Low energy forward osmosis desalination process and a comparison with conventional Reverse Osmosis

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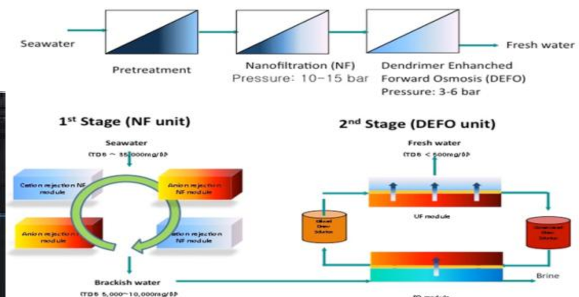
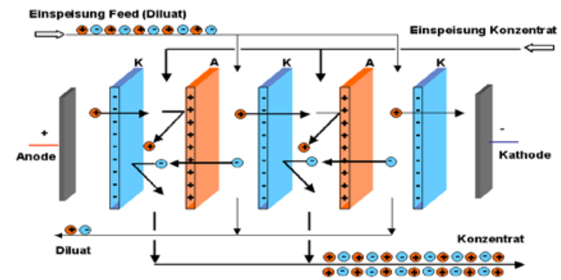
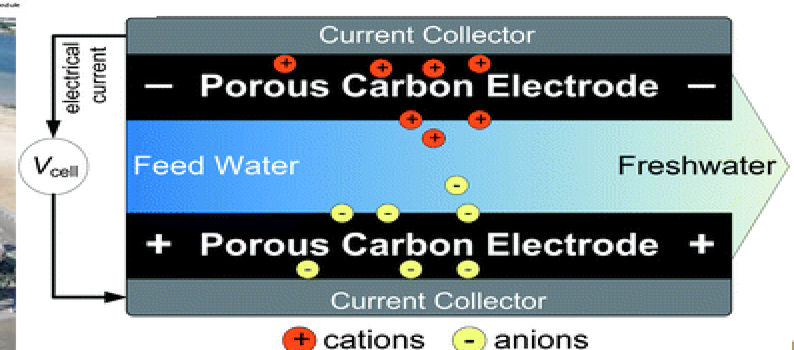
Desalination Processes

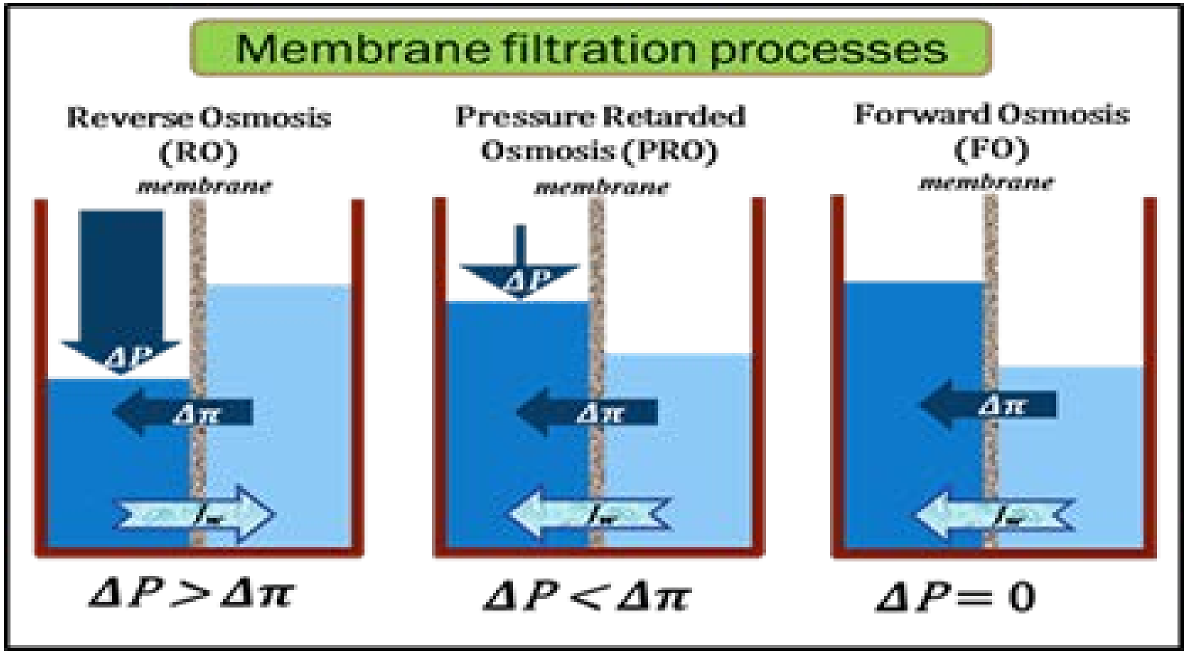
- **Thermal processes**: MED and MSF
- **Membrane processes**: RO, NF, FO, MD
- **Electrochemical**: Electrodialysis (ED), Capacitive Deionization (CDI)
- **Hybrid:** Thermal-MD, FO-RO, Thermal-RO, NF-NF etc







Forward and Reverse Osmosis



Water diffuses naturally through membrane from low osmotic pressure to high osmotic pressure side of the membrane while solute diffuses on other direction

Pressure is applied on the saline feed solution to overcome the osmotic pressure and allows water movement from the feed to the permeate side

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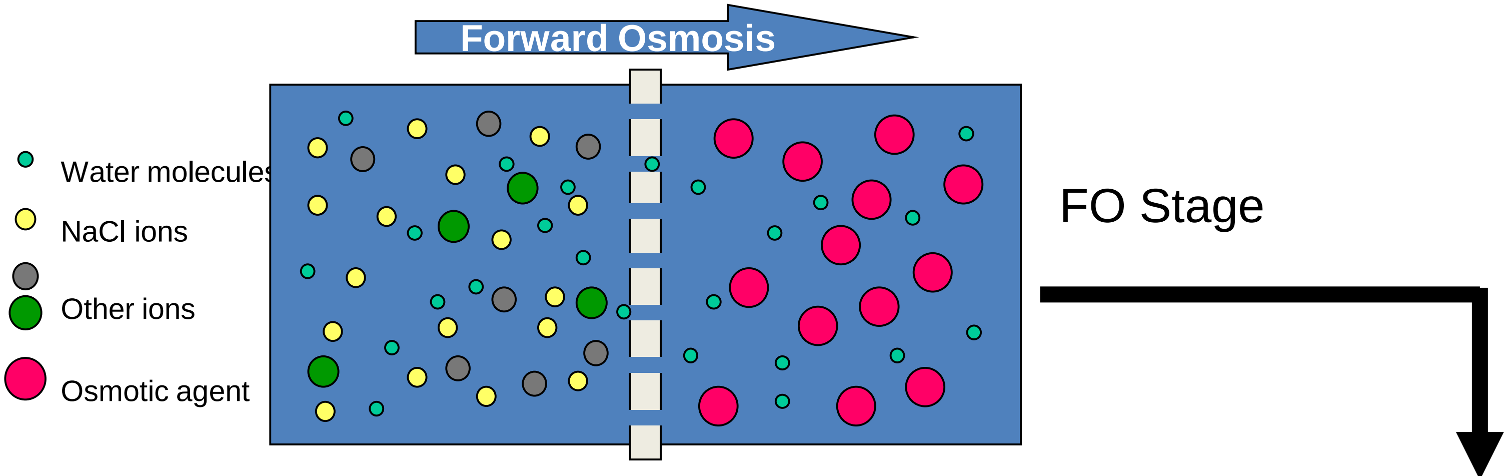
Two-Stage Forward Osmosis Desalination

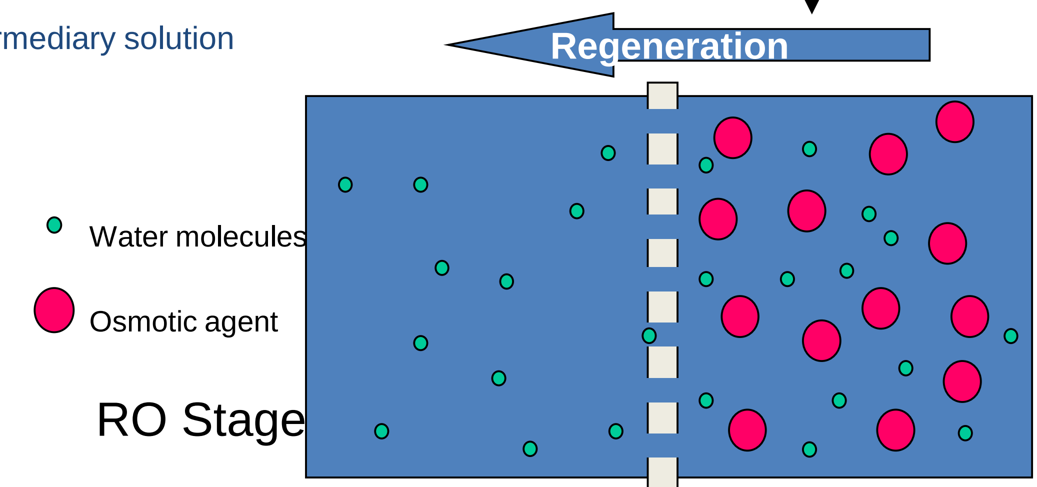
Two stage process



Stage 1: create a 'clean' intermediary solution

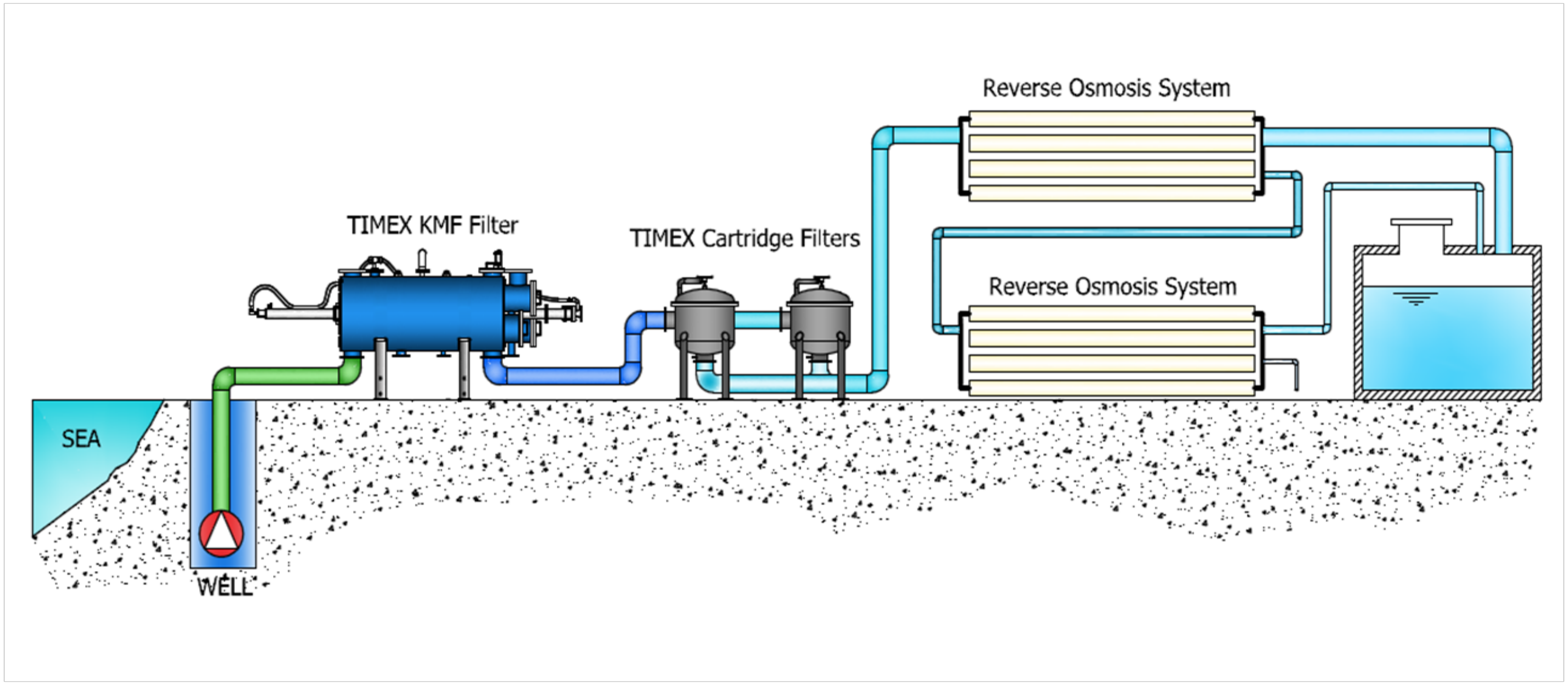
FO pretreatment: to extract freshwater from seawater and foulant materials

RO regeneration: low foulant stage for freshwater extraction and draw solution reuse



Stage 2: extract water and recover agent for reuse

Conventional Reverse Osmosis Desalination



RO system:

- Recovery rate is dependent on pretreatment process and seawater salinity, typically between 38%-45%

- Membrane performance: continuous decline in membrane flux (7% per year) and water quality degradation

FO-RO and RO systems

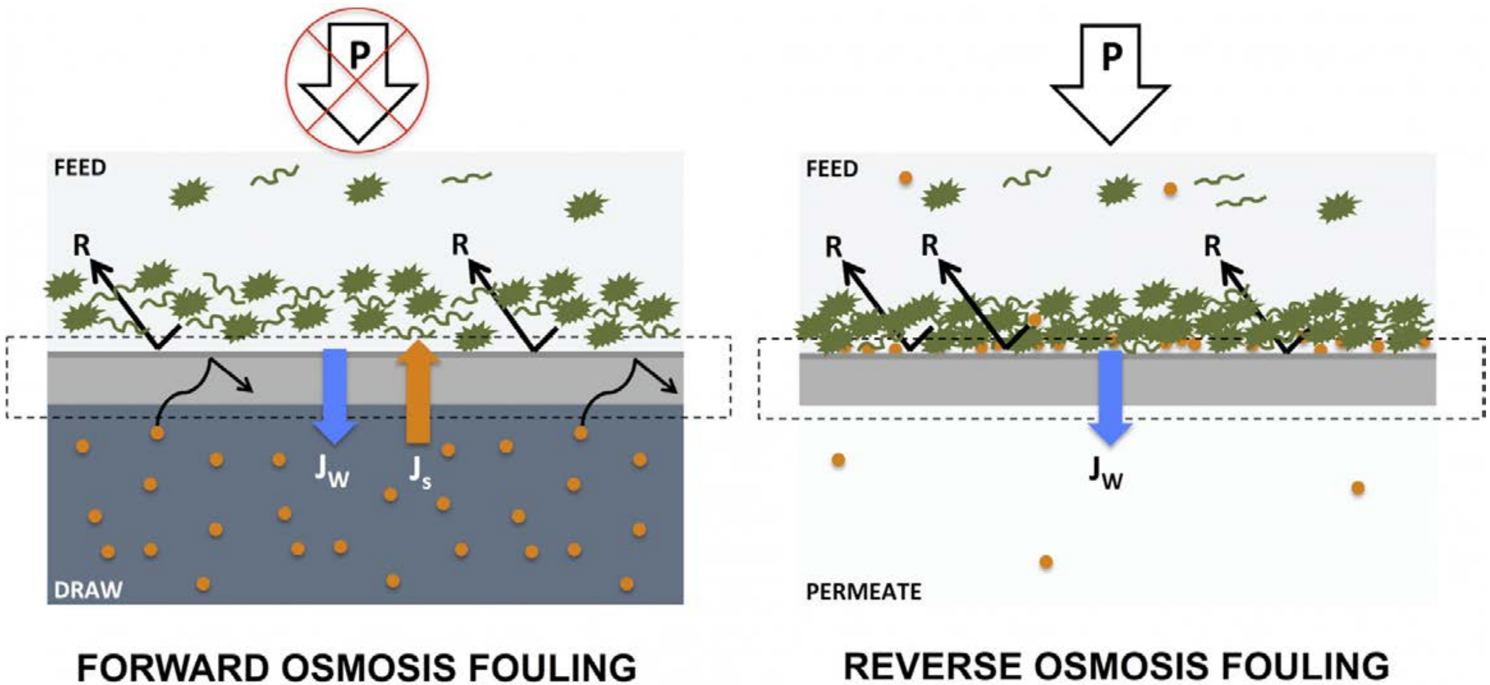
FO-RO pros and Cons

1. Can handle high feed salinities
2. Low RO fouling
3. High recovery rates
4. Draw solution regeneration cost?
5. FO membrane

RO Pros and Cons

1. High recovery rate
2. high permeate quality
3. Easy to operate
4. Membrane fouling
5. Performance degradation

Membrane Fouling



RO fouling is ***irreversible*** whereas FO fouling is ***reversible***

Process Design

FO-RO system

- Draw solutions: NaCl: 1 M
- Feed solutions: seawater TDS: 40 g/L and 50 g/L
- PAFO: feed pressure 2-6 bar
- $Q_{f\text{-}in}/Q_{ds\text{-}in}$: 4 to 8
- SDI of RO feed <1

RO system

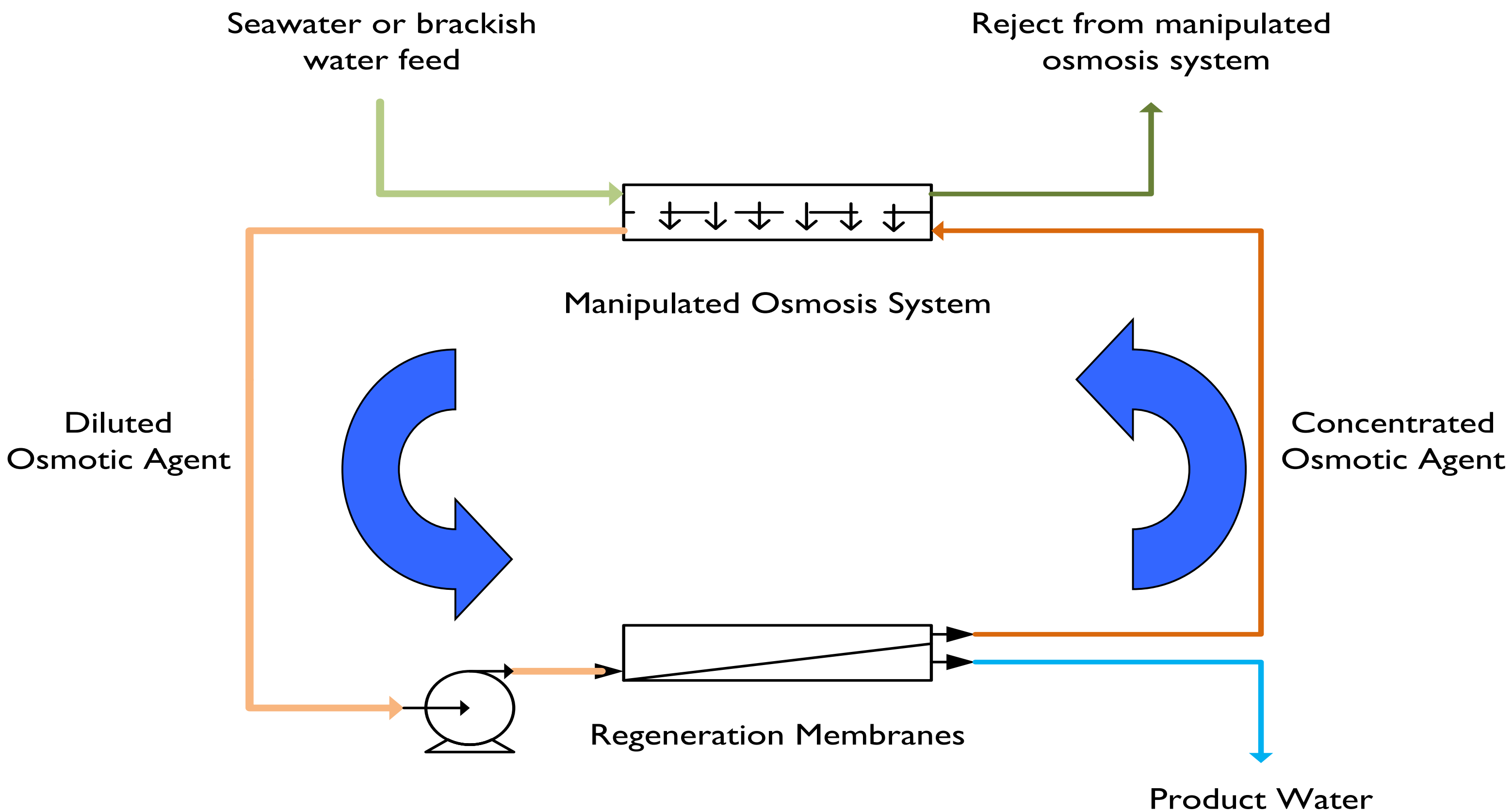
- Feed solution: seawater open intake
- RO membrane SW30HRLE440i
- SDI <5
- RO fouling: 7% decline per year in membrane flux
- Recovery rates: <40% for 40 g/L SW and <38% for 50 g/L SW

Draw Solution Selection

- Availability
- High osmotic pressure
- High rejection by membranes
- High solubility in water
- Low toxicity

Forward Osmosis Desalination

- For seawater desalination: HTI CTA-Filmtec SW30HRLE-400i
- Draw solution 1 M NaCl, and RO fouling is insignificant



Process Modelling

FO water flux:

$$J_w = A_w\left(\frac{\pi_{Db} e^{\left(\frac{-J_w}{k}\right)} - \pi_{Fb} e^{(J_w K)}}{1 + \frac{B}{J_w}\left(e^{(J_w K)} - e^{\left(\frac{-J_w}{k}\right)}\right)} - \Delta P\right)$$

FO salt Flux:

$$J_{s-r} = B\left(\frac{C_{Db} e^{\left(\frac{-J_w}{k}\right)} - C_{Fb} e^{(J_w K)}}{1 + \frac{B}{J_w}\left(e^{(J_w K)} - e^{\left(\frac{-J_w}{k}\right)}\right)}\right)$$

RO membrane fouling

$$J_n = J_o - (0.07 n.J_o)$$

$$CP_n = \exp\left(0.7 * \mathrm{Re}_{n-ave}\right)$$

$$\mathrm{Re}_{n-ave} = 1 - \left(1 - \mathrm{Re}_n\right)^{\frac{1}{x}}$$

Energy Consumption of RO Desalination

Water flux through a control element of RO membrane

$$J = A_W(\Delta P - \Delta \Pi)$$

Specific energy consumption (kWh/m³) or (KJ/Kg) is usually estimated by

$$E_s = \frac{P_f \cdot Q_f}{\eta Q_p}$$

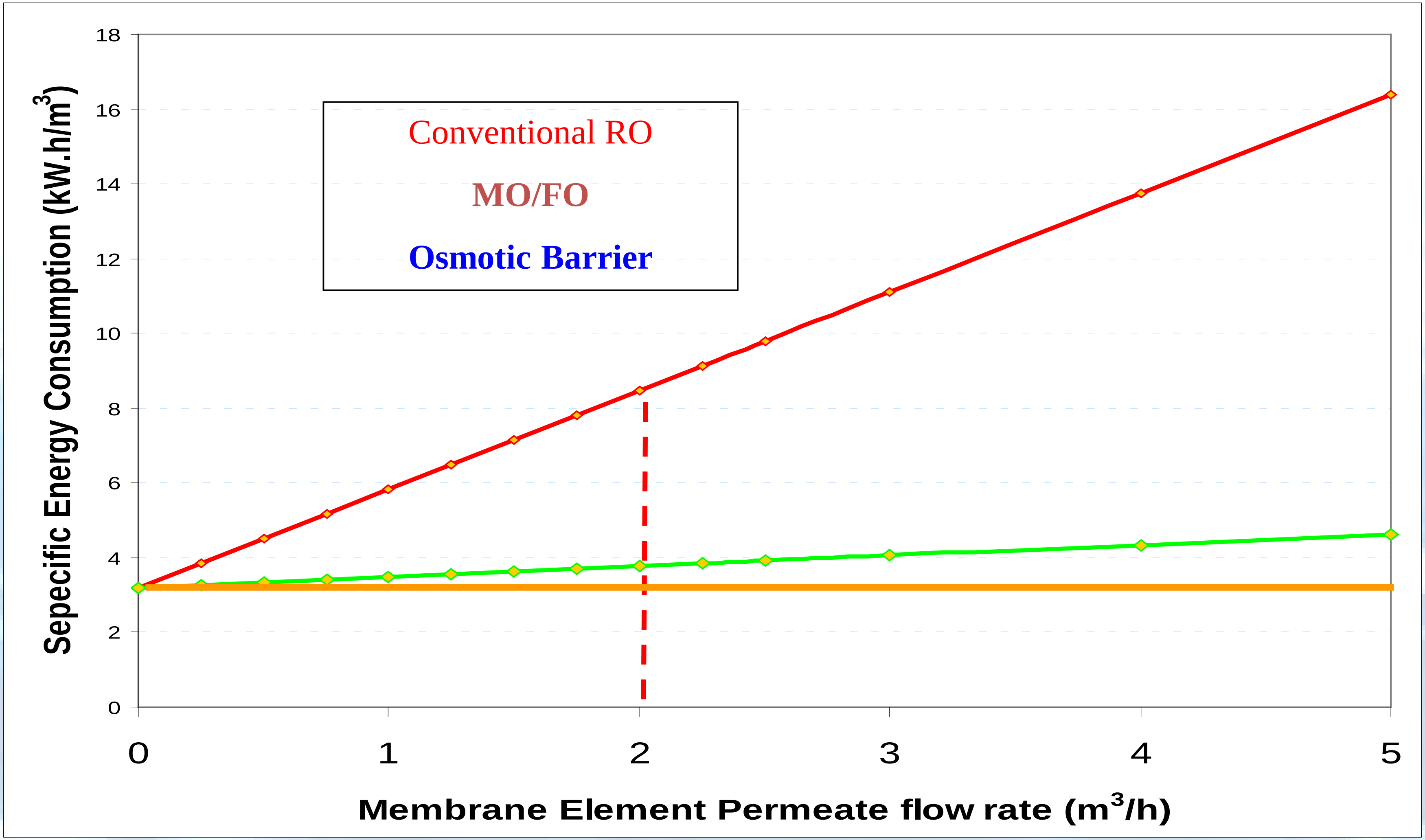
Newly derived equation*

$$E_s = \frac{1}{18\eta R(1+\alpha)}\left[\frac{J}{A_W} + \frac{2-R}{2-2R}\Pi_f\right]$$

* Sharif et al, Desalination and Water Treatment, **1,** (2009)1001-1013

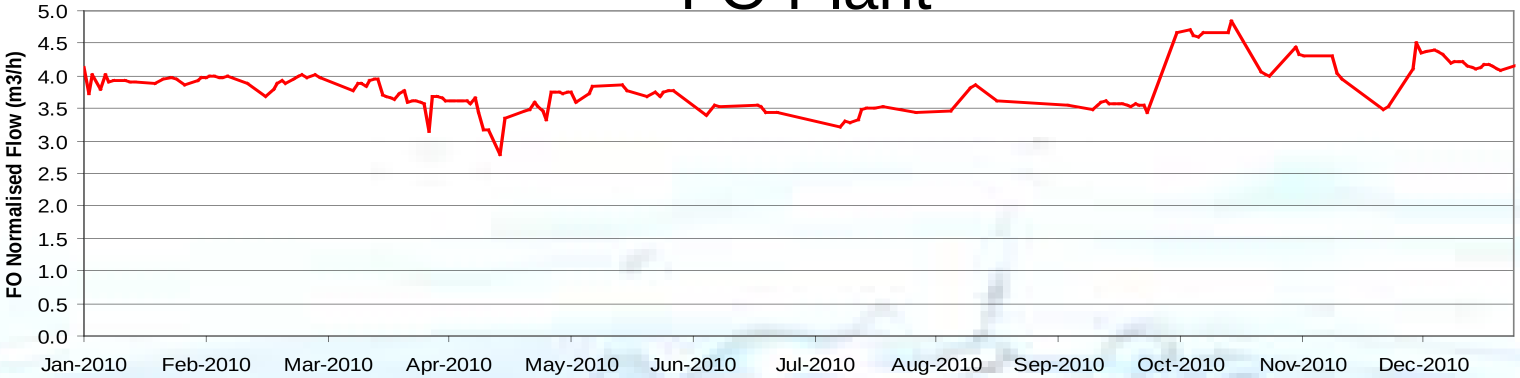
Theoretical Specific Energy Consumption of RO Process

(Desalting 32 *g/l* NaCl solution at 50% recovery rate)

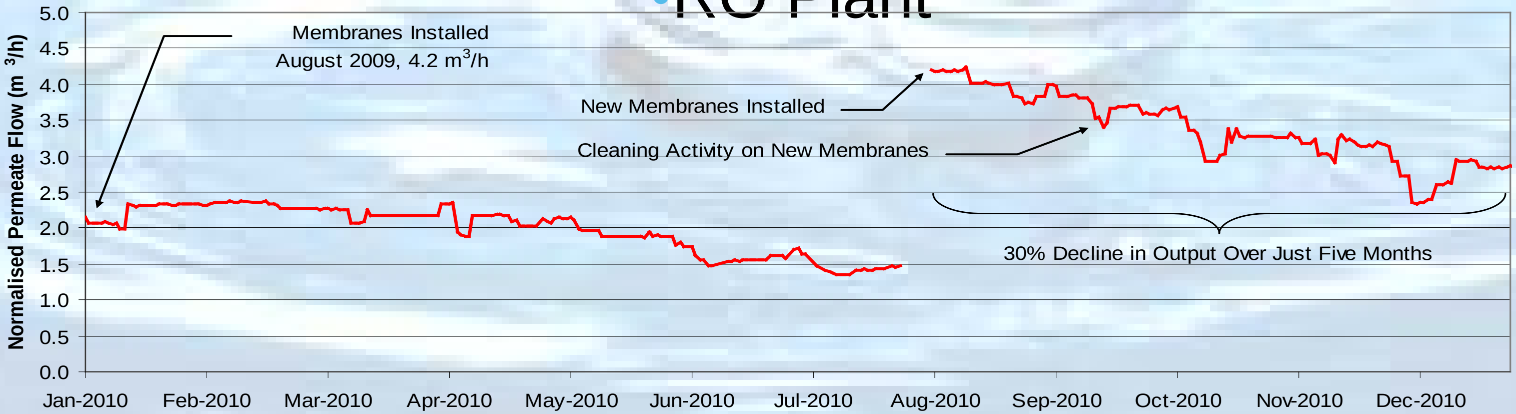


Normalised Flow

- FO Plant



- RO Plant



Source: Thompson N & Nicoll P 'Forward Osmosis Desalination: A Commercial Reality', Proceedings IDA World Congress, Perth, Western Australia, September 2011

From Labs to Market

Gibraltar

- First FO Desal PP of its kind in the world
- Operational with fresh water production to the public
- Plant demonstrates up to 30% energy saving, reduces chemical consumption and other operating costs compared with traditional methods

Oman

- Middle East is key market
- Commercial desalination plant operational and robust with positive results (2009)
- Water treatment for cooling towers proving plant (2010)
- World's first commercial FO desalination plant (2011)

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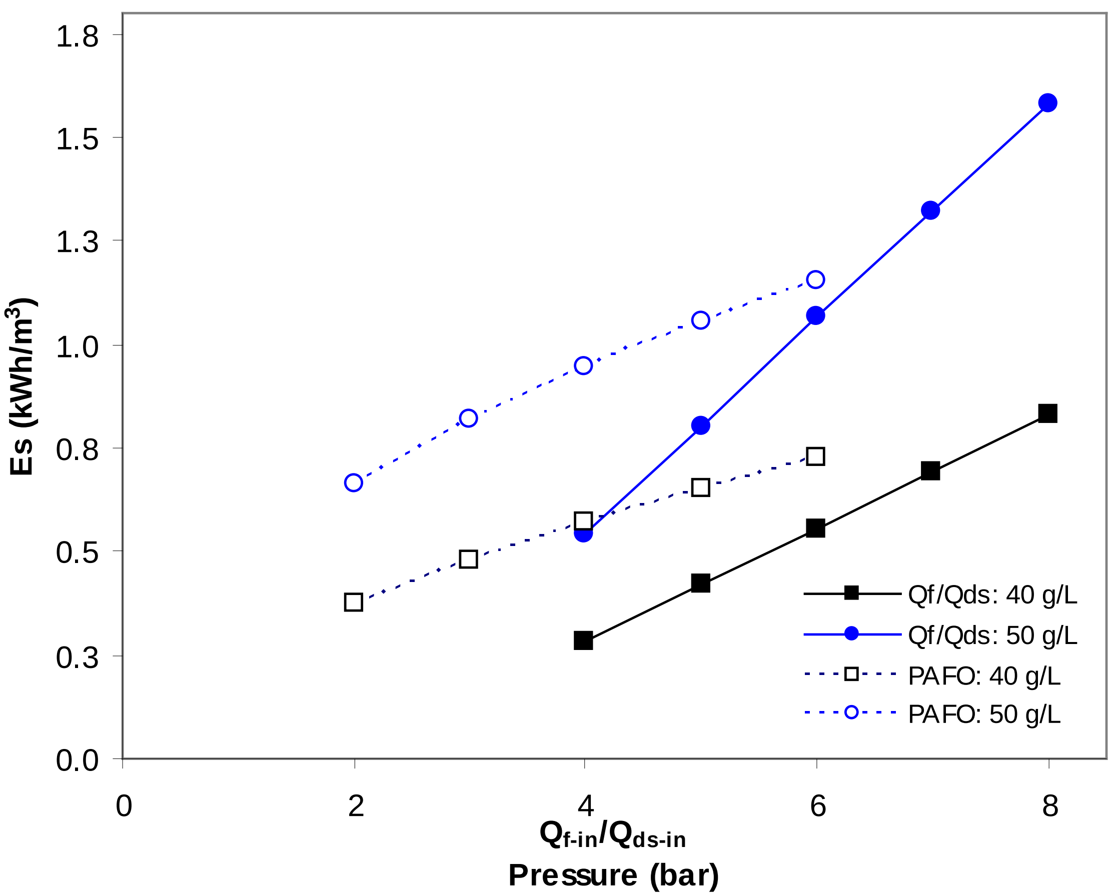
Modern Water FO Desal Commercial Plant World's 1st (Oman, Al-Khuluf, Nov (2009)-)

Assumptions

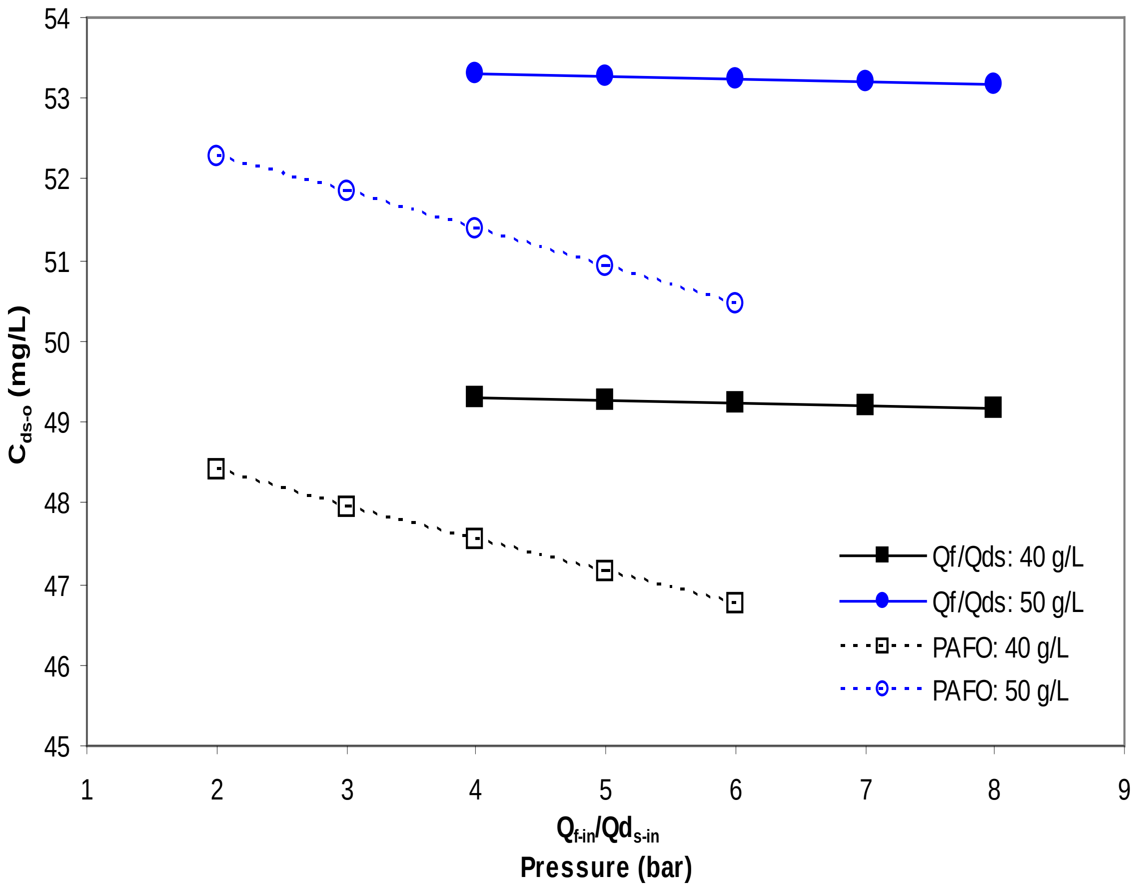
- There is 7% annual decline in the membrane flux, *Jw*, due to membrane fouling and scaling.
- RO membrane replacement is every five year due to the performance degradation.
- Fouling of RO membrane in the FO-RO is negligible
- FO fouling is ***reversible***

FO for SW: Permeate Flux



- For PAFO process, Es was 1.15 kWh/m3 and 0.73 kWh/m3, respectively, at 50 g/L and 40 g/L seawater salinity and 6 bar feed pressure.
- At 8 Qf-in/Qds-in ratio, Es was 1.58 kWh/m3 and 0.83 kWh/m3, respectively, at 50 g/L and 40 g/L seawater salinity.

TDS of DS from the FO Process



- the concentration of diluted draw solution from the PAFO-RO and enhanced flow FO.
- The impact of increasing the feed flow rate on the TDS of diluted draw solution, Cds-o, was insignificantly low, e.g. between 0.28% and 0.2%.

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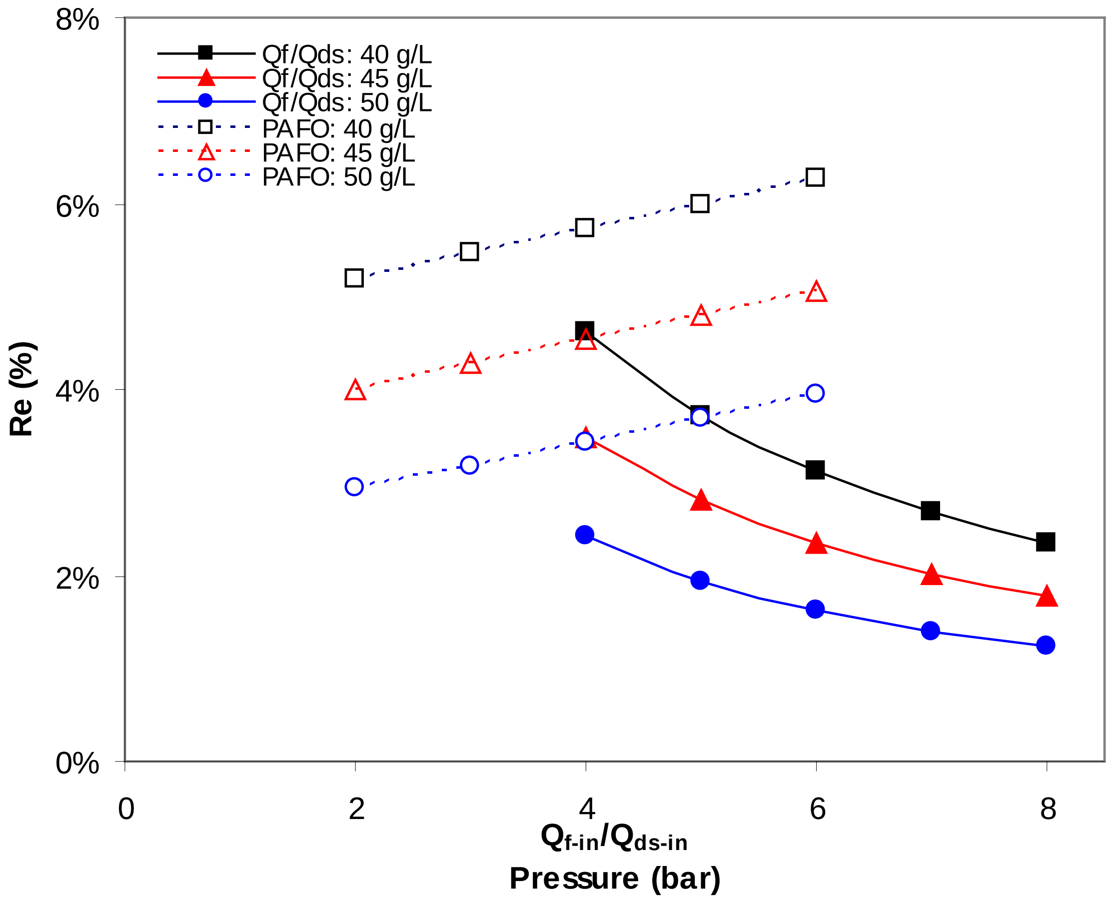
FO Recovery Rate



- FO recovery rate decreased with increasing the salinity of seawater from 40 g/L to 50 g/L

  the recovery rate of the FO membrane decreased with increasing the ratio of Qf-in/Qds-in in the enhance flow FO process. This was mainly due to the lower feed conversion ratio at higher Qf-in/Qds-in ratios.

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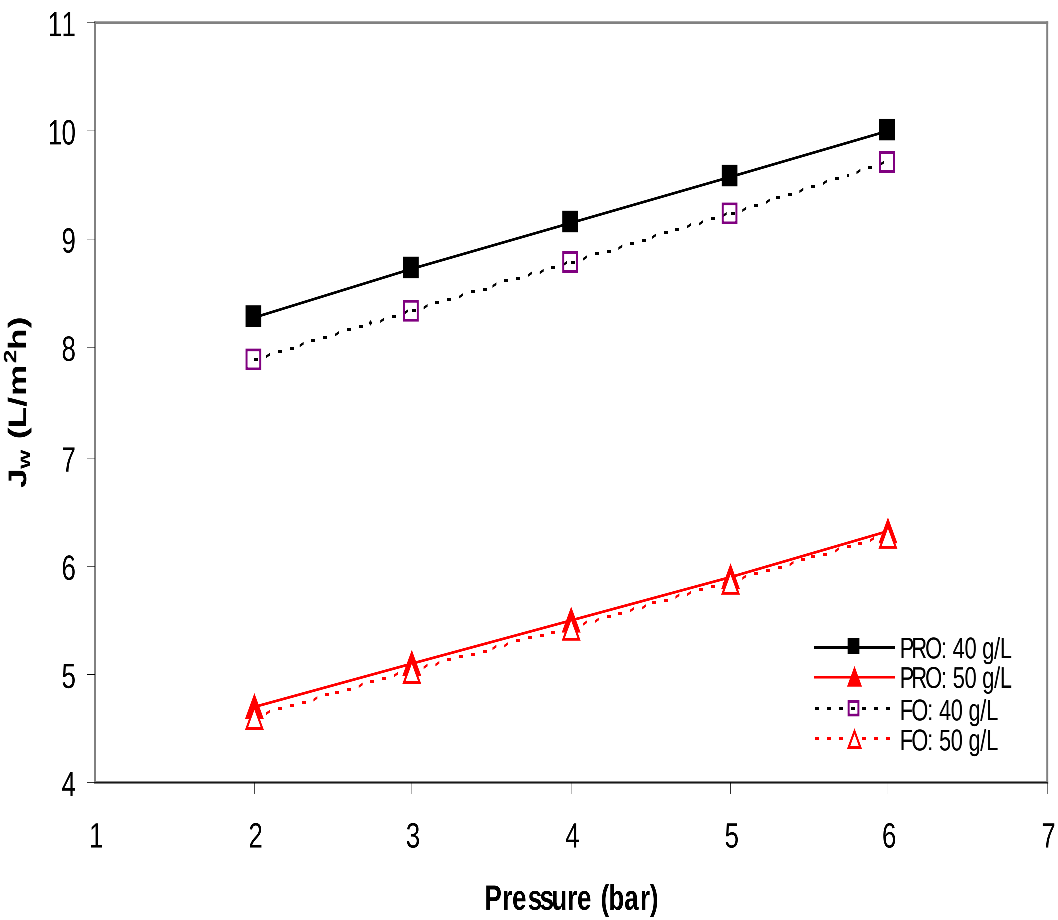
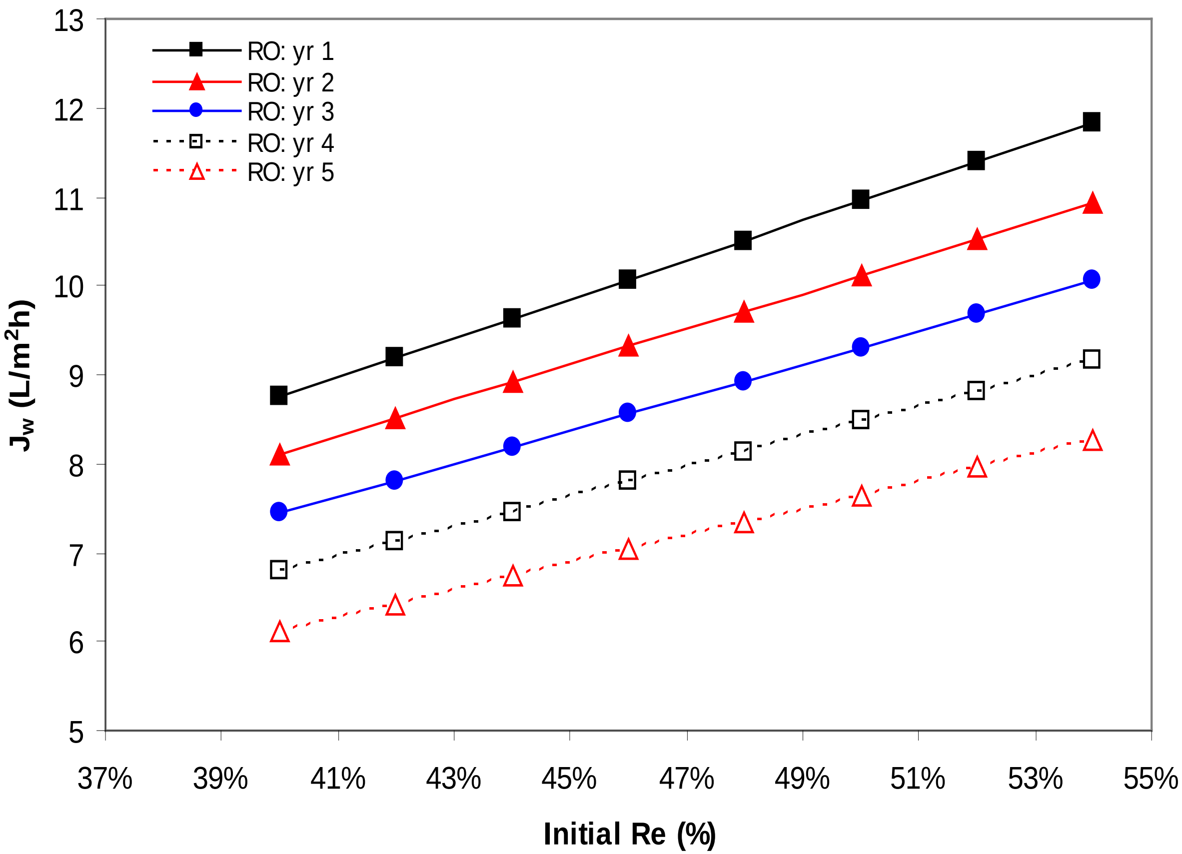
FO Membrane Orientation



- water flux was slightly higher when the membrane was operating in the PRO mode (draw solution was facing the active layer).
- The results showed that at 50 g/L and 6 bar feed pressure, *Jw* was 6.27 L/m2h and 6.31 L/m2h for the operating modes FO and PRO respectively. At 40 g/L Jw value was slightly higher; 9.7 L/m2h and 10.02 L/m2h for the operating modes FO and PRO respectively.

RO Membrane Flux



Due to fouling, RO flux decreases 0.7% per yr. The five years membrane flux at different recovery rates are calculated from the following equation

$$J_n = J_o - (0.07n.J_o)$$

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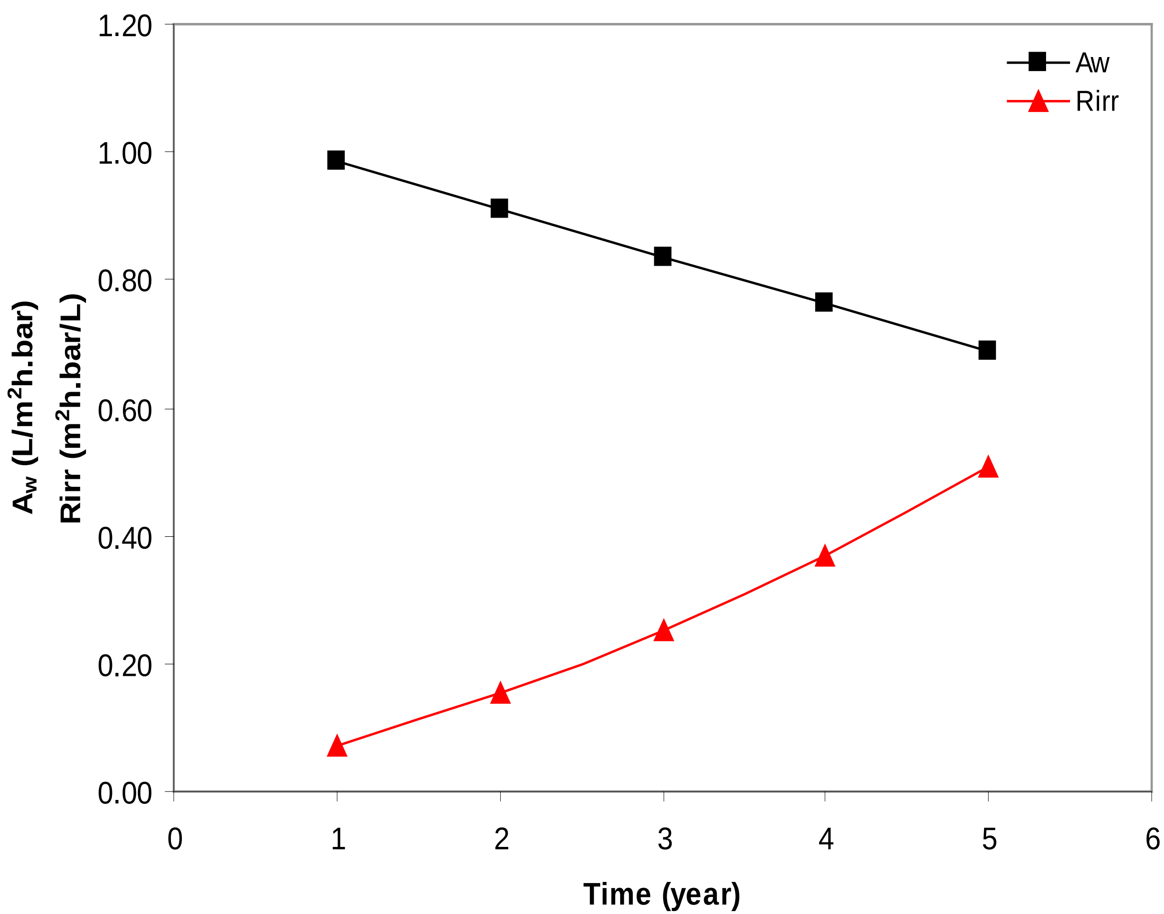
FO Water Permeability



The membrane permeability, A_w, was 0.98 L/m2h.bar in year one and decreased to 0.69 L/m2h.bar after five years; this shows 30% decline in the A_w of the RO membrane.

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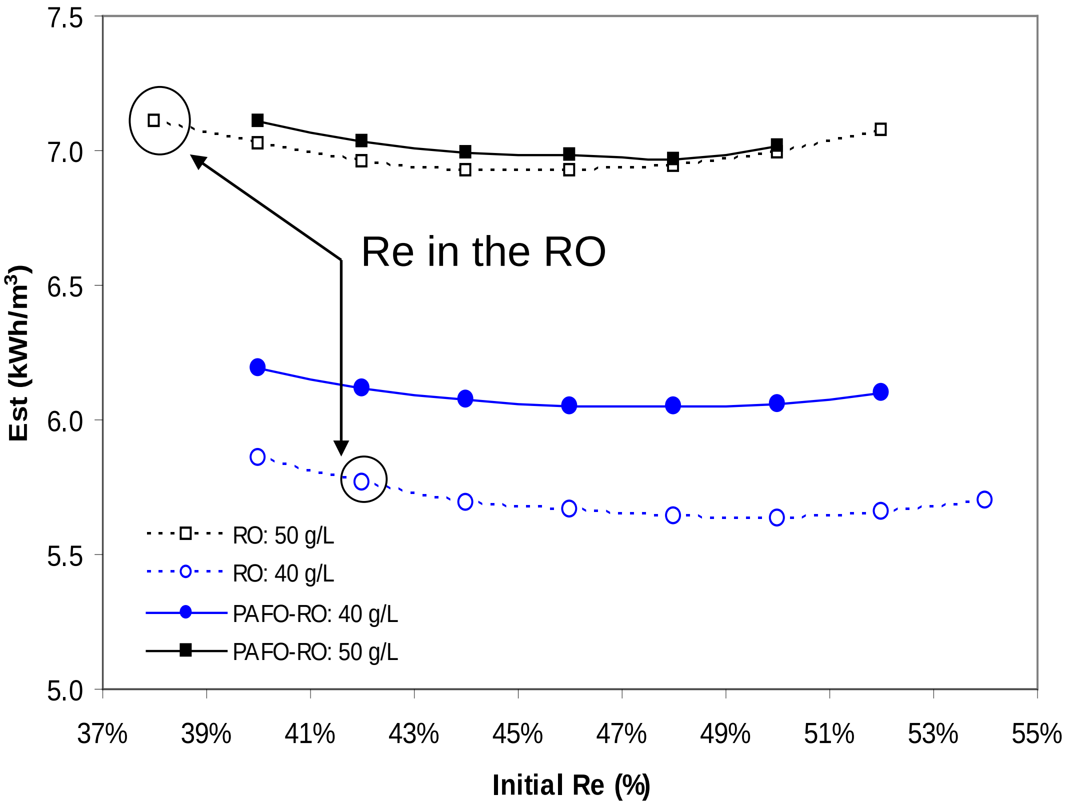
Regeneration: FO for BW



optimum recovery rate in the conventional RO system shouldn't exceed 38% for 50 g/L seawater salinity and 40% for 40 g/L seawater salinity to avoid accelerated and severe membrane fouling. RO step in the FO-RO can operates on high recovery rate because of the purity of draw solution

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Conclusions

- Forward osmosis now a proven technology at industrial scale
  - AquaGib, Al Khaluf and Sohar
- Robust process with proven resistance to membrane fouling
- Highly significant OPEX reductions
  - Lower energy in particular for FO evaporative cooling process
- Numerous potential applications
  - Desalination
  - Waste water recovery
- FO desalination a commercial reality
  - Commercially selected over established technologies
    - PAEW – Al Najdah (200 m3/day) seawater plant
- The Challenges are:
  - Low energy and practical re-generation methods
  - Suitable FO Membrane

Conclusions

- PAFO is more efficient than enhanced flow FO approach in increasing membrane flux
- PAFO performance was higher when it is operated in PRO modes than FO mode
- PAFO-RO system is more efficient than RO system especially at seawater salinities over 40 g/L

Acknowledgments

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