The Promise of Forward Osmosis

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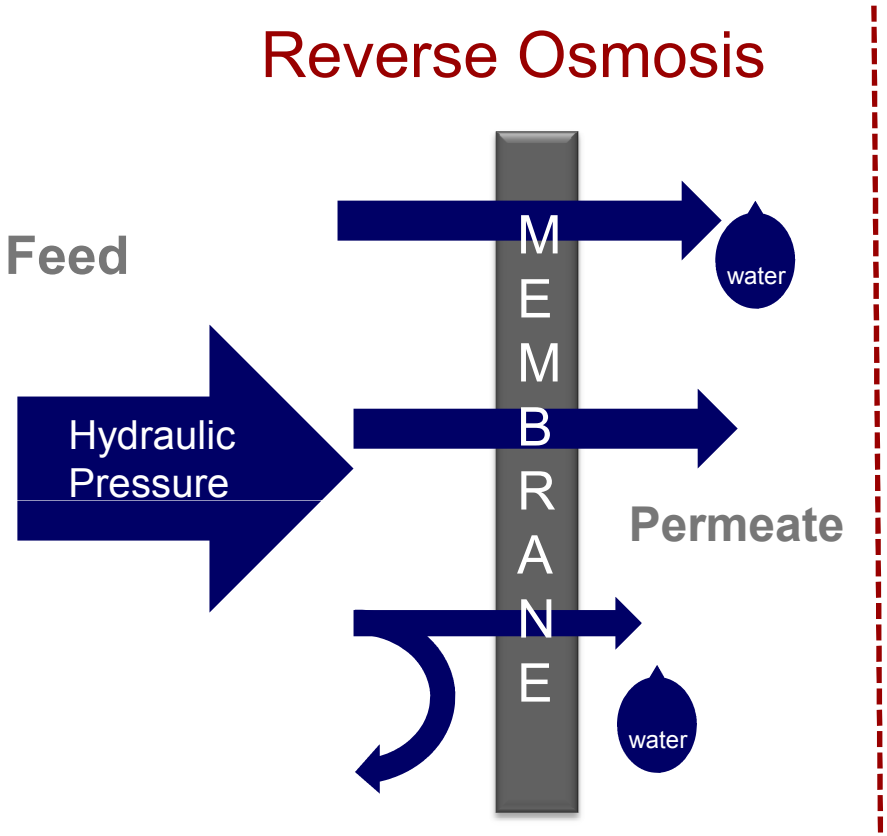
Motivation: Augment Water Supply

- Droughts and water shortages
- Need to increase water supply by producing new water
- Viable options for new water:
  - Wastewater reuse
  - Desalination of sea/brackish water

Need for Sustainable Technologies

- Develop water/wastewater treatment technologies that
  - Use less energy
  - Require less chemicals
  - Have lower impact on the environment
- Osmotically-driven membrane processes, or forward osmosis (FO), may be a promising option

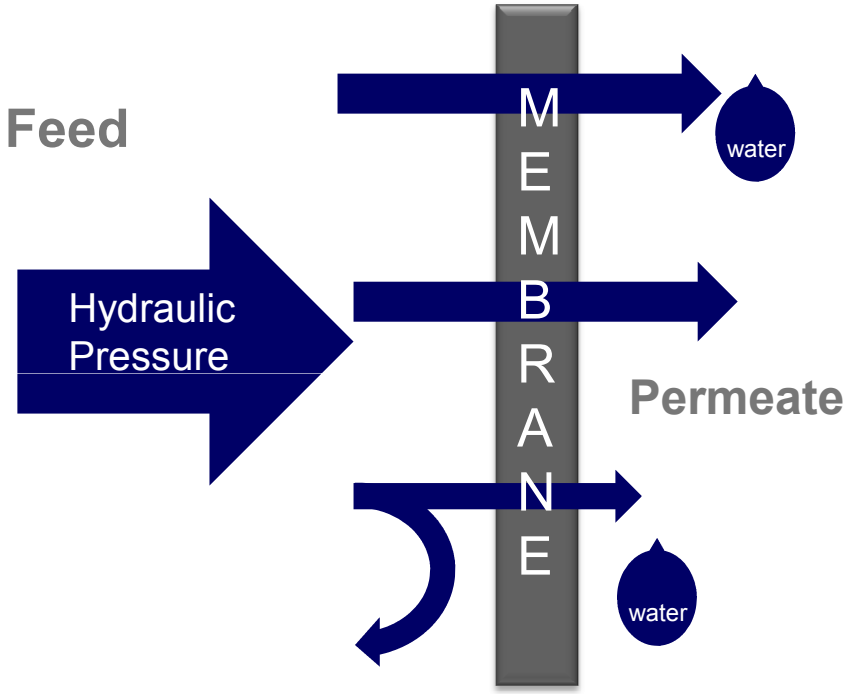
What is Forward Osmosis?



$$J_w = A\left(\Delta P - \Delta \Pi_m\right)$$

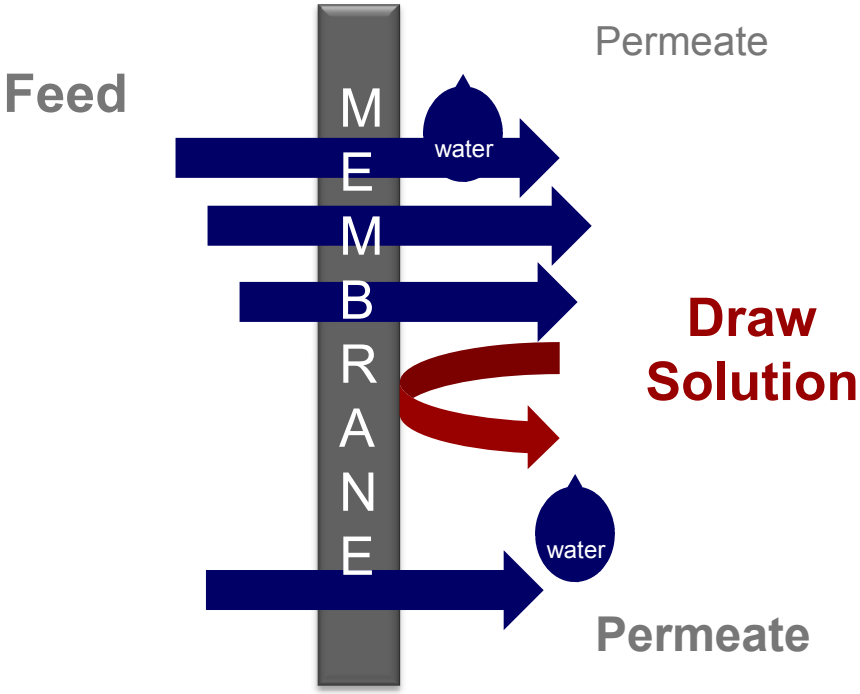
What is Forward Osmosis?

Reverse Osmosis

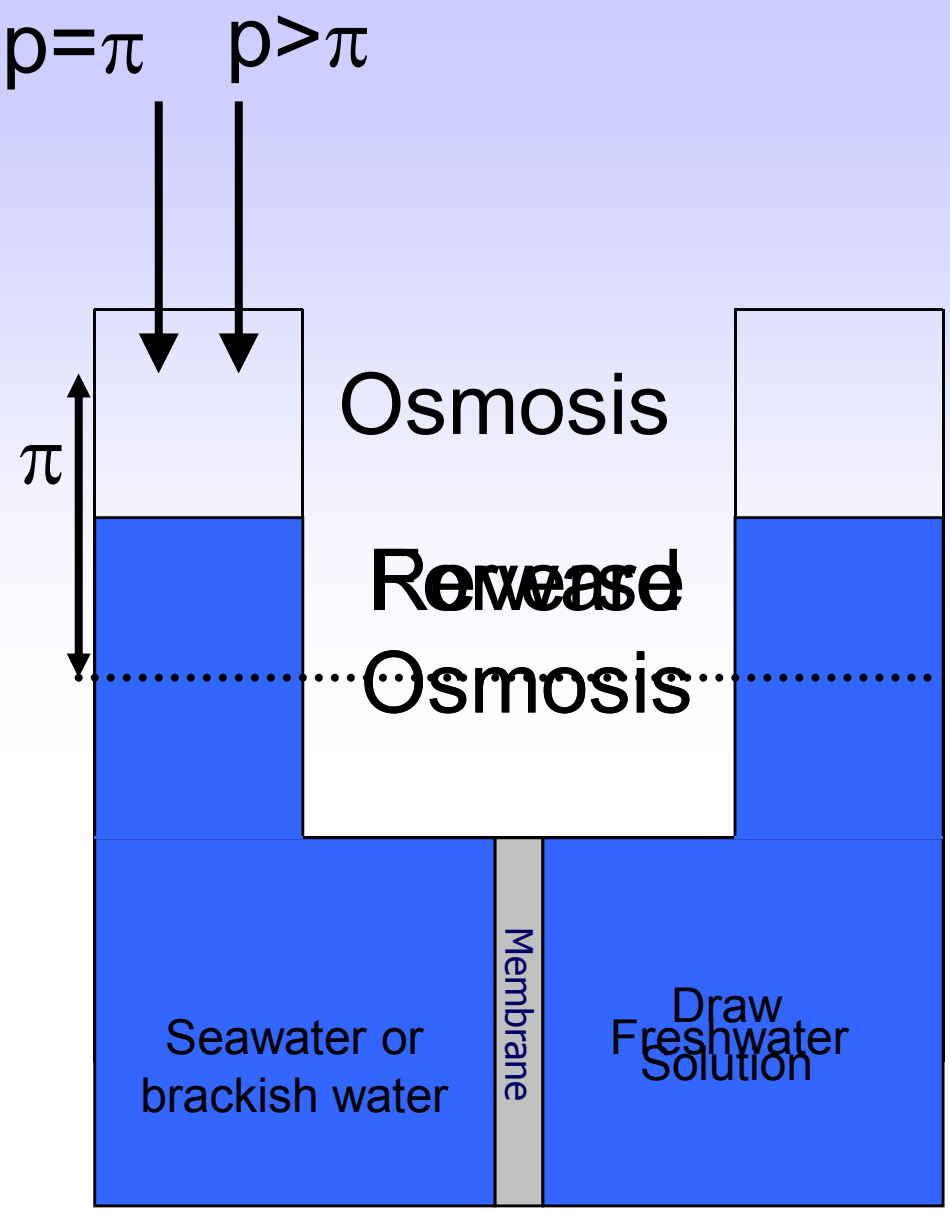


$$J_w = A(\Delta P - \Delta \Pi_m)$$

Forward Osmosis

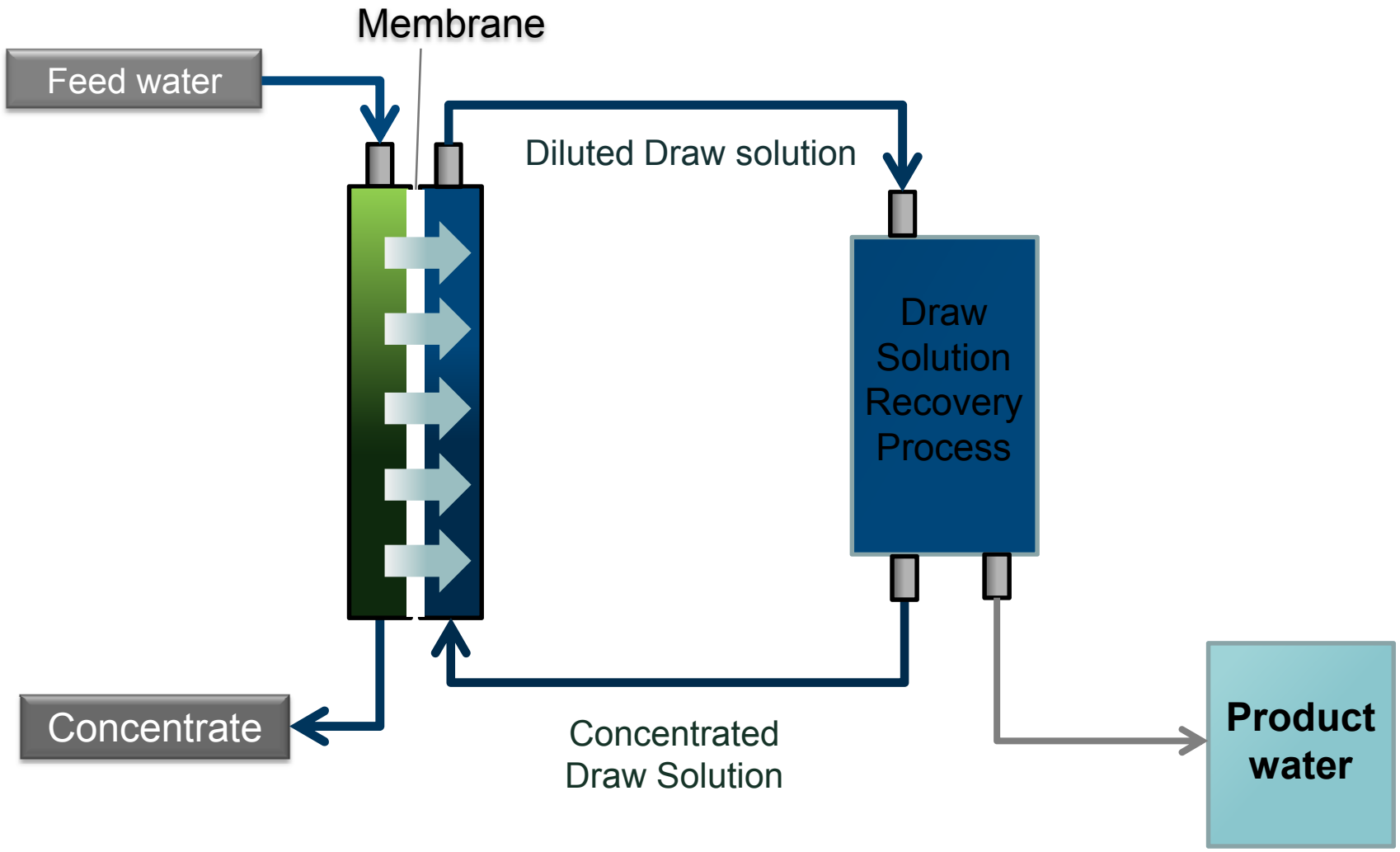


$$J_w = A\Delta \Pi_m$$



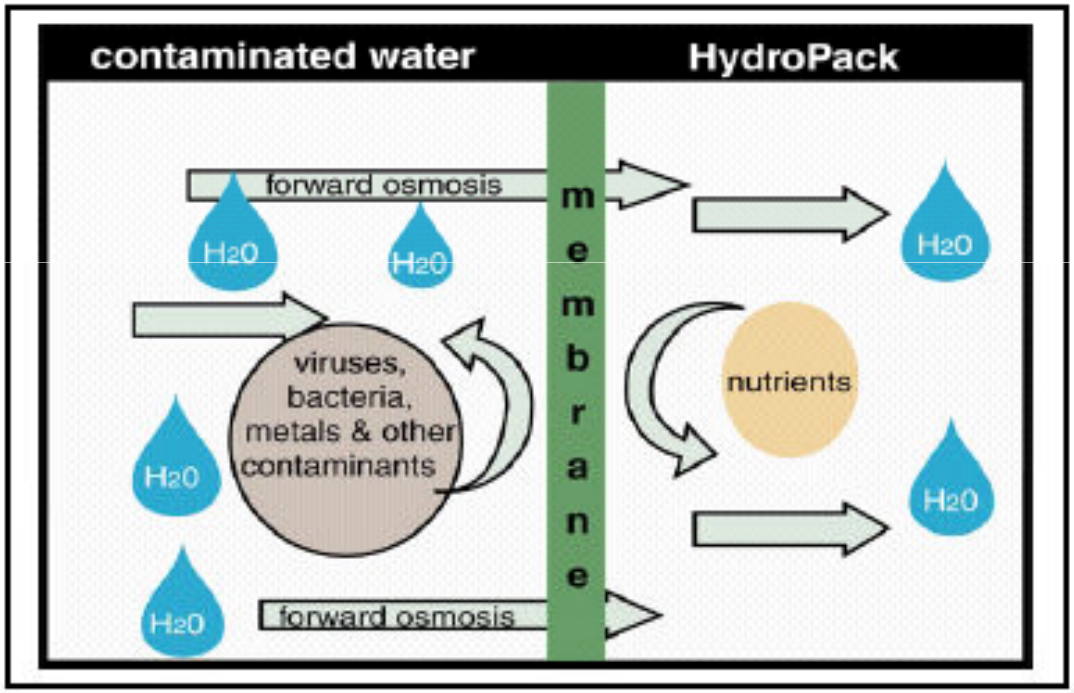
Forward Osmosis

Forward Osmosis Process

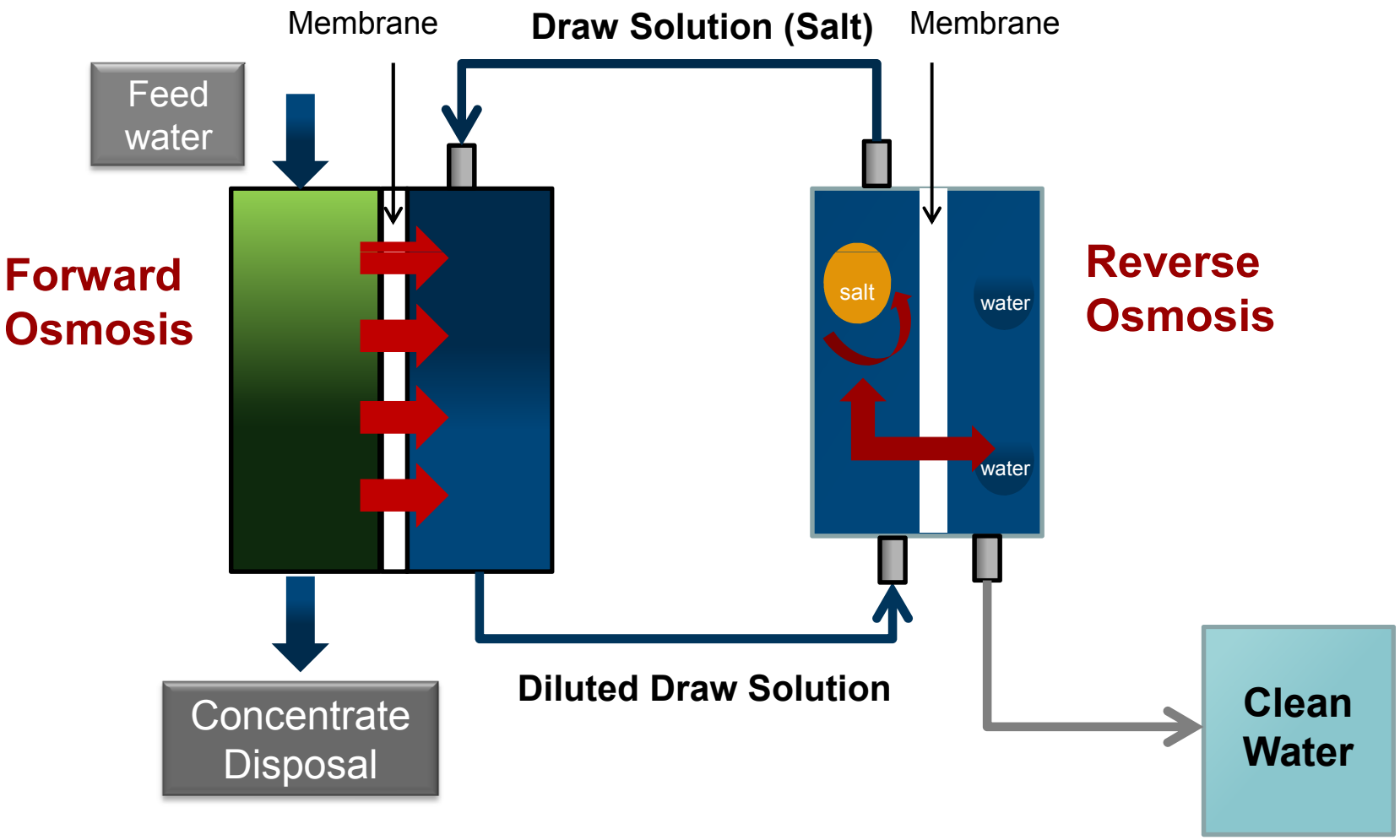


Applications of Forward Osmosis

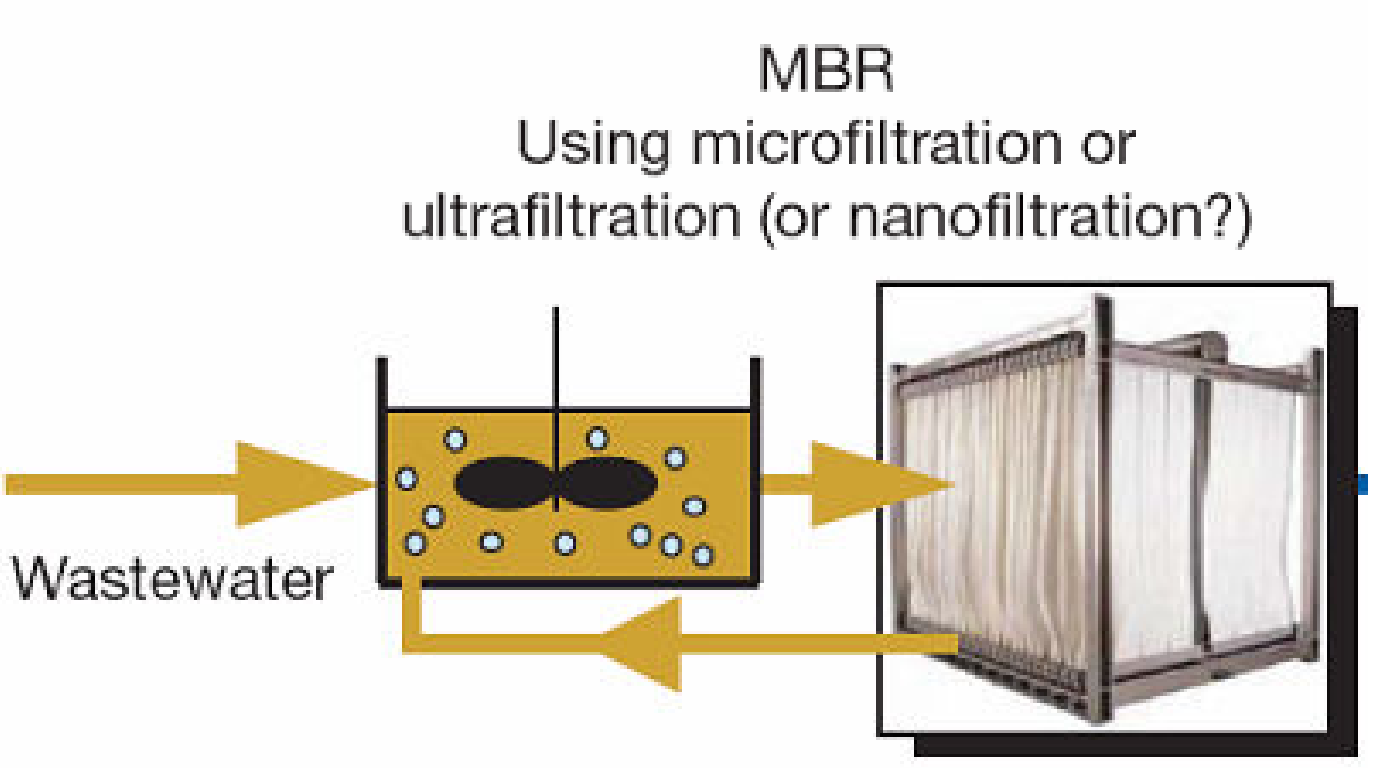
Hydration Bags



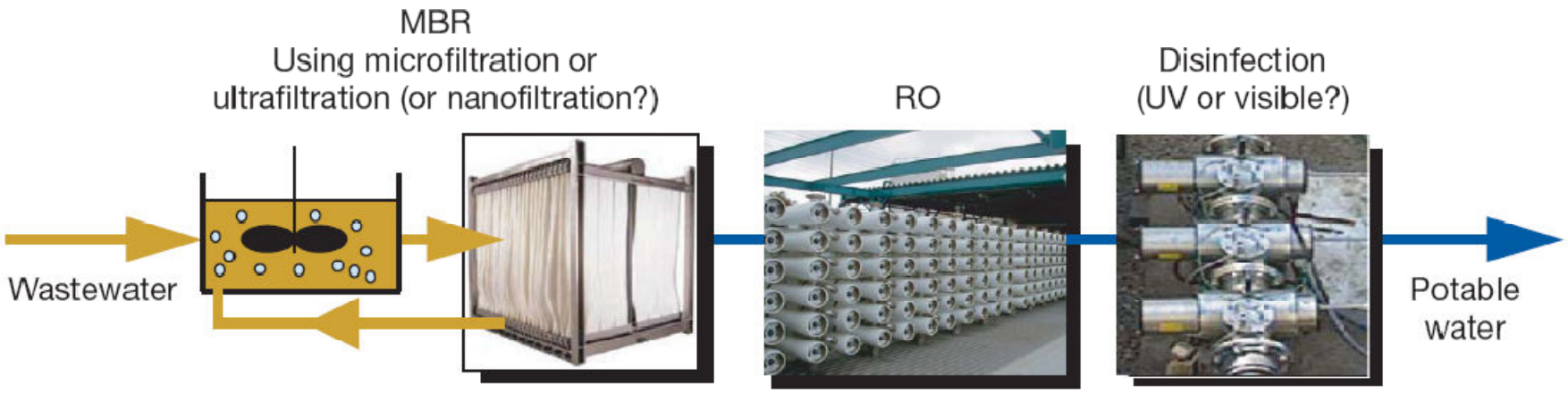
Wastewater Treatment with Forward Osmosis



Membrane Bioreactor (MBR) for Wastewater Treatment

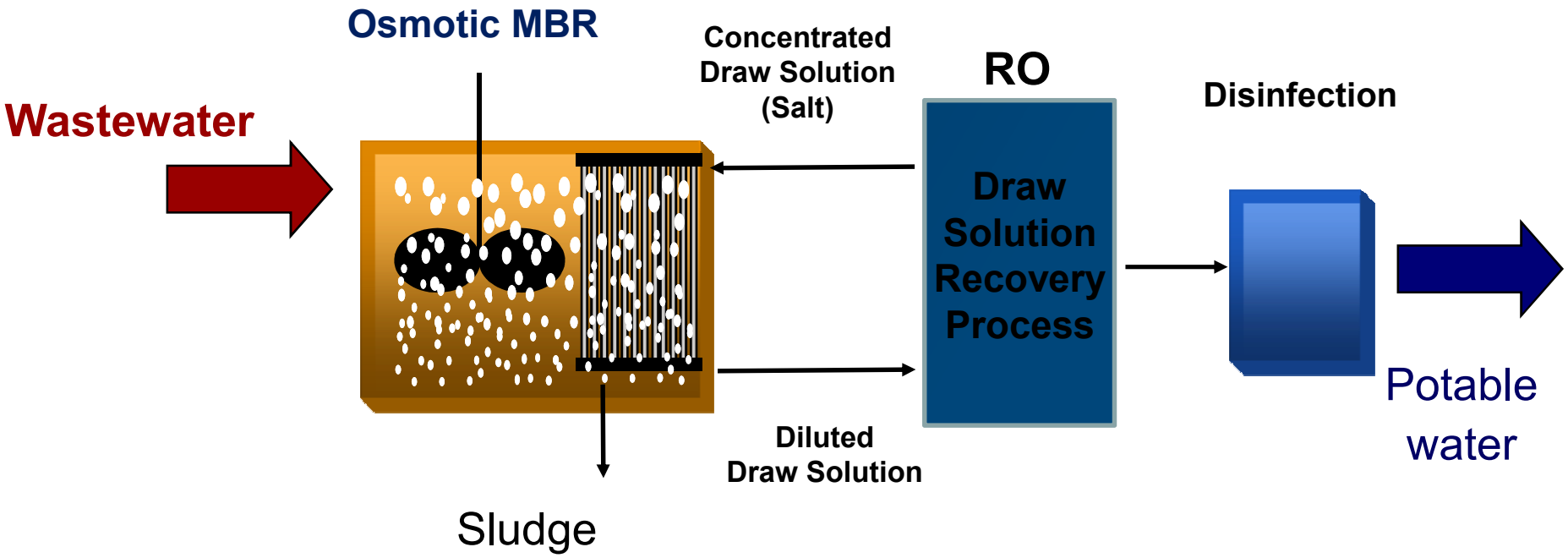


Wastewater Reuse: Membrane Bioreactor (MBR)-RO System



M1

Osmotic MBR-RO: Multiple Barrier Wastewater Treatment



Achilli et al., *Desalination*, 2008

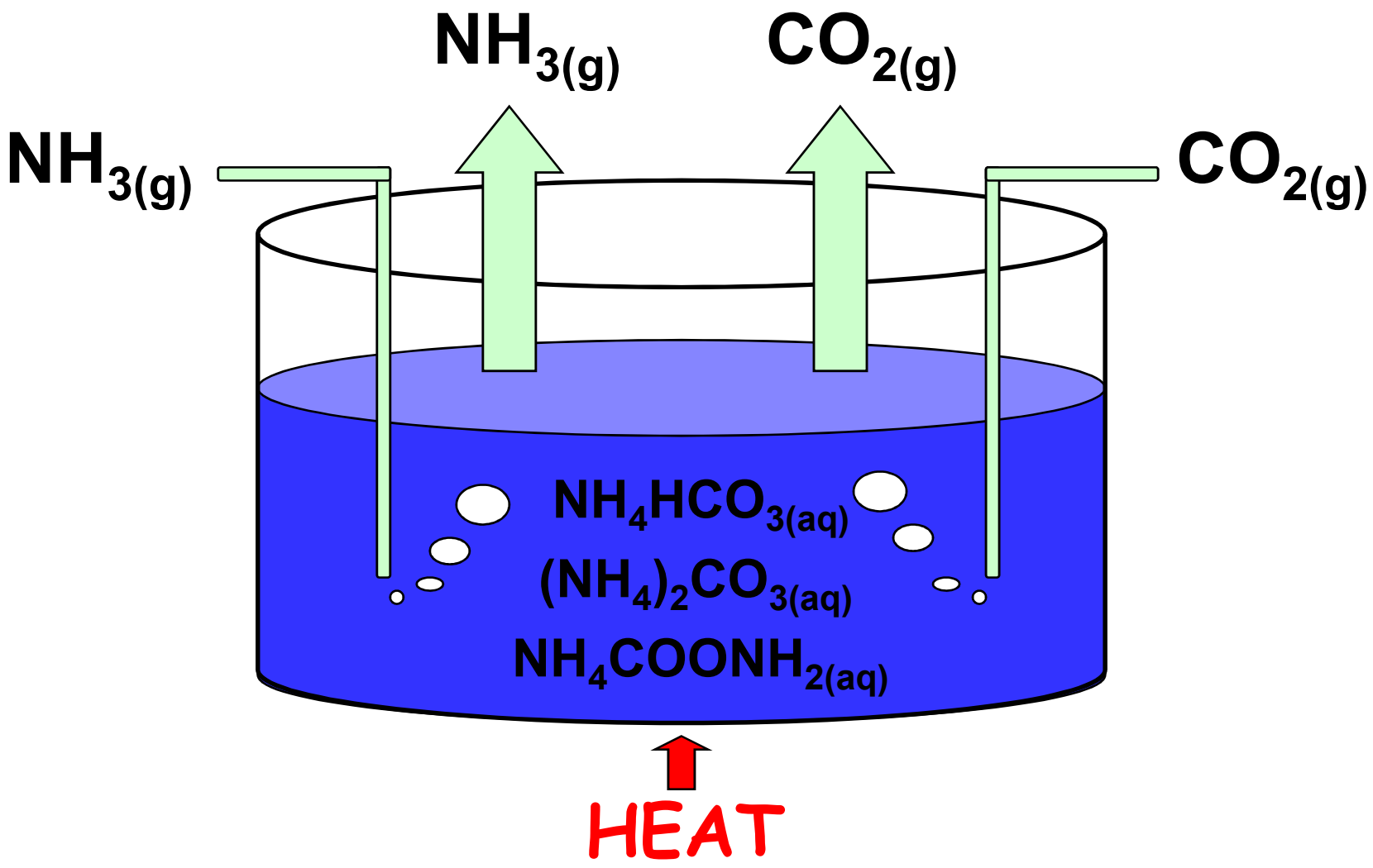
M1 This you can modifu as you wish. See original paper...

May use similar style as previous slide
Meny Elimelech, 2009-07-31

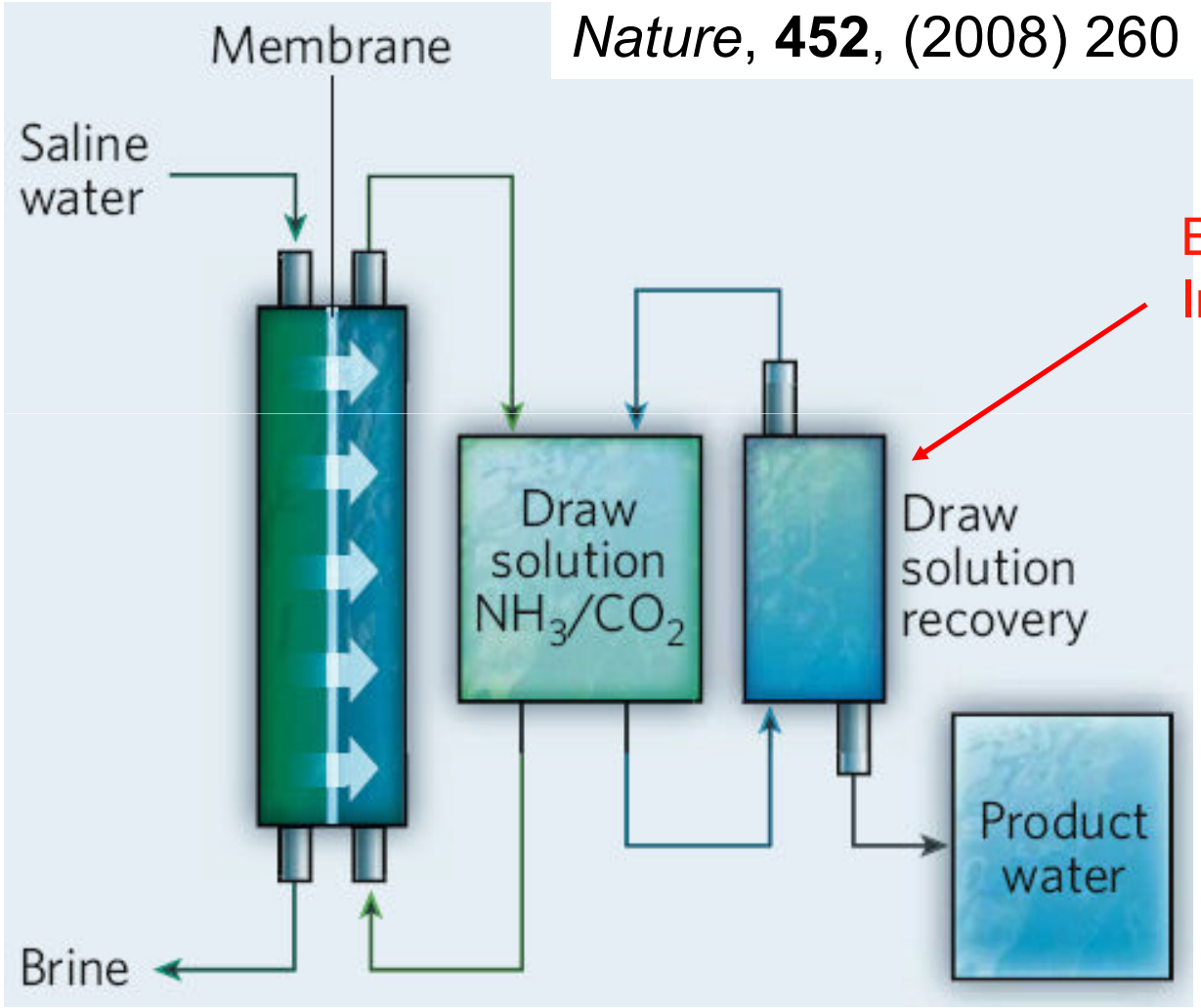
Desalination by Forward Osmosis: The Ideal Draw Solution

- Highly soluble solution to generate high osmotic pressure gradient
- Recoverable and recyclable
- Soluble species should not pass through the membrane

NH_3/CO_2 Draw Solution



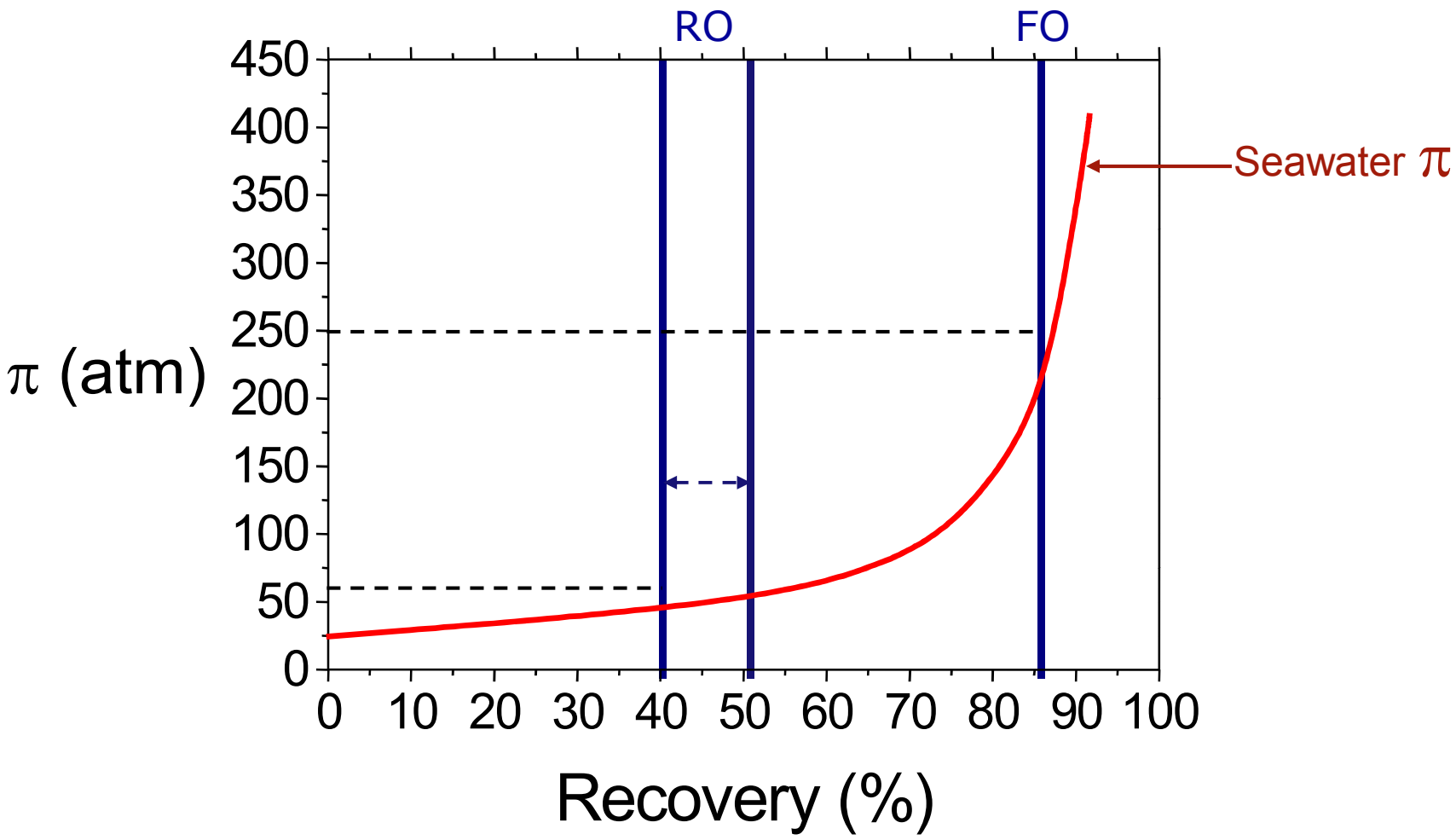
The Ammonia-Carbon Dioxide FO Desalination Process



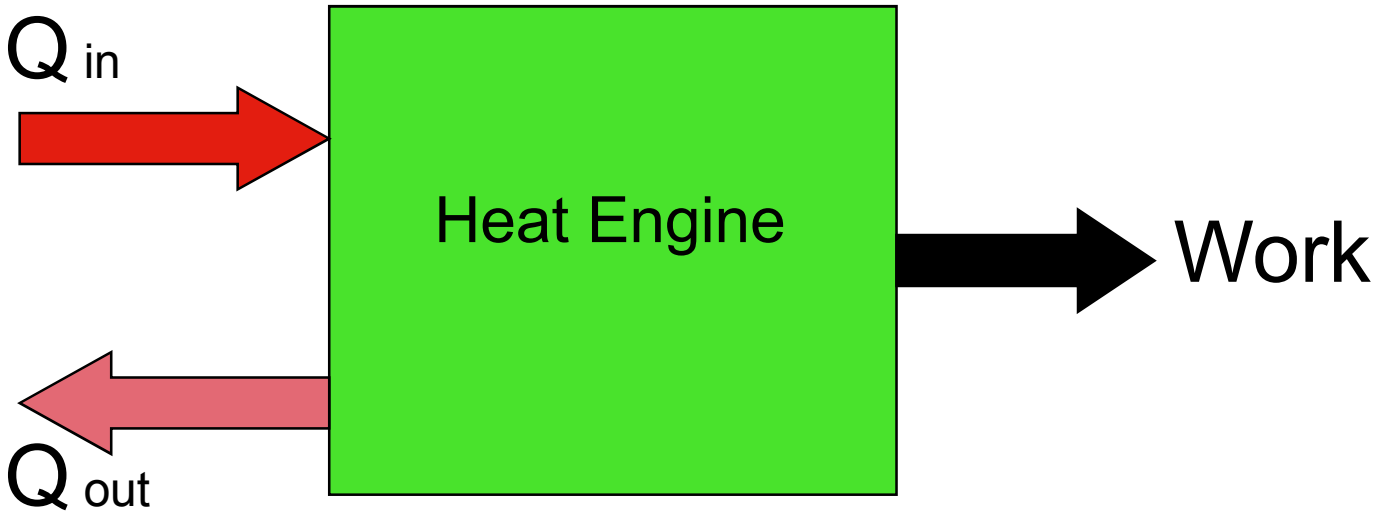
Nature, **452**, (2008) 260

Desalination, **174** (2005) 1-11.

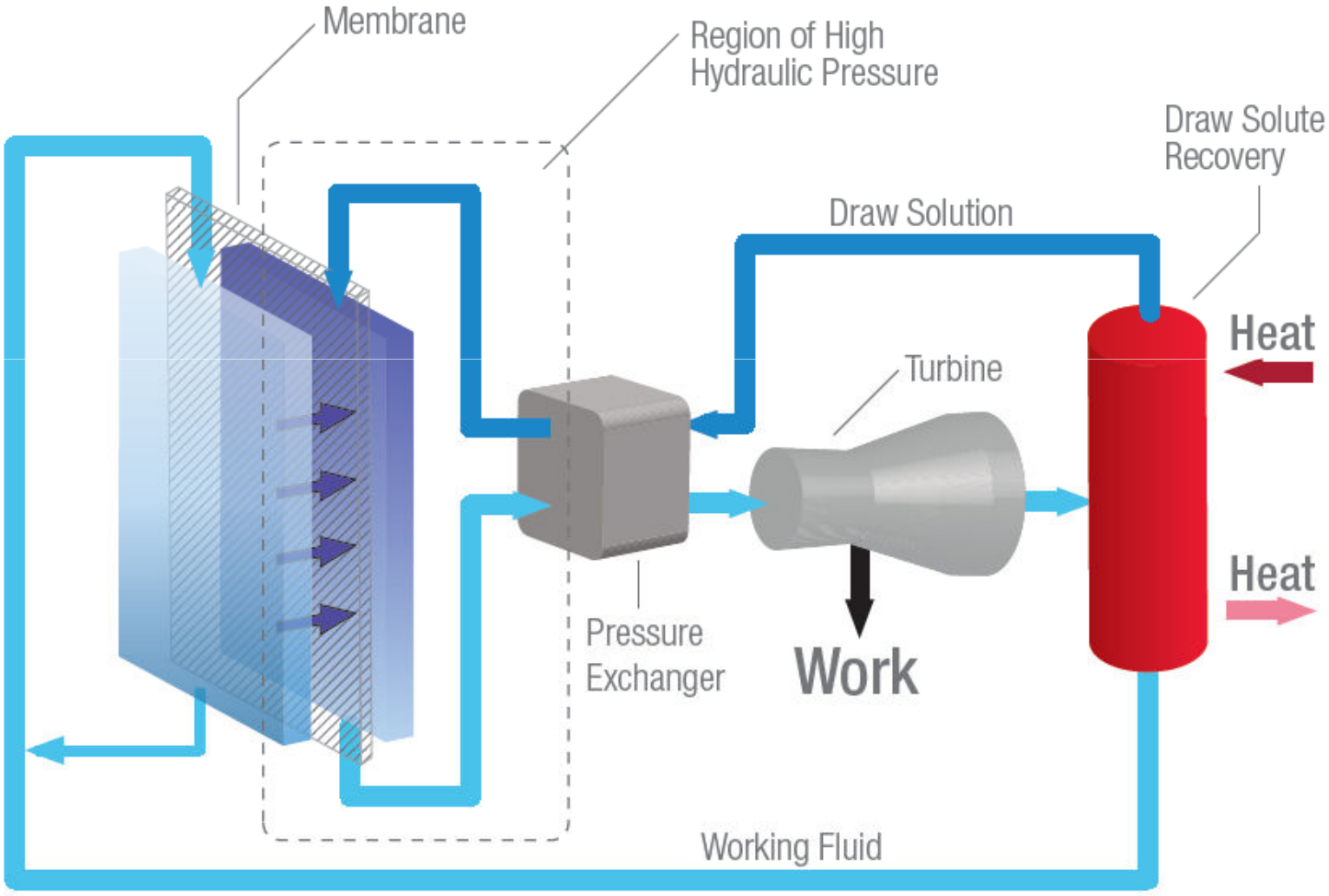
High Water Recovery with FO



Osmotic Heat Engine



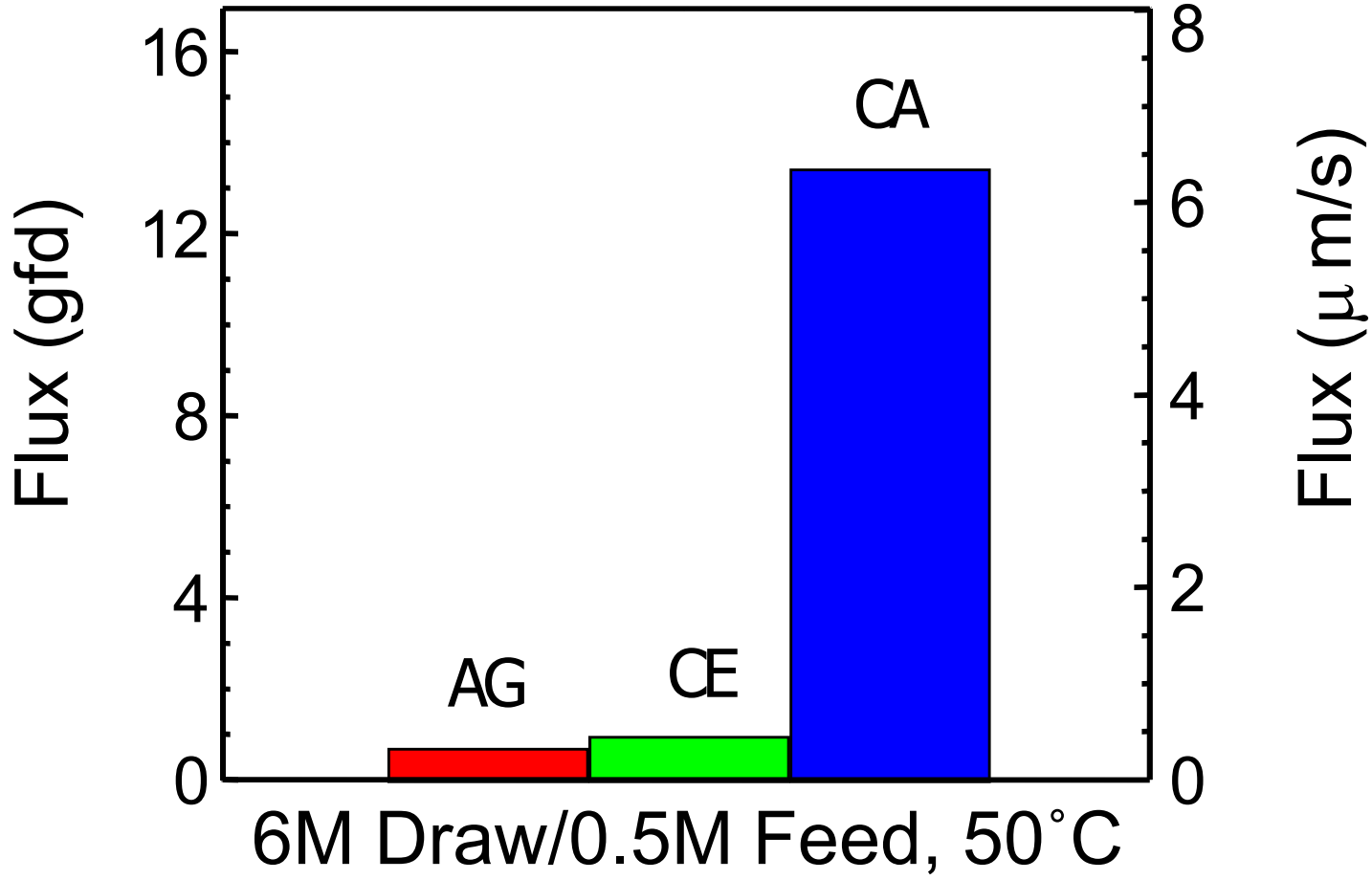
NH_3/CO_2 Osmotic Heat Engine: Closed Loop PRO



JMS, **305** (2007) 13-19; *ES&T,* **42** (2008) 8625-8629.

Water Flux in Forward Osmosis

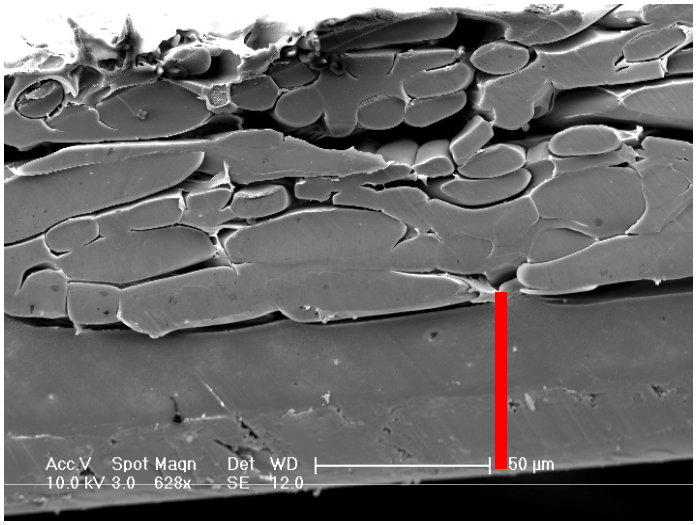
Effect of Membrane Design on FO Water Flux



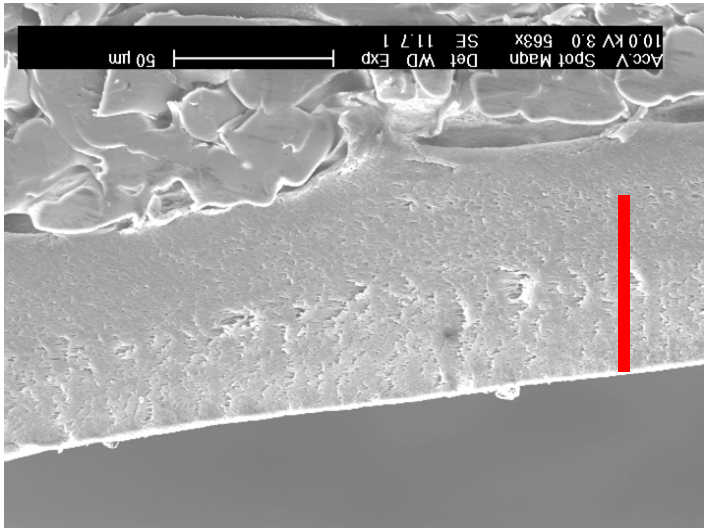
Desalination, **174** (2005) 1-11.

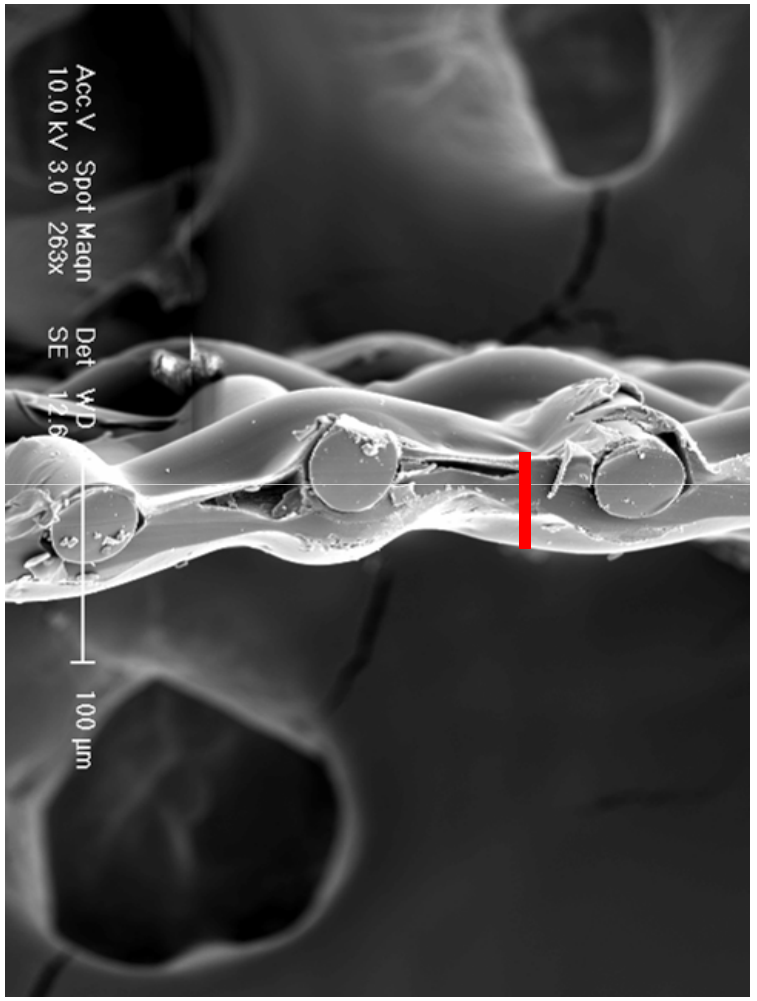
SEM Cross Sections

CE
(RO)



AG
(RO)

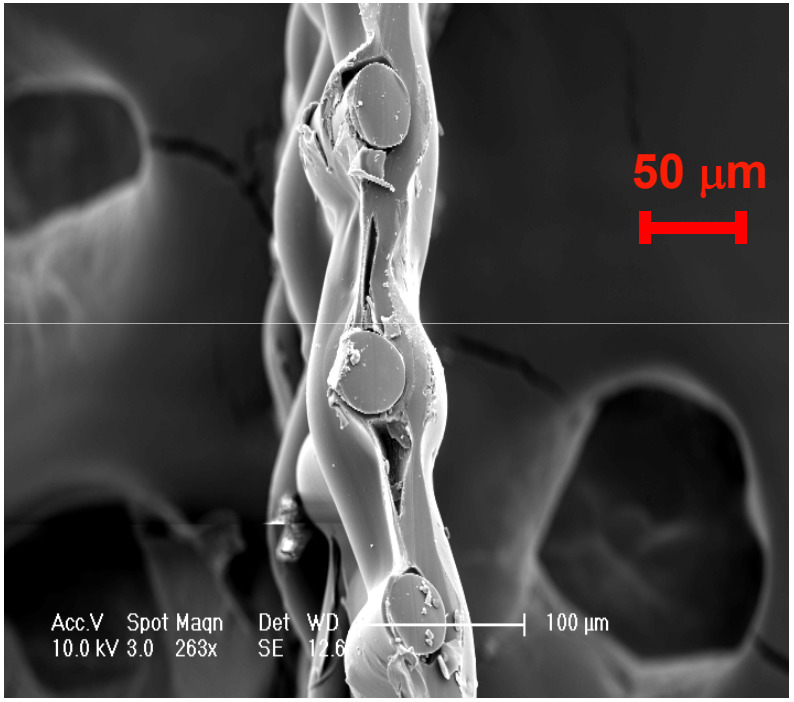


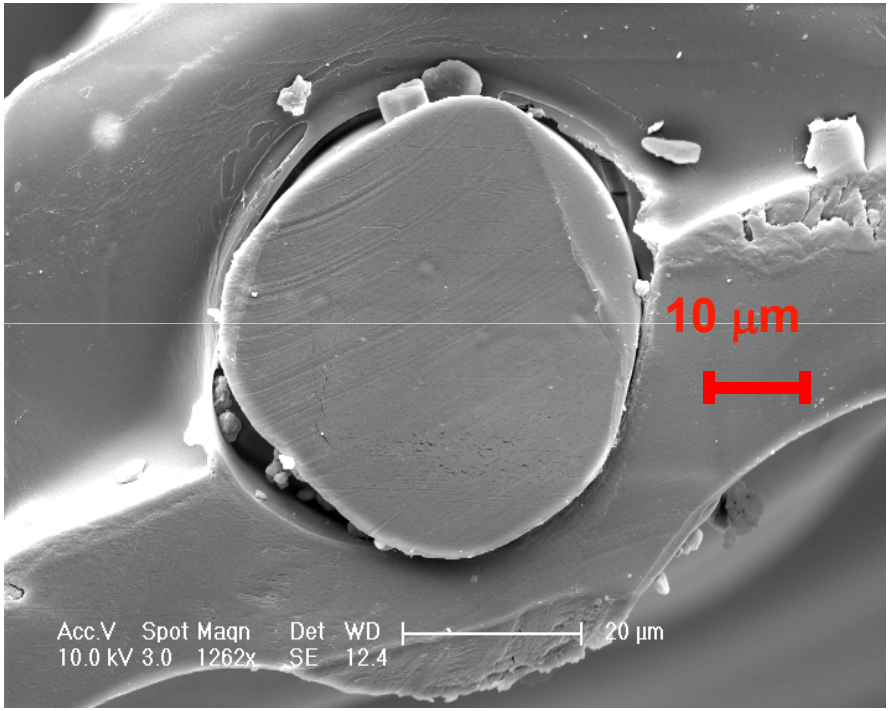


CA (FO)

Red lines indicate 50 µm

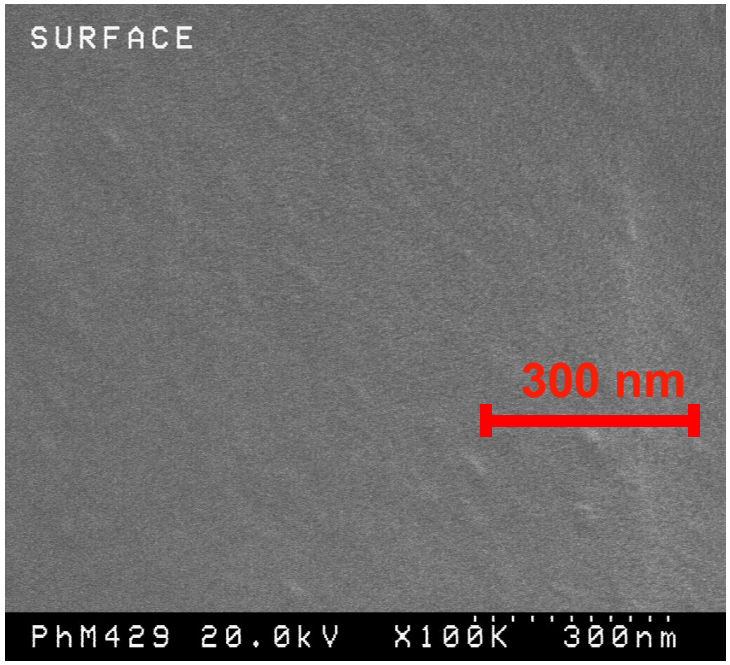
Forward Osmosis Membrane



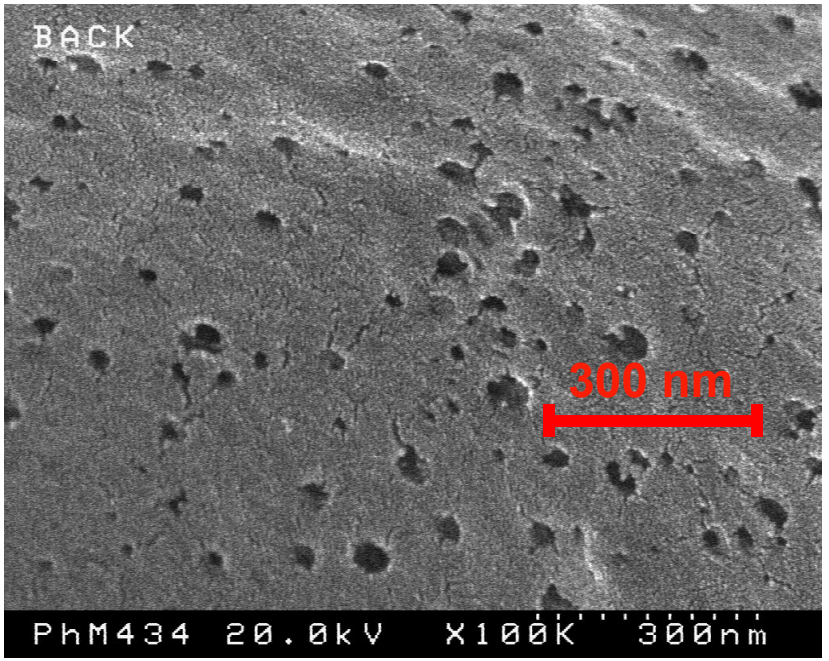


Forward Osmosis Membrane

Active Layer

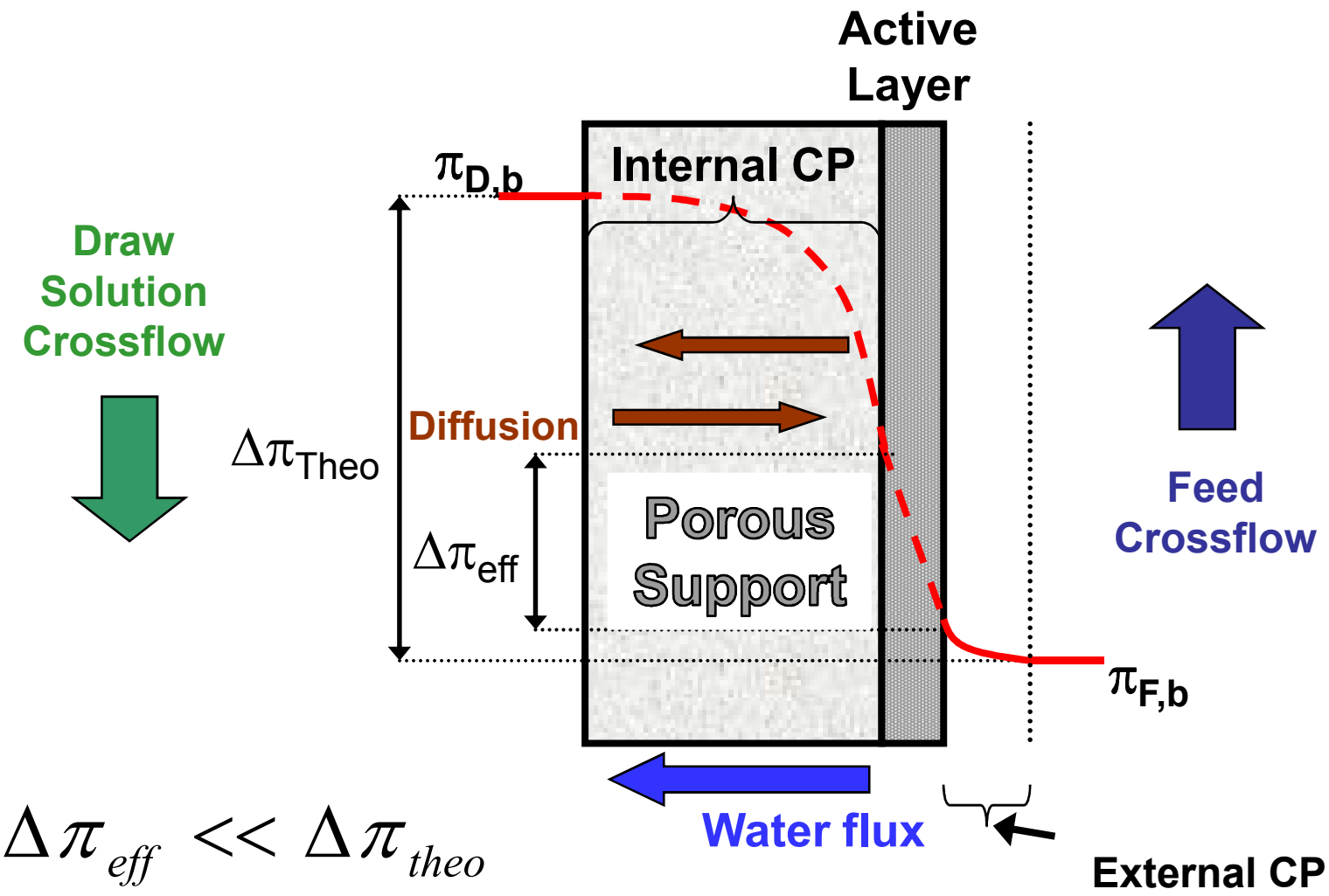


Backing Layer



– Asymmetry observed at high magnification

Major Challenge: Internal Concentration Polarization



$$\Delta\pi_{eff} << \Delta\pi_{theo}$$

Modeling Internal CP

Draw Side

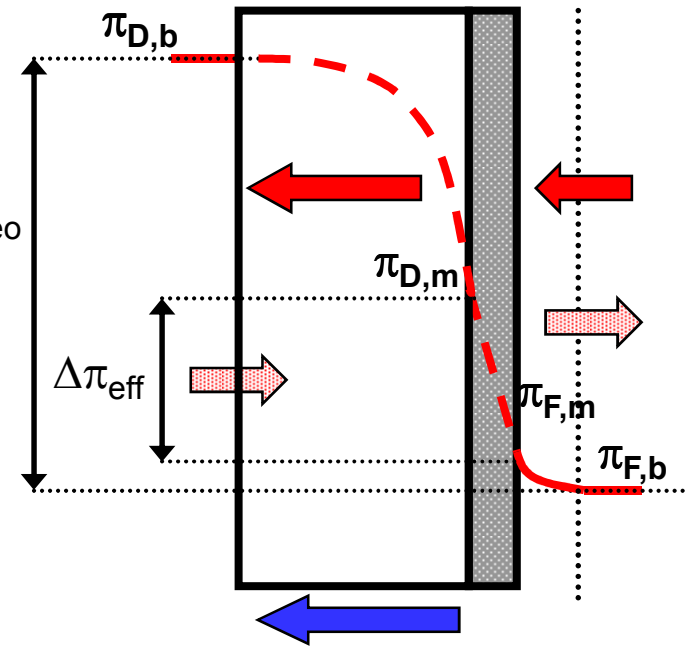
$$\frac{\pi_{D,m}}{\pi_{D,b}} = \exp(-J_W K)$$

Feed Side

$$\frac{\pi_{F,m}}{\pi_{F,b}} = \exp(J_W / k_F)$$

$$J_W = A(\pi_{D,m} - \pi_{F,m})$$

$$J_W = A\left[\pi_{D,b}\exp(-J_W K) - \pi_{F,b}\exp\left(J_W / k_F\right)\right]$$



Characterizing the Support Layer

$$K = \frac{t\tau}{D\varepsilon}$$

K solute resistance to diffusion

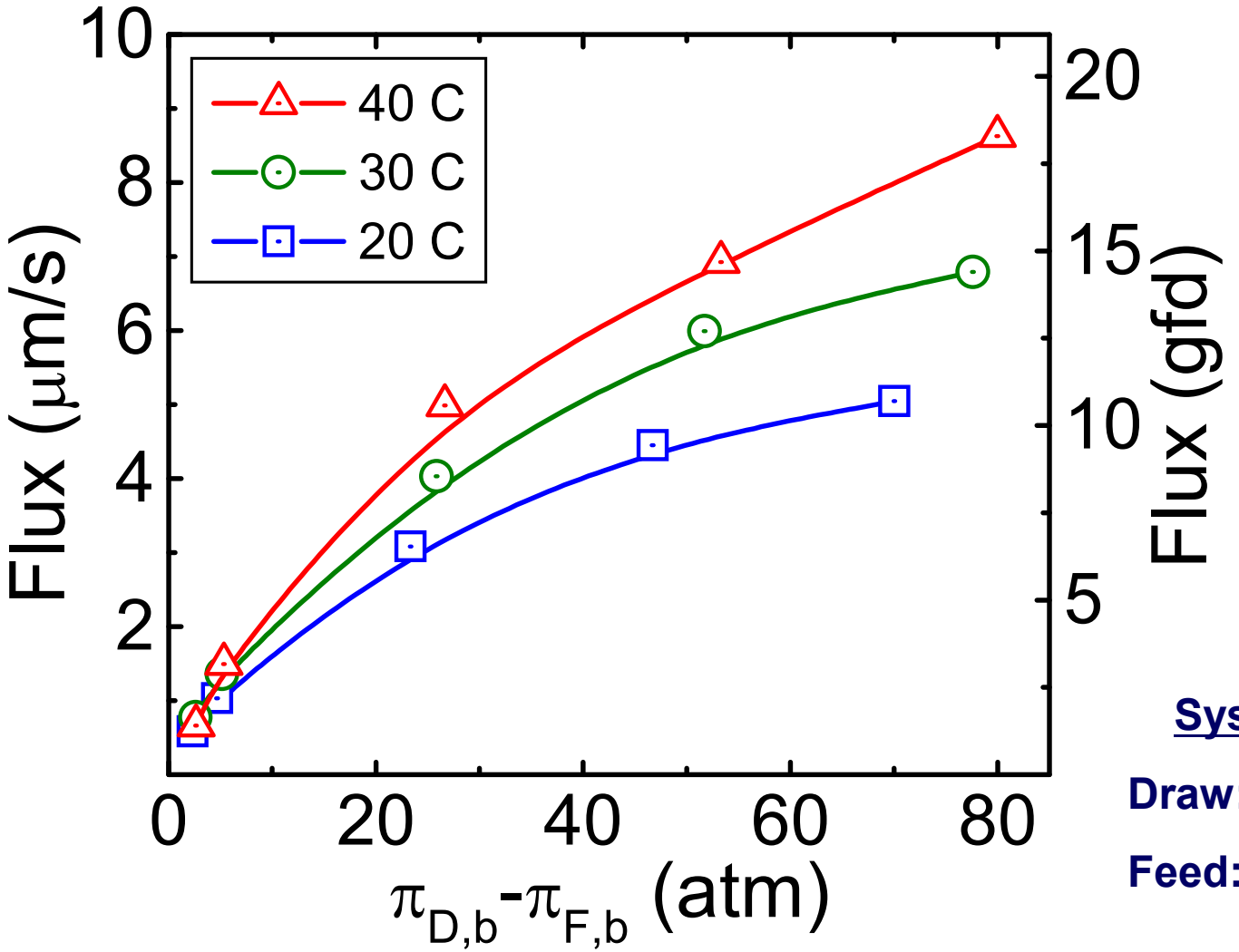
t support layer thickness

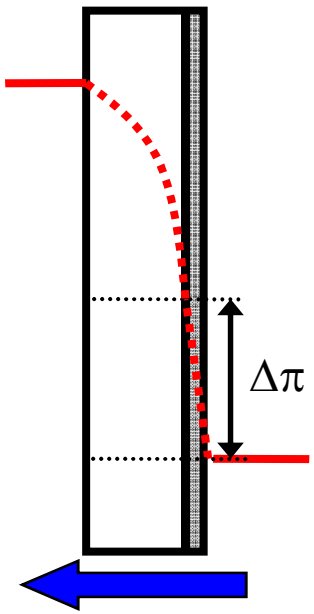
τ tortuosity

ε porosity

D draw solute diffusivity

Quantifying Internal CP



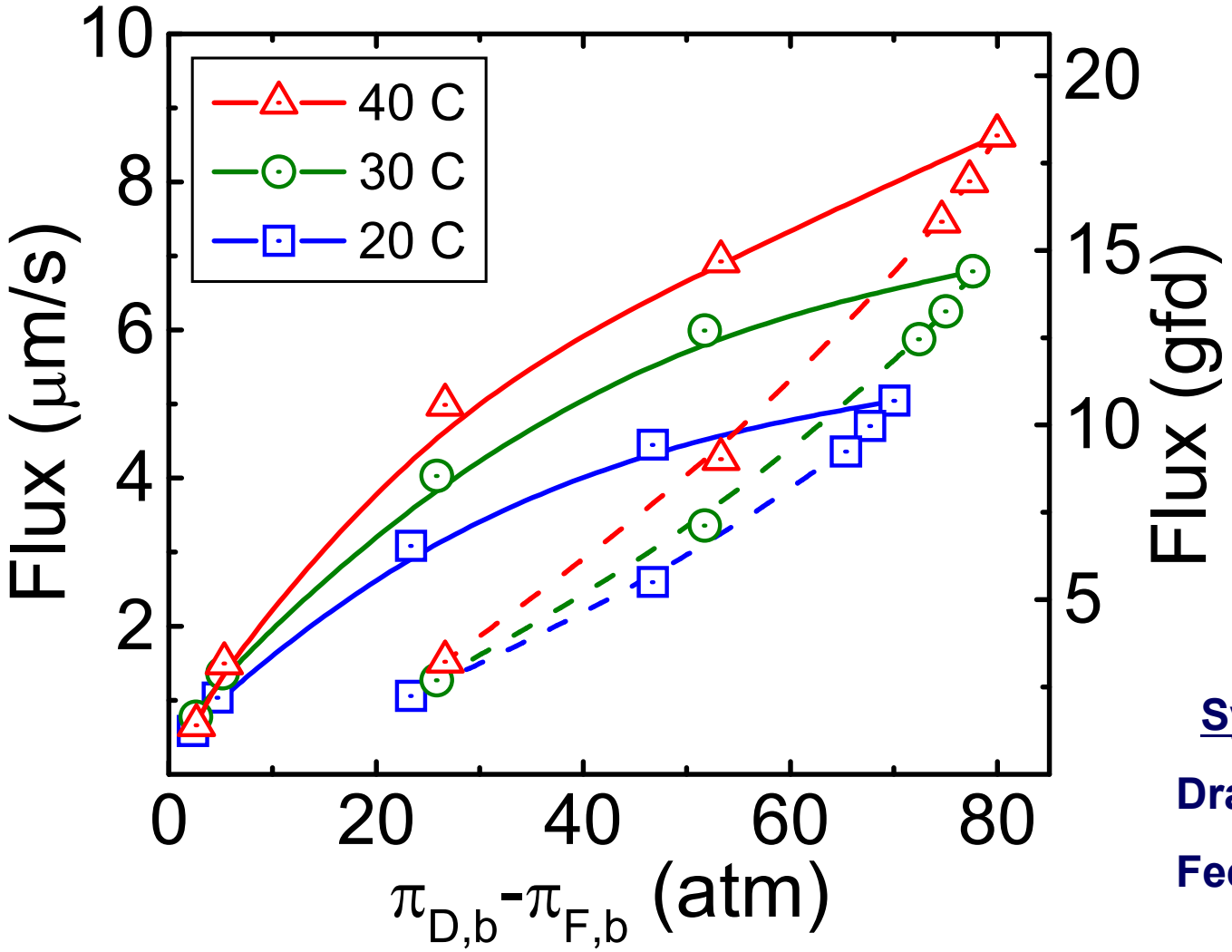


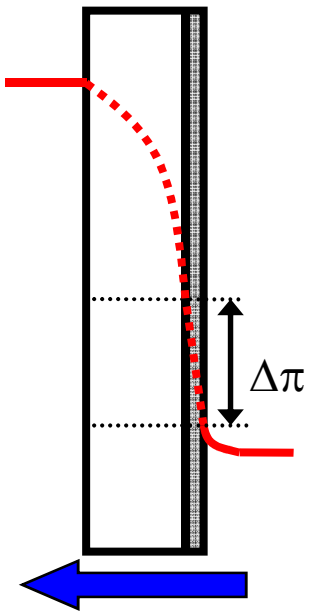
System Conditions

Draw: 0 to 1.5 M NaCl

Feed: Deionized water

Quantifying Internal CP





System Conditions

Draw: 1.5 M NaCl

Feed: 0 → 1 M NaCl

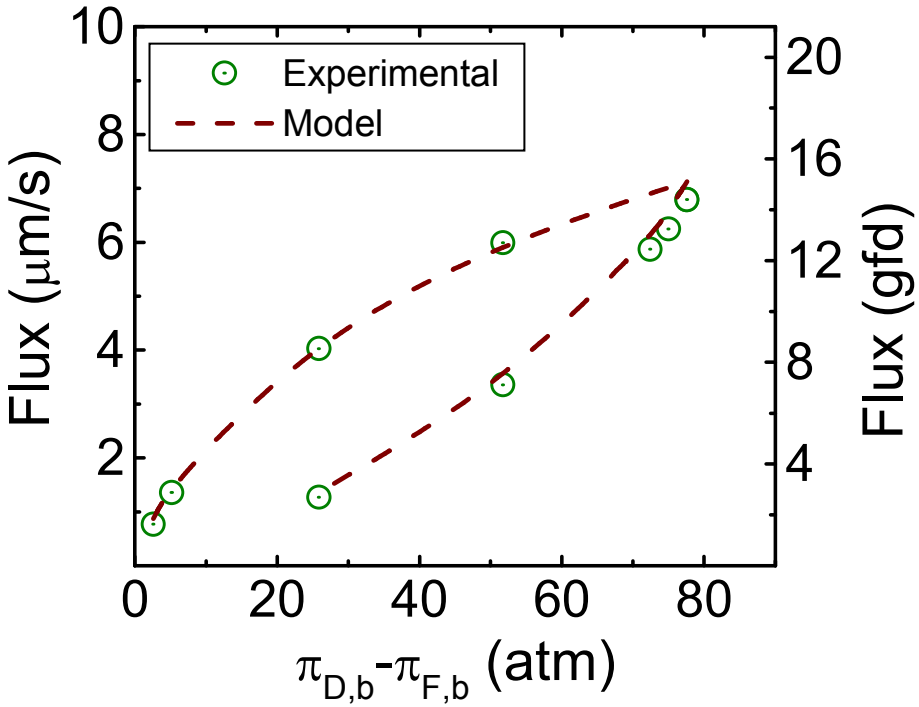
Modeling Internal CP

$$J_W = A\left[\pi_{D,b}\exp\left(-J_W K\right) - \pi_{F,b}\exp\left(J_W / k_F\right)\right]$$

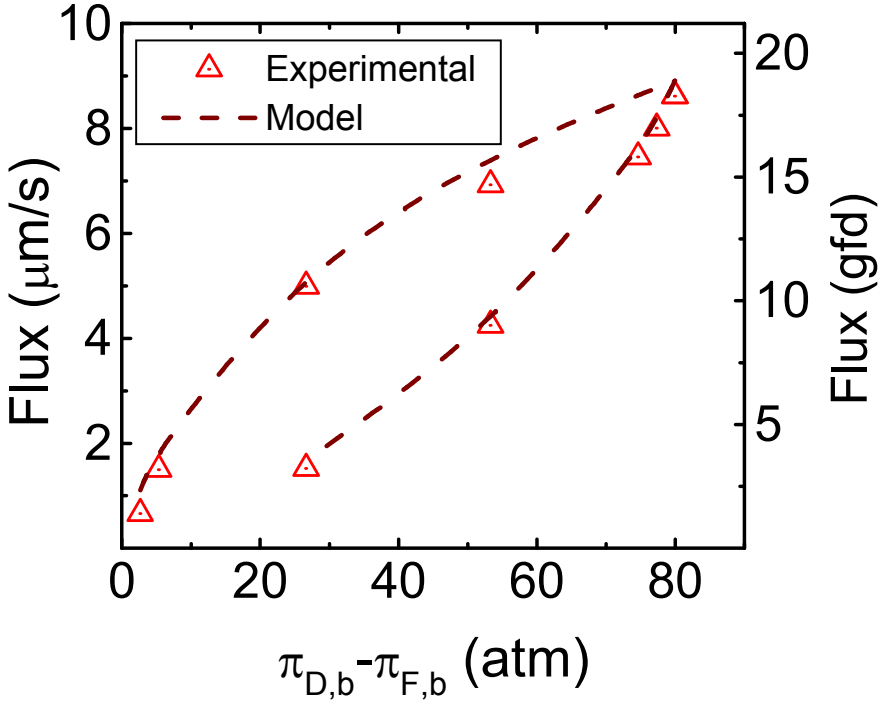
$$K = \frac{t\tau}{D\varepsilon}$$

Modeling Internal CP

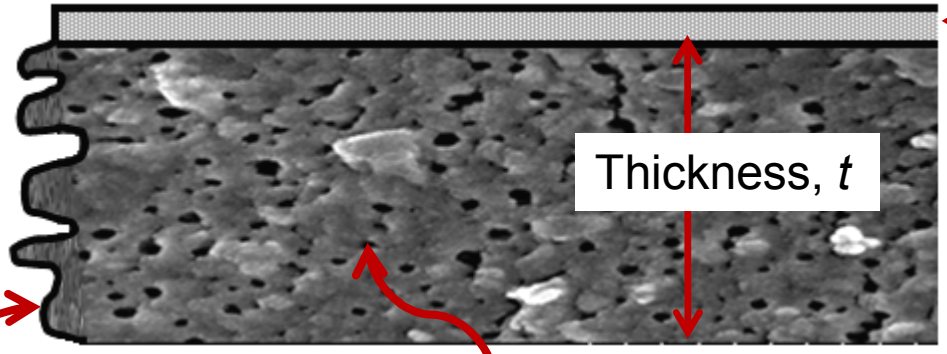
30 °C



40 °C



Characterizing the Support Layer



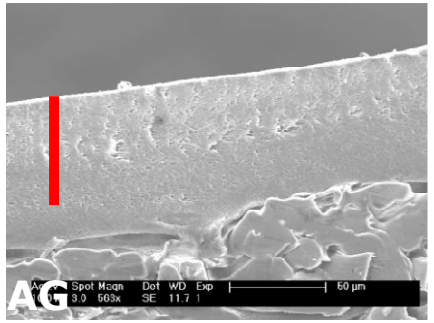
thin film (active layer)

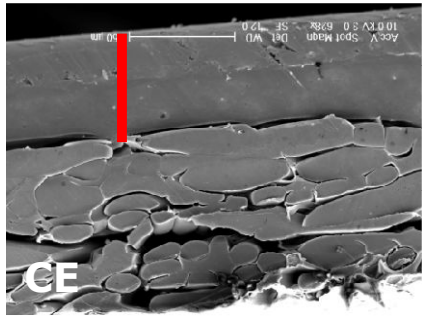
Support layer

Tortuosity, τ

Porosity, ε

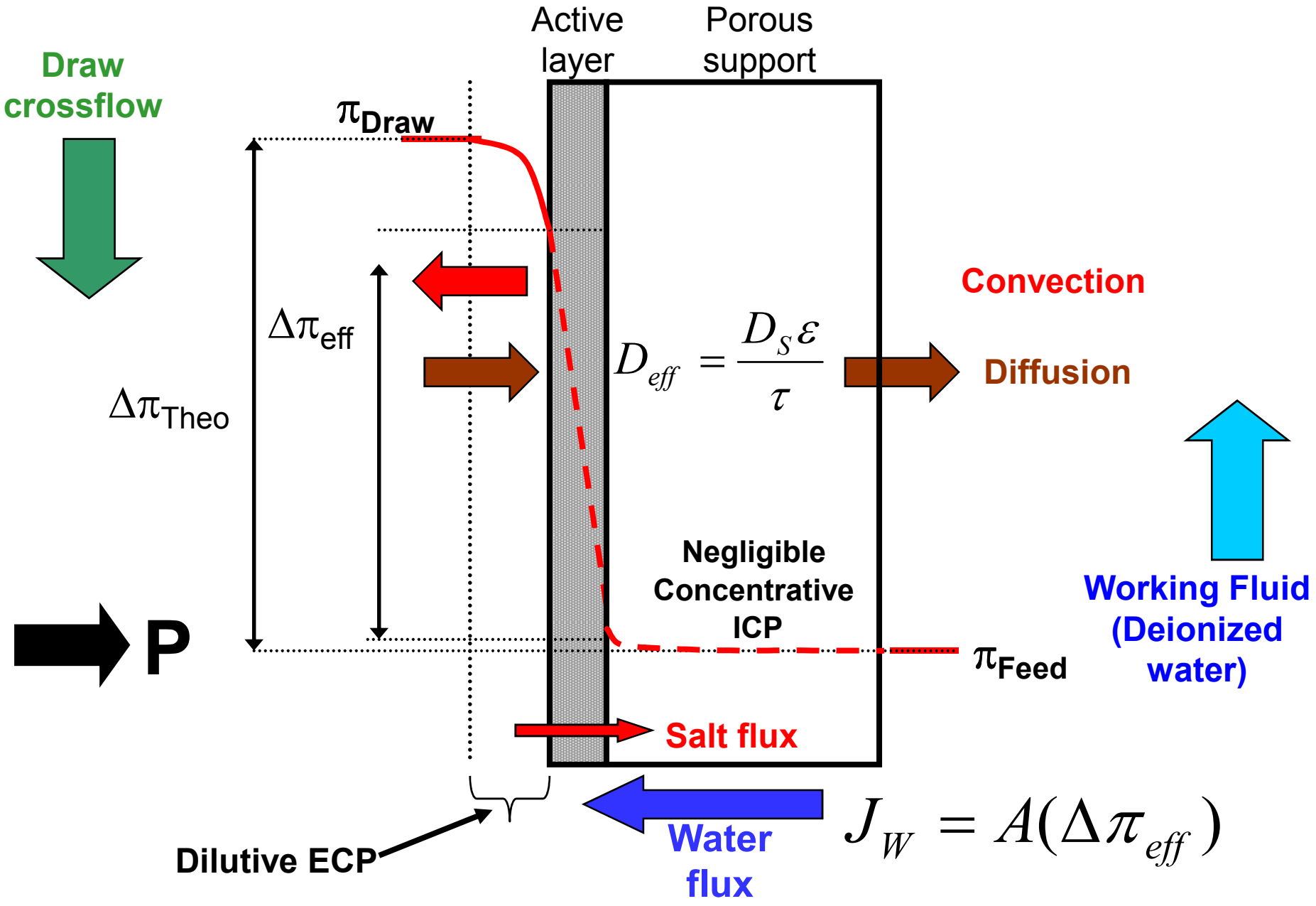
$$K = \frac{t\tau}{D\varepsilon}$$



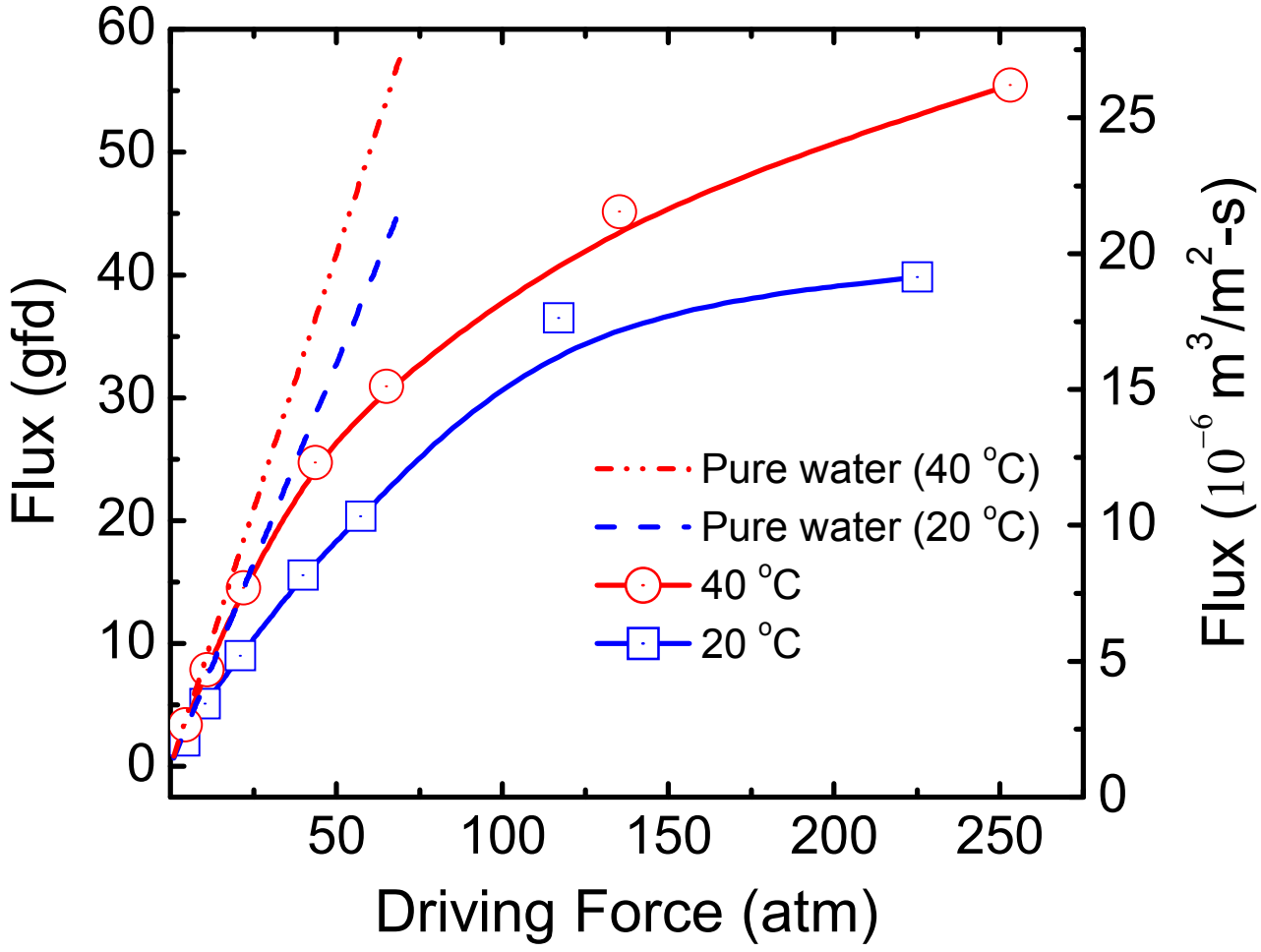


Red lines indicate 50 µm

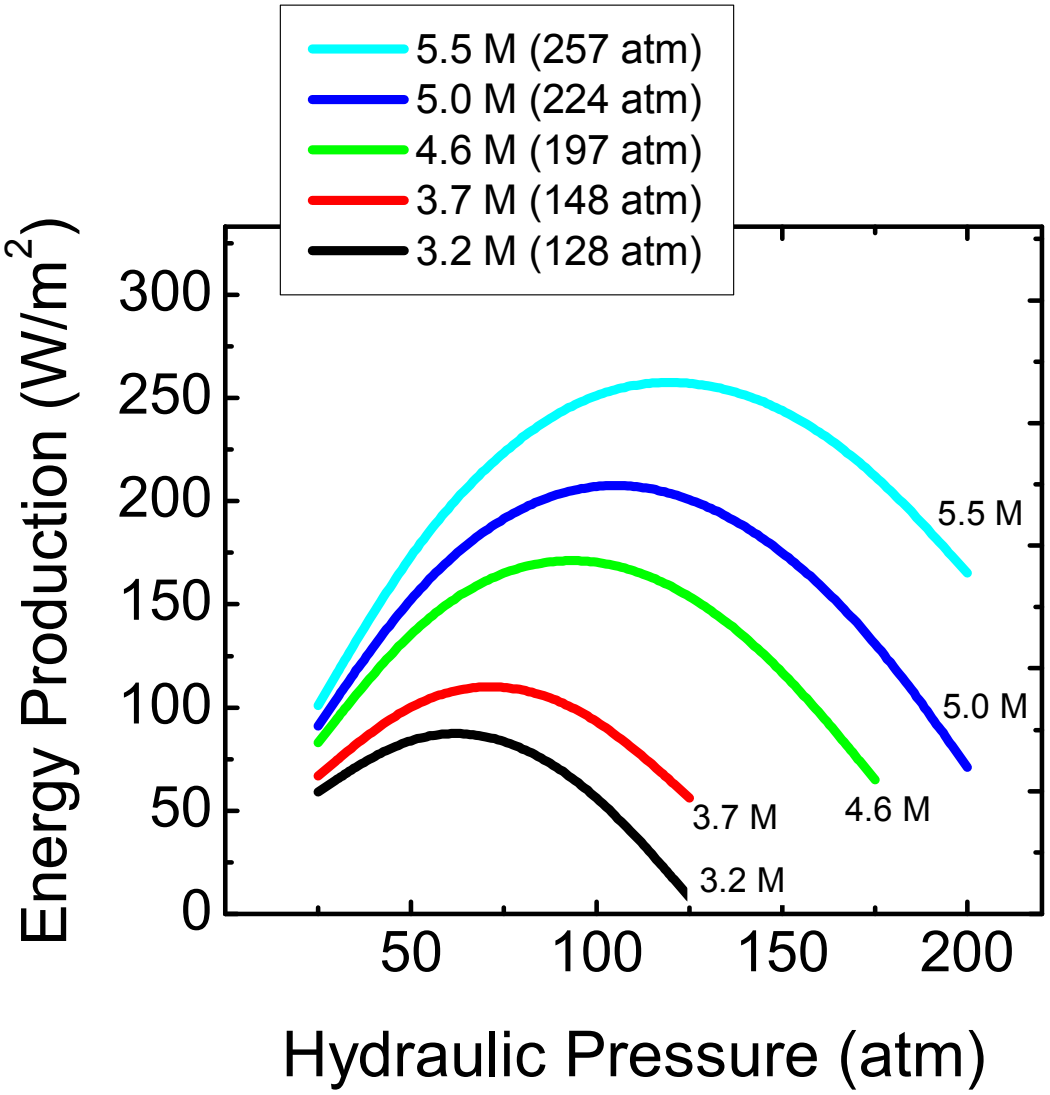
Driving Force in the NH_3/CO_2 OHE



Very High Water Fluxes



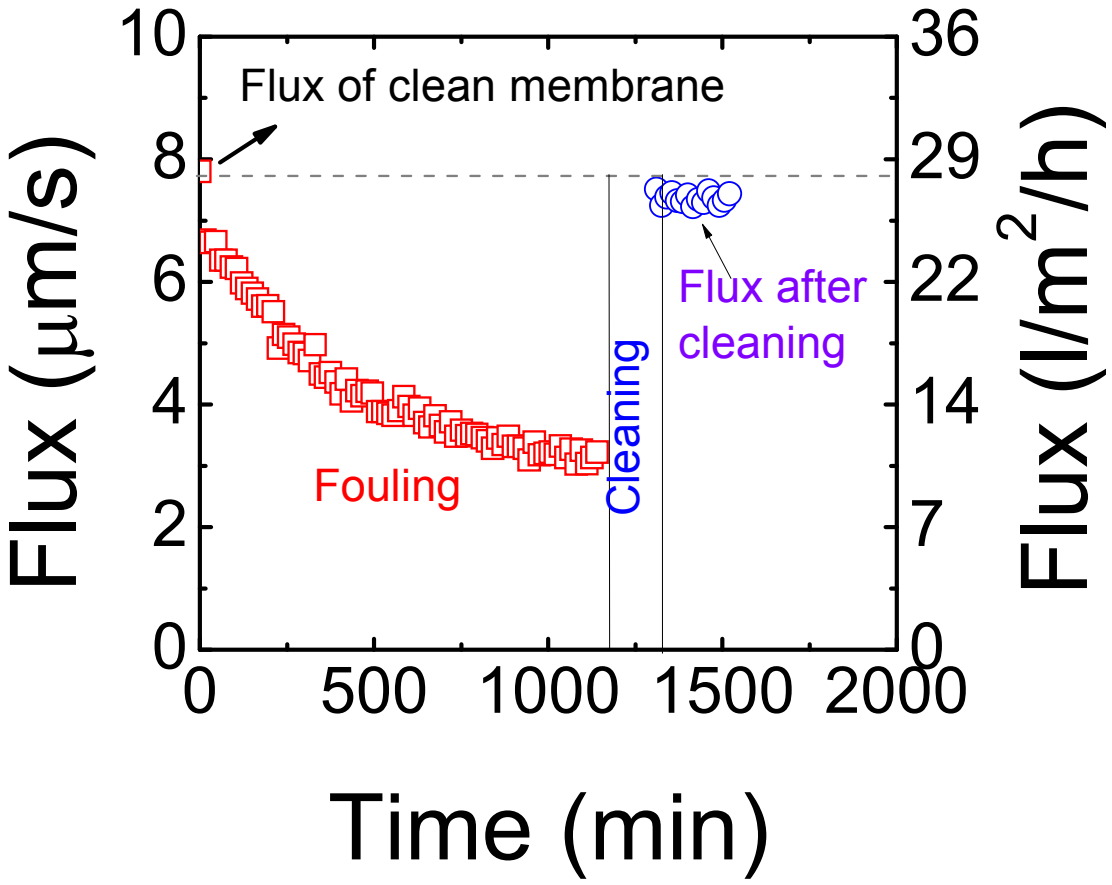
Very High Membrane Power Density



$$W = E\dot{V}\Delta P$$

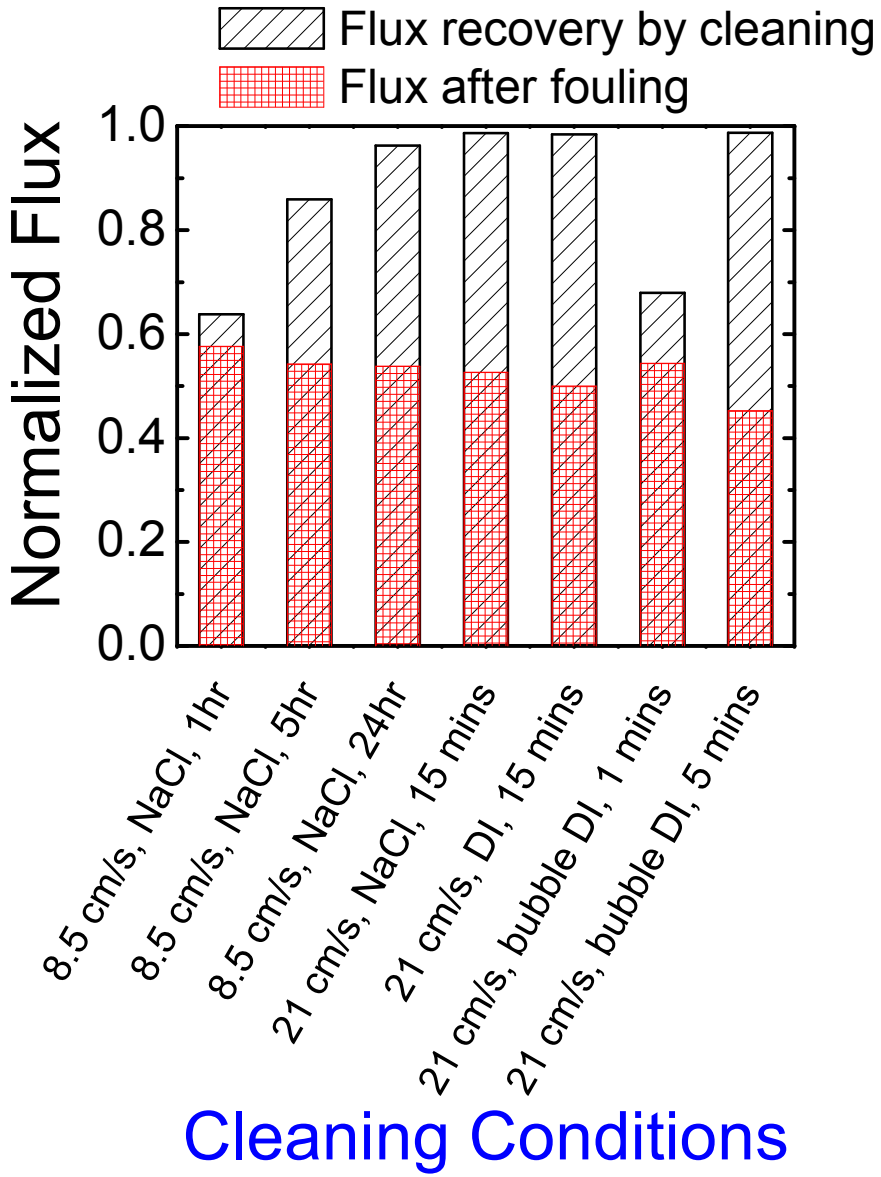
Fouling and Fouling Reversibility

Organic Fouling Reversibility in Forward Osmosis

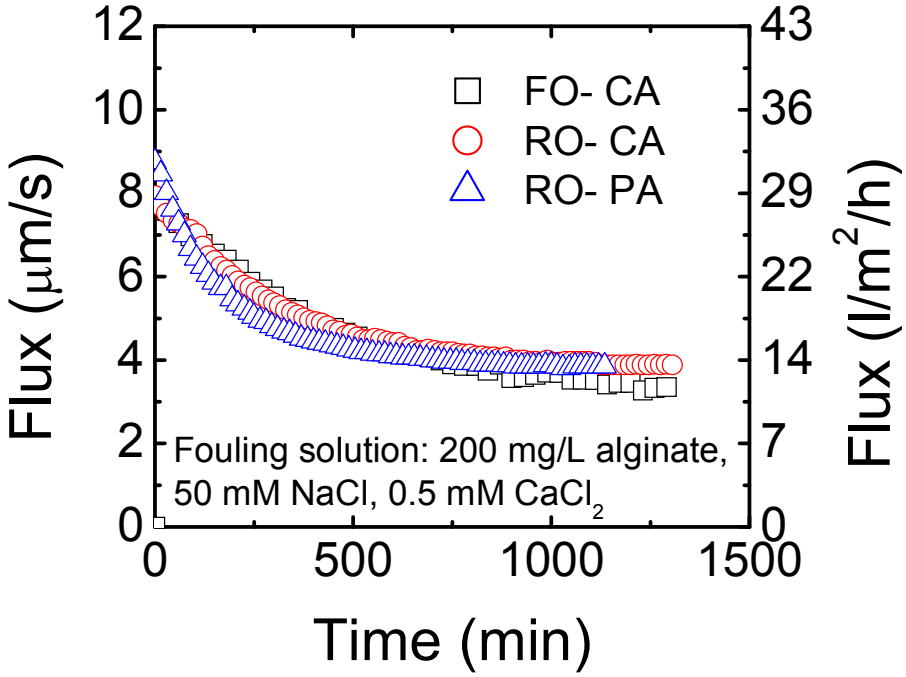


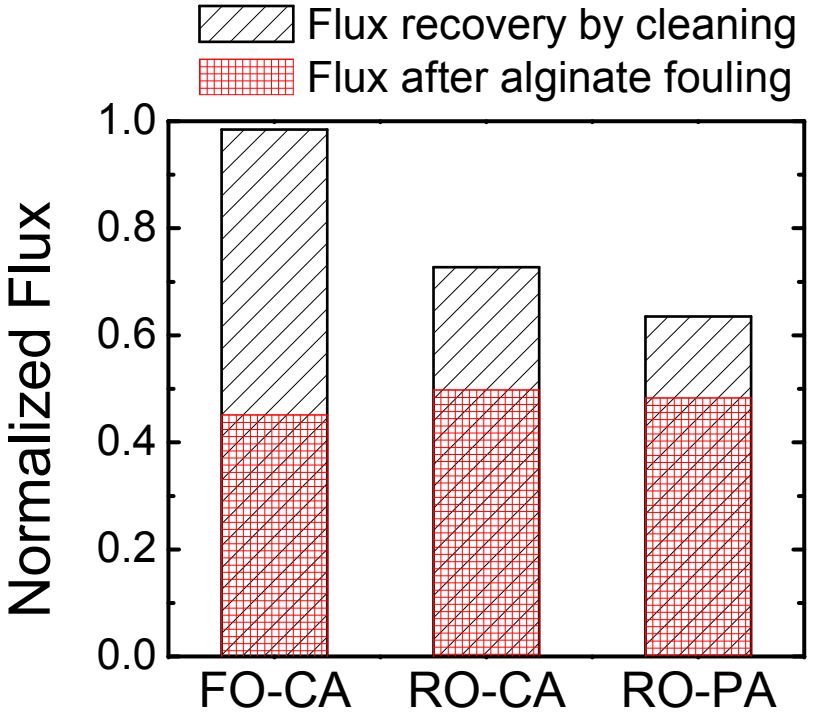
- FO membrane: CA (Hydration Tech)
- Organic foulant (200 mg/L alginate); 50 mM NaCl; 0.5 mM Ca^{2+}
- Cleaning: 50 mM NaCl, 15 min

Organic Fouling Reversibility



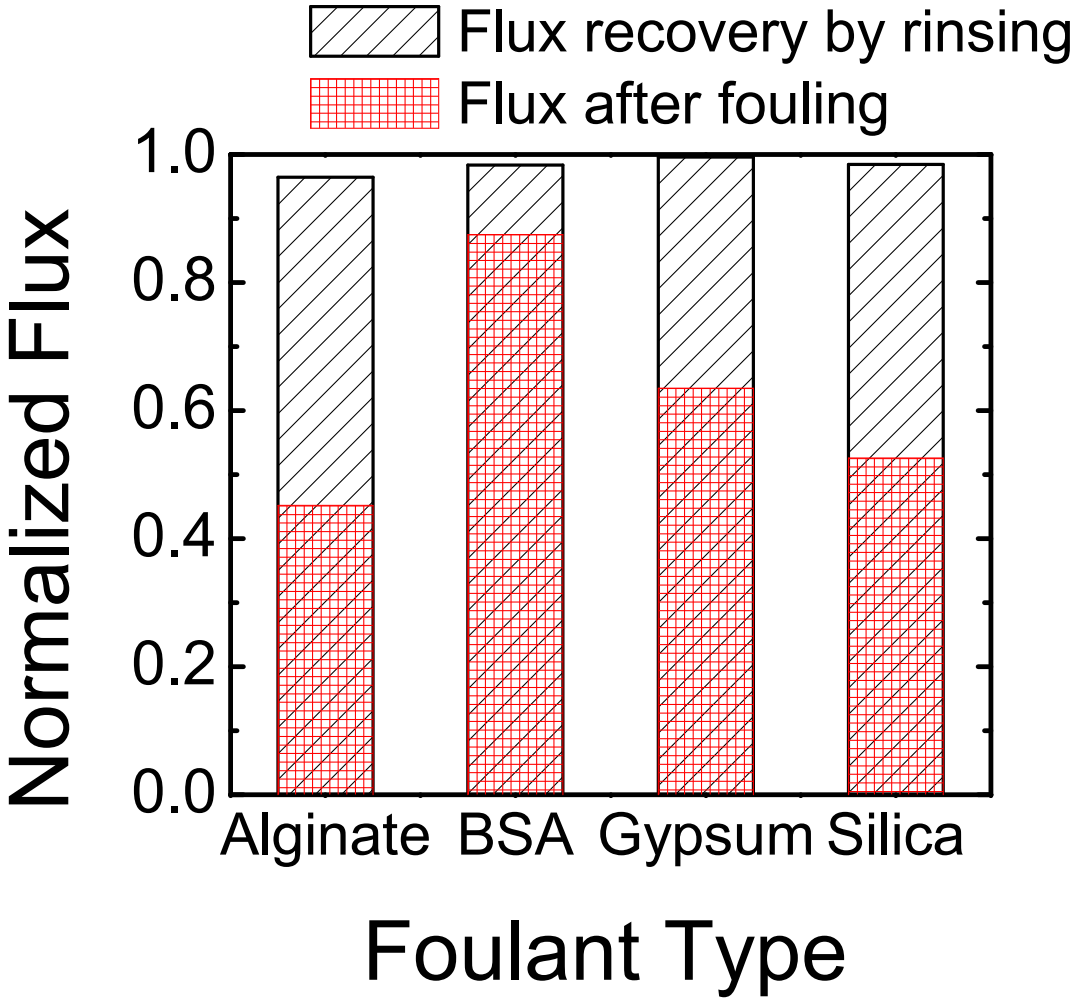
Organic Fouling Reversibility: FO versus RO





- FO – CA: CA membrane in FO mode
- RO – CA: CA membrane in RO mode (hydraulic pressure)
- RO – PA: Polyamide TFC membrane in RO mode

FO Exhibits Fouling Reversibility with a Wide Range of Foulants



Concluding Remarks

- Forward osmosis can be used as a standalone process or as part of an hybrid system (e.g. FO-RO)
- Forward osmosis is less prone to fouling; may use less prime (electric) energy
- Need to develop an appropriate membrane with low internal concentration polarization

Acknowledgments

- Graduate Students/Postdocs: Jeffrey McCutcheon, Robert McGinnis, Baoxia Mi, Sangyoup Lee
- World Class University (WCU) project (No. R33-2008-000-10046-0)
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