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Reservoir Technology Research at the INEL

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Introduction

Reservoir engineering research at INEL was aimed at developing a better understanding of The Geysers and developing better tools with which to study flow in fractured geothermal reservoirs in general. Two specific topics were studied in the last year: matrix fracture interactions and decline curve analysis. A third project, revisiting the behavior of the "high-temperature reservoir" (HTR), was started near the end of 1995. These projects are being conducted in collaboration with other researchers and/or private industry. For example, our HTR studies are motivated in part because of new isotopic analyses conducted elsewhere (Walters et al., in preparation). The ultimate goal of these projects is to improve predictive capabilities and reservoir management practices and to extend the commercial life of The Geysers.

In addition to conducting engineering research for the Reservoir Technology Program, INEL also continued to assist the Geothermal Technology Organization (GTO) with the development and execution of cooperative research projects. In support of the overall mission of the Reservoir Technology program, INEL also entered into a broad program of subcontracts with industrial groups and universities. These programs support the Reservoir Technology mission by providing support for research topics considered particularly important by the geothermal industry. The GTO projects are summarized below.

Reservoir Engineering Studies

Matrix-Fracture Interactions in Dual Continua Simulators

Due in large part to complex fracture geometries, irregular fracture spacing, and lack of detailed information regarding contact areas between rock matrix and fracture, a Warren and Root (1963) dual continua approach is most frequently taken to describe storage and flow in fractured reservoirs. Interaction between the two is assumed to be linearly dependent on the pressure difference between the (numerical) grid block fracture pressure and average matrix pressure. This linear dependence, frequently referred to as the "pseudo steady-state assumption," is valid only at long time and for slightly compressible fluids. Work began in the last year to identify an improved matrix-fracture interaction term that removes these restrictions.

The most promising functional form identified thus far that describes the pressure in the matrix as a function of position is

$$P(\eta) = \overline{P} + (P_f - \overline{P})\, e^{(\eta - a)/D}$$

Only parallelepiped rock matrix blocks have been considered thus far; therefore, η is the distance from the centroid of the rock matrix (effectively a radial distance) and a is the effective radius of the matrix. P_f and $\overline{P}$ are the fracture and average matrix pressures, respectively. D is a characteristic distance associated with a change in pressure, and is related to the diffusivity of the medium and time by

$$D = \left[\frac{k\,t}{\varphi\,\mu\,c}\right]^{1/2}$$

This function has been tested against several analytical solutions. One such comparison, given in Figure 1, represents a step function change in pressure in the fracture, and the corresponding pressure transient in the rock matrix. The entire system is initially at a constant pressure of 1000 kPa. At t = 0, the fracture pressure is reduced to 100 kPa. Other data for the rock matrix are: $k = 10^{-16}$ m^2, $\varphi = 0.1$, $\mu = 10^{-3}$ Pa-s, and $c = 10^{-6}$ Pa^{-1}. The diffusivity is calculated as 10^{-6} m^2/s. The solutions shown in Figure 1 are truncated at $\eta/a = 0.9$, since we are primarily concerned with the pressure profile at the fracture-matrix interface (i.e., where the pressure gradient must be accurately resolved). This figure shows that excellent agreement is obtained with the test function on this particular problem. The largest errors near the interface occur at small times. Calculated pressure gradients at the fracture-matrix interface agree within about 25% at t = 10^4 seconds; in contrast, the pressure gradient calculated from the pseudo steady-state assumption is low by a factor of 40.

This function has been implemented in an existing dual continua simulator and is being tested and compared against fine-grid simulation. Additional testing is planned for single phase, slightly compressible, isothermal fluids before attempting to incorporate multi-phase simulations. For example, the functional form given above is known to be inaccurate for non-monotonic behavior at the fracture-matrix interface, and a correction term will be required. This project will continue through FY-96.

Fetkovich Analysis at The Geysers
Faulder (1996) shows that the Fetkovich (1980) type curve equations can be modified for use in vapor-dominated steam reservoirs. The dimensionless decline rate, q_{Dd}, is given in customary geothermal field units of mass flow as

$$q_{Dd} = \frac{\dot{m}(t)}{\dot{m}_I} = \frac{\dot{m}(t)}{\frac{kh}{1207}\left(\frac{\rho z}{p}\right)_{res} \frac{[m(p_I) - m(p_{wf})]}{\left[\ln\frac{r_e}{r_w} - \frac{1}{2} + s\right]}}$$

and the dimensionless decline time is

$$t_{Dd} = \frac{t_D}{\frac{1}{2}\left[\left(\frac{r_e}{r_w}\right)^2 - 1\right]\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right]}$$

where

$$t_D = \frac{k\,t}{\phi\,\mu\,c\,r_w^2}$$

These equations form the basis for applying the Fetkovich type curve technique to saturated steam in customary geothermal mass rate units. In applying this technique, mass production rate is plotted against production time on log-log paper. Faulder (1996) suggests using the method of Hinchman et al. (1987) to determine the onset of pseudo steady-state flow. That time corresponds to a t_{Dd} of 0.3 (Fetkovich, 1980), which identifies the match point $m(t)/q_{Dd}$ for the analysis. Permeability-thickness is then calculated as

$$kh = 1207\left(\frac{\rho z}{p}\right)_{res} \frac{\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right]}{[m(p_I) - m(p_{wf})]} \left(\frac{\dot{m}(t)}{q_{Dd}}\right)_{match\ pt}$$

The method was validated using numerical simulations of the rate-time response for a bounded, cylindrical, vapor-dominated reservoir (Faulder, 1996). Estimated kh values were within 16% of the input value.

This modified Fetkovich type curve analysis has been applied to 48 wells in the southeastern portion of The Geysers (Faulder, 1996). This area of The Geysers was also the subject of an extensive history match study, originally described by Faulder (1992). Results from this analysis will be implemented in that reservoir model to further reduce the degrees of freedom inherent in a modeling study. The frequency distribution of kh for the 48 wells in the study area is presented in Figure 2. Estimates of kh from this study range from 18,000 to 270,000 mD-ft and are in good agreement with other published estimates (e.g., Bodvarsson et al., 1989).

HTR Studies
We have recently renewed investigations into the formation of the HTR as observed in Northwest Geysers. Walters et al. (in preparation) show that isotopic signatures in Northwest Geysers indicate significant compartmentalization of the reservoir. While an HTR is observed in all compartments, isotopes and non-condensible gas concentrations vary significantly. Their analysis suggests that HTR characteristics may be sensitive to water throughput and recharge and communication across faults. Using the HTR model of Shook (1995) as a starting point, we have begun evaluating the effects of partially-communicating faults, the degree of venting, and the presence of non-condensible gases on formation of a HTR. This study will ultimately be used to evaluate the utility of reinjection into the HTR, as compared with reinjection into the "normal" reservoir.

Figure 1. Comparisons between analytical solutions and a test function for step change in fracture pressure at t=0. Differences are largest at small time. Solid lines are the analytical solutions.

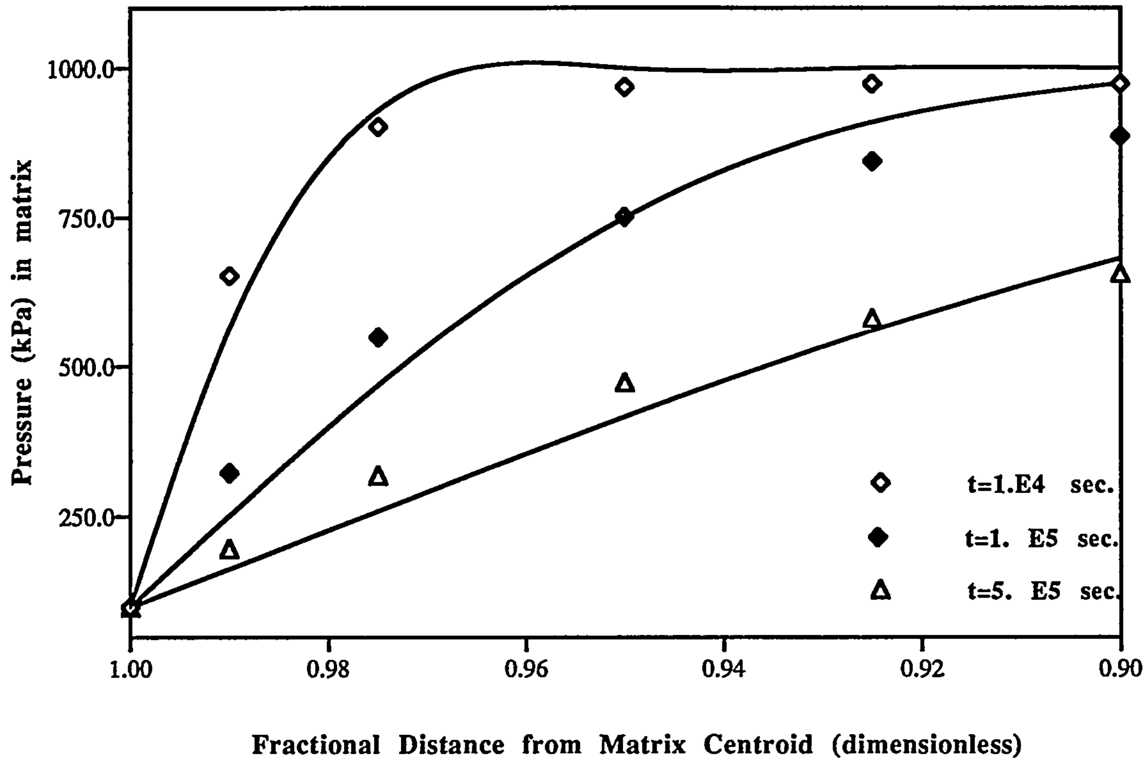
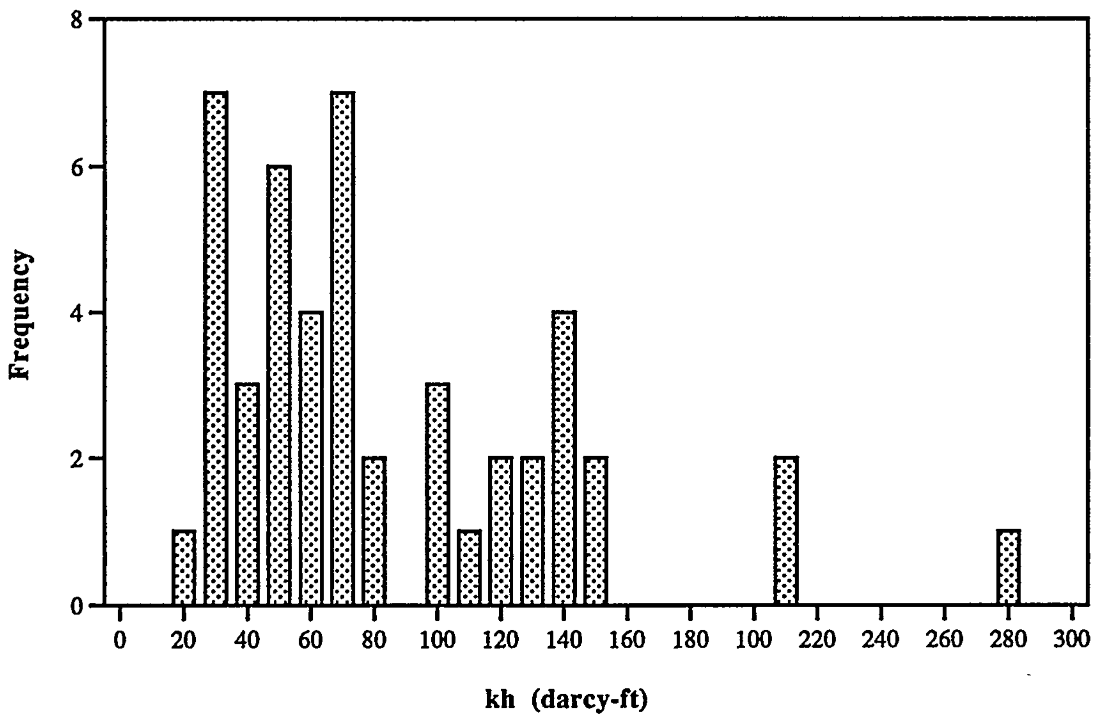


Figure 2. Frequency distribution for 48 wells in southeast Geysers study area. Data from Faulder (1996).



Reservoir Technology Support

INEL assisted the geothermal industry in forming a cooperative research organization, the GTO, and in developing an agreement with the U.S. Department of Energy (DOE) to perform cost-shared geothermal research. This agreement has provided a cornerstone for the cooperative research between the geothermal industry and DOE. The agreement specifies that technology development that has, in the short term, a high probability of yielding benefits in the areas of reservoir performance and energy conversion is available for cost-sharing. Since the inception of the DOE-GTO agreement in 1988, the INEL has facilitated the submittal and selection of GTO proposals, provided organizational support to GTO, and placed the subcontracts that have been necessary to accomplish the research. DOE Idaho Operations Office is now placing the necessary contracts. Three projects were underway during FY-95.

Seismologists at the University of North Carolina are completing a project characterizing subsurface fracture patterns and fracture density by analyzing shear-wave splitting. The study showed that the analysis is able to determine fracture orientation but not dip. Resolution of crack density is limited; however, analysis of a larger number of events may provide more precise identification of crack density. A final report to the participants is nearing completion. Preliminary results were reported by Lou and Rial (1994).

Researchers at the University of Kansas are completing a two-year project developing a structural model for the Coso and Argus ranges adjacent to the Coso geothermal field. The study will provide a better quantification of Basin and Range extension and its relationship to the eastern front of the Sierras. Early in FY-96, GTO approved an additional project by these researchers to study distal epiclastic and pyroclastic rocks in the Coso region. Their goal is to develop an analog model of geothermal systems associated with releasing bends of lateral fault systems.

Calpine, Northern California Power Agency, Pacific Gas & Electric, and Unocal have been conducting a long-term injection test in the Unit 18 area of The Geysers. Recently, the operators and DOE decided to move the test to the Units 7 and 8 area. This location may provide a unique opportunity to investigate the effect of injection into a high-chloride, high-temperature zone of The Geysers. Barker (this volume) discusses the Unit 18 test in more detail.

Late in FY-95, GTO and DOE also reached an agreement to develop a turbine-driven non-condensible gas compressor. The unit is being designed and built by Barber Nichols and will be installed at The Geysers in May 1996.

In addition to the GTO subcontracts, INEL also sponsored several other research projects covering a broad spectrum of research related to exploration and development of geothermal resources. These projects are summarized in Table 1.

Summary

Production decline curve analysis and reservoir simulation coupled with models of geothermal systems are important tools used to predict and manage reservoir performance. The results of our investigations of matrix-fracture interactions, decline curve analysis, and conceptual models of high-temperature, vapor-dominated reservoirs will be used in the following years to improve the ability of the geothermal community to manage the sustainable development of geothermal resources.

Acknowledgments

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Table 1. INEL FY-95 GTO Projects and Subcontracts

Subcontractor/Principal Investigator	Project Summary
Unocal Ed Voge	Geysers Long-Term Injection Test
University of North Carolina Min Lou and Jose Rial	Characterizing subsurface fracture patterns by analyzing shear-wave splitting
University of Kansas Douglas Walker and Eric Whitmarsh	Developing regional structural model for Coso geothermal area
Nevada Bureau of Mines Larry Garside	Archiving geothermal exploration data for Nevada.
New England Research Greg Boitnott	Laboratory measurements on reservoirs rocks from The Geysers
New Mexico Institute of Technology Larry Teufel and Her-Yuan Chen	Coupling variable-rate pulsing/interference testing techniques and tidal pressure changes to evaluate geothermal reservoirs.
Oregon Department of Geology and Mineral Industries Ian Madin	Reconnaissance of geothermal potential in southeastern Oregon.
S-Cubed Sabodh Garg and John Pritchett	Developing analog models of volcanics-hosted geothermal systems and studies of productivity of small diameter geothermal wells.
Southern Methodist University David Blackwell	Development of temperature and heat flow models for the central and eastern United States.
University of Nevada Lisa Shevnell and Ted DeRocher	Geochemical modeling at Nevada geothermal powerplants.
Virginia Polytechnic Institute and State University John Costain	Archiving geophysical data related to low-temperature geothermal systems in the eastern United States.
Mark Walters	Oxygen isotope systematics and evolution of the Northwest Geysers

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