Final Report:

**Modeling, Design, and Life Performance
Prediction for Energy Production from
Geothermal Reservoirs**

Grant DE-FG07-97ID13533

Daniel Swenson
Mechanical Engineering Department
Kansas State University
Manhattan, KS 66506
(785)532-2320, swenson@ksu.edu

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

HH

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Table of Contents

1	SUMMARY OF PROJECT GOALS:	1
2	INDUSTRY INTERACTION:	2
2.1	Visit to Unocal Corporation	2
2.2	Visit to Oxbow Power Services	2
2.3	Visit to Itasca Consulting	2
2.4	Booth at October GRC Meeting	3
2.5	Papers Presented at 23 rd Stanford Geothermal Workshop	3
2.6	Proposal Preparation and Collaborative Research	3
3	NATIONAL AND INTERNATIONAL COLLABORATION	4
3.1	Web Site	4
3.2	Collaboration with Proposed Australian HDR Project	4
3.3	GeoView Program	4
3.4	Collaboration with Hijiori Project	6
4	MODEL DEVELOPMENT:	7
4.1	Geocrack2D Maintenance	7
4.2	Geocrack3D Development	7
5	SUMMARY AND CONCLUSIONS	11

Attachment 1: Paper "A Geometric Modeling Framework for the Numerical Analysis of Geothermal Reservoirs," Brian Hardeman and Daniel Swenson, presented at 23rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, January 26-28, 1998.

*Removed
for
Separate
Processing*

Attachment 2: A thesis "A Geometric Modeling Framework for the Analysis of Fractured Rock Volumes," Brian Hardeman, 1998, Mechanical and Nuclear Engineering Department, Kansas State University, Manhattan, KS, 66505.

*removed for
separate
Processing*

Modeling, Design, and Life Performance Prediction for Energy Production from Geothermal Reservoirs

Grant DE-FG07-97ID13533

Daniel Swenson
Mechanical Engineering Department
Kansas State University
Manhattan, KS 66506
(785)532-2320, swenson@ksu.edu

1 SUMMARY OF PROJECT GOALS:

System modeling supports the design and long-term, commercially successful operation of geothermal reservoirs. Modeling guides in the placement of the injection and production wells, in the stimulation of the reservoir, and in the operational strategies used to ensure continuing production. Without an understanding of the reservoir, it is possible to harm the reservoir by inappropriate operation (especially break-through of cold injection fluid) and the desired profitable lifetimes will not be reached.

In this project we have continued to develop models for predicting the life of geothermal reservoirs. One of our goals has been to maintain and transfer existing Hot Dry Rock two-dimensional fractured reservoir analysis capability to the geothermal industry and to begin the extension of the analysis concepts to three dimensions. Our primary focus has been on interaction with industry, maintenance of Geocrack2D, and development of the Geocrack3D model. It is important to emphasize that our modeling is complementary to current industry modeling, in that we focus on flow in fractured rock and on the coupled effect of thermal cooling.

In each of the sections below, we document our activities as part of this research project.

2 INDUSTRY INTERACTION:

One important goal of this project was to interact with industry to show what had been previously accomplished under the former Hot Dry Rock project and to solicit their input and support for continuing research. We have responded to this commitment by interacting at industry conferences (Stanford Workshop on Geothermal Energy and the Geothermal Energy Association trade show) and by meeting with individual companies. We have also established collaborative research efforts with Oxbow Power Services and the Energy & Geoscience Institute at the University of Utah. These activities are documented below.

2.1 Visit to Unocal Corporation

We visited Unocal Corporation (Santa Rosa, CA) on July 9, 1997, to meet with Tim Anderson, Ken Williamson, Julie Sheneta, and Glenn Melosh of Unocal Geothermal of Indonesia. Ron Schroeder (consultant) and Bob DuTeaux also participated.

The goal of the meeting was to provide Unocal with a better understanding of our current Geocrack2D model and to discuss how it could be applied to problems of interest to Unocal. The meeting was initiated by Glenn Melosh, who was interested in using Geocrack2D to help understand the significance of microseismic signals observed in Unocal geothermal fields. Some questions include the cause of seismicity (pressure opening or thermal stress relief) and whether the signals indicate significant flow. We also presented our goals for 3D model development, especially the rigorous approach to geometric description and the interactive user interface.

While no formal projects have been defined between Kansas State and Unocal, we have maintained communication with Unocal, with Unocal supporting the goals of our research.

2.2 Visit to Oxbow Power Services

On July 10, 1997, we visited Oxbow Power Services and met with Dick Benoit to discuss Geocrack2D and our future goals. The intent of this meeting was to present a concept for collaborative work between Kansas State University, the Energy and Geoscience Institute (EGI) at the University of Utah, and Oxbow Power Services. This meeting resulted in a decision to write a collaborative research proposal to apply modeling of flow in fractures to the Dixie Valley reservoir. This proposal is discussed further below.

2.3 Visit to Itasca Consulting

We visited Itasca Consulting (Minneapolis, Minn.) on May 20, 1997. Itasca is a well known geotechnical company, with most of their work related to mining. The goal of the meeting was to demonstrate the current Geocrack2D capabilities and, primarily, to focus on the 3D geometric modeling work. Itasca representatives included Peter Cundall and Dave Potyondy. Itasca also demonstrated their present analysis capabilities. The meeting was primarily an exchange of information, especially with respect to the use of topology to describe geometry and approaches to cross-platform development. While no formal collaboration was established, Itasca has been closely following our 3D

development, including a detailed review of the thesis described below. The concept of a geometric approach to 3D modeling will be incorporated in their current code development activities.

2.4 Booth at October GRC Meeting

We participated in the annual GRC meeting (September, 1997) by having a booth that described geothermal research at Kansas State University. The booth included posters, a continuously cycling presentation, handouts, and the opportunity to talk to visitors one-on-one. Several new contacts were made, in addition to allowing us to show the current status of our work to people we already knew.

This was the first time a University had run a booth at the meeting. We have just committed to having a booth at the 1998 meeting.

2.5 Papers Presented at 23rd Stanford Geothermal Workshop

Two papers were presented at the 23rd Stanford Geothermal Workshop, January 1998. The first paper, "Strategies for the Hijiori Long Term Flow Test," was the result of work sponsored by the Geothermal Energy Research and Development Company, Japan (GERD). Collaborating authors included R. Schroeder (Berkeley Group Inc.) and S. Okabe, N. Shinohara, and S. Takasugi (GERD). The paper presented Geocrack2D analyses of past testing at Hijiori and made initial predictions of the long-term flow test. The challenge at Hijiori is to both maintain adequate water recovery and avoid cooling of the production wells. Downhole pumps could be used to increase recovery, but because the wells are so close together, significant cooling is expected at the production wells.

The second paper, "A Geometric Modeling Framework for the Numerical Analysis of Geothermal Reservoirs," documented the work done to develop the geometric foundation for future modeling efforts. The paper demonstrated how, by working at the feature level (fractures, wellbores, reservoir boundaries) it is much easier for the user to develop a reservoir model independent of the solution scheme to be used. Response to the paper was very positive.

2.6 Proposal Preparation and Collaborative Research

In collaboration with Pete Rose and Denise Apperson at the Energy & Geoscience Institute and Dick Benoit at Oxbow Power Services, we submitted a proposal in response to DOE solicitation DE-PS07-96ID13399, "Geothermal Reservoir Technology Research, Development, and Demonstration." The research will develop capability to model flow in reservoirs dominated by fractures and will apply this capability to improve injection/production strategies to maximize economic extraction of geothermal energy.

The proposal has been funded. A coordination meeting with TOUGH-2 and TETRAD users was held at the Stanford Geothermal Workshop, January, 1998. We have started the research defined in the proposal.

3 NATIONAL AND INTERNATIONAL COLLABORATION

3.1 Web Site

Information and the executable programs for Geocrack2D are available on the world wide web. We continue to update and maintain the world wide web page (<http://www.mne.ksu.edu/~geocrack>). This site includes a description of our work and is a location at which the Geocrack2D software can be downloaded.

3.2 Collaboration with Proposed Australian HDR Project

In collaboration with Prame Chopra and Doone Wyborn of the Department of Geology, Australian National University, Geocrack2D calculations were made of a proposed Australian HDR project.

Australia is unique in that most of the crust in Australia is subject to a crustal shortening stress field, in which the minimum principal stress direction is sub-vertical to vertical in orientation. This means that a reservoir created by stimulation should lie predominantly in a horizontal plane.

Geocrack2D is being used to provide estimates of the performance of such a reservoir. Figure 1 illustrates temperature contours predicted after ten years of operation. The figure shows a vertical plane through the reservoir, with injection in the center and two producing wells at each end of the reservoir.

Figure 1: Temperatures after 10 years (Vertical section, including boreholes)

3.3 GeoView Program

The GeoView program, developed by Heather Bradford, has been released and is available at the geocrack web site (www.mne.ksu.edu/~geocrack). This software allows the user to view seismic data, wellbores, and fractures interactively on a PC. The

software was developed as a result of discussions at the Structured Academic Review of HDR/HWR held at Tohoku University, Japan, in March of 1997.

The software was written in approximately 3 1/2 months by Heather Bradford. Such rapid development was possible as a result of the object-oriented methods being used on our 3-D modeling development. Brian Hardeman, working on the 3-D development, had previously written camera, OpenGL display, and list objects that were re-used in the GeoView program. Figure 2 shows a display of Fenton Hill micro-seismic data and wellbores. Data for Soultz is also available for display.

The software has been delivered to researchers in the USA, UK, France, and Japan.

Figure 2: Example display of Fenton Hill data using GeoView

3.4 Collaboration with Hijiori Project

Geocrack2D is being used for an analysis of the Hijiori reservoir in Japan. The objective of the analysis is to match testing performed in 1991-1996 and to predict the results of the Long Term Circulation Test scheduled to start in 2000. During this project, we have visited Japan four times to report on progress and coordinate research. This work is being performed independently of this project, but is mentioned because it is an application of tools related to the project.

4 MODEL DEVELOPMENT:

4.1 *Geocrack2D Maintenance*

During the course of this project, Geocrack2D has been continuously used for reservoir analysis. This has resulted in both the identification of bugs and new improvements to the code. These are listed below and include:

- Improved font selection for lower resolution displays (640x480).
- Correcting a bug in the contour plots of stresses.
- Fixing a bug related to monitored node data.
- Adding the new capability to improve the representation of flow to a well intersecting a fracture.
- Adding flux heat transfer boundary conditions to the release version of the code.
- Adding the capability to map arbitrary temperature solutions for initial conditions.
- Adding a cubic boundary condition term for far-field leak-off. The cubic term more closely approximates the expected behavior of flow in a fracture into the far-field.

All these improvements have been included in the version that can be downloaded from the web at <http://www.mne.ksu.edu/~geocrack>

4.2 *Geocrack3D Development*

Primary effort has been devoted to development of Geocrack3D. The goal of this software is to allow the user to work at the geometry level of a problem, while the details of meshing and solution are handled automatically. What is meant by the "geometry level" is that the user defines the boundary of a reservoir and then the geometric features (fractures, wellbores) of the model. Working at this level simplifies the task of the analyst and allows easy modification of the model. After the geometry is defined the mesh will be automatically developed. This approach is similar to the work at Kansas State University and Cornell University that is being applied to NASA research on crack growth in aircraft structures.

In order to implement the geometric approach reliably, it is necessary to use topology to describe the relationships between the vertices, edges, faces, and volumes of a model. The development of the Euler operators that accomplish this has been completed. Figure 3 through Figure 6 show the current state of the program, demonstrating the definition of fractures and wells in the Hijiori reservoir. In Figure 3 the boundary of the reservoir has been defined. Figure 4 shows the model after the wells and dominant fractures have been added. Figure 5 and Figure 6 and 5 show interior and wireframe views of the model. To create this model, the user simply defined a point on each fracture and a normal to the fracture. All the intersections with wells and other fractures were calculated by the program.

In the illustrated model, the program knows all volumes and boundaries. This information will make it possible to create a numerical mesh that is a subset of the geometric model. In addition, the fractures (faces) that bound each volume can be used to define the boundary conditions, independent of the mesh. Such an approach simplifies the task of the analyst preparing the model.

As part of this research, Brian Hardeman, the graduate student developing the software, successfully defended his thesis. The thesis documents the details of the topology, including a *multi-link* structure developed as a generalization of previous work in non-manifold topology. This thesis is attached to this report to document a significant accomplishment of this project.

Figure 3: Initial definition of reservoir boundary

Figure 4: After insertion of fractures and wells

Figure 5: View of interior of model

Figure 6: Wireframe view

5 SUMMARY AND CONCLUSIONS

All objectives of this research project have been met: we established interactions with industry, we initiated collaborative research with other universities and industry, we updated and maintained current Geocrack2D analysis capability, and we laid the foundation for new capability in the development of Geocrack3D. This work is now continuing under the new DOE grant.