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HEAT EXTRACTION FROM FRACTURED HYDROTHERMAL RESERVOIRS

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ABSTRACT

Initial results are available from the first experiment to calibrate the heat extraction history of a physically simulated fractured hydrothermal reservoir using a rock loading of large, regular-shaped granite blocks. Thermocouples embedded in a set of the rock blocks and in water at various locations in the model provide heat extraction data. The data are also used to evaluate the effects of thermal stressing on heat transfer properties. A finite element heat transfer computer model has been developed to assist in the analysis of these experiments.

The results of the first experiment show a surprisingly uniform cross-sectional water temperature throughout the physical model indicating effective cross mixing between fracture channels. The temperature difference between rock centers and surrounding fluid reached 100°F during the cooling process, decreasing to smaller values by the end of the experiment, indicating that the rock energy extraction was relatively complete, with a high, constant temperature of the produced water. Additional experiments are planned with increased rates of cold water injection to result in heat-transfer-limited reservoir conditions, and to extend the magnitude of thermal stress.

INTRODUCTION

A major facet of the Stanford Geothermal Program since its inception in 1972 has been the realization that long-term commercial development of geothermal resources for electric power production will depend on optimum heat extraction from hydrothermal reservoirs. Optimum extraction is analogous to secondary and tertiary recovery of oil from petroleum reservoirs; in the geothermal case, the resource may be either heat-transfer limited or convecting-fluid limited. The effort in the Stanford Geothermal Program has been a combination of physical and mathematical modeling of heat extraction from fractured geothermal reservoirs. Experiments have included several rock loadings in the SGP physical model of a rechargeable hydrothermal reservoir, examination of thermal stressing on rock heat transfer properties, and development of mass transfer tracer methods for comparative analysis.

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The physical modeling of heat extraction from loadings of rubblized rock and its mathematical interpretation as a lumped parameter system was developed by Hunsbedt, Kruger, and London (1975,1977, 1978). The correlation of shape factors for transient heat transfer for single, irregular-shaped rocks was added by Kuo, Kruger, and Brigham (1976). Models to extend these correlations to assemblies of fractured rock were developed by Iregui et al (1979) and by Hunsbedt et al (1979). This one-dimensional analytical model examines a hydrothermal rock system with cold water reinjection using a single spherical rock with an "effective radius" as the heat source.

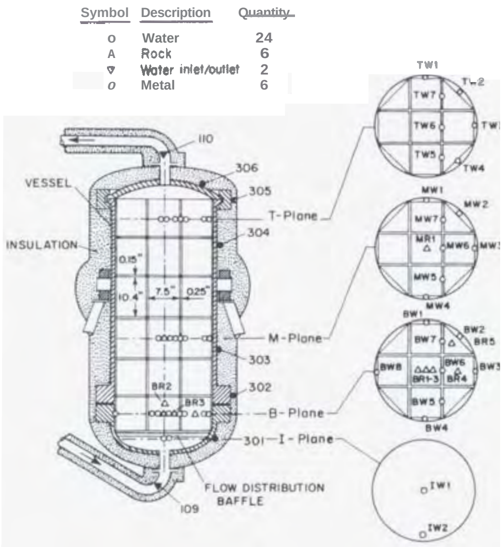
Although the present model predicts the overall energy extraction of the experimental reservoir quite well, it has several shortcomings with respect to modeling large scale systems. One of these was the uncertainty of axial heat conduction and heat transfer from the physical model itself. This paper discusses the present work to improve the heat extraction modeling to distributed-parameter form, calibrate the model using a rock loading of known geometric shape, and investigate extended thermal stressing on heat transfer properties.

HEAT EXTRACTION EXPERIMENTS

The SGP physical model of a fractured hydrothermal reservoir has been described in several reports, e.g. Hunsbedt, Kruger, and London (1977, 1978). The main component is a 5 ft high by 2 ft diameter insulated pressure vessel rated at 800 psig at 500°F. The rock matrix for the calibration experiments consist of 30 granite rock blocks of 7.5" x 7.5" rectangular cross section and 24 triangular blocks in the vessel as shown in Figure 1. The blocks are 10.4 inches in height. The average porosity of the matrix is 17.5 percent. Vertical channels between blocks are spaced at 0.25 inch and horizontal channels between layers are spaced at 0.15 inch.

Cold water is injected at the bottom of the vessel by a high pressure pump through a flow-distribution baffle at the bottom. During the experiment, system pressure is maintained above saturation by a flow control valve downstream of the outlet. Most of the system pressure drop is in this valve. Thus the rock matrix can be considered to have essentially infinite permeability. Significant vertical flow can also occur in the relatively large edge channels between the outer rock blocks and the pressure vessel.

During production, the hot water is cooled in a heat exchanger and the mass flow is measured gravimetrically as a function of time. The water temperature is measured at the several locations shown in Figure 1: at the inlet to the vessel, the I-plane just below the baffle, the E-plane half-way up the first rock layer, the M-plane half way up the third rock layer, the T-plane at the top of the matrix, and at the vessel outlet. Temperatures were also measured at the center of four rock blocks. Two additional thermocouples were placed in the bottom central rock for thermal stress evaluation. Temperature measurements were made by emplaced thermocouples read on two multipoint recorders.



Fig, 1. Experimental rock Matrix Configuration and Thermocouple locations

The rock-water-vessel system was heated to uniform initial temperature of 463± 2°F, by electric strap heaters outside the vessel and inside the insulation. The experiment was initiated by starting the injection pump and opening the flow control value to maintain constant system pressure. The injection rate was constant during the experiment.

Experimental Run 5-1 has been completed using this rock matrix with a water injection rate sufficient to result in complete cooling and energy extraction from the rock. Data for the experimental conditions and parameter values are summarized in Table 1. Data for the measured water and rock temperatures at the various thermocouple locations are given in Figure 2.

TABLE 1

Average Reservoir Pressure (psia)	545
Initial Reservoir Temperature (°F)	463
Final Top Temperature (°F)	312
Final Bottom Temperature (°F)	67
Injection Water Temperature (°F)	59
Initial Water Mass (lbm)	148
Injected Water Mass (lbm)	749
Water Injection Rate (lbm/hr)	150
Production Time (hr)	5

Table 1. Experimental Parameters Run 5-1

The results indicate that water temperature at the I-plane is initially slightly hotter near the surface wall due to heating by the steel. The injected water approached a uniform, constant temperature of 59°F, after about one hour. The data also show that the cross-sectional water temperatures were essentially uniform in each of the planes, with a maximum deviation of ±4°F, well within the estimated uncertainty of thermocouple temperature difference of ±5°F.

Also given in Figure 2 are several representative rock center temperature transients. Comparison of these temperatures with the corresponding surrounding water temperatures showed that the maximum rock center to water temperature differences of abour 100°F, developed during the cooling process decreasing to smaller values toward the end of the experiment. These data indicate that the rock energy extraction was relatively complete and the energy extracted from the rock resulted in a high, constant exit water temperature.

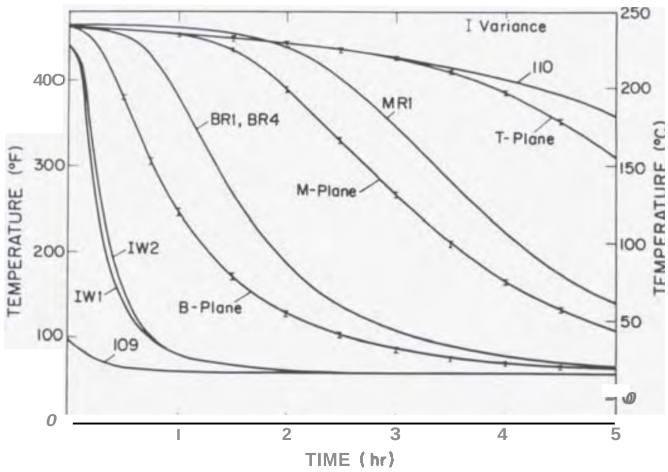


Fig. 2. Water and Rock Temperatures as Junctions of Time

THE NUMERICAL MODEL

For analysis of this and future experiments, a finite element model has been developed so that individual blocks, or groups of blocks can be represented as single elements. This approach allows less restraints on element shapes compared to finite difference models and provides possible application to full-size reservoirs.

The finite element computer code can evaluate a class of problems described by conduction/conduction-convection partial differential equations with boundary conditions consisting of specified temperature-time histories and specified heat flux-time histories controlled either by a direct source or by convection means. Internal heat production (or loss) functions can also be included.

The model spatial discretization can be performed in two- or three-dimensional Cartesian coordinates or in axisymmetric cylindrical coordinates. An arbitrary number of anisotropic material properties can be used to describe the particular reservoir, a feature that may be very desirable for modeling real fractured reservoirs.

THE THERMAL STRESS EXPERIMENT

Secondary heat extraction by cool-water reinjection will induce tensile thermal stresses in reservoir regions just below the fracture surfaces. Such stresses may result in important changes in reservoir energy extraction behavior, such as creation and growth of new cracks with additional heat transfer area and alterations in the mechanical and heat transfer properties of the rock itself.

The former change in behavior is the study of the hot dry rock (HDR) reservoirs proposed by the Los Alamos Scientific Laboratory in New Mexico. The physics of thermsl stress crakcing and propagation have been reported by Murphy (1978), Nemat-Nasser et al (1978), Barr (1980), and Hsu and Lu (1980). It is estimated that thermal cracks could increase the energy extracted from a HDR reservoir by about 40% after fifty days of reservoir operation. These predictions await experimental data and operating experience.

Efforts under the SGP arefocusedon experimental analysis of thermal stressing on rock heat transfer properties in hydrothermal reservoirs. Early experiments showed the influence of thermal stressing on the strength and porosity of granite specimens. The data were reported by Nelson and Hunsbedt (1979) and Nelson, Kruger, and Hunsbedt (1980). Granite slabs heated to a uniform temperature of 450°F, and face-sprayed with 70°F, water produced tensile thermal stresses below the sprayed face and compressive stresses in deeper regions. The thermal stress distribution is shown in Figure 3a and its effect on bending strength as a function of location and number of quenches is shown in Figure 3b. The results showed a significant reduction in strength under tensile thermal stress. Porosity of sections taken from the region of tensile thermal stress showed a significant increase of 300 percent.

Current efforts involve a longer-term test as part of the large block loading in the physical reservoir model. The instrumented block in the bottom layer of the loading will experience the largest set of thermal stresses over the several planned cold water sweep experiments. The total thermal stresses can be computed in closed form solution from the observed spacial temperature-time histories determined from the finite element heat transfer model. On completion of the experiments, specific blocks having had different thermal stressing histories will be sectioned for measurement of thermal conductivity, strength, and porosity.

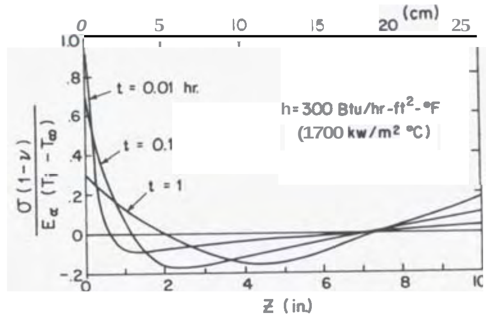


Fig. 3a. Estimated Thermal Stress Distribution in Granite Slab

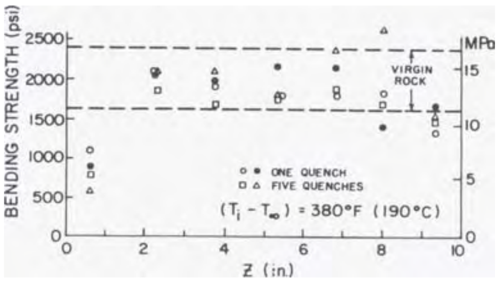


Fig. 3b. Bending Strength of Specimens Taken from Slab

DISCUSSION

The results of the first experiment using the large, regular-shaped granite blocks indicates that the attempt to calibrate the spacial time-temperature history of the loading will be successful. Several additional experiments are planned with larger injection flow rates to produce "heat transfer limited" reservoir conditions, in which substantial rock-water temperature differences exist throughout the transient. Such conditions should result in a much more rapid exit water temperature decrease.

In the completed experiment, the observed cross-sectional water temperatures were relatively uniform even with the relatively large flow area at the edge channels between the rock loading and the vessel. Possible explanations of this apparent uniform cross-sectional water temperature, inter-block channel area, include: (1) relative magnitudes of the heat available at the various channels; (2) relative pressure drops in each channel; and (3) cross mixing between channels.

Estimates of the heat transfer from around the edge channels (including heat from the steel vessel) compared to the inter-block channels were about 1.65, not quite as large as the flow area ratio of 2.07. Thus, the edge channels may be lower in temperature than the inter-block channels. The perforated flow distribution baffle at the bottom of the vessel has been shown to be sufficiently efficient in providing uniform flow entering the rock matrix below the lowest rock layer. Channel to channel pressure drop differences are not expected to be sufficiently large to affect the average channel flow velocities at the mean flow rate of only 5.5 ft/hr. The most likely reason for the observed uniform water temperatures appears to be the energy exchange between channels due to mass transfer. This aspect of the analysis warrants further observations in the future experiments and in the analysis.

The coupling of the thermal stress effects on heat transfer properties with this set of calibration experiments in the physical model offers three potential advantages: (1) a basis to observe if such changes will occur under controlled observable conditions; (2) an opportunity to re-evaluate the experimental data if indeed such changes in heat transfer properties do occur during the experiments; and (3) an opportunity to modify the finite element heat transfer model to account for such changes. It is expected that any observed changes in strength or porosity will be evaluated in terms of available models for thermal stressing.

Extension of the finite element heat transfer model is continuing with the development of features that allow for free-field data input, coordinate and element generation capabilities, and plotting of the finite element mesh. This last feature is especially useful for checking accuracy of the mesh data for three-dimensional models. The solution display of the temperature and temperature rate histories can be printed and graphically plotted. The code has been designed in modular form to allow individual-need modifications and future extensions, such as porous media matrix modeling.

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