 13.15 LMH
- Feed Water Recovery: 46%
- Feed Water TDS: 41,660 mg/L
- Feed Water Temperature: 27.6° C (81.7° F)

After the first 24 hours of operation, membrane performance stabilized, producing permeate water that met the contractor's specifications for quality and capacity. As seen from the normalized permeate flow (Figure 3), the NanoH$_2$O elements did not experience any flux decline after the first three weeks of operation. It is common for other manufacturers' elements to experience significant flux decline as a result of membrane compaction and/or deformation of other components of the spiral-wound element during the first few weeks of operation.

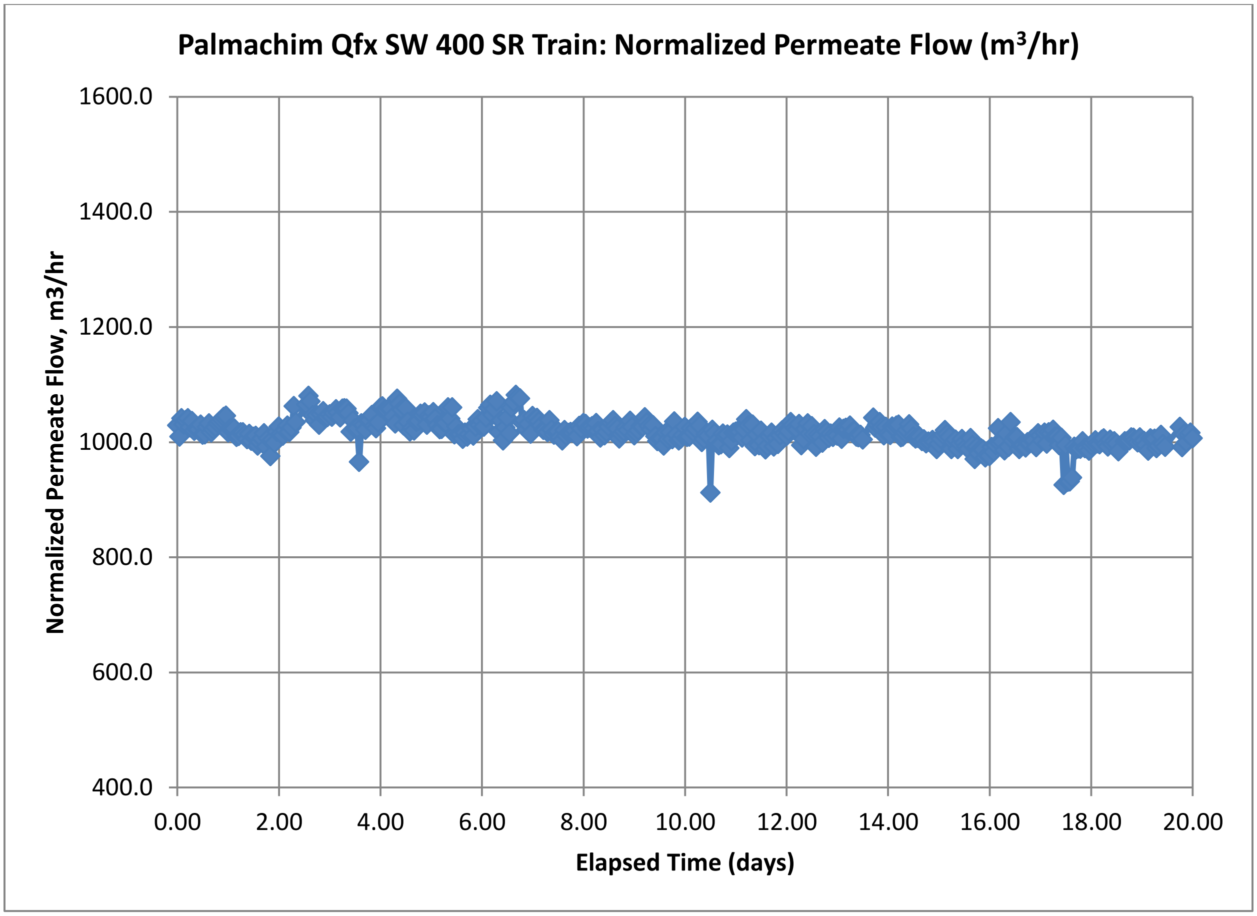

Figure 3. Normalized permeate flow from the Qfx SW 400 SR elements in the full-scale train at Palmachim

Figure 4 presents the normalized system rejection results for the full-scale trial. A system average rejection of 99.5% is expected and falls in line with the system projections made prior to plant commissioning. RO system rejection was calculated based on the logarithmic mean average feed concentration within the RO unit at the average flux of all the membrane elements in actual operation, which in this case is 13.15 LMH. All membrane manufacturers test and rate their single membrane element rejection at a flux much higher than the flux used for actual operation. If the actual salt rejection for this trial was normalized to the membrane test flux of 27.6 LMH, the normalized salt rejection would be approximately 99.85%, which is the rated average salt rejection of the Qfx SW 400 SR element.

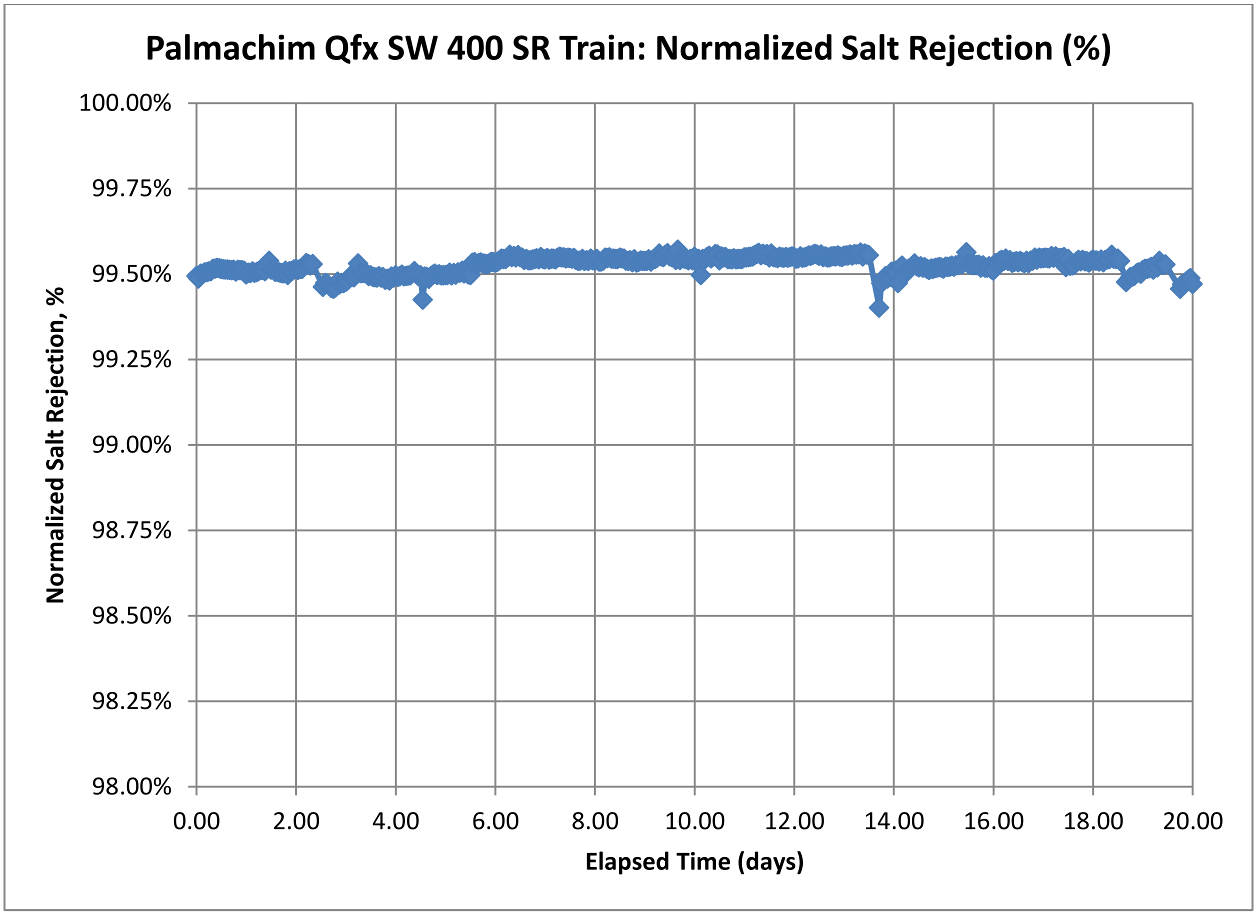

Figure 4. Normalized system salt rejection from the Qfx SW 400 SR elements in the full-scale train at Palmachim

These data show that the Qfx SW 400 SR has reliable performance in terms of flow and rejection. This gives designers and operators the confidence to reduce the size of future second-pass installments as illustrated in this paper, knowing that permeate specifications will be met.

V. CONCLUSIONS

This paper demonstrates how to reduce the need for a second pass using high-rejection membranes featuring 99.85% NaCl rejection. This is illustrated by: 1) undertaking projections using the element performance outlined in Table 1 to show the decrease in the amount of water requiring treatment by a second pass; and, 2) an example of how the need for a second pass can be completely avoided by using a 99.85% rejection membrane in the first pass. This simulation uses parameters from a well-known full-scale plant, El Prat de Llobregat, in Barcelona. A second example using the Shuwaikh Desalination Plant in Kuwait shows that despite high seawater TDS, the size of a second pass can still be dramatically reduced. Finally, operational data from both the pilot test and the full-scale system at the Palmachim Desalination Plant illustrate how these high-rejection TFN elements deliver the reliability and quality to encourage designers to reduce the size of the second pass. Reduced dependence on a second pass has the potential to decrease capital expenditure by minimizing membrane and equipment needs, and lower operating expenditures through energy and maintenance savings.

VI. REFERENCES

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