Model-Based Extracted Water Desalination System for Carbon Sequestration

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Imagination at work. Crosscutting Research & Rare Earth Elements Portfolios Review
March 23, 2017
## GE Global Research Team

<table>
<thead>
<tr>
<th>Name</th>
<th>Background</th>
<th>Role</th>
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</thead>
<tbody>
<tr>
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</tbody>
</table>

## The Pennsylvania State University (subcontractor)

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
<tr>
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<td>Task 2: Site identification</td>
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<td>Task 3: High pressure RO</td>
</tr>
</tbody>
</table>
Objective: Defining Water Recovery Process

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

Energy Sources
- Flare gas
- "Waste" heat

Define Water Recovery Process

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

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 & Alternative 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
1. Define Base Case

Pretreatment

Extracted Water Feed: 500 gpm (113.5 m³/hr)
- 180 g/L TDS
- 500 mg/L TSS

Pretreatment:
- Deoiling
- Filtration
- Softening (optional)
- Dissolved organics removal

TSS Filtration
- Sludge to RCRA-D disposal
  (5.5 tonne/day 25 wt% solids)

Option 1
- Brine Concentrator
  - Concentrate to reinjection:
    - 295 g/L TDS
    - 69.3 m³/hr

Option 2A
- NaCl Crystallizer
  - NaCl[^s]: 460 tonne/day
  - Purge: 3.9 m³/hr

Option 2B
- Brine Concentrator
  - NaCl Crystallizer
  - 95.8 m³/hr distillate
1. Define Base Case
Conventional Desalination

Extracted Water Feed: 500 gpm (113.5 m³/hr)
180 g/L TDS
500 mg/L TSS

Pretreatment:
Deoiling
Filtration
Softening (optional)
Dissolved organics removal

TSS Filtration
Sludge to RCRA-D disposal (5.5 tonne/day 25 wt% solids)

Option 1
Brine Concentrator
Concentrate to reinjection:
295 g/L TDS
69.3 m³/hr

Option 2A
NaCl Crystallizer
Distillate: 44.6 m³/hr
NaCl(s): 460 tonne/day
Purge: 3.9 m³/hr

Option 2B
Brine Concentrator
NaCl Crystallizer
Distillate: 95.8 m³/hr

44.6 m³/hr distillate
95.8 m³/hr distillate
95.8 m³/hr distillate
1. Define Base Case
   Desalination Options

Base Case Desalination Options Comparison

Cost model details
- Feed: 113.5 m³/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...selected for base case
1. Define Base Case

**FF-MVR**

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

- **Feed Brine**
  - 500 gpm
  - 180 g/L TDS
  - 937 g/L H₂O
  - 84 wt% H₂O

- **Pretreat**

- **Distillate**
  - 206 gpm

- **Concentrated Brine**
  - 294 gpm
  - 304 g/L TDS
  - 890 gm/L H₂O
  - 75 wt% H₂O

- **Re-injection to deep saline formation**

- **Electricity**
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
6. High Pressure Reverse Osmosis

High cost of softening hard waters limits alternate desalination options.
RO Preconcentration for Brine Concentrator Size & Energy Reduction

Technical risks of RO at high TDS:

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Need</th>
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<tbody>
<tr>
<td>Scaling</td>
<td>Fouling-resistant membrane &amp; module; adequate pretreatment</td>
</tr>
<tr>
<td>Compaction</td>
<td>Membrane &amp; module performance stable at high feed pressure</td>
</tr>
</tbody>
</table>
3. Pilot Readiness
Model refinement

Technoeconomics: Hybrid HPRO + FF-MVR vs. FF-MVR

<table>
<thead>
<tr>
<th>HPRO concentrate TDS (mg/L)</th>
<th>Normalized cost (HPRO+FF-MVR/FF-MVR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130,000</td>
<td>0.53</td>
</tr>
<tr>
<td>175,000</td>
<td>0.47</td>
</tr>
<tr>
<td>245,000</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Hybrid HPRO + FF-MVR system estimated to be ~1/2 the cost of FF-MVR

Technical risks: membrane & element performance, compaction, water chemistry (scaling)
SWRO + HPRO Hybrid Technoeconomics Summary

SWRO + HPRO hybrid reduces system cost in many cases (dependent on HPRO material, pretreatment & concentrate disposal costs)
3. Pilot Readiness Model refinement

Current vs. Ideal HPRO techno-economics

**Current:** based on real system specs from RCC

**Hybrid:** estimates based on upscaling SeaPRO-84 for high pressure/TDS and current GRC performance @ 2000 psi (aspirational performance @ 3000 psi)

**Ideal:** estimate based on upscaling SeaPRO-84 for high pressure/TDS and aspirational membrane performance

- **Base case FF-MVR**
  - Current: FF-MVR
  - 2000 psi (130k TDS) HPRO
  - 3000 psi (175k) HPRO
  - Ideal: 6800 psi (295k) HPRO

- **Current:**
  - Savings: 47%, 53%, 61%

- **Ideal:**
  - Savings: 53%, 61%

Feed (SWRO concentrate):
- 500 gpm
- 70,000 mg/L TDS

Concentrate:
- 295,000 mg/L TDS

Permeate:
- 395 gpm
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

**Ultrafiltration Unit**: ≤ 5 GPM permeate for removing fines, oily colloids

**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
GRC High Pressure Test Bench

High pressure bench can test an 1812 module or flat sheet membrane at pressures up to 4000-5000 psig
Components Critical for High Pressure RO

1. Identify components responsible for performance loss at high TDS/pressure
2. Replace components with suitable alternatives to maximize TDS/pressure operation range of spiral-wound RO module

https://www.freshwatersystems.com/c-238-ro-membranes.aspx
3. Pilot Readiness
Bench and Pre-Pilot Scale Testing

GRC Results

Existing

Permeate tube crushed at 2900 psi

Cracks in membrane and permeate tube

Eliminate Gross Failure

Re-enforced core tube: intact to 4800 psi (did not fail)

Minimize Compaction

Compaction onset (NDP):
PC1: 1000 psi
PC2: 1500 psi

Maximum pressure achieved: 4800 psi (no failure)
Compaction onset NDP increased from 1000 to 1500 psi
## Module Improvements

- **Existing**
- **Eliminate Gross Failure**
- **Minimize Compaction**

<table>
<thead>
<tr>
<th>Component</th>
<th>Standard 1812</th>
<th>1(^{st}) HPRO elements</th>
<th>2(^{nd}) HPRO elements</th>
<th>Next steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>AG</td>
<td>AG</td>
<td>AG</td>
<td>AD</td>
</tr>
<tr>
<td>Feed spacer</td>
<td>34 mil</td>
<td>30 mil</td>
<td>30 mil</td>
<td>30, 45 or 65 mil</td>
</tr>
<tr>
<td>Permeate carrier</td>
<td>Standard</td>
<td>PC1(a)</td>
<td>PC1(b)</td>
<td>Alternate materials</td>
</tr>
<tr>
<td>Core tube</td>
<td>Standard</td>
<td>Reinforced</td>
<td>Reinforced</td>
<td>-</td>
</tr>
<tr>
<td>Failure pressure</td>
<td>2900 psi – crushed core tube</td>
<td>n/a (up to 3200 psi)</td>
<td>n/a (up to 4800 psi)</td>
<td>-</td>
</tr>
<tr>
<td>Compaction NDP</td>
<td>800</td>
<td>1000</td>
<td>1500</td>
<td>Membrane Development</td>
</tr>
</tbody>
</table>

**Reinforced core tube prevents gross failure**
Next steps: identify/develop materials to minimize membrane compaction
Acknowledgments
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**SWRO + HPRO Hybrid Technoeconomics Summary**

**Base Case 2x SWRO System for Comparison to Hybrid SWRO + HPRO System**

- **200 GPM**
- **445 GPM/35k TDS**
- **35k TDS Feed 890 GPM**
- **445 GPM/35k TDS**

**Total Permeate 400 GPM**

**Concentrate to Disposal:**
- **245 GPM/63k TDS**

**HPRO Feed Pressure and Concentrate Concentration**

- **SWRO Permeate:**
  - a) 200 GPM
  - b) 219 GPM
  - c) 250 GPM
  - d) 281 GPM

- **HPRO Permeate:**
  - a) 199 GPM
  - b) 181 GPM
  - c) 150 GPM
  - d) 119 GPM

**Total Permeate 400 GPM**

- **35k TDS SWRO Feed:**
  - a) 445 GPM
  - b) 486 GPM
  - c) 556 GPM
  - d) 625 GPM

- **63k TDS HPRO Feed:**
  - a) 245 GPM
  - b) 267 GPM
  - c) 306 GPM
  - d) 344 GPM

**Concentrate to Disposal:**
- **46 GPM/295k TDS**
- **86 GPM/181k TDS**
- **156 GPM/119k TDS**
- **225 GPM/94k TDS**

**Normalized Cost of Hybrid SWRO + HPRO System Cases Studied**

<table>
<thead>
<tr>
<th>Case</th>
<th>System Feed Flowrate (GPM)</th>
<th>System Concentrate Flowrate (GPM)</th>
<th>System Concentrate TDS (mg/L)</th>
<th>Normalized Cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>445</td>
<td>46</td>
<td>295,000</td>
<td>0.90</td>
</tr>
<tr>
<td>(b)</td>
<td>486</td>
<td>86</td>
<td>181,000</td>
<td>0.76</td>
</tr>
<tr>
<td>(c)</td>
<td>556</td>
<td>156</td>
<td>119,000</td>
<td>0.82</td>
</tr>
<tr>
<td>(d)</td>
<td>625</td>
<td>225</td>
<td>94,000</td>
<td>0.91</td>
</tr>
</tbody>
</table>

*Normalized cost = (hybrid SWRO + HPRO system cost)/(2x SWRO system cost); cost per m3 product water

**HPRO Feed Pressure and Concentrate Concentration**

<table>
<thead>
<tr>
<th>Case</th>
<th>HPRO Concentrate TDS (mg/L)</th>
<th>HPRO Operating Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>295,000</td>
<td>6800</td>
</tr>
<tr>
<td>(b)</td>
<td>181,000</td>
<td>3200</td>
</tr>
<tr>
<td>(c)</td>
<td>119,000</td>
<td>1900</td>
</tr>
<tr>
<td>(d)</td>
<td>94,000</td>
<td>1500</td>
</tr>
</tbody>
</table>

**Costs included: SWRO/HPRO (Capex, Energy, Membrane Replacement), Pretreatment and Disposal**
Increasing SWRO + HPRO system size:
- More permeate production from SWRO
- Lower recovery required of HPRO
- More concentrate remaining for disposal
TEM details

Opex
- Key Assumption:
  - Flux linear with pressure

Capex
- High pressure system estimate:
  \[ C_V = C_B F_t (B_1 + B_2 F_M F_P) F_C \]
- Base cost: SeaPRO-84 cost
- Key assumption:
  - HPRO system has same flowrates, number of elements & housings as SeaPRO system
- Ongoing improvements:
  - Quotes for high cost components (pumps, ERDs, pressure gauges, controls (VFD)) to validate factored estimate approach
  - Element cost estimate from components
  - Account for corrosion (\( F_C \))
  - Use real (not ideal) membrane performance (i.e., with compaction)

<table>
<thead>
<tr>
<th>ID</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_V)</td>
<td>High pressure component cost</td>
</tr>
<tr>
<td>(C_B)</td>
<td>Base component cost</td>
</tr>
<tr>
<td>(F_t)</td>
<td>Time factor (assumed = 1 b/c base cost quoted 7/2016)</td>
</tr>
<tr>
<td>(F_M)</td>
<td>Material factor (for corrosion resistance)</td>
</tr>
<tr>
<td>(F_P)</td>
<td>Pressure factor (material thickness for high pressure)</td>
</tr>
<tr>
<td>(F_C)</td>
<td>Corrosion factor (additional thickness to allow for corrosion rate over system lifetime; assumed = 1 but needs to be included)</td>
</tr>
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</table>