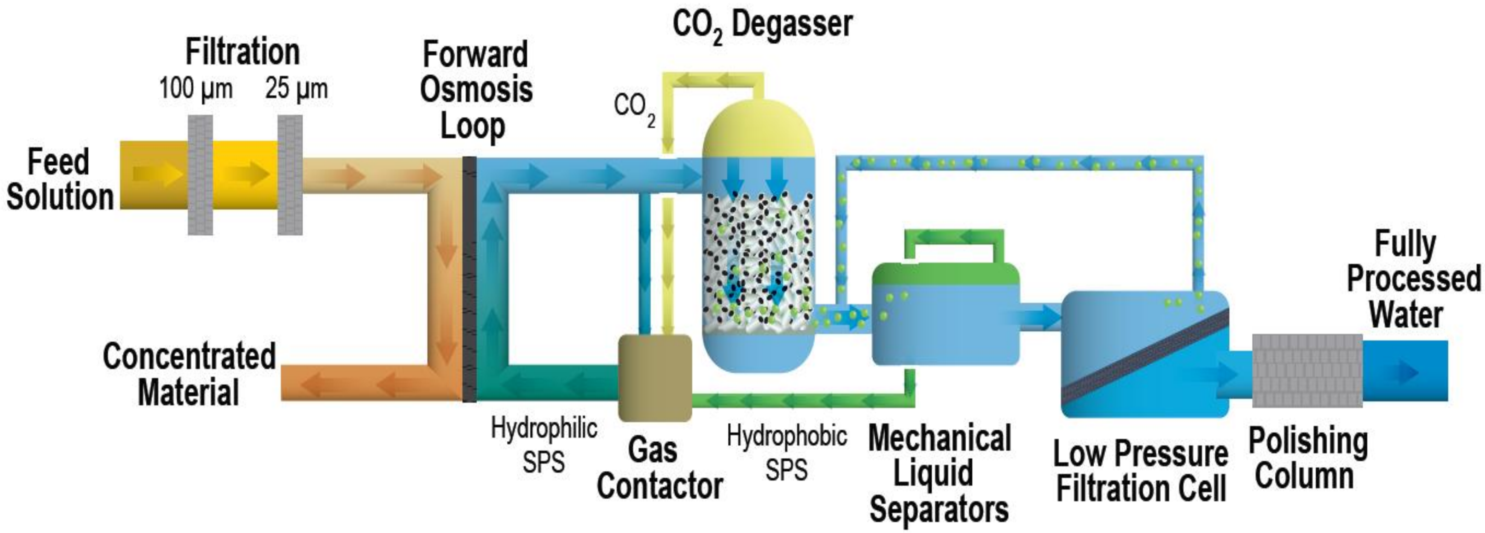
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Forward Osmosis Purification of Co-Produced Water

Project Officer: Tim Reinhardt

Total Project Funding: $950K (FY14 & FY15)

May 12, 2015

Greg Mines

Dan Wendt, Aaron Wilson

Idaho National Laboratory

Low Temp: Hybrid Value Added Systems

Relevance/Impact of Research

Objective:

- Validate that it is technically feasible to purify produced waters from oil and gas operations using a switchable polarity solvent forward osmosis (SPS-FO) process where the produced waters provide sufficient energy to operate the purification process.

Benefits:

- Purifying the co-produced water stream will reduce the volume of fluid that will otherwise require disposal at a cost to the operator
- SPS-FO operates over wide range of co-produced water chemistries, with the potential to recover up to 90% of the flow
- Potential for stand-alone operation: the energy content of co-produced fluid is sufficient to satisfy thermal and electrical energy requirements

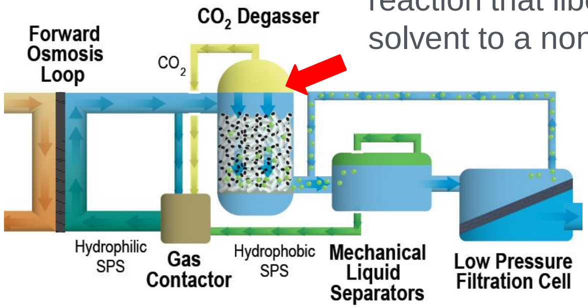
Relevance/Impact of Research

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Innovation:

- Solvent polarity changes produces hydrophobic or hydrophilic FO draw solution
- Change to hydrophobic solution is an endothermic reaction occurring at temperatures of 60º-80ºC). The amount of energy required can be entirely provided by the produced water stream being treated.

Heat added – bicarbonate decomposition reaction that liberates CO_2 which changes solvent to a non-polar form (hydrophobic)



Relevance to GTO Goals

- Reducing disposal costs could provide operators with an incentive to use the co-produced water thermal energy for power production as well as water purification. If so, it could impact GTO goals to increase low temp generation capacity and lower LCOE.

Scientific/Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Approach:

- *Leverage work from other projects*: demonstrated functionality of individual process operations and identified 2nd generation solvent
- *Engineering analysis and design*: process models developed to assess technical and economic feasibility, and to assist in equipment selection and sizing
- *Testing*:
  - Bench scale testing of both individual components and entire system
    - fill chemical property data gaps
    - establish chemical reaction rates and their sensitivity to process conditions
    - maximize mass transfer processes
    - confirmation that integrated system meets performance targets
  - Field testing of a prototype unit to confirm technical viability and attract industry partnerships
- *Economics*: utilize test results to revise/improve process models and revisit potential for economic viability as models are updated

Priorities for Bench Scale Testing (FY-15):

- Process equipment screening and selection
  - Gas Contactor
    - Column
    - Pressure vessel
    - Novel concept contactor (IP position under investigation)
  - Degasser
    - Column
    - Flash vessel
    - Novel concept degasser (IP position under investigation)
- Quantitative studies of mass transfer rates and effect of process conditions
  - Gas contactor
  - Degasser
- Identify process constraints (temperature, pressure)
- Develop strategy for obtaining preferred switchable polarity solvent

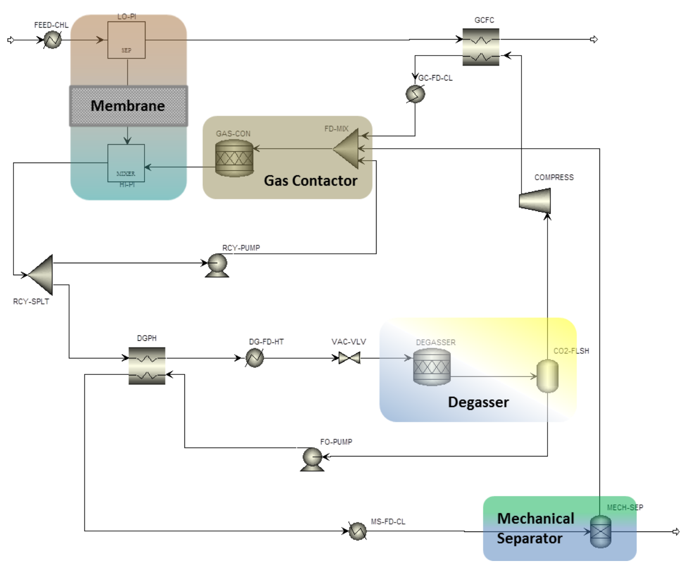
Scientific/Technical Approach

Key Issues:

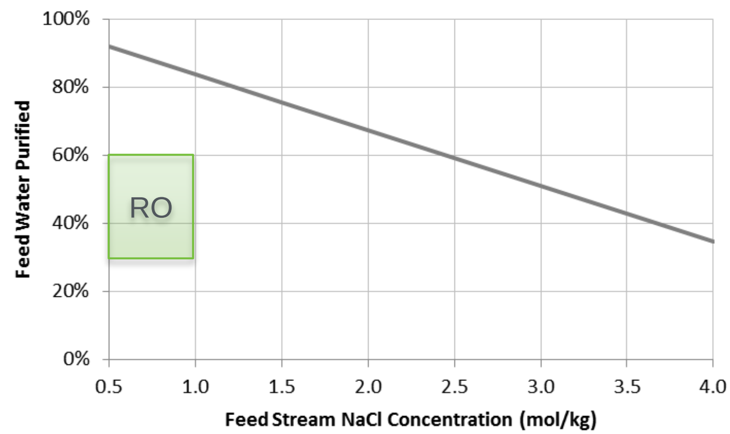
- Switchable polarity solvents
  - Corrosive
  - Degassing kinetics
  - Availability/Cost
- Absence of thermo-physical property and reaction kinetics data introduces uncertainty in selection and sizing of equipment
- Individual processes have been demonstrated in lab; they've not been integrated and tested as a 'system'

FY-14

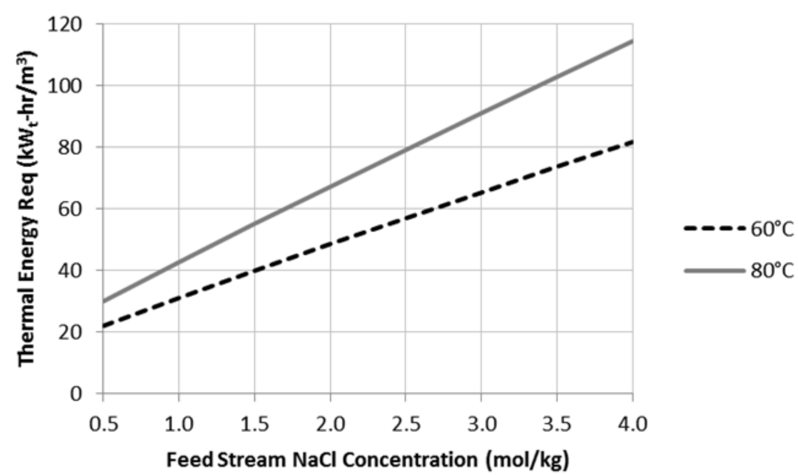
- Identified less corrosive 2nd gen solvent (1-cyclohexyl piperidine) with FO draw performance comparable to 1st gen solvent (N,N-dimethylcyclohexylamine)
- Aspen models developed characterizing system processes
- Estimates made of water recovery and energy requirements



Percentage of Saline Feed Water Stream Purified



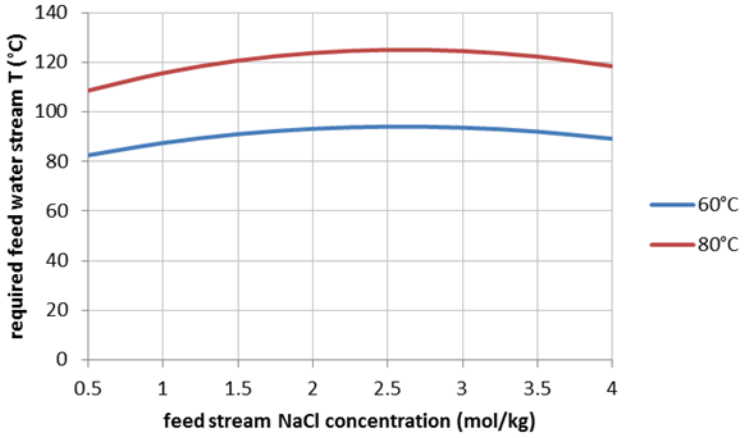
Impact of Degasser Temperature on Thermal Energy Required



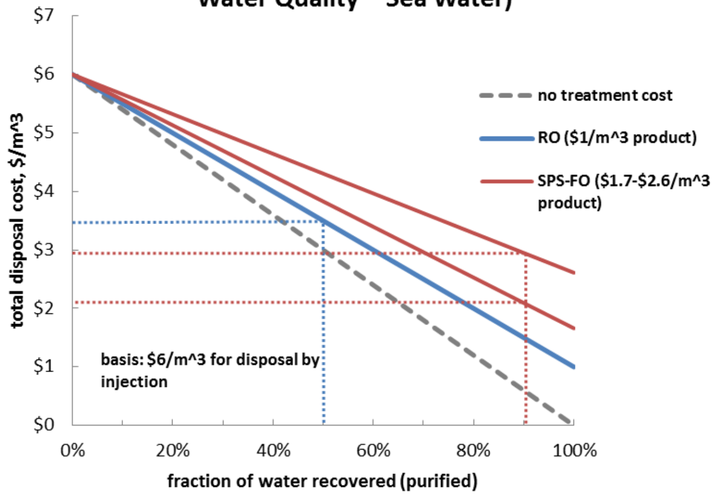
FY-14 (cont'd)

- Estimates made of feedwater temperatures needed for thermal energy and for power production
- Cost for product water estimated to be ~$1.7 to $2.6/ m^3 of treated water
- Economic potential identified for treatment of produced water in lieu of injection

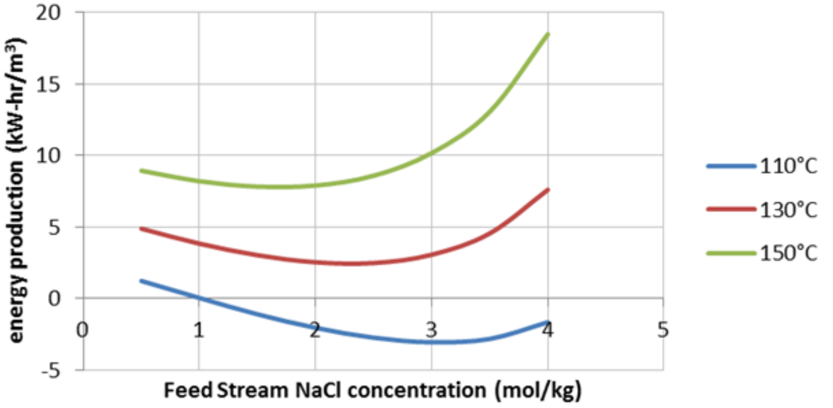
Impact of Degasser Temperature on Required Feed Water Temperatures



Impact of Water Purification on Disposal Cost (Feed Water Quality ~ Sea Water)



Potential for Power Production with Different Feed Water Temperatures (for 60^{0}C Degasser



FY15 Accomplishments, Results and Progress

- Preliminary energy requirements analysis completed and manuscript submitted to *Desalination*
- Evaluation and selection of novel gas contactor equipment type with improved performance and operational characteristics
- Selection and purchase of FO module
- Obtained internal approval to perform experimentation
- Experimental campaign
  - FO flux experiments
  - Gas contactor (pressure system, novel concept gas contactor)
  - Degasser (gas contactor results and subsequent analyses have resulted in investigation of new degasser equipment relative to initial, immersed heating coil design)

Gas Contactor Investigations

Prior Work (not funded by GTO) – Batch process, long time to full conversion

Glass Gas Wash Bottle

- Pressure: ~ambient
- Volume: ~0.5 L
- Full Conversion
  - Batch
  - ~2 weeks

Analytical System

- Pressure: ~ambient
- Volume: ~0.015 L
- Full Conversion
  - Batch
  - ~3 days

FY15 Work (funded by GTO) – Moved to continuous process with markedly reduced time to full conversion

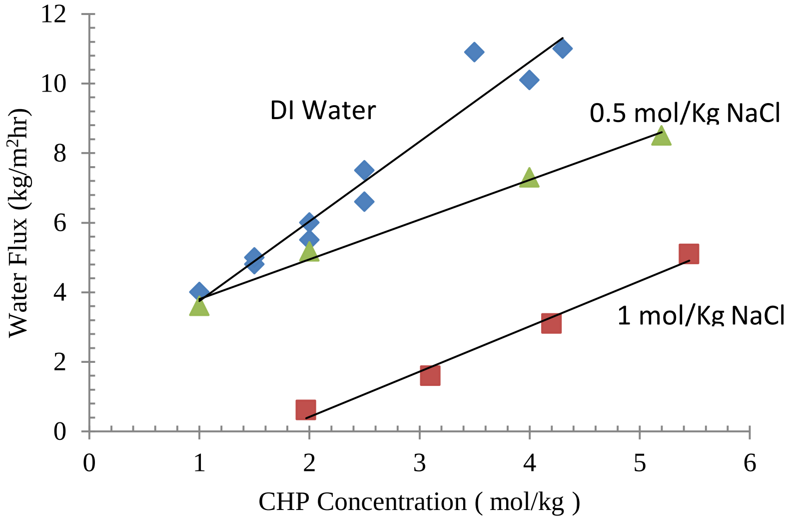
Pressure system

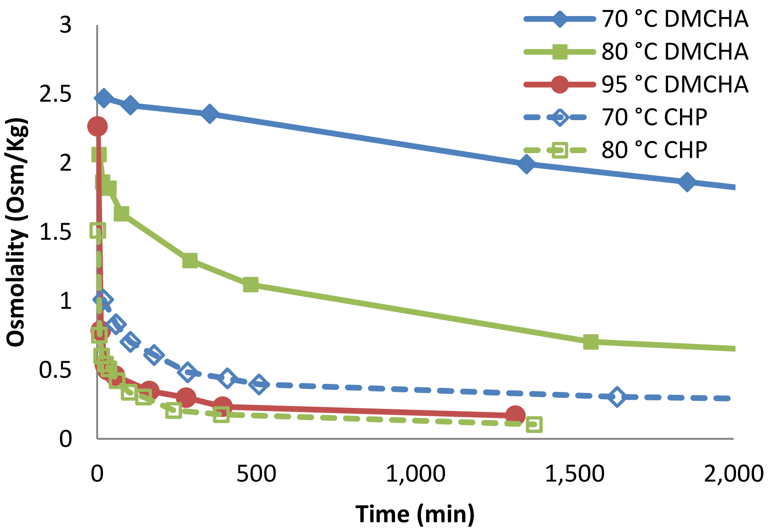
- Pressure: ~40 psi
- Volume: ~0.5 L
- Full Conversion
  - Batch
  - ~3 hours

2nd Gen Gas Contactor

- Pressure: ~ambient
- Volume: any
- Full Conversion
  - Continuous
  - ~0.5 L/hour
  - Easily scalable

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy





FO membrane flux studies:

- FO flux demonstrated over a range of concentrations for three feed concentrations.
- FO flux demonstrated stable for 32 hours for single membrane.
- Water flux achieved with 1st and 2nd generation SPS draw are comparable
- 2nd generation SPS significantly less corrosive than 1st generation

2nd generation SPS degassing studies:

- Multiple order of magnitude decrease in time required to remove SPS from aqueous phase
- Superior degassing performance can be achieved at lower temperatures with 2nd generation SPS

Accomplishments, Results and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Develop integrated model of SPS-FO processes	An Aspen model was developed that characterized major components of the SPS-FO process	June 2014
Complete feasibility assessment and provide recommendations as to whether to proceed	Determined that thermal energy to operate system could be provided by co-produced fluids at an cost less than injection disposal costs – recommend to proceed to bench scale testing	Sept 2014
Initial Design of Degasser	An initial design of the degasser was completed	Dec 2014
Imitate testing of assembled process equipment	Testing of the gas contactor has started	Mar 2015

Delayed receipt of FY15 funds has required adjustment of test schedule. Testing is initiated on individual components as they are received.

Future Directions

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Remainder of FY15

- The priorities for remainder of FY15 will focus on the bench scale testing of the gas contactor and the degasser
  - finalize equipment selection to provide preferred mass transfer rates
  - identify sensitivity of the kinetics to process conditions.
- The project has a milestone of demonstrating an FO membrane flux of 3 liter/hr for 100 hrs by the end of June. This milestone can not be met because of the delayed receipt of funding. We are currently testing equipment as it is received, which we've found to be preferable to testing the integrated system. We expect to have the integrated system assembled and testing begun prior to the end of FY15.
- As data is being generated from the testing, the Aspen process models will be revised

Future Directions

FY16

- Complete equipment screening and testing for the gas contactor and degasser
- Develop methods for final purification of product waters
- Revisit the feasibility analysis and confirm there is potential for economic viability
- Complete equipment specification and design of prototype system to be field tested
- Identify location for field testing and begin soliciting industrial partnerships

FY17

- Procure equipment and construct prototype system
- Deploy at selected site and perform testing to confirm technical viability

Mandatory Summary Slide

- The SPS-Forward Osmosis process development is at a TRL-3. The individual processes have been demonstrated in the laboratory, but the basic information needed to move to field testing a prototype system is not available.
- Co-produced waters with temperatures in excess of ~100ºC are likely to have sufficient thermal energy to drive the process. Those with temperatures above ~120ºC may allow for a cascaded system that also produces electrical power
- Though this process is likely to have higher costs than RO, it has an advantage in that it can recover a larger fraction of the feed stream over a wider range of salinity. This can make it economically attractive in offsetting disposal costs of co-produced waters.