Development of Advanced Thermal-Hydrological-Mechanical-Chemical (THMC) Modeling Capabilities for Enhanced Geothermal Systems

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Colorado School of Mines

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This presentation does not contain any proprietary confidential, or otherwise restricted information.
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- Project Objectives
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- Work Plan and Progress
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Overview

• Timeline

<table>
<thead>
<tr>
<th>Start Date</th>
<th>End Date</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/01/10</td>
<td>12/31/2013</td>
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• Budget

<table>
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<tr>
<th>Contributor</th>
<th>Fund</th>
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<tbody>
<tr>
<td>Department of Energy (DOE)</td>
<td>$1,191,893</td>
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<tr>
<td>Computer Modeling Group Ltd. (CMG)</td>
<td>$441,600</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>$1,633,493</strong></td>
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</tbody>
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• Barriers

- few data or constitutive relations available for correlating flow/rock properties and rock deformation and fluid-rock interactions in non-isothermal fractured or porous media rock of geothermal reservoirs

• Partners

- Colorado School of Mines
- Lawrence Berkeley National Laboratory
- Computer Modeling Group
Project Objectives

• **Develop a general framework** for effective flow of water, steam and heat in porous and fractured geothermal formations

• **Develop a computational module** for handling coupled effects of pressure, temperature, and induced rock deformations

• **Develop a reliable model** of heat transfer and fluid flow in fractured rocks

• **Develop a chemical reaction module** to include important chemical reactions in EGS

• **Develop an efficient parallel computing** methodology for simulation purposes

• **Apply the EGS simulator** to laboratory and field data of geothermal reservoirs
The reservoir simulator developed from this project will be among the first rigorous fully-coupled hydro-thermal-mechanical-chemical (THMC) reservoir simulator.

This simulator will substantially enhance our ability to characterize EGS systems and provide practical approaches to assess the following:

- Long-term performance
- Optimum design
- Operation strategies, and
- Commercial feasibility
### Project Team Members

<table>
<thead>
<tr>
<th>Member</th>
<th>Qualifications</th>
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</table>
| Dr. Yu-Shu Wu     | **Colorado School of Mines**  
- CMG Reservoir Modeling Chair Professor in Petroleum Engineering Dept.  
- Professor of Petroleum Engineering Department (2008-Current)  
**Lawrence Berkeley National Laboratory (LBNL)**  
**Research Area of Interest**  
- Multiphase flow and heat transfer in subsurface, CO₂ sequestration, reservoir simulation and geothermal energy                                                                                                                                                                                     |
| Dr. Hossein Kazemi| **Colorado School of Mines**  
- Chesebro’ Distinguished Chair Professor in Petroleum Engineering Dept.  
- Professor of Petroleum Engineering Department (1980-Current)  
**Marathon Oil Company** (1969-2000)  
- Research Scientist, Senior Technical Consultant, Director of Production Research, Manager of Reservoir Technology, and Executive Technical Fellow at Marathon Petroleum Technology Center  
**Research Area of Interest**  
- Reservoir Simulation (Naturally-Fractured Reservoirs, IOR/EOR), Geomechanics and Transient Well Testing  
**Awards & Honors**  
- Member of the National Academy of Engineering  
- SPE Honorary and Distinguished Membership  
- SPE Improved Oil Recovery Pioneer Award (2006)  
- SPE Rocky Mountain North America Regional Reservoir Description and Dynamics Award (2008), etc.                                                                                                                                                                                                 |


### Project Team Members

<table>
<thead>
<tr>
<th>Member</th>
<th>Qualifications</th>
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<tbody>
<tr>
<td>Dr. Tianfu Xu</td>
<td><strong>Lawrence Berkeley National Laboratory (LBNL)</strong>&lt;br&gt;- Staff scientist: 16 years experience in development of numerical modeling of multiphase non-isothermal fluid flow and reactive transport in unsaturated and saturated porous media and fractured rock systems.&lt;br&gt;- Chief developer of LBNL’s multi-phase non-isothermal reactive flow and chemical transport simulator: “TOUGHREACT.”&lt;br&gt;<strong>Research Area of Interest</strong>&lt;br&gt;  - <em>Geothermal energy development:</em> formation scaling due to water injection, optimization of injection water chemistry, chemical stimulation for enhanced geothermal system (EGS), use of CO₂ as working fluid for EGS (CO₂-EGS), controlling and mineral dissolution and precipitation in the reservoir.&lt;br&gt;  - <em>CO₂ sequestration:</em> fate and transport of injected CO₂ in storage reservoirs, mineral trapping, caprock and cement alterations due to CO₂ intrusion, and the impact of CO₂ leakage on groundwater quality.</td>
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<tr>
<td>Dr. Keni Zhang</td>
<td><strong>Lawrence Berkeley National Laboratory (LBNL)</strong>&lt;br&gt;- Geological scientist (2000-current)&lt;br&gt;- Primary developer of LBNL’s parallel computing simulators: TOUGH2-MP, TMVOC-MP, and parallel TOUGH+HYDRATE.&lt;br&gt;<strong>Research Area of Interest</strong>&lt;br&gt;  - Large-scale, multi-component, multi-phase fluid and heat flow simulation for CO₂ geological sequestration, nuclear waste disposal, and gas hydrate studies.</td>
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## Project Team Members

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<tr>
<th>Member</th>
<th>Qualifications</th>
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</table>
| **Computer Modeling Group (CMG)** | • The Largest Independent Developer of Reservoir Simulation Software  
- Providing oil/gas reservoir simulation tools for EOR/IOR processes especially thermal reservoir modeling  
- Market leader: 300+ clients world wide - in 45 countries  
- Thousands of users world wide  

• **Products**  
  - IMEX (Black oil modeling)  
  - STARS (Advanced processes i.e. thermal modeling, naturally-fractured reservoir modeling, geomechanical modeling, compositional modeling, etc.)  
  - GEM and WinProp (Compositional modeling)  
  - Builder and Results (Visualization animation) |
Technical Approach

General framework: Integral Finite Differences

\[ \frac{d}{dt} \int_{V_n} M \, dV_n = \int_{\Gamma_n} F \cdot n \, d\Gamma_n + \int_{V_n} q \, dV_n \]

Mass Balance for Component \( \kappa \)

\[ M^\kappa = \sum \phi S_\beta \rho_\beta X_\beta^\kappa \]

\[ F_\beta = -k_0 (1 + \frac{b}{P_\beta}) \frac{k_{r\beta} \rho_\beta}{\mu_\beta} (\nabla P_\beta - \rho_\beta g) \]

Heat Equation

\[ M^h = (1 - \phi) \rho_R C_R T + \phi \sum S_\beta \rho_\beta u_\beta \]

\[ F^h = -[(1 - \phi) K_R + \phi \sum S_\beta K_\beta] \nabla T + f_\sigma \sigma_0 \nabla T^4 + \sum h_\beta F_\beta \]
Technical Approach

\[ \frac{d}{dt} \int_V M \, dV = \int_{\Gamma} F \cdot n \, d\Gamma + \int_V q \, dV \]

\[ \int_V M \, dV = V_n M_n \]

\[ \int_{\Gamma_n} F \cdot n \, d\Gamma = \sum_m A_{nm} F_{nm} \]

\[ \frac{dM_n}{dt} = \frac{1}{V_n} \sum_m A_{nm} F_{nm} + q_n \]
Stress Dependent Rock Properties

- Apply the continuum modeling approach to simulate multiphase fluid and heat flow, coupled with rock deformation in fractured and porous rock

- Develop or adopt constitutive correlations for describing how rock properties (intrinsic permeability, porosity, fracture aperture, capillary pressure, etc.) change with effective stress, fluid pressure, temperature, and other state variables

- Porosity and permeability of porous rock and fractures in an EGS system are assumed to correlate with the mean effective stress ($\sigma'_m$)

$$\phi = \phi(\sigma'_m, T) \quad k = k(\sigma'_m, T) \quad P_c = P_{c_0} \left( \frac{\sqrt{k_i / \phi_i}}{\sqrt{k / \phi}} \right)$$

Ref: Rutqvist et al. 2002; Wu et al. 2008
Chemical Reaction

- Aqueous-based reservoir stimulation is likely to promote dissolution of some rock minerals, while precipitating others, and lead to large impact on the permeability of the fracture network.

- Mineral dissolution and precipitation are considered under kinetic conditions and the temperature dependence of the reaction rate constant can be expressed via an Arrhenius equation.

- **Transport equations**: Mass balance (transport) equations for chemical components can be expressed as:

  \[
  \frac{d}{dt} \int \limits_{V_n} M^\kappa dV_n = \int \limits_{\Gamma_n} F^\kappa \cdot n d\Gamma_n + \int \limits_{V_n} q^\kappa dV_n + \int \limits_{V_n} R^\kappa dV_n
  \]

  where \( \kappa \) is chemical component index, such as Ca\(^{2+} \), SiO\(_2\)(aq), and R is mass transfer from solid phases such as calcite and silica mineral dissolution and precipitation.

- Chemical reactions are considered as secondary equations.
Fracture Models

- Generalized dual-continuum methodology: treats fracture and matrix flow and interactions using a multi-continuum numerical approach

- The Approach can be applied for
  - Discrete fracture i.e. hydraulic fracture (man made) and faults
  - Fracture network or naturally fractured reservoirs
Task 1: Development of framework model
  - The work has started on the formulation for the framework model.

Task 2: Rock Deformation Module
  - Literature survey of laboratory and field studies relating rock deformation to flow properties

Task 3: Chemical Reaction Module
  - The work has started on the selection of chemical species and model incorporation coding.

Task 4: Parallel Computation Scheme
  - The work has started on the domain partitioning.

Task 5: Fracture Models
  - The work has started on the conceptual modeling development of fractured reservoirs.
### Project Schedule

<table>
<thead>
<tr>
<th>Tasks</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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<tr>
<td><strong>Task 1: Development of framework model</strong></td>
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<tr>
<td>Phase I- Formulation and coding</td>
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<tr>
<td>Phase II- Finalizing program</td>
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<tr>
<td><strong>Task 2: rock deformation module</strong></td>
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<tr>
<td>Phase I- Literature review</td>
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<td>Phase I- Formulation and coding</td>
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<td>Phase II- Formulation and initial verification</td>
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<tr>
<td>Phase III- implementation and verification</td>
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<tr>
<td>Phase IV- integration and application</td>
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<td><strong>Task 3: chemical reaction module</strong></td>
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<tr>
<td>Phase I- selection of chemical species and incorporation coding</td>
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<tr>
<td>Phase II- model testing and verification</td>
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<tr>
<td>Phase III- finalizing coding, integration and documentation</td>
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<td><strong>Task 4: parallel computing scheme</strong></td>
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<tr>
<td>Phase I- Domain partitioning</td>
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<td>Phase II- Jacobian matrix calculations</td>
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<td>Phase III- Parallel solver implementation</td>
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<td>Phase IV- Software test and verification</td>
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<td>Phase V- Model integration</td>
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<td><strong>Task 5: fracture models</strong></td>
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<td>Phase I- Conceptual model development</td>
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<tr>
<td>Phase II- formulation and coding</td>
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<tr>
<td>Phase III- verification and improvement</td>
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<td>Phase IV- integration and application</td>
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<td><strong>Task 6: verification and application</strong></td>
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<tr>
<td>Phase I- against other simulators</td>
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<td>Phase II- against lab data</td>
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<tr>
<td>Phase III- against field data</td>
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- **Completed Task**
- **Uncompleted Task**
• The research will be carried at Colorado School of Mines (CSM) and at Lawrence Berkeley National Laboratory (LBNL)

• To ensure effective communication between CSM and LBNL and among the PI and CO-PI’s, the Project PI: Dr. Yu-Shu Wu plans to work two days every month at LBNL over the three-year period of the project

• Monthly teleconferences will be held among the PI and CO-PI’s to exchange information, update progress, discuss problems, and coordinate efforts
Project organization chart

Task 1: Yu-Shu Wu (CSM)
Task 2: Yu-Shu Wu (CSM)
Task 3: Tianfu Xu (LBNL)
Task 4: Keni Zhang (LBNL)
Task 5: Hossein Kazemi (CSM)
Task 6: Yu-Shu Wu (CSM)

Model Integration
All Pis-CO Pis: CSM and LBNL
The reservoir simulator developed from this project will be among the first rigorous fully-coupled hydro-thermal-mechanical-chemical (THMC) reservoir simulator.

This simulator will substantially enhance our ability to characterize EGS systems and provide practical approaches to assess the following:

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