2024

MEMBRANE TECHNOLOGY CONFERENCE & EXPOSITION

March 4–7, 2024 | West Palm Beach, FL
Palm Beach County Convention Center

AMTA
American Membrane Technology Association

American Water Works Association



Membrane Brine Concentration for Salt Production from Seawater

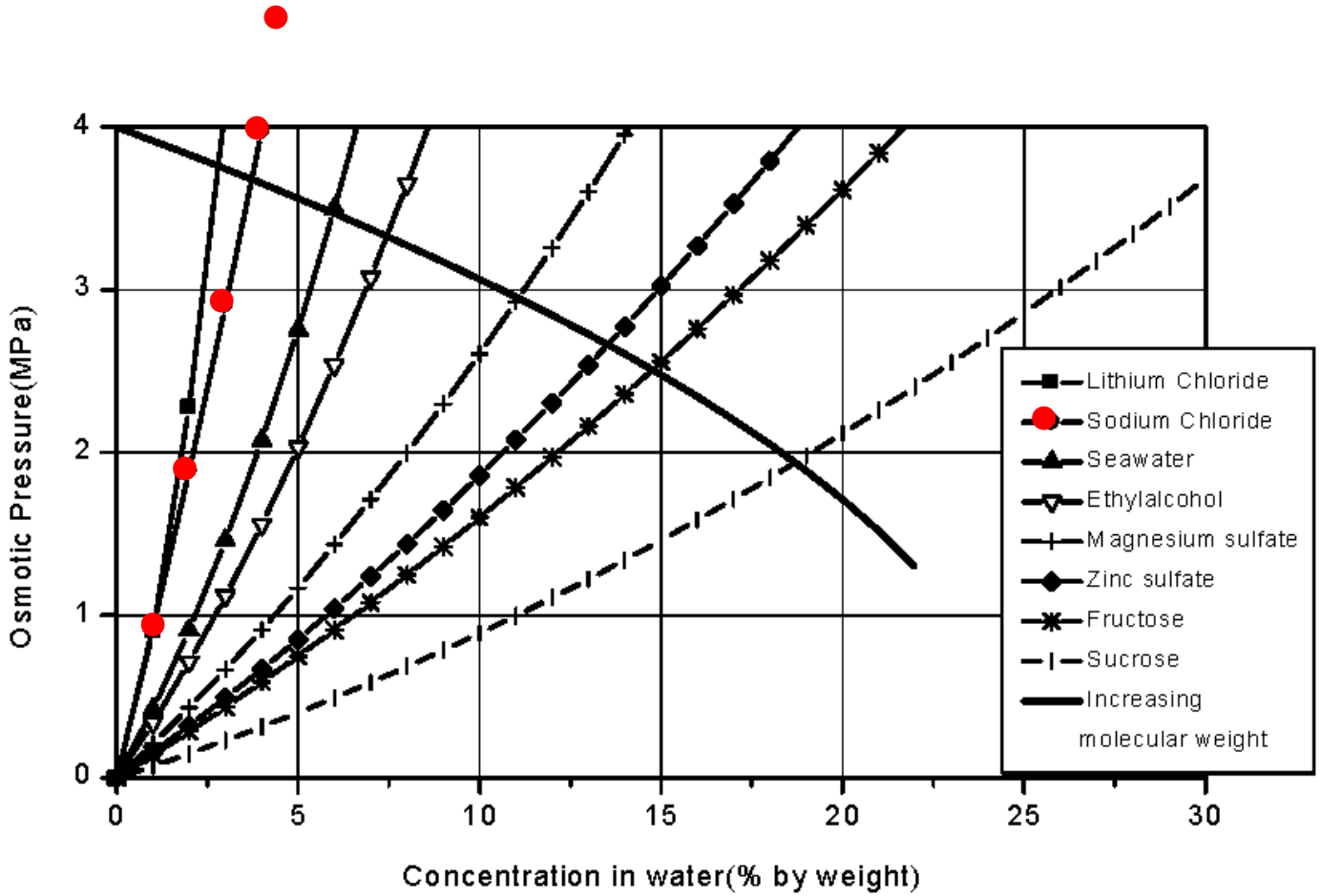
Richard Stover, Wed Mar 6, 2024, 10:30a

Recent advances in Nanofiltration (NF) and Osmotically Assisted Reverse Osmosis (OARO) have opened new opportunities for employing membranes in high salinity applications traditionally only served with thermal techniques.

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Brine Concentration - Pressure Limits

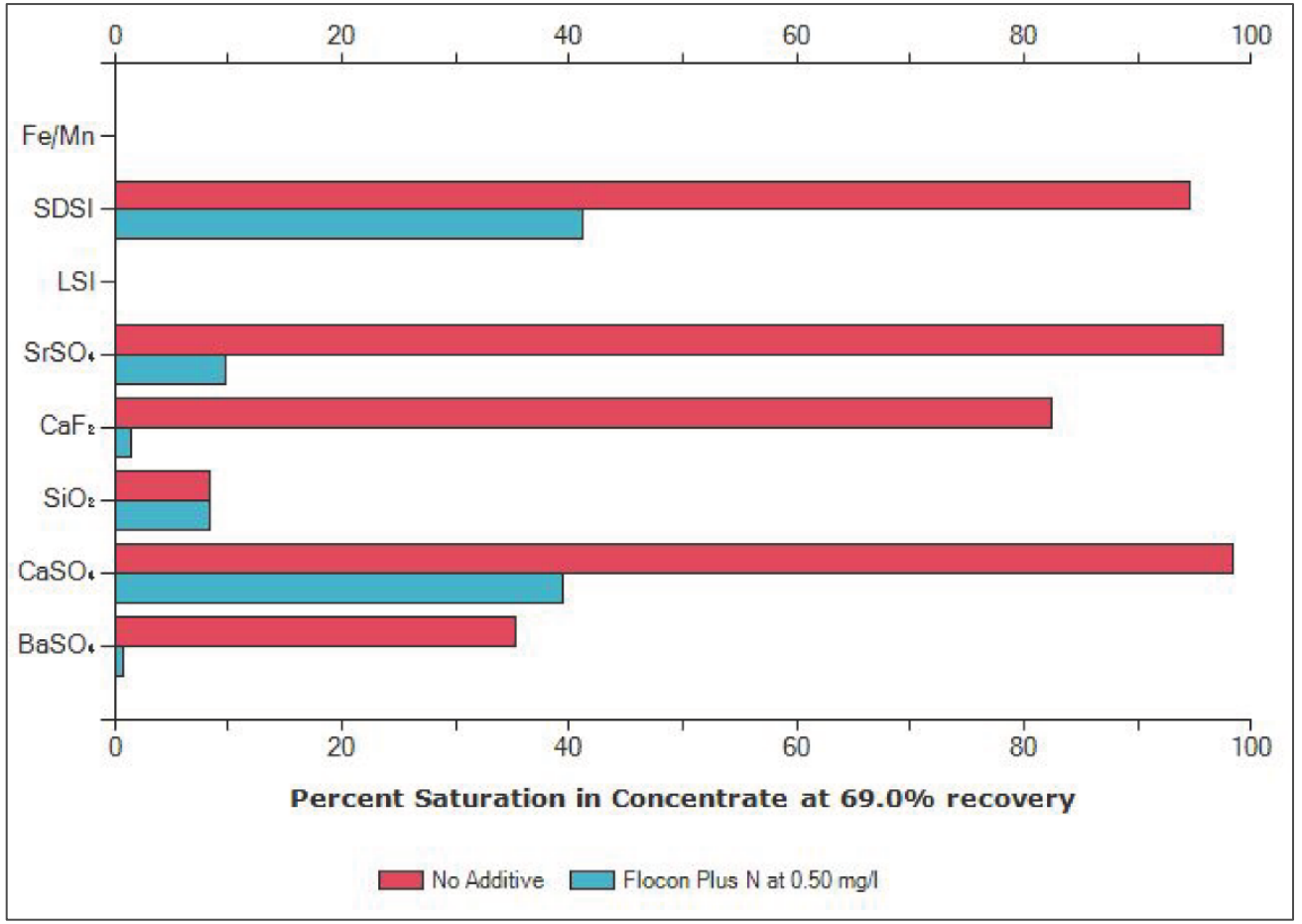
- Osmotic pressure increases with salinity
- RO feed pressure increases with osmotic pressure
- **UNLESS we can break the dependence between feed pressure and osmotic pressure.**



Toray (2009)

Brine Concentration – Scaling Limits

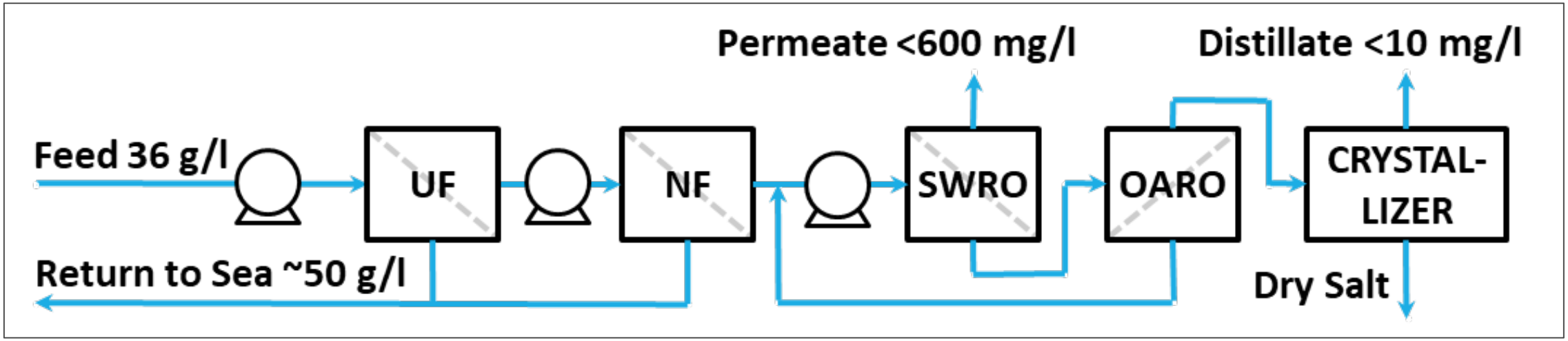
- Standard 36 g/l seawater.
- High ionic strength can increase solubility.
- 69% recovery = 114 g/l possible with no antiscalant.
- 90% recovery = >300 g/l possible with antiscalant.??
- Sulfate salts limit recovery.



red bars are without antiscalant

BWA (2023)

Sodium Chloride Production Process



- UF & NF reject organics and sulfates back to the sea.
- Multi-stage high-pressure RO treats NF and OARO permeates.
- OARO membrane brine concentration to near saturation.
- Minimum flow to crystallizer.
- Unique opportunity to combine NF and OARO.

Nano Filtration (NF)

- ~~NF rejects divalents and passes monovalents.~~
- NF membrane selectivity varies widely by model/manufacturer.
- “NF A” higher NaCl passage and purity.
- 75% recovery provides a good balance of efficiency and selectivity.

		NF A		NF B	
	feed	reject	perm	reject	perm
NaCl	86%	68%	98%	77%	95%
Ca, mg/l	410	1,299	113	1,076	188
Mg, mg/l	1,310	4,962	91	3,567	558
SO_4, mg/l	2,740	10,939	11	10,723	100
TDS, g/l	35.8	56.2	28.7	71.5	23.9

Veolia (2023); Dupont (2022)

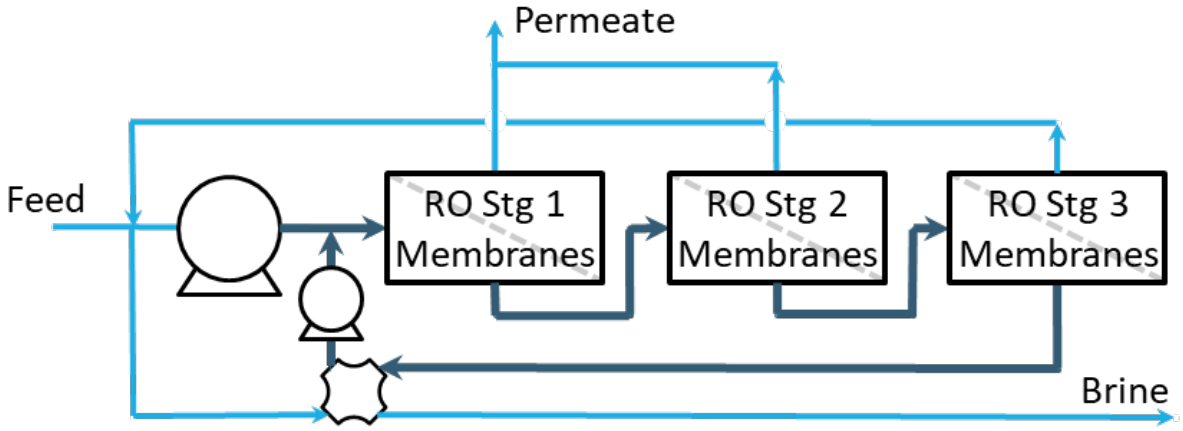
Multi-stage Seawater RO (SWRO)

Traditional

- Interstage pressure boosted to overcome osmotic barrier.
- Inefficient energy recovery.
- Ultra-high pressure required.

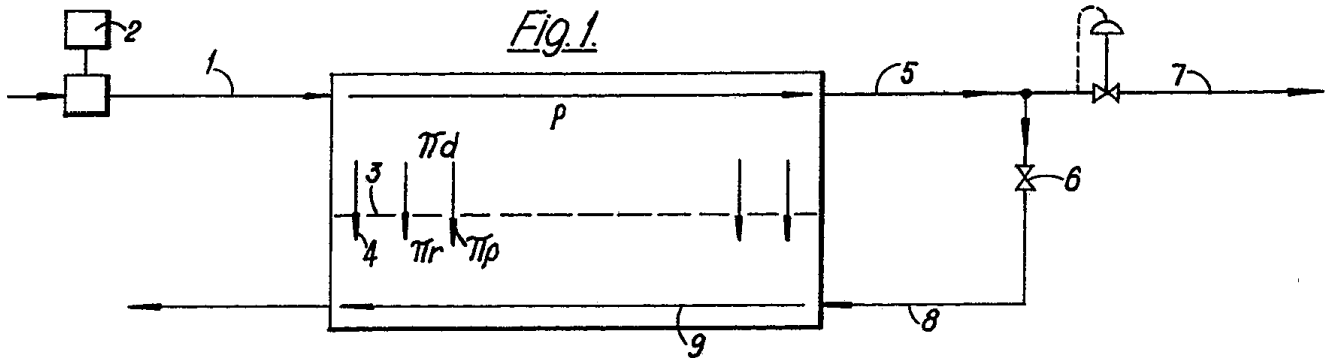
Alternative

- “Loose” membranes in later stages with no boosting.
- Salty permeate recycled/polished.
- More 1st stage feed, lower salinity.
- Efficient energy recovery.
- <1200 psi / 83 bar



Osmotically Assisted RO (OARO)

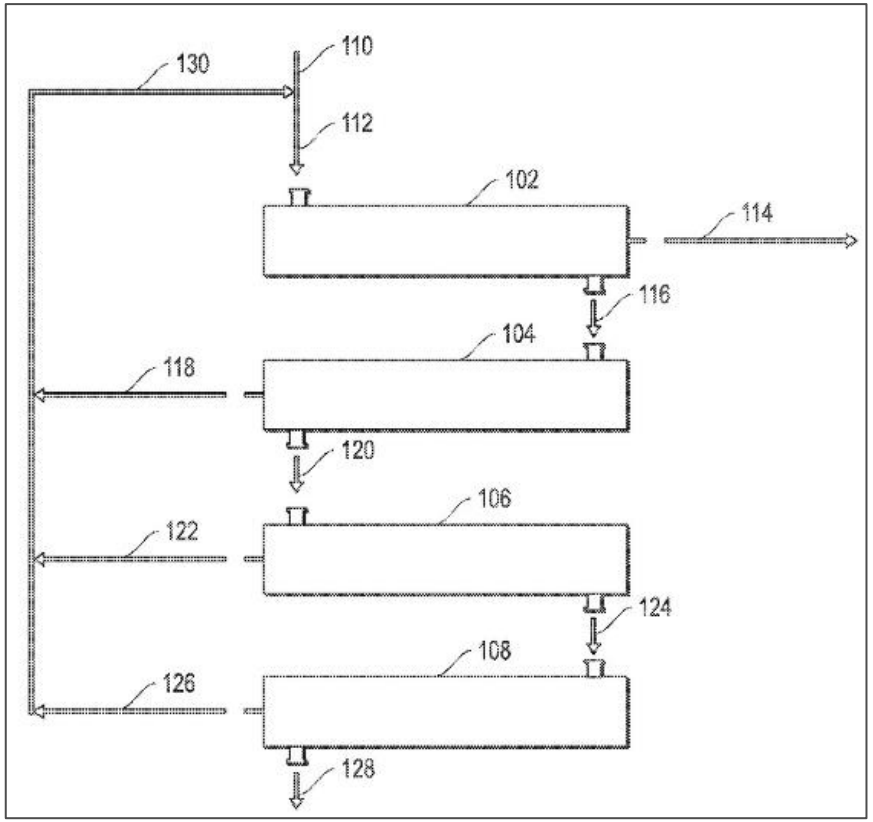
- Saline water on permeate side reduces osmotic pressure difference.
- Feed pressure and feed osmotic pressure become independent.
- Permeate side is fed salt water so hollow fiber membranes are required.
- Old idea, recently feasible.



Loeb (1971)

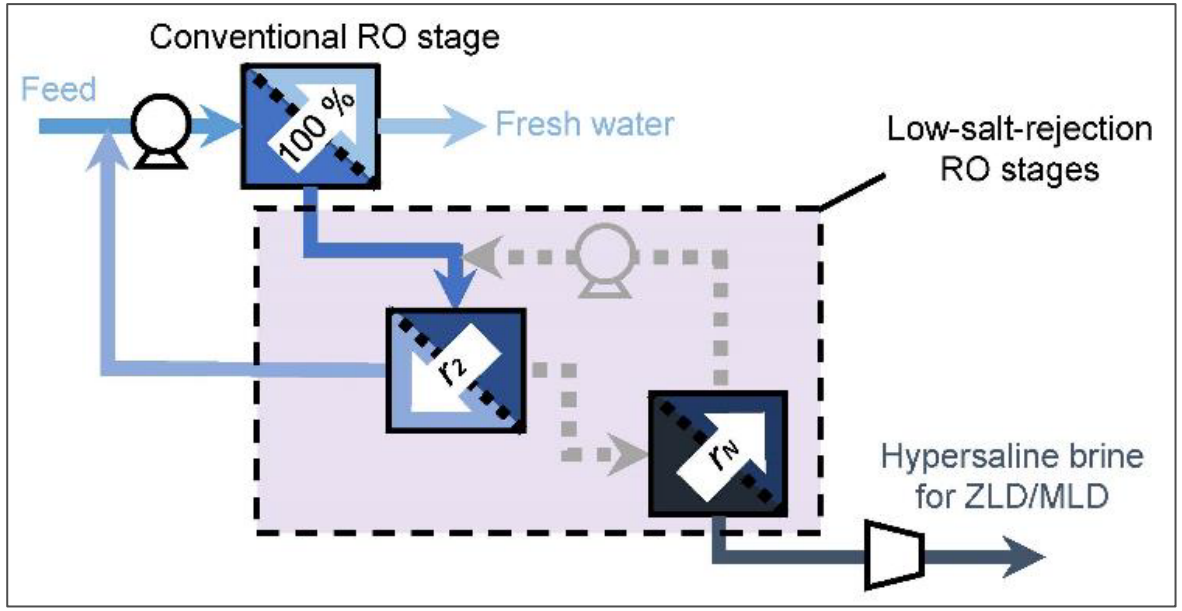
OARO with Spiral Membranes

Hydration Technology Innovations (HTI) “HiCor” process



Herron, Beaudry, Lampi (2013)

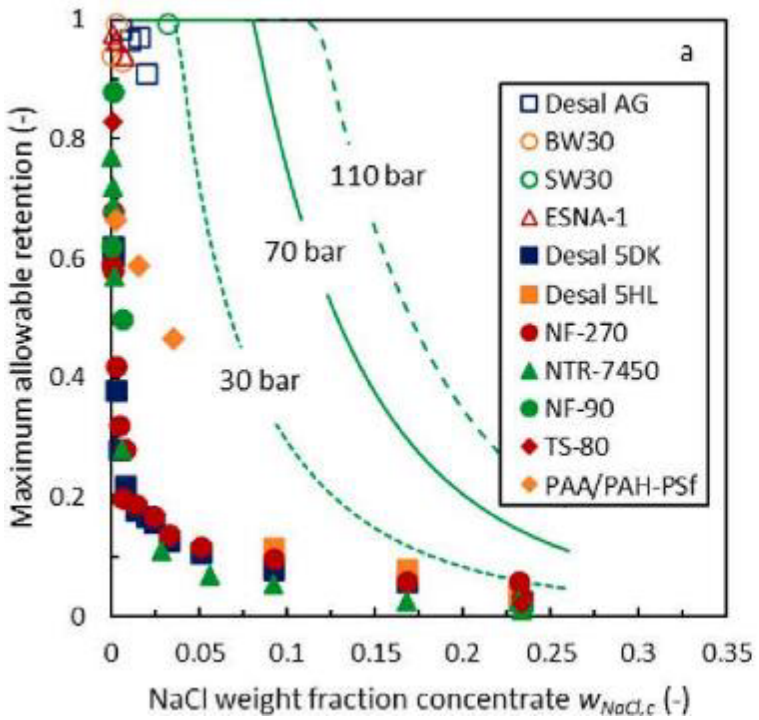
Yale Low Salt Rejection RO (LSRRO) process

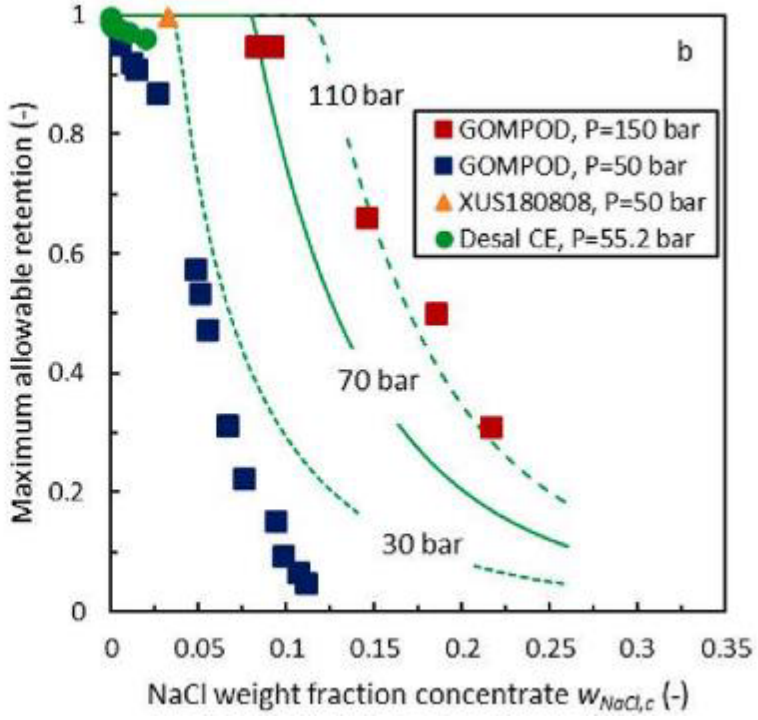


Wang, Deshmukh, Du, Elimelech (2020)

OARO - Ideal Salt Rejection Concept

- Higher salt passage in later stages.
- New generation of membranes with permeabilities between NF and RO.
- Ideal salt rejection
  - Flux balanced
  - Maximum concentration per stage
  - Minimum permeate recycle

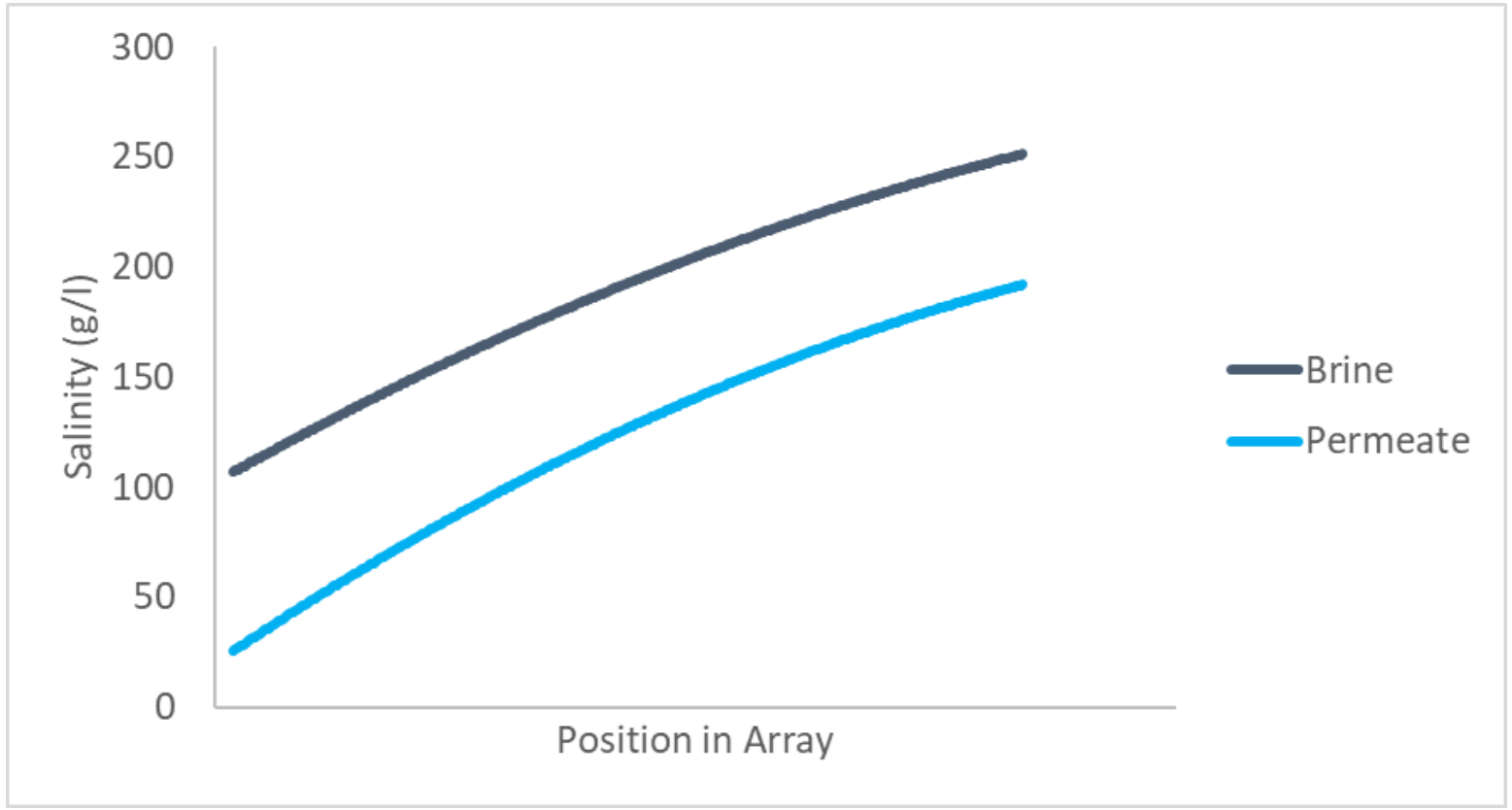




Bargeman (2023)

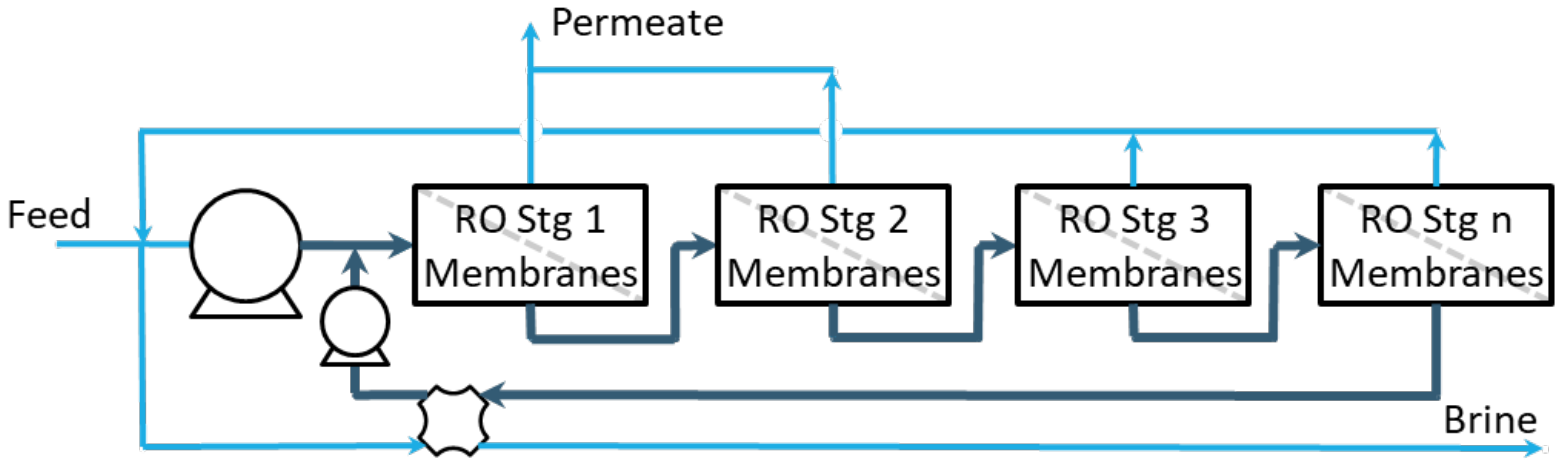
OARO - Ideal Salt Rejection Concept

Brine-permeate salinity delta reduces slightly along array.



OARO

- Permeance ramp – ideal permeability in each stage.
  - Max conc/stage (minimizes stages)
  - Min permeate recycle (minimizes pumping)
- Salty permeate optimally recycled.
- Higher final brine concentrations with more stages.

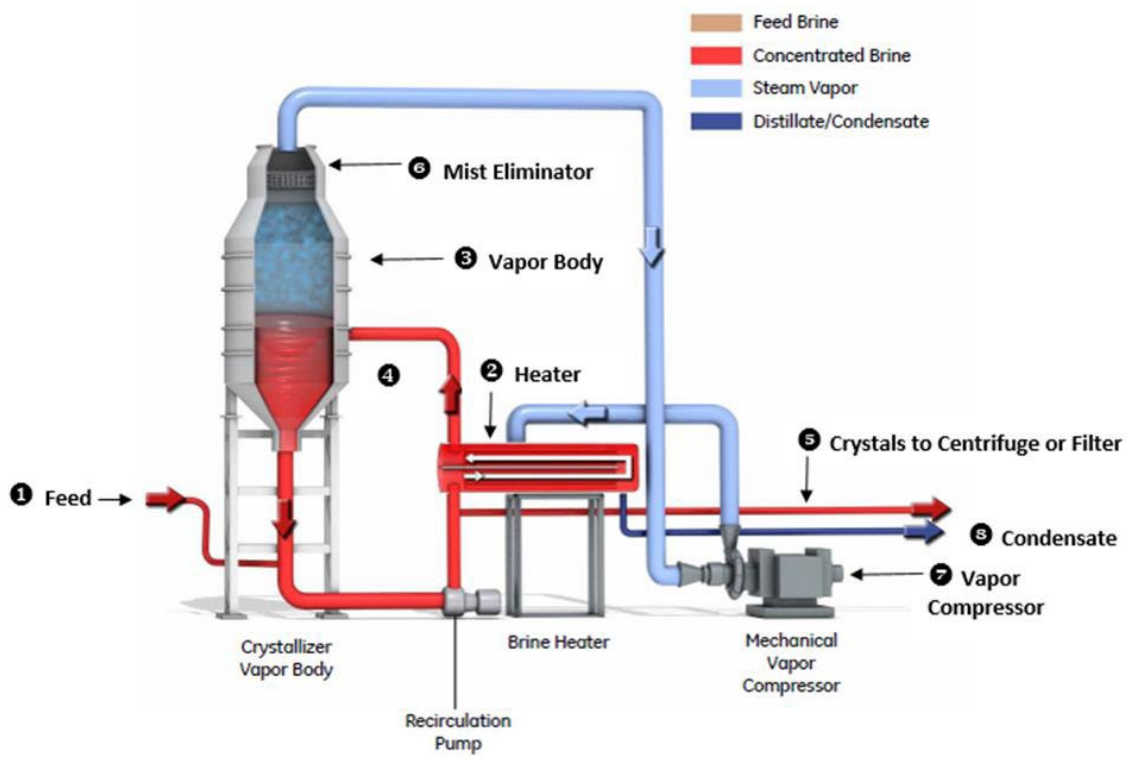




Full scale OARO process Saudi Arabia (2023)

Crystallizer

- Receives OARO brine.
- No thermal brine concentrator required.
- Produces distillate and salt slurry.



Centrifuge or filter press not shown

Suez (2022)

Sodium Chloride Production Process Performance

- NF: monovalent passage, multivalent rejection.
- SWRO-OARO: mono-and multi-valent rejection.
- >250 g/l OARO brine.
- 97.5% pure NaCl to crystallizer.

Stream Compositions

mg/l TDS	raw feed	NF reject	NF perm	OARO brine	SWRO perm	Dist-tillate
Na	10,982	11,498	10,809	93,994	225	
Cl	19,700	26,706	17,361	151,016	355	
Ca	410	1,299	113	1,001	0	
Mg	1,310	4,962	91	808	0	
K	390	438	374	3,239	10	
SO4	2,745	10,939	11	100	0	
Br	65	68	64	547	3	
TDS	35,776	56,167	28,697	251,189	597	10
NaCl	85.8%		98.2%	97.5%		

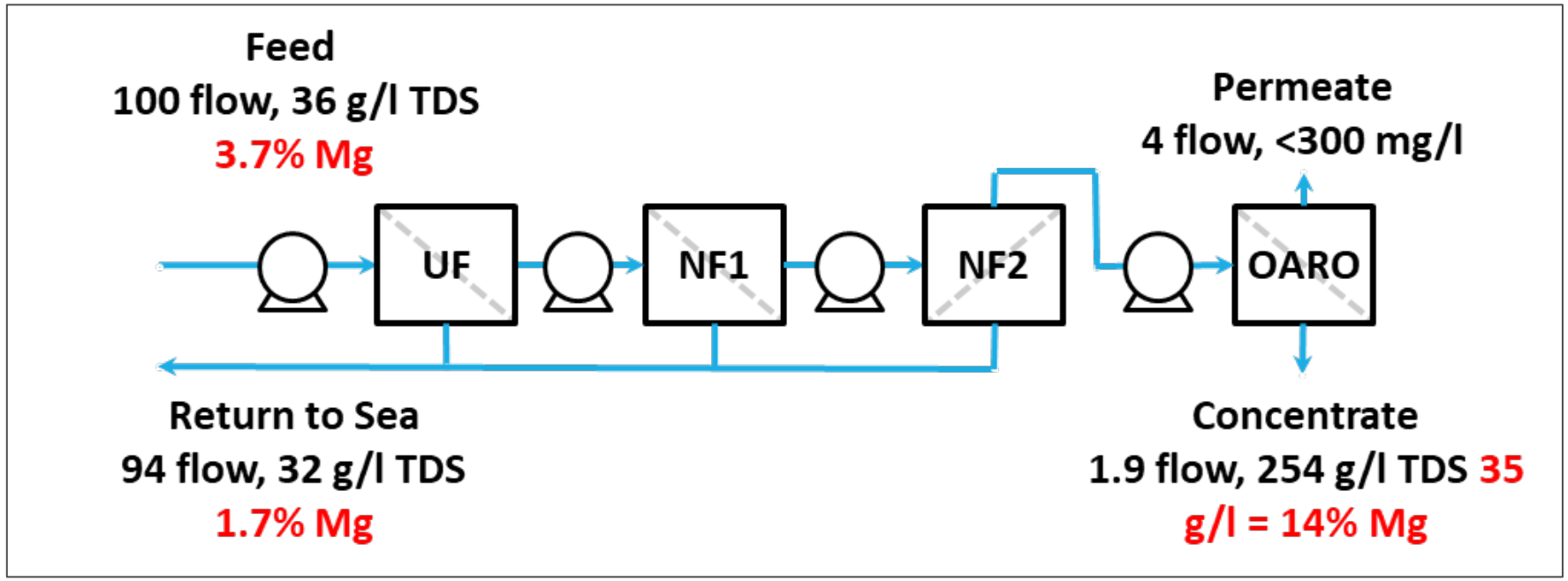
Sodium Chloride Production Process Performance

- Specific costs per ton of salt.
- Bulk NaCl $130/ton *Statista (2023)*

62 tons/d Dry NaCl	Feed Flow, m^3/d	Feed Flow, MGD	CAPEX /ton NaCl	OPEX /ton NaCl
UF	8,421	2.22	$ 2.30	$ 5.08
NF	8,000	2.11	$ 2.71	$ 4.51
SWRO	8,552	2.26	$ 8.78	$ 23.48
Crystallizer	684	0.18	$ 10.68	$ 35.39
TOTAL			$ 24.47	$ 68.47
			$ 92.94	

3-stage NF, 2-stage SWRO, 6-stage OARO
CAPEX includes process equipment, engineering, freight
CAPEX does not include civil works, intake/outfall, legal
CAPEX amortized over 20 years at 6% interest
OPEX includes spares, membranes, chemicals, power $0.10/kWh

Mineral Production



Ihm, Al-Amoudi, Yoo, Fellows, Farooque, Al-Waznani, Jehani, Al-Shaikh, Al-Biladi, Al-Senani, Voutchkov (2024)

Summary and Conclusions

- NF+OARO for salt or mineral production from seawater.
- 90% recovery to 250 g/l TDS, 98% NaCl purity.
- NF membrane selectivity varies widely by model/manufacturer.
- Permeance ramp in OARO staging design – alternative to interstage boosting.
- This approach makes rapid NaCl production from seawater economically viable.

Acknowledgements

- Co-authors: Omkar Lokare and Kurt Blohm
- Gradiant
- Membrane companies
- You

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Flows	with OARO	no OARO
UF feed flow, m^3/d	8,421	8,421
NF feed flow, m^3/d	8,000	8,000
SWRO feed flow, m^3/d	8,552	6,000
Crystallizer feed flow, m^3/d	684	1,807
Crystallizer feed TDS, g/l	251	95
Permeate flow, m^3/d	5,836	5,836
NaCl, ton/d	62,092	62,092

$/ton NaCl	with OARO			no OARO	
	CAPEX	OPEX		CAPEX	OPEX
UF	$ 2.30	$ 5.08		$ 2.31	$ 5.29
NF	$ 2.71	$ 4.51		$ 2.70	$ 4.63
SWRO+OARO	$ 8.78	$ 23.48		$ 3.84	$ 13.64
Crystallizer	$ 10.68	$ 35.39		$ 19.16	$ 92.45
TOTAL	$ 24.47	$ 68.47		$ 28.00	$116.01
		$ 92.94			$144.01

Flows	
UF feed flow, m^3/d	8,421
NF feed flow, m^3/d	8,000
SWRO feed flow, m^3/d	8,552
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Crystallizer feed TDS, g/l	251
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