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Novel Membrane Technologies for Cost Effective Hydrogen Production by Electrolysis

Phase 2 Project Number: 1172061-1-93083

Damian Amiruddin, Dufei Fang, Devinder Mahajan and Benjamin S. Hsiao,

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Outline

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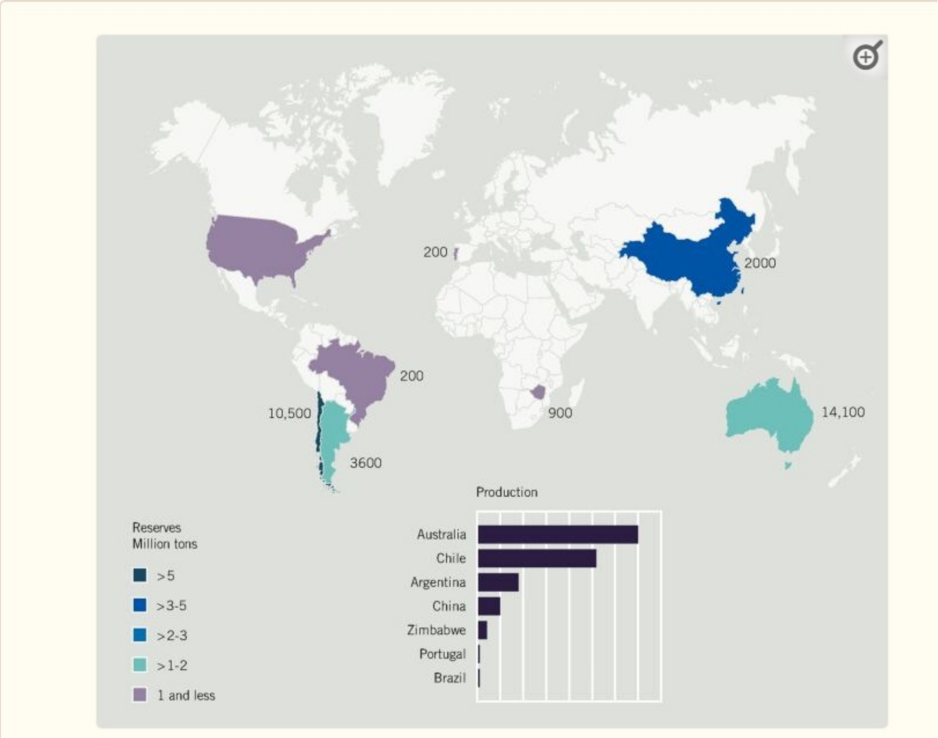
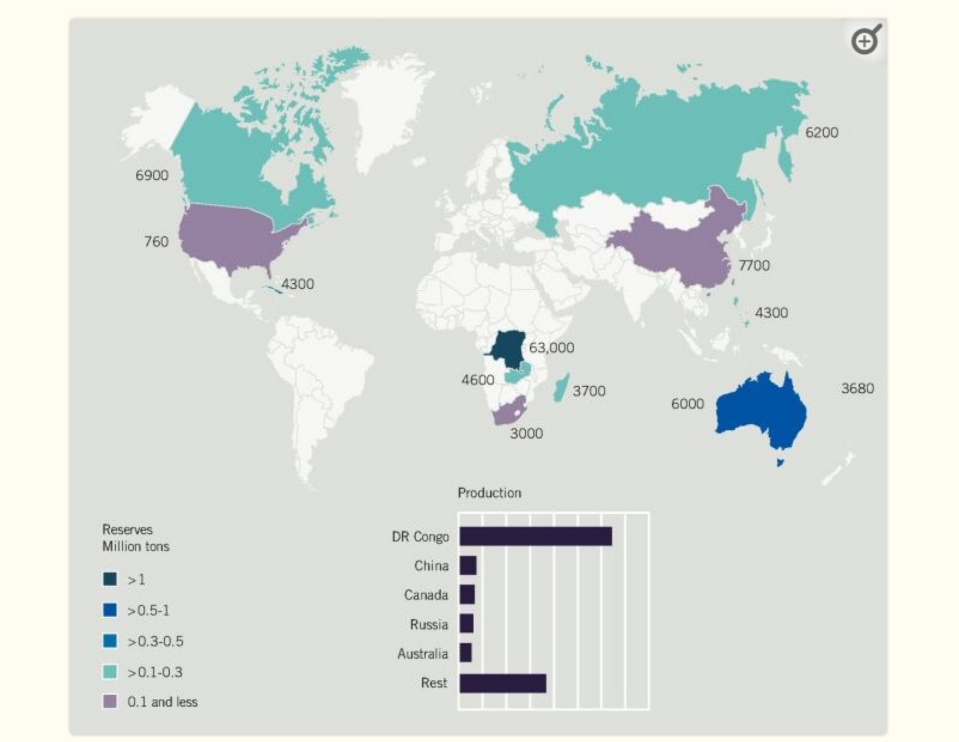
Non-Sustainable Resources for Battery Needs



Global mined lithium production in 2015, plus reserves (the color of the countries indicates the reserves; the data in the countries represent the annual production)



Global mined cobalt production in 2015, plus reserves (the color of the countries indicates the reserves; the data in the countries represent the annual production)

By 2030, expected to need production of

- 250,000-450,000 t of lithium
- 250,000-420,000 t cobalt
- 1.3-2.4 million t of nickel

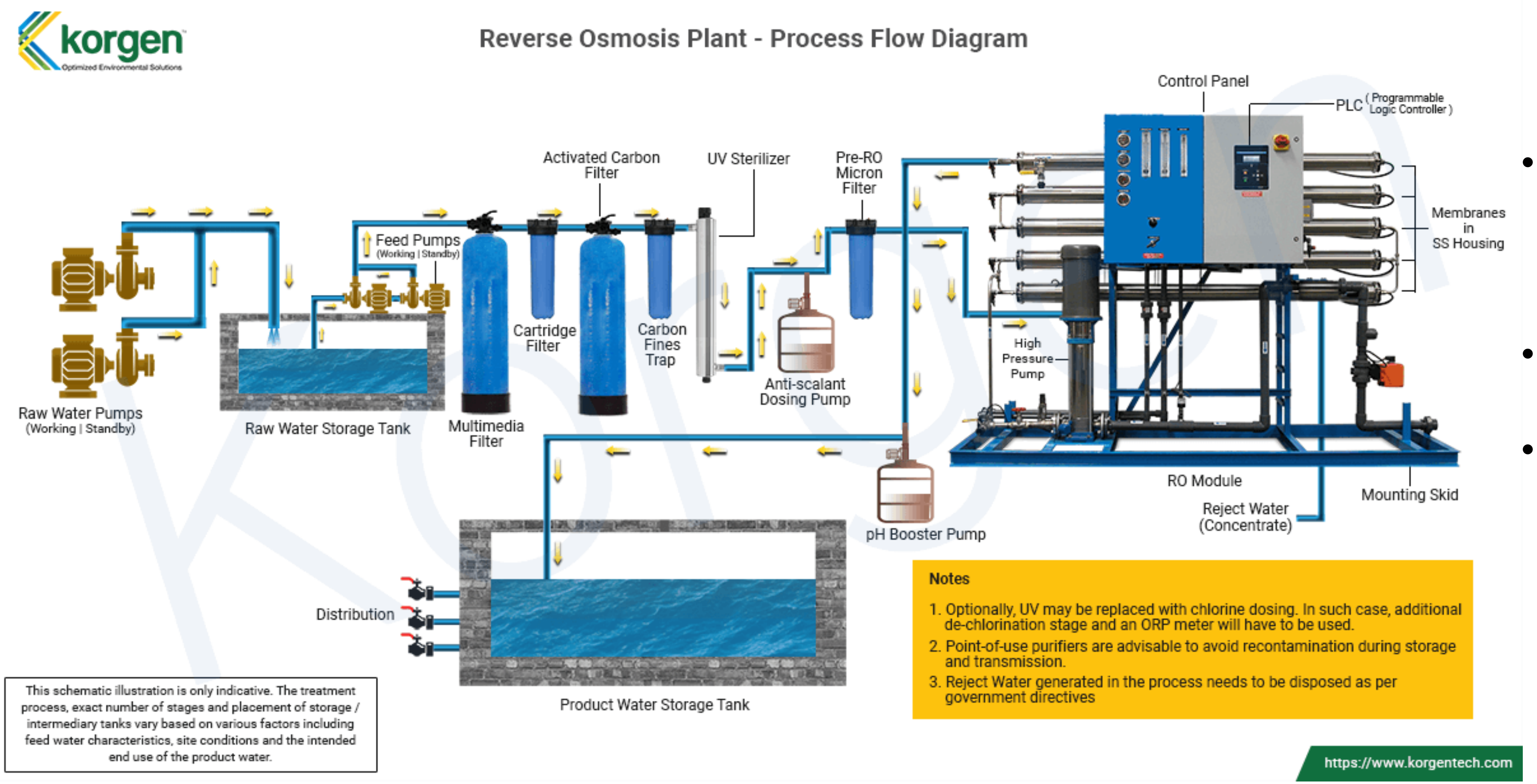
National library of medicine, ATZ Worldw. 2021; 123(9): 8–13. PMhttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC8390110/C (nih.gov)

Hydrogen Shot "Earthshot" [1:1:1]

- Development of a method to produce low-cost ultra pure water
- Development of a low-cost membrane for separation of gases after water splitting

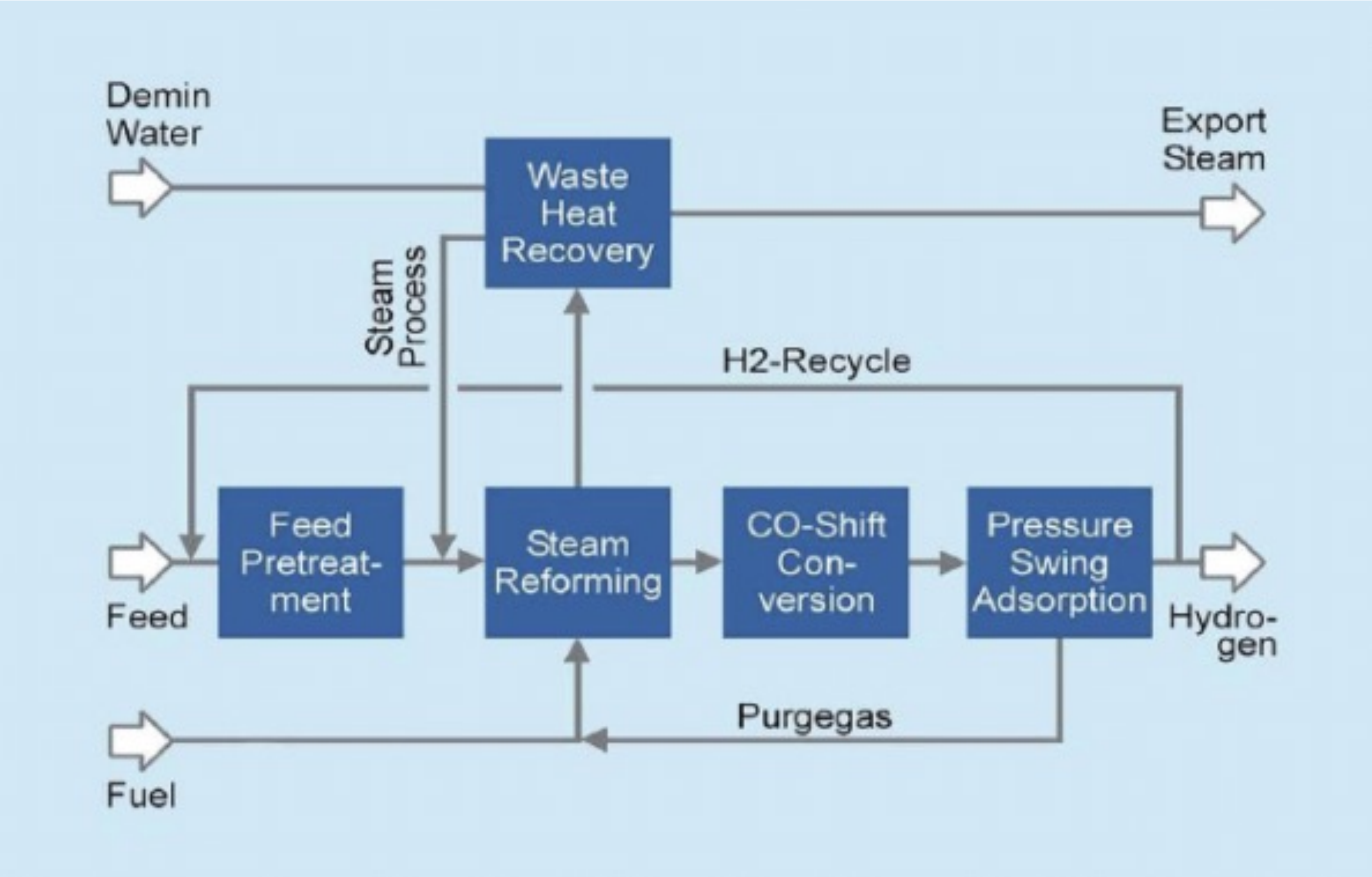
DOE National Clean Hydrogen Strategy roadmap, September 2022, U.S Department of Energy

Current Industrial Ultrapure Water Production – Reverse Osmosis



- Large systems that require lots of energy
- Excess water usage
- Prone to fouling

Current H_2 Gas Production Method - Steam Methane Reformation



$CH_4 + H_2O \longleftrightarrow CO + 3H_2$ ΔH_{295}= -206 Kj/mol

$CO + H_2O \longleftrightarrow CO_2 + H_2$ ΔH_{298}= -41 Kj/mol

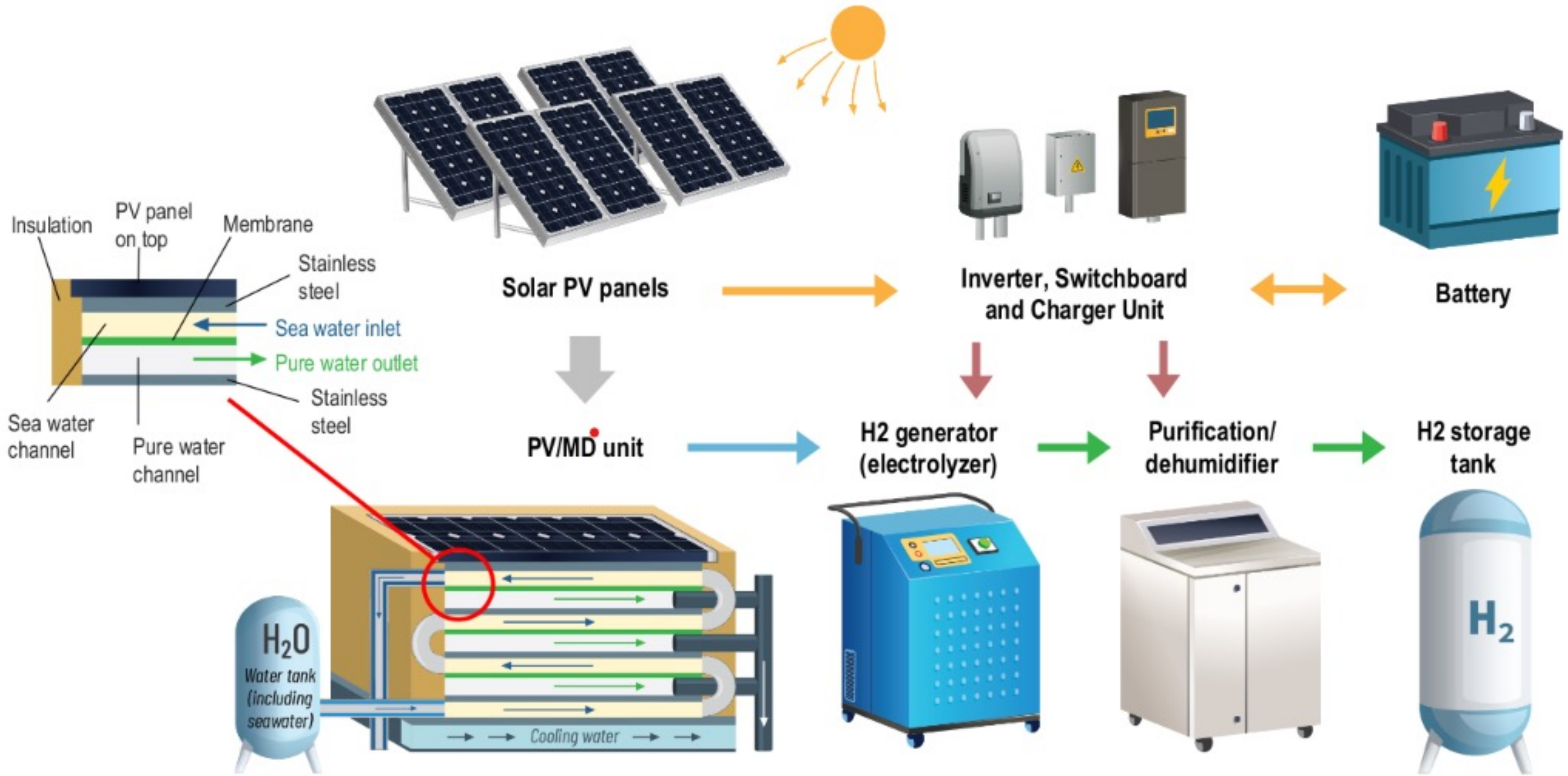
$CH_4 + 2H_2O \longleftrightarrow CO_2 + 4H_2$ ΔH_{295}= 165 Kj/mol

- Cheapest and most utilized production of hydrogen gas
- Around $2/kg of hydrogen
- Large production of unwanted products

Energy Procedia 37 (2013) 7221-7230

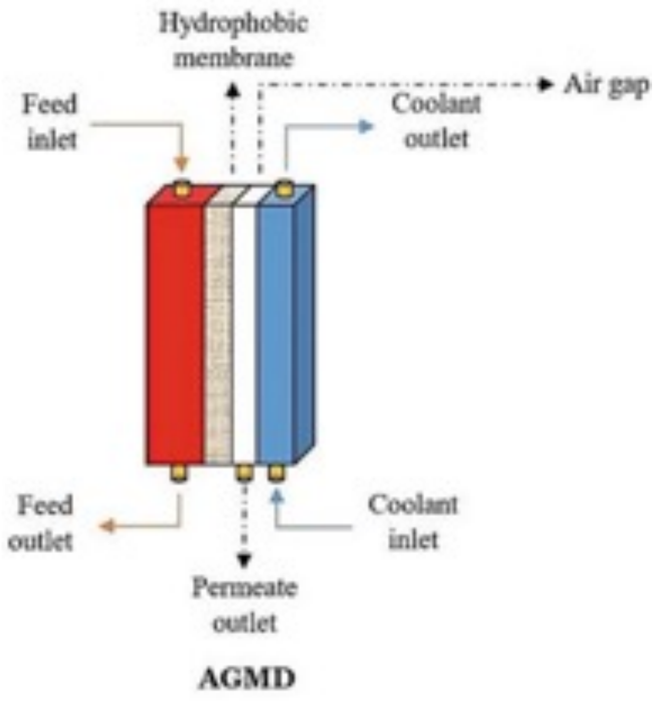
J. Am. Chem. Soc. 2008, 130, 4, 1402–1414

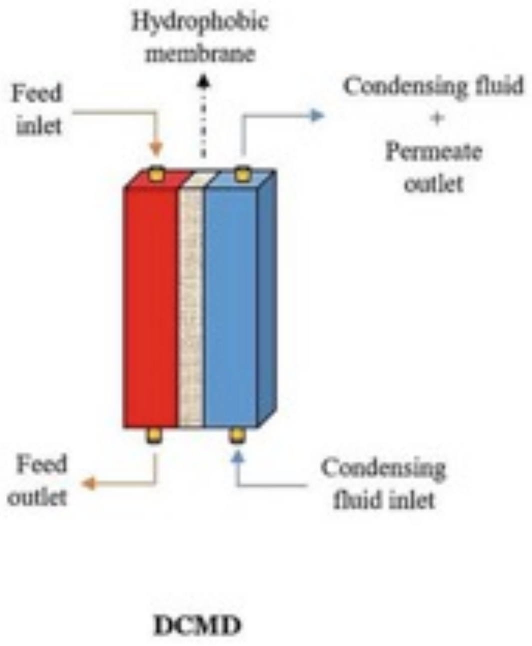
Project Overview



Membrane Distillation

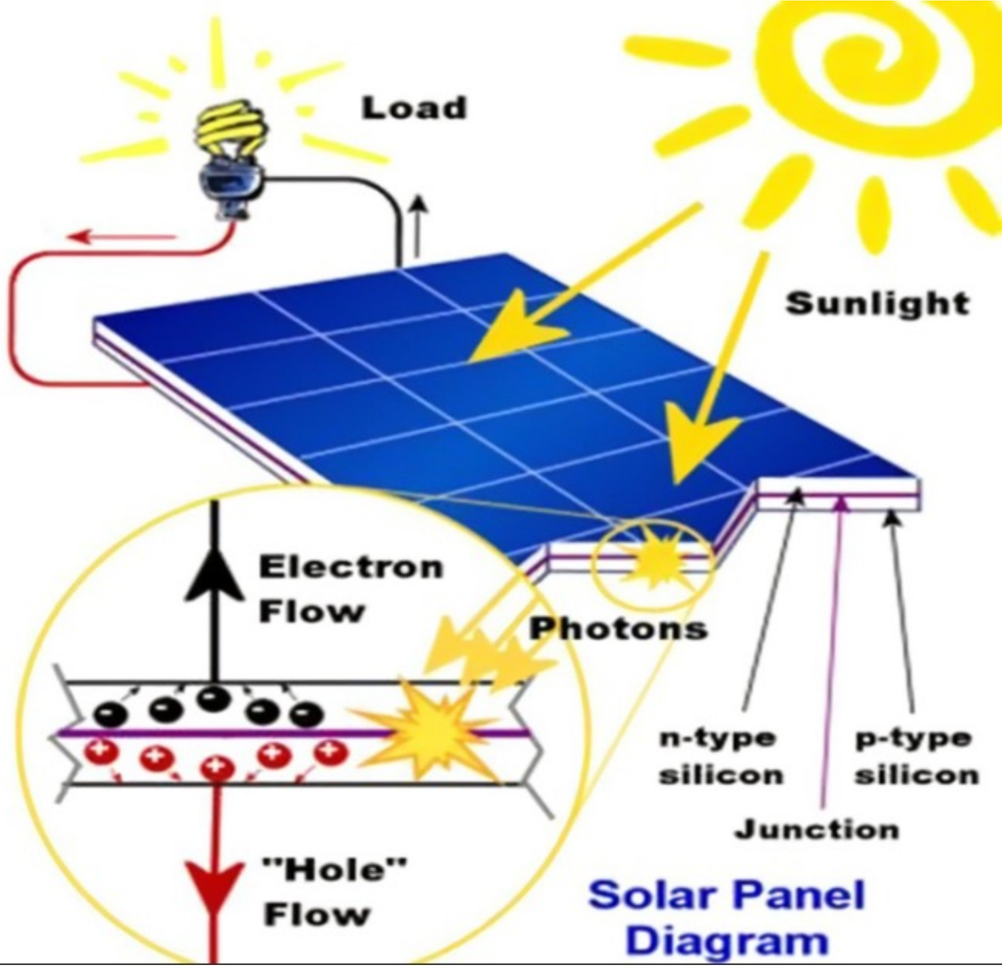
- Nonisothermal membrane separation process
- Driving force is partial pressure differences induced by temperature gradients
- Hydrophobic membrane
- Requires a source of heat

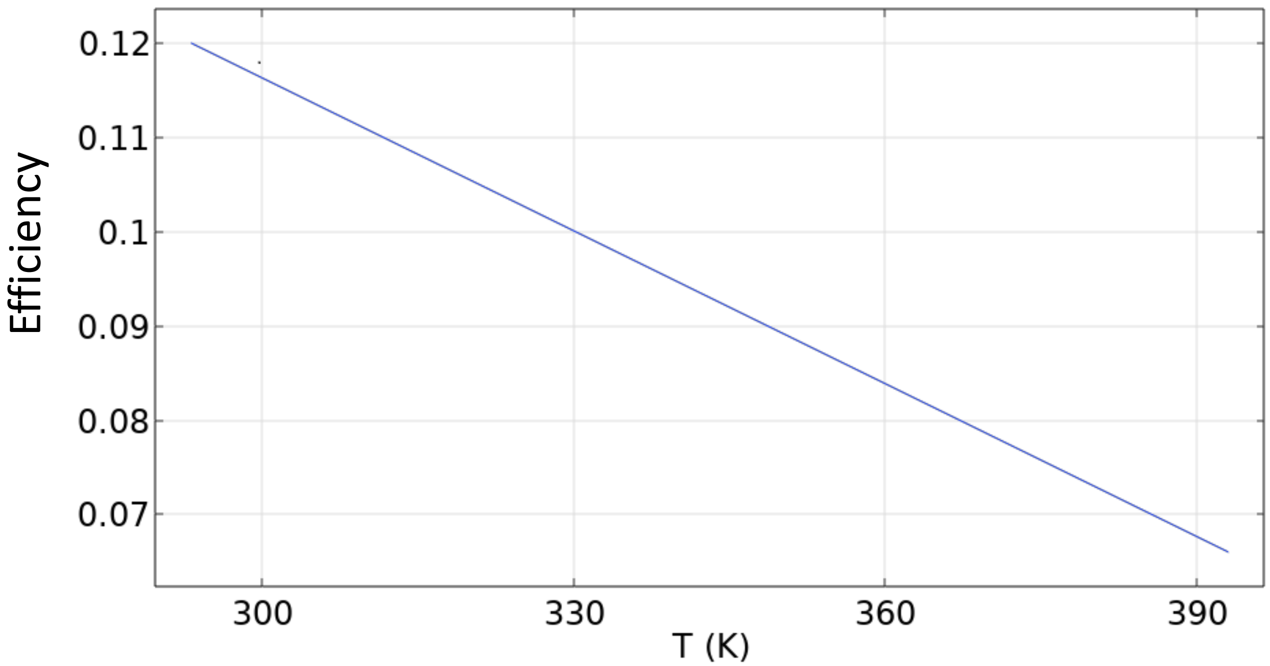




https://www.intechopen.com/chapters/67689

Waste Heat Source

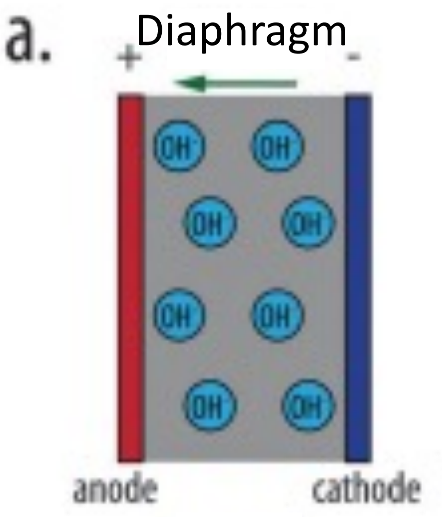




- As temperature increases, efficiency of the Solar cells decreases
- Efficiency drops, and creates excess heat (>80% solar energy)

Voudoukis, Nikolaos. (2018). Photovoltaic Technology and Innovative Solar Cells. European Journal of Electrical Engineering and Computer Science. 2. 10.24018/ejece.2018.2.1.13.
www.sciencedirect.com Energy Procedia 33 (2013) 311 – 321
Nature Communications, 10, 3012, (2019)

Water Splitting by Electrolysis

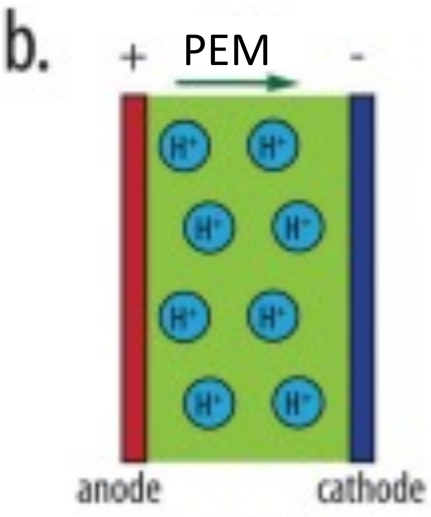


60-80 °C

$$4\,H_2O(l) + 4e^- \longrightarrow 2\,H_2(g) + 4\,OH^-(aq)$$

$$4\,OH^-(aq) \longrightarrow O_2(g) + 2\,H_2O + 4e^-$$

Alkaline water electrolyzer

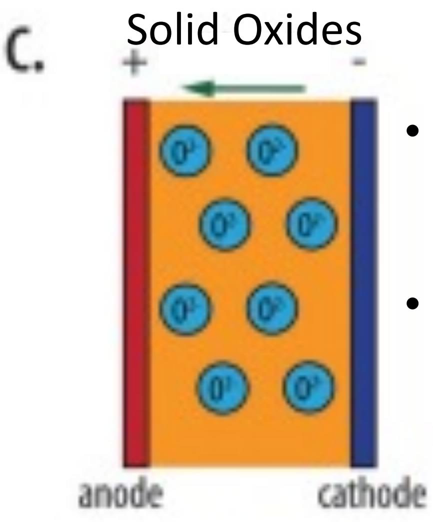


50-80 °C

$$4H^+(l) + 4e^- \longrightarrow 2H_2(g)$$

$$2H_2O(l) \longrightarrow O_2(g) + 4e^- + 4H_2(l)$$

Polymer-electrolyte-membrane electrolyzer



600-900 °C

$$2H_2O(g) + 4e^- \longrightarrow 2H_2(g) + 2\,O^{2-}$$

$$2\,O^{2-} \longrightarrow O_2(g) + 4e^-$$

High temperature solid-oxide electrolyzer

- Electrolyzer will produce dry Hydrogen and water vapor
- Must separate dry hydrogen for storage, or the storage cells will be damage by water or oxygen

Mater. Horiz., 2016, 3, 169—173, DOI: 10.1039/c6mh00016a
International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-4 Issue-3, February 2015

COMSOL Multiphysics Simulation Software

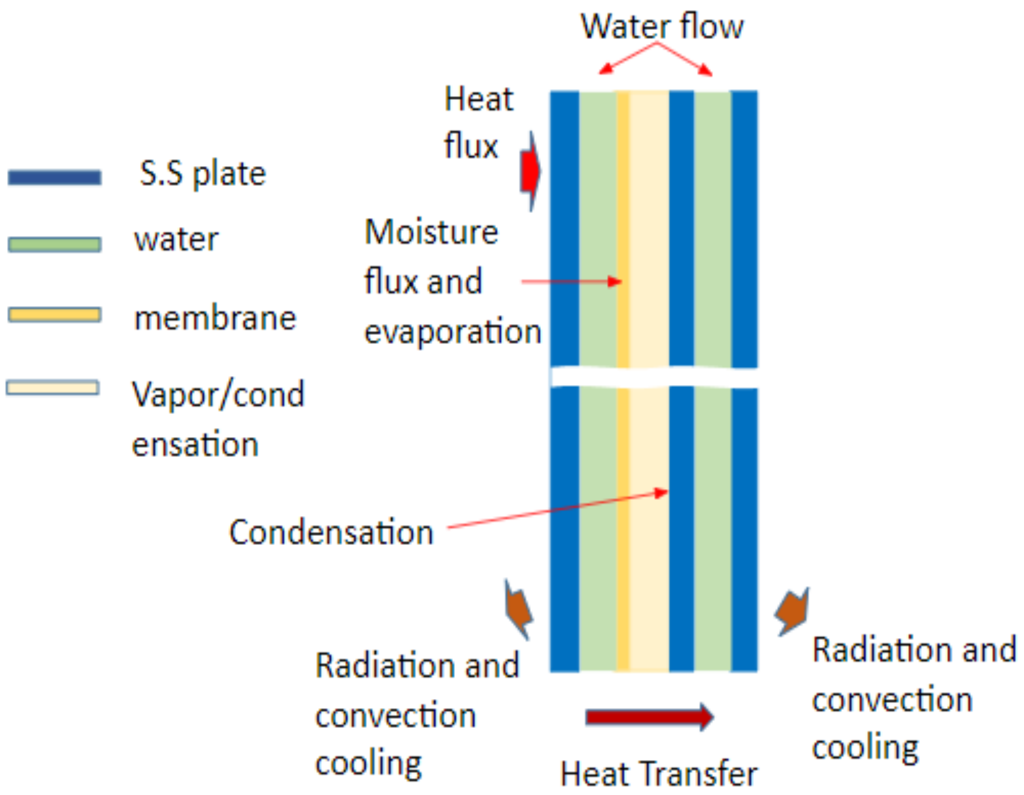
- Analysis, solver, design and simulation software

- Utilized for physics and engineering applications

- Used for the simulation and development of the flat top membrane distillation system

https://www.comsol.com/comsol-multiphysics

Layer Considerations in PV-MD System Simulations



1. Heat Transfer
   - Whole domain
2. Fluid (water) Flow
   - Flow type
   - Heat convection
3. Moist Air Flow
   - Moisture flux (through membrane)
   - Moisture evaporation (in membrane)
   - Moisture transportation
   - Moisture condensation
4. Coupling of Physics
   - Heat transfer and water flow
   - Moisture transportation and Moisture flow
   - Heat transfer and moisture flow

Membrane Properties

- Mass transfer judged by Knudsen Number

$$K_n = \frac{\gamma}{d}$$

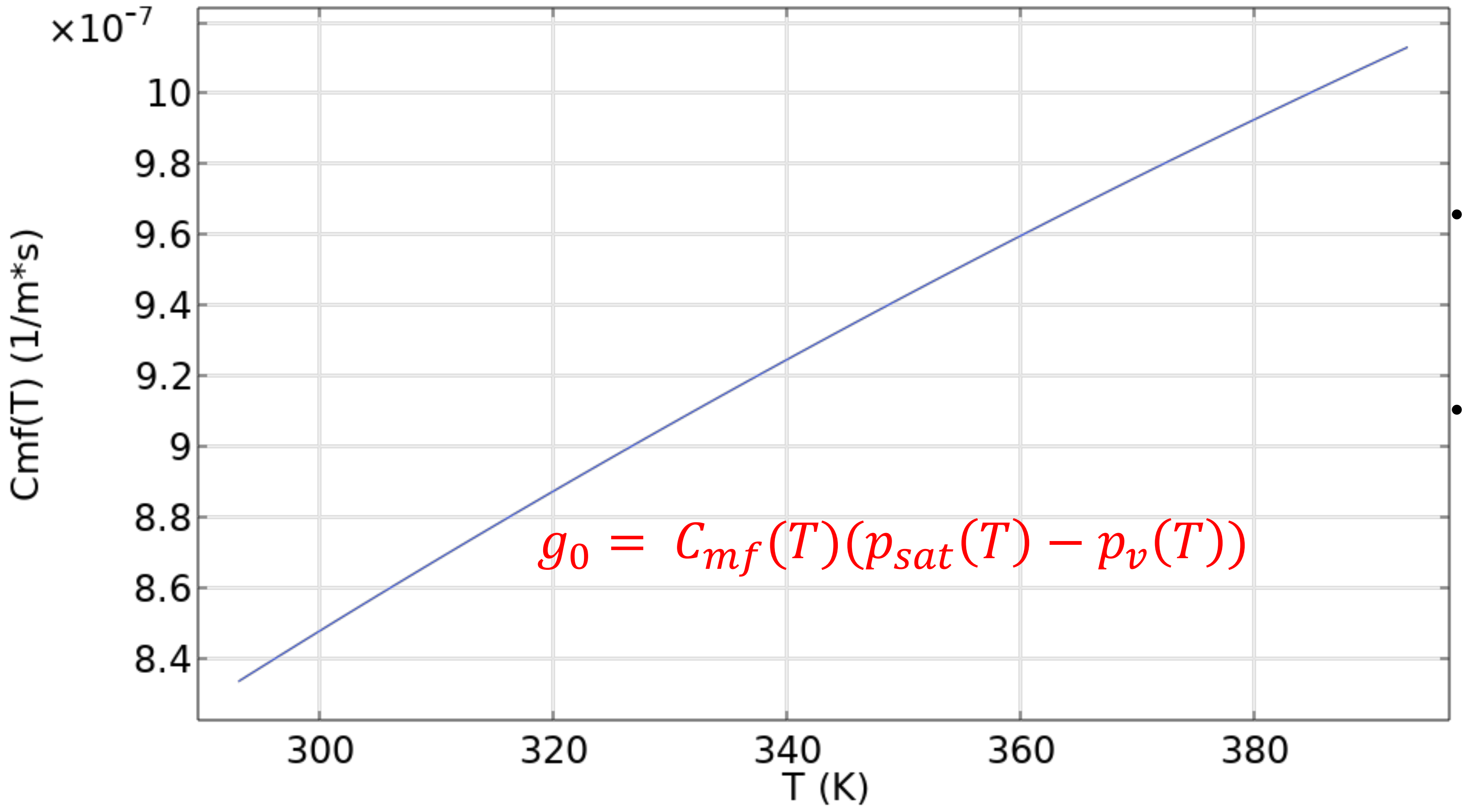
- Knudsen Number is the ratio of the molecular mean free path length to physical length scale

$$\gamma = \frac{K_B T}{P\sqrt{2}\pi\sigma^2}$$

Three possible cases for Knudsen Number

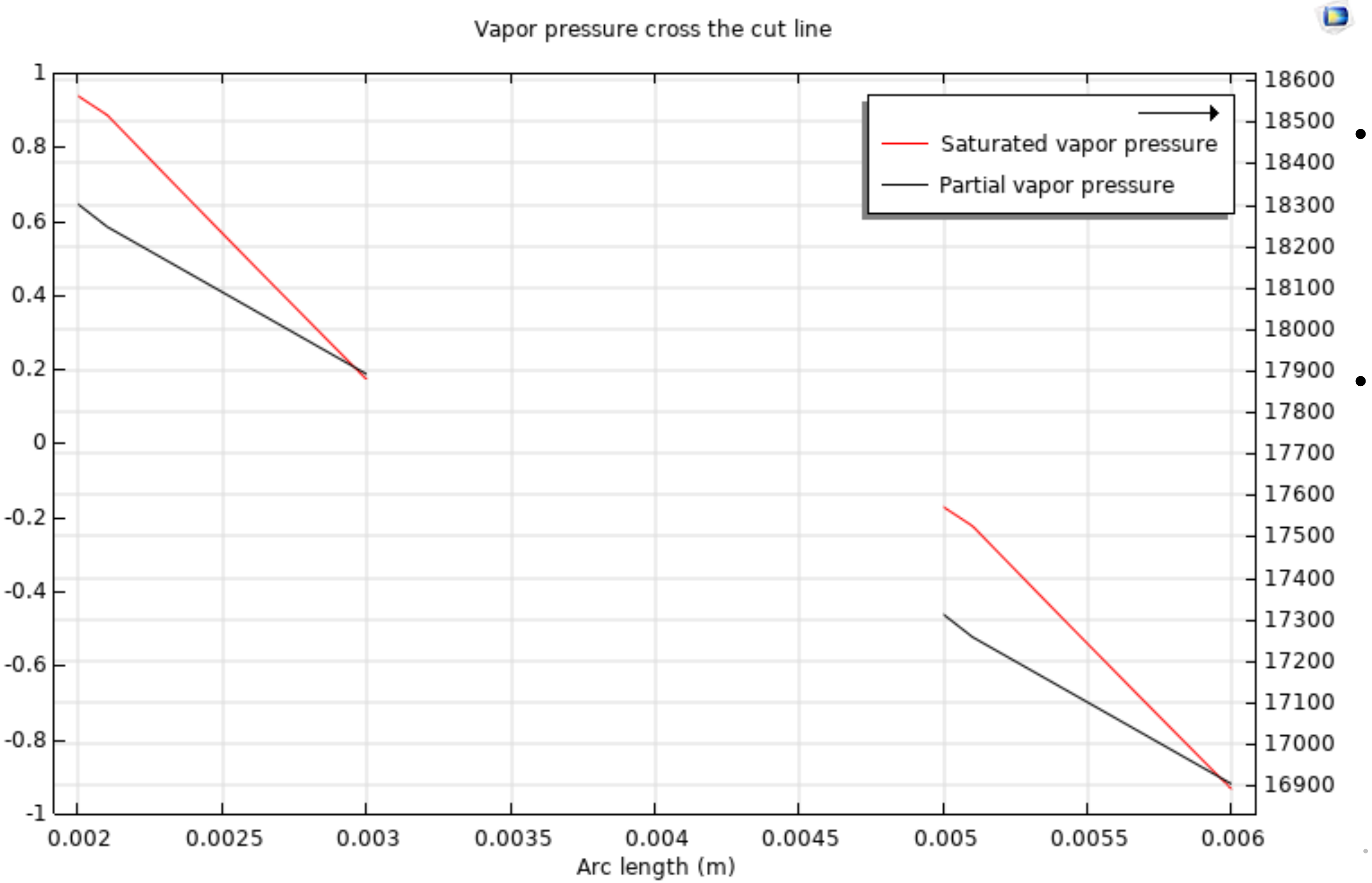
1. K_n > 1, the influence of pore radius dominates due to collision of diffusion molecules with membrane pore wall, known as Knudson Diffusion
2. K_n < .01, mass transfer resistance is the primary collision between diffusion molecules
3. .01 < K_n < 1, mass transfer is combined with the molecular diffusion mechanism known as Knudson Diffusion

Coefficient C_{mf} $(= \beta_p)$vs Temperature T



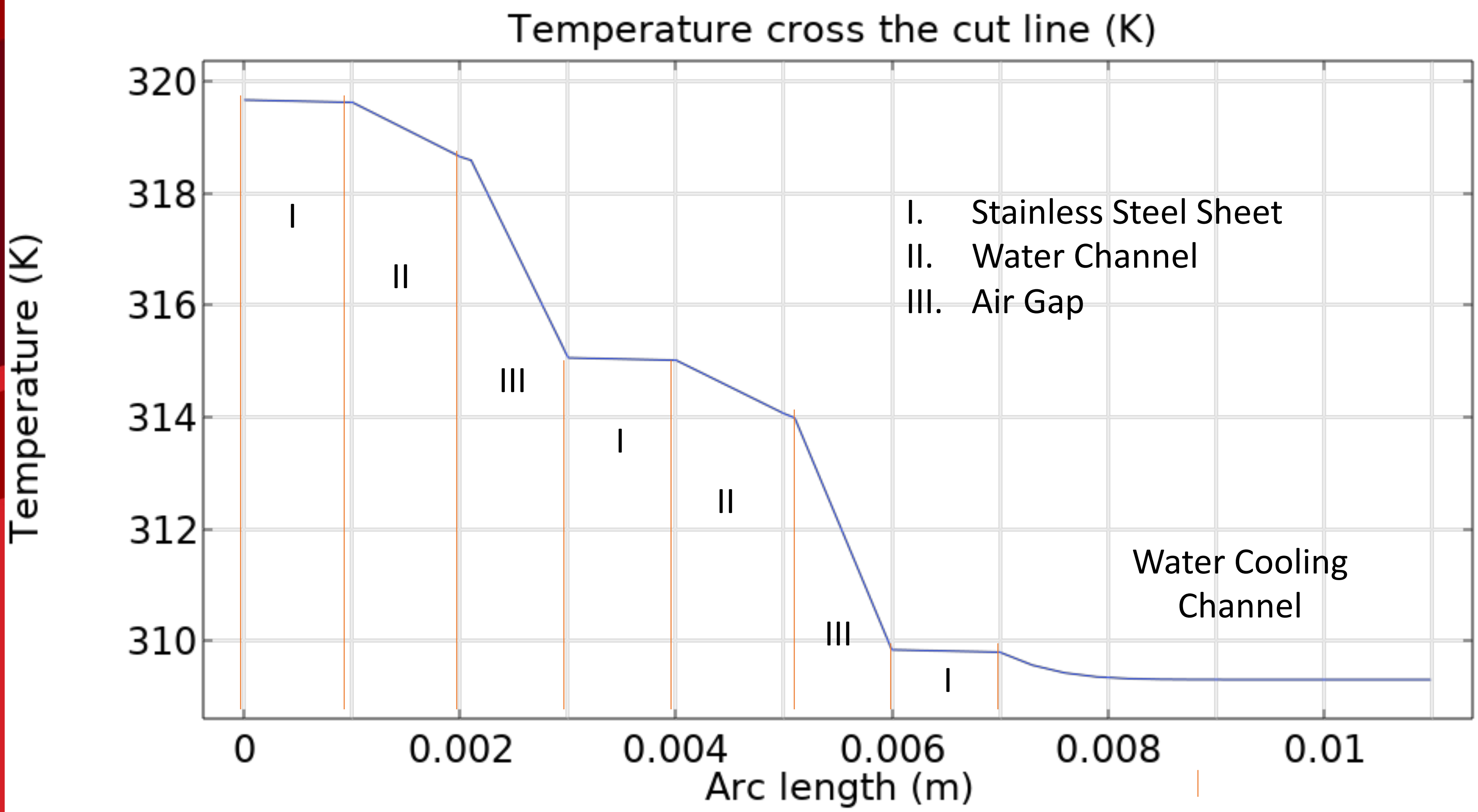
- Simulation utilized the equation $g_0 = C_{mf}(T)(p_{sat}(T) - p_v(T))$,,
- As temperature increases the coefficient increases

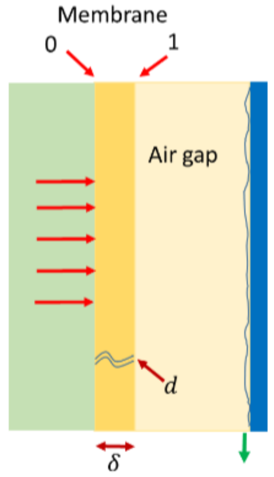
p_{sat} and p_v Differences Across Condensation Layer



- The partial pressure difference between channels is similar at each step
- Driving force of membrane distillation

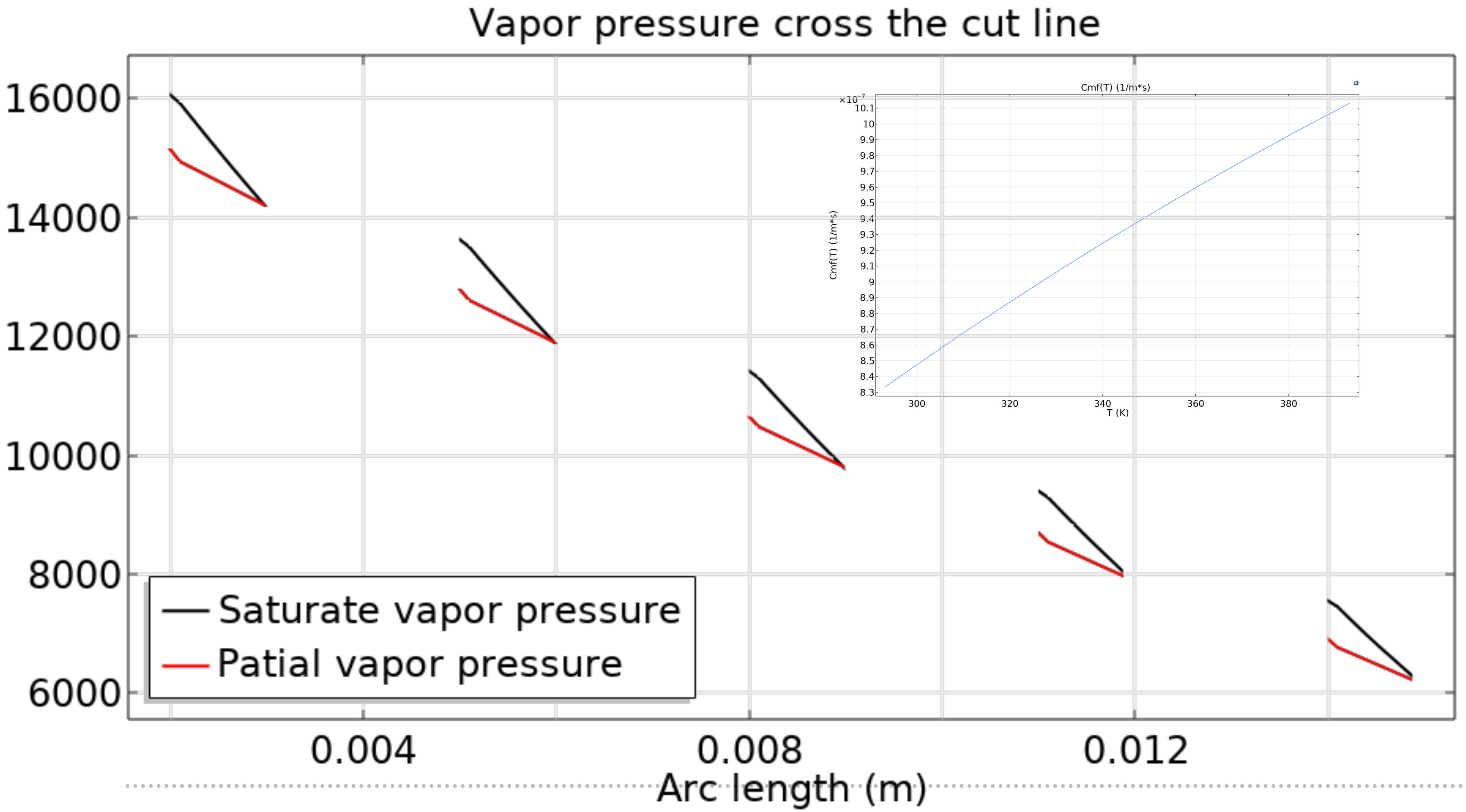
2-Layer Temperature Cross Section





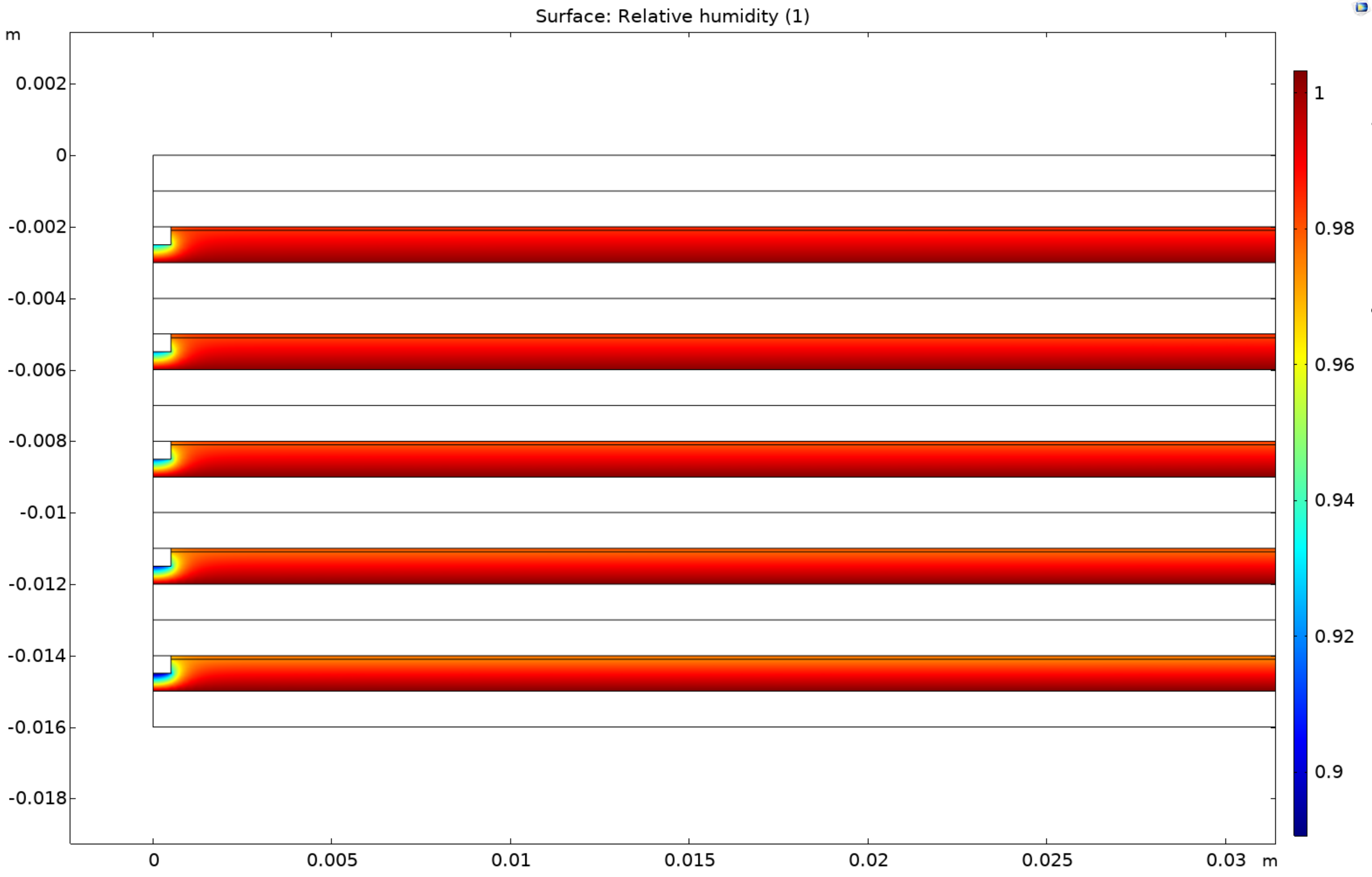
- MD production rate is approximately 400 $g/(m^2 h)$
- Attached water cooling channel

Five-Layer PV-MD p_{sat} and p_v Differences



- Partial pressure difference is the same gap with each layer

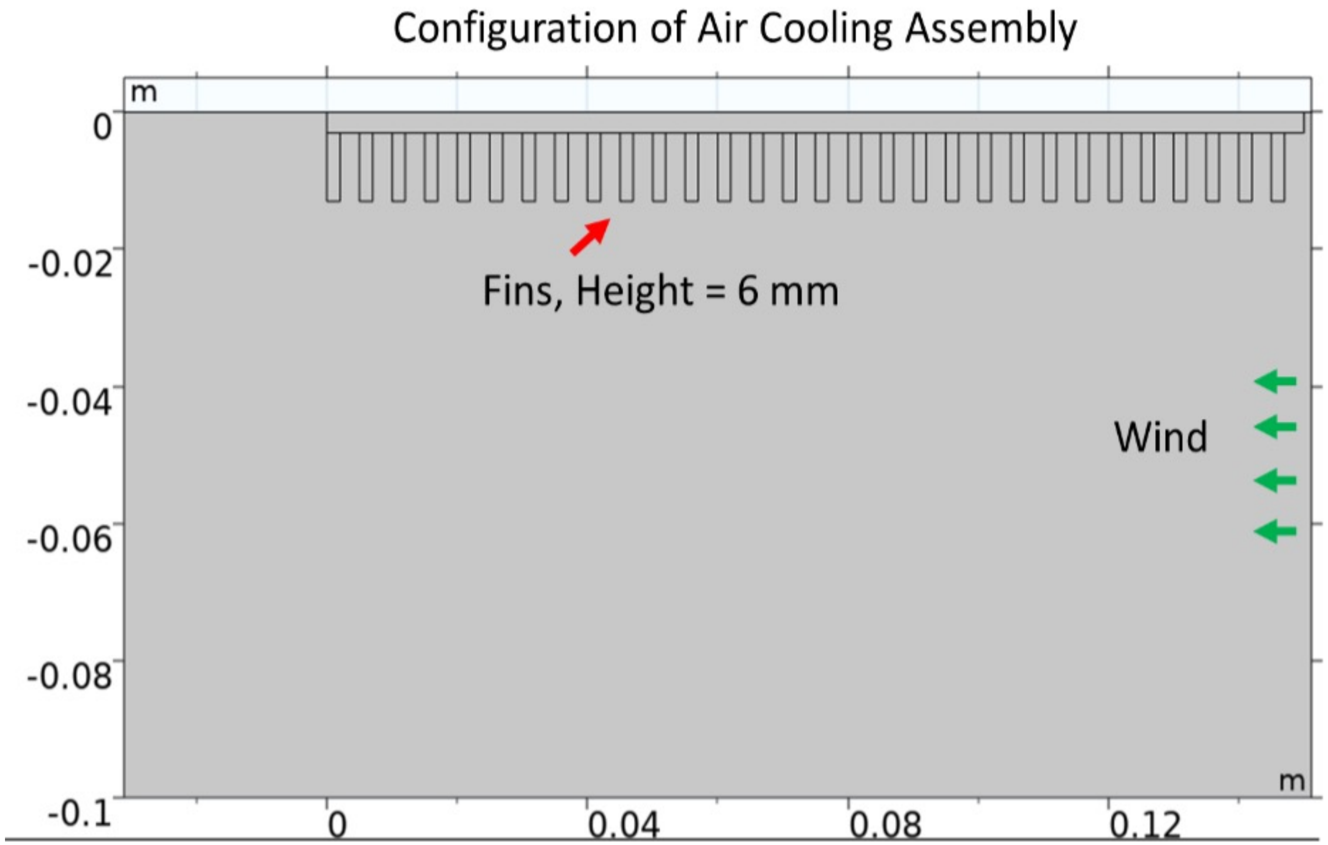
Five-Layer MD Condensation Channel Humidity



Set end plate temperature T_{amb}+ 5 (K)

1st layer rate is approximately 671 g/$(m^2 h)$

Air Cooling Simulation Design



- Cooling system designed to increase surface area
- Wind meant to come in contact with as much surface area as possible
- Difficult to control windspeed and keep it constant

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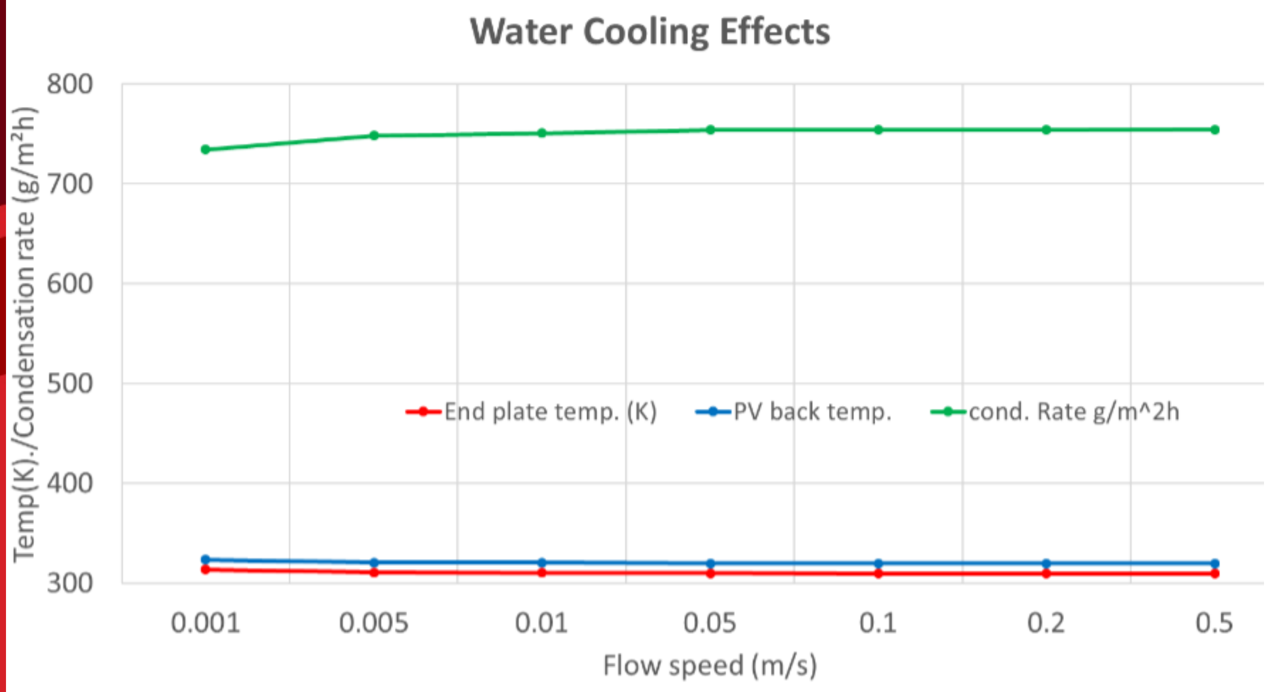
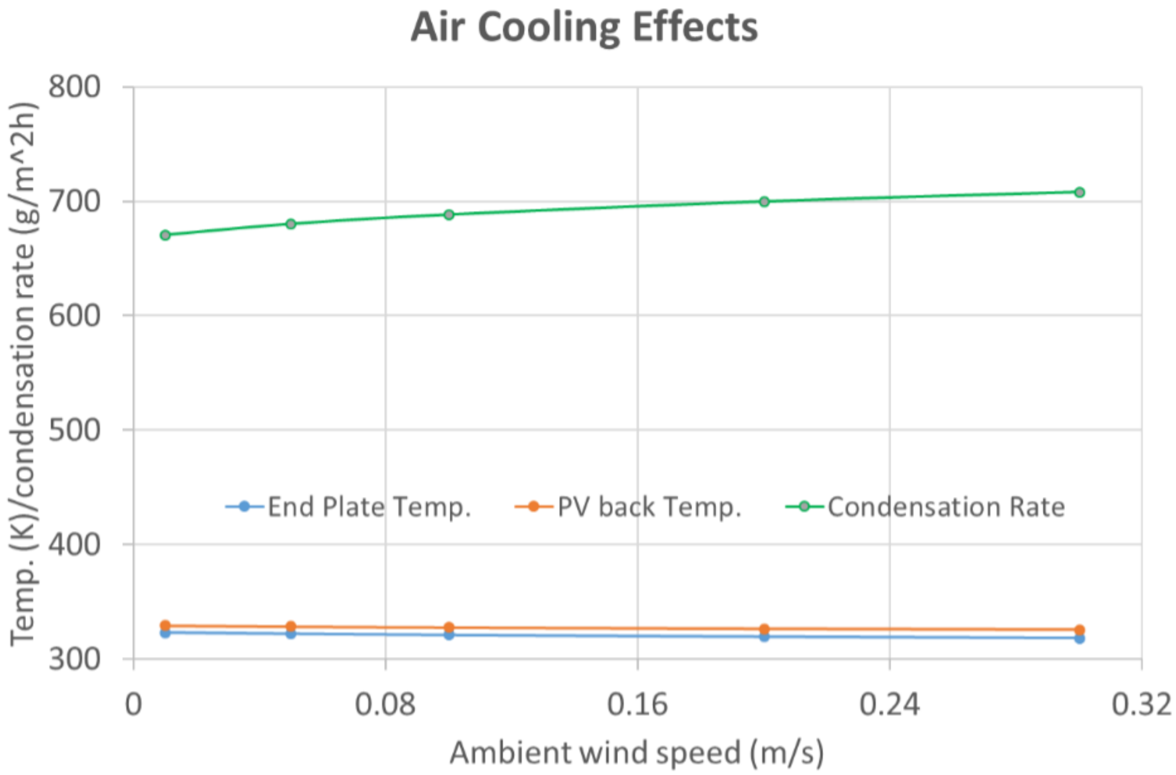
Water Cooling Vs. Air Cooling Simulation Results





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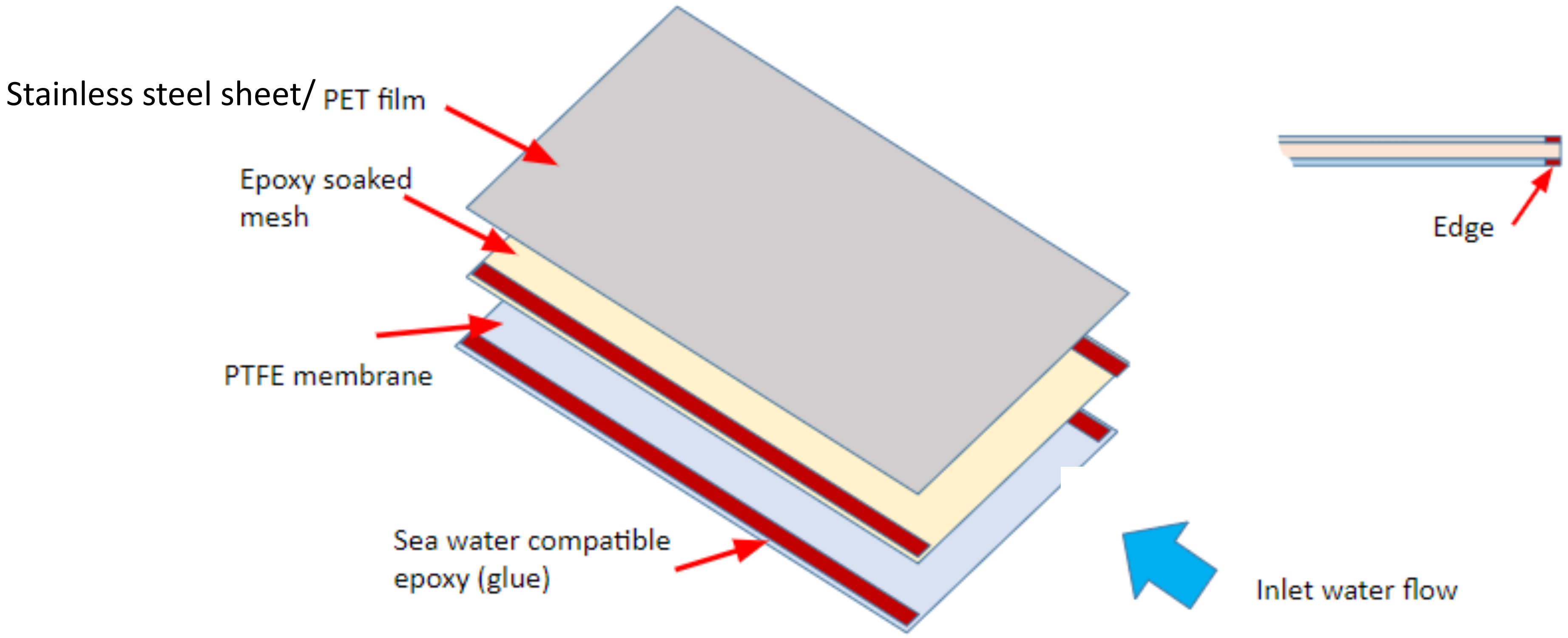
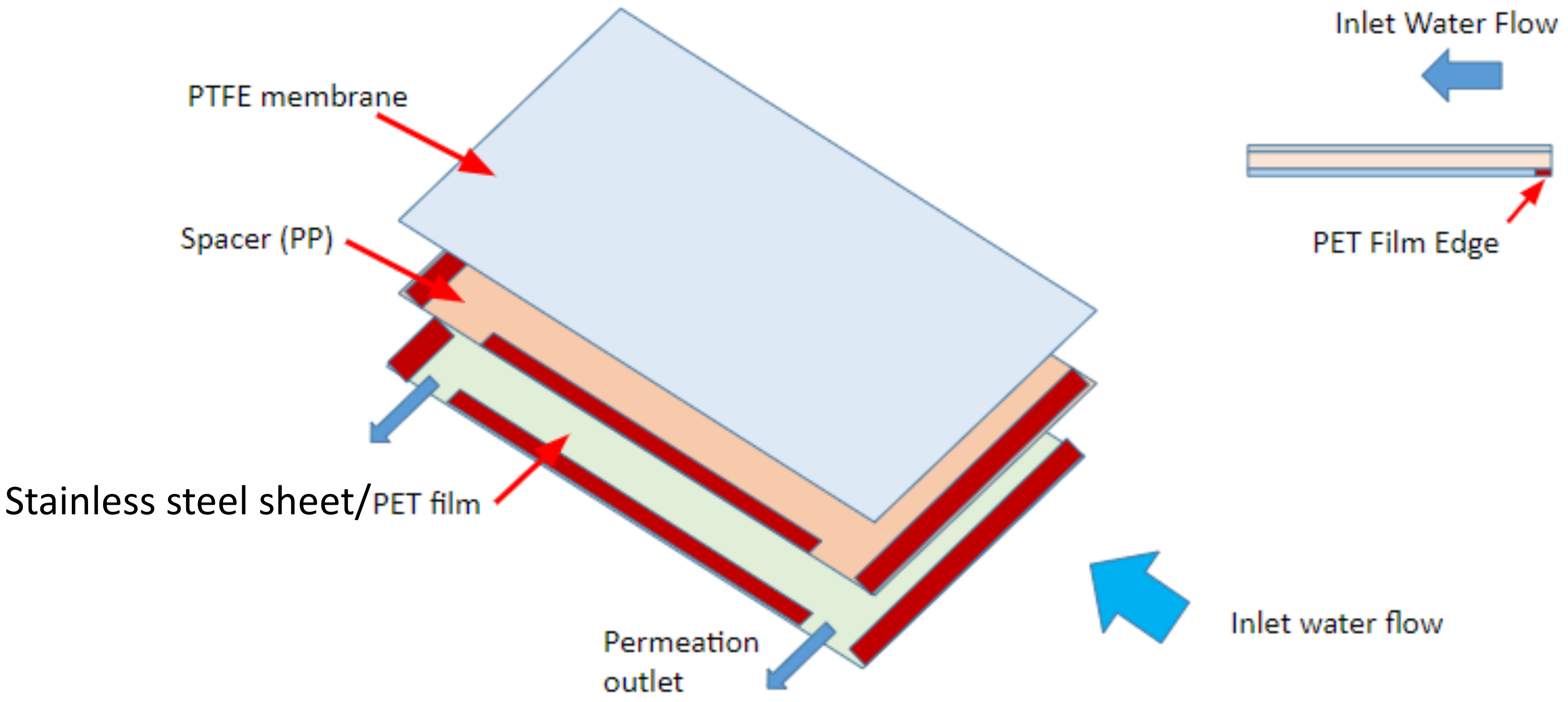
PV-MD System Schematic – Evaporation Channel

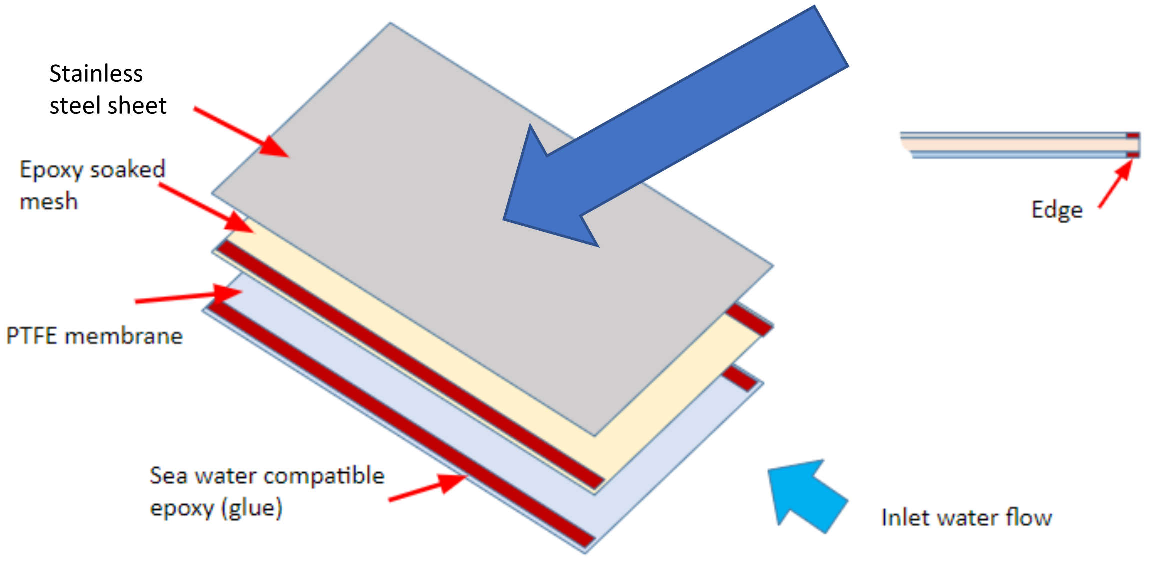


PV-MD System Schematic – Condensation Channel

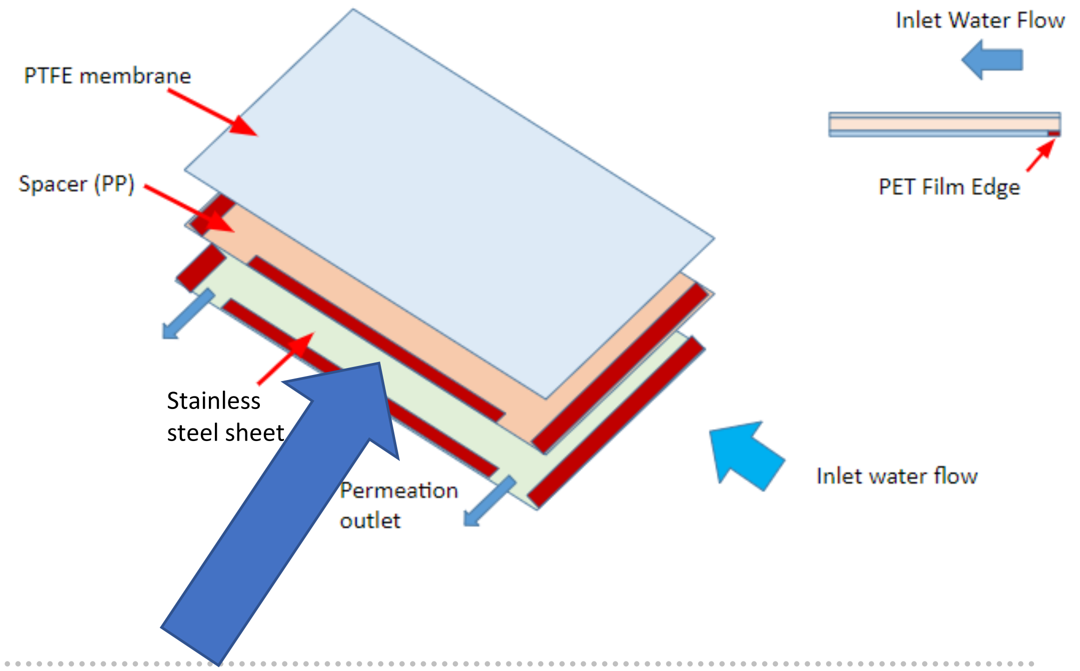


Material Selection- Condensation Sheet

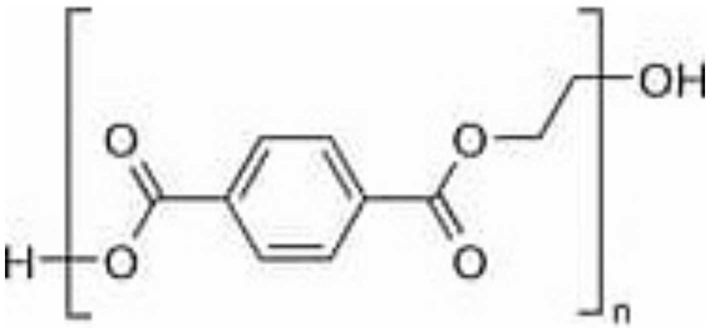
Evaporation Channel assembly



Condensation Channel Assembly



Polyethylene Terephthalate (PET)



Name	PET
Phase at STP	solid
Density	1350 kg/m3
Ultimate Tensile Strength	150 MPa
Yield Strength	40 MPa
Young's Modulus of Elasticity	9 GPa
Brinell Hardness	20 BHN
Melting Point	267 °C
Thermal Conductivity	0.3 W/mK
Heat Capacity	1250 J/g K
Price	0.8 $/kg

- Low surface energy
- Inert
- Quite Cheap to utilize

https://material-properties.org/pet-density-strength-melting-point-thermal-conductivity

304 vs 316 Stainless Steel sheet

	304 SS	316 SS
Tensile Strength	520-750 MPa	520-700 Mpa
Yield Strength	215 MPa	290 MPa
Hardness	70 Rockwell B	79 Rockwell B
Modulus of elasticity	193-200 Gpa	164 Gpa
Thermal Conductivity	16.2/21.5 W/m·K	16.2/21.5 W/m·K
Price per kg	$5	$6.57

Comparison of the Elements of Series 304 Stainless Steel and Series 316 Stainless Steel

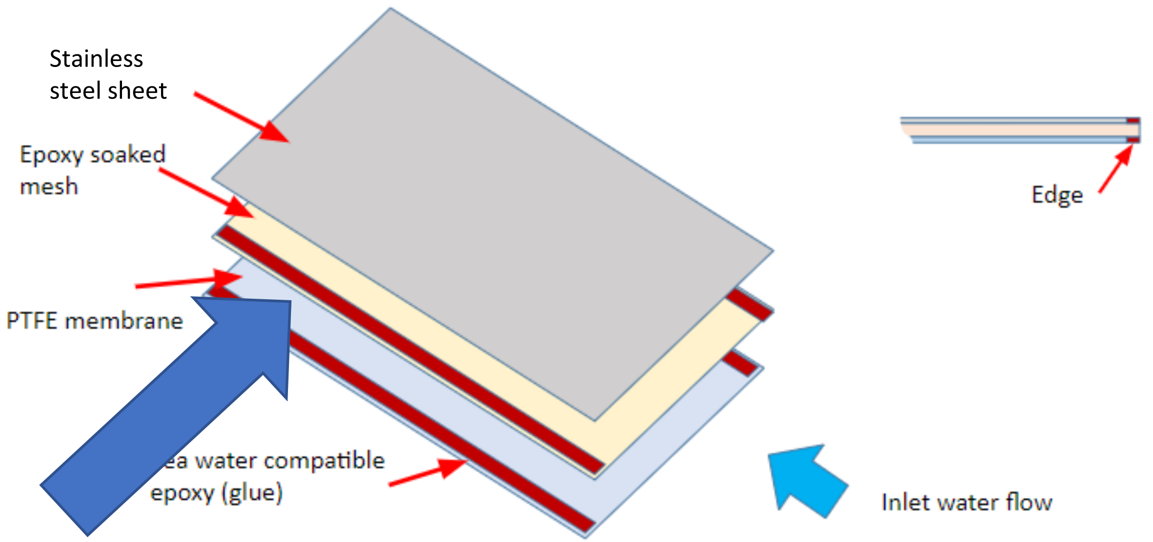
	Type 304	Type 316
Carbon	0.08% Max.	0.08% Max.
Manganese	2.00% Max.	2.00% Max.
Phosphorus	0.045% Max.	0.045% Max.
Sulfur	0.030% Max.	0.030% Max.
Silicon	1.00% Max.	1.00% Max.
Chromium	18.00 - 20.00	16.00 - 18.00
Nickel	8.00 - 10.50%	10.00 - 14.00
Molybdenum	-	2.00 - 3.00%

- Chemical composition of the different types of stainless-steel sheets is very similar
- Molybdenum is the major difference in 316 steel

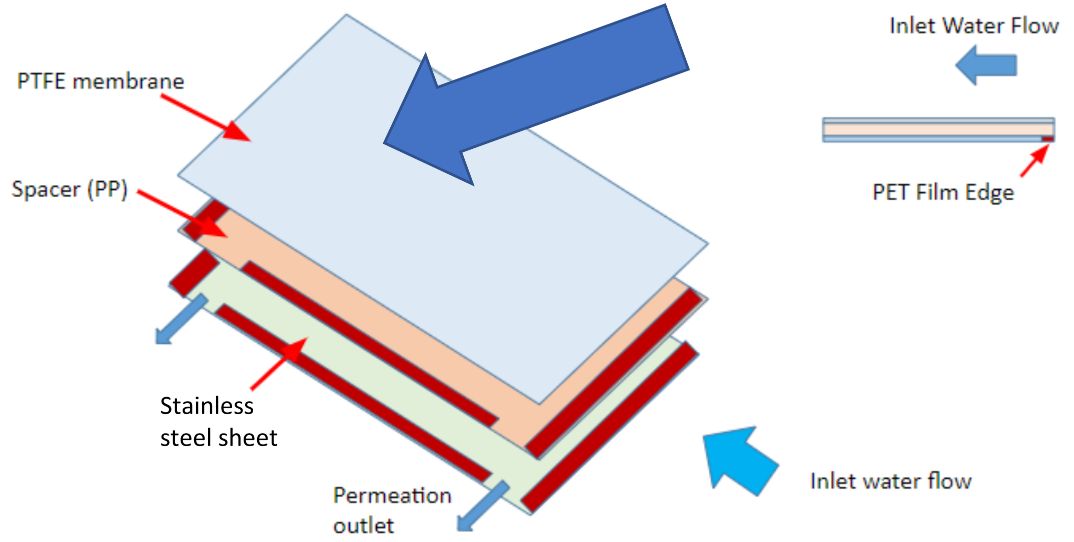
https://www.rapiddirect.com/blog/304vs-316-stainless-steel/-
https://www.iqsdirectory.com/articles/stainless-steel/stainless-steel-316.html
https://www.stindia.com/316-stainless-steel-supplier.html

Material Selection- Membrane

Evaporation Channel assembly

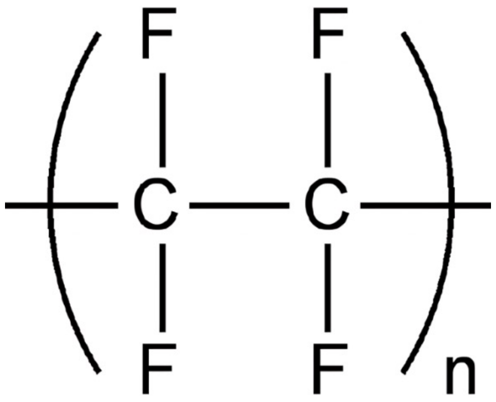


Condensation Channel Assembly



Polytetrafluoroethylene (PTFE)

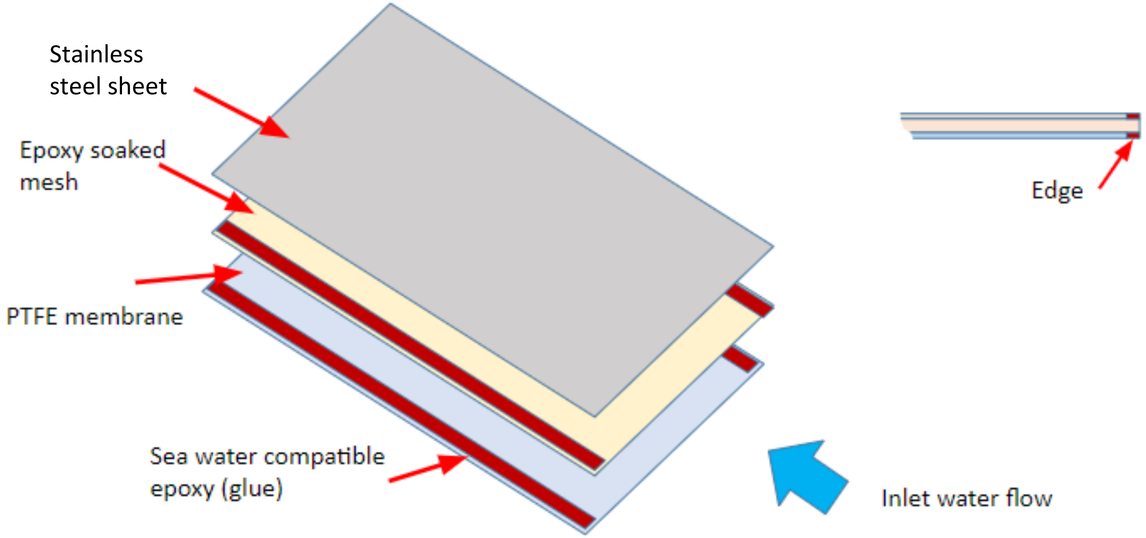
Property	Value
Melting Temperature (°C)	317-337
Tensile Modulus (MPa)	550
Elongation at Break (%)	300-550
Dielectric strength (kV/mm)	19.7
Dielectric Constant	2.0
Dynamic Co-efficient of Friction	0.04
Surface Energy (Dynes/g)	18
Appl. Temperature (°C)	260
Refractive Index	1.35



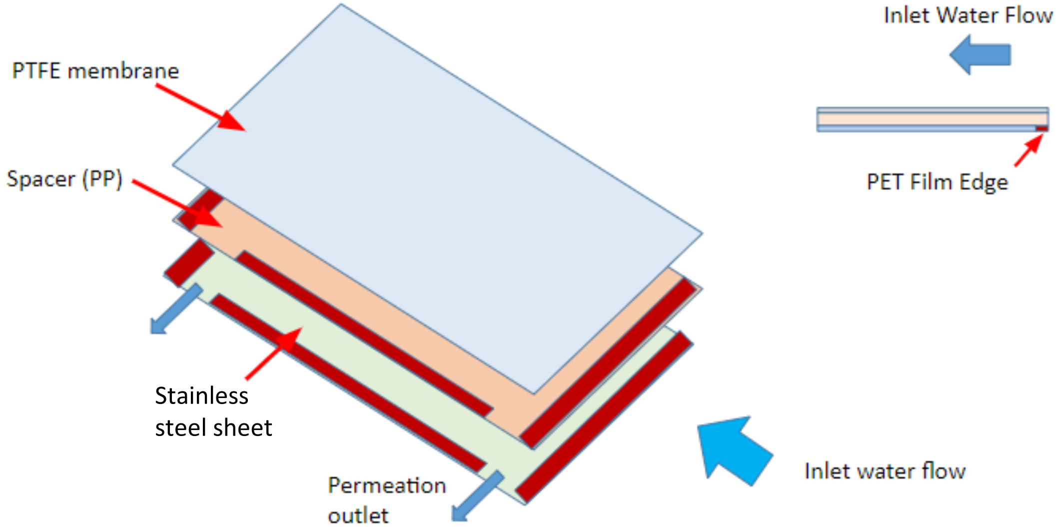
- Contact angle of 125 degrees
- Highly hydrophobic
- Low thermal conductivity

Material Selection - Compatible Glue

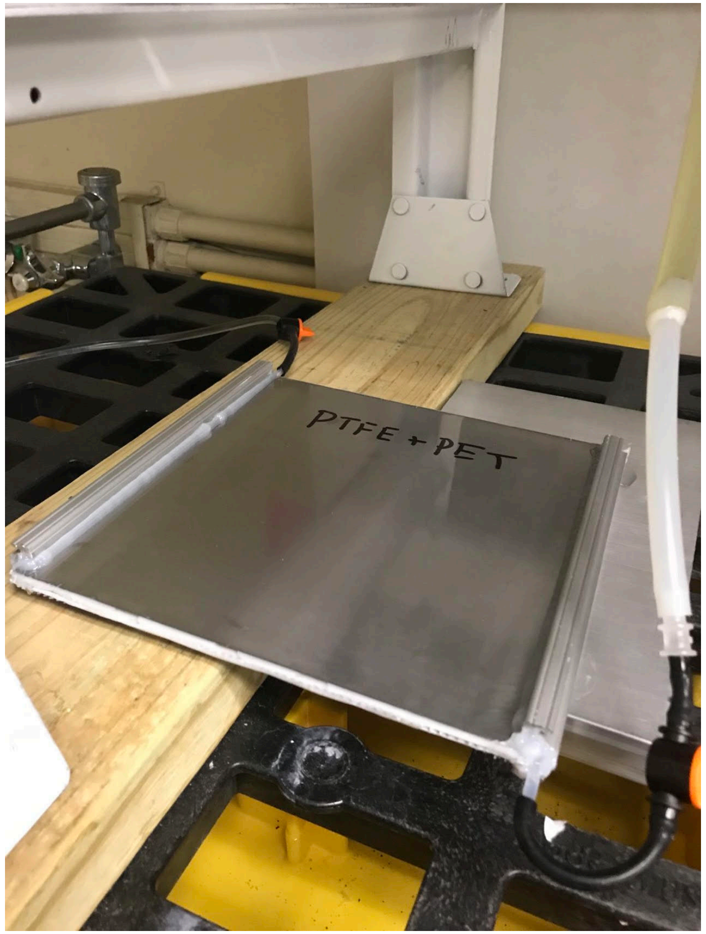
Evaporation Channel assembly

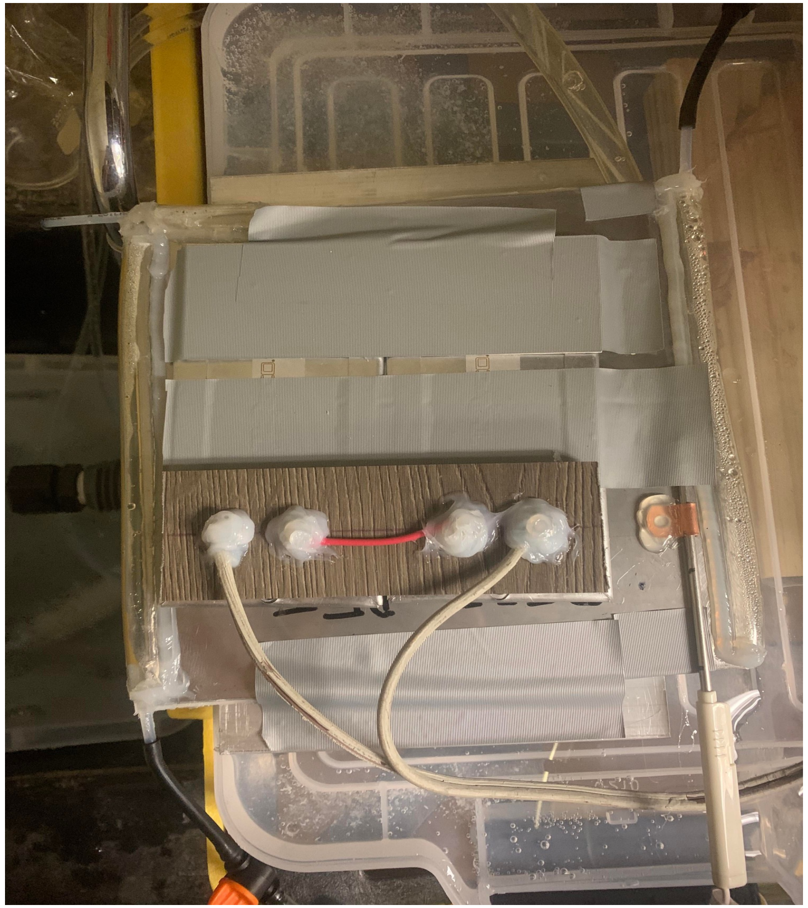


Condensation Channel Assembly



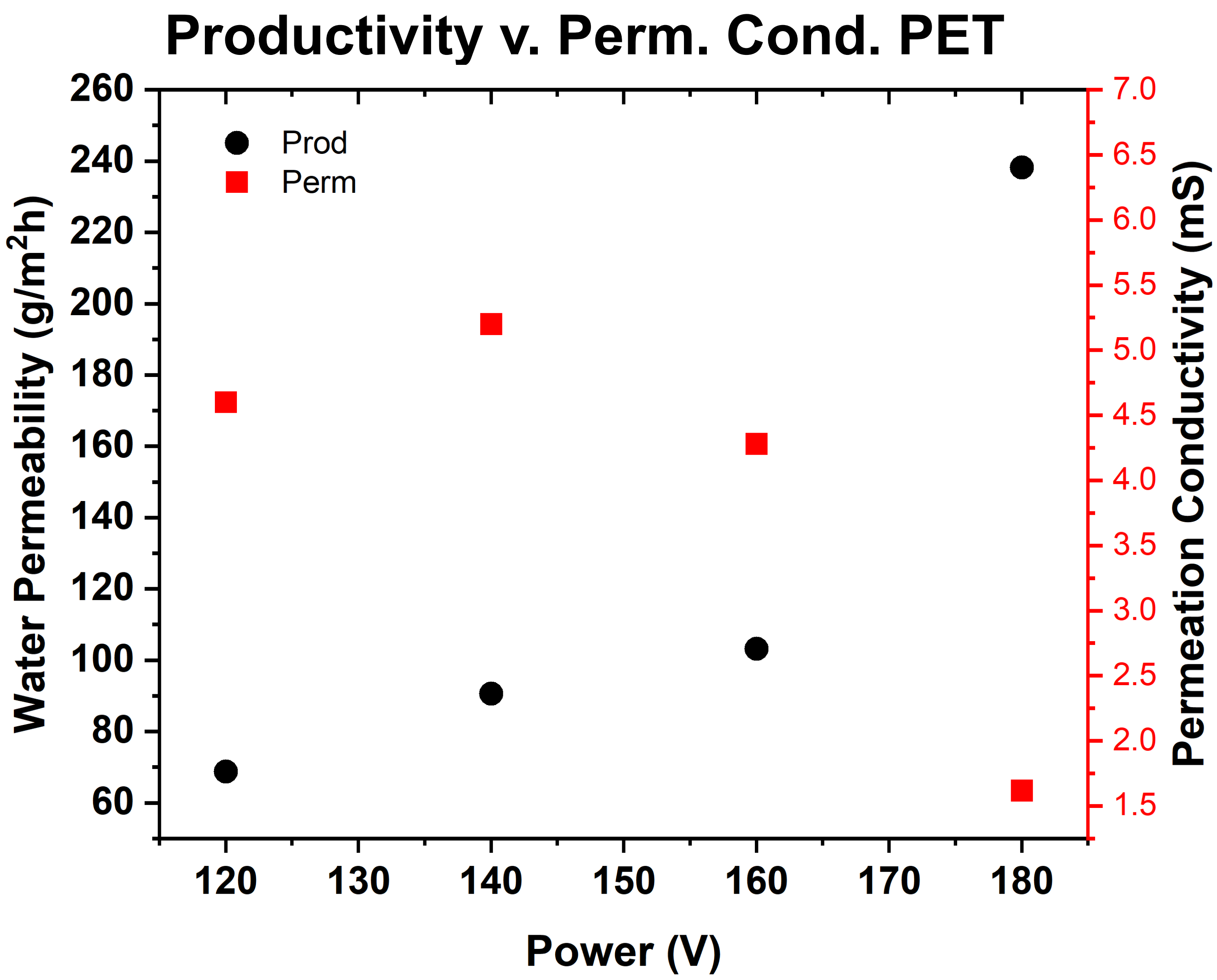
Small Scale Prototype Design





Water Cooling Assembly

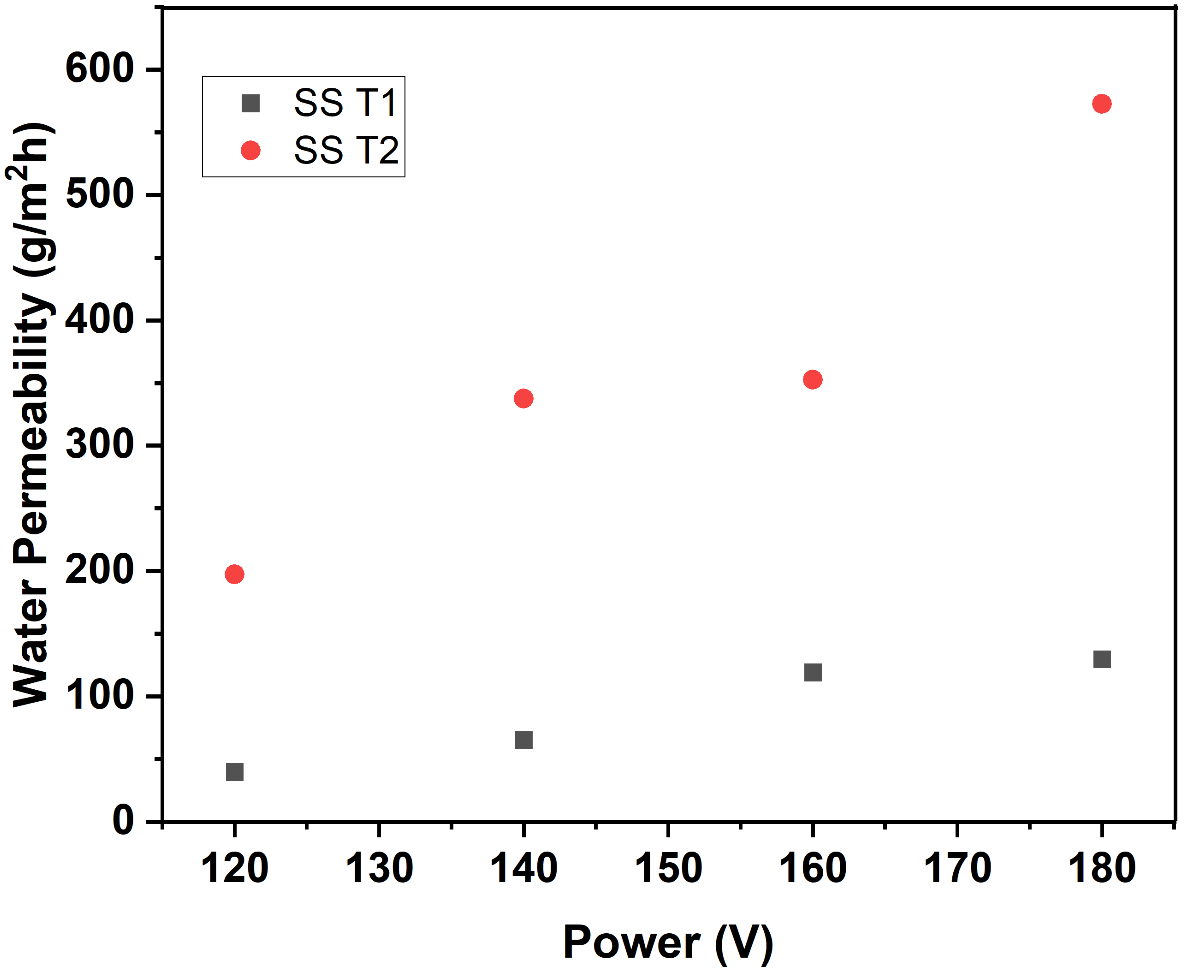
Current Shortcomings of the 4-Layer PET System

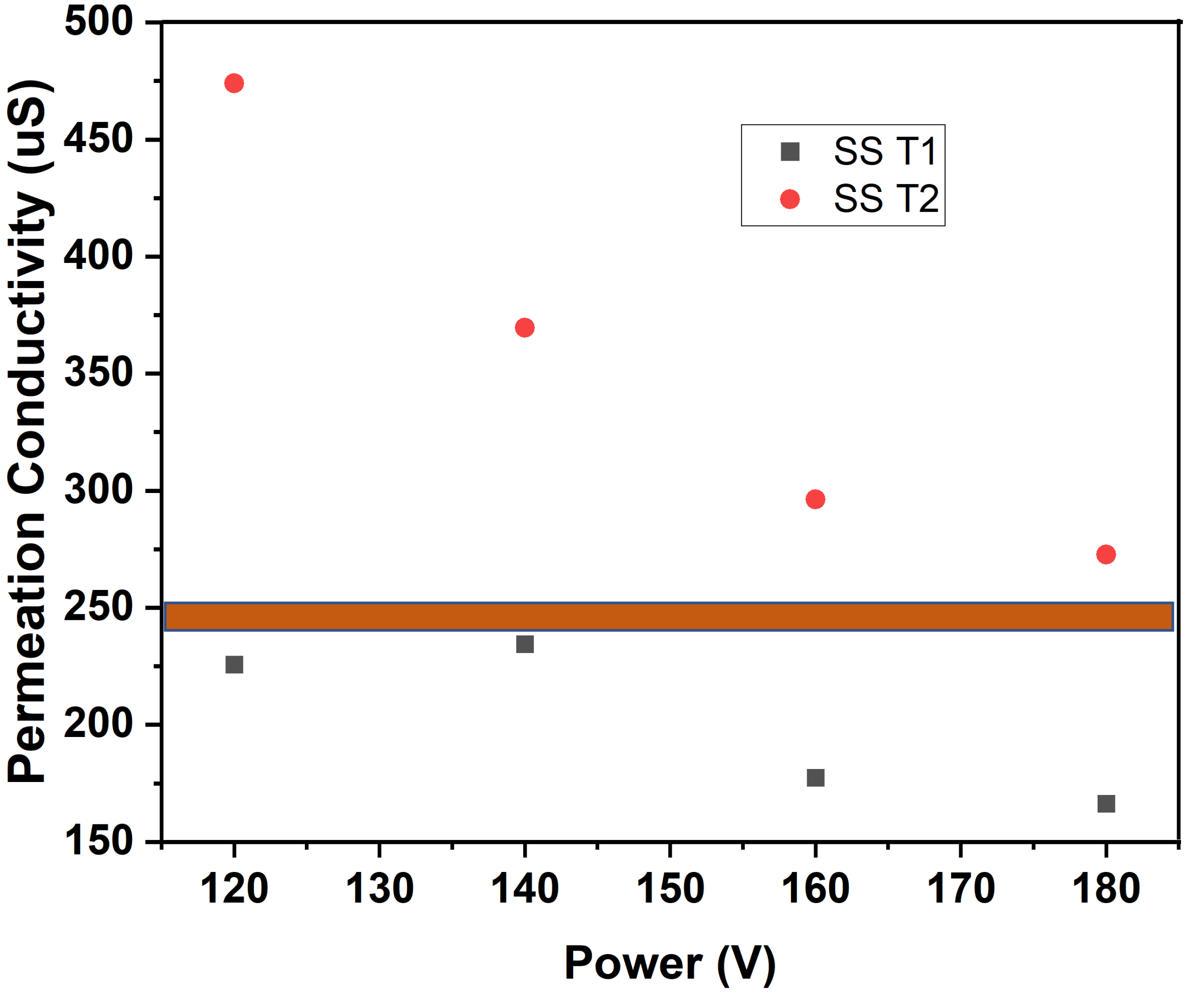


- Acceptable productivity
- Permeation conductivity unacceptable due to high conductivity measurements
- System was not abandoned but pushed to side for the moment being
- Feed water conductivity was around 58 mS

Synthetic Seawater tests

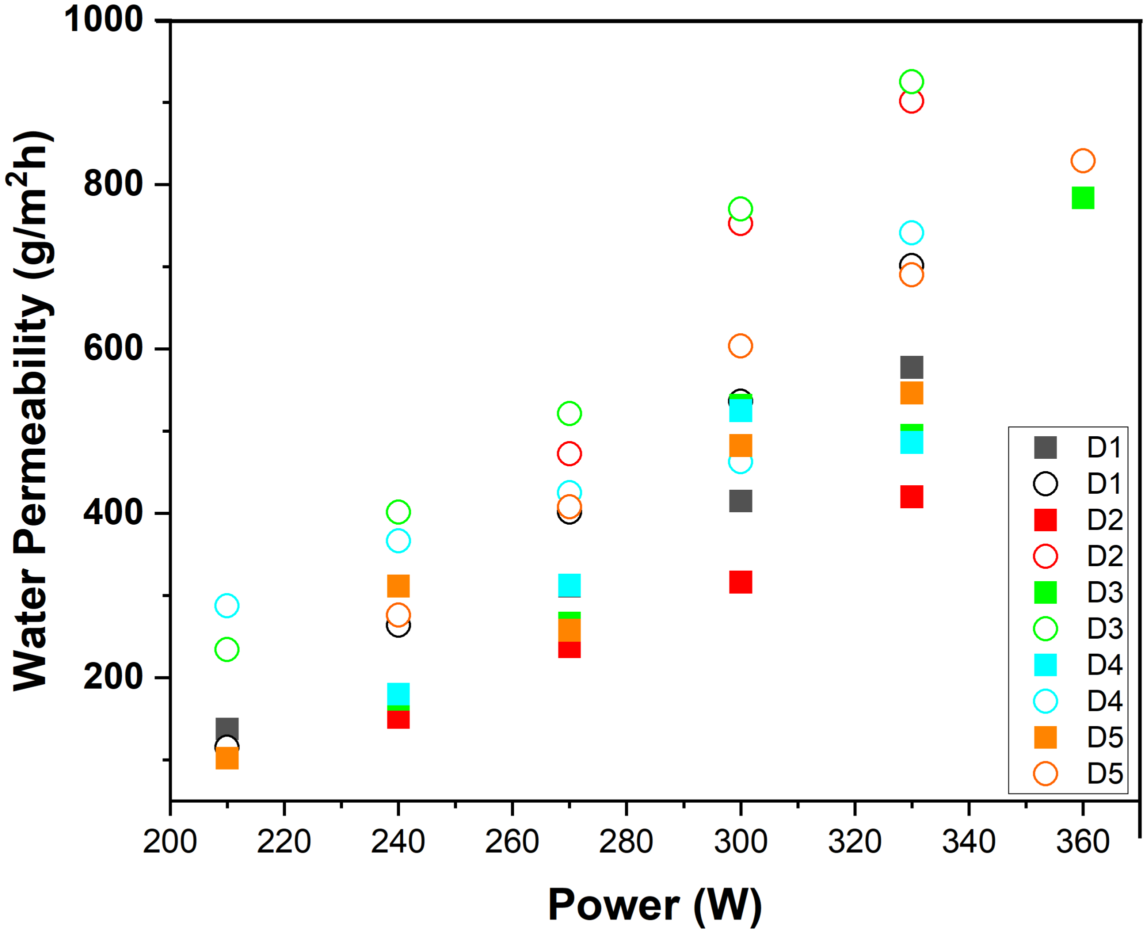
2-Layer Stainless Steel Test

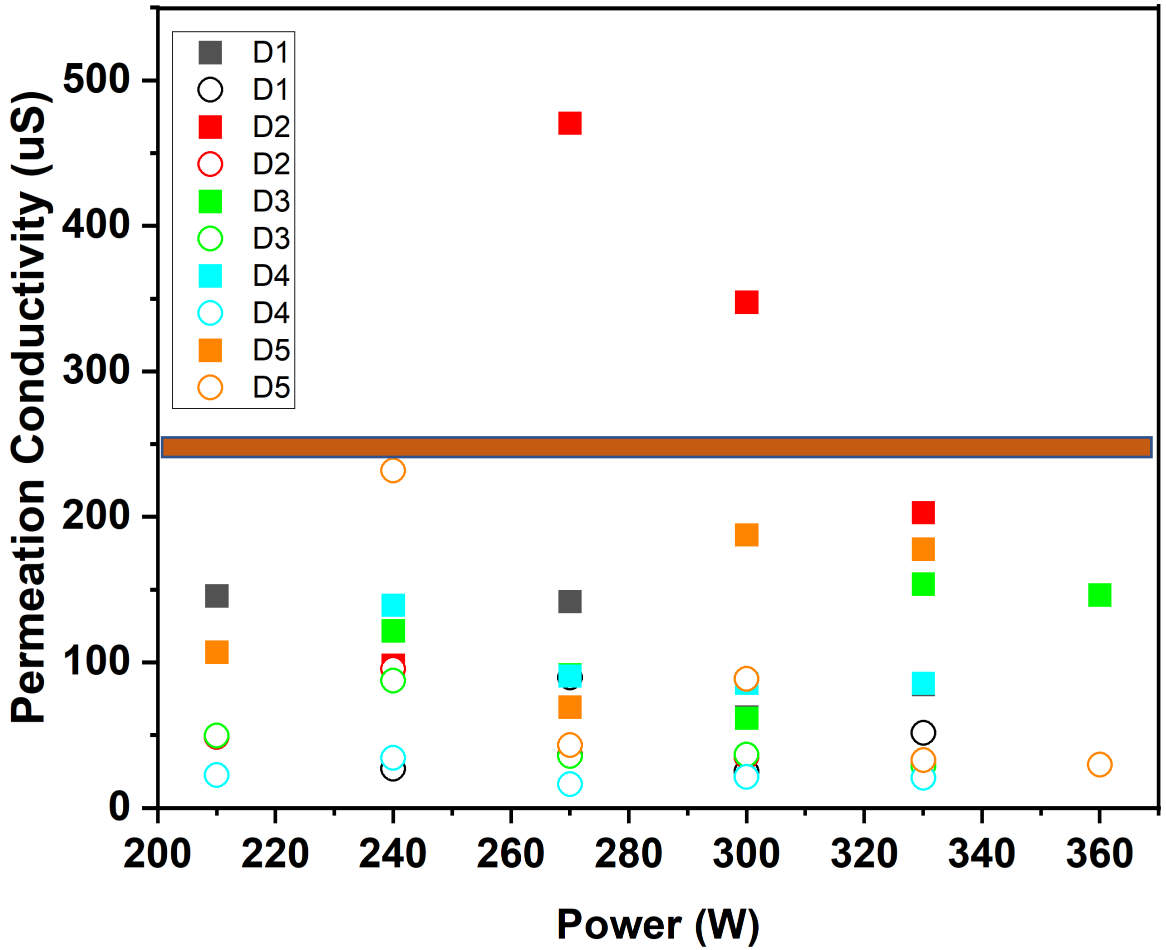




- Low productivity measurements
- Permeation conductivity ideal
- Feed water around 58 mS

West System G/Flex 650 vs 655 Comparison





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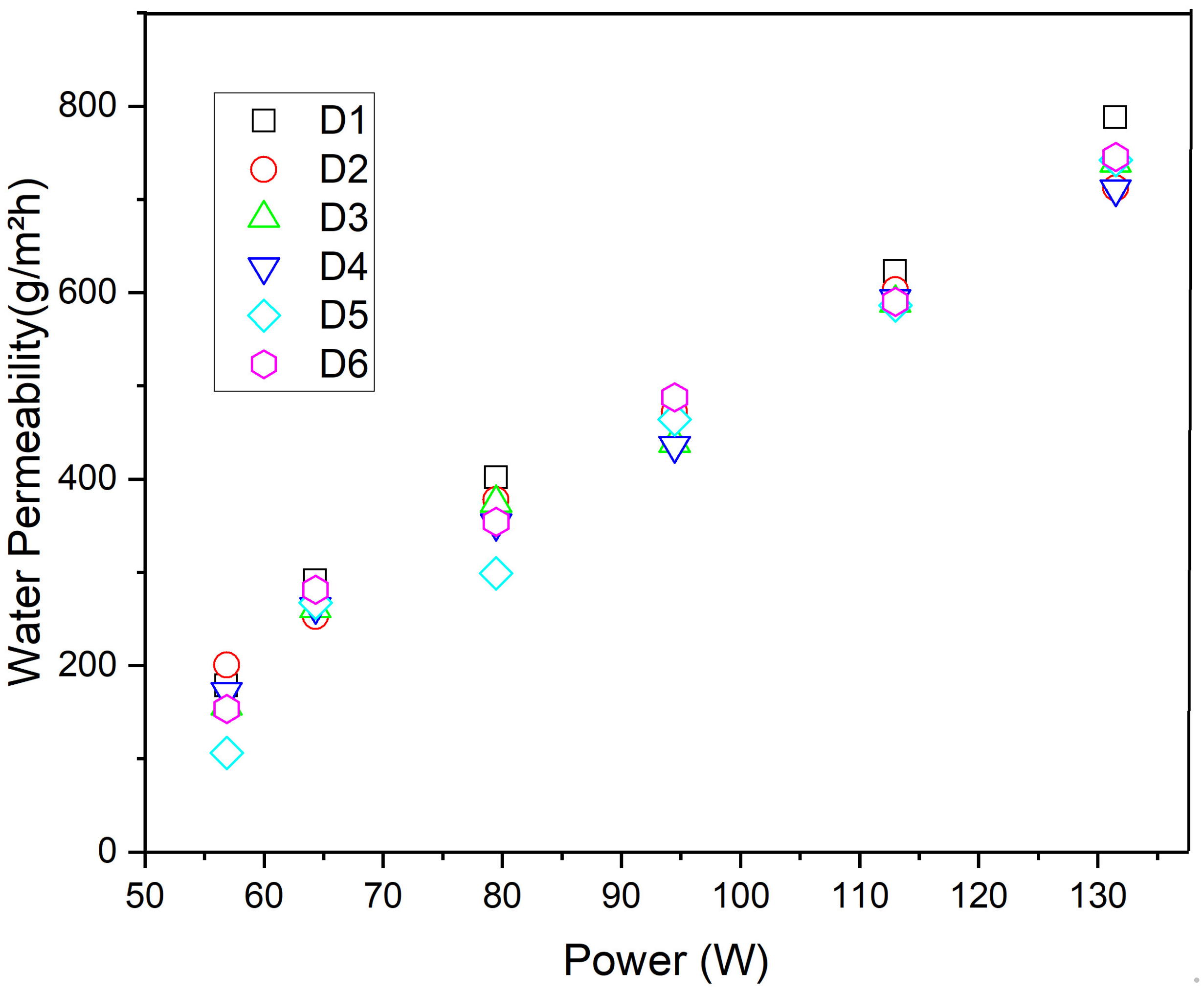
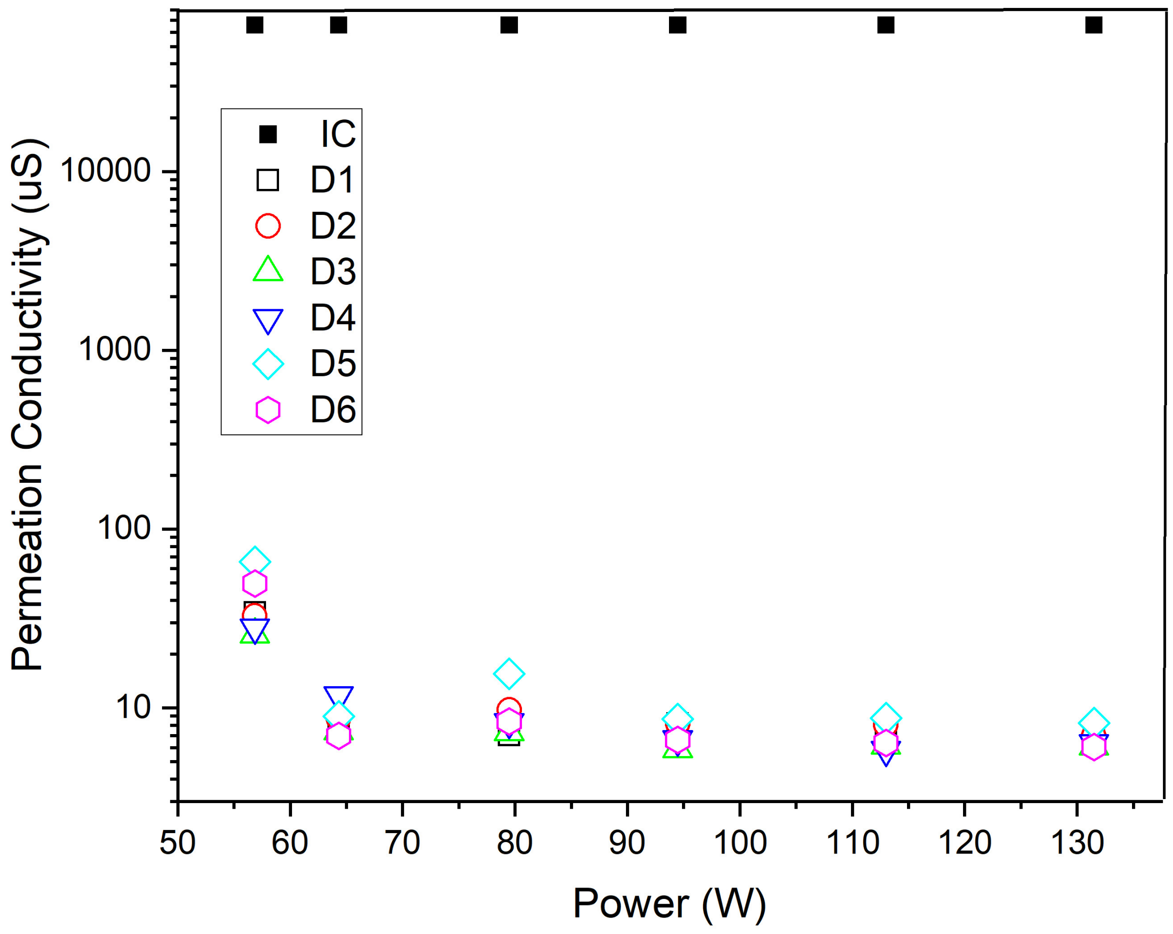
2-Layer 12x12 System





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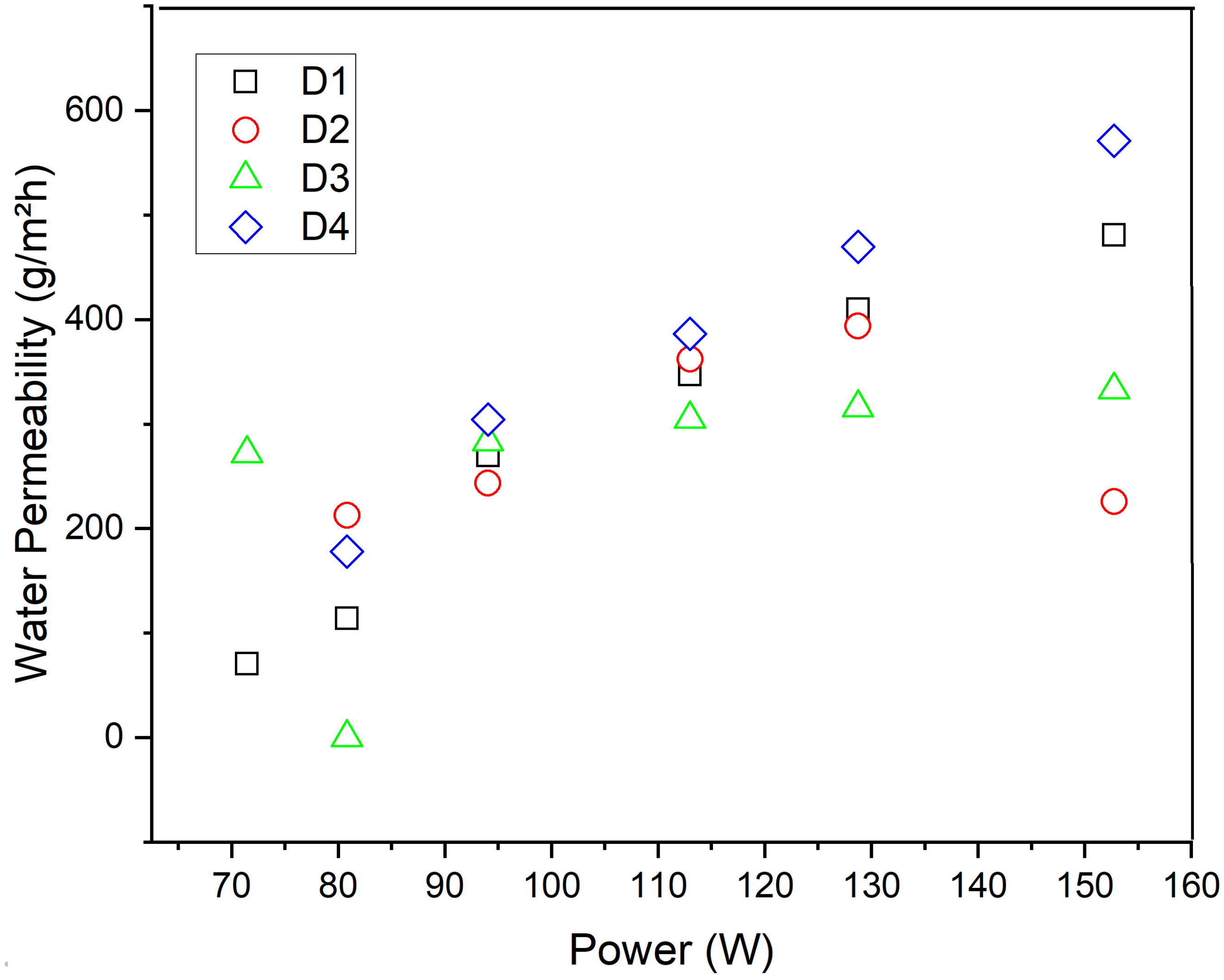
12x12 with Honeycomb Plate Design

- Configuration: 2 layer with 50 micron thick 316L stainless steel as the middle condensation plate.
- The top plate is a 1/4" aluminum honeycomb plate and the bottom plate are 0.9 mm thick 316 stainless steel plate.



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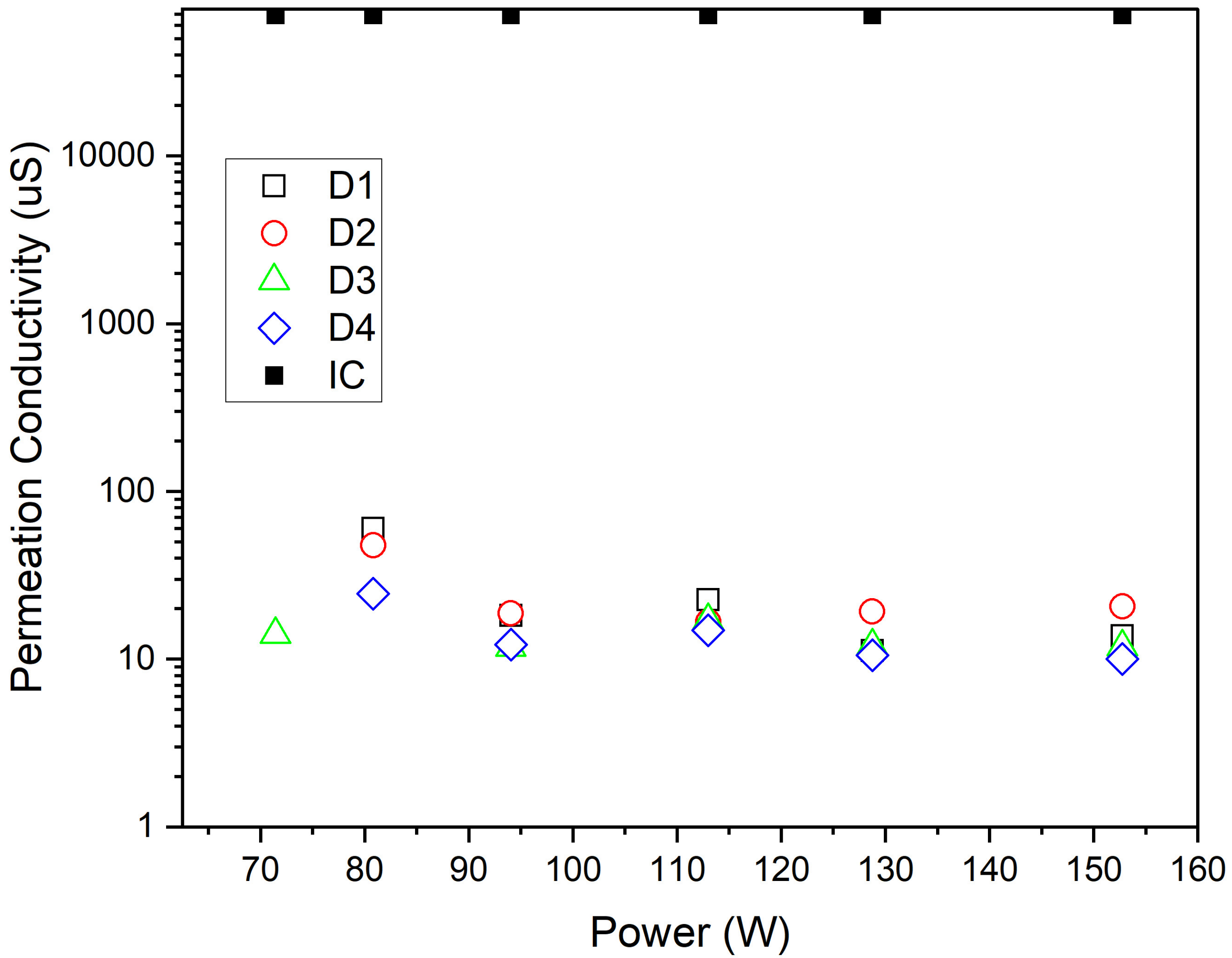
12x12 with Honeycomb Plate Design

- Honeycomb design still works to a degree
- Does not produce good water for electrolysis
- Leak also developed



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Concluding Remarks

- The team has proved that waste heat can be utilized as an impressive energy source for membrane distillation
- Ultrapure water can be achieved through the desalination of salt water by the developed membrane distillation device
- With further study, the team has the capabilities of propelling hydrogen production to lower costs and has the potential of achieving the ambitious 1:1:1 goal

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Acknowledgments

I would like to take the time to thank the Office of Naval Research for providing funding for the investigation and development of the membrane distillation device

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