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

Development of an Advanced Stimulation/Production Predictive Simulator for Enhanced Geothermal Systems

John W. Pritchett

SAIC

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Project Overview

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- Timeline
  - Start date: *01/29/2010.* End date: *01/31/2013.*
  - Percentage of work completed so far: *zero.*
- Budget
  - Total project funding: *$1,282,445.*
  - DOE share: *$1,025,953.* Awardee share: *$256,492.*
  - Received FY09: *zero.* Received FY10: *$1,025,953* (100%).
- Barriers addressed
  - Locate post-stimulation open fractures and flow paths.
  - Forecast long-term mass and heat flow, energy recovery.
- Awardee
  - Science Applications International Corporation (SAIC), San Diego, California.
- Partner
  - Geowatt AG (Zurich, Switzerland), as subcontractor.

Objective: to develop a 3-D numerical simulator to model the following aspects of stimulation and long-term operation -

(1) perturbation of natural stress, pore pressure, and formation temperature distributions caused by cold water injection,

(2) shear slippage and aperture increase along “fracture patches” and aperture change caused by changes in effective normal stress,

(3) “fracture patch” linkup to form connected permeable volume and both reversible and irreversible permeability changes,

(4) cooling-induced thermal shrinkage effects on permeability,

(5) transport of conservative and/or non-conservative tracers, and

(6) effects of pressure/stress/temperature changes upon “geophysical observables,” particularly electrokinetic self-potential.

Relevance/Impact of Research

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Relevance: a detailed underground heat exchanger description, based on data obtainable during reservoir stimulation, provides a predictive capability to help optimize resource management and minimize costs.

(1) New wells may be targeted to intersect known permeable fractures, reducing “trial-and-error” dry holes and overall project drilling costs.

(2) Premature thermal breakthrough may be anticipated and remedial steps taken before the actual onset of resource decline.

(3) Optimum monitoring programs may be devised to provide system performance oversight and verification/calibration information at minimum expense.

Scientific/Technical Approach

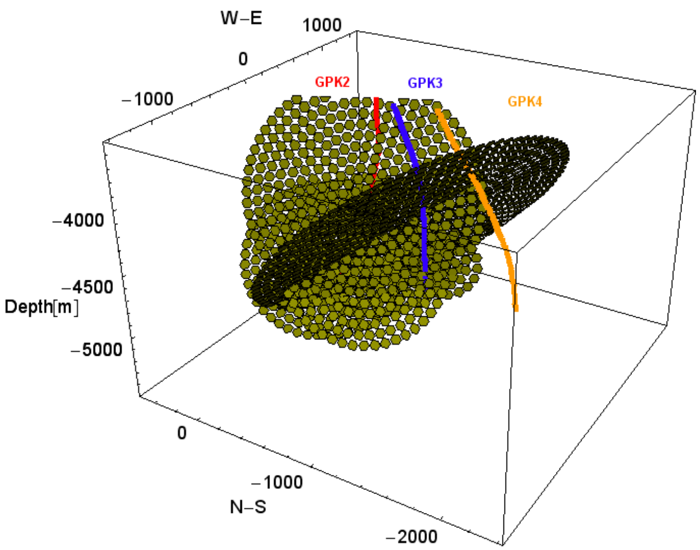
- We will develop a new numerical reservoir simulator suitable for describing both the creation of an EGS reservoir by hydraulic stimulation and its subsequent evolution during exploitation.
- The new simulator will be based on a combination of the techniques employed by three existing geothermal reservoir simulators:
  - **Geowatt’s “HEX-S” simulator,**
  - **SAIC’s “STAR” simulator with its “geophysical postprocessors”, and**
  - **SAIC’s new “SPFRAC” simulator (developed for DOE in 2008 to describe underground electrokinetic signals from hydrofracturing operations).**

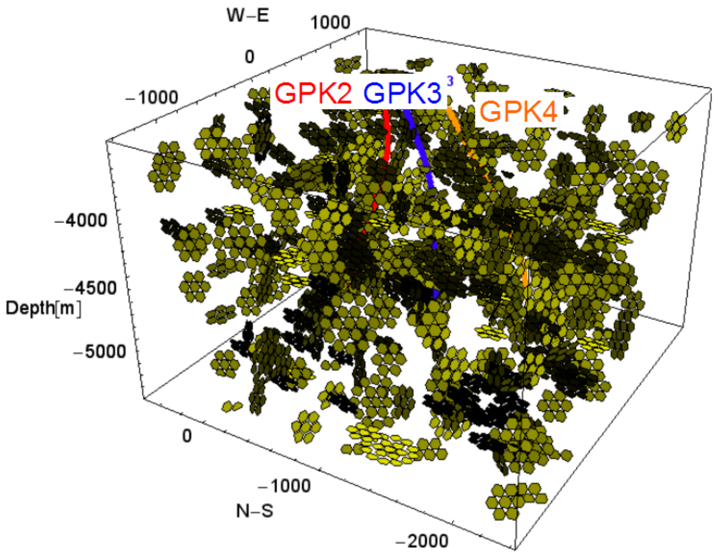
HEX-S attributes:

- Developed to compute the time-dependent evolution of fracture apertures and of the resulting anisotropic permeability distribution caused by fluid injection.
- HEX-S's tensor permeability distribution depends on the location, orientation, aperture, and size of the fractures that are incorporated in the model.
- Fractures are subdivided into a large number of disk-like "patches" with radii that are based on microseismic data interpretation.
- The "fracture patches" are then overlaid on a conventional 3-D computational grid used for flow calculations.

HEX-S "fracture patches":

- *Left:* deterministic model for intersecting large-scale fractures.
- *Right:* stochastic model for Soultz EGS reservoir.





HEX-S shortcomings for present application:

- Far-field stresses are used to update fracture apertures; local stress perturbations due to fluid pressure changes are neglected.
- No energy conservation equation, so temperature changes due to heat mining are not considered.
- Resulting local thermal stress changes are not modeled. These can influence evolution of fracture permeability.
- Lack of energy equation precludes long-term simulation of reservoir evolution with production and injection.
- HEX-S also does not treat tracers or other interesting phenomena such as electrokinetic effects.

STAR attributes:

- General-purpose 3-D geothermal reservoir simulator.
- Solves multiple simultaneous fluid mass balances (*i.e.* water, dissolved salts, dissolved gases, tracers) under multiphase conditions (aqueous phase, gaseous phase, solid precipitates).
- Also simultaneously solves the heat balance equation.
- Contains various optional internal “fracture system models” of the statistical (“MINC”) type.
- Fully implicit methods – robust, extensively tested and reliable.

STAR's "geophysical postprocessors":

- Developed to aid in history-matching studies. Repeat time-lapse geophysical surveys in operating fields can exhibit temporal changes that may be used to further constrain reservoir models and improve forecasts.
- STAR's postprocessors are designed to predict probable survey changes arising from particular forward reservoir model calculations. Survey types considered include:
  - microgravity surveys,
  - resistivity surveys (DC, MT, and/or CSAMT),
  - seismic reflection surveys, VSP/crosshole tomography, and
  - electrokinetic self-potential (SP) surveys.

STAR shortcomings for present application:

- Statistical ("MINC"-type) fracture modeling inappropriate for EGS systems where fractures are relatively sparse.
- No detailed modeling of individual fractures as in HEX-S.
- No true tensor anisotropic permeability (with STAR, permeability is a scalar or at most a vector, differing in the horizontal and vertical directions).
- No calculation of stress/strain equilibrium for solid rock.
- General-purpose multiphase treatment not needed for single-phase EGS systems. Computational "overkill" would be inefficient for practical calculations.

SPFRAC attributes:

- Developed as part of a DOE project to evaluate deep SP electrical signals that will emanate from pressurized fractures during EGS hydrofracturing operations.
- These signals will propagate hundreds of meters from the fracture in just a few weeks. Using monitoring wells with downhole sensors, interpretation of such signals can improve fracture system characterization in combination with microseismic monitoring.
- Problem first attacked with STAR and its electrokinetic SP postprocessor, but computational costs were high.
- SPFRAC is a specialized code to permit routine history-matching calculations of this general type.

SPFRAC shortcomings for present application:

- Fracture modeling uses "overlay" technique similar to that of HEX-S, but not nearly so general or powerful.
- No calculation of rock stress distribution.
- No true tensor anisotropic permeability.
- No "compositional" effects or tracers.
- Like HEX-S, no energy conservation equation – restricted to short-term response.

Accomplishments, Expected Outcomes and Progress

The project is just getting started now (SAIC's contract with DOE was signed in mid-March 2010; Geowatt's subcontract was signed late in April 2010).

Separate simulator modules will be coded and tested during Year 1. Prototype integrated simulator will be assembled and tested against Soultz data during Year 2. If this testing is successful, we will seek newer field data sets from DOE EGS projects and conduct further testing in Year 3, as well as completing software documentation and dissemination.

The project team includes:

John Pritchett (SAIC), author of STAR and SPFRAC.

Thomas Kohl (Geowatt), author of HEX-S.

Thomas Megel (Geowatt), Sabodh Garg (SAIC) and a graduate-student summer intern will assist with various aspects of the project.

Project Management/Coordination

- **YEAR 1:**
  - Formulate and finalize detailed mathematical formulation.
  - Start coding basic thermoporoelastic simulator and most specialized modules.
  - ***Go/No-Go:*** completion of basic TPE framework and good progress on modules.
- **YEAR 2:**
  - Complete modules and assemble prototype simulator.
  - Test prototype simulator against Soultz GPK-4 test data (September 2004).
  - ***Go/No-Go:*** successful simulation of Soultz experiments.
- **YEAR 3:**
  - Verification/testing against new DOE EGS data.
  - Finalize software, document, and disseminate.
- The project will be performed under overall direction of John Pritchett (SAIC-PI), who will also author most of the new simulator software in consultation with Thomas Kohl (Geowatt). Sabodh Garg (SAIC) will coordinate liaison with EGS field projects and data validation studies.

Future Directions

If successful, this project will deliver a model for the analysis of the stimulated reservoir's volume and for determining whether or not adequate fracture connectivity/permeability is present for sustained commercial operations. Beyond the third year, it may become desirable to extend the simulator's capabilities to incorporate results from other DOE-supported research efforts, such as chemical reaction effects. If this appears feasible, we would expect to propose such further developments to DOE at that time.

Summary

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- Efficient creation and development of the reservoir without excessive “short circuits” or “dry holes” is the key to successful growth of the EGS industry.
- A need exists for a new EGS reservoir simulator that can use data acquired early in the development cycle and describe both the reservoir stimulation process itself and the subsequent long-term resource evolution.
- The technical approach is based upon robust and well-established numerical techniques used in existing software, and the new simulator represents a relatively modest step forward from the current state-of-the-art.
- The project team has been engaged in the development and application of software for geothermal reservoir simulation studies since the mid-1970’s, and is well qualified to undertake this challenge.