Active CO_2 Reservoir Management

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Developing the Technologies and Building the Infrastructure for CO_2 Storage

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Team Members

- Roger Aines
- Bill Bourcier
- Tom Wolery
- Tom Buscheck
- Tom Wolfe (consultant)
- Mike DiFilippo (consultant)
- Larry Lien (Membrane Development Specialists)

Presentation Outline

- Overview of Active CO_2 Reservoir Management (ACRM)
- Subsurface Reservoir Management: Made Possible by Brine Production, Yielding Many Benefits
- Brine Disposal Options
  - What brines are out there?
  - What are the treatment options?

Benefit to the Program

- This project is identifying and evaluating methodologies and technologies to support actively managing the subsurface storage system by means of brine production. This project contributes to the Carbon Storage Program’s effort of ensuring that 99% of injected CO_2 remains in the injection zones (Goal 2).

Project Overview: Goals and Objectives

- Develop the concept of actively managing the subsurface storage system by incorporating brine production
  - Develop and evaluate options for storage reservoir management
  - Provide and evaluate the most promising options for treatment and disposal of produced brine
  - Overall, find ways to improve the likelihood of CO_2 containment and reduce total system cost
- This project is developing the framework of an alternative to “conventional” CO_2 disposal.

What is ACRM?

- ACRM is a holistic approach based producing brine from the storage formation to make room for CO_2
- It allows the storage system to be managed in some important ways:
  - Limiting the overpressure (magnitude, affected geographic area)
  - Influencing the shape and migration of the CO_2 plume

ACRM Requires Disposal of Large Volumes of Brine

- Produced brine may be treated to make freshwater or saline cooling water
- Treatment produces some fraction of more concentrated residual brine that can be reinjected into the storage formation
- Untreated produced brine or residual brine may be reinjected elsewhere

Origins at LLNL

- Our project began as a narrowly focused brine treatment project
- A peer review panel encouraged us to add a “subsurface systems” component
- We began to see connections
- We evolved to develop and evaluate options for storage reservoir management and treatment/disposal of produced brine

Broader Origins

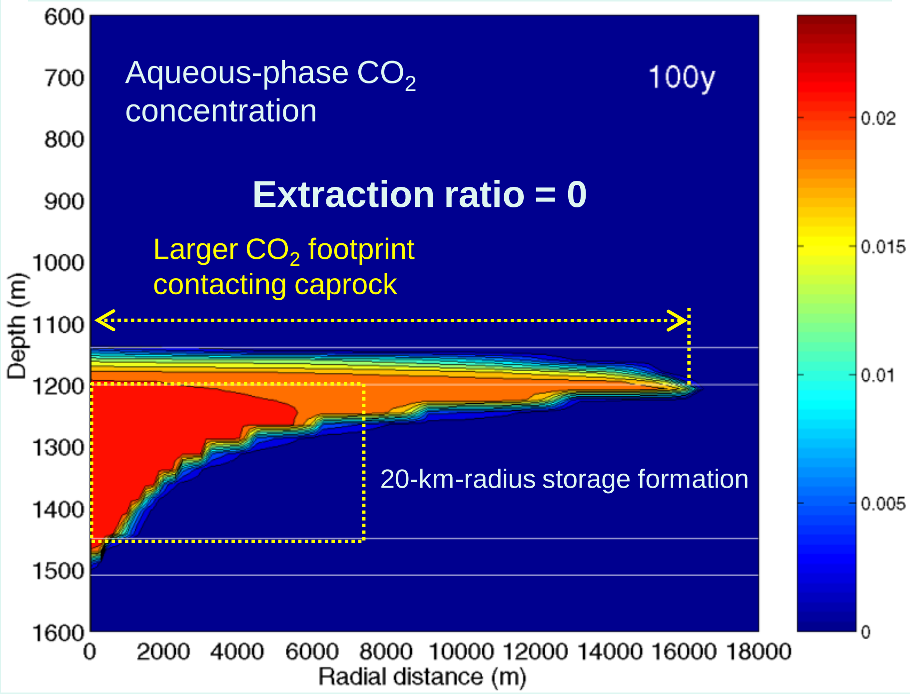
- LLNL and Princeton jointly proposed the term ACRM
- A review of literature from the period 2009-2011 suggests that perhaps as many as six groups could reasonably claim to have originated the idea that brine production was necessary or desirable

Simulations of the Storage System Show the Potential of ACRM

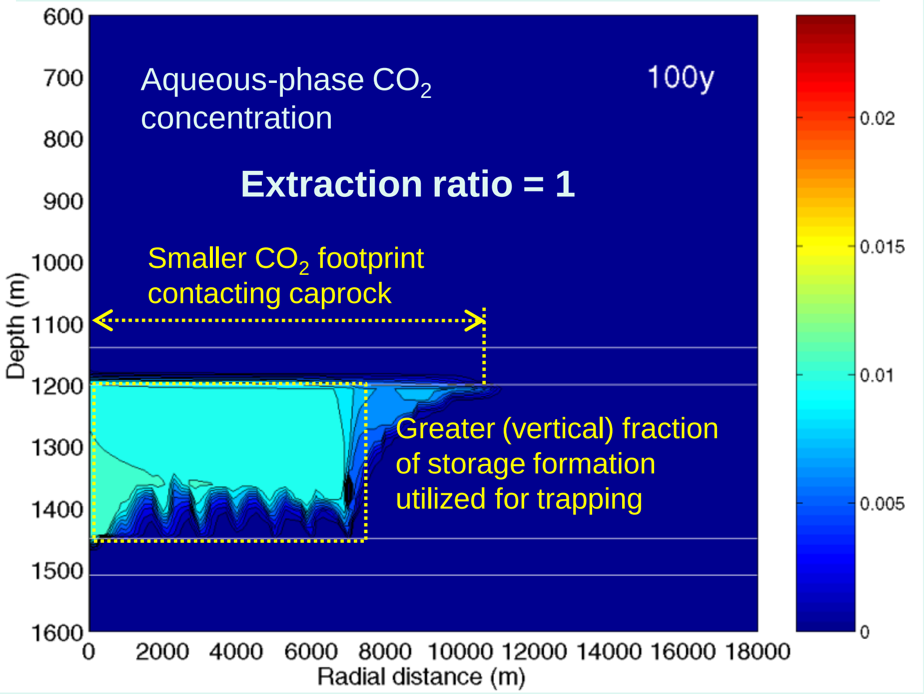
- We used the NUFT code
- The models include a CO_2 injection well and one or more brine production wells
- These results are intended to be illustrative
- They are not for a specific geologic disposal site and similar calculations would be needed for any such site

Plume Behavior is Strongly Affected by Brine Production

No brine production



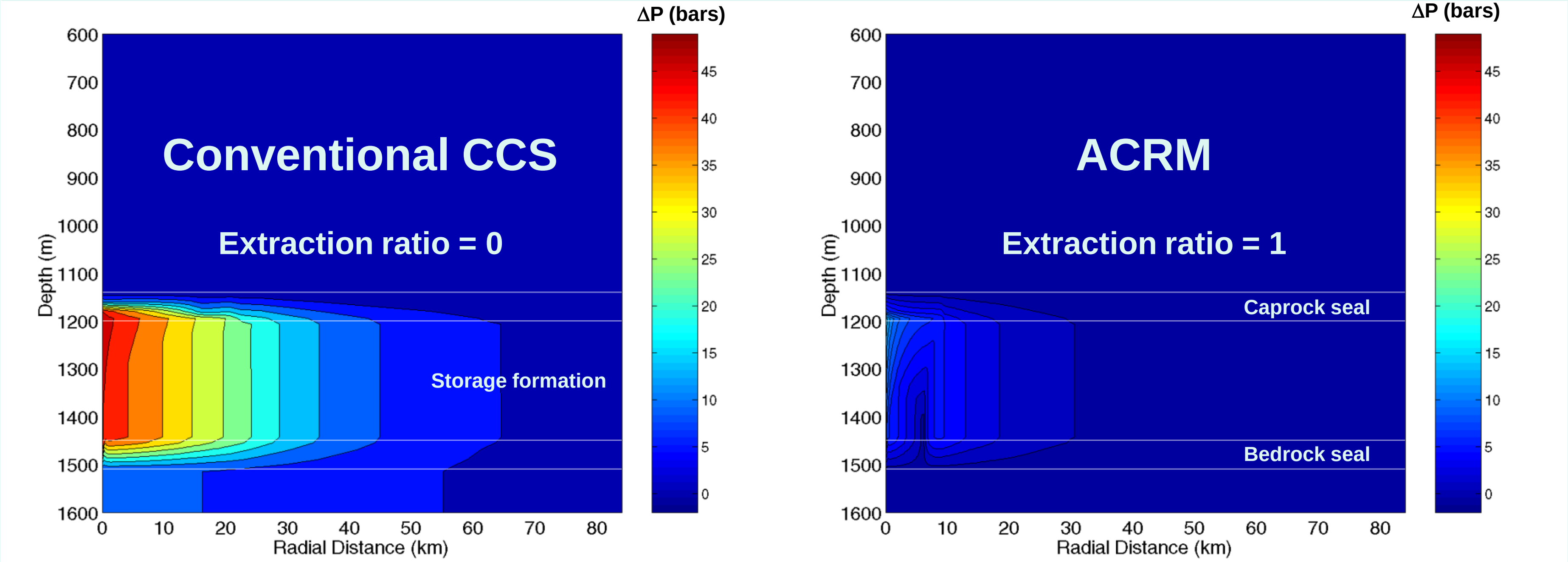
ACRM



- **Reservoir permeability = 100 mD**
- **Caprock-seal permeability = 0.001 mD**
- **20-km-radius storage formation**
- **15.1 million ton/yr injection for 100 yr**
- **Total injected mass = 1515 million metric tons**

More Significantly, the Pressure Field is Strongly Affected

Pressure buildup at the end of injection



- **Seal permeability = 1 x 10^{-18} m^2**
- **100-km-radius storage formation**
- **15.1 million ton/yr injection for 100 yr**
- **Total injected mass = 1515 million metric tons**

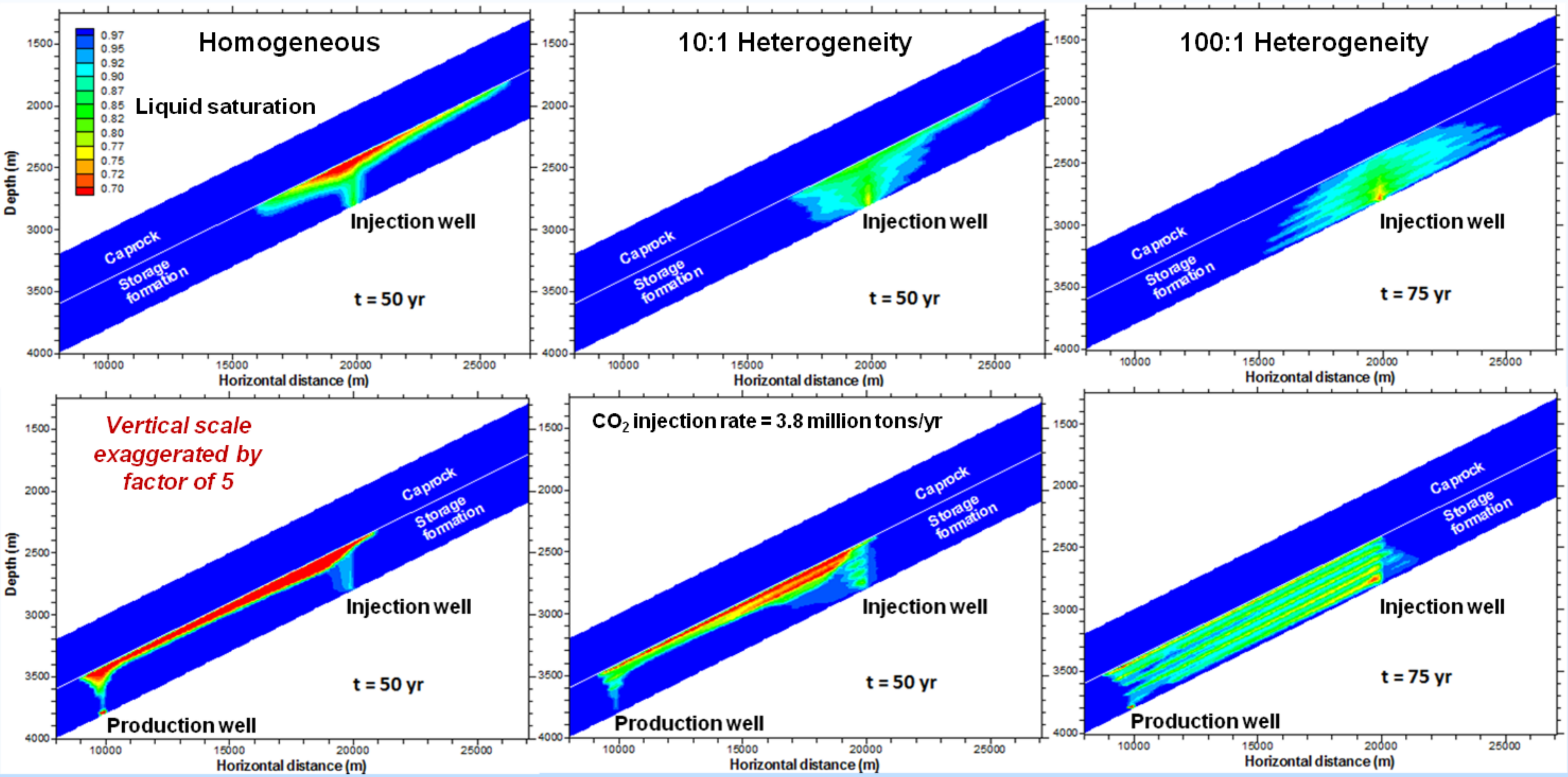
Notable Results

- The plume is confined to a smaller area
- CO_2 is more effectively distributed vertically in the storage formation
- The magnitude of the overpressure is reduced
- The geographic area overlying the overpressure field is smaller

Several Benefits are Apparent

- Reduced lateral migration of the plume
- Increased storage capacity per unit area
- Reduction of the major driving force (overpressure) for
  - Migration of CO_2 or brine through caprock
  - Seismicity
- Reduced Area of Review (AoR), which is tied to the extent of the overpressure field

Effect of Brine Production on Plume Behavior in a Dipping Formation



Brine Treatment

- Brine treatment is attractive because it reduces the volume of brine that must be disposed of
- Furthermore, it produces a useful product
  - Freshwater
  - Saline cooling water

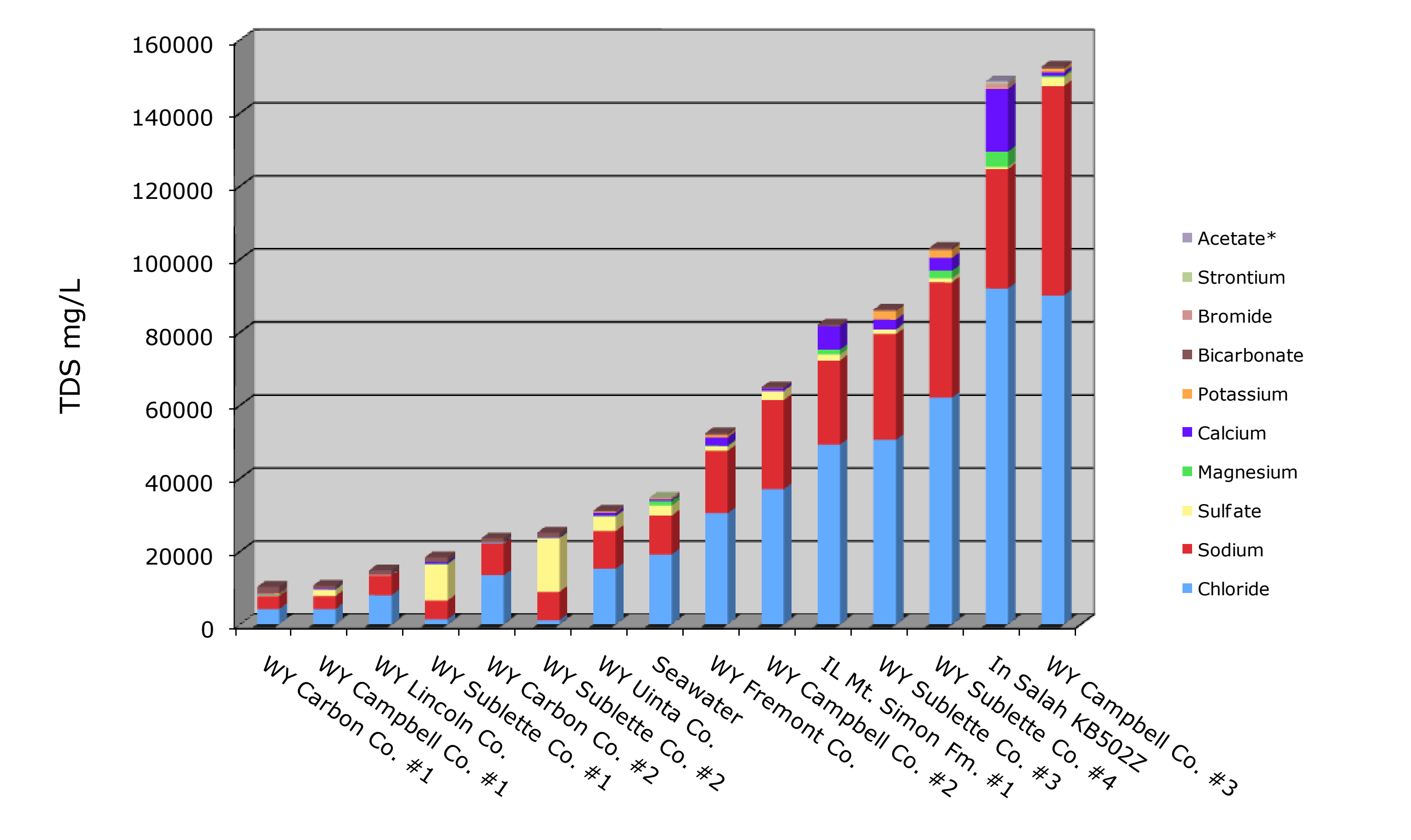
Two Questions

- What kinds of saline formation waters are treatable, and how? We need to keep in mind that:
  - Treatment technologies will improve
  - Economic analysis must consider the whole disposal system (i.e., recognize cost off-sets)
- What kinds of saline formation waters are out there?

Total Dissolved Solids (TDS) is a key descriptor of saline water composition

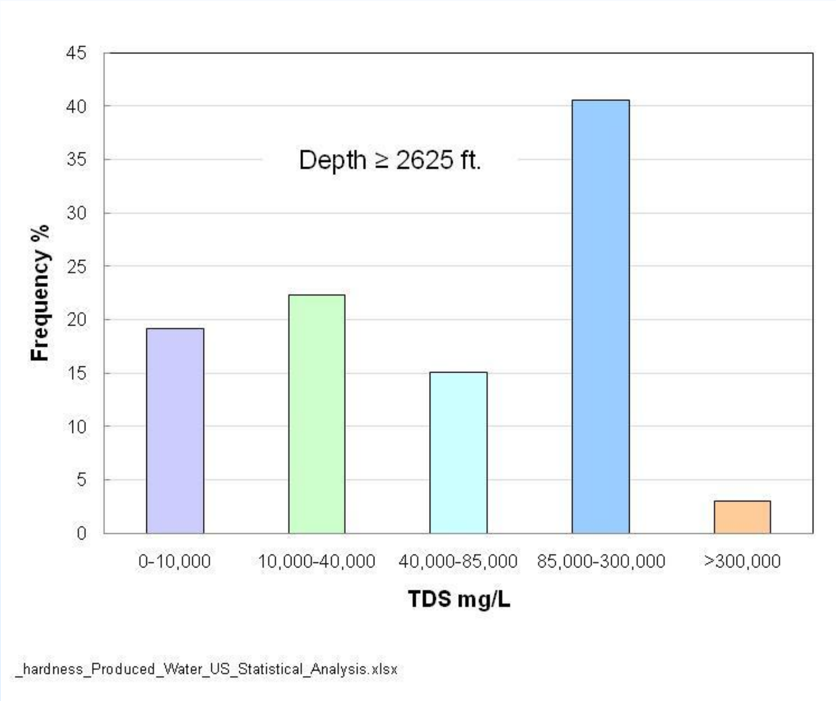
- The TDS of natural formation waters spans approximately 1,000-400,000 mg/L
- EPA requirement: the TDS of the storage formation water must exceed 10,000 mg/L
- We expect that lower TDS brine will be more treatable than higher TDS brine
  – Better results and lower cost, regardless of specific approach or technology

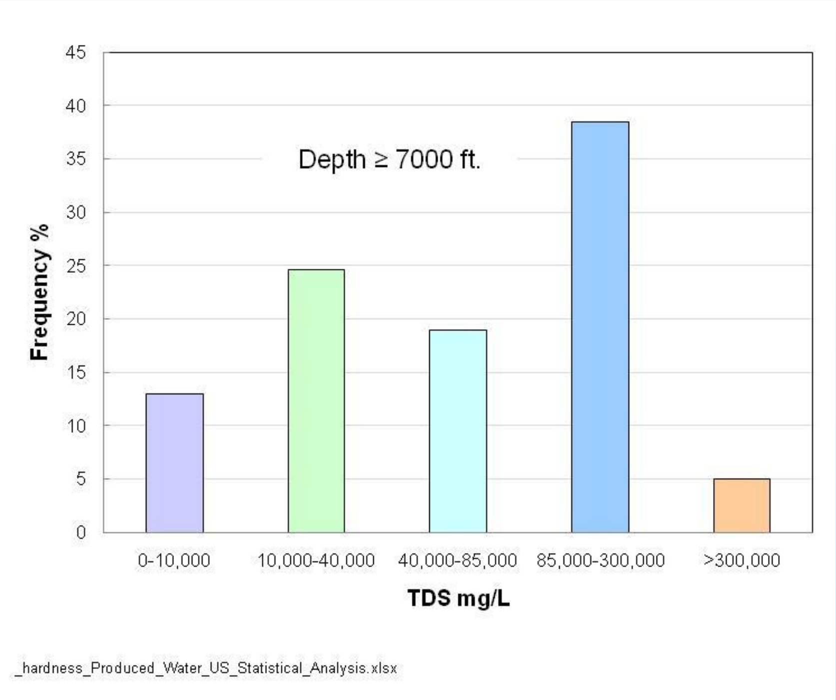
A Catalog of Representative Brine Compositions (shown here to only 160,000 mg/L TDS)



Most of the data shown here are from the USGS Produced Waters Database.

TDS (mg/L) distributions in formation waters of the United States (strongly skewed to the western states). Left: for depth ≥ 2625 ft (800m). Right: for depth ≥ 7000 ft.





Treatable brine appears to be relatively common. Also, the TDS distribution does not change much with depth. The data shown here are from the USGS Produced Waters Database.

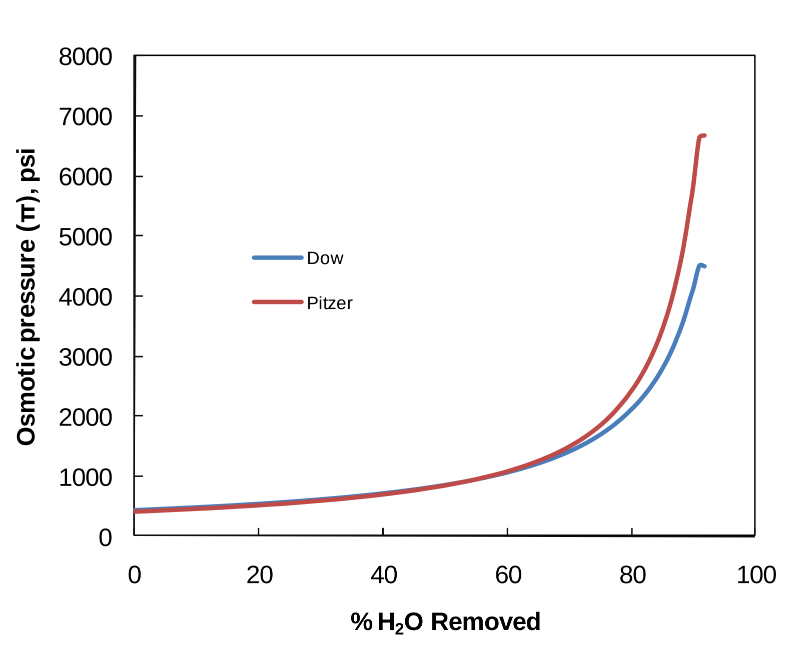
Reverse Osmosis (RO) is a Mature Desalination Technology

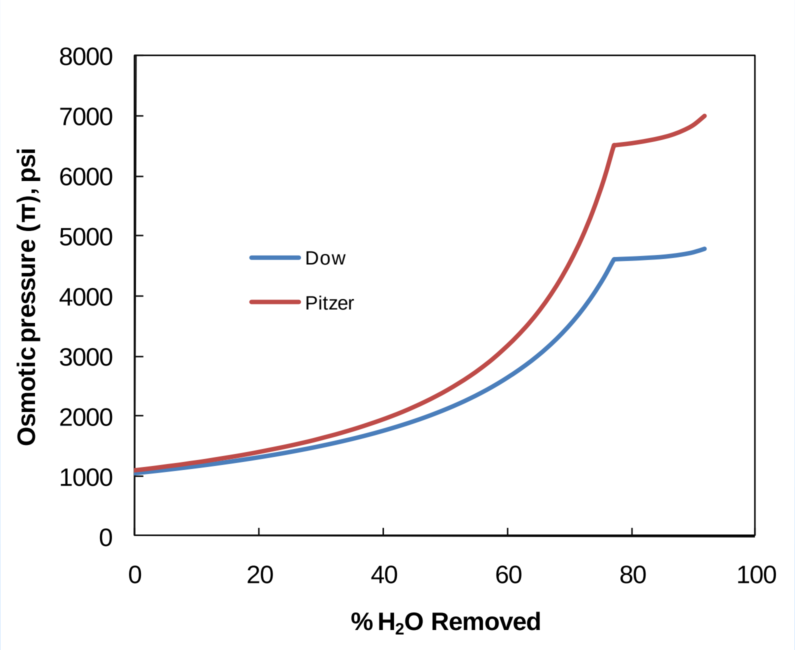
- This is a membrane-based technology that produces freshwater, requiring pressure on the feed water side to overcome that water’s osmotic pressure, which increases with TDS
- RO treatment of seawater (typical TDS of 36,000 mg/L) is a mature commercial process

Thermodynamic Analysis of the Limits of Reverse Osmosis

- Osmotic pressure is more limiting to freshwater recovery than mineral scaling
- The RO membrane has limited strength (commonly now about 1200 psi)
- Recovery goes to near-zero around TDS of 80,000-85,000 mg/L for a 1200 psi membrane
- Low-recovery RO may still be useful for reservoir pressure management

Osmotic Pressure Increases as Water is Removed by RO





Seawater brine,
TDS = 35,928 mg/L

WY Sublette Co. #3,
TDS = 85,926 mg/L

Other Treatment Methods May Work for Higher TDS Brines

- A modified (leaky) RO membrane permits step-wise desalination to freshwater
- Nanofiltration (NF) membrane could also be used to support step-wise desalination
  - NF is better known for selectively reducing divalent ions: Ca, Mg, and SO_4

Other Treatment Methods (Cont.)

- Forward Osmosis (FO), which uses a carrier electrolyte to draw ions across a membrane (the carrier electrolyte can be removed and recycled)
- Thermal distillation/vapor compression (energy intensive)
- A plethora of other thermal methods and electrical methods exists

Saline Cooling Water May be an Attractive Alternative to Freshwater

- Use ion exchange or NF to remove the components (Ca, Mg, SO_4) that contribute to typical mineral scaling
- Cycle through a power plant cooling tower to very high TDS, possibly near 300,000 mg/L (avoid precipitation of NaCl)
- Commercial examples taking the TDS to 150,000 mg/L TDS exist (zero-liquid-discharge cogen plants)

A Potential Saline Cooling Water Scenario

- Feed in 100,000 mg/L water
- Run to a final (“blowdown”) TDS of 200,000 mg/L
- Get a volume reduction of 50%
- Save the freshwater that might have been used for cooling

We Are Now Starting a Series of Bench Tests of Membrane Treatment of Brines Covering a Wide TDS Range

- This involves Larry Lien of MDS
- Straight RO tests to validate our thermodynamics-based calculations
- Test of a stepped desalination process using modified RO membranes to obtain freshwater from 200,000 mg/L feed water
- NF tests, mainly to support the saline cooling water option

Future Work

- Completing the bench top tests and integrating them into the overall analysis
- Finishing the evaluation of the saline cooling water option
- Evaluating thermal distillation/vapor compression
- Evaluation of the applicability of Forward Osmosis (FO) based on existing knowledge and data
- Modeling the effect of reinjection of residual brines

Accomplishments to Date

- Conducted simulations of the subsurface storage system showing the benefits of active management (brine production)
- Conducted a sensitivity study of how active management performs in relation to various system parameters including geologic parameters
- Made a study of what saline formation waters are out there, based on data from the oil and gas industry
- Evaluated Reverse Osmosis (RO) as a means of brine treatment
- Began evaluation of some other treatment technologies
- Conducted a preliminary assessment of the saline cooling water option

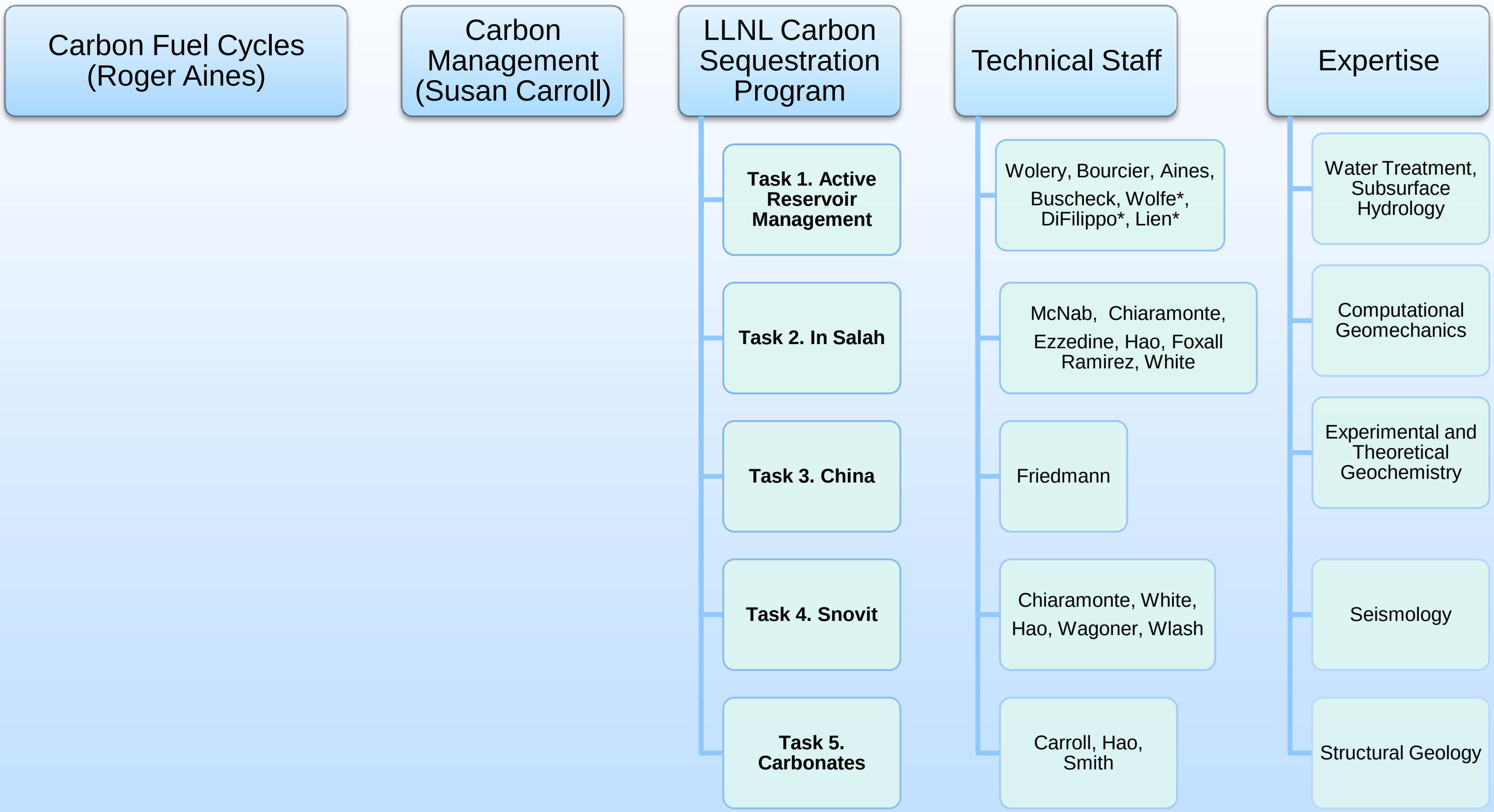
Summary

- Active management (requiring brine production) has the potential to improve CO_2 storage in deep saline formations by
  - Reducing overpressure, the driving force for CO_2 and brine leakage through caprock and also the driving force for seismicity
  - Limiting lateral plume migration and better distributing the CO_2 vertically in the storage formation
  - Substantially reducing the area of the overpressurized zone, thus substantially reducing the Area of Review (AoR)
  - Yielding some useful product water (freshwater or saline cooling water) from produced brine

Appendix

– These slides will not be discussed during the presentation, but are mandatory

Organization Chart



*Subcontractor

Organization Chart Supplementary Information for Task 1

- Tom Wolery (LLNL, geochemist) is the Task 1 PI
- Bill Bourcier (LLNL, geochemist) is a water treatment specialist
- Roger Aines (LLNL, geochemist) is also the Carbon Fuel Cycle PL
- Tom Buscheck (LLNL, hydrologist) is the reservoir engineer
- Tom Wolfe (consultant) is an expert on water treatment technology and cost estimation
- Mike DiFilippo (consultant) is an expert on saline cooling water and cost estimation
- Larry Lien (Membrane Development Specialists) is a water treatment expert conducting bench testing of treatment processes

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Note: Buscheck has established a collaboration with Prof. Mike Celia's group at Princeton University

Gantt Chart

Task or Activity	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013
Evaluate the range of possible saline formation water compositions, with attention to possible treatment options	>==================X=========+=======X					
Evaluate the technical feasibility and cost of largely conventional Reverse Osmosis (RO) treatment		>==============================X				
Evaluate options for producing and using saline cooling water in place of freshwaer in cooling towers				>=======/	/===X===========X===X	
Evaluate the range of brine compositions to use in bench testing of RO, step-wise modified RO, and NF					>====/ /==X	
Conduct bench testing of RO, step-wise modified RO, and NF treatment of brines over a wide TDS range					>=/ /===========X	
Complete final evaluation of options for brine treatment, based on the most recent data						>==============X
Evaluate the technical feasibility and cost of thermal distillation/vapor compression					>=/	/=========X=====X
Evaluate the applicability of Forward Osmosis (FO) to treatment of saline formation waters						>==============X
Conduct analysis and evaluation of subsurface reservoir management using NUFT simulations		>====================X==/		/=X=====X/	/=X==========X====X	
Potential field test of brine treatment, if the right opportunity becomes available		>????????????????????????????/		/?????T		

Notes: This project began in July 2008. In FY2011, most of our NETL funding was pledged as matching funds as part of a proposal to the State of Wyoming's Carbon Management Program. After a lengthy part of the fiscal year during which the pledged NETL funding was tied up, the DOE Livermore Site Office disallowed that arrangement. The FY2012 funding was delayed for most of the FY. "/ /" indicate stop work due to these funding issues. Consequently, work has been swept forward. X = milestone, T = terminated. Technically, all our milestones are quarterly and annual reports.

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- Journal, one author:
  - None.
- Journal, multiple authors:

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- Publication:
  - None.