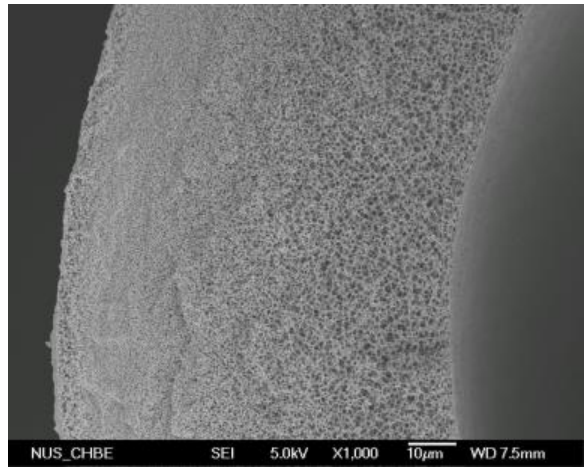
Polymeric Membranes for Clean Water and Clean Energy

(Prof. YM Cao, my former staff,
Now a famous Professor at Dalian)



(Dr. Li DF, my flormer PhD student,
Now a VIP at Hyflux)

Prof. Neal Tai-Shung Chung (鍾台生)

Department of Chemical & Biomolecular Engineering, National University of Singapore

Visiting Professor; Water Desalination & Reuse (WDR) Center, King Abdullah University of Science and Technology, Saudi Arabia

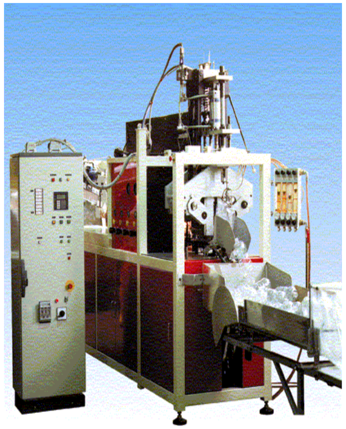
PUB Water for All: Conserve, Value, Enjoy

King Abdullah University of Science and Technology KAUST

NUS National University of Singapore

From a Polymer Engineer to a Membrane Scientist

(Hoechst Celanese (USA), 1980-1993; Aeroquip (USA), 1993-1995)



Stretch blow molding
1980-1982

PET bottles
1980-1982

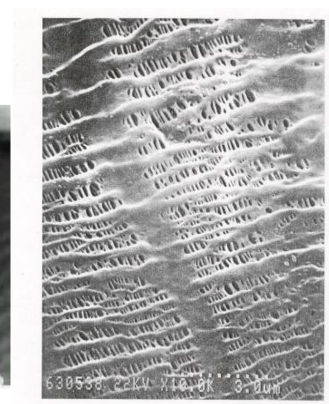
Carbon/polymer composites
1982-1983

Liquid crystalline polymer
1983-1988

Kidney dialysis membrane
1988-1989

Life science products
1994-1995

Polyimide hollow fiber
1990-1993



Celgard PP Membrane
1990-1992

Polyimide films
1990-1992

Membrane separator
for rechargeable battery
1988-1989

Membrane R & D in the last 20 years at NUS

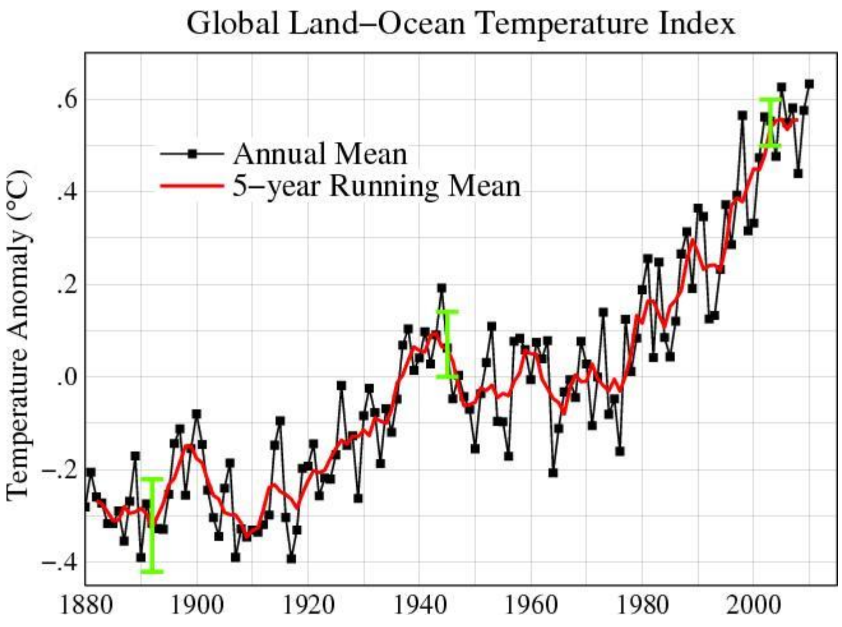
Mature Business	Growth Business	Embryonic Business
O_2/N_2 , H_2/N_2 Separation (NUS, A-Star, Mitsui Chemicals)	CO_2/CH_4 Separation (BG, UOP, Mitsui Chemicals, NRF) H_2/CO_2 Separation (NRF) CO_2 capture (A-Star) Biofuel separation (A-Star, Mitsui Chemicals, PBI)	Carbon membranes C_2-C_4 Separation (Mitsui Chemicals, NUS, NRF) Osmotic power (NRF/EWI/PUB)
UF/MF (Hyflux)	Membrane bioreactor (Hyflux) Nano-filtration (NUS, GSK, China Gansu) Oil-water separation (BASF, Kraton)	Forward osmosis & osmotic power (NUS, Saudi KAUST, Eastman Chemicals, BASF, NRF/EWI) Biomimetic membranes (NRF/EWI) Membrane distillation (A-Star)
Kidney dialysis (BASF)	Pervaporation (A-Star, Merck, Mitsui Chemicals, GSK) Pharmaceutics Separation (NUS, GSK)	Membranes for protein, isomers, and chiral separation (NUS, A-Star, SMA)

Green: water related research
Red: energy related
Purple: life science related

Grants > S$70 millions (≈ US$51 millions) received in 20 years
S$11 millions (≈ US$8.7 millions) from industries and foreign Institutes

Four Major Issues on Earth

1. Clean water shortage
2. High energy cost
3. Global warming
4. Affordable healthcare



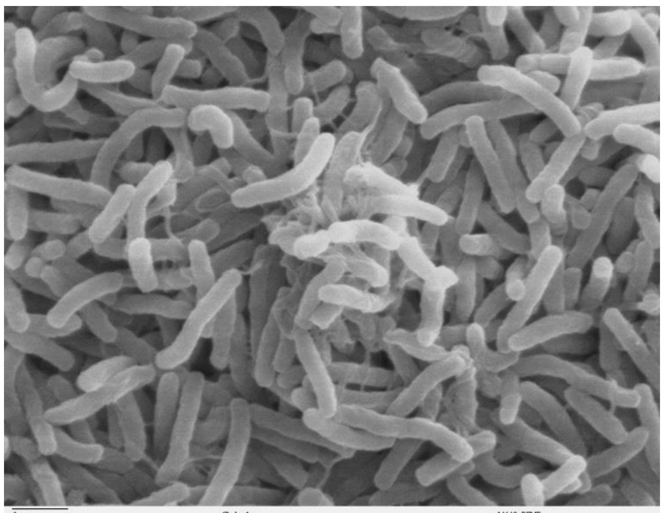
Earth surface temperature

http://co2now.org.

Water Quality and Public Health are Inter-connected

- The outbreak of cholera (霍乱) in London in 1854 - Dr. John Snow discovered that it was spread by contaminated water (and food)

- Arsenic poisoning (砷中毒) and black foot (乌脚病) are related to natural contamination in groundwater



— 1 micron

bacteria *Vibrio cholerae*

Black foot
乌脚病

http://topworldofhealth.blogspot.sg/2011/12/cholera-and-impetigo-treatment.html
http://healthystate.org/2010/11/central-florida-sees-case-cholera/

Energy and Prosperity Go Hand in Hand

Singapore downtown

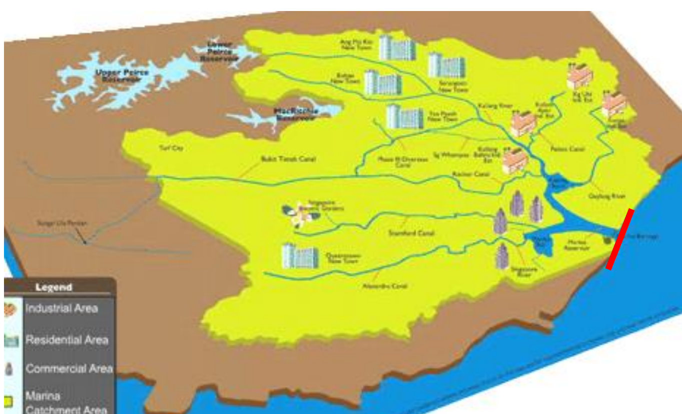
http://triphobby.blogspot.sg/2011/01/experience-night-of-singapore.html
http://www.shell.com/home/content/aboutshell/our_strategy/major_projects_2/eastern_petrochemicals_complex/

Importance of Water and Energy in Singapore

	Imported water & reservoir	NEWater 	Desalination
Now	60%	30%	10-15%
2060	20%	50%	30%

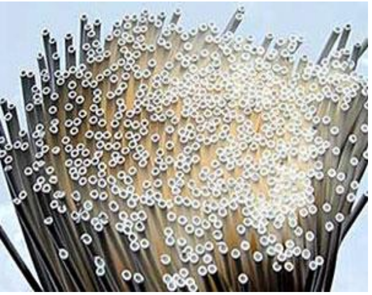
dam (Marina Barrage)

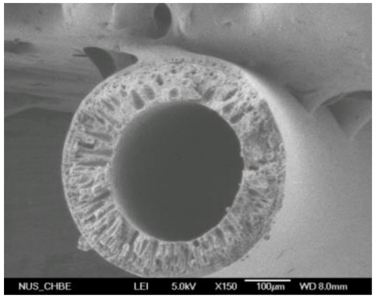
Singapore's first RO desalination plant at Tuas (2005).

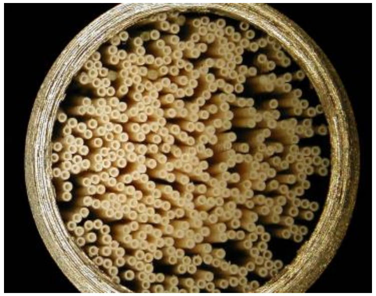


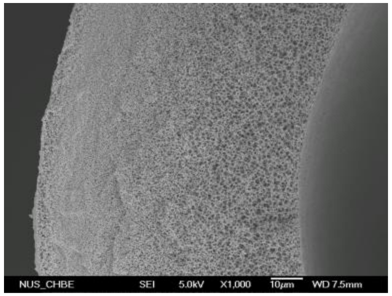
The Marina Barrage, a catchment area of 10,000 ha (1/6 Singapore's land area)

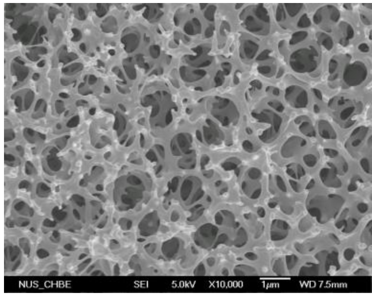
Advances in membrane technology are one of the most direct, effective and feasible approaches to solve these sophisticated issues









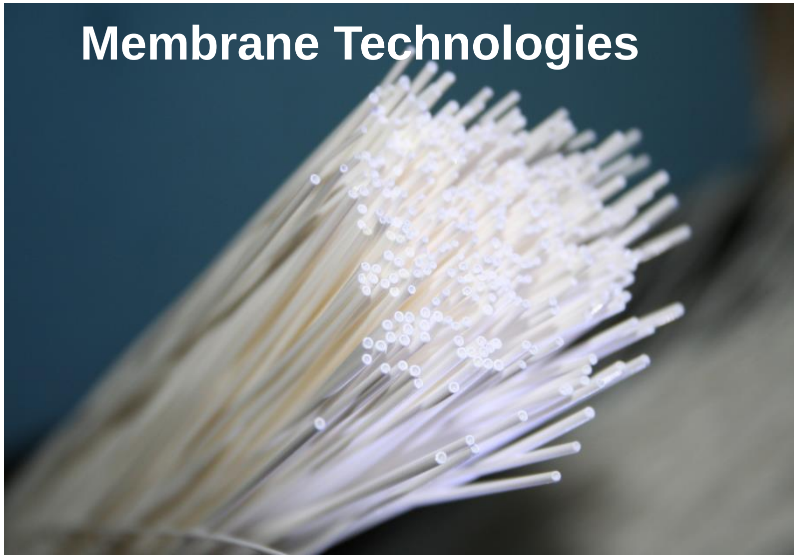


Water recycle and production

1. Micro-filtration (MF) and ultra-filtration (UF) membranes, membrane bioreactor (MBR) for water reuse
2. Reverse osmosis (RO) membranes, forward osmosis (FO) and membrane distillation (MD) for seawater desalination

Energy

1. Batteries & fuel cell
2. High purity CH_4, H_2, production
3. Concentrate biofuel, biogas



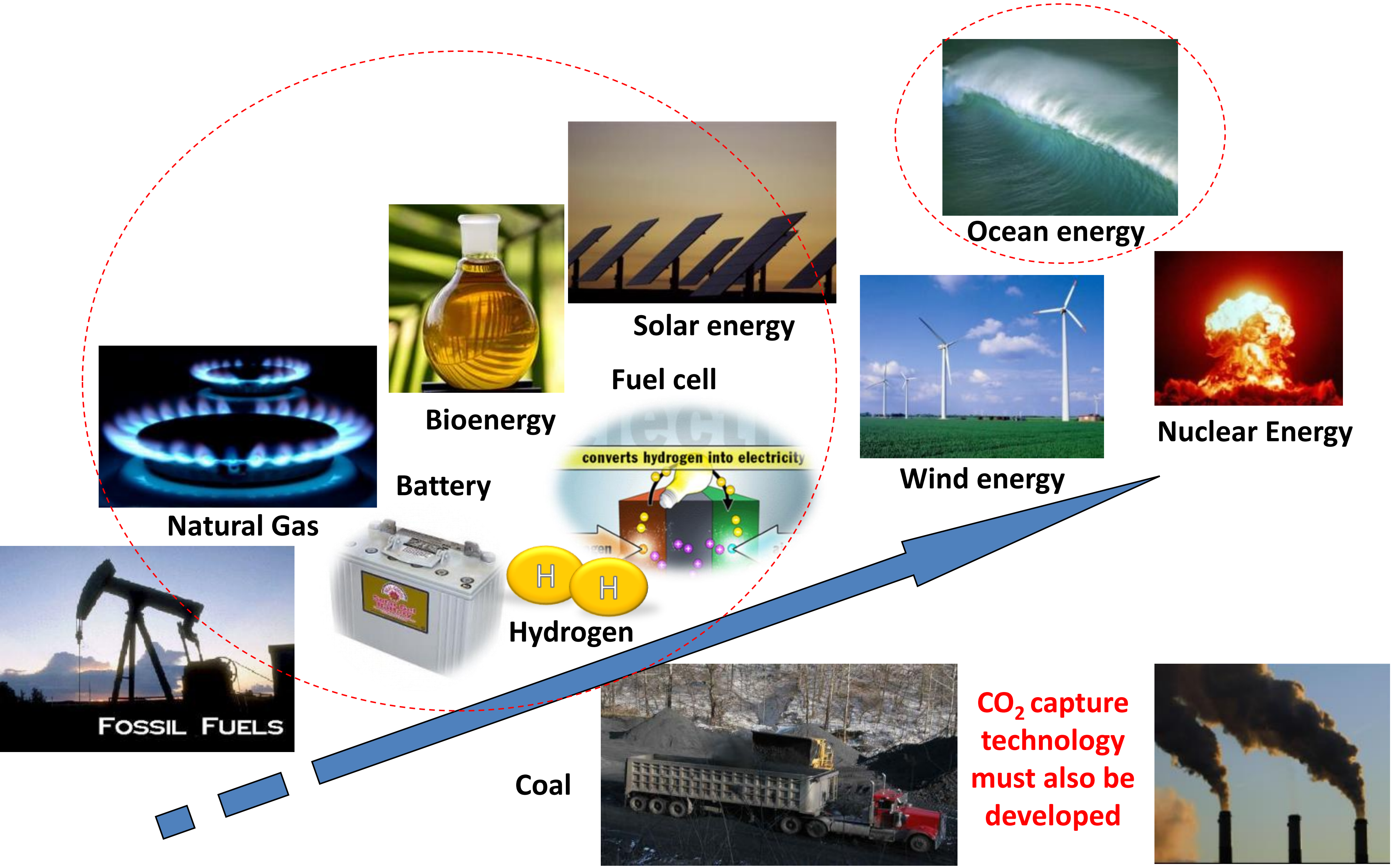
Global warming

1. Capture CO_2 from flue gas and power plants
2. Capture other green house gases

Affordable healthcare

1. Artificial kidney, skins, and lungs
2. Control release for drug delivery
3. Purification and separation of proteins
4. Chiral drug separation
5. Pharmaceutical and medicine purification

What are the next clean energy sources?



Polymeric Membranes for Energy (Natural Gas)

British Gas-NUS-IMRE-ETI collaboration of S$2 millions (1999-2001)
UOP (Universal Oil Products)-NUS collaboration of S$0.65 million (2004-2006)
Mitsui Chemical-NUS collaboration (2004-2012)
NRF-CRP grant of about S$10 millions (2008-2013)
NUS grants of $0.90 million (2014-2016)

Well Fluids → Oil/Gas separation; Phase separation; Acid gas treating → Crude oil; Solids, H_2O, H_2S; Hydrocarbons

CH_4 ↓ CO_2 < (10-50%)

CH_4
$CO_2 \leq$ 2-4%
$H_2S \leq$ 4 ppm

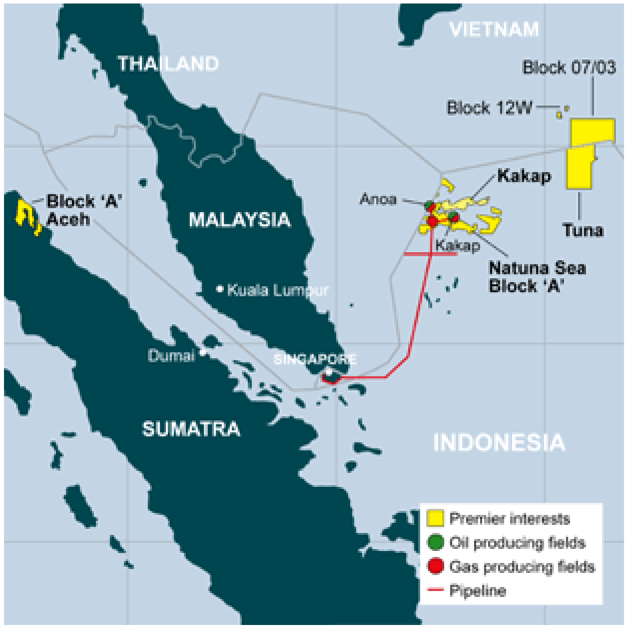
CO_2
H_2S

Hollow Fiber Membrane Module

Off-shore platform

Ideal Membranes:
High flux, High selectivity, No ageing, Inert to hydrocarbons, No plasticization to CO_2 and H_2S

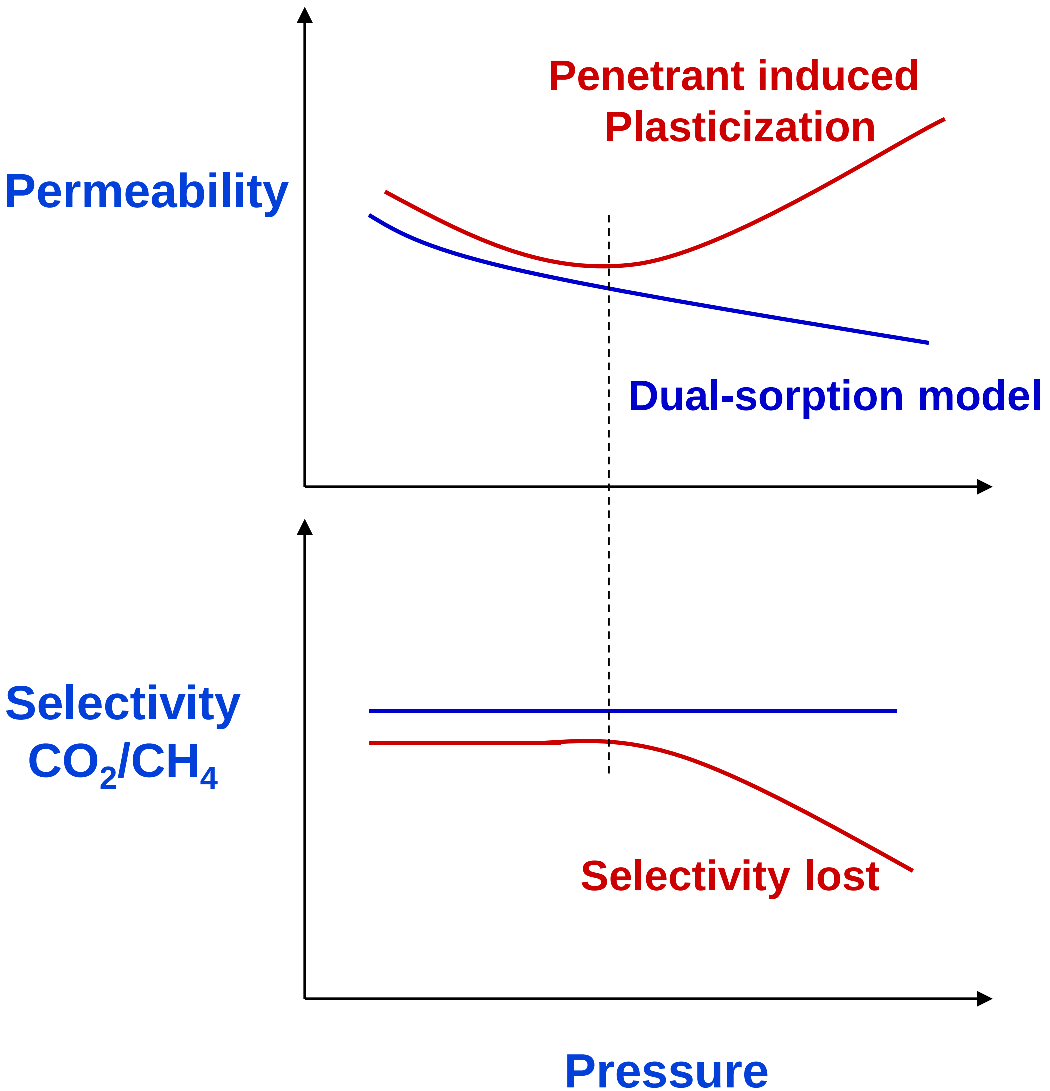
Southeast Asia Pipelines map - Crude Oil (petroleum) pipelines (green) - Natural Gas pipelines (red) - Products pipelines

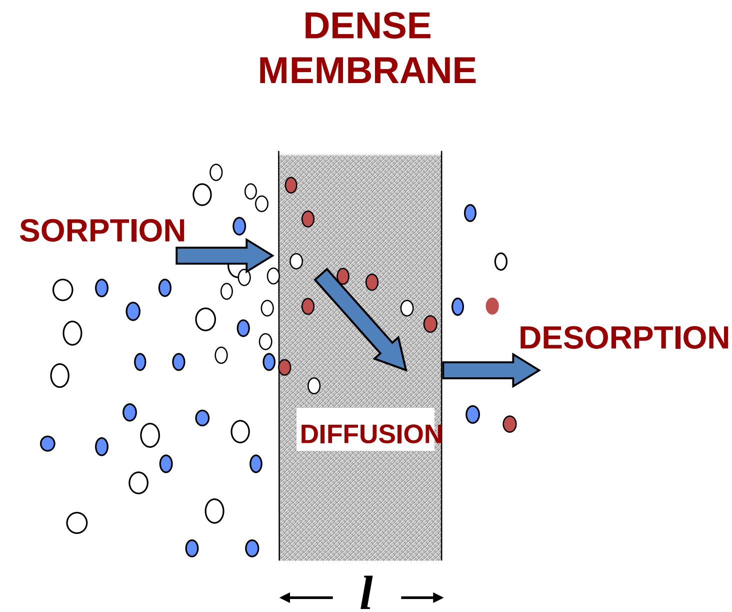


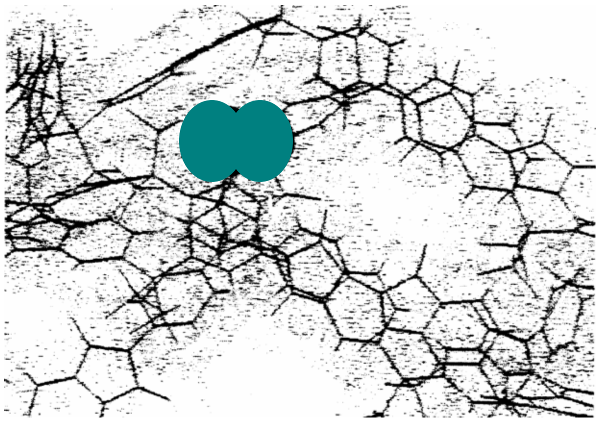
http://www.premier-oil.com/render.aspx?siteID=1&navIDs=19,310,313,335

A 477-kilometer natural gas pipeline from South Sumatra to Singapore; allowing Indonesia to sell $9 billion worth of natural gas to Singapore over the next 20 years. The pipeline, which has cost $420 million for construction, will supply 350 million **standard cubic feet** per day of **natural gas** from South Sumatra, said in February 2001 as a venture between Singapore's government-linked PowerGas Ltd. and Indonesia's PT Perusahaan Gas Negara (PGN), with Singapore owning the 9-km portion of the pipeline.

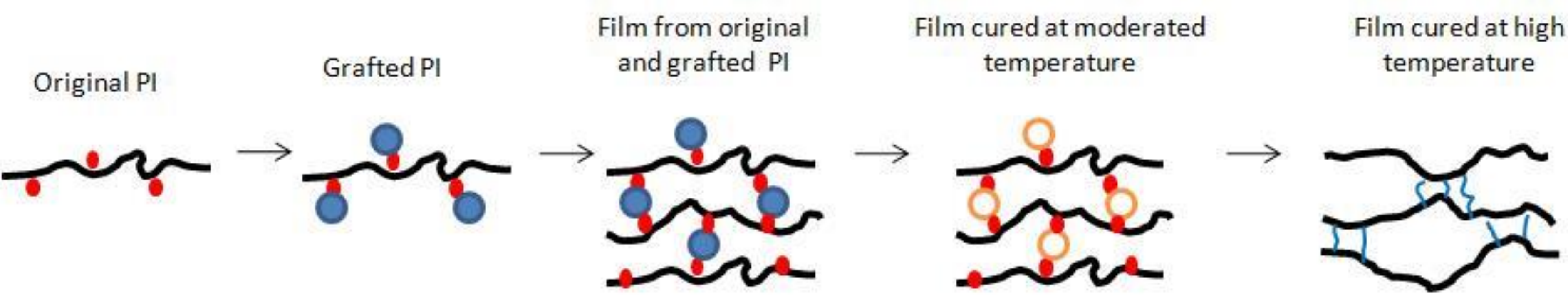
Plasticization Phenomenon

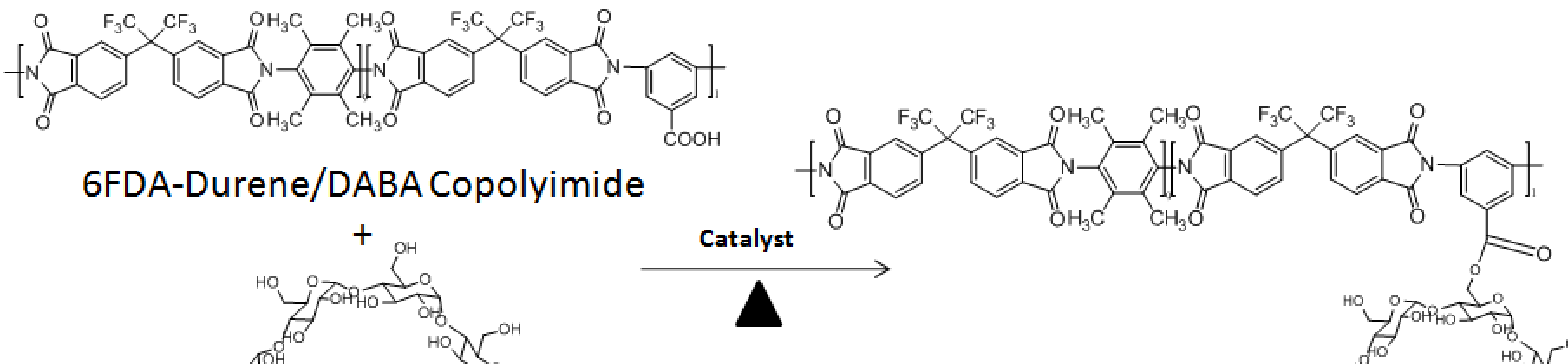


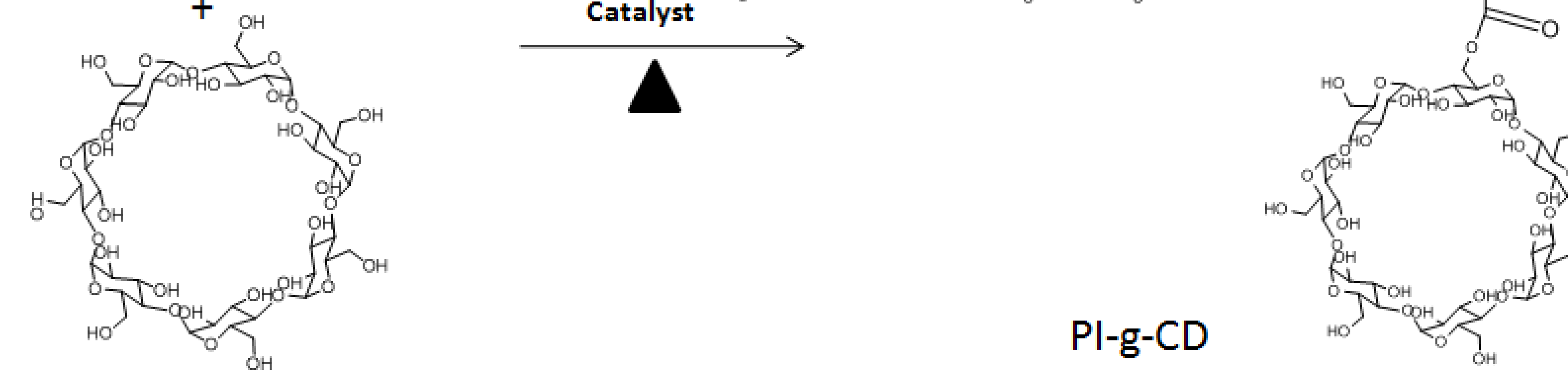




Our approach for CO_2/CH_4: Cross-linkable polyimides grafted with thermally labile molecules







6FDA-Durene/DABA Copolyimide

+

Beta-Cyclodextrin (CD)

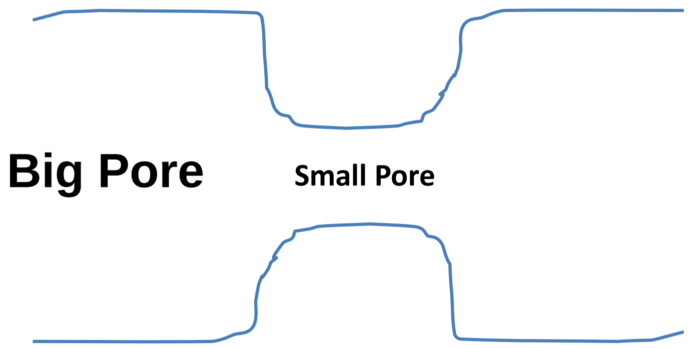
Dr. Xiao Youchan

US patent 8,772,417 (2014); **Chinese Patent** ZL 201180023724.2 (2014)

Y. C. Xiao, T. S. Chung, *Energy and Environmental Science*. 4, 201-208 (2011)

Polymers of Extrinsic Microporosity

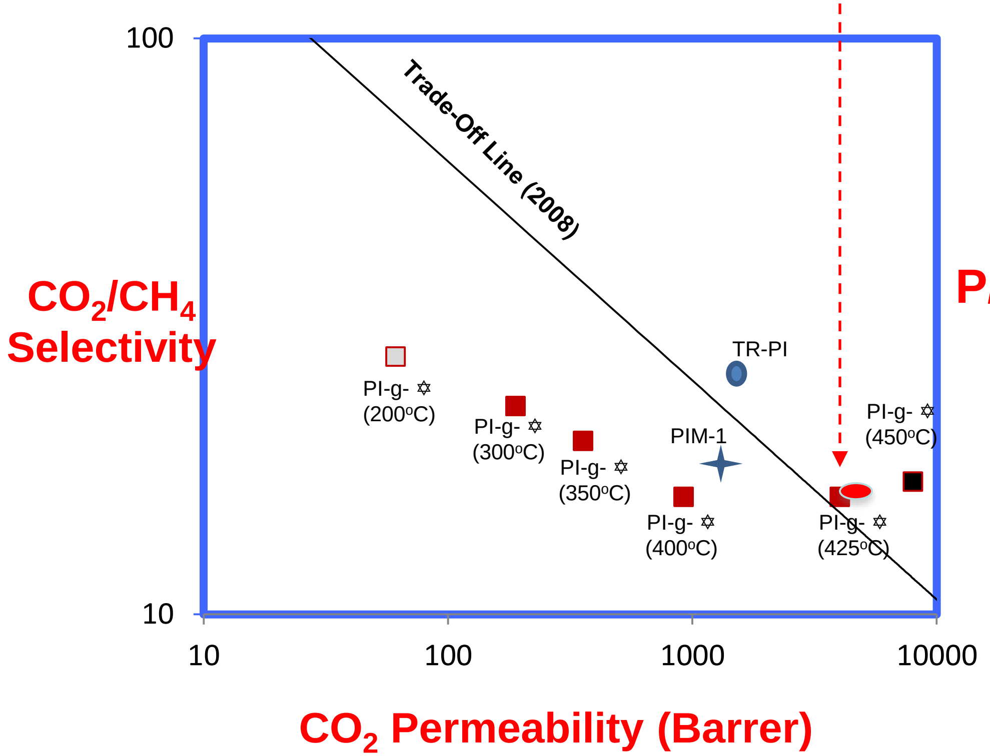
1. Polymer of thermal template removal (PI-g-CD, TR polymer)
2. Composite polymers containing advanced porous additives (MOF and ZIF)

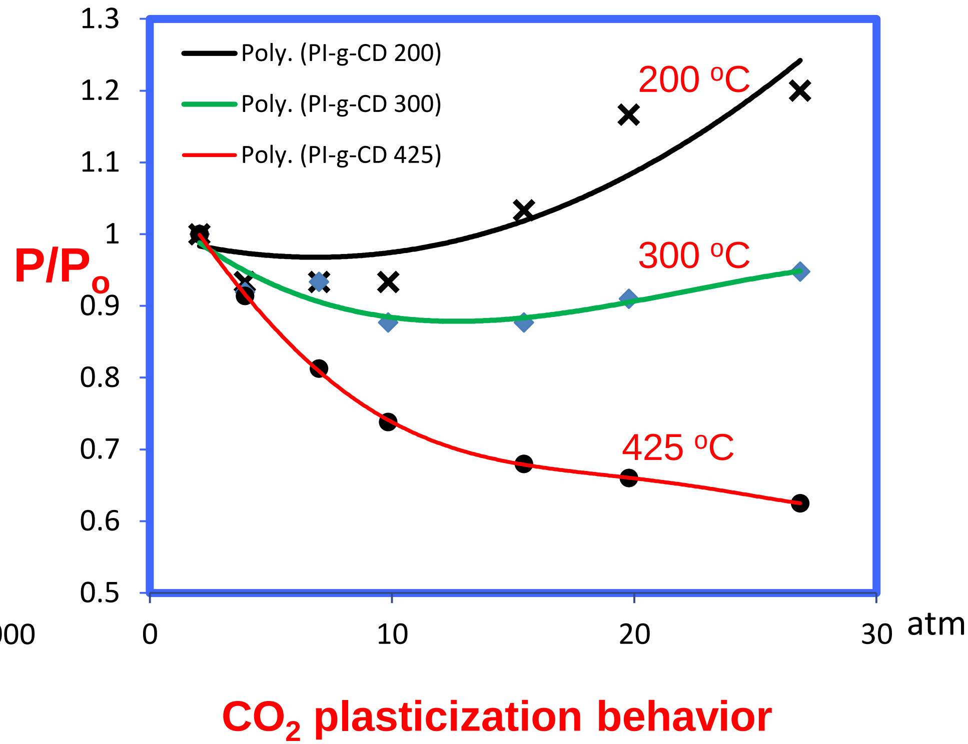


- Big pores improve gas solubility and diffusivity
- Small pores improve gas-pair selectivity.

Gas Separation Performance of PI-g-CD membranes

Pure gas (35ºC): P_{CO2} = 4016, α =16
Mixed gas (25ºC): P_{CO2} = 4289 , α =16

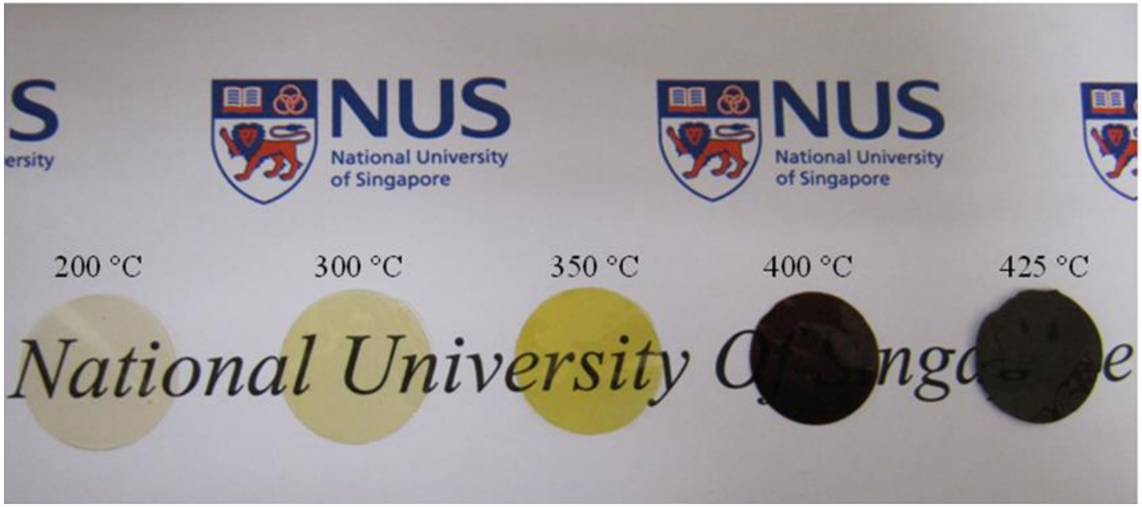


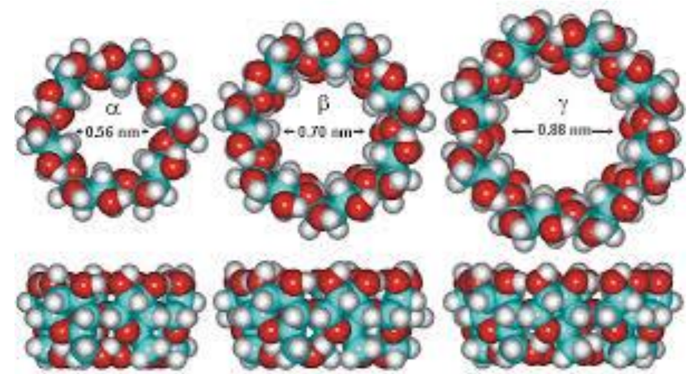


US patent 8,772,417 (2014); **Chinese Patent** ZL 201180023724.2 (2014)

Y. C. Xiao, T. S. Chung, *Energy and Environmental Science*. 4, 201-208 (2011)

1barrer=1×10^{-10} cm^3 (STP)-cm/cm^2 sec cm-Hg)





α CD
6-membered ring

β CD
7-membered ring

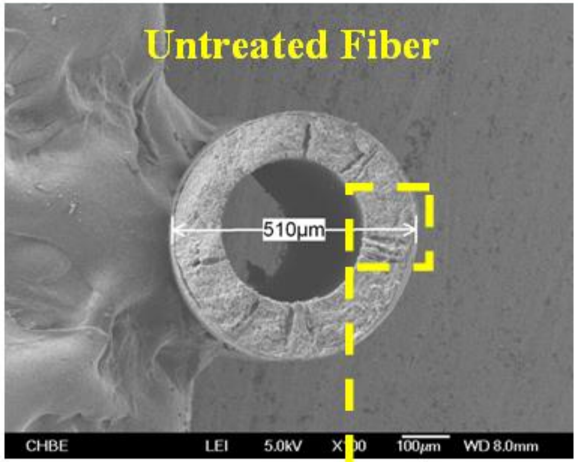
γ CD
8-membered ring

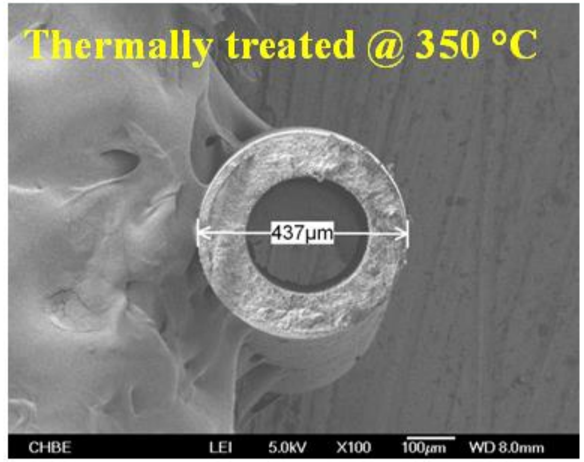
Mr.Mohammad Askari

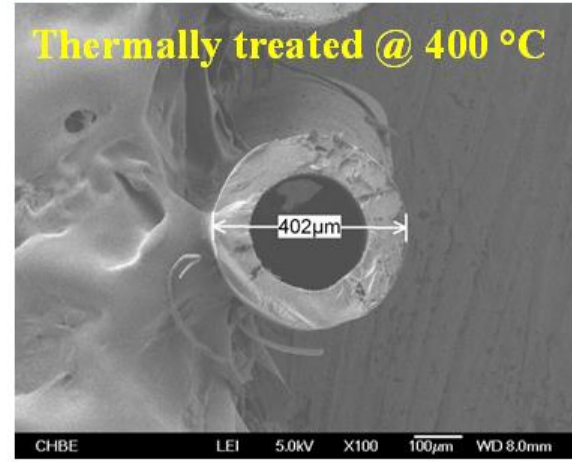
Flexibility of the co-polyimide grafted with γ-CD membrane and thermally treated at 425 °C

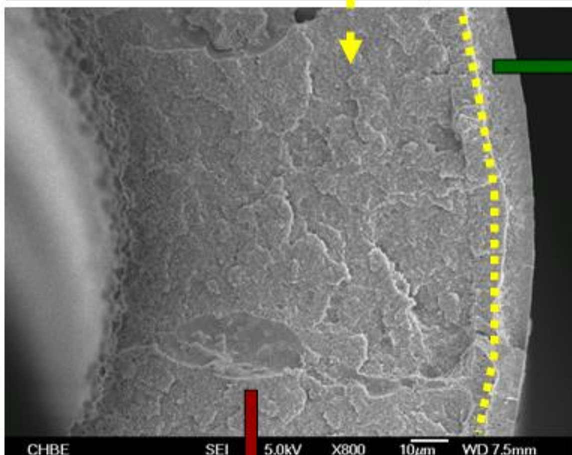
M. Askari, Y. C. Xiao, P. Li, T. S. Chung, Natural gas purification and olefin/paraffin separation using cross-linkable 6FDA-Durene/DABA co-polyimides grafted with α, β, and γ-cyclodextrin, *J. Membrane Science* 390– 391, 141– 151 (2012).

Thermally Cross-linkable Co-polyimide Dual-layer Hollow Fiber Membranes

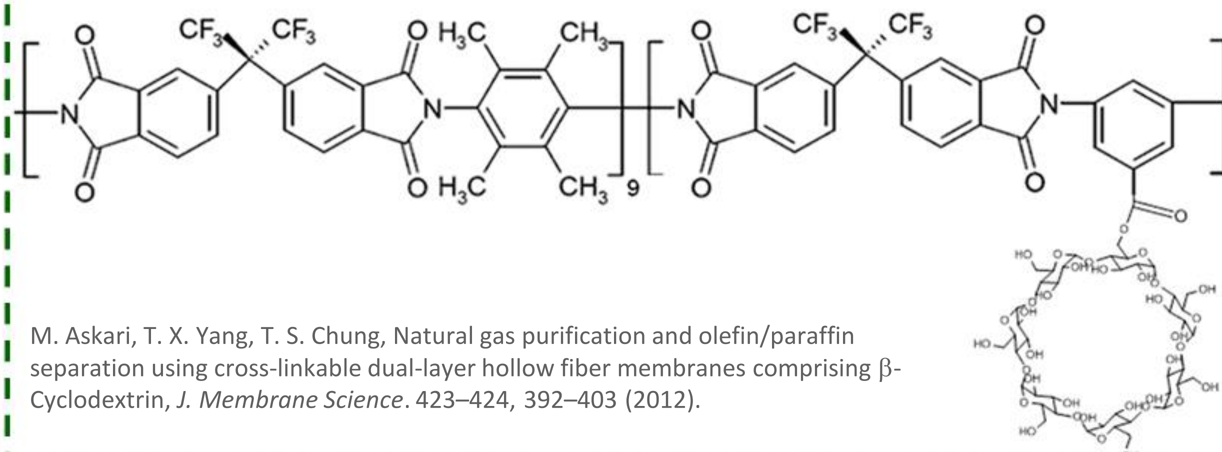






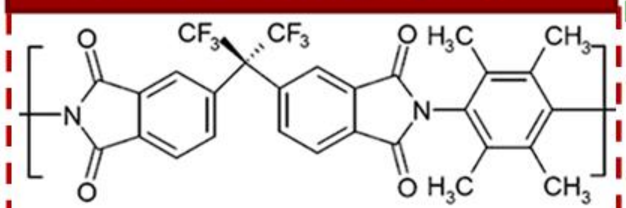


6FDA-Durene/DABA (9/1) grafted β-Cyclodextrin Co-polyimide



M. Askari, T. X. Yang, T. S. Chung, Natural gas purification and olefin/paraffin separation using cross-linkable dual-layer hollow fiber membranes comprising β-Cyclodextrin, *J. Membrane Science*. 423–424, 392–403 (2012).

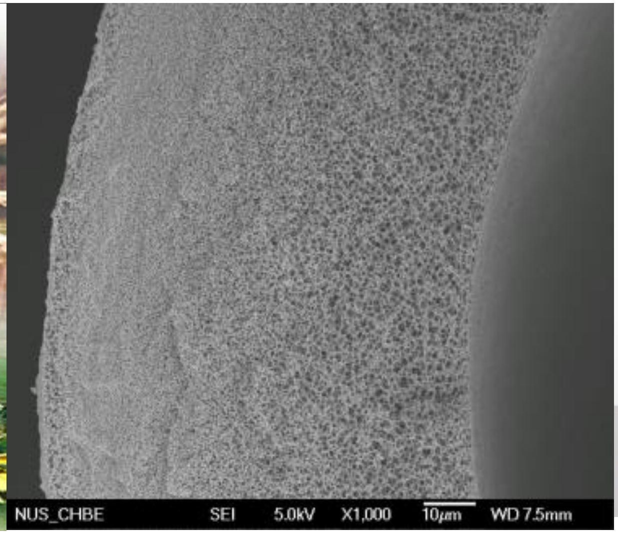
6FDA-Durene Polyimide



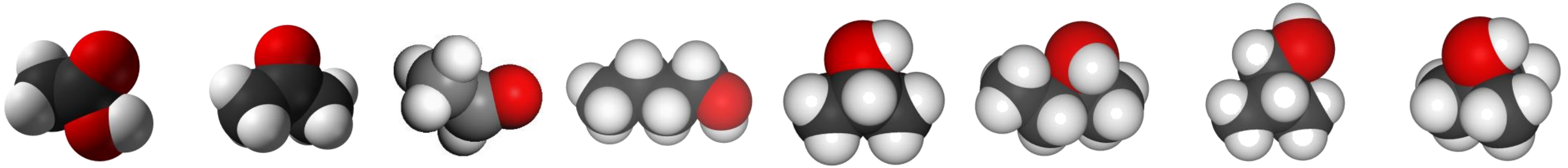
CO_2 Permeance of ***82 GPU*** with ***19.9*** CO_2/CH_4 Selectivity

C_3H_6 Permeance of ***29 GPU*** with ***15.3*** C_3H_6/C_3H_8 Selectivity

Membranes for Biofuel



Our goal is to sustain Singapore's leadership in both petrochemical-refinery and biofuel-refinery

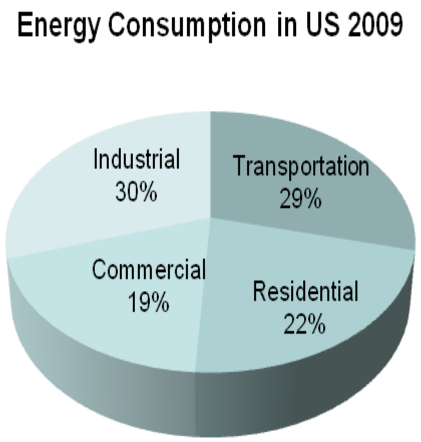


Acetic acid | Acetone | Ethanol | Isopropanol | 1-butanol | 2-butanol | iso-butanol | tert-butanol

Jurong Island: Singapore’s Petrochemical Hub

ExxonMobil’s Singapore complex is one of the largest integrated manufacturing sites in the world

Other limitations, energy for current technologies liquid fuel for long distance transportations



Liquid fuel

http://www.eia.doe.gov/emeu/aer/pdf/pages/sec2_4.pdf

Liquid fuel, Natural gas, Battery, Fuel cell

Natural gas, Solar and Wind energy

Battery
Fuel cell

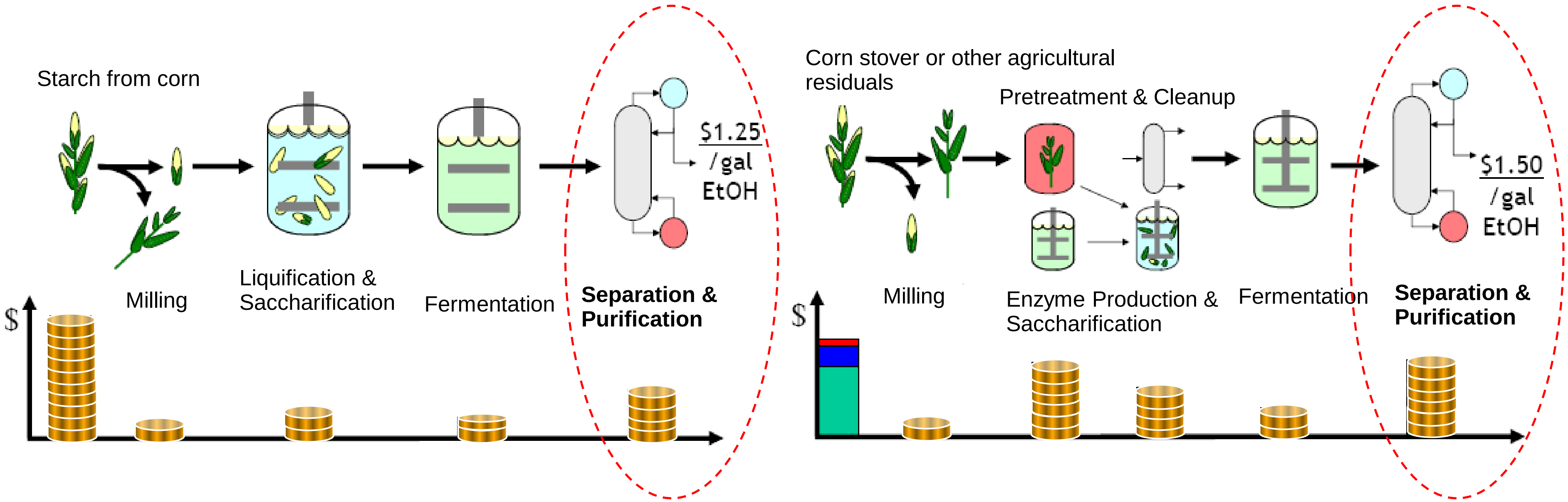
A Comparison of Process Costs for Biofuel

1st generation biofuel

Feed stocks: grain corn or sugar cane

2nd generation biofuel

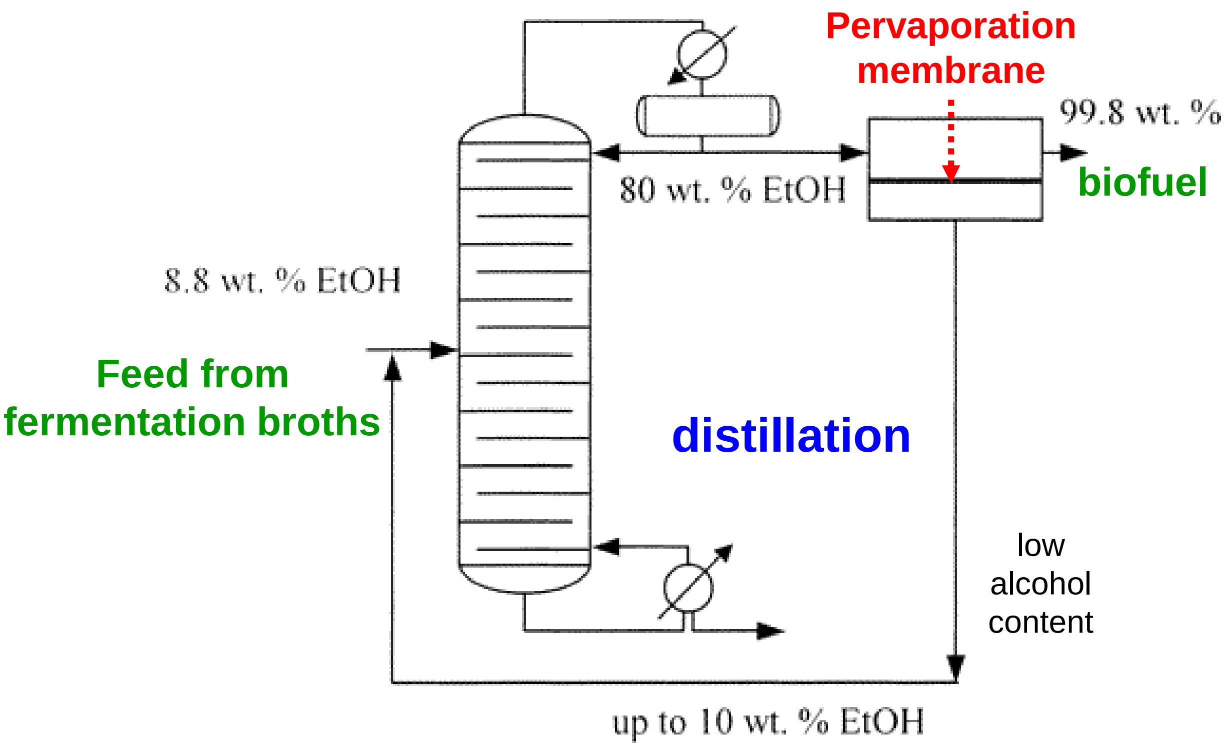
Feed stock: Lignin-cellulosic residuals



The separation and purification stage for either generation biofuel accounts for at least 40% (up to 80%*) of the process cost.

A.J. Ragauskas et al., The path forward for biofuels and biomaterials, Science, 311 (2006), 484.

Hybrid processes (distillation and pervaporation) will be the future for the dehydration of biofuels

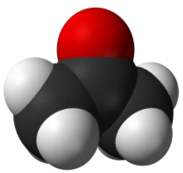


Pervaporation is used to remove a small amount of H_2O from an azeotropic liquid mixture where simple distillation can't make the separation.

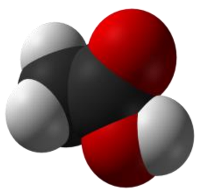
Pervaporation membranes for the dehydration of biofuel (ethanol & butanol) and other alcohols

UOP-NUS (2002-2005), Merck-NUS (2004-2007), A-Star & NRF CRP grants (2008-2015)

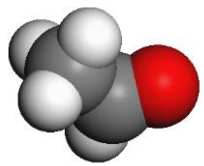
- Concentrate ethanol, IPA, and biofuel
- Separate non-aqueous solvent mixtures
- Facilitate pharmaceutical syntheses



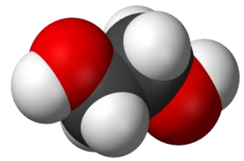
Acetone



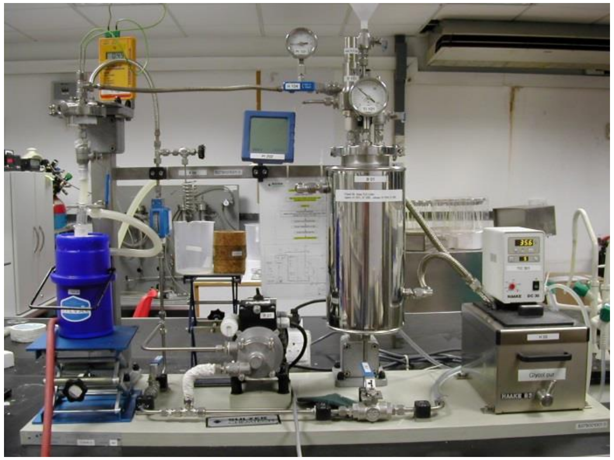
Acetic acid



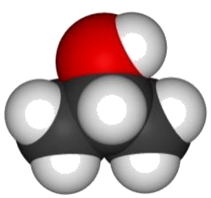
Ethanol



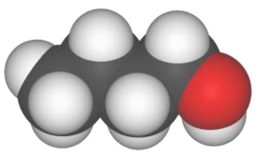
ethylene glycol



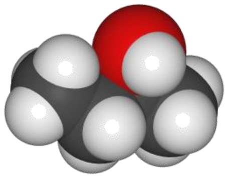
Flat membranes



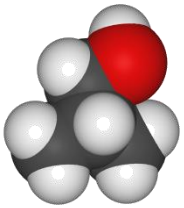
Isopropanol (IPA)



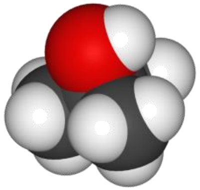
1-butanol



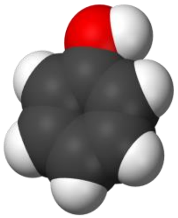
2-butanol



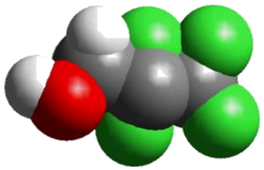
iso-butanol



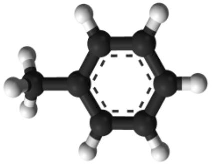
tert-butanol



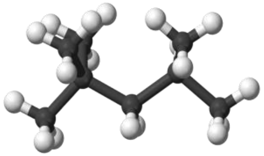
Phenol



Tetrafluoro-propanol (TFP)



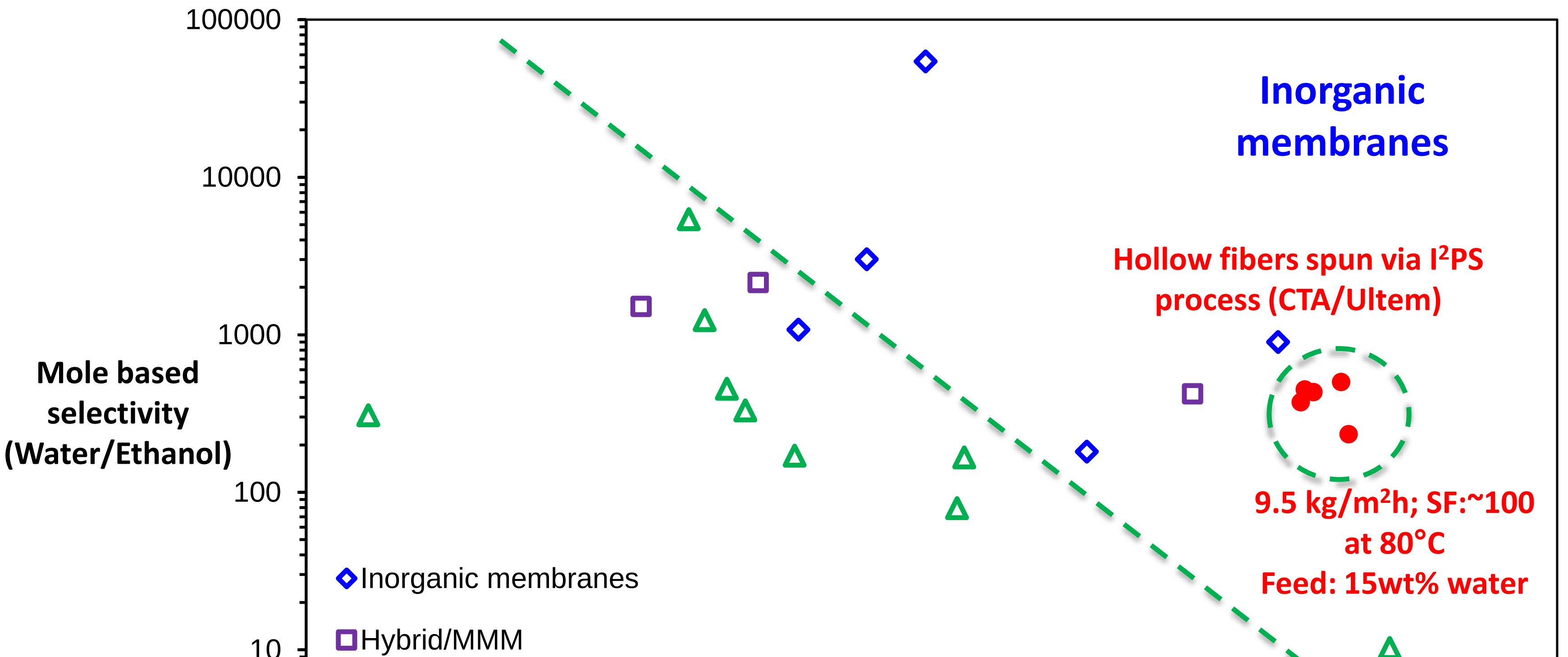
Toluene



Iso-octane

Hollow fiber membranes

Benchmarking (Dehydration of Ethanol)



Mr. Ong YK

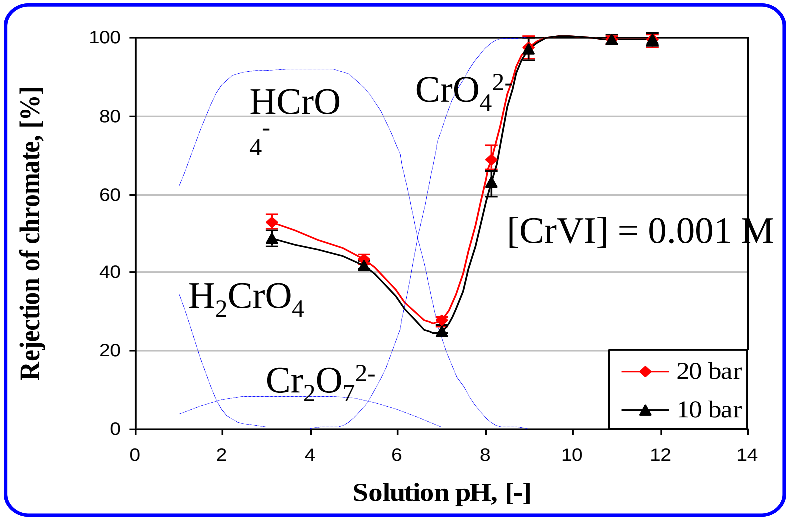
Y. K. Ong, T. S. Chung, Pushing the limits of high performance dual-layer hollow fiber fabricated via I²PS process in dehydration of ethanol, *AIChE J. 59,* 1245–1254 (2013).

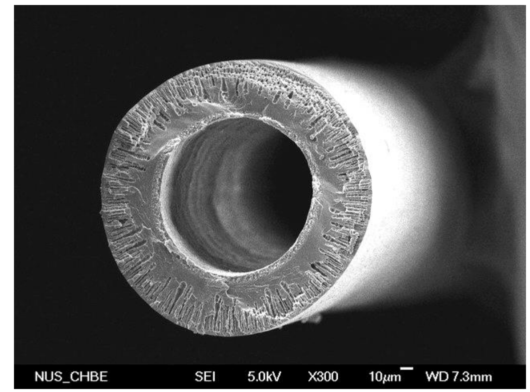
Global Innovation Award, TechConnect 2014, Washington, D.C. USA (June 15-18, 2014)

Membranes for water reuse, desalination and osmotic energy generation

Nano-filtration (NF) Hollow Fiber Membranes to Remove Toxic Ions in Water

- Toxic and heavy metal ions such as **phosphate, lead, arsenate, arsenite, borate, chromate, copper and cadmium ions**

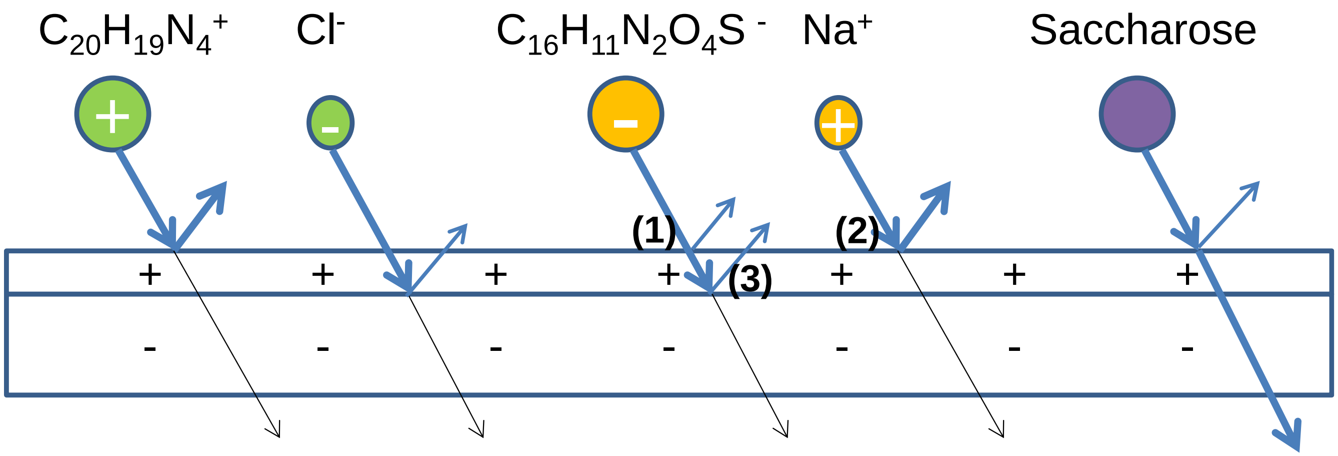




PBI NF fiber

Wang & Chung, Investigation of polybenzimidazole (PBI) nanofiltration hollow fiber membranes for the removal of chromate, *J. Membrane Science* 281, 307 (2006).
Lv et al., Investigation of amphoteric polybenzimidazole (PBI) nanofiltration hollow fiber membrane for both cation and anion removal, *J. Membrane Science* 310, 557 (2008).
Sun et al., Novel polyamide-imide/cellulose acetate dual-layer hollow fiber membranes for nanofiltration, *J. Membrane Science* 363, 232–242 (2010).
Sun et al., Hyperbranched polyethyleneimine induced cross-linking of polyamide-imide nanofiltration hollow fiber membranes for effective removal of ciprofloxacin, *Envir Sci Tech* 45, 4003 (2011).
Gao et al., Polyethyleneimine (PEI) cross-linked P84 nanofiltration (NF) hollow fiber membranes for Pb^{2+} removal, *J. Membrane Science 452,* 300–310 (2014).
Zhu et al., Dual-layer Polybenzimidazole/Polyethersulfone (PBI/PES) Nanofiltration (NF) Hollow Fiber Membranes for Heavy Metals Removal from Wastewater, J. Membrane Science (2014).

Double-Repulsive NF Hollow Fiber Membranes

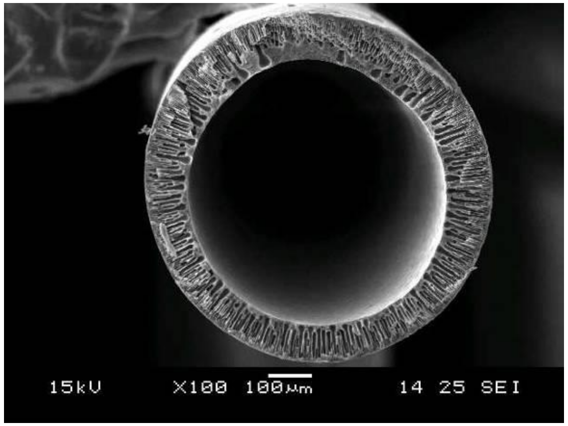


the NF membrane possesses a negatively charged substrate and a positively charged selective layer with a mean effective pore radius of 0.36 nm, molecular weight cut off of 500 Da, and pure water permeability of 4.9 $L m^{-2} bar^{-1} h^{-1}$.

Sun SP, Hatton TA and Chung TS*, ***Environ. Sci. Technol***. 45 (2011) 4003

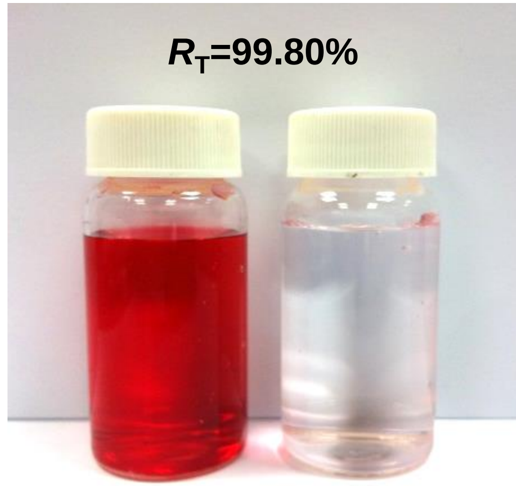
Sun SP, Hatton TA Chan SY and Chung TS*, ***J. Membr. Sci***. 401-402(2012) 152-162

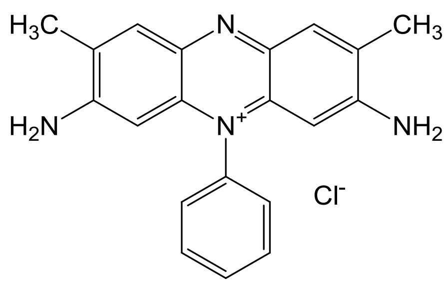
Textile dyes



Thin film composite nano-filtration hollow fiber membrane

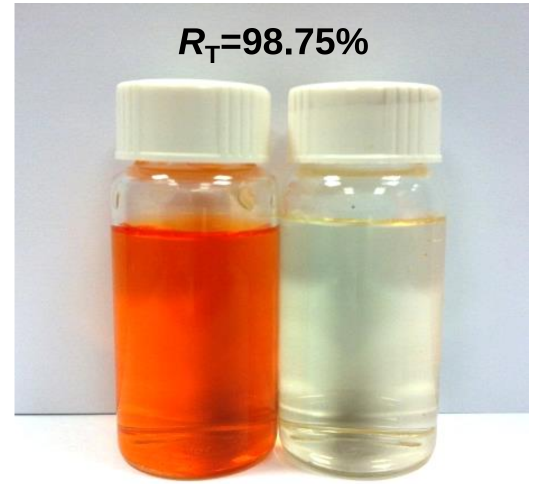
(a) Safranin O

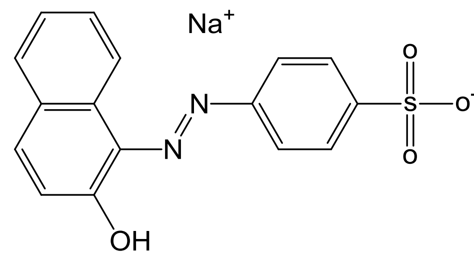




$C_{20}H_{19}N_4^+$, Cl^-, 350.84 Da

(b) Orange II sodium salt





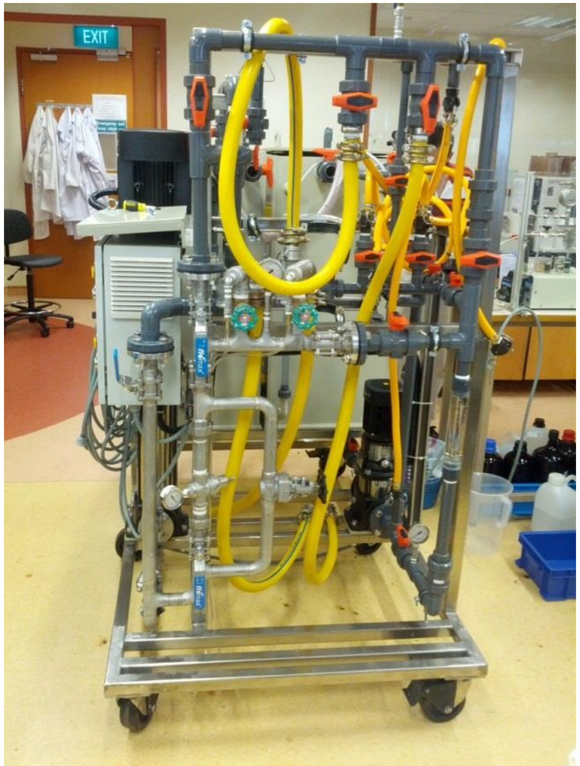
$C_{16}H_{11}N_2O_4S^-$, Na^+, 350.32 Da

Rejection of (a) positively charged dye, Safranin O, and (b) negatively charged dye, Orange II sodium salt, solutions.

The left bottle is the feed solution while the right bottle is the permeate.
(The feed solution concentration: 50ppm, pH 5.75. Pressure:5 bar)

Sun et al, Env. Sci. & Tech, 2011.

Pilot Plant System and Modules



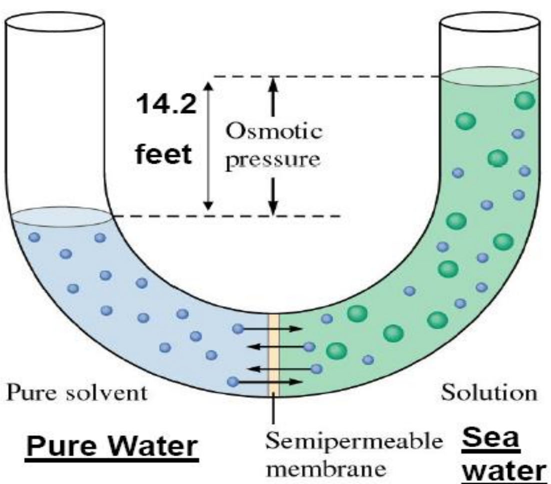
- 2 inch membrane module
- Surface area: ~ 2.3 m^2
- Pure water flux: 3.8 LMH

Licensed to 2 companies for the reuse of industrial wastewater

Y. K. Ong, F. Y. Li, S. P. Sun, B. W. Zhao, C. Z. Liang, T. S. Chung, Nanofiltration hollow fiber membranes for textile wastewater treatment: lab-scale and pilot-scale studies, *Chemical Engineering Science* 114, 51–57 (2014). (IF = 2.386)

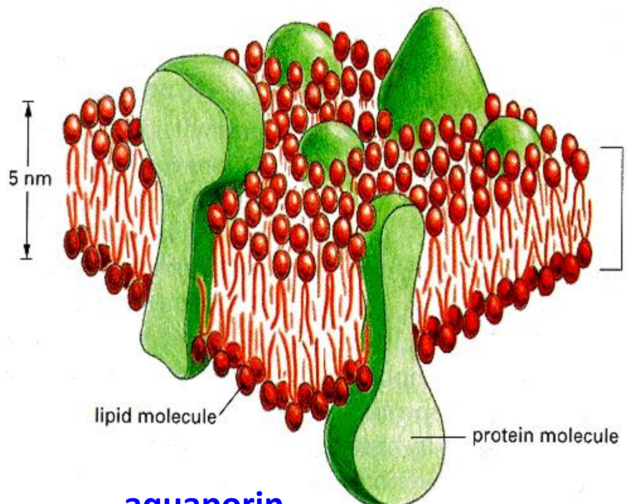
Emerging Membrane Technologies for Water Reuse, Desalination & osmotic power generation

1. Forward Osmosis

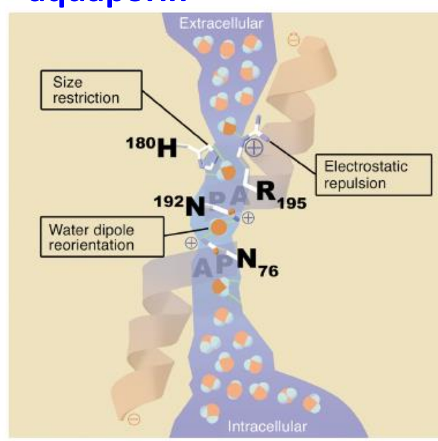


> 30 journal papers

2. Biomimetic Membrane



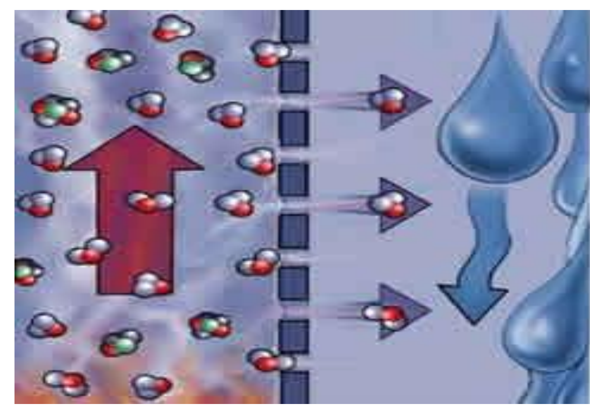
aquaporin



Wang et al., *Soft Matter* 2011, *Small* 2012, *JMS* 2013
Zhong et al., *JMS* 2012, Duong et al *JMS* 2012
Sun et al., *Colloids and Surfaces*, 2011 and 2012
RSC Advances 2013

3. Membrane distillation

(a small MD pilot system at NUS)



> 20 journal papers

4. Osmotic power generation + RO retentate = Energy + Water

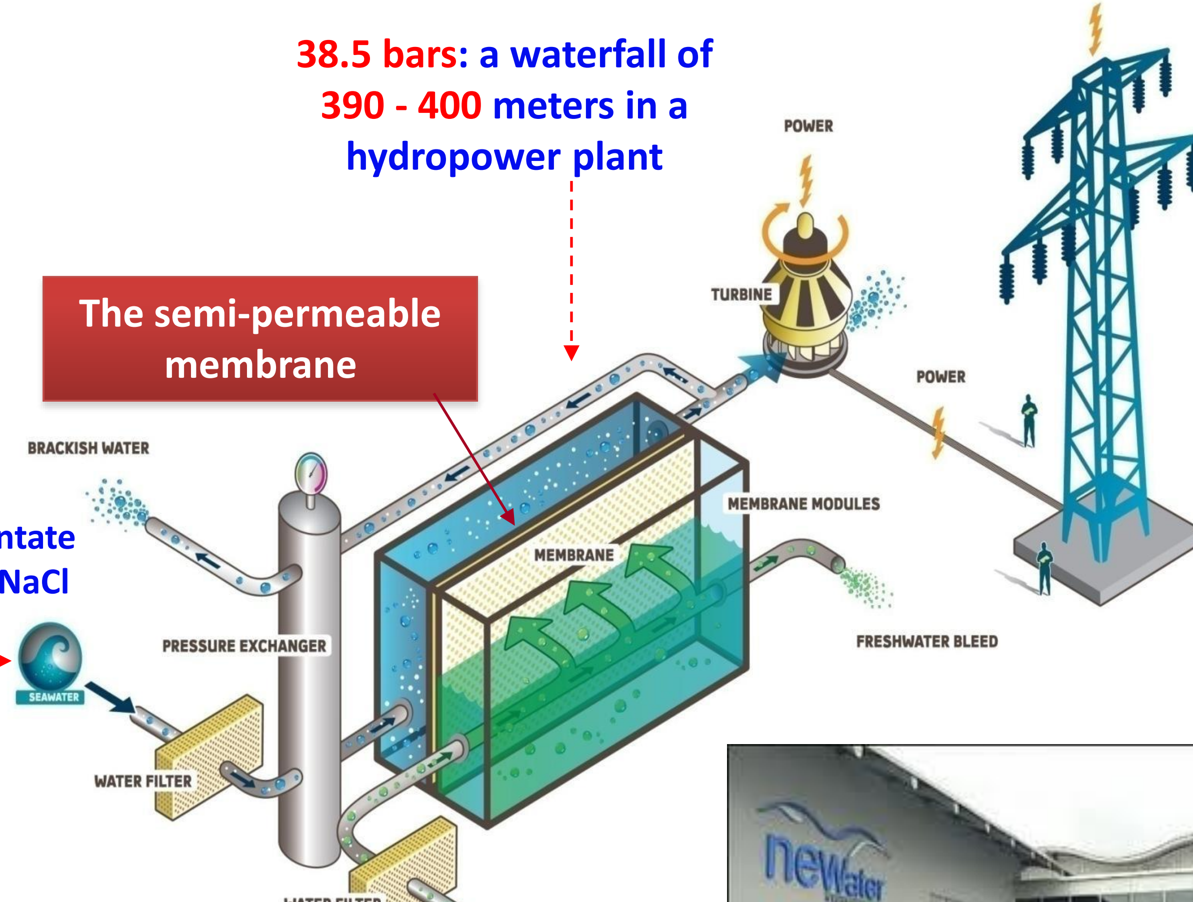
Singapore desalination plant

RO plant

RO retentate
8-8.8% NaCl

38.5 bars: a waterfall of
390 - 400 meters in a
hydropower plant

The semi-permeable membrane



NEWater retentate
(waste of recycled water)

http://osmoticpower.com/

T. S. Chung, S. Zhang, K. Y. Wang, J. C. Su, M. M. Ling, Forward osmosis processes: yesterday, today and tomorrow, *Desalination* (2012)

NUS was recognized to be the World Best on water research by Lux Research USA in 2013

luxresearch

Lux Research is an independent research and advisory firm providing strategic advice and ongoing intelligence on emerging technologies.

Top universities in Water research

Rank	University	Country	Strengths
1	**National University of Singapore**	Singapore	Membrane, Desalination and Reuse
2	Nanyang Technological University	Singapore	Membrane, Desalination and Reuse
3	Delft University	Netherlands	Infrastructure, drinking water and waste water
4	University of California Davis	US	Drinking water and reuse
5	Wageningen University	Netherlands	Nutrient recovery, Infrastructure

Top universities in Desalination research

University
1. National University of Singapore
2. Massachusetts Institute of Technology (MIT)
3. Nanyang Technological University
4. University of Texas at Austin
5. University of California Los Angeles (UCLA)

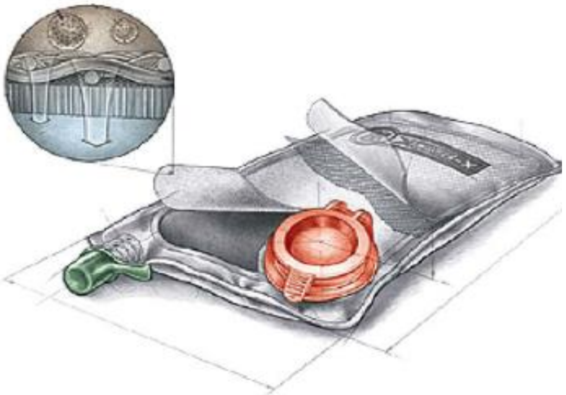
Top universities in Membrane research

University
1. National University of Singapore
2. Nanyang Technological University
3. Penn State University
4. Delft University of Technology
5. Lund University

Top universities in Water Reuse

University
1. National University of Singapore
2. Colorado School of Mines
3. University of Nottingham Malaysia
4. Nanyang Technological University
5. Taxes A&M

Forward Osmosis (FO) Process

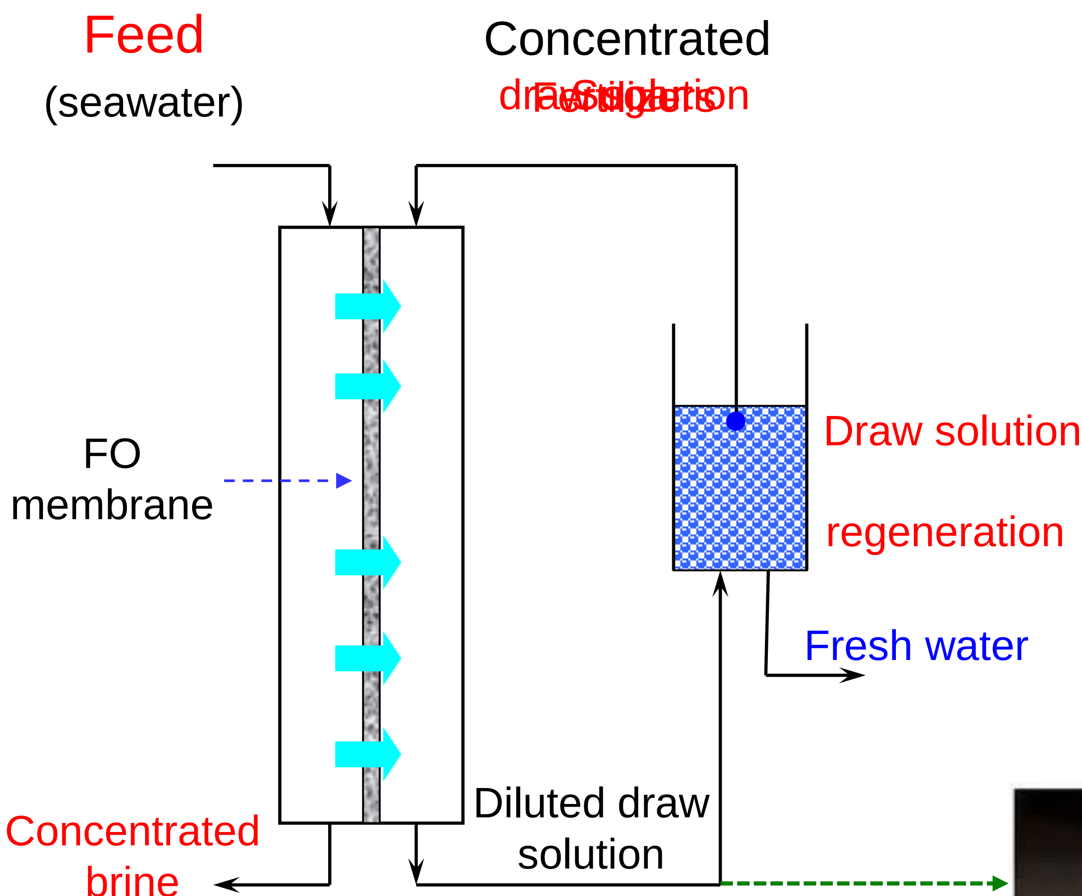


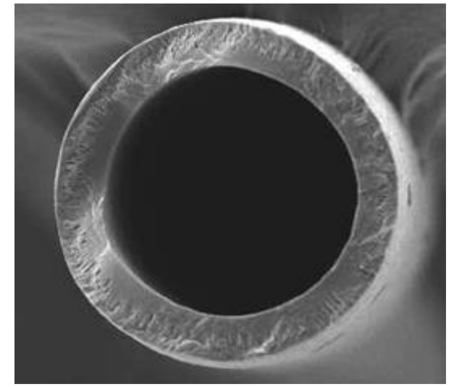
hydration bag

HTI's forward osmosis filtration systems

http://www.gizmag.com/go/8107/

Forward Osmosis (FO) Process for Water Production





Draw solutions:
1) Concentrated salts
2) NH_4HCO_3
3) Magnetic particles
4) Sugar
5) Fertilizers
6) Many others

Dr. Wang Kaiyu

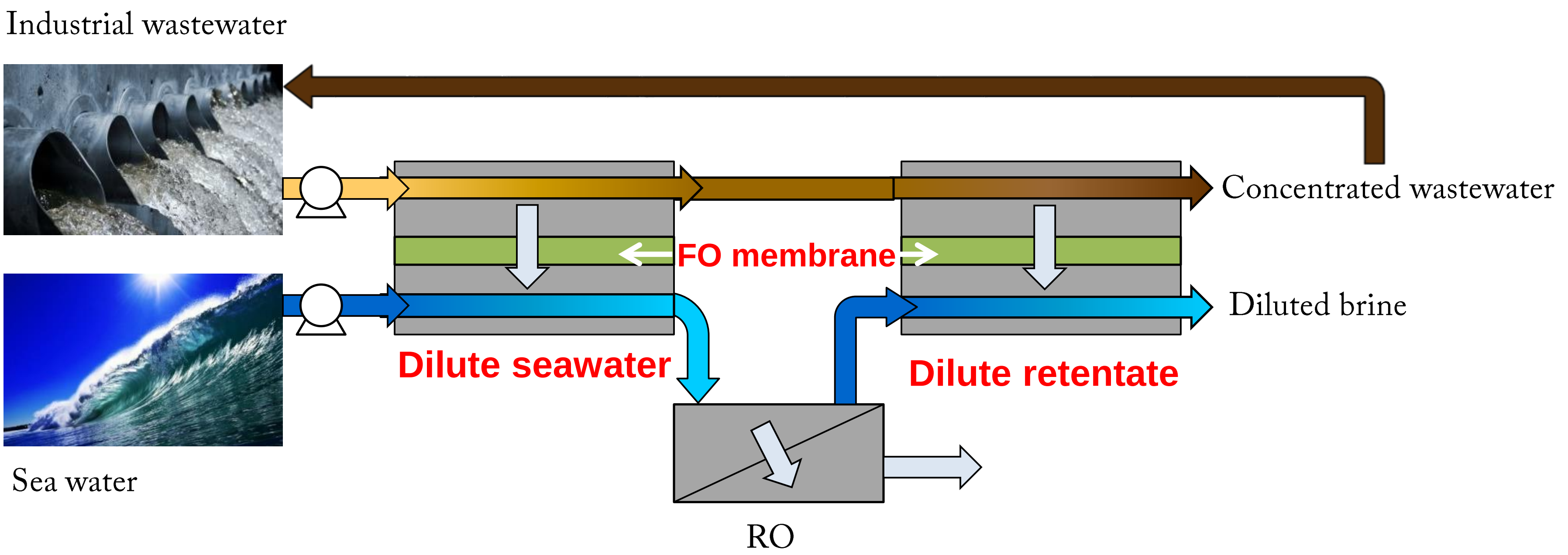
Miss Ong Rui Chin

Dr. Zhang Sui

FO + RO integration for seawater desalination

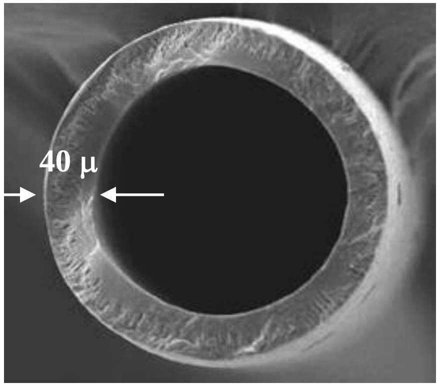
Why do this way?

(1) Recycle industrial wastewater
(2) Lower NaCl conc. in seawater before entering RO
(3) No cycle on draw solutes
(4) RO retentate can be diluted
(5) Foulants in industrial wastewater can be taken care by FO membranes

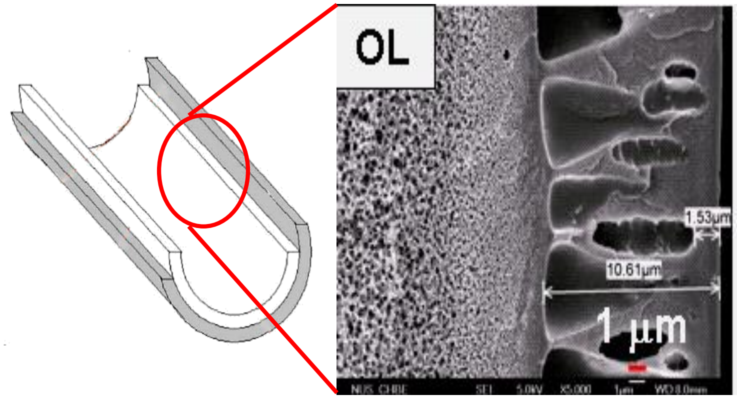


N. T. Hancock, P. X, Molly J. Roby, J. D. Gomez, T. Y. Cath, Towards direct assessment of long-term process performance at the pilots scale, J. Membrane Science 445 (2013) 34–46

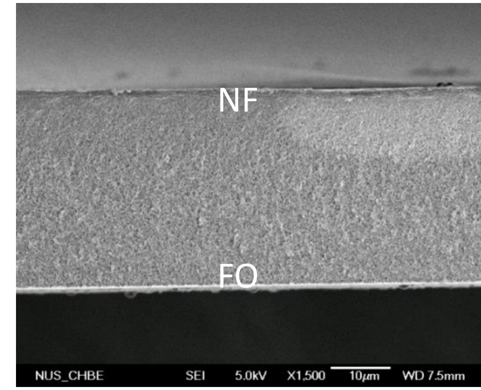
T. S. Chung, S. Zhang, K. Y. Wang, J. C. Su, M. M. Ling, Forward osmosis processes: yesterday, today and tomorrow, Desalination 287, 78–81 (2012).



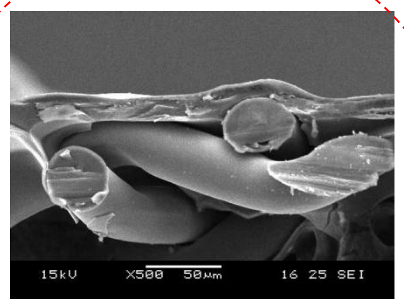
(a) Single-layer PBI membrane



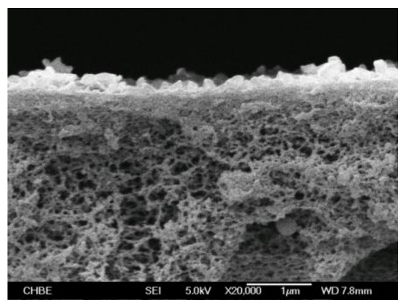
(b) Dual Layer PBI/PES membrane



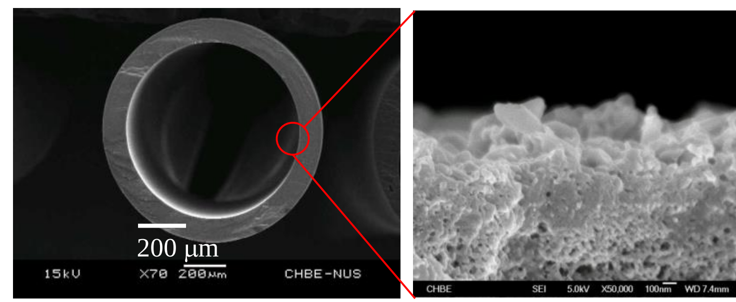
(b) CA flat sheet membrane



(d) HTI CTA membrane



(e) Thin-film interfacial polymerized flat-sheet FO membrane

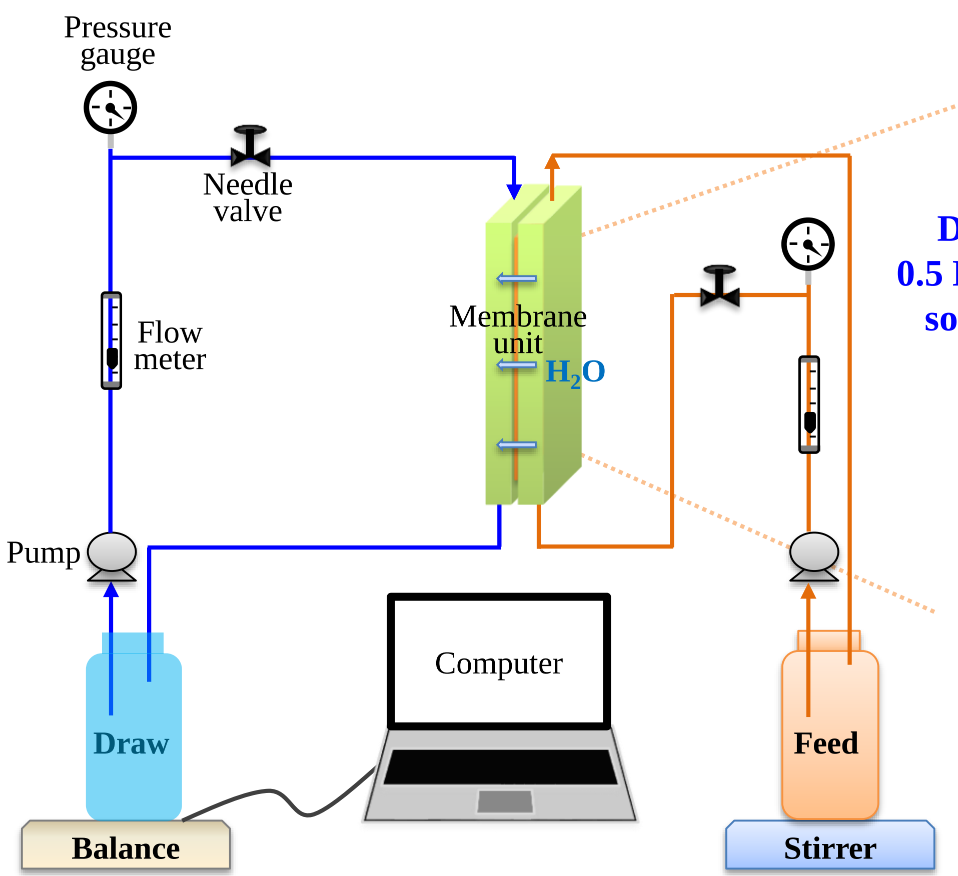


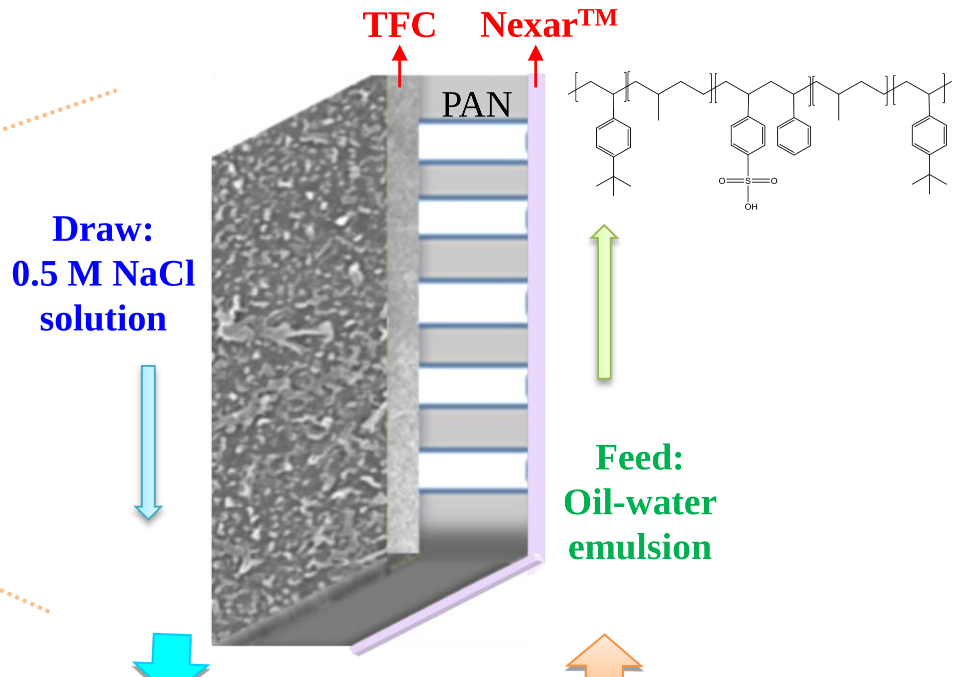
(f) Thin-film interfacial polymerized FO hollow fiber

Some of NUS and HTI FO membranes for water reuse and desalination. (a) polybenzimidazole (PBI) membrane; (b) Dual-layer PBI/polyethersulfone (PES) membrane; (c) CA flat sheet membrane; (d) Hydration Technology Innovations (HTI) CTA membrane; (e) Thin-film interfacial polymerized flat-sheet FO membrane; and (f) Thin-film interfacial polymerized FO hollow fiber.

Oil-water separation by double-skinned FO membranes

(Nexar^{TM} , a Kraton sulfonated pentablock copolymer)



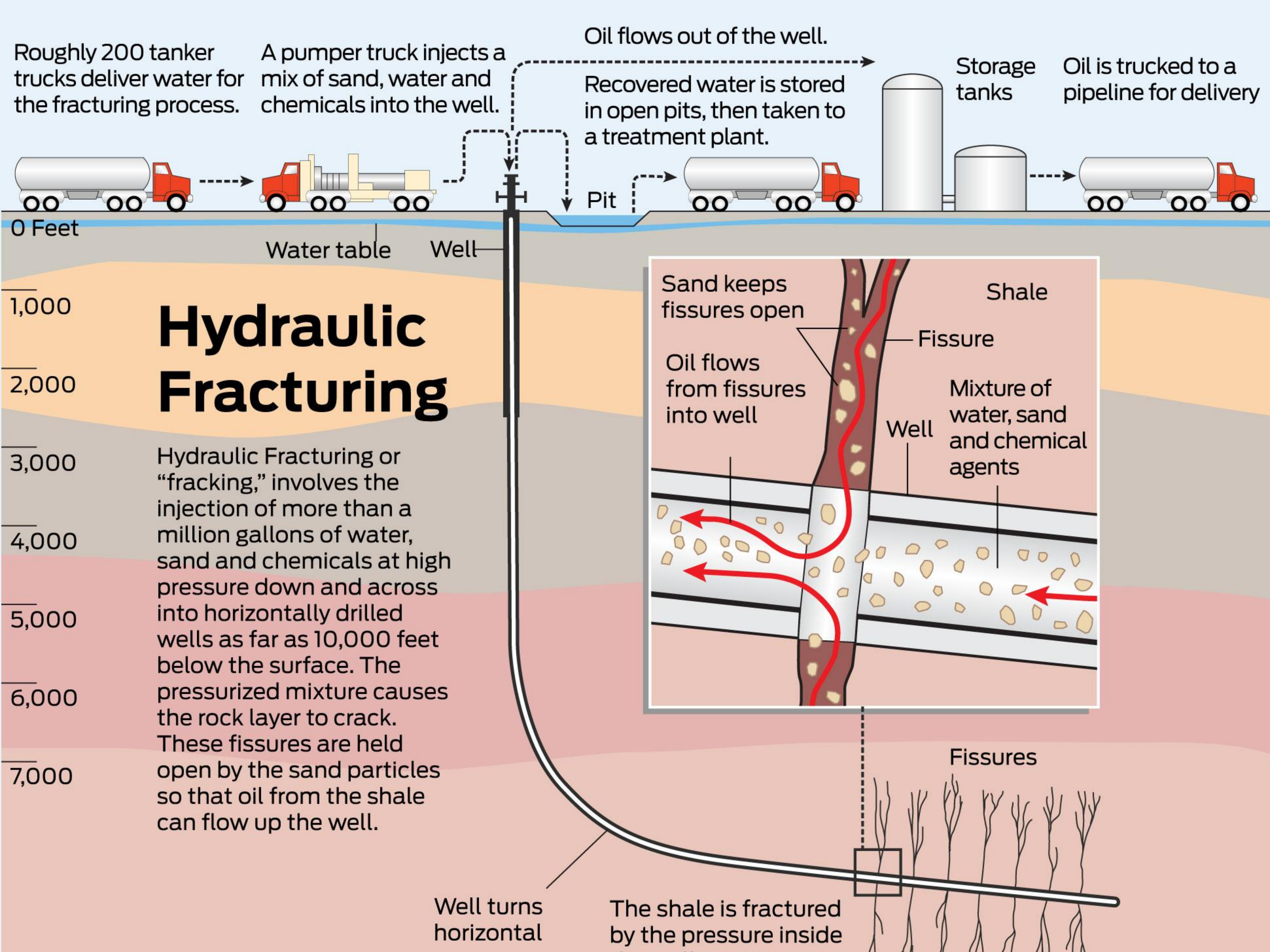


Feed: Oil-water emulsion (200,000 ppm ~ 20 wt%)

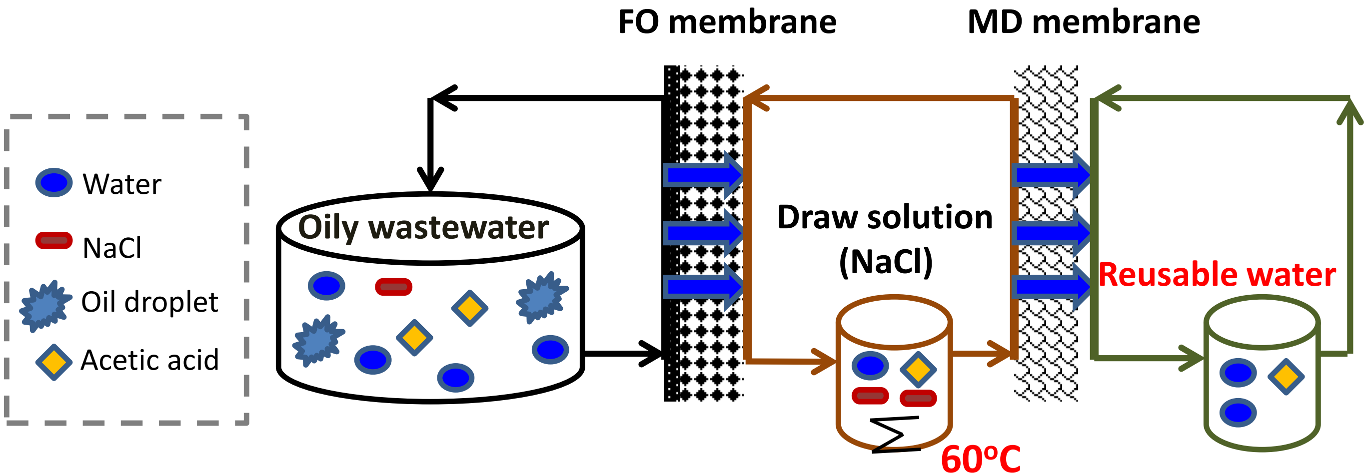
- ♦ Water flux (PRO mode): 10.9 ± 1.0 (LMH)
- ♦ Reverse salt flux: 2.8 ± 0.4 (gMH)
- ♦ Oil rejection: >99.9 %

Dr. Phuoc Duong

P. H. H. Duong, T. S. Chung, W, Shawn; I. Lana, Highly permeable double-skinned forward osmosis membranes for anti-fouling in the emulsified oil-water separation process, *Environmental Science & Technology* 48, 4537-4545 (2014).


Roughly 200 tanker trucks deliver water for the fracturing process.
A pumper truck injects a mix of sand, water and chemicals into the well.
Oil flows out of the well.
Recovered water is stored in open pits, then taken to a treatment plant.
Storage tanks
Oil is trucked to a pipeline for delivery
Pit
0 Feet
Water table
Well
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Hydraulic Fracturing
Hydraulic Fracturing or "fracking," involves the injection of more than a million gallons of water, sand and chemicals at high pressure down and across into horizontally drilled wells as far as 10,000 feet below the surface. The pressurized mixture causes the rock layer to crack. These fissures are held open by the sand particles so that oil from the shale can flow up the well.
Sand keeps fissures open
Shale
Fissure
Oil flows from fissures into well
Well
Mixture of water, sand and chemical agents
Fissures
Well turns horizontal
The shale is fractured by the pressure inside

FO + MD for the treatment of produced water from oil fields



- Water flux (FO): 40.2 ± 2.1 (LMH)
- Reverse salt flux:7.3 ± 1.3 (gMH)
- Initial draw solution: 2 M NaCl
- Oil rejection: > 99.9%

- Water flux (MD): 5.8 ± 0.5 (LMH)
- Final draw solution: 2 M NaCl
- Salt rejection: 99.99%
- Acetic acid rejection: 47.1 ± 3.1%

Dr. Zhang Sui

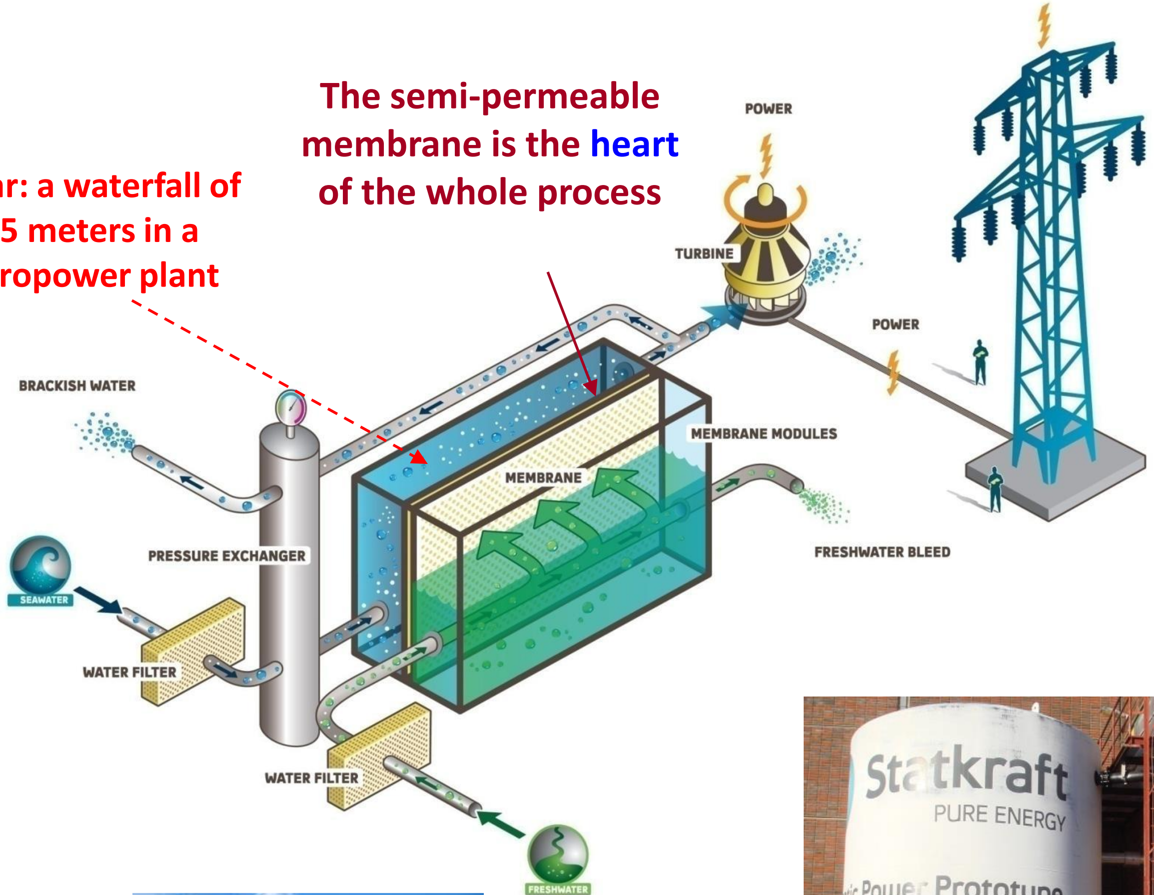
S. Zhang, P. Wang, X. Z. Fu, T. S. Chung, Sustainable water recovery from oily wastewater via forward osmosis - membrane distillation (FO-MD), *Water Research* 52, 112- 121 (2014).

Osmotic power generation from the mixing of seawater and fresh water (Statkraft 2010-2014)

13 bar: a waterfall of 135 meters in a hydropower plant

The semi-permeable membrane is the heart of the whole process

Seawater



River water

Niagara Falls

http://osmoticpower.com/

Osmotic power generation + RO retentate = Energy + Water

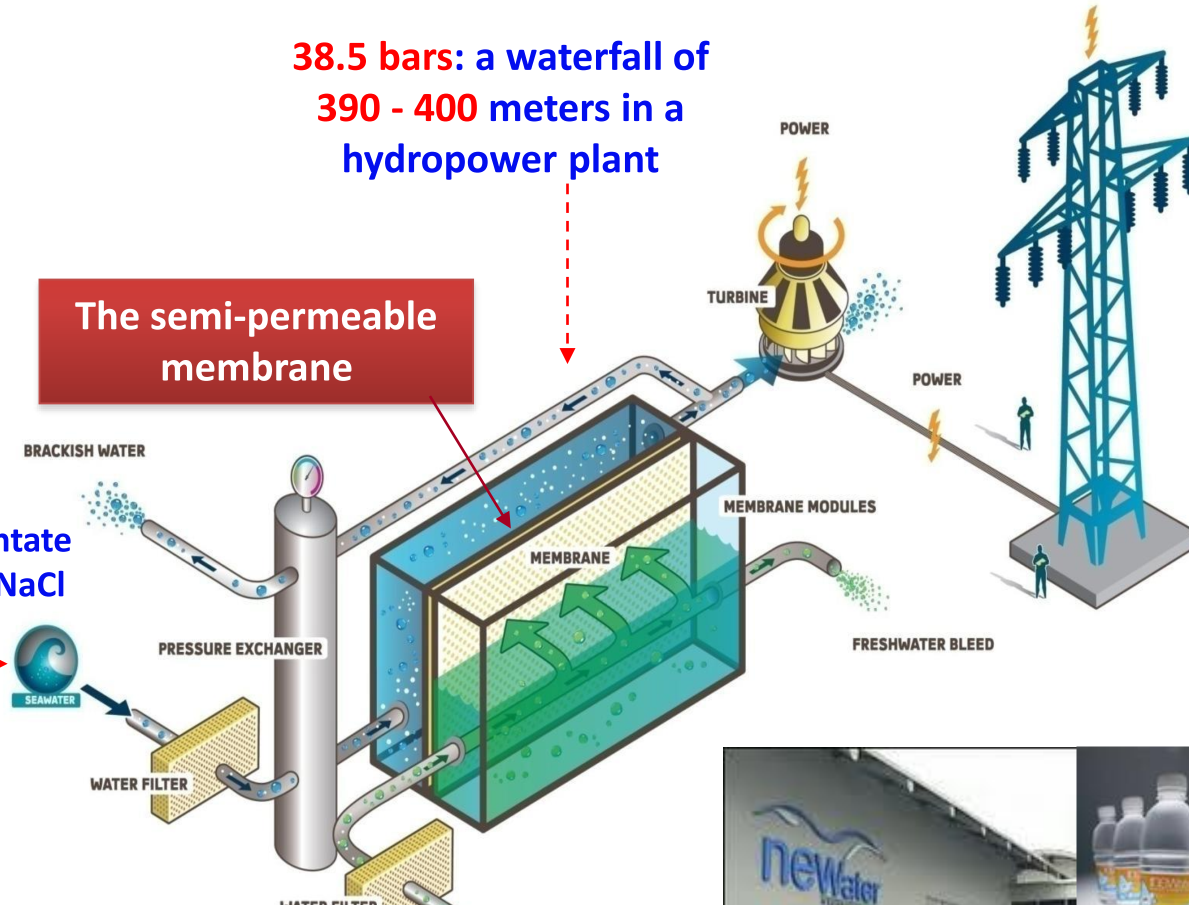
Singapore desalination plant

RO plant

RO retentate
8-8.8% NaCl

38.5 bars: a waterfall of
390 - 400 meters in a
hydropower plant

The semi-permeable
membrane



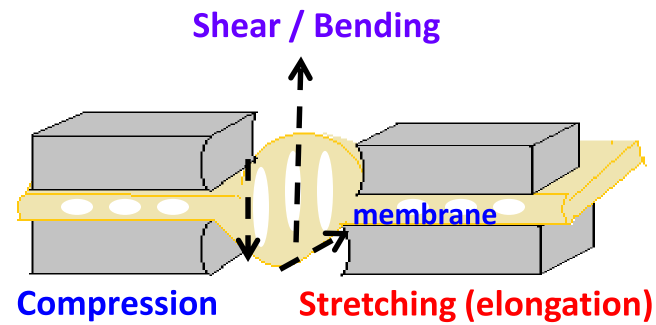
NEWater retentate
(waste of recycled water)

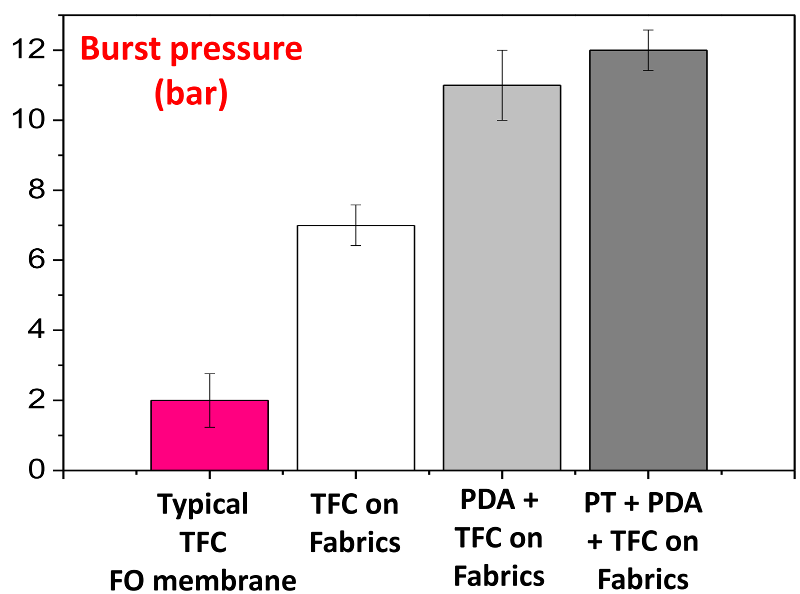
http://osmoticpower.com/

T. S. Chung, S. Zhang, K. Y. Wang, J. C. Su, M. M. Ling, Forward osmosis processes: yesterday, today and tomorrow, *Desalination* (2012)

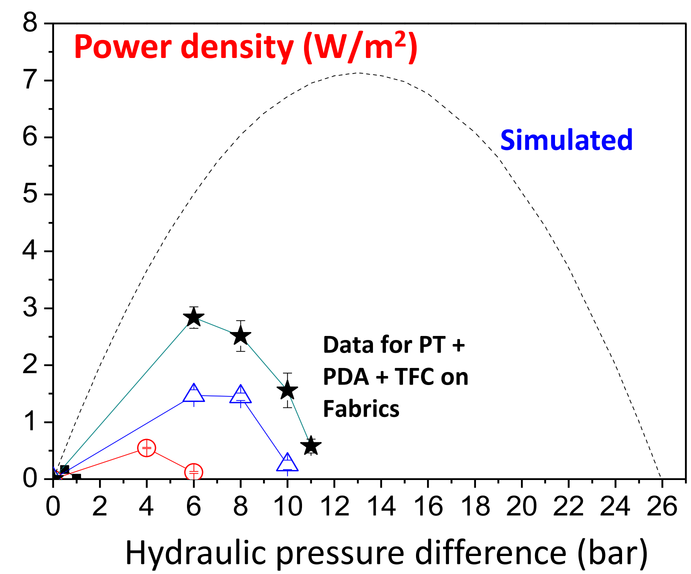
Desirable Membrane Characteristics

1) Semi-permeable (only water can go through)
2) High water flux
3) High salt rejection
4) High resistance to chlorine
5) Mechanically super strong, high toughness





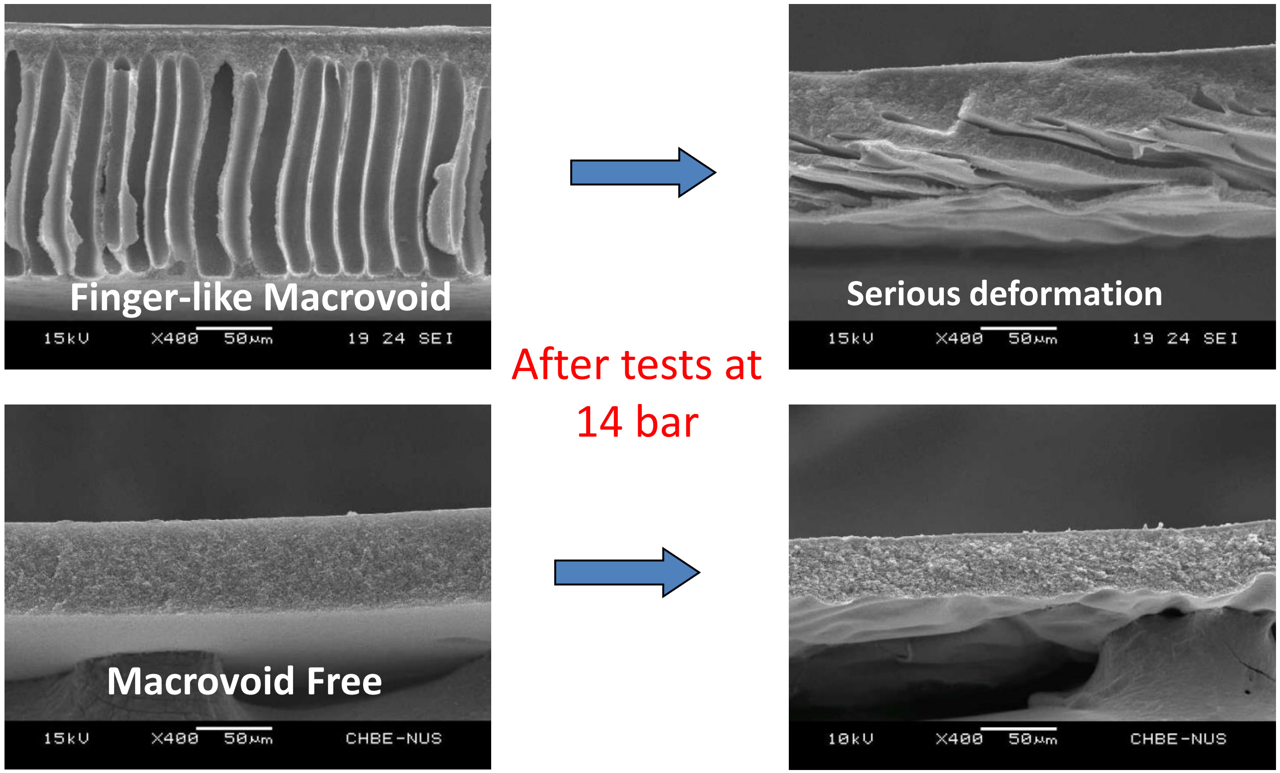
PDA: polydopamine



S. Zhang, F. J. Fu, T. S. Chung, Substrate modifications and alcohol treatment on thin film composite, membranes for osmotic power, Chemical Engineering Science 87, 40–50 (2013).

A comparison of ideal and real power density

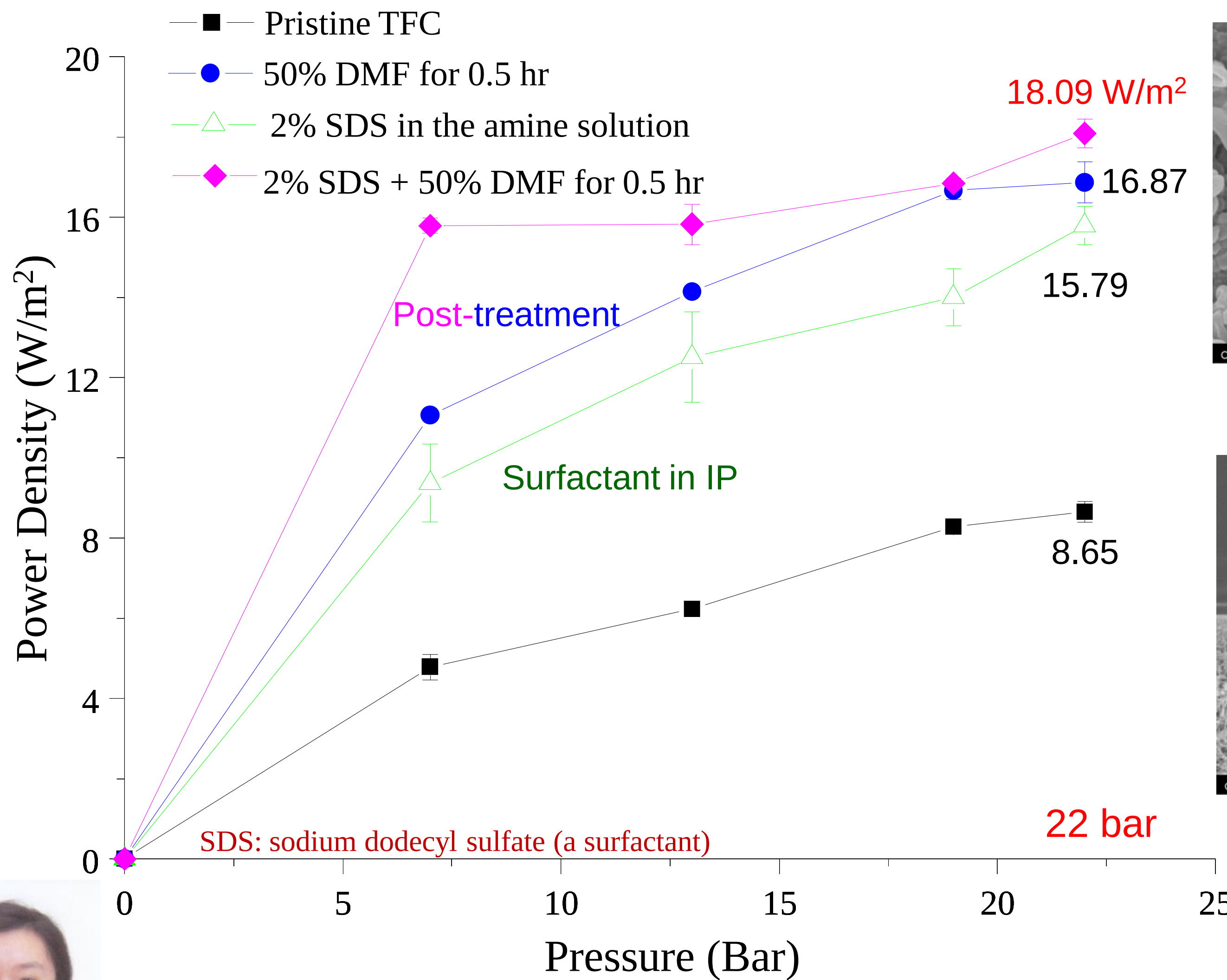
As-cast

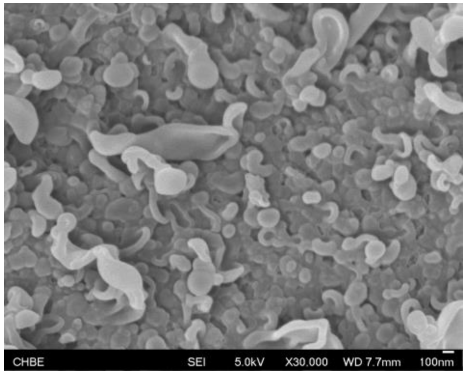


Dr. Li Xue

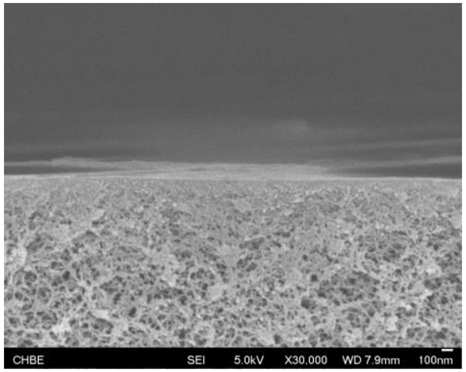
Membrane	PRO (Δp = 0 bar), 3.5 wt% NaCl		Projected power density, W_{max}/m^2	Burst pressure (bar) in PRO tests	Real power density, W_{max}/m^2 $W = J_w \Delta P$
	Water flux, LMH	J_s/J_w, g/L			
PAN-TFC	35	0.26	6.6	**0.5**	**0.1**
PAN-TFC-post treated	64	0.49	12.0	**2**	**0.3**

Dope: 10 wt% PAN/ 90 wt% NMP; IP process: 2 wt% MPD 2min, 0.1 wt% TMC 2min.





TFC membrane



Macro-void free Matrimid substrate

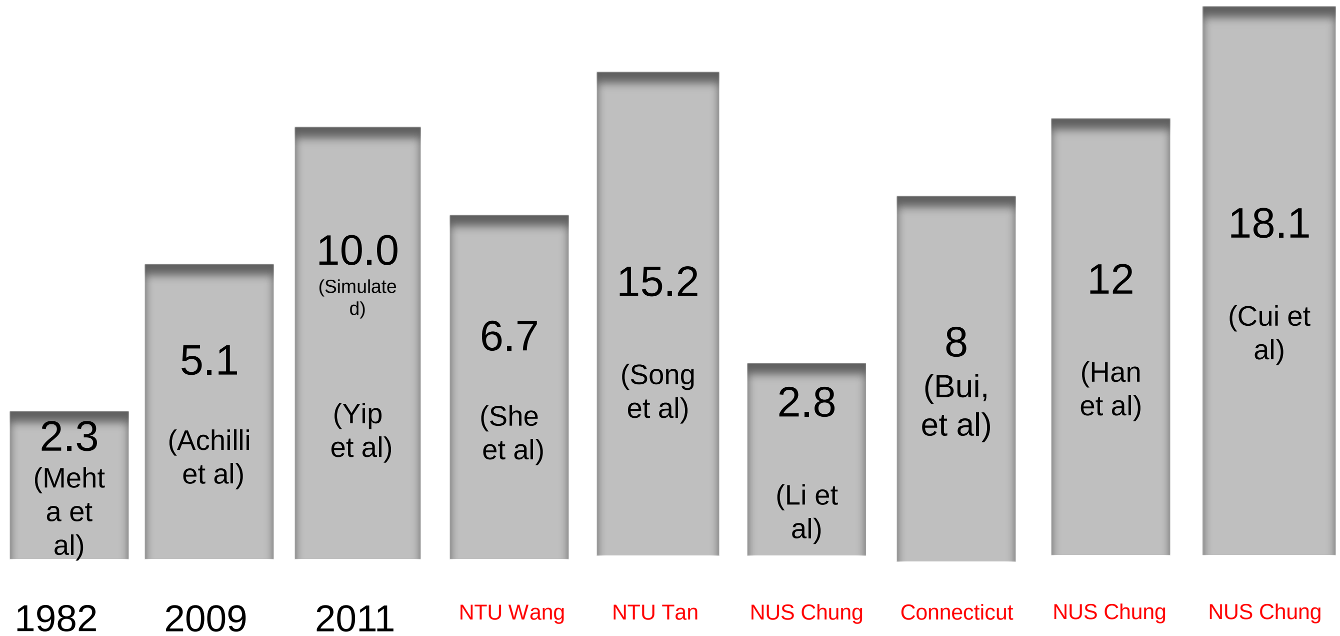
Power density of the TFC membranes with different treatments

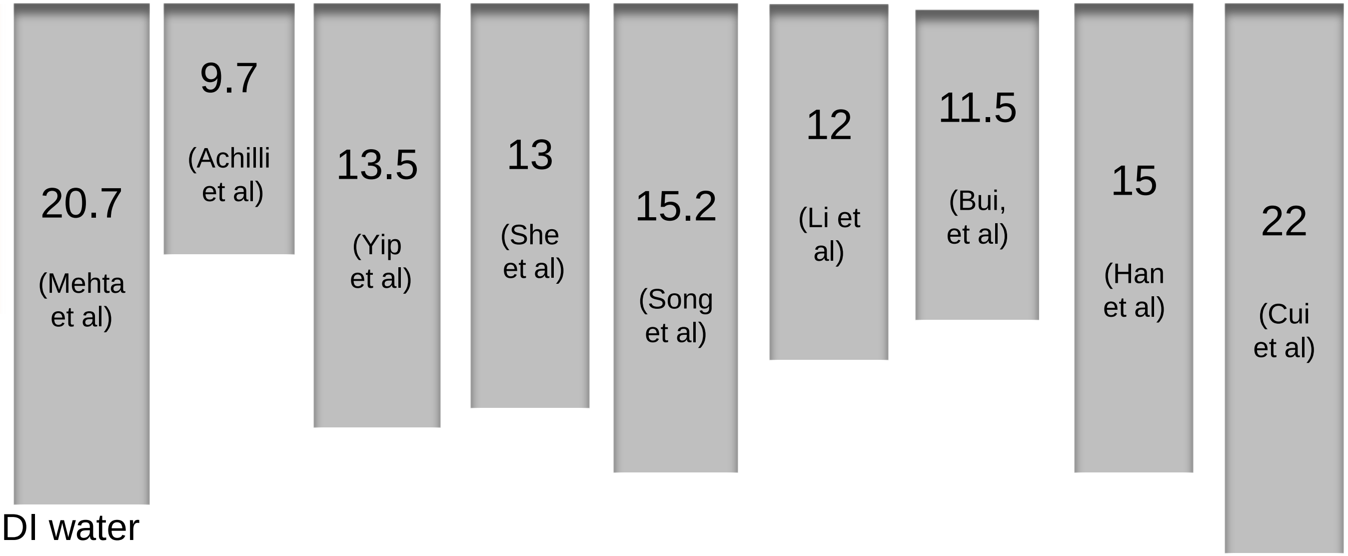
(using brine (1M NaCl) as the draw solution, and DI water as the feed solution)

Y. Cui, X. Y. Liu, T. S. Chung, Enhanced osmotic energy generation from salinity gradients by modifying thin film composite membranes, *Chemical Engineering Journal* 242, 195-203 (2014).

Benchmark

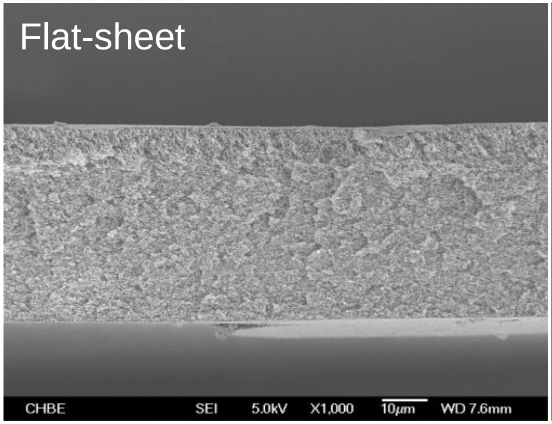
Flat-sheet PRO membranes

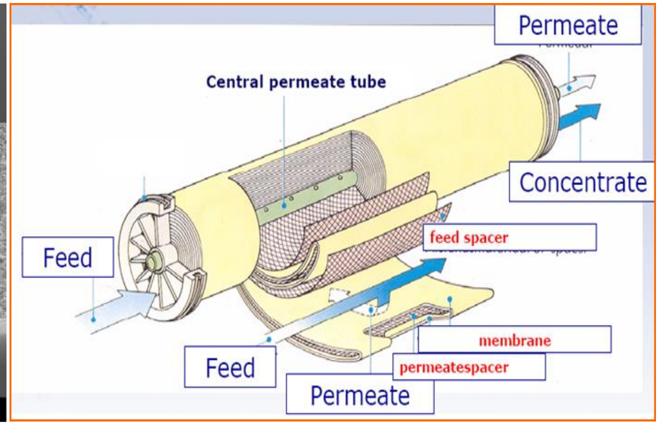




Draw: 0.59/1/2 M NaCl
Feed: 40/10/0.9 mM NaCl or DI water

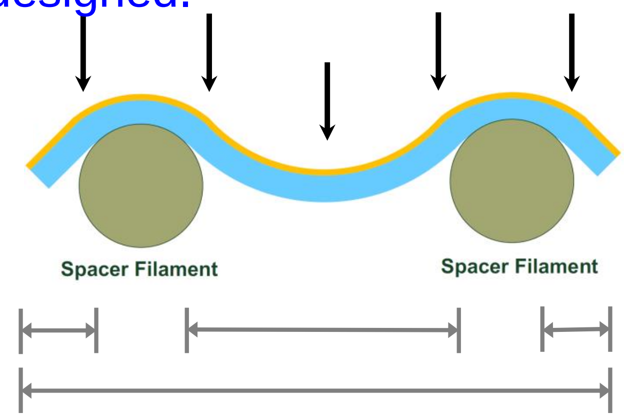
Desired Membrane Configuration for PRO





➢ Membrane spacer should be purposely re-designed.

- Membrane deformation against feed spacer and reduction in effective membrane area (shadow effect)
- Reduce in water flux and increase in hydraulic pressure loss



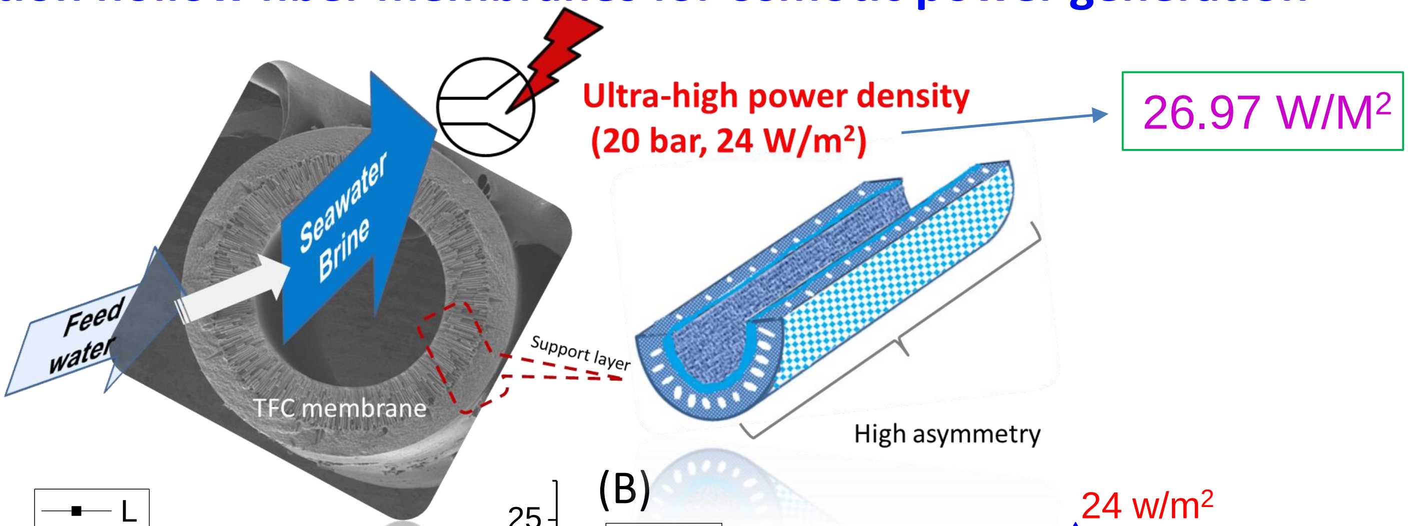
Feed spacer induced membrane deformation during PRO operation

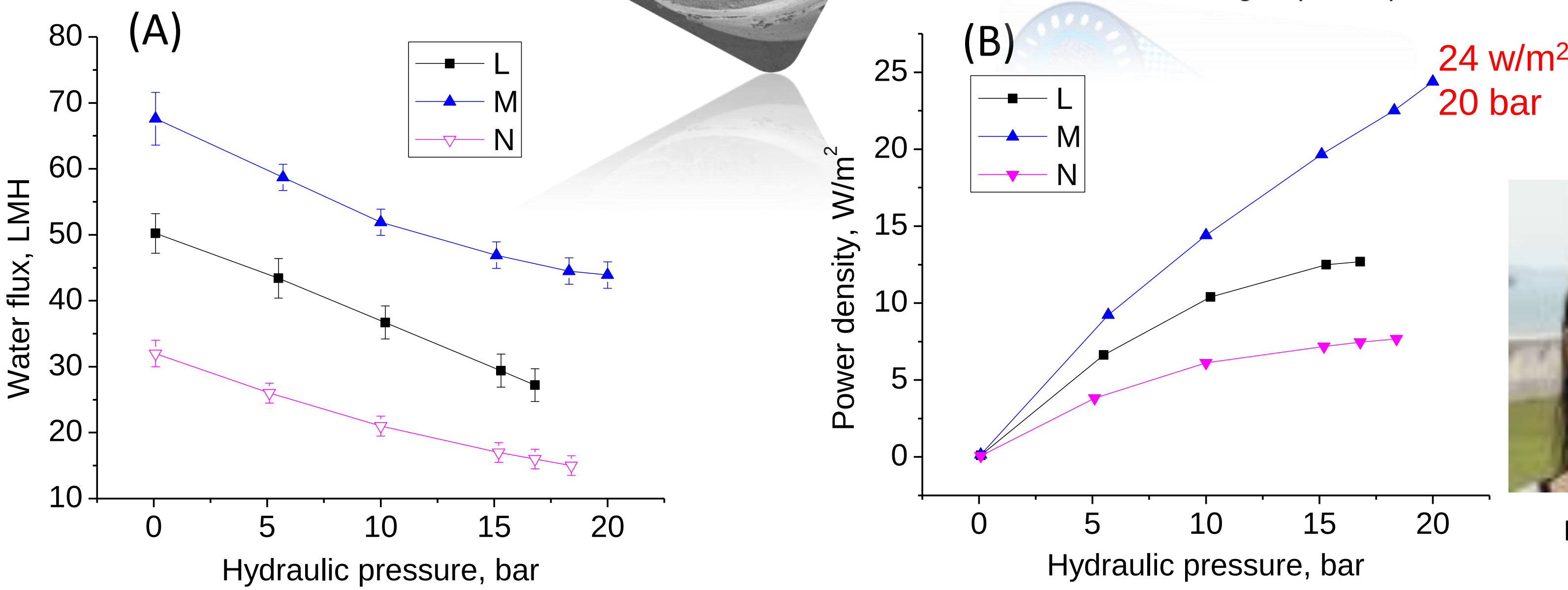
selective layer
support layer
effective membrane area

Q. She, D. Hou, J. Liu, K.H. Tan, C.Y. Tang, Effect of feed spacer induced membrane deformation on the performance of pressure retarded osmosis (PRO): implications for PRO process operation, *Journal of Membrane Science*, 445 (2013) 170-182

Y. C. Kim, et al. Environmental Science & Technology 2012.

New generation hollow fiber membranes for osmotic power generation





Dr. Zhang Sui

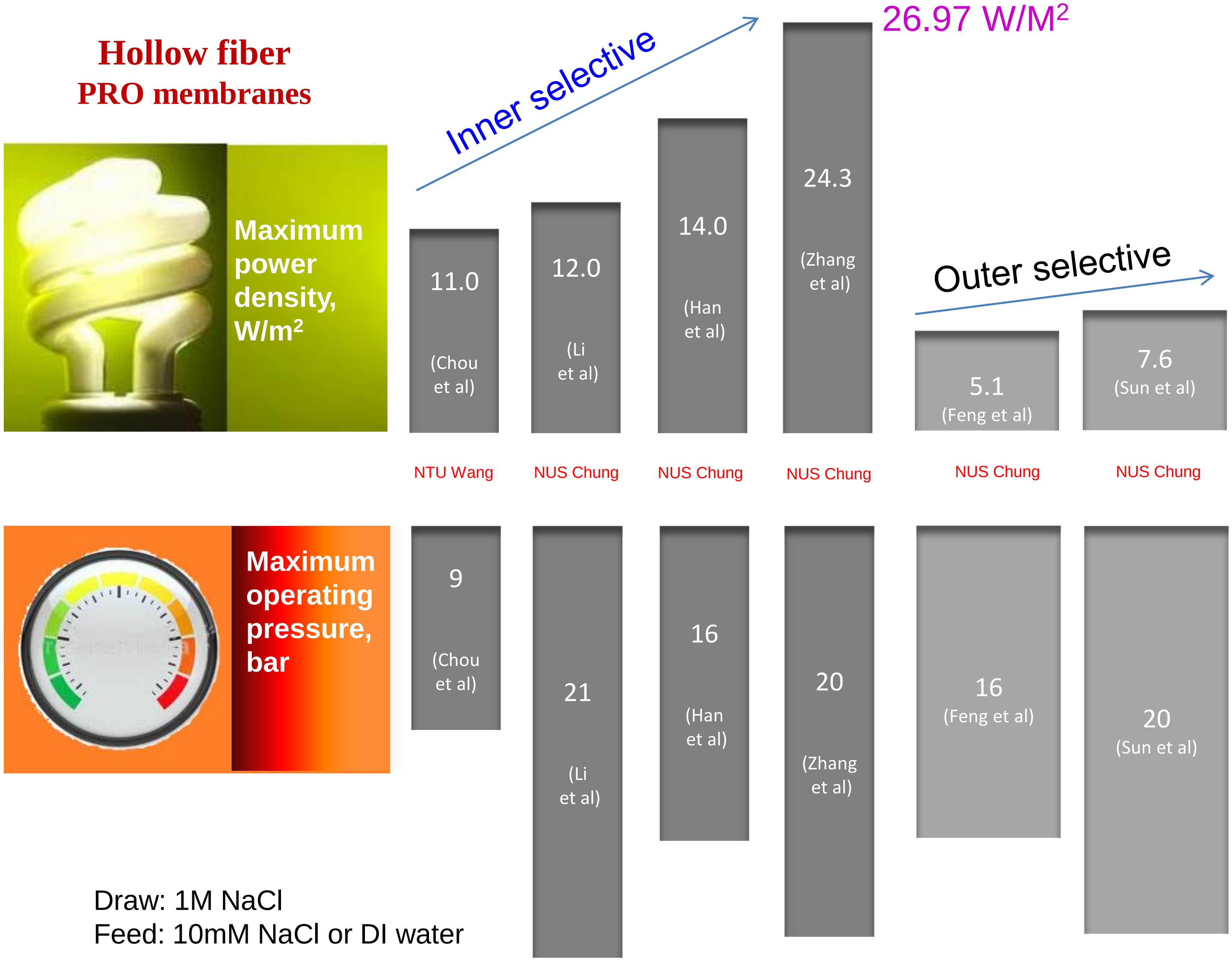
The (A) water flux, (B) power density of PES TFC hollow fiber membranes for osmotic power generation.

The draw solution is 1M NaCl, and feed solution is DI water.

The B value (salt permeability) of the TFC layer must be low

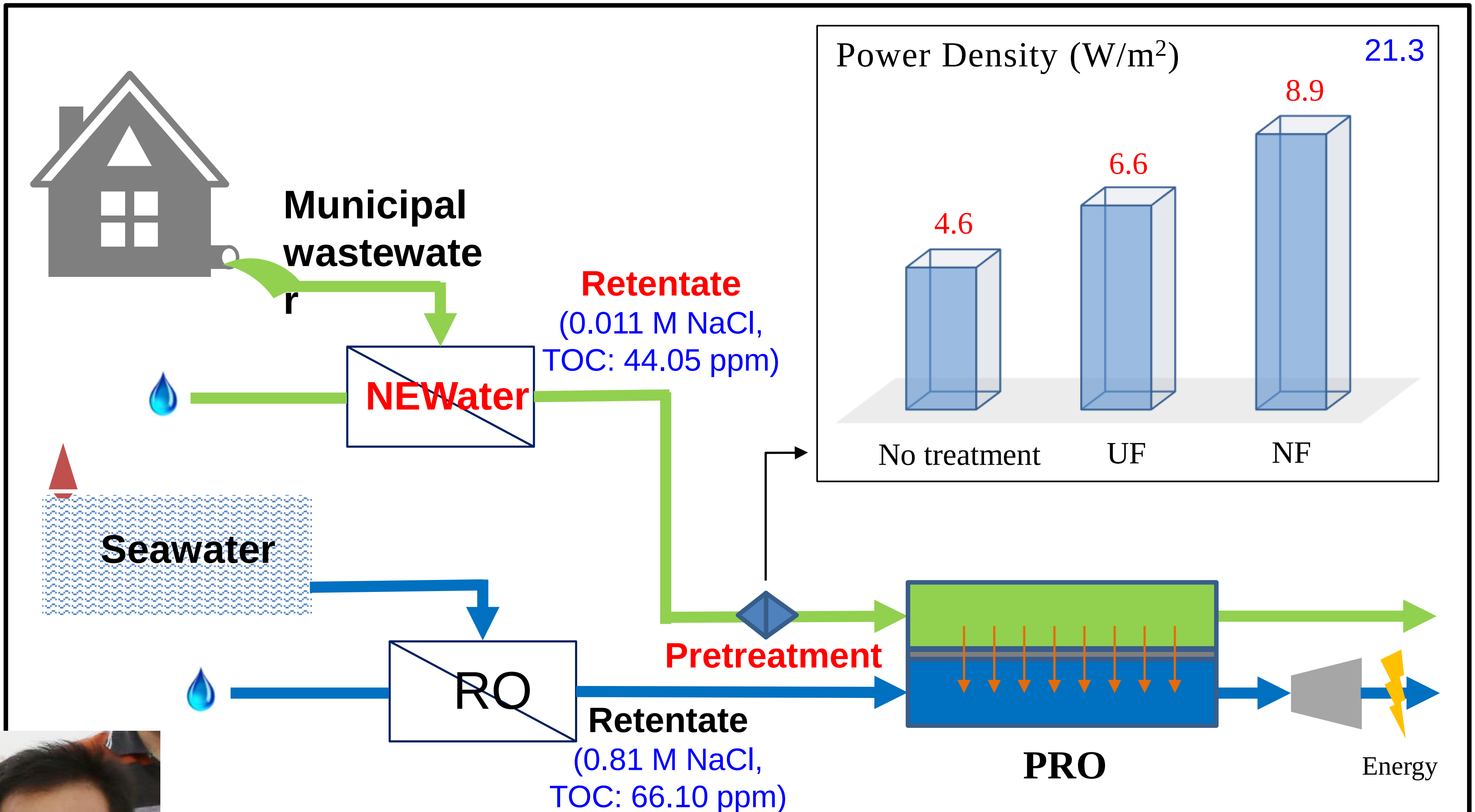
S. Zhang and T. S. Chung, Environmental Science & Technology, 47, 10085−10092 (2013).
C. F. Wan, and T. S. Chung, Osmotic power generation by pressure retarded osmosis using seawater brine as the draw solution and wastewater retentate as the feed, Submitted (2014)

Hollow fiber PRO membranes



Draw: 1M NaCl
Feed: 10mM NaCl or DI water

PRO tests with real feeds

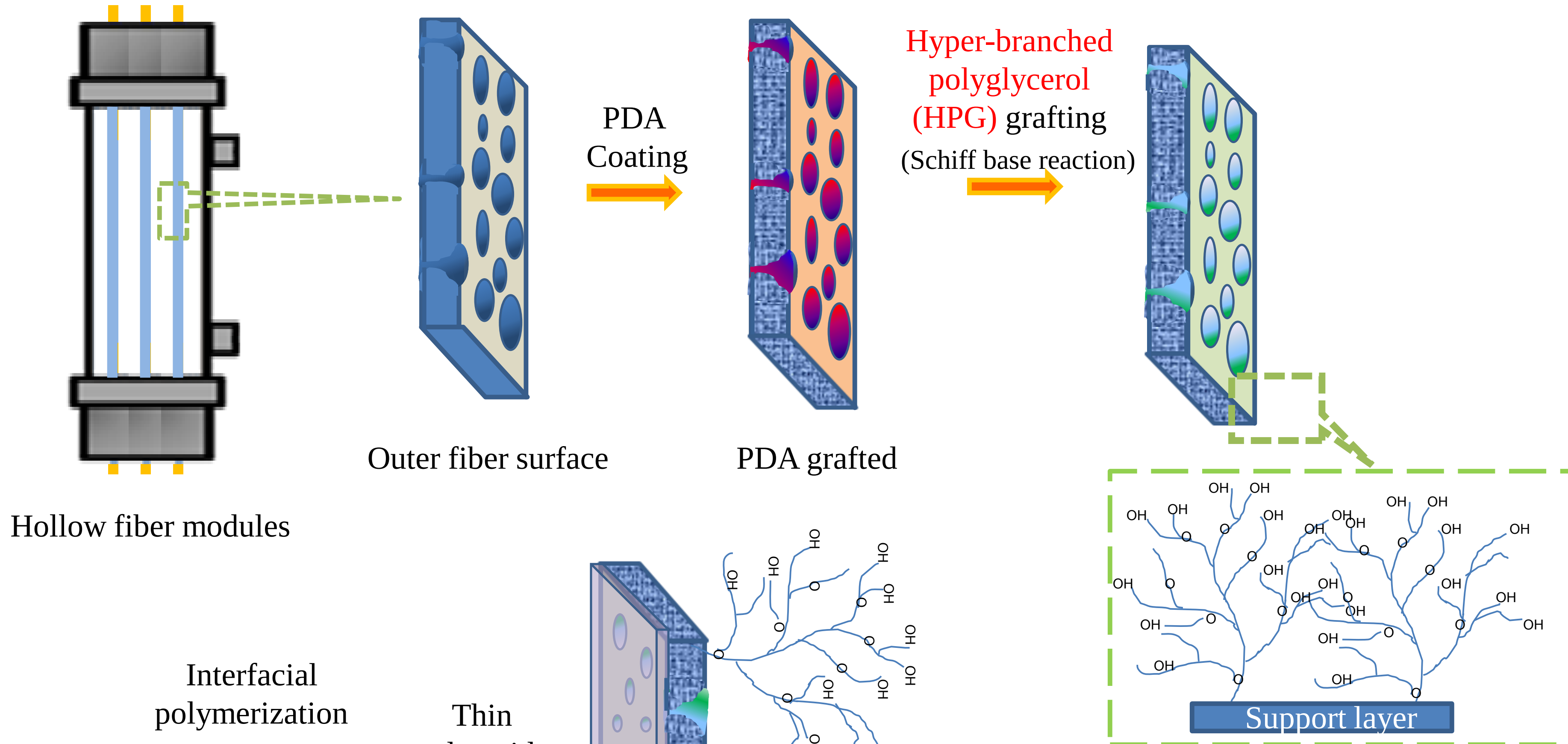


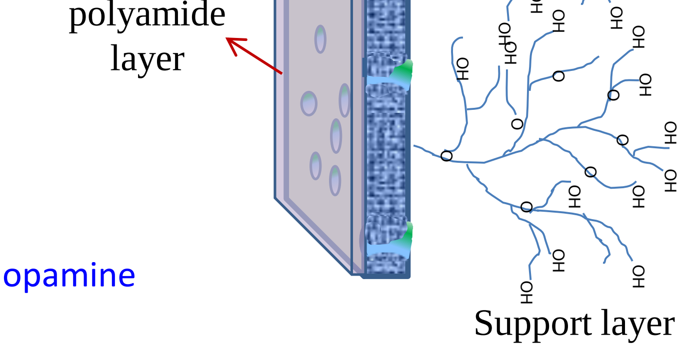
Mr. CF Wan

C. F. Wan, T. S. Chung, Osmotic power generation by pressure retarded osmosis using seawater brine as the draw solution and wastewater brine as the feed, *Journal of Membrane Science* 479 (2015) 148–158.

1st genrattion anti-fouling PRO hollow fiber membranes

Schematic procedure for the fabrication of HPG-*g*-TFC membranes.





Dr. Xue Li

PDA: polydopamine

X. Li, T. Cai, T. S. Chung, Anti-fouling behavior of hyper-branched polyglycerol grafted polyethersulfone hollow fiber membranes for osmotic power generation, *Environmental Science & Technology* 48, 9898–9907 (2014).

Acknowledgement

Prof Chung's Group Team Building Day, 22 Jan 2015

1. **As a Christian, I thank God for the provision of many good PhD students (12-15), good staff (8-10 Post-doctors, 12-15 Research Engineers, 3 Lab Officers), and plenty of research funds (> US$45 millions).**

2. **Thank British Gas (UK), UOP (USA), Merck (USA), Mitsui Chemicals (Japan), Hyflux (Singapore), BASF (Germany), KAUST (Saudi Arabia), PBI (USA), Eastman Chemicals (USA), GSK (UK), China Gansu, Kraton, Singapore's A-Star, NRF, EWI, PUB, and NUS for funding my membrane research during the last 19 years.**

Welcome you to visit Singapore

collaboration
career opportunities

Prof. (Neal) Tai-Shung Chung

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