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**S-CUBED
GEOTHERMAL TECHNOLOGY
AND
EXPERIENCE**

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S-CUBED GEOTHERMAL TECHNOLOGY AND EXPERIENCE

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TITLE: Equations Describing Various Geothermal Systems (1973)

CONTRACT/CUSTOMER: Company-Sponsored

SUMMARY: The objective of this early study was to formulate the systems of equations adequately describing various classes of geothermal systems. General governing equations were formulated to account for the following effects: (1) thermally induced fluid convection, (2) pore collapse (or fracture) and subsidence due to fluid withdrawal, and (3) effect of pore collapse on fluid withdrawal. The general governing equations are thus concerned with a fully interacting rock-fluid system. These interactions involve mass, momentum and energy transfer, variable porosity and permeability. In addition, the system may be anisotropic and inhomogeneous in the large. The general approach in this study was to then simplify the general equations as appropriate to various geothermal systems. Of particular interest is the "quasi-active" geothermal formulation which properly treats the effects of phase changes (liquid $\rightleftharpoons$ vapor) within the pores of the reservoir rock. The quasi-active case is midway in sophistication between the "rigid-matrix" model in which all rock properties (porosity, permeability, thermal conductivity, etc.) are treated as functions of position only and the "fully interactive" case in which the entire rock stress and the deformation fields are calculated along with the heat and fluid flow.

TITLE: Geohydrological Environmental Effects of Geothermal Power Production (1974-1976)

CONTRACT/CUSTOMER: NSF Grant

SUMMARY: The goal of this continuing research is to develop and validate a computational capability whereby field information for a given hydrothermal geothermal reservoir system can be used to predict the behavior of the reservoir under specified conditions of fluid withdrawal or injection. Of particular interest is the evaluation of any associated land surface subsidence, ground water pollution, or increased seismicity.

During the first phase of the project, basic energy-mass transport equations and thermodynamic relations were developed to apply to a geothermal reservoir system. A comprehensive computer program was written for solving the governing equations in one, two, or three dimensions, under the assumption that the rock response is "quasi-active". The program (QUAGMR) incorporates a sophisticated equation of state for pure water to handle the liquid/vapor regime encountered in a geothermal system. A three-dimensional program was also developed to handle the deformation of the rock matrix.

As part of the current second phase of the research, the fluid response code is being coupled with the rock deformation code to produce a "fully interactive" program. This program is being used to study the fluid production history and the induced subsidence in the Wairakei geothermal field in New Zealand. In addition, an equation of state for brines is being developed and calculations will be made to analyze the effects of salt deposition due to subsurface flashing.

Projected work next year will include the use of the coupled code to analyze the long-term performance and subsidence hazards associated with the production and injection of fluids in the Salton Sea geothermal field. In addition, the associated seismic hazard will be characterized, as will the effects of waste fluid injection on the permeability of the formation.

TITLE: Simulation of Linear Bench-Scale Experiments (1975)

CONTRACT/CUSTOMER: NSF Grant

SUMMARY: The purpose of this study was to test the S³ geothermal reservoir simulator, QUAGMR, against laboratory data generated at Stanford University. The experimental studies on bench-scale linear flow models were designed to test fundamental concepts for nonisothermal single-phase (liquid water) and boiling two-phase (water/water vapor) flow through porous media. The experimental set-up consisted of a core holder (containing the test model) provided with inlet and outlet pipes, which was held in an oven. The core rock in the experiments was a synthetic 60 cm long consolidated sandstone with a porosity of 36 percent and a permeability of 100 millidarcies. Fluid flow through the core was numerically simulated, with QUAGMR, as a one-dimensional problem.

Two experimental runs were simulated. These were (1) injection of cold water into a core containing hot water and (2) production of hot water and steam from a system containing pressurized water. The fluid flow in the first experiment was entirely single phase. The second experiment represented a more severe test of the theoretical model insofar as the fluid flow through the core was two-phase (water/steam). In both cases, experimental data were seen to be in good agreement with theoretical results. This agreement was all the more gratifying when we considered the uncertainties in input data for rock properties and vapor pressure for water.

On the basis of the excellent agreement obtained between theoretical predictions and experimental data on single and two-phase flow through bench-scale linear flow models, it is safe to conclude that the theoretical model

employed contains all the significant thermomechanical effects associated with multi-phase water flow through porous media.

TITLE: Simulation of Fluid-Rock Interactions in a Geothermal Basin (1974-1975)

CONTRACT/CUSTOMER: University of Colorado (NSF Supported)

SUMMARY: The objective of this S³ subcontract was to support the University of Colorado in its study of the fundamental phenomenology common to a large number of geothermal systems. Detailed analytical analyses were made of heat exchange and species transport for a fluid percolating through porous media. The S³ reservoir simulator (QUAGMR) was applied to study the long-term convective patterns evolving in the vicinity of a geothermal formation intersected by a vertical fault; such fault zones are probably most responsible for the upwelling of hot water from depths that recharge geothermal reservoirs (e.g., Imperial Valley, Wairakei).

In the QUAGMR calculation, the vertical fault was a narrow zone of highly fractured material with large effective permeability, which provided a conduit for the upwelling hot water. The problem was designed so that net flow would occur from the fault into the aquifer. At early times, the cold fluid in the aquifer was slowly driven out by the hot fluid coming into the reservoir from the fault zone. With increasing time an eddy of the hot fluid formed in the lower part of the grid; met and mixed with the colder fluid and rose up and out of the computational grid. A temperature inversion occurred; this is possibly an explanation for the local temperature maximum and inversions which are sometimes observed in borehole measurements. The calculation has only a qualitative significance in view of the various assumptions made for the reservoir and fault geometries, and the boundary conditions. QUAGMR could be used to develop a thorough understanding of the effects of geological structure on fluid flow for a specific system by taking into account actual fault geometries, different boundary conditions, and additional factors such as heterogeneous rock formations.

TITLE: Geopressured Geothermal Reservoir Simulator (1976)

CONTRACT/CUSTOMER: University of Texas at Austin (ERDA Supported)

SUMMARY: The objective of this S³ subcontract is to collaborate with the reservoir modeling group of the University of Texas in the development of a computer technique which can simulate the performance of geopressured reservoirs. The

release, migration and production of the methane gas absorbed in the geothermal fluid will be treated as well as the transport of the kinetic and thermal energy in the fluid. A "fully interactive" rock/fluid model will be used since decrease in formation porosity is an important consideration in predicting the life of the reservoir and the possibility of land surface subsidence. The computer models will provide a theoretical tool for evaluating the relative importance of the force driving mechanisms which tend to expel fluid from the producing stratum (1) water compressibility, (2) pore collapse, (3) evolution of methane gas, (4) shale dewatering, and two which tend to impede fluid flow (decrease in permeability which accompanies pore collapse; relative permeability effect due to evolution of gas).

S³ is modifying its "fully interactive" hydrothermal geothermal reservoir simulator to include phenomena appropriate to geopressured reservoirs. Sensitivity calculations will be carried out to define the important parameters influencing the behavior of geopressured systems. Thermo-mechanical response models for a representative geopressured system - selected by UTA - will be developed on the basis of theoretical considerations and existing data on similar rocks.

It is anticipated that in a subsequent phase of the research, predictive calculations will be performed for a specific field test site to be selected by UTA and ERDA.

TITLE: User-Oriented Geothermal Reservoir Simulator (1975-1976)

CONTRACT/CUSTOMER: Company-Sponsored

SUMMARY: The purpose of this project was to rewrite the "quasi-active" reservoir version of QUAGMR developed under NSF funding. The new version has been streamlined for minimum computer time and easy use. This user-oriented code employs the same sophisticated numerical scheme as the basic version of QUAGMR but is specially designed for reservoir management applications which require inexpensive and efficient calculation of small amplitude flow problems, whereas the NSF project requires treatment of large amplitude phenomena associated with subsurface environmental effects (subsidence and seismic effects). Auxiliary computer programs for displaying the calculations in graphical form to assist in the interpretation of the results have also been developed.

TITLE: Geothermal Well Test Analyses (1975-1976)

CONTRACT/CUSTOMER: Company-Sponsored

SUMMARY: Classical well analyses were performed using S³'s user-oriented version of the QUAGMR geothermal reservoir simulator. QUAGMR solves the equations of heat flow and unsteady Darcian fluid flow in one, two, or three space dimensions. The computer model is capable of handling a single phase liquid water system or a multiphase liquid/vapor system. The "quasi-active" formulation encoded in QUAGMR is adequate for most reservoir management applications.

Pressure drawdown and buildup well-tests were performed to acquire permeability data for the reservoir. Classical well-test interpretation assumes that only a single phase is flowing during the test. This assumption can lead to dramatic errors in the permeability data if, in fact, there is multiphase flow during the test.

Several calculations were performed which demonstrate these errors in interpretation. A suite of four problems was posed to demonstrate these results. One and two-dimensional problems were formulated with single and multiphase flow during the well test. In the single phase problems, very good agreement with the classical theory was demonstrated. However, in the multiphase problems, the classical interpretation led to gross errors in the permeability data.

These results indicate the necessity of a simulator which will handle multiphase flow in a geothermal system. Without this capability, error in the interpretation of well flow data could lead to mismanagement of the reservoir engineering of the geothermal field.

TITLE: Geothermal Seismic Exploration (1975-1976)

CONTRACT/CUSTOMER: Company-Sponsored

SUMMARY: Geophysicists at S³ are developing active and passive seismic methods, involving both modeling and experimental verification, that can provide high resolution information about a geothermal field in a cost effective manner.

The subsurface location and dimensions of a geothermal reservoir must be established prior to the economic development of the resource. Furthermore, estimates of key rock properties, such as fracture porosity, within the producing zones would improve predictions of flow rates and the useful lifetime of a reservoir. A methodology for interpreting and modeling information obtained from state-of-the-art active seismic exploration methods involving compression (P)

and shear (S) wave reflection profiling is being developed as a means for delineating a geothermal reservoir.

Passive seismic methods being developed for geothermal exploration and evaluation include:

1. Inversion of teleseismic data to delineate the properties and dimensions of a reservoir.
2. The monitoring and modeling of key diagnostic parameters of seismic noise in geothermal fields.
3. Investigation of local earthquakes for characteristics unique to geothermal regions.

TITLE: High Resolution Seismic Mapping of a Geothermal Reservoir (1976)

CONTRACT/CUSTOMER: ERDA Contract

SUMMARY: This project will evaluate the capability of P and S VIBROSEIS reflection prospecting to determine the detailed geologic structure and the fracture porosity for a specific geothermal reservoir. At least two candidate sites in the Imperial Valley will be considered: the Niland area and the East Mesa area. Preliminary selection of the site for the reflection survey will be based on availability of reservoir characteristics from exploratory wells and analysis of results of other geophysical surveys including gravity, magnetic, microearthquake and refraction data. Final site selection will be based on optimum site characteristics regarding seismic data acquisition and record quality. S³ will be responsible for the overall coordination of the project including planning the experiment, supervision of the seismic exploration field work and final interpretation of the data. During all phases of the project, S³ will maintain a close interactive relationship with the industrial and governmental organizations involved in the development of the selected site.

TITLE: Experimental Evaluation of Geothermal Well Logging Cables (1976)

CONTRACT/CUSTOMER: ERDA Contract

SUMMARY: The objectives of this research are to determine the modes of failure of electromechanical cables in the environments expected in geothermal wells and to make recommendations for design improvements.

A facility is being built at the U.S. Government Green Farm Test Site which will be used to apply tensile loads to

cable samples in a simulated geothermal environment, except for high pressure. Those cables which demonstrate the most promise will then be tested in a pressure facility designed to handle brine and the H₂S environment. This test facility at Green Farm will be specifically designed for the complete experimental study and evaluation of logging cables. Later this facility will be adaptable for testing geothermal logging tools. The best cables will ultimately undergo field tests, possibly in the Imperial Valley.

As a result of this research, and with the consultation of cable manufacturers, recommendations to improve the design of geothermal well-logging cables will be made.

RELATED S³ PUBLICATIONS

- Blake, T. R. and S. K. Garg, "On the Species Transport Equation for Flow in Porous Media," To be published, in Water Resources Research, 1976.
- Brownell, D. H., Jr., S. K. Garg and J. W. Pritchett, "Computer Simulation of Geothermal Reservoirs," Society of Petroleum Engineers, Paper No. SPE 5381, 1975.
- Garg, S. K., "Wave Propagation Effects in a Fluid-Saturated Porous Solid," J. Geophys. Res., 76, p. 7947, 1971.
- Garg, S. K., "Land Surface Subsidence Associated with Geothermal Energy Production," Proc. Workshop on Geothermal Reservoir Engineering, Stanford, California, December 15-17, 1975.
- Garg, S. K. and A. Nur, "Effective Stress Laws for Fluid-Saturated Porous Rocks," J. Geophys. Res., 78, p. 5911, 1973.
- Garg, S. K., D. H. Brownell, Jr., J. W. Pritchett and R. G. Herrmann, "Shock Wave Propagation in Fluid-Saturated Porous Media," J. Appl. Phys., 46, p. 702, 1975.
- Garg, S. K., J. W. Pritchett and D. H. Brownell, Jr., "Transport of Mass and Energy in Porous Media," Proc. 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, California, May 19-29, 1975.
- Garg, S. K., T. R. Blake, D. H. Brownell, Jr., A. H. Nayfeh and J. W. Pritchett, "Simulation of Fluid-Rock Interactions in a Geothermal Basin," Final Report to the University of Colorado, Systems, Science and Software Report SSS-R-76-2734, September 1975.
- Jordan, T. H., "The Solution of Linear Inverse Problems," Systems, Science and Software Report SSS-IR-75-2590, March 1975.
- Jordan, T. H. and J. M. Savino, "Modeling of Geothermal Noise," Systems, Science and Software Report SSS-IR-76-2895, March 1976.

- Knapp, R. M. and T. D. Riney, "Numerical Simulation of Geopressured Geothermal Reservoirs," Proc. of First Geopressured Geothermal Energy Conference, University of Texas at Austin, June 2-4, 1975.
- Nayfeh, A. H., D. H. Brownell, Jr. and S. K. Garg, "Heat Exchange in a Fluid Percolating Through Porous Media," Proc. Society of Engineering Science Meeting, University of Texas at Austin, pp. 1125-1137, 1975.
- Pritchett, J. W., S. K. Garg, D. H. Brownell, Jr., and H. B. Levine, "Geohydrological Environmental Effects of Geothermal Power Production - Phase I," Final Report NSF Grant No. GI-43885, Systems, Science and Software Report SSS-R-76-2733, September 1975.
- Pritchett, J. W., "Numerical Calculation of Multiphase Fluid and Heat Flow in Hydrothermal Reservoirs," Proc. Workshop on Geothermal Reservoir Engineering, Stanford, California, December 15-17, 1975.
- Rice, L. F., "Pressure Drawdown and Build-Up Analyses in Geothermal Reservoirs," Systems, Science and Software Report SSS-R-76-2845, March 1976. Also submitted to the Eleventh Intersociety Energy Conversion Engineering Conference in State Line, Nevada, September 12-17, 1976.
- Savino, J. M. and T. H. Jordan, "Near-Surface Structure from Teleseismic Residuals," Systems, Science and Software Report SSS-IR-76-2894, March 1976.
- Savino, J. M. and D. G. Lambert, "Signal Processing Capabilities: The Multiple Arrival Recognition System (MARS)," Systems, Science and Software Report SSS-IR-2896, March 1976.
- Sweet, J., S. K. Garg, J. W. Pritchett and D. H. Brownell, Jr., "Modeling of Subsidence Resulting from Reservoir Production," Trans. Am. Geophys. Union - EOS, Vol. 56, (12), p. 986, 1975 (Abstract only).