Model-Based Extracted Water Desalination System for Carbon Sequestration

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Imagination at work.

Crosscutting Research & Rare Earth Elements Portfolios Review
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GE Global Research Team

Name	Background	Role
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Liz Dees	PhD, Chemical Engineering	co-PI, Techno-economic modeling
Ryan Adams	PhD, Chemical Engineering	Piloting, techno-economic models
Rachel Gettings	MS, Marine Biology	Piloting, techno-economic models
Paul Smigelski	MS, Chemistry	Piloting/chemistry/logistics
Tim Sivavec	PhD, Chemistry	Chemistry, analytical, sensing
Mark Harkness	MS, Chemical Engineering	Piloting, techno-economics (SRS)
Elliott Shanklin	BS, Chemistry	Piloting
Jianmin Zhang	PhD, Mechanical Engineering	Brine concentrator design
Mike Salerno	PhD, Chemical Engineering	Piloting, process engineering
Matt Meketa	PhD, Chemistry	Piloting, water chemistry

The Pennsylvania State University (subcontractor)

Name	Background	Role
Li Li	PhD, Environmental Engineering	Task 2: Site identification

Objective

Formation Water
- TDS (salinity)
- TSS (solids)
- Biological O_2 demand
- Organics
- Hardness

Concentrate Disposal
- Underground injection control (UIC)
- Well-kill fluid
- Blendstock for hydrofracturing

Energy Sources
- Flare gas
- “Waste” heat

Define Water Recovery Process

Solids Disposal
- RCRA-D
- NORM, industrial
- Incineration

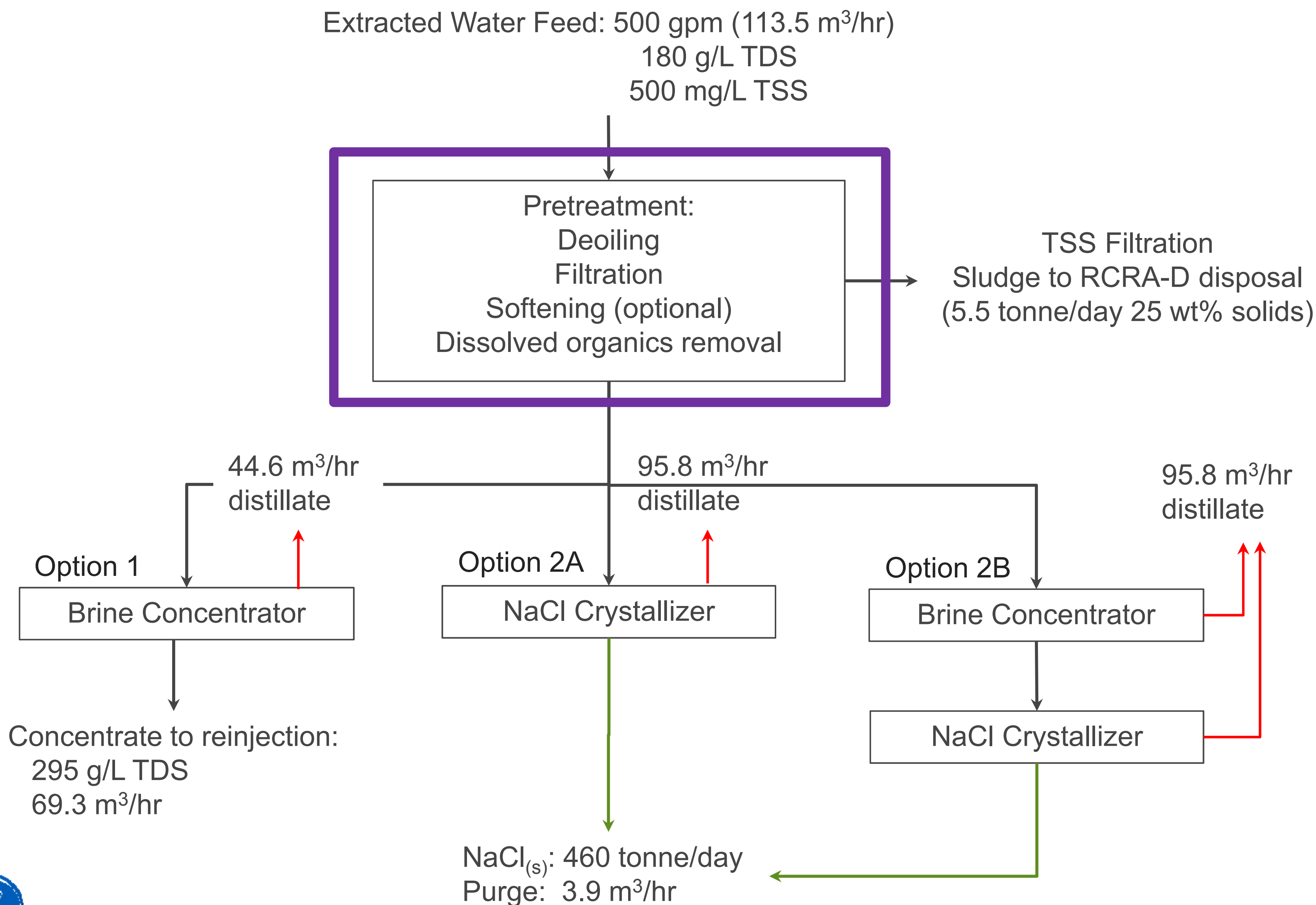
Treatment Chemicals
- Local availability
- Cost

Product Off-takes
- Recovered water
- Salt
- Value-added minerals

Strategy for Defining Water Recovery Process

1. Define Base Case
    - Conventional desalination technology
    - Assess required pretreatment needs
    - Key question: generate a solid NaCl product?
2. Compare Base Case & Alternate Desalination Technologies
    - Softening required?
        - Aspen Plus and Excel models
        - Cost of softening chemicals
    - Techno-economic modeling of desalination processes
        - Aspen Plus and Excel models
        - Cost results (normalized by base case cost)
3. Validation of Pilot-readiness
    - Bench & pre-pilot scale experiments
    - Model refinement

Base Case Definition



Produced Water Treatment Facility

On-site pilot-scale proving grounds for separation materials & unit operations R&D

Microfiltration Unit: 2 GPM permeate with < 10 NTU, auto-backwash, flowrates can be scaled up/down	**Ultrafiltration Unit**: ≤ 5 GPM permeate for removing fines, oily colloids; can be converted to NF/RO

Steam Regenerable Sorbent (SRS) Unit: ≤ 2 kg resin, ≥ 0.5 LPM, "field" flow profile, ≤ 235 psig steam (≤ 200 °C)

Feed: Tank + Controls

Resin Column

Backwash/Steam Controls

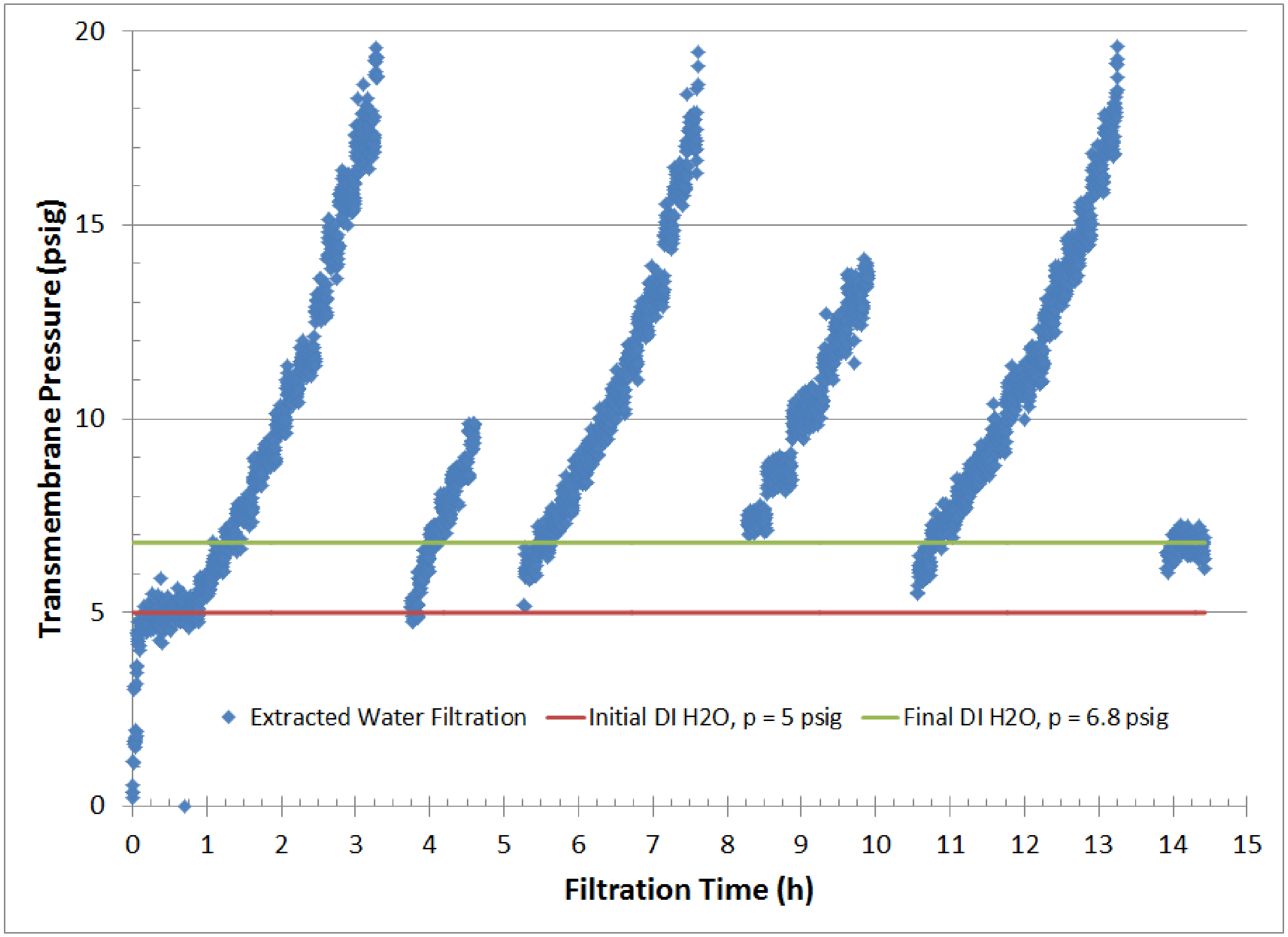
Steam Generator

- Comprehensive analytics on-site & off-site: LC-OCND, TDS, TSS, TOC, cond., BTEX/GRO/DRO

Microfiltration (MF)

- Validation with Williston Formation produced water diluted to 180 g/L TDS
- Pre-pilot performance of commercial-scale MF element for produced water filtration

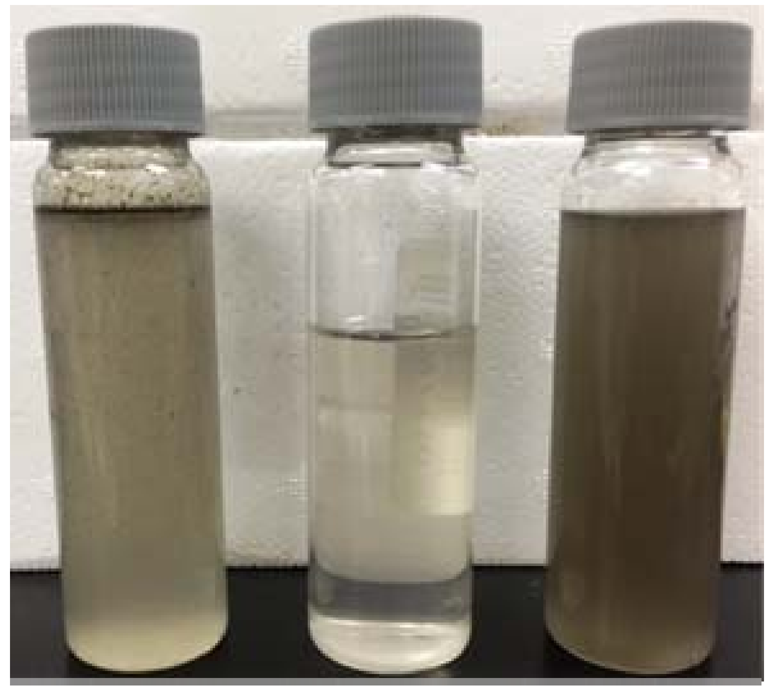
– Good recovery of distilled water flux after filtration cycles suggests efficient backwashing and long times



Microclarification (MC)

- Validation with Eagle-Ford Formation produced water
- Pre-pilot performance of prototype MC unit for produced water solids removal

– Rapid and effective bulk separation achieved with ~ 1/40 the residence time of a clarifier

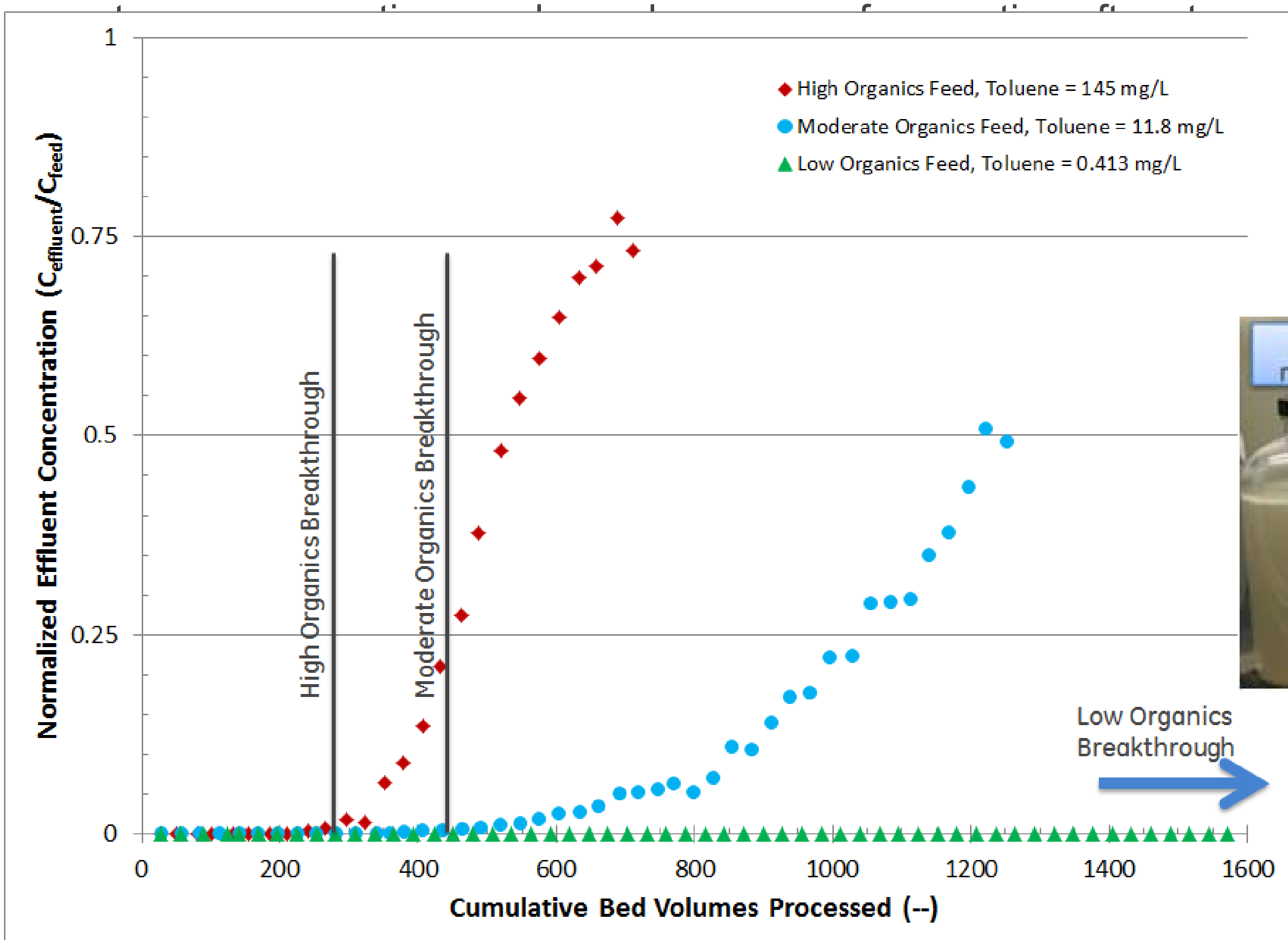


Feed	Effluent	Purge
305 NTU	30 NTU	>2,000 NTU

Steam-Regenerable Sorption (SRS)

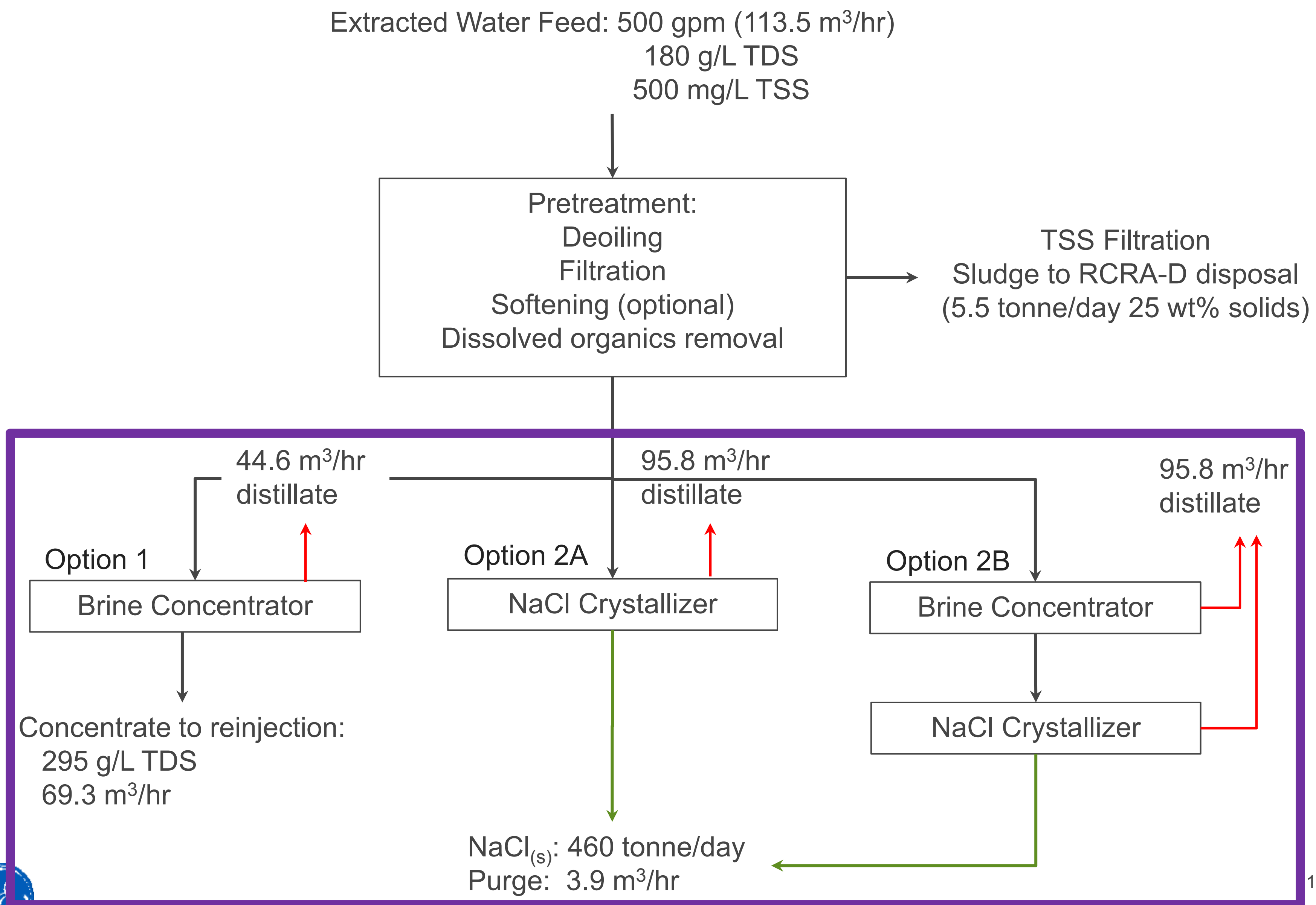
- Validation with various produced waters up to 180 g/L TDS
- Pre-pilot performance of SRS resin bed for removal of organics from produced water

– GE's R&D resin and a commercial resin both show high sorption capacity & kinetics, rapid ... generations



Regeneration Condensate
(~ 160 °C steam, ~ 1.5 GPH condensate):
all organics removed in 30 min

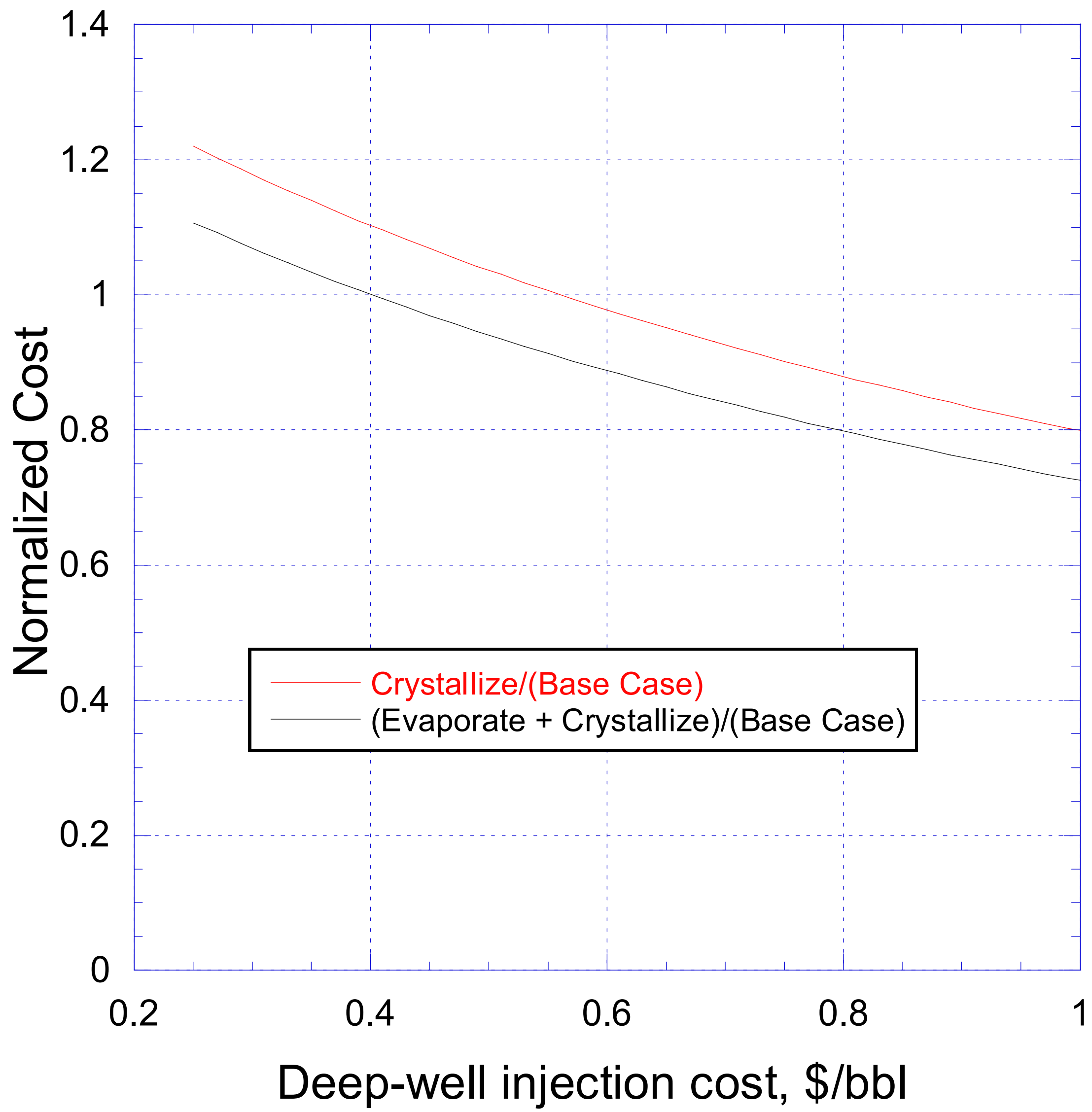
Base Case Definition



Base Case Desalination Options Comparison

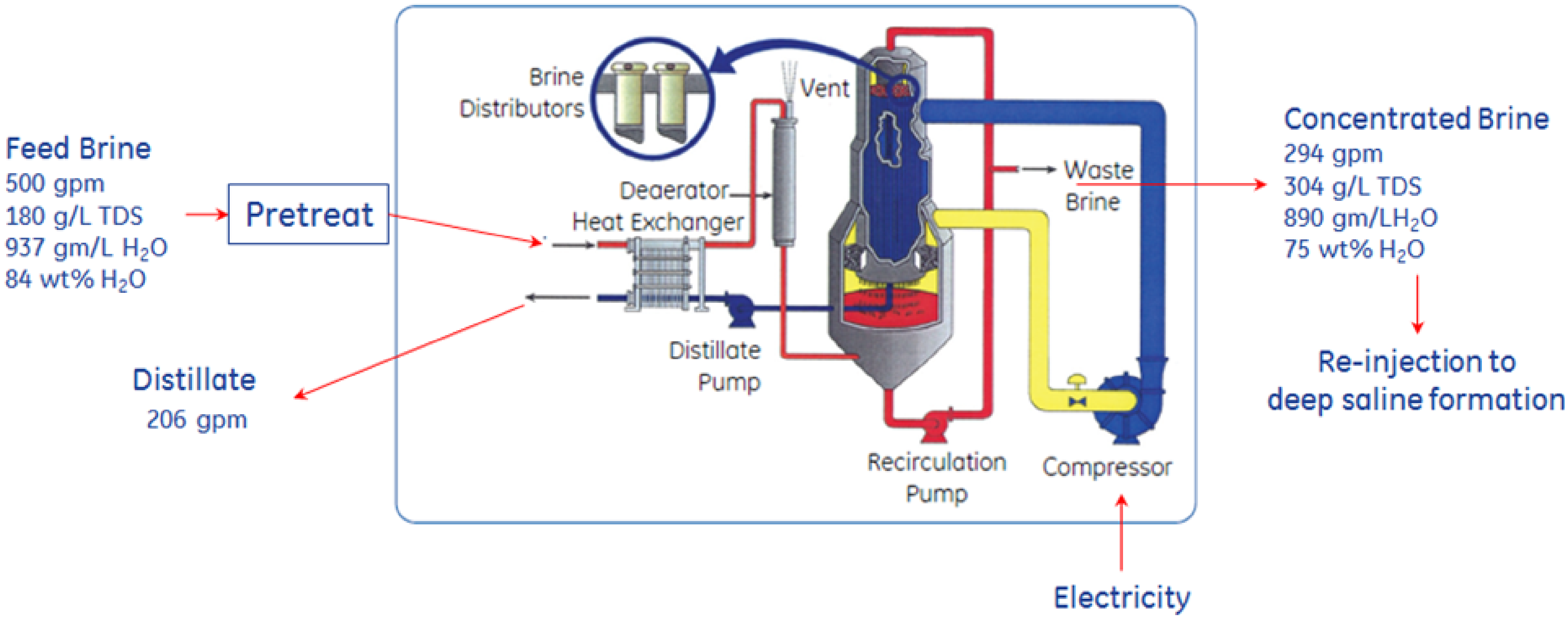
Cost model details

- Feed: 113.5 m^3/hr, 180 gm/L TDS, $0.40/bbl reinjection cost
- Installed CAPEX
- Electricity for compressor
- Concentrate or purge disposal
- Pretreatment ($0.25/bbl), no softening
- No credit for distilled water, salt
- Out-of-scope: effect of parasitic load on process economics



Option 1 lowest cost for UIC < $0.40/bbl…select for base case

Base Brine Concentrator: Falling Film Mechanical Vapor Recompression (FF-MVR)



Schematic of FF-MVR desalination system courtesy of GE Water.

Alternate Brine Concentration Technologies

Suitable for high TDS (180 g/L) extracted water:

1. Forward Osmosis (FO)
2. Membrane Distillation (MD)
3. Humidification-Dehumidification (HDH)
4. Clathrate Chemical Complexation
5. Turbo-Expander-based Freezing

High cost of softening hard waters (e.g. Williston Formation) limits alternate desalination options

Softening Chemistry

$$MgCl_2 + 2NaOH \rightarrow Mg(OH)_{2(s)} + 2NaCl$$

$$CaCl_2 + Na_2CO_3 \rightarrow CaCO_{3(s)} + 2NaCl$$

$$SrCl_2 + Na_2CO_3 \rightarrow SrCO_{3(s)} + 2NaCl$$

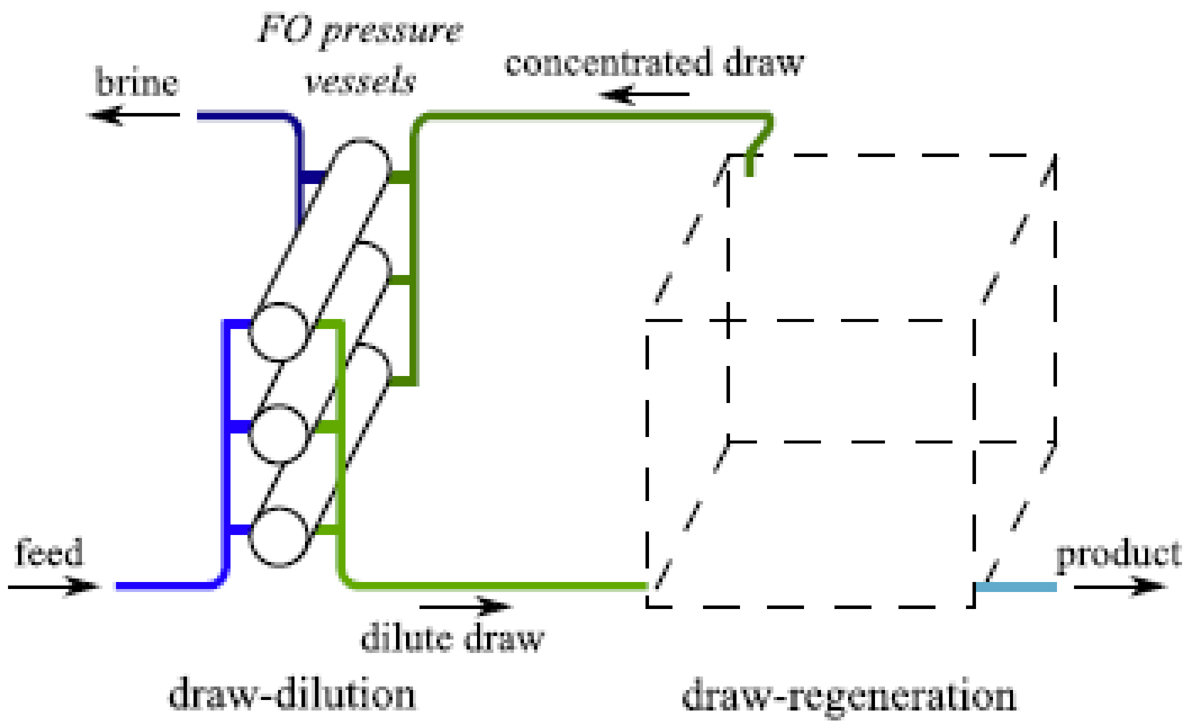
Feed Mg^{++}	lb-mole/hr	14.704
Feed Ca^{++} + Sr^{++}	lb-mole/hr	63.838
Na_2SO_4 added as 100% (optional)	lb/hr	4.85
NaOH added (100%)	lb/hr	1175.0
Na_2CO_3 added (100%)	lb/hr	7203.0
HCl for neutralization (100%)	lb/hr	105.4
Sludge generated (25 wt% solids)	short ton/hr	14.82
Na_2SO_4 cost	\$/hr	\$0.325
NaOH cost	\$/hr	\$325.1
Na_2CO_3 cost	\$/hr	\$1149
HCl cost	\$/hr	\$25.10
Sludge disposal	\$/hr	\$741.1
Total softening cost	\$/hr	\$2240
Net distillate	m^3/hr	44.58
Softening cost	**\$/m^3 net distillate**	**\$50.25**

Marginally-suitable technologies:

1. High Pressure Reverse Osmosis
   - Not feasible > 70 g/L TDS
2. Electrodialysis
   - High energy consumption at high TDS; questionable feasibility with hard waters

Forward Osmosis Desalination

- Draw solution creates osmotic pressure gradient across membrane
- Water permeates from feed brine to draw solution
- Draw solution and fresh water recovered thermally
- Less fouling than RO due to low pressure requirement

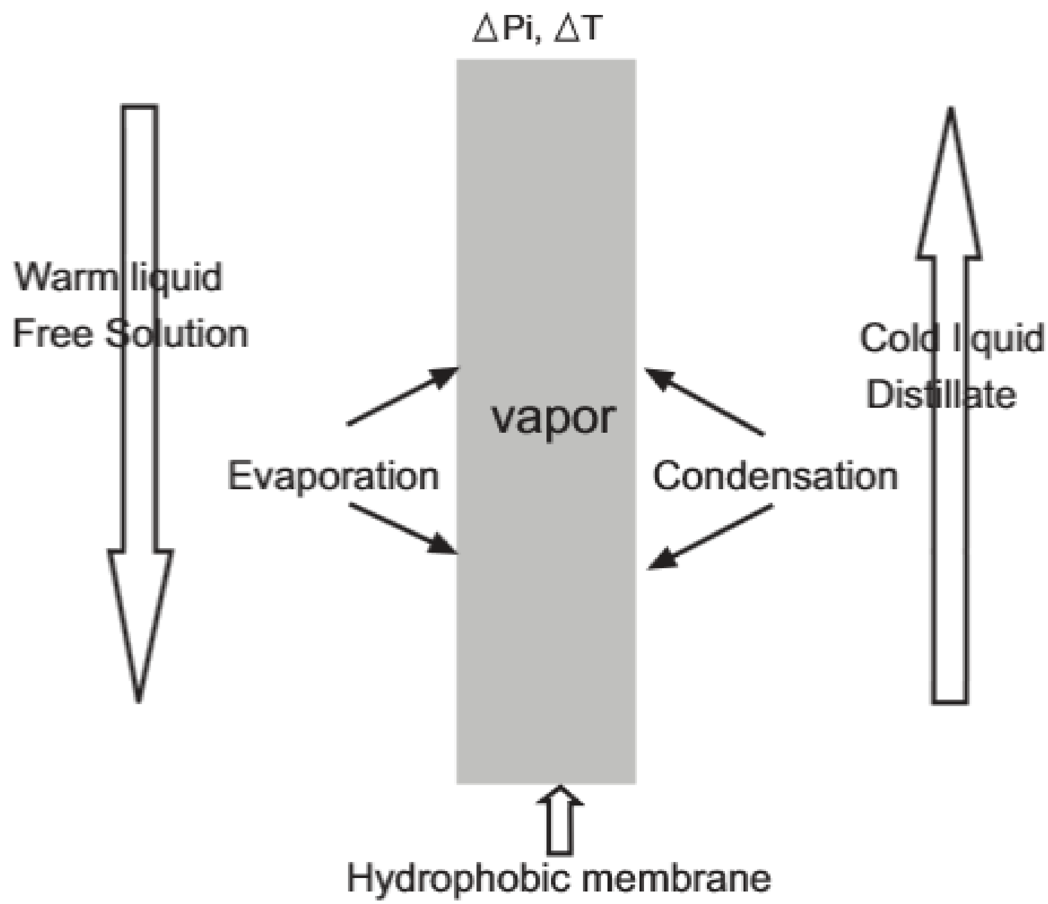


Schematic of FO Desalination System (McGovern & Lienhard, 2014)

With heat integration: <u>0.58X the cost of base case falling-film MVR</u>

Membrane Distillation Desalination

- Hydrophobic, microporous membrane
- Water vapor partial pressure difference drives water flux across the membrane
- Low grade heat can be used
- Organics removal important

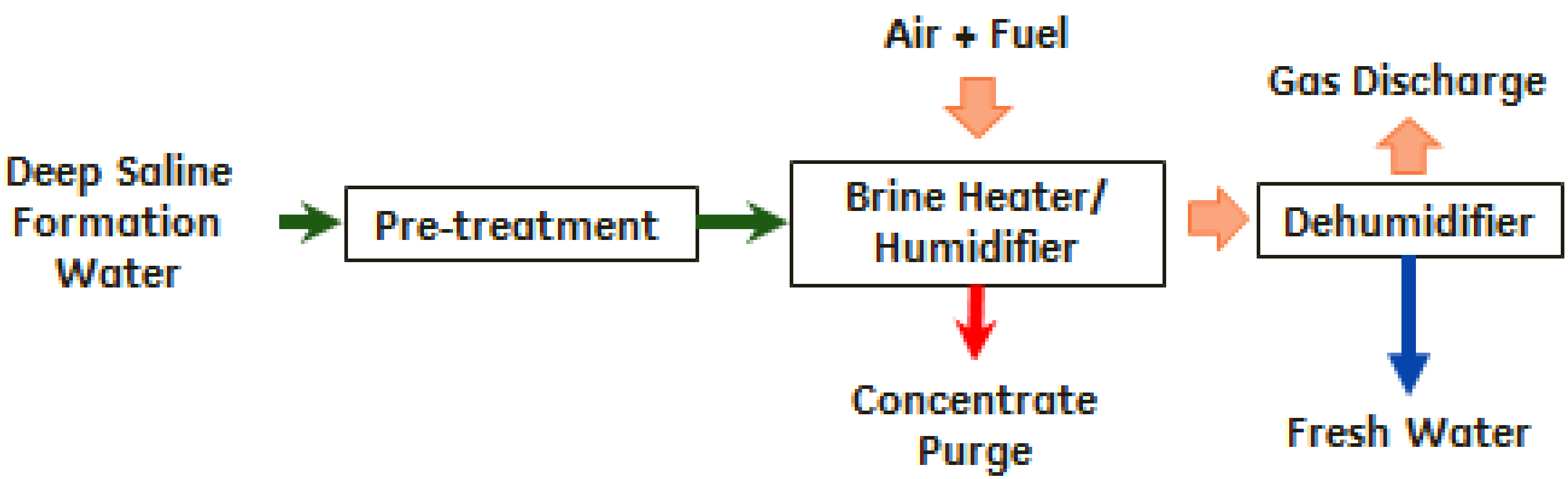


Membrane Distillation Schematic (Yarlagadda, Camacho, Gude, & Wei, 2009)

With heat integration: <u>0.85X the cost of base case falling-film MVR</u>

Humidification-Dehumidification (HDH) Desalination

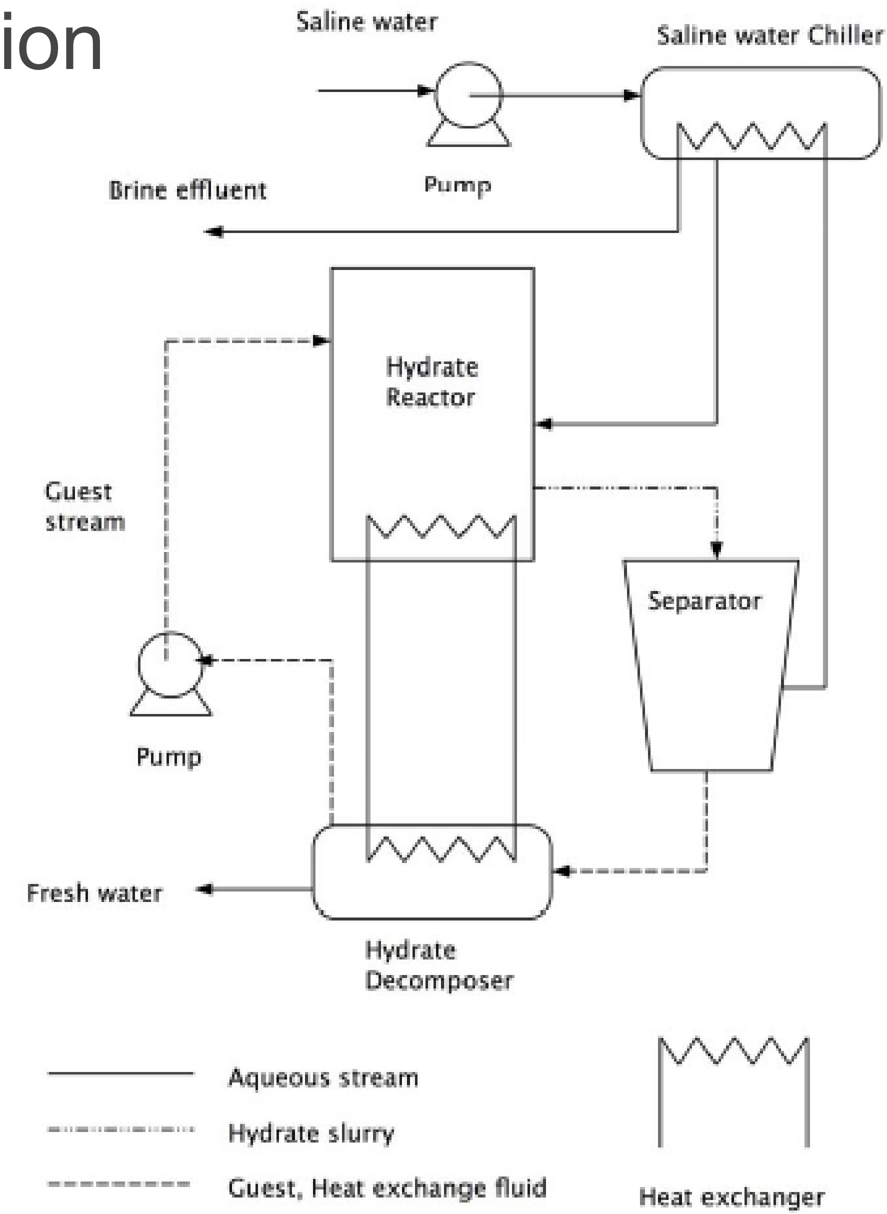
- Hot carrier gas contacts feed in a high mass transfer rate humidifier
- Distilled water recovered in a dehumidification chamber
- Potential to use CO_2-rich flue gas
- Without heat integration, HDH far more costly than base case



With heat integration: <u>0.22X the cost of base case falling-film</u> MVR

Clathrate-based Desalination

- Feed is chilled in presence of dispersed low density guest molecule
- Water complexes & freezes around guest molecule to form clathrate which then floats for facile separation
- Thermal regeneration of clathrate and recovery of distilled water
- Established process costs ~ 1.75X base case

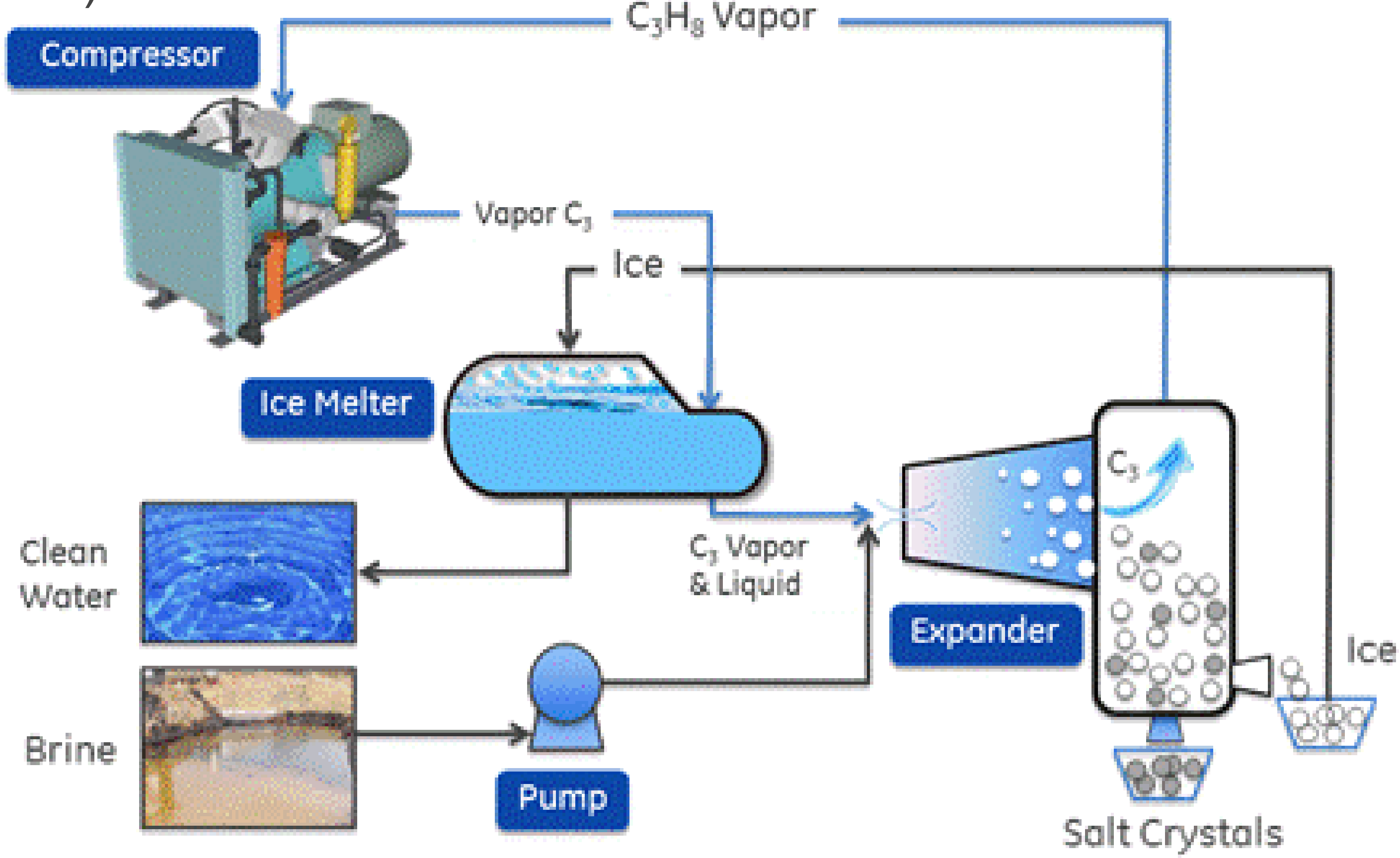


Schematic Diagram of Clathrate-based Dehydration Process (Bradshaw et al, 2008)

With improved guest dispersion: <u>0.52X the cost of base case falling film MVR</u>

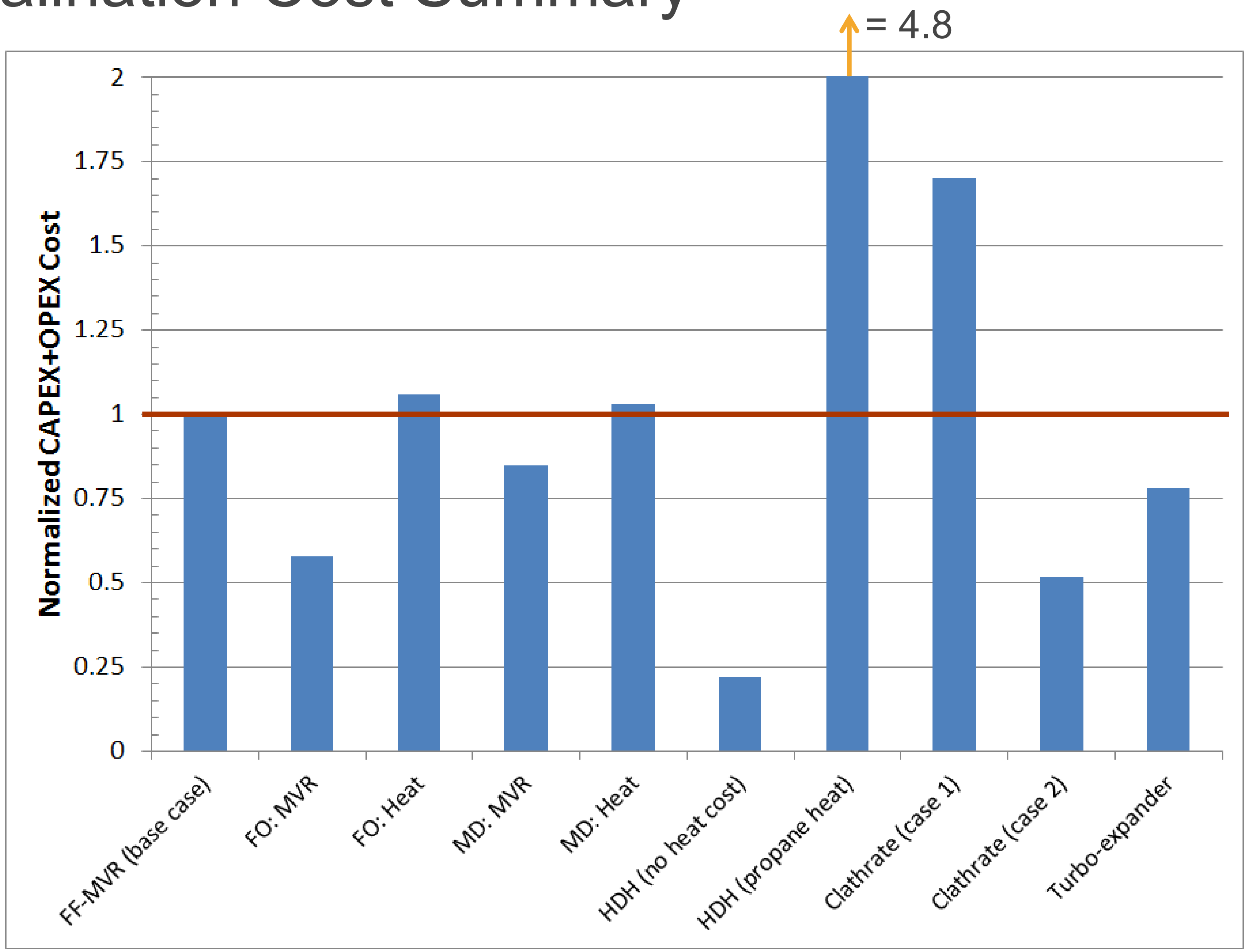
Turbo-Expander Based Desalination Process

- Water is frozen when injected into a cold stream of vapor/liquid propane
- Energy recovered by using propane to melt ice
- Technical risks: freezing brine (addressed); ice/salt separation (in progress)



Favorable economics: <u>0.78X the cost of base case falling-film MVR</u>

Desalination Cost Summary



Future work: refinement of pretreatment & desalination cost models via bench/pre-pilot scale runs with field-sourced extracted water

Acknowledgments

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Water & Process Technologies

Disclaimer

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