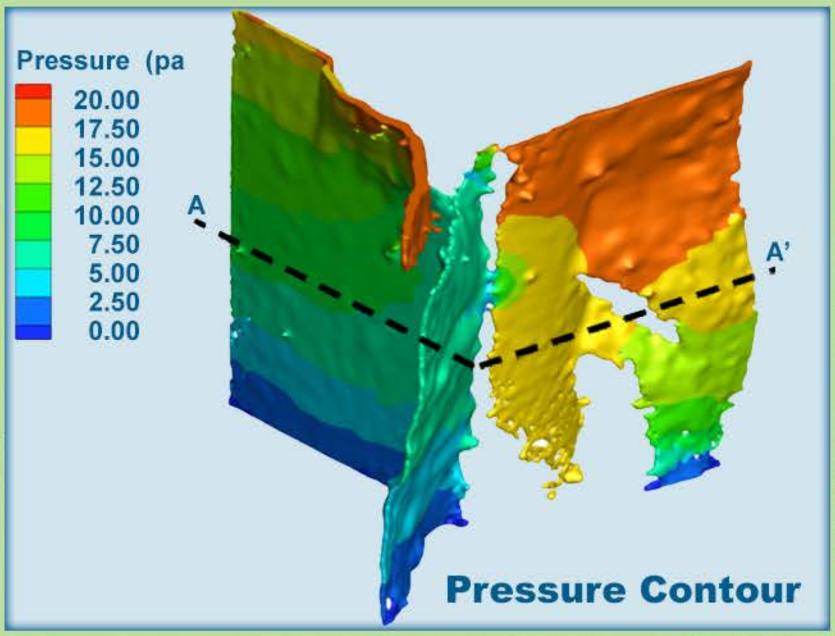
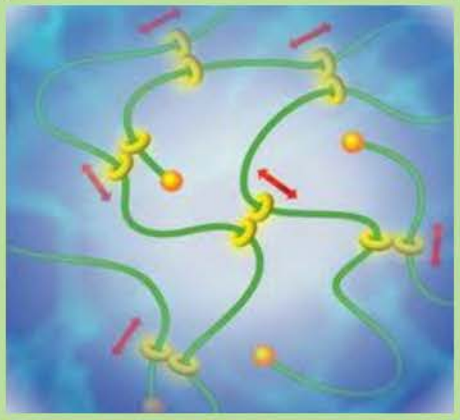
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy





Reservoir-Stimulation Optimization with Operational Monitoring for Creation of Enhanced Geothermal Systems

Project Officer: Lauren Boyd Total Project Funding: $155K

April 23, 2013

Carlos A. Fernandez

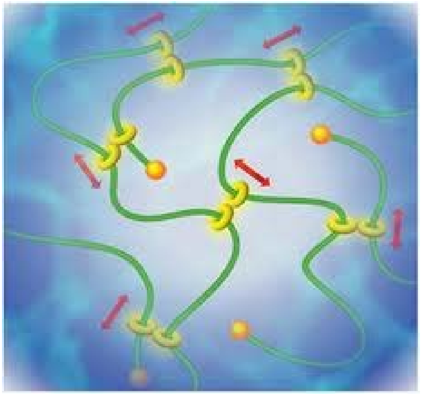
Pacific Northwest National Laboratory

This presentation does not contain any proprietary confidential, or otherwise restricted information.

Relevance/Impact of Research

The project will support the following areas:

- Advance geothermal reservoir stimulation methods
- Advance stimulation characterization/monitoring methods
- Ultimately enhance permeability of geothermal reservoirs and consequently increase current energy production rates



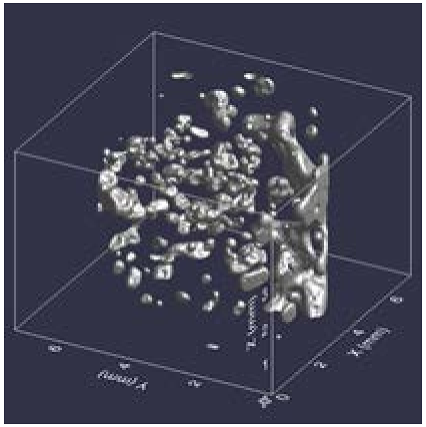
Cartoon of polymer/fluid system

How?

A. Development of new physical and chemical methods for reservoir creation and permeability stimulation using **novel rheo-reversible polymer/fluid systems**

B. Development of state-of-the-art *ex situ* as well as real-time geophysical monitoring tools

C. Provide data that can be used to validate modeling approaches.



Relevance/Impact of Research

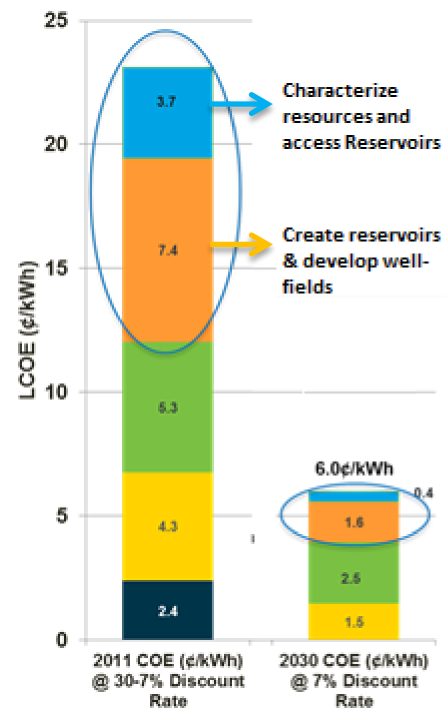
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

How? (cont.)

D. Optimize the implementation of stimulation methods toward increasing economic viability of EGS reservoir creation

E. Transition knowledge/expertise on monitoring and characterization from reservoir creation to reservoir operation management

PNNL contribution areas



2030 EGS cost reduction goals

Project will impact GTO goals as follow:

A. Lower levelized cost of electricity (LCOE, cents/kWh) through decreasing reservoir creation cost, i.e., increasing the well spacing and decreasing the number of wells needed.

B. Increase energy production feasibility for EGS reservoirs through increasing permeability and reservoir size via improving fracture stimulation.

Scientific/Technical Approach

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

- **Task 1 - Experimental Design**
  - Laboratory system for controlled fracturing and fracture-cleanup exps
  - Real-time monitoring of changes in geophysical responses
  - Pre/post fracture distribution and permeability characterization
  - Pre/post effluent sample characterization


Dr. C.A. Fernandez


Dr. A. Bonneville


Dr. K.C. Carroll

- **Task 2 - Reactive-Polymer Fracturing**
  - CO_2-reactive polymers. High P/T triggered expansion to hydrogels
  - Increase fluid volume (≥ 10 %)
  - Demonstrate polymer stability and reversibility, to be readily removed from the formation

- **Task 3 - Documentation and Dissemination**
  - Publication in peer-review journals and presentation to conference in the field
  - Generate IP and patent portfolio

Scientific/Technical Approach

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

Stimulation optimization

Task 1 Fracturing fluid

Task 2 Fracturing Monitoring

Iterative, mutually dependent tasks

High P/T viscosity analysis

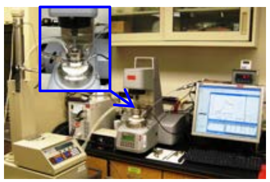
Rheology and reversibility

High P/T view cell and video recording

Stability/ recyclability

High P/T MAS-NMR

Chemistry



Viscosity analysis

Pre- and post-Fracturing Fluid chemistry/stability

Solution NMR

Real-time Fracturing characterization

In-situ Acoustic pulsed echo analysis

Specialized high P/T flow-through reaction cell

Pre- and post-Fracturing Rock Physical & chemical characterization

Solid state NMR

Dual energy XMT

ICP-MS

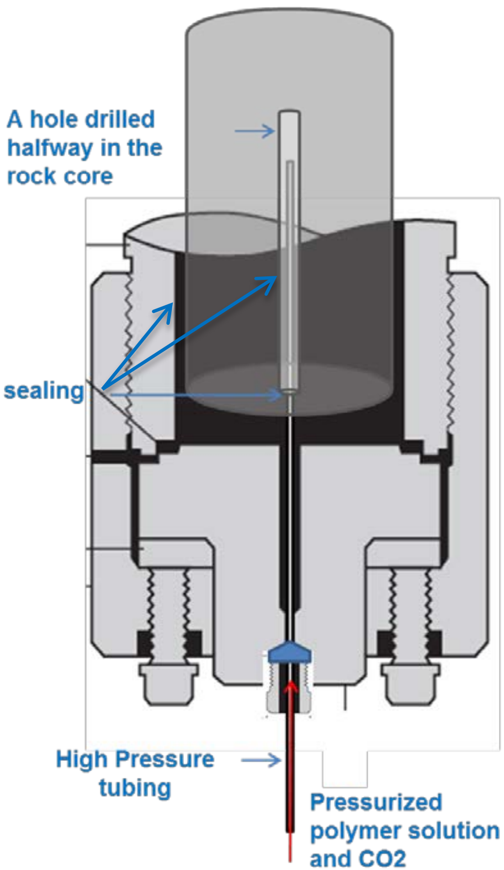
- **Advance hydraulic shearing fluids**
- **Advance our characterization/validation capability**
- **Optimize stimulation to increase energy production rates**

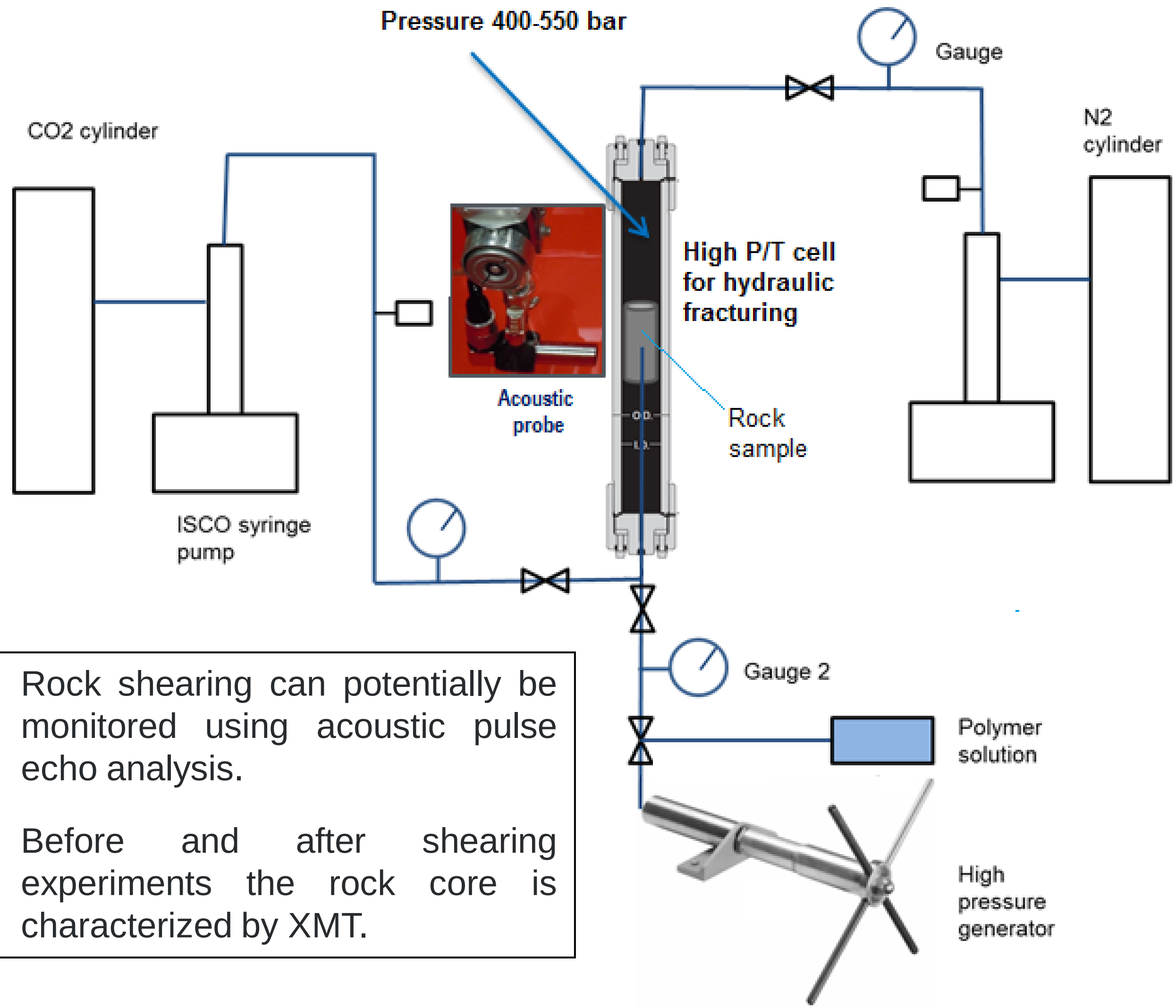
Accomplishments, Results and Progress

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

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
1. Laboratory equipment development and testing (months 0-3)	High P/T system built including view cell with video recording tested. **Completed**	03/01/2013
2. Monitoring system development and testing (months 3-6)	• Acoustic analysis tested, rock sample **Completed** • XMT tested on cement/basalt samples **Completed** • NMR cell tested with polymer fluids. **Challenge.** • **BONUS**: high P/T **fluid viscosity**. **Challenge.**	Anticipated completion date 05/01/2013
3. Obtain and characterize samples (months 0-3)	• Acoustic analysis tested on rock samples • XMT on standard minerals and rock samples testing underway.	Anticipated completion date 04/01/2013
4. Batch test reactive-polymer rheology and high P/T range polymer stability and proppant suspension. **Show 10% volume expansion** (months 3-6)	• **SUCCESS** with **100 % volume expansion** at EGS P/T. **Completed** • **Need to: test stability/recyclability, compare to current state-of-the-art.** Manuscript in preparation	03/15/2013
5. Baseline hydraulic fracturing testing (months 6&7)	Specialized high P/T flow-through reaction cell arrived. **Challenge:** *In situ* monitoring	Anticipated completion date 05/01/2013
6. Preliminary reactive-polymer fracturing testing (months 8&9)	Began flow-through cell installation, hydraulic shearing on rock samples will follow.	Anticipated completion date 06/01/2013
7. Preliminary monitoring-enabled optimal permeability enhancement testing (mo 10&11)	Real-time acoustic analysis as potential monitoring technique	Anticipated completion date 08/01/2013
8. Annual Progress Report (end of FY)		09/13/2013

Task 1: Experimental design, simulation of reservoir stimulation





- Rock shearing can potentially be monitored using acoustic pulse echo analysis.
- Before and after shearing experiments the rock core is characterized by XMT.

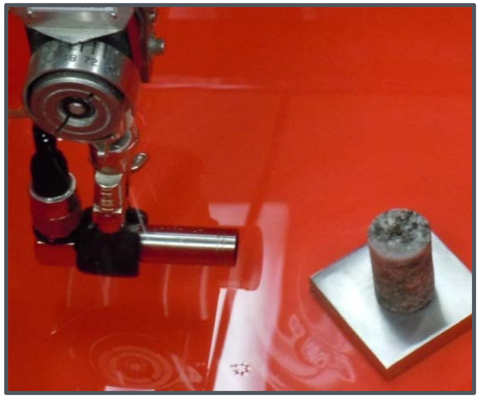
Task 1: Experimental Design



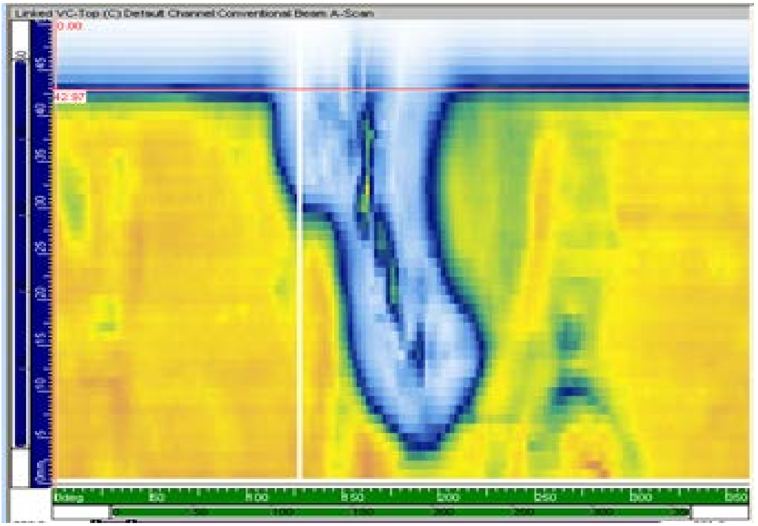
Dr. P. Ramuhalli   Dr. R. Meyer   Mr. M. Prowant

Real-time monitoring of fractures: Acoustic Pulse Echo Analysis

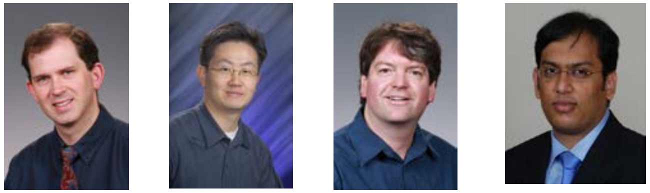
- A probe focuses ultrasonic energy into small regions on the specimen (360º scan).
- A change in acoustic impedance (due to changes in material density, fracturing, composition) results in different amplitudes of reflected ultrasonic energy.
- **Challenge**: *In situ* monitoring is difficult. High frequencies will not transmit on stainless steel-rock interface if air gaps are present.



Missing section in rock sample shows up clearly as a (blue) low-amplitude return signal (red = highest amplitude)



Task 1: Experimental Design

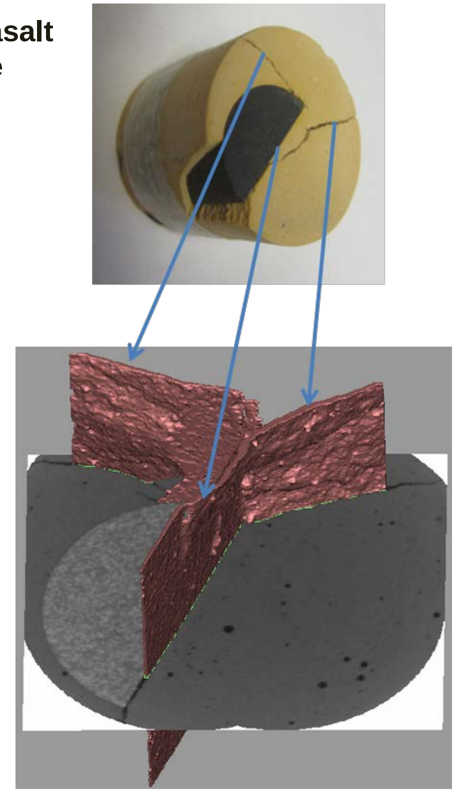


Dr. J. Carson Dr. W. Um Dr. A. Kuprat Dr. K. Senthil

Pre and post shearing monitoring: X-ray Microtomography (XMT)

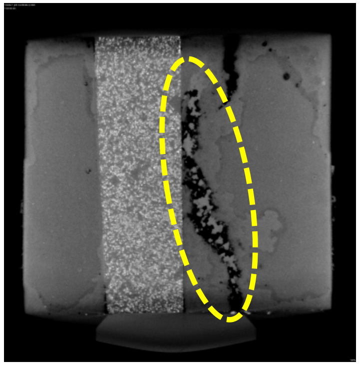
Generation of highly detailed three-dimensional (3D) representation of the fractures (density and elemental composition dependent)

Cement-basalt sample

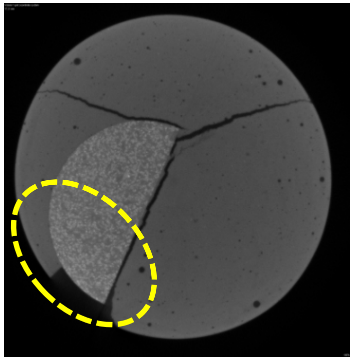


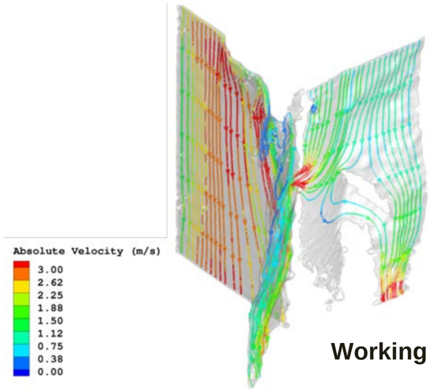
Final surfaces of the fractures

Vertical XMT image



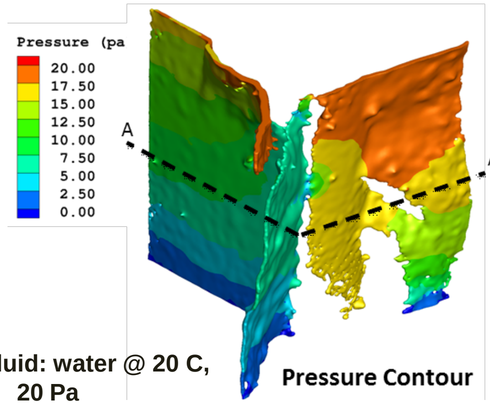
Horizontal XMT image





Working fluid: water @ 20 C, 20 Pa

Absolute fluid velocities and permeability factors



Contours of absolute pressure

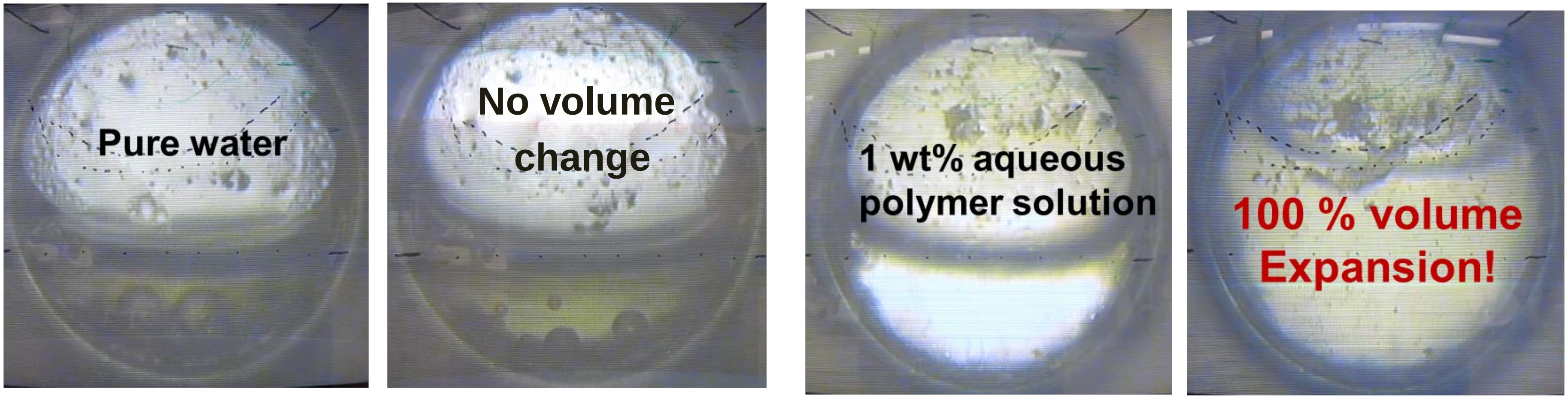
Task 2: Reactive-Polymer Fracturing

Dr. H. B. Jung

Dr. D. Heldebrant

- **Real-time monitoring of fluid P, T, rheology**
- **Objective:** Demonstrate at least 10 % volume expansion at reservoir T/P
- **Accomplishment:** Success with **100 % volume expansion** at reservoir T/P (Manuscript in prep.)

Control | Polymer experiment



Before CO_2 addition | After CO_2 addition | Before CO_2 addition | After CO_2 addition

Conditions: 300 bar, 300 ºC

Task 2: Reactive-Polymer Fracturing

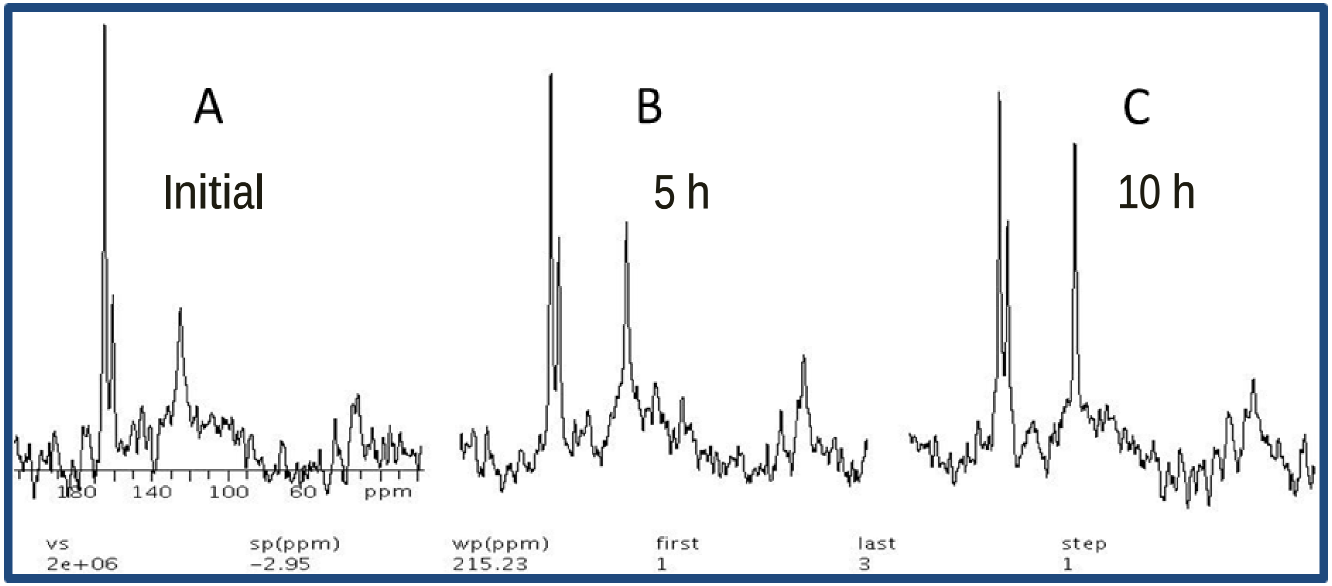
Dr. D. Heldebrant

Dr. D. Hoyt

Real-time monitoring of fluid chemistry

- Unique High-Pressure Rotor capability for **Magic Angle Spinning ^{13}C NMR (MAS-NMR)** developed by Dr. David Hoyt at EMSL
- Unparalleled real-time analysis of kinetics and speciation of H_2O/CO_2 fluid with polymer under geothermal conditions

In situ time-resolved ^{13}C NMR spectra of 1% aqueous polymer.
Temperature 100 ^{o}C
Pressure = 120 bar H_2O/CO_2

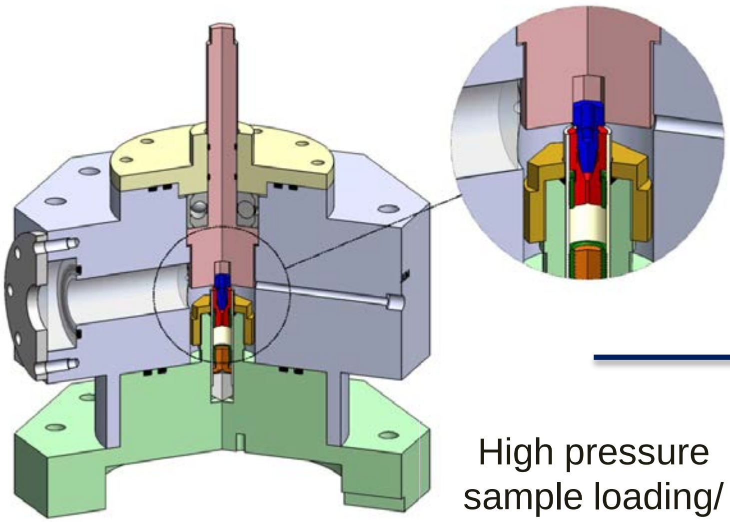


Task 2: Reactive-Polymer Fracturing

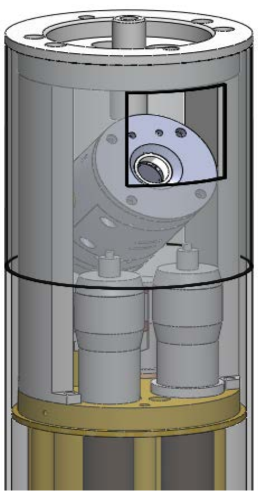
Dr. D. Hoyt

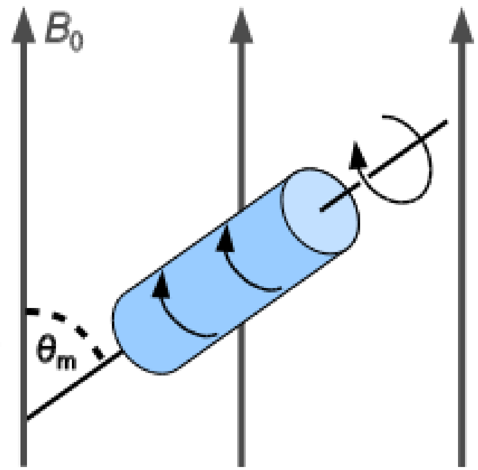
- Current cell performance **limited to 120 bar and 150 ˚C**
  - Current data is higher than any other *in situ* measurement capability but still short of geothermal conditions

- Projected cell performance **requirements are 300 bar, 300 ˚C**



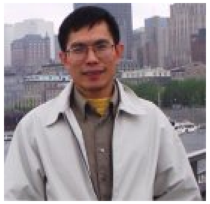
High pressure sample loading/ reaction chamber





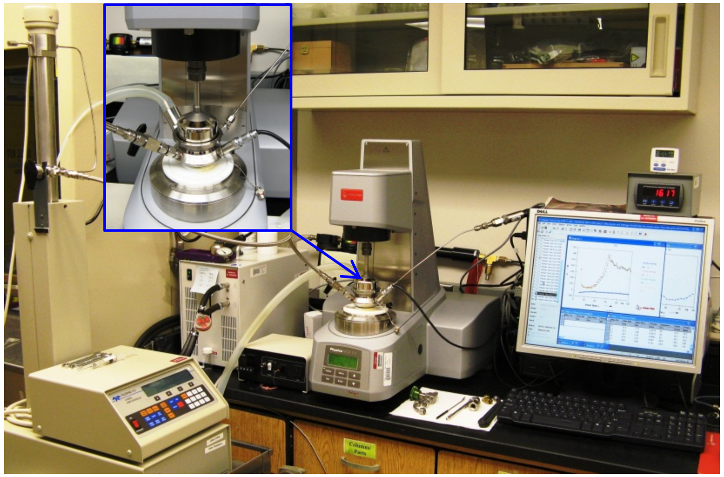
Sample MAS NMR probe

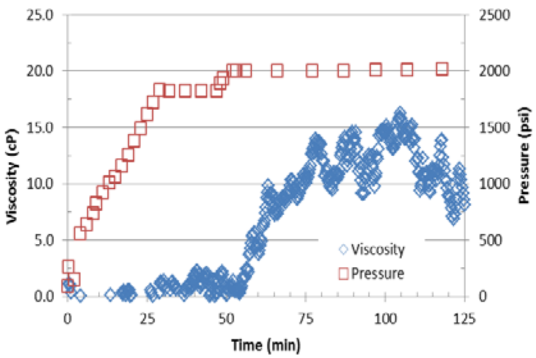
Task 2: Reactive-Polymer Fracturing


Dr. L. Zhong

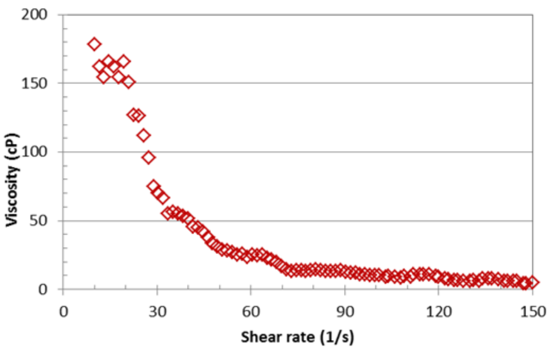
Real-time monitoring of fluid viscosity:

- Anton Paar Physica MCR101 rheometer equipped with a temperature control system and a pressure cell **limited to 130 bar and 190 ˚C**
- Projected cell performance **requirements are 300 bar, 300 ˚C**





Viscosity of H2O-CO_2-polymer mixture vs. pressure @ 190°C. Note: H2O-CO2 viscosity: comparatively low, data not shown



Shear thinning behavior at higher shear rates (190°C, 130 bar.)

KEY FLUID PROPERTY: After a fracture is initiated, the shear thinning property enables ready propagation of the fluid into the opening. When the fluid fills the fracture, its viscosity and volume will increase due to the reduction in shear rate, propagating the fracture further.

Future Directions

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

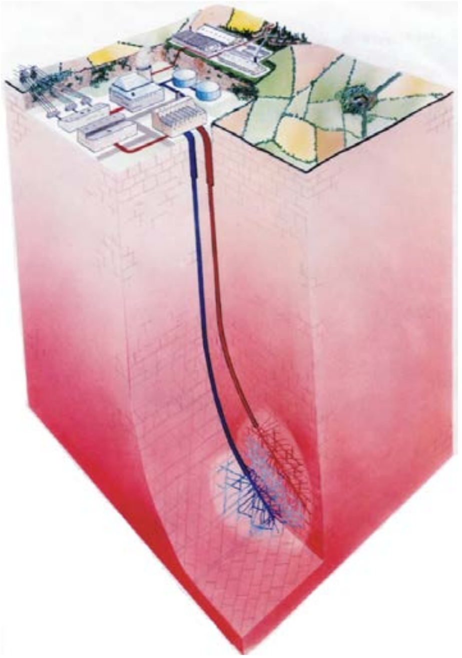
- **Engage industry partners to discuss:**
  - *Transition novel rheoreversible fluids to reservoir creation applications*
  - *Transition knowledge/expertise on monitoring and characterization from reservoir creation to reservoir operation management*
- **Coordination/collaboration with two PNNL on-going projects; Thermally Degrading Tracers (Dr. Vermeul) and Metal-Organic Heat Carrier Nanofluids (Dr. McGrail) to:**
  - *Expand fluid chemistry and monitoring tools beyond hydraulic shearing optimization.*

SMART Milestone or Go/No-Go	Status & Expected Completion Date
FY13. Demonstrate less than 15% decay of the reactor polymer compounds at EGS temperatures and pressures of 300°C and 550 bar	On track. Currently developing high P/T NMR rotor for MAS-NMR chemical characterization of reactive polymer at reservoir conditions for stability studies. **Expected completion date: 06/01/2013**
FY13. Achieve greater than 10% volume increase with gel formation at 300°C and 550 bar	**Completed.** Demonstrated **100% volume increase** in gel formation at 300°C and 300 bar
FY13. Demonstrate capability to switch from liquid to gel multiple times.	On track. Currently modifying the high pressure system to recycle polymer at least three times. **Expected completion date: 09/01/2013**
FY14. Demonstrate a measureable 10% or greater increase in fracture permeability compared to standard hydraulic fracturing.	TBD
FY15. Demonstrate the ability to optimize/ tune the fracturing procedure using real-time monitoring with a minimum of 10% increase in fracture permeability.	TBD

Summary

Novel Rheo-reversible fracturing fluid

- *Successfully developed a fracturing polymer-fluid system that shows **100 % volume expansion** at reservoir P /T conditions*
- *Fluid shear thinning properties:*
  - *Support propagation and proppant transport into the reservoir.*
  - *At the fractures, increase viscosity & volume further increasing fracture size.*



Project Capabilities

- *Obtained a high-P/T, three-window, view cell coupled to high-resolution video recording to study reactive-polymer/fluid rheology*
- *Obtained a specialized high-P/T, flow-through reaction cell for hydraulic fracturing studies simulating actual reservoir conditions*
- *Developed state-of-the-art in situ chemical characterization tools for studying reactive-polymer/fluid chemistry and stability after a number of fracturing/cleanup cycles*
- *Demonstrated fracturing characterization techniques, including acoustic echo analysis and XMT, to explore and optimize stimulation methods*

Project Management

Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Estimated End Date
10/1/2012	9/30/2015	10/20/2012	9/30/2015

FY13 Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	% of Work Left to Complete	Funding needed to Complete Work
$155,000	$0	$100,000	$79,000	64%	$275,000

- **Management activities or approaches:**

  Project management plan, project reviews, budget tracking, data review and QA/QC, data/file organization/sharing/transfer/backup, and team meetings

- **Application of resources and leveraged funds/budget/spend plan:**

  Leveraging funds and capabilities including mechanical testing lab, EMSL, CFD modeling (DOE Office of Science), XMT data (DOE NRAP), CSI

- **Project integration with other projects in the Office:**

  Coordination and collaboration with two on-going PNNL projects Thermally Degrading Tracers (Dr. Vermeul) and Metal-Organic Heat Carrier Nanofluids (Dr. McGrail)

- **Coordination with industry & stakeholders:**

  Industry samples from (Univ. Utah), present results at conference, plan to engage industry by end of project, and would be interested in possible field demonstration