Membrane Processes to Address the Global Challenge of Desalination

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Outline

- Salinity
  - The Global Challenge
  - Conventional Processes: Reverse Osmosis and Distillation
  - Novel Processes: Forward Osmosis and Membrane Distillation
  - Water Reuse
- Direct Potable Reuse
  - Mind Over Matter?
  - NASA Test System for Long-Term Space Missions
- Sustainability: Water and Energy
  - Brine Concentration to Achieve Zero Liquid Discharge
  - Membrane Distillation driven by Renewable Energy
- Concluding Remarks

Salinity

- What is it?
  - Presence of soluble salts in soils and waters
  - Sodium, calcium, magnesium, chloride, carbonate, bicarbonate, sulfate, silica
- What are typical concentrations?
  - Drinking Water: <500 mg/L total dissolved solids
  - Fresh water: <1,500 mg/L
  - Brackish water: 1,500-20,000 mg/L
  - Seawater: 35,000-41,000 mg/L
  - Brine or concentrate: >40,000 mg/L
- Why is it an issue?
  - Salts do not degrade naturally over time; accumulate until removed
  - Increasing salinity is exacerbated by human activities
  - Rising salinity levels have environmental and economic costs

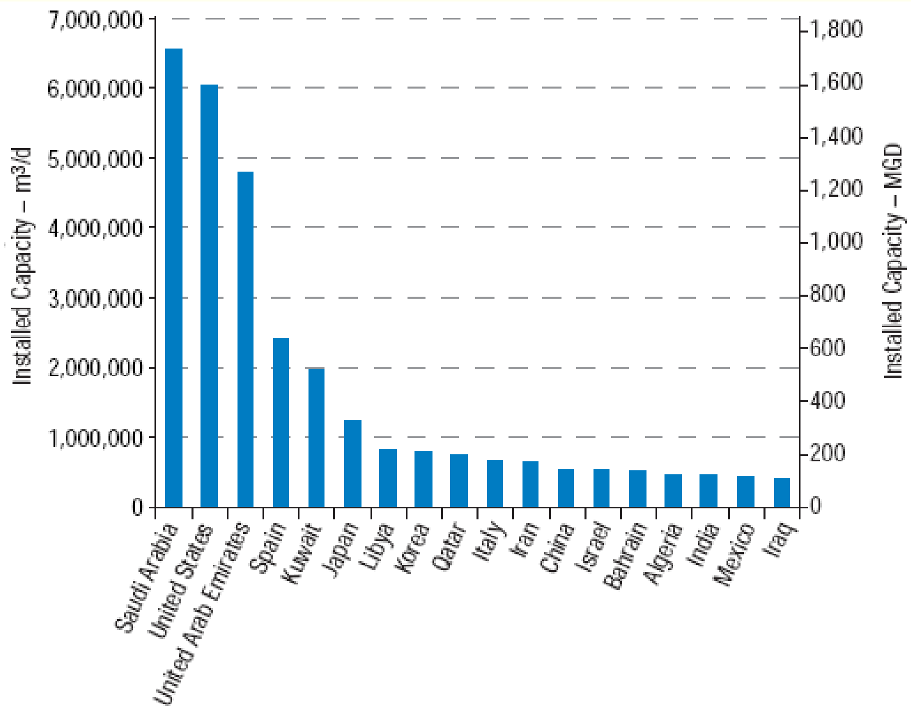
Why are Engineers Concerned with Salinity?

- Engineered Systems
  - for drinking water treatment
  - to achieve total maximum daily loads for wastewater discharges
- Natural Systems
  - Increased salinity in terminal lakes

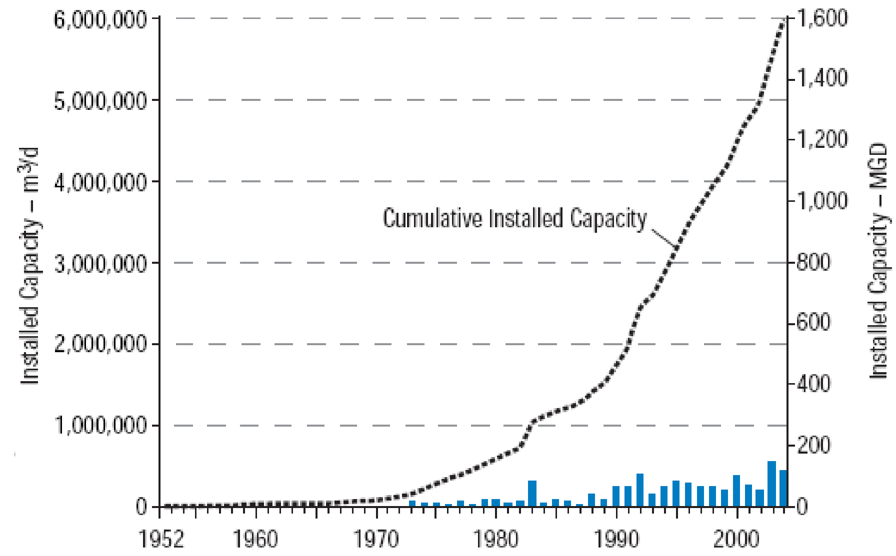
Mono Lake, CA

Desalination Today

Countries with more than 1%
of global desalination capacity

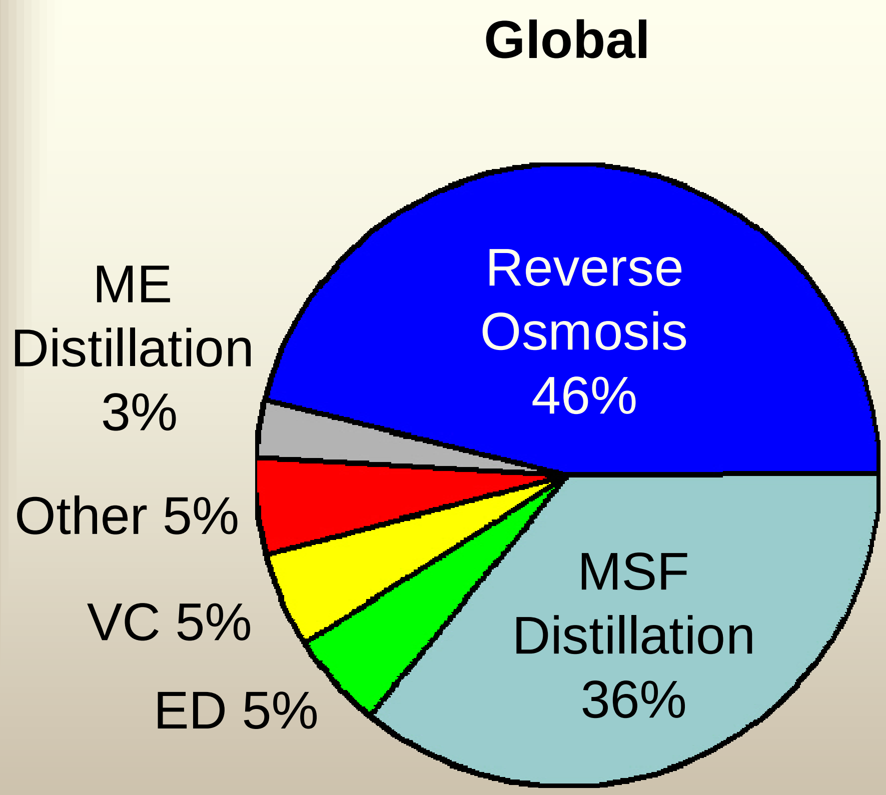


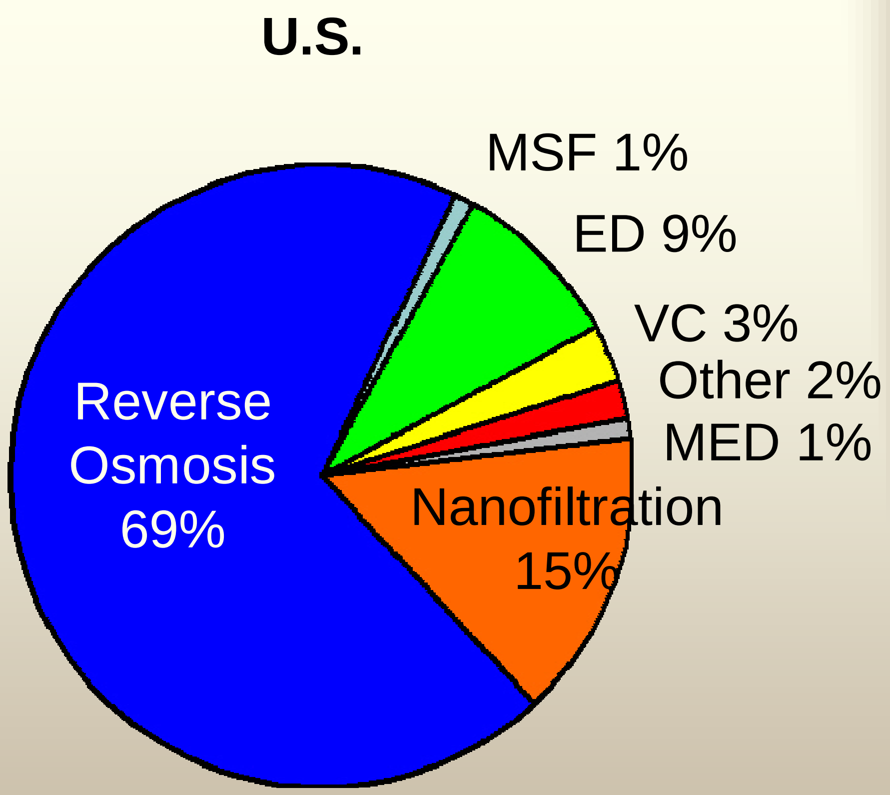
U.S. desalination capacity



Source: Wagnick/GWI 2005

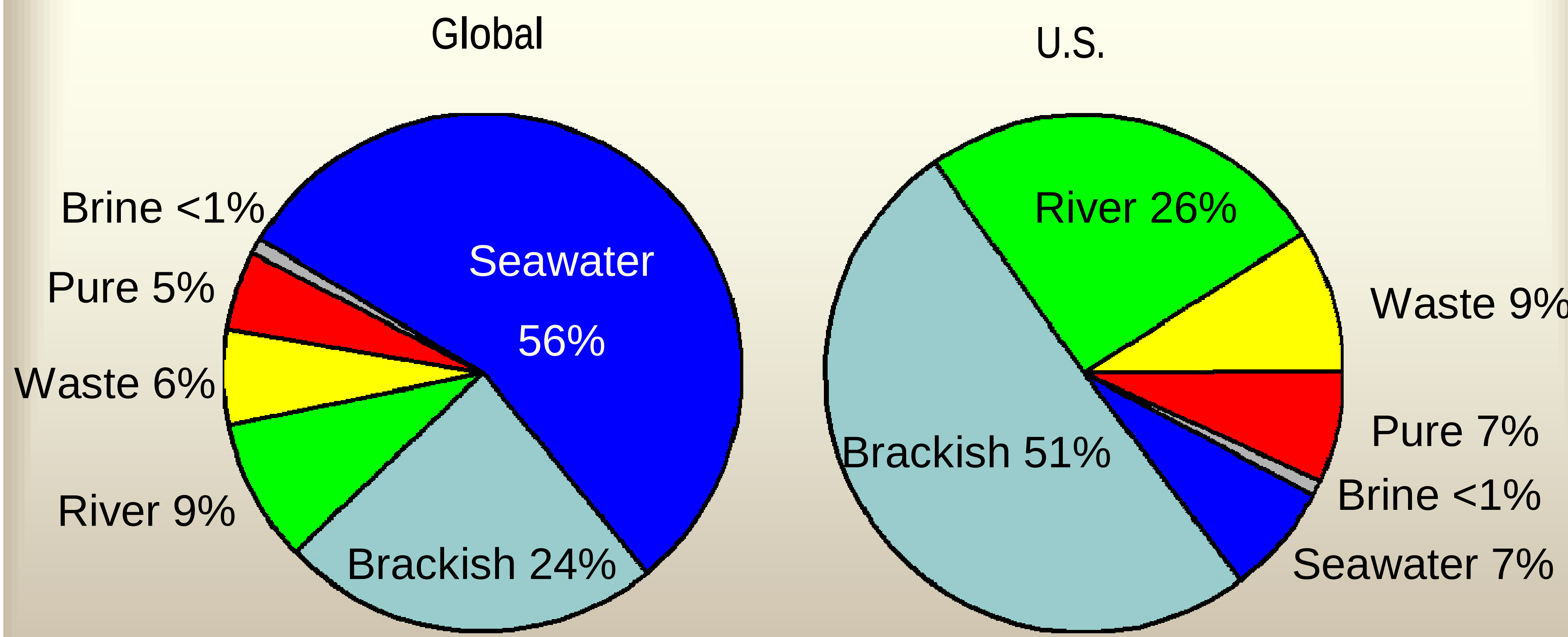
Desalination Capacity by Processes





Source: Wagnick/GWI 2005

Desalination Capacity by Source



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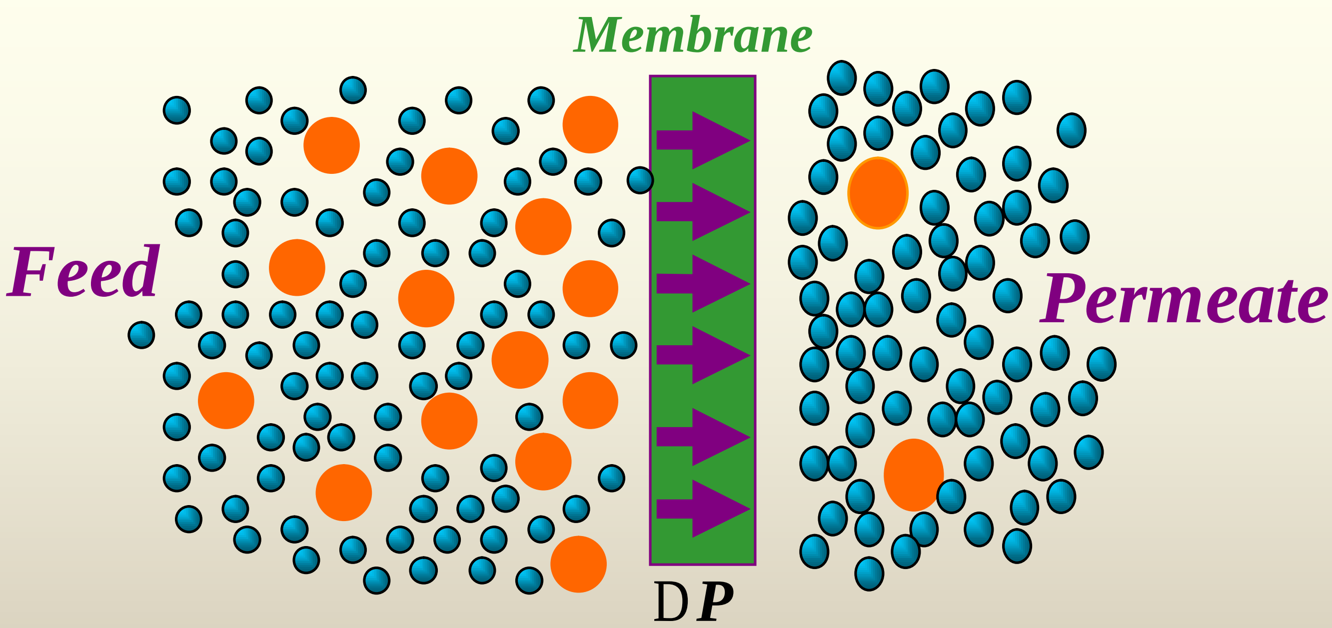
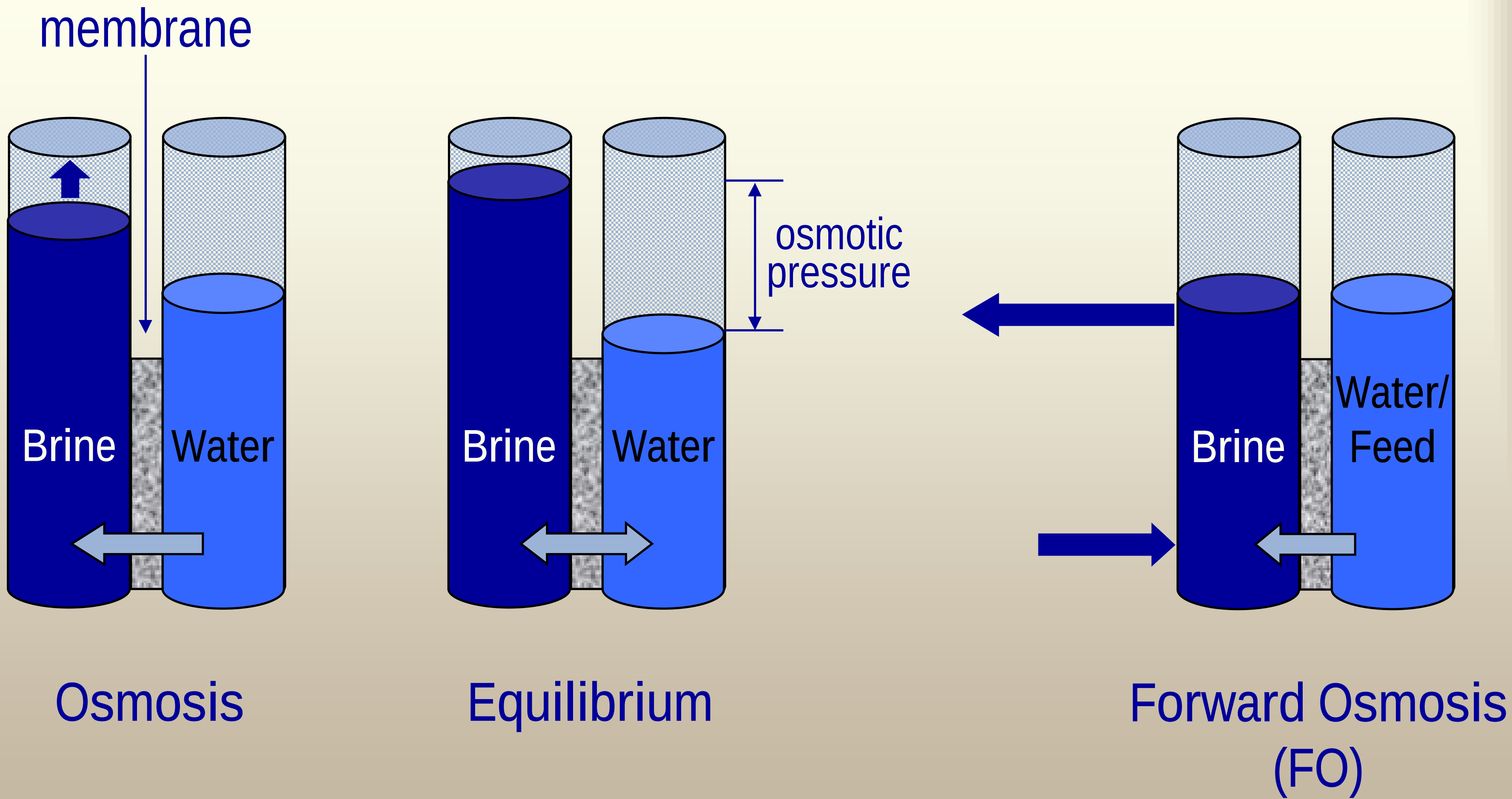
Reverse Osmosis Separation



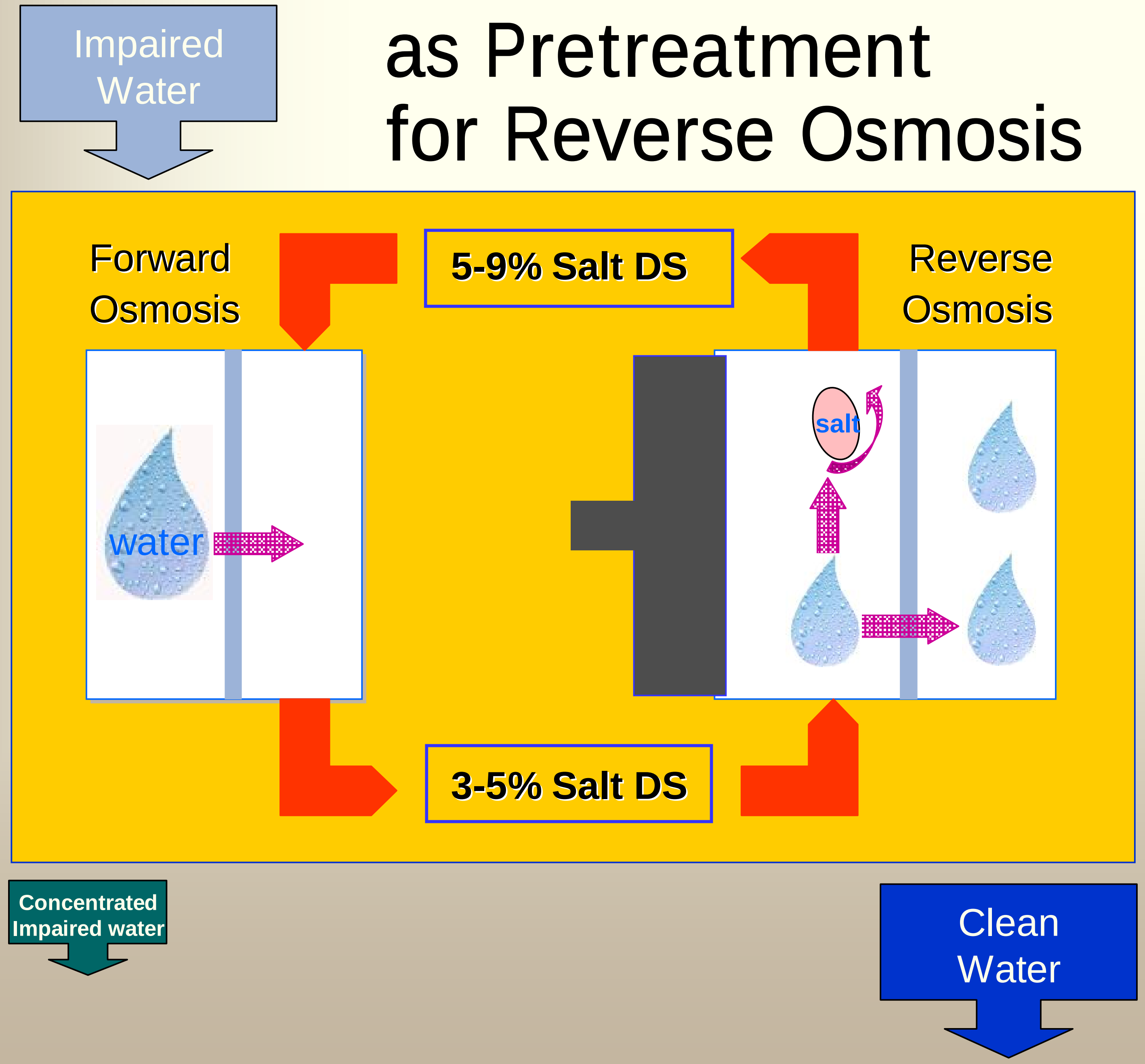
- Produces water with <500 mg/L salts
- Less energy intensive than distillation (~10x less)
- But… complicated by membrane fouling issues
- Possible solution: forward osmosis as pretreatment for reverse osmosis

Osmosis and Forward Osmosis



Brine ≡ Draw Solution (DS)

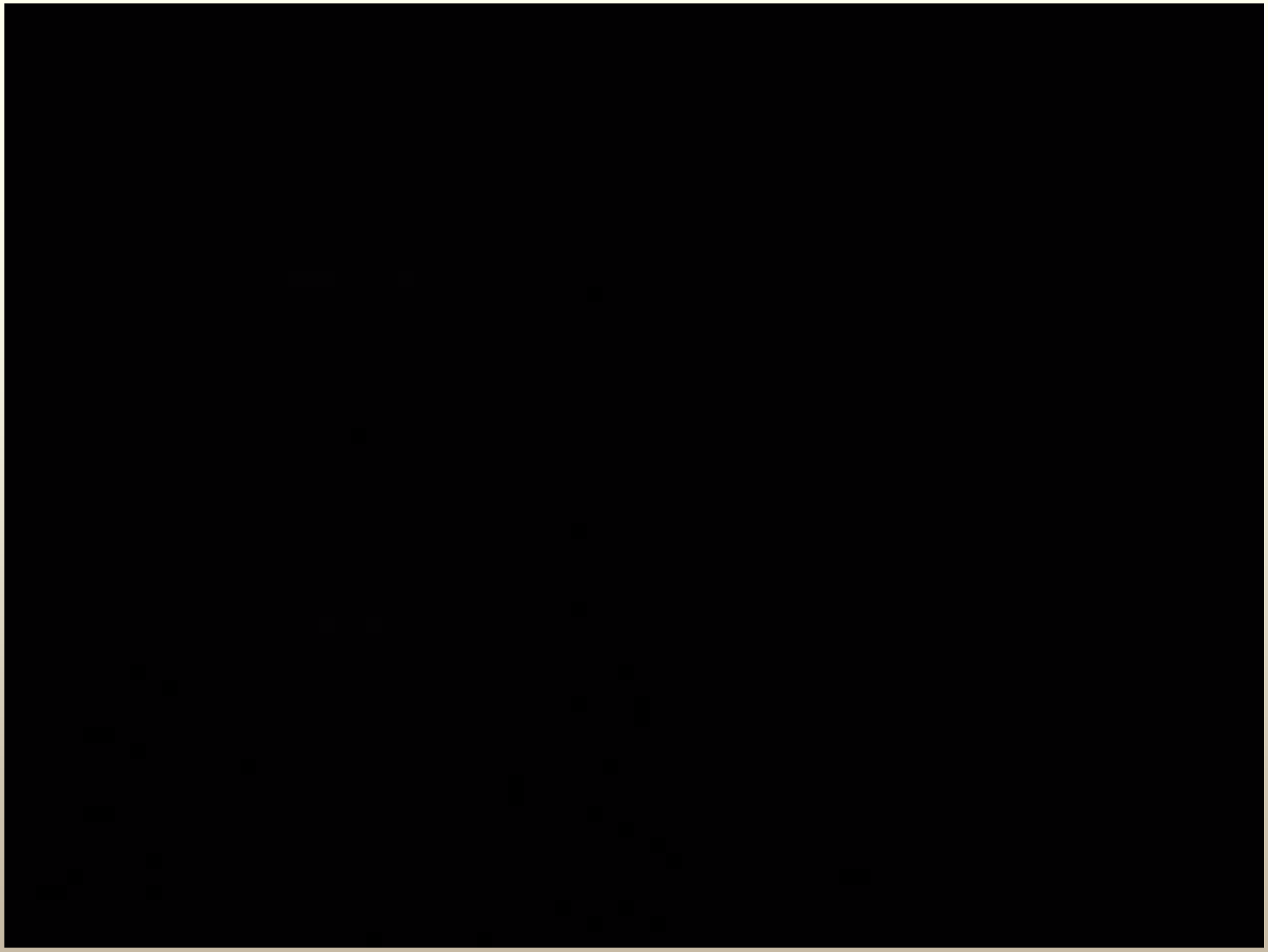
Forward Osmosis as Pretreatment for Reverse Osmosis



Water Reuse

- Indirect nonpotable – aquifer recharge for subsequent nonpotable use
- Direct nonpotable – water reclaimed for watering golf courses, public parks,…
- Indirect potable – aquifer recharge for subsequent potable use (e.g., OCWD) or when a drinking water intake lies downstream of another municipality's wastewater facility (e.g., Las Vegas wash)
- Direct potable reuse…

Waterworld “Test Unit”



NASA Test Unit

Water and Wastewater in Space

- Fresh water supply:
  - Short missions – full supply taken from earth
  - International Space Station (ISS) – periodic resupply
  - Long-range, long-duration – MUST RECYCLE AND REUSE
- Without careful recycling, 40,000 pounds of water from Earth would be required to resupply a minimum of four crewmembers per year

Space Water Recycling System

- needs to reclaim wastewater from several sources:
  - Hygiene (~25 l/person/day)
  - Humidity condensed from the air (~1.8 l/person/day)
  - Urine (~2 l/person/day)
- needs to:
  - be reliable, durable, redundant, capable of high recoveries, economical, and lightweight
  - operate autonomically with low maintenance
  - have minimal consumables

Membrane Processes and specifically, the reverse osmosis process

- Advantages:
  - High rejection, durability, small footprint, simple operation, minimal resupply of consumables
- Disadvantages:
  - Susceptible to fouling by dissolved and particulate materials such as surfactants
  - Allows the passage of small molecules such as urea and endocrine disrupting compounds
- Must be used in combination with other processes

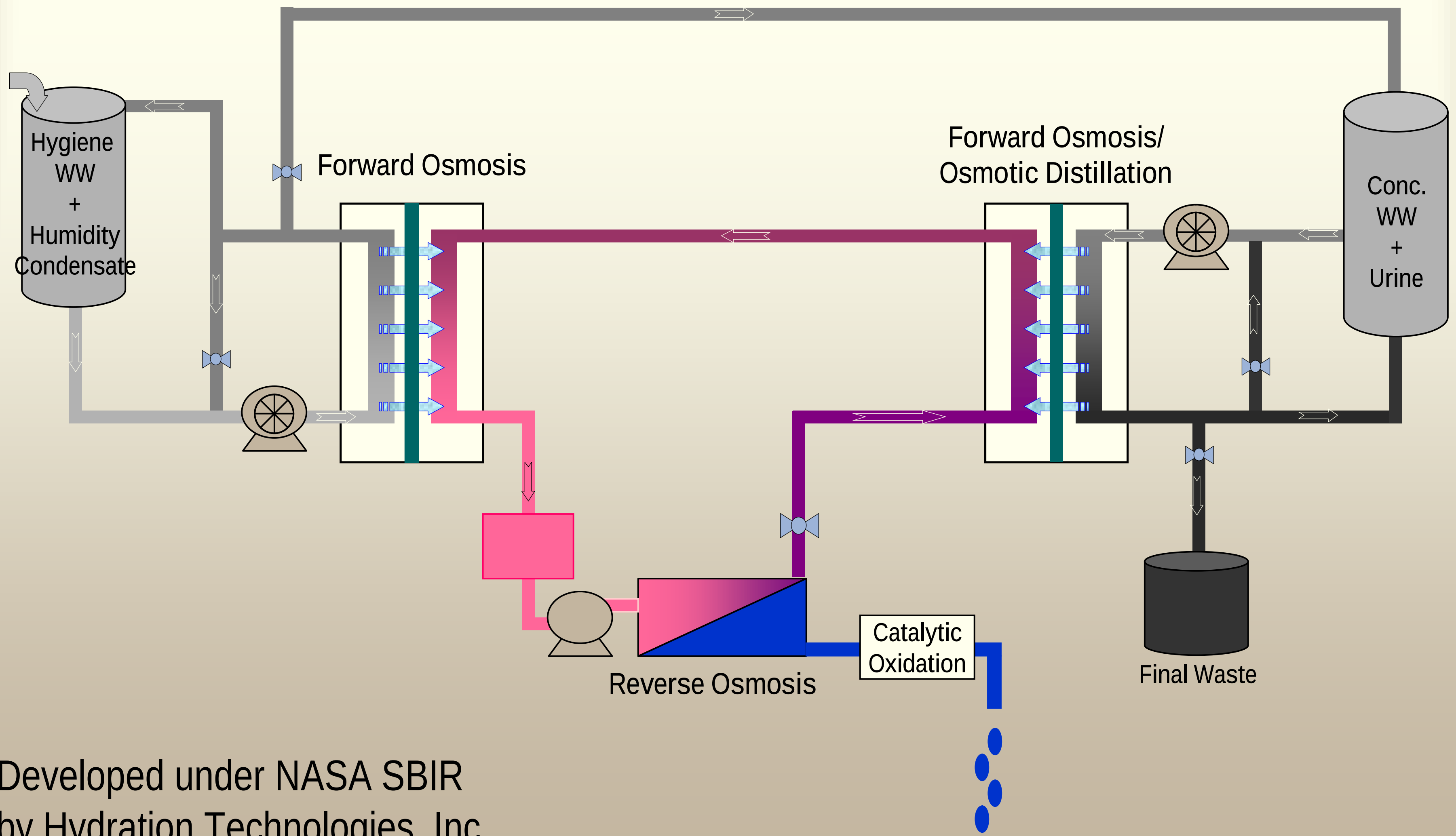
Original Direct Osmotic Concentration Concept

Original NASA DOC System

Comparison of System Performance

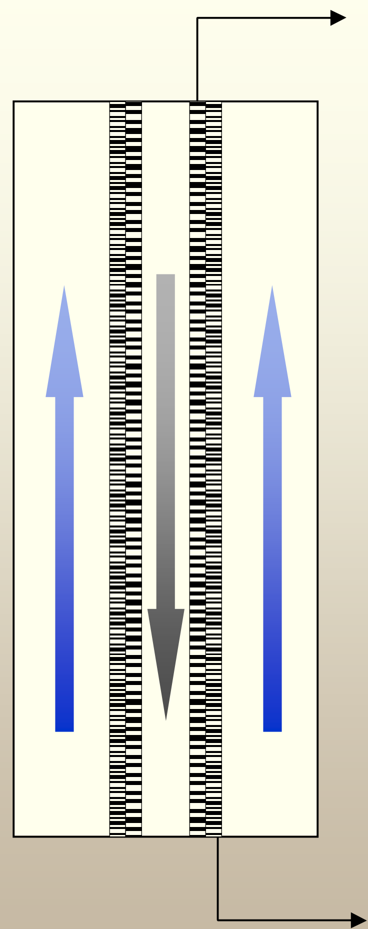
	ISS Water Recycling System	Bio-Reactor	VPCAR	Direct Osmotic Concentration System
Re-supply	413 kg/year	119 kg/year	0 kg/year	?
# of Independent Processors	4	6	2	3
Feed Streams	2	1	1	2
Weight	193 kg	396 kg	68 kg	163 kg
Volume	1.1 m^3	1.9 m^3	0.39 m^3	0.78 m^3
Total subsystem power	61.5 Whr/kg	1108 Whr/kg	311.7 Whr/kg	?
Recovery Rate	99%	85-100%	97%	?
Scheduled Maintenance	every 50 days	Unknown	0	?

Schematic of Original DOC Test Unit

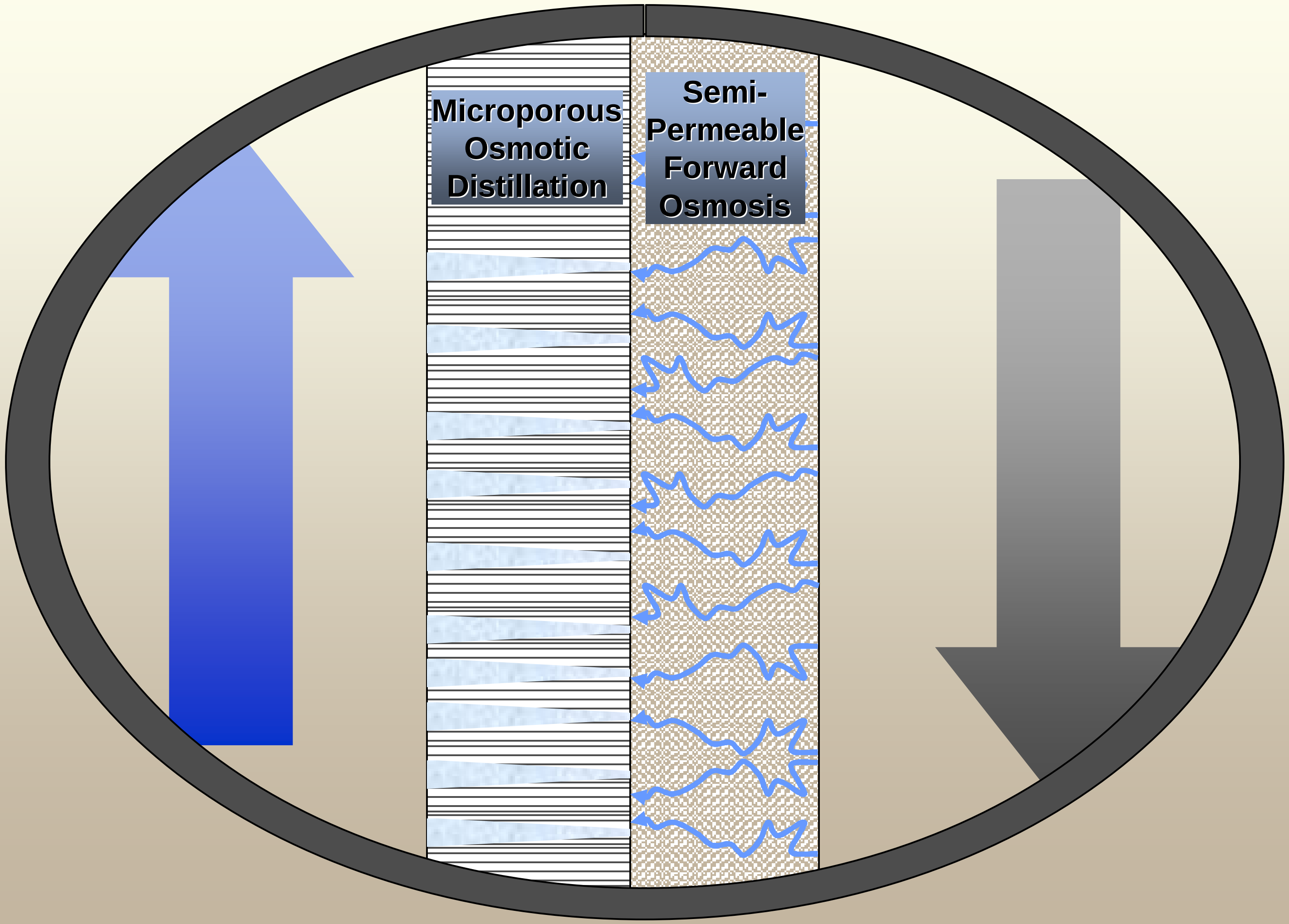


Developed under NASA SBIR
by Hydration Technologies, Inc.

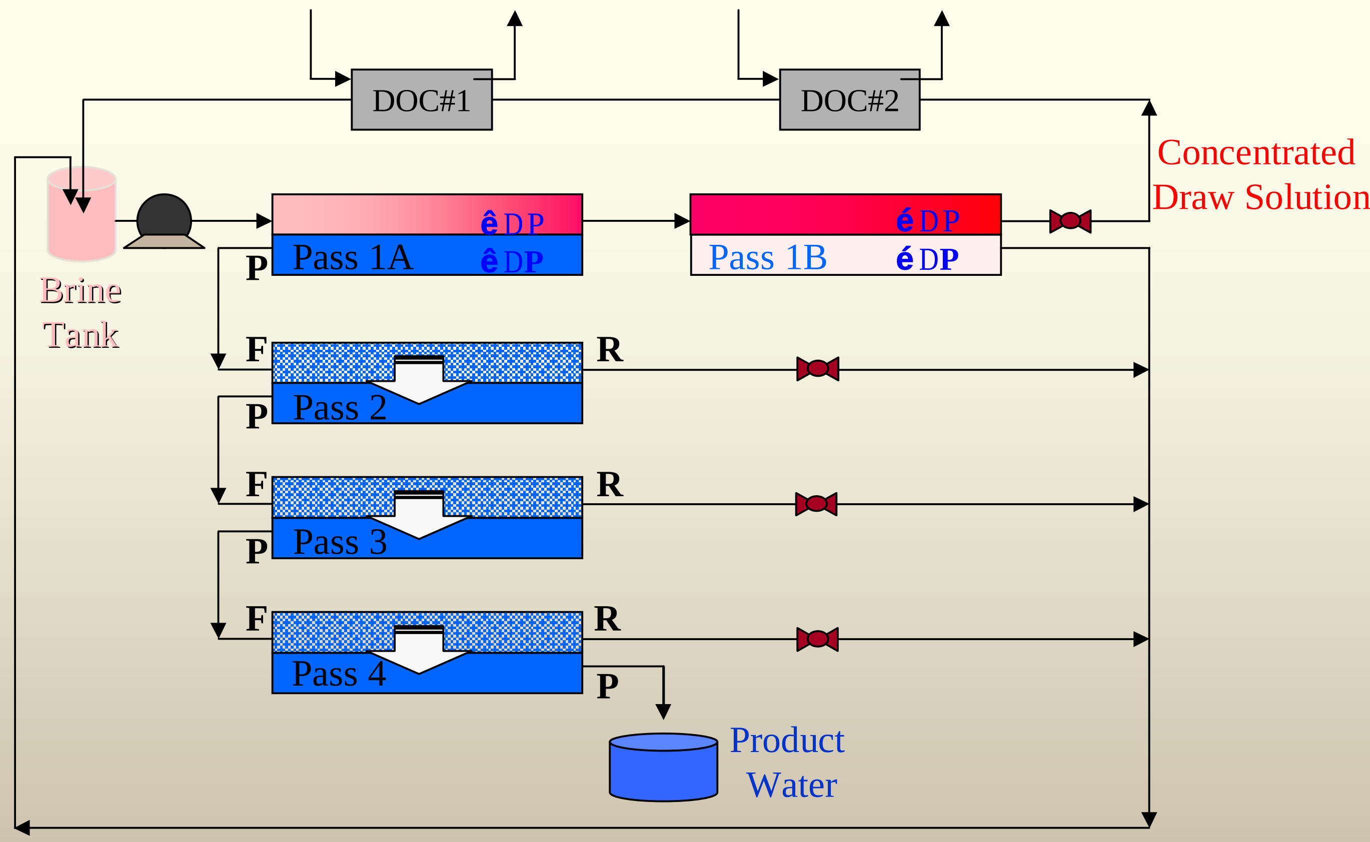
Forward Osmosis/Osmotic Distillation Dual-Membrane Contactor



Dual-Membrane Contactor



The RO Subsystem



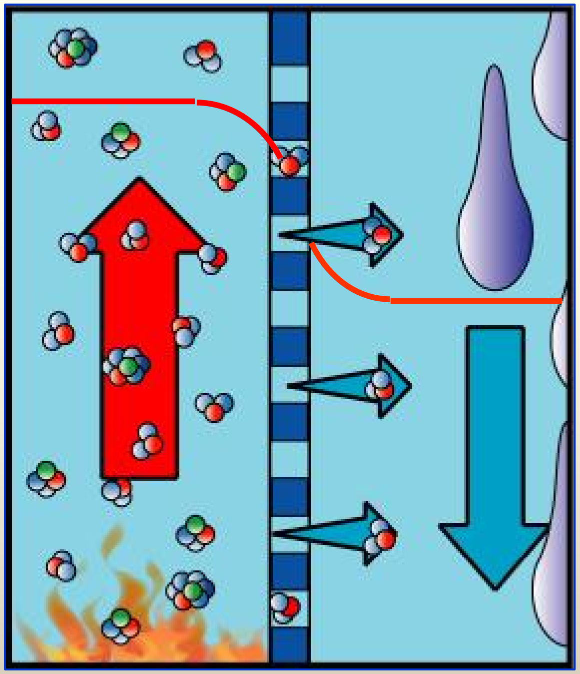
Comparison of System Performance

	ISS Water Recycling System	Bio-Reactor	VPCAR	Direct Osmotic Concentration System
Re-supply	413 kg/year	119 kg/year	0 kg/year	~20 kg/year
# of Independent Processors	4	6	2	3
Feed Streams	2	1	1	2
Weight	193 kg	396 kg	68 kg	163 kg
Volume	1.1 m^3	1.9 m^3	0.39 m^3	0.78 m^3
Total subsystem power	61.5 Whr/kg	1108 Whr/kg	311.7 Whr/kg	20-30 Wh/kg
Recovery Rate	99%	85-100%	97%	> 92%
Scheduled Maintenance	every 50 days	Unknown	0	Unknown

Major Issue: Low Mass Transport in Dual Membrane Contactor

- Low mass transport in forward osmosis/osmotic distillation subsystem
  - Low flux and recovery (was designed to recover approximately 10% of the wastewater; practically recover less than 2%)
  - Flooding of osmotic distillation membrane resulting in passage of urea
- Potential solution: replace dual forward osmosis/osmotic distillation process with membrane distillation

Membrane Distillation Flux



vapors diffuse through pores and directly condense into cold stream

$$J = A \cdot (P^*_{wf} - P^*_{wp})$$

Membrane Distillation

- Compared to distillation, requires only small temperature differences

  → Can use low-grade energy/waste heat sources

- Compared to reverse osmosis, does not allow the passage of small non-volatile molecules

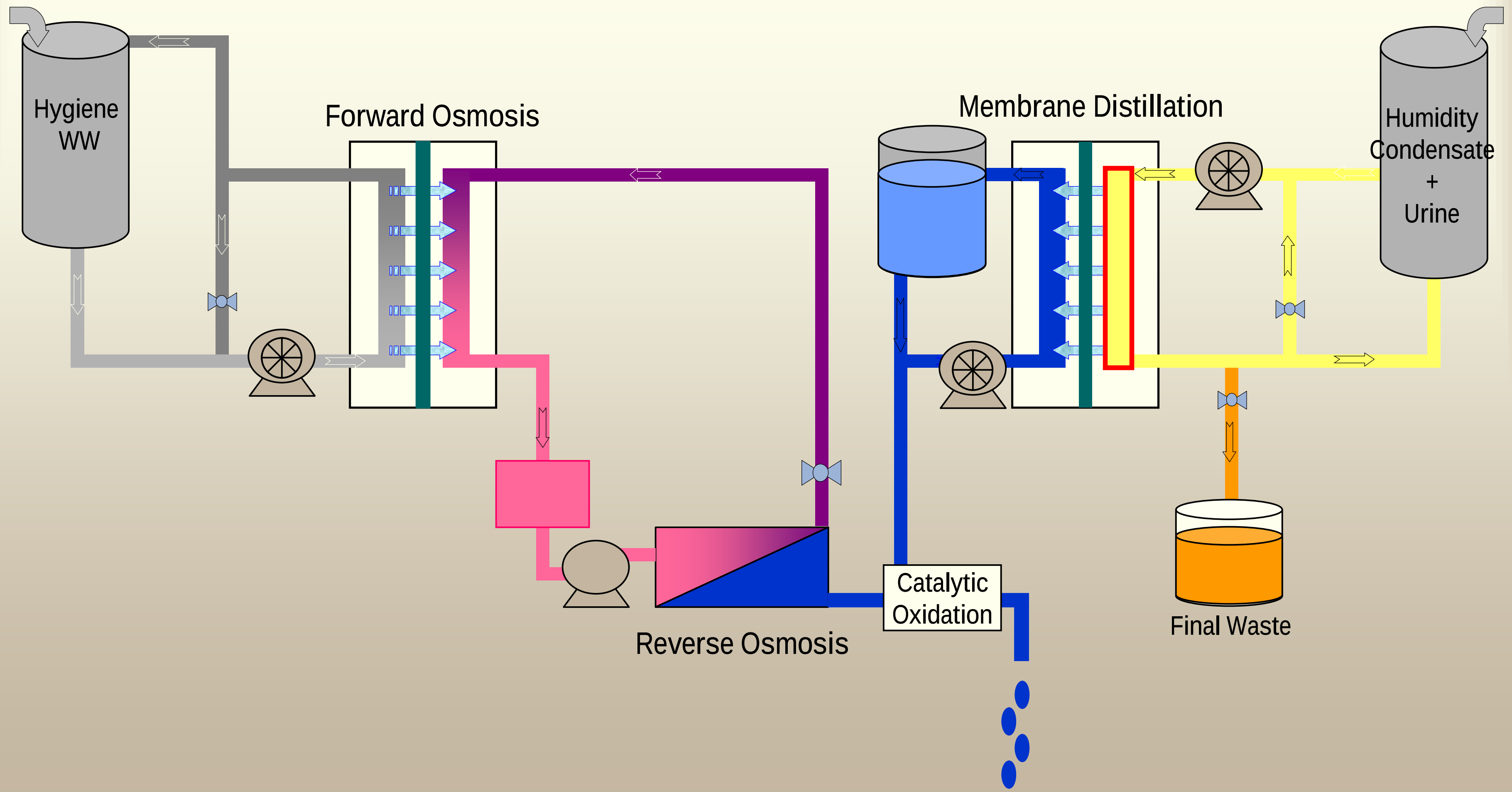
  → Can provide removal of urea and endocrine-disrupting chemicals

- Compared to osmotic distillation, has much higher driving force for mass transfer

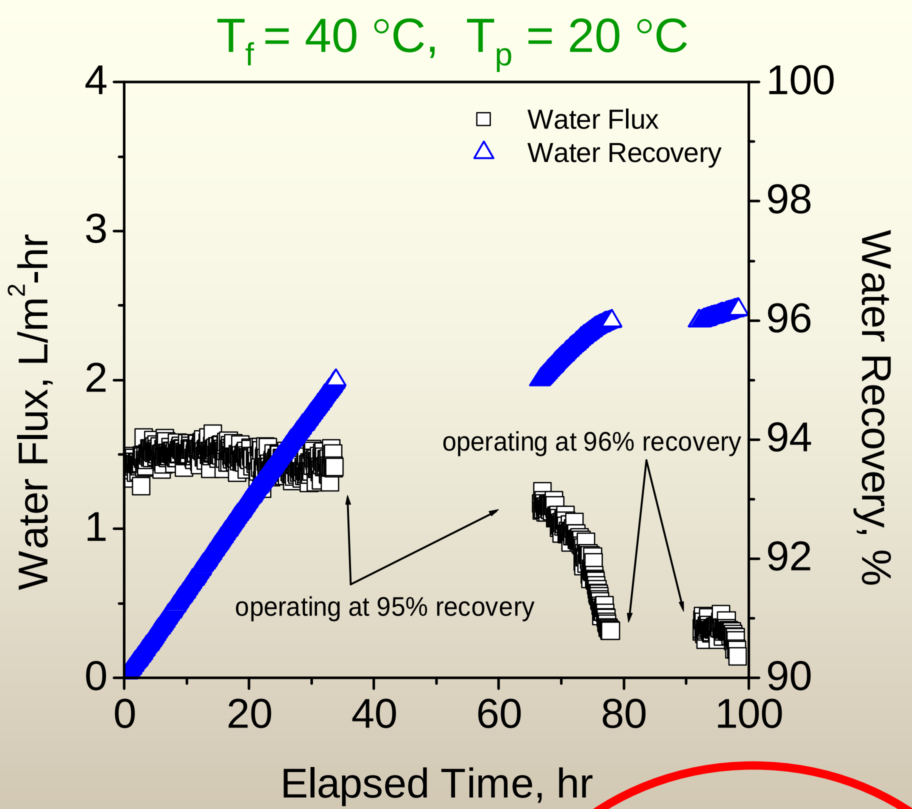
  → Will produce higher fluxes

Improved DOC Concept

FO/MD Potable Reuse Test Unit



Membrane Distillation for Urea Removal

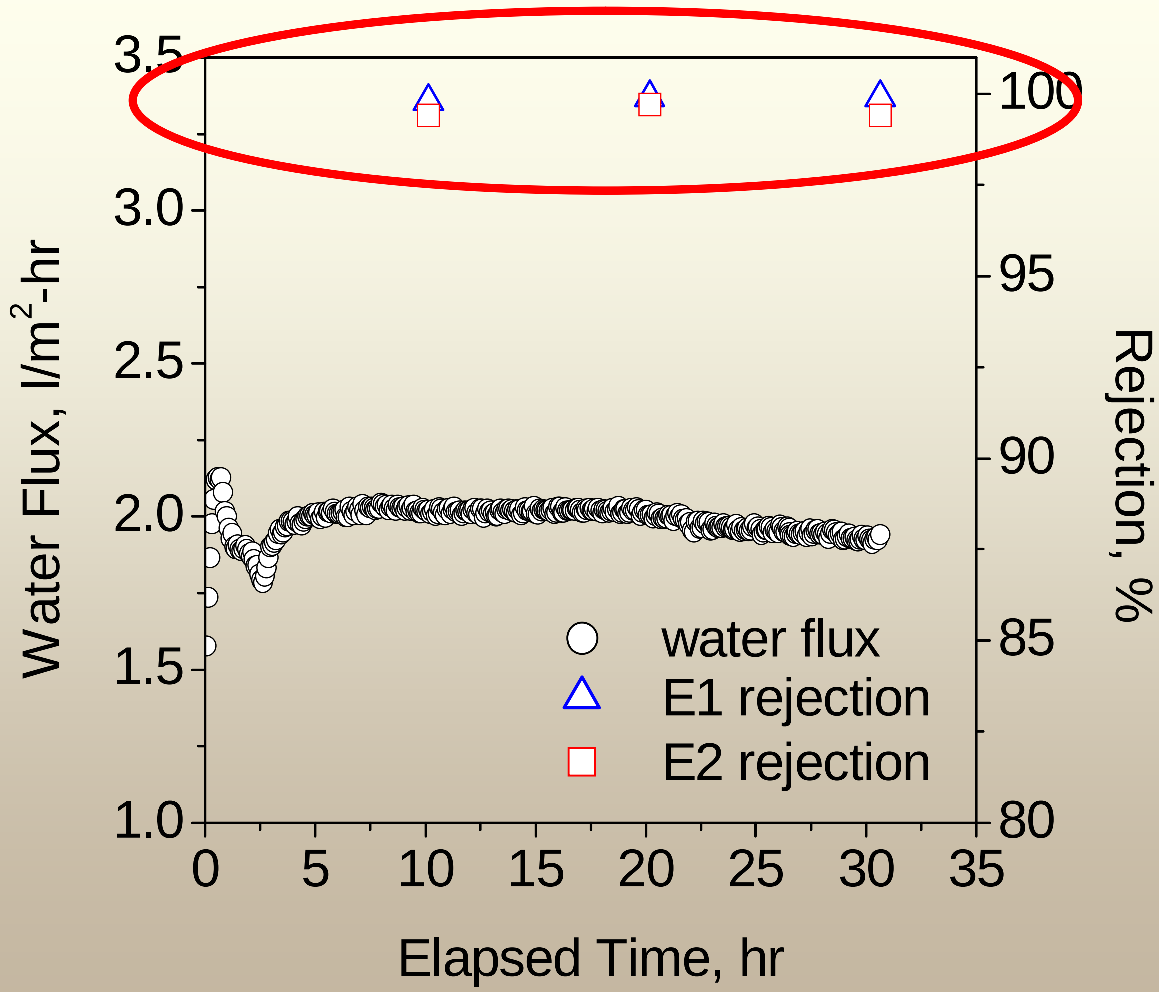


Sample	Water Recovery %	Rejection, %	
		Urea	Ammonia
1	50	>99.9	>99.9
2	90	>99.9	>99.9
3	95	>99.9	>99.9

Endocrine Disrupting Chemicals

- The effect in fish has been proven; but is the effect transferable to humans?
- During long-term space missions, crew members will consume water that is continuously recycled; contaminants may be concentrated
- Trace contaminants, and particularly endocrine-disrupting chemicals (EDCs), must be removed

Endocrine Disrupting Chemical Rejection by Membrane Distillation



Where is the Technology Now?

- In terms of NASA
  - undergoing long-term testing at NASA ARC
  - going into “competition” in 2008 (against 3 distillation processes)

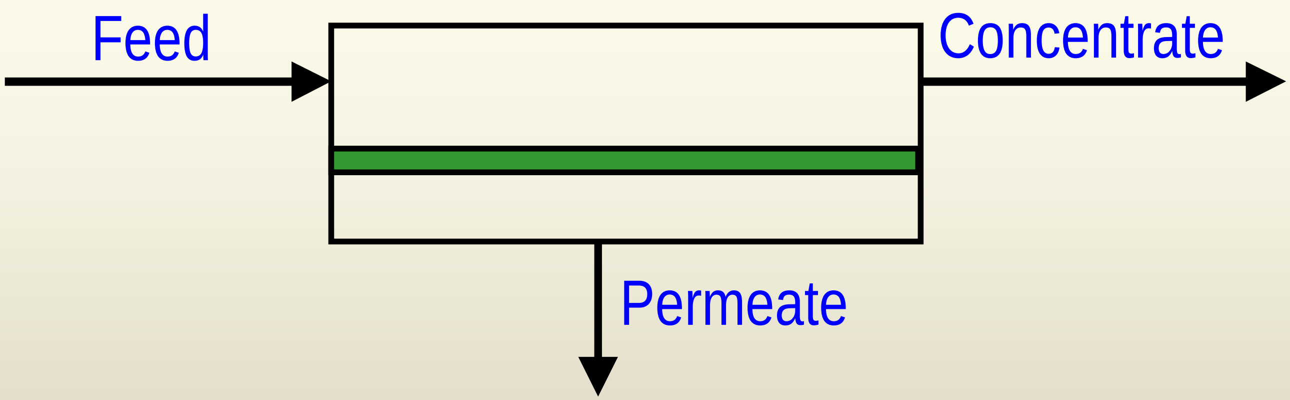
- In terms of terrestrial applications
  - MD for seawater desalination
  - FO as pretreatment for desalination
  - MD and FO for brine concentration
  - FO for centrate treatment
  - MD for solar pond energy recovery

Water and Energy: Inextricably Bound

- Brine Concentration to Achieve Zero Liquid Discharge
- Membrane Distillation Driven by Renewable Energy

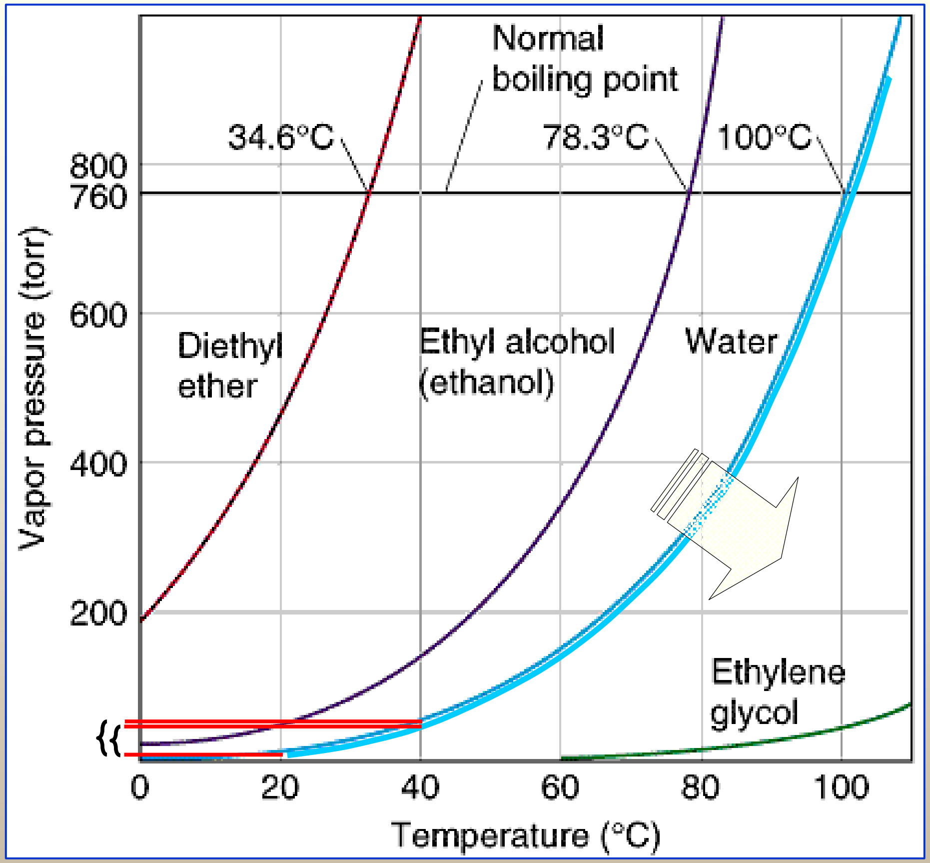
Zero Liquid Discharge

Cross Flow Operation



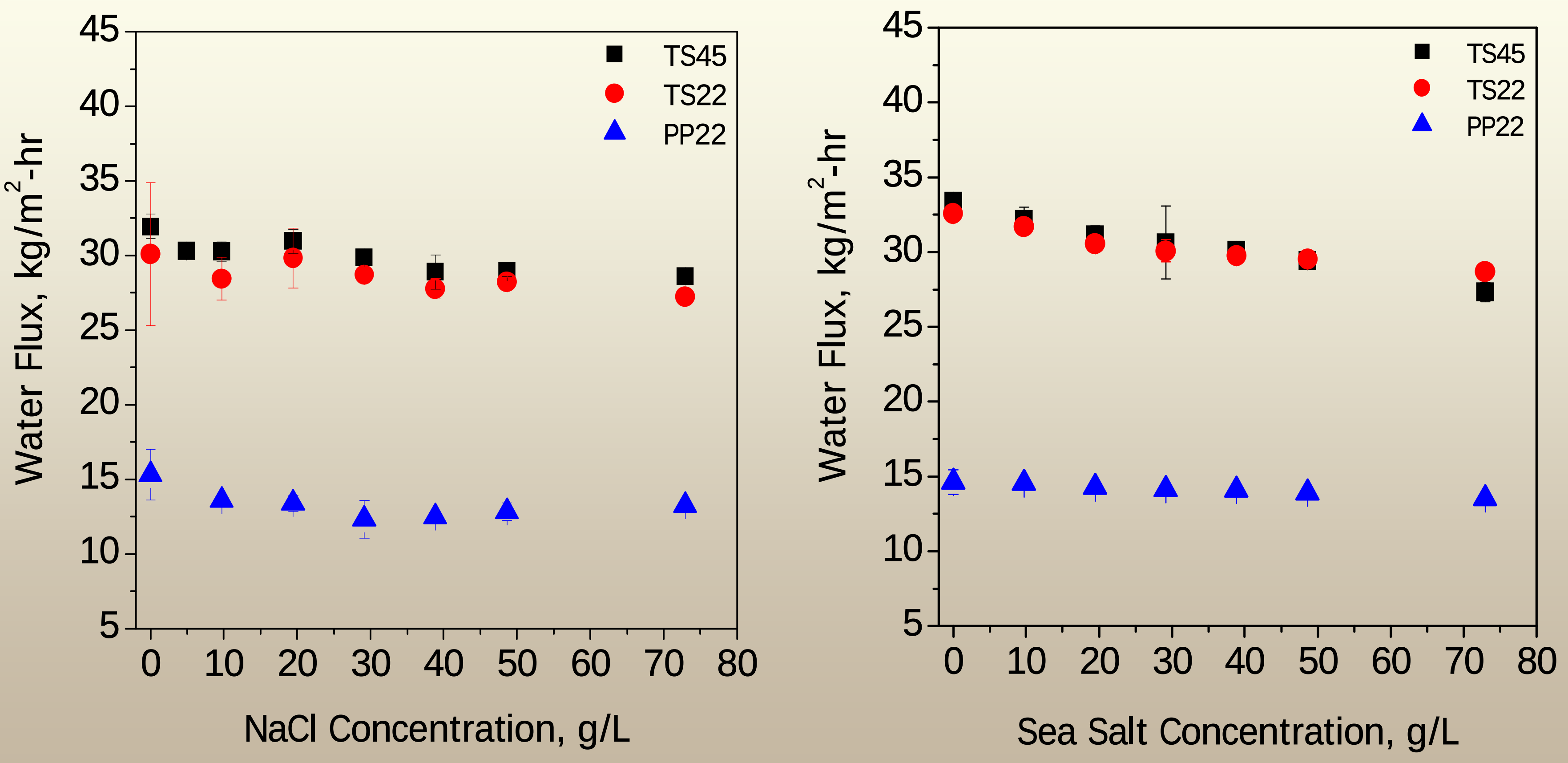
- To achieve zero liquid discharge, the reverse osmosis concentrate stream needs to be further treated
- This can become energy intensive

Driving Force in Membrane Distillation

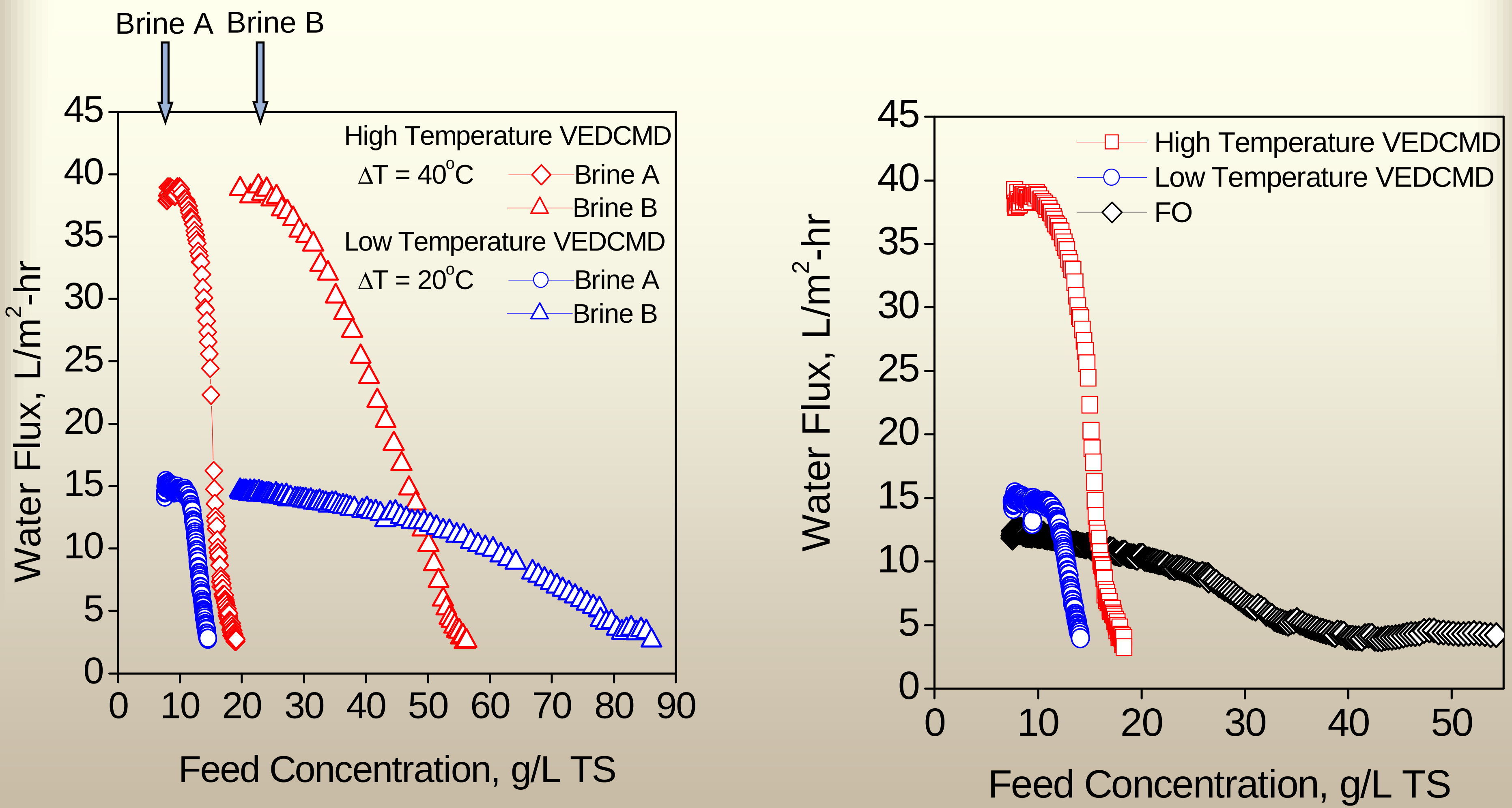


Effect of Feed Salt Concentration on Flux in Membrane Distillation

T_f = 40°C, T_p = 20°C, P_f = 1.1 atm, P_p = 0.64 atm



Brine Concentration



Solar-Powered Membrane Distillation

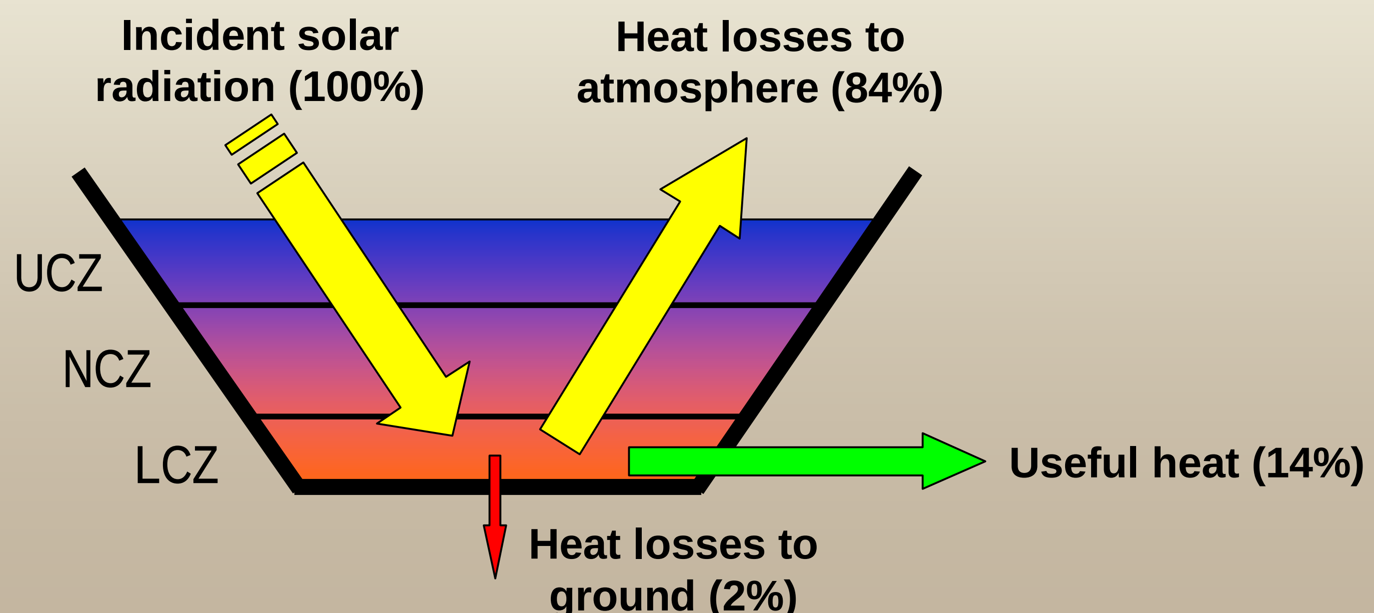
- Targeting remote, developing regions
- Small-scale, autonomous solutions
- Combination of two technologies
  - Energy conversion
  - Desalination

Desalination by using alternative energy: Review and state of the art
E. Mathioulakis, V. Belessiotis, and E. Delyannis
Desalination 203 (2007) 346-365

Membrane Distillation Powered by Solar Pond

Promising solution to treat concentrate from membrane processes or to decrease salinity in terminal lakes

- saline water concentrated in solar pond
- pond provides thermal storage and energy to drive membrane distillation
- salinity of lake is diluted and slowly reduced



Concluding Remarks

- There is no single best method for desalination
  - Hybrid technologies
- We will use direct potable reuse…. one day!
- Immediate applications of membrane distillation appear to be more niche-type applications instead of large-scale seawater desalination
- Forward osmosis as pretreatment for reverse osmosis (or other desalination processes) has numerous applications
  - Elimelech research group at Yale University studying novel NH_3/CO_2 forward osmosis process
- Needs
  - New membranes specifically developed for membrane distillation
  - Commercial competition for forward osmosis membrane
  - New membrane modules / packing for forward osmosis and membrane distillation

Acknowledgements

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