Can we save lives with thermodynamics?

Nanoengineering and Thermofluids for the Water-Food-Energy Nexus

Dr. David Martin Warsinger

Cornell University	B.S., M.Eng.
Massachusetts Institute of Technology	Ph.D., PostDoc
HARVARD John A. Paulson School of Engineering and Applied Sciences	PostDoc

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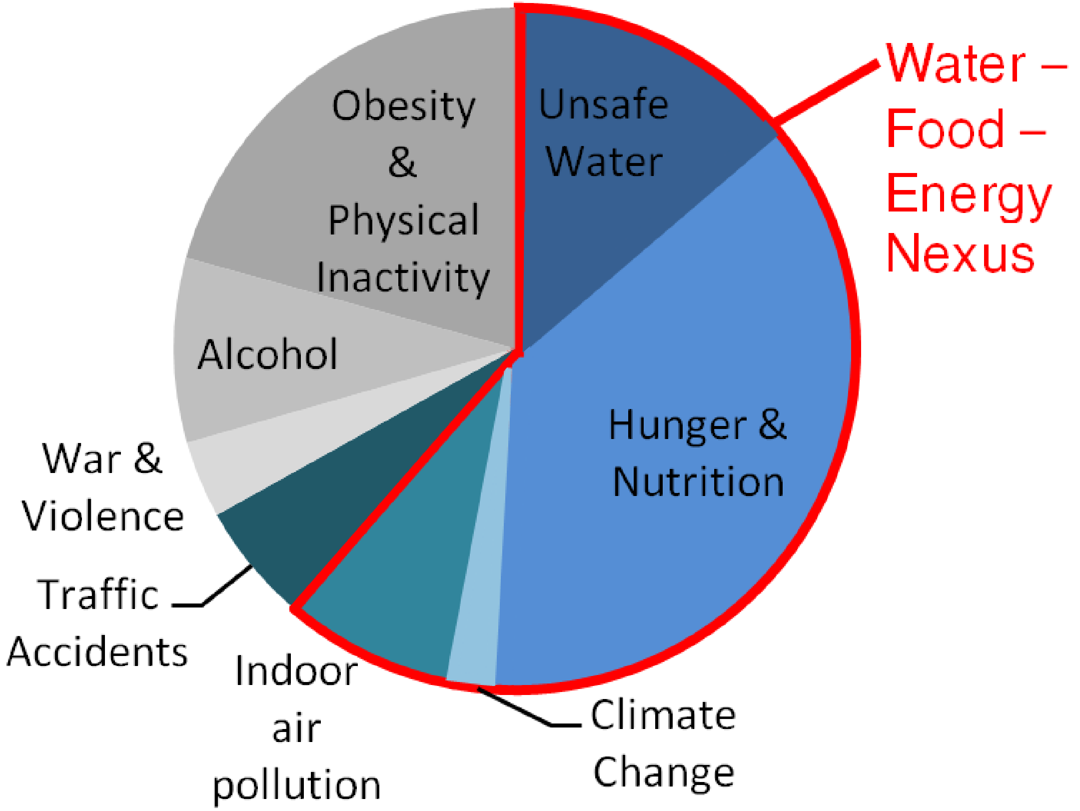
Global Preventable Causes of Death



Global Preventable Causes of Death

WHO, -factsheets 2014

In 2015 World Economic Forum named “Water Crisis” as the most likely and most impactful global economic risk

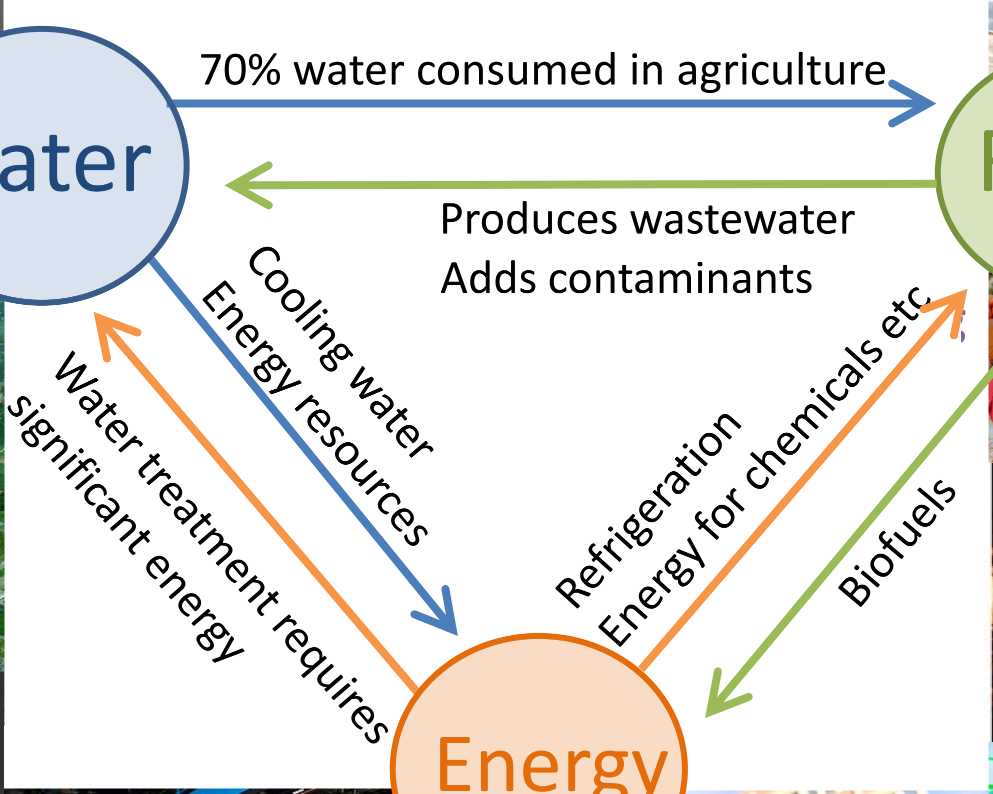
World Economic Forum, Geneva, Switzerland, “Global risks 2015 10th edition,” 2015.


http://managewaste.org


http://www.science20.com


http://www.agricultureguide.org


http://remf.dartmouth.ed


Water

70% water consumed in agriculture

Food

Produces wastewater
Adds contaminants

Cooling water
Energy resources

Water treatment requires
significant energy

Refrigeration
Energy for chemicals etc

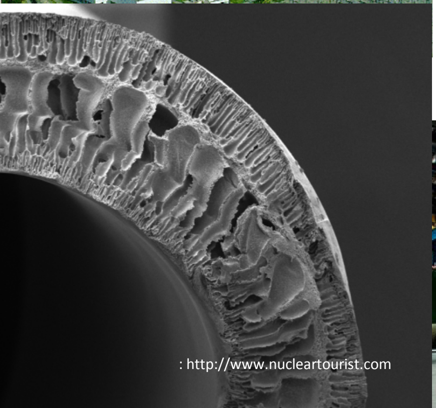
Biofuels

Energy

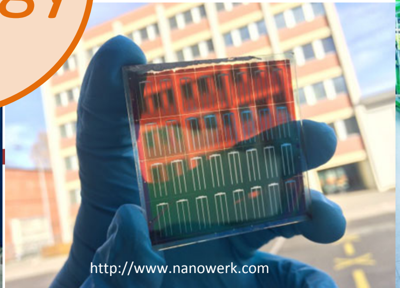

http://montcalm.co.uk


http://www.sustainable-desalination.net


http://news.mit.edu

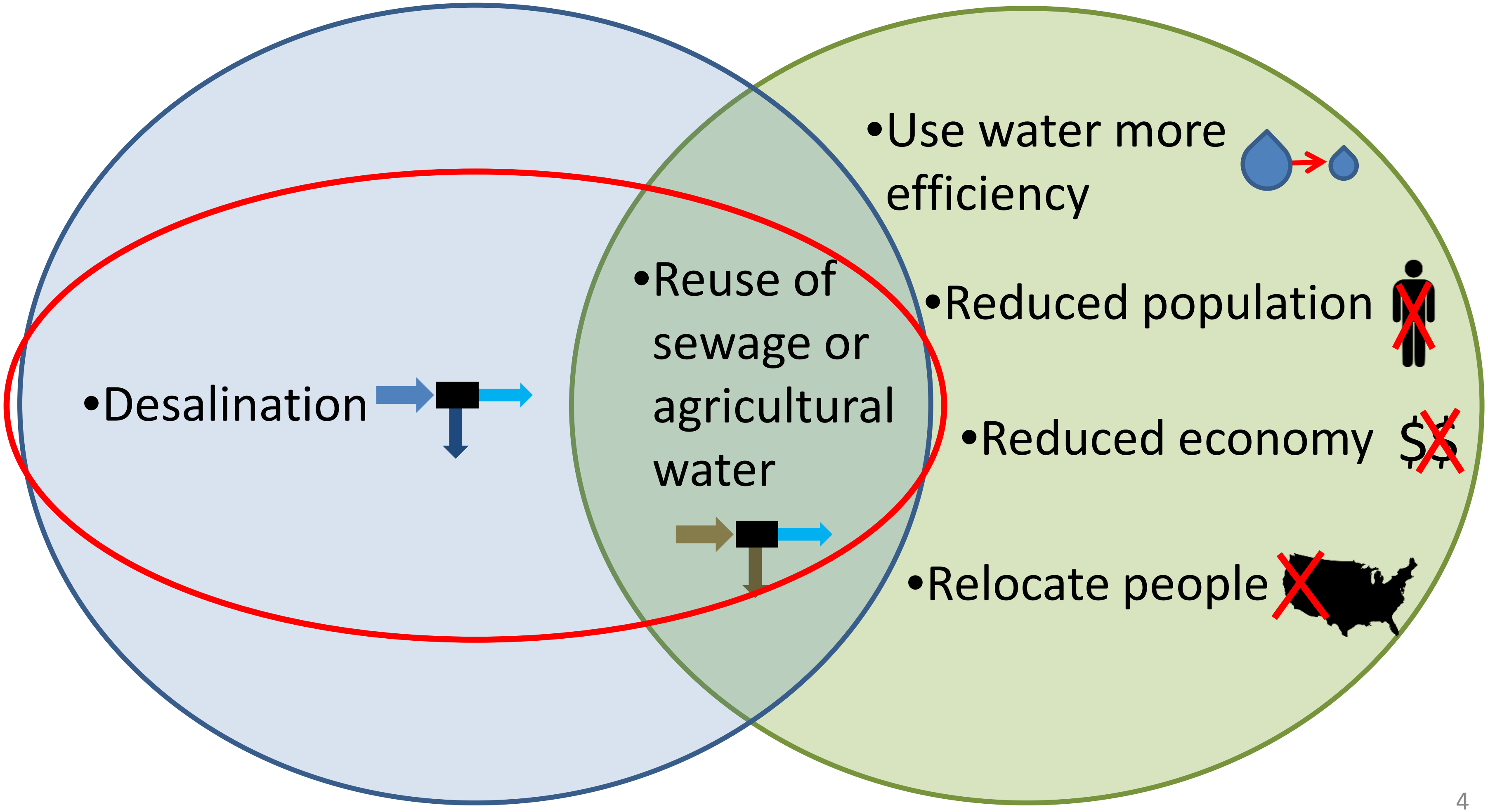

: http://www.nucleartourist.com


http://www.water-technology.net/


http://www.nanowerk.com


: http://blog.dicksondata.com

Options to Provide Water



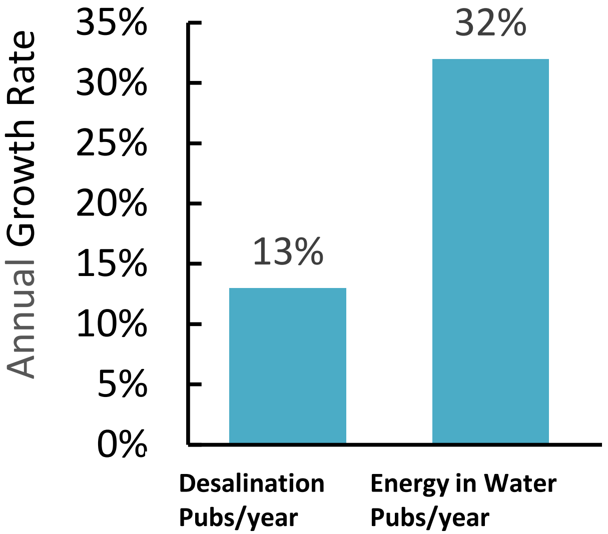
Supply

Demand

- Desalination
- Reuse of sewage or agricultural water
- Use water more efficiency
- Reduced population
- Reduced economy $
- Relocate people

Growing Water Focus

Water Researchers



Government

(funding)

NSF

USDA

EPA United States Environmental Protection Agency

U.S. Department of the Interior Bureau of Reclamation

U.S. Department of Energy

Example:
$72 million/year NSF: Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) (2016)

Publishers: Two new journals in 2016:

Royal Society of Chemistry **Environmental Science: Water Research & Technology**

npj nature partner journals npj | Clean Water

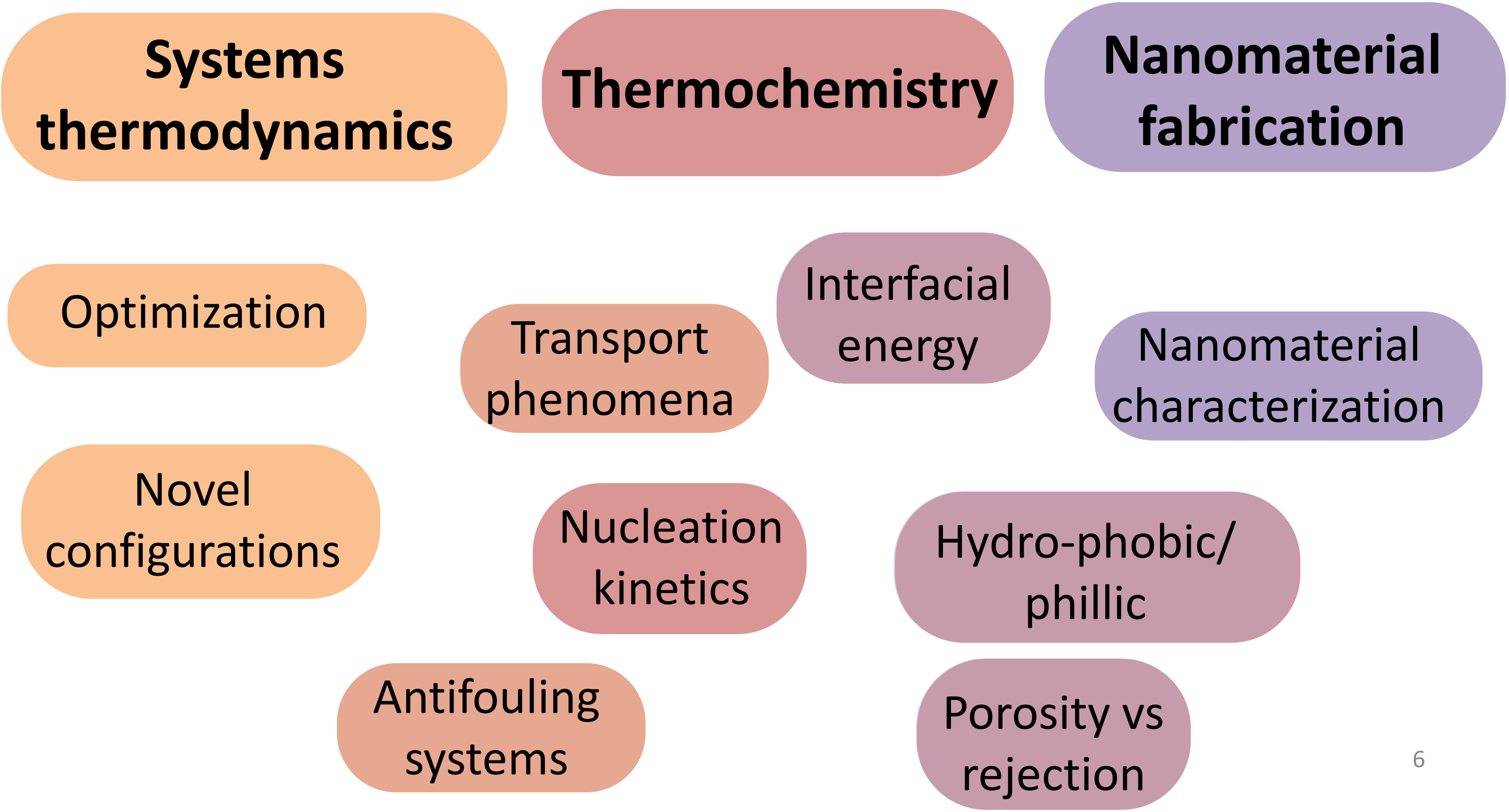
Sources

[1] "Global desalination market set to grow 320.3% by 2020 - driven by RO," Membrane Technology, vol. 2011, no. 10, pp. 7 –, 2011.

[2] U. E. I. Administration, International Energy Outlook 2016. U.S. Department of Energy, 2015.

[3] The Water and Food Nexus: Trends and Development of the Research Landscape, Stockholm International Water Institute and Elsevier, 2012

Thermo-nano scientific techniques for water



Systems thermodynamics

Thermochemistry

Nanomaterial fabrication

Optimization

Transport phenomena

Interfacial energy

Nanomaterial characterization

Novel configurations

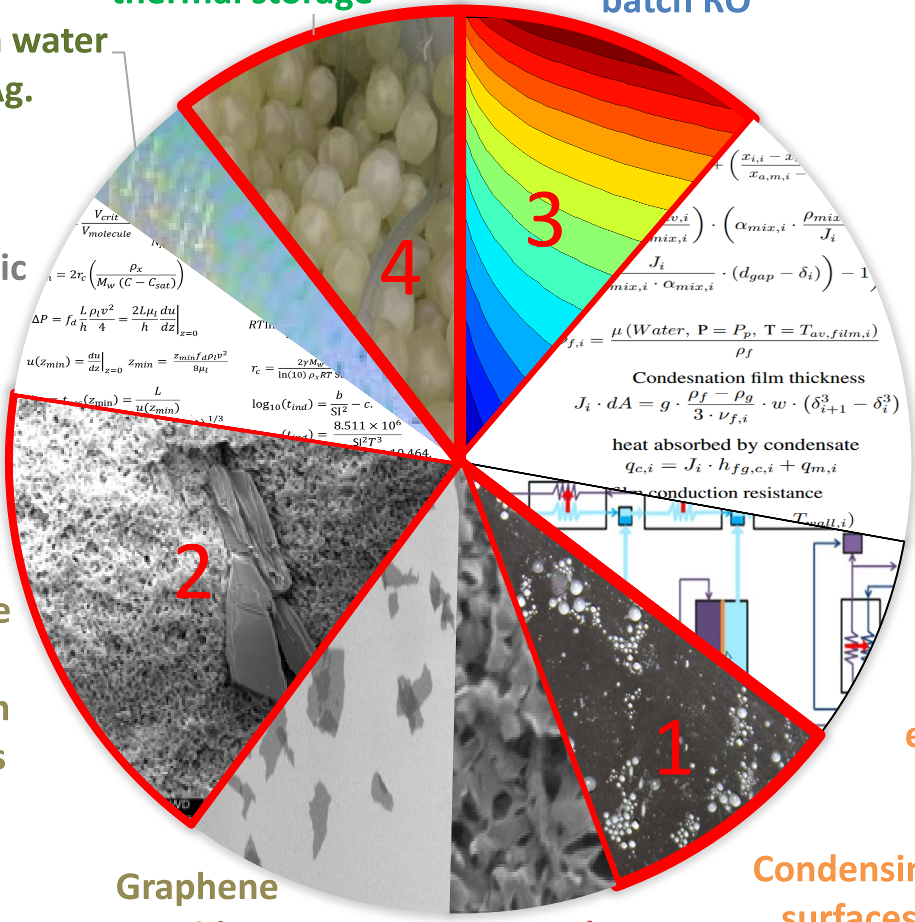
Nucleation kinetics

Hydro-phobic/ phillic

Antifouling systems

Porosity vs rejection

My Research



Phase-change thermal storage

Energy efficiency: batch RO

Energy in water for Ag.

Membrane fouling: thermodynamic theory

Energy efficiency: MD

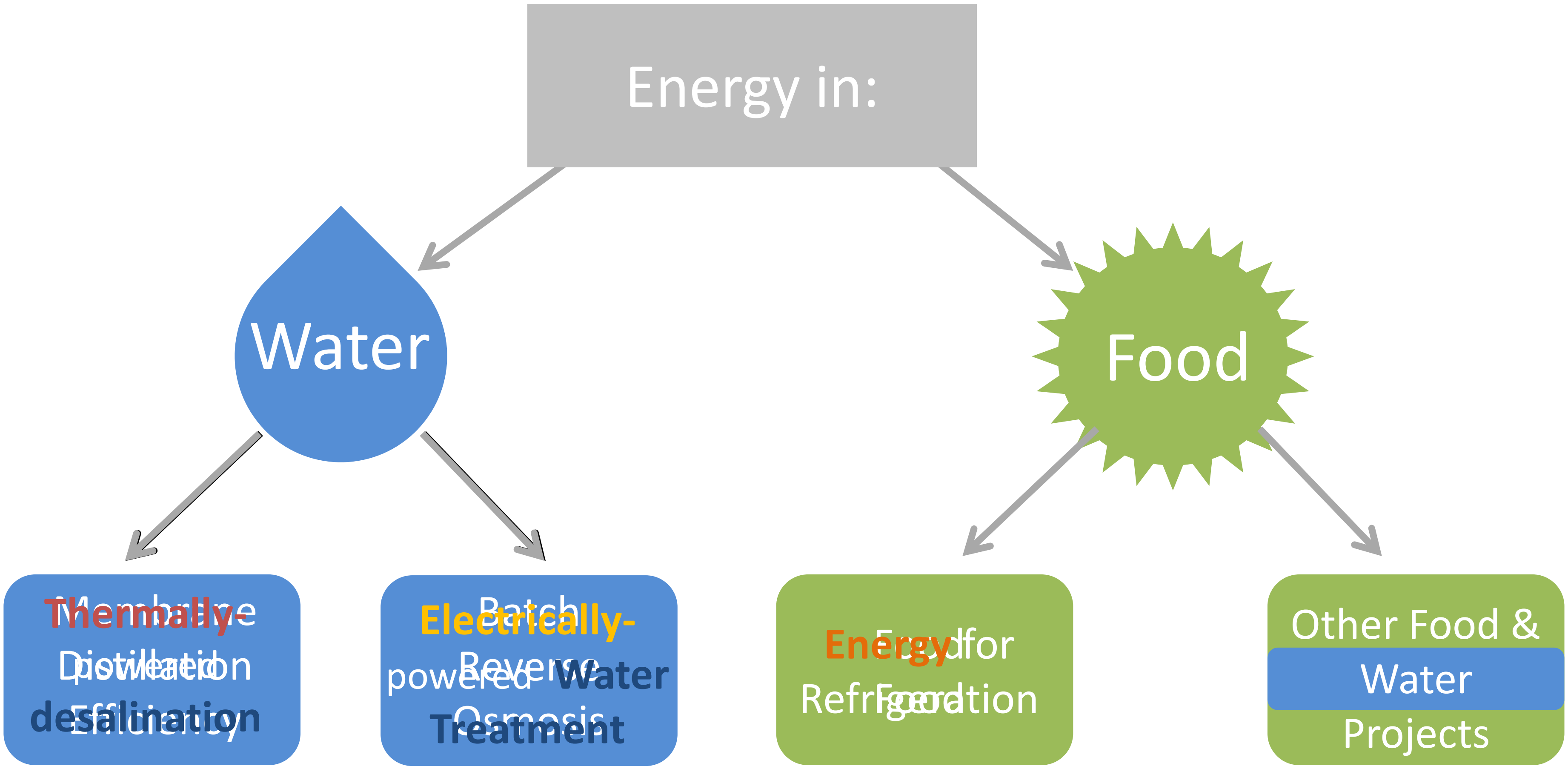
Membrane fouling prevention inventions

Desalination component exergy analysis

Condensing surfaces

Graphene Oxide membranes

Membrane coatings



Energy in:

Water

Food

Membrane Distillation Efficiency

Thermally-powered desalination

Batch Reverse Osmosis

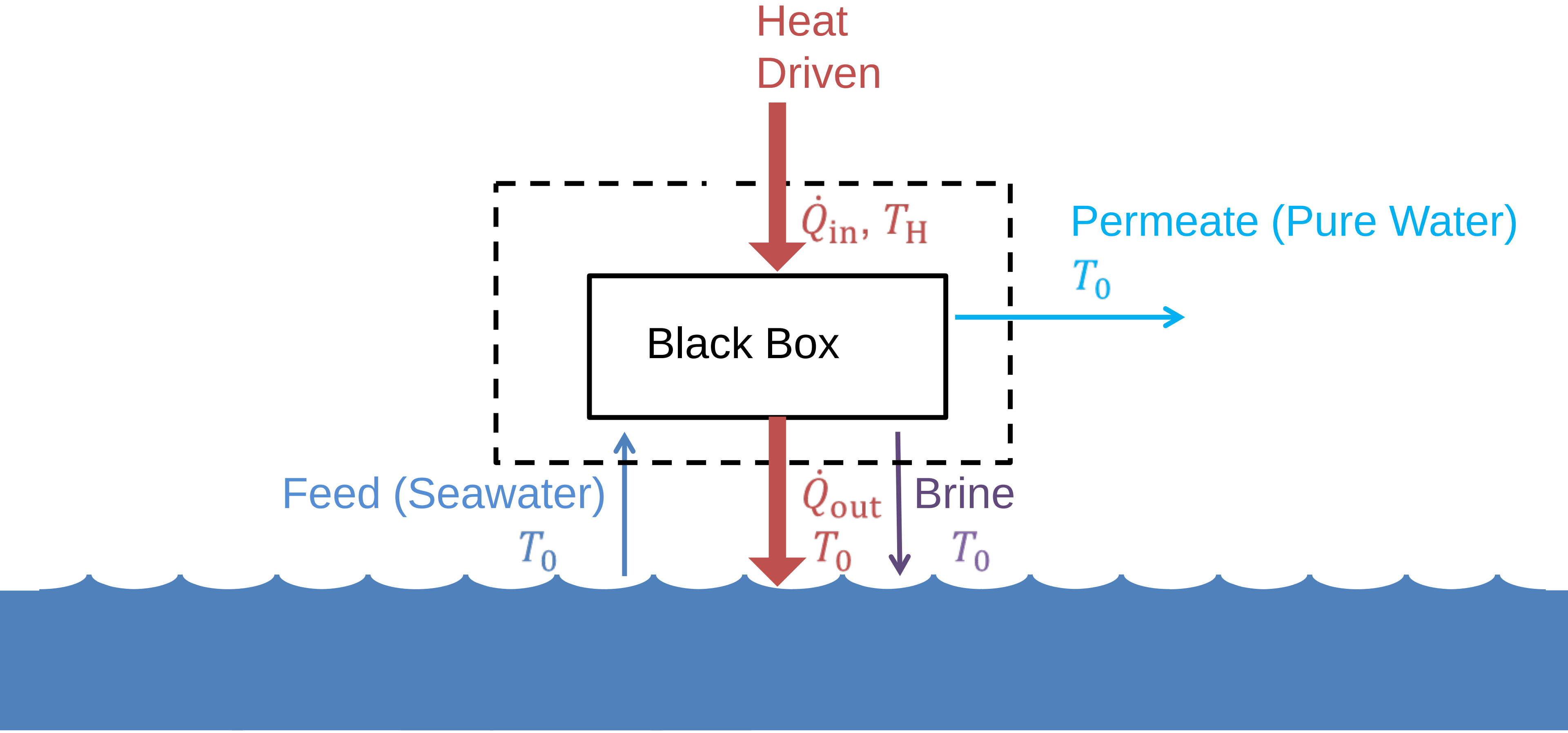
Electrically-powered Water Treatment

Food Refrigeration

Energy for Food

Other Food & Water Projects

Desalination Systems Level



Warsinger et al. *Entropy* **17**, 7530–7566 (2015).

Definitions

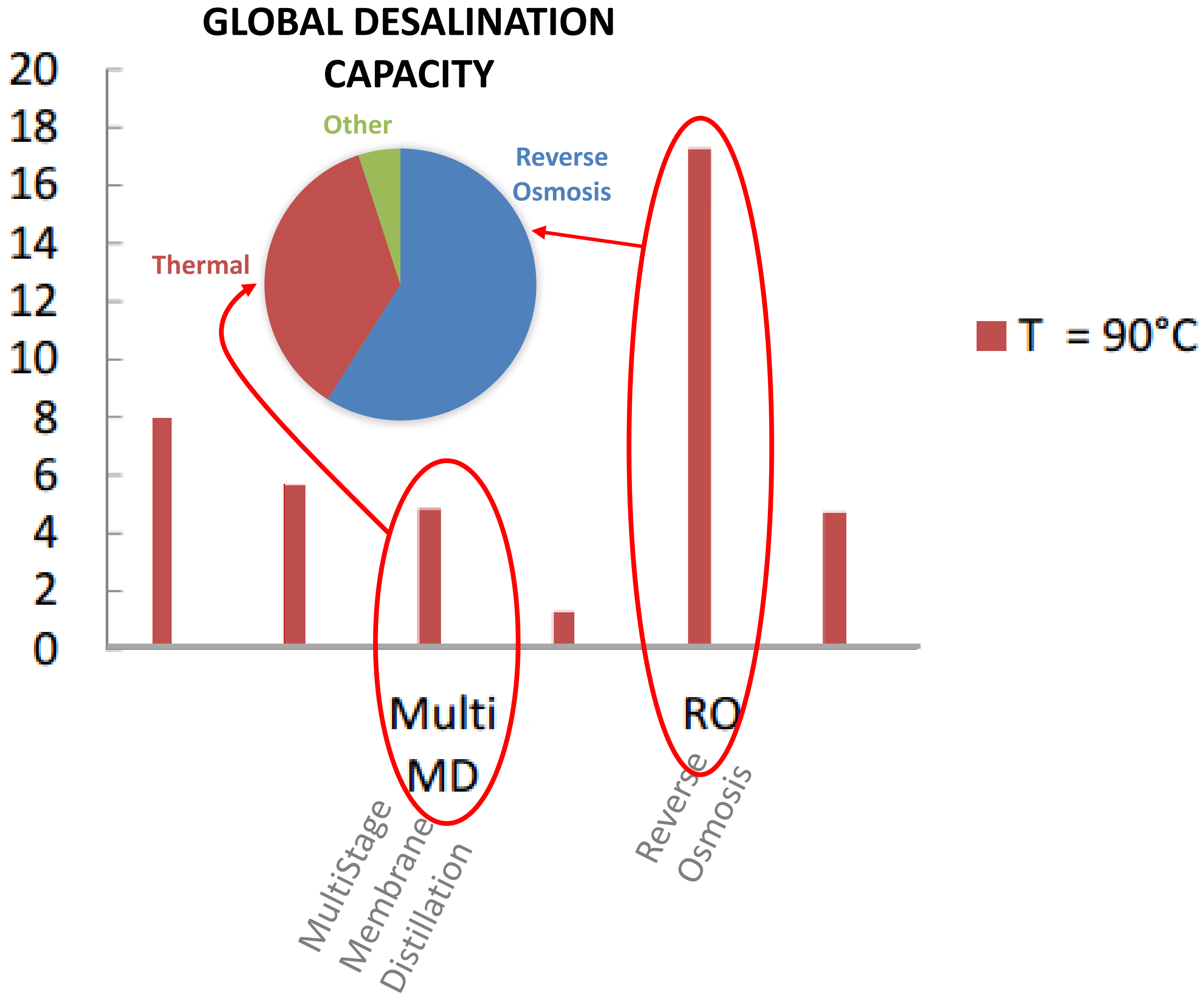
Recovery Ratio

$$\mathrm{RR} = \frac{\dot{m}_{\mathrm{permeate}}}{\dot{m}_{\mathrm{feed}}}$$

2nd-law efficiency

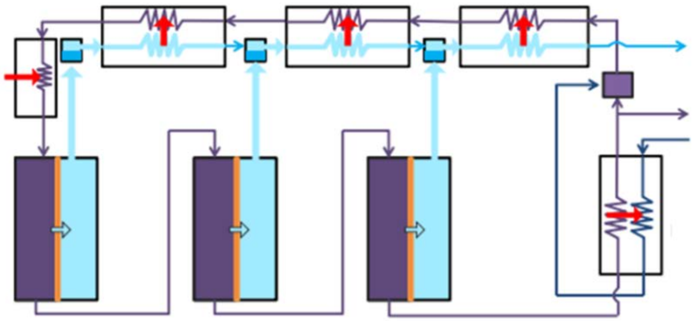
$$\eta_{II} = \frac{\dot{W}^{\mathrm{min}}_{\mathrm{least}}}{\dot{W}_{used}}$$

Des y η_{II}

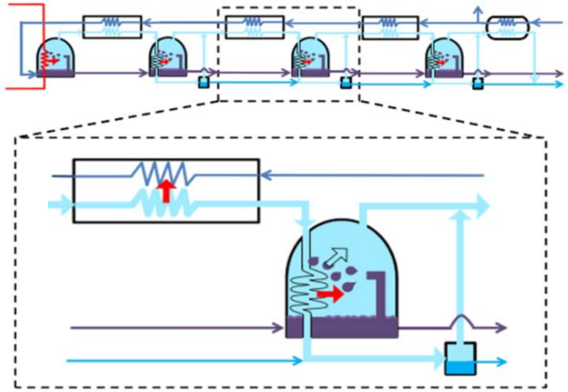


Warsinger et al. *Entropy* **17**, 7530–7566 (2015).

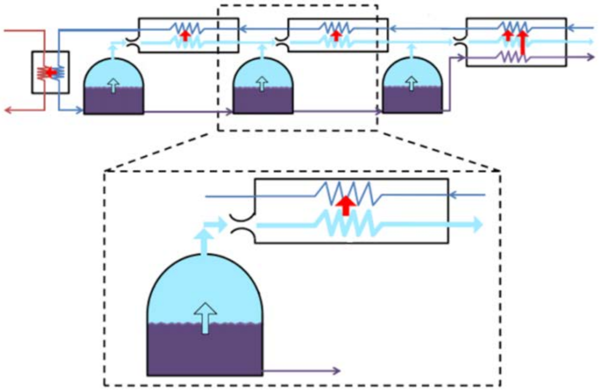
Multistage Vacuum MD



Multiple Effect Distillation (MED)

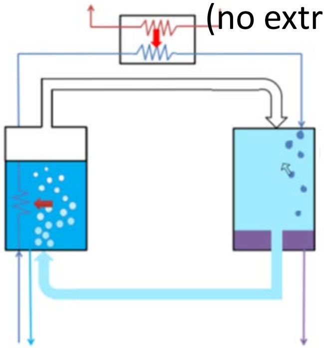


Multistage Flash (MSF) (once through)



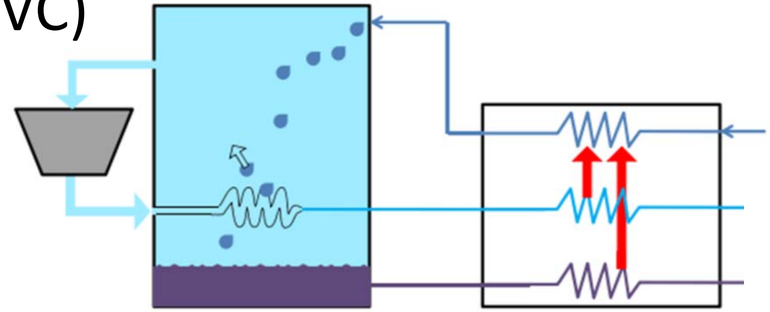
Humidification-Dehumidification (HDH)

(no extraction)

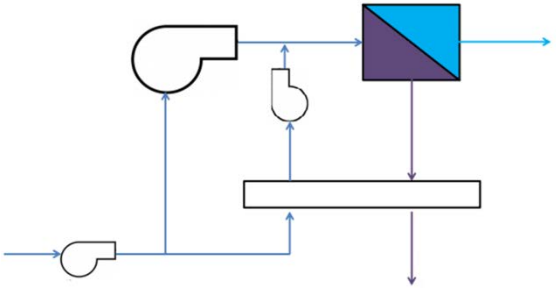


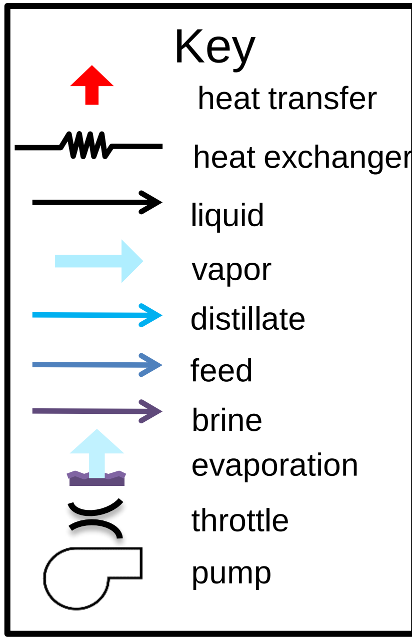
Mechanical Vapor Compression (MVC)

(single effect)



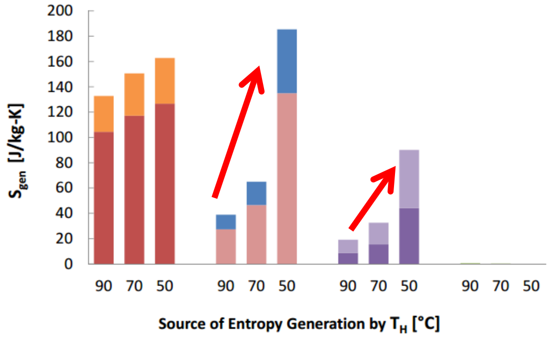
Reverse Osmosis (RO)



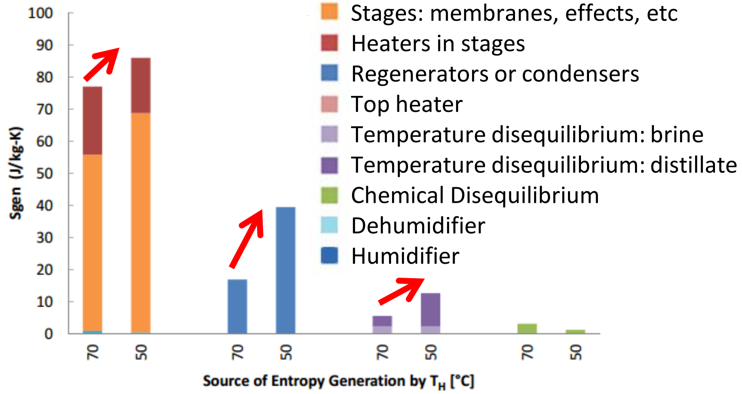


Key
- heat transfer
- heat exchanger
- liquid
- vapor
- distillate
- feed
- brine
- evaporation
- throttle
- pump

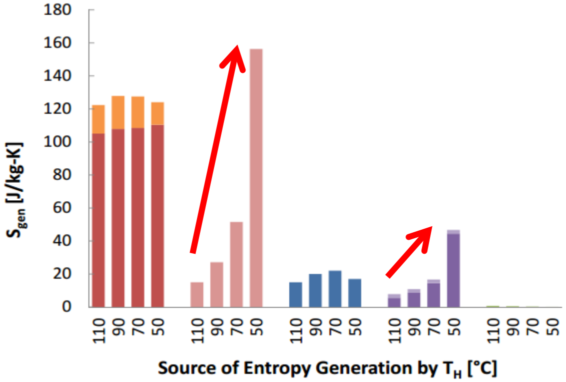
Multistage Vacuum MD



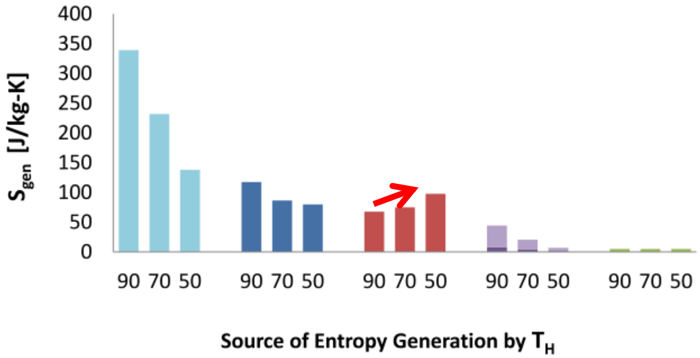
Multiple Effect Distillation (MED)



Multistage Flash (MSF) (once through)



Humidification-Dehumidification (HDH)



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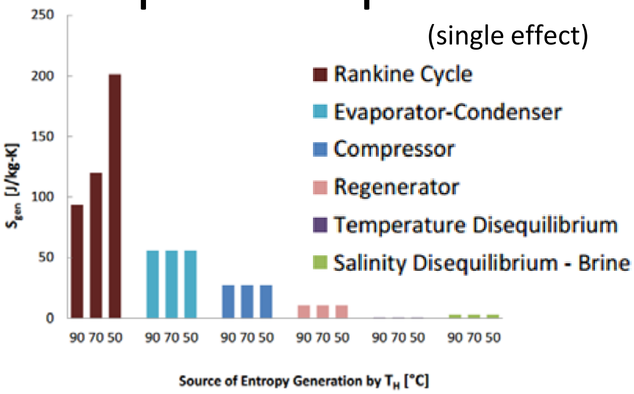
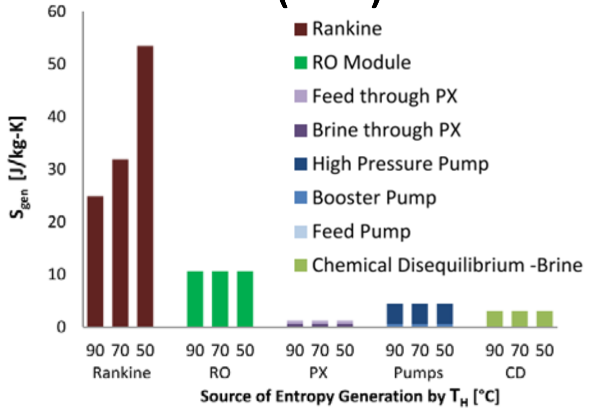
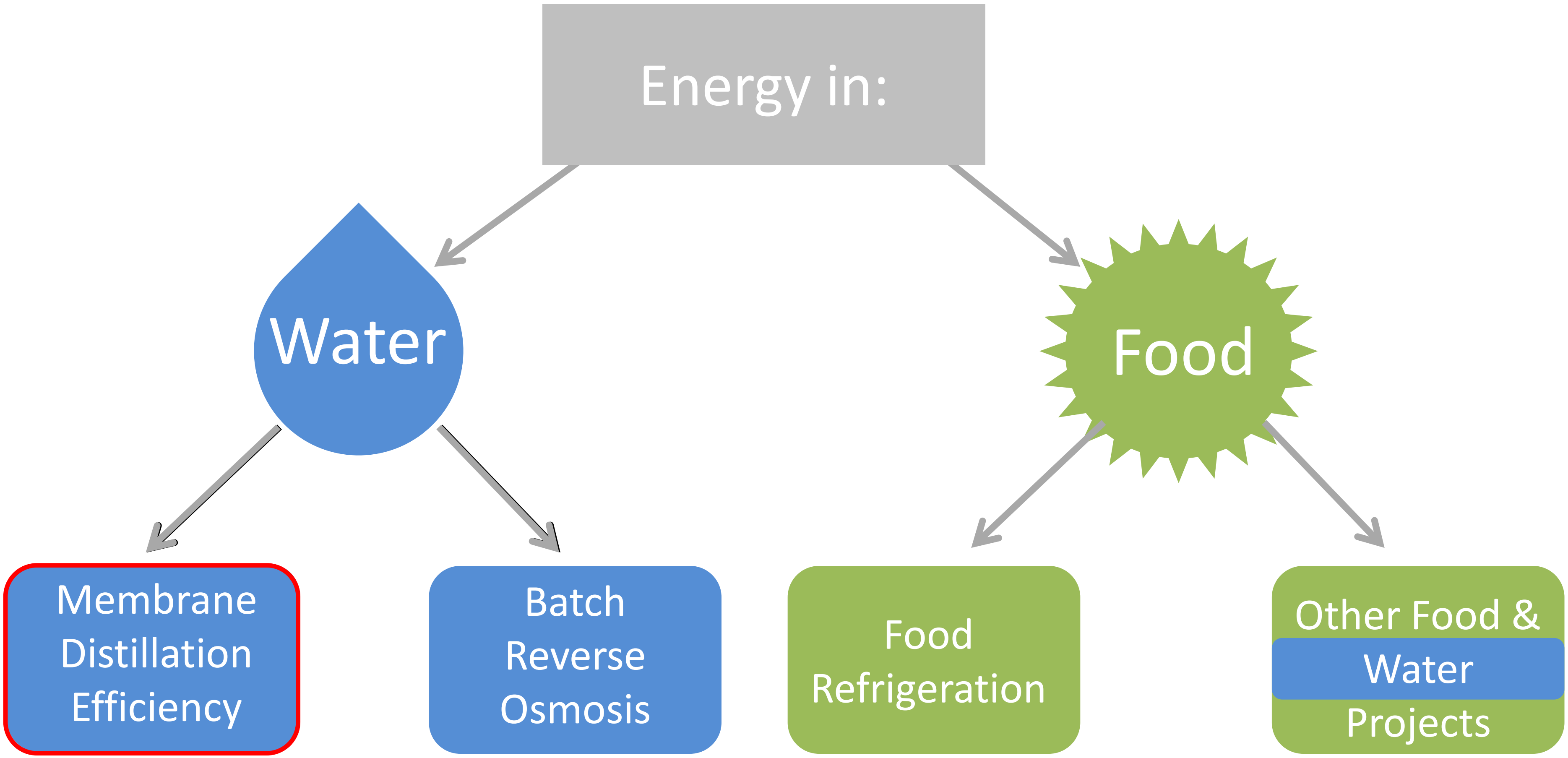


Reverse Osmosis (RO)





Energy in:

Water

Food

Membrane Distillation Efficiency

Batch Reverse Osmosis

Food Refrigeration

Other Food & Water Projects

Thermal power
with **desalination**

Membrane Distillation Advantages

η

Large
or
small

99.9%

~~fouling~~

memsys®
thermal separation processes

Keppel Seghers
Solutions for a Cleaner Future

MEMSTILL

GE

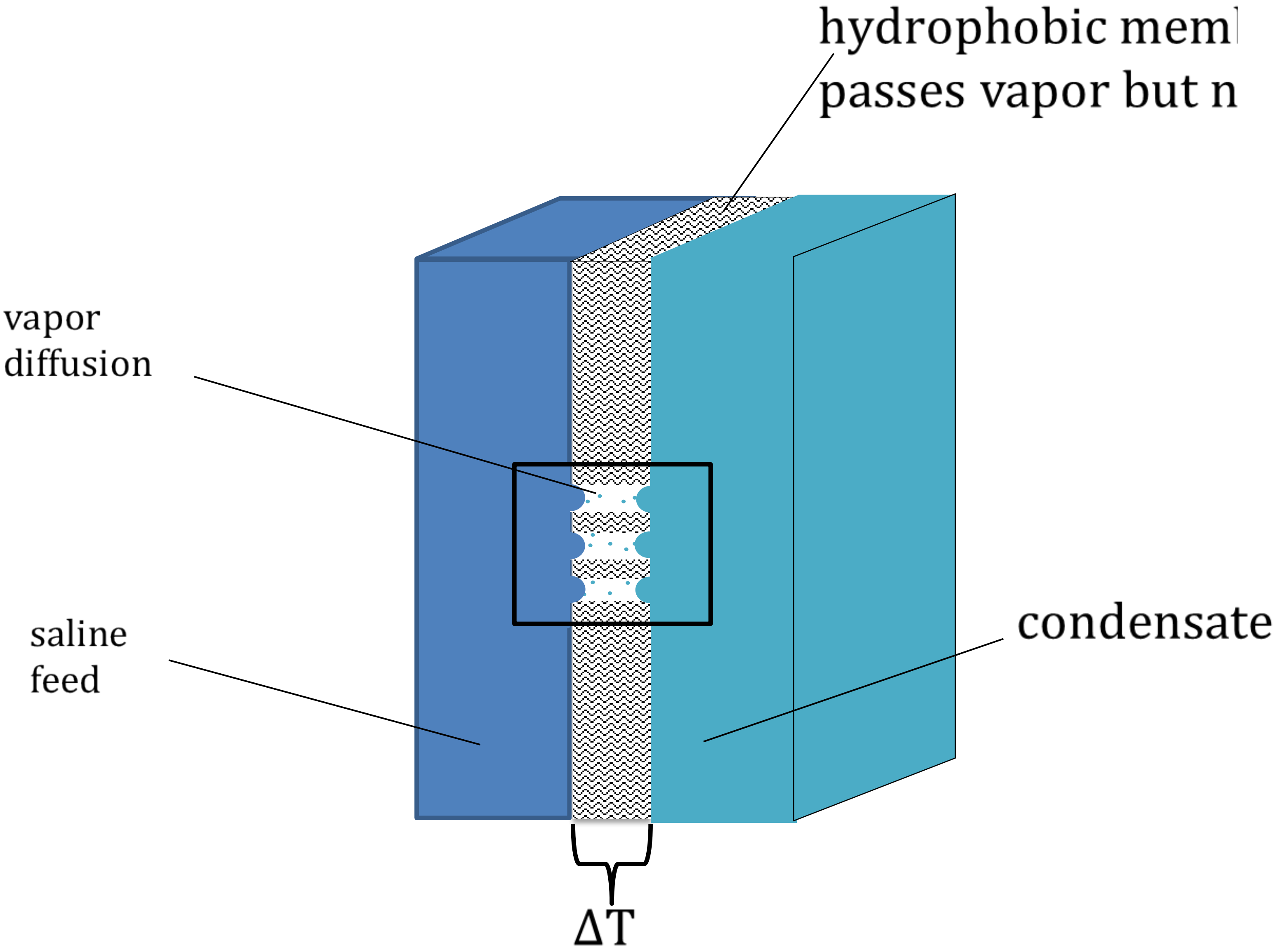
XZERO AB

aquaver

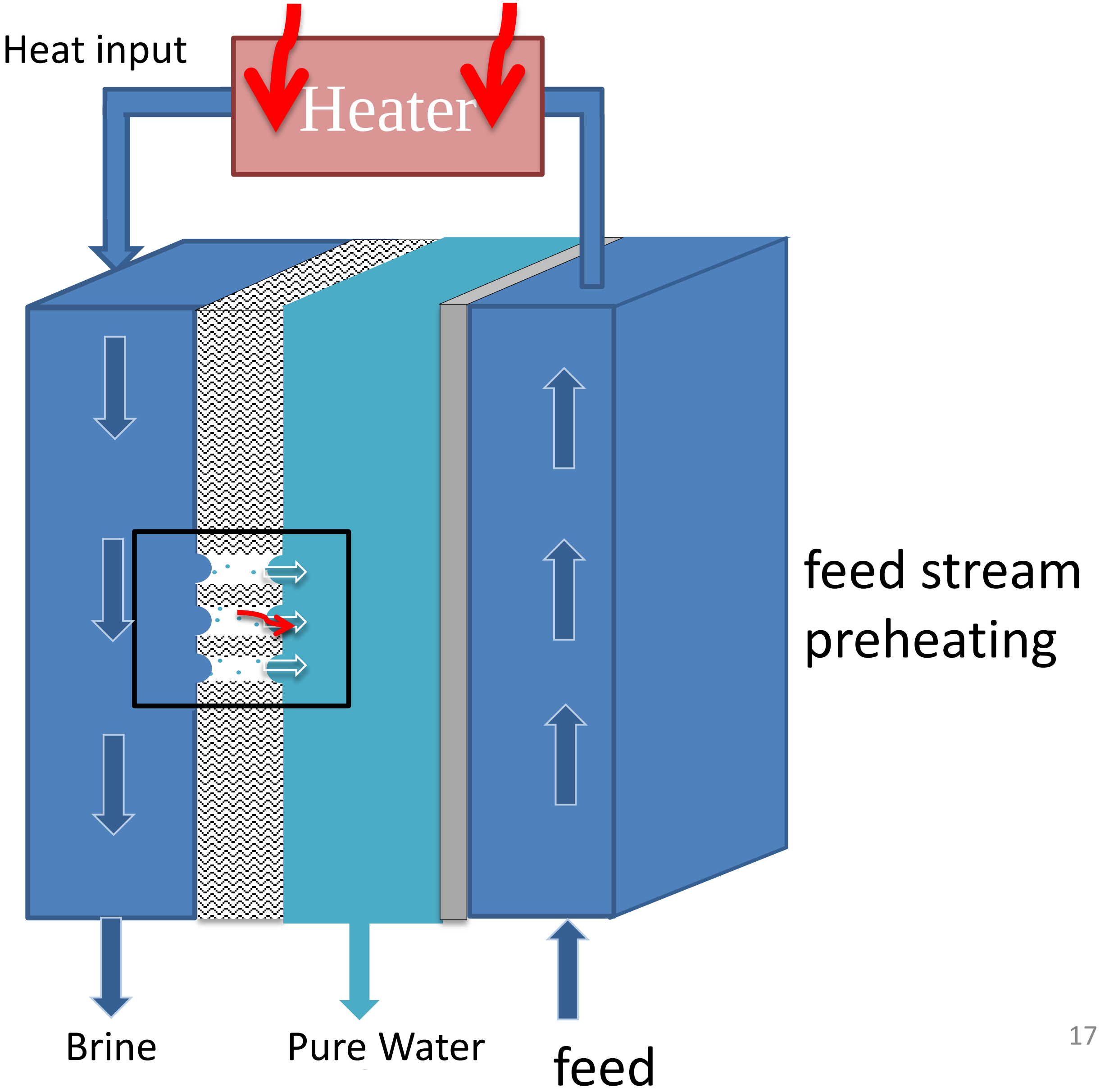
KmX

SolarSpring
Solar-Driven Water Treatment

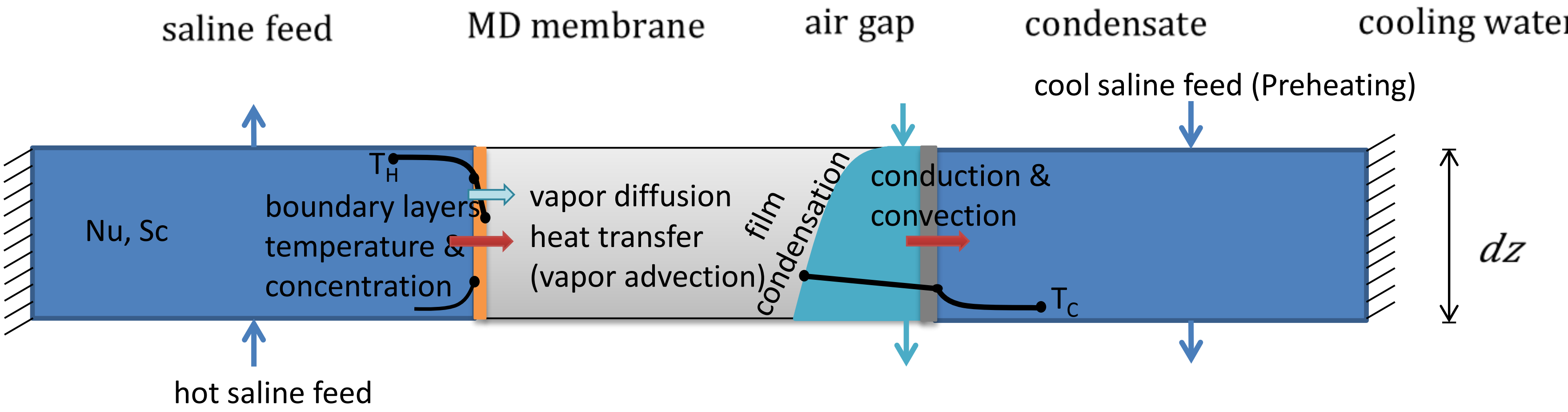
Membrane Distillation Process



Membrane Distillation Process



AGMD Computational Cell



Primary trade off:

Flux $$J = B * \Delta P_{vapor\ pressure}$$

thermal efficiency $$\eta_{MD} = \frac{\dot{Q}_{evap}}{\dot{Q}_{evap} + \dot{Q}_{cond}}$$

J	flux	[kg/m^{2}s]
B	MD membrane permeability	m^{2}s/kg
$\dot{Q}$	Heat transfer rate	[W]

Subscript Key

$_{evap}$ evaporation

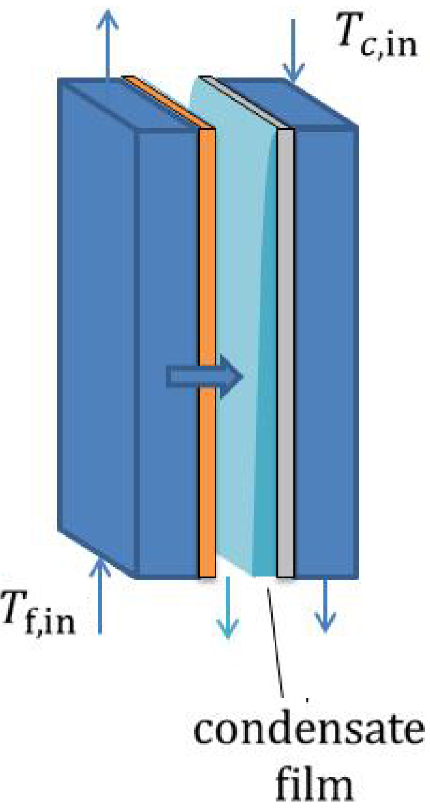
$_{cond}$ conduction

[21] Warsinger et al., *IHTC-15, Paper No. IHTC15-9351*, (Kyoto, Japan August 2014).

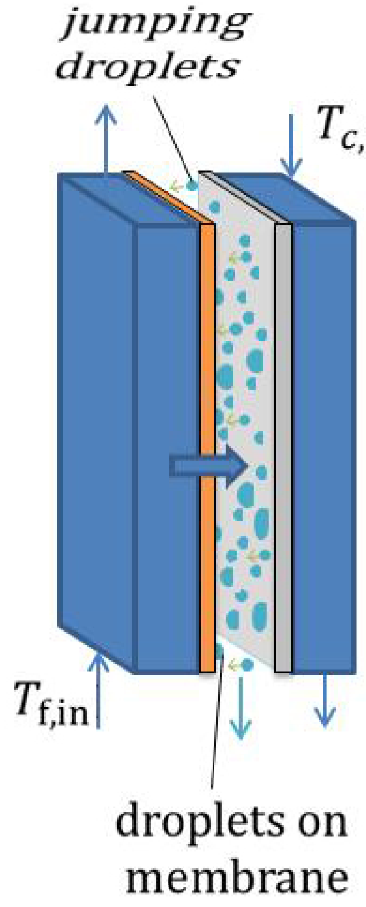
Jumping droplet condensation

Video recorded by N. Miljikovic

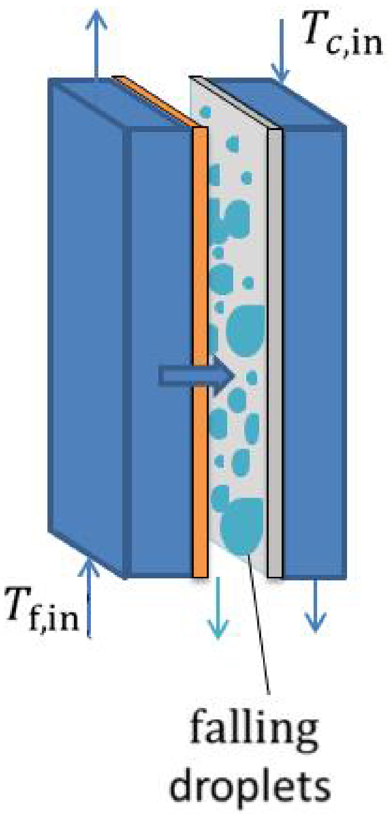
Air Gap Membrane Distillation: *Flow Regimes*



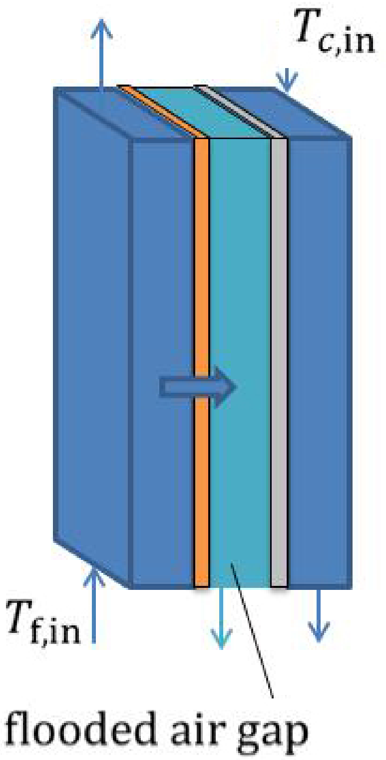
film



jumping droplets



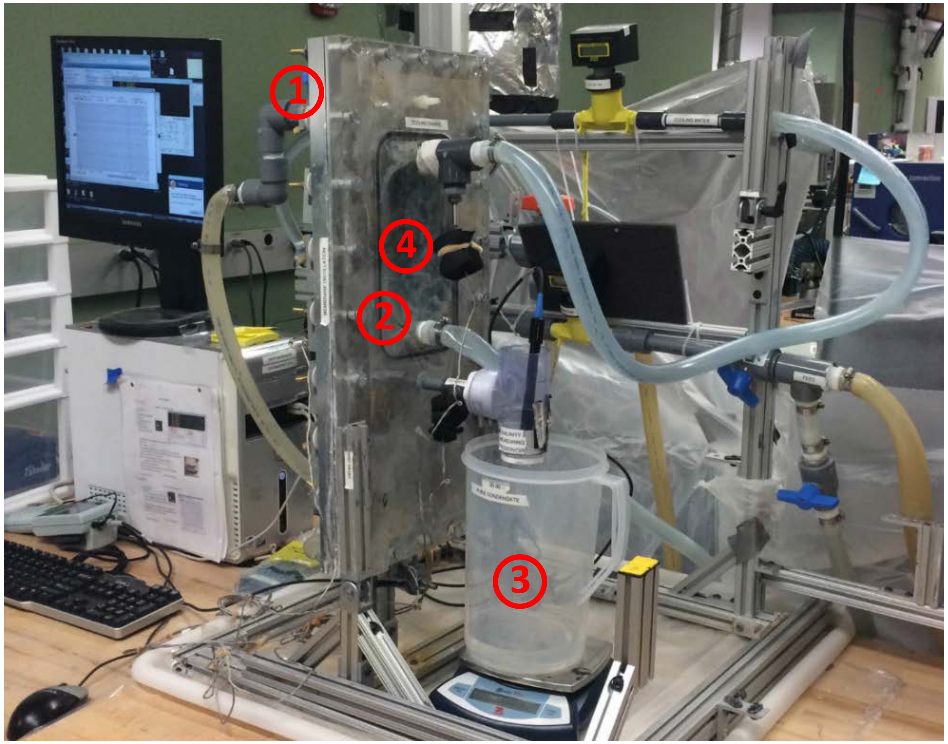
dropwise

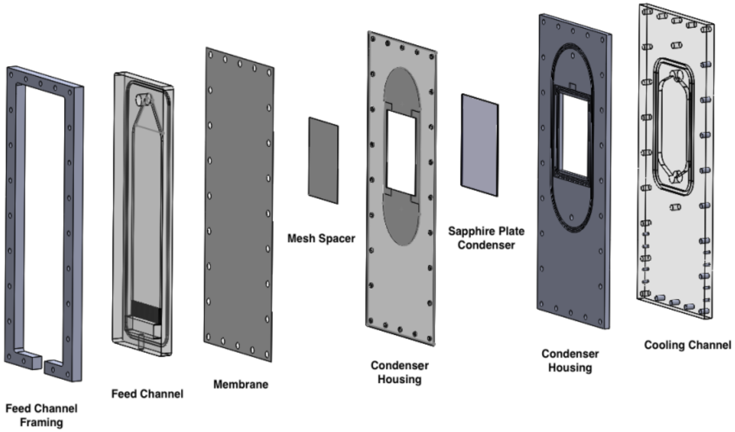


flooded

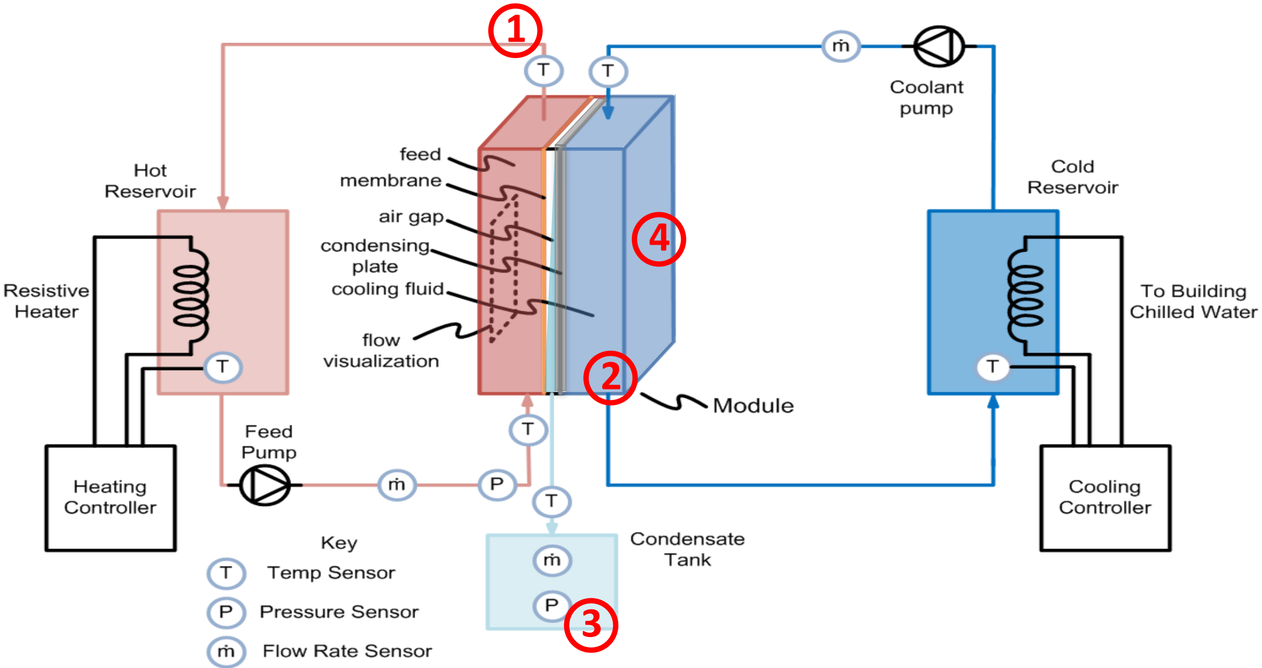
1. David Warsinger, Jaichander Swaminathan, Laith Maswadeh, and John Lienhard V. Superhydrophobic condenser surfaces for air gap membrane distillation. In *planned submission to Desalination*, October 2014.
2. 2. David Warsinger, Jaichander Swaminathan, and John. Lienhard V. Superhydrophobic condensing surfaces for air gap membrane distillation, October 2014. reference number 16942.

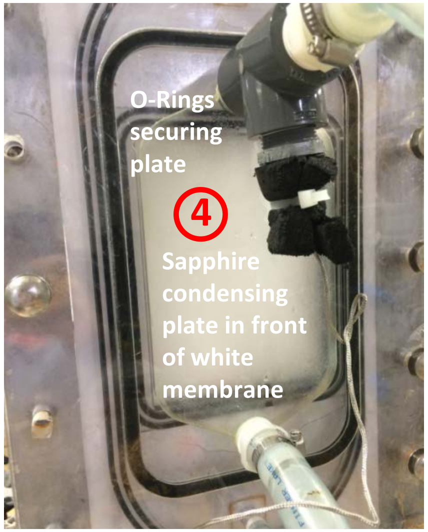
Air-Gap Membrane Distillation Experimental Setup





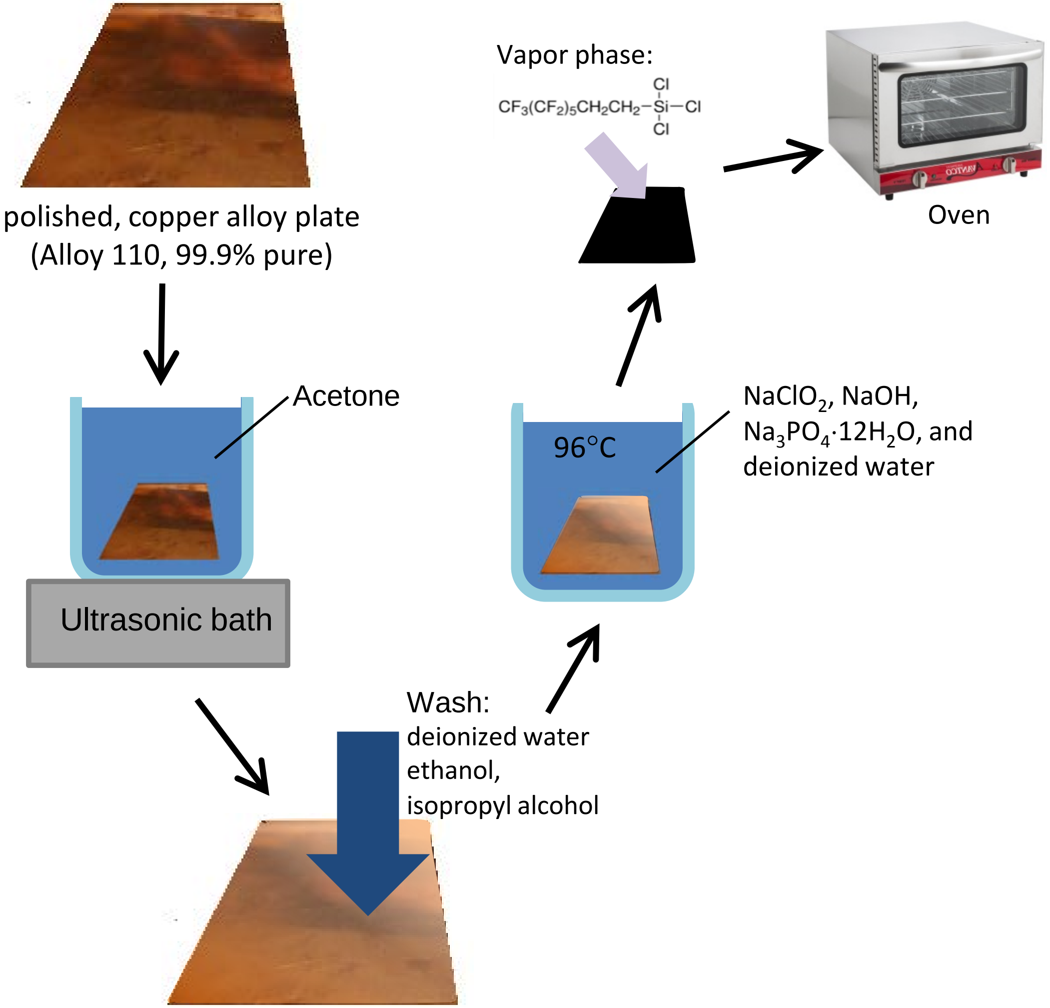
CNC Plates for Membrane Module





Sapphire condensing surface (visualization)

CuO Superhydrophobic Surface Fabrication



polished, copper alloy plate
(Alloy 110, 99.9% pure)

Acetone

Ultrasonic bath

Wash:
deionized water
ethanol,
isopropyl alcohol

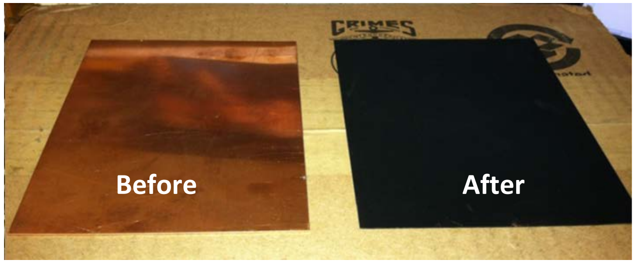
96°C

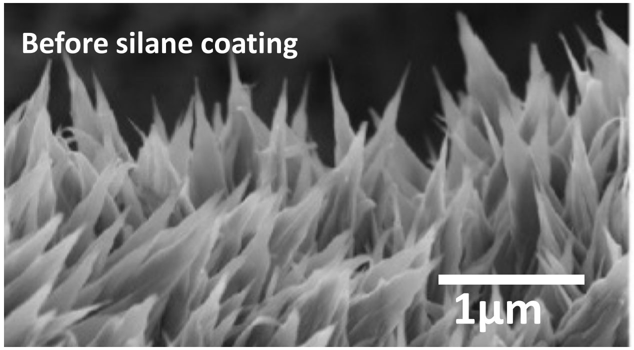
$NaClO_2$, $NaOH$,
$Na_3PO_4 \cdot 12H_2O$, and
deionized water

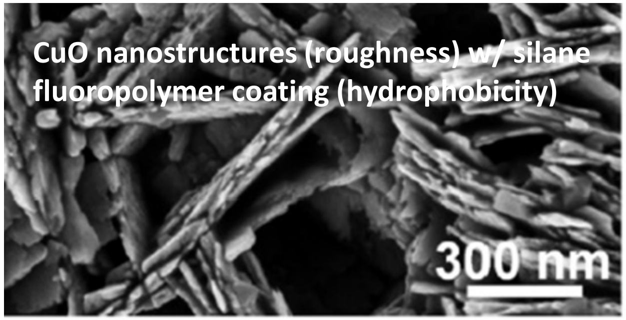
Vapor phase:

$\mathrm{CF_3(CF_2)_5CH_2CH_2{-}\overset{Cl}{\underset{Cl}{Si}}{-}Cl}$

Oven





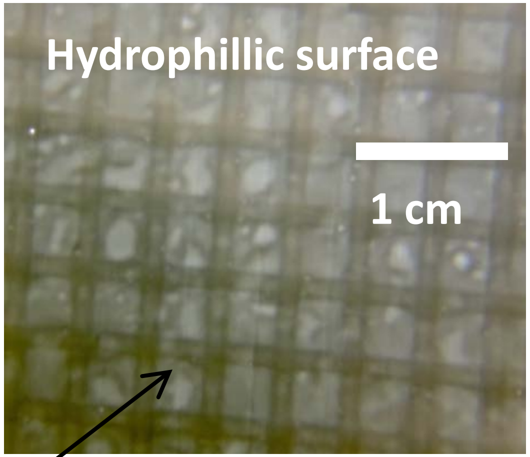


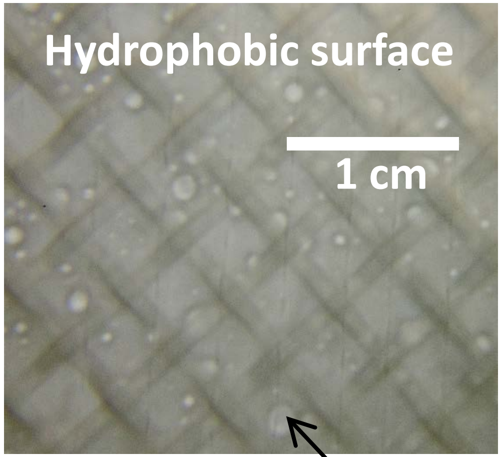
1. D. M. Warsinger et al., Journal of Membrane Science, vol. 492, pp. 578–587, 2015.
2. N. Miljkovic et al. Nanoletters, vol. 13, pp. 179–187, 2012.

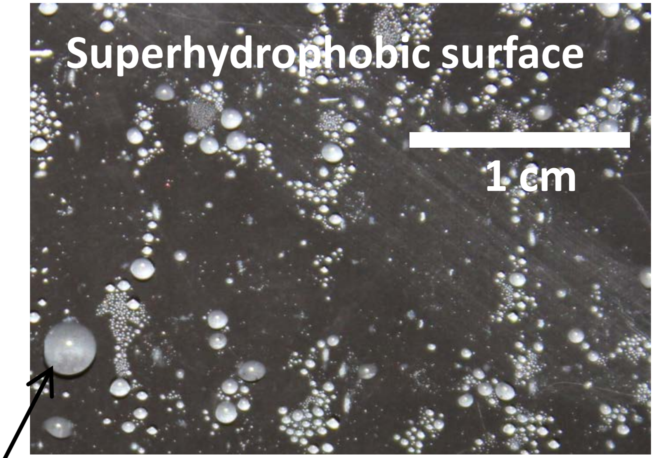
CuO Superhydrophobic surface desired properties

- High roughness (hydrophobicity)
- Low surface energy coating (hydrophobicity)
- Thin self-limiting layer (thermal conductivity)
- Materials with high thermal conductivity (CuO)
- Robustness for long duration operation
- Scalable to large sizes cheaply (via bath process)

Hydrophobic condensing in MD







Plugflow,
complex
trapped fluid

Visuallized through sapphire condensing surface

Small droplets

After operation, membrane removed

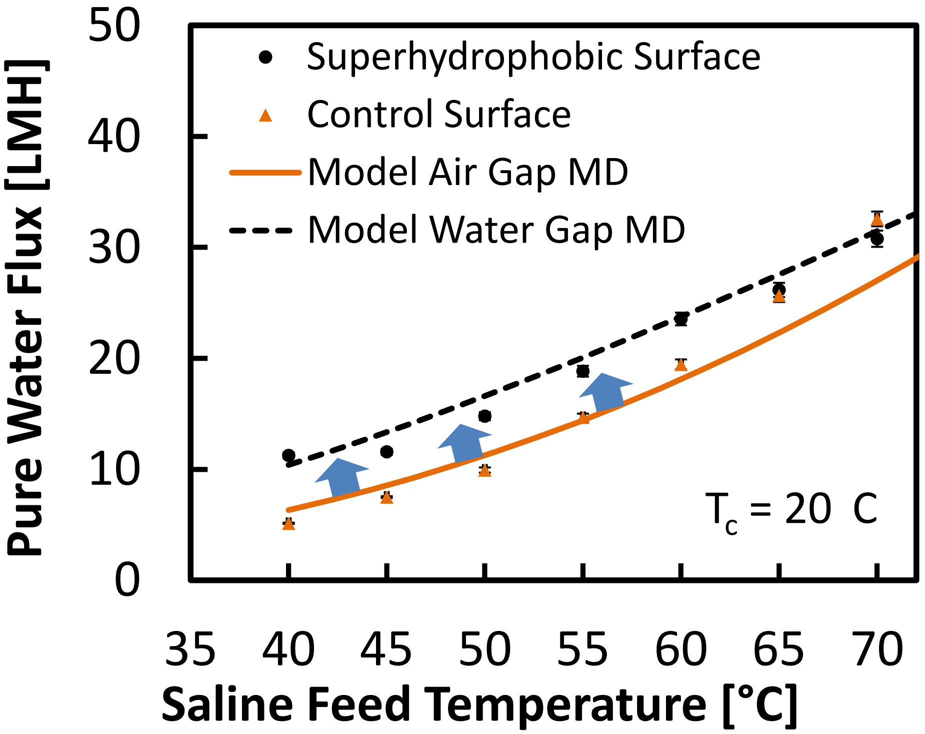
Summary of the influence of gap and configuration changes on permeate flux

parameter	Spacer Orientation	Surface Hydrophobicity	Spacer Hydrophobicity	Mesh Thermal Conductivity	Tilt Angle
range/details	horizontal & diagonal	Contact angle of <20° to 164°	Contact angle of ~80° to ~150°	~0.3 to 400 W/m^2K	Module tilt of -60° to 85°
Flux Increase	<5%	0-110%	-22-2%	21-119%	0-54%

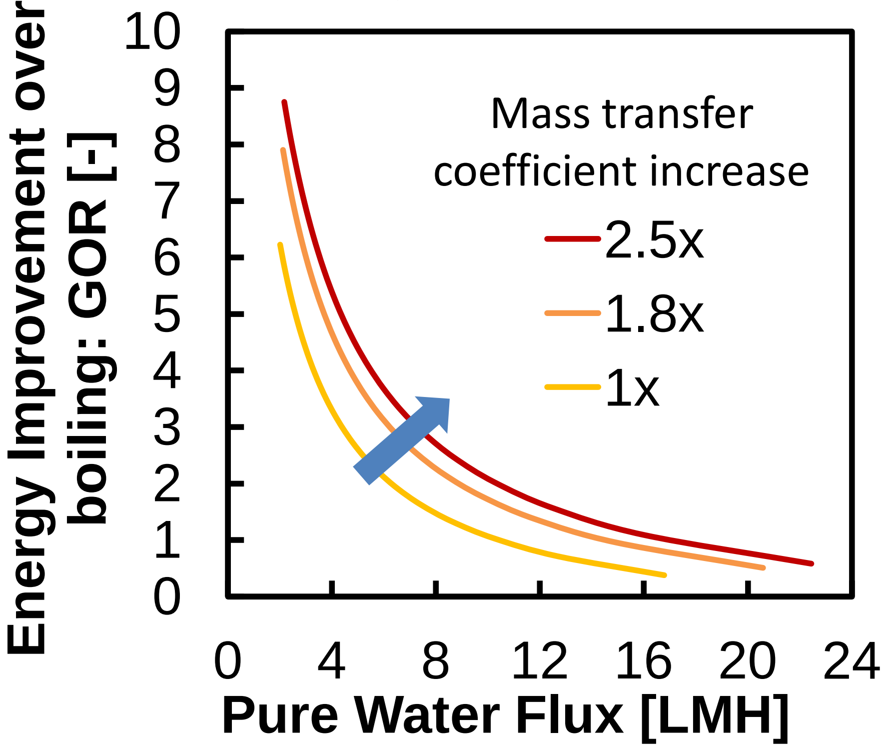
Jumping Droplet Condensation in Membrane Distillation

CuO Coated and silanized surfaces

Improved Condensate Flux



Improved Flux vs Energy Tradeoff



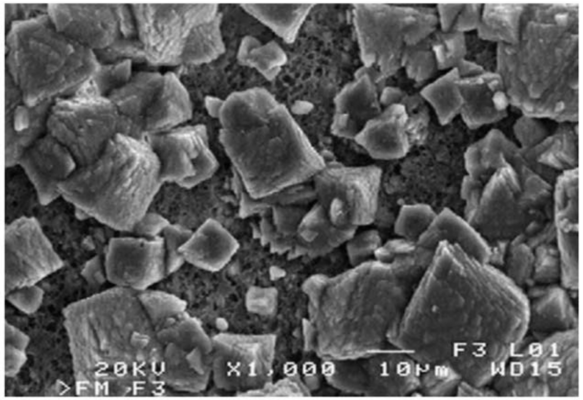
1. Warsinger et al., Journal of Membrane Science, vol. 492, pp. 578–587, 2015.
2. Warsinger et al., October 2014. Full Patent Application, US Application No. 14/517,342

Implications of hydrophobic condensing

- It improves **flux** substantially, and overall **efficiency** (GOR). Are similar gains possible in other thermal desalination technologies?
- Can other condensing and micro-fluidic nanotechnologies improve this and others, including directional **wicking**?
- How will technologies be **designed differently** at the nano and system-level with these techniques?

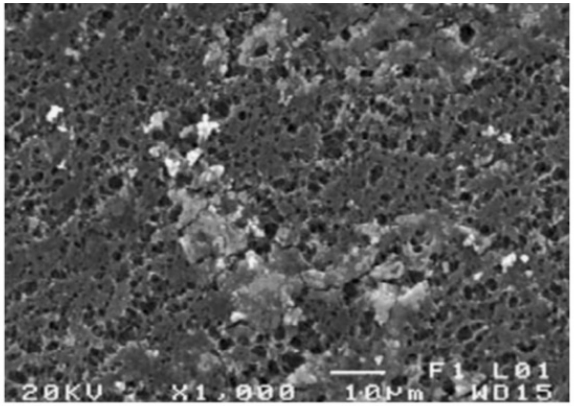
Fouling Types in MD

Inorganic scale



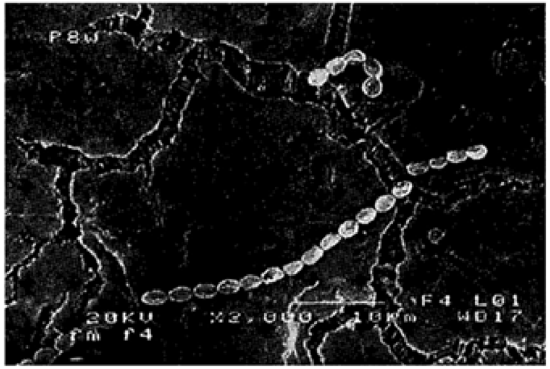
$CaSO_4$

Particulate fouling



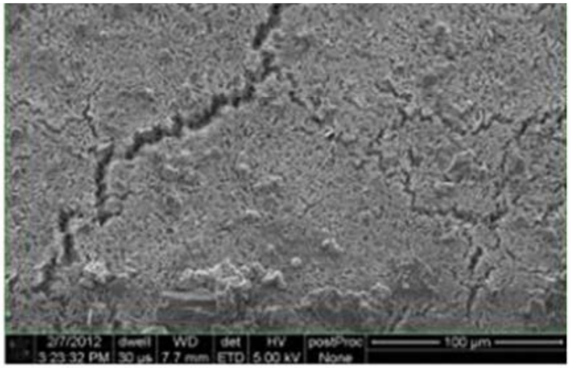
Iron Oxide

Biofouling



Streptococcus faecalis

Membrane degradation

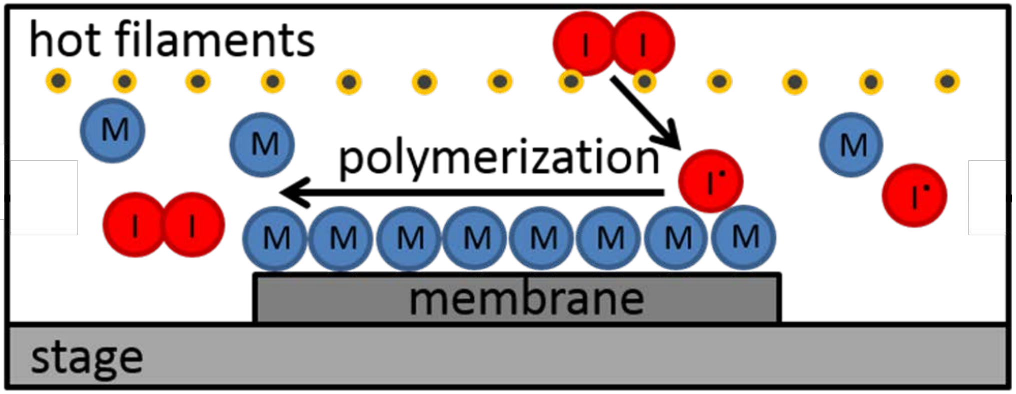


cracking from intermittent operation

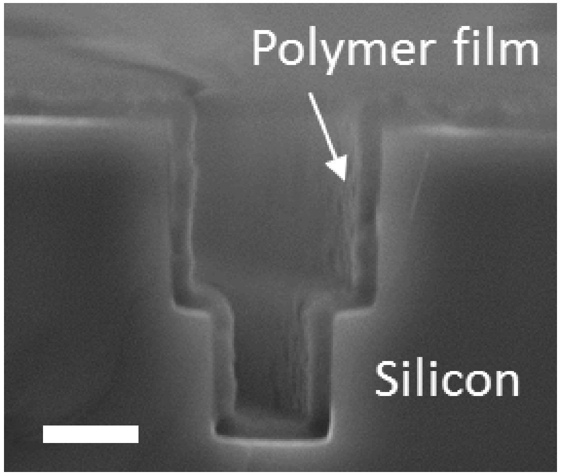
David M. Warsinger, **Jaichander Swaminathan, Elena Guillen-Burrieza, Hassan A. Arafat, and John H. Lienhard V.** Scaling and fouling in membrane distillation for desalination applications: A review. *Desalination*, in press, 2014.

Polymer thin films deposited using initiated chemical vapor deposition (iCVD)

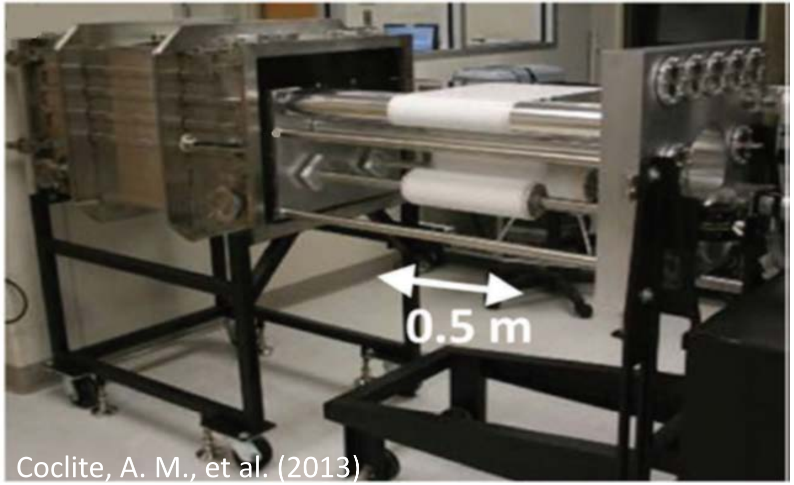
iCVD chamber



iCVD polymer film



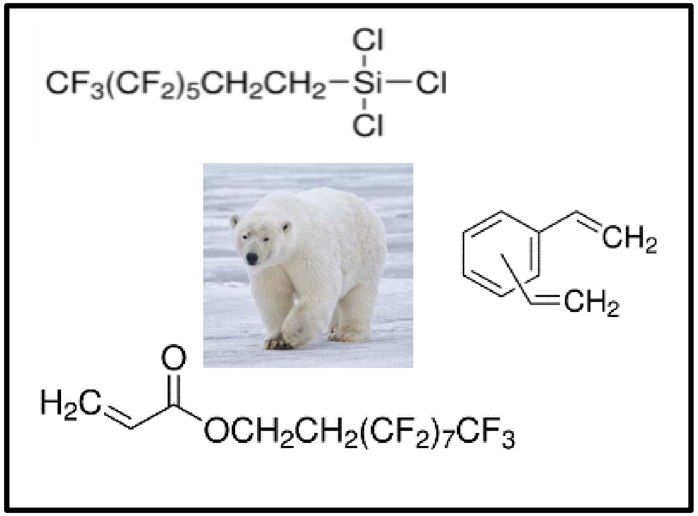
Roll-to-roll iCVD system



Coclite, A. M., et al. (2013)

iCVD for hydrophobic membranes

iCVD parameters to optimize

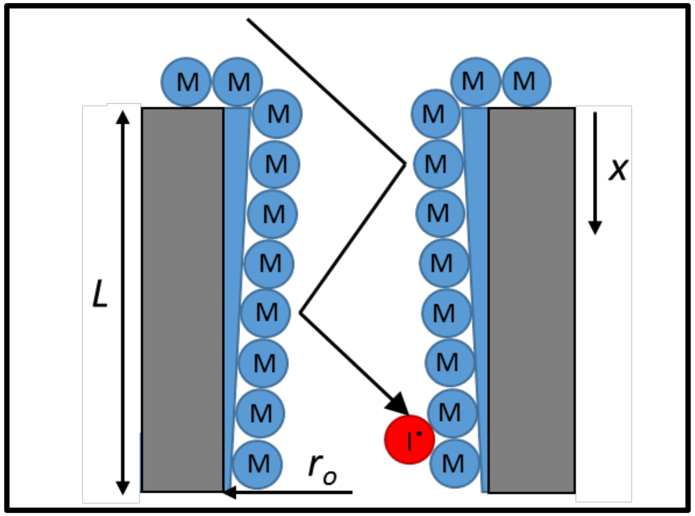


1. Chemistry

-Safe?

-Hydrophobicity?

-Stability & performance



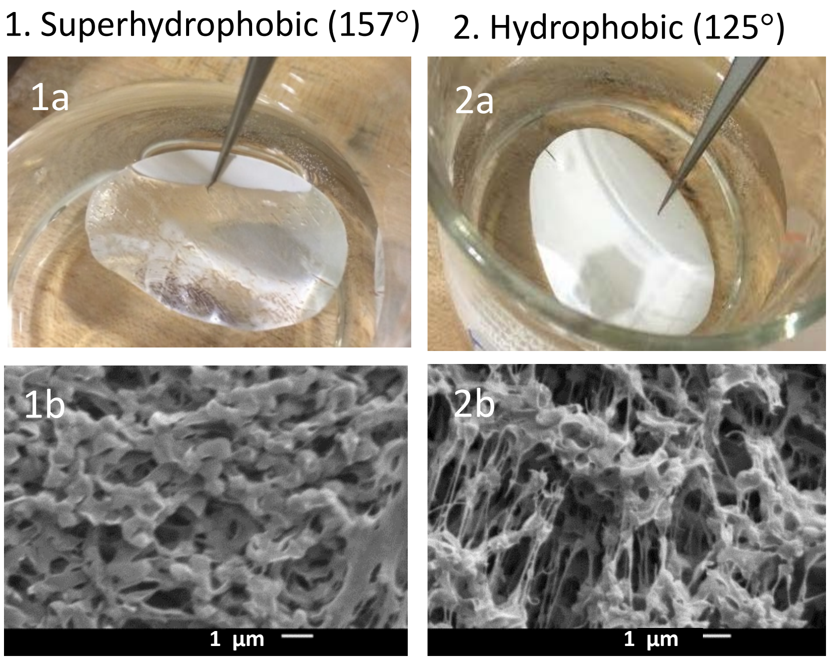
2. Thickness and conformality

-Avoids pore blocking

-Avoids gaps in surface coverage

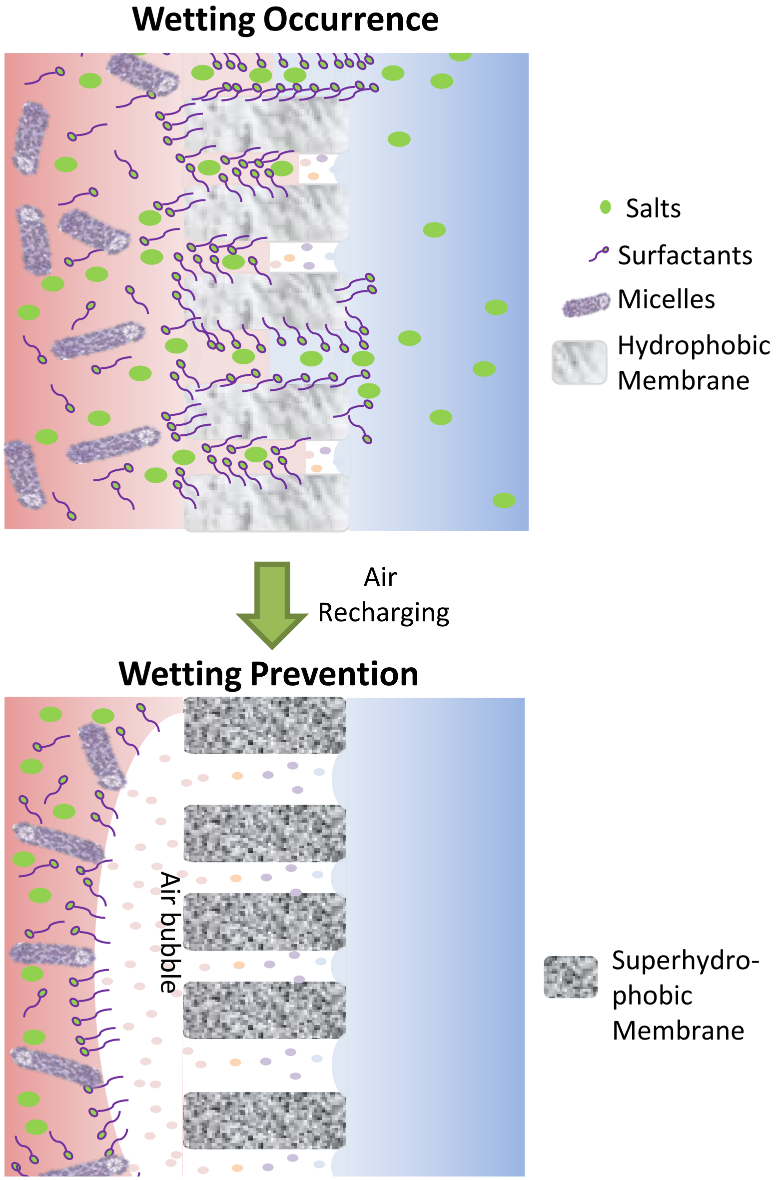
Fouling Resistant Nanoengineered Membranes

Superhydrophobicity & Air Layers

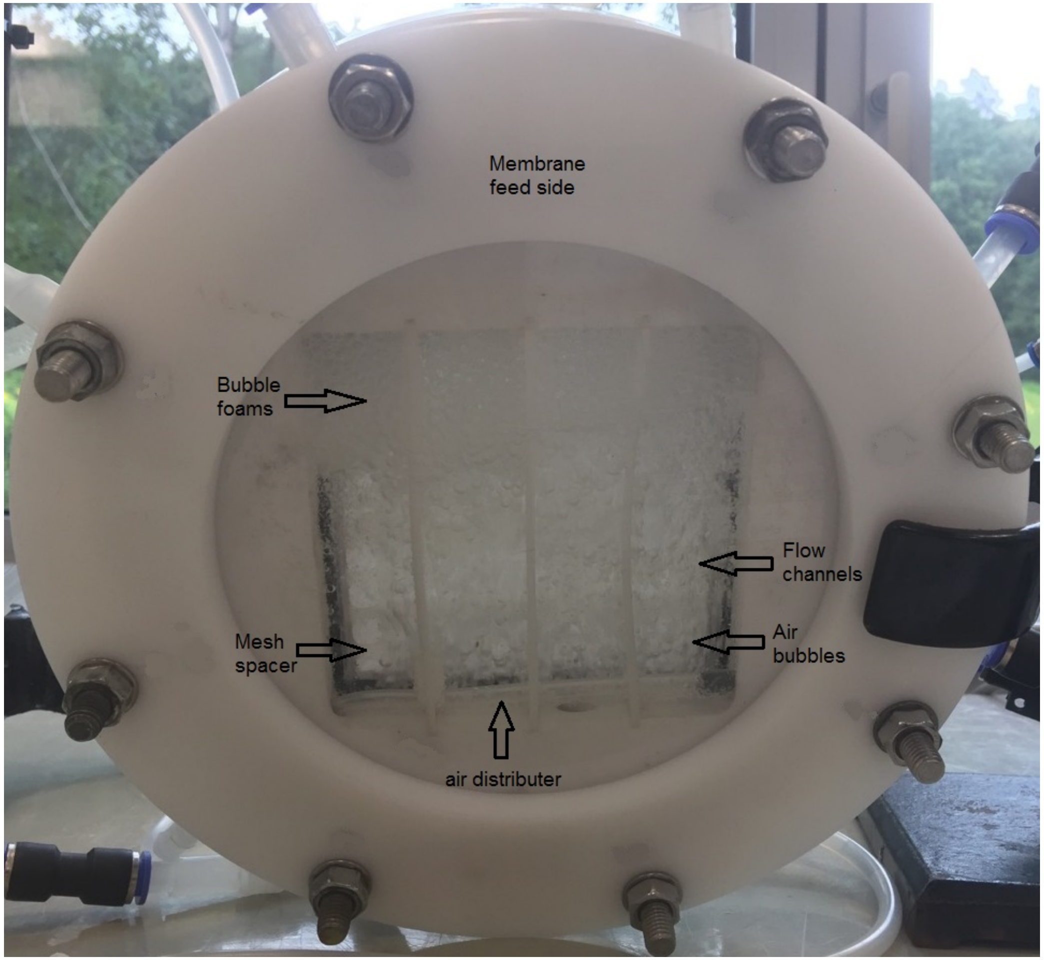

1. Superhydrophobic (157°)

2. Hydrophobic (125°)

Top: submerged superhydrophobic MD membrane, visibly shiny due to the thin air layer on its surface.
Bottom: SEM images of MD membrane surface. PVDF membrane coated with PFDA via iCVD for superhydrophobicity



[6] Warsinger et al. *Journal of Membrane Science in June 2015* **505**, 241–252 (2016).
[19] Warsinger et al. In *Proceedings of ACE15, Anaheim, CA, USA*, (2015).
[29] Warsinger et al. ” *Provisional Patent Application Submitted, mit-17920pro*, 2015

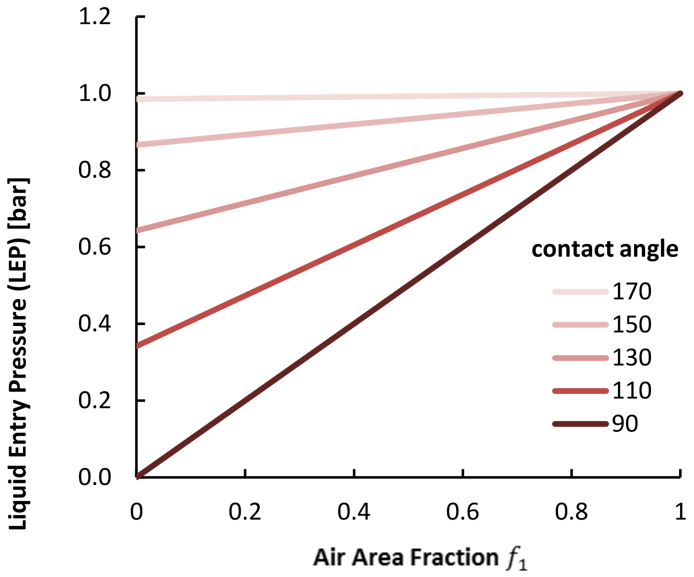


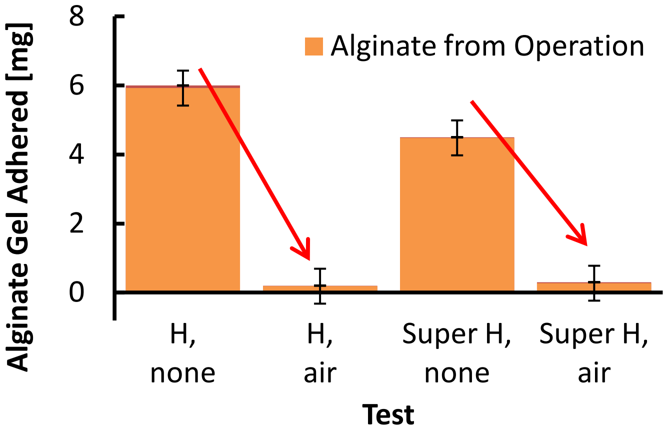
Properties of polymeric membranes

Membrane type	Manufacturer	Trade name	Polymer	Thickness (µm)	Nominal pore size (µm)	IPA bubble point (kPa)	Air flowrate (l/min/cm^2 @ 0.7 bar)	Contact angle
Flat sheet	Enka	Accurel 2E-PP	PP	177	0.2	114.5	1.3	113°
Flat sheet	Donaldson	Tetratex 6532	PTFE/ PES	130	0.1	200	3	153°

Fouling Resistant Nanoengineered Membranes

Superhydrophobicity & Air Layers





H = hydrophobic

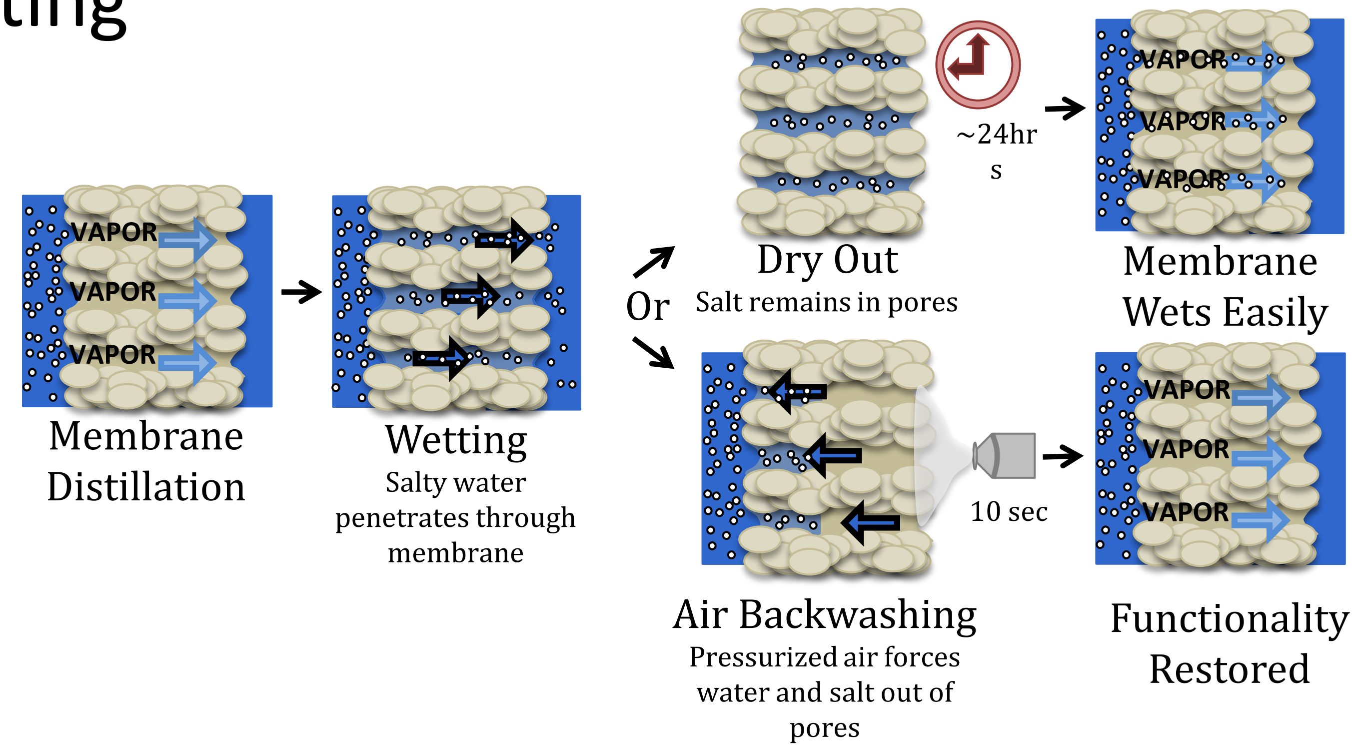
air vs none = with air layer recharging or not

Experiment	Membrane	Feed side		Permeate side		Maximum SDS Conc. before wetting
		Air recharg-ing	Spacer	Air recharg-ing	Spacer	
E1 (Default 1)	PP	-	-	-	-	0.2
E2	PP	-	+	+	+	0.3
E3	PP	+	-	-	+	0.3
E4 (Default 2)	PTFE	-	-	-	-	0.4
E5	PP	+	+	-	+	0.4
E6	PTFE	+	+	-	+	0.8< (no wetting)

Fouling Resistant Nanoengineered Membranes

Superhydrophobicity & Air Layers

Concept: providing air at high pressure from the backside (from pure permeate) to reverse wetting



Membrane Distillation

Wetting

Salty water penetrates through membrane

Or

Dry Out

Salt remains in pores

~24hrs

Membrane Wets Easily

Air Backwashing

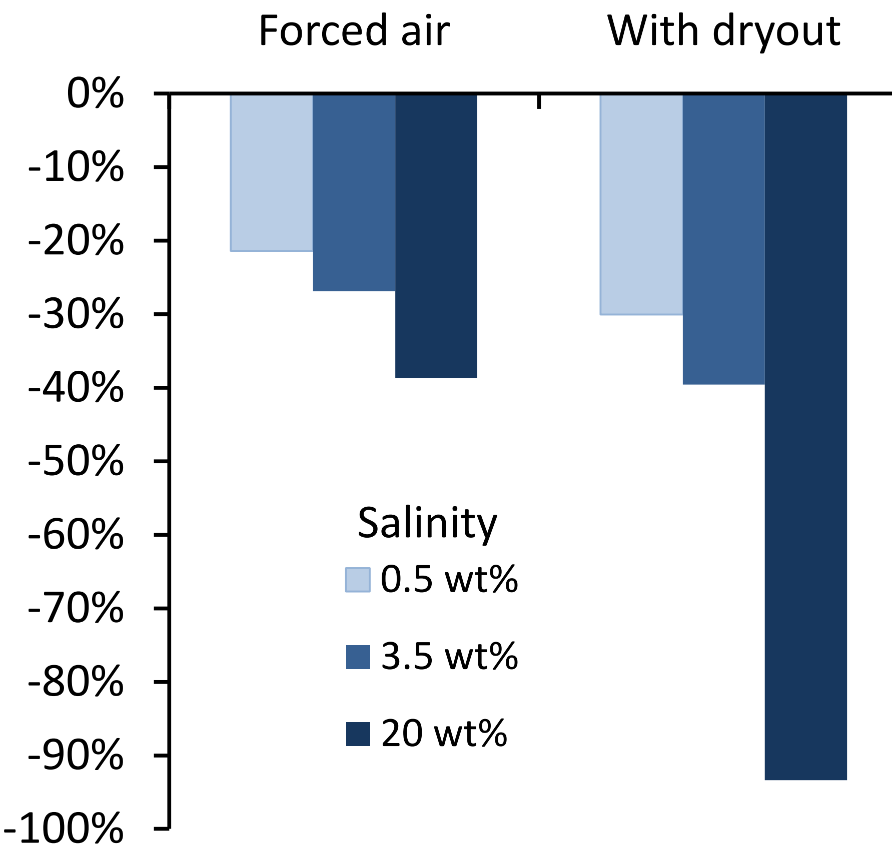
Pressurized air forces water and salt out of pores

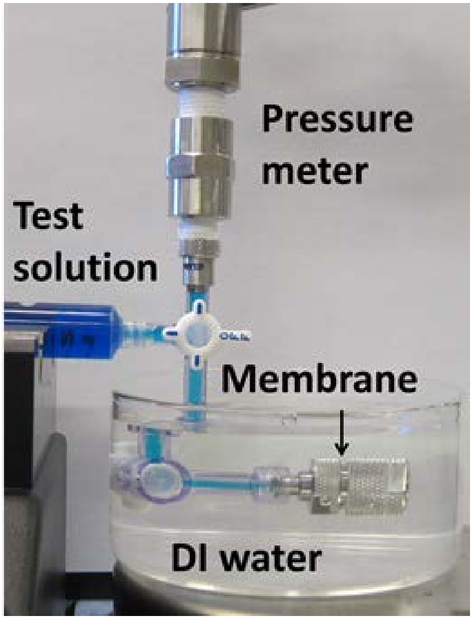
10 sec

Functionality Restored

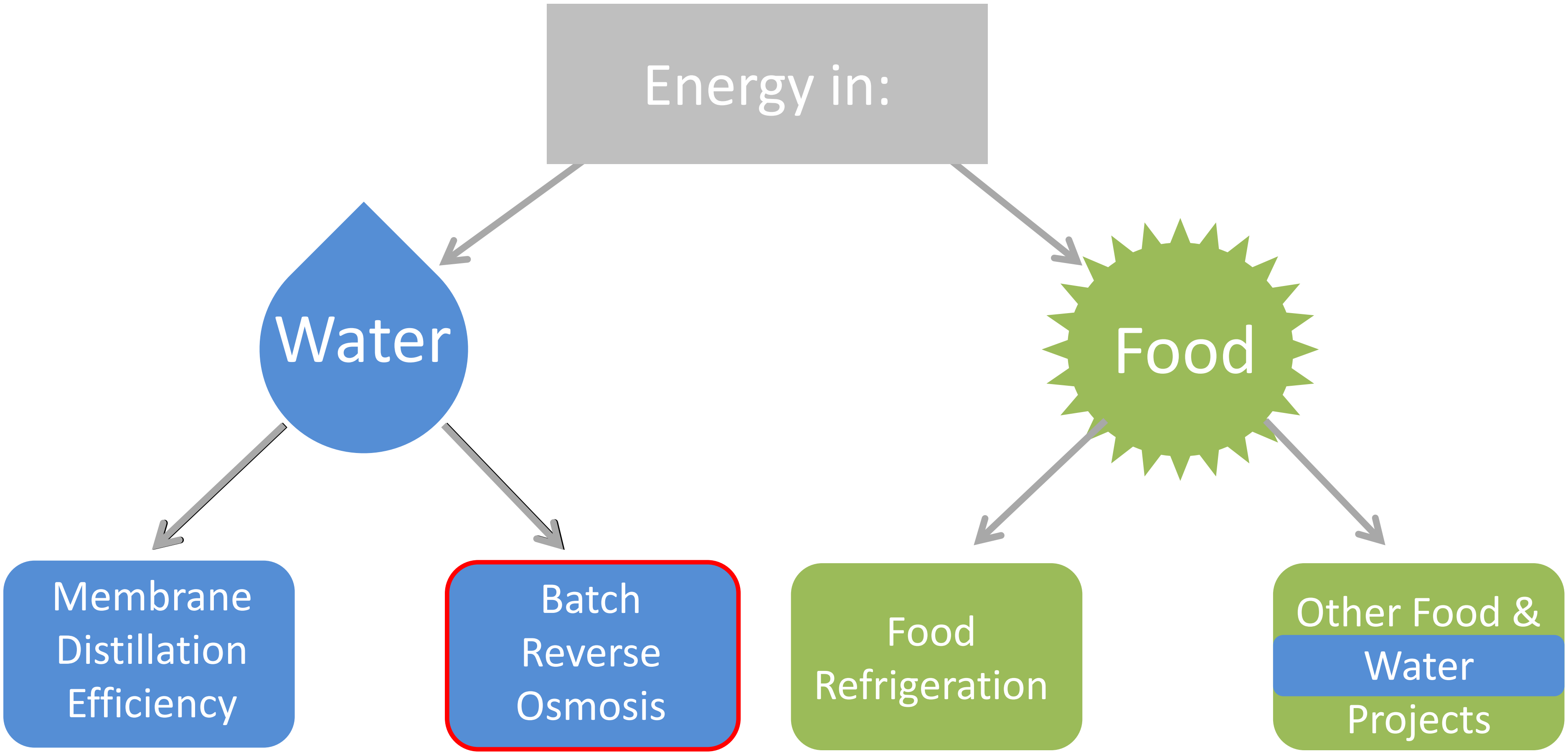
Fouling Resistant Nanoengineered Membranes
Superhydrophobicity & Air Layers

Percent Change in Liquid Entry Pressure (LEP) after breakthrough





Warsinger et al. *Provisional Patent Application Submitted, mit-18467Kpro (2016).*
Warsinger et al. , *MTC16, February 1-5, 2015, San Antonio, Texas*, February (2016).



Energy in:

Water

Food

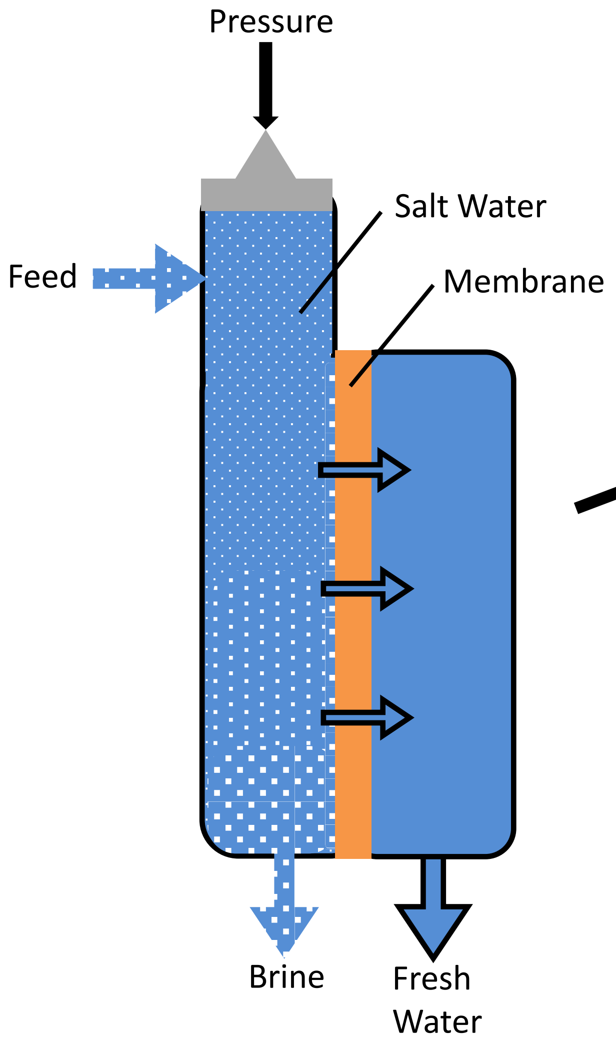
Membrane Distillation Efficiency

Batch Reverse Osmosis

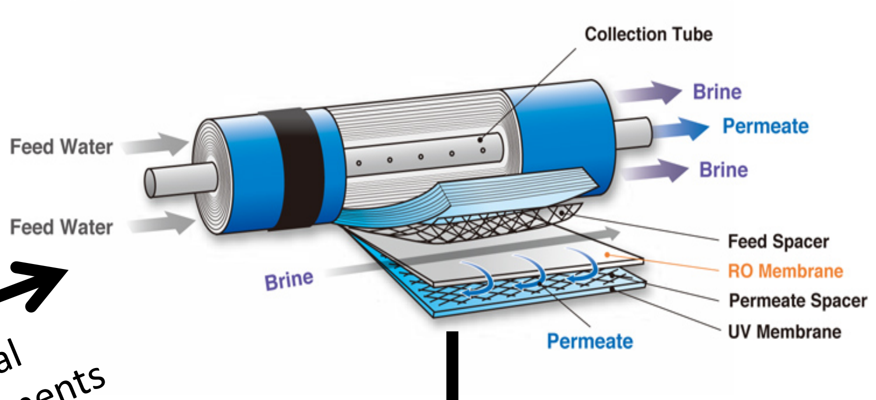
Food Refrigeration

Other Food & Water Projects

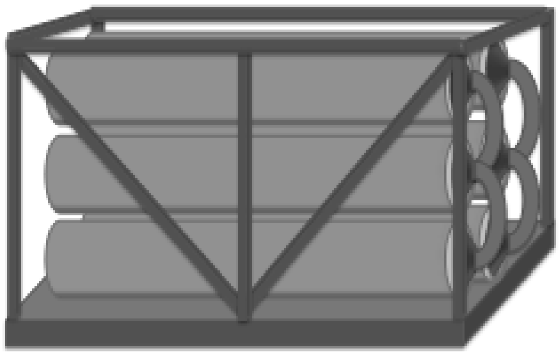
Reverse Osmosis (RO)



Kept in Spiral Wound Elements



Many elements to an RO membrane module



$$W_{lost} = \int \Delta P_{\text{applied}-\text{osmotic}}\, dV$$

aquanext Inc. URL: http://www.aquanext-inc.com/en/product/desalination02.html

RO Energy Modeling

Osmotic pressure

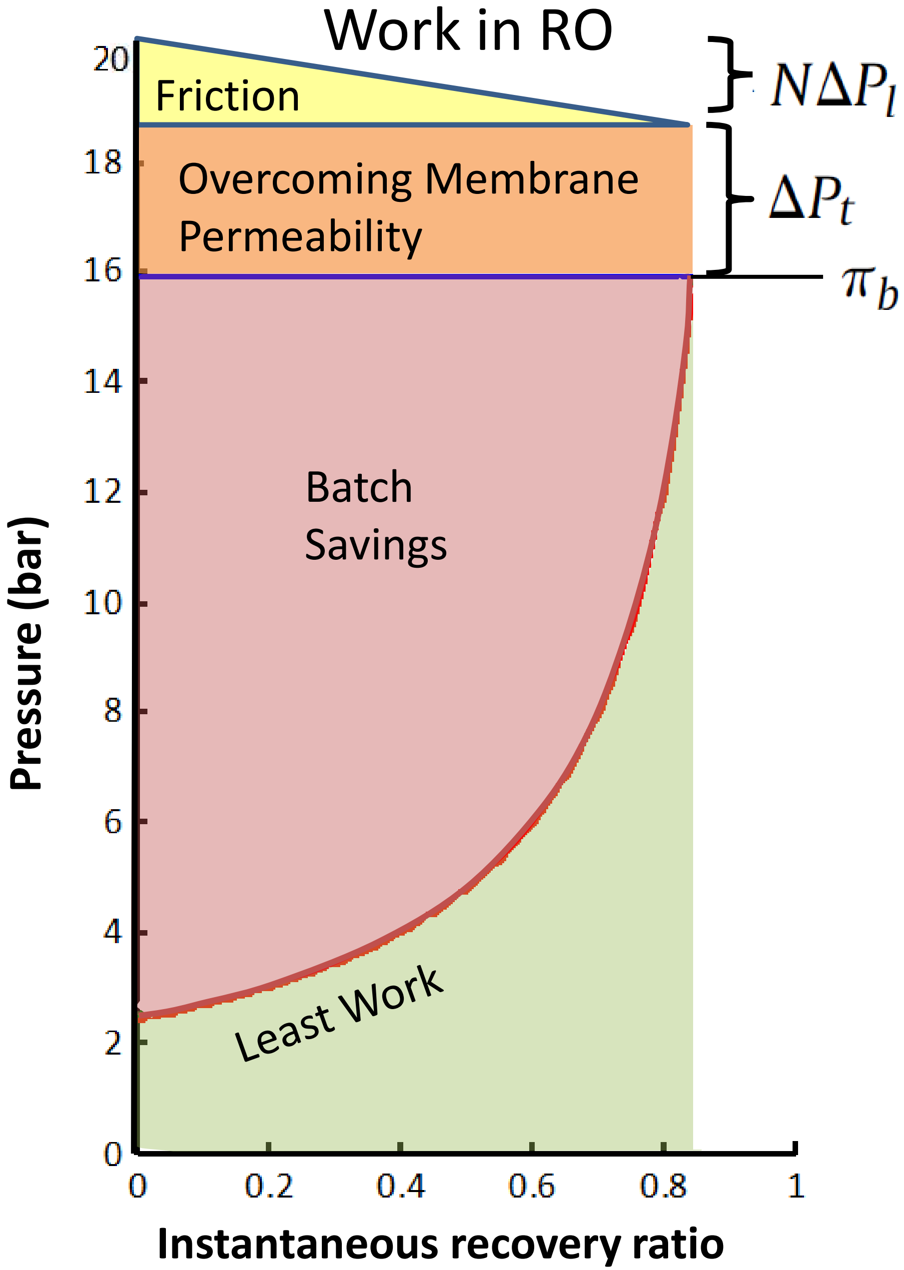
Terminal Overpressure

Viscous losses each pass

$$w_{RO} = \frac{\pi_b + \Delta P_t + N\Delta P_l}{\eta_p \mathrm{RR}}$$

Pump efficiency

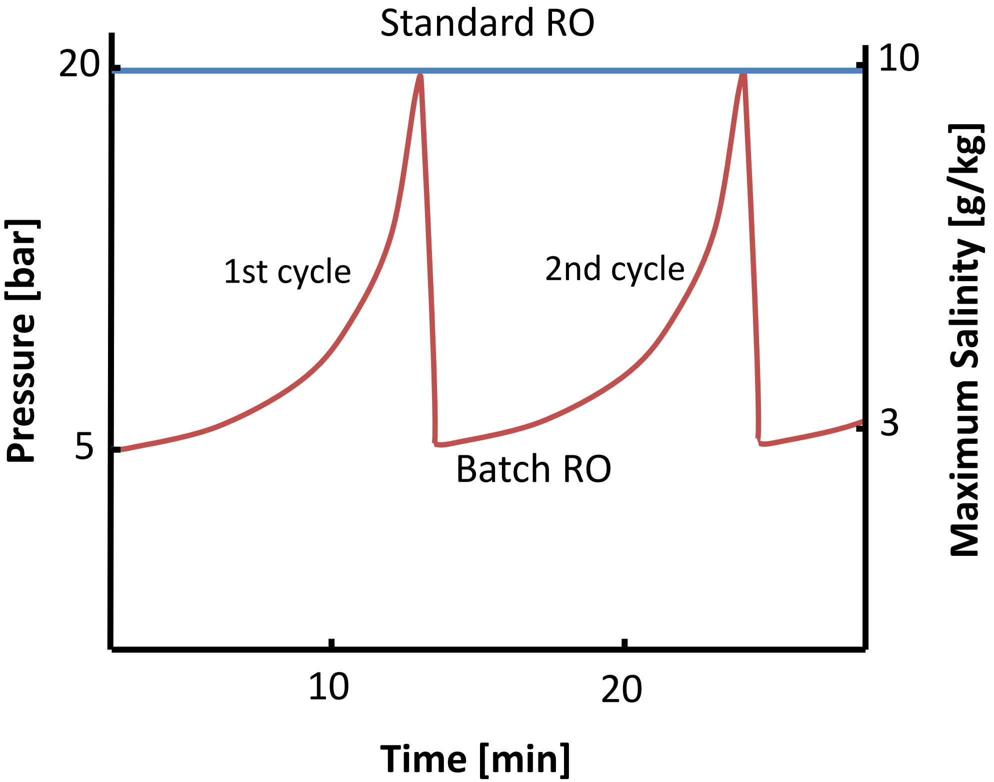
Recovery Ratio



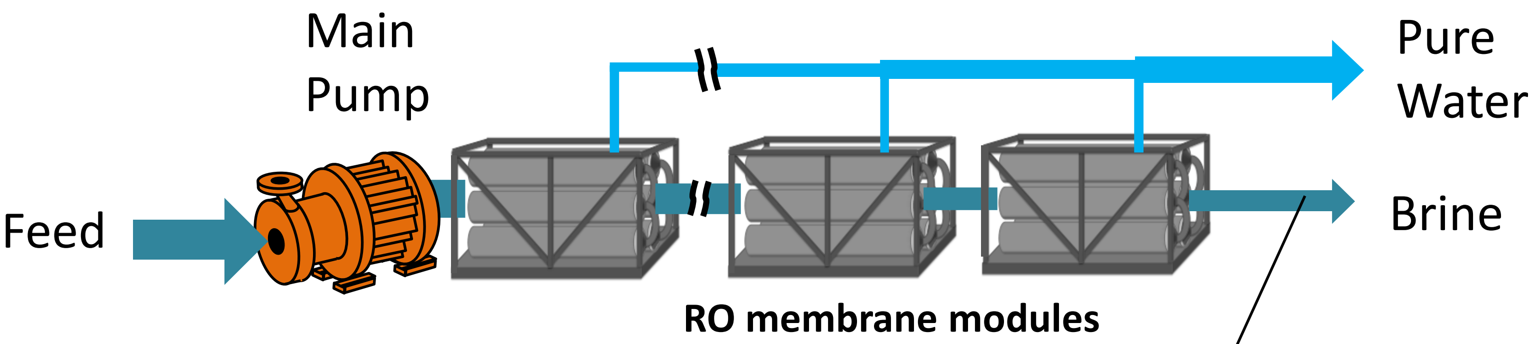
D. M. Warsinger et al., *Water Research*, vol. 106, pp. 272-282, 2016.

What is Batch?

- A set volume of liquid is concentrated
- Pressure varies over time

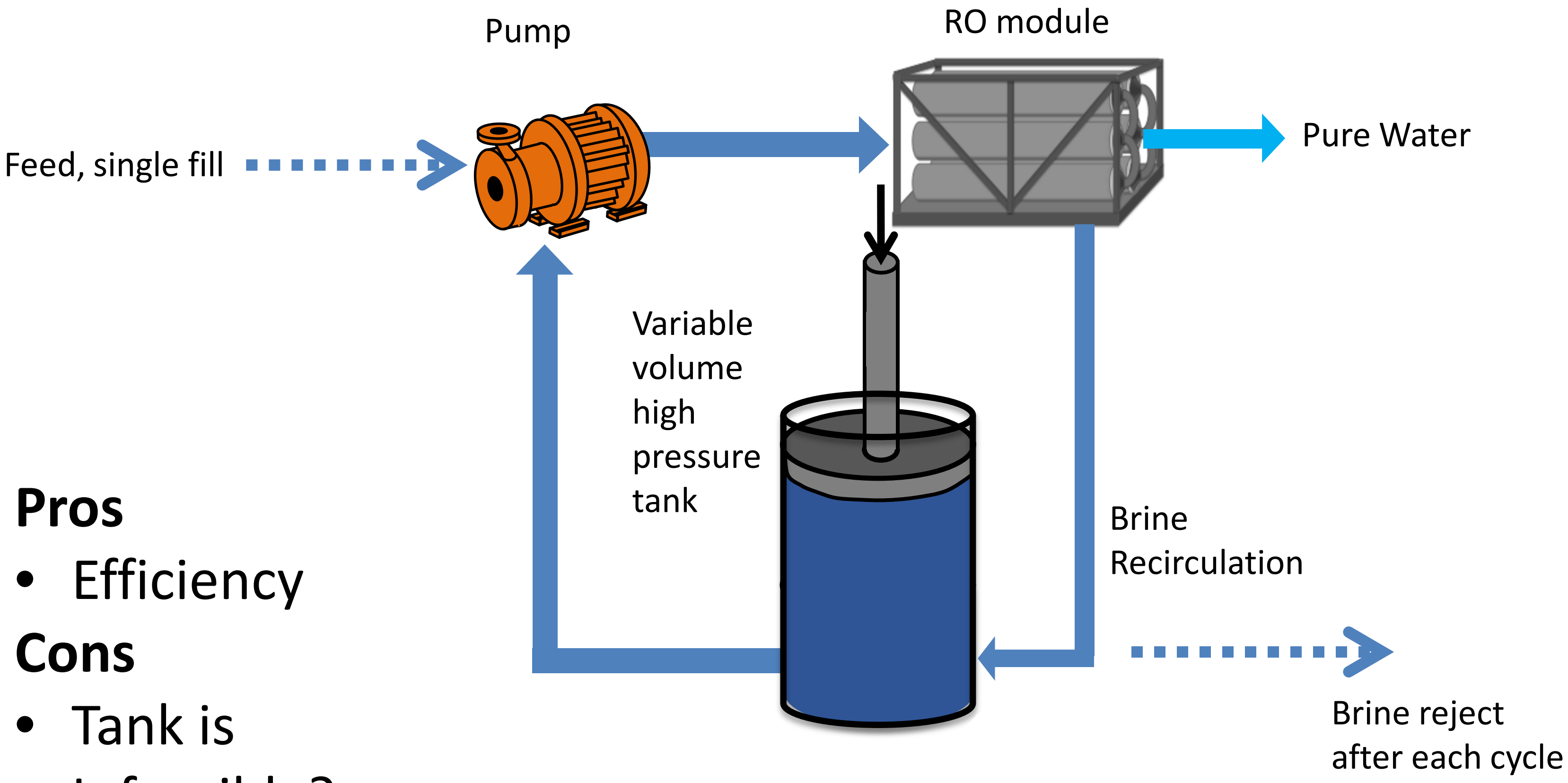


Standard RO



Pressure energy can be
recovered from brine

Batch RO: High Pressure Tank Concept



Pros

- Efficiency

Cons

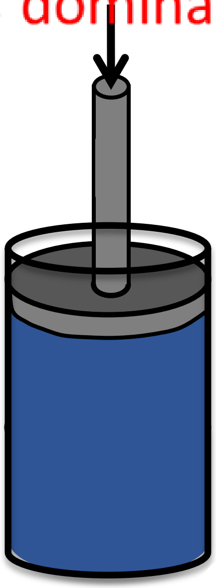
- Tank is Infeasible?

How to make a high pressure tank Batch Process?

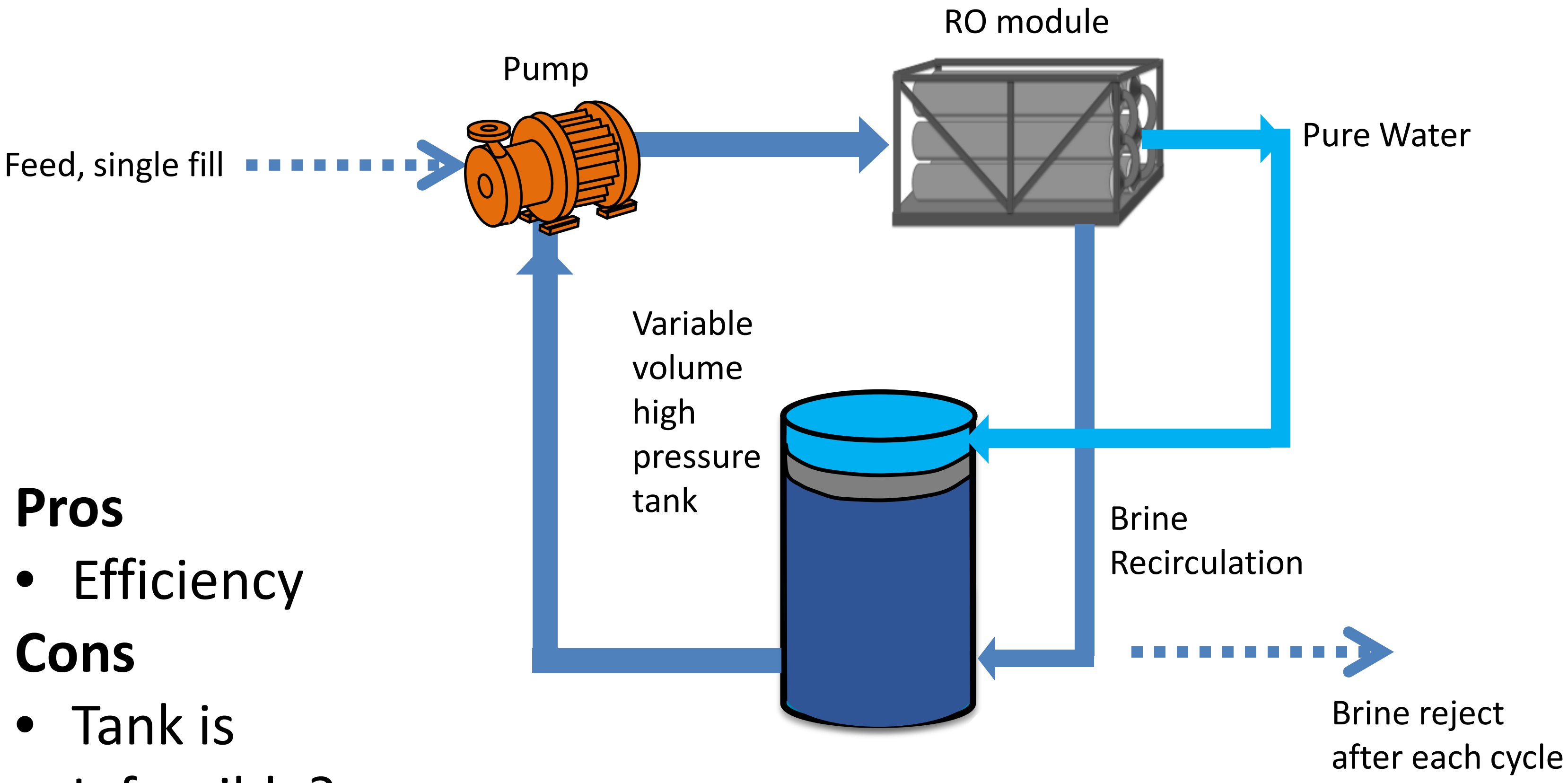
Need: simultaneously set ideal pressure while volume changes over time, done reversibly!

Idea?

- Motor? Small inefficiencies dominate
- Springs? No $\frac{dP}{dt}$ control



Batch RO: High Pressure Tank Concept



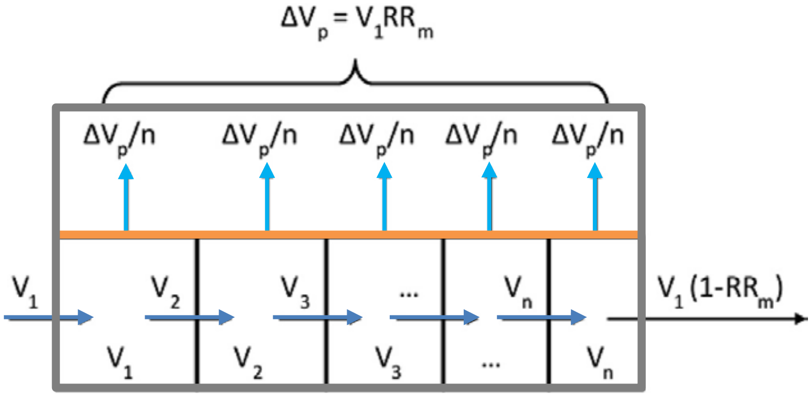
Pros

- Efficiency

Cons

- Tank is Infeasible?

Analysis details

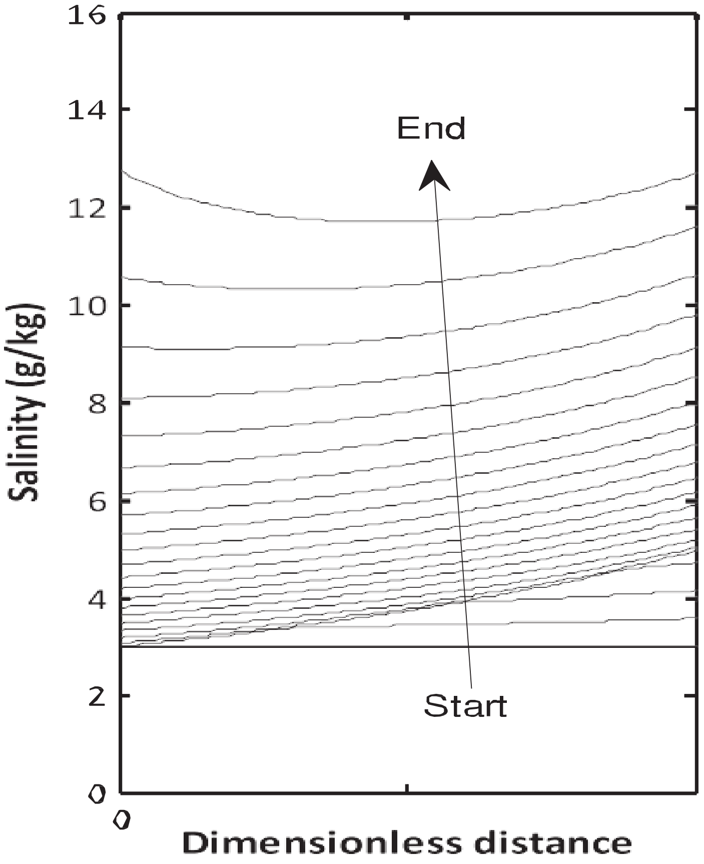


Volume discretization of membrane module for batch models.

The module is divided into unequal volumes, and in each step, equal amounts of permeate are removed from each section and the remaining liquid moves to the next section.

$$w_{\text{batch,HP}} = \overbrace{\frac{\Delta V_p \sum_{j=1}^{V_p/\Delta V_p} (\pi_{n,j} + \Delta P_t)}{V_p \eta_p}}^{\text{high pressure permeate pump work}} + \overbrace{\frac{\Delta P_l}{\eta_c \text{RR}_m}}^{\text{circulation pump work}} + \overbrace{\frac{1-\text{RR}}{\text{RR}} \frac{\Delta P_l}{\eta_c}}^{\text{brine ejection}}$$

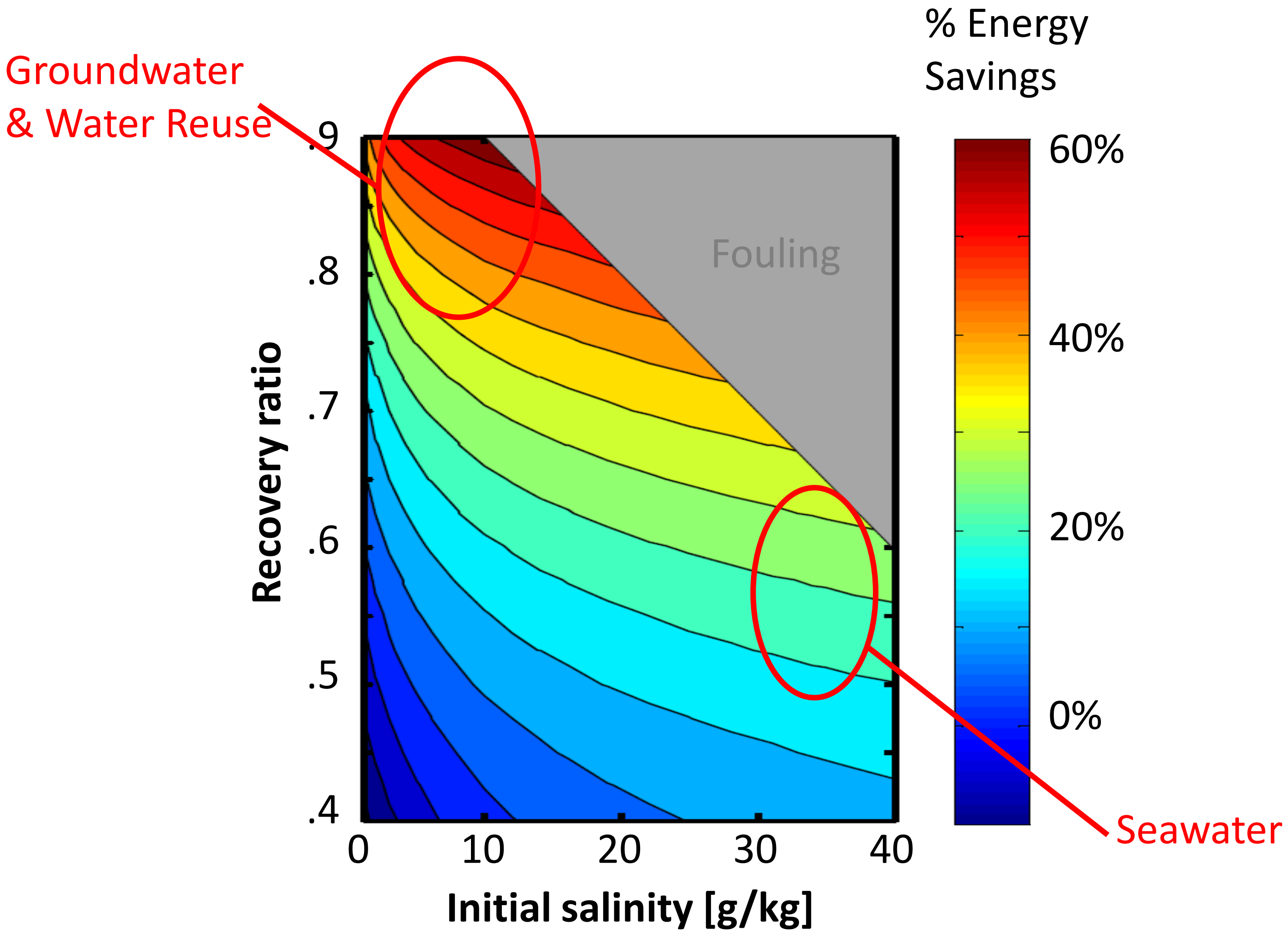
Which is discretized across the membrane module for spatial effects, and also calculated over time



Salinity profiles in the membrane module as recovery increases during each cycle for the batch process with 3 ppt at 75% recovery.

Dimensionless distance (The abscissa) is defined as the fraction of the module recovery achieved as the fluid traverses the module (equivalently, i/n). Lines are equally spaced by permeate production; arrows indicate the direction of cycle progression.

Batch Improvement



Percent reduction in energy requirements of batch RO systems compared to continuous, single-stage RO with pressure recovery.

D. M. Warsinger et al., *Water Research*, vol. 106, pp. 272-282, 2016.

Applications

- **Large-scale desalination**

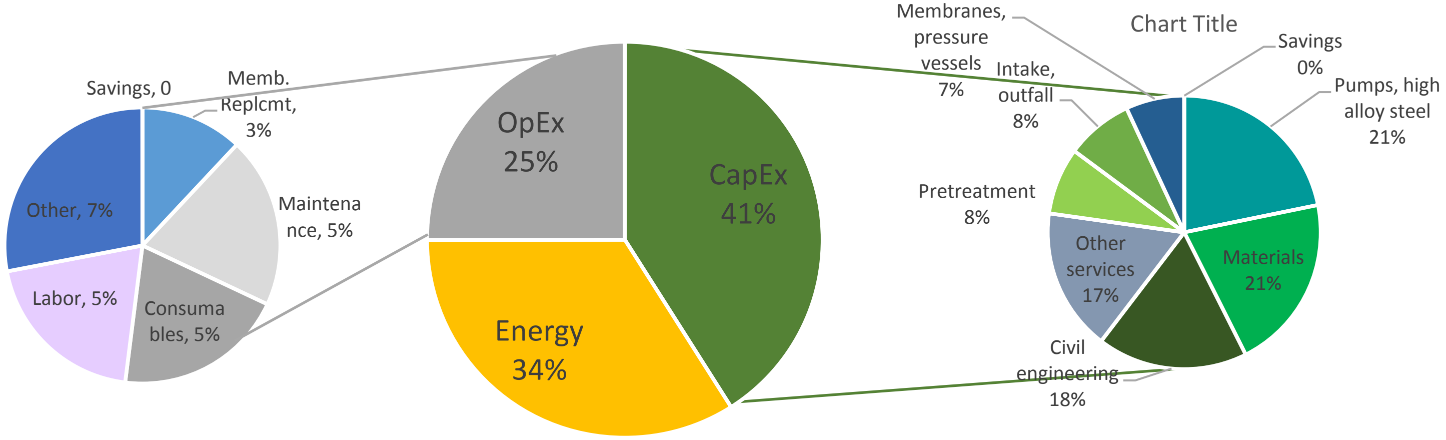
- **Agricultural water** use: more efficient, cheaper, water savings

- **Household disinfection** for India etc. 70% water savings

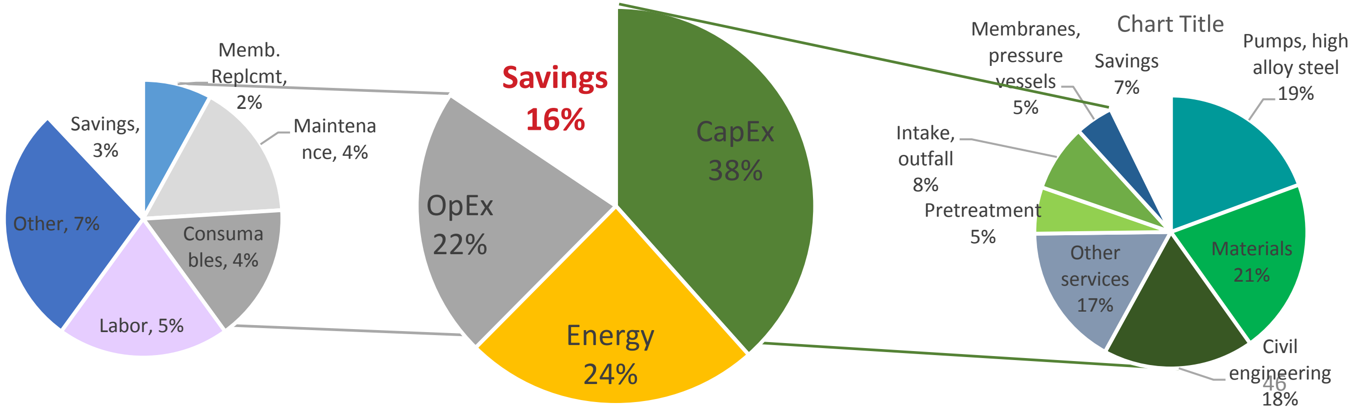
- **Mining Water** treatment

Batch Cost Savings

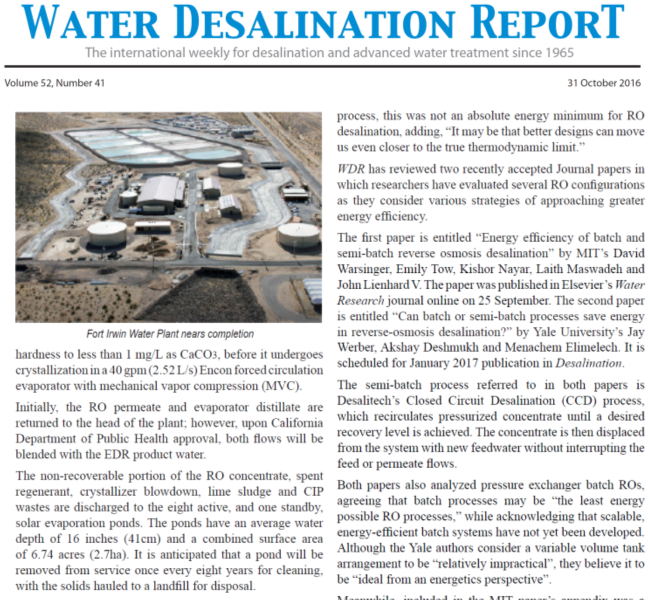
Current RO costs



Batch RO costs (estimate)



Batch RO in the News



WATER DESALINATION REPORT

The international weekly for desalination and advanced water treatment since 1965

Volume 52, Number 41

31 October 2016

Fort Irwin Water Plant nears completion

hardness to less than 1 mg/L as CaCO3, before it undergoes crystallization in a 40 gpm (2.52 L/s) Encon forced circulation evaporator with mechanical vapor compression (MVC).

Initially, the RO permeate and evaporator distillate are returned to the head of the plant; however, upon California Department of Public Health approval, both flows will be blended with the EDR product water.

The non-recoverable portion of the RO concentrate, spent regenerant, crystallizer blowdown, lime sludge and CIP wastes are discharged to the eight active, and one standby, solar evaporation ponds. The ponds have an average water depth of 16 inches (41cm) and a combined surface area of 6.74 acres (2.7ha). It is anticipated that a pond will be removed from service once every eight years for cleaning, with the solids hauled to a landfill for disposal.

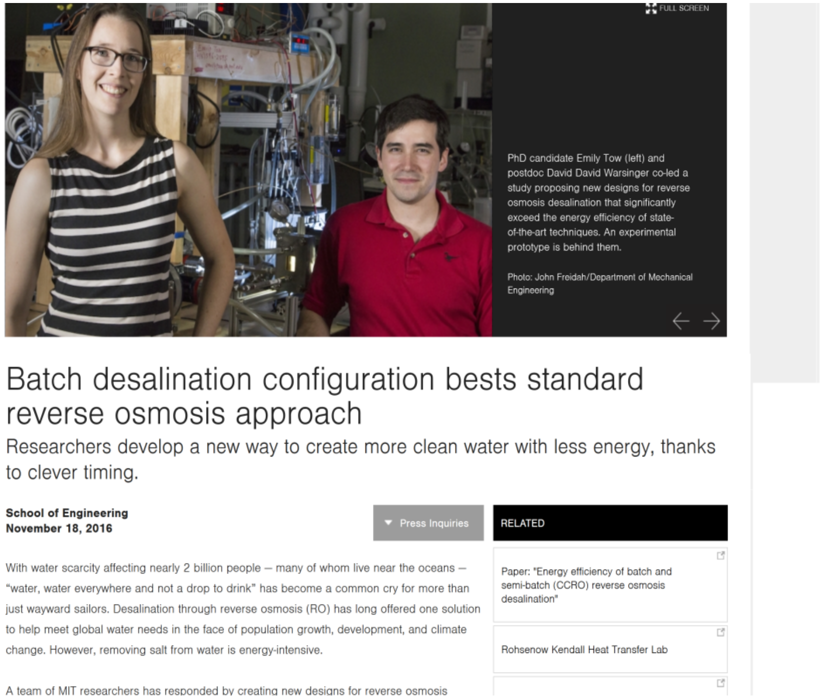
process, this was not an absolute energy minimum for RO desalination, adding, "It may be that better designs can move us even closer to the true thermodynamic limit."

WDR has reviewed two recently accepted Journal papers in which researchers have evaluated several RO configurations as they consider various strategies of approaching greater energy efficiency.

The first paper is entitled "Energy efficiency of batch and semi-batch reverse osmosis desalination" by MIT's David Warsinger, Emily Tow, Kishor Nayar, Laith Maswadeh and John Lienhard V. The paper was published in Elsevier's *Water Research* journal online on 25 September. The second paper is entitled "Can batch or semi-batch processes save energy in reverse-osmosis desalination?" by Yale University's Jay Werber, Akshay Deshmukh and Menachem Elimelech. It is scheduled for January 2017 publication in *Desalination*.

The semi-batch process referred to in both papers is Desalitech's Closed Circuit Desalination (CCD) process, which recirculates pressurized concentrate until a desired recovery level is achieved. The concentrate is then displaced from the system with new feedwater without interrupting the feed or permeate flows.

Both papers also analyzed pressure exchanger batch ROs, agreeing that batch processes may be "the least energy possible RO processes," while acknowledging that scalable, energy-efficient batch systems have not yet been developed. Although the Yale authors consider a variable volume tank arrangement to be "relatively impractical", they believe it to be "ideal from an energetics perspective".



PhD candidate Emily Tow (left) and postdoc David David Warsinger co-led a study proposing new designs for reverse osmosis desalination that significantly exceed the energy efficiency of state-of-the-art techniques. An experimental prototype is behind them.

Photo: John Freidah/Department of Mechanical Engineering

Batch desalination configuration bests standard reverse osmosis approach

Researchers develop a new way to create more clean water with less energy, thanks to clever timing.

School of Engineering
November 18, 2016

With water scarcity affecting nearly 2 billion people — many of whom live near the oceans — "water, water everywhere and not a drop to drink" has become a common cry for more than just wayward sailors. Desalination through reverse osmosis (RO) has long offered one solution to help meet global water needs in the face of population growth, development, and climate change. However, removing salt from water is energy-intensive.

A team of MIT researchers has responded by creating new designs for reverse osmosis

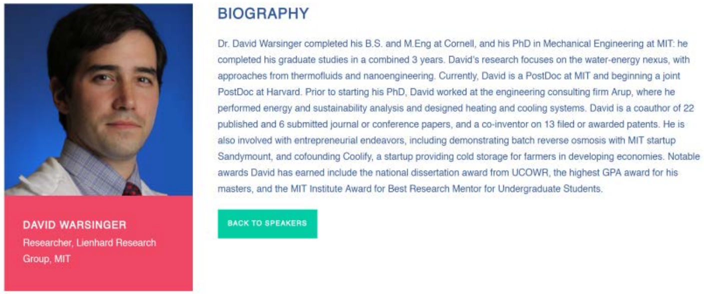
RELATED

Paper: "Energy efficiency of batch and semi-batch (CCRO) reverse osmosis desalination"

Rohsenow Kendall Heat Transfer Lab

AMERICAN WATER
SUMMIT 2016
CATALYZING COLLABORATION

TECH IDOL



DAVID WARSINGER
Researcher, Lienhard Research Group, MIT

BIOGRAPHY

Dr. David Warsinger completed his B.S. and M.Eng at Cornell, and his PhD in Mechanical Engineering at MIT: he completed his graduate studies in a combined 3 years. David's research focuses on the water-energy nexus, with approaches from thermofluids and nanoengineering. Currently, David is a PostDoc at MIT and beginning a joint PostDoc at Harvard. Prior to starting his PhD, David worked at the engineering consulting firm Arup, where he performed energy and sustainability analysis and designed heating and cooling systems. David is a coauthor of 22 published and 6 submitted journal or conference papers, and a co-inventor on 13 filed or awarded patents. He is also involved with entrepreneurial endeavors, including demonstrating batch reverse osmosis with MIT startup Sandymount, and cofounding Coolify, a startup providing cold storage for farmers in developing economies. Notable awards David has earned include the national dissertation award from UCOWR, the highest GPA award for his masters, and the MIT Institute Award for Best Research Mentor for Undergraduate Students.

The 9th International Desalination Workshop
13- 15 November 2016, Abu Dhabi, UAE

Certificate of KAIA AWARD

In Honor of Best Oral Presentation

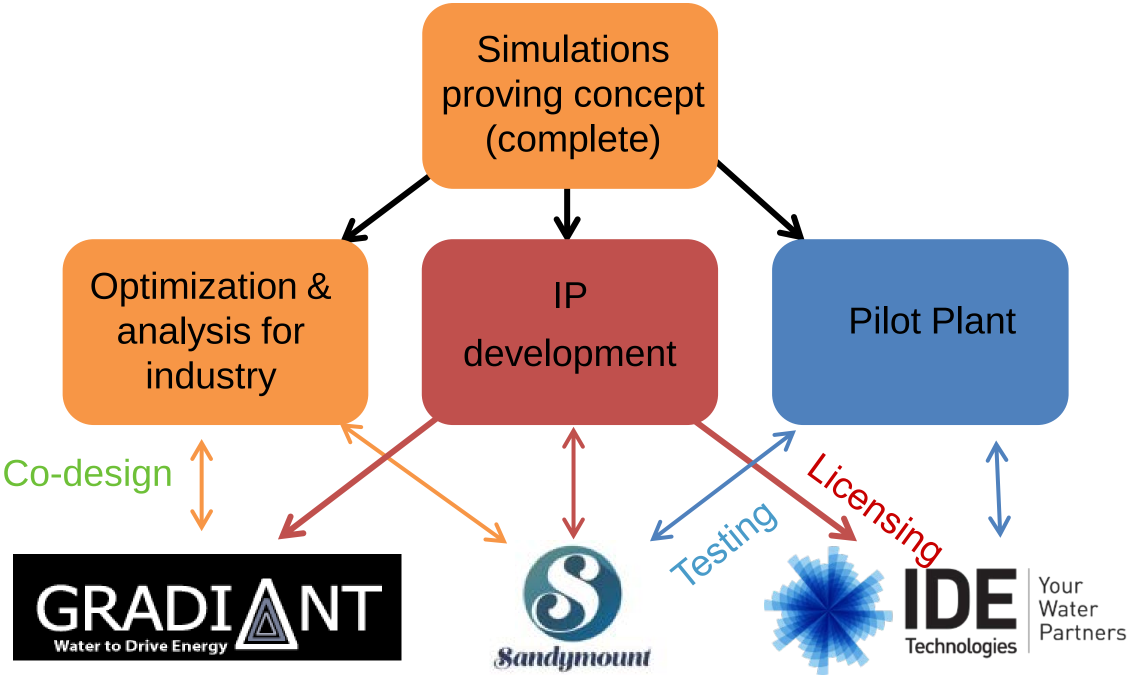
DAVID WARSINGER

"Enhancing Energy Efficiency of Reverse Osmosis with Batch and Semi-batch Processes"

In recognition of Korea Agency for Infrastructure Technology Advancement Award of the year of 2016 of the 9th International Desalination Workshop

Korea Agency for Infrastructure Technology Advancement
President
Byung-soo

Commercialization Strategy



Simulations proving concept (complete)

Optimization & analysis for industry

IP development

Pilot Plant

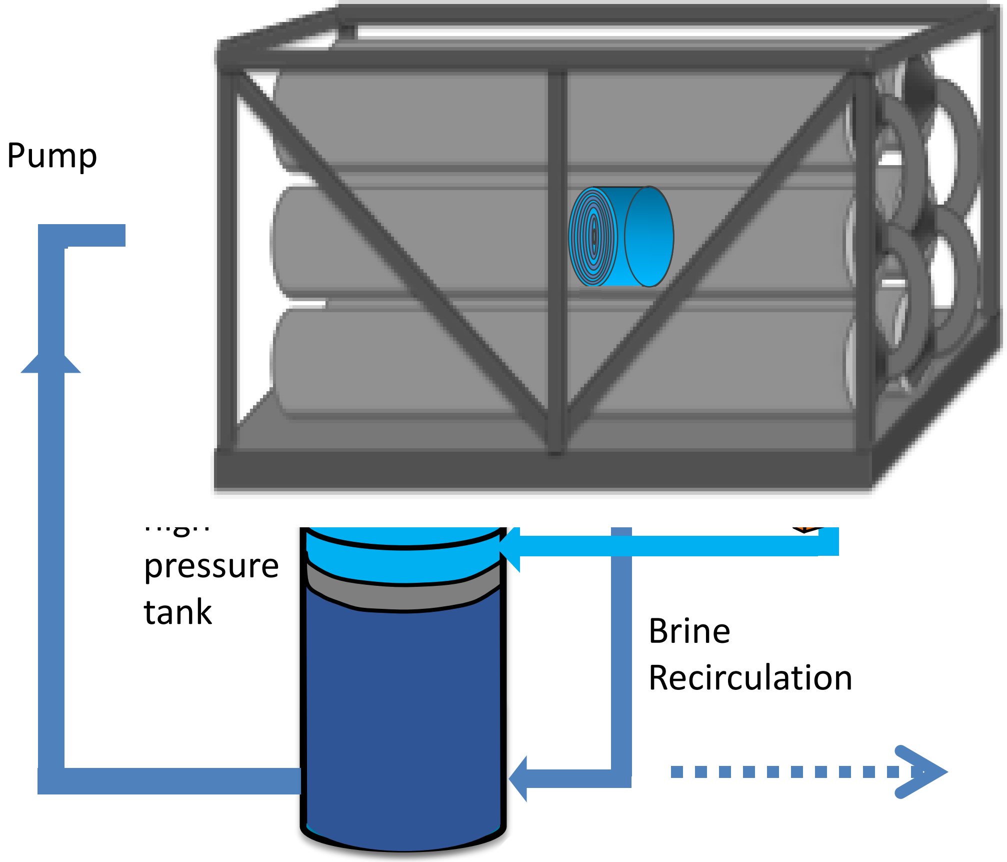
(Young company)
Industrial wastewater

(Startup)
Beverage

(World Leader)
Large-scale water

Commercialization and additional funding implementation plan of batch desalination research

Can we get big benefits too from improving not just the process, but its nanomaterials?



Pump

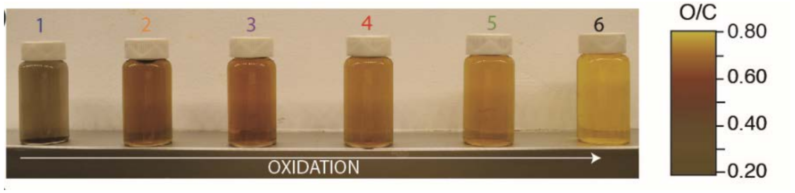
High pressure tank

Brine Recirculation

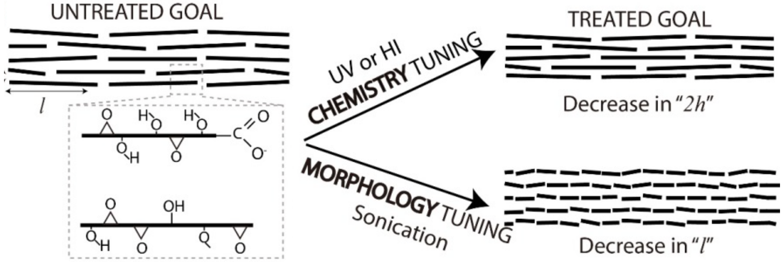
Ultrapermeable RO Membranes: Graphene Oxide (GO)

- Reduces membrane area ($↓)
- Energy savings: less overpressure
- Potentially fouling resistant
- Emerging contaminants (PFOA)

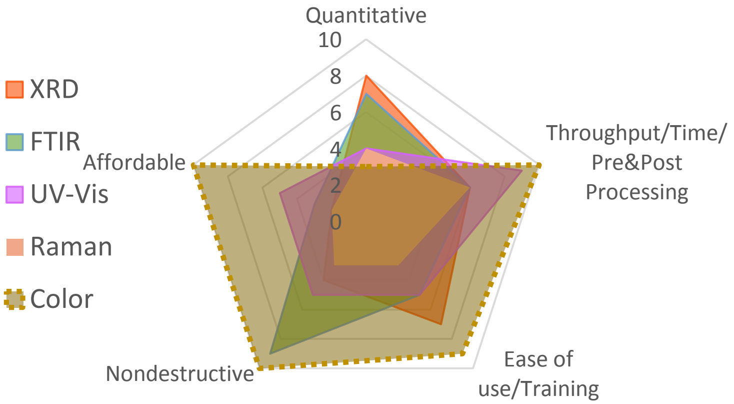
GO Oxidation



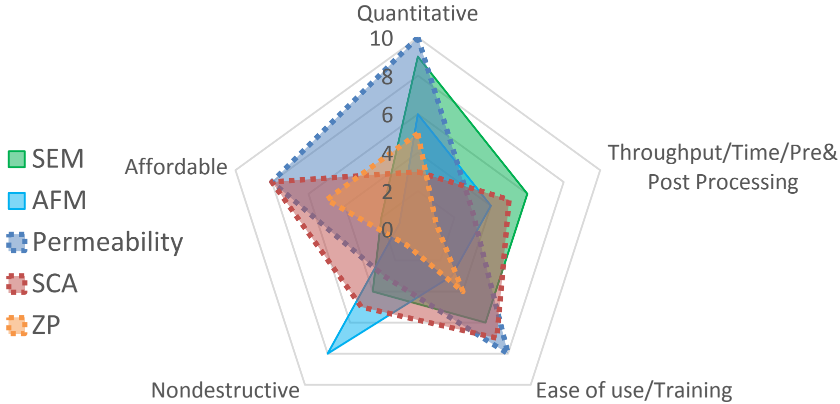
GO Membrane Fabrication



CHEMISTRY

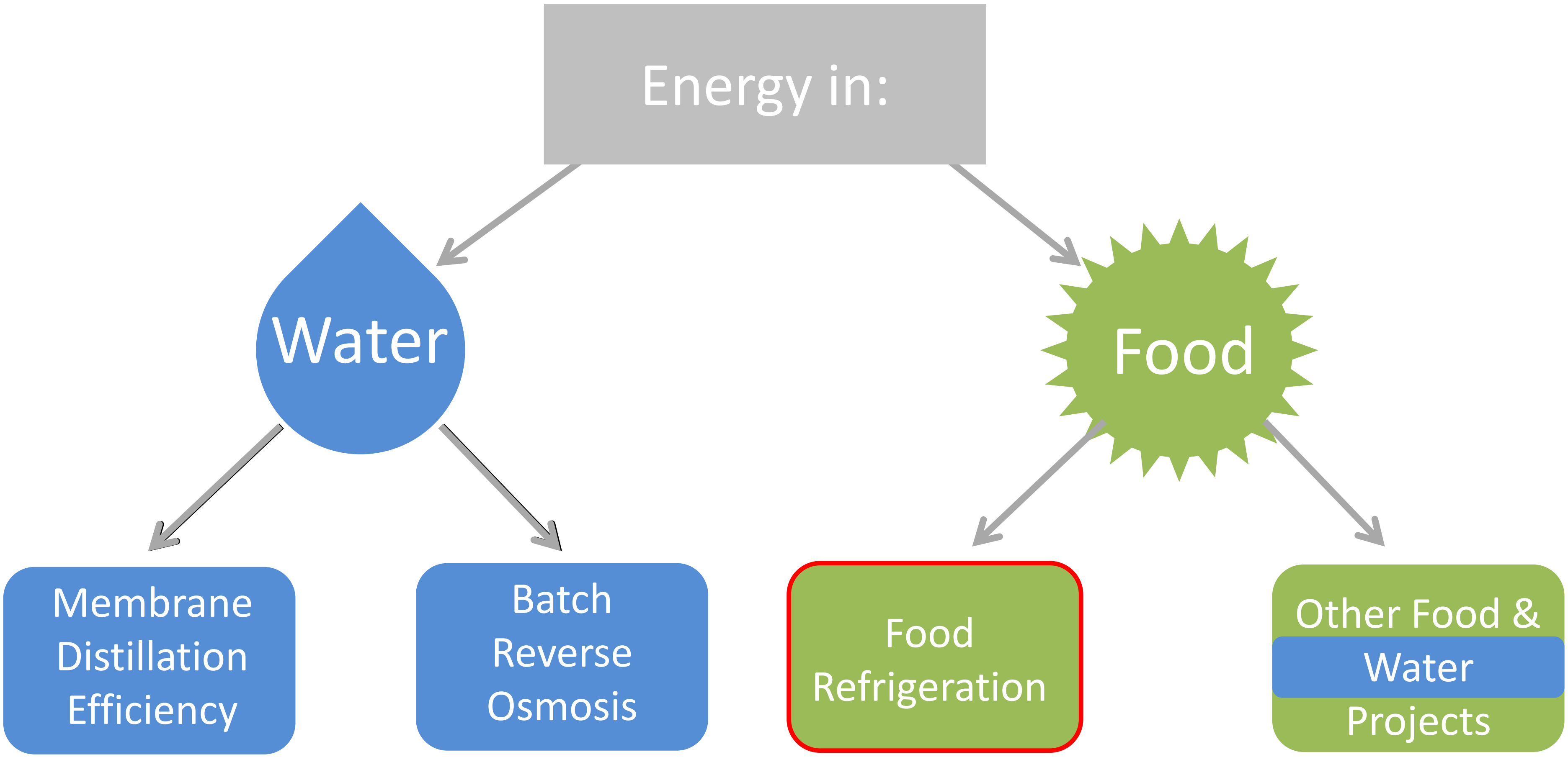


MORPHOLOGY



D. M. Warsinger et al. (in progress)

C. Amandei D. M. Warsinger et al. (in progress)



Energy in:

Water

Food

Membrane Distillation Efficiency

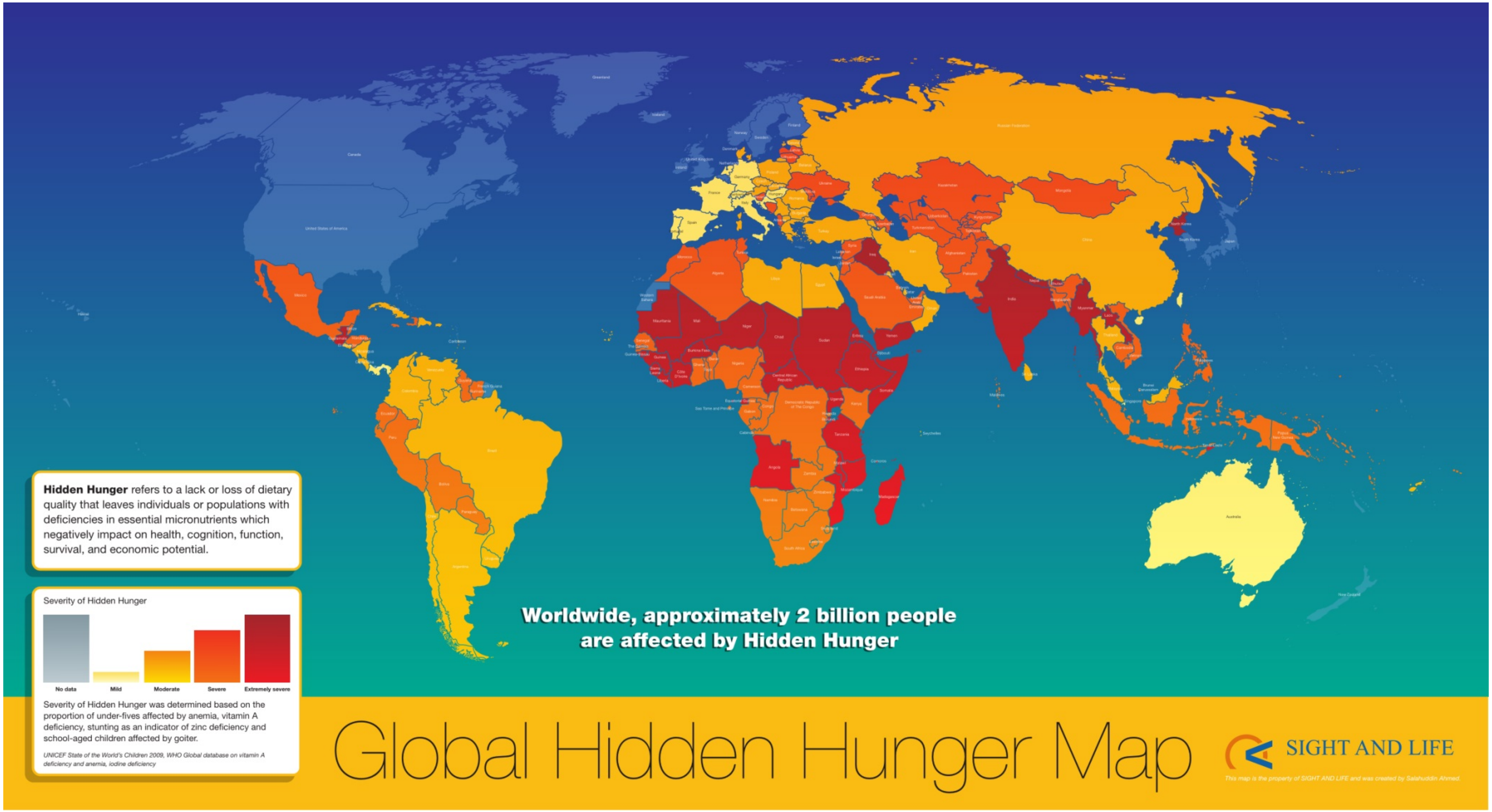
Batch Reverse Osmosis

Food Refrigeration

Other Food & Water Projects

Energy and **thermofluids** strategies for intermittent **power**

Visualizing Water Stress



Hidden Hunger refers to a lack or loss of dietary quality that leaves individuals or populations with deficiencies in essential micronutrients which negatively impact on health, cognition, function, survival, and economic potential.

Severity of Hidden Hunger was determined based on the proportion of under-fives affected by anemia, vitamin A deficiency, stunting as an indicator of zinc deficiency and school-aged children affected by goiter.

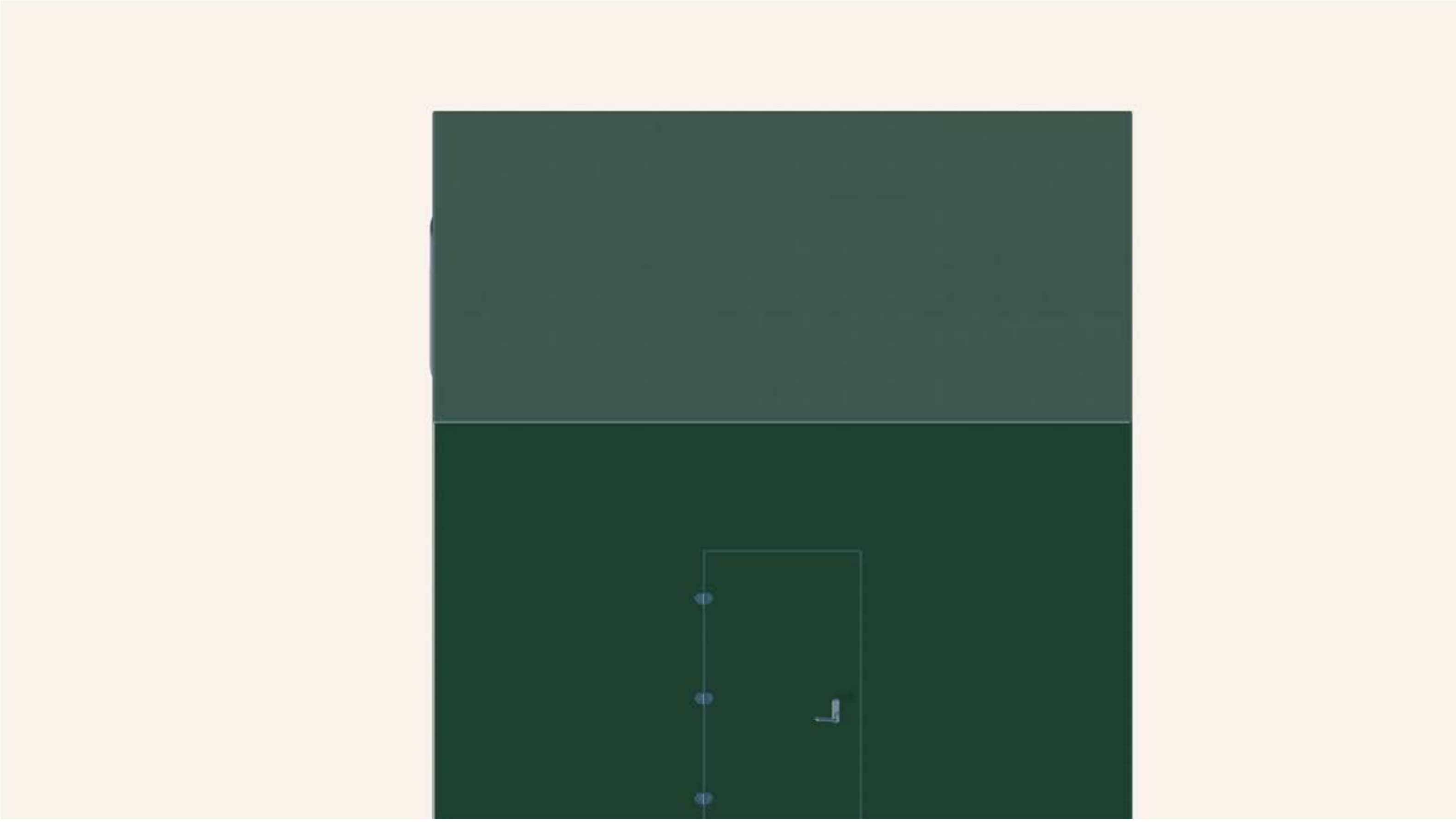
UNICEF State of the World's Children 2009, WHO Global database on vitamin A deficiency and anemia, iodine deficiency

Worldwide, approximately 2 billion people are affected by Hidden Hunger

Global Hidden Hunger Map

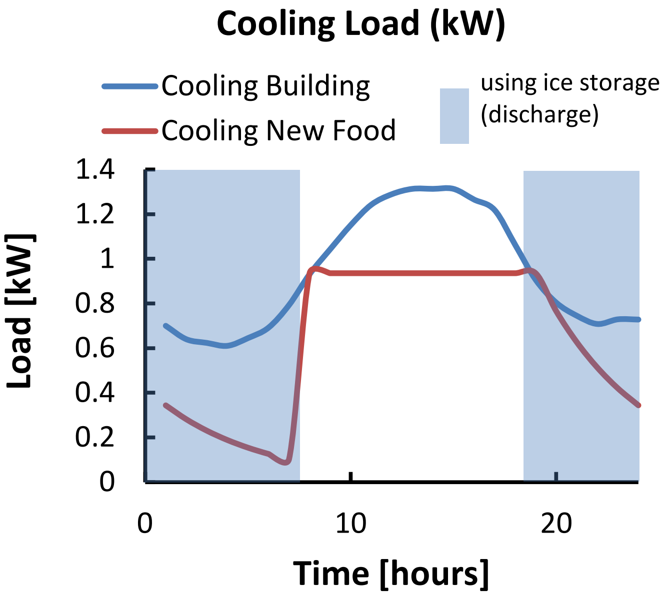
This map is the property of SIGHT AND LIFE and was created by Salahuddin Ahmed.

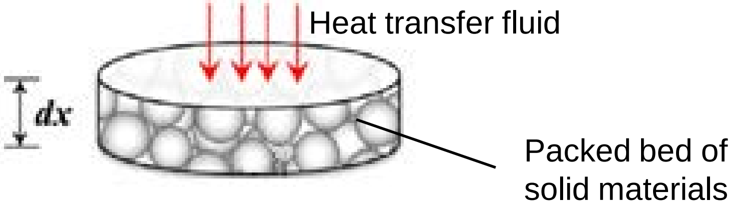
Coolify®

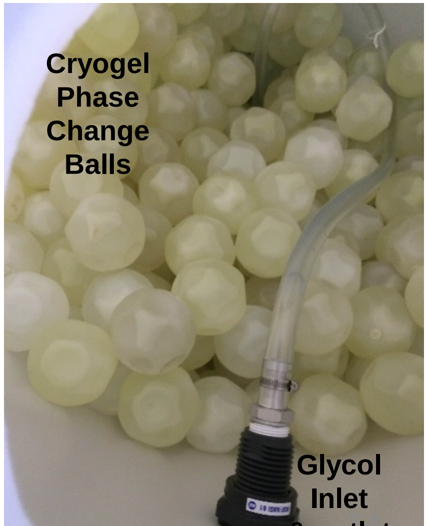


Phase-change thermal storage

- Freezing packed-bed heat transfer
- Thermodynamic system design
- Phase change materials







Vision & Collaboration

Experts in each tech.

Thermodynamic systems design

Multiphase flow

coatings

Transport enhancement

Carbon nano-materials.

Polymer chemistry

Mechanics, fatigue

Membrane nanomaterials

O&G companies

Thermofluids

Nanoengineering

Bio & inorganic chem

IP Licensing

Desal. firms

Food & drink

Integration with renewables

Energy storage

Solar

Wind

Startups by grad students

Business school

Selective solute removal

Ag., electrochem, contaminants

Water resources

Membrane fouling

Interface science

Energy-Water Nexus
Funding Ecosystem

Federal **University** **Institutions** **Foreign Gov** **Industry**

- >$627,000 raised in grant applications and pitch competitions in last 2.5 years
- ~$1 milli n submitte

U.S. DEPARTMENT OF ENERGY

NSF

MIT

Hi Harvard innovation lab

TLO MIT Technology Licensing Office

J-WAFS Abdul Latif Jameel World Water and Food Security Lab

Agricultural Innovation Prize powered by 40 Forty Chances

TATA CENTER TECHNOLOGY + DESIGN

DESHPANDE CENTER FOR TECHNOLOGICAL INNOVATION

MASDAR INSTITUTE OF SCIENCE AND TECHNOLOGY

Arab Republic of Egypt Ministry of Foreign Affairs

Ministry of Scientific Research Arab Republic of Egypt

cadagua

Chevron

Sandymount

GRADIANT Water to Drive Energy

Funding sources used so far

Future funding sources

USGS science for a changing world

USDA

DEPARTMENT OF STATE UNITED STATES OF AMERICA

EPA United States Environmental Protection Agency

U.S. DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION

TomKatCenter FOR SUSTAINABLE ENERGY STANFORD UNIVERSITY

SNSF

STANFORD UNIVERSITY OFFICE OF TECHNOLOGY LICENSING

Stanford University

BASES

USAID FROM THE AMERICAN PEOPLE

EPRI

BROAD INSTITUTE

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KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

KAUST

STDF Science and Technology Development Fund (STDF)

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GE Power & Water

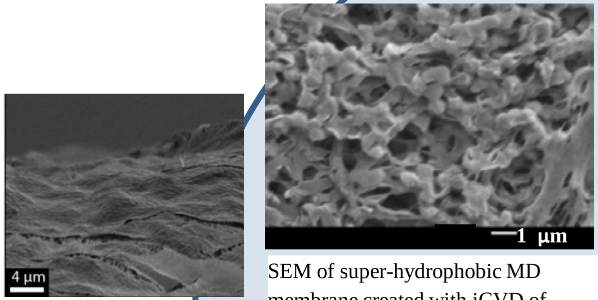
Desalitech

Keppel Seghers Solutions for a Cleaner Future

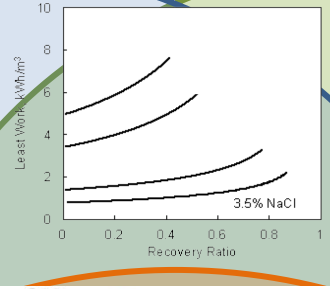
Water-Energy-Food Nexus

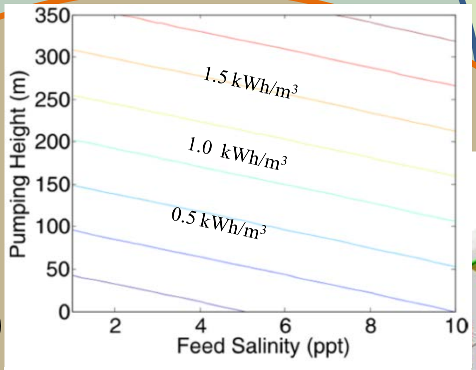
Water

Food

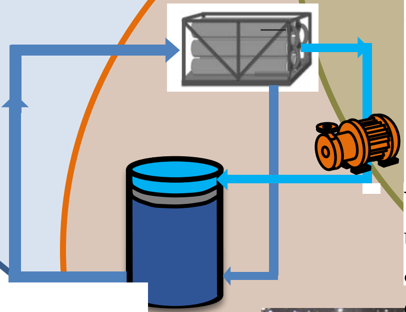


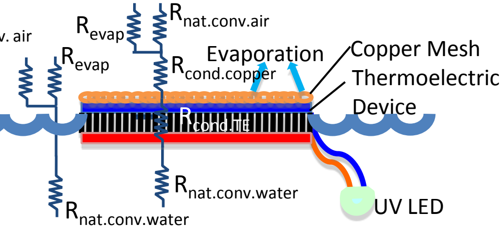
SEM of super-hydrophobic MD membrane created with iCVD of PPFDA on PVDF [24]



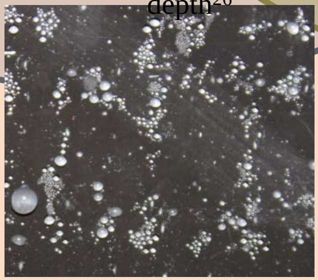


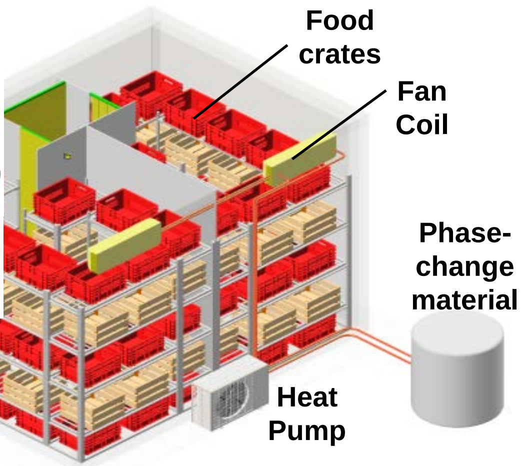
Water-Food-Energy Nexus: Energy use of desalinating groundwater for agriculture, by salinity and water table depth[26]





Powering UV disinfection with evaporation





Coolify refrigeration unit with Phase-Change thermal storage

Energy

Acknowledgements

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DESHPANDE CENTER
FOR TECHNOLOGICAL INNOVATION

TATA CENTER
TECHNOLOGY + DESIGN

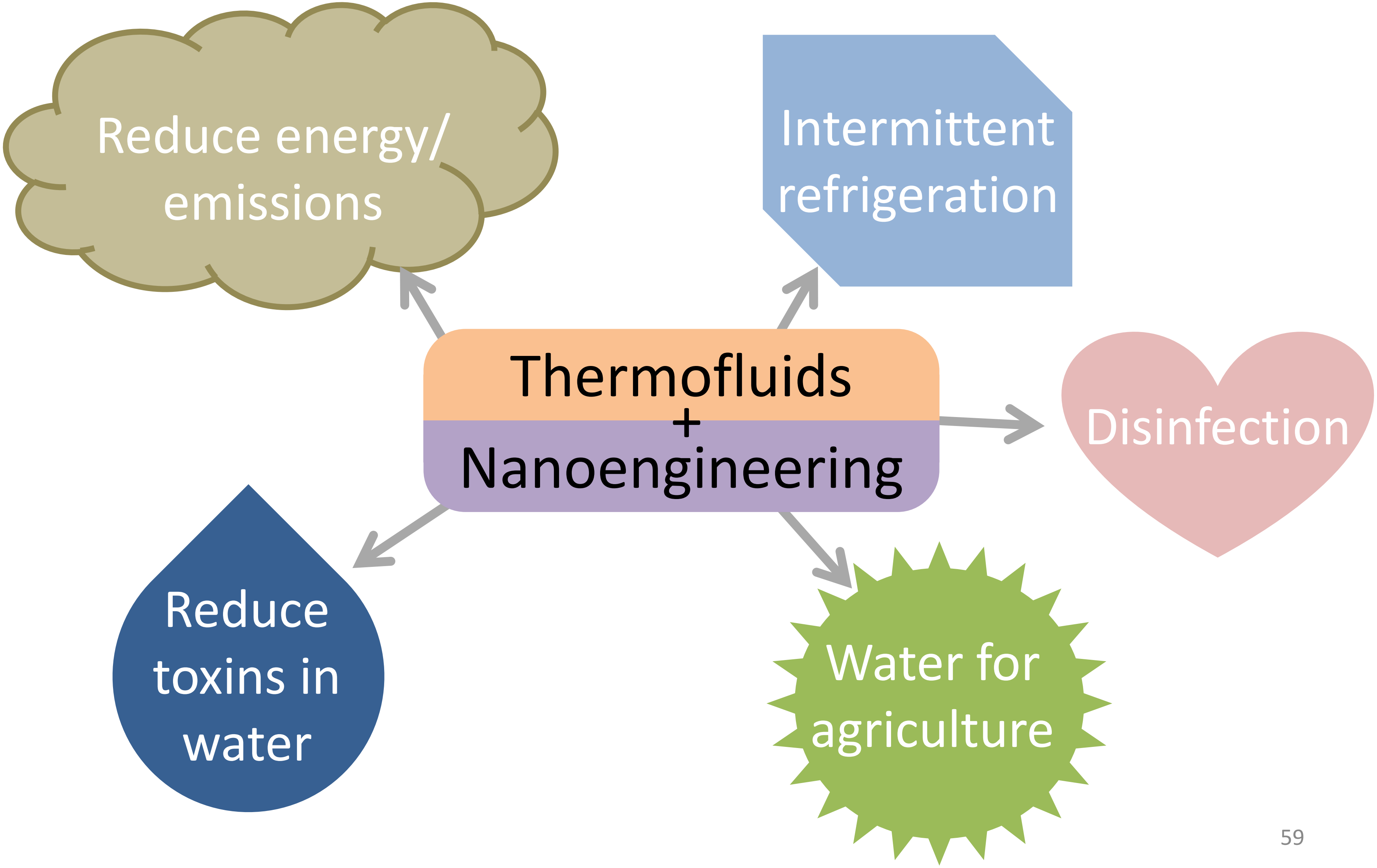
Agricultural Innovation Prize
powered by FORTY CHANCES 40


Lab

MIT

Undergrad + Grad Team

Can we save lives with thermodynamics?



Thermofluids
+
Nanoengineering

Reduce energy/ emissions

Intermittent refrigeration

Disinfection

Water for agriculture

Reduce toxins in water

Questions?

Feed Modeling

$$Nu = \frac{(f/8)\cdot(Re-1000)\cdot Pr}{1+12.7\cdot(f/8)^{1/2}\cdot\left(Pr^{2/3}-1\right)}$$

$$Sc_f = \frac{\mu_f}{(\rho_{feed}\cdot D_{s,w})}$$

$$K_{cond} = \frac{k_m\cdot(1-\xi)+k_{air}\cdot\xi}{\delta_m}$$

Main Flux eqn

$$J_i = B\cdot(P_{f,m,i}-P_p\cdot x_{a,m,i})$$

Concentration along flow direction

$$x_{f,b,i} = S_{in}\cdot\left(\frac{m_{f,i}}{\dot{m}_{f,in}/n_{sheets}}\right)$$

Effect of concentration polorization

$$x_{f,m,i} = x_{f,b,i}\cdot\exp\left(\frac{J_i}{k_{mass}\cdot\rho_{feed}}\right)$$

$$P_{f,m,i} = \mathrm{P_{sat}}\left(Water,\ \mathrm{T}=T_{f,m,i}\right)\cdot\left(1-\left(\frac{\frac{x_{f,m,i}}{MW_{solute}}}{\left(\frac{x_{f,m,i}}{MW_{solute}}\right)+\left(\frac{1000\ [\mathrm{g/kg}]-x_{f,m,i}}{MW_{water}}\right)}\right)\right)$$

$$q_{out,i} = J_i\cdot(h_{fg,f,i})+q_{m,i}-J_i\cdot(h_{f,b,i}-h_{f,m,i})$$

Air Gap & Condensate

Diffusion Equation

$$\left(\frac{J_i}{M_{H2O}}\right) = \frac{c_{a,i} \cdot D_{wa}}{d_{gap} - \delta_i} \cdot \ln\left(1 + \left(\frac{x_{i,i} - x_{a,m,i}}{x_{a,m,i} - 1}\right)\right)$$

$$T_{a,m,i} - T_{i,i} = \left(\frac{q_{conv,i}}{k_{mix,i}}\right) \cdot \left(\alpha_{mix,i} \cdot \frac{\rho_{mix,i}}{J_i}\right) \cdot \left(\exp\left(\frac{J_i}{\rho_{mix,i} \cdot \alpha_{mix,i}} \cdot (d_{gap} - \delta_i)\right) - 1\right)$$

$$\nu_{f,i} = \frac{\mu\left(Water,\ \mathrm{P} = P_p,\ \mathrm{T} = T_{av,film,i}\right)}{\rho_f}$$

Condesnation film thickness

$$J_i \cdot dA = g \cdot \frac{\rho_f - \rho_g}{3 \cdot \nu_{f,i}} \cdot w \cdot \left(\delta_{i+1}^3 - \delta_i^3\right)$$

heat absorbed by condensate

$$q_{c,i} = J_i \cdot h_{fg,c,i} + q_{m,i}$$

film conduction resistance

$$q_{c,i} = \frac{k_{film,i}}{\delta_i} \cdot (T_{i,i} - T_{wall,i})$$

Cooling Channel Modeling

$$d_{h,c} = 4 \cdot \frac{w \cdot d_{cond}}{2 \cdot (w + d_{cond})}$$

BL resistance

$$T_{wall,i} = T_{c,b,i} + \left(\frac{q_{c,i} + J_i \cdot (h_{c,i,i} - h_{c,wall,i})}{h_{t,c}} \right)$$

conserve energy in bulk stream

$$h_{c,b,i+1} = h_{c,b,i} - (q_{c,i} + J_i \cdot (h_{c,i,i} - h_{c,wall,i})) \cdot \frac{dA}{\dot{m}_{f,1} + (\dot{m}_{c,ex}/1)}$$

Efficiency Definitions

Parameter	Typical Value	Definitions
J Flux $J = \frac{\dot{m}_\text{p}}{A}$	2-10 L/m²hr	pure water flux (J, measured in L/m^2-hr). Where $\dot{m}_\text{p}$ is the mass flow rate of feed, A is the area.
GOR Energy Efficiency $\text{GOR} = \frac{\dot{m}_\text{p} h_\text{fg}}{\dot{Q}_\text{f}}$	1.5-15	h_fg is the enthalpy of vaporization (2257 kJ/kg $\dot{Q}_\text{f}$ is the total heat energy input.
η MD Thermal Efficiency $\eta = \frac{\dot{Q}_\text{vap}}{\dot{Q}_\text{vap} + \dot{Q}_\text{cond}}$	.5-.93	Heat transfer by conduction across the membrane ($\dot{Q}_\text{cond}$)
NTU Dimensionless size $\text{NTU} = \frac{UA}{\dot{m}c_\text{p}}$	4-35	NTU, or number of transfer units U is the overall heat transfer coefficient c_p is the specific heat.
ε Heat transfer effectiveness	0.3-0.95	

$$\varepsilon = \frac{h_\text{c,out} - h_\text{c,in}}{h_\text{f,in} - h_\text{c,in}} = \frac{T_\text{c,out} - T_\text{c,in}}{T_\text{f,in} - T_\text{c,in}}$$

Model Validation

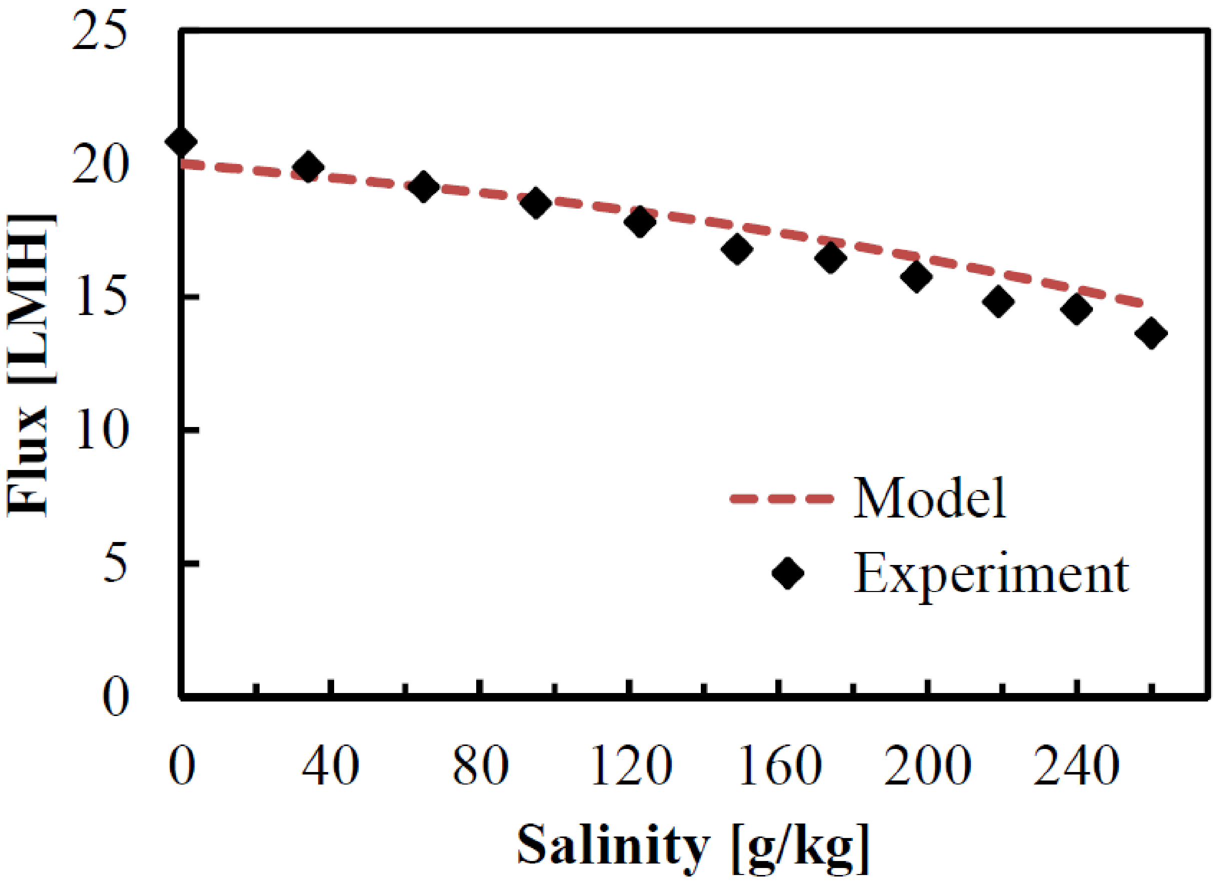
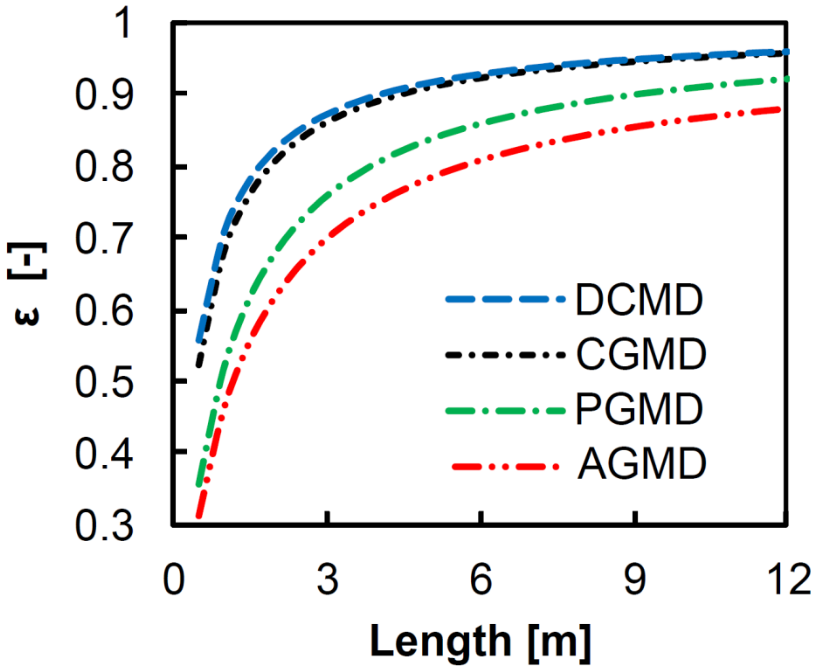
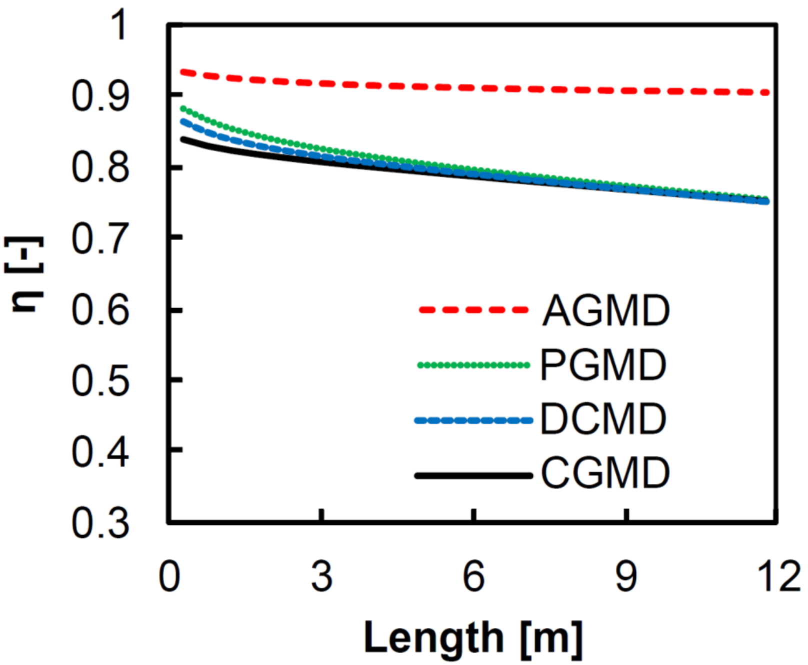


Figure 4: Validation of the 1-D Numerical Model with experimental data from [32]

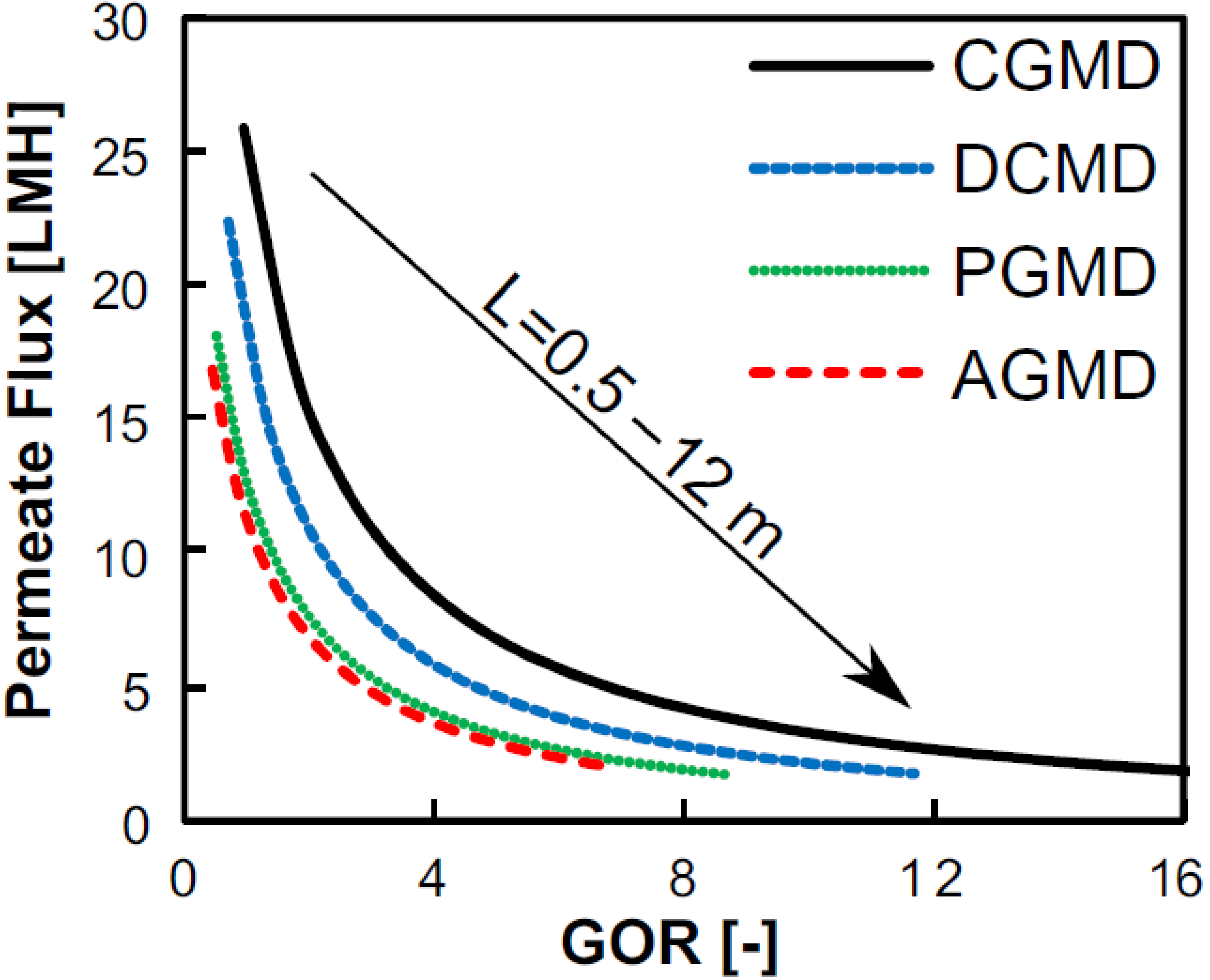
η and ε





GOR vs Flux

Seawater salinity



GOR vs Flux

High salinity

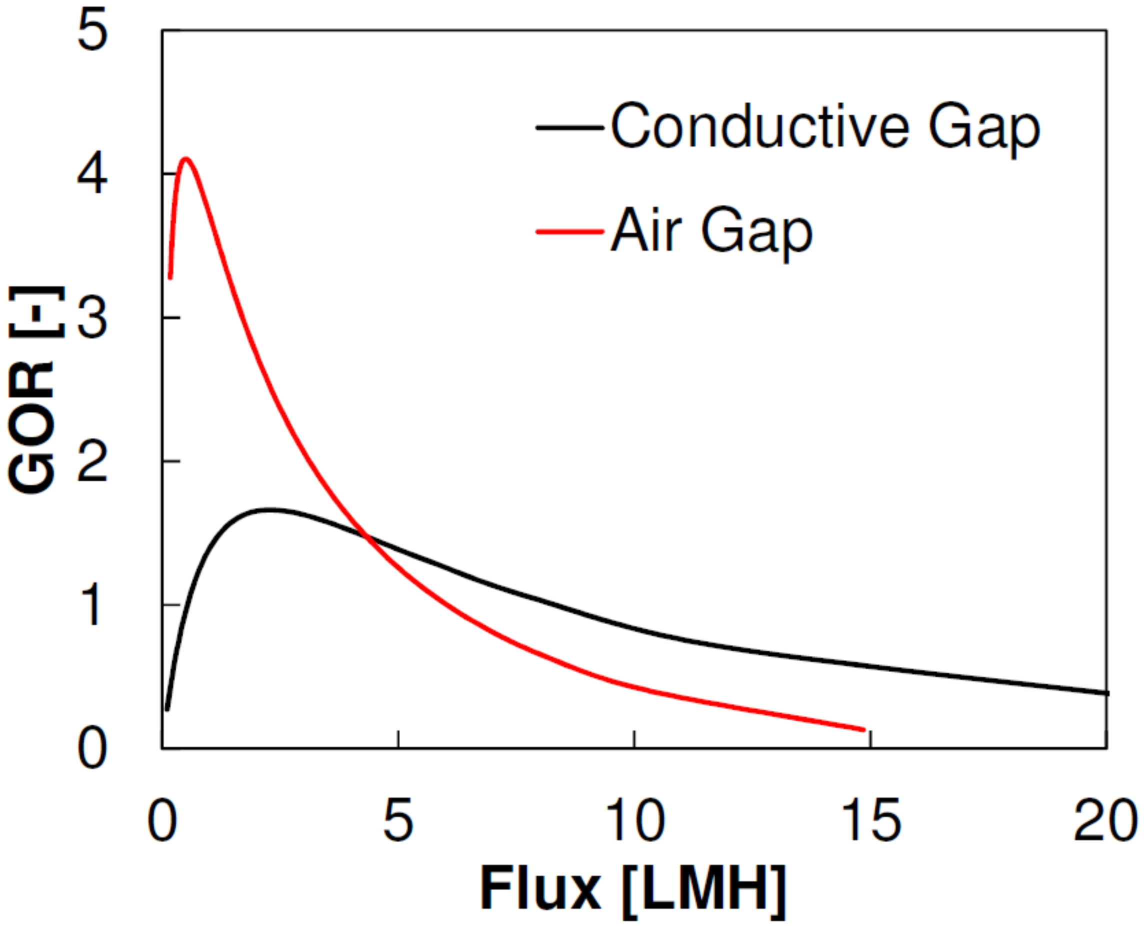
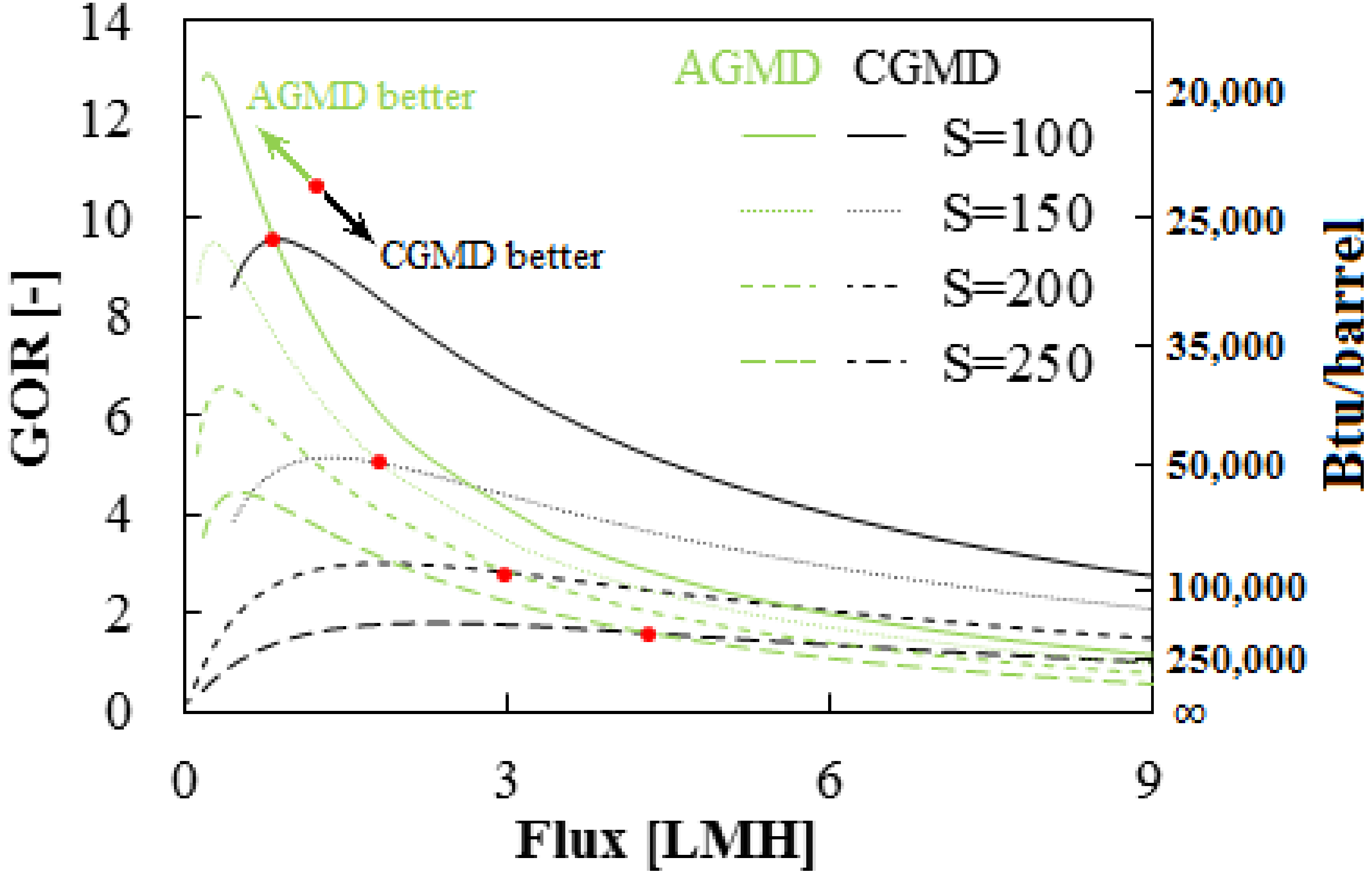


Figure 7: A comparison of GOR and Flux for AGMD and CGMD, $s_f = 250$ g/kg

GOR vs Flux

High salinity



Impact of salinity

AGMD

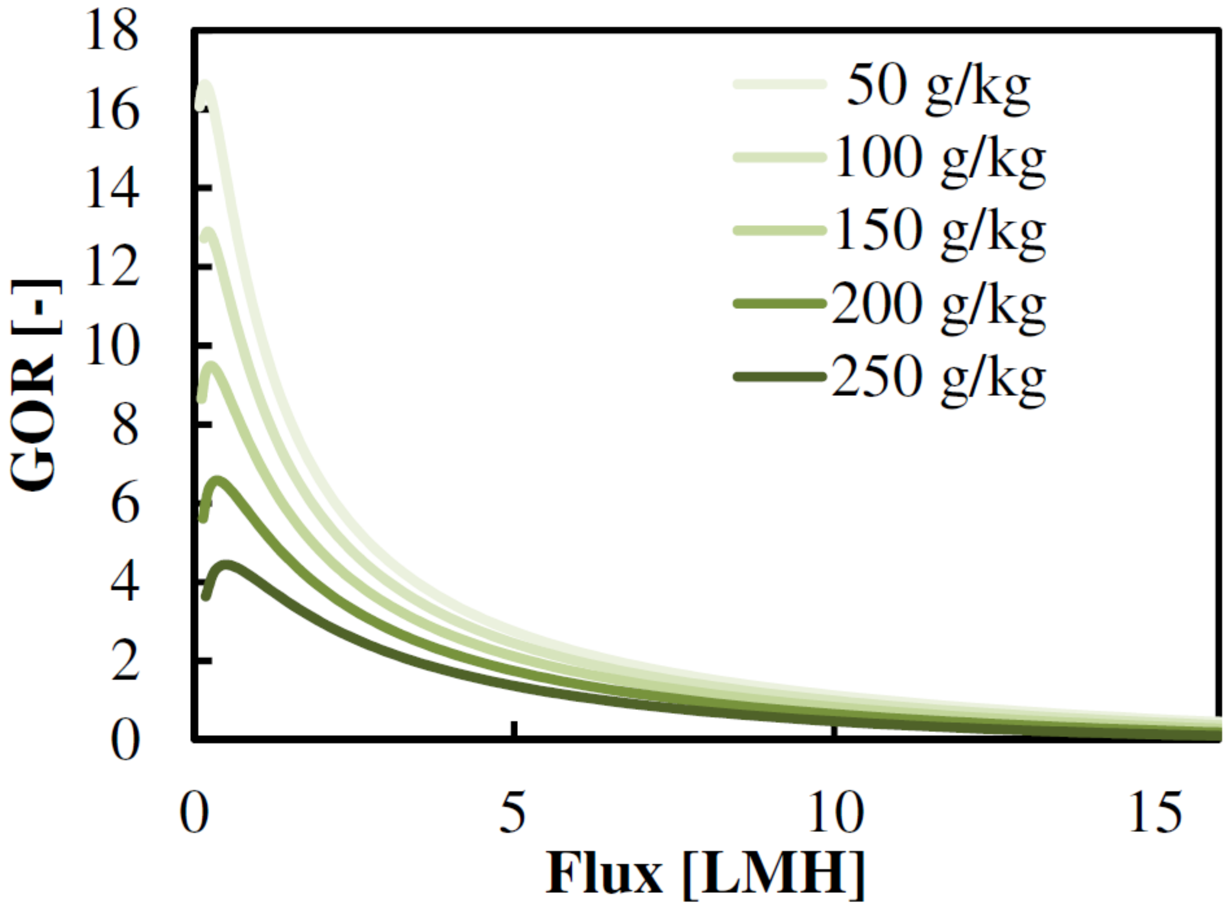


Figure 8: AGMD. The GOR-flux curves at high salinity exhibit decreasing GOR and flux at large system size ($L > L^*$) or correspondingly $J < J*$. The J^* value increases as s_f increases, but is not as easy to see.

Dimensionless framework

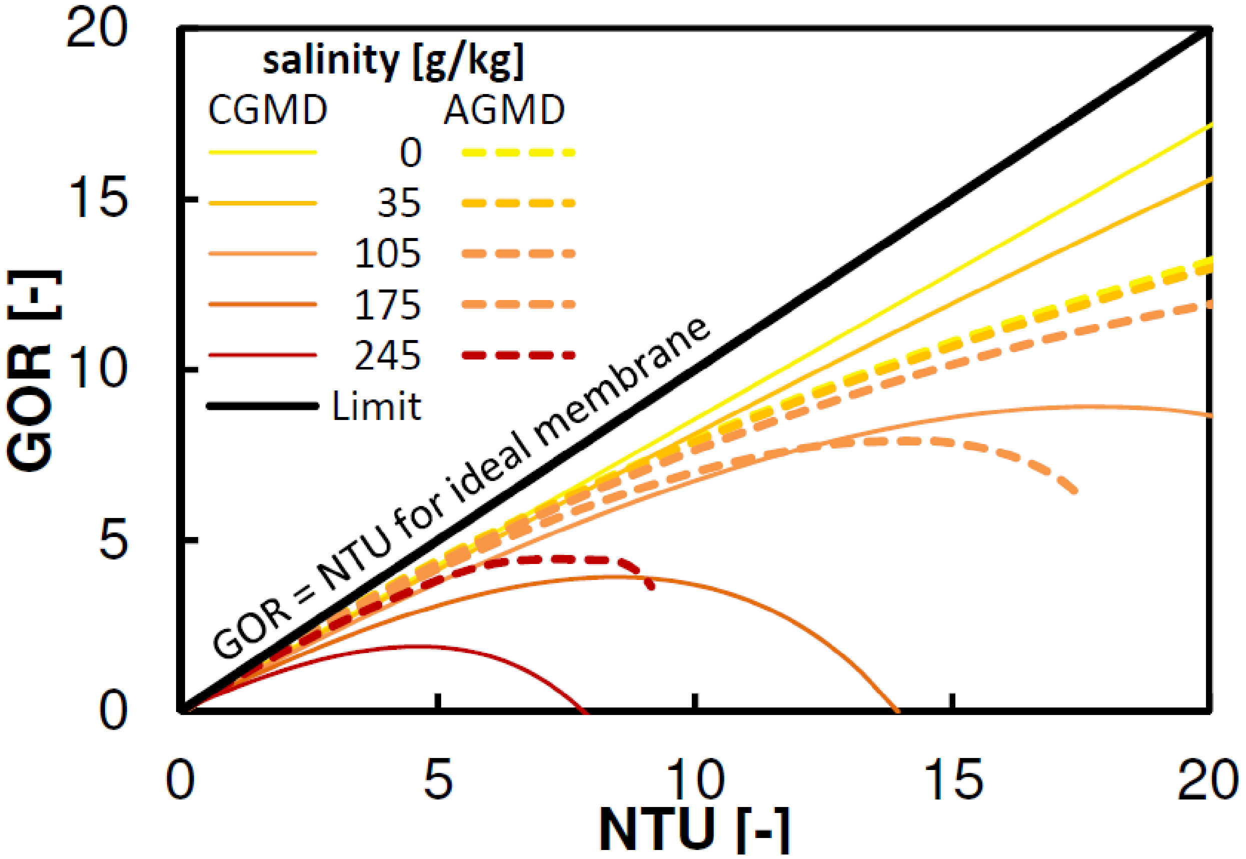


Figure 12: GOR as a function of NTU from the discretized and simplified HX model of MD. Dotted lines are results from the HX model, and show that the HX model is also capable of capturing the NTU* beyond which flux begins to decline. Just like $J*$ increases at high salinity, the critical system size (or NTU*) decreases with feed salinity. Shorter module lengths have to be used when treating high salinity water with MD. The $*$ indicates optimal system size to maximize GOR

Maximum Performance

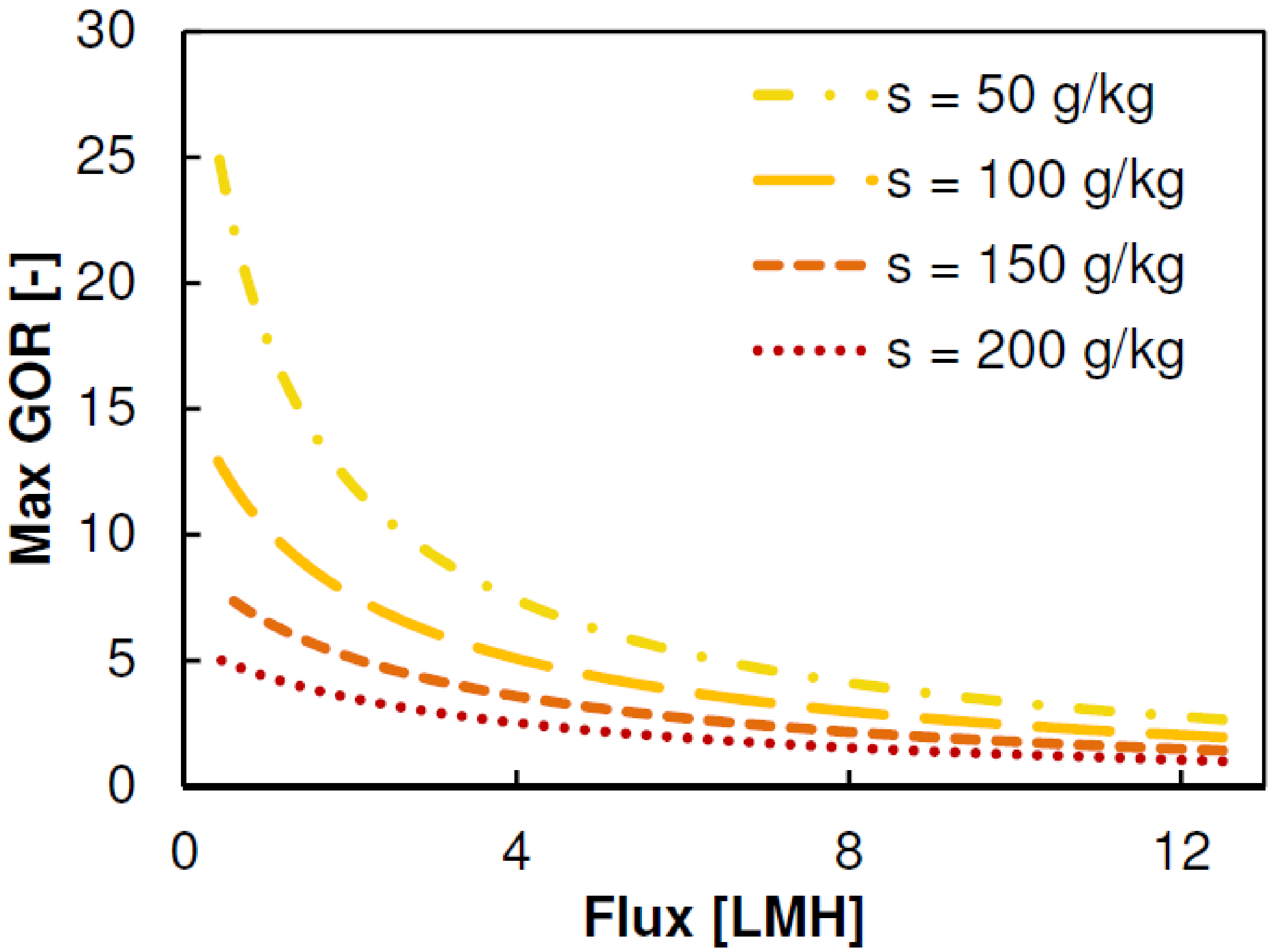


Figure 16: Max GOR possible by using the ideal membrane thickness at each salinity and flux for CGMD