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Consideration of energy savings in SWRO

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ABSTRACT

Seawater reverse osmosis (SWRO) processes have become the dominant desalination technology in the industry due to the low energy costs of this process. Thanks in large part to improvements in membrane and energy recovery devices, the SWRO process has become the accepted technology for desalination. In one report, current energy costs of SWRO processes have reduced by nearly 90% compared to SWRO in the 1970s and by 75% compared to SWRO in the 1980s. The best current SWRO processes require 2–2.5 kWh/m^3 of electrical energy. The question is how much further reduction can be made with a conventional SWRO process. Recent theoretical analysis has shown that there is a diminishing potential for further energy savings in any desalination process. One such report has stated that the ideal SWRO energy consumption is 1.06 kWh/m^3 for a 50% recovery plant treating 35,000 mg/l total dissolved solids, while the more realistic practical minimum energy consumption is thought to be 1.56 kWh/m^3. With current plants at 2 kWh/m^3, there seems to be only another 0.5 kWh/m^3 of further savings available. New plants are now using the new high permeable membrane technology and high efficiency energy recovery devices. The energy consumption of a state-of-the-art existing plant, the Gold Coast desalination plant in Australia, is described. This plant is operating at around 3 kW/h/m^3 of energy consumption at 19˚C and 35,500 mg/l feed salinity. The potential for further savings in a traditional SWRO plant is evaluated. Many of the new process improvements result in very minimal reduction in energy consumption. Furthermore, many of these will raise issues with flux distribution, fouling, pressure drop, and permeate quality. The impact of these issues needs to be included when trying to design a SWRO system for stable performance. One example of a hybrid system design is considered, but these will only give a marginal improvement in energy consumption.

Keywords: Desalination; Energy consumption; Hybrid design; Osmotic pressure

1. Introduction

Recent advances in seawater reverse osmosis (SWRO) technology have led to a significant reduction in the cost of this technology and have led to the growth of SWRO industry. In particular, the total cost of SWRO is dominated by the energy costs needed to achieve the high pressure required for RO. It is the significant improvement in energy efficiency that has led to much of the savings in total cost and made SWRO a more feasible solution for many communities. For example, Bates [1] reported that that the high pressure pump in the design of the Tampa SWRO

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plant accounted for 87% of the energy in the plant. As reported by Huehmer [2], since 1970 energy consumption of SWRO has reduced from 20 kWh/m^3 to a current value in the range of 1.5 kWh/m^3. In another paper [3], Stover reports that the specific energy for the RO process has been reduced from 7.3 kWh/m^3 to a current value of 2.4 kWh/m^3. This reduction in energy consumption is attributed mainly to improvement in the increased permeability of the membranes and the introduction of high efficiency energy recovery devices [2]. Other system design improvements have led to some marginal improvements; however, these additional gains have been relatively small.

As engineers continue to seek greater efficiencies and lower costs of treatment, there is much interest in technology that lowers SWRO energy consumption. This raises the question of how much more can the cost of SWRO be reduced, and in particular, how much more can the energy consumption be reduced. Although there are a number of literature claims of further significant improvements in energy reduction for desalination, there is ultimately a limit in the potential energy that can be saved. Some recent papers have sought to define the energy limits of desalination. As reported by Elimelech and Phillip [4], the minimum energy of desalination is achieved when the process is a reversible thermodynamic process. Further, they state that the energy of desalination is independent of the method and is equal in magnitude to the free energy of mixing, ΔG [4]:

$$-d(\Delta G_{\max}) = -RT\ \ln a_{\mathrm{v}} dn_{\mathrm{w}} = \Pi\ V_{\mathrm{w}} dn_{\mathrm{w}}$$

where R is the ideal gas constant, T is the absolute temperature, $\ln a_{\mathrm{w}}$ is the activity of water, n_{w} is the number of moles of water, Π is the osmotic pressure of seawater, and V_{w} is the molar volume of water. If the separation could truly be carried out at thermodynamically reversible conditions, for example, they state that a 35,000 mg/l total dissolved solids (TDS) seawater, being recovered at 50%, could be desalinated with only 1.06 kWh/m^3 of energy. However, they go on to explain that the process cannot be carried out at thermodynamic equilibrium and that the practical limit is when the applied pressure is equal to the osmotic pressure of the concentrate, which would be 0.5 kWh/m^3 more than the thermodynamic minimum for the example cited. Likewise, Song et al. [5] state that when thermodynamic equilibrium is achieved in a RO process, the recovery is determined by the salinity concentration of the seawater and the applied pressure. This is because of the reality that when the applied pressure reaches the instantaneous osmotic pressure of the system, further permeation and concentration will stop. They further explain that RO processes are controlled by mass transfer at low pressure, but by thermodynamic restrictions at high pressure. This is shown pictorially in Fig. 1.

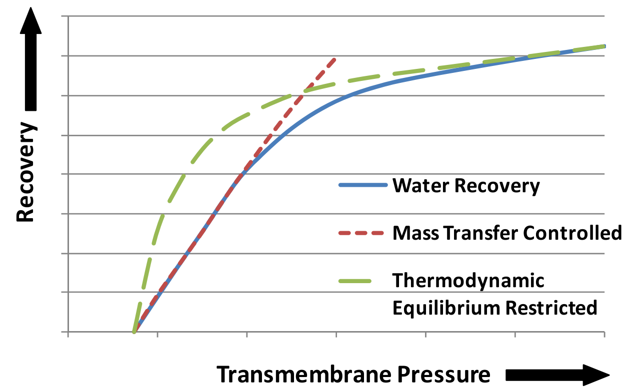

Fig. 1. Controlling mechanism in SWRO as a function of operation pressure. Source—Song et al. [5].

Considering these restrictions, it is worthwhile to consider the efficiency of current SWRO plants and how close they are to these theoretical limits. Seacord [6] reported pilot testing of low energy seawater membranes with the achievement of 1.58 kWh/m^3, but these operated at low recoveries and low fluxes, which would greatly increase the capital cost of the SWRO system.

Another paper [7] reported the energy consumption at the Kindasa, KSA, SWRO plant, in which, the RO process is operating at 3.07 kWh/m^3 on a feed of 42,500 mg/l TDS at about 30˚C and 48% recovery. These plants have demonstrated very low energy consumption, with values approaching the practical limits mentioned above, but still nearly double in magnitude.

2. Evaluation of current technology

The Gold Coast plant in Australia is a good example of a plant operating with much of this recent energy efficient SWRO technology. As reported by Andes et al. [8], this is a 125 ML/d plant (133 ML/d maximum flow) on the east coast of Australia treating Pacific Seawater. It has conventional pretreatment consisting of a drum screen, chemical addition, dual media filtration, and cartridge filters. The pretreated water has excellent quality with approximately 0.02 NTU turbidity. The RO portion of the plant is a two pass design with Hydranautics' SWC5 membrane in the first pass and ESPA2 MAX in the second pass. The second pass utilizes the concept of split permeate treatment, where a portion of the permeate from the

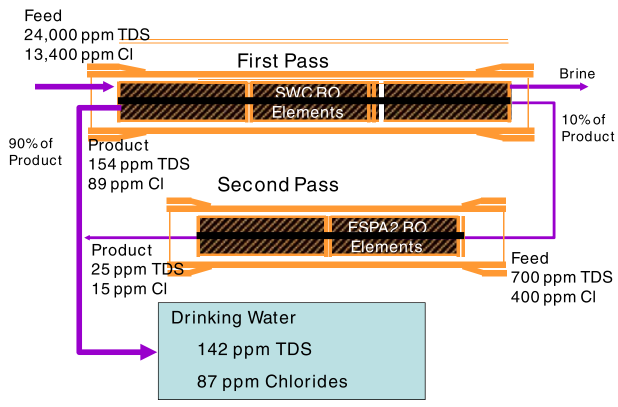

Fig. 2. Example of a split permeate, two pass system.

front of the SWRO vessels goes directly to the product water tank, while the remainder of the permeate removed from the back of the SWRO pressure vessel is sent to a second pass for further desalting. The latter is much higher salinity owing to the concentration process that is occurring in the SWRO pressure vessels. An example of a split two pass process is shown in Fig. 2.

The SWRO system consists of nine trains with 186 pressure vessels, each vessel containing eight elements. This first pass runs at 45% recovery and a typical flux of 13.6 lmh. The second pass consists of three trains in a two-stage 108:36 array; again each vessel has eight elements. This system runs at 85% recovery and elevated pH to achieve high boron rejection. The plant uses Calder DWEER energy recovery equipment which recovers 97% of the energy of the brine stream.

The plant treats seawater with 34,000–39,000 mg/l TDS and achieves less than 220 mg/l TDS. Additionally, the feed chloride (21,500 mg/l) and boron (5 mg/l) are reduced to less than 50 and 1.0 mg/l, respec-

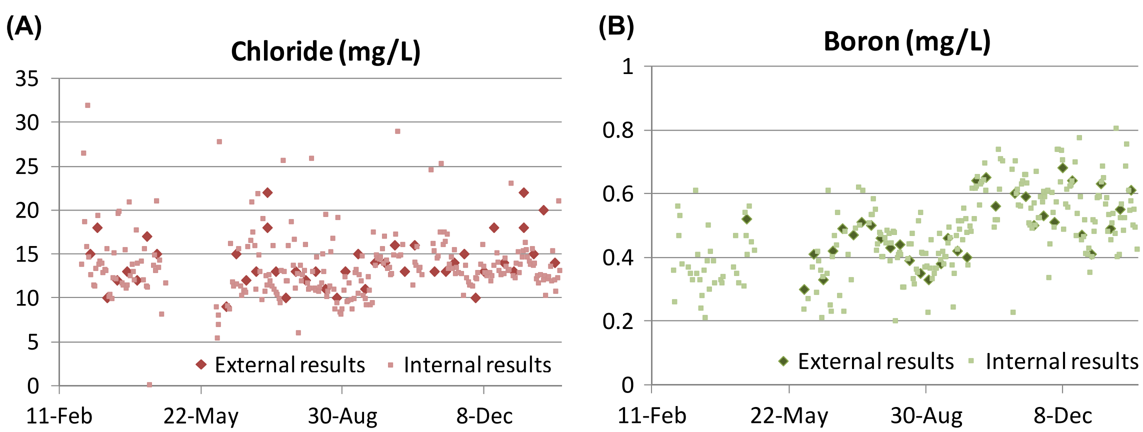

Fig. 3. Permeate water quality trends for (A) chloride and (B) boron during 2011.

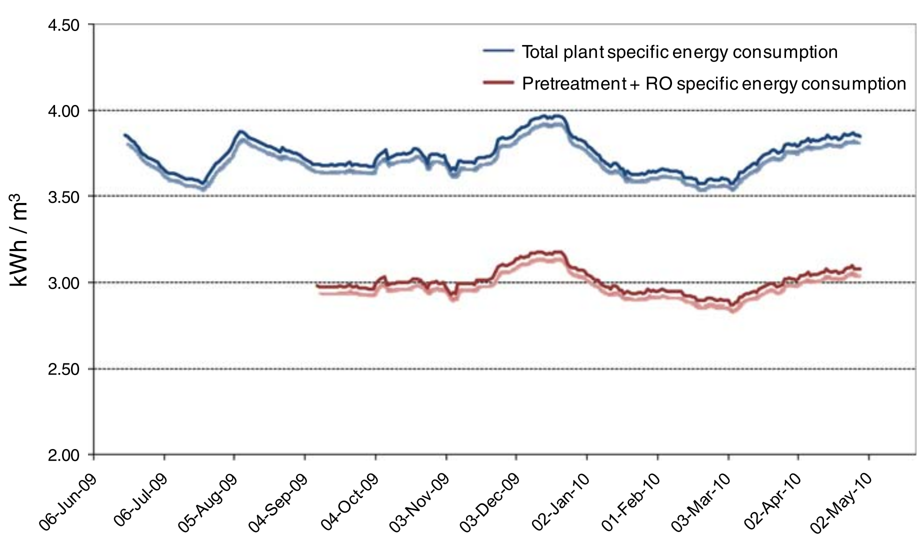

Fig. 4. Specific energy consumption trend of the Gold Coast SWRO plant.

tively. The feed water temperature can range from 17 to 28°C. Actual data for the recent chloride and boron permeate concentrations are shown in Fig. 3.

The historical energy consumption of this plant is shown in Fig. 4. This graph shows both the total plant specific energy consumption and the energy consumption of just the combined RO and pretreatment process. During a run at full capacity in July 2009, with the temperature at 19.2°C and feed salinity of 35,000 mg/l, the plant measured a full energy consumption of 3.6 kWh/m^3, while the RO and pretreatment processes accounted for 3.1 kWh/m^3. Almost all of the latter can be attributed to the RO processes. This is shown in Fig. 5. When operating at >100,000 m^3/d, the RO process would consume 2.9 kWh/m^3. The next largest user of energy is the potable water pumps, followed by transformer losses and intake pumps.

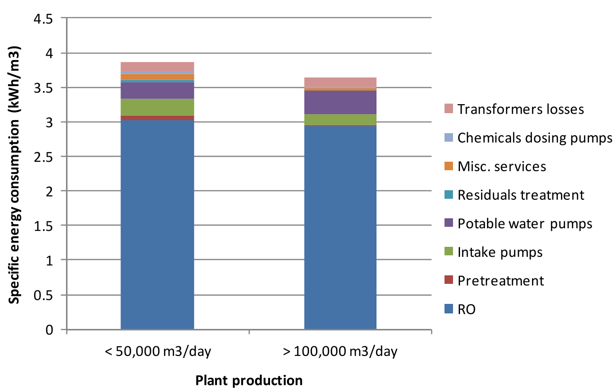

Fig. 5. Energy use breakdown at the Gold Coast plant.

Thus, this plant treating 35,000 mg/l at 45% recovery is operating at 2.9 kWh/m^3, while in comparison the example of Elimelech stated that the thermodynamic limit of a RO running on 35,000 mg/l TDS feed at 50% recovery would be 1.06 kWh/m^3 and the practical minimum energy would be 1.56 kWh/m^3. The value here is about twice that value, but it should be remembered that the Gold Coast plant includes a two pass system, which add extra energy consumption.

3. Future technology considerations

Designers should understand that further improvements in SWRO processes are also likely to have impacts on the stability and sustainability of the process, and these must be carefully considered. We next consider some potential improvements and some

Project name:	Pacific Water		Permeate flow:	23200.00	m3/d
HP Pump flow:	978.5	m3/hr	Raw water flow:	51555.6	m3/d
Feed pressure:	58.4	bar	Permeate recovery:	45.0	%
Feedwater Temperature:	25.0	C(77F)			
Feed water pH:	8.00		Element age:	0.0	years
Chem dose, ppm (100%):	0.0	H2SO4	Flux decline % per year:	7.0	
			Fouling Factor	1.00	
			Salt passage increase, %/yr:	10.0	
Average flux rate:	14.4	lm2hr	Feed type:	Seawater - well	

Stage	Perm. Flow m3/hr	Flow/Vessel Feed m3/hr	Flow/Vessel Conc m3/hr	Flux l/m2-hr	Beta	Conc.&Throt. Pressures bar	Conc.&Throt. Pressures bar	Element Type	Elem. No.	Array
1-1	966.7	8.3	4.6	14.4	1.01	57.2	0.0	SWC5	1806	258x7

	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	410.0	421.6	0.585	766.1	744.9
Mg	1337.0	1337.0	1374.8	1.909	2498.1	2429.1
Na	12363.0	12363.0	12710.7	84.597	23041.2	22406.9
K	229.0	229.0	235.4	1.958	426.5	414.7
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	17.3	17.3	18.2	0.011	39.2	37.9
HCO3	150.0	150.0	153.9	1.669	270.9	263.7
SO4	2802.0	2802.0	2881.2	4.350	5235.0	5090.5
Cl	21700.0	21700.0	22310.7	134.578	40454.8	39340.8
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	5.00	5.00	5.11	0.982	8.49	8.3
SiO2	4.0	4.0	4.1	0.02	7.5	7.3
CO2	0.74	0.74	0.76	0.76	0.76	0.76
TDS	39017.3	39017.3	40115.8	230.7	72747.6	70744.0
pH	8.00	8.00	8.00	6.55	7.92	

Fig. 6. Typical SWRO plant design.

implications of these more efficient SWRO processes. In these examples, we consider a typical system treating 39,000 mg/l TDS at 45% recovery, 14.4 lmh flux, and 25˚C. For this design, the feed pressure would be 58.4 bar and the brine pressure would be 57.2 bar with a brine osmotic pressure of 53.5 bar. The design of this system is shown in Fig. 6. In this example, the brine osmotic pressure accounts for 94% of the brine pressure, leaving very little net driving pressure available to push water across the membrane.

Additionally, this paper will explore the other practical issues that can arise when very high permeable SWRO membranes are used. One example is the flux imbalance that can occur in a pressure vessel. It is not unusual for the net driving pressure of the feed end to result in flux rates which differ by a factor of 10 times from the first to last element in the vessel. This and other design concerns will be discussed. The specific energy consumption for this design is calculated to be 2.26 kWh/m^3.

3.1. High flow membranes and increased salt passage

Many engineers are taking advantage of the new higher flow, low energy SWRO elements. Although there is a trade-off between the salt rejection and energy consumption, it is possible in many cases to achieve the necessary permeate quality with the higher flow SWRO elements. An example of such a performance trade-off is shown in Fig. 7. It can be seen that although the feed pressure has been reduced only about 10%, the net driving pressure has been decreased by about 40%, which is a substantial savings and reflective of the improved membrane permeability.

However, the concern with the use of high permeable membranes is the flux balance that results from the osmotic pressure increase through the pressure vessel. This is shown in Fig. 8. The data show that the feed pressure is closely approaching the brine osmotic pressure, which is determined by the recovery of the process and the feed salinity. It must be remembered that regardless of the permeability of the membrane, there is still a need to provide pressure equal to the brine osmotic pressure before any permeate can be made. Thus, various membrane products and process designs can only lower the net driving pressure (NDP).

As stated here and in literature, the limit of energy reduction in SWRO is the brine osmotic pressure. This limit is shown in Fig. 9 for two different highly permeable RO membranes, SWC5 and SWC6, running at the same process conditions. It can be seen that the more permeable membrane has a concentrate pressure very close to the brine osmotic pressure. Thus, new, higher permeable membranes would have very little capability to significantly reduce energy consumption—perhaps 1 bar more of energy savings, when using a conventional SWRO process.

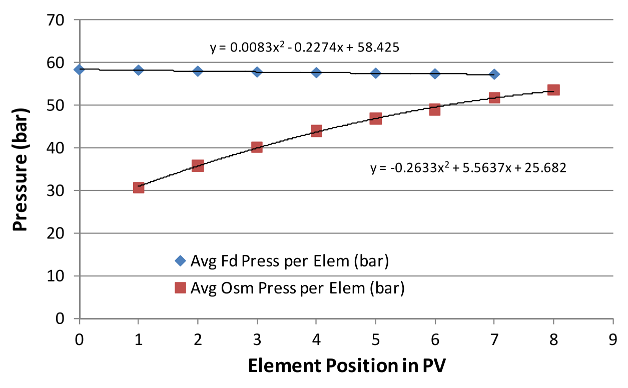

Fig. 8. Feed and osmotic pressure changes in a SWRO 7 M pressure vessel.

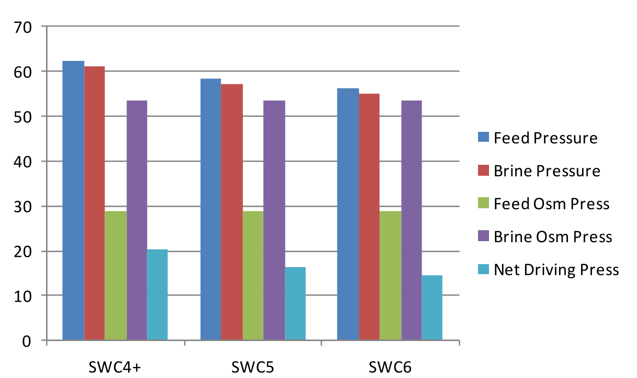

Fig. 7. Comparative pressure requirement of a series of more permeable SWRO membranes.

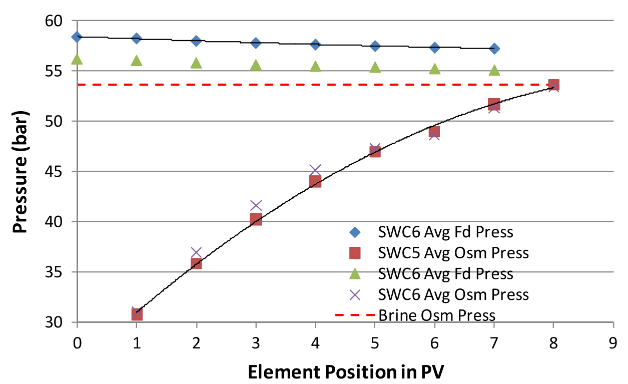

Fig. 9. Net driving pressure trend for high and moderate permeable membranes.

Furthermore, to achieve further savings by improving the permeability of SWRO membranes, the improved SWRO membrane permeability would have to be very high. Fig. 10 shows the wet test flow for seawater elements at standard test conditions (55.2 bar [800 psi] and 25˚C) relative to the energy consumption of that membrane for the example listed above. It shows that from earlier generations to the latest, high permeability element, the flow has increased from 6,500 gpd to the current 12,000 gpd. This improvement results in a reduction of energy from 2.4 to 2.17 kWh/m^3. To get a significant further improvement, the wet test flow of a SWRO membrane would have to go to 15,000 gpd or more. Based on a simple extrapolation, the energy savings of a 15,000 gpd element would only be 0.05 kWh/m^3 less compared to the 12,000 gpd membrane.

As previously mentioned, there is currently a worsening of permeate quality to increase the flow from 24.6 m^3/d (6,500 gpd) to 45.5 m^3/d (12,000 gpd). One goal for new membranes should be the improvement of flow, without sacrificing salt passage. This has to be characterized correctly to ensure that the salt passage coefficient has not changed. The current standard in the industry is to test at 55.2 bar (800 psi), 25˚C, and a 10% recovery. For this test, the pressure is constant and the flow changes. This results in a change in flux, which results in better permeate TDS and better rejection. Thus, all three of these elements can have 99.8% rejection at standard test conditions, but not the same salt passage coefficient. If the salt passage coefficient was the same, the rejection should be increasing with the flow rate. Alternatively, the tests for new high flow membranes should be made at lower pressure to equalize the flow. Table 1 shows the test of high rejection SWC4 membrane performance at 55.2 bar (800 psi) compared to high permeable membrane SWC6 tested at 55.2 bar (800 psi) and 41.4 bar (600 psi). It is apparent that the test at 41.4 bar for SWC6 gives almost the same flow as SWC4 at 55.2 bar. At this condition of equal flux, it is now possible to compare rejection, which shows that SWC6 will be 99.6% at this flow. Based on this analysis, it is apparent that SWC4 rejection is much superior. Thus, a new SWRO membrane with flow of 24.6 m^3/d (6,500 gpd) at 41.4 bar (600 psi) and a rejection of 99.8% would be an attractive membrane and truly lead to a more valuable solution for SWRO plants.

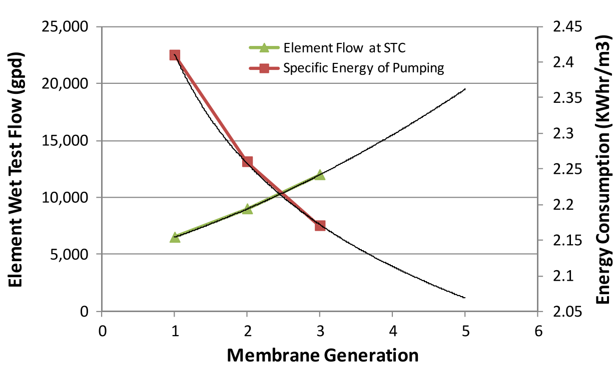

Fig. 10. Variation of energy consumption and standard test condition flow.

3.2. High flow membranes and flux imbalance

Most SWRO systems operate in the range of 12.7–14.4 lmh (7.5–8.5 gfd). In cases where the feedwater has low turbidity (such as seawells or UF/MF pretreatment), it is possible to operate at higher flux rates. Production from a SWRO system is never determined by the permeability of the membrane, it is determined by the quality of the feedwater, which in turn governs the choice of flux. Thus, higher permeable membranes do not make more product water in a commercial system, if stable operation is desired. The only case where this is not true is when flux rates are low due to the undersizing of the high pressure pumps. Then, a retrofit with high permeable SWRO membranes can lead to increased water production, at a stable condition.

Table 1
Comparison of seawater membranes tested at two pressures

Element	Memb area (ft2)	Test pressure (psi)	Salt rejection (%)	Salt passage (%)	Increase in SP (%)	Flow[a] (gpd)	Recovery (%)
SWC4	400	800	99.83	0.17		6,460	10.9
SWC6	400	800	99.76	0.24		12,341	17.8
		600	99.66	0.34	42		10.9
SWC6 MAX	440	800	99.82	0.18		12,700	18.5
		600	99.74	0.26	44	6,410	11

[a]Flow is normalized to standard recovery (10%) and temperature (25˚C).

When operating at high flux, the main concern is the very high flux in the first few elements. This will result in the lead element having the highest concentration polarization values, which can lead to lower rejection and lower permeation through the membrane. As shown earlier, the average NDP decreases for each subsequent element in a pressure vessel (Fig. 8). This is due to the friction losses as the water flows through the elements and the increasing osmotic pressure. The decreasing NDP results in reduced flow and flux from each subsequent element in the vessel.

Thus, the consequence of using higher permeable membranes is flux imbalance, as shown in Fig. 11. Here the two highest permeable membranes are compared at similar design conditions. It can be seen that the lead element flux of the SWC6 is much higher than the less permeable membrane, even though the average system flux is the same in both cases. The lead element flux of the high permeable seawater membrane is 17% higher than the lead element flux of the lower permeable SWC5. Also, the SWC5 membrane has an average lead element flux that is nine times higher than the average flux of the tail element, while the high permeable SWC6 has a lead element flux that is 17 times greater than the average flux of the tail element. The relatively higher flux of the lead element will lead to greater concentration polarization, which can lead to higher salt passage, decreased NDP, and can increase the fouling rate of the lead element because the cross-flow may be insufficient to flush the foulant from the membrane surface.

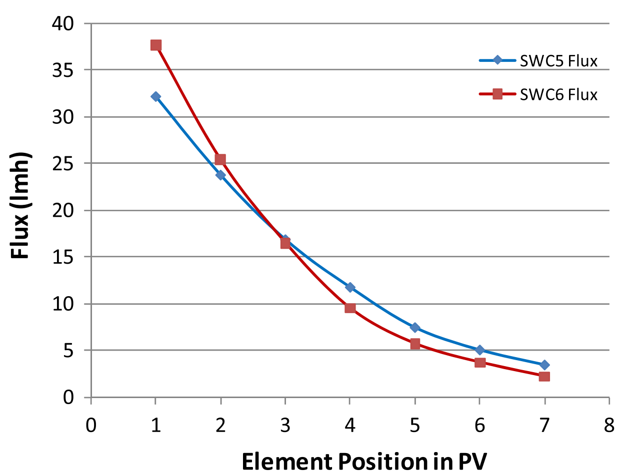

Fig. 11. Flux distribution in a 7 M SWRO pressure vessel.

3.3. Hybrid SWRO systems

To overcome the issues that arise from the use of higher permeable SWRO elements, namely higher salt passage and greater flux imbalance, engineers have turned to new designs. One of these is the use of hybrid array, where two types of elements are used in the same vessel. Generally, a higher rejection, lower flow element is used in the front of the vessel and a higher flow, lower rejection element is used in the rear of the vessel. This helps to balance the flux at the expense of sacrificing some of the energy reduction of using all highly permeable elements.

From Fig. 7, an example of a hybrid design was shown in recent pilot testing with the highest rejection and highest flow elements. Performance of this pilot testing is shown in Table 2. In this pilot testing, high rejection SWC4B elements were used in the first four positions of a two-stage 4 M pressure vessel. The design of the system is shown in Fig. 12. The results show that the salinity of the higher permeable membranes, 461 mg/l, is almost 10 times higher than the permeate from the first four high rejection membranes, 55.2 mg/l. As expected, the water production from the 2nd vessel with the high permeable SWRO membranes has higher flow than a system with all SWC4 membranes. Still, the flux of the back vessel, 9.7 lmh, is much lower than the flux of the front elements, 18.3 lmh. It should be noted that the actual flows and permeate qualities agree very well with the projected performance of these elements.

Table 2
Pilot performance of a hybrid SWRO process design

	Flow (gpm)	Flux (lmh)	Meas. recovery (%)	Meas. pressure (psi)	Meas. pH	Temp. (°C)	Cond. (μS/cm)	Meas. TDS (mg/l)	Meas. B (mg/l)
Feed	39			811	7.62	19.5	49,640		
Conc.	19.5			799	7.4	21.4	90,410		
Vessel 1 (SWC4B-MAX)	13.2	18.3	33.85	×	6.9	19.7	120	55.2	0.37
Vessel 2 (SWC6)	6.3	9.7	24.42	×	6.9	20	1,002	461	2.3
Total permeate	19.5	14.2	50.0	×	7	19.9	390	180	0.962

Project name:	Carlsbad		Permeate flow:	19.50	gpm
HP Pump flow:	39.0	gpm	Raw water flow:	39.0	gpm
			Permeate throttling(All st.)	8.0	psi
Feed pressure:	808.6	psi	Permeate recovery:	50.0	%
Feedwater Temperature:	19.5	C(67F)			
Feed water pH:	7.62		Element age:	0.0	years
Chem dose, ppm (100%):	0.0	H2SO4	Flux decline % per year:	7.0	
			Fouling Factor	1.00	
			Salt passage increase, %/yr:	10.0	
Average flux rate:	14.2	lm2hr	Feed type:	Seawater - open intake	

Stage	Perm. Flow	Flow/Vessel Feed	Flow/Vessel Conc	Flux	Beta	Conc.&Throt. Pressures	Conc.&Throt. Pressures	Element Type	Elem. No.	Array
	gpm	gpm	gpm	l/m2-hr		psi	psi			
1-1	13.1	39.0	25.9	18.3	1.03	795.0	8.0	SWC4B MAX	4	1x4
1-2	6.4	25.9	19.5	9.7	1.01	783.9	8.0	SWC6	4	1x4

	Raw water		Feed water		Permeate		Concentrate	
Ion	mg/l	CaCO3	mg/l	CaCO3	mg/l	CaCO3	mg/l	CaCO3
Ca	378.0	942.6	378.0	942.6	0.496	1.2	755.5	1884.1
Mg	1170.0	4814.8	1170.0	4814.8	1.534	6.3	2338.5	9623.3
Na	10811.0	23502.2	10811.0	23502.2	67.930	147.7	21554.1	46856.7
K	350.0	448.7	350.0	448.7	2.748	3.5	697.3	893.9
NH4	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
Ba	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
Sr	7.000	8.0	7.000	8.0	0.009	0.0	13.991	16.0
CO3	5.0	0.2	5.0	8.3	0.000	0.0	9.9	16.5
HCO3	139.0	113.9	139.0	113.9	1.417	1.2	276.6	226.7
SO4	2480.0	2583.3	2480.0	2583.3	3.513	3.7	4956.5	5163.0
Cl	19286.0	27201.7	19286.0	27201.7	109.138	153.9	38462.9	54249.5
F	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
NO3	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
B	5.02		5.02		1.016		9.02	
SiO2	1.9		1.9		0.01		3.8	
CO2	1.90		1.91		1.91		1.91	
TDS	34632.9		34632.9		187.8		69077.9	
pH	7.62		7.62		6.11		7.74	

	Raw water	Feed water	Concentrate
CaSO4 / Ksp * 100:	19%	19%	45%
SrSO4 / Ksp * 100:	22%	22%	51%
BaSO4 / Ksp * 100:	0%	0%	0%
SiO2 saturation:	2%	2%	3%
Langelier Saturation Index	0.53	0.53	1.23
Stiff & Davis Saturation Index	-0.38	-0.38	0.23
Ionic strength	0.68	0.68	1.36
Osmotic pressure	361.9 psi	361.9 psi	721.7 psi

Fig. 12. Design of the hybrid SWRO pilot trials.

4. Effect of flux on salt passage

The other effect of flux is on the salt passage. When a system is operated at higher flux, there is a greater rate of water passage through the membrane, while the salt passage remains essentially the same. Salt transport rate is not a function of pressure. The result is that the higher water passage at higher pressure results in dilution of the permeate. The improvement of permeate quality as a function of flux is shown in Fig. 13. It can be seen in Fig. 13 that the permeate quality from the first element is not so different (25%), but the final permeate from the SWC6 is 46% higher. This is due to the fact that the lead element of the SWC6 is running at much higher flux, while the SWC6 tail element runs at much lower flux than the SWC5 tail element, which further increases the already intrinsically higher salt passage of SWC6.

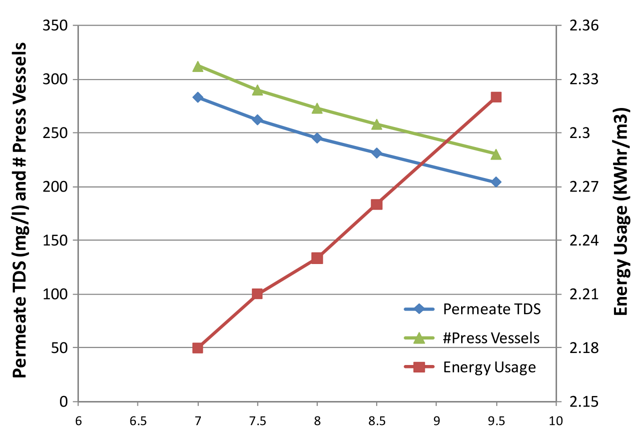

Fig. 13. Effect of RO flux on the permeate quality and energy use.

5. Conclusions

There has been significant new technology that is lowering the cost of SWRO. Much of the focus has been on energy savings, which accounts for the largest operating cost at a SWRO plant. As a result of these improvements, the latest SWRO plants are very efficient with the energy consumption approaching two times the practical limit of SWRO energy consumption.

Although there has been substantial reduction in energy consumption in the past 10 years, it is becoming apparent that there is diminishing further energy savings potential in SWRO. This is especially true of improved, low energy SWRO membranes. Also, if there is any further improvement in the permeability of SWRO membranes, there must be a substantial improvement in the rejection of that membrane, so that the overall salt passage is not increased at real operating conditions. Further, our analysis shows that most of the improvement in reduced energy consumption will lead to increased flux imbalance. This points out a second major need for any improved system, namely, that the quality of the feedwater has to be much improved.

Many other processes and specialized membranes are being considered, such as carbon nanotubes and polyamide membranes with imbedded nanoparticles [9]. These claim to enhance the water transport process and greatly reduce energy consumption. Further understanding of the characteristics and performance of the membranes is needed, but consideration must be remembered that energy must be supplied to overcome the energy of mixing. As reported in [4], this energy is roughly equal to the energy of the brine osmotic pressure times the permeate flow. It is not clear at this time; however, this basic law could be circumvented by any of these new membranes.

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