Core holder for CO₂ heat extraction experiments

Quizix C-6000-5K high pressure, high flow rate pump

Enhanced Geothermal Systems (EGS) with CO₂ as Heat Transmission Fluid

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Lawrence Berkeley National Lab.
The project started in FY10
- Collaboration between LBNL (Pruess) and INL (Redden)
  - Berkeley leads modeling, CO$_2$-brine flow and heat extraction experiments, development of field test
  - INL leads CO$_2$-brine-rock chemical reaction experiments
- Work plan conceived for 3 years
- ARRA funding for 1.5 years, then ???
- Total budget 622 k$ (LBNL)
- The project continues earlier work that had been funded internally by the LBNL Director as Contractor Supporting Research (CSR)
- The research addresses the following barriers identified in the multi-year geothermal R&D plan: F, G, L, M, N, O, W, Y
The overall objective of the research is to explore the feasibility of operating enhanced geothermal systems (EGS) with CO$_2$ as heat transmission fluid.

Specific objectives are as follows.

- test crucial predictions from theoretical models about the heat transfer and fluid flow properties of CO$_2$;
- obtain essential data to be incorporated into mathematical models;
- determine how water is removed from a permeable medium by continuous circulation of dry anhydrous CO$_2$;
- build mathematical models for EGS with CO$_2$ that allow to analyze, optimize, and scale-up all aspects of stimulation, development, and operation of EGS with CO$_2$; and
- identify favorable as well as unfavorable geologic conditions for a field test of EGS with CO$_2$. 
Scientific/Technical Approach

• Employ a combination of laboratory, theoretical, modeling, and field studies to address
  – theoretical and practical issues of fluid dynamics,
  – heat transfer in CO₂-brine systems, and
  – rock-fluid chemical and mechanical interactions.

• Prioritize and integrate research tasks by adopting an overarching goal of designing a field test of EGS with CO₂.

• Perform natural analogue studies, to provide reality checks on modeling and upscaling (CO₂ reservoirs, gas-rich geothermal systems).
Accomplishments and Progress

• Developed a model for representing brine-CO₂ mixtures over the relevant range of fluid compositions and thermodynamic conditions, from injection to production (temperatures 12–300 °C, pressures 1–600 bar, salinities 0–6m NaCl).

• The model was implemented in our TOUGH2/ECO2N reservoir simulator, and was used to explore the process of EGS-CO₂ reservoir development (continuous CO₂ injection to remove the aqueous phase).

• Began to investigate the possibility of using aqueous solutions of CO₂ for chemical stimulation of EGS reservoirs.

• We have acquired laboratory equipment and are assembling an apparatus for core floods to study heat extraction from hot porous systems by injection of cold CO₂.

• Reactive chemistry experiments for CO₂-brine-rock are being assembled (INL).
Accomplishments and Progress

A Phase-Partitioning Model for CO$_2$-Brine Mixtures at Elevated Temperatures and Pressures

(solid lines: Spycher and Pruess, TiPM, 2010)
Zone 1
Central zone and core of EGS system, where most of the fluid circulation and heat extraction is taking place. This zone contains supercritical CO$_2$; all water has been removed by dissolution into the flowing CO$_2$ (rock-fluid interactions weak).

Zone 2
An intermediate region with weaker fluid circulation and heat extraction, which contains a two-phase mixture of CO$_2$ and water (expect dominant dissolution).

Zone 3
The outer region affected by EGS activities. The fluid is a single aqueous phase with dissolved CO$_2$ (expect dominant precipitation).

Comparing Operating Fluids for EGS: CO$_2$ vs. Water

- monitor mass flow, heat extraction rates

<table>
<thead>
<tr>
<th>Fractured Reservoir</th>
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<tbody>
<tr>
<td>$T_{res} = 200^\circ C$</td>
</tr>
<tr>
<td>$P_{res} = 100 - 500$ bar</td>
</tr>
<tr>
<td>Pore Fluid: all CO$_2$, all water</td>
</tr>
</tbody>
</table>

- Injection (20°C)

- 1/8 of five-spot

- Production

- Injection
Accomplishments and Progress

Heat Extraction, Mass Flow in 2-D

- Energy extraction rate with CO₂ is approximately 50% larger than with water (average of 75 MW(th) = 13 MWe)
- Relative advantage of CO₂ becomes larger for lower reservoir temperatures
- CO₂ inventory: 1.8 Megatonnes
- For 1,000 MWe, would require 138.5 Megatonnes of CO₂
CO₂-EGS Reservoir Development: \textit{Inject CO₂, Drive out the Water}

- At early time (≤ 0.1 year), produce single-phase water
- This is followed by a two-phase water-CO₂ mixture (0.1 - 2.5 yr)
- Total production rate during two-phase period is low due to phase interference
- Subsequently produce a single supercritical CO₂-rich phase with dissolved water
  \hspace{1cm} (Pruess and Spycher, WGC 2010)
Accomplishments and Progress

Schematic of Core Holder for Heat Extraction Experiments
Laboratory Apparatus for Heat Extraction Experiments with scCO$_2$
Accomplishments and Progress

Design Calculations for Heat Extraction Experiments

TOUGH2 simulation results for temperatures at the core outlet, for different pore fluids and applied pressure increments.

Screen shot of a data browser, displaying results of multiple TOUGH2 runs for different permutations of experimental parameters.
Accomplishments and Progress

Reactive Chemistry Experiments for CO$_2$-Brine-Rock (Collaboration INL - USGS)

Reactor schematic

Example reactor vessel

Schematic of scCO$_2$/brine/rock reactor charging and sample extraction facility
Accomplishments and Progress

USGS High T-P Reactor Facility (Bob Rosenbauer)

Heater blocks for high T-P reactors

Reactor charging/discharging apparatus
The project is a collaboration between LBNL (Pruess) and INL (Redden). UC Berkeley is involved as well (PhD student).

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Role in project</th>
<th>Experience</th>
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<tbody>
<tr>
<td>Pruess</td>
<td>overall direction; in charge of fluid and heat flow modeling</td>
<td>more than 30 years in geothermal engineering; 10 years in geologic storage of CO₂</td>
</tr>
<tr>
<td>Kneafsey</td>
<td>lead flow and heat transfer experiments</td>
<td>more than 12 years experience with laboratory fluid and heat flow experiments</td>
</tr>
<tr>
<td>Xu</td>
<td>lead reactive chemical transport modeling</td>
<td>more than 10 years experience with chemical transport modeling applied to geothermal and CO₂ storage</td>
</tr>
<tr>
<td>Spycher</td>
<td>lead thermodynamic s and thermophysical modeling</td>
<td>over 20 years experience with thermodynamic modeling of multicomponent, multiphase fluids</td>
</tr>
<tr>
<td>Apps</td>
<td>geologic and geochemical modeling of specific sites</td>
<td>over 35 years experience in analysis of multi-mineralic geologic media</td>
</tr>
<tr>
<td>Redden</td>
<td>overall direction; in charge of rock-fluid reaction experiments</td>
<td>over 20 years experience with environmental chemistry</td>
</tr>
<tr>
<td>Mattson</td>
<td>conduct chemically reactive rock-fluid experiments</td>
<td>over 10 years experience with laboratory experiments on permeable media</td>
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Project is funded for only 1.5 out of 3 years (ARRA).
Will need support through regular DOE geothermal appropriations.
Other LBNL geothermal and CCS projects can provide ancillary support.
Future Directions

• Continue development and application of mathematical models for analysis of EGS-CO$_2$ reservoir behavior.
• Work with UC Berkeley on CO$_2$-brine fluid flow and heat transfer experiments.
• Collaborate with INL on reactive chemistry of CO$_2$-brine-rock.
• Perform studies of natural analogues.
• Identify favorable as well as unfavorable geologic conditions for a field test of EGS with CO$_2$.
• Develop hypotheses, objectives, site selection criteria and designs for field tests.
Summary

- Operating EGS with CO$_2$ is a potentially game-changing concept, that could combine production of renewable energy with utilization and storage of CO$_2$.
- Initial assessment using models from geothermal and CCS backgrounds suggests favorable heat extraction behavior.
- Laboratory flow experiments are being assembled to test model predictions and provide crucial input data for models.
- Continuing model development aims to cover the full range of thermodynamic and chemical conditions that would be encountered in EGS with CO$_2$.
- We are also pursuing serendipitous directions, such as use of CO$_2$ for chemical stimulation of “conventional” (water-based) EGS.
