Active CO_2 Reservoir Management

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Developing the Technologies and
Infrastructure for CCS

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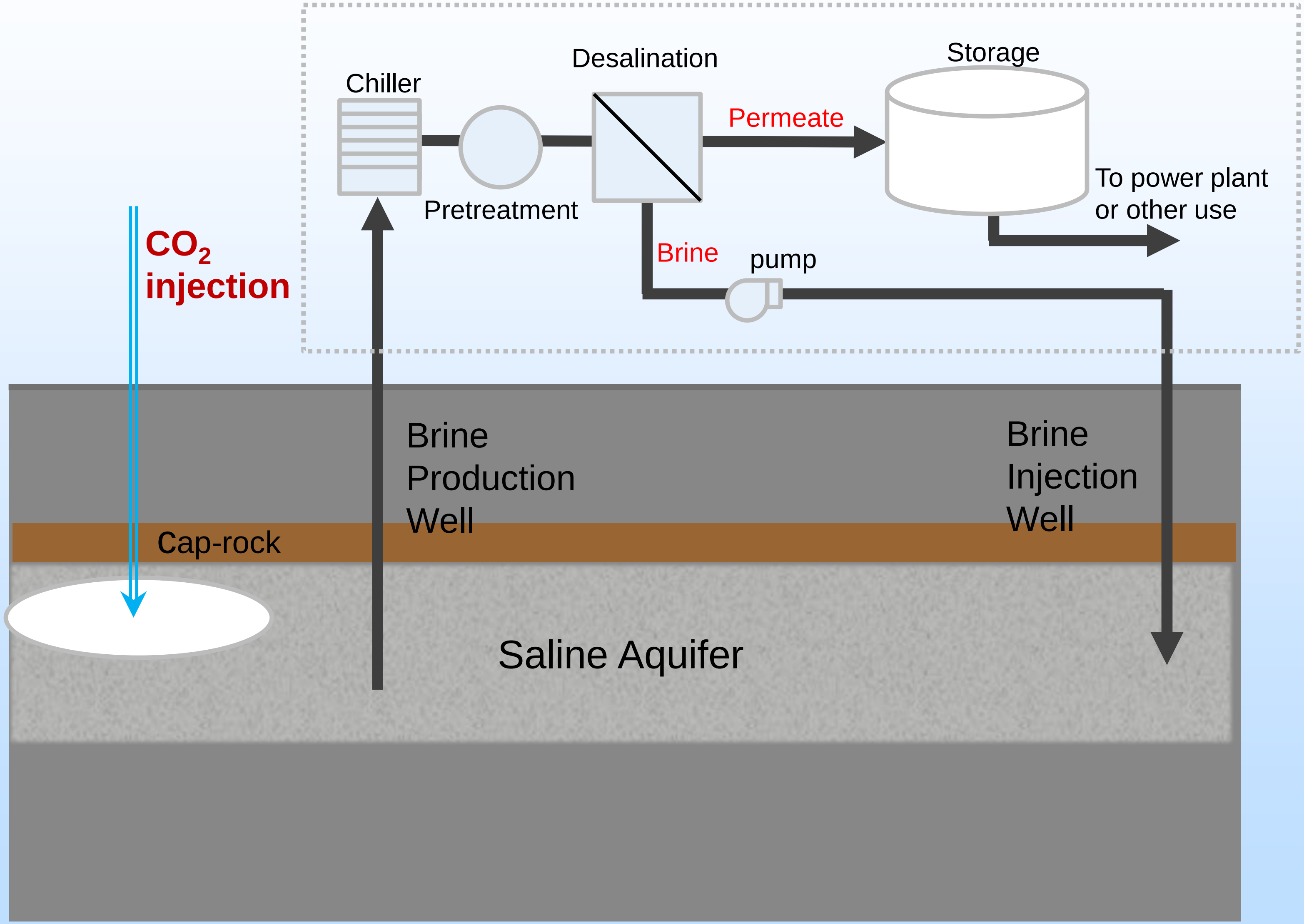
Concept is to extract and desalinate aquifer brines to create fresh water and space for CO_2 storage



Presentation Outline

- Overview, Purpose, Goals and Benefits
- Technical status
  - Brine treatment and disposition
  - Reservoir management
- Accomplishments
- Summary and Planned work

Goals and Objectives

Technical Goals

Potential advantages of brine extraction:

• Allow reduction and active management of pressure in the subsurface

• Reduce the risks of cap rock failure and induced seismicity

• Provide a source of water for power plant cooling or other uses

Project Goals

• Use modeling to provide brine extraction/injection strategies that maximize CO_2 storage and minimize storage risk

• Identify technologies and cost estimates for brine disposition

• Provide quantitative input for overall cost-benefit analysis of brine extraction as a process used in carbon storage

Benefit to the Program

This project addresses all four program goals:

- Predict capacity
  - Brine removal affects/enhances storage capacity
- Assure permanent storage
  - Enhances cap-rock integrity and reduces induced seismicity
- Improve storage efficiency
  - Allows manipulation of sub-surface pressure field to maximize storage efficiency
- Best practices, especially site selection
  - Identifies preferred sites in terms of brine compositions

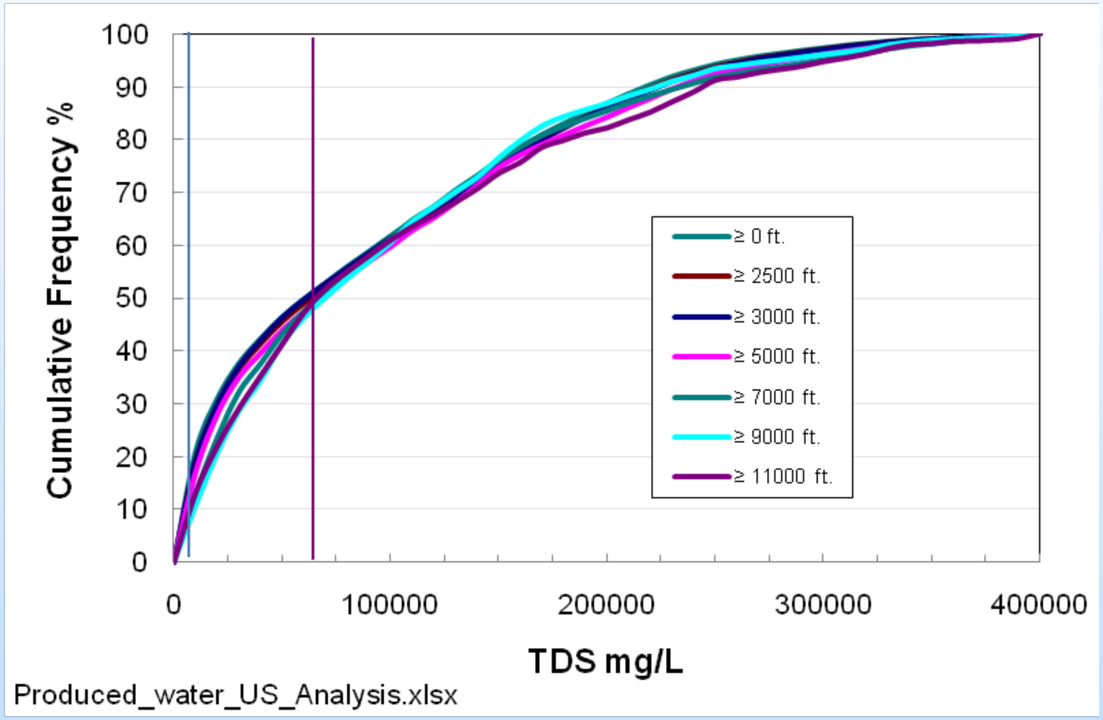
This project provides an analysis of brine extraction as a method for increasing the storage capacity and reducing the risk of failure at carbon storage sites.

Technical Status Outline

- Brine disposition
  - Expected brine compositions and characteristics
  - Appropriate desalination technologies
  - Analysis of membrane technologies
  - Markets for fresh/saline water derived from the brine
  - Estimated costs for desalination
- Reservoir engineering
  - Summary of progress on brine extraction/injection strategies

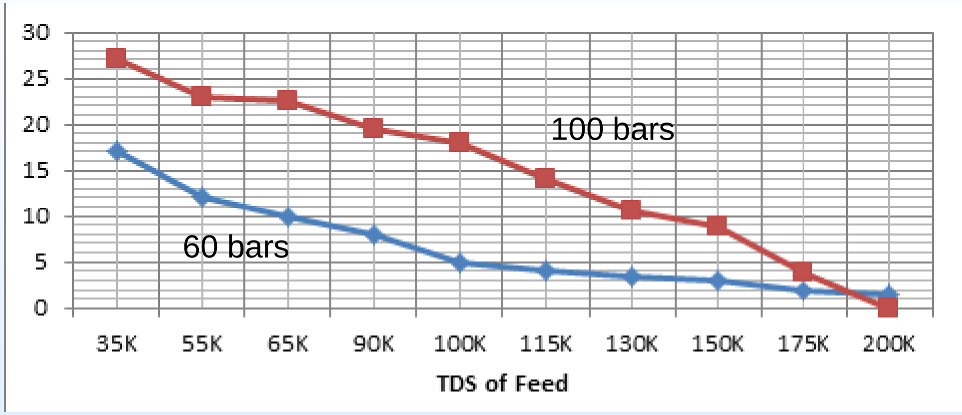
We should consider the compositions of formation fluids when choosing potential sequestration sites

- Formation fluids DO NOT become more saline with depth – to lower desal costs choose a site with lower salinity
- Membrane-based technologies are least expensive
- Thermal methods are needed to treat the highest salinity fluids (>20 wt% salt).
- High sulfate contents help enable nanofiltration to remove hardness in staged treatment
- Reservoir/brine temperatures up to at least 120^{o}C are favorable for membrane desalination



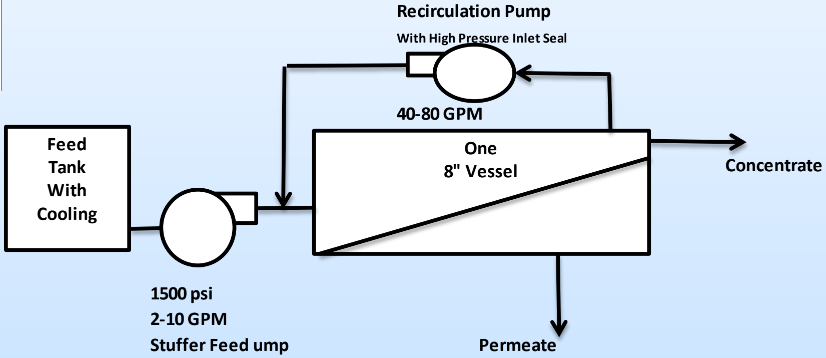
Bench-top tests of high pressure RO and NF were carried out and results used for cost estimation

Permeate flux (GFD) vs. Salinity



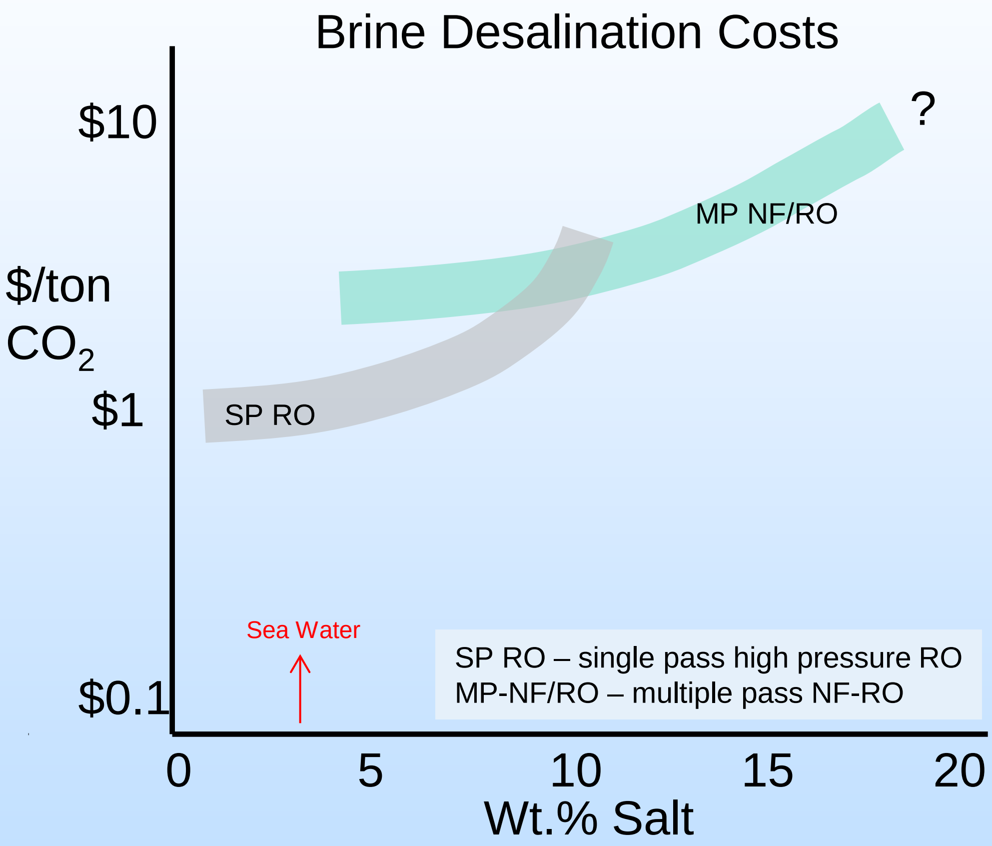
- Osmotic pressures increase with salinity
  - Sea water ~ 25-30 bars
  - 10 wt% brine ~ 80 bars
- Commercial membranes become impermeable at these pressures
- Staged treatment is possible using “loose” membranes that allow some salt passage

- Few data exist for desalination of brines more saline than sea water
- We carried out membrane desalination tests of brines up to 20 wt % to help extrapolate costs
- Membrane Development Specialists (MDS) carried out the tests



Staged treatment can extend the salinity range to cover brines up to 18 wt% - but at additional expense

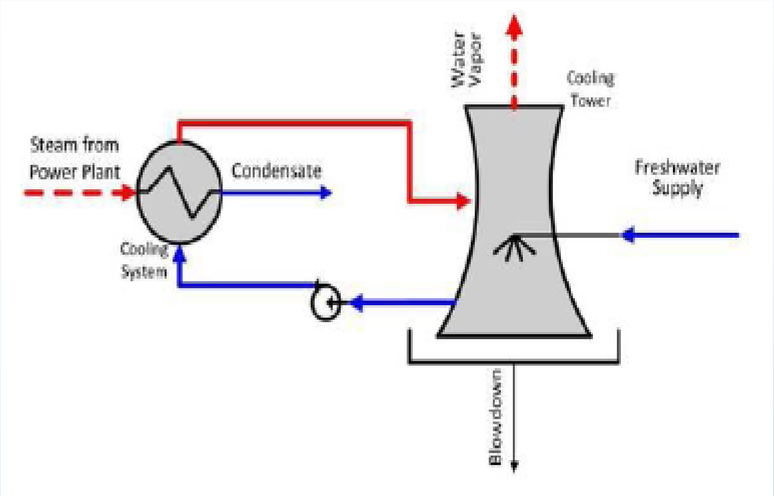
- Plot shows costs for surface treatment facilities
  - Does not include well-field costs
- Conversion to \$/ton assumes vol/vol of CO_2 at density $0.75 cm^3/g$
- Single pass high pressure RO can desalinate brines up to about 8-10 wt%
- Multiple-pass NF-RO systems can extend this limit to almost 20 wt % but at substantial additional cost
- Costs are significant but not large compared to overall CCS costs



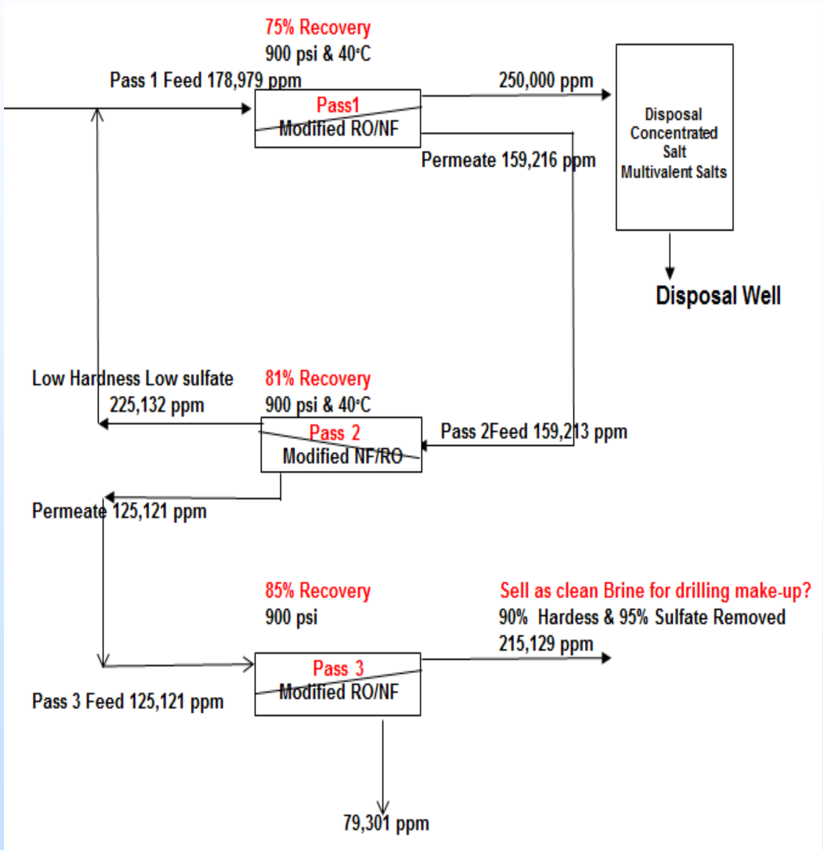
Rule of thumb: \$Cost per ton CO_2 = (Brine Salinity/Sea water salinity)

Multiple options are available for surface disposition of the treated saline water

- How much water?
  - 1 GW plant = 8000 acre-feet/y
  - Supply domestic needs of a town of 60,000 people
- That volume will supply about half the cooling water needed for a coal-powered plant
  - Important in arid regions and may make a power plant possible
- Other options:
  - Agricultural and potable water for local use
  - Saline cooling towers
    - Use softened water from NF
  - Saline oil-field make-up waters (11 wt % NaCl)
    - Use softened water from NF



Staged membrane treatment allows generation of tailored fluids for alternate uses



3-pass process flow diagram using NF membranes

- NF membranes separate monovalent from divalent species
- NF permeates are saline but lack hardness (Ca + Mg)
- Strategic combinations of RO and NF can generate useful saline fluids as well as potable water

Limits of membrane desalination technologies

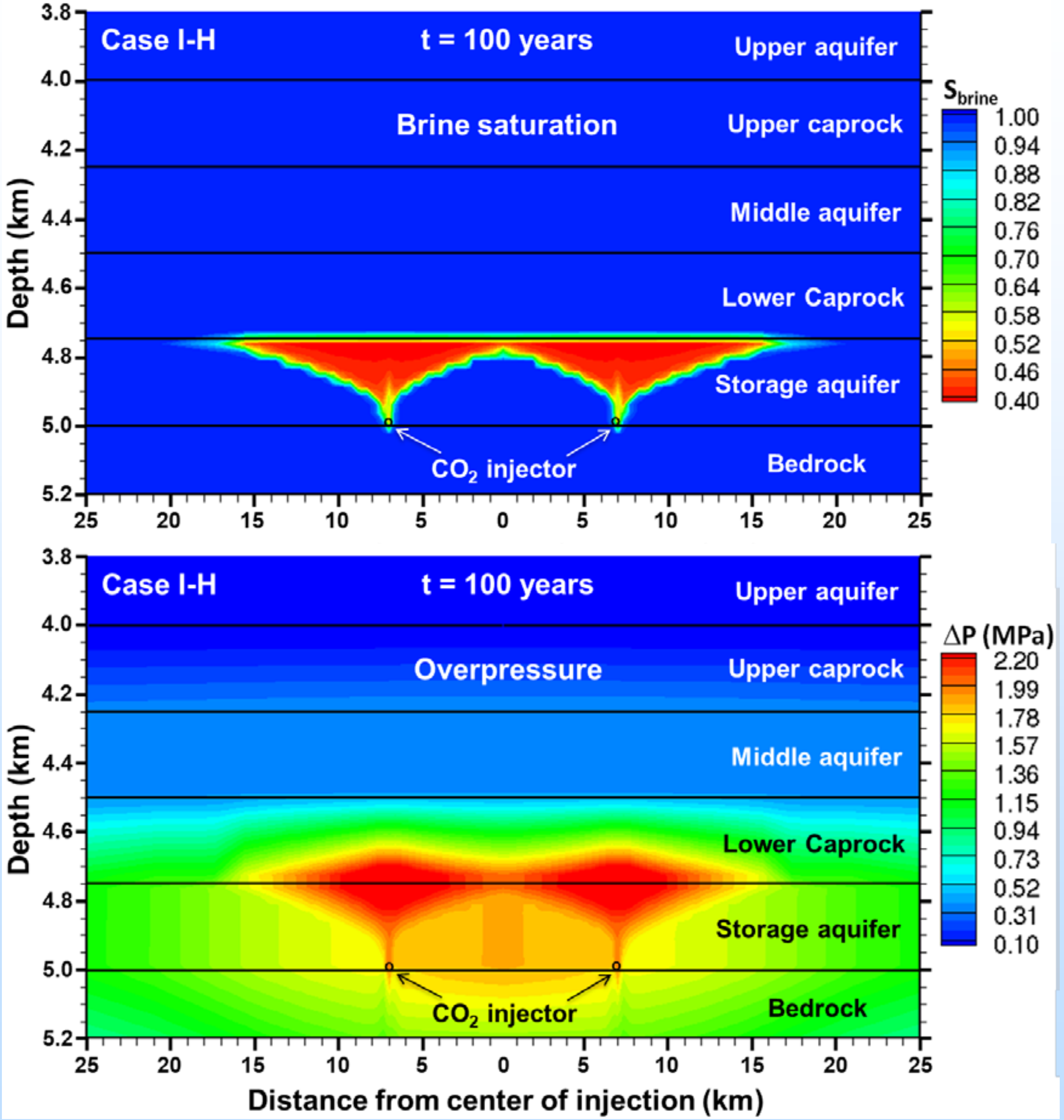
10,000-40,000 mg/L:	Standard RO with ≥ 50% recovery
40,000-85,000 mg/L:	Standard RO with ≥ 10% recovery; higher recovery possible using 1500 psi RO membranes and/or multi-stage incremental desalination including nanofiltation
85,000-300,000 mg/L:	Multi-stage process (NF + RO) using process design that may differ significantly from seawater systems
> 300,000 mg/L:	Not likely to be treatable

Overview of Pressure Management

- Strategies for pressure management using:
  - brine consumption via beneficial use
  - brine redistribution within a stack of saline aquifers (separated by impermeable seal units)
- Goals:
  - reduced risk of cap-rock fracturing and induced seismicity
  - suppressed CO_2 migration and leakage, reduced AOR
  - hydraulic isolation from neighboring subsurface activities
- Constraints
  - avoid CO_2 and brine breakthrough in well-field
  - limit well-field costs
    - Dual use wells
    - Vertical displacement strategies

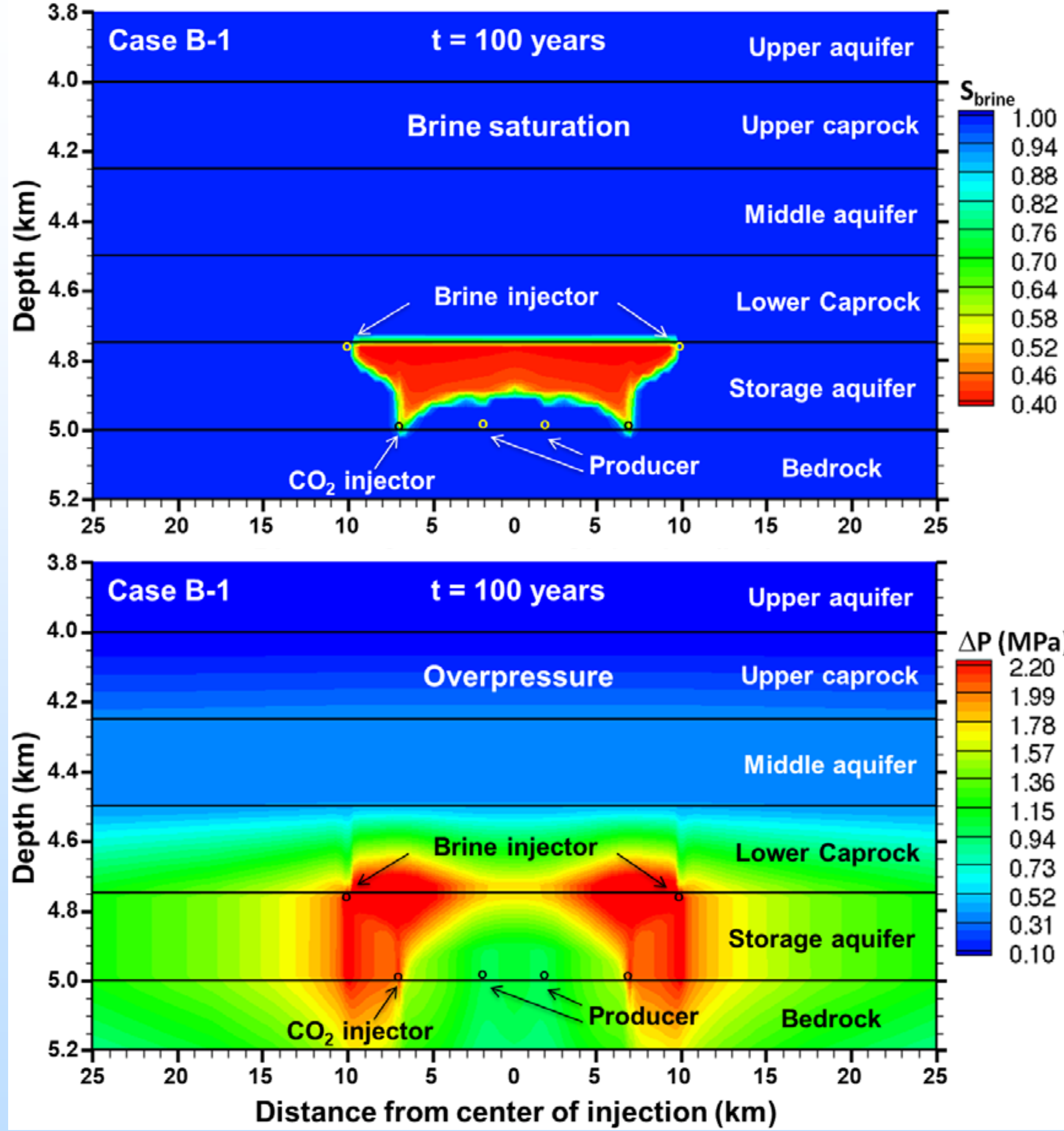
CO_2 injection with horizontal wells - baseline

- **30,000 km² semi-closed reservoir**
  - similar in size to Illinois basin
  - stack of 250-m-thick,100-md saline aquifers and 10^{-3}-md seal units
  - bottom of storage aquifer at 2.5 km depth
- **2 horizontal injectors**
  - running normal to the figures
  - 4-km perforated length
  - spaced 14 km apart at bottom of storage aquifer
- **CO_2 injection = 15 MT/yr**
  - CO_2 from 2 GWe of coal power plants
  - 100 years of injection



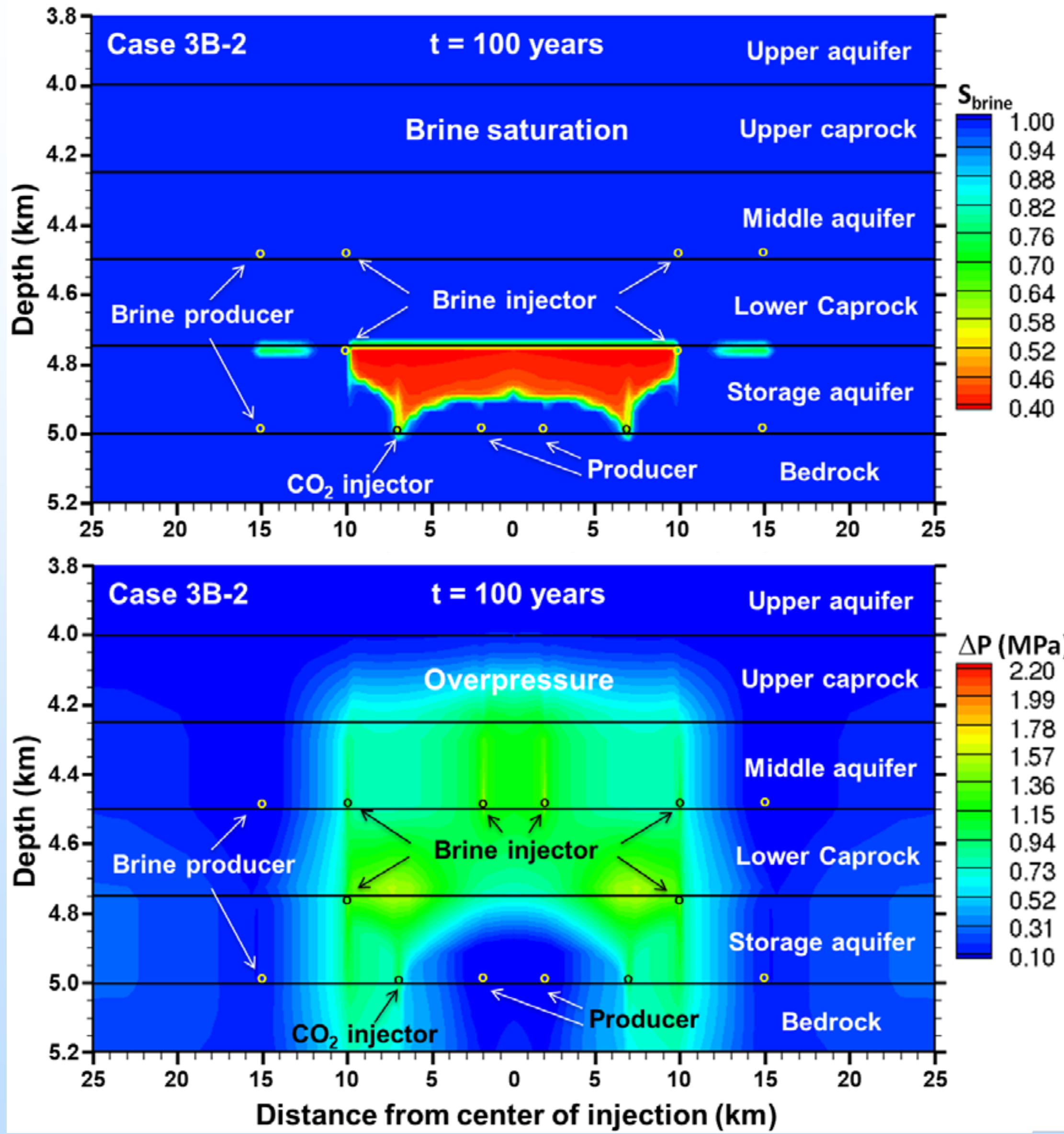
Brine production and reinjection in storage aquifer

- **4 horizontal brine producers**
  - at bottom of storage aquifer with 1-km perforated length
  - spaced 4 km apart and 5 km from CO_2 injectors
  - each producing 120 kg/sec for 100 yr
- **2 horizontal brine injectors**
  - 4-km perforated length at top of storage aquifer
  - spaced 3 km from CO_2 injectors
  - no brine consumption (reinject all produced brine)
- **Overpressure redistribution**
  - hydraulic barrier confines lateral CO_2 migration
  - no changes above lower caprock or laterally in the far field

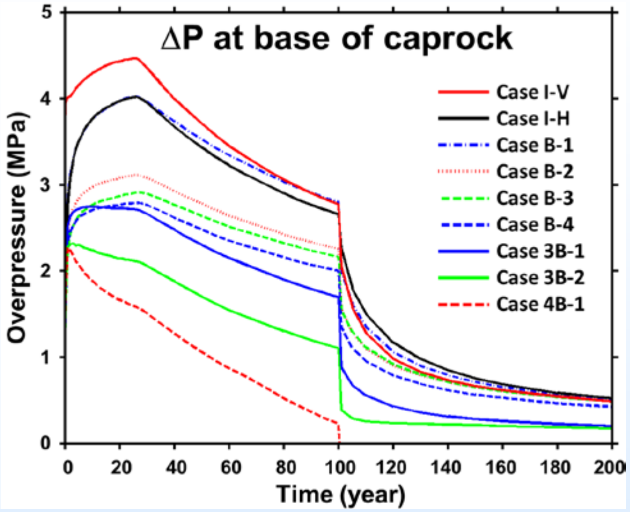


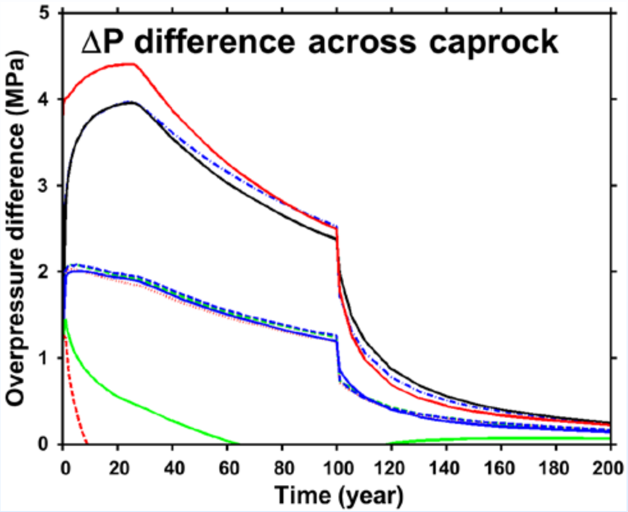
Brine production with desalination

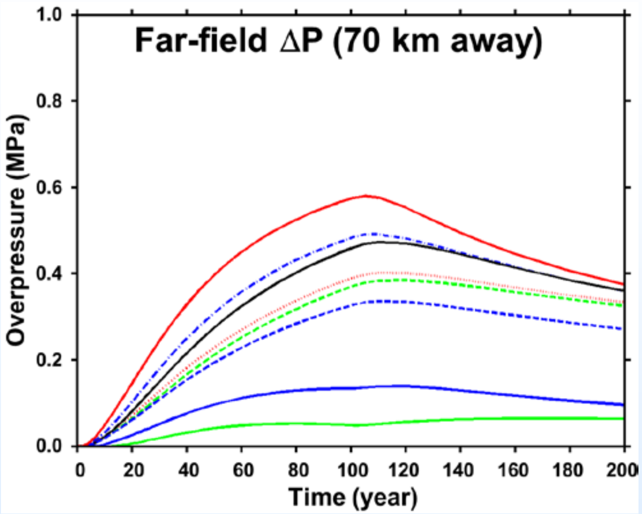
- **16 horizontal brine producers**
  - 4 in middle of storage aquifer
  - 8 at outer of storage aquifer
  - 4 at outer of overlying aquifer
  - 34% of produced brine (16,701 acre-ft/yr) is recovered for beneficial use
  - 66% of produced (residual) brine is reinjected
- **Overpressure redistribution**
  - hydraulic barrier (ridge) suppresses CO_2 migration and leakage
  - brine consumption creates a hydraulic trough, isolating the GCS operation from neighboring subsurface activities, reducing the Area of Review (AoR) and risk of induced seismicity



Overpressure reduction can be achieved by a combination of brine consumption and brine redistribution







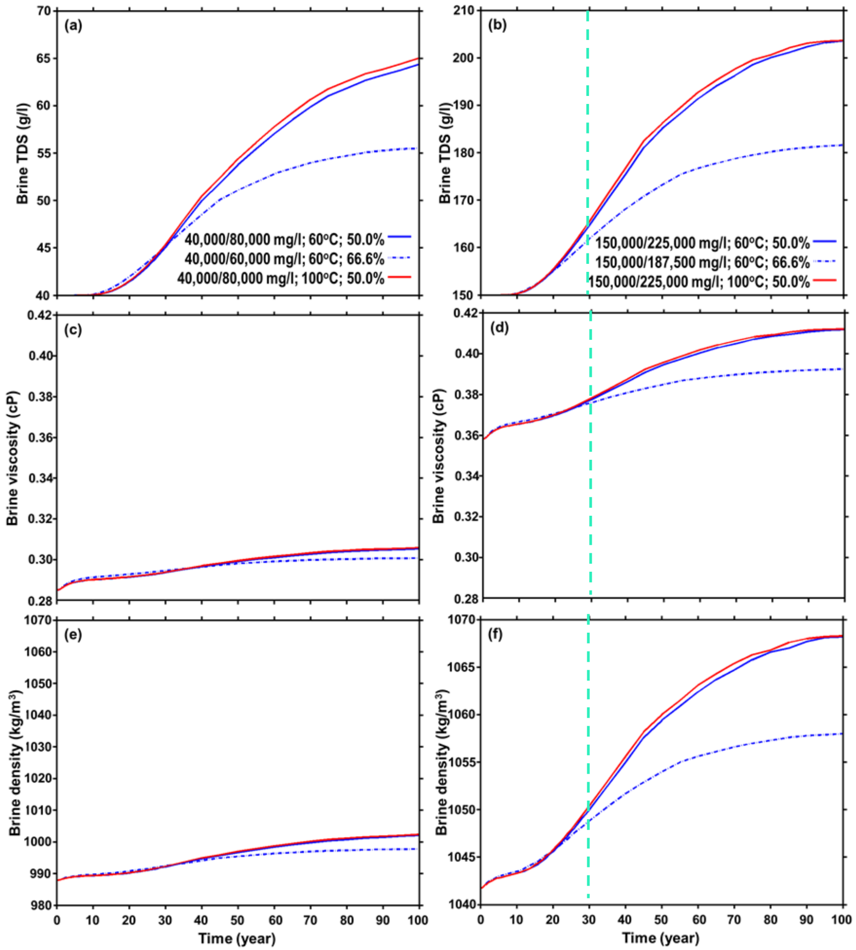
- **A range of brine consumption and redistribution scenarios were considered**
- **Overpressure difference across caprock and far-field pressure perturbation can be nullified while reinjecting a majority (66%) of the produced brine**

Case	Production/ injection mass ratio	Net mass (CO_2+H_2O) injection rate (kg/sec)	Product water generation rate (acre-ft/yr)	CO_2-injector-to-brine-injector spacing	Brine injectors in overlying saline aquifer	Brine-injection-to-production mass ratio	Number of brine producers	Notes
I-V	0	480	N/A	N/A	N/A	N/A	N/A	Vertical
I-H	0	480	N/A	N/A	N/A	N/A	N/A	Horizontal
B-1	1	480	0.0	3 km	0	1.0	0	Horizontal
B-2	1	480	0.0	3 km	2	1.0	0	Horizontal
B-3	1	480	0.0	6 km	2	1.0	0	Horizontal
B-4	1	316.8	4,175	3 km	2	0.66	0	Horizontal
3B-1	3	-9.6	12,526	3 km	4	0.66	8	Horizontal
3B-2	3	-9.6	12,526	3 km	4	0.66	8	Horizontal
4B-1	4	-172.8	16,701	3 km	4	0.66	12	Horizontal

Residual-brine breakthrough occurs around 10 years for all cases considered

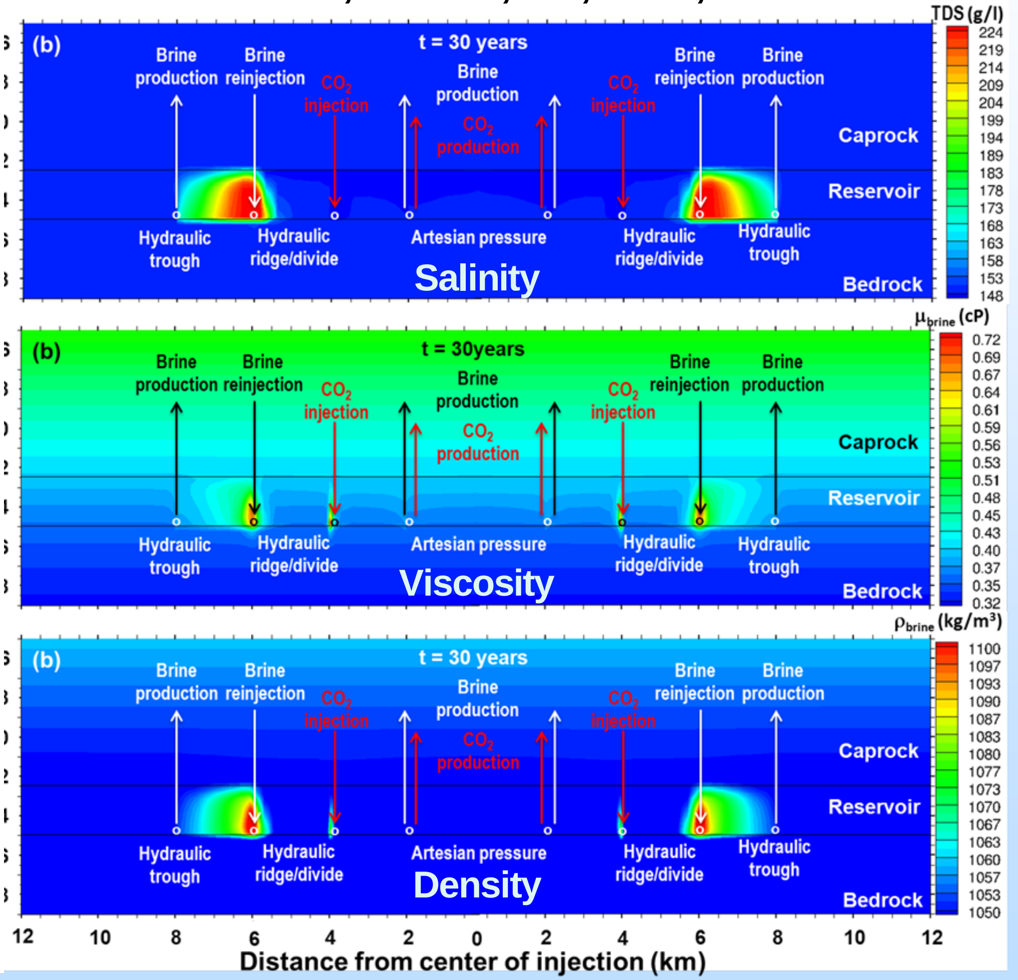
History at outer brine producers

Cases 1-3 **Cases 4-6**



Vertical cross section at 30 years

Case 4: 150,000/225,000; 60°C; 66.6%



Summary

Reservoir Management Task

- Pressure management can be achieved using a combination of
  - brine consumption
  - brine redistribution within a stack of saline aquifers separated by impermeable seals
- We have developed well patterns that achieve one or more of the following
  - reduced overpressure in the subsurface
  - creation of a hydraulic ridge to suppress CO_2 migration and leakage
  - creation of a hydraulic trough to isolate the GCS operation from neighboring subsurface activities and to limit pore-space competition and the AOR

Brine management task

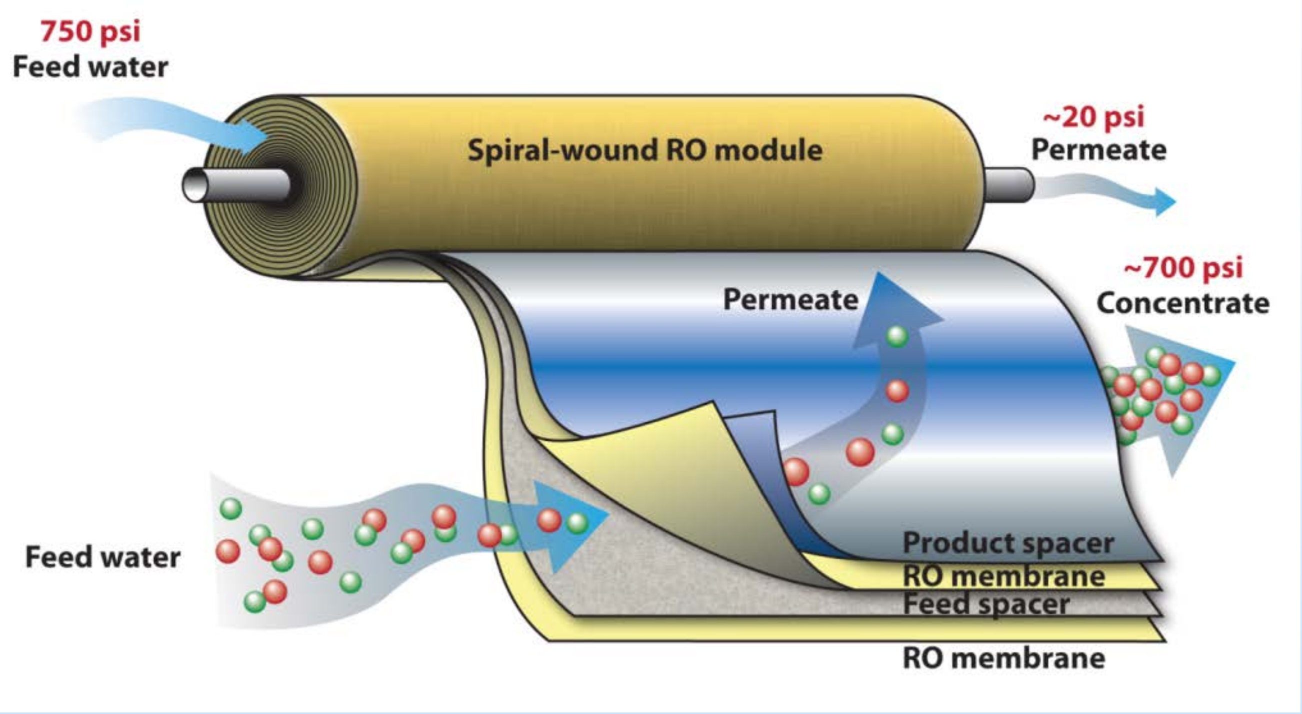
- We have competed an analysis of likely brine compositions
- Carried out laboratory work to enable desalination cost estimates for treatment of high salinity fluids

Future Plans

- Begin work to field test brine extraction
  - Select partner and site
- Re-focus reservoir modeling on simple systems
  - Minimize well-field costs while getting maximum pressure management benefit

A low-risk R&D effort could extend the range of RO technology to at least 150^{o}C and 100 bars

The polyamide membrane is not the limiting factor

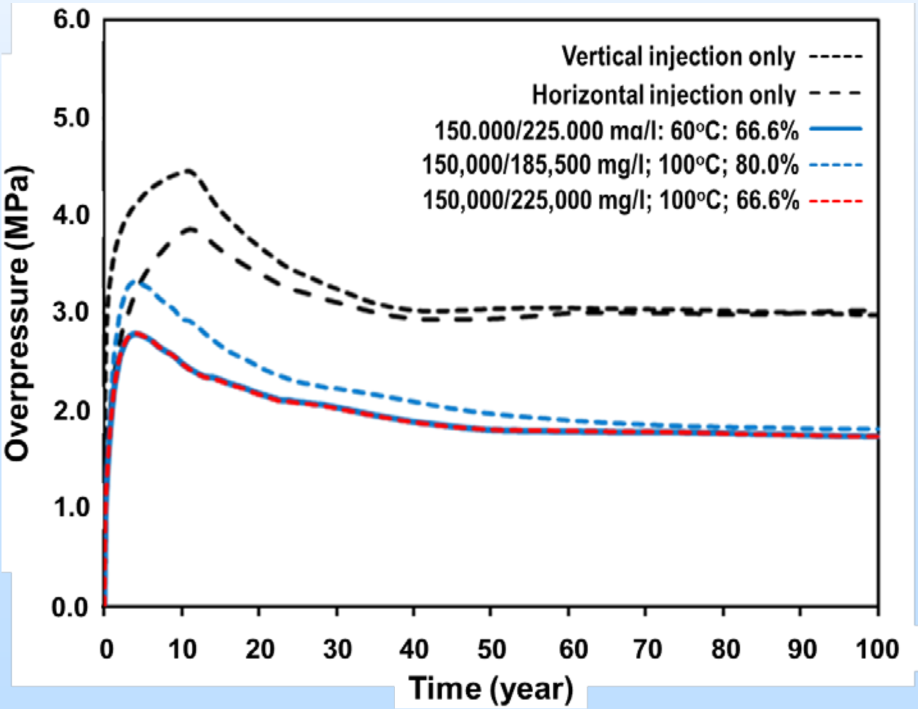


Allows desalination of brines with salinities up to 15 wt %

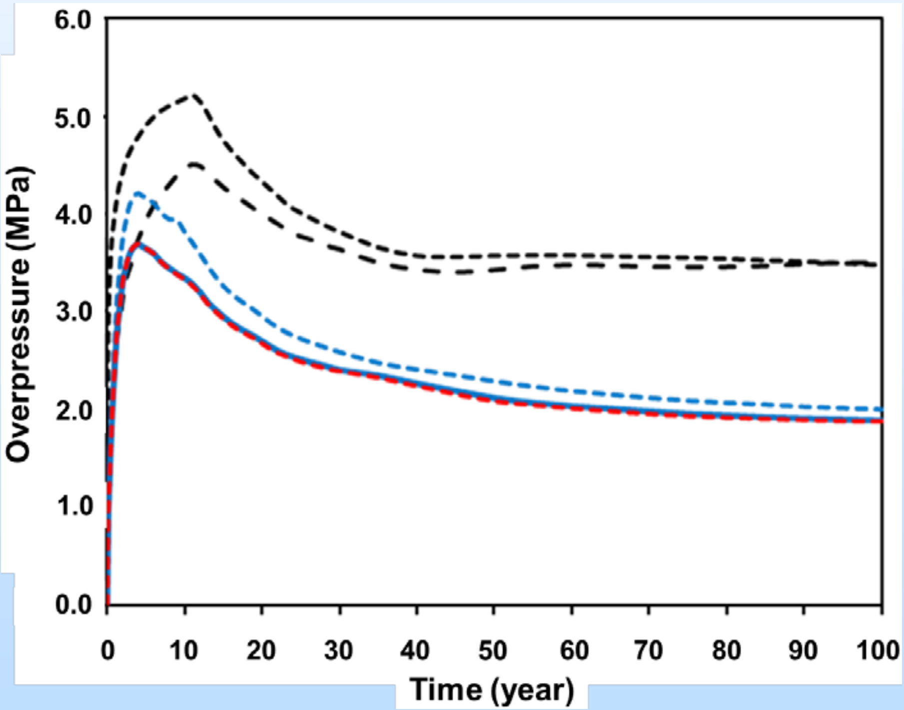
Brine redistribution can achieve substantial pressure reduction while reinjecting a majority of the residual brine

- Maximum overpressure is sensitive to formation salinity and temperature
  - increasing with salinity
  - decreasing with temperature
- Maximum overpressure is insensitive to salinity and temperature of injected residual brine
- Overpressure is reduced with increased brine consumption

Cases 1-3



Cases 4-6



Accomplishments and Findings

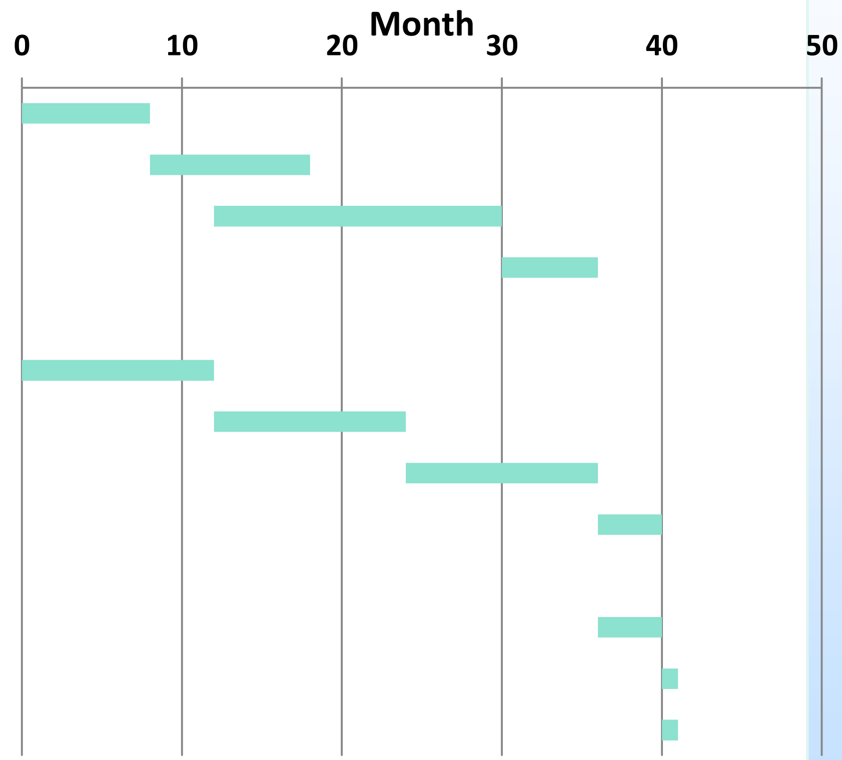
- Finished analysis of expected brine compositions
  - Types and salinities
- Desalination technology selection
  - Membrane methods preferred over thermal
- Completed high pressure membrane desalination tests
  - Showed existing membrane technologies to be useful for fluids up to 175,000 ppm TDS
- Carried out modeling of simple to complex reservoir systems

Organization Chart

- Project team:
  - Lawrence Livermore National Laboratory
    - William Bourcier P.I. – brine disposition
    - Thomas Buscheck – reservoir modeling
    - Thomas Wolery (ret.) – brine disposition
    - Susan Carroll – Project Manager
    - Roger Aines – Carbon Program Leader
  - Membrane Development Specialists (MDS)
    - Subcontractor – Membrane desalination testing
  - Water System Specialists (in negotiation)
    - Subcontractor – Thermal desalination

Project Timeline

Tasks		Start	Duration	Finish
Brine Disposition	1.0			
Brine characterization	1.1	0	8	8
Desalination technology evaluation	1.2	8	10	18
Treatment cost analysis	1.3	12	18	30
Reporting	1.4	30	6	36
Reservoir Management	2.0			
Preliminary analysis	2.1	0	12	12
Integration with CO2 injection	2.2	12	12	24
Optimization	2.3	24	12	36
Analysis in support of partnering	2.4	36	4	40
Site Demonstration	3.0			
Site selection and partnering	3.1	36	4	40
Modeling to support site demonstration	3.2	40	1	41
Setup and site work	3.3	40	1	41



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