PHYSICAL MODEL STUDIES OF EXPLOSION-FRACTURED GEOTHERMAL RESERVOIRS

Anstein Hunsbedt,* Roberto Iregui, and Paul Kruger
Civil Engineering Department
and A. Louis London
Mechanical Engineering Department
Stanford University
Stanford, CA 94305

Large scale utilization of geothermal energy will require means for enhanced energy extraction from geothermal reservoirs since the higher quality hydrothermal resources adequate for commercial electricity generation represent only a small fraction of the estimated resource base. Technologies are being developed for artificial fracturing of hydrothermal and dry hot rock geothermal resources to obtain adequate permeability for water circulation and to expose new rock surface area. Non-isothermal processes such as in-place boiling or artificial circulation of cooler fluids can be used to extract the energy from the fractured formation. To evaluate non-isothermal heat transfer processes, physical model studies were conducted in the Stanford Geothermal Program fractured-rock reservoir model capable of operating at a maximum pressure of 800 psig at 500°F. The 17-ft^3 physical model has been described previously [Hunsbedt, Kruger, and London (1975), Hunsbedt (1975), and Hunsbedt, Kruger and London (1976)]. A summary of the characteristics of the relatively large fracture-permeability rock systems tested in the model are summarized in Table 1. The porosity and permeability characteristics of these systems resembled those of fracture-stimulated created by high-energy explosives.

TABLE 1

Summary of Rock System Characteristics

	Rock System		
	1	2	3
Rock type	Gabbro	Granite	Granite**
Mean rock equivalent diameter, inches	0.99	2.65	1.62
Drainage porosity, percent	44	35	43

A description of the in-place boiling experiments (flashing by pressure reduction) conducted with the first two rock systems were given by Hunsbedt (1976) and by Hunsbedt, Kruger and London (1976). The results showed that

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*Now at General Electric Company, Sunnyvale, CA 94086

**Obtained from the underground "Piledriver" rock chimney.

the fraction of rock energy extracted by in-place boiling* was in excess of 75 percent of maximum for a broad range of production conditions. Heat transfer from the rock resulted in an increase in the total energy extraction from the hydrothermal (liquid and rock) system ranging from 1.25 to 2.57 times the energy obtained by flashing the fluid alone. Gravity segregation resulted in the production of slightly superheated steam from the producing zone located at the top of the reservoir model. Fluid production and rock heat transfer analyses were developed which closely predict the behavior of the physical model as long as the axial liquid temperature gradients are small. Application of the rock heat transfer analysis to large-scale systems with a 30-year production time showed that a maximum rock size of about 200 feet would give energy extraction fractions of the same order as those obtained experimentally.

Non-isothermal production of the reservoir model was also achieved by recharging cool fluids at the bottom, a process often referred to as the sweep process. Experiments of this type were conducted with the second rock system. The results of one such experiment are given in Fig. 1 which show the axial temperature profiles measured at various times during production. The zone of production at the top is seen to remain at nearly constant temperature until cool fluid recharged at the bottom breaks through to the producing zone after about 4 hours. At that time there is a rapid drop in the temperature of the liquid being produced. It is also noted that significant thermal energy still remains in the top rock zone when liquid production was terminated. This also tends to be true in large-scale systems because the power generating equipment requires fluids at temperatures above a minimum level to operate efficiently. In analogy to the experimental results, there will be a tendency to achieve incomplete energy extraction from the rock near the producing zone of a large-scale system as well. The estimated mean rock temperatures also given in Fig. 1 are seen to be only slightly higher than the liquid temperature indicating effective heat transfer from the rock. The liquid temperature distribution and the mean rock to liquid temperature difference at the end of production both determine the magnitude of the rock energy extraction fraction defined in terms of the initial and recharge fluid temperatures. The rock energy extraction fraction for this experiment was estimated to be 0.85. The rock heat transfer analysis developed for the model system was used to estimate the mean rock size of a large-scale system. The results show that a maximum rock size of about 150 feet would give rock energy extraction fractions of the same order as those achieved in the model. This assumes a 30-year production time, mean rock to liquid temperature difference of 15°F, and similar permeability characteristics of the model and large-scale systems.

Fluid production experiments were conducted with the producing zone located at the bottom of the model to investigate the possible development of axial temperature gradients in the steam zone observed to occur in the in-place boiling experiments. The fluid production reservoir pressure behavior for one such experiment is shown in Fig. 2. The results show that all liquid was produced at nearly constant pressure (between points D and D') followed

*The rock energy extraction factor is defined as the thermal energy extracted from the rock to the thermal energy stored in the rock between initial and final liquid temperatures.

by a sharp pressure decline when vapor production is initiated (at point D'). It is noted that the corresponding reservoir pressure characteristic for in-place boiling with vapor production from the top, also shown in Fig. 2, declines more uniformly. Note also that only 60 percent of the fluids were produced (as high enthalpy superheated steam) in the in-place boiling experiment while about 99 percent of the fluids were produced (as low enthalpy liquid) in the steam drive experiment. The rock temperature decreased only slightly during the production process indicating that this is an ineffective rock energy extraction process. Examination of the temperature behavior in the model reservoir showed that the axial temperature profiles were nearly uniform and that the liquid was slightly subcooled, indicating the presence of a non-condensable gas (argon used for pressurization during heatup) in addition to water vapor in the zone above the liquid. Further evaluation of this steam/gas drive production process appears warranted to determine the major parameters and the extent to which it may be important in large-scale systems.

Experiments are currently in progress with the third rock system. The rock was obtained from the rubble chimney formed by collapse of the overburden formation into the cavity created by the 61 kt "Piledriver" nuclear explosion. The Piledriver nuclear explosive was detonated on June 2, 1966 at a depth of 1,500 feet in a formation of granodiorite. The explosion produced a cavity radius of 131.5 feet and a collapsed rubble chimney 890 feet high and 160 feet in width measured in the reentry tunnel 103 feet above the explosive. The rubble chimney is estimated to contain about 67 million ft^3 of fractured rock with a zone of fractures created by the immense shock wave out to a distance of more than 1,000 feet. The rubble rock is expected to be microfractured, and thus may have thermal properties measurably different from naturally fractured granites.

The current rock system in the physical model consists of Piledriver rock obtained from the reentry tunnel at a distance of about 100 feet from the chimney axis. The size distribution after conveyance in 30-gallon drums to Stanford from the Nevada Test Site was still approximately log normal. Six of the rocks of various sizes have thermocouples installed to obtain center rock temperature measurements.

In-place boiling and cool fluid recharge energy extraction experiments similar to those performed previously with the first two rock systems will be performed with the current rock system under similar test conditions to provide comparative rock thermal transient data. Furthermore, the steam production rates will be as high as practical to obtain large rock/steam temperature differences and consequently lower measurement uncertainties. An analysis of the conduction error in the rock center temperature measurements will be performed and corrections will be applied to both previous experimental data and the Piledriver rock system data. An improved analysis for predicting the rock/steam temperature differences for non-constant cooling rate will be developed using the shape factor correlation proposed by Kuo (1976). Kuo has shown from sensitive heat transfer experiments that the heat transfer behavior of irregularly-shaped rocks can be correlated to equivalent spherical rocks of equal mass, to a sphericity shape parameter and to the rock surface area to volume ratio.

A qualitative assessment of microfractures on the heat transfer and energy extraction processes will be made by comparing the measured rock temperature transient with those obtained for the second rock loading. The rock/steam temperature difference measurements will be compared to analytic predictions for individual instrumented rocks before applying it to the model rock system as a whole. The ultimate goal of this analysis is to develop a generalized thermal model for a collection of rocks that can be applied to large-scale fracture-stimulated geothermal systems with known or assumed rock-size and shape-factor distributions.

Future experimental efforts are anticipated with two other rock systems. Experiments with a fourth rock system will explore the effect of finite permeability and low porosity on the energy recovery process from fractured geothermal systems. Experiments with a fifth rock system will explore the potential improvement in the heat transfer by thermal cracking processes. Measurements of radon emanation from the Piledriver granites into surrounding air and water are underway in the Stanford Geothermal Program. Radon emanation characteristics appear promising as an indicator of changes in rock surface area. Thus, it is anticipated that changes in the radon emanation rate as well as in the heat transfer rate from the rock system will be important indicators that thermal cracking and exposure of new heat transfer surface area have occurred.

References

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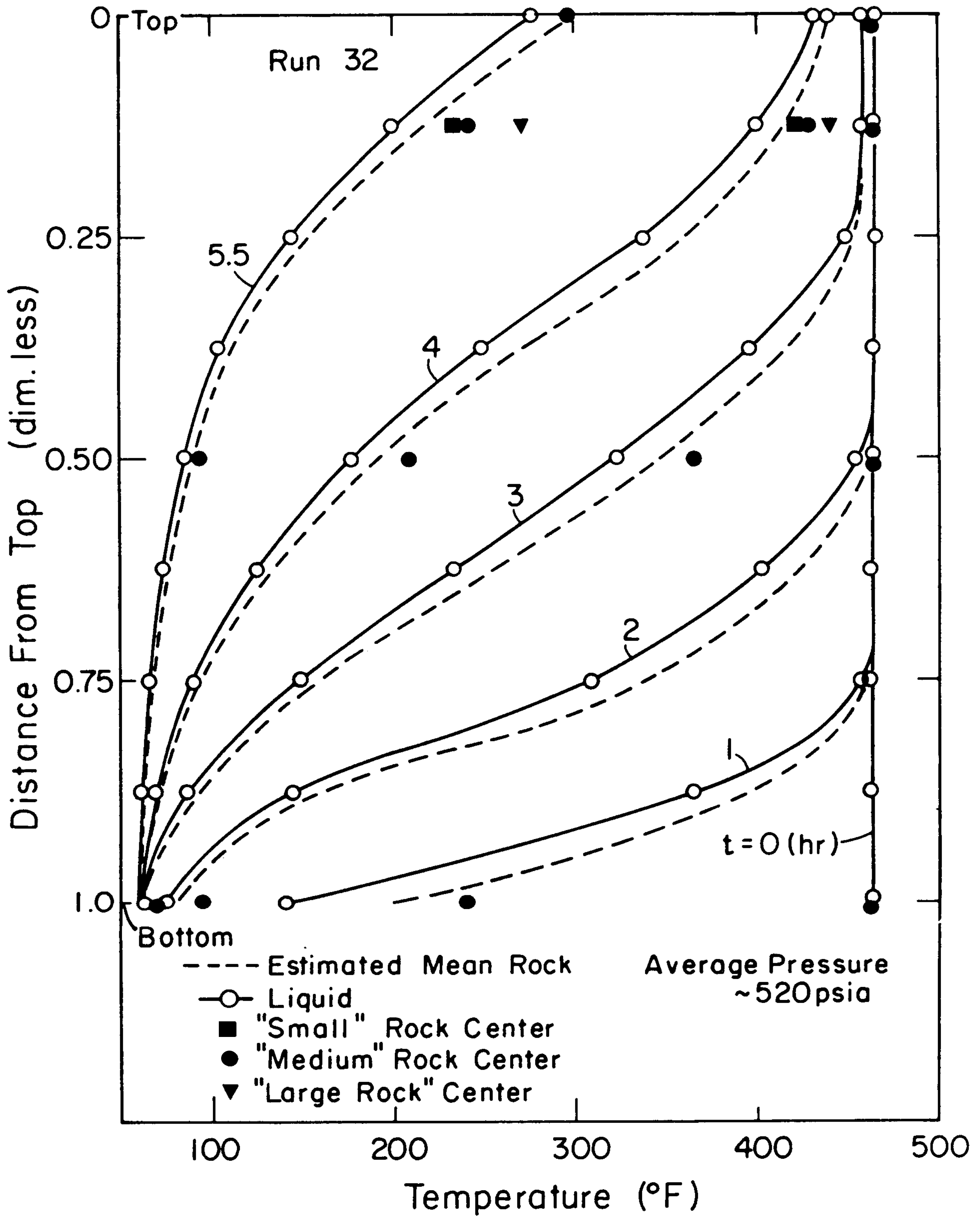

Figure 1 Liquid and rock temperature distributions as functions of time with cool liquid recharge

Figure 2. Pressure as a function of mass production.