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Design Advantages for SWRO using Advanced Membrane Technology

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~~Abstract~~

Seawater desalination has been growing rapidly in the past five years, due in part to the many new membranes that are available to designers. These new membranes have significantly improved performance, which results in lower permeate salinity and lower operating pressure. Recently, new low pressure seawater elements have been developed, and the optimum design with these elements must be carefully considered. This paper analyzes the trade-offs which exist when choosing these membranes. In cases of lower feed temperatures, which are more common in the Pacific coastal area of the USA, and lower salinities, these lower energy seawater elements can provide sufficiently low permeate salinity, generally less than 500 mg/l. Alternatively, designers can use hybrid designs, where higher rejection, higher energy consumption elements are used in the front of the vessel and lower energy elements are used in the back of the vessel. This approach results in a feed pressure and permeate salinity between the two. Use of these new products can result in as much as 1 kw/hr/kgal of energy savings. The advantage of this type of approach is that the lower permeable lead elements will have lower flux, resulting in a more balanced element flux distribution. Alternatively, these new membranes can be used in high area configurations, which have as much as 440 ft² of membrane area. The higher area can result in about \$0.1/gpd in capital costs savings. Thus, these new design offer a variety of advantages, but detailed analysis is needed to select the optimum element and configuration.

Introduction

The growth of the seawater reverse osmosis (SWRO) business has been sparked by the growing demand for water in coastal regions and the economic attractiveness of low energy membrane processes. One important point about SWRO is that it is a sustainable supply of freshwater, which is an attractive alternative for many cities which depend on imported water or dwindling groundwater supplies. The development of high rejection (Wilf 2005), low energy membrane products and high efficiency energy recovery devices (Stover, 2008) has made the SWRO technology very competitive. For example, importing water from the Delta region of the Bay Area to Southern California requires about 2.8 kWhr per m³, compared to 2-3 kWhr per m³ for the production of fresh water from seawater. Membrane produced potable water has the added benefit that it has passed through “barrier” technology which ensures added protection from pathogens, pharmaceutical, and other harmful water contaminants.

A key development is the high flow, low energy seawater membrane. In addition to the current low pressure seawater membranes which give 99.8% rejection and 9000 gpd at standard conditions, new ultra low pressure SWRO elements have been developed which have 99.8% rej and 12,000 gpd flow.

Other improvements are now being introduced which will make membrane technology even more cost effective. One of these is the new high area seawater element. This development has resulted in the production of 440 sq ft elements, having 10% more area than the standard 400 ft² element.

However, the system designer needs to consider optimum array configurations, flux rates and recoveries to take best advantage of the properties of these new products. Design considerations for optimum design conditions will be proposed and discussed.

Table 1 High Performance Seawater Product Evolution

Date	Type	Area		Flow		Rejection	
		(ft ²)	(m ²)	(gpd)	(m ³ /d)	TDS(%)	B (%)
1987	SWC1	320	29.7	5000	19	99.5	
2000	SWC3	370	34.4	5900	22.4	99.7	87
2006	SWC5	400	37.2	9000	34.2	99.8	92
2008	SWC4+ Max	440	40.9	7200	27.4	99.83	93
2008	SWC5 Max	440	40.9	9900	37.6	99.8	92
2009	SWC6	400	37.2	12000	45.6	99.8	91

Test Conditions: Feed Pressure 55.2 bar (800 psi), Feed Salinity 32,000 mg/l NaCl, 25 C, 10% recovery

Design Concepts

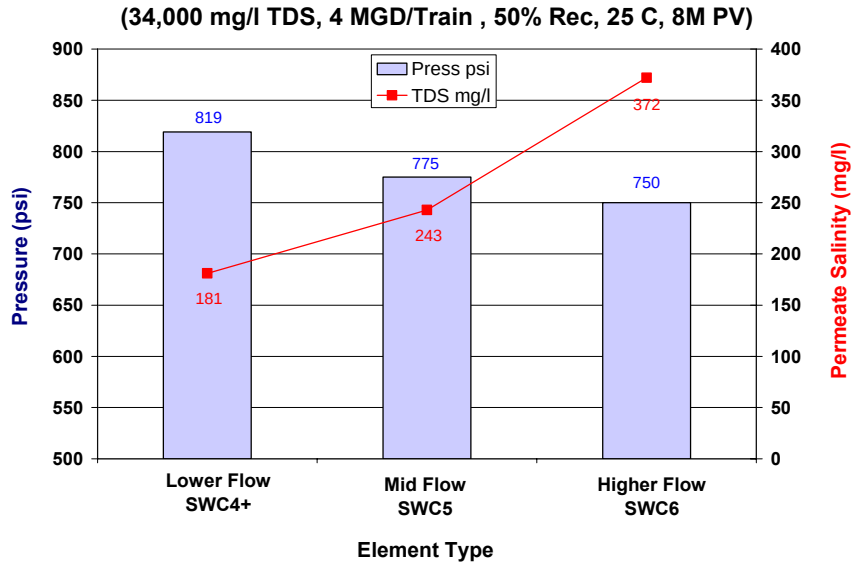
With so many new elements and various performances, it is difficult to determine which RO process design will be the most advantageous. The primary consideration is the required permeate salinity and the pressure of operation. An analysis was carried out to evaluate the effect of various element configurations to determine which would be optimum. The design was based on Pacific seawater which would be typical off the coast of California. The total dissolved solids (TDS) of the water used was 33,800 mg/l, and the temperature was taken as 25 C. This is on the high side of the typical temperatures for that region, but if the intake is on the outfall line from a power plant, this would be a reasonable average temperature. The plant considered was a 40 mgd plant that had 10 trains and operated at 8.1 gfd flux and 50% recovery.

Higher Flow SWRO Elements

Three high rejection elements were considered for the comparison. These included a lower flow (higher energy), mid-flow, and high-flow (lower energy) elements. The results are shown in Figure 1. It can be seen that the lower flow SWC4+ element operates at the highest pressure as expected, 44 psi higher than the mid flow SWC5, and 69 psi higher than the higher-flow SWC6. However, it also produces a permeate that is 191 mg/l lower in salinity. As expected, SWC5 is between these two values. When selecting the optimum membrane, the permeate generated must meet the customer specifications. If the 372 mg/l salinity is acceptable, say the customer wants less than 450 mg/l, the SWC6 would be the most economical choice based on energy savings. However, if the temperature was higher, the salinity higher of the required TDS lower, then the SWC5 or SWC4+ would be required. High flow seawater membranes such as the SWC6 do pass much more salt than the lower flow, high rejection elements. This is a common trade-off in the membrane industry. However, for some applications such as lower feed salinity, lower feed temperatures or Hybrid elements designs, the higher-flow elements can be advantageous.

Another option available to system designers is the use of hybrid element designs. This is a common approach that has been used for years in brackish water plants. It consists of the blending of different element types to better balance the water permeability of the element with the salt rejection. It gives the engineer more control to exactly balance the trade-off between permeability and rejection. In most hybrid brackish plants, the two different elements are split into the two different stages. This makes membrane management more simple. However, plants like the Peele Dixie in Ft Lauderdale do use a mixture of elements in a given pressure vessel. For seawater plants, there is generally only one stage, so the hybrid must be made by mixing elements in a single pressure vessel. Although this may optimize the performance, it does make management of elements at site much more difficult.

Figure 1 Comparison of Various Flow SWRO Elements



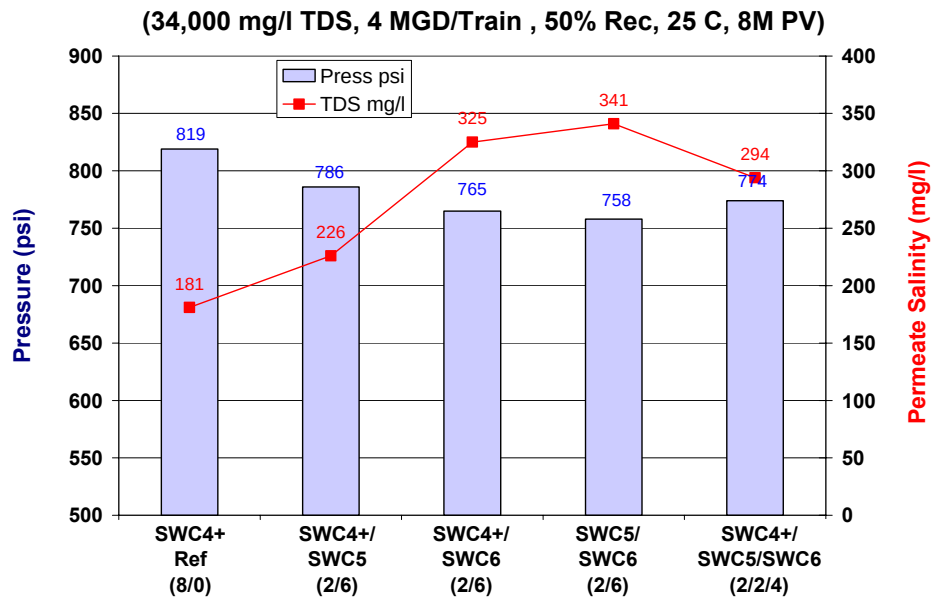
Hybrid Element Designs

A comparison of various hybrid designs is shown in Figure 2. The reference condition was the lower-flow, high rejection SWC4+ element from Figure 1. The first hybrid considered uses 2 lower flow elements in the lead position and 6 higher flow elements in the back positions. The final condition considered was the use of three element types, 2 lower rejection elements in the front, 2 mid-flow in the middle, and 4 higher-flow elements in the back. It can be seen that all conditions give lower energy, but at the expense of rejection. The lowest pressure configuration was the use of 2 SWC5 and 6 SWC6. It can be seen that the 3 element configuration had about the same performance as the SWC4+/SWC6 hybrid. Thus, it would be better to use the simpler SWC4+/SWC6 design. As in the previous discussion, the selection of the best combination or the use of a non-hybrid design will depend on the salinity requirements of the plant. Also, the energy consumption must be very critical since the savings will be a small value and the use of multiple element types will complicate the management of elements at site. The projected permeate quality and energy consumption of various hybrid and non-hybrid designs is shown in Table 2.

Table 2 Permeate Quality and Energy Consumption for Various High Performance SWRO Element Designs

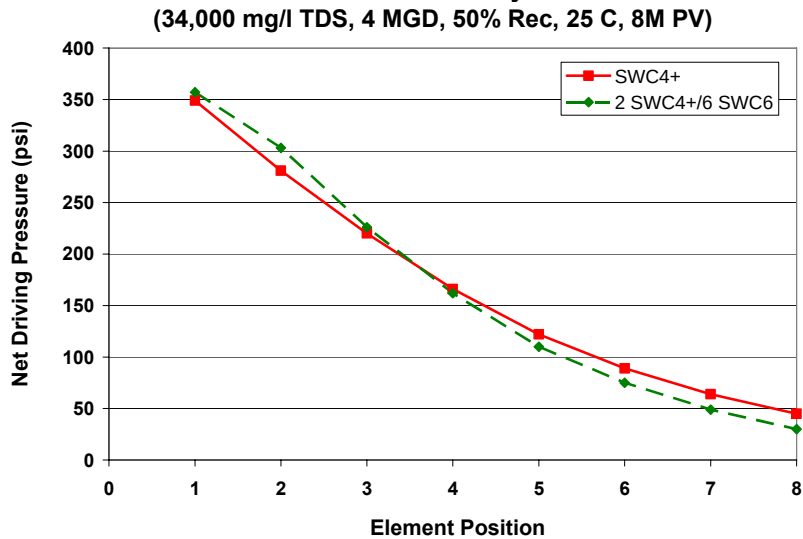
Case	TDS	Cl	B	Energy
	mg/l	mg/l	mg/l	kwhr/kgal
SWC4+	181	105	0.99	10.19
SWC5	243	140	1.6	9.64
SWC6	372	216	2.1	9.33
2 SWC4+/6 SWC5	226	131	1.46	9.8
2 SWC4+/6 SWC6	325	188	1.95	9.54

Figure 2 Comparison of Operating Pressure and Permeate Salinity for Various SWRO



A critical part of understanding the performance of SWRO plants is the relative performance of each element in the array. Because of the rapidly increasing salinity on the feed side of the membrane when water is removed, the net driving pressure pushing water through the membrane is rapidly decreasing. An example of the calculated net driving pressure (NDP) for each element in the array is shown in Figure 3. The figure shows that the NDP decreases from 350 psi to about 50 psi for the lower-flow SWC4+ element type. The NDP of a hybrid is also shown, and is essentially the same, varying slightly due to the difference in permeate flow in the elements.

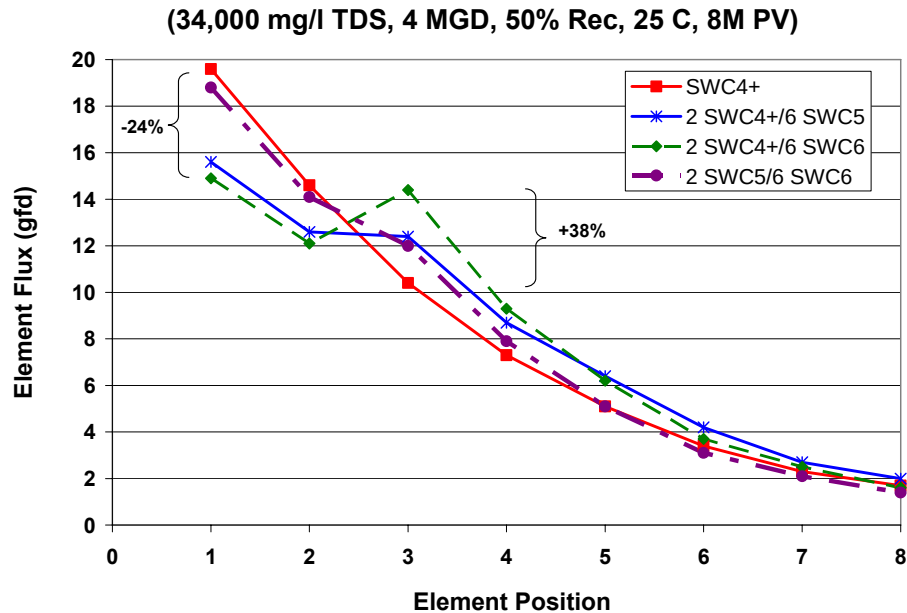
Figure 3 Net Driving Pressure for Each Element in the Pressure Vessel for Various Element Types and Configurations



The consequence of having such a large range of NDP is that the flux of element will also vary. Figure 4 shows the flux distribution of the various elements in a 8M pressure vessel. It is apparent and expected that the more permeable elements like SWC6 will have a greater flux variation in the vessel. Since the SWC6 has a higher membrane permeability, but the NDP is about the same, the flux of the lead elements will be higher. To make the same net amount of permeate from the vessel, the tail elements will thus make less water. High lead element flux can accentuate fouling, if the feedwater does not have sufficiently low turbidity and SDI. There are plants, such as Qidfa III and al Zawra in UAE that operate at greater than 9 gfd total flux and more than a calculated 18 gfd lead element flux (Bartels 2007). With very good pretreatment, it is possible to use the higher-flow SWRO elements without worrying about lead element fouling due to insufficient cross flow.

If there is a concern that feed water quality may not be optimum, then the lead element flux should be carefully considered. One way to lower lead element flux is the use of Hybrid element designs. As shown in Figure 4, the use of the 2 SWC4+/6 SWC6 element array lowers the lead element flux by 24%. As a result of placing SWC6 higher flow elements in position 3, the flux of the first SWC6 will be higher than for SWC4+ in position 3. However, it can be seen that the position 3 SWC6 element flux, 14.4 gfd, is still less than the flux of the lead SWC4+ element, 14.9 gfd.

Figure 4 Flux Distribution by Element in a 8 Element Pressure Vessel for Various Element Configuration

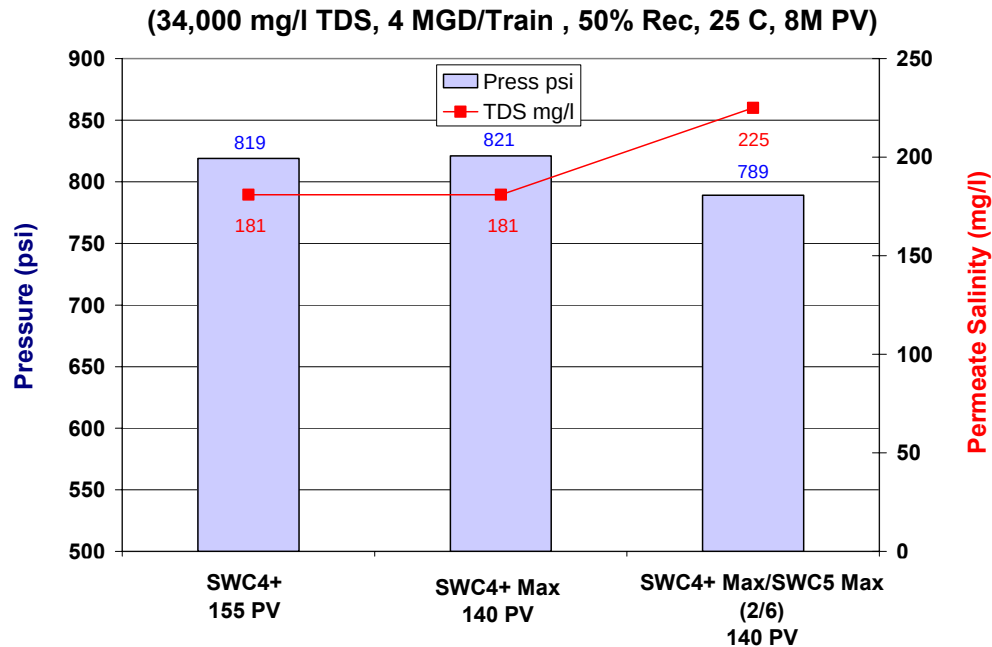


High Area SWRO Elements

Finally, one other design condition should be considered in the light of the new seawater element products. High area seawater elements are now available as shown in Table 1. These elements have 440 ft², similar to the brackish high area elements. With manufacturing automation and control, these high area elements can be made using the same feed and permeate spacer that have been used in conventional 400 ft² seawater elements operating for years around the world. They also use the same sheet membrane. As a result of the higher membrane area, the water production is increased by 10% than a conventional element when tested at the same pressure. This means that the same water can be produced, but with 10% fewer pressure vessels, thus decreasing capital costs. Alternatively, the capacity of an existing plant can be increased by filling all existing vessels with the high area elements. This would allow 10% additional product water to be made at the same pressure. This can be a very attractive alternative design for areas that are short of water.

A design with the lower flow SWC4+ element is shown in Figure 5, where the conventional 400ft² design is compared to the design with high area 440 ft² SWC4+ Max elements. It can be seen that the pressure and permeate salinity are identical, which is because the flux rate is 8.1 gfd in both cases. The only difference is that the SWC4+ Max design uses 140 pressure vessels, compared to 155 for the SWC4+ design. This 10% savings results in significant capital savings, and could potential mean that 10% less trains would be needed, which would also mean that the RO building would be smaller. A hybrid design with the higher area elements is also shown in Figure 5. As in previous cases, the salinity is higher, but the pressure lower.

Figure 5 Comparison of Element Performance for Conventional and High Area Elements



Economic Evaluations of New Designs

To further analyze the membrane designs discussed in the previous section, an economic evaluation of various designs was considered. For this analysis, the assumptions shown in Table 3 were used. Three different membrane configurations were considered:

1. High Rejection, Moderate Flow SWC5 in all 8 positions
2. Lower Flow SWC4+ in positions 1-3, Higher-Flow SWC6 in the last 5 positions
3. High area, Moderate Flow SWC5 Max in all 8 positions

The goal of the design was to keep permeate TDS less than 450 mg/l.

Table 3 Assumptions used in the SWRO Element Design Economic Analysis

Seawater Design Assumptions		
Product Flow	40.00	mgd
	151,400	m3/d
No. Trains	10	
Recovery	50.0%	
Feed Salinity	33900	mg/l
Temperature	25	deg C
Membrane Flux	8.1	gfd
Train Array (MAX)	155x8	(140x8)
Energy Recovery	Isobaric	97% Eff

Memb Cost, \$ (MAX)	500	(550)
Vessel Cost, \$	1500	
Electricity Cost	0.08	\$/kwhr
Membrane Life	4.5	years
Interest Rate	6	%
Depreciation	20	years

The results of the economic analysis are shown in Table 4. Of the three designs, they all produce similar permeate quality, between 240 and 300 mg/l TDS. The hybrid design gives the highest salinity, but slightly lower energy, 2.47 kwhr/m³, compared to 2.49 or 2.50 kwhr/m³. Since energy accounts 30-40% of the water cost (Taub 2007), even small savings of pressure can result in significantly lower operating costs. The capital cost of the SWC 5 and the SWC4+/SWC6 hybrid were the same, because they use the same number of pressure vessels and element. In contrast, the capital cost of the SWC5 Max was noticeably lower, 2.48 \$/gpd compared to 2.56 \$/gpd for the other two designs. This is a direct result of the reduction of the number of pressure vessels and associated piping. Additional savings could be realized if the number of trains was actually reduced from 10 to 9.

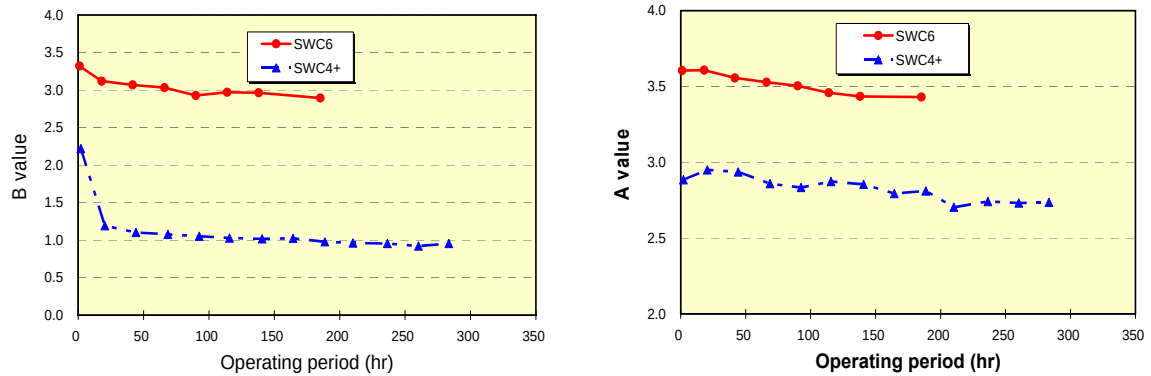
Table 4 Summary of the Economic Analysis of Various Membrane Design Alternatives.

ECONOMIC SUMMARY		SWC5	SW4+/SW6 (3+5)	SWC5 Max
RO Plant Installed Cost	\$/gpd	2.56	2.56	2.48
Total Plant Cost	\$/gpd	5.09	5.09	4.97
RO Plant Footprint*	ft ²	23,182	23,182	23,182
Specific Power	kwhr/m ³	2.49	2.47	2.50
Feed Press	psi	777.20	771.40	780.10
Perm TDS	mg/l	243	301	241
Perm B	mg/l	1.60	1.83	1.59

Performance Testing

To confirm the expected performance of the new high performance seawater elements, field trials have been carried out at multiple pilot sites as well as extensive laboratory testing. The new SWC6 was tested at a pilot trial on the Pacific Ocean. The results of the testing are shown in Figure 7. The Water Transport Coefficient, or A Value shows that the water permeability is about 20% higher than the SWC4+. However, with this higher permeable membrane, there is some trade-off in terms of salt passage. It can be seen that the Salt Transport Coefficient, or B Value, of SWC6 is almost twice as high as that of SWC5.

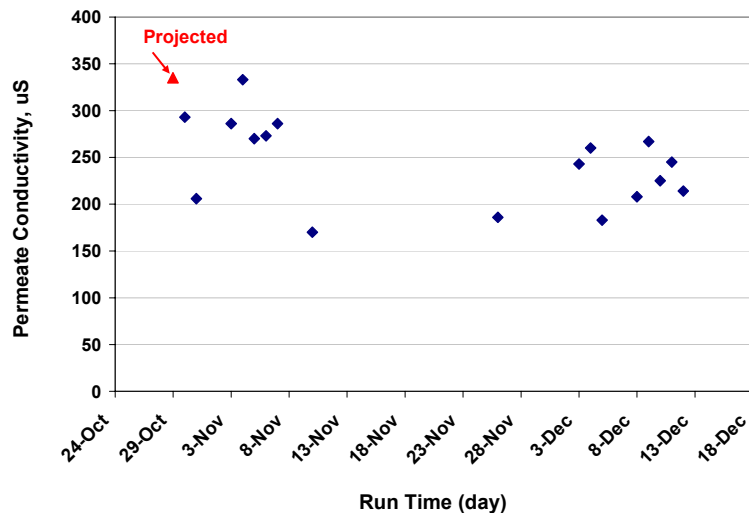
Figure 6 Pilot testing results for new high flow SWRO elements



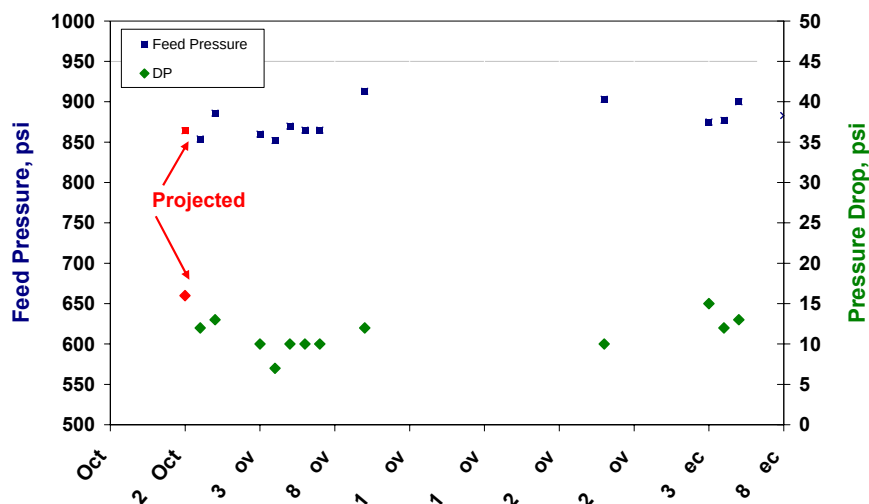
The SWC4+ Max elements are being tested at a pilot site also on the Pacific Ocean. This test is operating at 8.9 gfd flux, 21 to 23 C, and 51% recovery with 6 elements in the pressure vessel.

Figure 7 Actual and projected SWC4+ Max performance trend at a Pacific Ocean pilot trial

A) Permeate Conductivity.



B) Feed pressure and pressure drop



The results show that the performance of these new high area elements is very stable over the three month trial period. The projected feed pressure agrees quite well with the actual results, and the normalized pressure drop is actually lower than the actual value, 16 psi, versus 13 psi. Thus, it can be seen that the high area element performance is a logical extrapolation from the current, know membrane performance.

Conclusions

In conclusion, the new SWRO elements have improved permeability and area. These features provide system designers with new options to reduce the capital cost of the system as well as the operating cost. Although the new low energy membranes run at lower pressure, they do allow higher passage of salinity. For some plant designs, this is acceptable though, if they can meet the permeate quality target. For those plants that have more demanding requirements, a hybrid design of low and high permeable membranes may offer some savings. The combination of these elements, can optimize performance, but it does complicate the operation of the plant by having to manage additional elements in the system. High area elements offer the greatest savings for the capital cost, through the reduction of pressure vessels and associated piping. The proper application of these products can result in millions of dollars of savings in capital and operating costs.

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