Center for Clean **Water** and Clean **Energy** at MIT & KFUPM

J-WAFS

ENERGY REQUIREMENTS OF DESALINATION: HOW DO THERMAL SYSTEMS LOOK?

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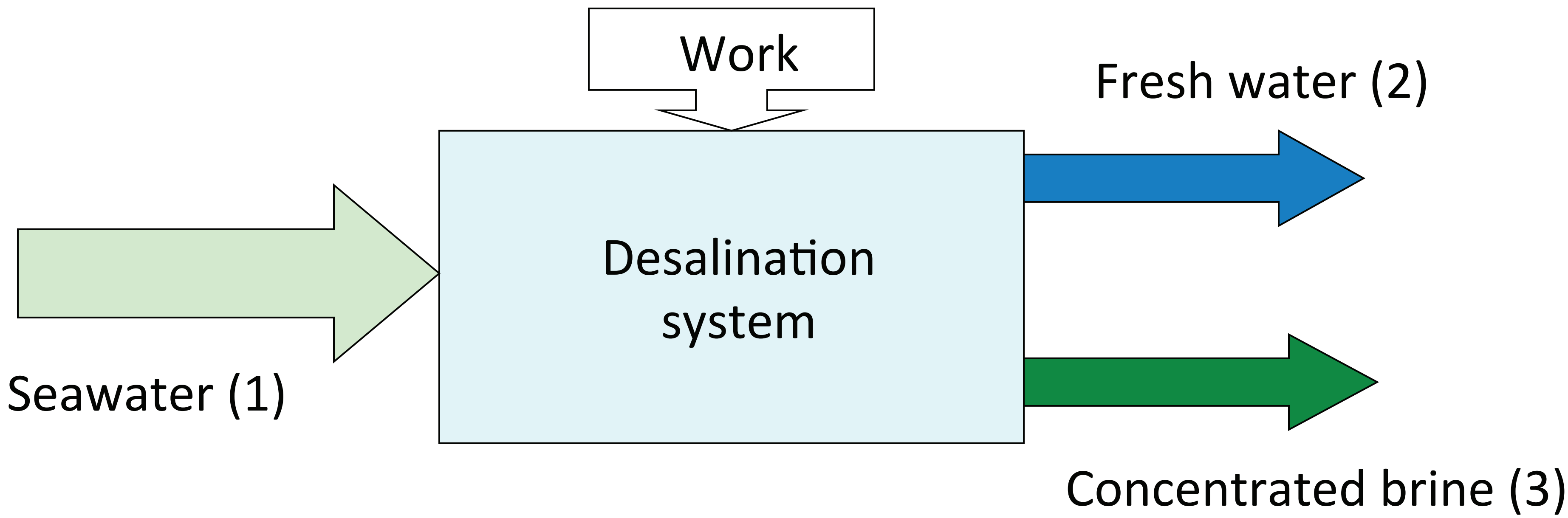
Director, Center for Clean Water and Clean Energy

Massachusetts Institute of Technology

DOE Energy Efficient Desalination Workshop
5 November 2015, San Francisco, CA

Desalination: separate dissolved ions to make potable water

$$\dot{W}_{least} = [(\dot{N}\underline{G})_2 + (\dot{N}\underline{G})_3] - (\dot{N}\underline{G})_1$$



Thermodynamic limit: ≈ 1 kWh_e/m^3 fresh water (3.6 kJ/kg) at 50% recovery from seawater

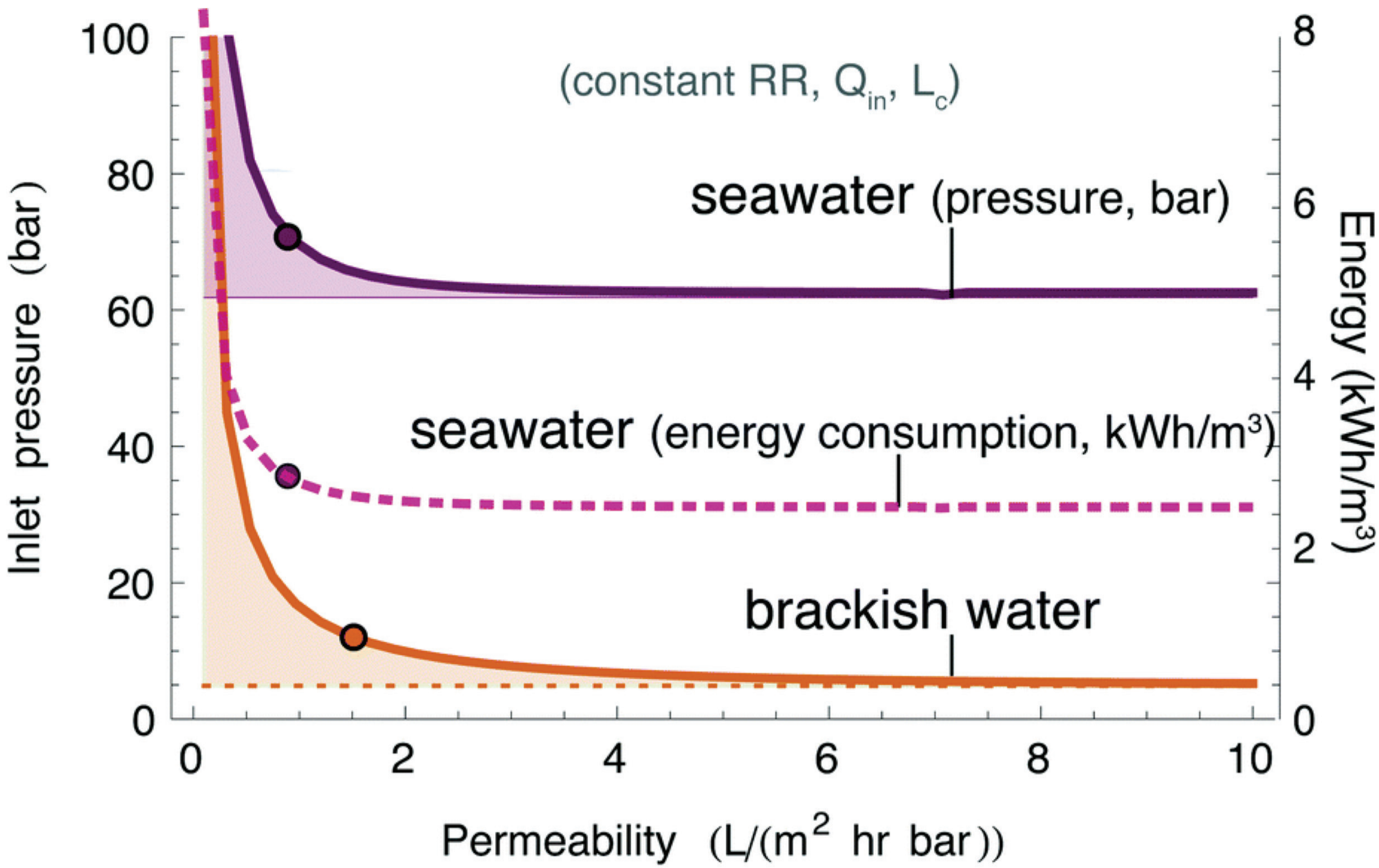
Current systems: ≈ 2 to 4 kWh_e/m^3 (7 to 14 kJ/kg)

Energy cost: 30-40% for seawater RO

Confusing high flux with reduced energy (examples)

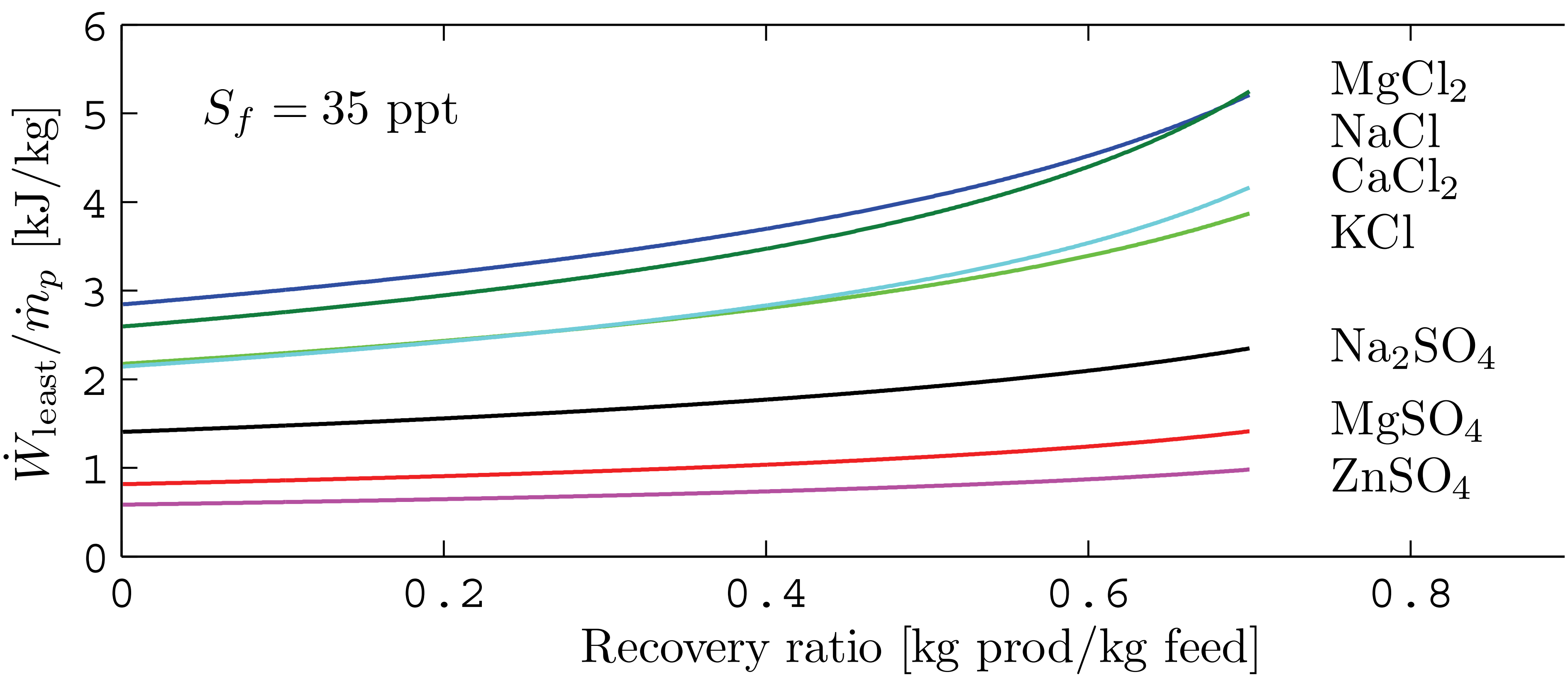
exhibits intriguing nonlinear dependence on the pore size owing to the quantized nature of water flow at the nanoscale. Such novel transport behavior has important implications to the design of highly effective and efficient desalination membranes.

Feed pressure vs. Permeability



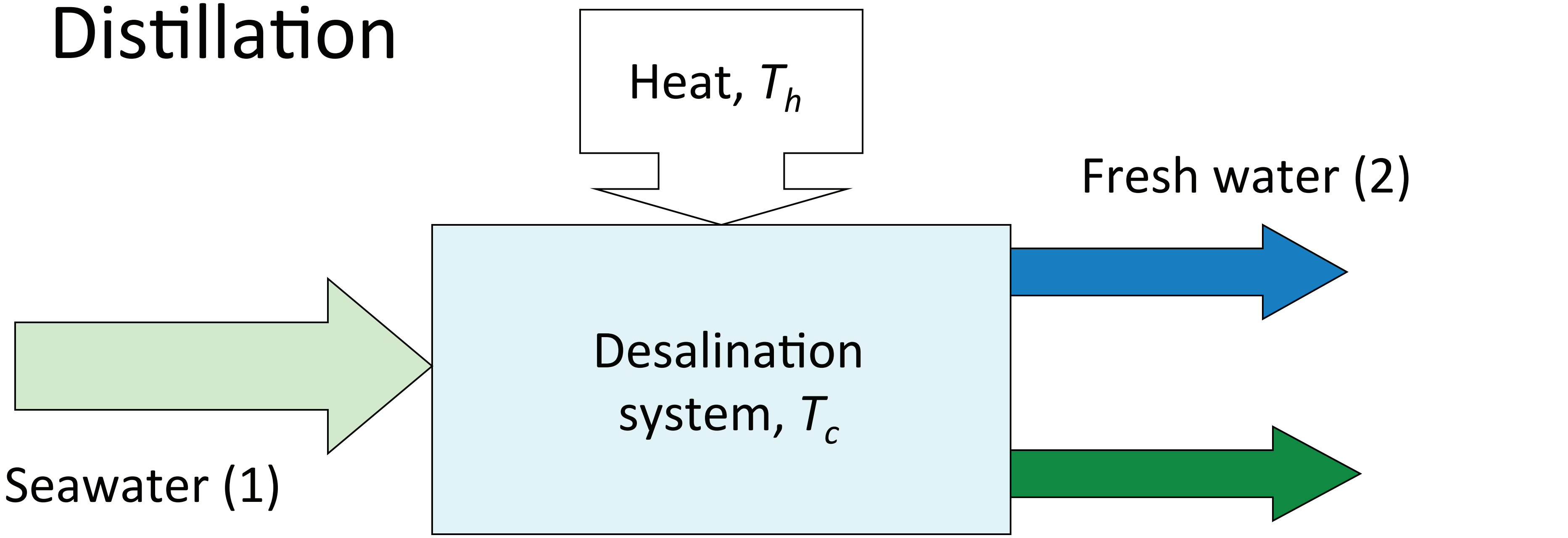
Cohen-Tanugi et al., *Energy Environ. Sci.*, **7**:1134-1141, 2014

Composition affects separation energy



Mistry, Hunter, Lienhard, "Effect of composition and nonideal solution behavior on desalination calculations for mixed electrolyte solutions with comparison to seawater," *Desalination*, **318**:34-47, 2013

Distillation



$$\dot{Q}_{least} = \frac{\dot{W}_{least}}{(1 - T_c / T_h)}$$

Thermodynamic limit: 12 -18 kJ_t/kg fresh water

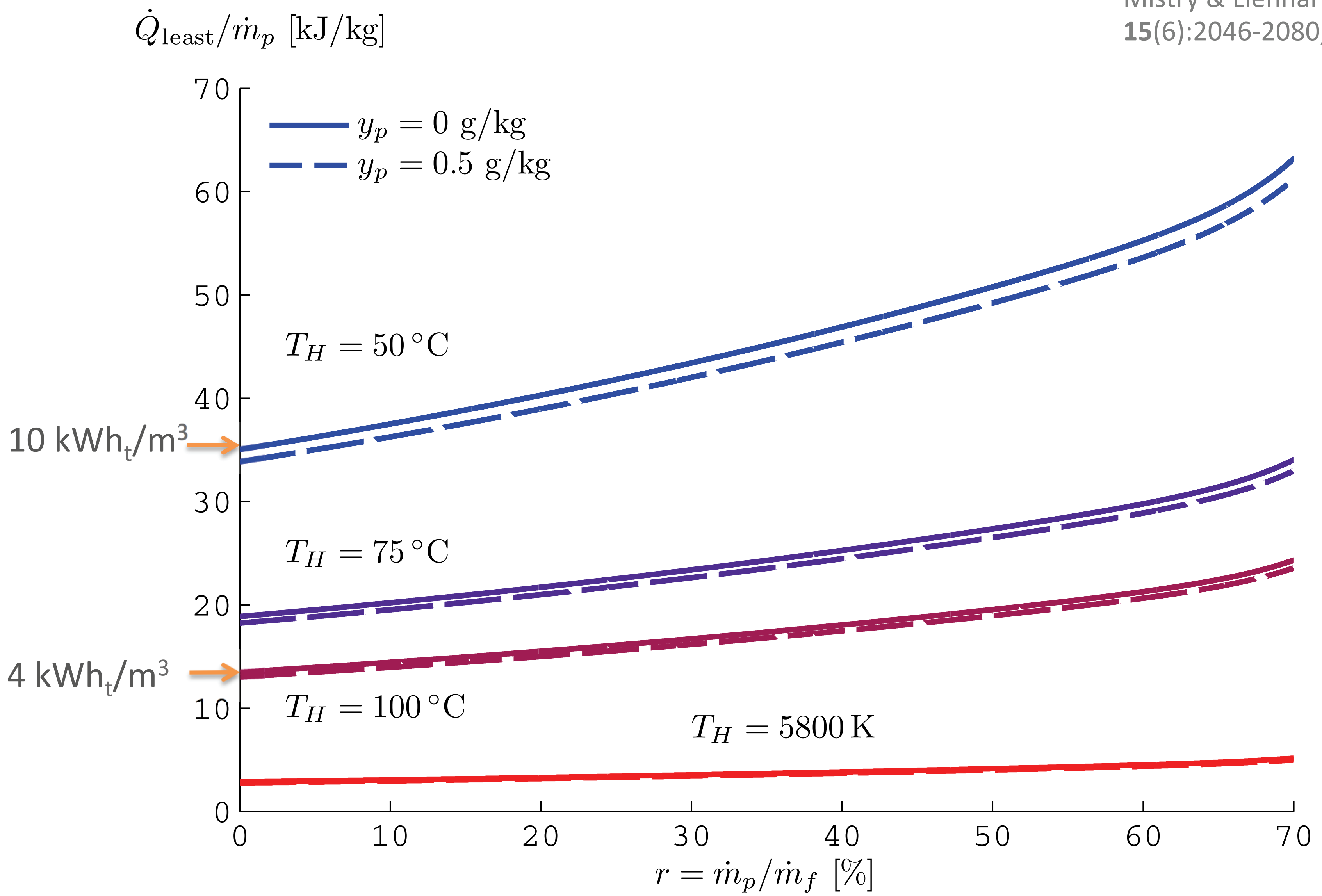
NB: thermal, not electrical, energy!

Typical thermal systems: ≈260 kJ_t/kg from low temp. steam; electrical equivalent is 9-14 kWh_e/m^3

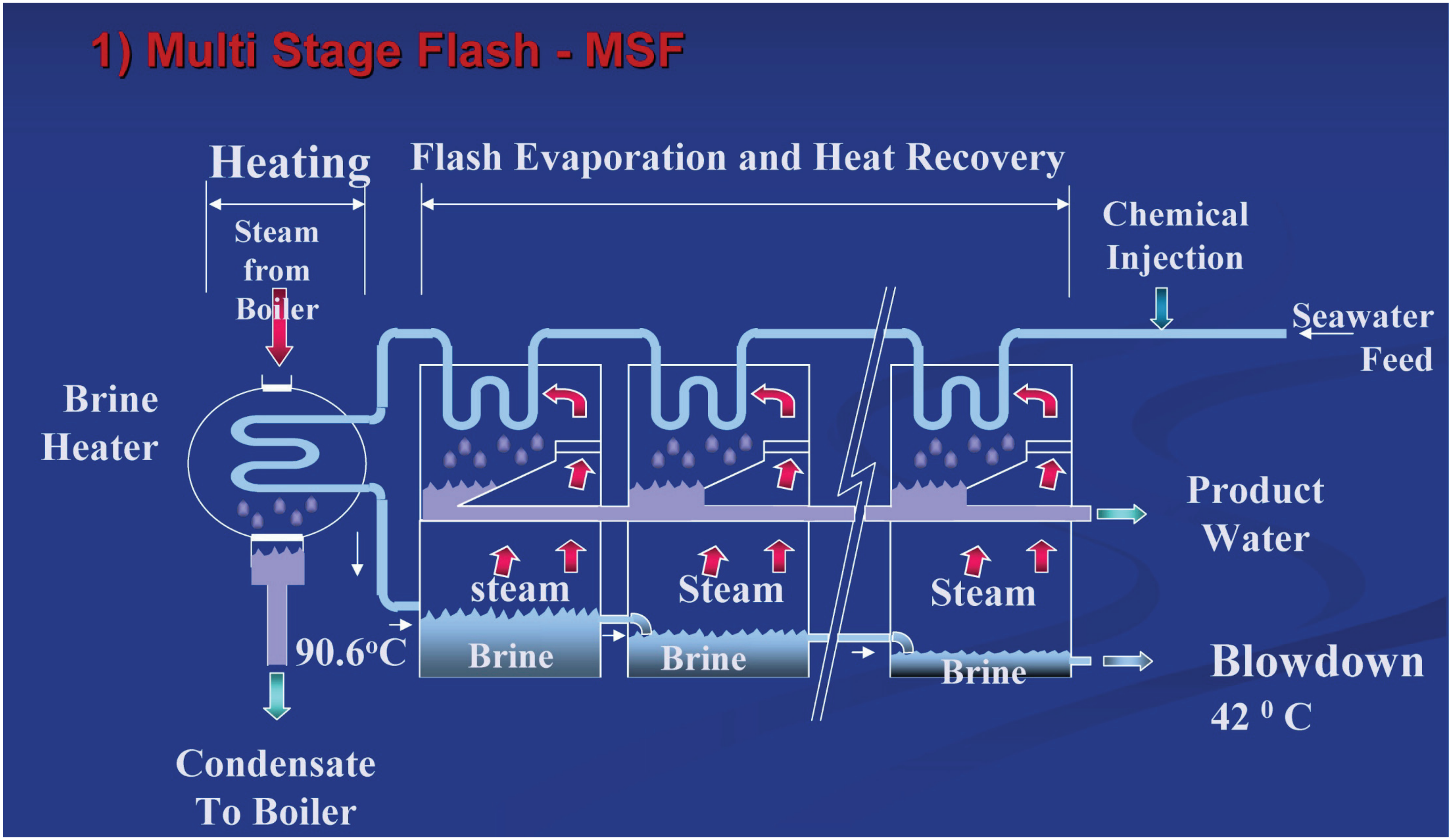
Effect of source temperature on Q_{least}

(T_0 = 25°C, 35 ppt feed)

Mistry & Lienhard, *Entropy*, **15**(6):2046-2080, May 2013.



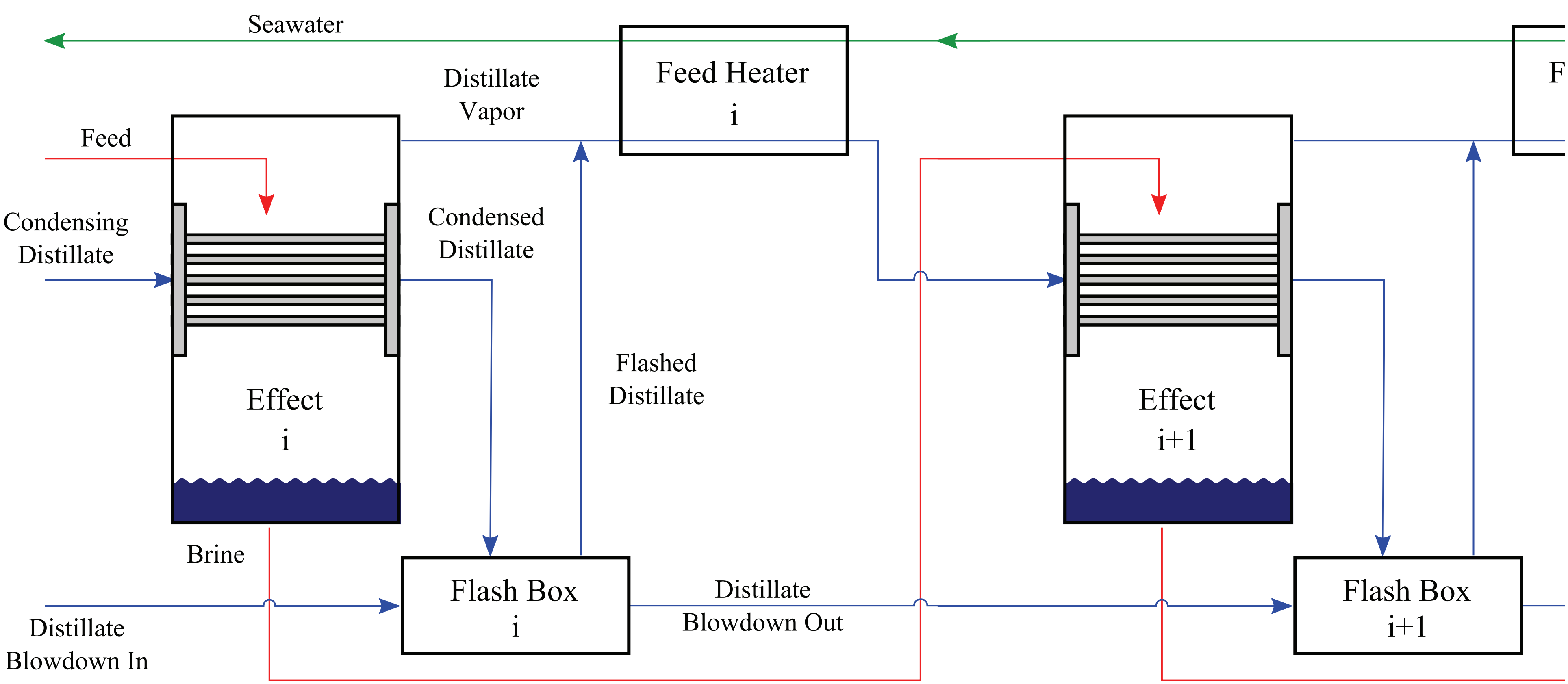
Thermal Desalination (Distillation) Technologies



Top brine temperature limited to ~110 °C to avoid scale formation

Ref: M. Al-Ghamdi, 2006

Multieffect Distillation



K. Mistry, M.A. Antar, and J.H. Lienhard V, "An Improved Model for Multiple Effect Distillation," *Desalination and Water Treatment,* **51:**807–821, Jan. 2013

Rabigh Refinery Saudi Arabia

Case study

- Effect 1 tube bundle,
- June 2010 after 2 ½ years operation

Charles Desportes
Director Thermal Desalination - AQUATECH- ICD

© 2010 International Desalination Association

Corrugated Tubes installed in an MVC plant

Oval corrugated tubes are more economically incorporated in a MED and have demonstrated a 70% increase of H.T coefficients in an operating plant compared to flat surface round tubes.

Fredi Lokiec
IDE Technologies Ltd.

© 2010 International Desalination Association

Increased GOR

Gained-output-ratio

$$GOR = \frac{\dot{m}_{pw} h_{fg}}{Q_{in}}$$

- Design impact of higher GOR

GOR	8.5	10	11.5	13
Number of effects	5	7	8	8
Total area effects	49,200 m²	72,000 m²	83,500 m²	98,400 m²
Number of preheaters	2	2	2	4
Total area preheaters	2,300 m²	2,400 m²	2,600 m²	3,800 m²
Area condenser	4,800 m²	3,700 m²	2,900 m²	2,100 m²
Total area installed	56,300 m²	78,100 m²	89,000 m²	104,300 m²

Multi-effect distillation at different GOR
C. Desportes, IDA Conf., Nov. 2010

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Emerging Thermal Technologies

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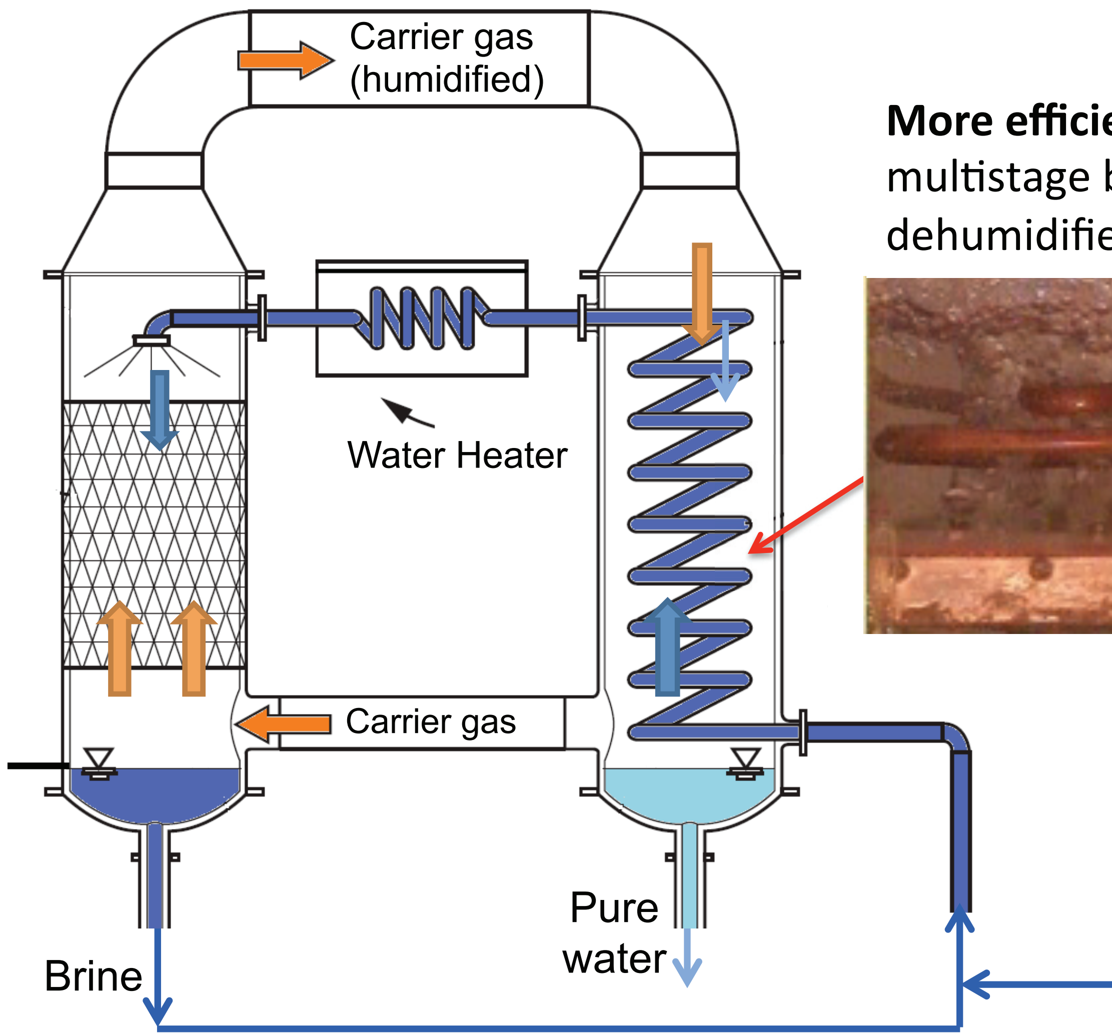
J.H. Lienhard V

Humidification-dehumidification desalination

simple, membrane-free, robust under high TDS water

- Humidifier and dehumidifier performance sensitive to air and water mass flow rates
- HCR depends temperature via vapor pressure (nonlinear)
- Component performance is coupled



More efficient approach: multistage bubble column dehumidifier

J.H. Lienhard V

Prototype demonstration

G.P. Narayan, G.P. Thiel, R.K. McGovern, J.H. Lienhard V, and M.H. Sharqawy, "Multi-Stage Bubble Column Dehumidifier," US Patent #8525447, 3 September 2013

G.P. Narayan and J.H. Lienhard V, *IDA Journal,* **4**(3):24-34, Sept. 2012

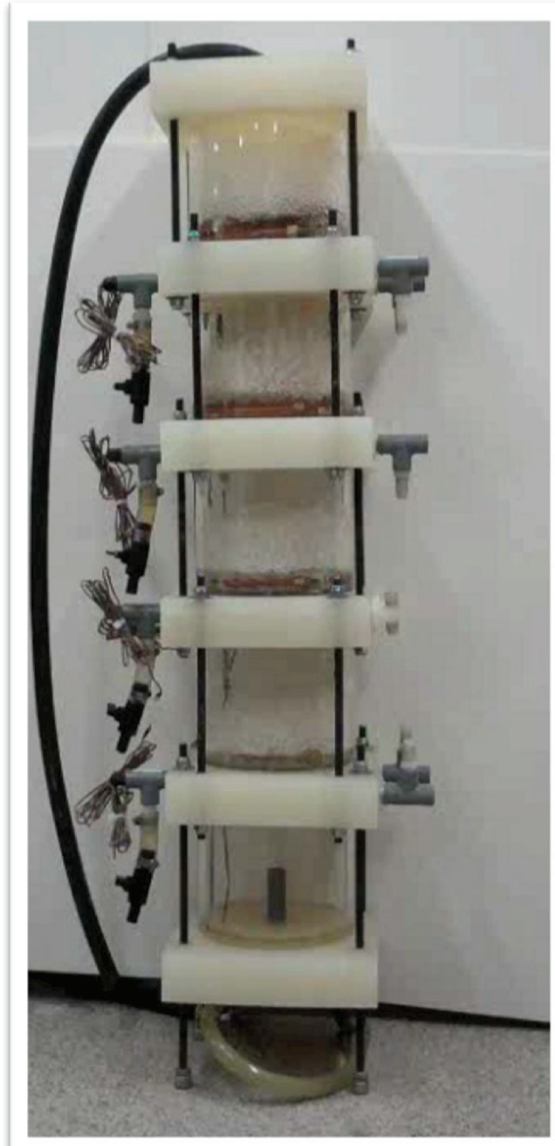
G.P. Narayan, M.H. Sharqawy, S. Lam, S.K. Das, and J.H. Lienhard V, *AIChE Journal*, **59**(5):1780-1790, May 2013

G.P. Narayan, M.S. St. John, S.M. Zubair, and J.H. Lienhard, *Intl. J. Heat Mass Transfer,* 58:740-748, March 2013.

G.P. Narayan, K.M. Chehayeb, R.K. McGovern, G.P. Thiel, S.M. Zubair, and J.H. Lienhard V, *Intl. J. Heat Mass Transfer,* 57(2):756-770, Feb. 2013

E.W. Tow and J.H. Lienhard V, *Intl. J. Thermal Sciences*, **80**:65-75, June 2014

E.W. Tow and J.H. Lienhard V, *Intl. J. Heat Mass Transfer*, **79**:353-361, Dec. 2014.



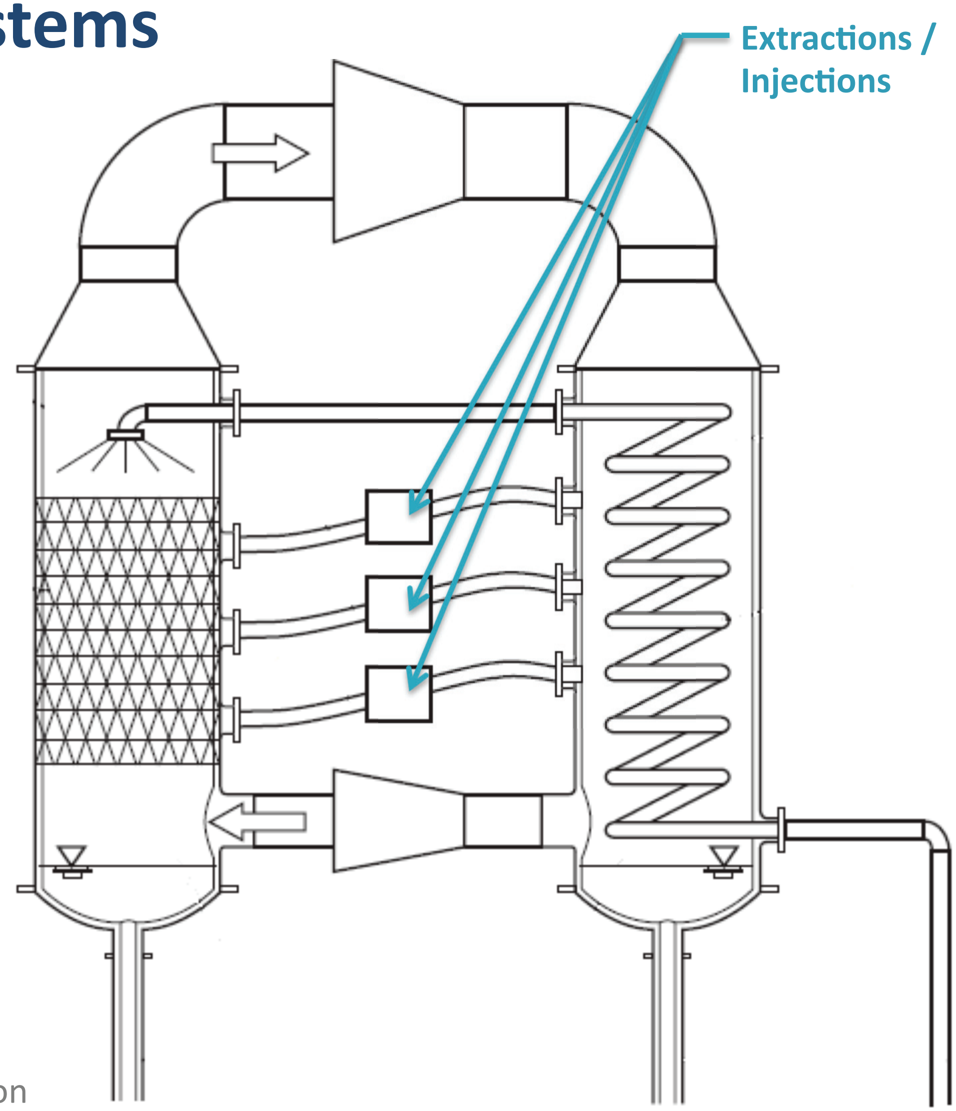
Video of bubble column dehumidifier

Multi-Extraction in HDH Systems

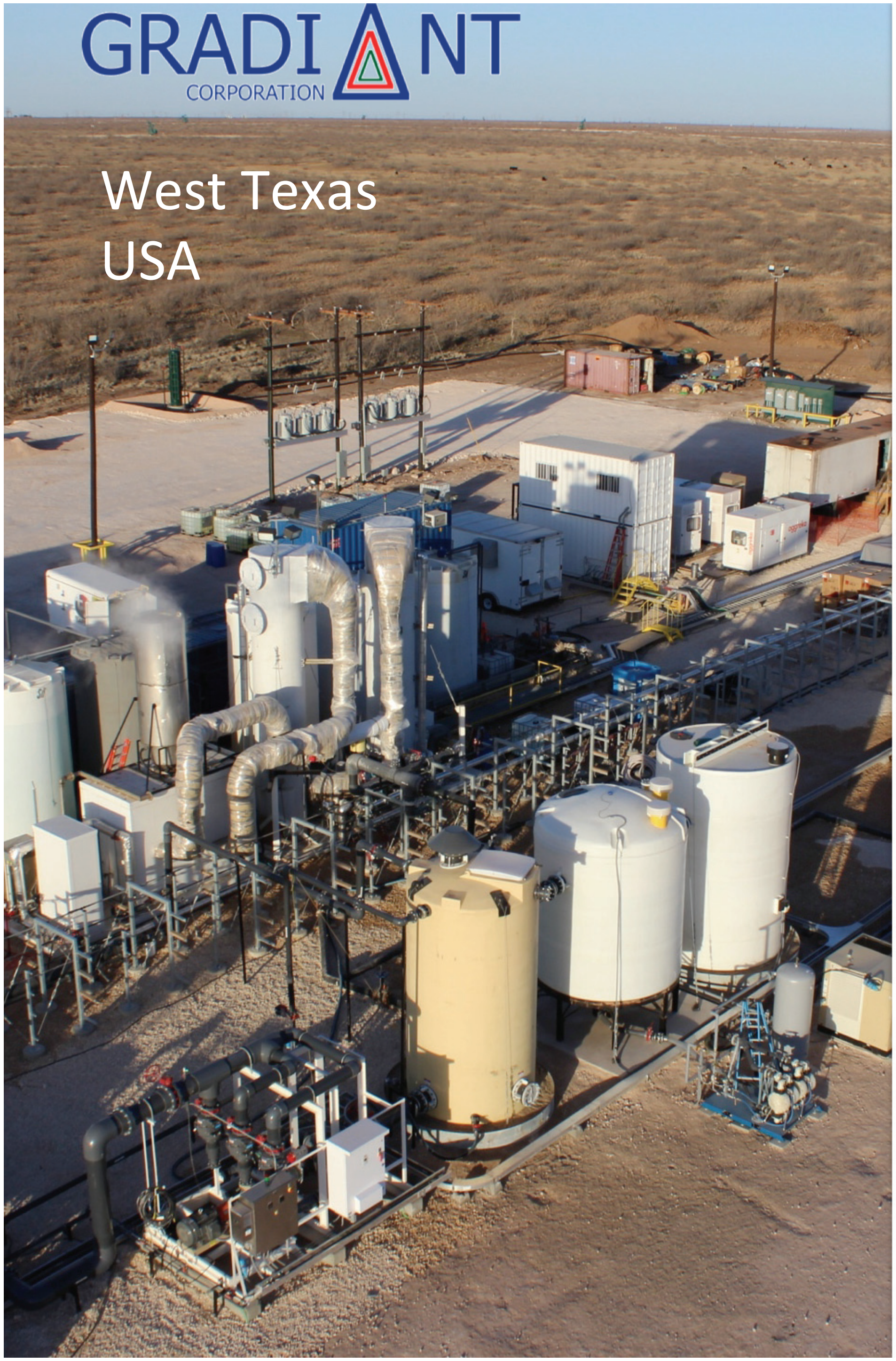
- Entropy generation increases when either humidity or temperature differences increase through device
- These differences cannot be held constant by adjusting end states & mass flows alone – $\omega_{sat}(T)$ is nonlinear

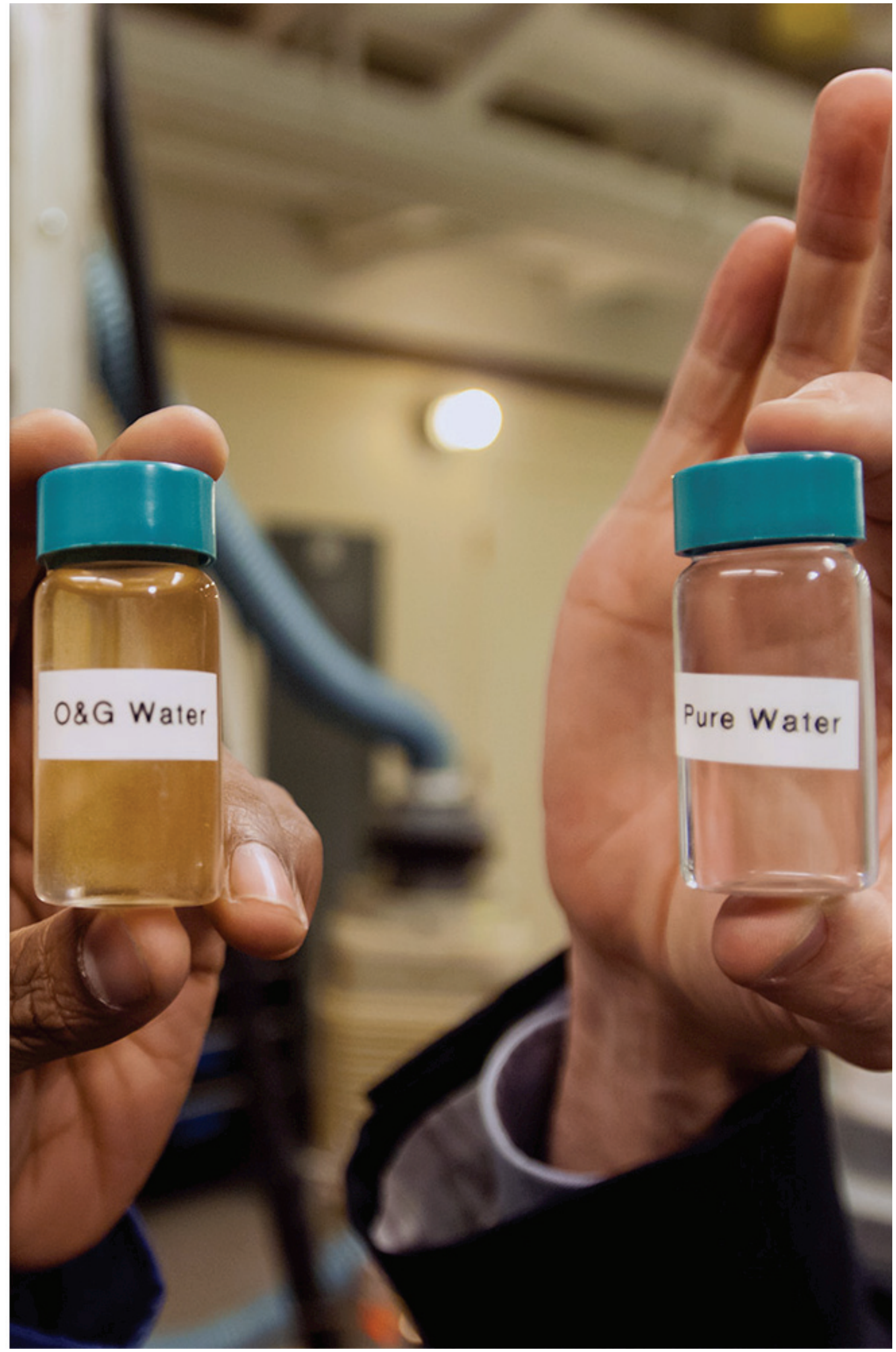
- Extractions & injections can be used to rebalance *locally* along component
- Challenge is to determine what variable to balance and where to extract or inject
- Complex coupling of inlet/outlet states and components

GOR > 4



G.P. Narayan et al., "Thermal design of the humidification dehumidification desalination system: an experimental investigation," *Intl. J. Heat Mass Transfer*, **58**:740-748, 2013.


GRADIANT
CORPORATION
West Texas
USA

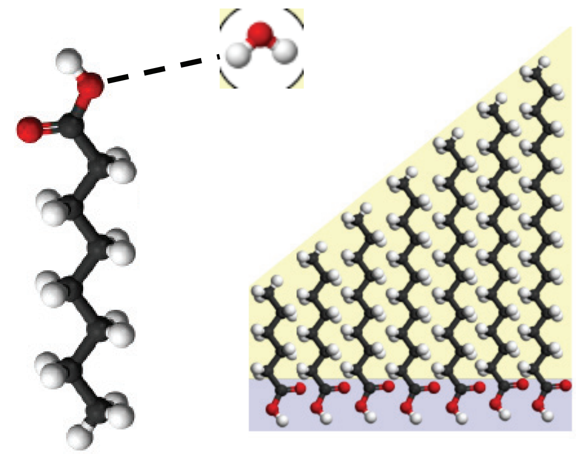

O&G Water
Pure Water

Directional Solvent Extraction: Low Temperature, Membrane free Desalination

Anurag Bajpayee, Tengfei Luo, Stephan Kress, and Gang Chen

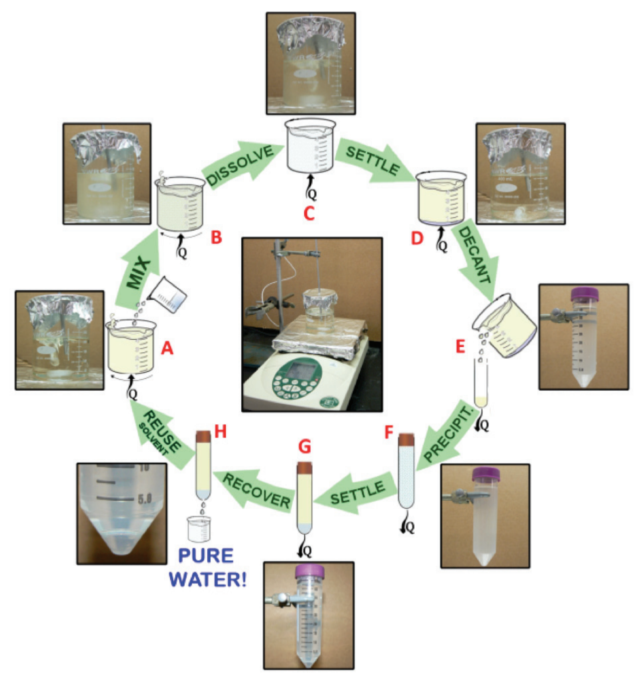
A Molecular Approach to Desalination

- **Directional Solvent:**
  - Dissolves water
  - Does NOT dissolve salts
  - Does not dissolve IN water
  - Non-toxic
- **Temperature dependent solubility**
- **Directionality based on molecular structure and bond-strengths**



A simple cyclic process without membranes that can use low grade energy

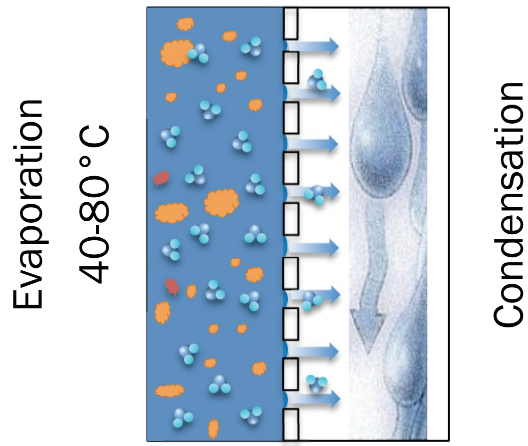
- **>98% salt rejection demonstrated to function at temperatures as low as 40 °C**
- **Simple system with low capital, no membrane, and low grade energy could reduce desalination cost and complexity**
- **Robust over wide TDS range**, varying temperatures, and operational scale



Bajpayee et. al., "Very Low Temperature, Membrane-free Desalination by Direction Solvent Extraction," *Energy and Environmental Science,* **2011, 4,** 1672

Membrane Distillation Process

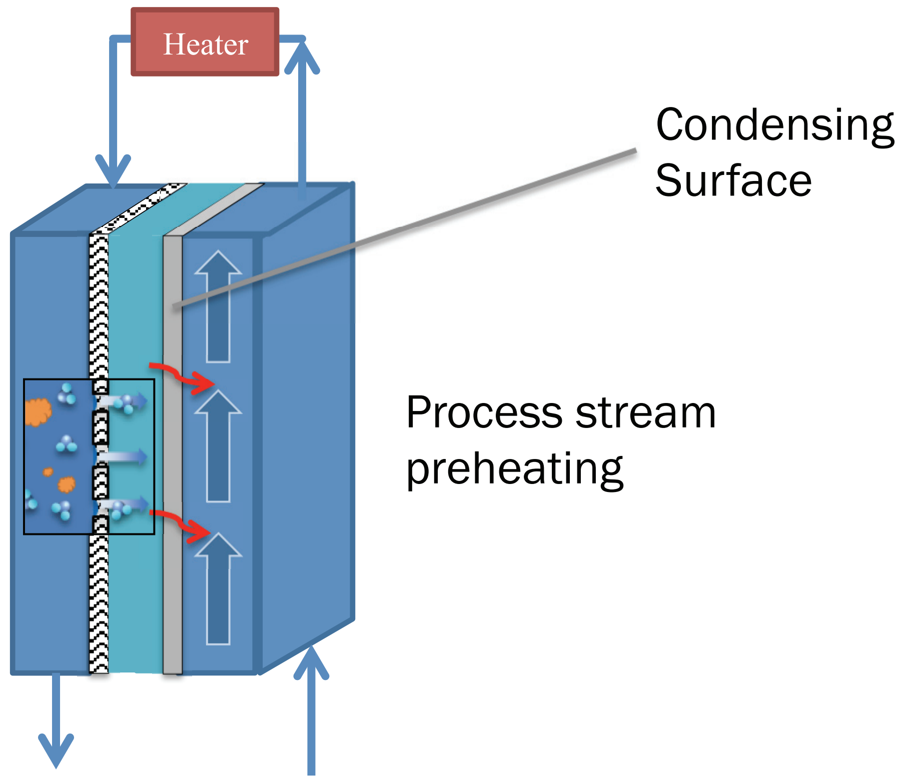
Distillation through a
hydrophobic membrane



Pure vapor passes through,
leaving behind all dissolved
contaminants

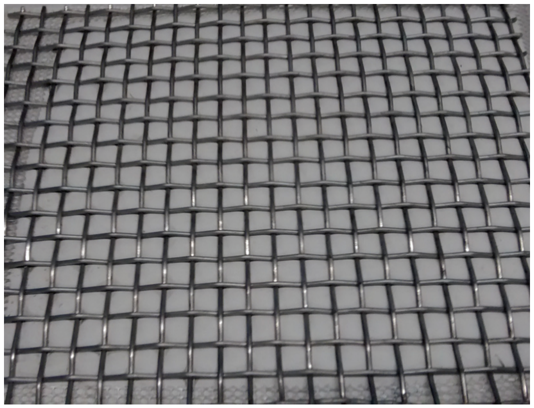
J. Swaminathan, J.H. Lienhard V, MIT, 2015

Membrane Distillation Process

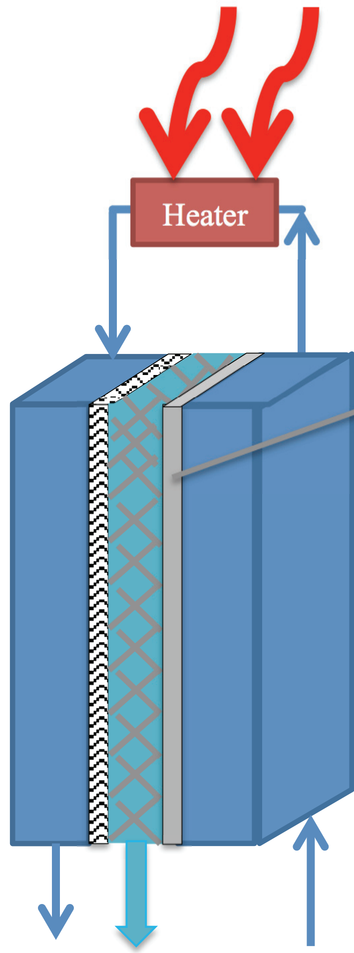


J. Swaminathan, H.W. Chung, D.M. Warsinger, F. AlMarzooqi, H.A. Arafat, and J.H. Lienhard V, "Energy Efficiency of Permeate Gap and Novel Conductive Gap Membrane Distillation," J. Membrane Sci., accepted, Dec. 2015

Redesigned Gap

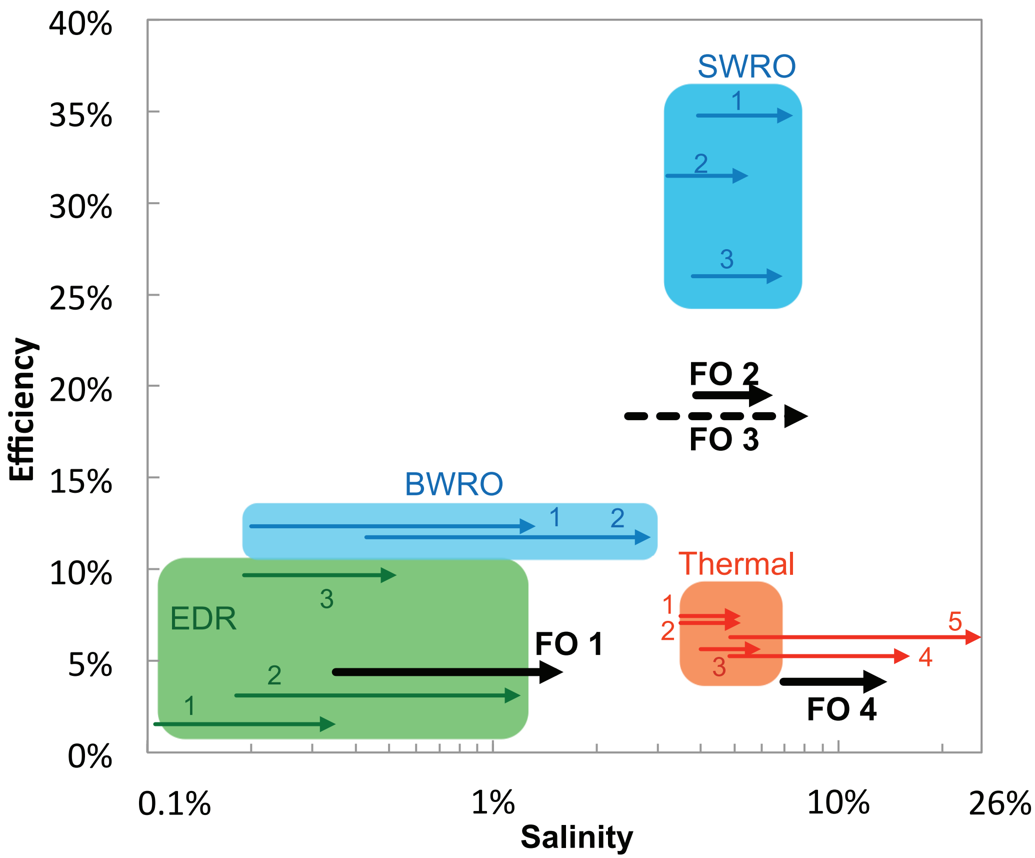


Mesh introduced in the gap



Efficiency for various systems and salinities

$$\eta = \frac{\text{least exergy of separation}}{\text{actual exergy consumption}} = \frac{\dot{m}_p g_p + \dot{m}_c g_c - \dot{m}_f g_f}{\dot{Q}\left(1 - \frac{T_0}{T}\right) + \dot{m}_h\left(\xi_{h,i} - \xi_{h,o}\right) + \dot{m}_F \xi_F + \dot{W}}$$



Key: Feed —Process→ Concentrate

Legend:

FO	1	FO-RO pilot
	2	FO-RO model
	3	Dilution pilot (non-regenerating
	4	Thermal draw regen. pilot
Thermal	1	MVC (typical SW)
	2	TVC-MED (typical SW)
	3	MSF, Shuweihat, Saudi Arabia
	4	MVC, Barnett Shale, USA
	5	MVC model
SWRO	1	Skikda, Algeria
	2	Tampa Bay, USA
	3	Hadera, Israel
BWRO	1	Wadi Ma'in, Jordan
	2	El Paso, USA
EDR	1	Melville, Canada
	2	Yuma, USA
	3	Foss Reservoir, USA

E.W. Tow, R.K. McGovern, J.H. Lienhard V, *Desalination*, **366**:71–79, 15 June 2015.

CLEAN H_2O + E

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Coproduction of water and electricity

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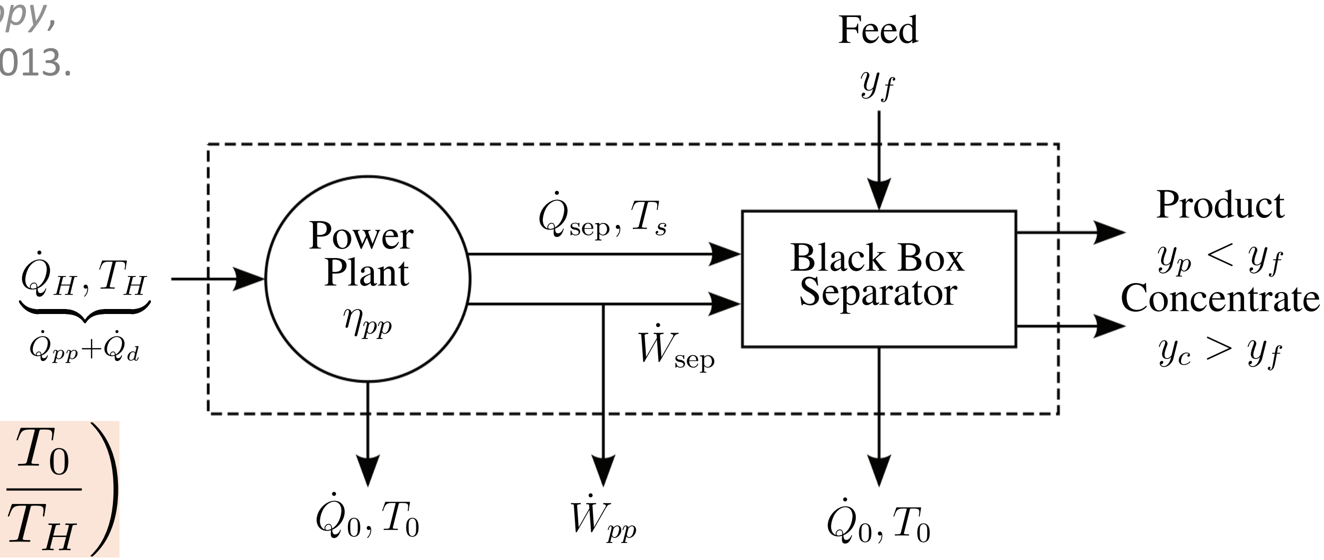
Combined power production and MSF distillation – substantially lowers cost of energy for distillation

Ref: Sommariva, 2007

Second Law Efficiency: RO vs. Thermal coproduction

Mistry & Lienhard, *Entropy*, 15(6):2046-2080, May 2013.



Additional exergy for desalination

$$\dot{\Xi}_{\text{input}} = \dot{Q}_{\text{d}}\left(1 - \frac{T_0}{T_H}\right)$$

2nd law efficiency:

$$\eta_{II} \equiv \frac{\text{least exergy of separation}}{\text{exergy input}} = \frac{\dot{W}^{\text{min}}_{\text{least}}}{\dfrac{\dot{W}_{\text{sep}}}{\eta_{pp}} + \dot{Q}_{\text{sep}}\left(1 - \dfrac{T_0}{T_s}\right)}$$

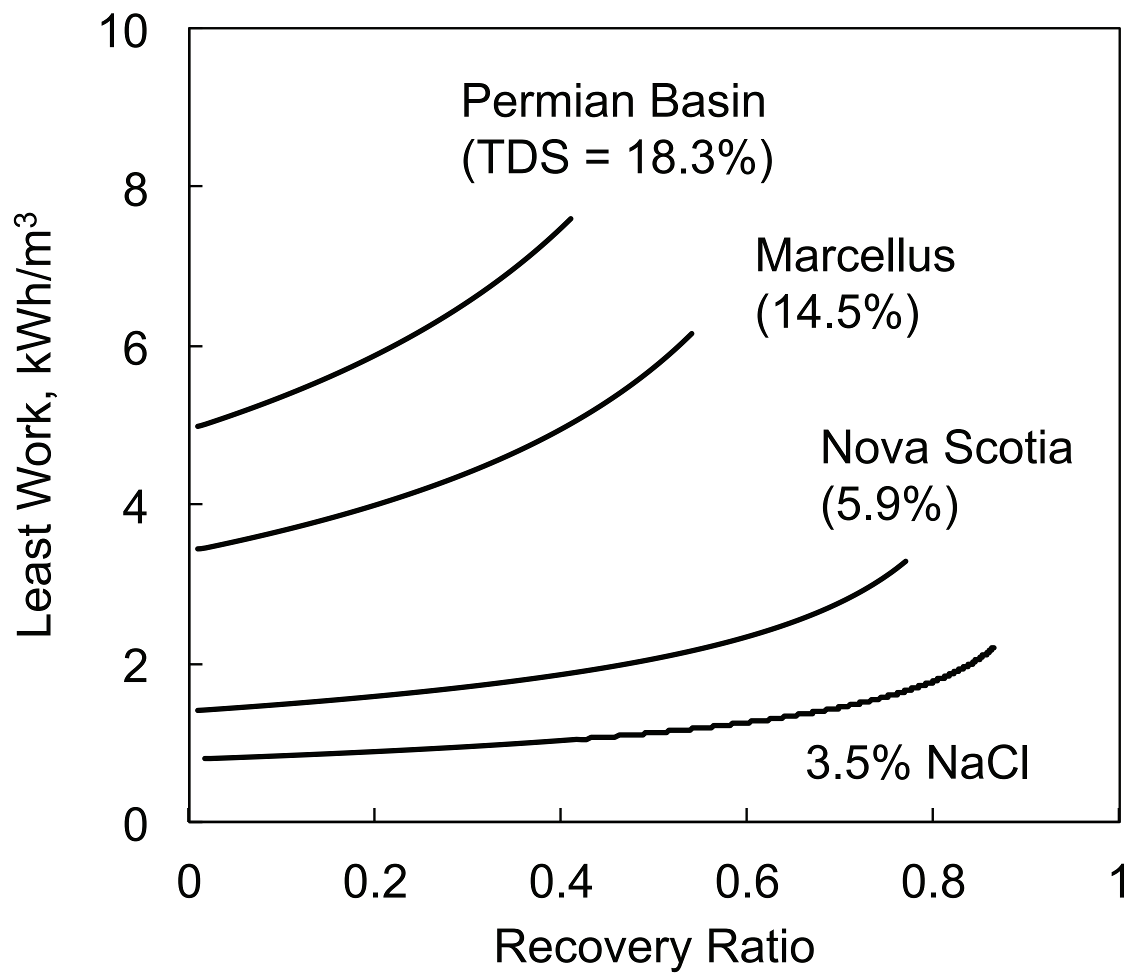
$$\eta_{II} \approx \begin{cases} 10-20\% & \text{for SWRO with } \eta_{pp} = 67\% \\ 7-9\% & \text{for MED excl. pumping} \\ 5\% & \text{for MSF excl. pumping} \\ < 6\% & \text{for MED with pumping} \\ < 3\% & \text{for MSF with pumping} \end{cases}$$

NB: the typical performance of thermal systems is limited by CAPEX considerations


Water is a major factor in shale gas production

Least Work for Higher Salinity O&G Wastewater from Various Locations

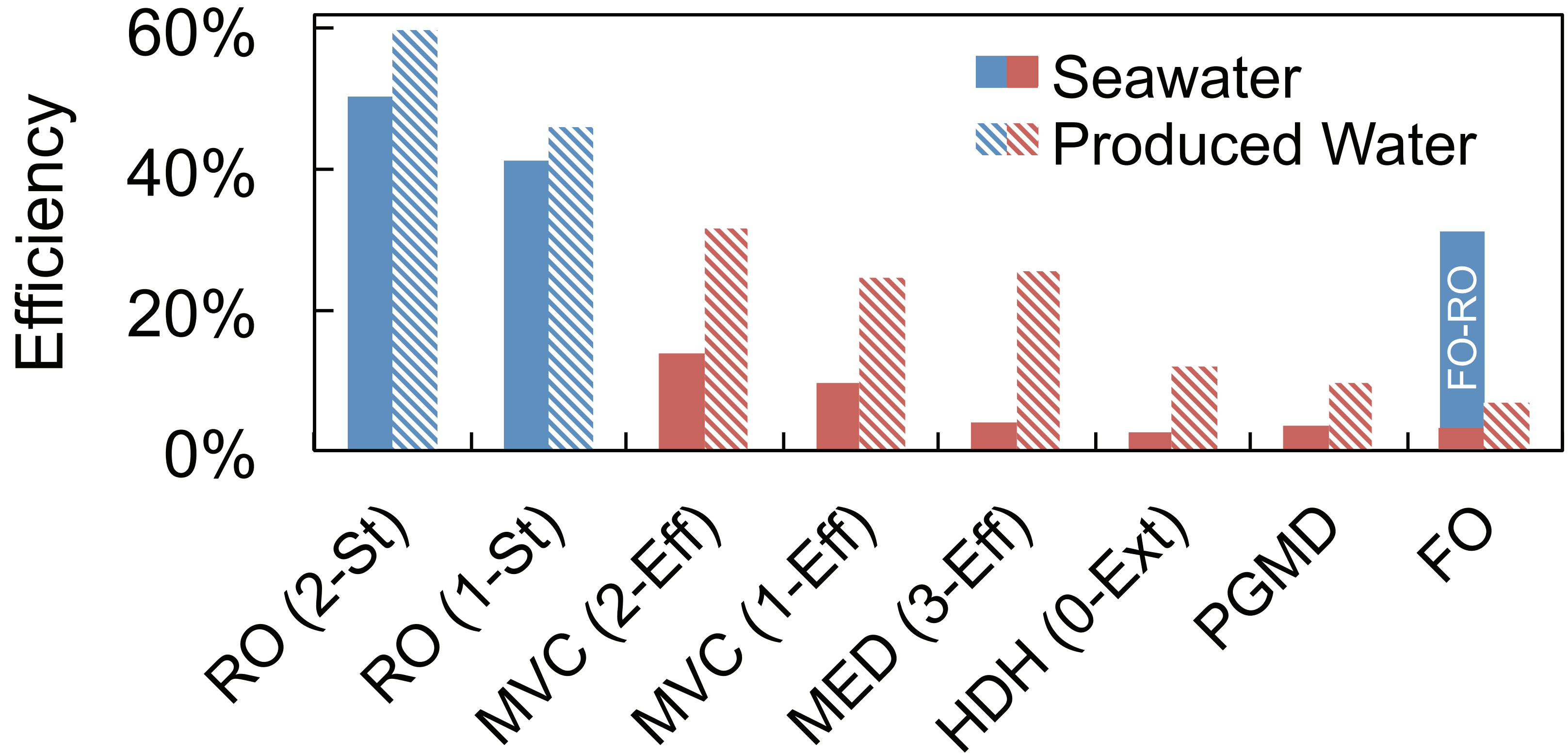
Least work is approx. 1 kWh/m³ for seawater at 50% recovery, but up to **8 kWh/m³ for 183 ppt** Permian Basin sample at maximum recovery



$$\frac{\dot{W}_{\text{least}}}{\dot{N}_w RT} = \left(\ln \frac{a_{w,p}}{a_{w,b}} + \sum_s b_{s,p} M_w \ln \frac{a_{s,p}}{a_{s,b}} \right) - \frac{1}{\text{RR}} \left(\ln \frac{a_{w,f}}{a_{w,b}} + \sum_s b_{s,f} M_w \ln \frac{a_{s,f}}{a_{s,b}} \right)$$

Mistry, Hunter, Lienhard, *Desalination*, **318**:34-47, June 2013.
Thiel, Tow, Banchik, Chung, Lienhard, *Desalination*, **366**:94-112, 15 June 2015.

Efficiency at SW versus PW Salinity



Thiel, Tow, Banchik, Chung, Lienhard, "Energy consumption in desalinating produced water from shale oil and gas extraction," Desalination, 366:94-112, 15 June 2015.

Essential ideas in thermal desalination

1. Top and bottom temperatures affect performance strongly (higher T_{top} is better)
2. Heat recovery during vapor condensation is essential to good performance
3. Minimizing temperature differences during heat transfer is essential: staging essential, high heat transfer coefficients essential
4. Composition: a) insoluble salts may have declining solubility with rising temperature, limits T_{top}; b) higher salinity requires higher energy to desalinate; thermal technology has advantages in this domain
5. Solar heat input is not free (incurs CAPEX) and has variable temperature. Similar concerns for "waste heat"

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Energy Consumption for Alternative Water Supplies

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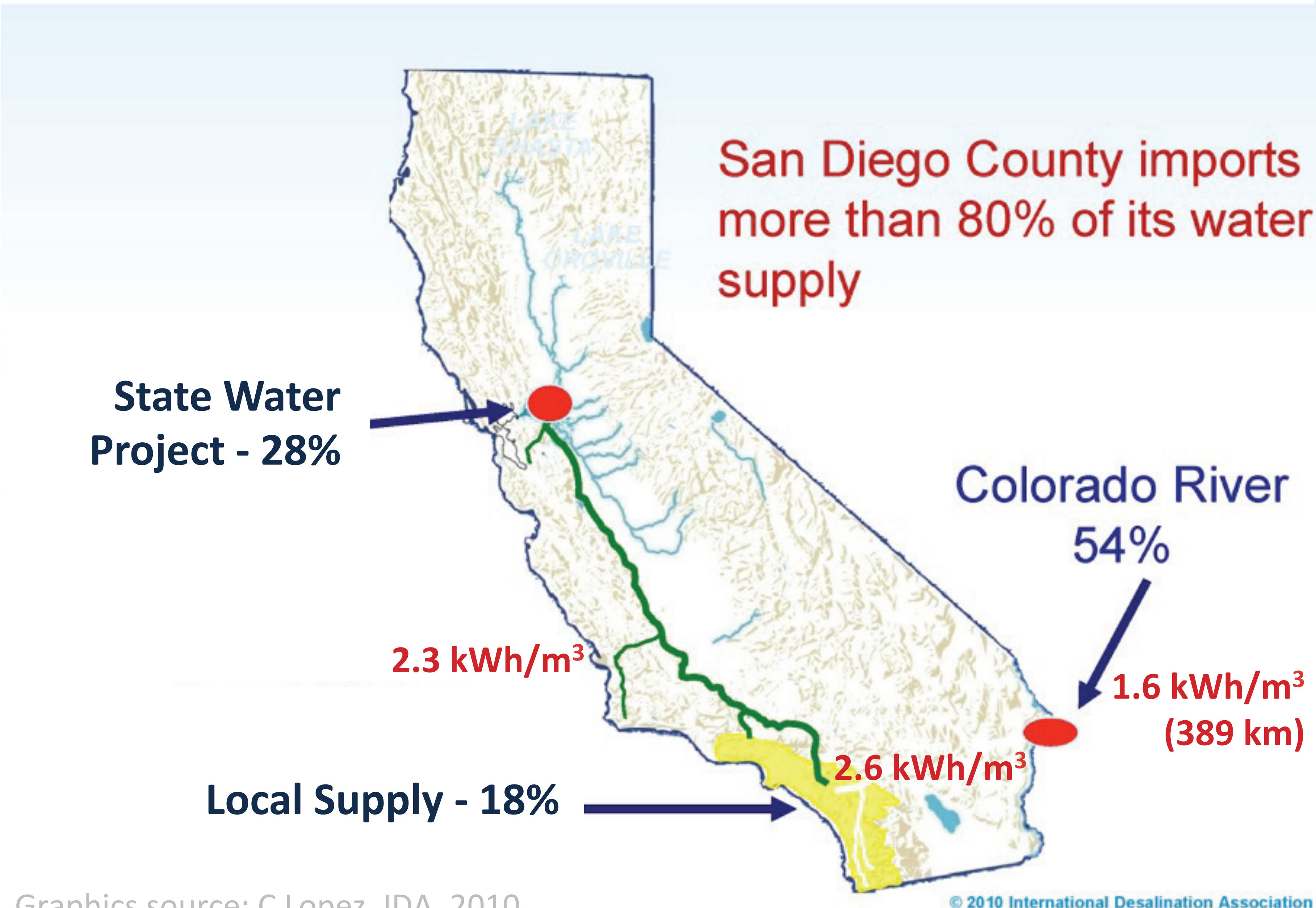
Long distance water transfer is energy intensive…



Graphics source: C Lopez, IDA, 2010

Plappally and Lienhard, Renewable and Sustainable Energy Reviews, 16(7):4818-4848, Sept. 2012.

Carlsbad, CA SWRO plant (190,000 m^3/day)
6,000 kW motor
About 3.6 kWh/m^3, all processes included (about 2.7 for RO only)
\$1.65/m^3

CLEAN $H_2O + E$

Recycling Water

- **Less energy than SWRO** ≈0.7 kWh/m^3
- Meets 30% of Singapore's demand
- Mostly nonpotable use
- *Used* water is treated by ultrafiltration, RO, and UV disinfection
- Several reuse projects being initiated in US as well… both indirect and direct potable reuse…

…including San Diego

Thank you!

For further reading (1)

Ultrapermeable membranes:

D. Cohen-Tanugi, R.K. McGovern, S. Dave, J.H. Lienhard V, and J.C. Grossman, "Quantifying the Potential of Ultra-permeable Desalination Membranes," *Energy Environ. Sci.*, **7**(3):1134-1141, Feb. 2014.

General energetics of desalination systems:

K.H. Mistry, R.K. McGovern, G.P. Thiel, E.K. Summers, S.M. Zubair, and J.H. Lienhard V, "Entropy generation analysis of desalination technologies," *Entropy*, **13**(10):1829-1864, Sept. 2011.
pdf. http://www.mdpi.com/1099-4300/13/10/1829

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pdf. http://www.mdpi.com/1099-4300/15/6/2046

K. Mistry, H.A. Hunter, and J.H. Lienhard V, "Effect of composition and nonideal solution behavior on desalination calculations for mixed electrolyte solutions with comparison to seawater," *Desalination*, **318**:34-47, June 2013. http://dx.doi.org/10.1016/j.desal.2013.03.015

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pdf. http://web.mit.edu/lienhard/www/papers/reviews/HDH-Desalination-chapter-2014.pdf

K.M. Chehayeb, G.P. Narayan, S.M. Zubair, and J.H. Lienhard V, "Thermodynamic balancing of a fixed-size two-stage humidification dehumidification desalination system," *Desalination*, **369**:125-139, 3 August 2015. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.025

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G.P. Narayan, M.S. St. John, S.M. Zubair, and J.H. Lienhard V, "Thermal design of the humidification dehumidification desalination system: an experimental investigation," *Intl. J. Heat Mass Transfer*, **58:**740-748, March 2013.

Membrane Distillation Desalination:

J. Swaminathan, H.W. Chung, D.M. Warsinger, F. AlMarzooqi, H.A. Arafat, and J.H. Lienhard V, "Energy Efficiency of Permeate Gap and Novel Conductive Gap Membrane Distillation," *J. Membrane Sci.*, accepted, Dec. 2015.

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http://dx.doi.org/10.1016/j.desal.2014.10.034

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http://dx.doi.org/10.1016/j.desal.2014.05.001