Water Management At Coal Power Systems

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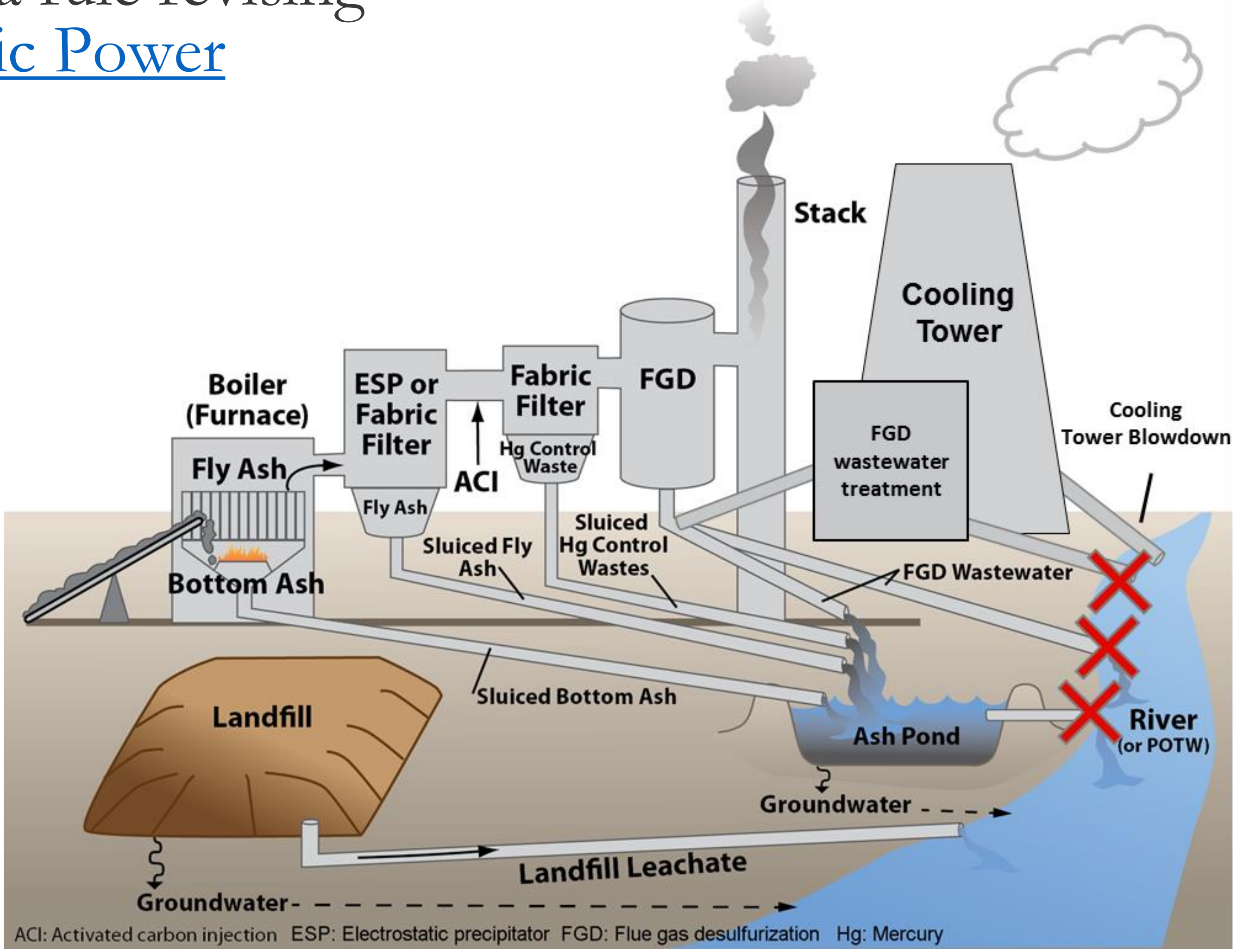
Effluent water from coal-fired power plants are regulated by U.S. EPA

- September 30, 2015, EPA finalized a rule revising the regulations for the Steam Electric Power Generating Effluent Guidelines

- Sources of effluent streams include:
  - Fly & Bottom Ash
  - Flue Gas Desulfurization (FGD)
  - Ash Pond
  - Flue Gas Mercury Control Water

- 5 regulated species

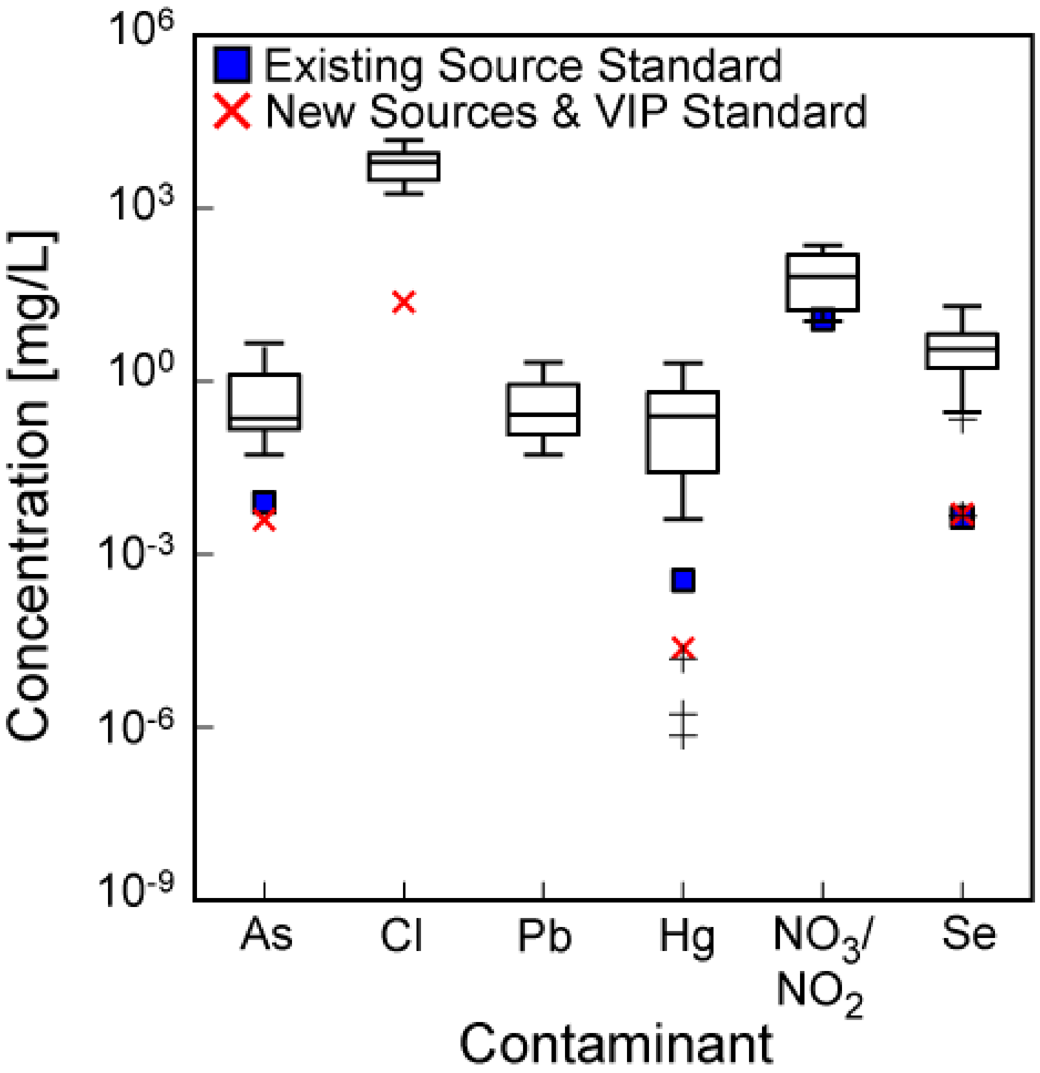
  As, Cl (TDS), Hg, $NO_{2\&3}$, Se



ACI: Activated carbon injection ESP: Electrostatic precipitator FGD: Flue gas desulfurization Hg: Mercury

https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines-2015-final-rule

Flue gas desulfurization (FGD) wastewater has a complex array of constituents



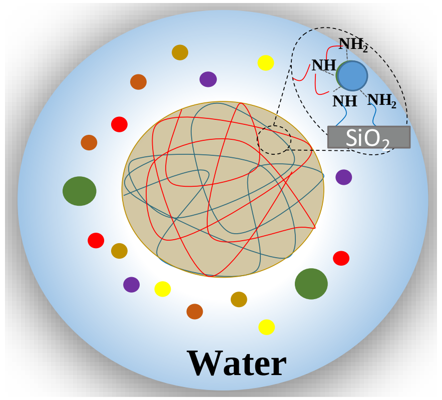
- ELGs regulate arsenic, TDS, mercury, and selenium from ZLD
- Wastewater slip stream to maintain low Cl concentration in FGD slurry
- Composition is highly variable and depends on source coal and air pollution control devices installed
- **ELGs provide two compliance pathways:**
  - **Chemical precipitation and biological treatment**
  - **Zero Liquid Discharge (ZLD)**

Gingerich, Grol, and Mauter *Env. Sci: Water Res & Technol, 2018*

Chemical absorption for precipitation

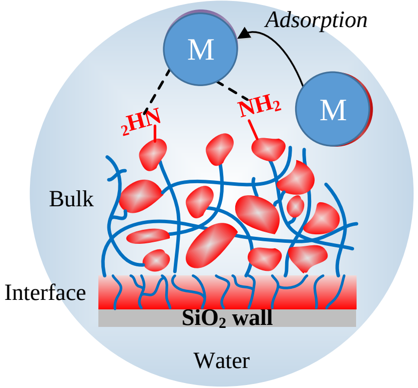
Patent Application 16N-10 (US patent #: 15/782315)

Stable Immobilized Amine Sorbents for REE and Heavy Metals Recovery from Liquid Sources



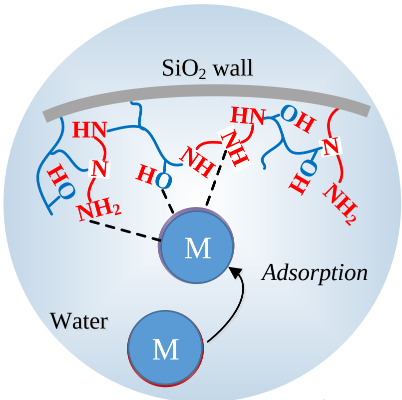
(Polyethylenimine-acrylamide/SiO_2)

HYDROGEL-BASED



(Polyethylenimine-crosslinker/SiO_2)

ORIGINAL SORBENT: LAYER-BASED



Polyamine-triepoxide/SiO_2

Monolith-BASED

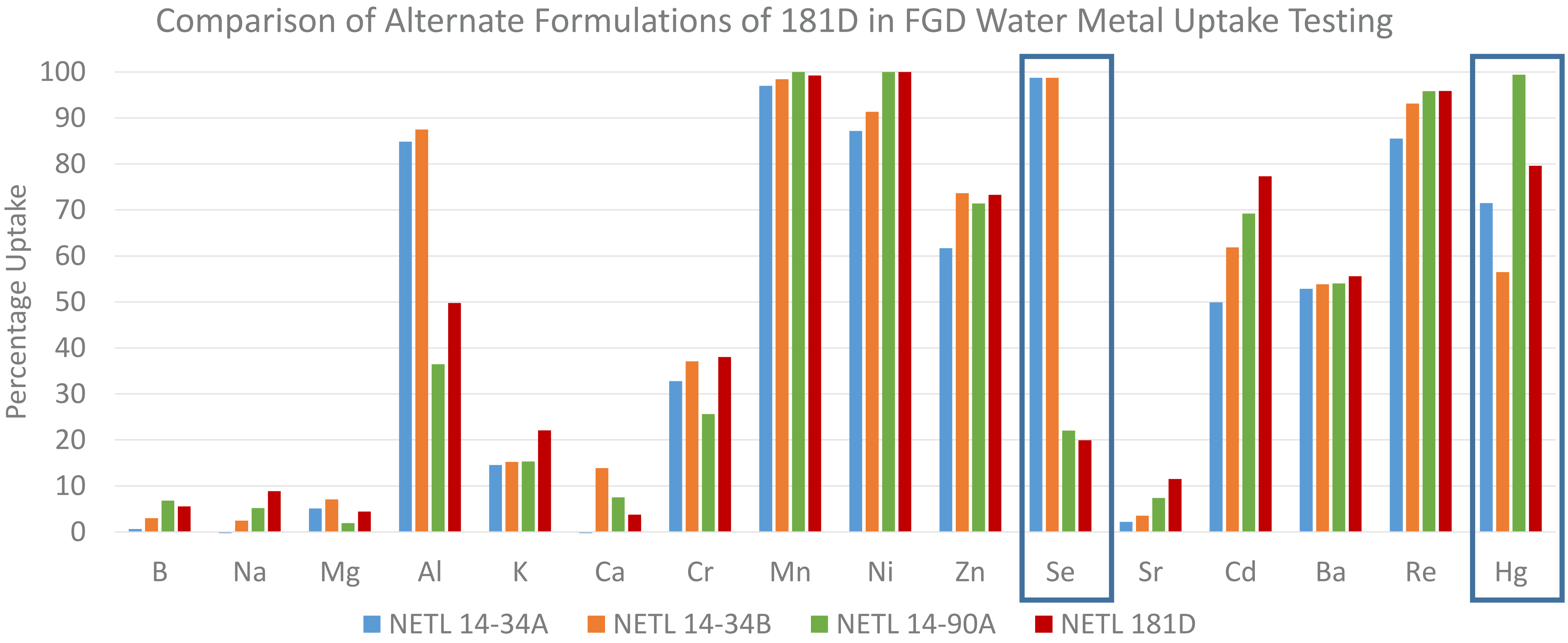
- Sorbents are made from inexpensive feedstock materials (silica, polyamines) using a low-cost production method (Pan Drying)
- Sorbents can be tailored for individual applications

16N-10 S-144,139

- AMD (acid mine drainage) REE
- Frack Water Ba, Sr
- Lead Pb
- Coal Waste As, Se, Hg, Cd, Cr, Pb

- Existing licensing agreement with PQ cooperation for:
  -**Pb and As**
- Potential new licensing agreement under discussion PQ for:
  -Se, Hg, Cd and Cr

FGD Water Flow-Through Performance



FGD Effluent Water used in this study was collected by AquaTech©

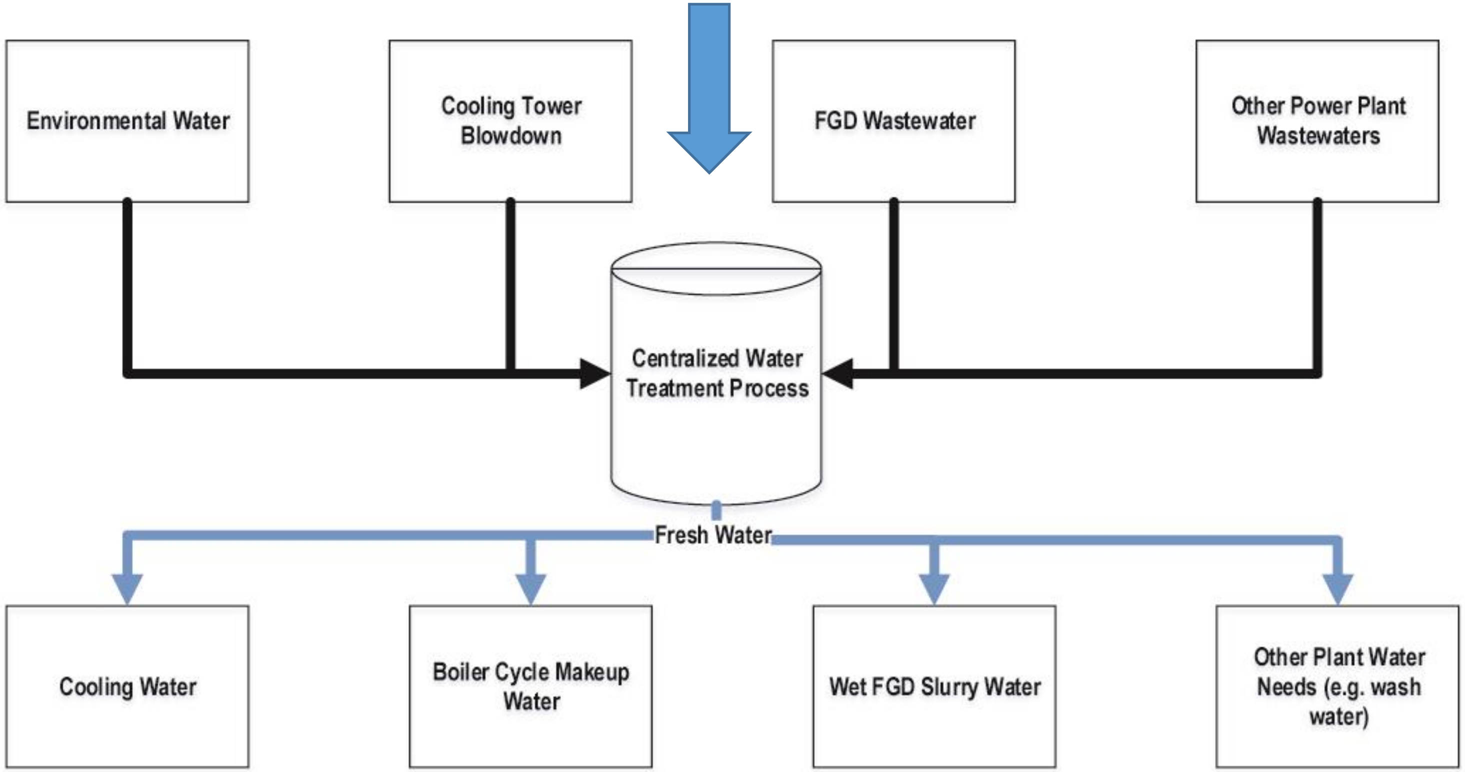
Synergies with other current and future plant water treatment requirements

- Conventional technologies include:
  - softening for hardness removal
  - MVC for ZLD

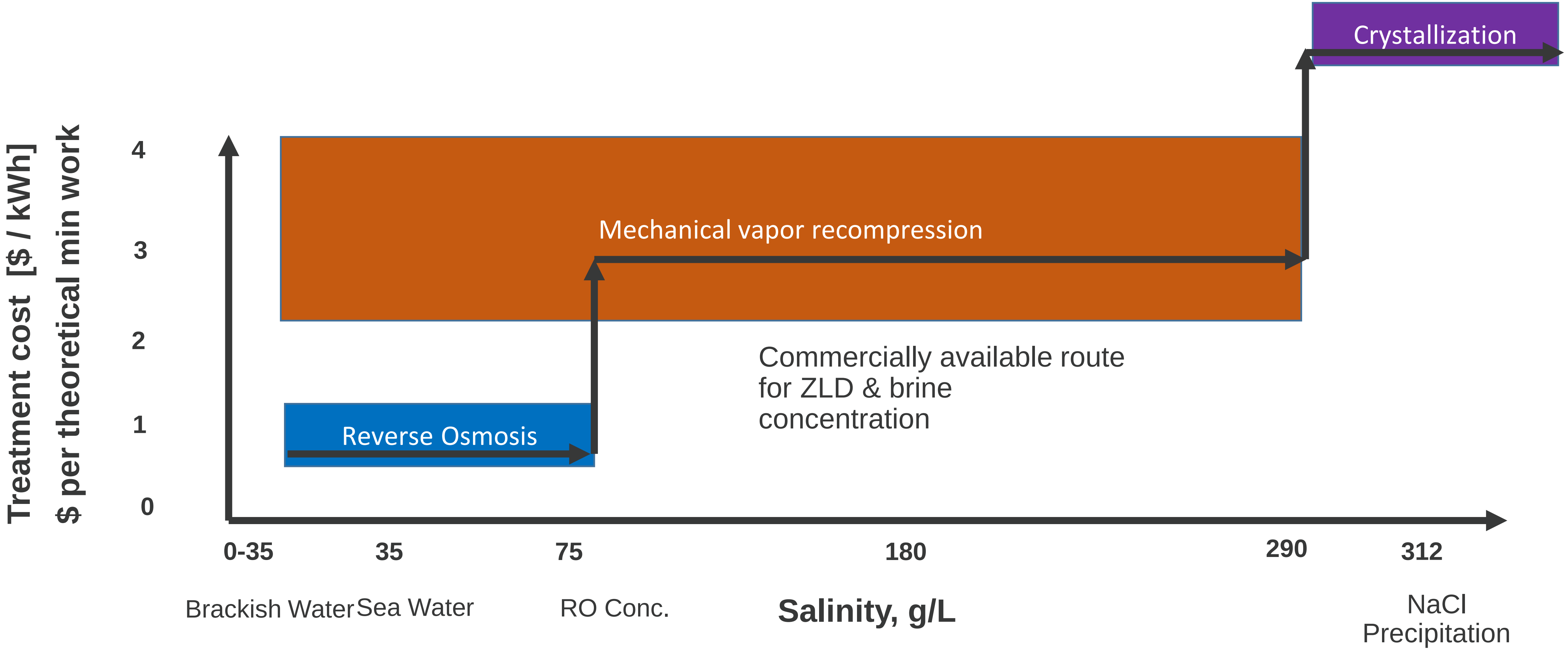
- Emerging technologies include membrane processes (RO, FO, MD) and electrocoagulation

- High recovery will minimize concentrate disposal costs

E.g. recirculating cooling water blowdown is high in silica, hardness, TDS, bacteria

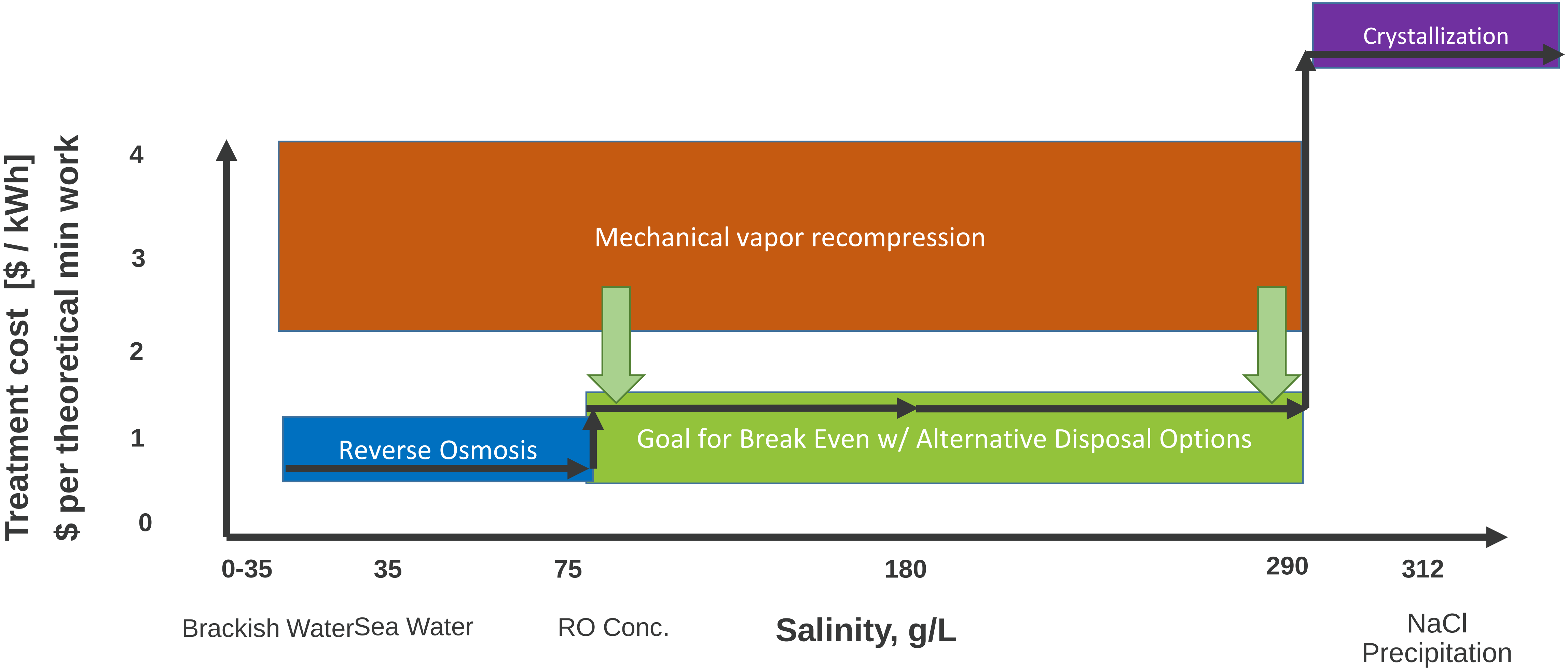


Grand challenge for concentrating effluent streams

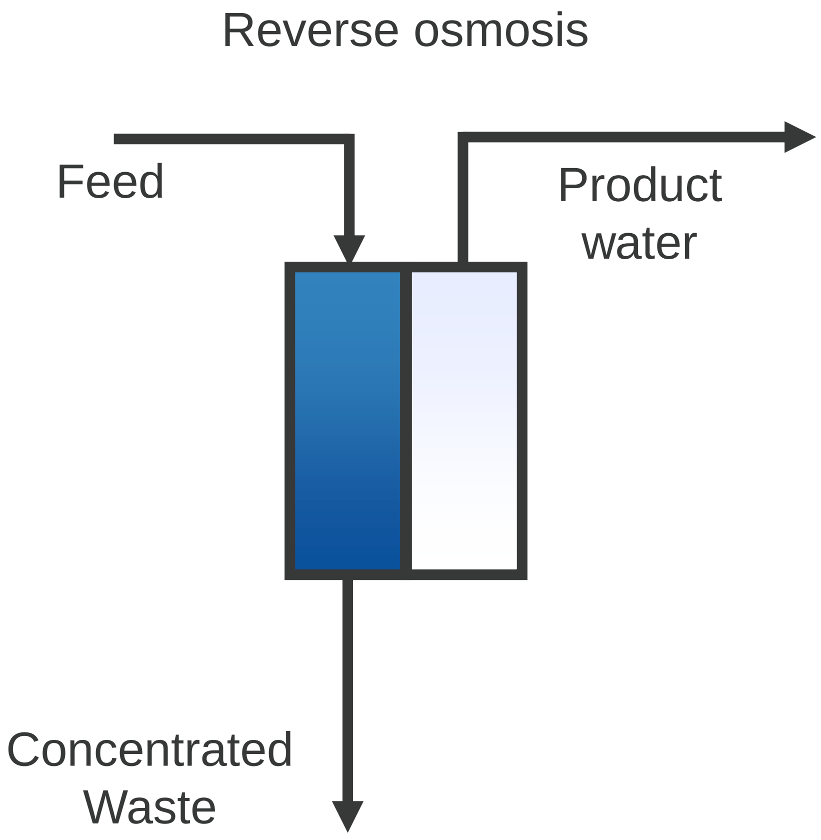


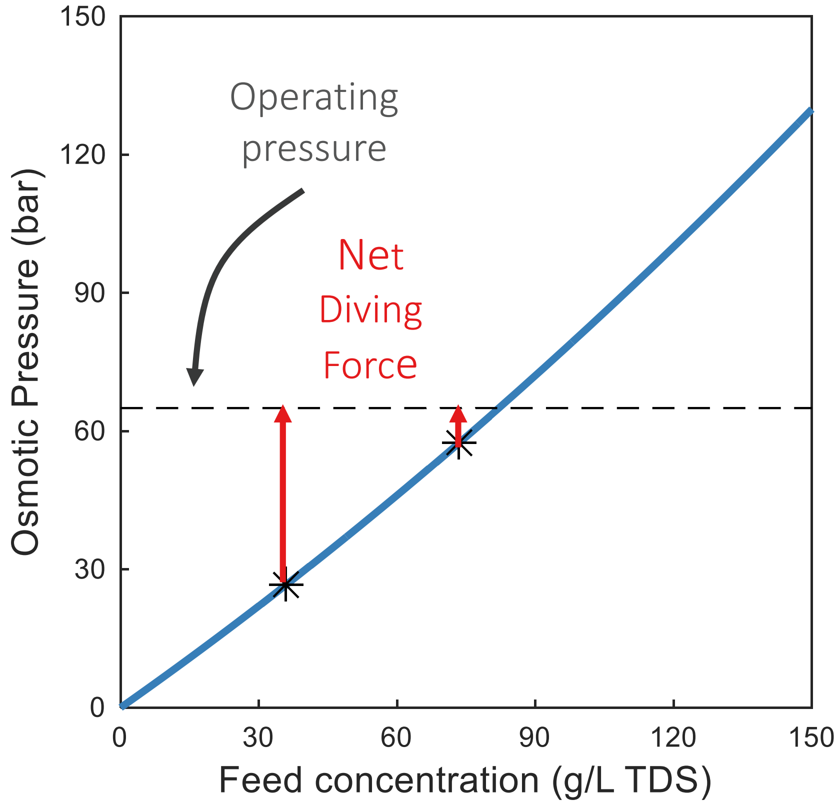
Commercially available route for ZLD & brine concentration

Project Objective: Reduce cost of concentrating effluent streams by 50% compared with MVR

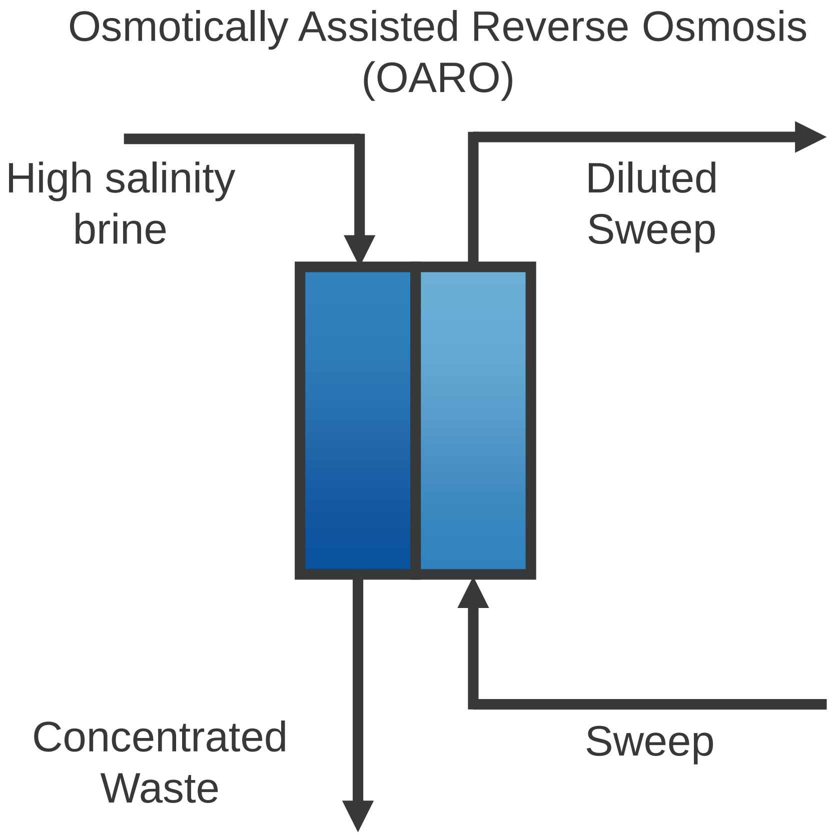


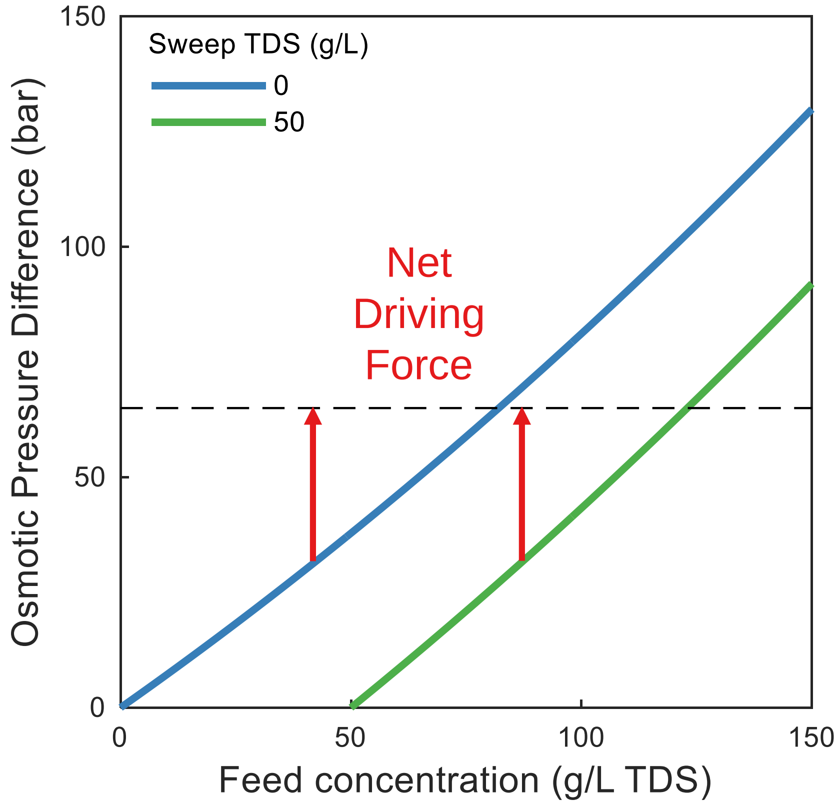
Recovery in RO is limited by membrane burst pressure



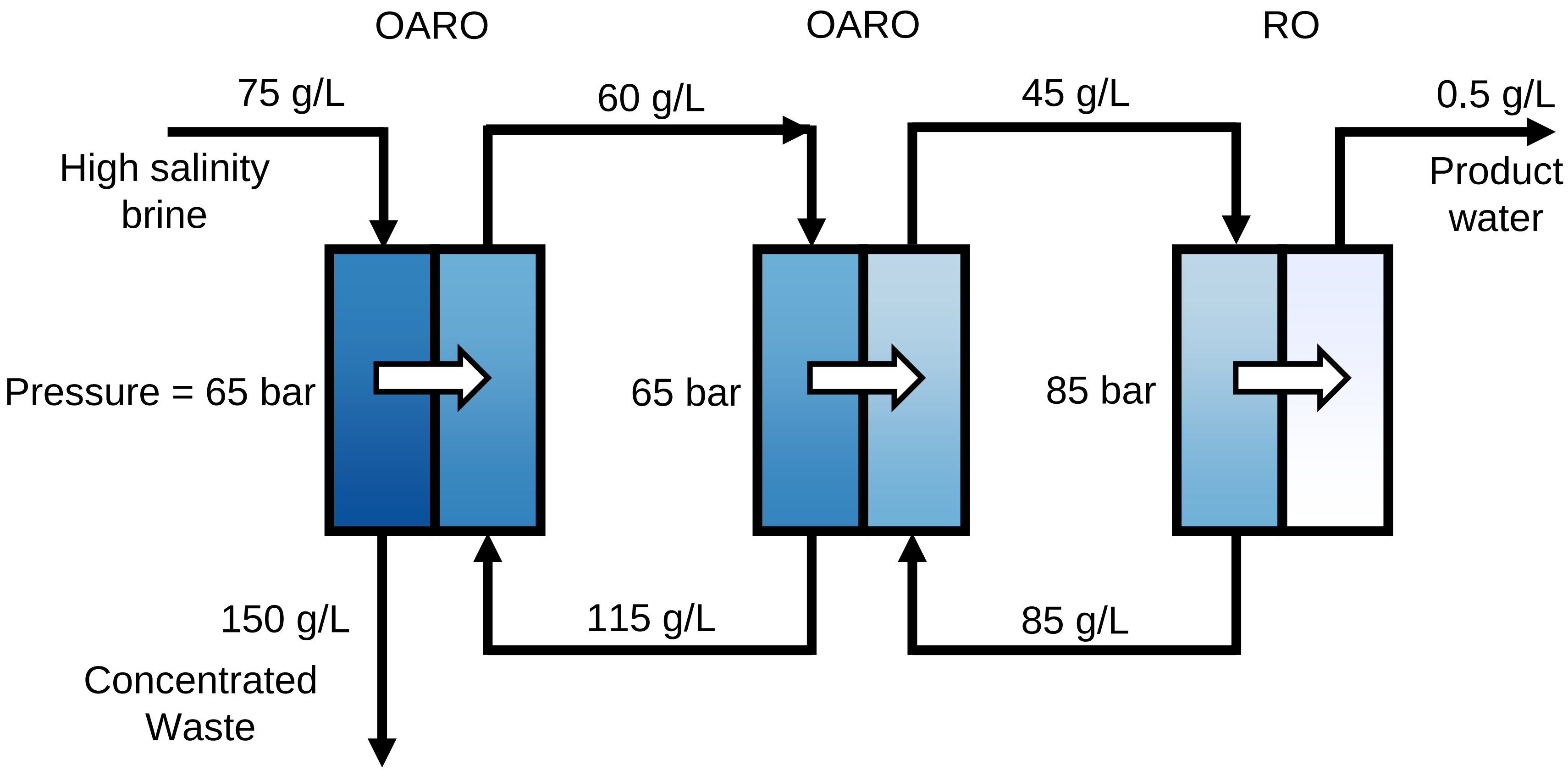


OARO uses a saline sweep to reduce the pressure difference across membrane





OARO uses multiple stages to desalinate a high salinity feed



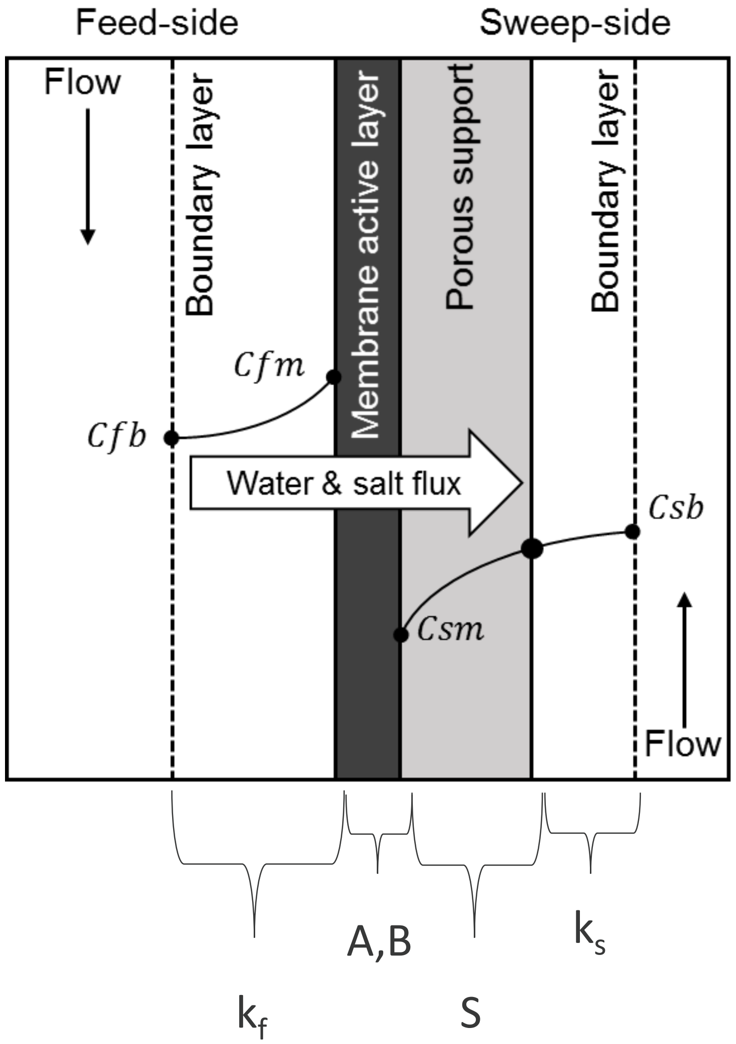
Modeling OARO process performance

Water and salt flux:

$$J_w = A \cdot (\Delta P - \Delta\pi) = A \cdot \left[\Delta P - \pi\left(C_{f_m}\right) + \pi\left(C_{s_m}\right)\right]$$
$$J_s = B \cdot\ \Delta C = B \cdot \left(C_{f_m} - C_{s_m}\right)$$

Concentration polarization:

$$C_{f_m} = C_{f_b} \cdot \exp\left(\frac{Jw}{k_f}\right) + \frac{Js}{Jw} \cdot \left[1 - \exp\left(\frac{Jw}{k_f}\right)\right]$$
$$C_{s_m} = C_{s_b} \cdot \exp\left(-Jw\left(\frac{1}{k_s} + \frac{S}{D}\right)\right) + \frac{Js}{Jw} \cdot \left[1 - \exp\left(-Jw\left(\frac{1}{k_s} + \frac{S}{D}\right)\right)\right]$$

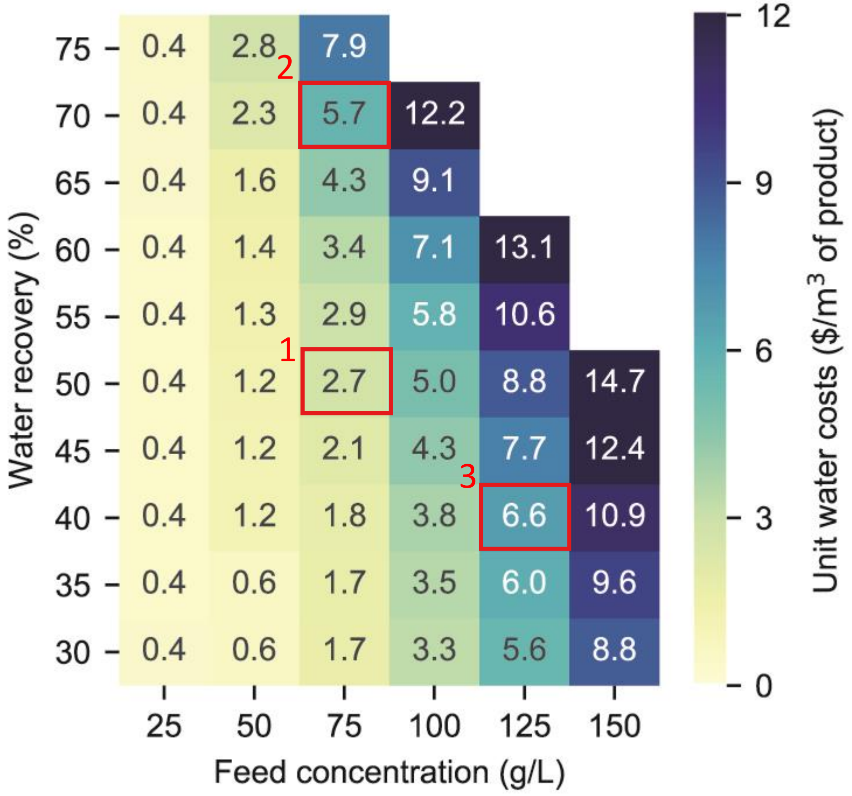


Notation:

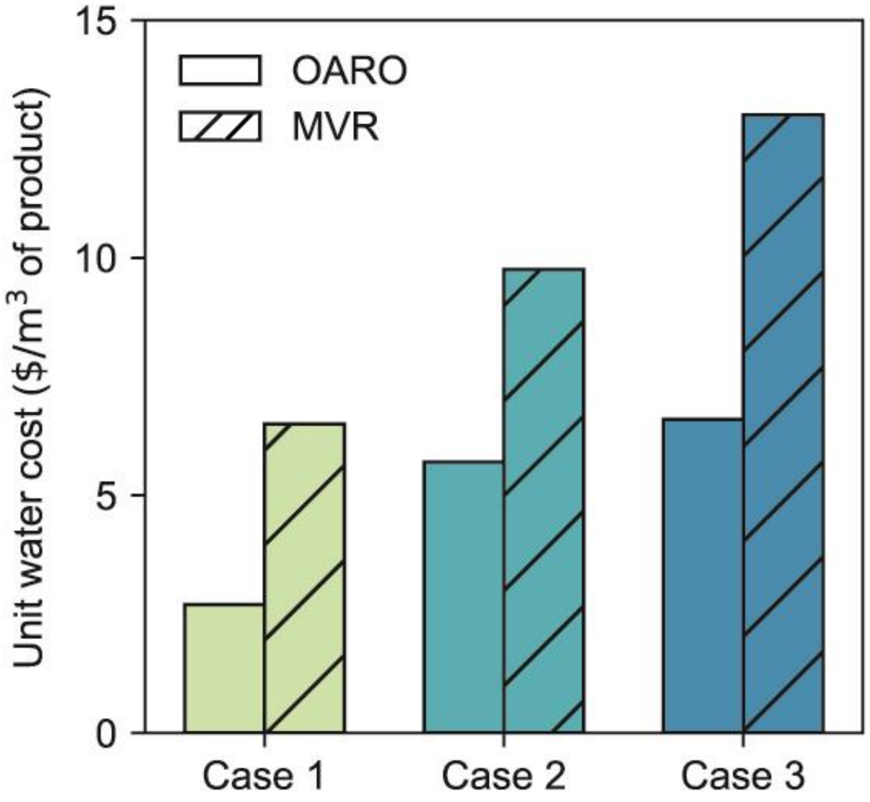
J_w – water flux
J_s – salt flux
A – water permeability coef.
B – solute permeability coef.
P – hydraulic pressure
π – osmotic pressure

C – solute conc.
C_m – interfacial conc.
C_b – bulk conc.
k – mass transfer coef.
S – structural parameter
D – diffusion coeff. of solute

OARO is cost competitive across a range of water qualities/recovery targets



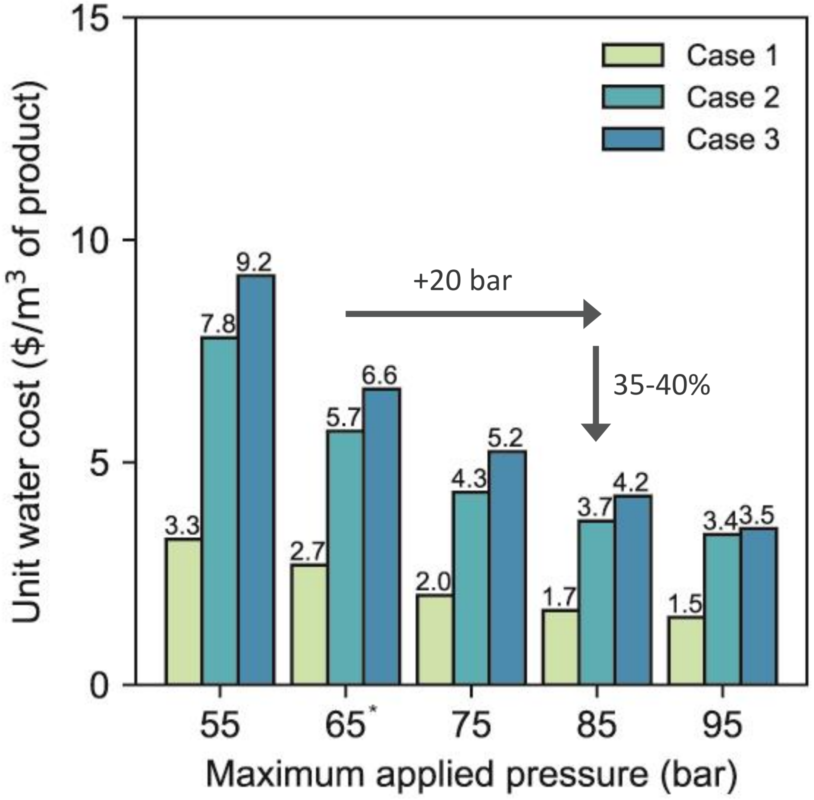
Water recovery (%)	25	50	75	100	125	150
75	0.4	2.8	7.9			
70	0.4	2.3	5.7	12.2		
65	0.4	1.6	4.3	9.1		
60	0.4	1.4	3.4	7.1	13.1	
55	0.4	1.3	2.9	5.8	10.6	
50	0.4	1.2	2.7	5.0	8.8	14.7
45	0.4	1.2	2.1	4.3	7.7	12.4
40	0.4	1.2	1.8	3.8	6.6	10.9
35	0.4	0.6	1.7	3.5	6.0	9.6
30	0.4	0.6	1.7	3.3	5.6	8.8



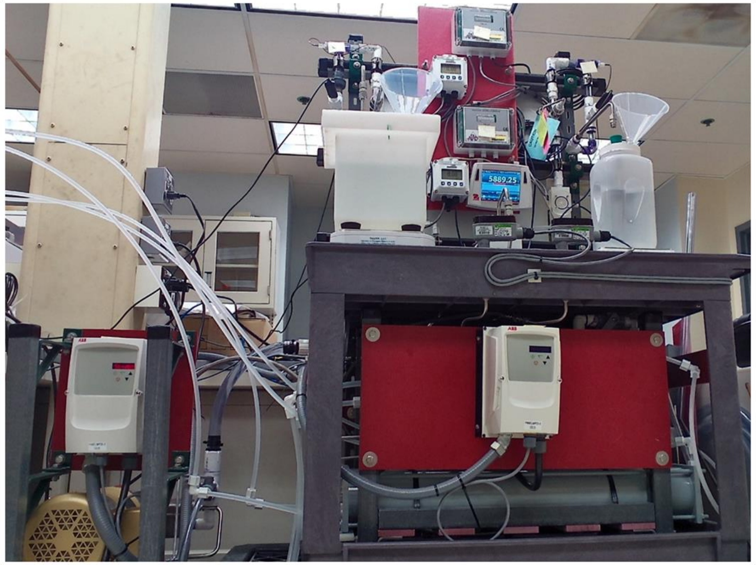
Bartholomew et al. *Environ. Sci. Technol., 2018*
Wenzlick et al. *URTC*, 2018

Sensitivity analysis can guide future OARO research

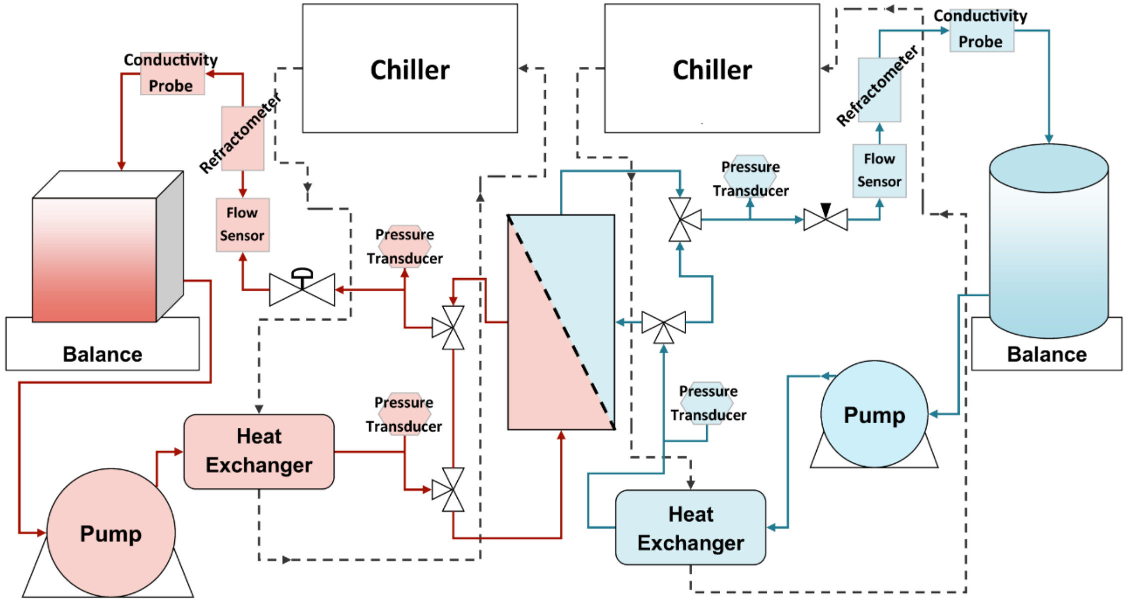
- Doubling the water permeability reduces cost by less than 10%
- Halving the structural parameter reduces cost by 15-25%
- Increasing the maximum applied pressure reduces cost by 35-40%



Experimental work characterizes membranes at OARO conditions

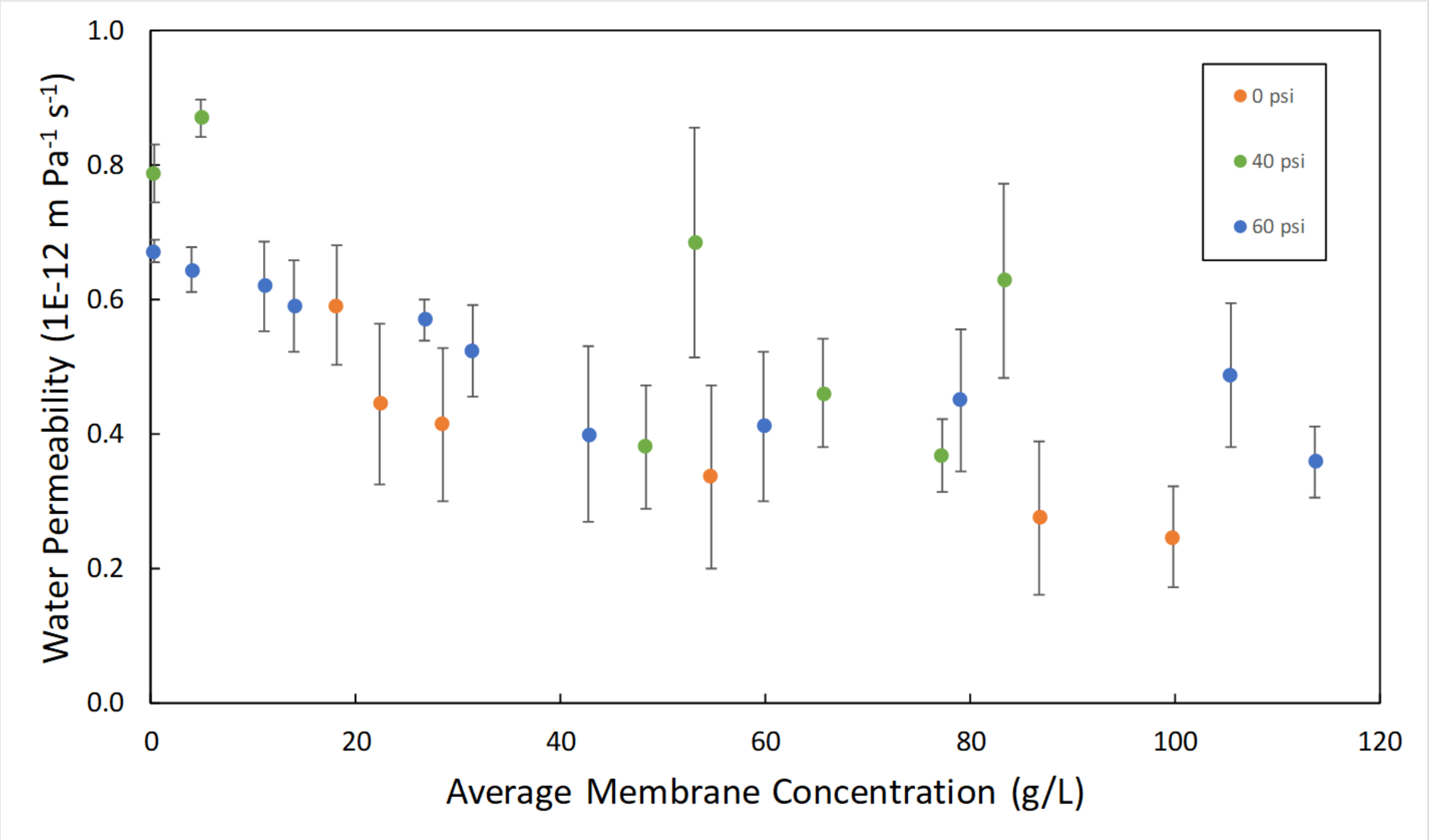


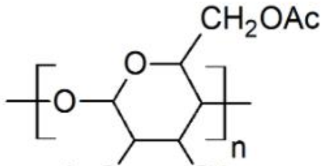
- Estimate A, B, and S for a range of feed pressures, and feed and sweep solute concentrations



Estimating water permeability at varying operating conditions

$$J_w = A \cdot \{[P_f - P_s] - [\pi(c_{f,m}) - \pi(c_{s,m})]\}$$





Cellulose Triacetate

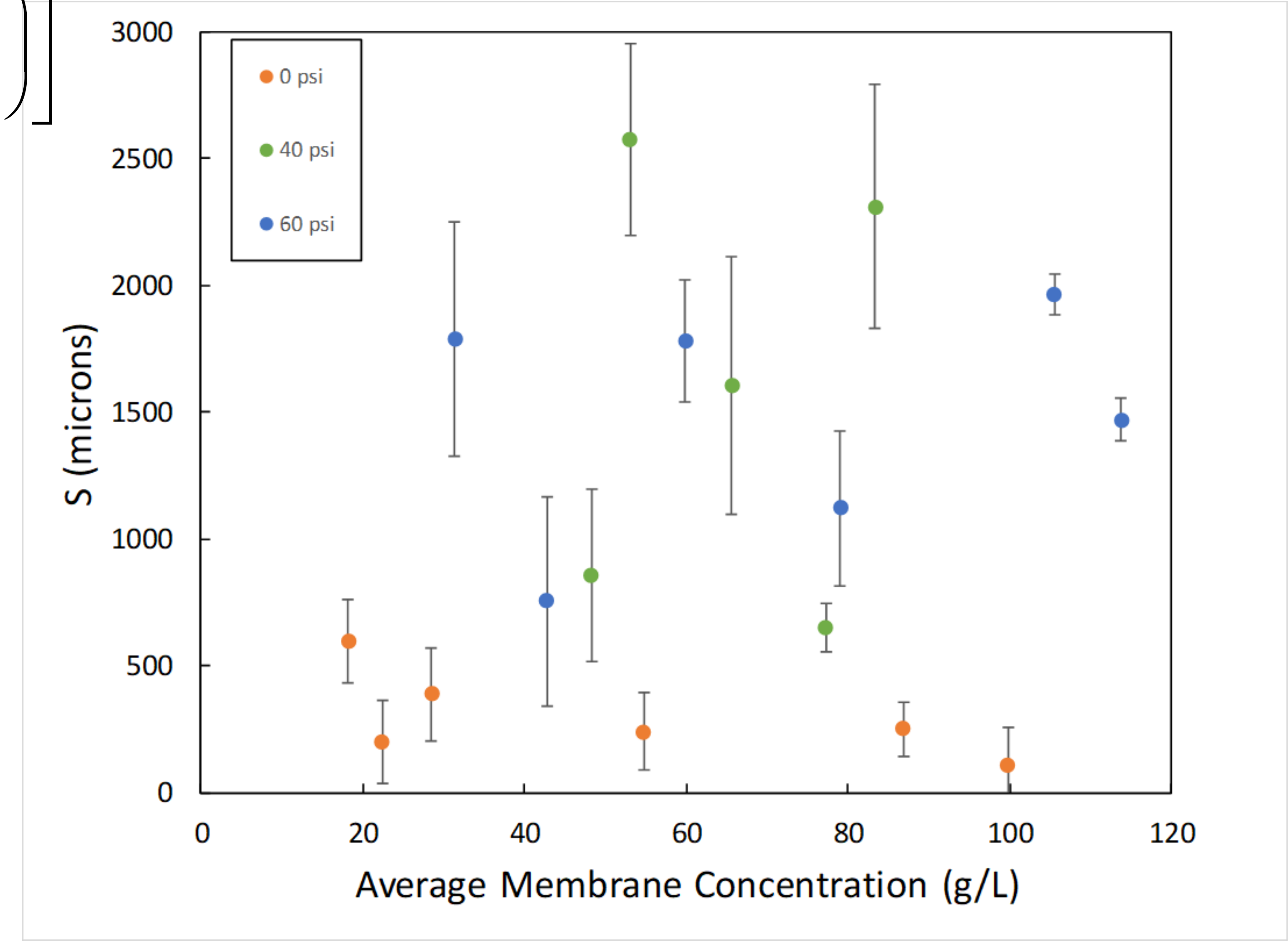
- Permeability decreases with average salinity
- Possible dehydration of CTA membrane surface
- No major effect of pressure
- Further tests to determine how salinity changes membrane

Zhang, et al. *J. Membr. Sci.* 498 (2016) 365-373

Estimating structure parameter at varying operating conditions

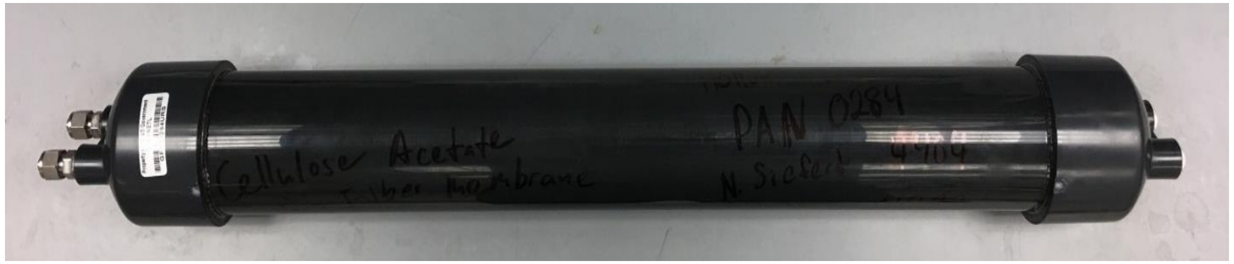
$$c_{s,m} = c_{s,b} \cdot \exp\left(-\frac{J_w S}{D}\right) + \frac{J_s}{J_w} \cdot \left[1 - \exp\left(-\frac{J_w S}{D}\right)\right]$$

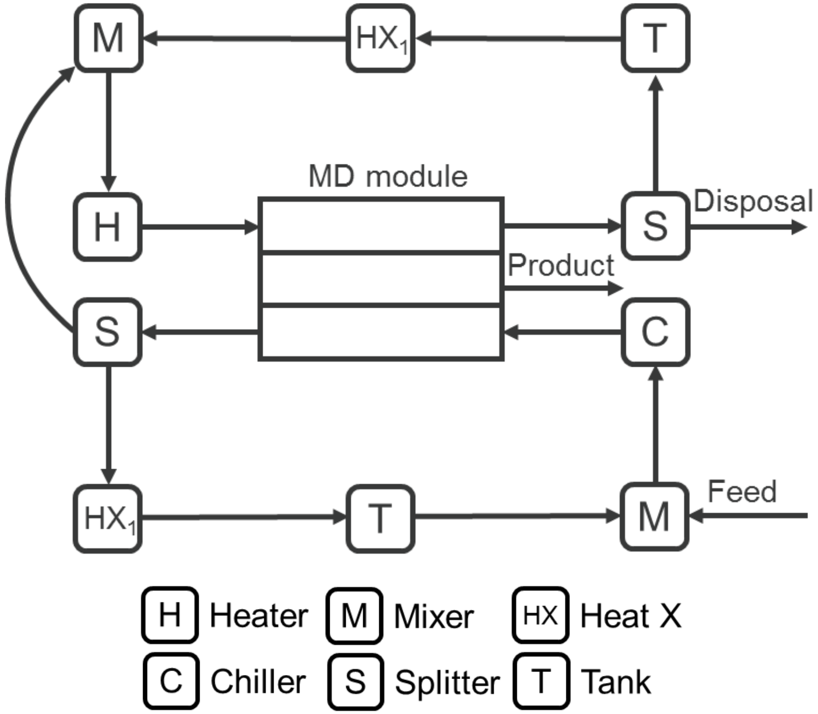
- Possible compression of support layer and spacers with pressure
- Expected value from literature around 150-300 microns
- SW30 even higher- significant loss of applied pressure



Remaining technical gaps

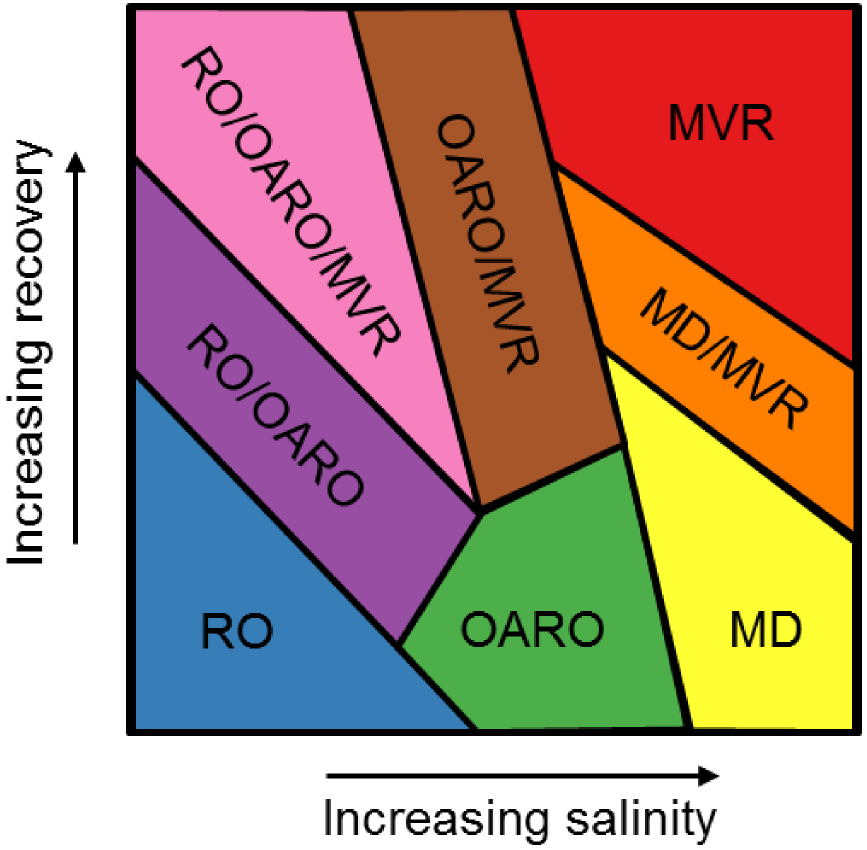
- Developing membranes with high burst pressure and low structural parameters
- Testing the OARO process at pilot scale
- Modeling the integration of OARO with other technologies (RO, MVR, MD) to minimize the cost/energy of meeting treatment specifications for different effluent streams
  - Accounting for variable water quality
  - Assessing the role for alternative membrane and thermal processes
  - Building a comprehensive decision matrix





Future Work: Developing decision matrix for concentrating effluent

- Identify low cost technology or technology combinations across the broad range of potential treatment needs at power plants
- Assess energy implications of the low cost technology



Conclusions

Key findings

- OARO can potentially lower cost to concentration compared against the baseline MVR technology

Lessons learned:

- Optimization modeling is a critical tool for techno-economic assessment

Remaining Steps:

- Develop hollow fiber membrane modules with high burst pressure, high permeability, and low structural parameter
- Optimize treatment trains that incorporate OARO
- Compare against cost/energy of other membrane processes

References

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