Switchable Polarity Solvent Forward Osmosis (SPS FO): Technology Development Status and Economic Potential for Produced Water Treatment

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Significant quantities of produced water are brought to the surface during oil and gas production operations. In 2007 approximately 21 billion barrels of water were produced from oil & gas operations. Produced water can contain a wide range of constituents including dissolved salt, petroleum and other organic compounds, suspended solids, trace elements, bacteria, naturally occurring radioactive materials, and anything injected into the well (Clark and Veil, 2009).

The majority of produced water from hydrocarbon resource development is reinjected into the subsurface. Approximately 45% of produced water is reinjected for enhanced oil recovery (to maintain reservoir pressure) and ~40% is disposed of in deep injection wells that are commonly located offsite at commercial disposal facilities. There are numerous potential environmental concerns associated with the handling and disposal of produced water from oil & gas operations, including spills during transport and earthquakes from deep injection disposal activities. Additionally, disposal of produced water is a significant operating cost for oil & gas producers, with typical injection disposal costs of a dollar per barrel or more.

Cost effective treatment of produced water streams from oil and gas operations can reduce the volume of fluid that otherwise requires disposal at a cost to the operator. Switchable Polarity Solvent Forward Osmosis (SPS FO) desalination technology, which is currently being developed at the Idaho National Laboratory (INL), could be used for treating produced water streams to reduce the overall volume of fluid that requires disposal while simultaneously creating a purified water product stream that could be utilized for a variety of beneficial uses.

SPS FO is a semi-permeable membrane-based thermal desalination process. The SPS FO process uses a forward osmosis (FO) membrane and a high osmotic pressure switchable polarity solvent (SPS) draw solution to extract water from an impaired water feed stream, which dilutes the draw solution with purified water from the feed stream. Addition of low-grade heat to the dilute draw solution drives a bicarbonate decomposition reaction that removes CO_2 and changes the SPS from the polar to non-polar form. The non-polar form of the SPS partitions into an organic phase that can be gravity separated (decanted) from the aqueous phase containing the water recovered from the feed stream. The SPS draw solution is then recombined with CO_2 to regenerate a high concentration FO draw solution for reuse in the process.

The SPS FO process is able to achieve high water recovery of up to 90% from a feed stream with TDS similar to seawater (reverse osmosis (RO) recovery is limited to ~50% for such a feed stream) with low membrane fouling. Additionally, the SPS FO process has low energy cost requirements, with low grade heat serving as the primary energy input (electrical power is required for fluid pumping and compression). Approximately 4 billion bbl/yr of produced water has a temperature of 80°C or greater (Augustine and Falkenstern, 2014); The low grade heat contained in produced water streams of these temperatures could be used to provide some or all of the required heat input to the SPS FO process, which would reduce external process energy requirements while simultaneously leveraging a currently underutilized geothermal energy resource.

A recent techno-economic analysis based on experimental data collected in INL laboratories predicts a water treatment cost of \$0.55/bbl (\$3.44/m^3). The economic analysis concluded that the cost of produced water treatment using SPS FO (with injection disposal of brine concentrate) is lower than the cost of injection disposal of the entire volume of produced water assuming an injection cost of \$1.00/bbl (\$6.30/m^3). The treated water could be either surface discharged or utilized for industrial or agricultural beneficial use; there are numerous location in the U.S. where cost-effective reuse of oil & gas wastewater could address multiple industrial, environmental, and economic challenges.

This poster provides additional information about SPS FO process operation and development status, observations on co-location challenges associated with desalination using geothermal heat and how SPS FO treatment of produced water inherently addresses these challenges, as well as additional economic analysis details including a summary of the design basis and an illustration of the impact of water recovery on total water management costs.

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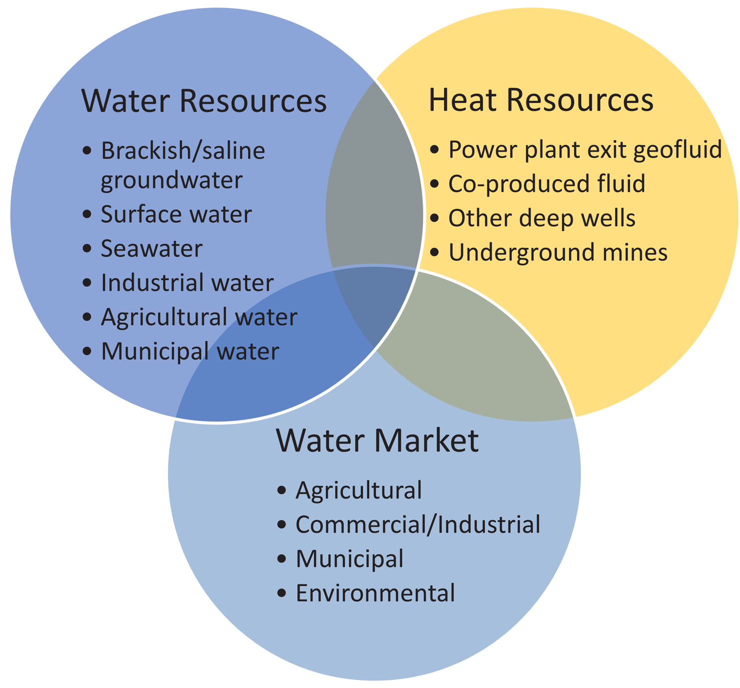
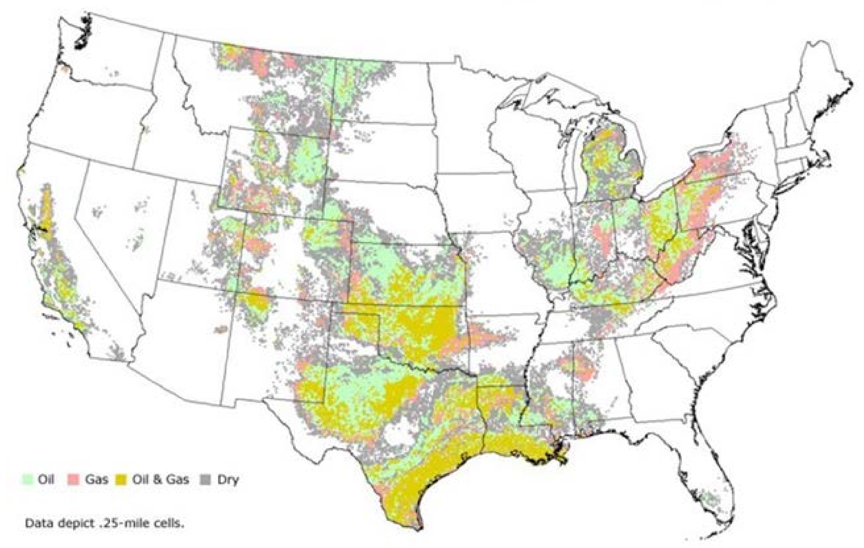
Motivation

Only a small number of geothermal heat driven desalination plants have been deployed

- Geothermal desalination economics unfavorable when geothermal resource development costs are high (exploration, drilling, etc.)
- Co-location of feed water sources, a suitable water market, and a low-cost geothermal heat source is uncommon



Distribution of Oil & Gas Wells



Source: J. K. Otton and T. Mercier, "Produced water brine and stream salinity," United States Geological Survey. https://water.usgs.gov/orh/nrwww/Otten.pdf

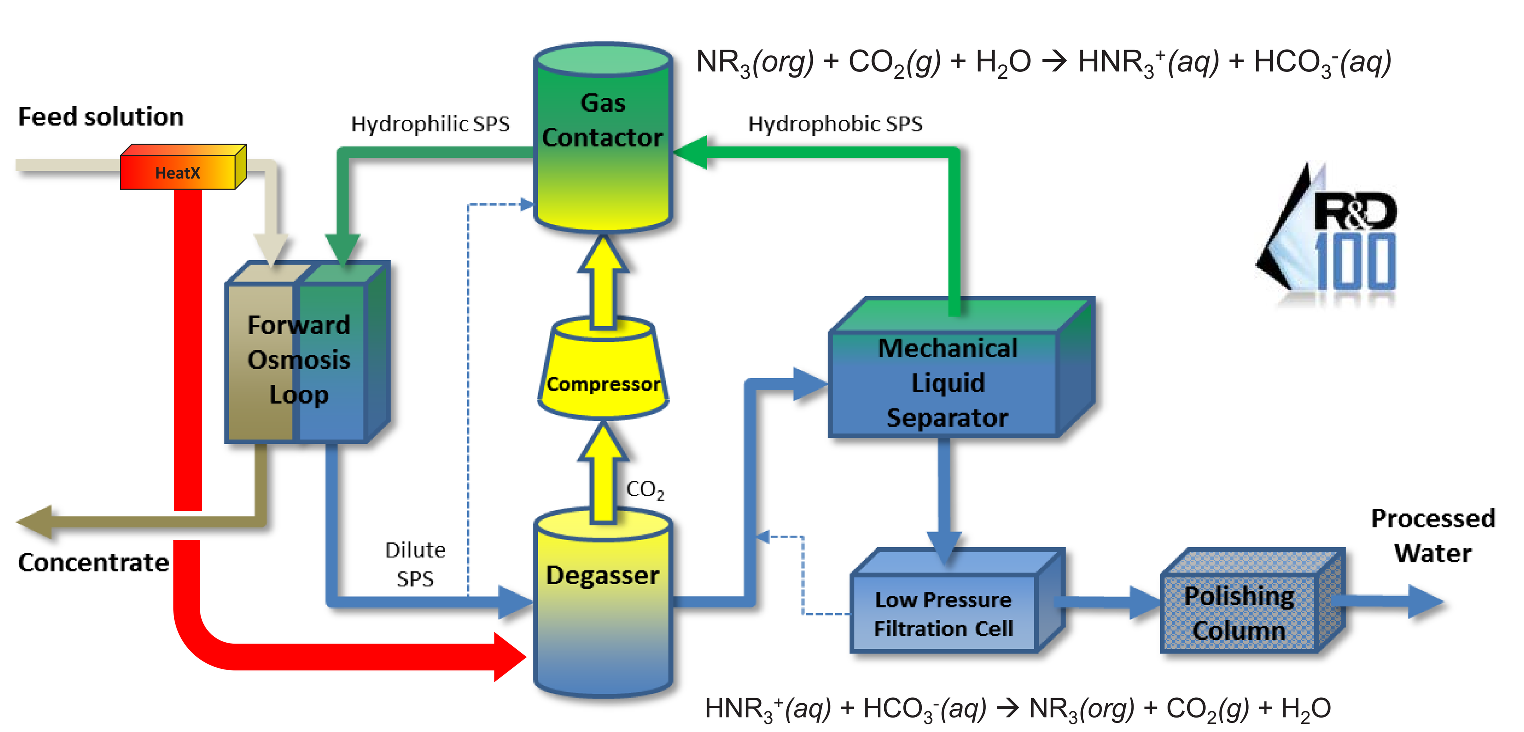
Waste water treatment costs are significantly greater than the majority of fresh water purchase costs; waste water treatment is therefore likely to present more opportunities for new water treatment technologies to enter the market.

Over 20 billion bbl/yr of co-produced water from U.S. oil & gas production operations; ~4 billion bbl/yr have temperature >80°C (Augustine and Falkenstern, 2014)

Majority of produced water is disposed of via injection at a typical cost of ~$1/bbl ($6.3/m^3). Cost effective treatment could:

- Reduce volume requiring disposal
- Decrease environmental risks including spills and induced seismicity
- Provide additional water source for subsequent beneficial uses

SPS FO Desalination Process

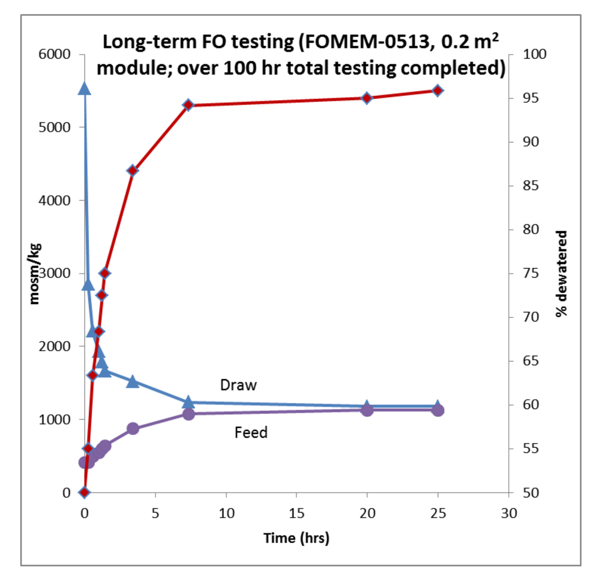


Thermally driven process with the majority of energy input at the CO_2 degasser

SPS FO process is well-suited for produced water treatment application

- Intrinsically fouling resistant technology that can treat high salinity brines
- High water recovery possible (~90% demonstrated in lab testing of produced water samples)
- Process thermal energy can be obtained from low-grade heat sources (process operates at T≤80°C)
- Heat input provided through sensible heat transfer (process steam not required)
- Low pressure operation in main process loop, moderate pressure polishing filtration operations

Forward Osmosis Unit



Removal of contaminants from the feed water stream via semi-permeable FO membrane

Test	Draw solution	Flux, LMH	Feed type
1	0.5 m SPS	4.4	DI water
2	0.25 m SPS	2.5	DI water
3	0.8 m SPS	4.4	DI water
4	0.5 m NaCl	7.5	DI water
5	2 m SPS	5.1	O&G water type 1
6	1 m SPS	4.2	O&G water type 2

FO water flux correlates well with draw concentration

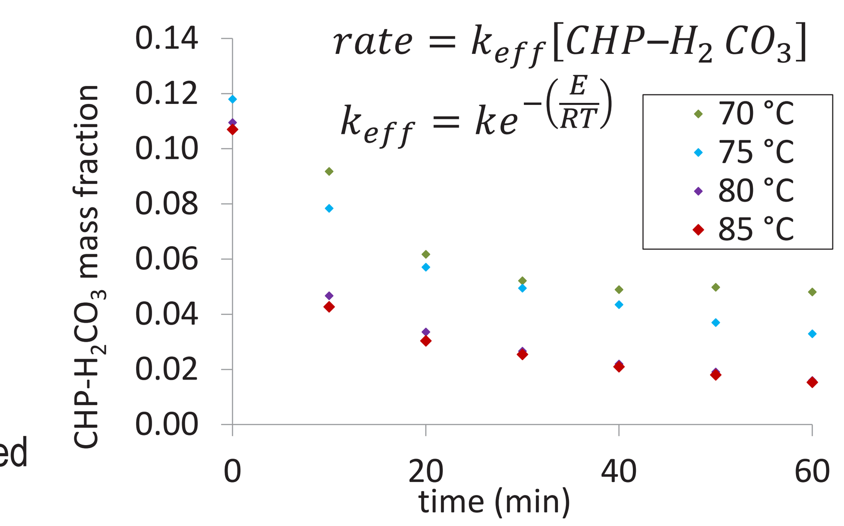
Degasser

$$\underbrace{CHPH^+(aq) + HCO_3^-(aq)}_{\text{miscible}} \rightleftharpoons \underbrace{CHP(org) + CO_2(g) + H_2O}_{\text{immiscible}}$$

Recovery of 1-cyclohexylpiperidine (CHP) SPS from diluted draw stream through application of heat to drive bicarbonate decomposition reaction

Degasser Optimization

- •Modest Vacuum (-0.25 bar)
- •Regulation of T (target 80°C)
- •A well-designed conventional column is targeted



Gas Contactor

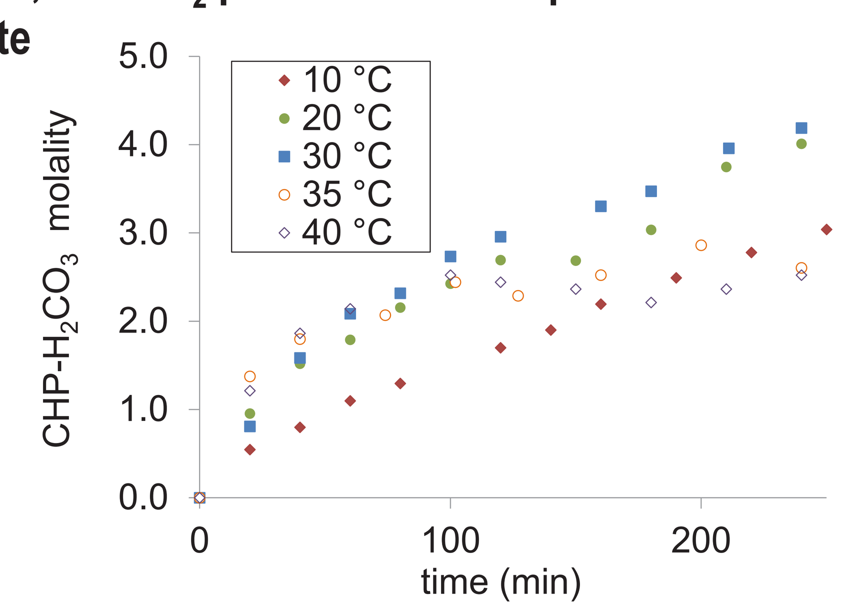
$$\underbrace{CHP(org) + CO_2(g) + H_2O}_{\text{immiscible}} \rightleftharpoons \underbrace{CHPH^+(aq) + HCO_3^-(aq)}_{\text{miscible}}$$

Mixing and reaction of organic, aqueous, and CO_2 phases to form aqueous solution of 1-cyclohexylpiperidinium bicarbonate

Gas Contactor Optimization

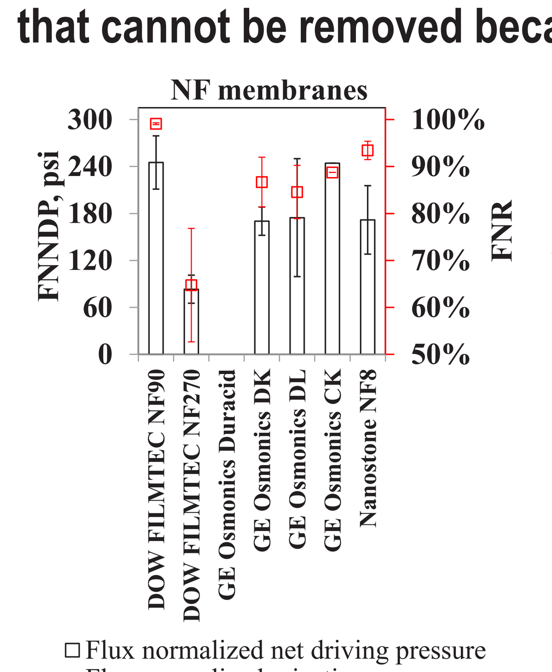
- •Use of membrane gas contactors
- •Regulation of temperature (target ~30 °C)
- •Fluid pressure
- •Flow rate
- •Membrane surface area (to a point)

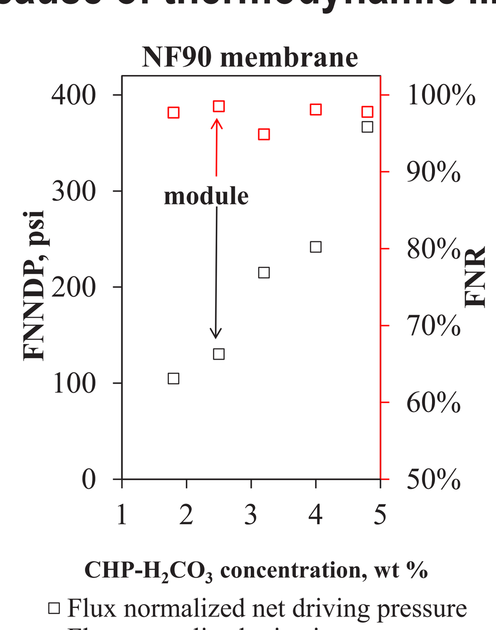
Process time reduced from days to ~1 hour and patent filed

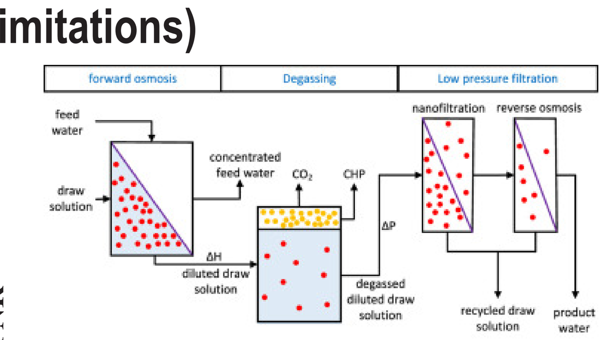


Polishing Filtration

Removal of trace concentrations of CHP from product water stream (material that cannot be removed because of thermodynamic limitations)



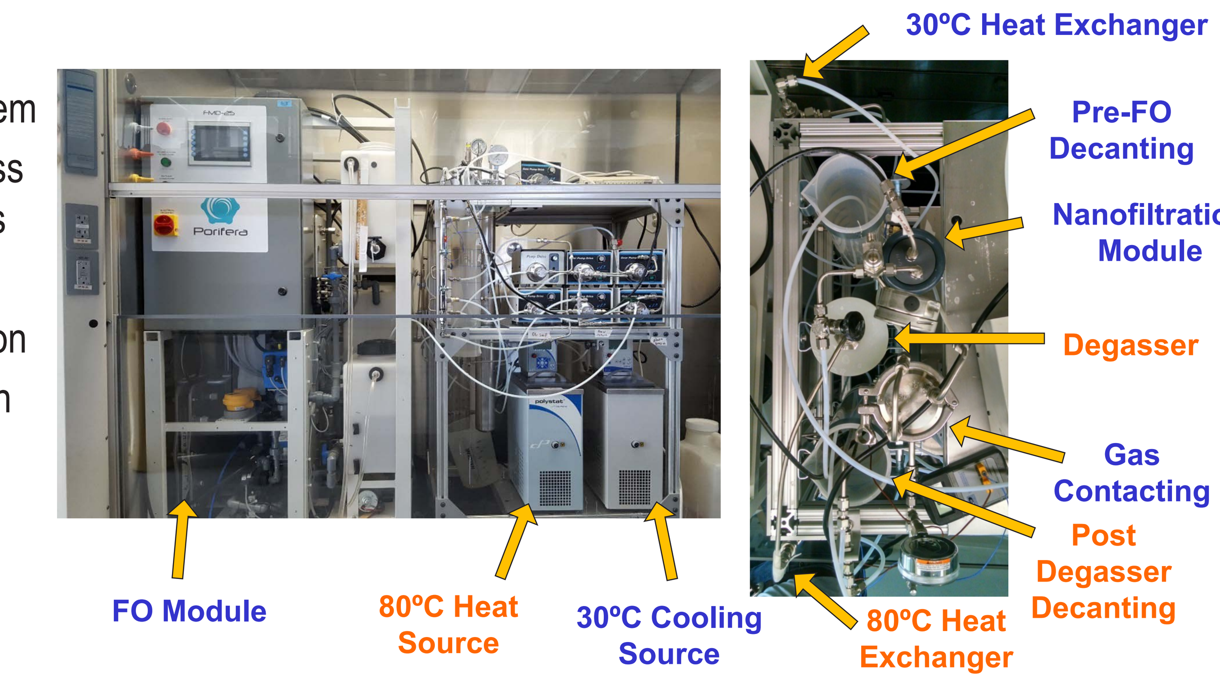




Integrated Lab Scale Unit

Continuous testing of system

- Integration of all process equipment components
- 4 LMH FO productivity
- 20°C cold side operation
- 70°C hot side operation
- 9 L/h system flow rate



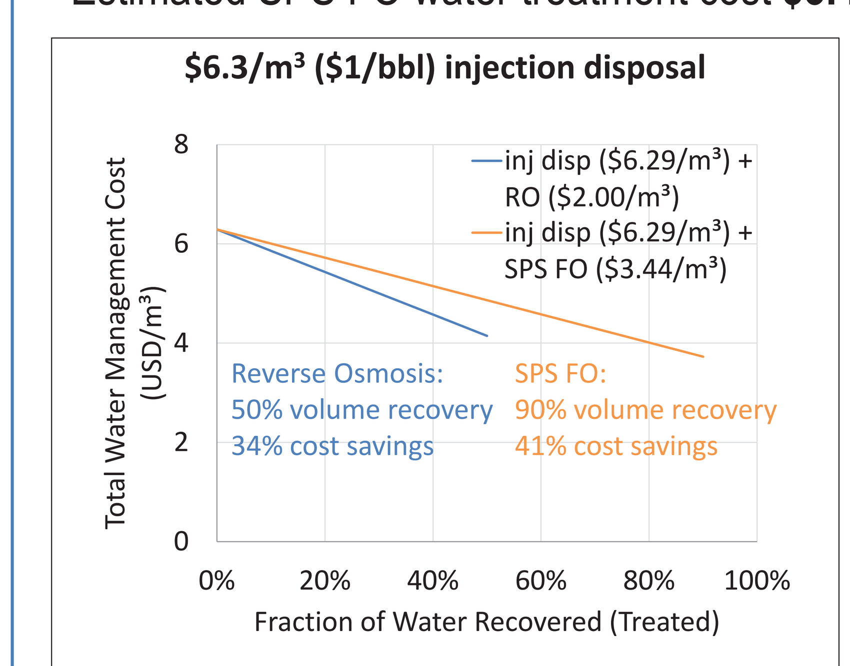
Estimated Water Treatment Cost

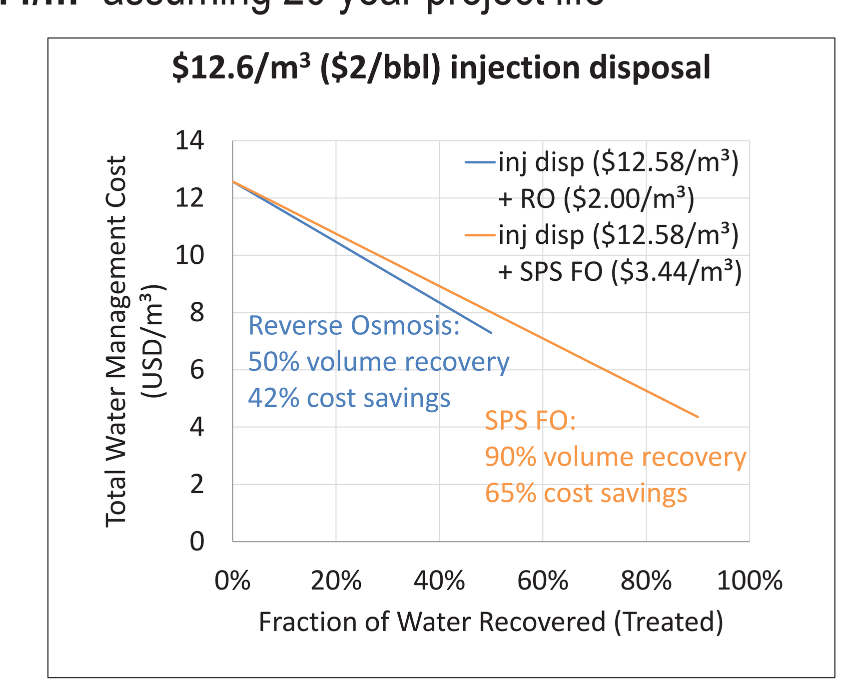
Water treatment costs estimated for an SPS FO process design for purifying 20 m³/hr of saline water with total TDS concentration similar to seawater (~30,000 ppm)

- FO Unit: Porifera FO MEM-0513 membranes, 3 countercurrent stages, 50% water recovery per stage, 4700 m² total membrane area
- Degasser: packed columns (3 recirculated stages, 20 min RT per stage) with inter-stage decanting and heat exchange, T=80°C, P=0.7 bar (absolute)
- Gas Contactor: Gas diffusion membrane unit, Single-pass with continuous operation, T=28°C, P_{liq}=1.4 bar, P_{CO2}=2.8 bar, 1200 m² total membrane area
- Polishing Filtration: DOW Filmtec NF90 and TW30 membranes in series

CAPEX estimate: $2.696 MM; OPEX estimate: $308 K per year

Estimated SPS FO water treatment cost **$3.44/m³** assuming 20 year project life





- Economic potential identified for treatment of produced water in lieu of injection
- SPS FO treatment results in lower total water management costs (treatment + disposal) than use of RO treatment or injection disposal

Current Research

- Investigation of strategies for thermal integration of SPS FO water purification process with oil & gas production operations
- Evaluation of membrane fouling compounds and process pretreatment requirements
- Identify oil & gas producers interested in hosting a potential future field demonstration

Acknowledgement

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