U.S. DEPARTMENT OF ENERGY
GEOTHERMAL TECHNOLOGIES PROGRAM
ENHANCED GEOTHERMAL SYSTEMS
PEER REVIEW

Project Title: Geothermal Reservoir Dynamics - TOUGHREACT

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Sponsoring Organization: Lawrence Berkeley National Laboratory

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Collaborations
University of Utah, Calpine, NCPA, GeothermEx, Shell International, Electric Power Development Company (EPDC, Japan), GESAL (El Salvador), Kansas State University, U of Neuchatel (Switzerland), The University of Auckland (New Zealand), IGG (Italy)

Project Purpose

This project has been active for several years and has focused on developing, enhancing and applying mathematical modeling capabilities for fractured geothermal systems. The emphasis of our work has recently shifted towards enhanced geothermal systems (EGS) and hot dry rock (HDR), and FY05 is the first year that the DOE-AOP actually lists this project under Enhanced Geothermal Systems. Our overall purpose is to develop new engineering tools and a better understanding of the coupling between fluid flow, heat transfer, chemical reactions, and rock-mechanical deformation, to demonstrate new EGS technology through field applications, and to make technical information and computer programs available for field applications.

Project Objective(s)

Improve fundamental understanding and engineering methods for geothermal systems, primarily focusing on EGS and HDR systems and on critical issues in geothermal systems that are difficult to produce. Improve techniques for characterizing reservoir conditions and processes through new modeling and monitoring techniques based on “active” tracers and coupled processes. Improve techniques for targeting injection towards specific engineering objectives, including maintaining and controlling injectivity, controlling non-condensible and corrosive gases, avoiding scale formation, and optimizing energy recovery. Seek opportunities for field testing and applying new technologies, and work with industrial partners and other research organizations.

Funding

Fiscal Year	DOE Funding ($k)	Cost Share ($k)	Total
FY03	195	150	345
FY04	180	50	230
FY05	210	240*	450
FY06	220	220*	440

* California Energy Commission (expected)

Plans and Approach

Develop tracer testing methods for characterizing heat transfer in HFR and EGS reservoirs. Apply the TOUGHREACT code and collaborate with EGI (Pete Rose) to study chemically coupled processes in hydrothermal and EGS systems. Collaborate with the group at Kansas State University (KSU; Dan Swenson) on a geomechanically coupled version of TOUGH2. Investigate impact of mechanically and chemically coupled processes on design, operation and management of EGS systems. Use mathematical modeling and laboratory experiments to determine the feasibility of targeted water injection as a means for controlling acidity of steam produced in the northwest Geysers.

Results

1. Rock-Fluid Interactions

This task focuses primarily on reactive chemical transport modeling, although processes involving rock mechanical deformation are also being addressed (Todesco et al., 2004). Development of Version 1.0 of our TOUGHREACT simulation program for reactive chemical transport in multiphase, non-isothermal systems was completed, and the code with documentation was transferred to DOE's Energy Science and Technology Software Center (ESTSC) in August, 2004 (Xu et al., 2004b). An important component in the development process was thorough beta-testing by interested parties, including private companies and research organizations. ESTSC began distributing the program in November, 2004, for the first time making comprehensive capabilities for modeling coupled physical and chemical processes in non-isothermal multiphase flow systems available to the public (http://www-esd.lbl.gov/TOUGHREACT/).

We continually seek external collaborations and opportunities for applications of reactive chemical transport modeling to geothermal field problems, as a means to transfer this new technology to practical use. We have conducted a number of collaborative studies with industrial and other partners (Todaka et al., 2004, 2005; Kiryukhin et al., 2004; Xu et al. 2004a, Montalvo et al., 2005).

2. Tracer Testing

Determining the fracture-matrix interface area available for heat transfer is a critical need in the characterization of fractured reservoirs, and in appraising their productive capacity and longevity. We have investigated the use of reversibly sorbing solute tracers for this task. Collaborating with Shell International Exploration and Production Company, we have performed numerical simulation studies to demonstrate that such tracers impart a unique signature on breakthrough curves (BTCs), which may allow fracture-matrix interface area to be estimated (Pruess et al., 2005). We also developed a new analytical solution for migration of solute tracers in idealized fracture systems, which provides unique insight into the role of diffusion and sorption in BTCs, and can be used as a screening tool for identifying suitable chemicals for use as solute tracers (Shan and Pruess, 2005). Studies of phase-partitioning tracers have been performed, and a new fluid property module for noble gases was developed for TOUGH2 (Shan and Pruess, 2004).

3. Injectivity in EGS and HDR Systems

Management of injection water chemistry is the key to successful long-term operation of EGS systems. Sophisticated and field-proven capabilities for chemically reactive transport modeling are essential to achieve this goal.

In cooperation with the European HDR project at Soultz, we have performed studies of rock-fluid interaction in HDR systems, with special emphasis on modifying injection water chemistry to maintain injectivity. Issues addressed include kinetic precipitation of minerals that may be supersaturated in injected fluid, such as amorphous silica, precipitation of minerals with retrograde solubility such as calcite, and swelling of clay minerals. Permeability maintenance can be optimized by diluting injection water with fresh water, and through pH modification (Xu and Pruess, 2004). Injection behavior of HDR systems with fluids of high ionic strength has been modeled with a recently enhanced version of the TOUGHREACT simulator, that incorporates the Pitzer model for ion-ion interactions. Dissolution and precipitation effects were found to be dramatically different in some cases from low-ionic strength solutions (Xu et al., 2005).

4. Heat Transmission in EGS and HDR Systems

We have adapted the semi-analytical technique of Vinsome and Westerveld (1980) for heat exchange between a non-isothermal flow system and adjacent rock of negligibly small permeability to the problem of heat transfer at a linear flow channel embedded in impermeable rock (Pruess and Zhang, 2005). Possible applications include heat transmission effects at production or injection wellbores, and at localized preferential flow paths in fractured rock. Initial results demonstrated excellent accuracy for time scales of a few days, while at later time rates of heat transfer tend to be underestimated by increasing amounts. Work is continuing to obtain better approximations for temperature profiles over longer time scales.

Impact of Work/Merit

We regularly report the results of our work at conferences and through professional journals (see Publications, below), and we make our simulation codes available to the public. The TOUGH codes are currently in use in approximately 300 installations in over 30 countries. We are providing technical support to users. Expanded versions of selected papers from the TOUGH Symposium 2003 were published in August 2004 in a Special Issue of the journal *Geothermics*, guest-edited by the PI of this project (Pruess, 2004a).

Cooperation with industry has been vital for developing capabilities for reactive chemical transport modeling. This involved an active role by industry partners (Unocal, ExxonMobil, Shell, GeothermEx, Thunderhead Engineering, EPDC, Taisei Corp.) and research collaborators (U of Utah, Ohio State University, U of Nevada, IRL New Zealand, Kamchatka Institute of Volcanology) in beta-testing our TOUGHREACT code, and in developing prototypical applications to field problems.

Selected Publications

Kiryukhin, A., T. Xu, K. Pruess, J. Apps and I. Slovtsov. Thermal-Hydrodynamic-Chemical (THC) Modeling Based on Geothermal Field Data, *Geothermics,* Vol. 33, No. 3, pp. 349 - 381, doi:10.1016/j.geothermics.2003.09.005, 2004.

Montalvo, F., T. Xu and K. Pruess. A Study on Calcite and Silica Scaling in Geothermal Production-Injection Wells Using Reactive Geochemical Transport Simulator TOUGHREACT, to be presented at World Geothermal Congress, Antalya, Turkey, April 24-29, 2005.

Pruess, K. Special Issue: Selected papers from the TOUGH Symposium 2003, Berkeley, 12-14 May, 2003 - Preface, *Geothermics,* Vol. 33, No. 4, pp. 399 - 400, August 2004a.

Pruess, K. The TOUGH Codes—A Family of Simulation Tools for Multiphase Flow and Transport Processes in Permeable Media, *Vadose Zone J.,* Vol. 3, pp. 738 - 746, 2004b.

Pruess, K., T.v. Heel and C. Shan. Tracer Testing for Estimating Heat Transfer Area in Fractured Reservoirs, to be presented at World Geothermal Congress, Antalya, Turkey, April 24-29, 2005.

Pruess, K. and Y. Zhang. A Hybrid Semi-Analytical and Numerical Method for Modeling Wellbore Heat Transmission, presented at Stanford Geothermal Workshop, 2005.

Rutqvist J. and O. Stephansson. The Role of Hydromechanical Coupling in Fractured Rock Engineering, *Hydrogeology Journal,* Vol. 11 pp. 7-40, 2003.

Rutqvist J. and C.-F. Tsang C.-F. TOUGH-FLAC: a Numerical Simulator for Analysis of Coupled Thermal-Hydrological-Mechanical Processes in Fractured and Porous Geological Media under Multi-phase Flow Conditions, *Proceedings,* TOUGH Symposium 2003, Lawrence Berkeley National Laboratory, Berkeley, May 12-14, 2003.

Shan, C. and K. Pruess. EOSN - A New TOUGH2 Module for Simulating Transport of Noble Gases in the Subsurface, *Geothermics,* Vol. 33, No. 4, pp. 521 - 529, August 2004.

Shan, C. and K. Pruess. Sorbing Tracers - A Potential Tool for Determining Effective Heat Transfer Area in Hot Fractured Rock Systems, presented at Stanford Geothermal Workshop, 2005.

Todaka, N., C. Akasaka, T. Xu and K. Pruess. Reactive Geothermal Transport Simulation to Study the Formation Mechanism of Impermeable Barrier between Acidic and Neutral Fluid Zones in the Onikobe Geothermal Field, Japan, *J. Geophys. Res. Solid Earth,* Vol. 109(B5):5209, doi: 10.1029/2003JB002792, May 2004.

Todaka, N., C. Akasaka, T. Xu and K. Pruess. Reactive Geothermal Transport Simulations to Study Incomplete Neutralization of Acid Fluid Using Multiple Interacting Continua Method in Onikobe Geothermal Field, Japan, to be presented at World Geothermal Congress, Antalya, Turkey, April 24-29, 2005.

Todesco, M., J. Rutqvist, G. Chiodini, K Pruess and C. Oldenburg. Modeling of Recent Volcanic Episodes at Phlegrean Fields (Italy): Geochemical Variations and Ground Deformation, *Geothermics,* Vol. 33, No. 4, pp. 531 - 547, August 2004.

Xu, T. and K. Pruess. Numerical Simulation of Injectivity Effects of Mineral Scaling and Clay Swelling in a Fractured Geothermal Reservoir, presented at Annual Meeting of GRC, 2004.

Xu, T., Y. Ontoy, P. Molling, N. Spycher, M. Parini and K. Pruess. Reactive Transport Modeling of Injection Well Scaling and Acidizing at Tiwi Field, Philippines, *Geothermics,* Vol. 33, No. 4, pp. 477 - 491, August 2004a.

Xu, T., E. Sonnenthal, N. Spycher and K. Pruess. TOUGHREACT User's Guide: A Simulation Program for Non-isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Geologic Media, Lawrence Berkeley National Laboratory Report LBNL-55460, September 2004b.

Xu, T., G. Zhang and K. Pruess. Use of TOUGHREACT to Simulate Effects of Fluid Chemistry on Injectivity in Fractured Geothermal Reservoirs with High Ionic Strength Fluids, presented at Stanford Geothermal Workshop, 2005.

Plans for Completion

We are continuing to work on improving the realism of chemical data for rock-fluid interactions. Further applications of TOUGHREACT to EGS and HDR systems will be made, both to fundamental problems in rock-fluid interactions, and to practical engineering problems that arise in geothermal production and injection operations. We have begun to cooperate with the Coso EGS project and will participate in design and analysis of injection tests to enhance injectivity. Our research program takes advantage of synergies with geothermal-related problems in disposal of heat-generating nuclear wastes, and with emerging fields such as geologic disposal of greenhouse gases.

We continue to seek opportunities for conducting field tests with sorbing tracers.

Efforts are ongoing to obtain a more accurate representation of heat exchange between a linear flow channel and surrounding rock of low permeability over a broad range of time scales.

Pending receipt of funding from the California Energy Commission, we plan on setting up laboratory experiments to study retardation effects in the transport of corrosive gases under partially water-saturated conditions, such as could be achieved at The Geysers through targeted injection. The laboratory work will be complemented with modeling studies of reactive transport in multiphase conditions, in order to achieve a mechanistic understanding of gas retardation effects, which could provide a basis for designing injection tests at The Geysers.

We will continue technical exchanges with the group at Kansas State University (Dan Swenson) on their development of a poroelastic model for TOUGH2. We also will continue to develop and apply our in-house TOUGH-FLAC code for coupled analysis of fluid flow, heat transfer, and rock-mechanical deformation (Rutqvist and Stephansson, 2003; Rutqvist and Tsang, 2003).