ENERGY EXTRACTION EXPERIMENTS IN THE SGP RESERVOIR MODEL

A. Hunsbedt, A. L. London, R. Iregui, P. Kruger, and H. J. Ramey, Jr.
Stanford University, Stanford, CA 94305

Much of the immense quantity of geothermal energy stored in the earth's crust is widely dispersed and occurs as hot igneous rock with permeabilities that are too low for adequate fluid circulation. Fracture-stimulation of such systems is needed to improve fluid circulation and expose new heat transfer surface in the hot rock. Hydrothermal resources which may need fracture stimulation are those with inadequate fluid content for heat removal flow rates or those in which the transit time of reinjected fluids is too rapid for adequate reheating. Fracture-stimulation techniques proposed to enhance the energy recovery include hydraulic or explosive fracturing and thermal stress cracking. Experimental methods needed to evaluate the thermal extraction effectiveness of such stimulation practices and of hydrothermal reservoirs in general are a part of the Stanford Geothermal Program (SGP).

Experiments are being conducted in the SGP large geothermal reservoir model utilizing rock systems with several characteristics resembling high permeability, fracture-stimulated systems. The broad objective of these experiments is to evaluate nonisothermal fluid production and heat transfer processes and to analytically model these for such rock systems. Three nonisothermal energy extraction and production processes, referred to here as in-place boiling, sweep, and steam-drive, were considered during the early phases of this study. The general production, injection, and reservoir conditions maintained during the three different experiments are listed in Table 1.

Table 1. Types of Energy Extraction Experiments

Experiment Type	Description
In-Place Boiling	Pressure reduction and boiling in formation. Production of steam from a top producing zone with or without fluid recharge at the bottom.
Sweep	Injection of cold water at bottom. Hot water produced from a top producing zone. Compressed liquid reservoir.
Steam-Drive	Production of hot water from the bottom and no recharge. Steam and noncondensable gases above liquid/steam interface providing "steam-drive." Slightly subcooled reservoir conditions.

This work has been reported in previous reports and papers [References 1 through 3]. The results showed that all three processes are feasible in the experimental systems considered. However, the effectiveness of the processes, as illustrated in Table 2, varied widely.

Table 2. Results of Energy Extraction Experiments

Experiment Type	Specific Energy Extraction (Btu/lb_m)	Energy Extraction Fraction (dimensionless)
In-Place Boiling	> 36	> 0.75
Sweep	> 62	> 0.80*
Steam-Drive	> 9	> 0.22

*Based on the steady-state water injection temperature as the lower reference. The others are based on the saturation temperature corresponding to the end pressure.

The specific energy extraction (energy extracted per pound of rock) was greatest for the sweep process and smallest for the steam-drive process. The fraction of thermal energy stored in the rock between the initial temperature and reference lower temperature that was actually extracted is also seen to vary widely. The question of which of these energy extraction processes is practical in large-scale field development will depend on the particular conditions that prevail at the site.

The simple analytic models developed for the model reservoir and for the heat transfer from the rock successfully predicted the experimental results as long as the assumptions inherent in the models were not seriously violated. However, it was recognized that more detailed experimental and analytic studies of the heat transfer aspects were required, and such studies have since been performed by Iregui [Reference 4]. The final report of these results is in preparation and the highlights are given below.

Rock Heat Transfer Studies

Prediction of heat transfer from a collection of irregularly shaped rocks is complicated because the rocks vary in size and shape. The effect of rock shape was investigated by Kuo [Reference 5]. The results showed that a rock with an irregular shape can be treated analytically as a sphere with equivalent radii used in the Fourier and Biot numbers determined by a single parameter referred to as the sphericity of the rock. The sphericity is defined as the ratio of the surface area of the equivalent spherical rock having the same volume to the actual surface area of the rock. Additional work was performed utilizing this concept to predict the thermal behavior of a collection of rocks with given size distribution and shape for arbitrary boundary or cooldown conditions.

The basis for the rock temperature transient prediction for a single rock was the one lump, spherical solution presented in Reference 1 for constant cooldown conditions. This solution was modified to variable cooldown conditions by superposing constant cooldown rate solutions, a procedure frequently used in heat transfer analyses. The validity of this model was verified by comparing the predicted rock temperature to the measured rock temperature. An illustration of such a comparison is given in Figure 1 where the predicted and measured temperatures for instrumented Rock No. 1, located at the bottom of the reservoir model, are shown as functions of time. Another illustration is given in Figure 2 for Rock No. 2 located near the center. Two in-place boiling experiments and one sweep experiment were conducted to provide the data for the comparisons. The rock used in these experiments (third rock loading) consisted of granitic rock fragments with a mean equivalent diameter of 1.62 inches. It was obtained from the piledriver chimney produced by a nuclear explosion at the Nevada Test Site.

The results of the temperature transient comparisons, similar to those illustrated in Figures 1 and 2, showed that the one-lump thermal model utilizing the equivalent radii defined by Kuo predicts the rock temperature transients satisfactorily over a wide range of conditions and is preferred over exact solutions because of its relative simplicity. The transient model for a single rock was subsequently used to formulate an energy extraction model for a collection of rocks with a given size distribution. This model was applied to the laboratory system with known size distribution and average rock shape. The predicted energy extraction was compared to the measured energy extraction for one experiment. The results showed that the prediction was of the same order as the measured, but the model verification was not conclusive because of relatively large uncertainties in the measured energy extraction. Further work is needed to assess the uncertainties in the measurements.

The energy extraction model was used to determine the sensitivity of parameters such as mean rock size, average sphericity, cooldown history, rock size distribution, and the dispersion about the mean for hypothetical large-scale systems. These parameters will generally not be known precisely for such systems, and in many cases will have to be assumed. The effect of rock size distribution and the sphericity are given in Figures 3 and 4, respectively, where the rock energy extraction fraction is plotted as a function of total time to deplete the reservoir. The energy extraction fraction is defined as the ratio of thermal energy extracted to the theoretical maximum, i.e., the energy stored between the initial temperature and the instantaneous fluid temperature surrounding the rock. These results show that the fraction of energy that can be extracted from the rock decreases when the reservoir is produced over a shorter time period. The energy extraction also decreases when the proportion of large rocks increases. This is the case when the dispersion about their mean increases or the shape of distribution changes (e.g., from exponential to normal). Further details of these studies are presented in Reference 4.

Current and Future Experiments

The experiments performed in the SGP reservoir model have utilized rock systems with porosities between 35 and 44 percent and essentially infinite horizontal and vertical permeabilities. Thus, these systems are not very representative of naturally or artificially fractured geothermal reservoirs where a typical porosity may be in the range of <5 to 20 percent and the permeabilities in the range of 5 to 500 md. Experiments with a more representative rock system have, therefore, been initiated. This fourth rock system consists of the granitic rock utilized in the third rock system (piledriver rock), but the void spaces are filled with 80 to 100 mesh sand. The porosity of this system has been determined to be about 21 percent, and the vertical permeability is being measured. Several energy extraction experiments of the in-place and sweep type will be conducted with this rock system in the near future.

In the longer term, experiments to study the characteristics of thermal stress cracking in granite are being evaluated. Efforts to assess the usefulness and feasibility of such experiments have been initiated. The ability to detect small cracks created by thermally induced stresses is of particular concern. It is anticipated that preliminary experiments will be conducted in a small bench-scale model to determine major parameters for use in analytic modeling of proposed experiments in the SGP large geothermal reservoir model.

References

1. Hunsbedt, A., Kruger, P., and London, A. L., "Laboratory Studies of Stimulated Geothermal Reservoirs," SGP-TR-11, Advanced Technology Dept., RANN, National Science Foundation, Grant No. NSF-AER-72-03490, December 1975.

2. Hunsbedt, A., Kruger, P., and London, A. L., "Recovery of Energy from Fracture-Stimulated Geothermal Reservoirs," Paper No. SPE 5875, 46th Annual California Regional Meeting, SPE of AIME, Ventura, California, April 2-4, 1976. (Accepted for publication in Journal of Petroleum Technology, August 1977.)

3. Hunsbedt, A., Kruger, P., and London, A. L., "Laboratory Studies of Fluid Production from Artificially Fractured Geothermal Reservoirs," Paper No. SPE 6553, 47th Annual California Regional Meeting, SPE of AIME, Bakersfield, California, April 13-15, 1977. (Accepted for publication in Journal of Petroleum Technology.)

4. Iregui, R., "Heat Transfer in Fractured Rock Media," Engineer's degree dissertation, Stanford University, 1978.

5. Kuo, M.C.T., Kruger, P., and Brigham, W. E., "Shape Factor Correlations for Transient Heat Conduction from Irregular-Shaped Rock Fragments to Surrounding Fluid," SGP-TR-16, Advanced Technology Dept., RANN, National Science Foundation, Grant No. NSF-AER-72-03490, August 1976.

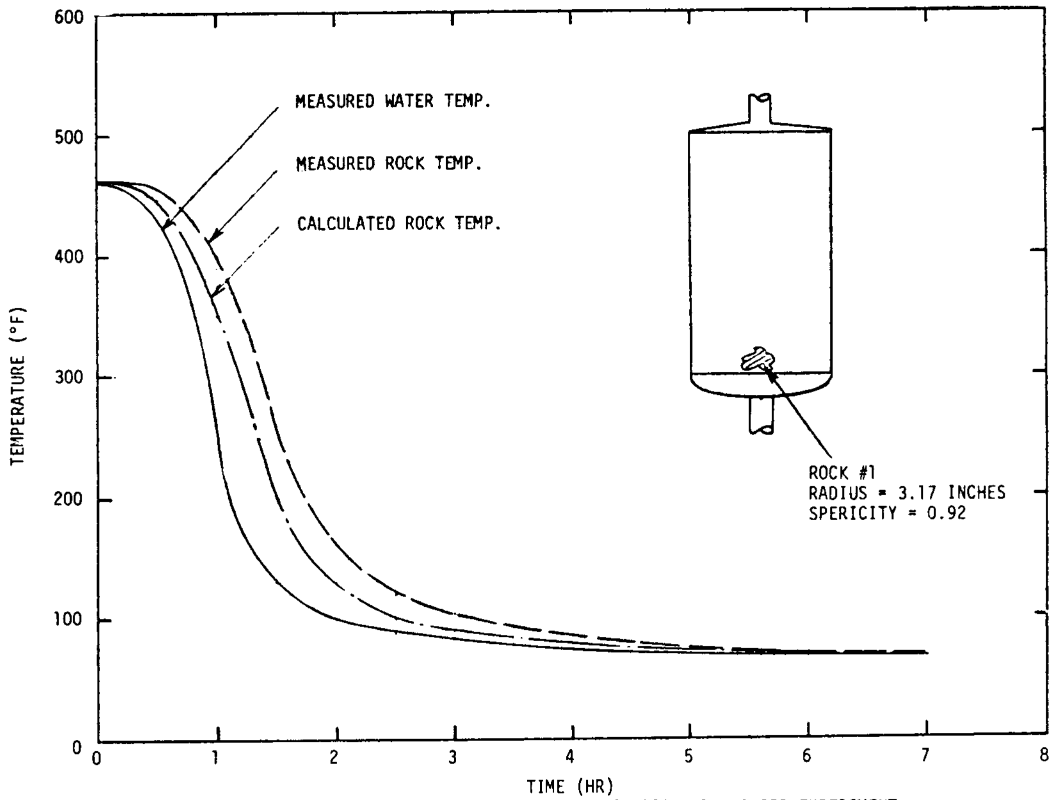

FIGURE 1. COMPARISON OF MEASURED AND CALCULATED TEMPERATURES FOR ROCK #1 - SWEEP EXPERIMENT

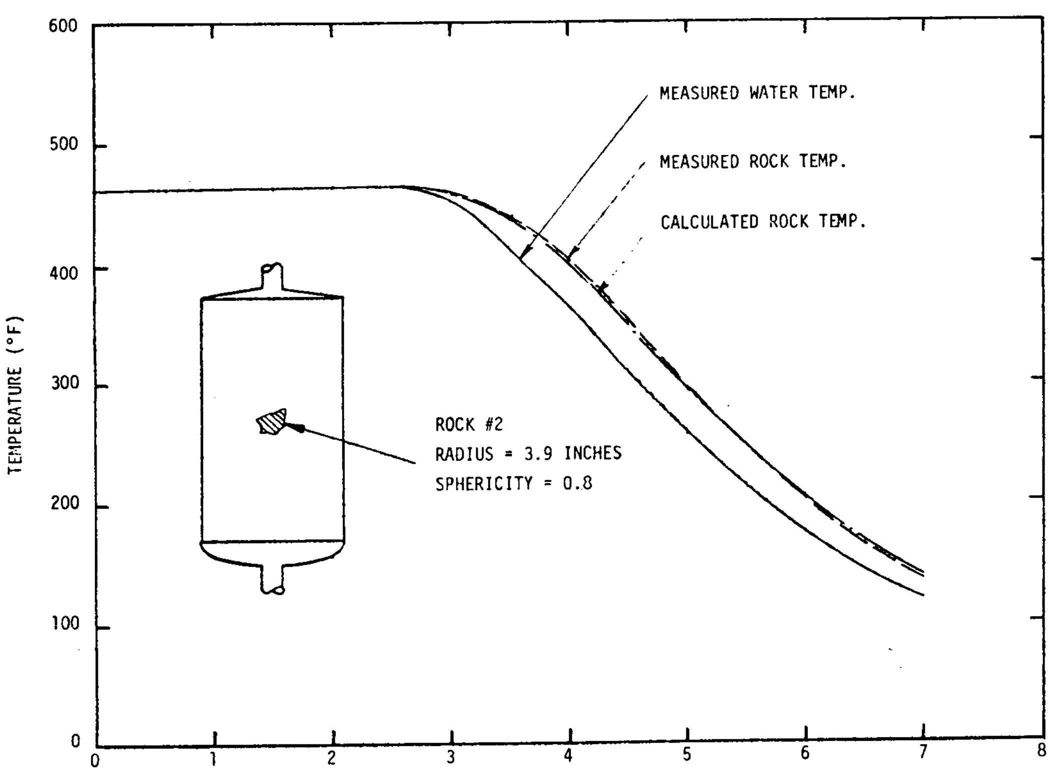

FIGURE 2. COMPARISON OF MEASURED AND CALCULATED TEMPERATURES FOR ROCK #2 - SWEEP EXPERIMENT

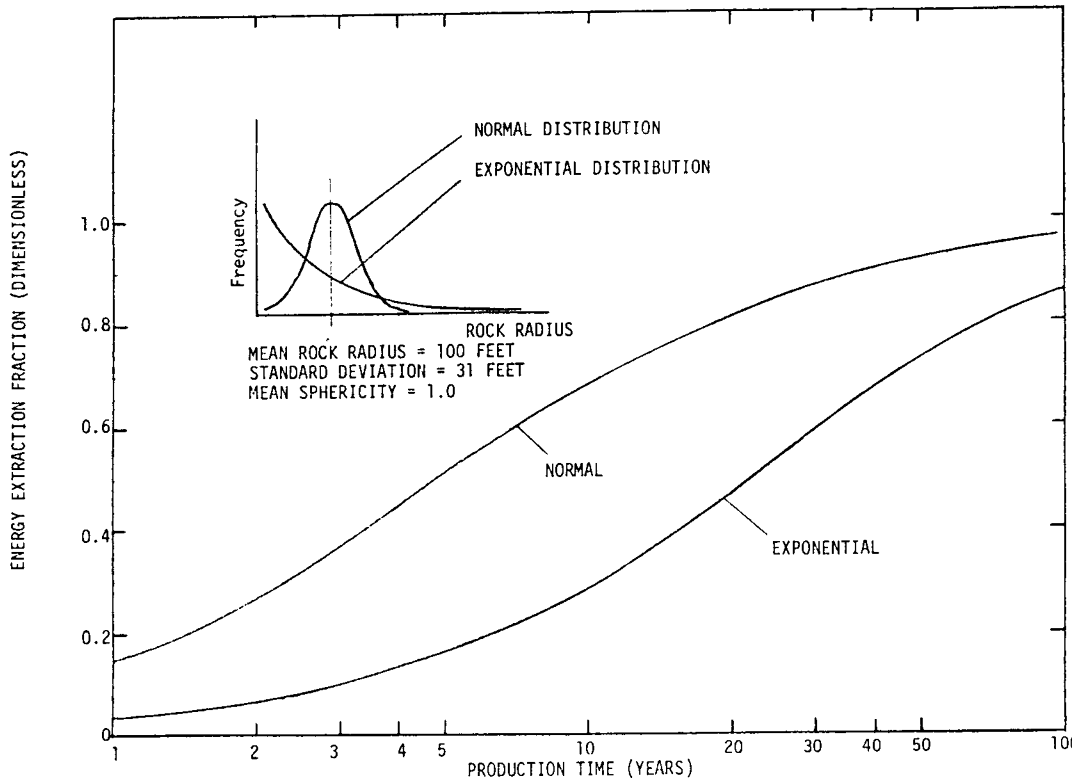

FIGURE 3. ENERGY EXTRACTION FRACTION AS A FUNCTION OF TOTAL PRODUCTION TIME FOR TWO DIFFERENT ROCK SIZE DISTRIBUTIONS.

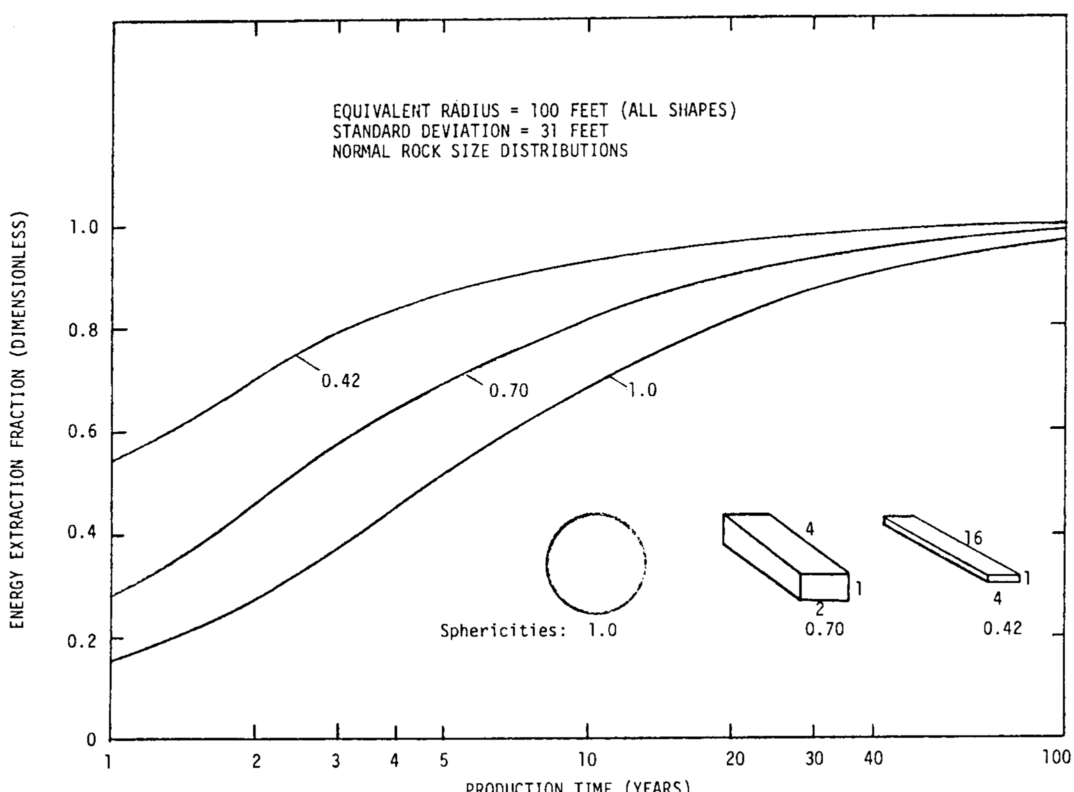

FIGURE 4. ENERGY EXTRACTION FRACTION AS A FUNCTION OF TOTAL PRODUCTION TIME FOR THREE DIFFERENT ROCK SHAPES