Optimized Removal of Boron and Other Specific Contaminants by SWRO Membranes

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Abstract

New seawater reverse osmosis (SWRO) plants are providing larger percentages of water used for potable supply. As these plants provide more water, the effects of certain low concentration impurities can become more critical. Two important elements or compounds are boron and bromide. A variety of recent papers have reviewed the need to increase pH of the 2nd pass SWRO permeate to be able to achieve the needed boron rejection. In contrast, bromide rejection is not well characterized and rejection cannot be improved by a pH change.

New seawater membrane products have been developed which can help reduce the levels of both boron and bromide in the permeate. Selection of the optimum membrane depends on the particular feedwater and operating conditions. In all cases, the designer would like to pick the membrane that just meets the required value of Total Dissolved Solids (TDS), chloride, boron and bromide, while operating at the lowest pressure possible. With so many low pressure membranes available, it is not always clear which membrane should be selected. This paper will give a process simulation comparison of various membranes and establish guidelines which can be used to select the optimum membrane.

Data from pilot plant tests and full-scale plants are also presented to validate the design simulations. The plant results compare high rejection and high flow elements. The results confirm that very high rejection can be obtained with new high rejection SWC4+ elements and that somewhat lower rejections can be obtained at much lower pressures with the high flow SWC5 or SWC6 elements.

In addition to the selection of the best membrane, the optimum process should also be selected. One design available to engineers is the use of 1st pass alkalization. By increasing the pH of the seawater feed, the boron in the SWRO permeate was reduced by 26-62%. In some cases, this can greatly reduce or eliminate the need for a second pass. Such process considerations are compared and contrasted to guide designers on the lowest cost options.

I. INTRODUCTION

Many seawater desalination plants are providing an ever increasing proportion of water for municipalities in arid regions and for agriculture irrigation. This has raised some new issues due to potable water and agriculture water quality requirements. In the past, the amount of water supplied by RO systems was smaller and when blended with other natural water sources, it was easier to meet various water quality targets. Alternatively, other communities, such as those in the Middle East, have had a significant blend of water from thermal desalination, which has extremely low values of salts and other contaminants. Today, RO membranes are proving to be the most economical process for desalination, and are being used more frequently. Therefore, significant development activities have focused on optimizing RO membranes and processes to meet these specific water quality targets at the minimum expense.

One of the contaminants of interest is boron. Much consideration has been given to this issue in recent years. (1-6) Although current SWRO membranes have high rejection of ionized salts like sodium and chloride, boron is more difficult to remove because it is only moderately ionized in natural seawater. A number a papers have addressed this issue in recent years and pointed out that second pass treatment of SWRO permeate can be much more effective when carried out at elevated pH. (3) Indeed, boron passage in a second pass RO can be reduced by as much as 70% if operated at pH 10 instead of pH 8.

In some cases, a second pass is only needed to reduce boron levels, which greatly increases the cost and complexity of the treatment plant. Also the added cost of caustic to raise pH further increases operating costs. This has motivated RO process design engineers to seek alternative designs to minimize this concern. One scheme being considered is the process of adding caustic to the seawater feed. (7) By raising the SWRO feed pH, the boron passage in the first pass can be significantly reduced. Changing pH from 8.1 to 8.6 can reduce boron passage by 40%. Especially for cases that require a maximum of 1 ppm boron in the permeate, this treatment will eliminate the need for a second pass and save hundreds of thousands of dollars of capital expense. The added benefit of this approach is that the expense of adding caustic to the seawater feed is only necessary infrequently, for cases such as high temperature and older membranes. On the contrary, the expense of a second pass occurs from the beginning of the plant, and there is frequent use of caustic to enhance brackish water RO (BWRO) performance.

This paper will look at the effect of various designs on the cost of boron treatment. The designs will compare seawater alkalization versus second pass alkalization to determine which is more economical. Plant data will also be shown to provide performance data for these calculations. The key advantage of seawater alkalization is seen when the permeate TDS can be achieved with high rejection first pass seawater elements. In those cases where TDS can be met, but not boron, seawater alkalization can prevent the need for a second pass. In addition, for those cases where a second pass is needed, the use of alkalization can help reduce the cost of second pass alkalization. This trade-off will be considered.

The selection of the optimum design is heavily influenced by the membrane's boron rejection. This paper will present recent data and development activities to provide SWRO elements with higher boron rejection. Most SWRO membranes today have boron rejection around 90 to 93%. However, new products have been developed which have as much as 95% boron rejection. Operating data for these new membranes will be presented, as well as a review of design considerations for the best use of these membranes to reduce desalination costs while still meeting the product water specifications for TDS, chloride and boron.

Another key concern for engineers developing SWRO processes is bromide removal. Bromide concentration in seawater is relatively low, on the order of 50 to 100 mg/L. At such low levels, it would not be considered to be a health concern. However, bromide can react with ozone to form bromates, which do pose significant health concerns, since they are considered a potential carcinogen. Additionally, communities which use desalinated seawater will often blend this treated water with chloraminated potable water. It has been found that bromide concentrations greater than 0.20 mg/L can make it difficult to maintain desired chloramine concentrations. It is understood that bromide can react with chloramine to form bromamine. Bromamine is a much more aggressive oxidant and will decay more rapidly. Thus, membrane processes are being closely studied to understand the ability to produce sufficiently low bromide concentrations. This paper will review the performance of state of the art RO membranes for the removal of bromide. Actual plant data will be shared, which shows that bromide rejection is on the order of 99.3% at high temperatures.

II. DESIGN CONSIDERATIONS

A. Boron Reduction

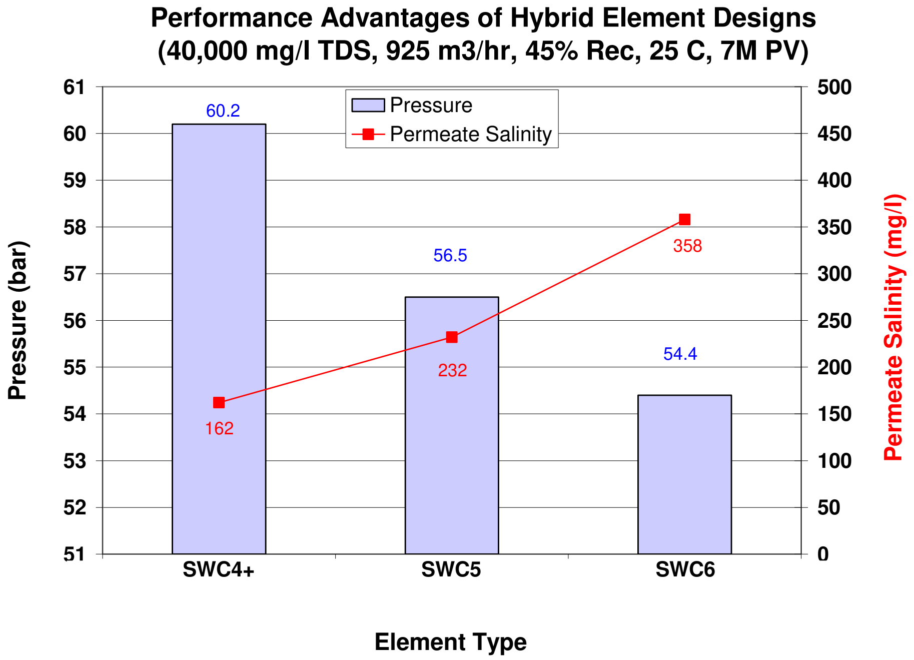
The design of a SWRO plant depends greatly on the feed salinity, feed temperature range, and permeate quality required. For applications with higher feed salinity, higher feed temperature and lower permeate salinity, higher rejection membranes will be needed. Today there are a range of SWRO elements available to choose from, so this selection must be carefully considered. A list of typical commercial seawater elements is shown in Table 1. Most membrane suppliers offer a series of SWRO elements which range between high rejection and high flow. Some suppliers may also offer products tailored specifically for boron removal. For most of these product ranges, there is a trade-off between higher flow or higher rejection. Designers should also be aware that the rejection listed on specification sheets is strongly affected by flux rate during the test, which is typically carried out at 55.2 bar (800 psi), 8-10% recovery, and 25 C. When elements are tested at the same flux rate and varying pressure, the relative change of permeate quality can be differentiated. An example of calculated system performance with various elements from Table 1 is shown in Figure 1.

Table 1 Performance of various seawater elements at standard test conditions

Element Description	Type	Area		Flow		Salt Rejection	Boron Rejection
		(ft2)	(m2)	(gpd)	(m3/d)	(%)	(%)
High Rejection	SWC4+	400	37.2	6500	24.7	99.83	93
High Boron Rejection	SWC4+B	400	37.2	6500	24.7	99.83	95
High Flow	SWC5	400	37.2	9000	34.2	99.8	92
Ultra High Flow	SWC6	400	37.2	12000	45.6	99.8	91

This figure shows that the ultra-high flow element produces a permeate which has 120% higher salinity than the high rejection seawater element, but 5 bar lower operating pressure. The high flow seawater element gives a pressure midway between these two extremes, but only 43% higher permeate salinity than the high rejection element. Thus, the ultra high flow SWRO element is generally suited to low temperature or low feed salinity cases. Selection between the high rejection and the high flow products is not as clear.

Figure 1 Comparative performance of three types of seawater elements operating at the same conditions



To better understand the factors driving the optimization process, we have considered a case study where the temperature varies between 35 and 15C. The basic assumptions used for this analysis are shown in Table 2. All projections were run to achieve a permeate salinity of 200 mg/l and a boron salinity of 0.75 mg/l after 3 years of operation. Two pass, split partial designs were used to achieve these parameters, if quality could not be achieved in one pass. The split partial design is characterized by permeate being withdrawn from both sides of the SWRO pressure vessel; the low salinity water to the product tank and the high salinity permeate to the second pass. The total product water production was kept the same in all cases and could represent the flow from 2 trains of a large-scale SWRO plant. If a second pass was needed, a high rejection, lower pressure 440 ft2 brackish water element (ESPA2+) was used. The number of pressure vessels in the second pass was varied to achieve the necessary flux of 34 lmh. However, the number of pressure vessels designed into the plant will be determined by the number required for the highest temperature.

Table 2 Assumptions for Economic Analysis

Parameter	**Value**	**Units**	**Parameter**	**Value**	**Units**
Feed Salinity	39,000	mg/l	Permeate Salinity	200	mg/l
Feed Boron	5.3	mg/l	Permeate Boron	.75	mg/l
Product Flow	22200	m3/d			
Recovery	50%	90%			
Element Age	3	yrs	Elements/PV	7	
Pump Eff	83%		Motor Eff	93%	
ERD Eff	97%				
1st Pass Flux	13.8	lmh	2nd Pass Flux	34	lmh
Caustic	0.616	$/kg	Electric Cost	0.06	$/kwhr

In all calculations, the SWRO system was considered to have a pressure exchange energy recovery process. The calculated energy savings was made using the Hydranautics IMSDesign2009 software assuming a high pressure differential pressure of 1 bar, a leakage factor of 1% and volumetric mixing of 6%. This resulted in an increase of the raw seawater salinity from 38,000 mg/l to 39,000 mg/l, which was used as the feed to the RO system. An example is shown in Chart 1.

Chart 1 Example of system design parameters used in case study.

Hydranautics Membrane Solutions Design Software, v. 2009 12/6/2000

SPLIT PARTIAL TWO PASS WITH Pressure/Work Exchanger

RO program licensed to:							
Calculation created by:				Blended flow:		22200.0	m3/d
Project name:	Med Water			Permeate flow:	22350.00	1350.00	m3/d
HP Pump flow:	1862.5	62.5	m3/hr	Raw water flow:		44550.0	m3/d
Feed pressure:	66.3	13.8	bar	Permeate recovery:	50.0	90.0	%
Feedwater Temperature:		15.0	C(59F)	Total system recovery:		49.8	%
Feed water pH:	8.0	10.5		Element age:		3.0	years
Chem dose, ppm, ppm	0.0	9.3		Flux decline % per year:	7.0	5.0	
				Salt passage increase, %/yr:	10.0	5.0	
Average flux rate:	13.9	32.8	lm2hr	Feed type:	Seawater - well		

Stage	Perm. Flow	Flow/Vessel		Flux	Beta	Conc.&Throt. Pressures		Element Type	Elem. No.	Array
		Feed	Conc							
	m3/hr	m3/hr	m3/hr	l/m2-hr		bar	bar			
1-1	931.2	7.2	3.6	13.9	1.02	65.4	0.0	SWC5	1806	258x7
2-1	42.8	15.6	4.9	37.4	1.24	11.1	0.0	ESPA2+	28	4x7
2-2	13.5	9.9	3.1	23.5	1.19	9.6	0.0	ESPA2+	14	2x7

	Raw water	Adjusted Water	Feed water	Permeate	Concentrate	ERD Reject
Ion	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Ca	410.0	408.7	421.5	0.458	842.5	816.8
Mg	1337.0	1332.7	1374.5	1.493	2747.3	2663.5
Na	12000.0	11966.5	12340.6	64.714	24603.8	23855.2
K	229.0	228.4	235.5	1.546	469.2	454.9
NH4	0.0	0.0	0.0	0.000	0.0	0.0
Ba	0.000	0.000	0.000	0.000	0.000	0.0
Sr	0.000	0.000	0.000	0.000	0.000	0.0
CO3	15.5	15.6	16.1	0.008	32.2	31.2
HCO3	150.0	149.6	154.2	1.211	306.9	297.6
SO4	2802.0	2793.1	2880.8	3.132	5757.6	5582.0
Cl	21000.0	20944.0	21599.1	94.469	43074.9	41763.6
F	0.0	0.0	0.0	0.000	0.0	0.0
NO3	0.0	0.0	0.0	0.000	0.0	0.0
B	5.30	5.36	5.50	0.751	10.10	9.8
SiO2	4.0	4.0	4.1	0.01	8.2	8.0
CO2	0.93	0.94	0.94	0.89	0.00	0.94
TDS	37952.8	37847.9	39032.1	167.79	77852.5	75482.5
pH	8.0	8.0	8.0	8.7	8.6	

	Raw water	Feed water	Concentrate
CaSO4 / Ksp * 100:	22%	23%	55%
SrSO4 / Ksp * 100:	0%	0%	0%
BaSO4 / Ksp * 100:	0%	0%	0%
SiO2 saturation:	3%	3%	7%
Langelier Saturation Index	0.93	0.95	2.12
Stiff & Davis Saturation Index	0.03	0.05	1.14
Ionic strength	0.75	0.77	1.54
Osmotic pressure	27.0 bar	27.7 bar	55.3 bar

H.P. Differential of Pressure/Work Exchanger:	1.0	bar	Pressure/Work Exchanger Leakage:	1 %
Pressure/Work Exchanger Pump Boost Pressure:	2.0	bar	Volumetric Mixing:	6 %

In addition to evaluating the optimum element type, the design analysis also considered the optimum boron reduction strategy. As stated previously, boron rejection is strongly affected by membrane type and feed pH. In these calculations, we considered the traditional alkalization of the second pass feed water, as well as the alkalization of the first pass raw seawater.

The results of the calculations can be seen in Figures 2-5. In this first set of results, we assumed that alkalization was only done on the second pass feed water, similar to most plant strategies used today. As expected when using the higher rejection SWRO element, the size of the second pass is much smaller than when using the high flow or ultra-high flow element (Figure 2). At 15 C, no second pass is needed for the high rejection element, while at 25 C, only 900 m3/d needs to be processed in the second pass. At 25 C, the second pass for the high rejection membrane is needed only to achieve the permeate boron quality. The amount of caustic needed in the second pass is shown in Figure 3. Thus, if the boron requirement was higher and the maximum temperature was 25 C, the customer would not need a second pass and would have substantial capital savings.

Figure 2 Effect of feed temperature and membrane type on the size of the second pass RO unit

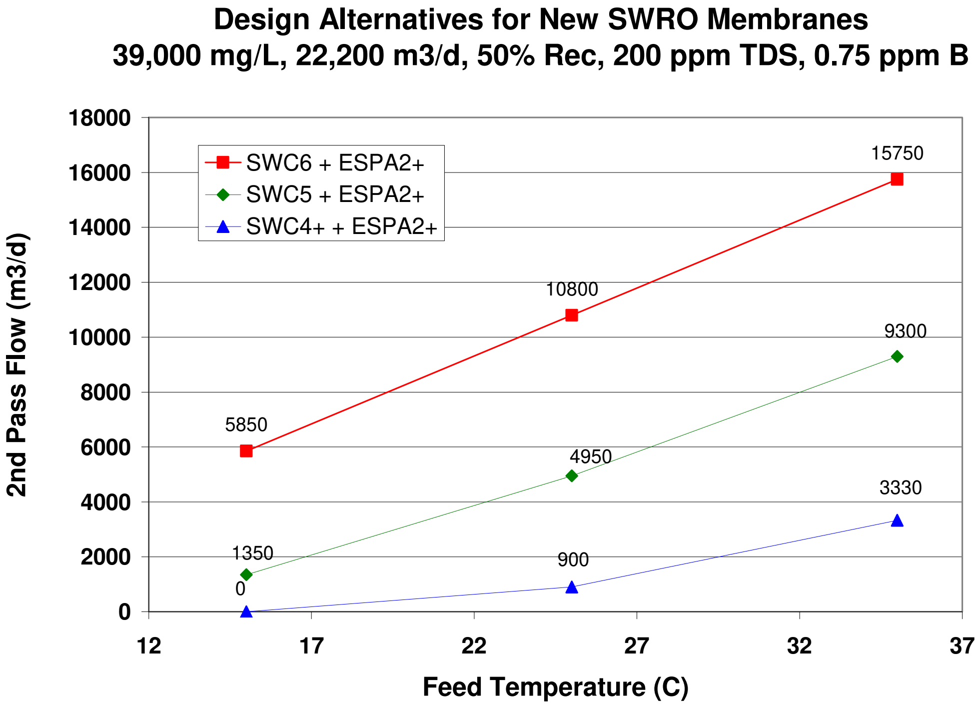
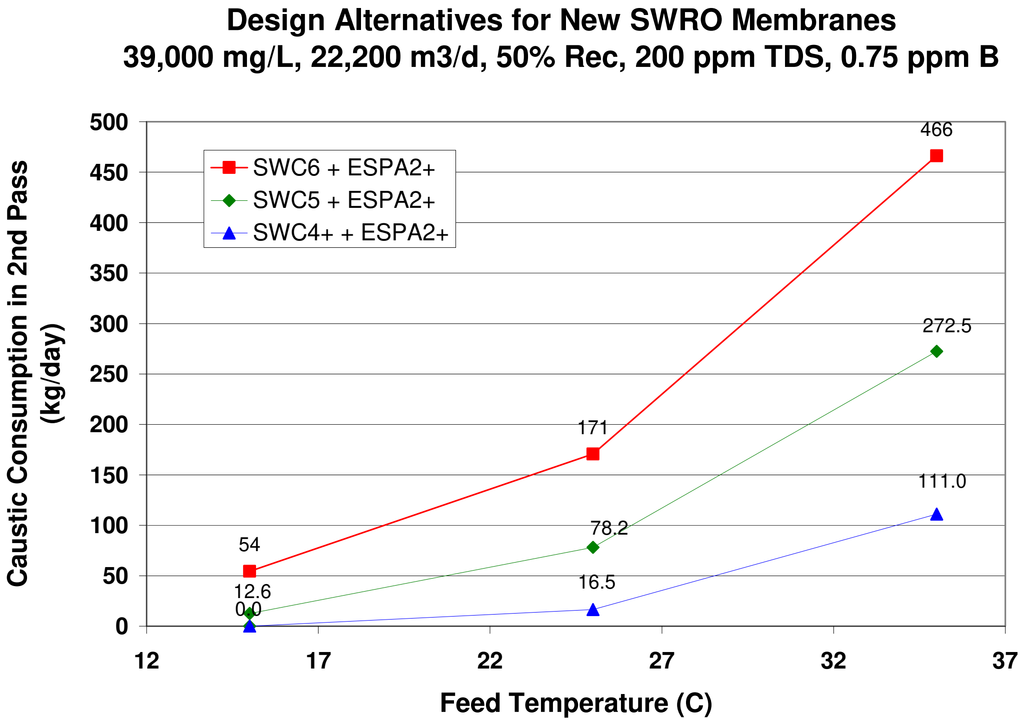


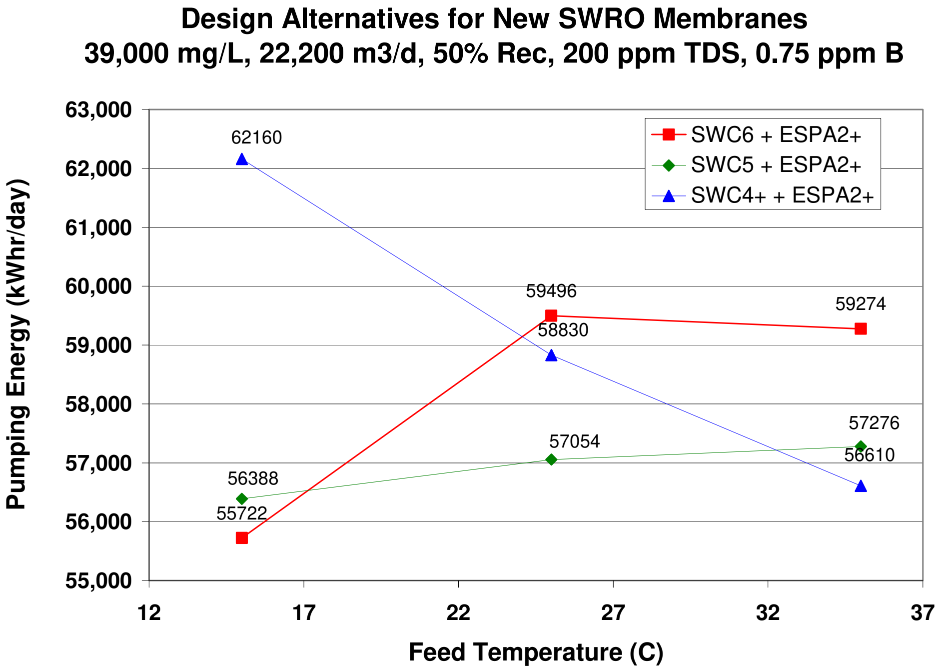
Figure 3 Effect of feed temperature and membrane type on caustic consumption in the second pass RO unit needed to achieve boron specification.



The advantage of the high flow and ultra-high flow SWRO elements is seen in Figure 4. This shows benefit of using the lower energy, higher flow SWRO elements. At low temperature of 15 C, the high rejection SWRO element requires much more energy. However, as the temperature goes to 25 C, there is a much smaller difference between the three types of membrane. At 35 C, there is surprisingly little difference between the three products. This is due to two main reasons, first is the requirement for a larger second pass at the higher temperature to achieve the required permeate quality. This gives rise to a second issue, which is the increased size of the second pass causes the overall recovery of the RO plant to decrease, so the first pass has to be larger. The high rejection SWRO needed 255 pressure vessels in the first pass, while the ultra-high flow SWRO needed 270 pressure vessels to achieve the same flux due to the higher permeate flow needed by the second pass. This is shown in Figure 5. It can also be seen that the ultra-high flow element only gives a small energy advantage over the high flow element at 15 C. This is again due to the high flow element having good rejection at 15 C, which meant that a only a small second pass was needed, while the ultra-high flow element still needs 5700 m3/d of permeate from the second pass. In the given example, the low pressure element runs at 66.3 bar, compared to the high rejection element which runs at 74.5 bar at 15 C. At this low temperature when little or no second pass is needed, the lower pressure of the SWC5 gives a substantial energy savings versus the high rejection element design.

The increased capital cost of the second pass systems can be judged by the number of pressure vessels and elements. In the example of Table 2, if the system needed to achieve the stated water quality at 35 C, the total number of pressure vessels in the system would be 338, 298, and 269 for the ultra-high flow element, high flow element, and high rejection element, respectively. There is also some trade-off regarding the pump cost. The high rejection membrane will require a pump that goes to higher pressure, but the pump will need to pump less volume. It is still expected, though, that the high rejection SWRO element would give the lowest capital cost.

Figure 4 Effect of feed temperature and membrane type on energy consumption in the second pass RO unit needed to achieve boron specification.



When all these factors are combined, the high rejection element type would give the lowest cost option to meet the requirements for the temperature range of 15 to 35 C. However, if the maximum temperature was 25 C, such as found in many plants more distant from the equator, the most economical design would be the low pressure seawater element.

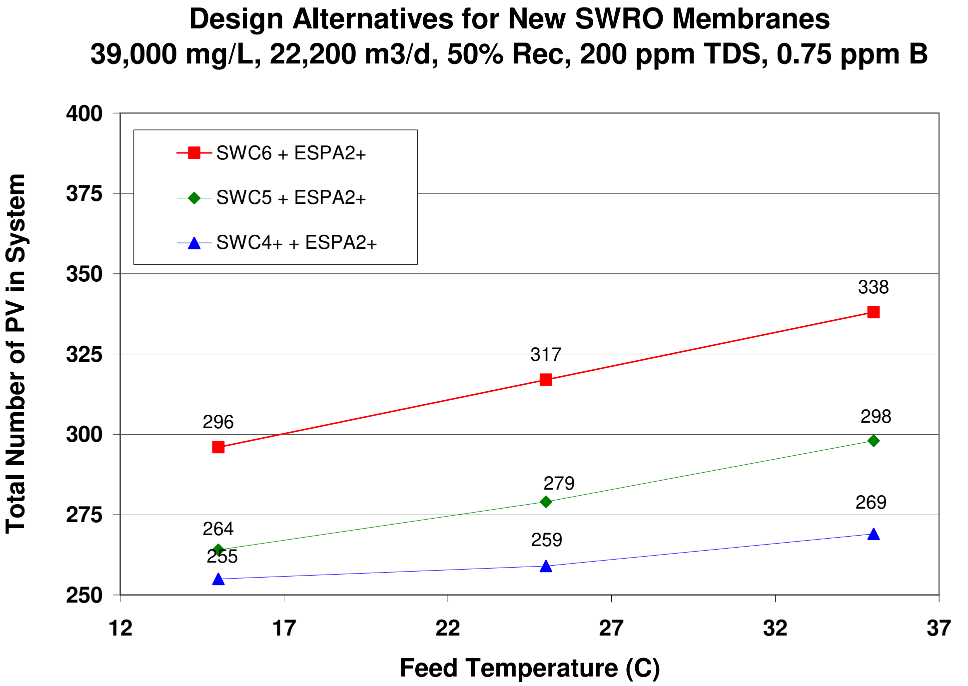
An additional scenario was considered where the seawater was alkalized with NaOH to improve boron rejection. This greatly reduced or eliminated the need for caustic addition in the second pass. In some cases for the previous example salinity could be achieved with the first pass elements, but not boron; so a second pass was needed just for boron removal. With the use of seawater feed alkalization in these cases, boron rejection can be achieved with one pass. The comparison of 1st pass versus 2nd pass alkalization was made for 15, 25 and 35 C using the high rejection and high flow elements. A summary of the results is shown in Figure 6.

From the results of this comparison it can be seen that Pass 1 Alkalization uses significantly more caustic, 4 times more, than 2nd Pass alkalization. This would result in approximately $35,000 more cost per year at 35 C and $55,000 at 25 C. Although the 2nd Pass Alkalization uses a higher concentration of caustic to achieve the higher pH (10.5 versus 8.5), the 1st Pass alkalization uses more caustic because there is a much greater flow of water in the first pass, and there is more alkalinity in the 1st pass feed water. Some questions have been raised about the cost of antiscalant at these elevated seawater pH. Some laboratory studies and pilot tests have indicated that antiscalant was not needed (7), however one large-scale plant trial used antiscant for security. (2) If antiscalant is used, it will add $0.0053/m3 ($0.02 kgal) of cost to the 1st pass alkalization scenario. This equates to $0.12/day of antiscalant.

However the total cost of treatment favors the 1st Pass alkalization. The advantage of the 1st Pass alkalization is the energy and capital savings. In regards to energy savings, the 1st Pass alkalization process uses less energy and saves $63,000 at 35 C and $39,000 at 25 C. In contrast, the 2nd pass alkalization results in $35,000 savings on caustic at 35 C and $51,000 at 25 C. If the plant was a predominantly high temperature plant, the 1st pass alkalization process would be the lowest operating cost, while if it were a low temperature plant, the 2nd pass alkalization would have lower operating cost. If the plant were assumed to operate 25% of the time at the 15 C, 50% at 25 C, and 25% at 35 C, the calculation shows that the operating cost would be about equal.

However, when you add in the capital savings, 9% less pressure vessels and elements for the 1st Pass alkalization at 35 C and 5% less for 25 C, then it is clear that the 1st pass alkalization process will be more cost effective, especially at higher temperatures. \

Figure 5 Effect of feed temperature and membrane type on total number of pressure vessels in the RO system needed to achieve boron specification.



The 1st Pass alkalization process has significant energy savings because of the fact that the second pass can be smaller. In this current example, the 2nd Pass alkalization process needs 600 m3/day more 1st pass permeate and 6000 m3/d more 2nd Pass permeate. The energy to produce this extra amount of water results in a much greater energy expense.

Figure 6 Effect of alkalizing the first or second pass to accomplish the required boron in the permeate.

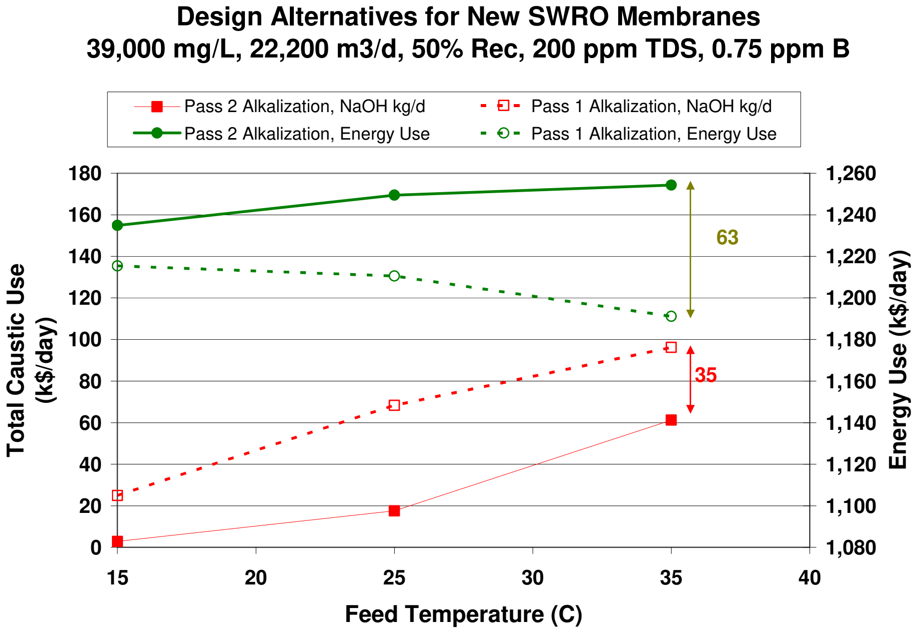


Table 3 Comparison of key operating cost values of a 1st Pass alkalization process compared to a 2nd Pass Alkalization process.

Feed Temperature	Daily Caustic Cost vs 2nd Pass Alk	Daily Energy Cost vs 2nd Pass Alk	Daily Operating Cost vs 2nd Pass Alk
deg C	k$/day	k$/day	k$/day
15	22.1	-19.4	2.7
25	50.7	-38.9	11.8
35	35.0	-63.2	-28.3

B. Bromide Removal

Seawater typically contains about 65 mg/l of bromide. It is present as an ionized salt, Br-, or organic bromine substances. The concern with bromide is that it can complicate the potablization of the treated water. In some communities, it is a common practice to add chloramines to desalted water to give it a disinfection residual while being transported to users. However, when bromide is present in water containing both chlorine and ammonia, bromamines can be formed instead of chloramines. (8) Bromamines are known to be less stable than chloramines, so that the residual is not as effectively maintained.

The other issue with bromide and bromamines, is that they increase the formation of trihalomethanes. Some analysis (9) have shown that up to 97% of the total THM's will contain brominated THM compounds. The WHO limit for these THM's is:

bromodichloromethane (BDCM) 60 µg/L
bromoform 100 µg/L
chloroform 200 µg/L.
bromate 10 µg/L.

One study found that exposure during pregnancy to BDCM concentrations of 20 µg/L or more resulted in elevated risk of birth defects.

Since bromide can not be effectively reduced by coagulation or media filtration processes, it is important that the RO membranes effectively reduce the bromide in the seawater to sufficiently low levels to prevent the formation of DPB's when the desalinated seawater is disinfected with chlorine. The current target used by some municipalities is 60 µg/l. This level is expected to produce sufficiently low levels of any brominated DBPs.

III. RESEARCH CONDUCTED

Testing was done at various full-scale and pilot plants to confirm the performance of new seawater products and processes. One of these tests was done on Pacific Seawater with the SWC4+ high rejection SWRO element. The test was done at the conditions shown in Table 4.

Table 4 Operating conditions for a pilot test of high rejection seawater element

Parameter	Value		Parameter	Value
Feed Salinity	34,000 mg/l		Recovery	49%
Feed Boron	4.95 mg/l		Permeate Flow	16.7 gpm
Feed Bromide	71 mg/l		Elements/Press Vessel	6
Feed Pressure	64.8 bar		Flux	8.9 gfd
Feed pH	7.9		Feed Temperature	20 C

The quality of the water streams from this test is shown in Table 5, which includes the feed, permeate and concentrate, as well as the calculated rejection. A few key points can be observed. First, when comparing the Cl and Br rejection, it is apparent that they are roughly the same, 99.8%. At this high rejection, the bromide is easily reduced below the required limit of 60 µg/l required to prevent the formation of disinfection by-products in the potable water.

The boron has been lowered from 5 mg/l to 0.70 mg/l for a rejection of about 90%. This rejection (calculated based on a feed/brine average concentration) is different than the value listed in Table 1 for two reasons, first is that the test was done at 20 C, not 25 C used in a standard test and secondly, this operating data was for a flux of 15.3 lmh (9 gfd), compared to 27.6 lmh (16.3 gfd) used in the standard test conditions. The former change should make rejection better, while the latter should make the rejection worse. When these factors are normalized to the standard test conditions, this boron rejection is in line with expected values.

Table 5 Water quality analysis for the test of a high rejection SWC4+ element

Water Sample	pH	Na (ppm)	Mg (ppm)	Ca (ppm)	Cl (ppm)	Br (ppm)	SO4 (ppm)	B (ppm)
Permeate		34.2	0.140	0.043	54.5	0.255	0.275	0.701
Feed	7.90	10200	1250	384	19074	70.9	2497	4.95
Concentrate		23500	2550	788	39353	156	5187	8.80
Rejection		99.80%	99.99%	99.99%	99.81%	99.78%	99.99%	89.80%

Testing is currently in progress to assess the boron and salt rejection of new high boron rejection SWC4+B elements. In one plant trial, the feed boron was 4.9 mg/l and the permeate was 0.436 mg/l. This was achieved at 14.4 lmh (8.5 gfd), 50% recovery and 19 C. This matches exactly with the expected boron rejection of 95% boron rejection at standard element test conditions. This confirms that higher boron rejection is possible with the latest SWRO products.

Similar testing was done at this site, but using the process of 1st Pass alkalization. In this case, the operating conditions were kept essentially the same, except the feed pH was increased using NaOH. The resulting boron in the permeate is shown in Table 6.

Table 6 Effect of 1st Pass Feedwater Alkalization Effects on Boron Rejection

Feed pH	Site	Feed Temp (C)	Permeate Boron (mg/l)	Boron Reduction (%)
8.14	Pacific Seawater	23	1.27	Reference
9.24	Pacific Seawater	23	0.48	62%
7.0	Mediterranean Seawater		1.3	Reference
8.1	Mediterranean Seawater		0.96	26%
8.6	Mediterranean Seawater		0.60	54%

Results have also been obtained for high flow SWC5 elements operating on a Pacific seawater. The operating conditions for the plant are shown in Table 7. This plant is again operating at a flux, 13 lmh, much lower than the standard wet test flux, but at a flux that is typical for large-scale plants. The feed and permeate water quality results are shown in Table 8.

Table 7 Performance of High Flow Seawater Element on Pacific Seawater

Parameter	Actual Value
Feed Temperature (C)	25.1
Feed Pressure (bar)	50.65
Feed Flow (m3/hr)	1589
Feed Salinity (mg/L)	35,309
Permeate Pressure (bar)	0.45
Permeate Flow (m3/hr)	716
Concentrate Pressure (bar)	49.7
Recovery (%)	45
Flux (lmh)	13
dP (bar)	0.45

Table 8 Water quality analysis for the test of a high flow SWC5 element

Water Sample	pH	Na (ppm)	Ca (ppm)	Mg (ppm)	Cl (ppm)	Br (ppm)	SO4 (ppm)	B (ppm)
Permeate		92.9	1.05	0.577	144	0.683	1.05	1.75
Feed	8.00	10500	395	1300	19925	64.4	2596	5.78
Rejection		99.45%	99.84%	99.97%	99.55%	99.34%	99.97%	81.21%

IV. RESULTS

When comparing the plant data of the high rejection and high flow elements, it can be seen that the rejection values are lower for the high flow SWC5, than those for the high rejection SWC4+ element. Part of the reason for the lower rejection is that this test was done at lower flux and higher temperature. Both will lead to increased salt passage for any membrane. The rejection difference between these two elements is expected, and the resulting values agree with the predicted results for these element types.

In the case of the high flow SWC5 element, the first pass permeate is not the product water. Instead, the water is further polished by a second pass. This was needed to reach the permeate quality targets for the project.

However, the high rejection element runs at much higher pressure, 64.8 bar, compared to the high flow SWC5 which operates at 50.65 bar. Part of this difference is again due to the different process conditions; the high rejection element operating at higher flux, higher recovery, and lower temperature.

However, the basic trends are similar to those explained in Section II Design Considerations. It may have been possible to design the full-scale plant with the high rejection element instead of the high flow element and possibly eliminate the second pass. However, in this case the customer wanted to achieve the lowest energy consumption.

In regards to bromide rejection, the high rejection SWC4+ elements give very high rejection, similar to that of the chloride rejection, but just slightly lower. The bromide rejection results in very low permeate bromide values. The rejection of Ca and Mg is very high, greater than 99.99% for the SWC4+ or 99.84% or better for the high flow SWC5. This high rejection of hardness is important if the second pass is being alkalized to remove boron. If there is too much Ca or Mg in the second pass feed water, it can result in scale formation (calcium carbonate or magnesium hydroxide) when operating at pH 10-11.

V. CONCLUSIONS

In conclusion, today it is not sufficient to design a SWRO process to meet TDS and chloride requirements. Consideration must also be taken to meet the requirements for these minor contaminants such as bromide and boron. There are unique designs which can be used that greatly minimize the cost of the SWRO so that it can meet these stringent requirements. The analysis shows that high flow or ultra-high flow elements are preferred for applications with lower feed temperatures and lower feed salinities. However, even at these feed conditions, there may be times where the high rejection SWRO elements may be used if they can prevent the need of a second pass. By eliminating or greatly reducing the size of the second pass, the first pass can also be scaled down. The resulting reduced feed flow means that much less energy is required to make the separation. Additionally, a smaller second pass will partially reduce the capital cost of the plant. These two combined benefits can make the use of high pressure, high rejection elements more attractive.

Plant data was collected for both high rejection and high flow SWRO elements. The performance of these elements matched closely with the predicted values, and shows the expected trends. The data in particular shows that the bromide rejection is very high, but slightly lower than that of chloride. In the case of SWC4+ is was 16% higher passage and in the case of SWC5 it was 47% higher. Some of this difference may be due to the difficulty of accurately measuring low concentrations of Br in a high Cl solution. The permeate value of bromide is below the required values needed for use as potable water.

VI. REFERENCES

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