Technical Application Bulletin

February 2022 TAB 114

Optimizing the Performance of the ESPA4

This application bulletin is taken from a paper (IWC-03-29) presented as part of the 64th Annual International Water Conference®, Pittsburgh, PA (USA), October 19-23, 2003

Introduction

Since the inception of the first cellulose acetate (CAB) reverse osmosis membrane in the early 1960s, advancements in membrane chemistry have greatly improved their performance and made reverse osmosis a practical and widely used process for the advanced treatment of municipal and industrial waters.

Hydranautics first moved beyond cellulose acetate in 1989 with the introduction of the composite polyamide (CPA) membrane chemistry. The CPA membrane, while having its own limitations such as susceptibility to chlorine degradation, greatly reduced pressure requirements while improving salt rejection.

Hydranautics' breakthrough in CPA technology occurred in 1995 with the introduction of the Energy Saving Polyamide (ESPA). The ESPA reduced pressure requirements by as much as 60 % without significantly compromising the high rejection of the CPA membrane. Nevertheless, many applications continued to require greater energy savings without high rejections.

Recent advancements in membrane chemistry have lead to the development of the fourth generation of reverse osmosis membrane, the ESPA4. This latest membrane is characterized by even lower pressures than those of previous generations while still maintaining high salt rejection. Though the ESPA4 may greatly reduce operating cost, certain design limitations must be considered for its benefits to be realized.

ESPA4 Membrane Characterization

Advancements in membrane performance may be gauged by two characteristics: rejection and permeability. A membrane's rejection is its ability to retain aqueous salts and ions while allowing for the passage of water. Rejection is derived from the feed/brine average concentration (Cf_{avg}) and the permeate concentration (Cp) in the following equation:

$$\text{Rej (\%)} = 100 \times (1 - Cp / Cf_{avg}) \qquad (1)$$

Membrane permeability or specific flux (Ka) is a function of the net driving pressure (NDP) and average permeate flux (Jp). Permeability is membrane specific and is determined by the following equation:

$$Ka = Jp / NDP \qquad (2)$$

NDP is given by:

$$NDP = Pf - dP/2 - Pp - \Delta\pi \qquad (3)$$

Where:

Pf = feed pressure
dP/2 = average hydraulic pressure losses through the membrane
Pp = permeate back pressure
$\Delta\pi$ = the average osmotic pressure difference between the concentrating salts and the permeate.

Using rejection and permeability as primary membrane characteristics, the advancement from CAB to the fourth generation of energy saving polyamides (ESPA4) can be followed in figure 1.

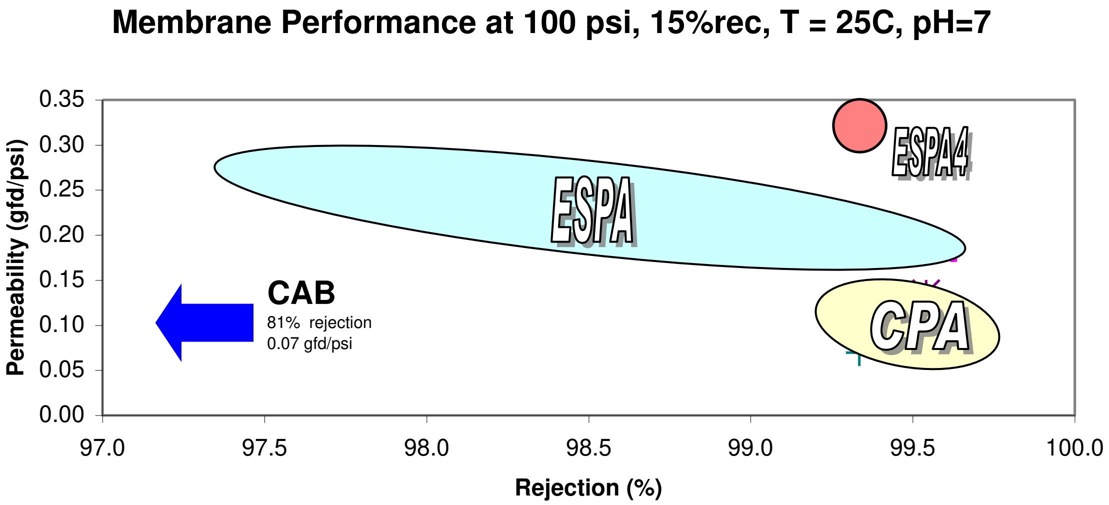

Membrane Performance at 100 psi, 15%rec, T = 25C, pH=7

Figure 1. Advancements in RO membrane performance as gauged by membrane permeability and rejection.

Referring to figure 1, the ESPA4 produces the greatest amount of water per unit of driving pressure. Conversely, the ESPA4 requires the least amount of driving pressure of all the membranes to produce a given flow - making it a very attractive choice for energy savings.

ESPA4 System Characterization

It is well known that RO membrane improvements do not directly translate into RO system improvements. With the increased permeability of this latest generation membrane, comes the need to assess its implications on the performance of a whole system.

As equation 2 and equation 3 suggest, a system equipped with lower permeability membranes (i.e. CPA) requires a higher NDP and therefore a greater feed pressure (Pf) - much greater than the osmotic pressure (π) of the concentrate which therefore has little influence on system performance. But as membrane permeability increases and the required Pf decreases, osmotic pressure increasingly influences system performance to a point where it completely governs system performance and membrane permeability is no longer a factor(1). To illustrate these limitations, a hypothetical two stage RO system, with operating conditions as found in table 1, is considered.

Sytem Operating Conditions	
Array	12 , 7
Elements/vessel	7
Flux	13.5 gfd
TDS	1500 ppm
Temp	25 C
Rec	85%

Table 1. Operating conditions for hypothetical RO system.

Figure 2 compares the loss of NDP through the two-stage system equipped with traditional CPA and ESPA membranes. Hydraulic pressure losses, as well as an increasing osmotic pressure, contribute to the rapid reduction in NDP so that the lead elements have a greater flux than the tail elements. Though the loss in NDP through the CPA system (75% reduction) is greater than that of the ESPA (71% reduction) system, the relative difference is not substantial. In both systems, all elements from lead to tail are seeing an NDP and therefore being utilized.

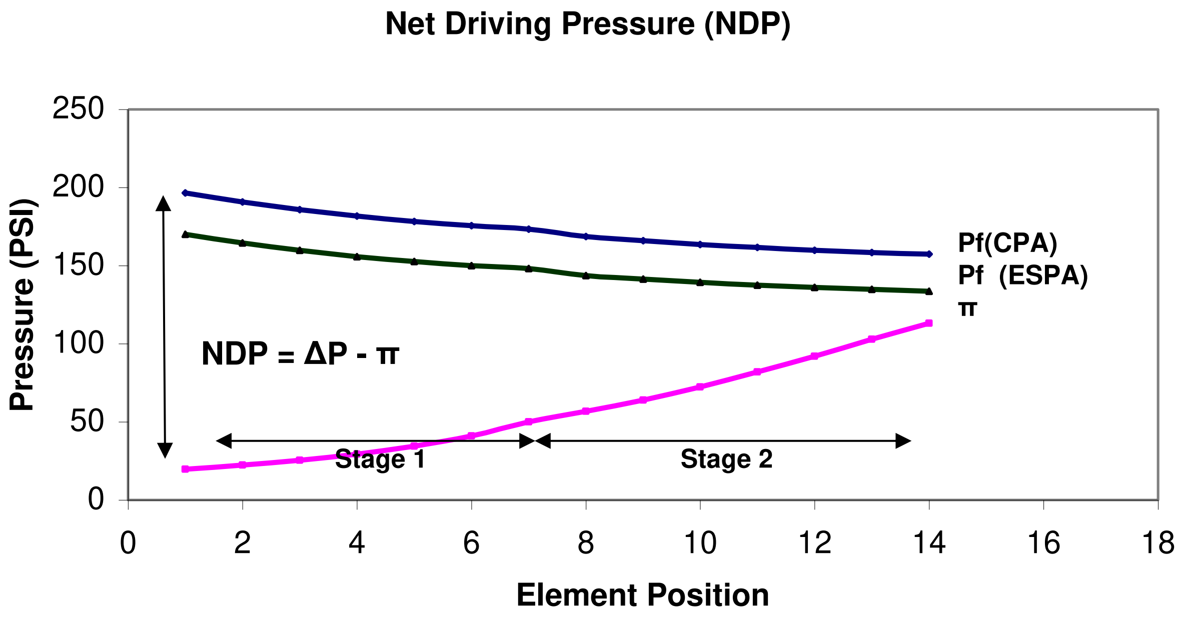


Figure 2. Loss in Net Driving Pressure through a two-stage system equipped with CPA and ESPA membranes.

A significant difference occurs when the same system is equipped with the ESPA4 membranes. As figure 3 illustrates, the initial feed pressure is so low and the loss of NDP is so great that the tail elements of the system see no NDP and produce no permeate.

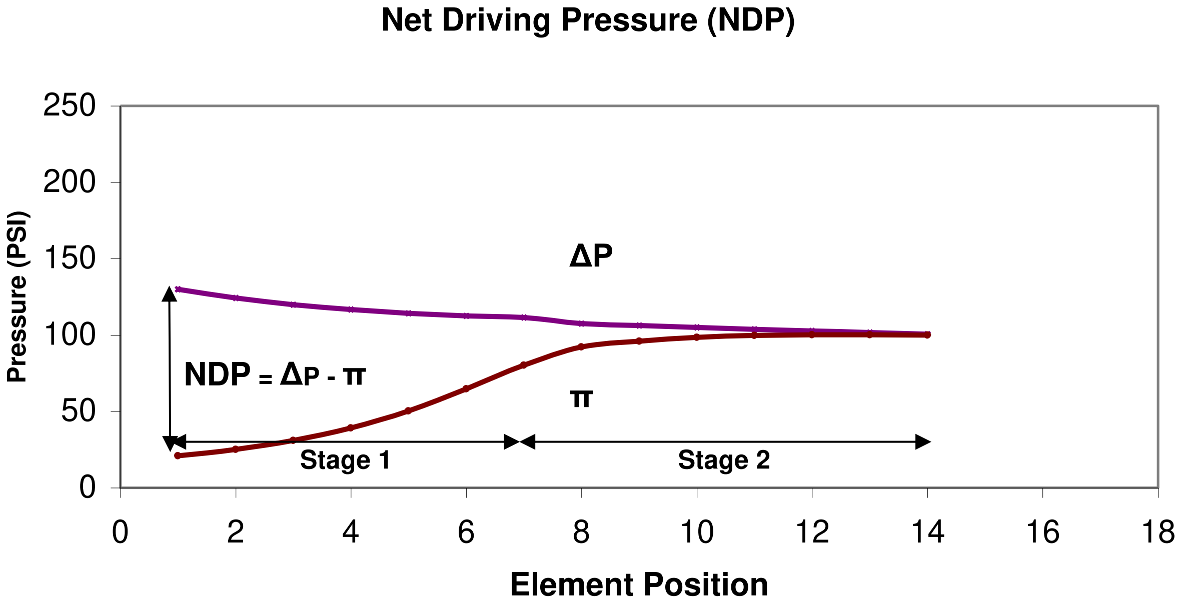


Figure 3. Loss in Net Driving Pressure through a two stage system equipped with ESPA4 membranes.

To better illustrate the impact that NDP loss has on system performance, consider the direct relationship between NDP and the permeate flux from each element in the system after rearranging equation 2:

Jp = Ka x NDP (4)

Figure 4 shows the flux through each of the 14 elements in the ESPA4 system and how the rapid loss in NDP results in a rapid loss of flux so that the first nine elements produce 95% of the system output rendering the tail elements almost useless. For comparison, the element flux in a system containing CPA and ESPA membranes are displayed. In this hypothetical system, the use of ESPA membranes over CPA membranes does not significantly reduce the efficiency of the system in the way the ESPA4 membrane does.

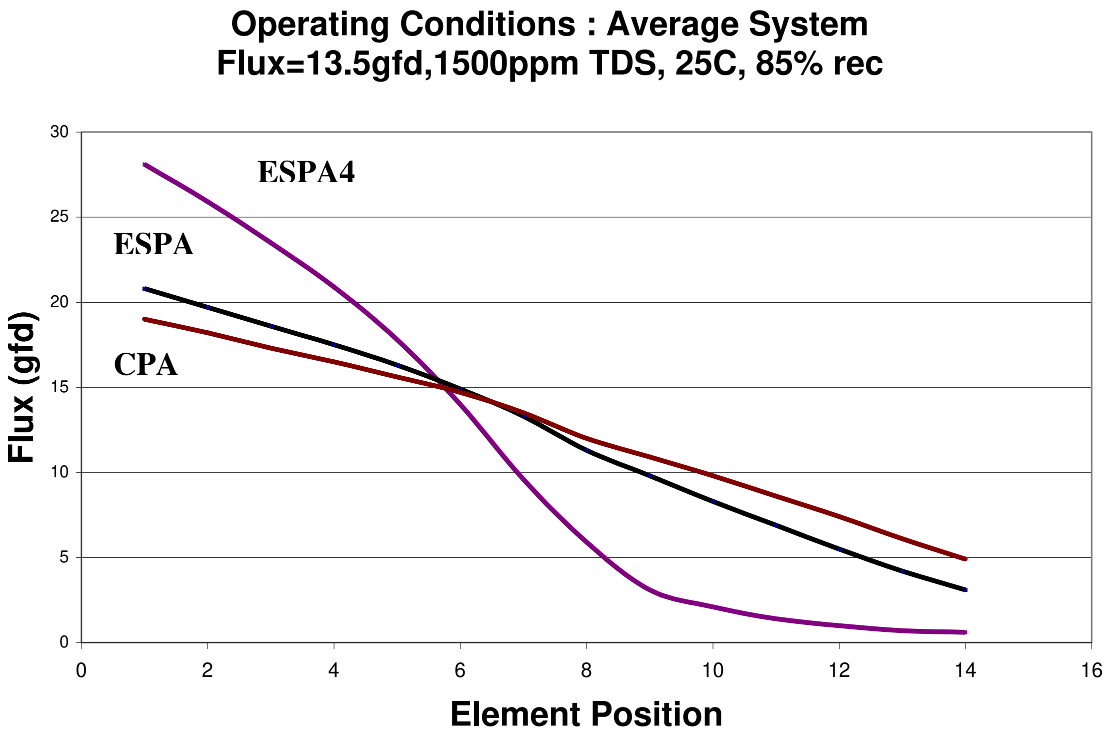


Figure 4. Flux loss through a hypothetical two-stage system equipped with three different generations of membranes.

ESPA4 System Design Modifications

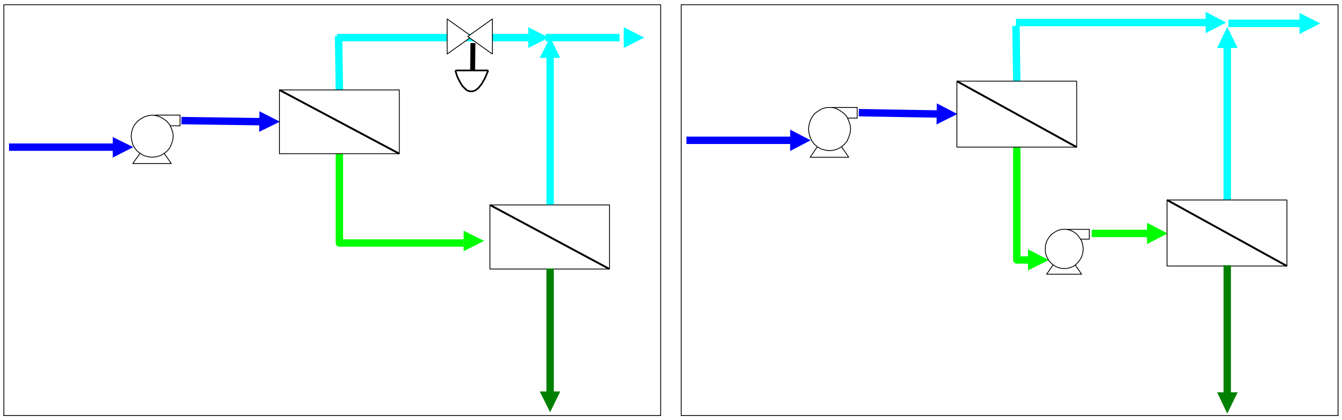
The system inefficiency described above is not a new phenomenon associated with the ESPA4 membranes only. At higher temperatures and higher feed salinities, tail elements in a system equipped with ESPA membranes may also be underutilized.

Since the introduction of the ESPA, several design modifications have been proposed and recognized as options to improve the efficiency of a system loaded with highly permeable membranes(2,3,4). These three designs, which include permeate throttling, booster pump, and hybrid designs, can also be used to improve the efficiency of an ESPA4 system.

As figure 5a shows, a valve may be installed on the permeate side of the first stage. This valve, when partially closed, will increase pressure in the permeate line. According to equation 3, increasing permeate back pressure will decrease NDP and in turn, decrease flux from the first stage elements. To compensate for lower water production in the first stage, system feed pressure must increase to produce adequate NDP and perm flow in the second stage. However, the increase in feed pressure diminishes the energy savings achieved when using the high permeability ESPA4 membranes.

To distribute the flux more efficiently between all stages while maximizing energy savings, the second design option places a booster pump before the last stage in the system (figure 5b). The installation of a booster pump avoids the increased feed pressure requirement in the first two design options by more evenly distributing the feed pressure between the two stages.

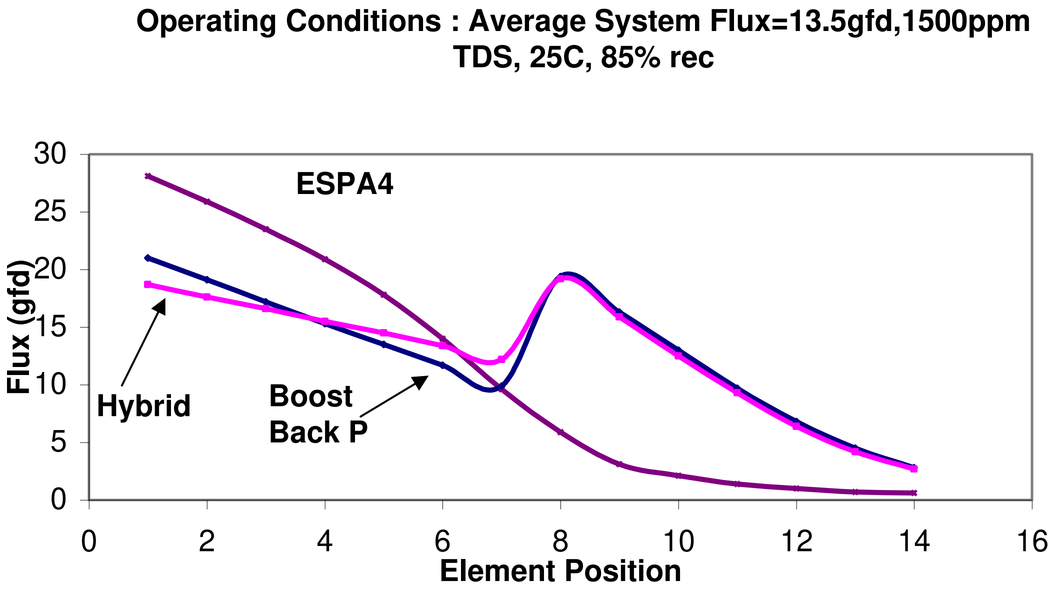
A different design modification with similar results is the hybrid design. Lower permeability membranes such as the ESPA or CPA are installed in the first stage while high permeability ESPA4 membranes are installed in the second stage. Like the other design options, the hybrid design results in higher feed pressures when compared to a system equipped solely with ESPA4. However, the benefit of lower permeability membranes in the first stages is their higher rejection. A hybrid system will not only resolve the flux distribution problem, but will also result in better overall permeate quality.



(a) (b)

Figure 5. Two Stage RO System with (a) Permeate Throttling Valve After First Stage (b) Booster Pump Before Last Stage.

Figure 6 shows the flux distribution which results from each of the design modifications. The addition of an inter-stage booster at 50 psi and permeate back pressure of 50 psi produce an identical flux distribution throughout the system. The hybrid system, with ESPA in the first stage and ESPA4 in the second stage produces the best flux distribution. Applying any of the three options clearly leads to a more efficient system in terms of flux distribution. Unfortunately, not all options take full advantage of the energy savings associated with the ESPA4.



Operating Conditions : Average System Flux=13.5gfd,1500ppm TDS, 25C, 85% rec

Figure 6. Effect design modifications on flux distribution

When modifying a system to achieve a more efficient flux distribution, the designer must also consider the trade off in energy savings resulting from that modification. Specific power consumption (SPC) provides an adequate means to compare the energy savings of the three design modifications relative to a standard system. SPC is a function of feed pressure (Pf), system recovery (R), and motor and pump efficiencies (Em, Ep). Using C as the units conversion factor, SPC is given by the following equation:

$$SPC = C \times Pf / (R \times Ep \times Em) \qquad (5)$$

Units for SPC are given here as kWhr/kgal. In the case of the booster pump design, the pumping power of the booster pump is added to the pumping power of the feed pump. Of the three design modifications, table 2 demonstrates the significant energy savings of the booster pump design. However, to avoid the design complexities and capital cost associated with a second pump, the hybrid and permeate throttling designs both take advantage of the ESPA4's increased permeability while still producing an efficient flux distribution.

Element	Modification	kWhr / kgal
ESPA	none	1.84
ESPA4	ESPA Hybrid	1.68
ESPA4	50 psi back P	1.65
ESPA4	none	1.41
ESPA4	50 psi boost	1.32

Table 2. Specific power consumption of different RO systems (Operating Conditions: Average System Flux=13.5gfd,1500ppm TDS, 25C, 85% rec)

ESPA4 Applications

Factory testing and pilot studies have demonstrated the capabilities of the ESPA4 over a range of operating conditions. One such study used the ESPA4 membrane to treat Colorado River Water for potential municipal use. Micro-filtered permeate fed a two stage RO array (2:1) with 6 elements per vessel. The pilot required 76 psi to produce 12.5 gpm. The 500ppm feed was reduced to 11ppm, achieving 99.1% system rejection (Table 3)

Parameter	**Unit**	**ESPA4**
Temperature feed	°C	13.3
Pressure feed	psi	76
Feed conductivity	ppm	500
Permeate conductivity	ppm	11
Perm Flux	gfd	11.8
Rec	%	71.8

Table 3. Pilot unit equipped with ESPA4 membranes treating Colorado River Water.

Other studies tested ESPA membranes along with the new ESPA4 membranes for comparison purposes. A study done in Germany treated softened city water for laboratory use. The system consisted of two pressure vessels in series with each vessel housing a single 4in x 40in element. Recirculation was used to obtain 75% recovery. The performance of the ESPA4 can be compared to that of the ESPA in table 4. In this case, the ESPA4 produced water quality comparable to that of the ESPA but at 22% less pressure.

Parameter	**Unit**	**ESPA**	**ESPA4**
Temperature feed	°C	10.2	9.5
Pressure feed	Psi	111	87
Feed conductivity	ųS/cm	330	325
Permeate conductivity	ųS/cm	4.83	4.79
System Rej	%	99.5	99.5
Perm Flux	gfd	12.7	12.7
Rec	%	77.3	77.3

Table 4. Pilot study comparing the performance of ESPA with that of ESPA4.

An existing full scale plant in Florida designed to augment the local municipal water supply, originally used CPA membrane to treat water from the local aquifer. After eight years of successful operation, there was a need to increase production and decrease energy requirements. The old CPA membranes were replaced with ESPA4. The booster pump design proved beyond the scope of the upgrade so the permeate backpressure design was chosen to better control flux distribution. Because the piping for permeate back pressure did not previously exist, valves had to be installed on the permeate lines. Figure 6-7 compares the previous operation of this system using CPA membranes with current startup data of the system using ESPA4 membranes.

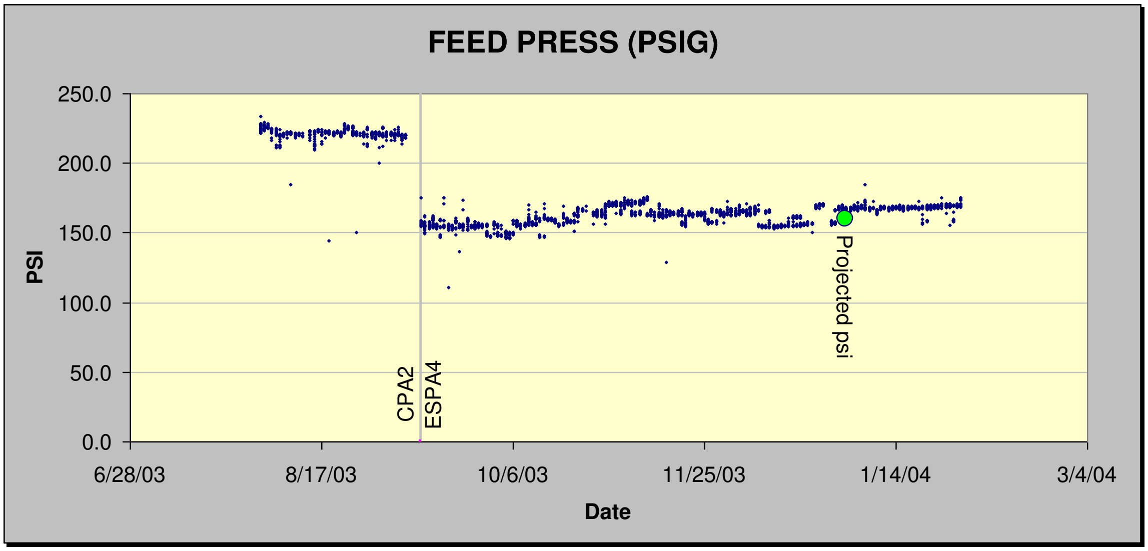


Figure 6. Reduction in feed pressure achieved when Floridian RO plant replaced CPA2 with ESPA4 membranes.

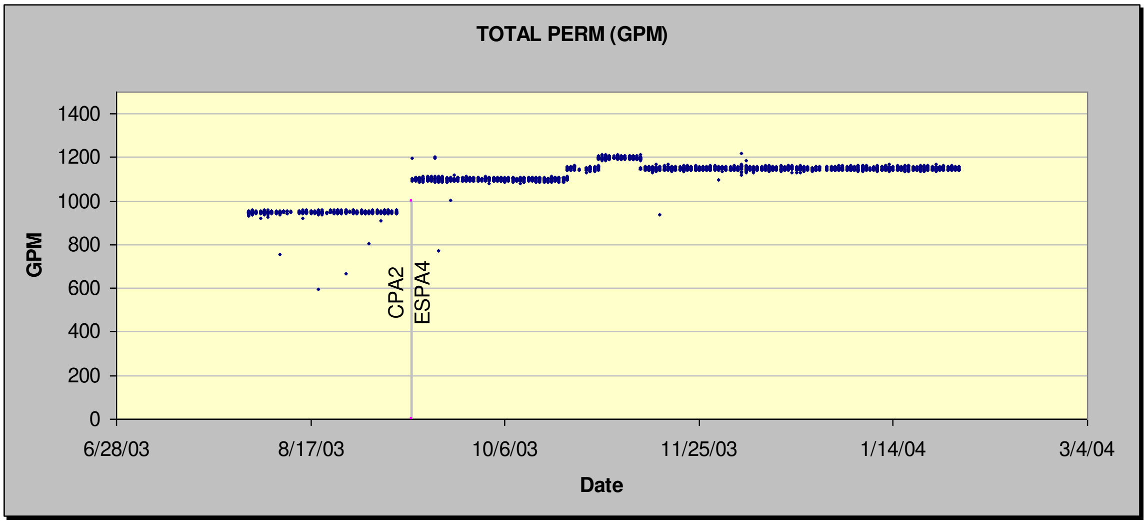


Figure 7. Increase in production when Floridian RO plant replaced CPA2 with ESPA4 membranes.

Discussion

With the increased permeability of the ESPA4, comes the increasing influence of osmotic pressure on system performance. For this reason, careful consideration should be given to feed TDS, design flexibility, energy requirements, and product water goals when considering the ESPA4.

If typical system recoveries are assumed, the use of ESPA4 is limited primarily by feed concentration. Waters with less than 1000 mg/L TDS could be treated by an ESPA4 system without any of the design modifications mentioned above. Additionally, the chemistry of the ESPA4 accentuates the effect of feed salinity on salt passage more than lower permeability membranes, increasing the elements rejection at lower feed salinities, but significantly decreasing rejection at higher feed salinities. The salt passage effect can be seen in figure 7 where the element's rejection begins to increase significantly when feed salinities drop below 2000 ppm. The passage of individual ions is also affected by feed salinity as well as ion charge and size. An example where ESPA4 might be used on low TDS water would be when targeting a specific contaminant-as when a municipal water supply contains an unacceptable level of arsenic or seeks partial softening. Another low TDS application for ESPA4 is the point of use markets such as commercial/residential sinks, laundry, or car washes.

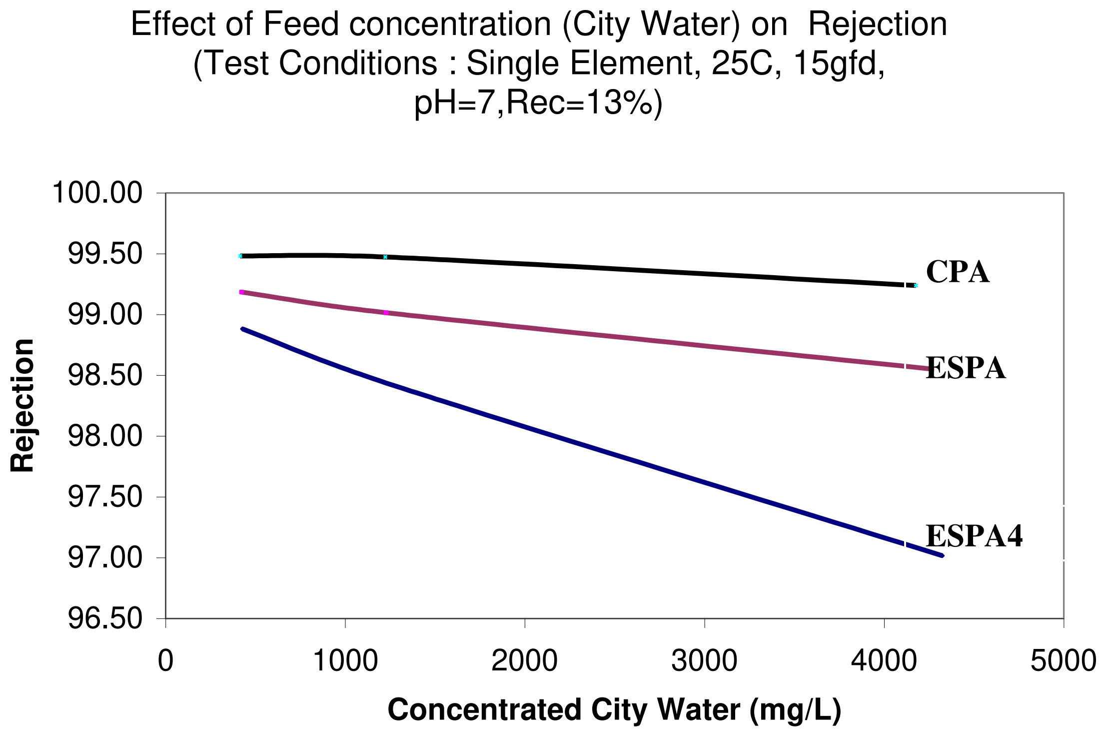


Figure 8. Effect of feed concentration on membrane rejection.

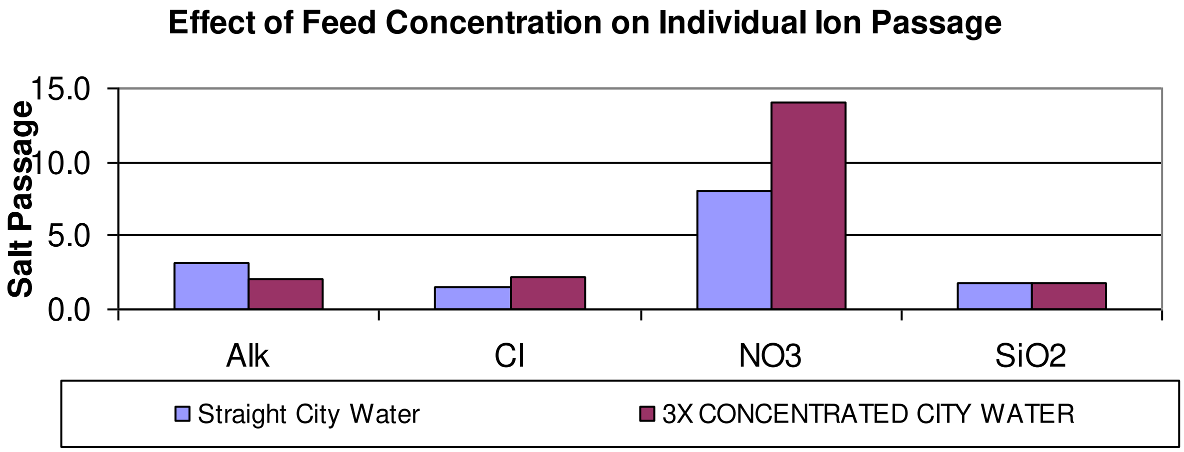


Figure 9. Effect of feed concentration on the passage of individual ions.

When designing a two-pass system, the low TDS of the first pass permeate and the high flux associated with the second pass make the ESPA4 an excellent candidate for the second pass. However, due to the higher recoveries associated with the second pass and, therefore, the rapid increase in osmotic pressure, a hybrid design may be necessary.

When using the ESPA4 for higher TDS waters (1000ppm < TDS < 2000ppm), one of the three previously mentioned design modifications should be considered. Out of the three design modifications, the least desirable is the permeate back pressure design which wastes much of the energy gains made by the ESPA4. In terms of specific power consumption, the hybrid design is comparable to the permeate back pressure design except that the hybrid design produces higher quality permeate. The hybrid design is also good for retrofitting existing systems when one wishes to avoid hardware changes.

When designing a new system to treat higher TDS waters and when seeking the greatest energy savings, the booster pump design is the most desirable option. This design may incur higher capital cost as well as more complex construction and piping, but the energy savings of the ESPA4, and the operational cost savings of the plant, is maximized.

Conclusion

With the fourth generation (ESPA4) membranes, comes the potential to significantly reduce energy consumption and further increase the cost competitiveness of reverse osmosis as a water treatment technology. However due to their high permeability, employing the ESPA4 in a system could lead to inefficient operation where excessive flux in early elements leaves little to no flux for tail elements. Several factors must be considered and optimized to take full advantage of these membranes. Matching the right design with a specific application and its requirements may save the customer anywhere from 10% to 35% on energy consumption. With this in mind, guidelines for the use of ESPA4 are as follows:

- Low TDS feed water sources (<1000 mg/L)
- Point of Use (POU) market.
- Second Pass of a two pass RO systems.
- Moderate TDS water sources (1000 to 2000 mg/L TDS) when using an interstage booster pump on new systems or a hybrid design to retrofit existing systems.

With the introduction of the ESPA4 comes the question of future advances. Referring back to figure 1 at the beginning of this paper, progress beyond ESPA4 means further increasing permeability and/or increasing salt rejection. But the design limitations associated with ESPA4 suggest that a permeability ceiling has been reached in which pressure is no longer limited by the membrane, but by osmotic pressures. Future improvements shall be in rejection-specifically higher rejection of mixed feeds.

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