A new analytic-adaptive model for EGS assessment, development and management support

May 19, 2010

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**Project: Desert Peak EGS**

<table>
<thead>
<tr>
<th>Location</th>
<th>Western Nevada</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator</td>
<td>Ormat Technologies, the Department of Energy and others</td>
</tr>
</tbody>
</table>

Principal Investigator
George Danko
University of Nevada, Reno
Overview

- **Timeline**
  - Project start date: 12/29/2009
  - Project end date: 1/31/2013
  - Percent complete: 20% of 2010

- **Budget**
  - Total project funding: $1,629,670
  - DOE share: $1,278,070
  - Awardee’s share: $351,600
  - Funding received in FY09: NA
  - Funding for FY10: $443,596

- **Barriers addressed in GTP 2008**
  - Reservoir Characterization (Barrier F)
  - Validation (Barrier I)
  - Scale Up (Barrier L)
  - Sustainability (Barrier M)

- **Partners**
  - Sub-Contractor: Lawrence Berkeley National Laboratory (LBNL)
  - Co-supporter: ORMAT
Relevance/Impact of Research

Overall:

1. Develop an in depth model of EGS systems that will allow engineers, practitioners, and researchers to more accurately predict how new fluid technologies would work in a reservoir.

2. Test and apply the new model to:
   - Cases with known solutions for benchmarking and comparison.
   - ORMAT’s EGS sites (Desert Peak, Brady) for capability demonstrations.

3. Study new fluid flow applications and cooling technologies to improve geothermal power extraction from an EGS.

Phase I, 1st year:

Develop a Geologic Heat Exchanger (GHE) model that simulates discrete fracture network flow and transport in a coupled way to a dual-porosity and dual-permeability rockmass.

The GHE, a coupled THMC (Thermal, Hydrologic, Mechanical, and Chemical) model is the core building element of a numerical simulator for the studies.
For discrete fracture flow and transport, apply the integrated-parameter CFD (Computational Fluid Dynamics) model-element of MULTIFLUX 5.0. Import previous model-elements developed for Yucca Mountain (YM) to EGS application.

<table>
<thead>
<tr>
<th>Fracture network CFD: T-H-M-C</th>
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</thead>
<tbody>
<tr>
<td>Thermal</td>
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<tr>
<td>Hydrological</td>
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<tr>
<td>Mechanical</td>
</tr>
<tr>
<td>Chemical</td>
</tr>
</tbody>
</table>

For coupling the discrete fracture CFD model to the rockmass, use the NTCF (Numerical Transport Code Functionalization) modeling technique (See supplemental material).

For the rockmass, separate and re-couple the Near-Field (NF) rockmass from the Far-Field (FF) rockmass:

<table>
<thead>
<tr>
<th>NF rockmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelopes the discrete fracture network</td>
</tr>
<tr>
<td>Short time transients or periodic variations are encaptured in the volume</td>
</tr>
<tr>
<td>Fine time and spatial divisions</td>
</tr>
<tr>
<td>Fully coupled to the fracture CFD with an NTCF-NF model</td>
</tr>
<tr>
<td>Data-driven, using TOUGH2 or THOUGHREACT, 3DEC</td>
</tr>
<tr>
<td>Leaky to heat and fluid flow to the FF model</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FF rockmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelopes or “absorbs” the NF rockmass</td>
</tr>
<tr>
<td>Long time period, coarse time division</td>
</tr>
<tr>
<td>Fully coupled to the NF rockmass with an NTCF-FF model</td>
</tr>
<tr>
<td>Data-driven, using TOUGH2 or THOUGHREACT, 3DEC</td>
</tr>
</tbody>
</table>
Discrete fracture network model in the GHE

An overlaid set of transport networks for T-H-M-C
Near-Field Model in the GHE

- Envelopes the fracture network in a near-field rockmass
- Fine-grid, it may be 2-D in normal direction to the fracture plane

NTCF-NF matrix model for heat and mass at the fracture surface:

\[
\begin{align*}
[qh_i^N] &= qh_i^F + hh_i^N \cdot [T_i^N - T_i^F] + hm_i^N \cdot (P_i^N - P_i^F) \\
[qm_i^N] &= qm_i^F + mm_i^N \cdot (P_i^N - P_i^F)
\end{align*}
\]

\(hh_i^N, hm_i^N,...\) : NTCF – NF matrices (fixed size)
\(T_i^N, P_i^N,...\) : vectors with finely – sampled variables with time
Scientific/Technical Research Methods

**Far-Field model in the GHE**

- Dual-porosity, dual permeability THMC model based on data from TOUGH or TOUGHREACT.
- Site-Scale, includes all relevant hydrogeology that affects energy flow
- NTCF-FF model evolves coarse time-step by time-step

NTCF-FF matrix model for heat and mass at the NF-FF contact boundary:

\[
\begin{align*}
[qh^F_i] &= h h^F_i \cdot [T^F_i - T_i^{VR}] + h m^F_i \cdot [P_i^F - P_i^{VR}] \\
[qm^F_i] &= h h^F_i \cdot [T^F_i - T_i^{VR}] + m m^F_i \cdot [P_i^F - P_i^{VR}]
\end{align*}
\]

\(hh^F_i, hm^F_i, ...,\): NTCF – FF matrices  
\(T^F_i, P_i^F, ...,\): vectors with coarsely – sampled variables with time
Coupling the CFD discrete fracture network model to the rockmass NF and FF model-elements in the GHE

1) Coupling between CFD and NTCF-NF and NTCF-FF

- Coupling to CFD uses both NTCF-NF and NTCF-FF model elements.
- NTCF-NF is a fixed-size matrix model capturing short-time transients in a limited time period, e.g., 10 to 20 days, prepared for the entire time period.
- NTCF-FF is a growing-size matrix model for slow and deep-penetrating transients covering the reservoir life span, prepared for one coarse, forward time step.
- Matrix equation coupling is derived for both NTCF-NF and NTCF-FF model-elements without iteration, a new and unique result from the project.

\[
\begin{align*}
q_h_i^N &= Fh_1(hh_i^N, hh_i^F, T_i^{VTR}, P_i^{VR}) + Fh_2(hh_i^N, hh_i^F) \cdot T_i^N + Fh_3(hm_i^N, hm_i^F) \cdot P_i^N \\
q_m_i^N &= Fm_1(mm_i^N, mm_i^F, P_i^{VR}) + Fh_2(mm_i^N, mm_i^F) \cdot P_i^N \\
Fh_1, Fm_1, ... : & \text{ heat and percolation fluid loss vectors sampled at fine time divisions;} \\
& \text{ all are functions of the } hh_i^N, hh_i^F, ... \text{ NTCF matrices} \\
Fh_2, Fh_3, Fm_2 : & \text{ heat and percolation matrices, all are functions of the } hh_i^N, hh_i^F, ... \text{ NTCF matrices}
\end{align*}
\]

Coupling to CFD is accomplished using the DISAC (Direct Iteration and Successive Approximation Coupler), imported from MULTIFLUX:

\[
\begin{align*}
q_h_i^N &= qh_i^{CFD}; qm_i^N = qm_i^{CFD} \\
T_i^N &= T_i^{CFD}; P_i^N = P_i^{CFD}
\end{align*}
\]
2) Coupling between NTCF-NF and NTCF-FF

- Explicit prediction without iteration:

\[
T_i^F = Fh_4(hh_i^N) \cdot T_i^N + Fh_5(hm_i^N) \cdot P_i^N + Fh_6(T_i^{VTR}) \\
P_i^F = Fm_3(mm_i^N) \cdot P_i^N + Fm_4(P_i^{VTR})
\]

Both can be refined by iteration if NTCF-FF is strongly-nonlinear (re run TOUGH, re-do \(hh_i^F\), re-solve for \(T_i^F, P_i^F\))

Fluxes can be directly calculated:

\[
q_{hi}^F = hh_i^F \cdot (T_i^F - T_i^{VR}) + hm_i^F \cdot (P_i^F - P_i^{VR}) \\
q_{mi}^F = mm_i^N \cdot (P_i^F - P_i^{VR})
\]

- Progress with NTCF-FF for next time step, assuming that the last flux vector elements hold constant over the next time period.
- Add new lines to \(hh_i^F, hm_i^F, \ldots\)

Note: \(T_i^F, q_{hi}^F, P_i^F, q_{mi}^F\) are used only for NTCF model identification, not as boundary conditions for coupled solution.
Coupling between the CFD and the combined NF and FF NTCF models

User input preparation for TOUGH2 model configuration

TOUGH2

TOUGH2 output data for NTCF model: T_s, T_1, T_2, P_s

User input data preparation for MULTIFLUX model configuration

CFD input deck

DISAC input deck

NTCF input deck

NTCF model identification

Matrix models for q_h, q_m

User’s activities

Inside Balance Iteration (IBI) cycle

DISAC with Inside Balance Iteration (IBI)

Coupled MULTIFLUX Result: T, P, q_h, q_m

Outside Balance Evaluation (OBE): max|T_s-T|<error limit for T; max(P_s-P)<error limit for P

Accept

No

Outside Balance Iteration (OBI): Prepare new boundary conditions from the balanced results for TOUGH2 run

Yes

Document results
Complete, 3-year project components:

Phase I. Multi-scale GHE sub-model (THMC) development
  - Fully coupled Thermal-Hydrologic (TH) model
  - Mechanical and Chemical (MC) models use surrogate models
  - TH model is fully iterated

Phase II. Life-cycle sub-model development of the EGS
  - Rock mechanics surrogate development
  - Fracture coating surrogate model development

Phase III. Total system model studies and verification exercises
  - Literature examples
  - ORMAT examples: Desert Peak, Brady
Accomplishments, Expected Outcomes and Progress

Progress:

• A Key Research Scientist position was created on Jan, 1st, 2010.
• A sub-contract to the Lawrence Berkeley National Laboratory (LBNL) has been set up.
• We have collected and organized the numerical model-elements in Tasks 1 through 3 during the first quarter of the work.
• A literature search was conducted on two-phase flow and heat transfer model-elements in Task 1.
• The TOUGH2 code was requested and installed at UNR to support Task 2.
• A structural coupling model configuration in MULTIFLUX was developed which allows for increasing the discretization distances to cover a large model domain with lower discretization error in Task 3.
• Multi-scale, near- and far-field rockmass model elements were separated and re-coupled non-iteratively using the NTCF technique.
• Organizational and two technical meetings with ORMAT took place.
Expected Outcome, Phase I:

- A functional GHE numerical model.
- Some numerical verification examples.
- Preparation for CFD network adaptation to an EGS site, based on matching borehole, seismic, pumping and tracer test data.
- To accelerate the numerical studies, it is of mutual interest of UNR as well as ORMAT to use the Desert Peak EGS field data for the first application example.
Project Management/Coordination

Management and Schedule:
- All tasks are worked on, shown in table below.
- Work contact with LBNL is according to the Subcontract.
- Work contact with ORMAT is according to the support pledge.

<table>
<thead>
<tr>
<th>PHASE 1</th>
<th>Multi-scale geologic heat exchanger sub-model</th>
<th>PHASE 1 (FY10)</th>
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<tbody>
<tr>
<td>Task 1</td>
<td>THMC model-elements for fracture network system</td>
<td>* * * *</td>
</tr>
<tr>
<td>Subtask 1.1</td>
<td>Two-phase flow and pressure fields model-element</td>
<td>* * * *</td>
</tr>
<tr>
<td>Subtask 1.2</td>
<td>Heat flow and temperature fields CFD model-element</td>
<td>* * * *</td>
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<tr>
<td>Subtask 1.3</td>
<td>Chemical species flow and concentration CFD model-element</td>
<td>* * * *</td>
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<tr>
<td>Subtask 1.4</td>
<td>Fracture aperture and morphology variation model-element</td>
<td>* * * *</td>
</tr>
<tr>
<td>Task 2</td>
<td>Model-element for TH transport in rockmass</td>
<td>* * * *</td>
</tr>
<tr>
<td>Task 3</td>
<td>Boundary coupler between fracture network and rockmass</td>
<td>* * * *</td>
</tr>
<tr>
<td>Delivery 1</td>
<td>Annual progress report, and publications as applicable. Closure of the working GHE sub-model.</td>
<td>* * * *</td>
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</table>
Plan for the rest of this year (FY10) and next year (FY11):

- Add new elements to MULTIFLUX:
  - Fracture aperture variation and
  - Two-phase heat transport surrogate model elements
  - Material properties database expansion
- Validate by numerical demonstration of the practical separation of domains between near-field and far-field model elements.
- Milestone I is a functional GHE model with functional near-field and far-field model-elements adaptable for EGS with variable discrete fracture network assumptions.
- The model uses MULTIFLUX, a qualified software with proven NTCF rockmass model technique and integrated-parameter, CFD model-elements.
- High ambitions, no threat to reach Milestone I. In cases of difficulties, we will cut back model size or increase computer computational capacity.
Summary

- A validated and qualified, integrated-parameter CFD model in MULTIFLUX is imported from Yucca mountain to EGS studies for flow and transport in a discrete fracture network. It is very efficient, and dramatically reduces the necessary number of grid nodes as compared to conventional CFD models.
- A validated and qualified NTCF modeling in MULTIFLUX is imported for separating a near-field model domain from the far-field THMC rockmass model domain, a new development.
- The near-field model for a hypothetical discrete fracture flow network offers a promise for adaptability to field data for a given set of seismic, borehole, pumping and tracer test results.
- The discrete fracture network model coupled with the near-field rockmass model will be a new reservoir assessment tool.
- The coupled near-field and far-field models offer a promise for energy recovery predictions to support management and operation.
- The discrete fracture network model coupled with the near-field rockmass model will run fast on fine time scale, and will be a new tool to study fluid flow delivery, and management support options.
Supplemental Slides
# Project Participants

A new analytic-adaptive model for EGS assessment, development and management support

<table>
<thead>
<tr>
<th>Role</th>
<th>Name</th>
<th>Institution</th>
</tr>
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<tbody>
<tr>
<td>PI</td>
<td>George Danko</td>
<td>University of Nevada, Reno</td>
</tr>
<tr>
<td>Co-PI</td>
<td>Jaak Daemen</td>
<td>University of Nevada, Reno</td>
</tr>
<tr>
<td>Co-PI at LBNL</td>
<td>Jens Birkholzer</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earth Sciences Division, 90-1116</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lawrence Berkeley National Laboratory</td>
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<tr>
<td>Key Research Person</td>
<td>Davood Bahrami</td>
<td>University of Nevada, Reno</td>
</tr>
<tr>
<td>Key Research Person</td>
<td>Liange Zheng</td>
<td>Lawrence Berkeley National Laboratory</td>
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<tr>
<td>Key Research Person</td>
<td>Dick Benoit</td>
<td>Sustainable Solutions</td>
</tr>
<tr>
<td>Industrial Partner</td>
<td>ORMAT Nevada, Inc.</td>
<td>Paul Speilman, Manager Operation support</td>
</tr>
<tr>
<td>Marketing Contributor</td>
<td>REA250</td>
<td>Susan Clark</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Renewable Energy Accelerator</td>
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</tbody>
</table>
Scientific/Technical Approach

Far-Field Model Capabilities – A previous example in TOUGH2

(from Bodvarsson, LBNL)
Scientific/Technical Approach

Phase I and Phase II: T-H-M-C model configuration with GHE and Life-Cycle model components

- **Rock Mech. 3DEC with thermal component model**
- **Tunable analytical-numerical thermo-mechanical fracture aperture model**
- **Fracture aperture and morphology model**
- **Accessible data for tests**
- **FLUENT**
- **MULTIFLUX**
- **Tunable analytical-numerical chemical fracture aperture model**
- **Accessible data for tests**
- **GHE model**
- **Thermo-mechanical fracture aperture model**
- **TOUGH2 model of the rockmass**
- **Reactive chemistry TOUGHREACT model**
- **Life-cycle model**
- **TOUGH2 model of the rockmass**
- **Discretization iterative coupler**
- **Converged?**
  - **Y**
    - **Pressure, flow field, temperature, species concentration, heat and mass transport network**
  - **N**
    - **Outside balance iteration**
- **Integrated THMC simulation is complete**
- **Is tuning necessary?**
  - **Y**
  - **N**

- **Converged**
- **N**
- **Y**
- **Is tuning necessary?**

Phase I and Phase II: T-H-M-C model configuration with GHE and Life-Cycle model components
Scientific/Technical Approach

Simplified diagram

Integrated-parameter flow and transport CFD model (THM C model)

3DEC Rock mechanics model (THM model)

TOUGH2 or TOUGHREACT rockmass model (THC model)

Coupled Model Solver (MULTIFLUX technology)

OUTPUT:
- Temperature field
- Humidity field
- Heat flow field
- Moisture flow field