Extending Swro Membrane Life And Controlling Biofouling Via Flux-Balanced Operation Enabled By Interstage Boosting

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Abstract

Over the past decade, the operational lifetime of seawater reverse osmosis (SWRO) membranes has declined significantly, coinciding with industry trends toward higher system recoveries and longer pressure vessels. While higher recovery improves water production efficiency, it often results in excessive flux and recovery at the lead membrane elements, leading to increased concentration polarization, accelerated biofouling, and premature membrane degradation. This review examines the underlying hydraulic and osmotic imbalances in conventional single-stage SWRO designs and identifies excessive element-level flux as the primary driver of reduced membrane lifespan rather than high recovery itself.

The study introduces and evaluates flux-balanced system concepts enabled by interstage pressure boosting, where net driving pressure is more evenly distributed along the membrane array. Several design scenarios—including a theoretical element-by-element boosted system, three-stage, two-stage, and traditional single-stage configurations—are analyzed and compared using membrane projection data. Results demonstrate that multi-stage designs significantly reduce peak membrane flux, maintain element recovery within recommended limits, and lower concentration polarization, thereby mitigating biofouling risks and extending membrane life. Among the practical options, the two-stage system with interstage boosting, particularly when combined with Biturbo energy recovery technology, offers the most favorable balance between capital cost, operational efficiency, membrane longevity, and energy consumption. These findings highlight flux-balanced operation as a critical design strategy for improving the sustainability and economics of modern SWRO plants.

Keywords: Seawater Reverse Osmosis (Swro), Membrane Flux Balance, Interstage Pressure Boosting, Biofouling Control, Concentration Polarization, Membrane Lifetime, Multi-Stage Desalination, Net Driving Pressure, Energy Efficiency.

Introduction

Over the past decade, SWRO membrane lifetime has declined significantly from 7-10 years to 3- 5 years. This trend has not been thoroughly investigated, perhaps because of the high drop in the membrane price has reduced the financial impact. These issues started when SWRO system recovery increased from 30-35% 10 years back to 40-45%. By deep analyses, it was found that the way to increase recovery is by increasing the pressure vessel length hence the number of elements, then increasing the feeding pressure to ensure permeate from the last element. But in reality, the first elements work in high flux and high recovery and last element work in low flux low recovery. Seven (7)

elements PVs have shortened the membrane lifetime as only 3 elements work with good flux good recovery.

Also, there is another phenomenon that increases the Biofouling At the seawater SWRO plant the high flux increases concentration polarization (CP). There is a positive relationship between high concentration polarization (CP) and Biofouling, and this explains why both issues happened when we increased the recovery by adding elements and increasing feed pressure.

These observations do not imply that the industry must return to lower recoveries. The core problem is not high recovery it-

self, but the excessive flux imposed on the lead elements. The solution is to design systems that achieve two objectives simultaneously: maintain a long series of membrane elements while keeping each element's flux and recovery within a relaxed, stable operating range—achieving true flux balance. This is only possible by applying the appropriate driving pressure to each element position. Front-end elements should operate at lower pressure because they treat low-TDS feedwater, while back-end elements require higher pressure to overcome the elevated osmotic pressure of concentrated brine.

This paper presents multiple BWRO and SWRO design scenarios based on this concept and compares their performance with conventional designs, highlighting the improvements in element-level flux distribution and concentration polarization.

General Concept

The main problem in high recovery systems is membrane flux as you need to increase the pressure to get product from last element but in reality, all this extra pressure provided to the 1st element which increase the flux and recovery for this element because this element work on feed water and don't need all this pressure. At the same time the rear elements work with high TDS water (high osmotic pressure) but with lower pressure compared with front elements.

Sea water desalination Membrane manufacturing design guidelines indeed recommended element recovery of around 8% and an element flux lower than 24 LMH (liters per square meter per hour), These guidelines are designed to optimize the performance and longevity of the desalination membranes.
 Regarding biofouling, which is a significant challenge in membrane processes, research has shown a tight relationship between element polarization and biofouling. Element polarization can exacerbate biofouling by creating conditions that favor the growth of biofilms on the membrane surface. This, in turn, can lead to a phenomenon known as biofilm-enhanced concentration polarization (BECP), which can degrade water quality and reduce membrane lifetime.

To mitigate biofouling, it is recommended to keep the element polarization below 13%. This helps in maintaining the quality of the permeates and the efficiency of the membrane process. By controlling element polarization, it is possible to reduce the risk of biofouling and extend the operational life of the desalination membranes.

Driven Pressure

Driven pressure is crucial for managing both the membrane flux and the recovery rate. The driven pressure is the difference between the applied pressure on the membrane and the osmotic pressure of the saline water.

To achieve the desired membrane flux and recovery, the applied pressure must be sufficient to overcome the osmotic pressure and any additional resistances to water flow through the membrane pores. This excess pressure ensures that water molecules are pushed through the membrane, while most salts and contaminants are rejected.

Here's a simplified expression of the net driving pressure.

$$P_{ND} = P_{applied} - P_{osmotic}$$

Where:
(P_{ND}) is the net driving pressure, (P_{applied}) is the applied pressure, (P_{osmotic}) is the osmotic pressure of the feed water.

By carefully controlling (P_{ND}), you can optimize the performance of the desalination process, ensuring efficient operation while minimizing issues like biofouling and concentration polarization.

Case study Design

There Are Several Factors We Considered In The Case Study: Capacity The skid's capacity of 5,000 CMD is substantial and should be designed to handle the daily volume efficiently.

Feed Water Salinity

A salinity of 43,000 PPM is on the higher end for seawater, which typically ranges from 35,000 to 45,000 PPM. This high salinity can increase the osmotic pressure, requiring more energy to achieve the desired permeate flow.

Feed Water Temperature

The temperature of 25°C is within the optimal range for desalination processes. Generally, an increase in temperature can lead to an increase in permeating flow rate, which can be beneficial for the process efficiency.

Membrane Age

Over time, membranes can experience wear and degradation, which can affect their performance. After 3 years, you may start to see a decline in permeate quality and quantity, necessitating more frequent cleaning or replacement.

In our analysis, we use typical projections and not necessarily optimized, and we use specific membrane projection software although many membrane brands and software may be used.

Case Study

We will compare different designs for a SWRO plant, which is a comprehensive approach to evaluating the membrane operation environmentally.

Theoretical Design

This design involves using a boost pressure between each element to maintain optimal drive pressure control. It's a more complex system that aims to optimize performance by adjusting the pressure throughout the process but would be impractical to implement.

Stage System

A 3-stage SWRO system is designed to be more economical while still providing maximum control over the desalination process. It typically involves multiple stages of pressure and recovery, allowing for better energy efficiency and potentially lower operational costs.

Stage System

The 2-stage system aims to maximize economic efficiency while maintaining good control. It usually involves two stages of membrane filtration, with the first stage operating at a lower pressure

than the second. This design can offer a balance between cost and performance, with a focus on reducing energy consumption.

Traditional Single Stage System

The single-stage system is the simplest design, where all membranes are housed in a single pressure vessel. This system is generally less complex and may have lower capital costs, but it might definitely not be the best as membrane lifetime and energy efficient as multi-stage systems.

Theoretical Design

Figures 1, Show the membrane array with single element PV and individual boost pressure, with this design we are able to control the driven pressure for each element to achieve a balance flux and recovery for each element as we will show in the membrane projection.
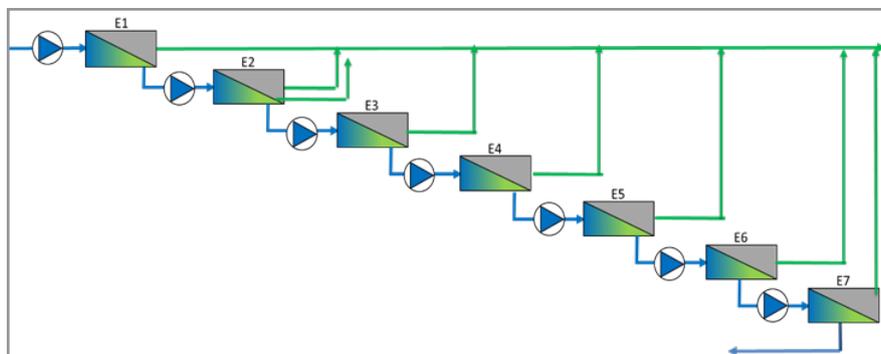
Figures 1: Theoretical Design

Figures 2 show membrane projection report for Theoretical Design, we used 3 bar to 5 bars boost pressure between each element to recover the osmotic pressure increase based on the element feed water salinity increasing.

**Figures 2:** Theoretical Membrane Projection

With this design we maintain an average element recovery of 8% and a maximum membrane flux of 15.07 LMH which definitely will provide ideal working environmental for the membranes which leads to extended Membrane Life because operating at a lower flux helps prevent physical stress and chemical degradation of the membranes, potentially extending their operational lifespan.

Also, with this design the membrane polarization is 9% which minimizes the accumulation of biological material on the membrane surface, thereby reducing the risk of biofouling. This design is clearly expensive because of the number of pressure vessel, pumps, and control.

3-Stage System Design

Figures 3, Show the membrane array with 3-Stages systems each stage includes 3 elements per pressure vessel (PV) and have boost pressure between each stage, with this design we able to reduce the capital cost but still keep a full control of driven pressure elements show in the membrane projection.
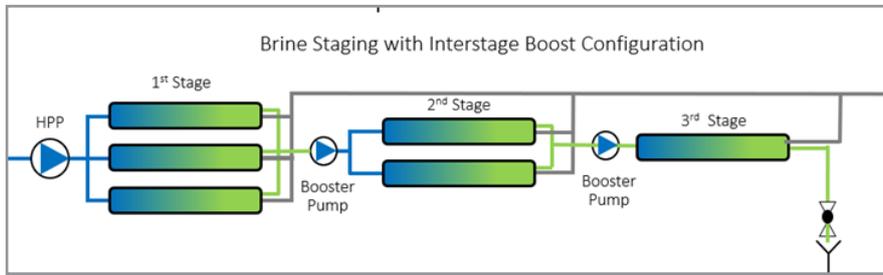
Figures 3: 3-Stages systems

Figures 4 show membrane projection report for 3-Stages Design, we used from 12 bar and 11 bar boost pressure between each stage to recover the osmotic pressure increase for each pressure vessel based on the set of 3 elements feed water salinity increasing.

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Project name: IDA Paper — Customer: IDA — Username: HAytham
Water type: Seawater, 42,000 ppm — Flux loss per year: 7.00% — Salt passage increase: 7.00%
Membrane age: 3 — Safety factor: 1

Overall System
Total permeate flow: 210 m3/hr — Raw water flow: 466.67 m3/hr — Total concentrate flow: 256.67 m3/hr — Overall recovery: 45 %
Water source: Seawater-Open Intake (SDI<5) — Raw water TDS: 41,999.94 mg/L — Feed osmotic pressure: 30.25 bar — Concentrate osmotic pressure: 54.88 bar
Feed pressure: 50.16 bar (1P)

System - Pass1
Permeate flow: 210 m3/hr — RO feed flow: 466.67 m3/hr — Concentrate flow: 256.67 m3/hr — Recovery: 45 % — Number of elements: 420 — ERD type: None — Recirculation:
Average flux: 12.23 lmh — Water source: Seawater-Open Intake (SDI<5) — Feed TDS: 41,999.94 mg/L — Feed osmotic pressure: 30.25 bar — Concentrate osmotic pressure: 54.88 bar — Pump efficiency: 80 %
Temperature: 25 °C — Average NDP: 17.39 bar — Specific energy: 4.34 kWh/m³ — Feed pressure: 50.16 bar — Permeate TDS: 259.36 mg/L — Fouling factor: 0.8

	# of vessels	# of elements	RO feed flow m3/hr	Permeate flow m3/hr	Conc. flow m3/hr	RO feed pressure bar	Conc. pressure bar	Vessel DP bar	Boost pressure bar	Back pressure bar	Inter-stage pressure loss bar	Average flux lmh	Perm. TDS mg/L
Stage 1	80	3	466.67	117.59	349.08	50.16	49.8	0.36	0	0	0	11.99	236.41
Stage 2	40	3	349.08	60.78	288.3	61.8	61.06	0.73	12	0	0	12.39	280.46
Stage 3	20	3	288.3	31.83	256.47	72.06	70.35	1.71	11	0	0	12.98	303.85

Within Vessels - Pass1

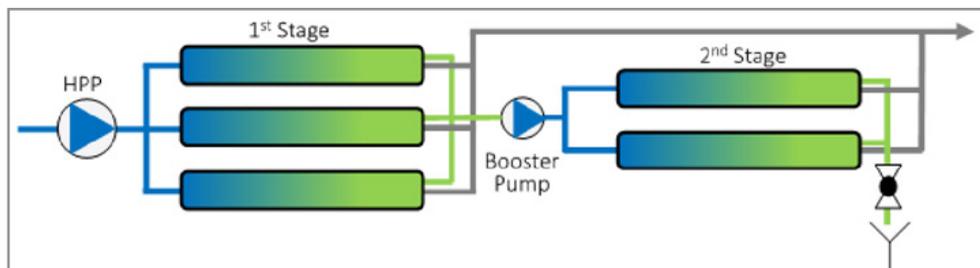|	Position	RO feed flow m3/hr	Permeate flow m3/hr	Flux lmh	Element recovery %	Element DP bar	Net driving pressure bar	Polarization	Feed TDS mg/L	Perm. TDS mg/L
Stage 1										
LG SW 440 R	1	5.83	0.65	15.94	11.17	0.14	14.18	1.12	41,996.22	164.42
LG SW 440 R	2	5.18	0.48	11.65	9.19	0.12	10.94	1.10	47,257.97	244.64
LG SW 440 R	3	4.71	0.34	8.37	7.27	0.10	8.29	1.08	52,013.76	362.42
Stage 2										
LG SW 440 R	1	8.73	0.64	15.54	7.28	0.27	16.46	1.08	56,064.10	212.24
LG SW 440 R	2	8.09	0.50	12.16	6.14	0.24	13.64	1.07	60,447.85	286.52
LG SW 440 R	3	7.59	0.39	9.47	5.10	0.22	11.22	1.06	64,386.07	384.63
Stage 3										
LG SW 440 R	1	14.41	0.63	15.42	4.37	0.61	19.43	1.05	67,824.75	247.40
LG SW 440 R	2	13.78	0.52	12.84	3.81	0.57	17.03	1.04	70,914.28	307.40
LG SW 440 R	3	13.26	0.44	10.68	3.29	0.54	14.88	1.04	73,708.94	380.48

Figures 4: 3-Stage   Membrane Projection

With this design we are maintaining 1st element recovery of 11.17% and a maximum membrane flux of 15.94 LMH which provides an ideal working environment for the membranes which leads to extended Membrane Life. Also, with this design the membrane polarization is 1.12 max which lowers the accumulation of biological material on the membrane surface, thereby reducing the risk of biofouling.

Cleary this design is less expensive compared with Theoretical design because of the reduce number of pressure vessel, pumps, and control.

2-Stage System Design
Figures 5 show a brine staged array with interstage pressure boosting. In this design we divided the total element into two (2) sets (front and rear) and provided a boost pressure between them. Now the front elements work in low pressure based on required osmotic pressure and rear elements work in higher pressure.

Figures 5: 3-Stages systems

Figures 6 show membrane projection report for 2-Stages Design, we used from 18 bar boost pressure between stages to recover the osmotic pressure increase for each pressure vessel based on the set of 5 elements feed water salinity increasing.
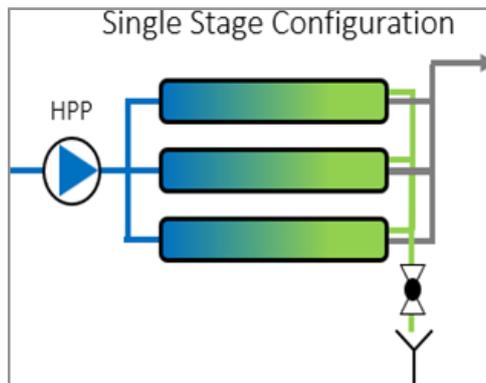
Figures 6: 2-Stage Membrane Projection

With this design we are maintaining 1st element recovery of 9% and a maximum membrane flux of 18.40 LMH which provides an ideal working environment for the membranes which leads to extended Membrane Life.

Also, with this design the membrane polarization is 1.10 max which minimizes the accumulation of biological material on the membrane surface, thereby reducing the risk of biofouling.

This design has the lowest capital cost compared with theoretical design and 3-stages system because of the reduced number of pressure vessel, pumps, and control.

Singel Stage System Design

Figure 7 show the membrane array with a single stages system PVs 7 elements per pressure vessel (PV).

Figures 7: Single Stages systems

Figures 8 show membrane projection report for 1-Stages Design,

**Figures 8:** Single Stage Membrane Projection

With this design 1st element recovery of 13.7% and a maximum membrane flux of 26.07 LMH which exceeds the design recommendation and because of that we see decrease in Membrane Life.

Also, with this design the membrane Polarization is 1.16 which increases the accumulation of biological material on the membrane surface, thereby increasing the risk of biofouling.

This design may have the lowest capital cost compared with other design, but it has the highest in operation and maintenance cost.

Research

Based on multi-stages design we will be able to control the flux and recovery for each element and keep it balance as show in Figures 9 and this will increase the membrane lifetime in the days when we are working in 30% recovery.
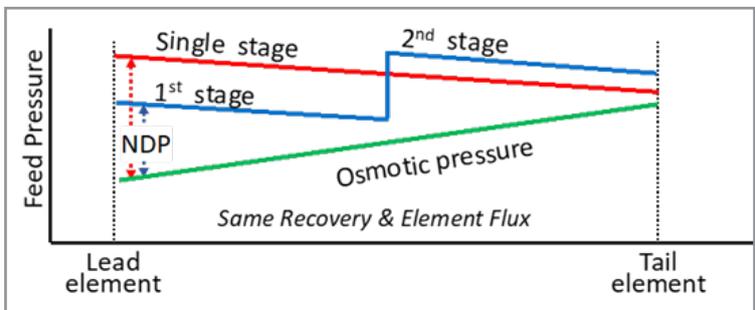
Figures 9: NDP and osmotic pressure in one and two stage arrays

Figures 10 show how most of the elements working on out-of-range flux in traditional design compare with 2 stages system.
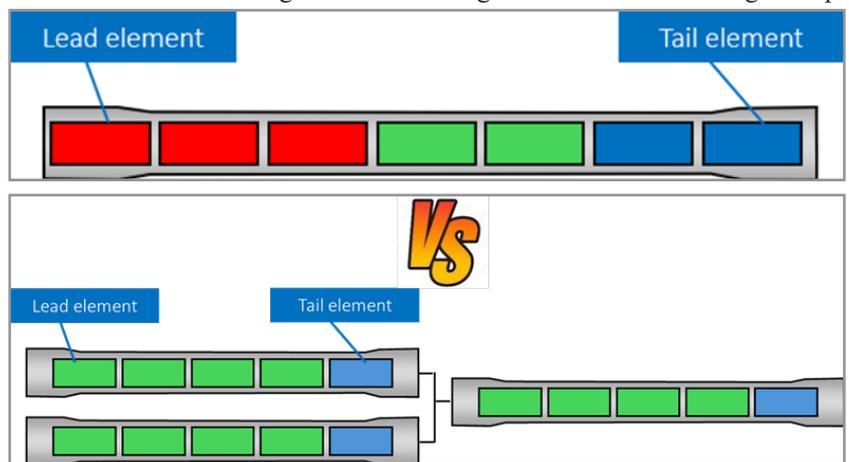

Figures 10: membrane Flux

Biturbo

With 2 stages system, we can use a Biturbo technology to not only increase the membrane lifetime but also to reduce power consumption, 1st turbo will be use as interstage booster but because of the low recovery and high operation pressure for the 2nd stage, the interstage turbo can produce too much boost and we only need 18 bar boost pressure for that we can send this extra boost to anther turbo in the 1st stage feed stream as shown in Figures 11.
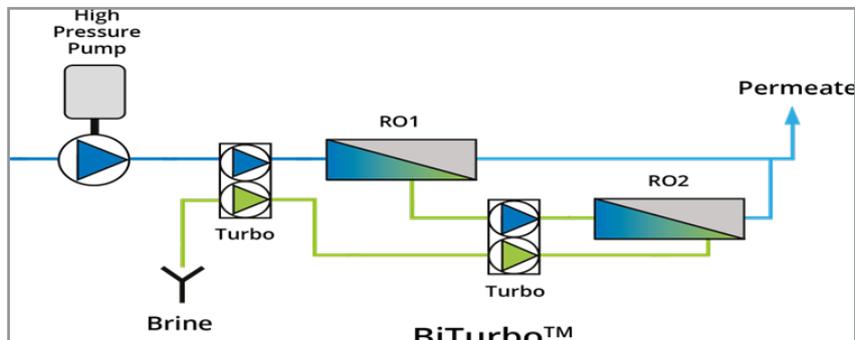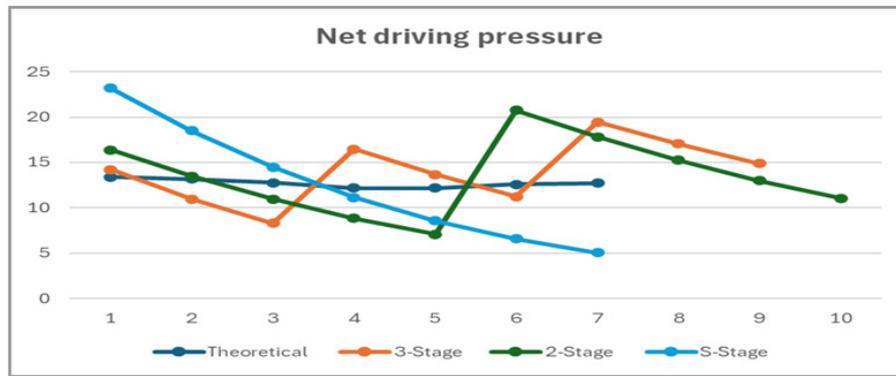

Figures 11: Biturbo Technology

Results

From this study we can see the best option to control the net driven pressure which give us best flux balance is by Theoretical design and both 3-stages and 2-stages system have good impact and the single stages have the lowest result.

Figures 12: Net Driving Pressure

Table 1: shows the comparison between the 4 designs in the element's recovery, Flux and Polarization

	Guidelines	Theoretical	3-Stage	2-Stage	S-Stage
1st element recovery	8	7.92	11.17	9.03	13.7
2nd element recovery	8	8.11	9.19	7.84	11.83
3rd element recovery	8	8.14	7.27	6.63	9.73
Last element recovery	8	8.54	3.29	3.44	3.46
1st element Flux	24	15.07	15.94	18.4	26.07
2nd element Flux	24	14.21	11.65	14.55	19.42
Last element Flux	6	9.77	8.37	6.73	3.75
1st element Polarization	1.13	1.09	1.12	1.1	1.16
2nd element Polarization	1.13	1.09	1.1	1.09	1.13

Conclusions

Each design has its advantages and trade-offs. The theoretical design with boost pressure may offer the best control and performance but could be more expensive to implement. The 3-stage system can provide a good balance between control and economy, while the 2-stage system may offer the best economic efficiency with reasonable control. The traditional single-stage system is likely the most straightforward and least expensive to set up but will typically have higher operational costs due to less efficient energy use, shorter membrane life and more frequent CIPS resulting in greater downtime and higher chemical consumption.

When comparing these systems, it's important to consider factors such as energy consumption, capital and operational costs, membrane lifespan, and the specific requirements of your SWRO plant. Additionally, the impact of feed water quality, temperature, and membrane fouling should be considered, as these can significantly affect the performance and cost-effectiveness of the desalination process.

The most economical and power saving solutions will be the 2-stages design with Biturbo design, this design will minimize the pressure vessel cost increase which is the major cost impact item, you will need to add another turbo but the saving in the membrane replacement cost will cover this cost plus the big savings in OPEX (power consumption and chemicals).

We can follow this study with a compete case study including CAPEX and OPEX impact.