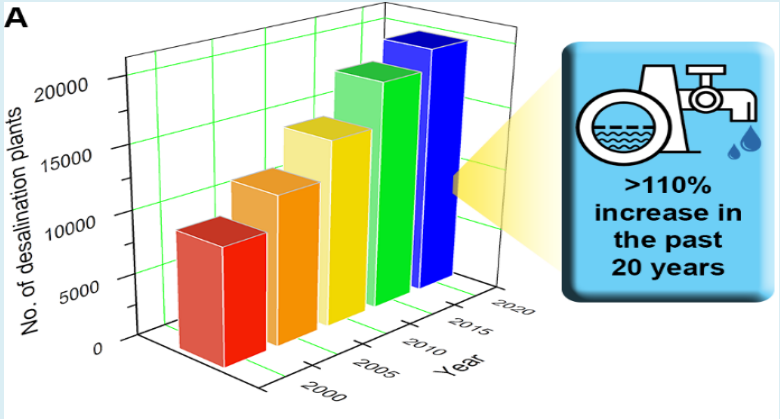
NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Development of pilot-scale high-performance bio-programmable RO membranes for water reclamation

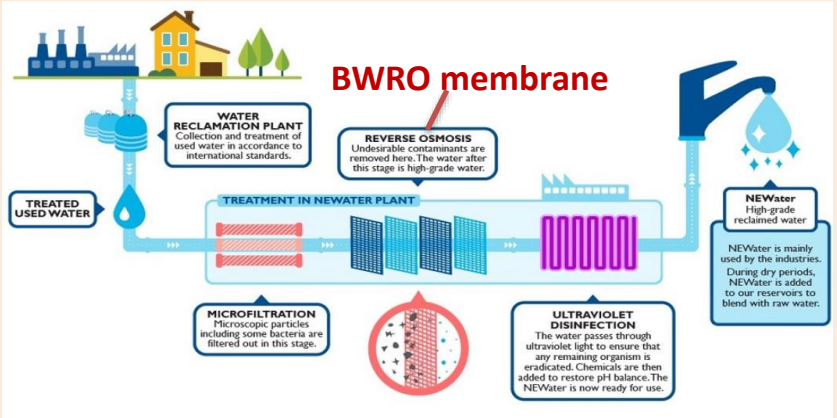
Prof. Rong WANG

SMTC/NEWRI, NTU
19 April 2022 @ SIWW
[2.3 Advances in membrane technologies and applications]

Growth of Desalination/Water Reuse and Membrane Technology



- There has been tremendous growth in the construction of desalination plants for sustainable water supply.
- **Seawater** reverse osmosis (**SWRO**) is dominant in the market due to its better energetics and lower footprint.
- Desalinated water can meet up to **25%** of Singapore's current water demand.

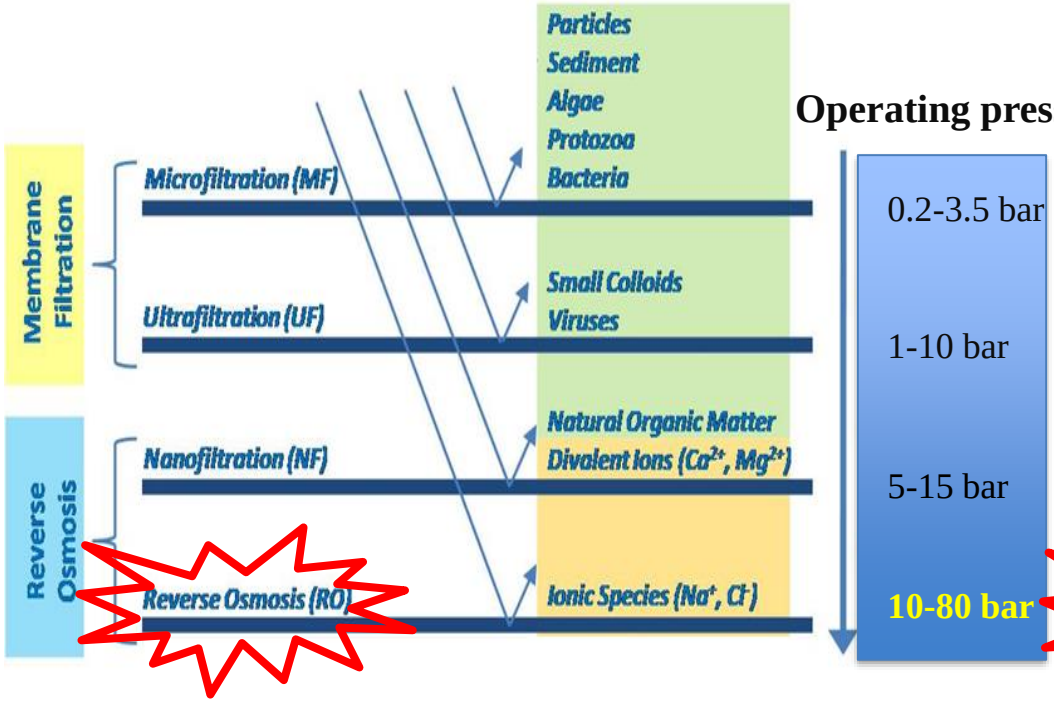


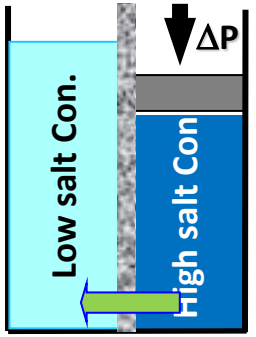
- Brackish water reverse osmosis (**BWRO**) membranes are widely used to remove salts and small molecules present in water.
- **NEWater** is produced from treated used water that is further purified using BWRO membrane and UV disinfection.
- NEWater meets up to **40%** of the nation's water needs.

Y. Lim, ….. R. Wang. JMS, 629, 2021, 119292

https://www.pub.gov.sg/PublishingImages/NEWaterDemographics.jpg

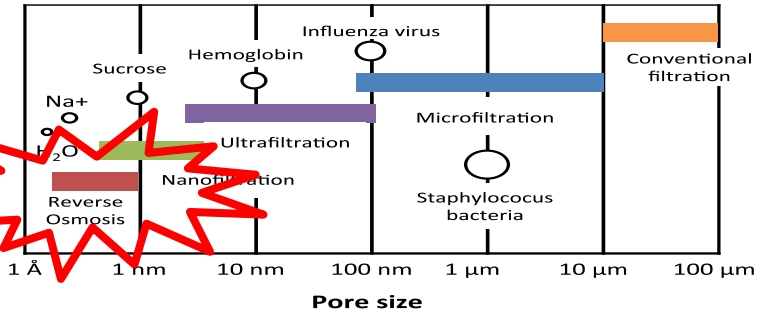
Various Pressure-Driven Membrane Processes





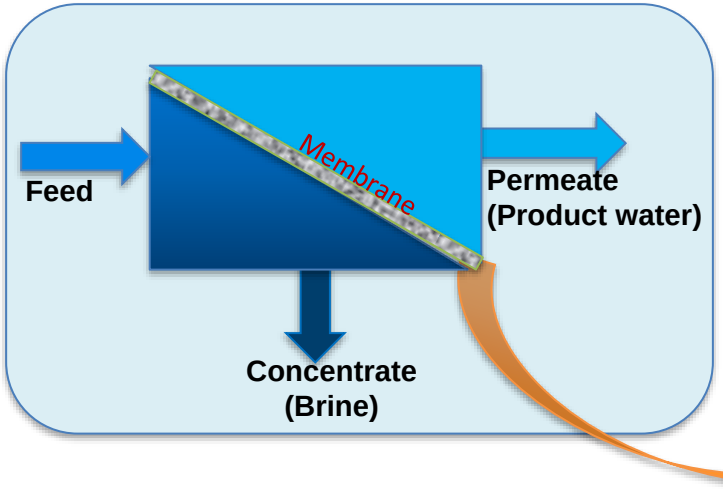
RO

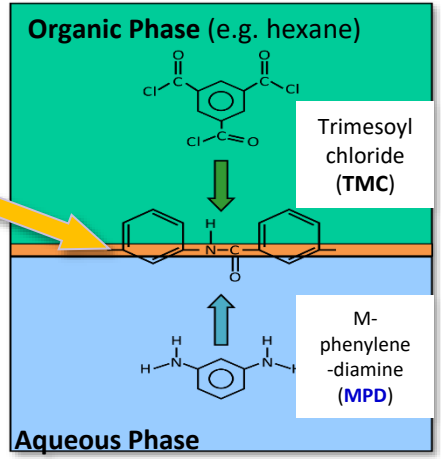
driving force=ΔP-$\Delta \pi$



State-of-the-art technology for water reuse and seawater desalination

- Thin film composite RO membrane





to assure stable operation with high separation performance

Challenges for RO Membranes

- **Efficiency**

  Water permeability of RO membranes is relatively low thus requiring more membranes or more energy to achieve a certain treatment capacity.

- **Energy**

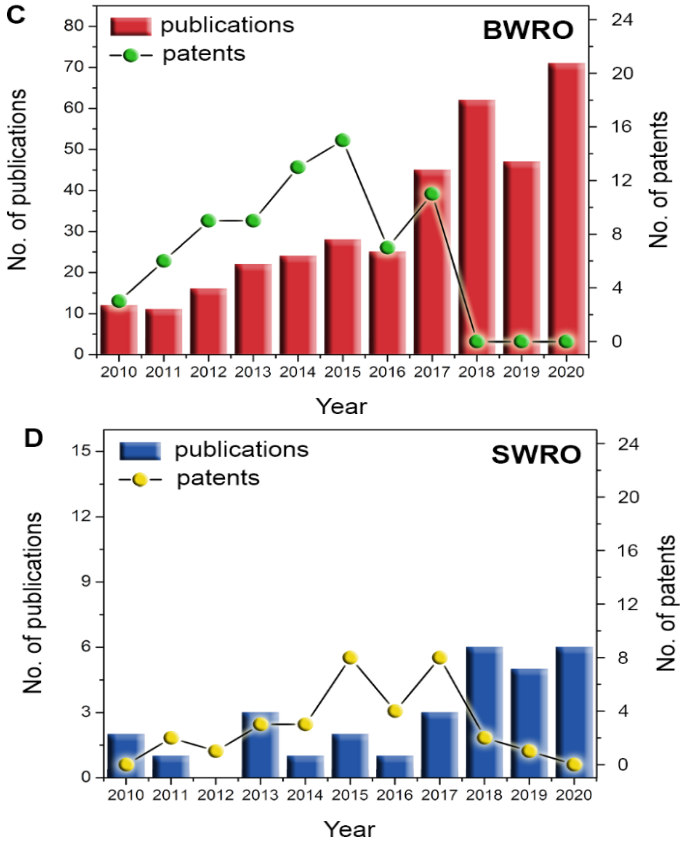
  RO Membranes have a dense selective layer to reject salts, thus requiring substantial hydraulic pressure to push water through the membrane and overcome the osmotic pressure of the salts.

- **Cost**

  Membrane systems are costly because they operate under high operating pressures resulting in the need for high pressure equipment and components

- **Maintenance**

  Membrane fouling issue is more severe for complex spiral wound modules under high operating pressure.



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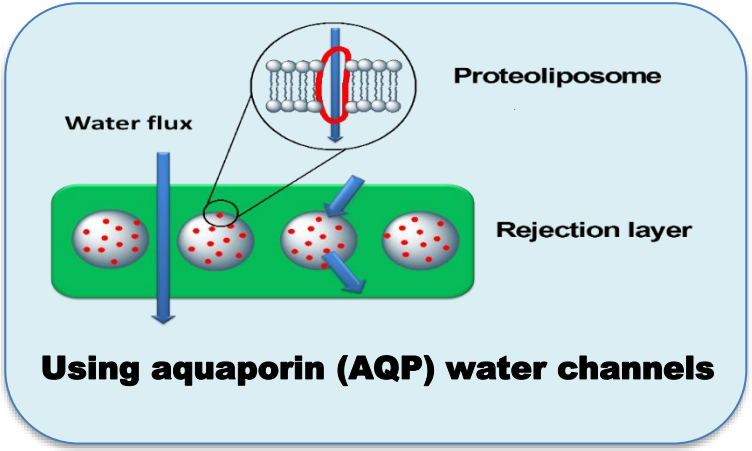
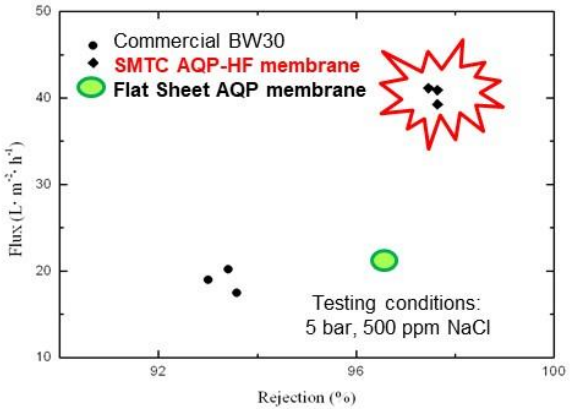
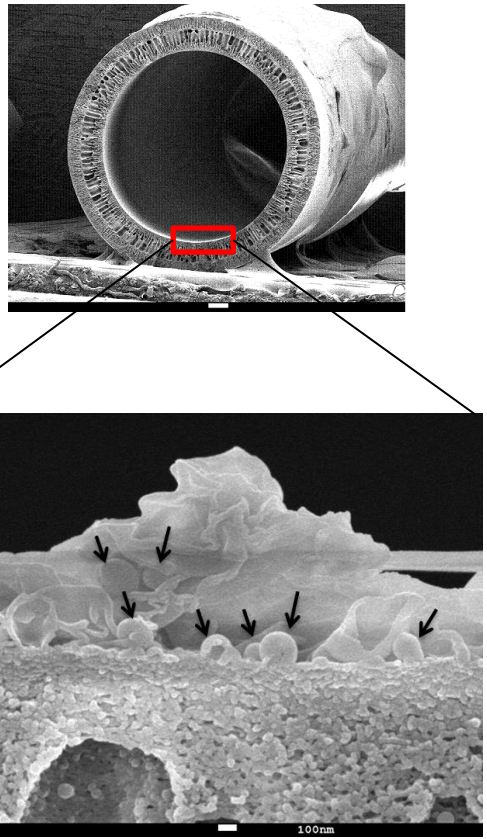
Aquaporin/Synthetic Channel-based Biomimetic Membrane Projects

No.	Project Reference No.	Project Title	Start Date	End Date	Extension Date
1	0804-IRIS-02	**Aquaporin Based** Biomimetic Membranes for Water Reuse and Desalination	15-Jun-09	14-Jun-12	14-Feb-13
2	PUB project	Performance Validation and Enhancement of Aquaporin-based Biomimetic Membranes for Water Reuse and Desalination	1-Aug-13	31-Jul-14	31-Oct-14
3	1301-IRIS-44	Robust and High Performance Aquaporin-Based Biomimetic Membranes for Water Reuse, Desalination and Energy Recovery	1-Sep-14	31-Aug-17	28-Feb-18
4	EWI -NRF	**Synthetic Channel-Based** Biomimetic Membranes for Desalination	1-May-16	30-April -19	3-April -21
5	IAF-PP	**Scale-up the Fabrication** of High Performance Aquaporin (AQP)-based Biomimetic Hollow Fiber Membranes for Water Reuse and Desalination	1-Apr-18	31-Mar-23	-
6	CRP-Water	**Scale-up the Fabrication** of High Performance Aquaporin (AQP)-based Biomimetic Flat-Sheet Membranes for Seawater Desalination	1-Apr-19	31-Mar-23	-

Aquaporin-Based Biomimetic RO membranes

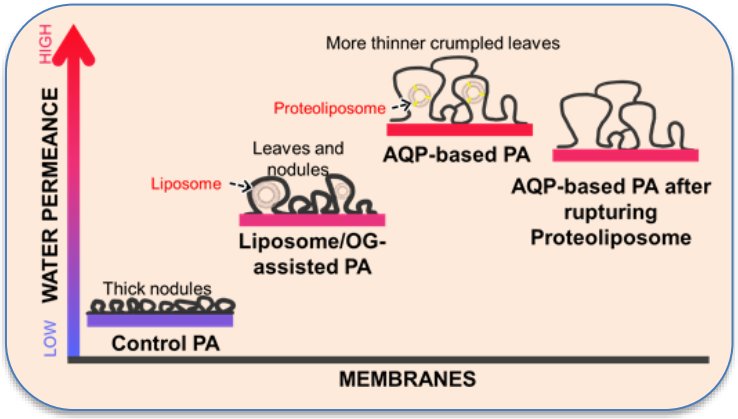


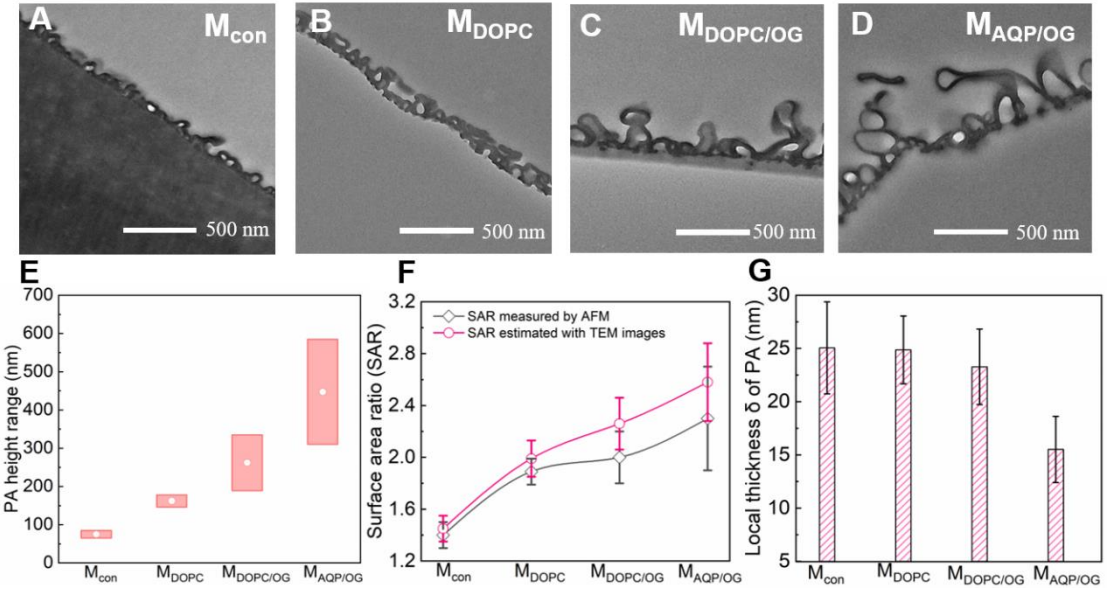




JMS, 508 (2016) 94-103
JMS 494 (2015) 68
JMS, 423–424 (2012) 422

Influences of the Constituents in Proteoliposomes on Separation Performance of TFC PA Membranes

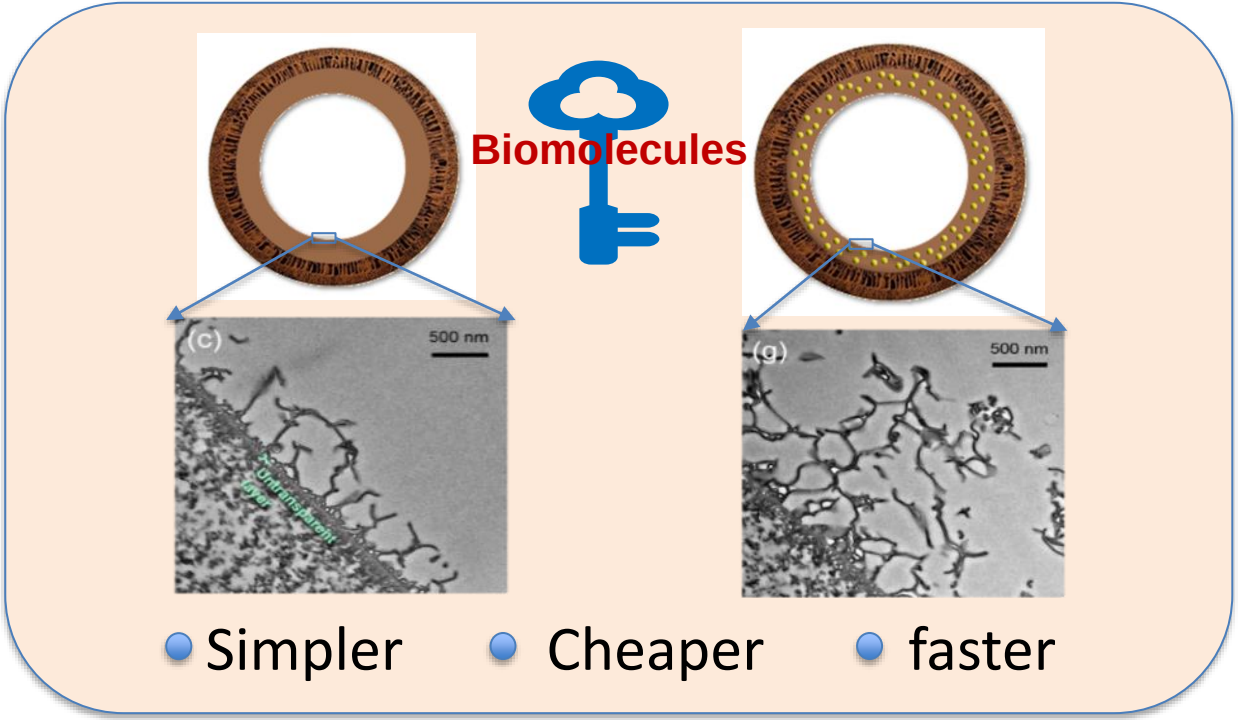




The constituents in the proteoliposome could facilitate the formation of a PA layer with enlarged protuberances and thinner crumples, resulting in a 79% increase in effective surface area.

New Invention:

Bio-programmable membrane (BPM) without AQPs RO membranes



- Simpler
- Cheaper
- faster

Comparison between AQP-based (ABM) and Bio-programmable (BPM) membranes

Water Permeability and Salt Rejection

Summary of 4-inch **ABM** module RO performances

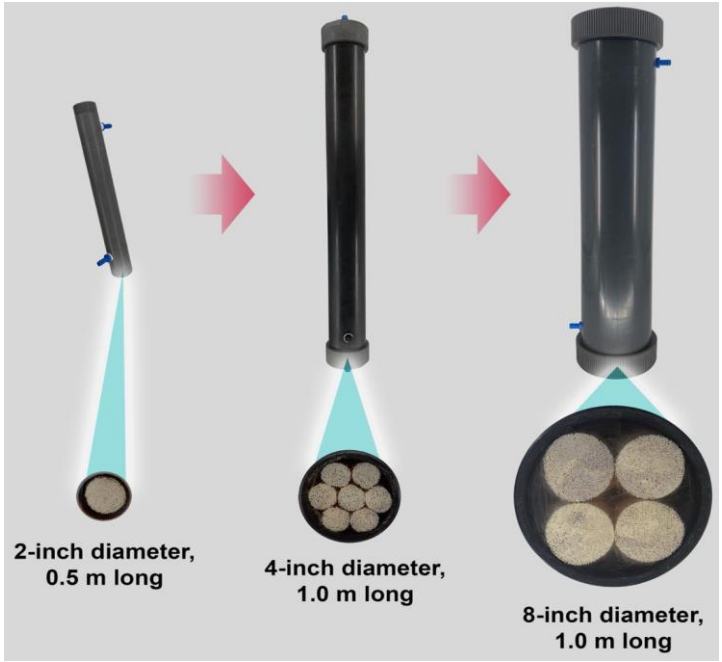
Module Name	Module size	Module Length (m)	Water Permeability [a] (LMH/bar)	Salt Rejection [b]
A-3200-1	4”	0.5	6.97	93.3%
A-3200-2	4”	0.5	7.74	91.5%
A-3200-3	4”	0.5	6.08	94.4%
A-7200-1	4”	1.0	6.26	93.1%
A-7200-4	4”	1.0	5.92	97.7%
A-7200-5	4”	1.0	7.30	96.2%
A-7200-6	4”	1.0	6.30	96.1%

Note:
[a] Tested using DI water under 2 bar
[b] Tested using 500 ppm NaCl solution under 2 bar

Summary of 4-inch **BPM** module RO performance **(new method)**

Module Name	Module size	Module Length (m)	Water Permeability [a] (LMH/bar)	Salt Rejection[b]
D-3200-14	4”	0.5	5.24	97.8%
D-3200-15	4”	0.5	5.18	97.5%
D-3200-16	4”	0.5	5.16	97.9%
D-7200-2	4”	1.0	5.25	96.7%
D-7200-3	4”	1.0	6.74	96.9%
D-7200-4	4”	1.0	7.38	96.4%
D-7200-5	4”	1.0	8.46	94.7%

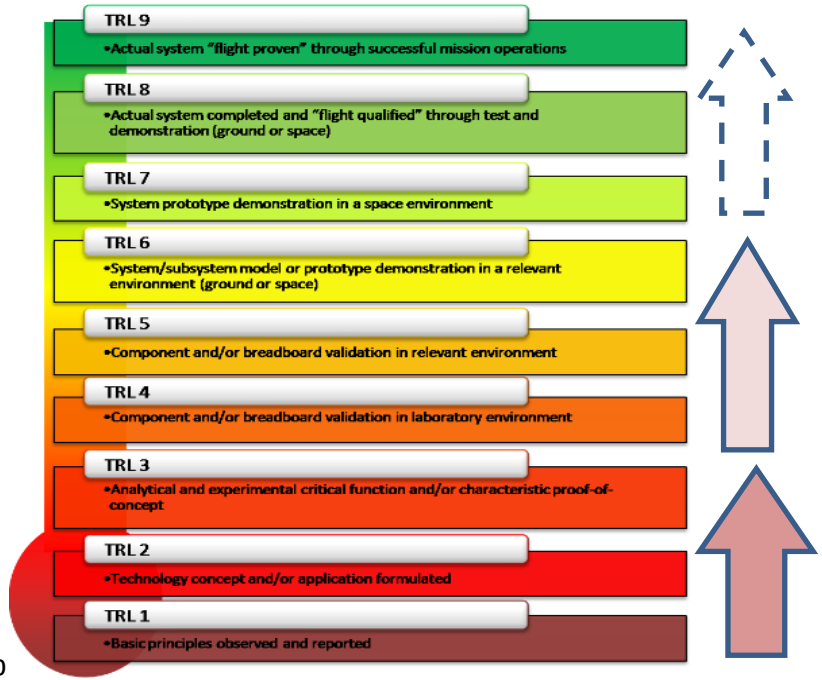
Scaling up & translation



SMTC RO hollow fiber membrane:

water permeability: >7 LMH/bar, salt rejection: >97%
(tested at 2 bar using 500 ppm)

Technology Readiness Level (TRL)



Membrane Production Line and Testing Skids

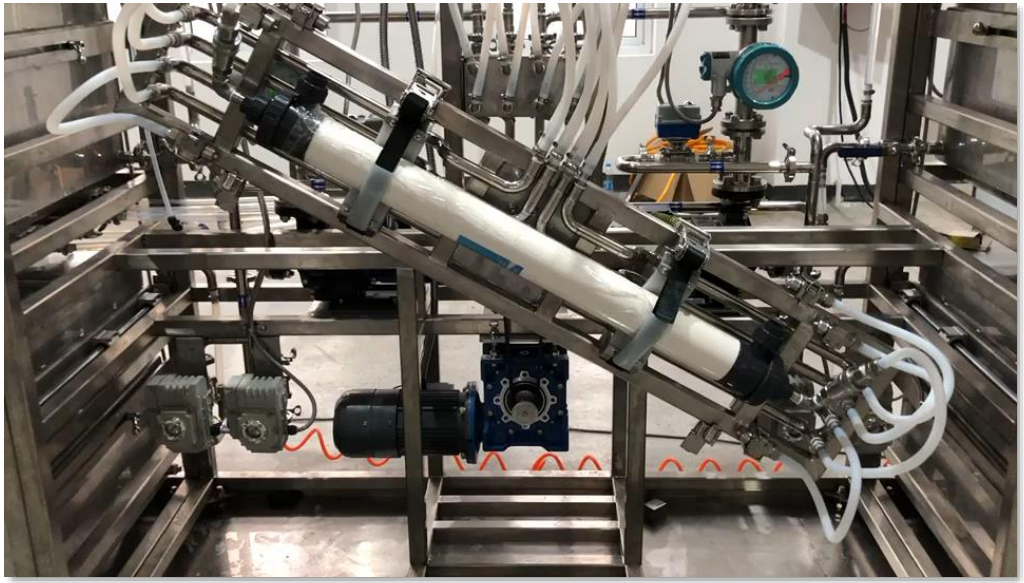
Commercial Level Spinning Machine

Automatic Membrane Coating Machine

8” Module Testing System

Automated Membrane Production Line

8-Channel Hollow-Fiber Spinning Line



Automatic Membrane Coating Machine

Automatic membrane coating system to conduct IP on 4- and 8-inch modules

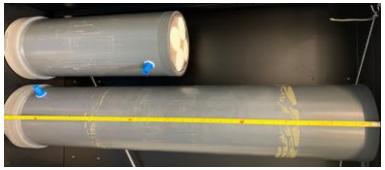
Performance of Bio-programmable Membranes

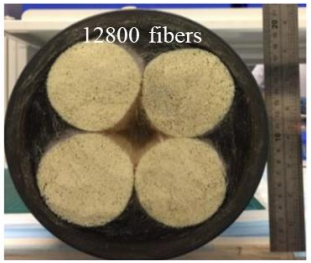
(Target: To reach the PWP of **5 LMH/bar** and NaCl rejection of **96%)**

BPM-RO modules (4040)

Module ID	Module size	Module Length (m)	Water Permeability * (LMH/bar)	Salt Rejection**
D-3200-14	4”	0.5	5.24	97.8%
D-3200-15	4”	0.5	5.18	97.5%
D-3200-16	4”	0.5	5.16	97.9%
D-7200-2	4”	1.0	5.25	96.7%
D-7200-3	4”	1.0	6.74	96.9%
D-7200-4	4”	1.0	7.38	96.4%
D-7200-5	4”	1.0	8.46	94.7%
D-7200-6	4”	1.0	8.0	98.1%
D-7200-7	4”	1.0	10.1	96.1%

*Tested at 2 bar using DI water.
**Tested at 2 bar using 500 ppm NaCl solution.

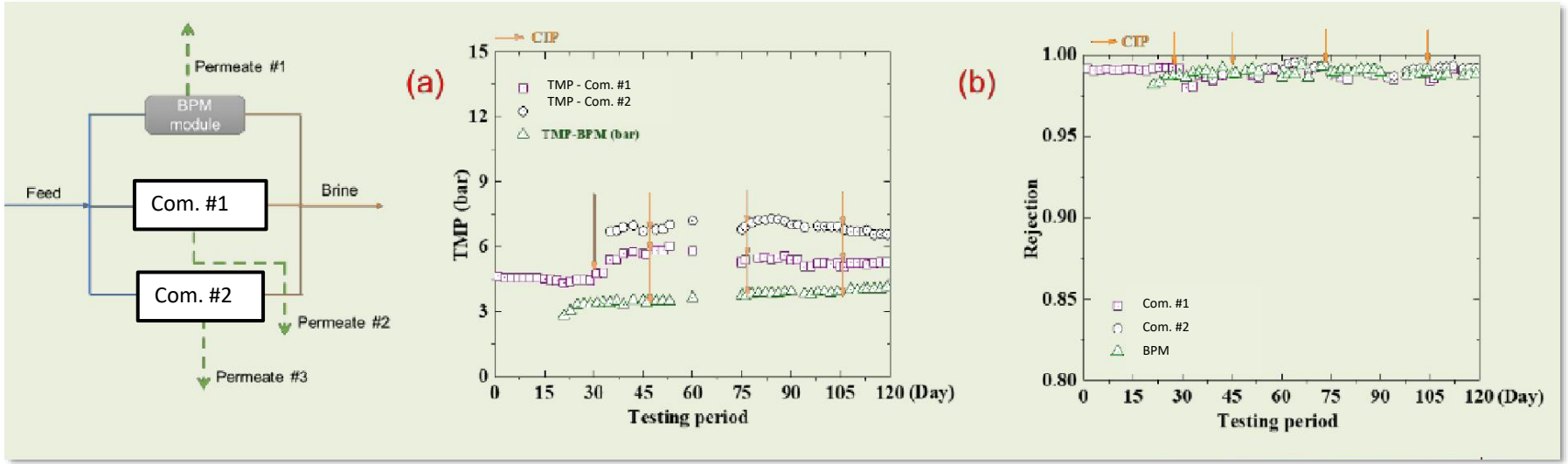




8-inch module

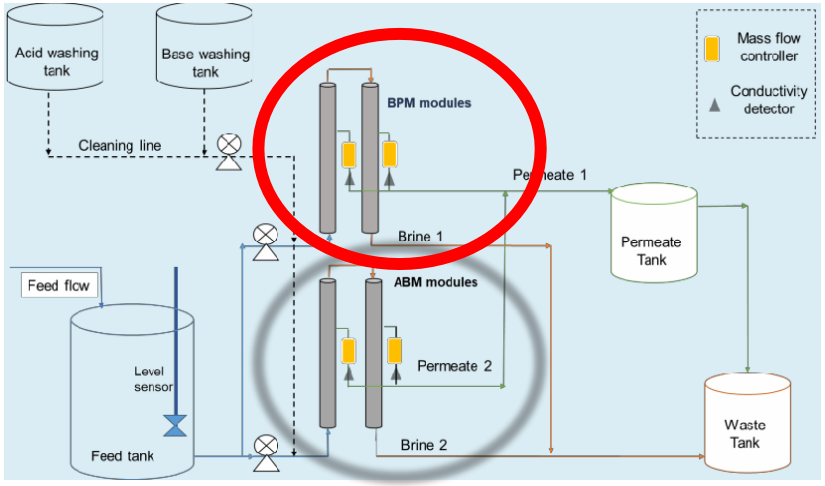
Long-term Benchmark with Commercial Membranes

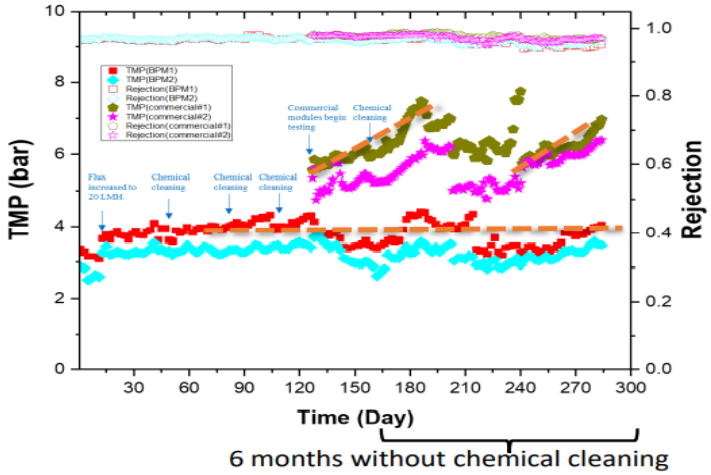
- Testing using real NEWater feed (MBR permeate collected from UPWRP)
- **Batch testing** (Fresh Newater feed was replaced on a weekly basis)
- Chemical cleaning was conducted periodically to recover the water flux
- Two commercial modules were operated in parallel at 20 LMH for comparison
- Commercial modules was operated at 5~6 bar and 6~7 bar, respectively



Continuous Pilot Testing at UPWRP

- **On-going** testing using fresh NEWater feed (MBR permeate)
- **Continuous testing**
- Two ABM modules and two BPM modules were operated in parallel at 17 LMH for comparison for 12 days
- The operating water flux was further increased to 20 LMH from day 13.
- Actual running capacity **14** m^3/d





Site Data on Energy Consumption

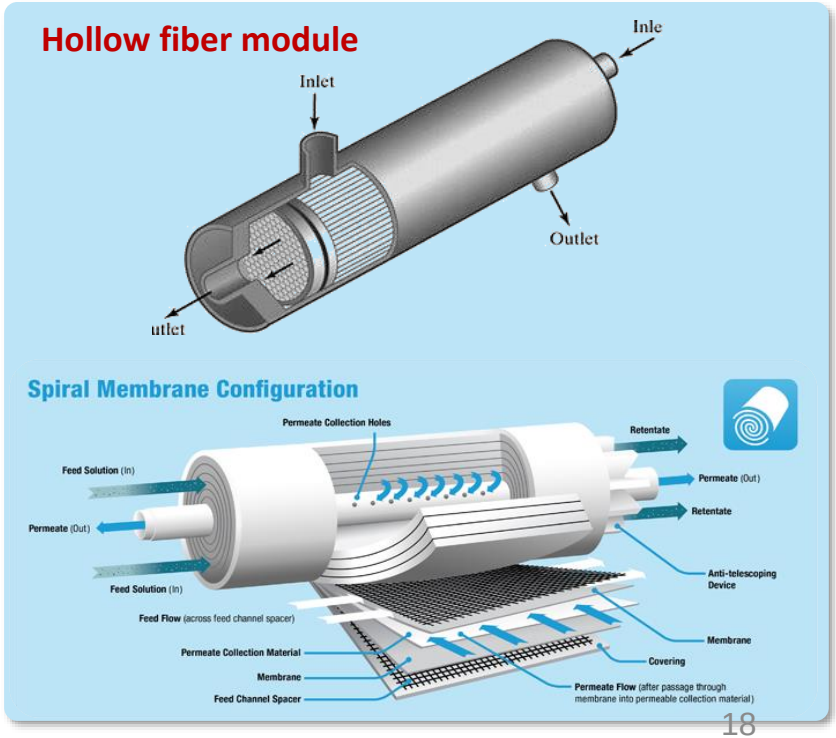
	PUB site	SMTC pilot testing
System pressure	**8~10 bar**	**4.5 bar**
Pumping power consumption	1 m^3/day x 9 bar =10.42 W	1 m^3/day x 4.5 bar =5.21 W
Specific energy consumption - 70% recovery - 90% pumping efficiency	10.42 W/(0.7 m^3/day) = 0.356 kWh/m^3 0.356/0.9= 0.396 kWh/m^3	5.21 W/(0.7 m^3/day) = 0.178 kWh/m^3 0.178/0.9= 0.198 kWh/m^3
Energy saving	0.198 kWh/m^3	

The energy saving is around 0.2 kWh/m^3

(~ 50% pumping energy saving)

Unique RO Hollow-Fiber Membrane

- Better Flow
- More Even Pressure
- Less Fouling and Easier Cleaning
- More Stable Performance



BPM-RO Hollow Fiber Membrane Commercialization

MEM+

http://www.memp.tech/

Conclusions

- The growth of membrane technology is assured due to impending water scarcity.
- We have successfully developed novel RO hollow fiber membranes for water reuse and desalination.
- It is important to improve the TRL for technology translation.
- Commercialization of advanced membrane technology should be the ultimate goal of membrane research.

Acknowledgements

- Collaborators, research staff and PhD students of SMTC-NEWRI, NTU
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- We are also grateful to Singapore Economic Development Board for funding SMTC-NEWRI.

Contact information: rwang@ntu.edu.sg

Looking Forward to Collaboration