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

Core holder for CO_2 heat extraction experiments

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

Enhanced Geothermal Systems (EGS) with CO_2 as Heat Transmission Fluid

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Overview

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- 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

Relevance/Impact of Research

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.

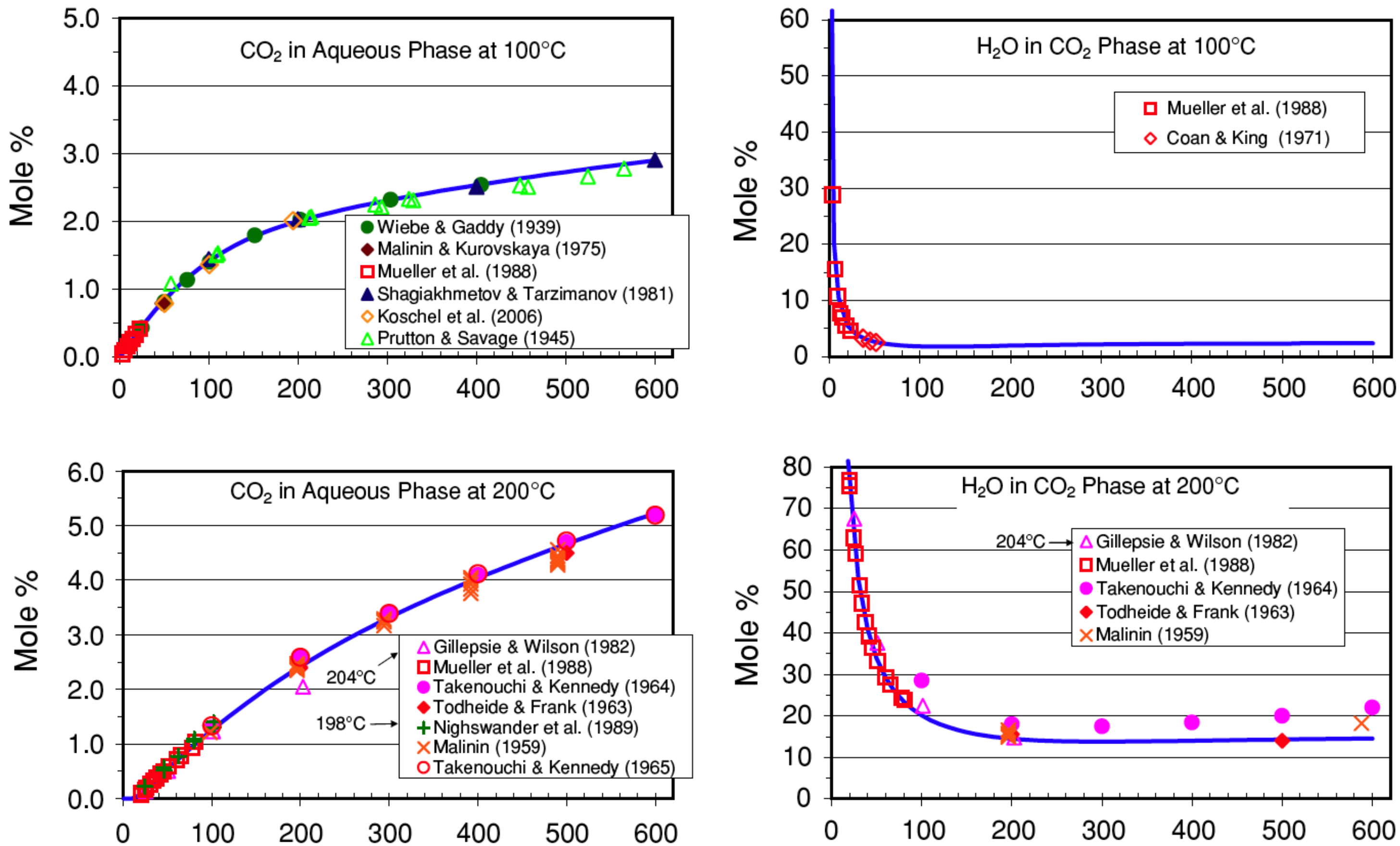
Scientific/Technical Approach

- Employ a combination of laboratory, theoretical, modeling, and field studies to address
  - theoretical and practical issues of fluid dynamics,
  - heat transfer in CO_2-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 CO_2.
- Perform natural analogue studies, to provide reality checks on modeling and upscaling (CO_2 reservoirs, gas-rich geothermal systems).

Accomplishments and Progress

- Developed a model for representing brine-CO_2 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-CO_2 reservoir development (continuous CO_2 injection to remove the aqueous phase).
- Began to investigate the possibility of using aqueous solutions of CO_2 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 CO_2.
- Reactive chemistry experiments for CO_2-brine-rock are being assembled (INL).

A Phase-Partitioning Model for CO_2-Brine Mixtures at Elevated Temperatures and Pressures



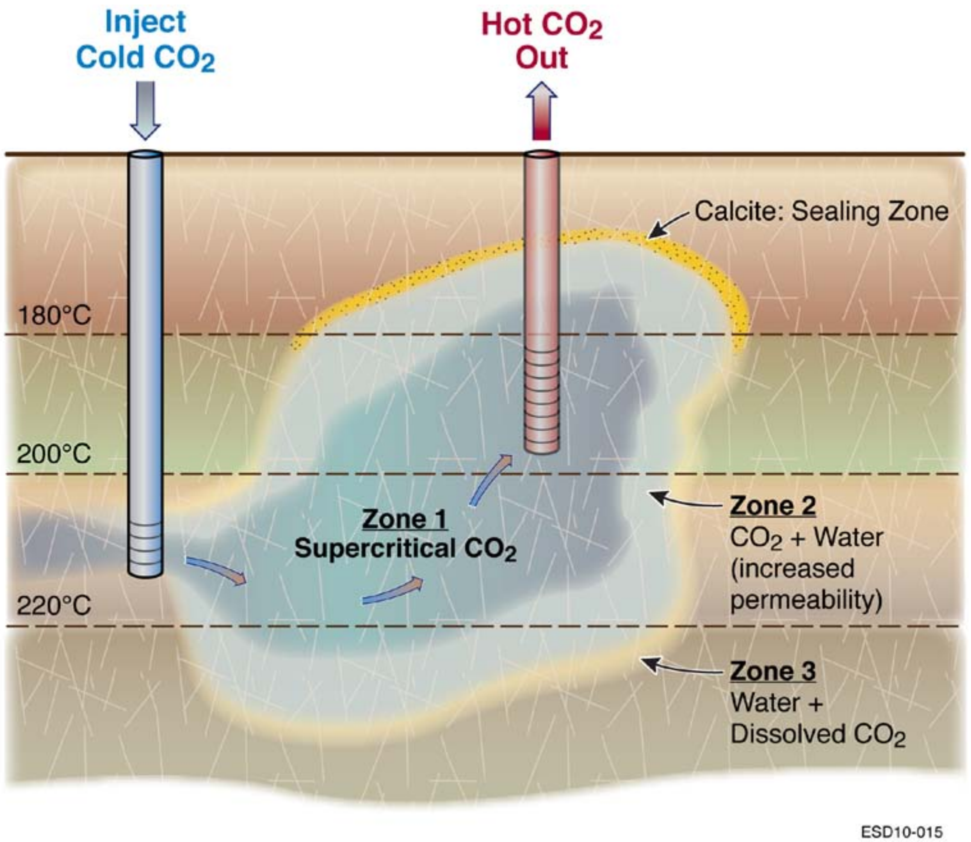
(solid lines: Spycher and Pruess, TiPM, 2010)

General Makeup of a CO_2-Based EGS Reservoir

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).

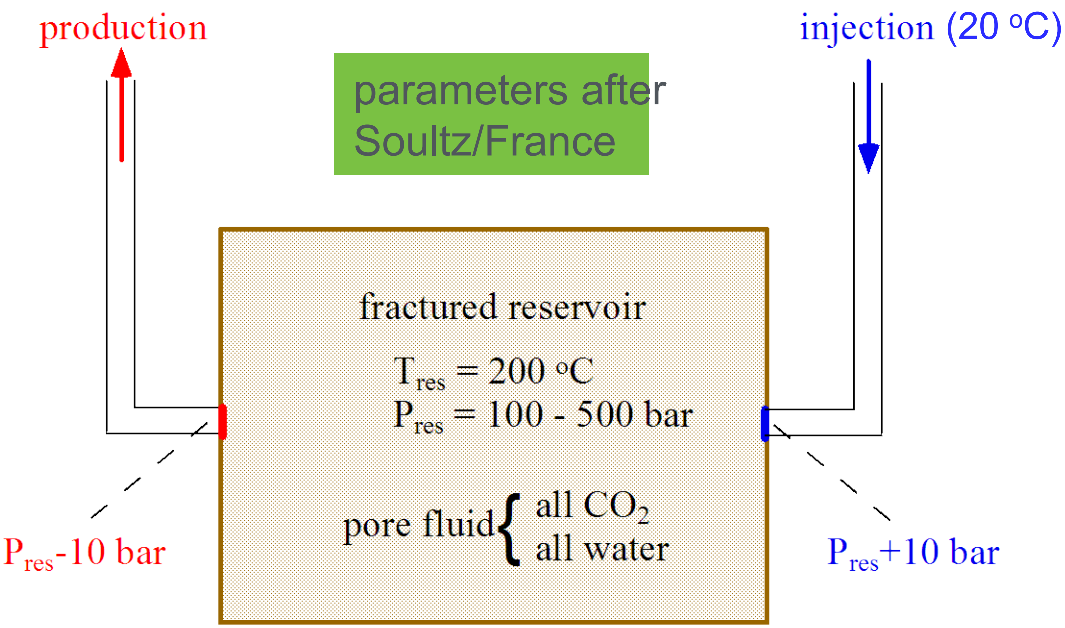
Zone 2
An **intermediate region** with weaker fluid circulation and heat extraction, which contains a **two-phase mixture** of CO_2 and water (expect dominant dissolution).

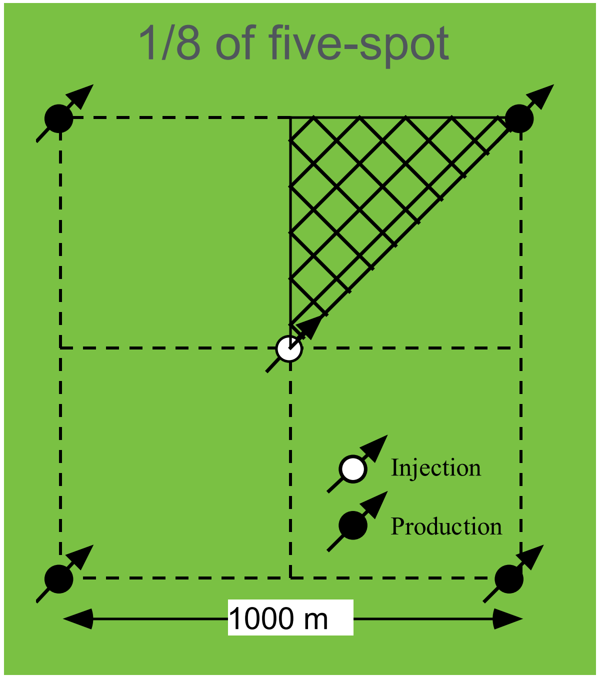
Zone 3
The **outer region** affected by EGS activities. The fluid is a **single aqueous phase** with dissolved CO_2 (expect dominant precipitation).



(after Christian Fouillac et al., *Third Annual Conference on Carbon Capture and Sequestration,* Alexandria, VA, May 3-6, 2004)

Comparing Operating Fluids for EGS: CO_2 vs. Water

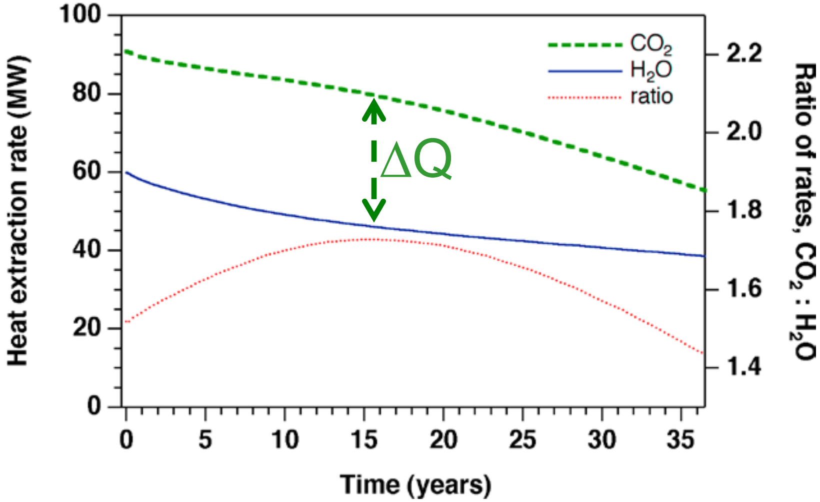




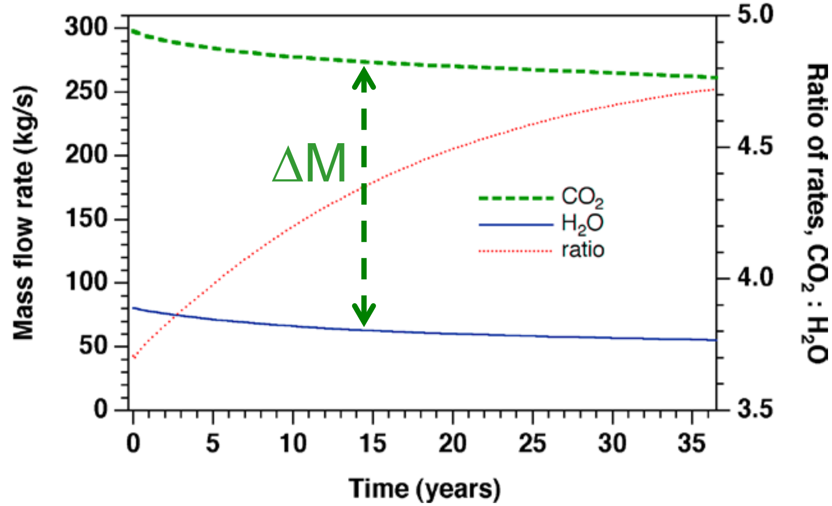
- ➢ monitor mass flow, heat extraction rates

Heat Extraction, Mass Flow in 2-D

heat extraction



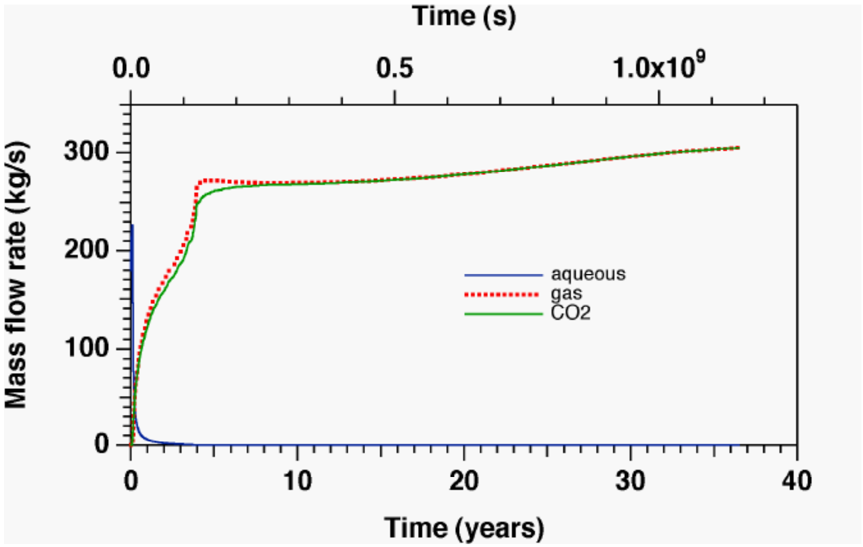
mass flow

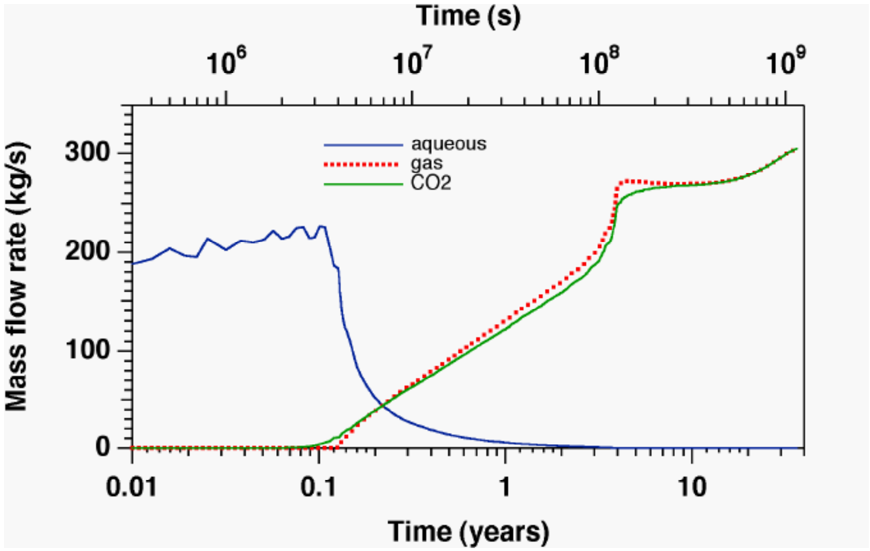


- Energy extraction rate with CO_2 is approximately 50 % larger than with water (average of 75 MW(th) = 13 MWe)
- Relative advantage of CO_2 becomes larger for lower reservoir temperatures
- CO_2 inventory: 1.8 Megatonnes
- For 1,000 MWe, would require 138.5 Megatonnes of CO_2

CO_2-EGS Reservoir Development:

Inject CO_2, Drive out the Water

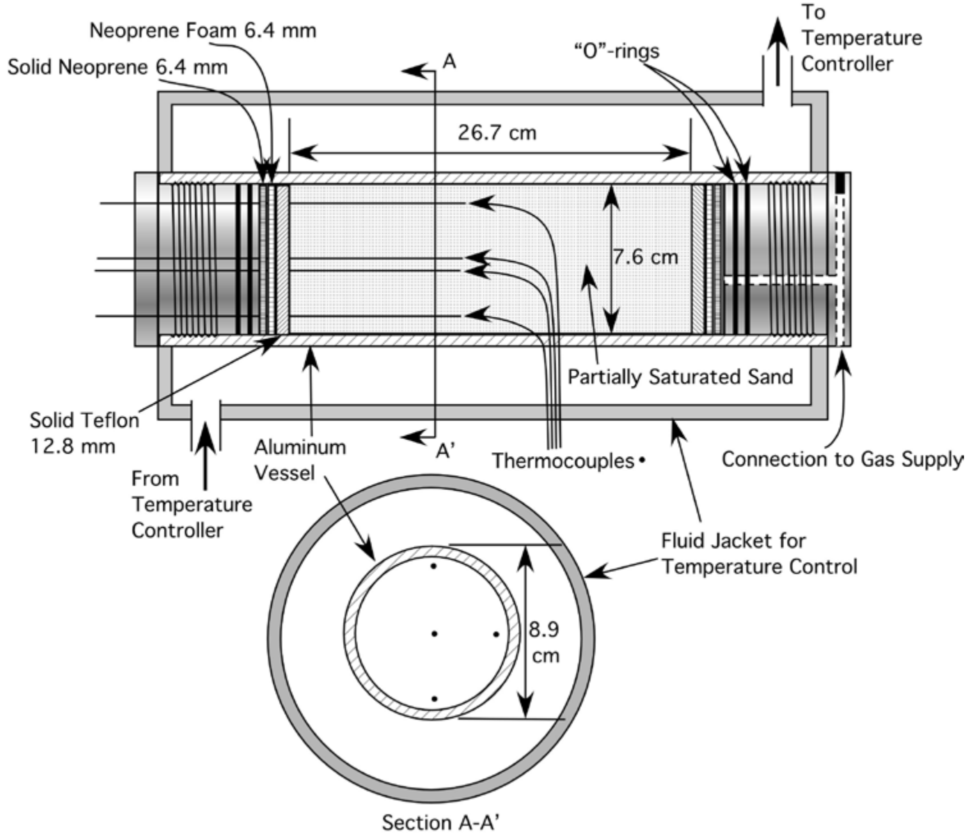




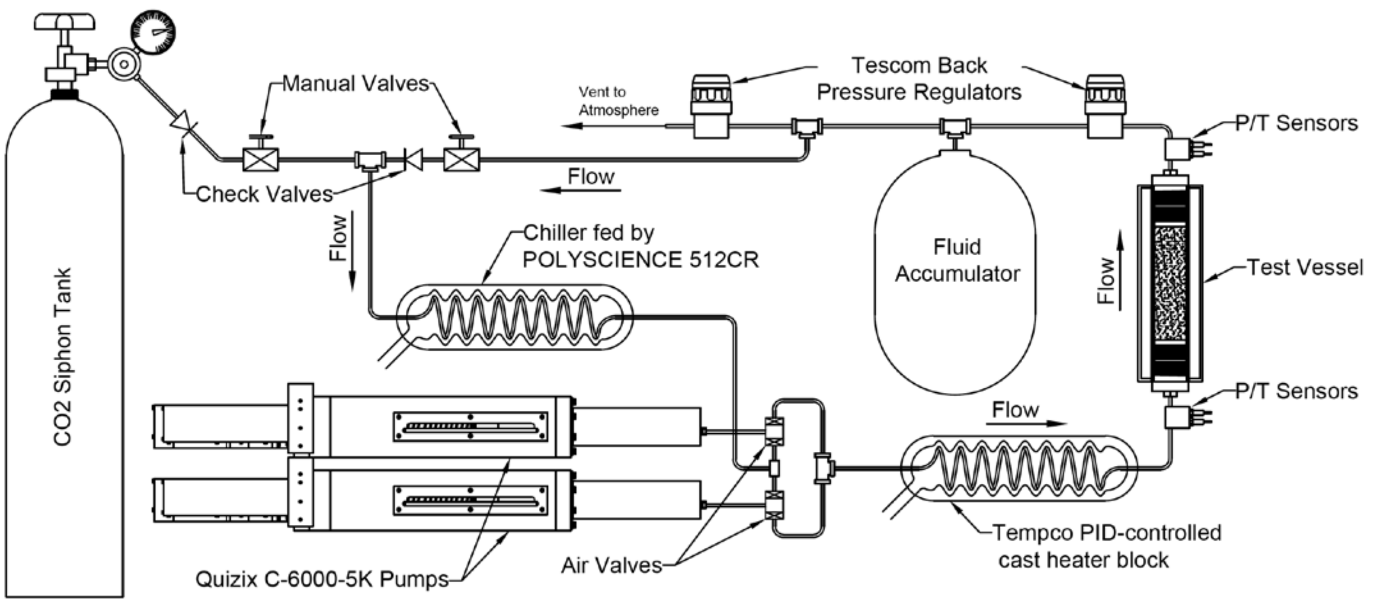
- At early time (≤ 0.1 year), produce single-phase water
- This is followed by a two-phase water-CO_2 mixture (0.1 - 2.5 yr)
- Total production rate during two-phase period is low due to phase interference
- Subsequently produce a single supercritical CO_2-rich phase with dissolved water

(Pruess and Spycher, WGC 2010)

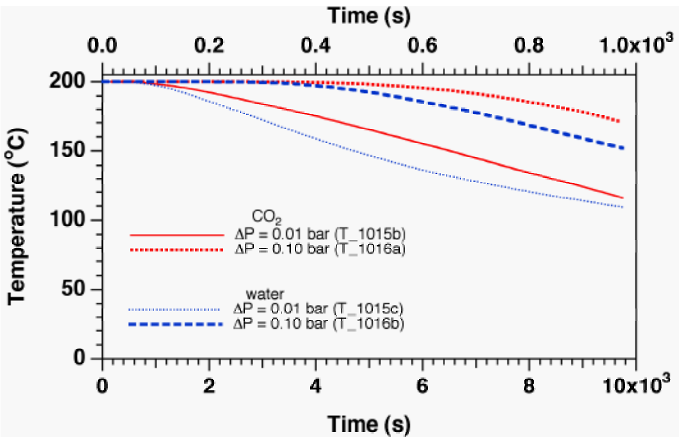
Schematic of Core Holder for Heat Extraction Experiments



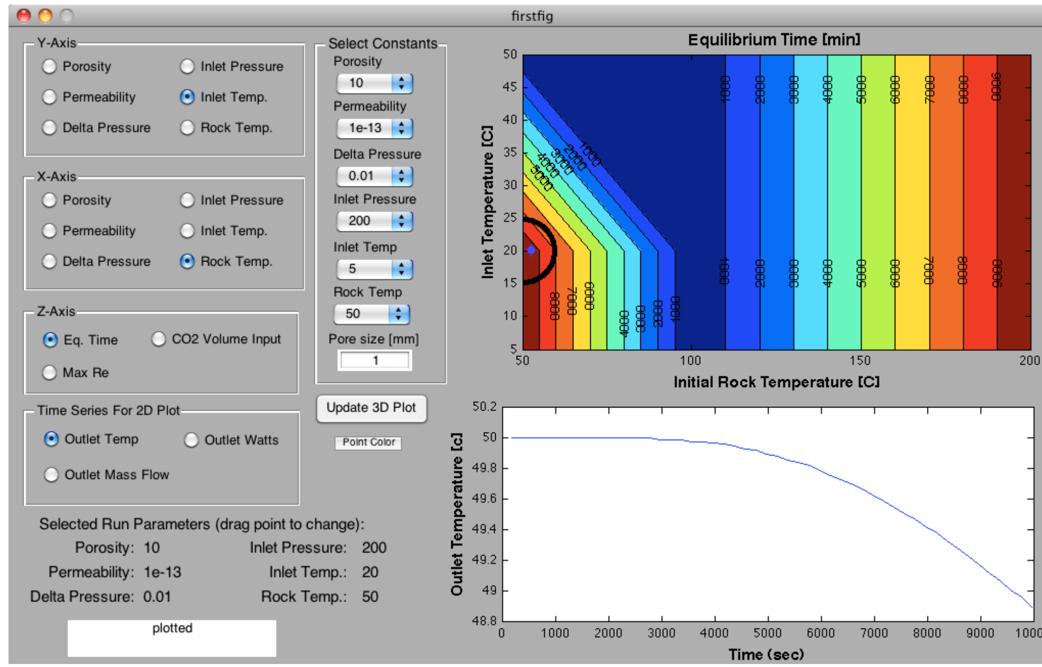
Laboratory Apparatus for Heat Extraction Experiments with $scCO_2$



Design Calculations for Heat Extraction Experiments

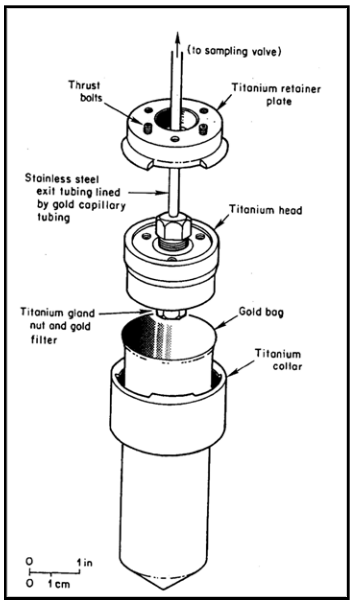


TOUGH2 simulation results for temperatures at the core outlet, for different pore fluids and applied pressure increments.



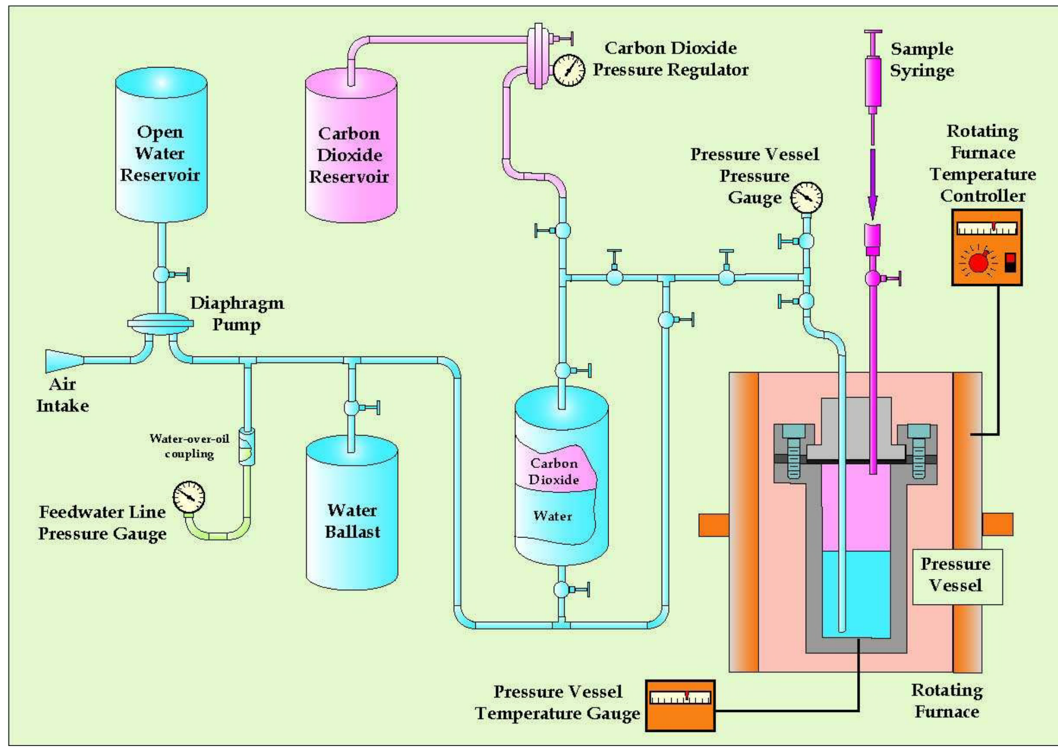
Screen shot of a data browser, displaying results of multiple TOUGH2 runs for different permutations of experimental parameters.

Reactive Chemistry Experiments for CO_2-Brine-Rock (Collaboration INL - USGS)



Reactor schematic

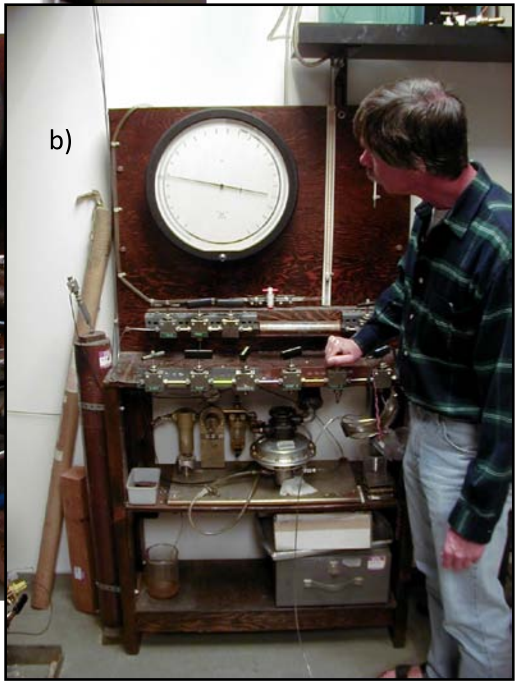
Example reactor vessel



Schematic of $scCO_2$/brine/rock reactor charging and sample extraction facility

USGS High T-P Reactor Facility (Bob Rosenbauer)

Heater blocks for high T-P reactors



Reactor charging/discharging apparatus

Project Management/Coordination

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- The project is a collaboration between LBNL (Pruess) and INL (Redden). UC Berkeley is involved as well (PhD student).

	Investigator	Role in project	Experience
LBNL	Pruess	overall direction; in charge of fluid and heat flow modeling	more than 30 years in geothermal engineering; 10 years in geologic storage of CO_2
LBNL	Kneafsey	lead flow and heat transfer experiments	more than 12 years experience with laboratory fluid and heat flow experiments
LBNL	Xu	lead reactive chemical transport modeling	more than 10 years experience with chemical transport modeling applied to geothermal and CO_2 storage
LBNL	Spycher	lead thermodynamics and thermophysical modeling	over 20 years experience with thermodynamic modeling of multicomponent, multiphase fluids
LBNL	Apps	geologic and geochemical modeling of specific sites	over 35 years experience in analysis of multi-mineralic geologic media
INL	Redden	overall direction; in charge of rock-fluid reaction experiments	over 20 years experience with environmental chemistry
INL	Mattson	conduct chemically reactive rock-fluid experiments	over 10 years experience with laboratory experiments on permeable media

- 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.

Publications and Presentations

Pruess, K. and N. Spycher. Enhanced Geothermal Systems (EGS) with CO_2 as Heat Transmission Fluid - A Scheme for Combining Recovery of Renewable Energy with Geologic Storage of CO_2, *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia, April 25-29, 2010.

Spycher, N. and K. Pruess. A Phase-Partitioning Model for CO_2-Brine Mixtures at Elevated Temperatures and Pressures: Application to CO_2-Enhanced Geothermal Systems, *Transport in Porous Media,* Vol. 82, No. 1, pp. 173–196, DOI 10.1007/s11242-009-9425-y, March 2010.

Xu, T., W. Zhang and K. Pruess. Numerical Simulation to Study Feasibility of Using CO_2 as a Stimulation Agent for Enhanced Geothermal Systems, *Proceedings*, Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 1-3, 2010.