STANFORD GEOTHERMAL PROGRAM

FIRST ANNUAL REPORT

to

U.S. DEPARTMENT OF ENERGY

LAWRENCE BERKELEY LABORATORY

for the period

June 1, 1977, through March 31, 1978

Contract DOE-LBL-167-3500

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1. INTRODUCTION

This report is the first annual progress report under the Department of Energy Contract DOE-LBL-167-3500 with Lawrence Berkeley Laboratory. It covers the period June 1, 1977, to March 31, 1978.

At the close of the first year of support from the Department of Energy, the Stanford Geothermal Program has maintained momentum built up under the previous National Science Foundation support. A number of current projects have been completed during the year, and others have begun and are underway.

The central thrust of the program has been the development of techniques of geothermal reservoir engineering. This crucial field holds a great deal of importance in the comparatively new industry of geothermal development, and it is through the greater understanding brought about in reservoir engineering that the geothermal energy business will reach maturity. The program has investigated applications over quite a broad area in two major categories: fundamental studies and field application studies.

Among the fundamental studies are the laboratory experiments examining the behavior of rock/water systems under geothermal conditions. The large geothermal reservoir model, built at Stanford by the program, has been used to investigate the specific energy extraction capabilities of various production methods. This model has also been used to determine the rate of heat loss from various rock formations, with a particular view to providing an empirical representation of heat extraction from rock. During the year, the large reservoir model was also packed with sand (in the interstices of the rock matrix) to provide a more realistic permeability/porosity formation. These results are presented in Section 2.

A parallel laboratory and field study in progress in the program is the radon analysis. Radon collections from geothermal fields at the

Geysers, Lardarello, Hawaii, and the hot, dry rock system at Los Alamos have provided a variety of responses that are now being evaluated as a means of illustrating reservoir properties. Radon is a particularly useful trace for this kind of application since it has a very useful half-life of about 4 days. The hot, dry rock radon samples appear to show an increase in surface area of the hydraulically produced fracture, suggesting the use of radon monitoring as an indicator of thermal stress cracking. In order to quantify the emission rates of radon from reservoir rocks, an experimental apparatus is under construction to provide exact information on the temperature, pressure, and rock property dependence of the radon production. These various studies are presented in Section 3.

Another set of fundamental investigations involve the use of laboratory cores in bench-scale experimental rigs. Three studies have been carried out: first, in pursuit of steam/water relative permeability curves for permeable formations; second, investigating the property of vapor pressure lowering of water confined in porous media at low saturations; and third, the determination of the effects of high confining pressures and temperatures on the absolute permeability of porous rocks. These investigations collectively provide an exact description of the flow through a geothermal formation on a microscopic scale. A beneficial sideline of this research is that it provides carefully controlled model situations that can be used as a basis for calibration of numerical models that may then be applied with greater confidence to the larger unknown of a geothermal reservoir. Section 4 describes the work in this field.

Finally, a major interest of the program is in the area of well test analysis. Although the laboratory data provides important data on fundamental properties of geothermal operations, at least an equal emphasis must be placed on information provided by the geothermal field itself. The conduit for this information is the geothermal wellbore, and thus the projects focus on the interpretation and design of well tests. The most important direction in this regard is in the field of pressure transient analysis, and three separate studies have been performed during the year. In the parallel area of discharge analysis, the program has addressed the problem of evaluating wellbore heat and pressure losses, as well as discharge variations due to relative permeability effects. These and the bench scale studies will be the starting point of new developments in pressure transient analysis of two-phase wells--a pressing need in the geothermal industry that has yet to be filled. Well test analysis is described in Section 5.

The Stanford Geothermal Program is a mobile and expansive group that fulfills other secondary roles in the geothermal community. Other than filling the University's task of providing training for new geothermal personnel, the program has provided several organized services to the nearby geothermal concerns. The Annual Stanford Geothermal Reservoir Engineering Workshop was held for the third time in December 1977, and was attended by representatives from the U.S., Italy, New Zealand, Mexico, and Japan. The weekly seminars continued to be popular this year, and were held throughout the fall, winter, and spring quarters. These seminars have produced many fruitful interchanges of information both into and from the Stanford program. This involvement of the program is described in the concluding remarks, Section 6.

2. ENERGY TRANSFER EXPERIMENTS

2.1 Energy Extraction Experiments

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 2.1.

This work has been reported in previous reports and papers (Hunsbedt, Kruger, and London, 1975, 1977, and 1978). The results showed that all three processes are feasible in the experimental systems considered. However, the effectiveness of the process, as illustrated in Table 2.2, varied widely.

TABLE 2.1: 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.

TABLE 2.2 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	> 9.80*
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, referred to as the energy extraction fraction, 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 (1978). The final report on 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, Kruger, and Brigham (1976). 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 artibrary boundary or cooldown conditions.

The basis for the rock temperature transient prediction for a single rock was the one-lump, spherical solution presented by Hunsbedt, Kruger, and London (1975) 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 Fig. 2.1, 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 Fig. 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 an arithmetic mean diameter of 1.62 inches. It was obtained from the piledriver chimney produced by a nuclear explosion at the Nevada Test Site.

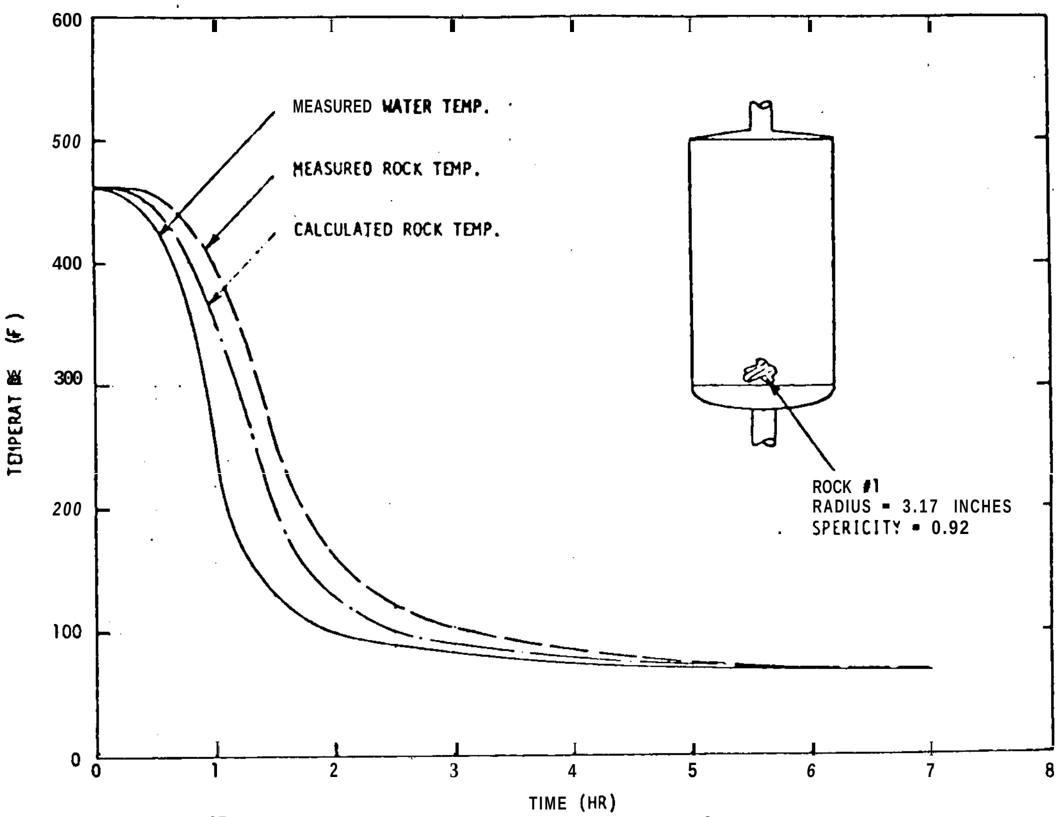

FIGURE 2.1 CWPARISON OF MEASURED AND CALCULATED TEMPERATURES FOR ROCK #1 - SWEEP EXPERIMENT

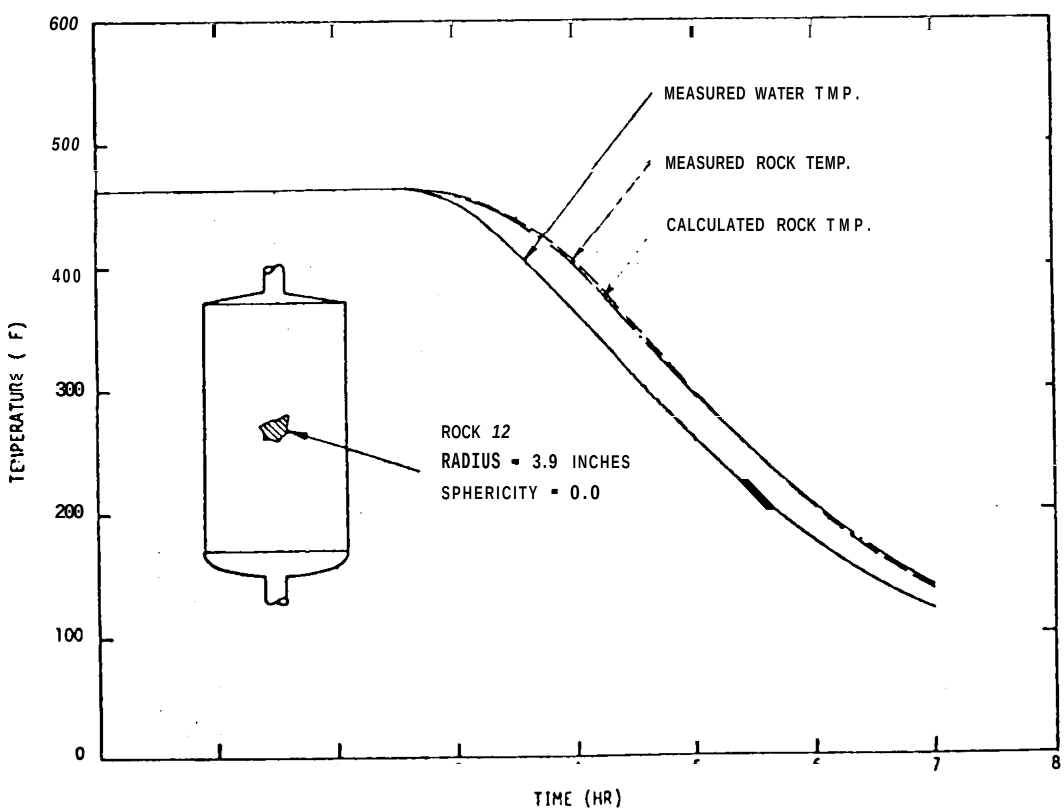

FIGURE 2.2 COMPARISON OF MEASURED AND CALCULATED TEMPERATURES FOR ROCK #2 - SWEEP EXPERIMENT

The results of the temperature transient comparisons showed that the one-lump thermal model utilizing an equivalent radius 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 and in many cases will have to be assumed. The effect of rock size distribution and the sphericity are given in Figs. 2.3 and 2.4, respectively, where the rock energy extraction fraction is plotted as a function of total time to deplete the reservoir. 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).

The heat transfer model was also used as a basis for formulating a mathematical model for rock energy extraction by the cold water sweep process in fracture-stimulated reservoirs. It predicts the water temperature profiles that develop in the rock matrix when cold water is recharged at one end of the reservoir and hot water is produced at the other. The formulation of this model showed that the energy extraction process was governed by a non-dimensional parameter referred to as the number of transfer units (N_{tu}). It is defined as the ratio of the water residue time to the time constant of a rock with a size corresponding to the mean

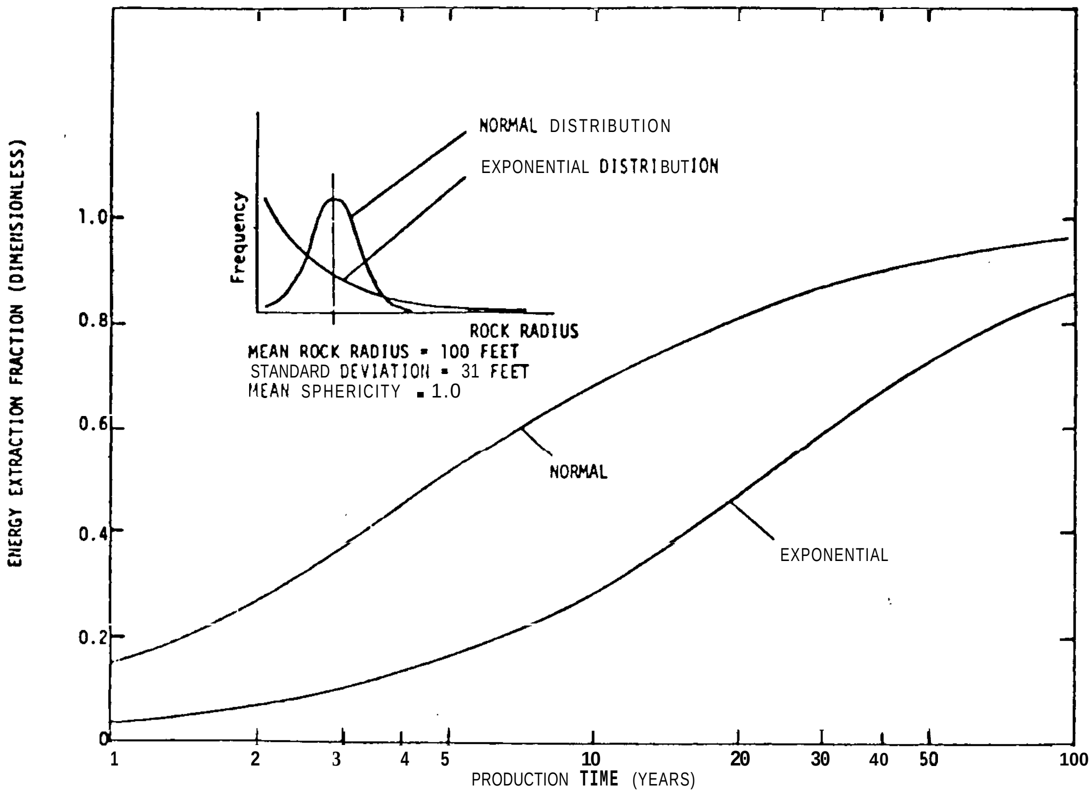

FIGURE 2.3 ENERGY EXTRACTION FRACTION AS A FUNCTION OF TOTAL PRODUCTION TIME FOR TWO DIFFERENT ROCK SIZE DISTRIBUTIONS.

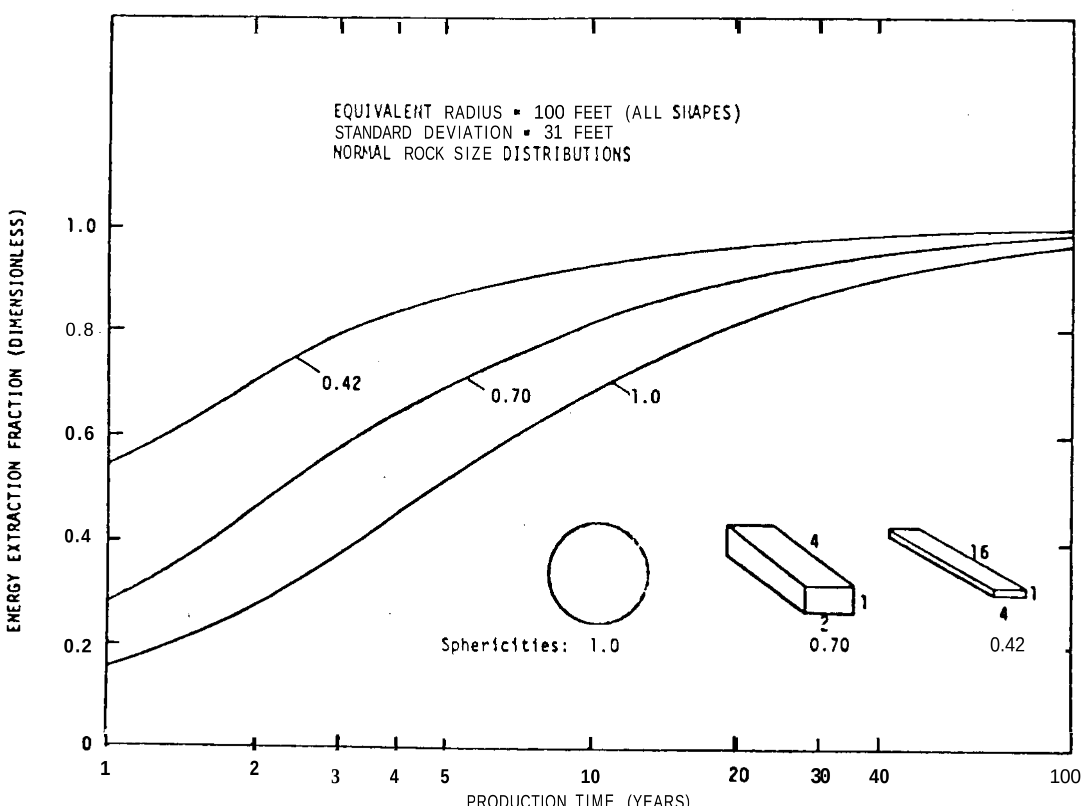

FIGURE 2.4 ENERGY EXTRACTION FRACTION AS A FUNCTION OF TOTAL PRODUCTION TIME FOR THREE DIFFERENT ROCK SHAPES

effective rock radius. The mean effective rock radius (R_e) is a type of mean radius for a collection of unequal size rocks that represents the entire rock collection when heat transfer rates are calculated. It is always greater than the arithmetic mean radius for the collection, but smaller than the maximum rock size.

A sensitivity analysis was performed to determine the effect of the number of transfer units parameter on the sweep energy extraction process. The computations were performed for an assumed rock porosity of 10%. The number of transfer units parameter was varied from 5 to 200. The results showed that the energy extraction is very ineffective for the lower N_{tu} values (smaller than 10). The physical explanation for this is that the fluid flow through the rock matrix is too fast for effective heat transfer to take place. Alternatively, tne rock sizes are too great and the rock heat transfer rate too slow. Larger N_{tu} values (greater than 30) resulted in slow enough fluid flow through the rock matrix (or rock sizes none small enough) to affect reasonably effective heat transfer.

The cold water sweep model was applied to a hypothetical fracture-stimulated geothermal reservoir with parameters and conditions listed in Table 2.3. Two energy extraction rates were assumed which corresponded to nominal net power plant outputs of 10 MW_e (case 1) and 50 MW_e (Case 2). The water residence times for the two cases were fixed at 30 and 6 years, respectively, for these conditions. Changes in N_{tu} were affected by varying the mean effective rock radius R_e from 25 to *400* feet.

The produced water temperature and the energy extraction fractions are given as functions of time in Fig. 5 for the two cases. The effect of rock size (and of N_{tu}) on the produced water temperature are seen in the left-hand diagrams. The water temperature generally drops earlier and at a faster rate for the larger rocks (smaller N_{tu}) values in both cases.

Moreover, the rock water temperature starts to drop at earlier production times for the higher energy extraction rate of case 2. The energy extraction fractions for the two cases seen as functions of time is the right-hand diagram of Fig. 2.5, are seen to be generally higher for Case 2. The main reason for this is the generally higher rock-to-water temperatures as a resu t of the faster cooling of the fluid. Also, the rock sizes are smaller in Case 2 to achieve comparable N_{tu} values for the two cases.

TABLE 2.3: HYPOTHETICAL RESERVOIR PARAMETERS

Initial Temperature (^{o}F)	550
Initial Temperature (^{o}F)	70
Reservoir Volume (km^3)	1
Specific Power Plant Flow Rate (lb_m/kWhr)	85*
Power Generation Rates (MW_e)	
Case 1	10
Case 2	50
Distance Between Injection Production Wells (km)	1
Reservoir Porosity (dimensionless)	0.1**
Water Residence Time (years)	
Case 1	30
Case 2	6
Mean Effective Radius (ft)	25-400
Number of Transfer Units (dimensionless)	1-55

*Power generation rate is based on average specific steam flow rate given above.

**Reservoir permeability assumed adequate to allow uniform water flow as required rates in both cases.

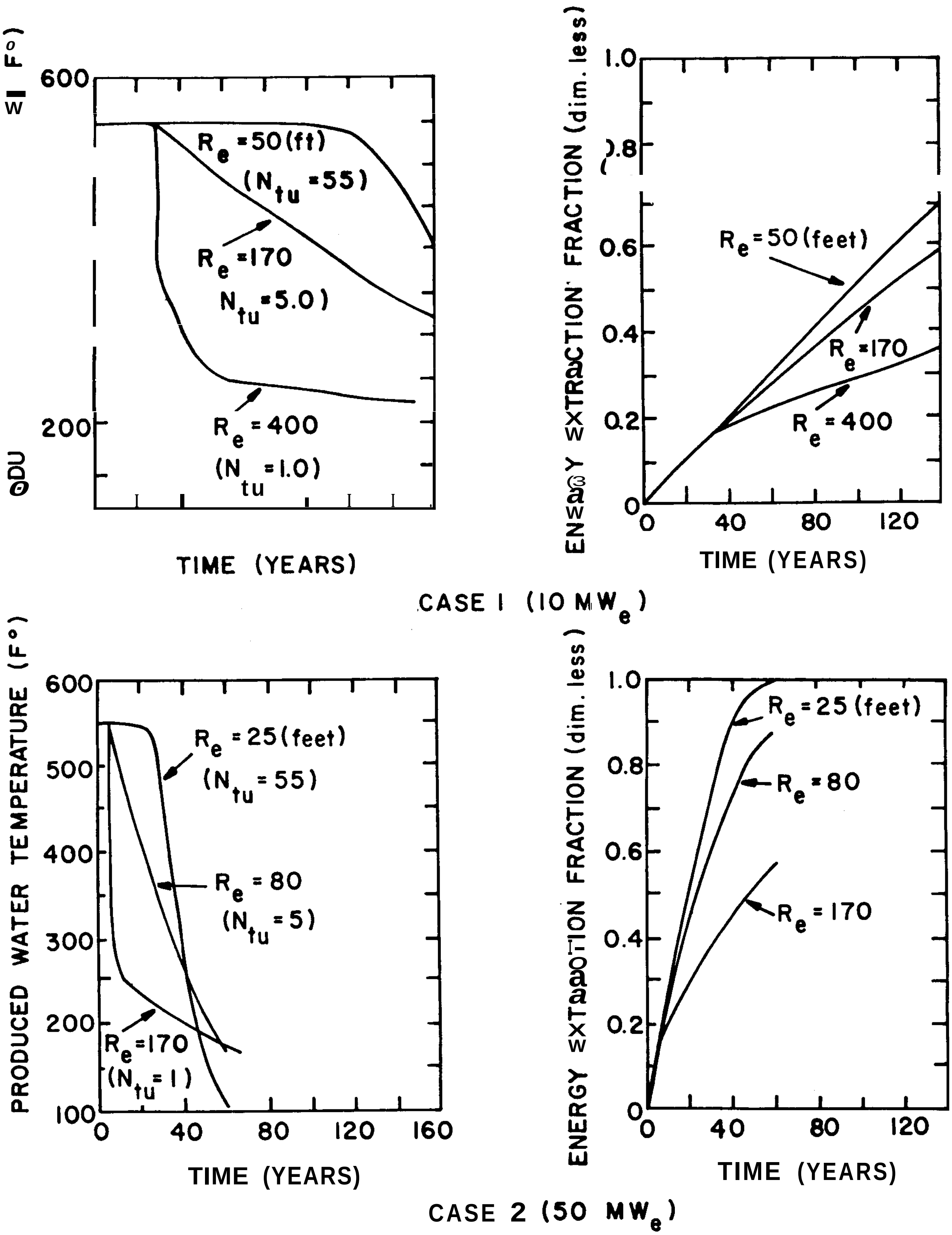

FIGURE 2.5 PRODUCED WATER TEMPERATURES AND ENERGY EXTRACTION FRACTIONS AS FUNCTIONS OF TIME

The results generally indicate that the energy stored in the rock of given sizes can be extracted effectively when the reservoir is produced at corresponding low rates. If higher energy extraction rates are desired, the rock has to be fractured more extensively to achieve an acceptable reservoir life. Further evaluation of the energy extraction process will continue in the future.

Current Experiments

The experiments performed in the SGP reservoir model have utilized rock systems with porosities between 35 and 44% 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% and the permeabilities in the range of 5 to 500 md. Experiments with a more representative rock system are being conducted. This fourth rock system consists of the granitic rock utilized in the third rock system piledriver rock having an average rock size of 1.62 inches), but the void spaces are filled with 80 to 100 mesh sand. The porosity has been determined to be about 21%; the vertical permeability is being measured. Two energy extraction experiments of the in-place type have been conducted with this rock system. A preliminary evaluation of the results are presented.

A summary of experimental conditions and parameters for the two experiments (denoted by 4-1 and 4-2) are given in Table 2.4. Additional tape heater capacity was added prior to conducting experiment 4-2 to provide higher initial pressure and temperature and a more uniform initial temperature distribution in the rock matrix relative to that of experiment 4-1.

Measured axial rock and steam/liquid temperature distributions for experiment 4-2 are given in Fig. 2.6 for different times during the production process. The initial temperature distribution (t=0) in Fig. 2.6 is seen to be uniform in the upper portions, but is slightly lower than the average at the bottom. Additional tape heater capacity may be added near the bottom to provide essentially uniform initial conditions.

TABLE 2.4: EXPERIMENTAL CONDITIONS AND PARAMETERS FOR TWO RECENT IN-PLACE BOILING RUNS

	Experiment No. 4-1	4-2
Initial Pressure (psia)	302	500
End Pressure (psia)	39	15
Initial Temperature – Top (^oF)	416	467
Initial Temperature – Bottom (^oF)	356	449
Average Initial Temperature (^oF)	405	465
End Temperature (^oF)	270	212
Initial Mass of Water in Matrix (lb_m)	195	187
Total Mass of Steam Produced (lb_m)	130	189
Production Time (hrs)	3.0	3.5
Mean Steam Production Rate (lb_m/hr)	44	54
External Heat Transfer Parameter (Btu/lb_m)	172	217

TABLE 2.5: SUMMARY OF RESULTS FOR TWO RECENT IN-PLACE BOILING EXPERIMENTS

	Experiment No. 4-1	4-2
Specific Energy Extraction (Btu/lb_m)	28.9	43.5
Energy Extraction Fraction (dimensionless)	0.99	0.82
Fraction of Steam Produced (dimensionless)	0.67	1.0
Recovery Factor (dimensionless)	4.5	3.8

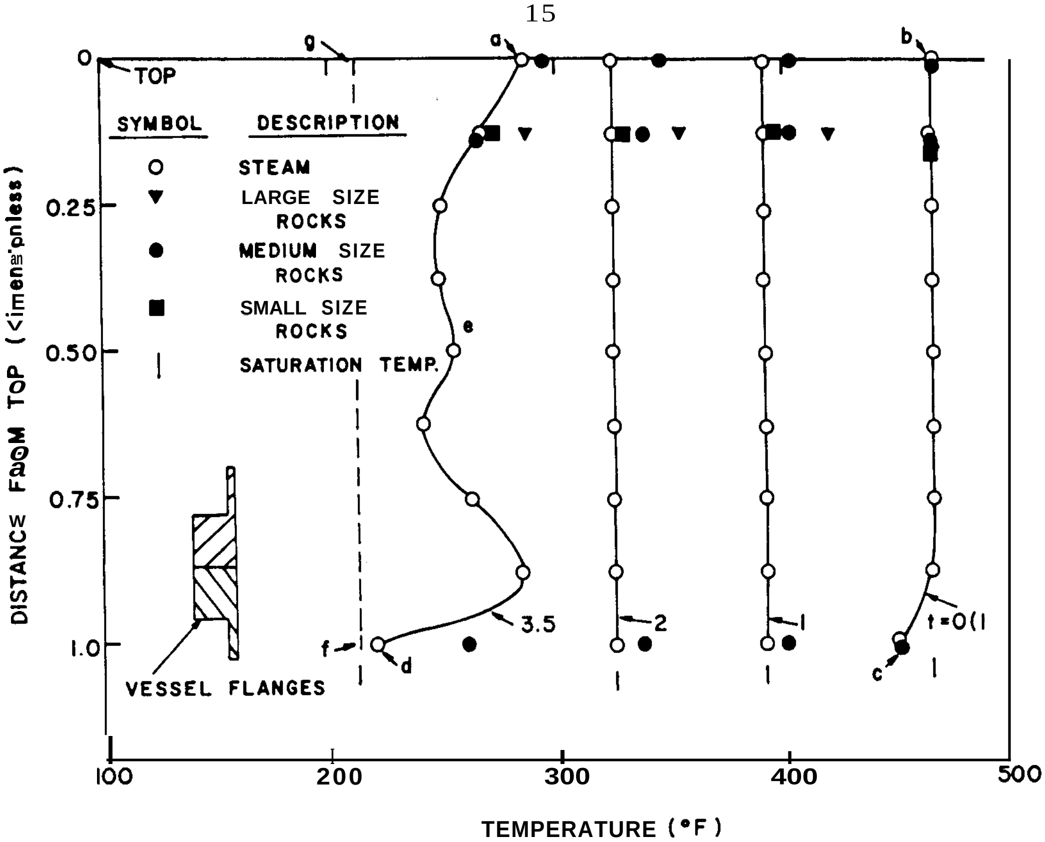

FIGURE 2.6 AXIAL FLUID AND ROCK TEMPERATURE DISTRIBUTIONS AT DIFFERENT PRODUCTION TIMES

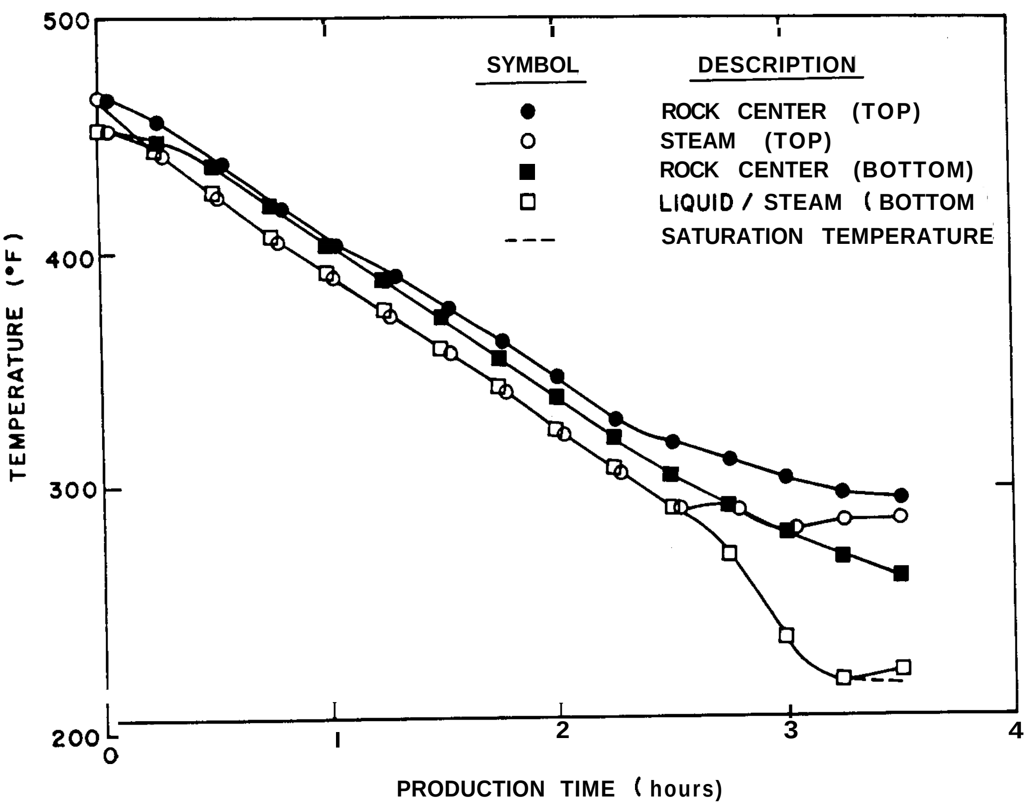

FIGURE 2.7 FLUID AND ROCK TEMPERATURE HISTORIES AT TOP AND BOTTOM OF ROCK MATRIX

The data in Fig. 2.6 indicate that saturated reservoir conditions are maintained uniformly throughout the reservoir during most of the production process. However, near the end, superheated steam conditions developed indicating that liquid water is being depleted and dryout initiated. The dryout and superheating effect is also noted in Fig. 2.7, which gives fluid and rock temperatures at the top and bottom of the rock matrix as functions of time.

These data show that the superheating effect started near the top at $5 \simeq 2.5$ hours and near the bottom at $t \simeq 3.25$ hours. Complete dryout of the rock matrix had occurred at this time. The steam production, seen in Fig. 2.8, leveled off sharply at this time, and the reservoir pressure measurements showed a rapid pressure decline. The high temperature zone in the lower half of the rock matrix is believed to be caused by heating of the steam/rock from the residual energy contained in the high heat capacitance level flanges located at this elevation.

The results for experiment 4-1 showed no evidence of liquid dryout. Major reasons for this are that the initial temperature and pressure were lower than for experiment 4-2, as indicated in Table 2.4, and the end pressure and temperature were higher. Sufficient energy was not available to evaporate all water in experiment 4-1.

A comparison of the specific energy extraction for both experiments given in Table 2.5 show a significantly higher value for experiment 4-2. The energy extraction fraction (proportional to the ratio of area a-b-c-d-e-a to area a-b-c-d-f-g-a in Fig. 2.6) was lower for experiment 4-2 because of the incomplete energy extraction caused by the dryout condition. The energy extraction fractions for these experiments, however, were generally of the same order (or higher) compared to those achieved in earlier experiments with higher porosity/permeability systems.

The recovery factor defined as the ratio of steam actually produced to that which would have been produced by flashing the steam alone (without energy from rock or vessel steel) is seen to be 4.5 and 3.8 for experiments 4-1 and 4-2, respectively. This is significantly higher than that achieved in earlier experiments with higher porosity/permeability systems where the maximum recovery factor was 2.58 (Hunsbedt, Kruger, and London, 1975, 1977).

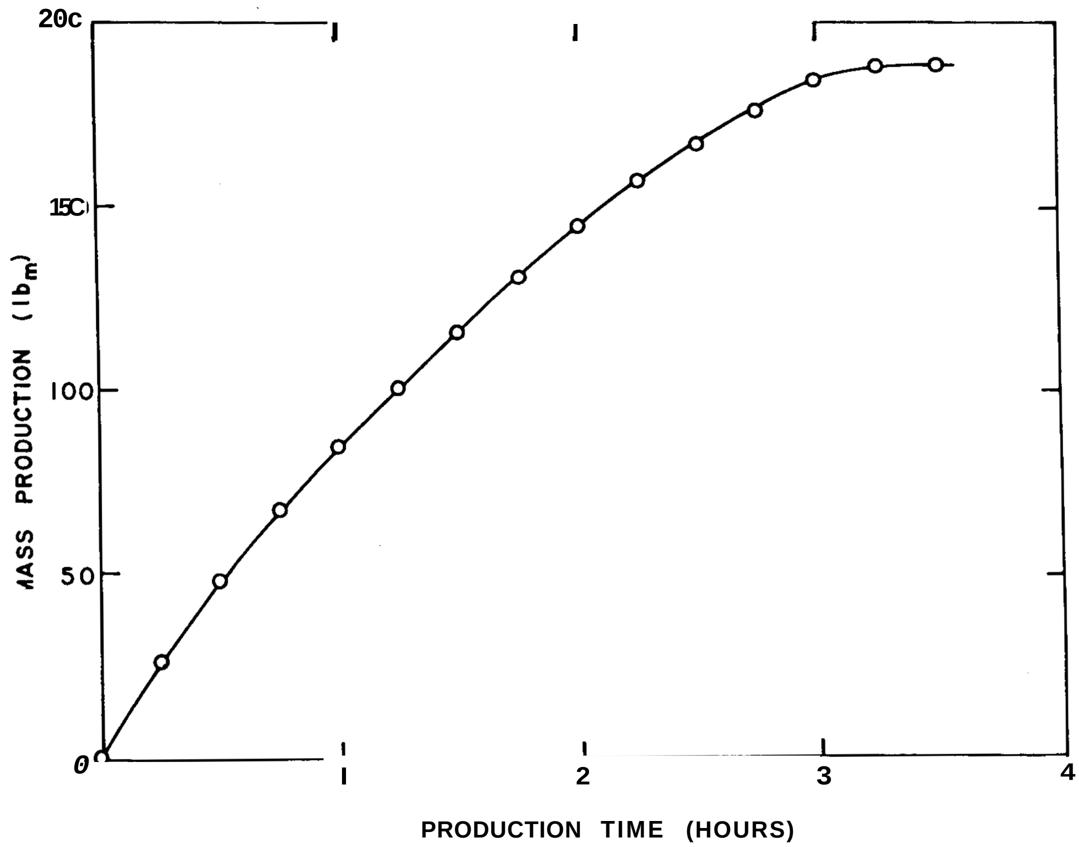

FIGURE 2.8 CUMMULATIVE MASS PRODUCTION HISTORY

The overall conclusion of the preliminary data evaluation is that energy recovery is improved for the present system relative to the other high porosity/permeability systems tested earlier. The natural convection and cooling of the rock is not impeded by the presence of sand in the voids of the laboratory model system. Further evaluations are needed to determine to what point the permeability can be lowered without significant deterioration of the energy extraction effectiveness.

2.2 Thermal Fracturing Experiments

The utilization of energy stored in a hot dry geothermal rock greatly depends on the ability to extract it from the rock. The technique of hydraulic fracturing creates long vertical cracks in the rock through which water can be circulated to extract the thermal energy. There has been a speculation that cooling of rocks would produce thermal stresses causing the rocks to crack further and thus provide new surface area for heat transfer. Pracht and Harlow (1972) have shown theoretically that if thermal cracking does happen, the life of the geothermal reservoir is greatly enhanced. This work is the first part of the project which involves the verification of thermal stress cracking experimentally.

Physical Model

A long vertical crack formed by hydraulic fracturing can be represented as shown in Fig. 2.9. As the temperature in the interior of the rock does not change with time, the temperature distribution near the surface can be determined by treating the rock as a semi-infinite solid. The above situation can also be realized for a slab of finite thickness which is insulated around its circumference (Fig. 2.10). The finite slab can be considered as a semi-infinite body as long as the temperature disturbance is not felt at the x=b face. Hence, to determine the effect of thermal stressing in actual systems, we would be doing an experiment on a finite slab (Fig. 2.10) which is preheated to a specified temperature and then quenched on the x=0 face by water while keeping other faces insulated.

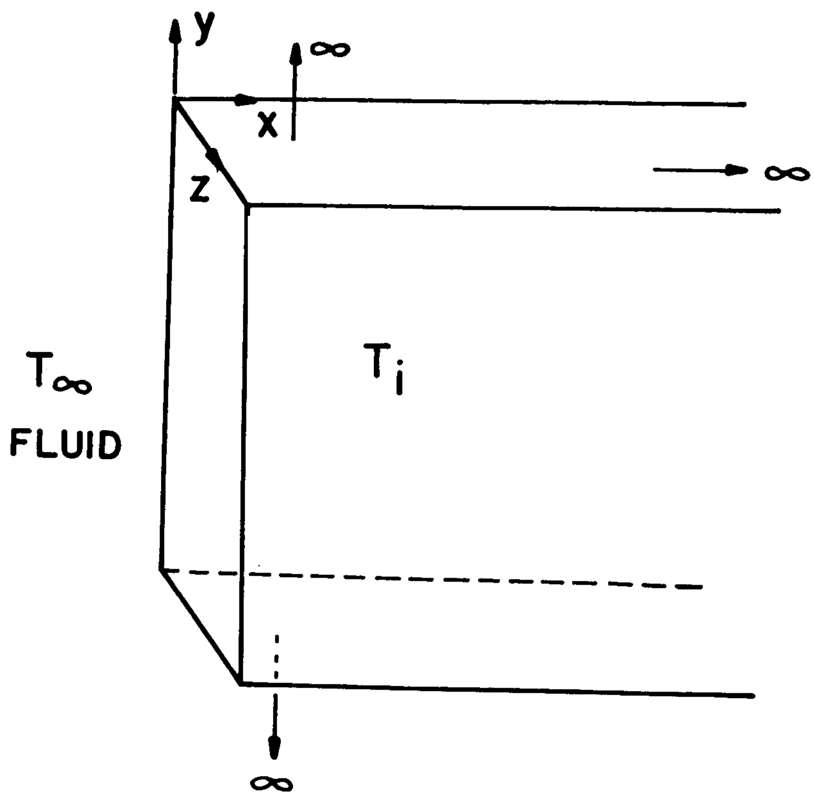

FIGURE **2.9** SCHEMATIC OF LONG VERTICAL **CRACK** FORMED BY HYDRAULIC FRACTURING

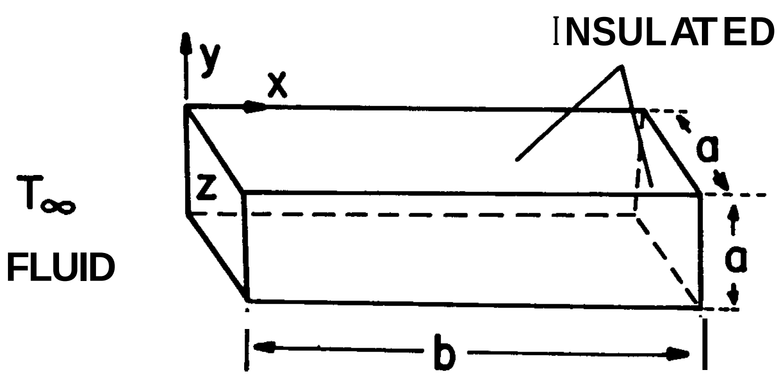

FIGURE 2.10 EWERIMENTAL EQUIVALENT – FINITE SLAB

Heat Transfer Analysis

The temperature distribution in the slab for a finite value of the surface conductance at the face is given by:

$$\frac{T_i - T(x,t)}{T_i - T_\infty} = 1 - \text{erf}\left[\frac{x}{2\sqrt{\alpha t}}\right] \exp\left[\frac{hx}{k_s} + \frac{h^2 \alpha t}{k_s^2}\right] \cdot$$

$$\left[1 - \text{erf}\left(\frac{x}{2\sqrt{\alpha t}} + \sqrt{\frac{h^2 \alpha t}{k_s^2}}\right)\right] \qquad (2.1)$$

where:

h = heat transfer coefficient

k_s = thermal conductivity of rock

$\alpha = \frac{k_s}{\rho c}$ - thermal diffusivity of the rock

t = time (hrs)

T = temperature

Since the rock temperature would be of the order of $400^{o}F$, nucleated boiling can be expected to occur on the surface of the body and thus result in a high heat transfer. The heat transfer coefficient in such a case would be of the order of 1,000 Btu/hr-ft^2-^{0}F. It can be shown that corresponding to such high heat transfer coefficients, the last term in Eq. 2.1 becomes insignificant and can be neglected for all practical purposes.

Thermal Stress Analysis

The free thermal contraction of elements in the y and z directions would result in thermal stresses in these directions. These thermal stresses are given by:

$$\frac{\sigma(1-\nu)}{E\alpha\,\theta_i} = 1 - \text{erf}\left(\frac{x}{a}\right) + \frac{6x}{b}\left[\frac{(a/b)}{\sqrt{\pi}} - \frac{1}{2}\left(\frac{a}{b}\right)^2 \text{erf}\,(b/a)\right]$$

$$- \left[1 - \text{erf}(b/a)\right] + \frac{(a/b)}{\sqrt{\pi}} e^{-(b/a)^2} + \frac{3}{2}\left(\frac{a}{b}\right)^2 \text{erf}(b/a)$$

$$- \frac{4}{\sqrt{\pi}}\,(ah) \qquad (2.2)$$

Crack Initiation and Propagation

The crack would be initiated when the thermal stress reaches the tensile strength of the rock at some point in the material. From Eq. 2.2, the maximum tensile stress occurs at x=0, and is given by:

$$\sigma = \frac{E\alpha_t \theta_i}{1-\nu}$$

For tensile strength (σ_t) of 1100 psi (granite), the temperature differential required for crack initiation would be:

$$\theta_i = \frac{1100(1-\nu)}{E\alpha_t}$$

Typical values of ν, E, and α_t for granite are 0.31, $8x10^6$ psi, and $4.0x10^{-6}/^oF$. Using these values, we get $\theta_i=24^oF$ for crack initiation. Once the crack is initiated, it would extend normal to the plane of maximum principal stress, i.e., x-direction provided there is enough driving force available. The stresses reduce because of stress re-distribution, and it can be expected that one would need much higher temperature differentials.

Experimental Setup

The rock specimen can be slowly heated to a specified initial temperature in an oven. The quenching can be performed in the experimental setup as shown in Fig. 2.11. The heated block is placed in the insulated box which is preheated to the same initial temperature by built-in heating elements. The rock and the insulation are protected from the water by putting a screen and the seal as shown. The experiment will be done for rock at different temperatures to determine the temperature differential required to form a thermal crack. This temperature would provide an estimate of thermal stresses in the rock which cause thermal stress-cracking. This information can then be used to simulate thermal stress-cracking of big rock systems to provide data on how much thermal cracking would occur and how it would influence the geothermal reservoirs.

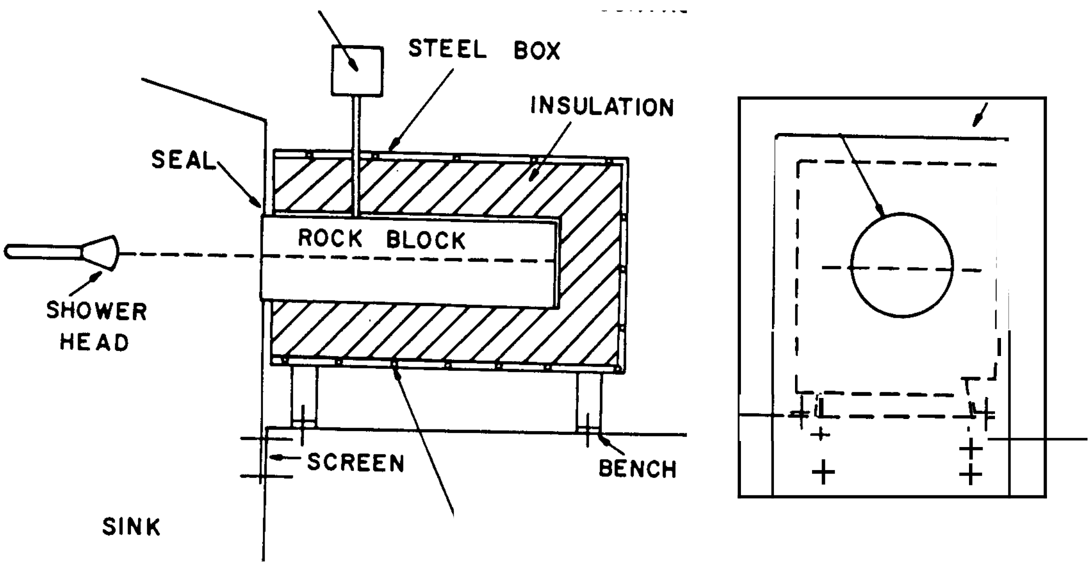

FIGURE 2.11 PROPOSED EXPERIMENTAL APPARATUS TO INVESTIGATE THERMAL STRESS CRACKING OF ROCK

3. RADON ANALYSIS PROJECTS

Radon is developing satisfactorily as an internal tracer for examination of reservoir properties in geothermal resources. During the current contract period, progress has been achieved in several projects involving the development of radon measurement analysis in geothermal reservoir engineering. Among them are experimental efforts to acquire data in the following projects: (1) continuation of the development of radon transient analysis, (2) initiation of flow pattern evaluations in hydrothermal reservoirs, (3) correlation of radon concentrations with other non-condensible gases, e.g., CO_2, (4) initiation of measurements in the experimental hot dry rock resource at LASL, and (5) initiation of emanation studies under laboratory-controlled reservoir conditions of pressure, temperature, and convecting fluid density.

The potential of radon in geothermal reservoir engineering has been adequately described in previous reports. Its use as a natural internal tracer is based cn a unique set of nuclear and geologic properties. Radon is the radioactive noble gas produced in nature from the decay of radon dispersed in the earth's crust. The principal isotope of radon is 3.83-day ^{222}Rn resulting from alpha-particle emission from its parent radionuclide, 1600-yr ^{226}Ra, which in turn is produced in the natural uranium series originating with 4.5×10^9-yr ^{238}U. Since radon is in radioactivity equilibrium in undisturbed radium-bearing rock, it will be produced ''forever'' in geothermal reservoirs, in quantities determined by the radium concentration in the rock. The quantity that escapes by recoil energy or diffusion into surrounding geofluids is determined by the geologic properties of the formation. Since radon decays with its characteristic half-life of 3.83 days following separation from its Ra parent radionuclide, it becomes a potentially useful internal radioactive tracer for geothermal reservoir structure and transport phenomena. Its radioactive property provides a "time element" in such studies, contrasting sharply with the stable components of the non-condensible gases, such as CO_2, H_2S, and $\delta(^{18}O)$.

Radon concentration in geofluids depends on several reservoir parameters, primarily the concentration and distribution of radium in the reservoir formation, the reservoir structural conditions affecting emanation and diffusion into pore fluids, and the hydrodynamic conditions from emanation sites to the wellhead. These parameters, in turn, are related to other geologic factors.

Radium is generally found uniformly distributed in sedimentary and igneous rocks at an average concentration of about 1 pg/g. Its distribution in a particular reservoir, however, depends on the local thermodynamic and hydrochemical history of the formation. Since radium is a chemical homolog of the alkaline earth elements calcium, strontium, and barium, it can be redistributed with these elements in hydrothermal resources. The emanation of radon in rock matrices depends on the chemical, mineral, structural, and thermodynamic properties of the rock. The recoil energy of ^{222}Rn on alpha decay of ^{226}Ra is 86 keV, sufficient to penetrate about 1 μm in rock. Radon emanation from rocks is thus strongly dependent on fracture density, exposed surface area, porosity, composition of cementing materials, and density of the surrounding fluids. The transport of radon depends on its solubility in the convecting fluid and the hydrodynamic properties of the reservoir, such as permeability, pressure gradients, and flow rate.

This set of tracer-reservoir properties allows two general types of information with radon as an internal tracer. Under steady flow conditions, changes in reservoir conditions which change the radium distribution in the reservoir or which result in emanation changes will result in changes in wellhead radon Concentration. And under steady emanation conditions, changes in flow patterns in the reservoir will also result in changes in wellhead radon concentration. Thus the realization of practical radon-reservoir analysis rests upon the attainment of known relationships between wellhead radon concentration and changes in reservoir and flow patterns. Sufficient data are needed to establish these relationships and to separate the changes due to each effect.

Attaining these relationships has been the goal of the radon studies in the Stanford Geothermal Program. The results of the several projects listed earlier are summarized here.

3.1 Radon Transient Analysis

A series of five radon transient tests have been completed during the past two years, as opportunities and approval from field operators have been realized. These tests involve rapid changes in flow rate to observe the resulting transient in wellhead radon concentration. Rapid flow rate changes constitute significant interferences with normal production operations. Therefore, they are scheduled during periods of field production convenient to the operators and therefore possibly under abnormal reservoir perturbations. However, they are run for a long enough period, generally longer than one week, so that the transient nature of the flow rate change can be adequately observed. Table 3.1 shows the variability of field tests conditions under which the five tests have been run, and the general nature of the observations.

The first test in a producing dry steam well at The Geysers showed a radon transient following a rapid decrease in flow rate in which the radon concentration decreased proportionally with an apparent "decay constant" of about 12 ±4 days. The data are shown in Fig. 3.1. This observation was evaluated in the context of the linear and radial flow models described in earlier reports in which the relationship between wellhead radon concentration and reservoir flow rate were affected by the two sets of parameters noted earlier; the radium distribution and the transport conditions. The emanation source might be: (1) hydrothermally deposited close to the wellbore, (2) dissolved in a boiling liquid deep in the reservoir, or (3) uniformly deposited over a large transport pathway. The pathway might contain a steam saturation profile in the reservoir ranging from all liquid to superheated steam. The results of this first test indicated that the radon was not coming from radium deposited around the wellbore and supported the idea of a boiling water table deep in the reservoir.

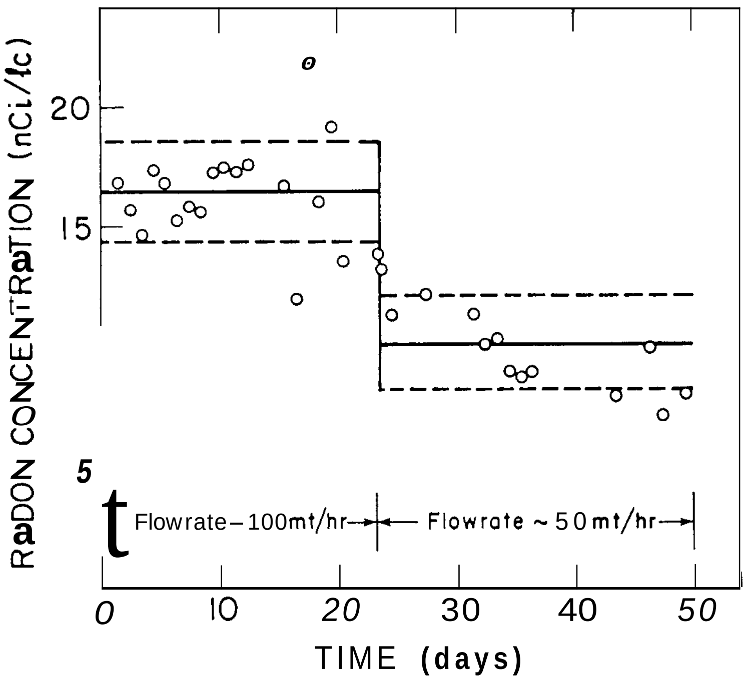

FIGURE 3.1 RADON CONCENTRATION AS A FUNCTION OF TIME, FLOW RATE TEST AT THE GEYSERS, CALIFORNIA

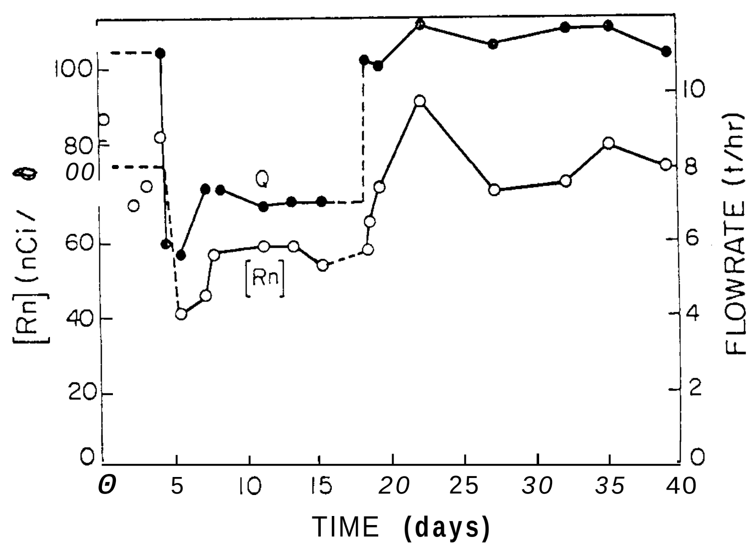

FIGURE 3.2 RADON CONCENTRATION AS A FUNCTION OF TINE, FLOW RATE TEST AT SERRAZANO, ITALY

The second test, in a producing dry steam well in the Italian Larderello fields, was a two-week test with a rapid decrease in flow rate for one week, followed by a rapid return to full flow. In contrast to the test at The Geysers, the radon concentrations followed the changes in flow rate, also proportionately, but in a time period short compared to the half-life of radon. The data are shown in Fig. 3.2. Over the three flow rate periods, the ratio of radon concentration to flow rate was constant within $\pm 10\%$ over some 40 samples, as noted in Fig. 3.3. These results also indicated that radon was not coming from radium deposited around the wellbore and supported the idea of a boiling water table close to the wells.

The next two tests broadened the range of application of radon transient analysis, in that it introduced the reservoir phenomenon of well interference. The transport conditions of radon flow might be: (1) from a producing well in a field without interference from nearby wells, where changes in flow rate produces major changes in reservoir flow pattern, (2) flow from a well interconnected to nearby producing wells, where changes in flow rate in the test well may not produce significant change in reservoir flow pattern, and (3) flow from a well in a newly producing field, where the thermodynamics and hydrologic conditions near the well may not yet be established under full scale production. The observations of radon concentration behavior in these two tests are currently the subject of a dissertation which should be completed in the coming period.

The last test listed in Table 3.1 is the first radon transient test in a hot water well, in Puna, Hawaii, one which has not yet been produced significantly. Due to local restrictions limiting flow testing to a maximum of 4 hours per day because of environmental concerns, the test consisted of two 2-hr flows with orifices giving maximum and minimum flow rates. The results of this test are shown in Fig. 3.4, and will be reported in the coming period. For these short-time periods, the observed lack of change in radon concentration supports the model of a large uniform deposit of radium in the reservoir in which the radon concentration is not a linear function of flow rate. However, longer transient testing under steady flow conditions at these two flow rates is needed to confirm the results of this short test.

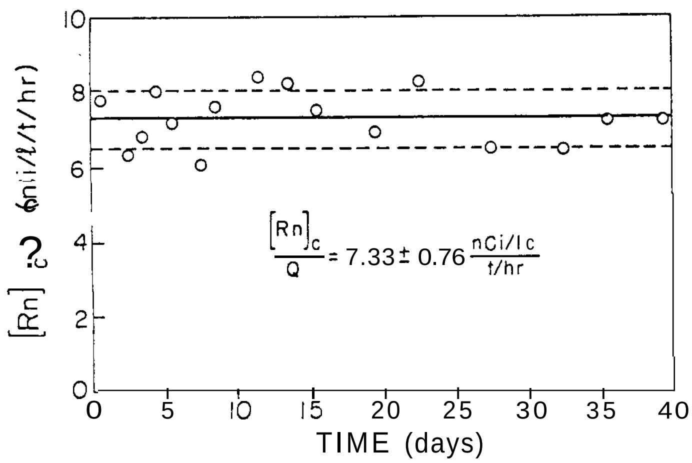

FIGURE 3.3 RATIO OF RADON CONCENTRATION TO FLOW RATE FOR THE SERRAZANO TEST

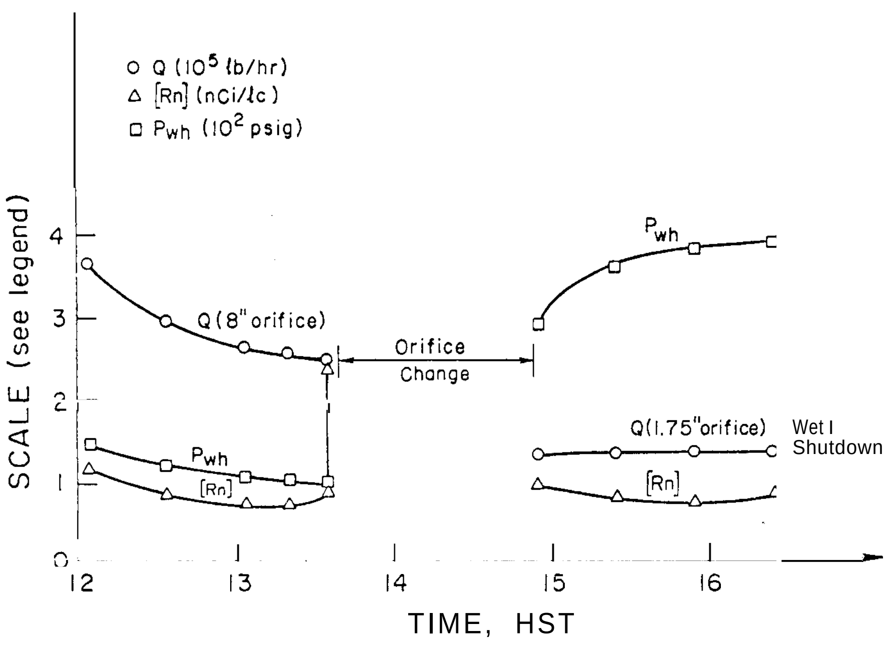

FIGURE 3.4 RADON FLOW RATE TEST AT THE HGP–A WELL IN HAWAII

TABLE 3.1: SUMMARY OF RADON TRANSIENT FLOW TESTS IN HYDROTHERMAL RESERVOIRS

SITE	CONDITIONS	OBSERVATIONS
Geysers, California	Rapid change in flow rate in one production well in a shut-in producing field.	Transient proportional change in (Rn) with a "decay-constant" ~ 12±4 days.
Larderello, Italy	Two rapid changes in flow rate in one production well in an isolated section of a producing field.	Transient proportional change in (Rn) with a "decay-constant" ~ 0.5±0.5 days.
Geysers, California	Two rapid changes in flow rate in one well and no changes in a nearby well in a partially shut-in field of 20 wells.	No change in (Rn) in either well with AQ in one.
Geysers, California	Two rapid changes in flow rate in one nonproducing well in a new field.	Transient (Rn) buildup during constant Q and change in (Rn) with ΔQ.
Puna, Hawaii	Short-term tests in HGP-A well at two flow rates.	No change in (Rn) over the two short test periods.

3.2 Flow Patterns in Hydrothermal Reservoirs

Several models have been proposed to describe the circulation of geofluids in geothermal reservoirs. Among them are the ideas of a boiling zone removed from the well-tapping formation, with barriers and conduits to flow supplied by faults in the geologic formations. Others consist of boiling in-place water or continuous flashing of recharge. The "time element" characteristic of radon released with convecting geofluids may allow examination of flow patterns in hydrothermal reservoirs on the basis of a constant uniform source at the sites of emanation. If the transport pathway is constant, then the wells tapping the fluids closer to the source of radon emanation should contain larger radon concentration decreasing along the pathway by a decay factor, $e^{-\lambda t}$. A first indication that differences in radon concentration among neighboring wells was obtained from the early tests at the Cerro Prieto field in Mexico, in which simultaneous sampling along a line of three wells was obtained. However, the reservoir structural data needed to interpret the radon data were not available. A more formal testing program was initiated at The Geysers where considerable information on reservoir structural properties have been deduced by the field operators. Two cross-sectional analyses have been completed to date and the data show flow patterns beyond the statistical uncertainties in radon analysis. These tests are being performed under an agreement with the field operators to examine the analytical data until full interpretation is completed and approval to publish is obtained, with the expectation that if useful information results, such approval will be forthcoming. The results of the first two initial tests are currently being evaluated to improve the program for the next tests planned for the coming period.

3.3 Radon/Carbon Dioxide Ratios

Studies have continued on the attempt to correlate radon measurements with analysis of other components of the noncondensible gases. One attempt was the joint efforts of the SGP with the USGS in the fourth transient test described in Part 1. The project is awaiting the data from the USGS of the stable rare gases analysis.

Current effort within SGP is to examine the suitability of relating radon to carbon dioxide, the most abundant of the noncondensible gases. The advantages for examining Rn/CO_2 ratios have been described earlier, and include the potential for more detailed information, by double tracers, on the origin and transport of geofluids through geothermal reservoirs. The analytical method is based on gas chromatography to measure CO_2 (and methane) peaks at concentrations down to 50 ppm by weight in the gas partitioner in the Stanford labs. Problems encountered in the analysis include the partition of CO_2 between the gas and liquid phase during sweep out of the noncondensible gases in the radon separation procedure. The partition is noted to be influenced by pH and temperature of the sample.

Samples of steam have been collected at The Geysers fields to improve the method of sample collection and analysis for CO_2 compatible with the measurement of radon in the same sample. Tests have been run with pH buffers and helium partial pressures in the wellhead sample collection bottles and for comparison to tests run under evacuated bottle collection for radon analysis. The measurements of CO_2 (and CH_4) have been completed for this initial set of tests and the data are being evaluated for further development during the coming contract period.

3.4 Radon Measurements in the Hot Dry Rock Experiments

The execution of the Phase I test in the GT-2 and EE-1 system of hydraulically fractured rock in the Los Alamos Scientific Laboratory program for development of hot dry rock geothermal resources provided the SGP with the first opportunity to examine the potential of radon in study of emanation characteristics under changes in fracture permeability. Under informal arrangements with LASL, a series of samples were collected during the 75-day Phase I test at the Fenton Hill experimental site and shipped to Stanford for radon analysis. Details of the test program are being prepared by LASL. The data for 9 samples collected during the test period are under analysis. The data show a quasi-exponential growth in radon concentration during the test and in the coming period will be examined under a model of logistic growth which is given by the general equation:

$$(Rn)_t = \frac{(Rn)^{\infty}}{1+ae^{-bt}}$$

which may be due to any of three possible explanations: (1) increase in emanating power following increase in secondary fracturing, (2) dissolution of radium bearing cementing materials in the host granites, and (3) increased solubility of radon as the formation temperature decreased.

Resolution of the second possibility will be forthcoming in the next project period when the later samples and the make-up water sample are re-analyzed to compare the total radon in the original sample to that regrown from the radium dissolved in the water. Resolution of the third possibility will be examined in the project to measure radon emanation under laboratory controlled conditions of temperature, pressure, and pore fluid density (see Part 5). Resolution of the first possibility may be achieved during the planned Phase II test by LASL to be run during the coming project period. A student from the SGP project will be resident at LASL during the coming summer quarter to assist in developing radon analytical capnbility at the site and conducting field measurements.

3.5 Emanation Studies in Bench-Scale Reservoirs

An important set of data not yet available for the interpretation of radon transient measurements is the dependence of emanating power of radon from geothermal formation rocks under reserynir conditions of temperature, pressure, and pore fluid density. These data will provide the "source term" for internal radon tracer studies of transient behavior. A preliminary set of data were acquired in the large SGP reservoir model after loading and before wetting of the piledriver explosion-fractured rock. The data, given in Table 3.4, show a marked dependence of radon emanation in gaseous pore fluids with temperature compared to the emanation in the liquid. These data are not reliable, however, because of the difficulty of keeping pressure control in the SGP model and the possibility of radon boilout from the liquid phase.

During the project contract period, a more definitive project has been initiated to measure radon emanation under bench-scale model conditions. The dissertation-topic project will consist of three rock loadings in closed vessels contained in a flow system in a large high-temperature

TABLE 3.4: RADON EMANATION FROM RUBBLE GRANITE*

	FLUID					
	AIR			WATER		
Temp (°F)	75	250	350	75	250	350
$[R_n]$ (pCi/ℓ)	240	620	1060	190	235	225
EP (%)	17	43	74	13	16	16

*Piledriver Rubble Loading:

$W = 1560$ lb

$V_f = 15.4$ ft^2 (436 ℓ)

$R_a = 0.9$ pg/g

$\phi = 0.42\%$

oven. During the next contract period, parametric experiments will be run with graywacke geologic rock loading from The Geysers area in the three reservoirs under the following experimental conditions:

(1) density of pore fluid; calibration with nitrogen, runs with steam, then water

(2) for each of the pore fluids; repeated 2–3 week tests at increasing temperatures

(3) for each temperature; a range of pressures in the three reservoirs in the oven.

The results of this dissertation should be a comprehensive analysis of radon emanation under varying thermodynamic conditions for a major geothermal rock type.

4. BENCH-SCALE FLOW EXPERIMENTS

4.1 Two-Phase Flow Bench-Scale Experiments

The purpose of the two-phase, non-isothermal, bench-scale flow model is to: (1) provide steam-water relative permeability curves for fresh water and brine, and (2) provide quantitative data on permeability reduction caused by salt deposition at the boiling front.

Relative permeability-fluid saturation relationships are needed to forecast the mass and energy recovery from liquid-saturated geothermal reservoirs. To date, adequate relative permeability data is not available. Quantitative data on salt deposition will help explain productivity decreases caused by reduced permeability.

Effect of Frequency

The frequency dependence of steam-water mixtures in porous media was studied to find the optimum operating frequency for the capacitance probe. The capacitance probe is used to determine liquid saturations in the relative permeability experiments. As shown in Fig. 4.1, the probe is reasonably sensitive to the entire water saturation range at frequencies greater than 750 kHz. Lower frequencies are only useful for measuring small water saturations.

The frequency dependence experiments were run with 20-30 mesh, unconsolidated sand at 300°F. Water saturations were determined by using a mass balance. A known mass of fluid was produced from the core. The resulting steam-water mixture was allowed to return to thermal equilibrium before the proble capacitance was recorded. The core was 2.7 inches in diameter and 24 inches in length. A Hewlett-Packard Q-Meter (Model 4342) was used to determine capacitance.

The frequency dependence experiments were run at a time when the probe electronics used by Chen (1976, SGP-TR-15) were being repaired. Once Chen's electronics, which operate at 7.5 MHz, were repaired, they were used for the remaining calibration experiments.

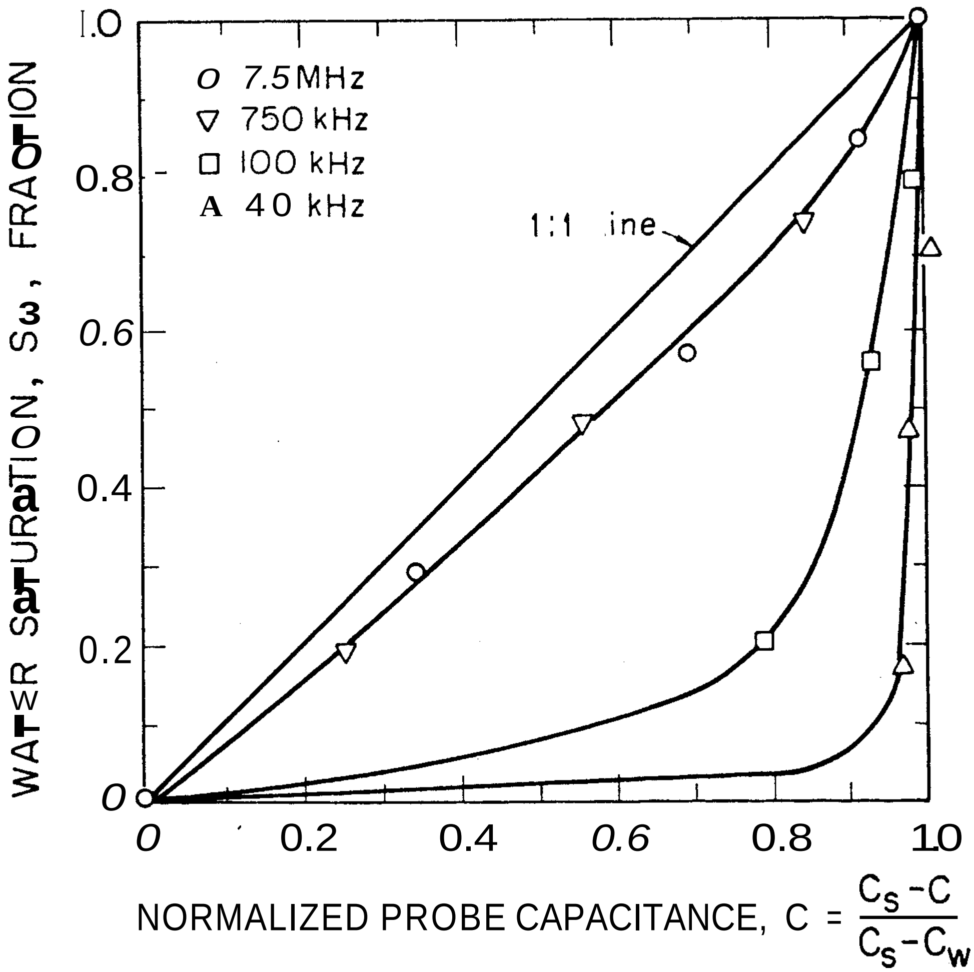

FIGURE 4.1 EFFECT OF FREQUENCY ON PROBE RESPONSE IN A STEAM–WATER SATURATED POROUS MEDIUM

Probe Calibration

The capacitance probe was then calibrated several times to: (1) establish the probe signal-liquid water saturation calibration curve, and (2) demonstrate the repeatability of the calibration. The results of three calibration runs at 300°F are shown in Fig. 4.2. The average curve is similar to Chen's (1976, SGP-TR-15) and shows good reproducibility. The scatter appears to be within ±3%.

The calibration curve is needed for the relative permeability runs, which are linear flow experiments through 2-inch diameter, 23-inch long cylindrical cores. The cores are synthetic cement-consolidated sandcores with capacitance and thermocouple probe guides cast in place. The capacitance probe signal is recorded along the length of the core. Water saturation can be determined using the calibration curve. Steam-water relative permeabilities can be calculated along the length of the core as described by Arihara (1974, SGP-TR-1) and Chen (1976, SGP-TR-15).

Now that the problems with the capacitance probe electronics have been overcome, work will continue on determining relative permeability curves. For cases where concentrated brines are used, short core lengths will be analyzed to determine the amount of salt deposition and the resulting permeability reduction. It is also desirable to calculate related permeability curves from capillary pressure data obtained on short cores.

4.2 Vapor Pressure Lowering Experiments

Due to the presence of solid boundaries, the saturated vapor pressure of water in a consolidated sandstone core may be lowered by as much as 15 psia at temperatures between 200°F and 290°F. See Fig. 4.3 (from Chicoine, Strobel, and Ramey, 1977). As a result, the water boils at a higher temperature. It is anticipated that vapor pressure lowering is due to capillarity and/or adsorption-desorption phenomena at low water saturation (below the irreducible water saturation).

Initial theoretical analysis of the experimental data of Calhoun, Lewis, and Newman (1949) produces strong evidence that the phenomenon is due to adsorption/desorption rather than capillary effects. Three facts are indicative of this:

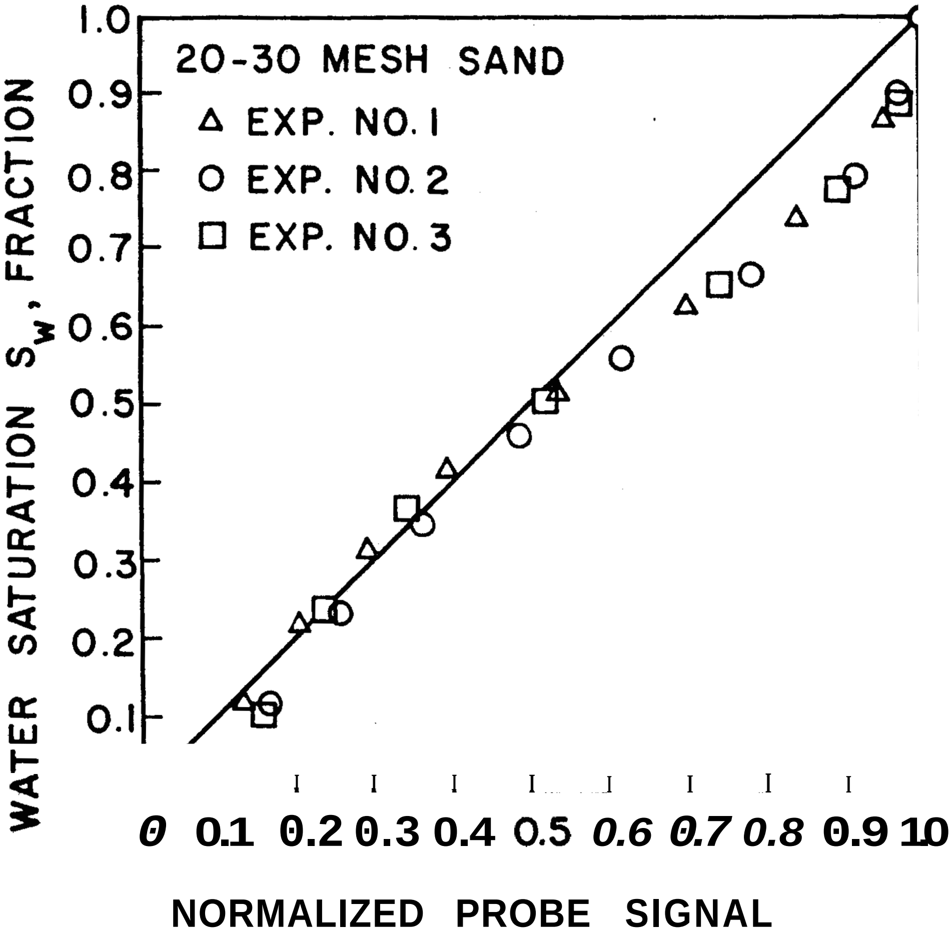

FIGURE 4.2 STEAM-WATER CALIBRATION CURVE FROM PROBE SIGNAL

(1) If the pore size implies a mean radius of curvature 10 Å in the experimental porous medium, which is about the minimum radius for which capillarity may be considered (for water), then vapor pressure lowering due to capillarity would result in a vapor pressure 0.61 times the "flat surface" value. In fact, the observed value is much lower (-0.03).

The relative orders of the effects of capillarity and adsorption can be estimated from the equation:

Capillarity: $$\ln \frac{p}{p_o} = - \frac{2rV}{RT} \frac{1}{R_m}$$ (from Leverett 1941) (can be obtained from thermodynamics)

where p/p_o is the saturated vapor pressure relative to that on a flat surface, r is the surface tension, V is the molar volume, R is Boltzman's constant, T is temperature, and R_m the mean radius.

Adsorption: $$\frac{p}{x(p_o-p)} = \frac{1}{x_m c} + \frac{c-1}{x_m c} \frac{P}{P_o}$$ (the BET eq., Brunauer, Emmett & Teller, 1938)

for $0.05 < \frac{P}{P_o} < 0.35$

where x is the volume of fluid adsorbed at pressure P and x_m is the volume of fluid required for monolayer adsorption. c is the ratio of activation energy for rock/water and water/water interactions. Performing a BET analysis of Calhoun's data (see Fig. 4.4), it is seen to fit the adsorption equation remarkably well.

(2) It can be seen from these equations that the adsorption effect is a function of surface area and not necessarily of permeability and porosity. Calhoun's (1949) data show this surface area dependence.

(3) In Calhoun's (1949) experimental data there is no noticeable hysteresis in the vapor pressure/saturation curve during a drainage/imbibition cycle. Such hysteresis would be anticipated if capillarity were significant, as the water/vapor interface would have a different shape during filling and emptying a pore.

The objectives of the program are to reevaluate the results of Chicoine et al. (1977) using steady rather than time-varying experiments. This

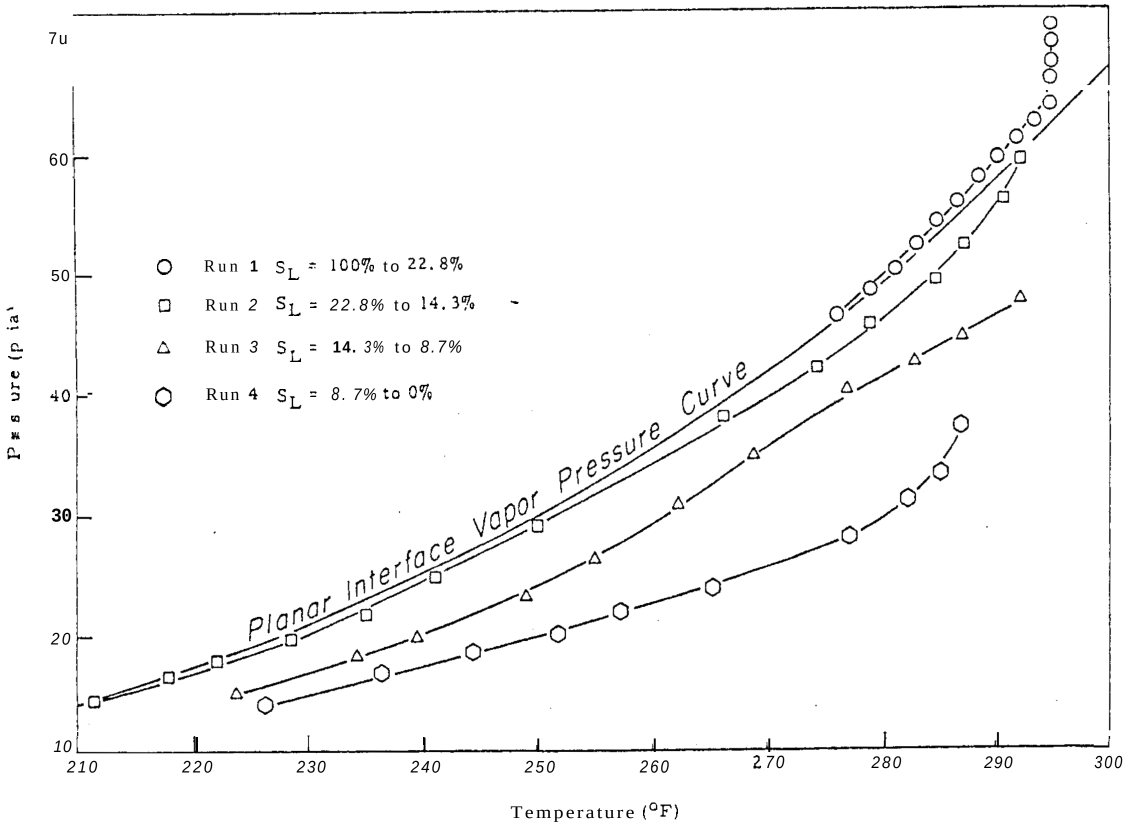

FIGURE 4.3 VAPOR PRESSURE VS. TEMPERATURE FROM CHICOINE ET AL.

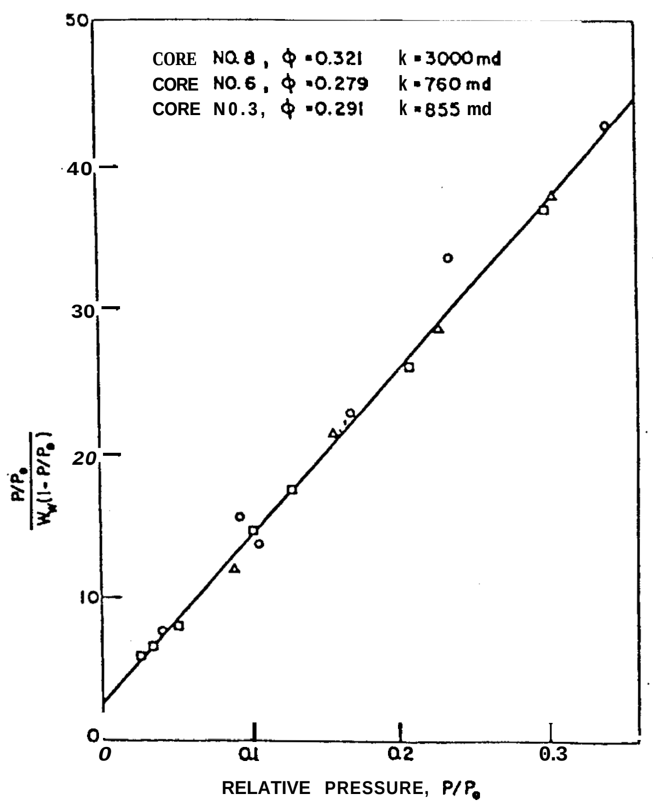

FIGURE 4.4 BET ANALYSIS OF THE EXPERIMENTAL DATA OF CALHOUN ET AL.

should represent the phenomenon of vapor pressure lowering better because it is not a transient effect. It is also intended that the range of temperatures for the experiment be increased. To these ends the apparatus has been redesigned and rebuilt.

Redesigned Apparatus

In order to increase the possible number of experiments, an assembly of four parallel coreholders has been built in the air bath. Four experi-iments may then be run simultaneously. A core inside the air bath is fed from a stainless steel bottle also inside the air bath. The pressure and temperature of the bottle give a measure of the quantity of water that has entered the core. Starting with an initially dry, vacuumed core, the coreholder is allowed to reach a steady state, its temperature and pressure are recorded, then the supply valve is reopened to allow steam into the core. This process is repeated until the internal pressure in the coreholder reaches the saturated vapor pressure. Following this a depletion sequence will be used, vacuuming the stainless steel bottle and measuring its temperature and pressure to determine the quantity of water leaving the core.

High temperature pressure transducers are used inside the air bath to measure the coreholder and the stainless steel bottle pressures. Previously, plate transducers outside the air bath were used, with the resulting problem of condensation of water in the connecting tubing.

Temperature measurements are made using a platinum resistor thermometer, which has the advantage of providing an absolute temperature reading without the need for a cold trap. The thermometers are calibrated by registering the phase change of various substances, for example, the melting and boiling of water and ethyl alcohol. The associated circuitry of this device has been designed to give a very low current (100μA) through the thermometer, thus avoiding a consequent inaccurate reading.

The quantities of liquid in the core will be at very low saturation, and a capacitance probe has been designed for this application. This probe is similar in concept to that used in the two-phase flow experiments, and monitors the dielectric constant of the water in the adsorption phase.

The vacuum pump to be used in the experiment is an important consideration, since the introduction of any oil vapor into the system would change the surface properties of the medium, particularly in the case of adsorption. Hence an adsorption pump is used to produce the vacuum. "Molecular sieves" made of porous alumina silicate adsorb gases when lowered to liquid nitrogen temperatures, and can produce a vacuum down to 104mmHg. The "molecular sieves" can be reused after being raised in temperature to release the adsorbed gases.

4.3 Effect of Temperature Level on Absolute Permeability Experiments

Introduction

Several experimental studies have demonstrated temperature effects on absolute permeability. Recent studies have indicated that the magnitude and direction of the permeability changes in response to changes in temperature may vary, depending upon the flowing fluid and the porous medium. The obvious importance of this effect, coupled with the need for more conclusive data, has motivated continued study of these phenomena.

Previous investigators include Greenberg *et al*. (1968), Afinogenov (1969), Weinbrandt (1972), Cassé (1974), and Aruna (1976). Although the results of Greenberg *et al*. were somewhat inconclusive, the results of Weinbrandt, Cassé, and Aruna all indicated significant reductions in permeability (up to 65%) with increasing temperatures for water flowing through consolidated and unconsolidated sandstones. Afinogenov found up to 95% permeability reduction for oil flowing through sandstone and temperatures ranging from room temperature to 200°F; but both Cassé and Aruna also found that the Klinkenberg corrected permeability to nitrogen was independent of temperature. For all of the fluids tested, the confining pressure affected the fluids in the same manner; i.e., permeability decreased with increasing confining pressure. Aruna also investigated the permeability of sandstone to octanol, chosen for its polar molecular structure, and found no change or a slight increase in permeability with temperature. Finally, Aruna found that the permeability of limestone, with water as the flowing fluid, did not change with increasing temperature.

Several explanations have been offered for the behavior described above. Greenberg suggested mechanical and thermal stresses as possible chemical reactions may be responsible for the permeability changes. Afinogenov hypothesized porosity reduction or changes in the physiochemical properties of the fluid-rock system. Because of the lack of absolute permeability variation with temperature for both nitrogen and mineral oil, Cassé concluded that the temperature effect observed for water flow was not caused by changes in the physical properties of the fluids, such as viscosity and density, or by thermally-induced mechanical stresses in the rock. Instead, the unique results obtained for water suggest that a temperature-dependent rock-fluid interaction was the dominant factor responsible for permeability reductions for water. Because the effect was not observed for water flowing through limestone, Aruna concluded that the permeability reduction may be due to increased attractive forces between water and silica at elevated temperatures.

The explanations offered thus far for the observed behavior are vague and suggest that further study is warranted. However, certain theoretical facts may clarify the situation somewhat. Hence, a brief discussion of the pertinent theoretical concepts is presented here. Then, the results of several experiments designed to isolate certain parameters that the theory suggests to be relevant are given.

Theory

It is known that below the surface of a liquid, a molecular force transition zone exists which extends through a considerable number of layers of molecules. This has been shown to affect some of the properties of the liquids in capillaries. Because the liquid viscosity depends strongly on molecular forces, it is conceivable that the bulk liquid viscosity may be different from the viscosity of capillary hold liquids, especially for polymer and polar liquids such as water. Extensive data on abnormally high viscosity of liquids in capillary tubes are available (Henniker, 1949), although the results are subject to the uncertainty of the flow passage area. The application of the "blow-off" method has also shown that the viscosity of the boundary layer for many polar liquids is different from the bulk value (Derjaguin, 1966). It has been well established that the structure of water at the interface differs from that of the bulk fluid. The extent of the interfacial effect is not yet clear, but it has been suspected that it could extend thousands of water molecules deep (Kirk and Othmer, 1970). The water molecules at the interface are less inclined to separate and hence result in a higher viscosity. They are also less susceptible to thermal destruction than the bulk fluid (Home, 1968); hence the properties at the interface should change less with temperature.

It has also been suggested that the surfaces of some solids such as quartz react with water and hold a layer of water of variable thickness (Sosman, 1965). This immobilization of water causes the narrowing of capillaries and reduces the mobility of the flow (Churayev et al., 1970). Thus it would be expected that for porous media where the flow through micro capillary openings is a significant part of the total flow, surface effects should become important.

Experimental Equipment

The basic equipment design was described previously by Cassé (1974). For experiments described in this work, the equipment was slightly modified to include a capillary tube viscometer connected in series to the outflow end of the coreholder. A schematic diagram of the apparatus is shown in Fig. 4.5.

All components were constructed of 316 stainless steel. Liquid flow was supplied by a positive displacement pump. An accumulator was charged with nitrogen to the desired line pressure in order to dampen pump pressure pulsations. Liquid flow rate was measured with a graduated cylinder and corrected for temperature. Pressure drops across the core and the capillary tube viscometer were measured continuously by a thermocouple inserted at the inlet face of the core. The confining pressure was maintained at the desired level using a hand pump. The confining fluid was Chevron white oil No. 15, and was isolated from the core by a "viton A" rubber sleeve.

The core materials used in these experiments were Ottawa sand (80–100 mesh) and stainless steel (80–100 and 100–120 mesh). The liquids used were filtered, deionized water and Chevron white oil No 3. Additional experiments are planned using amorphous quartz, limestone, and calcite.

The core material was loaded dry into the viton sleeve with a perforated aluminum outer sleeve provided to prevent increase in the core radius

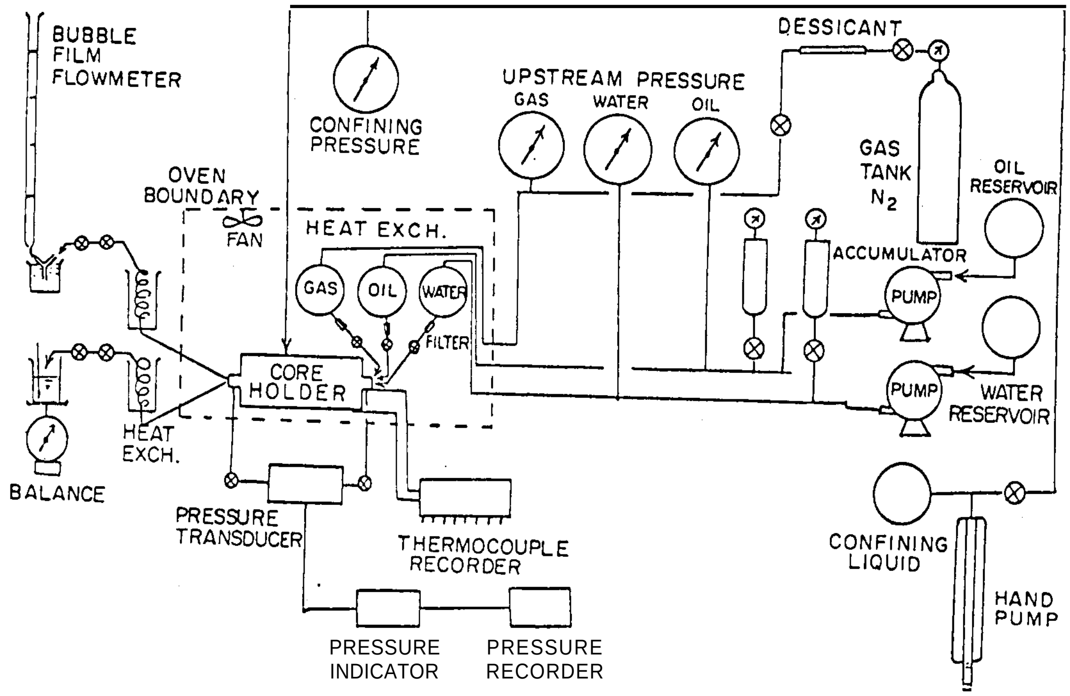

FIGURE *4.5* **SCHEMATIC DIAGRAM OF APPARATUS**

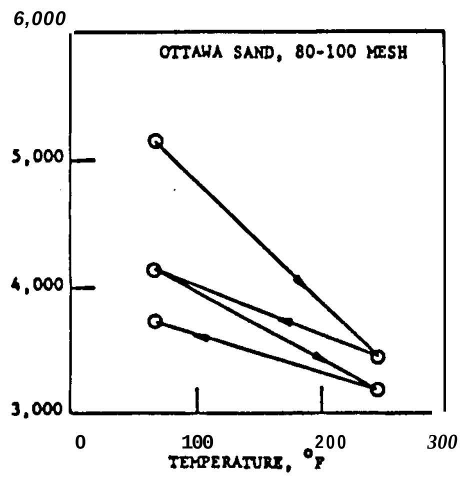

FIGURE *4.6* WATER PERMEABILITY VS. TEMPERATURE, OTTAWA SAND when axial pressure was applied. The confining pressure was applied, then the entire core apparatus was evacuated overnight and saturated under a vacuum the following day. When steady-state flow was evident, and the temperature stable, the necessary flowrate, temperature, and pressure measurements were taken. For each permeability value determined, a series of measurements of the flowrate and pressure drop were made. Pressure drop vs. flowrate was then plotted to make sure the flow was laminar. If the flow was laminar, the plot was linear, and the slope of the line was used to calculate the permeability.

Results

For each run, the line pressure was 200 psig and the confining pressure was maintained at 1200 psig. The permeability was measured at room temperature, at about 250°F, and then again at room temperature. The temperature cycle was repeated several times to see the effects of hysteresis.

Results for water flowing through Ottawa sand are shown in Fig. 4.6. Unlike the results reported by Aruna, the permeability reduction with increased temperature did not appear to be reversible, suggesting that some permanent thermal alteration of the sample was occurring. However, upon cooling, the permeability consistently returned to a value approximately 15% above the value recorded at the previous elevated temperature.

Similar results for water flowing through stainless steel were observed. Again the permeability decreased with each successive heating cycle, but the change observed after cooling to room temperature was about 15%. The results for 80-100 and 100-120 mesh stainless steel are shown in Fig. 4.7.

Finally, oil was flowed through an 80-100 mesh stainless steel core. These results are indicated in Fig. 4.8. In this case the permeability changes were far less pronounced than those observed for water and appear to be within the range of experimental error.

Conclusions

The absolute permeability of porous media may depend significantly on the flowing liquid. The permeabilities of unconsolidated samples of

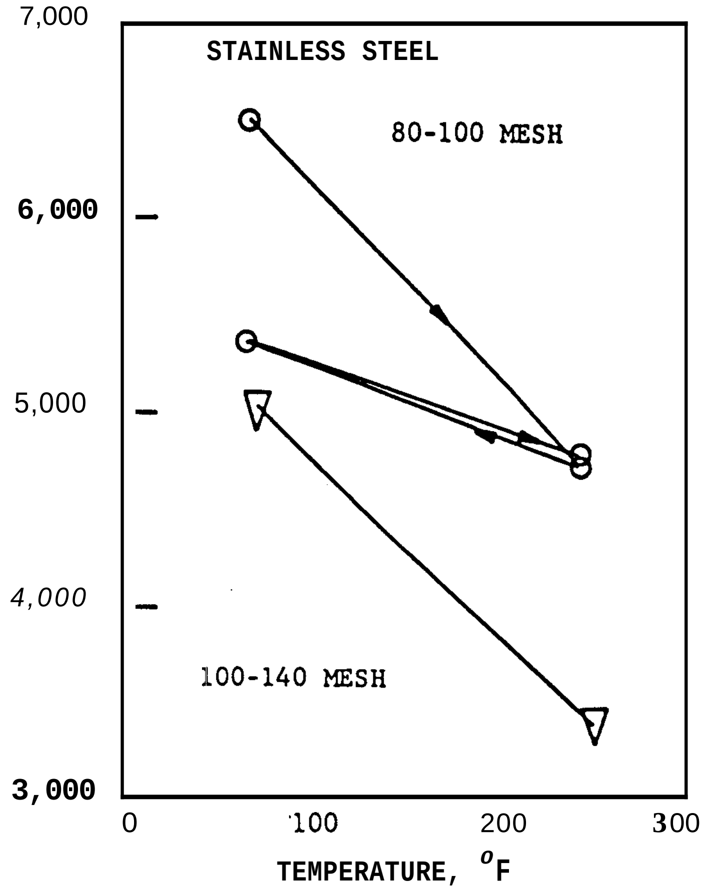

FIGURE 4.7 WATER PERMEABILITY VS. TEMPERATURE, STAINLESS STEEL

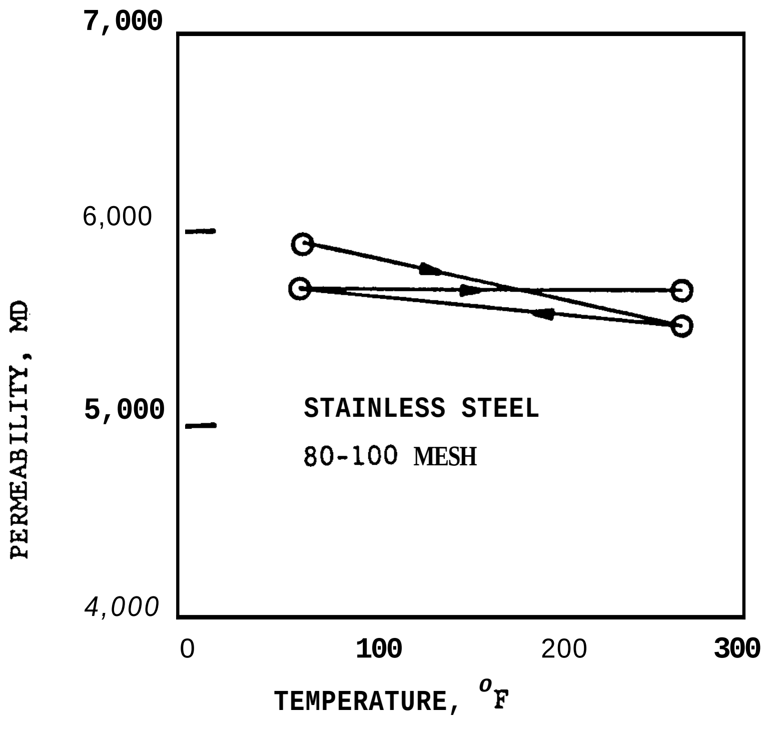

FIGURE 4.8 OIL PERMEABILITY VS. TEMPERATURE, STAINLESS STEEL

silica and stainless steel were shown to decrease with an increase in temperature for water flow. There was no effect with the temperature level for oil flow.

The phenomenon may be a result of the intermolecular force field within the boundary layer of water adjacent to the solid which is different from that of the bulk water. The dependence of the physical properties of this layer, e.g., viscosity, with temperature is different from those of the bulk liquid. Hence the effect of the temperature level on the mobility of water through porous media cannot be adequately explained by the change with temperature of the bulk water viscosity alone.

The verification of the preceding conclusions requires further studies which are currently underway.

5. WELL TEST ANALYSIS

5.1 Steam/Water Relative Permeabilities from Production Data

It was suggested by Grant (1977) that the steam/water relative permeability of the producing geothermal reservoir could be inferred from the production history of the Wairakei field. As production has occurred, most wells have shown enthalpy rises. Considering the enthalpy and discharge histories he obtained a curve of steam permeability against water saturation that was significantly different from the classical curve from Wyckoff and Botsett (1957, p. 161) for two immiscible fluids (one gas and the other liquid). However, Grant made a number of approximations, and together with the natural scatter of the field data the end result was a "regional" curve rather than a single line curve. It has been possible to achieve considerable improvement on these preliminary results, and a more precise pair of relative permeability curves has been obtained. It now seems possible to extend this analysis further to determine the relative permeabilities from well data without requiring a very long history of production. Furthermore, the behavior of two-phase flow in a fracture (for example, as in the Hot Dry Rock configuration) may be evaluated.

Original Analysis

The bulk permeability k of a reservoir can be obtained using classical pressure response analysis; however, the permeability of each of the two components flowing, steam and water, are reduced by factors of F_w and F_s respectively. These permeability reduction factors are functions of the water saturation s. If the flow of fluid into the wells is governed by Darcy flow, then the discharge Q_w and Q_s of the two phases will be proportional to the permeability reductions, so that

$$Q_w = -\rho_w \frac{k}{\mu_w} F_w(s)AP'$$

$$Q_s = -\rho_s \frac{k}{\mu_s} F_s(s)AP'$$

where p is the density of the phases, μ is the viscosity, A is the drainage area, and P' is the pressure gradient. All the quantities are written in terms of the down-hole values although in fact the parameters Grant (1977) used were measured at the wellhead. The enthalpy of the flow is given by

$$h = \frac{\rho_w h_w F_w(s)/\mu_w + {}_s h_s F_s(s)/\mu_s}{\rho_w F_w(s)/\mu_w + \rho_s F_s(s)/\mu_s}$$

Assuming kAP' was a constant B for any well even while it was changing in enthalpy over the years, Grant plotted enthalpy against total discharge $Q(=Q_w+Q_s)$ for 13 Wairakei wells. Then scaling the Q for each well by the assumed B for that well, he brought the scattered points onto a line or rather curved line region. Then, determining the all-water end point of the "line" he inferred an effective overall value for B, and thus solved the equations for Q and h in terms of F_w and F_s. The results of this analysis are shown in Fig. 5.1.

Improved Analysis

Grant made a number of assumptions that will be summarized here:

(i) wellhead steam and water discharges are the same as wellbore values--this is clearly untrue since the fluid flashes in the wells.

(ii) the driving pressure gradient P' is unchanging as the wells change enthalpy. This may be a gross assumption since the enthalpy changes occur over a period of years.

(iii) an average temperature may be used €or all wells. The statement that the analysis showed similar results with a different value of temperature is true only if the determination of the overall B parameter is based on the all-water end of the h-Q curve. It was found while repeating the analysis that using the all-steam end of the curve the results (particularly for F_s) were particularly sensitive to the choice of temperature used, even to the point of predicting negative permeabilities.

With these shortcomings in mind, the improved analysis proceeded as follows. First, the discharges of steam and water at the well-base were

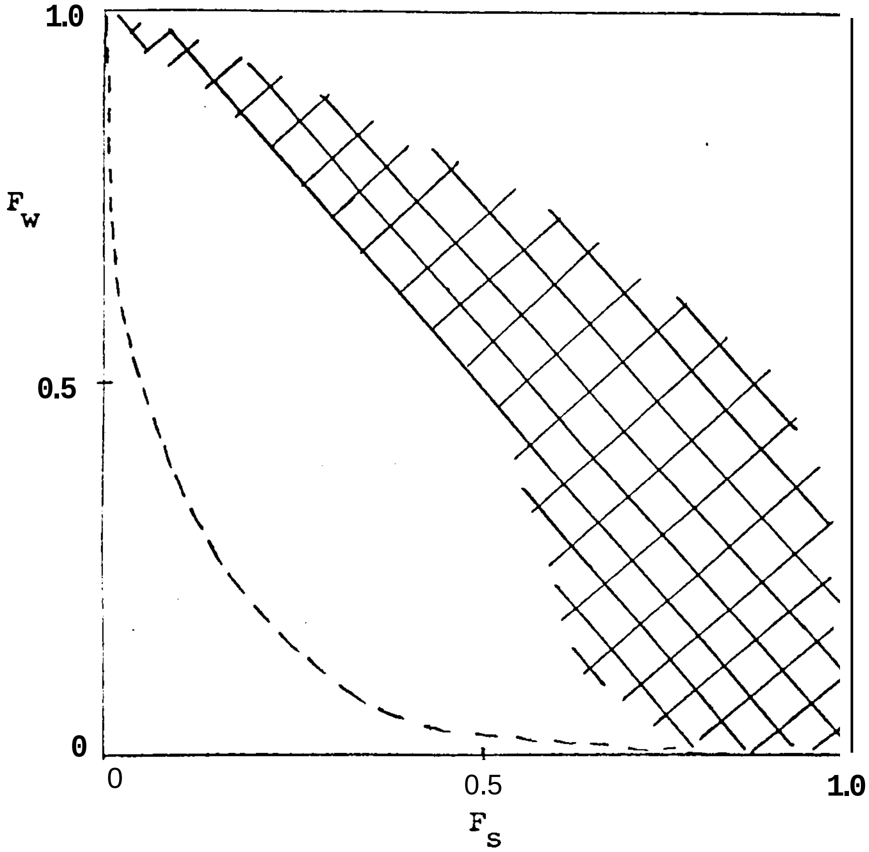

FIGURE 5.1 STEAM VS. WATER RELATIVE PERMEABILITIES FROM WYCKOFF AND BOTSETT (DOTTED LINE) AND FROM GRANT (HATCHED REGION)

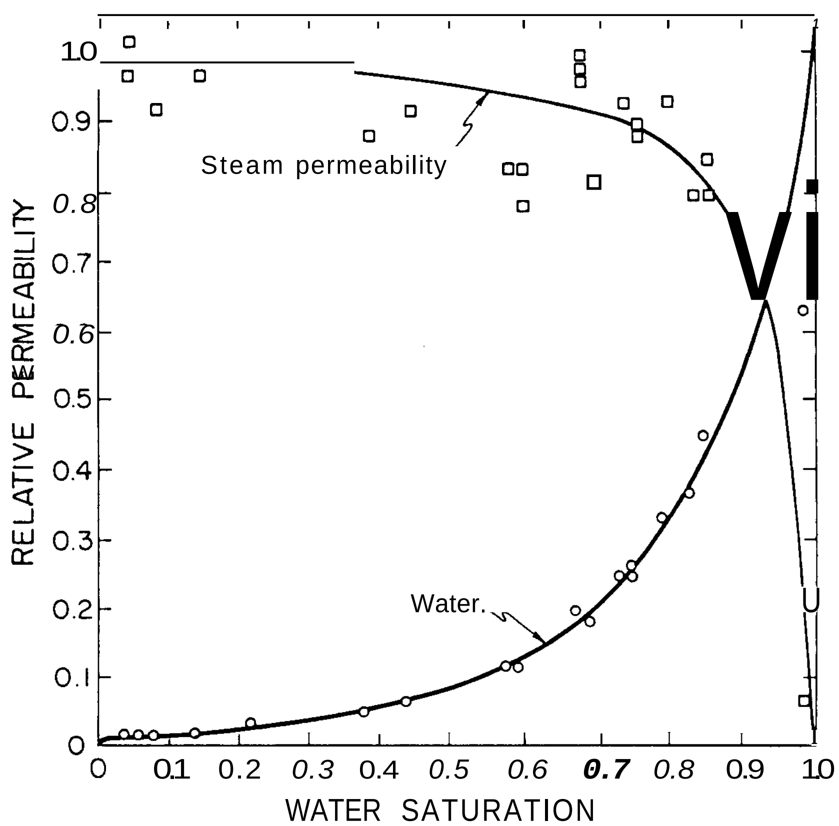

FIGURE 5.2 RELATIVE PERMEABILITIES INFERRED FROM WAIRAKEI DATA

back calculated using the wellhead and well-base pressures together with the values of the discharge measured at the wellhead. This calculation was done assuming no wellbore heat losses--the error incurred in doing this for these Wairakei wells is less than 1% since the wells have been producing for such a long time. However; for prototype fields this may be a factor that will need to be specifically included.

Second, since the pressure gradient P' changes as the wells "age," the values for the total discharge were divided by the wellhead pressure. This tends to filter out the change in discharge due only to pressure depletion in the reservoir, leaving only changes in discharge due to relative permeability effects.

Third, the actual downhole temperature, and thus density, viscosity, and enthalpy, was used for each bore. This avoided the inaccuracy caused by assuming an overall mean temperature.

In addition, by comparing the discharges of water and steam back calculated to the well-base, it was further possible to obtain a value for the flowing water saturation s. This does not take into account the immobile fluid in the reservoir; however, since it seems apparent from the results that the flow observed is largely due to fissures, this may not detract from the usefulness of the results, particularly in the case of a hydraulically fractured, hot dry rock system.

Using bore history data from the Ministry of Works in New Zealand, the best quality data were selected. In many cases the well discharges or enthalpies had been "scaled" to a wellhead pressure of 200 psia and the actual wellhead pressure was not given. These data were not of great use since the method of this scaling was not specified, and the actual. values of enthalpy, discharge, and wellhead pressure were required. An initial calculation using three wells (Wairakei 40, 61, and 72) that appeared to have similar values of B provides a very useful relative permeability curve (see Fig. 5.2). Notice that the steam permeability is relatively unaffected by the presence of the water until very high water saturations. This is characteristic of flow through fissures.

Further Analysis

This work is in progress. Future developments will begin with the complete analysis of Wairakei using remaining available data for those wells having different permeability drainage products. The study will then be generalized procedurally to incorporate wellbore heat losses so that it may be used to evaluate much newer resources.

The prospects for this work are extremely promising. Having already obtained a set of steam/water relative permeability curves for a fractured geothermal field, new developments in deriving pressure analysis techniques for two-phase systems will be possible. The complementary work being done by the Stanford Geothermal Program on determining the irreducible water saturation will enable the first complete steam/water relative permeability curves for a porous formation under actual geothermal conditions to be drawn. Second, in the current absence of practical two-phase pressure analysis techniques, this procedure provides a first picture of the nature of the flow in the reservoir, whether it be by flow in fissures or by flow through a homogeneous porous medium (or both).

5.2 Development of Pressure Transient Techniques

This program is aimed at the development of techniques for well testing and evaluating and forecasting the performance of geothermal reservoirs. A number of the subsidiary projects in this section reached completion during the year, and others are still in progress.

Among the completed projects is the work on layered systems. The behavior of layered systems is of particular interest in geothermal reservoirs which generally produce over a much wider range of levels than the simpler hydrocarbon-bearing formations seen in petroleum reservoirs. The effects of different layers producing into the same wellbore may be apparent even though the influences of separate volumes and permeabilities may be commingled. A technical report on this work is being prepared for release during 1978.

Another completed project addresses the problem of interference testing with storage and skin effect. The nature of geothermal well drilling procedures makes the consideration of skin effects of great importance in the pressure analysis of geothermal wells, since the high temperatures encountered during drilling can cause considerable wellbore damage due to mudcake buildup. Consequently, this problem was approached in order to examine the long-time type curves presented by Garcia, Rivera, and Raghavan (1977). The correlations used by these authors enabled them to reduce the number of independent parameters to four, with the result that the set of type curves must include one complete graph for each value of one of the four parameters. Thus one of the purposes of the study was to attempt to reduce the governing parameters to three, resulting in a more compact form--in fact, a single graph. The problem was solved in Laplace space and inverted using a numerical inverter described by Stehfest (1970). On examining the solution in Laplace space, various correlating groups were suggested; however it proved impossible to reduce the number of parameters to three without including the time variable in all three parameters--clearly an impractical situation for producing useful type curves. A short-time solution was also obtained with only three correlating parameters; however, in this case the resulting type curve turns out to be almost a straight line and therefore useless for matching. In the course of the investigation, the errors due to approximations made by Garcia, Rivera, and Raghavan (1977) became apparent, particularly at small times. It was possible to correct their results and thus describe the skin and wellbore storage effects very much more accurately than before. Since the past practice in geothermal reservoir development (particularly in New Zealand) has been to run extremely short pressure transient tests, the accurate short-time Techniques developed here should be particularly useful.

Currently very near to completion is the work on interpretation of earth tide effects in pressure transient data. This work examined the frequency response of a fluid-filled subsurface formation to the diurnal and semidiurnal variations caused by earth tides. This response was shown to be dependent on both fluid and formation properties. Following an analysis originally reported by Bodvarsson (1970), the pressure response of a formation penetrated by a closed well was determined. In this case since the well was closed and filled with fluid, it was necessary to also consider the dilatation of the well itself due to the tidal effects. This analysis was tested using information from several different types of oil and gas reservoirs (this data being easier to obtain), and showed clearly distinguishable responses to both the diurnal and semidiurnal tidal variations. The implications of this study are particularly significant since the responses are different for gas and liquid filled formations, and also vary with permeability. Thus with further work in this field it may finally be possible to differentiate between liquid and vapor dominated geothermal fields after analysis of the frequency dependence of their earth tide responses. Such a technique would only require sensitive pressure gauges (such as the Hewlett-Packard gauge) that are already available, and Fourier transform of the resulting data sequence. This work will be presented at the Annual Fall Meeting of the Society of Petroleum Engineers of AIME in October 1978.

5.3 Analysis of Wellbore Characteristics

In the process of well test analysis, it is very common to make use of information gathered at the wellhead to infer properties in the formation. Corrections can be made for wellbore heat losses and pressure losses; however, techniques developed in the petroleum industry may be inapplicable to the geothermal case since the flow in the wellbore is two-phase and nonisothermal. An extension of the classic work on wellbore heat losses by Ramey (1962) was performed here by Horne and Shinohara (1978), making a correction for the flow rate in the well. Figure 5.3 shows an example of the value of the heat loss as a function of flow rate for a typical producing geothermal well. The results of this analysis will be extremely important in the evaluation of early production of new wells in which wellbore heat losses are highly significant, particularly in cases of lower flow rates used during testing.

Further work on wellbore pressure losses has been done as part of the study on inferring relative permeabilities from wellhead data (see section 5.1). It proved impossible to accurately evaluate the downhole pressure using the techniques described by Nathenson (1974) who used a rather simplistic method of determining the friction factor in the well. Using the more complex techniques of Govier, Aziz, and Fogarasi (1975), it was shown that most of the flows encountered in geothermal bores are in the annular mist regime. It was then possible to determine the pressure drop in a

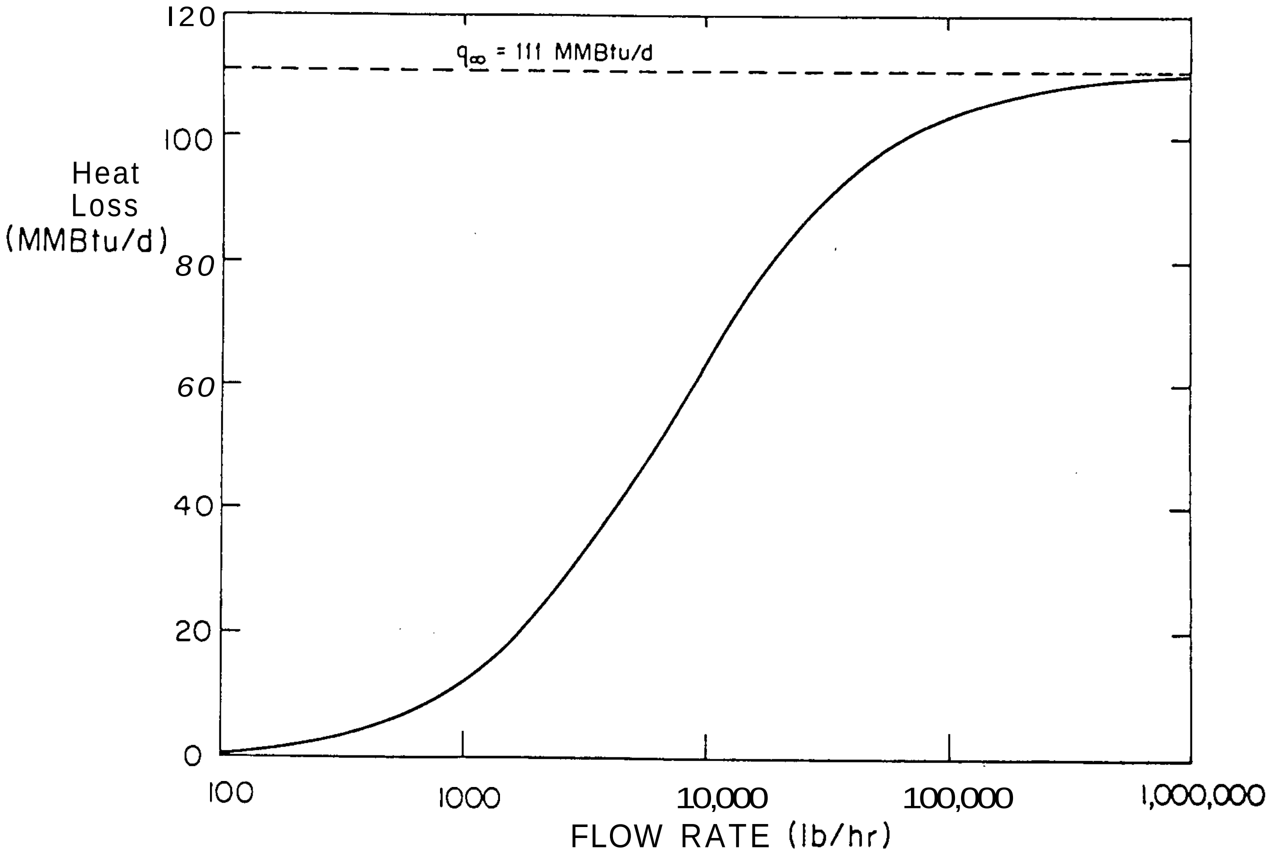

FIGURE **5.3** TOTAL **WELL BORE** HEAT LOSS RATE FOR **A** WELL PRODUCING HOT WATER, DOTTED LINE IS MAXIMUM HEAT LOSS RATE FOR INFINITE FLOW typical two-phase geothermal well with much improved accuracy, and several downhole pressures were correctly predicted for Wairakei wells. The calculated values agreed very well with actual values from data supplied by the Ministry of Works in New Zealand.

6. CONCLUDING REMARKS

The Stanford Geothermal Program has gained a place in the geothermal community at large, and held that place due to its involvement in providing services in addition to its research activities. Two of the major services organized by the program are the annual Stanford Geothermal Reservoir Engineering Workshop, held for the third time this year, and the weekly geothermal seminars. The Workshop was attended by over 100 people from four different countries with 34 technical papers and overviews from the academic, industrial, and governmental sectors. Held at Stanford University December 14-16, 1977, the Workshop provided much interesting discussion, and a proceedings of the meeting has since been produced and distributed as SGP technical report number 25. A listing of the technical presentations was given in the third quarterly progress report.

The weekly seminar is still proving popular among its attendees. The winter quarter talks were given by speakers from groups in the nearby area, and covered a range of topics including transient pressure analysis of two-phase reservoirs, a reservoir engineering evaluation of a Nicaraguan reservoir, well testing in the Salton Sea, and isotope geochemistry as a geothermal reservoir engineering tool. A list of the speakers and topics is included as Appendix A--previous seminar schedules have been included in the quarterly progress reports during the year. The next quarter's seminar schedule has been arranged and includes speakers both from the program and from other groups.

As well as organizing the program's own meetings, Stanford personnel have been participants in numerous other geothermal meetings during the year. Included in these were the AIChE/ASME Heat Transfer Conference in Salt Lake City in August 1977, the 52nd Annual Fall Meeting of the SPE of AIME in Denver in October 1977, and the Third International Conference on Nuclear Methods in Environmental and Energy Research in Columbia, Missouri, October 1977. Three papers will be presented at the Los Alamos Scientific Laboratory Hot Dry Rock Conference in Los Alamos, New Mexico, April 19-21, 1978;

Professor Ramey will also be session chairman for the session on transient analysis at that meeting. The Stanford Geothermal Program will also present seven papers at the coming Geothermal Resources Council Geothermal Meeting in Hilo, Hawaii, in July 1978. Also, a number of papers have already been submitted to the Society of Petroleum Engineers for their Fall Meeting in October 1978.

The personnel of the Stanford Geothermal Program has continued to include experts in a wide range of fields, and also has developed an international flavor. Professor Ping Cheng of the University of Hawaii was a guest of the program during the 1976-1977 academic year, and returned to Hawaii in August 1977. His work at Stanford included a study of convection in layered geothermal aquifers that was able to successfully reproduce the temperature profile of the HGP-A well in Hawaii. Dr. Paul Atkinson, program manager earlier in the year, left the program in July to take a position with Union Geothermal, and was replaced by Dr. Roland Horne, a visitor at Stanford from New Zealand. Dr. Horne has been able to provide fast access to New Zealand geothermal data and has introduced some experience in hot water geothermal development. Professor Heber Cinco of the University of Mexico was invited to join the program as visiting professor. His fields of eminence include the behavior of fractured wells and reservoirs, and it is expected that he will augment planned cooperative work on geothermal reservoir engineering with the Center for Electrical Research in Querna Vaca, Mexico. In the future it appears that the international participation will continue, since interest in coming to Stanford has been shown by scholars in France, Iceland, and New Zealand.

Graduates from Stanford active in the geothermal industry continue to grow in number. Students in the Departments of Petroleum Engineering and Civil Engineering gain experience in geothermal-related fields through participation in the program's research projects, or through the Petroleum Engineering course Geothermal Reservoir Development, which is taught by members of the program. A videotaped version of this course is also exhibited to industrial clients by the School of Engineering. In this way the Stanford Geothermal Program fulfills its dual purpose of the collection and dissemination of information relating to geothermal energy development.

REFERENCES

Afinogenov, Y.A.: "How the Liquid Permeability of Rocks is Affected by Pressure and Temperature," SNIIGIMS (1969). No. 6, 34-42 (translation from Consultants Bureau, 227 W. 17th St., N.Y., N.Y. 10011).

Arihara, N.: "A Study of Nonisothermal Single- and Two-Phase Flow through Consolidated Sandstones," SGP-TR-2, 1974.

Aruna, M.: "The Effects of Temperature and Pressure on Absolute Permeability of Sandstones," SGP-TR-13, 1976.

Bodvarsson, G.: "Confined Fluids as Strain Meters," J. Geoph. Res. (1970), 75, 2711-2718.

Brunauer, S., Emmett, P.H., and Teller, E.: "Adsorption of Gases in Multimolecular Layers," J. Am. Chem. Soc. (1938), 60, 309-319.

Calhoun, J.C., Jr., Lewis, M., Jr., and Newman, R.C.: "Experiments on the Capillary Properties of Porous Solids," Trans. AIME (1949), 186, 189-96.

Casse, F.J.: "The Effect of Temperature and Continuing Pressure on Single-Phase Flow in Consolidated Rocks," SGP-TR-3, 1974.

Chen, H.K.: "Measurement of Water Content in Porous Media under Geothermal Fluid Flow Conditions," SGP-TR-15, 1976.

Chicoine, S.D., Strobel, C.J., and Ramey, H.J., Jr.: "Vapor Pressure Lowering in Two-Phase Geothermal Systems,: Paper SPE 6767, presented at the 52nd Annual Fall Meeting of SPE, Denver, Oct. 1977.

Churayev, N.V., Sobolev, V.D., and Zorin, Z.M.: Special Discussion of Faraday Society No. 1 (1970), 213.

Derjaguin, B.V.: Discussion of Faraday Society (1966), 42, 109.

Garcia-Rivera, J., and Raghavan, R.: "Analysis of Short-Time Pressure Transient Data Dominated by Wellbore Storage and Skin at Unfractured Active and Observation Wells," Paper SPE 6546, presented at the 47th Annual California Regional Meeting of SPE of AIME, Bakersfield, Ca., Apr. 13-15, 1977.

Govier, G., Aziz, K., and Fogarosi, A.: J. Can. Pet. Tech. (Oct-Dec. 1975), 28-41.

Grant, M.A.: "Permeability Reduction Factors at Wairakei," presented at the AIChE-ASME Heat Transfer Conference, Salt Lake City, Aug. 15-17, 1977.

Greenberg, D.B., Cresap, R.S., and Malone, T.A.: "Intrinsic Permeability of Hydrological Porous Mediums: Variation with Temperature," Water Resources Research (Aug. 1968), 4, No. 4, 791.

Henniker, J.C.: Rev. Modern Physics (1949), 21, 322.

Horne, R.A.: Electrochim Acta (1968), 13, 397.

Horne, R.N., and Shinohara, K.: "A Note on Wellbore Heat Loss in Production and Injection," submitted to J. Pet. Tech. (1978).

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

Hunsbedt, A., Kruger, P., and London, A.L.: "Recovery of Energy from Fracture-Stimulated Geothermal Reservoirs," J. Pet. Tech. (Aug. 1977), p. 940.

Hunsbedt, A., Kruger, P., and London, A.L.: "Laboratory Studies of Fluid Production from Artificially Fractured Geothermal Reservoirs," J. Pet. Tech. (May 1978), p. 712.

Iregui, R.: "Heat Transfer in Fractured Rock Media," Engineer's Degree Dissertation, Stanford University, 1978 (in preparation).

Kirk, R.E., and Othmer, D.F.: Encyclopedia of Chemical Technology, 2nd Ed., New York: John Wiley and Sons (1970), 21, 681.

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 Department, RANN, National Science Foundation, Grant No. NSF-AER-72-03490, August 1976.

Leverett, M.C.: "Capillary Behavior in Porous Solids," Trans. AIME (1941), 142, 152-69,

Matheson, M.: "Flashing Flow in Hot-Water Geothermal Wells," J. Research U.S. Geol. Survey (1974), 2, 743-751.

Ramey, H.J., Jr.: "Wellbore Heat Transmission," J. Pet. Tech. (Apr. 1962), 427-435.

Sosman, R.B.: "The Phases of Silica," Rutgers University Press (1965).

Stehfest, H.: "Numerical Inversion of Laplace Transforms," Communications of the ACM (1970), 13, 47-49.

Wyckoff, B., and Botsett, R.: "The Physics of Flow Through Porous Media," reported in Schiedegger, University of Toronto, 1957.

PRESENTATIONS AND PUBLICATIONS

Atkinson, P.G., and Ramey, H.J., Jr.: "Simple Mathematical Models for Analyzing Problems of Heat Transfer in Porous Media," Paper SPE 6792, presented at the 52nd Annual Fall Meeting of the SPE of AIME, Denver, Oct. 10-12, 1977.

Bilhartz, H.L., Jr., and Ramey, H.J., Jr.: "The Combined Effects of Storage, Skin, and Partial Penetration on Well Test Analysis, Paper SPE 6753, presented at the 52nd Annual Fall Meeting of the SPE of AIME, Denver, Oct. 10-12, 1977.

Chen, H.K., Counsil, J.R., and Ramey, H.J., Jr.: "Experimental Steam-Water Relative Permeability Curves," to be presented at the GRC Annual Geothermal Meeting, Hilo, Hawaii, July 25-27, 1978.

Counsil, J.R.: "Pressure Transient Methods Applied to the Fenton Hill Reservoir, to be presented at the LASL Hot Dry Rock Workshop, Los Alamos, New Mexico, Apr. 20-21, 1978.

Horne, R.N., Counsil, J., Hsieh, C.H., Ramey, H.J., Jr., and Kruger, P.: Bench-Scale Experiments in the Stanford Geothermal Program," presented at the 3rd Stanford Geothermal Workshop, Stanford, California, Dec. 14-16, 1977.

Horne, R.N., and O'Sullivan, M.J.: Numerical Modeling of a Desaturating Geothermal Reservoir," to appear in Numerical Heat Transfer, 1978.

Horne, R.N., and O'Sullivan, M.J.: "Convection in a Porous Medium Heated from Below: The Effect of Temperature Dependent Viscosity and Thermal Expansion Coefficient," Paper No. 77-HT-56 ASME, presented at the AIChE-ASME Heat Transfer Conference, Salt Lake City, Utah, Aug. 15-17, 1977; also to appear in J. Heat Transfer, 1978.

Horne, R.N., and Ramey, H.J., Jr.: "Steam/Water Relative Permeabilities from Production Data," to be presented at the GRC Annual Geothermal Meeting, Hilo, Hawaii, July 25-27, 1978.

Horne, R.N.: "Relative Flow Conductance of Steam vs. Water in a Fractured Reservoir Inferred from Wellheat Data," to be presented at the LASL Hot Dry Rock Workshop, Los Alamos, New Mexico, Apr. 20-21, 1978.

Hsieh, C.H., and Ramey, H.J., Jr.: "An Inspection of Experimental Data on Vapor Pressure Lowering in Porous Media," to be presented at the GRC Annual Geothermal Meeting, Hilo, Hawaii, July 25-27, 1978.

Hunsbedt, A., Kruger, P., and London, A.L.: "Laboratory Studies of Non-Isothermal Fluid Production from Fractured Geothermal Reservoirs, Paper No. 77-HT-53, ASME, presented at the AIChE-ASME Heat Transfer Conference, Salt Lake City, Utah, Aug. 15-17, 1977.

Hunsbedt, A., Kruger, P., and London, A.L.: "Recovery of Energy from Fractured Geothermal Reservoirs," J. Pet. Tech. (1977), 29, 940-946.

Hunsbedt, A., and Kruger, P.: "Energy Extraction Experiments in the SGP Reservoir Model, to be presented at the GRC Annual Geothermal Meeting, Hilo, Hawaii, July 25-27, 1978.

Hunsbedt, A., London, A.L., Iregui, R., Kruger, P., and Ramey, H.J., Jr.: "Heat Extraction Experiments in the Large Geothermal Reservoir Model," presented at the 3rd Stanford Geothermal Workshop, Stanford, Ca., Dec. 14-16, 1977.

Kruger, P., and Warren, G.: "Radon Emanation in Geothermal Steam," Trans. Amer. Nucl. Soc. (1977), 26, 125.

Kruger, P., Warren, G.J., and Honeyman, B.D.: "Radon as an Internal Tracer in Geothermal Reservoirs." presented at the Third International Conference on Nuclear Methods in Environmental and Energy Research, Columbia, Mo., Oct. 10-12, 1977.

Kruger, P.: Radon in Geothermal Reservoir Engineering," to be presented at the GRC Annual Geothermal Meeting, Hilo, Hawaii, July 25-27, 1978.

Kruger, P.: "Radon in Geothermal Reservoir Engineering, to be presented at the LASL Hot Dry Rock Workshop, Los Alamos, New Mexico, Apr. 20-21, 1978.

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," Paper No. 77-HT-54, ASME, presented at the AIChE-ASME Heat Transfer Conference, Salt Lake City, Utah, Aug. 15-17, 1977.

Rivera-R., J., and Ramey, H.J., Jr.: "Application of Two-Rate Flow Test to the Determination of Geothermal Reservoir Parameters, Paper SPE 6887, presented at the 52nd Annual Fall Meeting of the SPE of AIME, Denver, Colorado, Oct. 10-12, 1977.

APPENDIX A - STANFORD GEOTHERMAL PROGRAM WEEKLY SEMINAR

SEMINAR SCHEDULE

WINTER QUARTER 1978 ROOM B67 MITCHELL BUILDING TH 1:15-2:30 p.m.

DATE	TOPIC	SPEAKER
JAN 19	GEOHYDROLOGICAL FRAMEWORK OF IMPERIAL VALLEY GEOTHERMAL SYSTEMS	R. WEISS CONSULTING GEOLOGIST
26	TRANSIENT PRESSURE ANALYSIS OF TWO-PHASE RESERVOIRS	A. MOENCH U.S.G.S.
FEB 2	STABLE ISOTOPES IN RESERVOIR STUDIES	A. TRUESDELL U.S.G.S.
9	VERTICAL PRESSURE DROP AND TWO-PHASE FLOW MEASUREMENTS	E. TANSEV CHEVRON RESOURCES
16	THE GEOTHERMAL RESOURCES COUNCIL 1978 PROGRAM	DAVE ANDERSON G.R.C.
23	RESERVOIR ENGINEERING EVALUATION OF THE MOMBOTOMBO RESERVOIR, NICARAGUA	H. DYKSTRA 'CONSULTING ENGINEER
MAR 2	WELL TESTING IN THE SALTON SEA GEOTHERMAL FIELD	J. MORSE L.L.L.