STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

SGP-TR-35

SECOND ANNUAL REPORT
TO
U.S. DEPARTMENT OF ENERGY
LAWRENCE BERKELEY LABORATORY

for the period
July 1, 1978, through September 30, 1979

Contract DOE-LBL-167-3500

Paul Kruger and Henry J. Ramey, Jr.
Co-Principal Investigators

INTRODUCTION

The research effort of the Stanford Geothermal Program is focused on geothermal reservoir engineering. The major objective of the program is to develop techniques for assessing geothermal reservoirs through better interpretation of physical models, mathematical analysis, and field experiments to obtain actual wellhead and reservoir data. Efficient utilization of geothermal. resources requires an understanding of reservoir productivity and longevity and methods to extend the resources through production stimulation and increased fluid and energy extraction.

To accomplish this objective, a balance is maintained between laboratory studies and field applications. One goal is to develop the mathematical description of observed reservoir behavior. Physical models are used to calibrate the: mathematical models from an understanding of the physical and chemical mechanisms occurring in the reservoir. Another goal is to develop new methods f'or observing reservoir behavior and to test them in the field.

In this report, individual projects are grouped under four main areas of study:

(1) Energy Extraction

(2) Bench-Scale Flow Experiments

(3) Radon Tracer Techniques

(4) Well Test Analysis

The section on energy extraction experiments concerns the efficiency with which the in-place heat and fluids can be produced in the most economical manner. Energy extraction considerations are becoming of increased

TABLE OF CONTENTS

PREFACE

This publication is the second annual progress report under the Department of Energy contract DOE-LBL-167-3500 with the Lawrence Berkeley Laboratory. It covers the period from July 1, 1978, through September 30, 1979.

The Stanford Geothermal Program, initiated by a grant from the National Science Foundation in 1972, has had an uninterrupted history in building a strong research program to assist in the national effort to stimulate the development of a commercial geothermal industry. The central thrust of the program has been the development of geothermal reservoir engineering techniques. A significant adjunct to this goal has been the training of a large number of students who are now employed in the geothermal industry.

An important objective of the Stanford Geothermal Program is to maintain a balance between laboratory studies of the geothermal resource (to understand and maximize the extraction of geothermal energy) and field experiments (to transfer the results of these studies as rapidly as possible to the user sectors of the industry).

In developing the Stanford Geothermal Program to contribute practical methods and data for geothermal reservoir engineering and reservoir assessment, individual projects were grouped into four main areas of study: (1) energy extraction, (2) bench-scale flow experiments, (3) reservoir tracer techniques, and (4) well test analysis. This annual report describes the results obtained in these four areas of geothermal reservoir assessment and the activities for transferring these results to the geothermal community.

importance to the geothermal industry in decisions on fluid recharge and potential commercialization liquid-dominated hydrothermal resources. The research on the large Geothermal Reservoir Model which evaluates extraction by prodiction mode will be of great value in these considerations. Feasibility experiments on thermal fracturing by hydrothermal stressing are also underway. The development of a model useful for assessing the heat extraction potential of hydrothermal resources is progressing satisfactorily. The section on energy extraction also contains a discussion of a new lumped-parameter model for two-phase flow.

The section on bench-scale flow experiments covers the results of three models used to examine the properties of flow through porous media at elevated temperatures and pressures. One model is used to study the effect of temperature level on absolute permeability, a second model containing a large core holder equipped with a capacitance probe for determining water and steam saturation in a porous medium is used to measure steam-water relative permeability, and a third model is designed to determine the mechanisms of vapor pressure lowering in porous media.

The section on radon tracer techniques describes accelerated efforts to field test several geothermal reservoirs by both transient and transect test procedures. Radon flow transients were completed in vapor-dominated reservoirs at The Geysers, California, and Serrazzano, Italy, and in liquid-dominated reservoirs at Pohoiki, Hawaii, and Cerro Prieto, Mexico. Initial studies were initiated at Mammoth Lakes, California, Raft River, Idaho, Wairakei, New Zealand, and Los Azufres, Mexico. Analysis of the first radon evaluation of reservoir performance was completed in the Phase I test of the LASL Hot Dry Rock Program. The potential of transect analysis using the unique capability of radiotracers for dating measurements is being evaluated to study the directional flow of geofluids in the reservoir. The bench-scale experiment to define the source term as a function of reservoir parameters has been initiated. To satisfy the need for multitracer evaluation of geothermal reservoirs, new efforts in comparing ammonia and boron concentrations were also initiated.

The section on well test analysis describes several new developments: analysis of sarth-tide effects, pressure transient analysis of multilayered systems, interference testing with storage and skin effects, determination of steam-water relative permeability from wellhead data, well test analysis for wells produced at constant pressure, the parallelepiped model, slug test DST analysis, and pressure transient behavior in naturally fractured reservoirs.

The research conducted over the past year has produced several important results and has opened new frontiers for future study. In the final section of this report, conclusions are offered along with recommendations for areas of future research leading to further utilization in the development of new geothermal resources.

The Appendices to the report describe some of the Stanford Geothermal Program activities that result in interactions with the geothermal community. These occur in the form of SGP Technical Reports, presentations at technical meetings, publications in the open literature, and the series of Quarterly Seminars and the Annual Workshop on Geothermal Reservoir Engineering.

1. ENERGY EXTRACTION

Although many conventional oil and gas reservoir engineering practices are employed in geothermal reservoirs, the essential commodity to be extracted from geothermal reservoirs is not only the fluid contained therein, but also the vast quantities of thermal energy stored in the formation rock. The assumption that geothermal reservoirs are an essentially infinitely renetable energy resource is generally not true because replenishment of thermal energy in a reservoir from the surrounding rock by conduction heat transfer alone is too slow. However, in some cases, some energy influx may te associated with mass flow from surrounding regions.

The goal of the geothermal reservoir engineer should be to develop production strategies which extract the maximum amount of energy from the reservoir. Thus fluid production methods applied in oil and gas reservoirs and groundwater aquifers are important, but understanding the heat transfer by which the energy extraction is achieved is equally essential for efficient and economical use of geothermal resources.

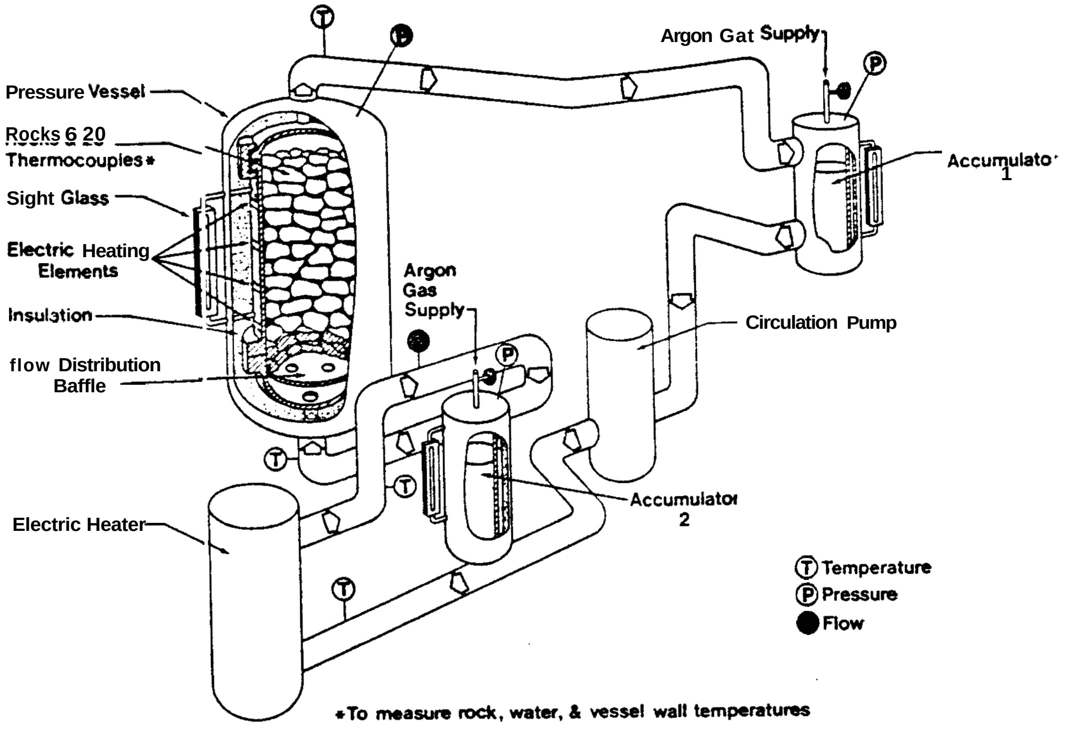
Heat transfer and enhancement of thermal energy extraction from fractured geothermal reservoirs have been studied as part of the Stacford Geothermal Program since its inception. This section contains project reports on experiments using the Large Reservoir Model and the new experimental apparatus for the study of thermal stress fracturing. A lumped-parameter model for simulating two-phase flow is described in the last part of this section.

(a) Large Reservoir Model, by R. Iregui, Engineer's Degree, A. Hunsbedt, Research Associate, Prof. P. Kruger, and Prof. A. L. London.

Since more than 70% of the energy available in a geothermal reservoir resides in the reservoir rock, the development of techniques to enhance the fraction of energy extracted from the rock itself is imperative for efficient exploitation of a geothermal resource. The rate of energy extraction from a geothermal resource is limited by slow conductive heat transfer from the large reservoir rocks to the convecting fluid and by the resistance to the flow of fluid through the formation. Total energy extraction is limited by the finite stored heat capacity of the reservoir.

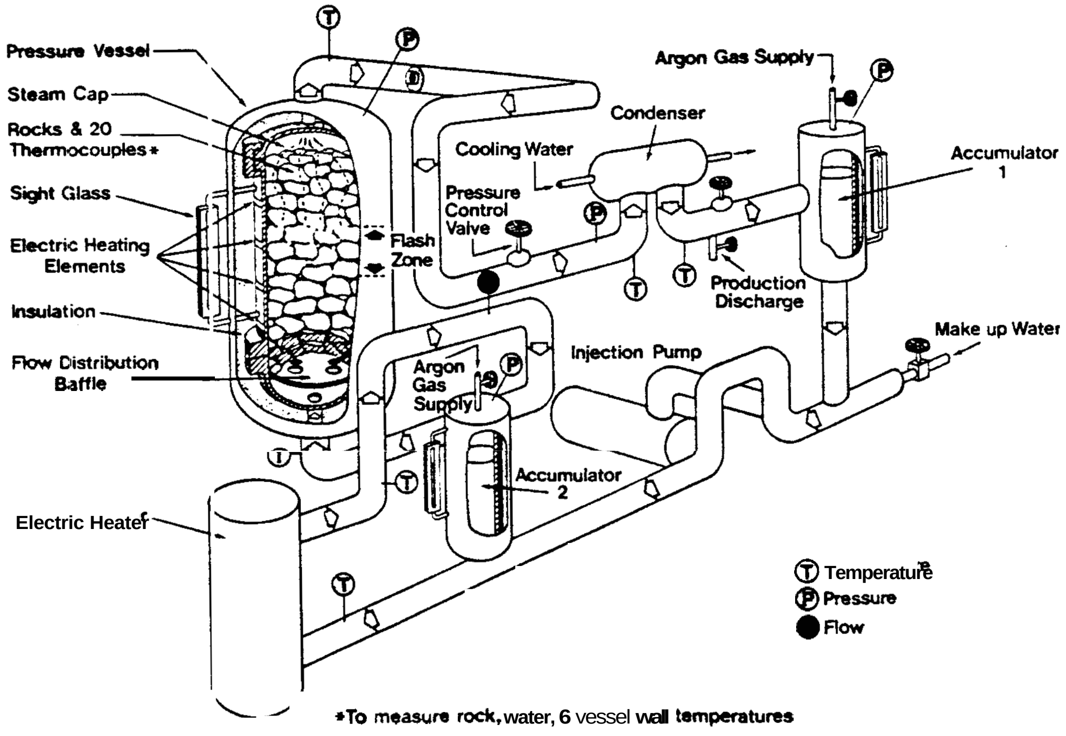
The SGP Large Reservoir Model, shown in the heating and production modes in Figs. 1.1a and b, respectively, has been used to study fundamental nonisothermal production methods and heat transfer from the rocks to the produced fluid. Three basic types of producing nonisothermal processes have been performed: in-place boiling, cold water injection (cold water sweep), and the steam drive process. The third process was shown to be ineffective in earlier work, and has not been considered further this year.

In the in-place boiling experiments, water heated under pressure was produced as steam by lowering the reservoir pressure until boiling was initiated. In previous experiments, the model was loaded with large impermeable rocks of various sizes and shapes. In the most recent experiments, 80-100 mesh sand was loaded into the void spaces between the large impermeable rocks to reduce porosity and permeability to more representative values. The porosity of the system was determined to be 21%, and the permeability was on the order of 20 to 40 darcies. Thermocouples were inserted at various points inside the vessel to measure temperatures in



*To measure rock, water, & vessel wall temperatures

FIG. 1.1a: DIAGRAM OF SGP LARGE RESERVOIR MODEL, HEATING MODE OPERATION



*To measure rock, water, 6 vessel wall temperatures

FIG. 1-1b: DIAGRAM OF SGP LARGE RESERVOIR MODEL, FLUID PRODUCTION **MODE** **OPERATION** the fluid and in selected rocks. As the water boiled in place and the reservoir pressure declined, the water in the system cooled, creating a temperature difference between rock and fluid which was the driving force for the heat transfer process.

In sand/rock experiments 4-1 and 4-2, the liquid water flashed to dry steam throughout the vessel before the end of the experiment, and the steam leaving at the end was superheated. Thus the total energy extracted was limited by the amount of fluid available to be produced. However, overall energy extraction efficiency from this system was not noticeably different from that achieved with earlier systems having porosities ranging from 35% to 44%, and essentially infinite permeability. The dry-out phenomenon is illustrated in Fig. 1.2, which shows the temperature distribution in the model at selected times. The data show that saturated fluid conditions (pressure-temperature equilibrium of fluid) exist for times less than about 2.25 hours. At a time of 2.5 hours, however, a slight superheating is noted near the vessel flanges. The entire reservoir was superheated at the end of the experiment (at 3.5 hours). The large temperature variations late in the production time are believed to be caused by the uneven heat transfer from the steel vessel wall.

Experiment 4-3 was of the cold water sweep type. In this experiment, room temperature water was injected into the bottom of the vessel containing the preheated rock/sand and water. Hot water was produced at the top with equal production and injection rates. Water temperatures were measured at several locations in the model as a function of time. Measured and computed water temperatures at various elevations in the reservoir are shown in Fig. 1.3. The computed water temperatures were calculated using the analytical solution developed for the sweep process by Iregui et al. (1978).

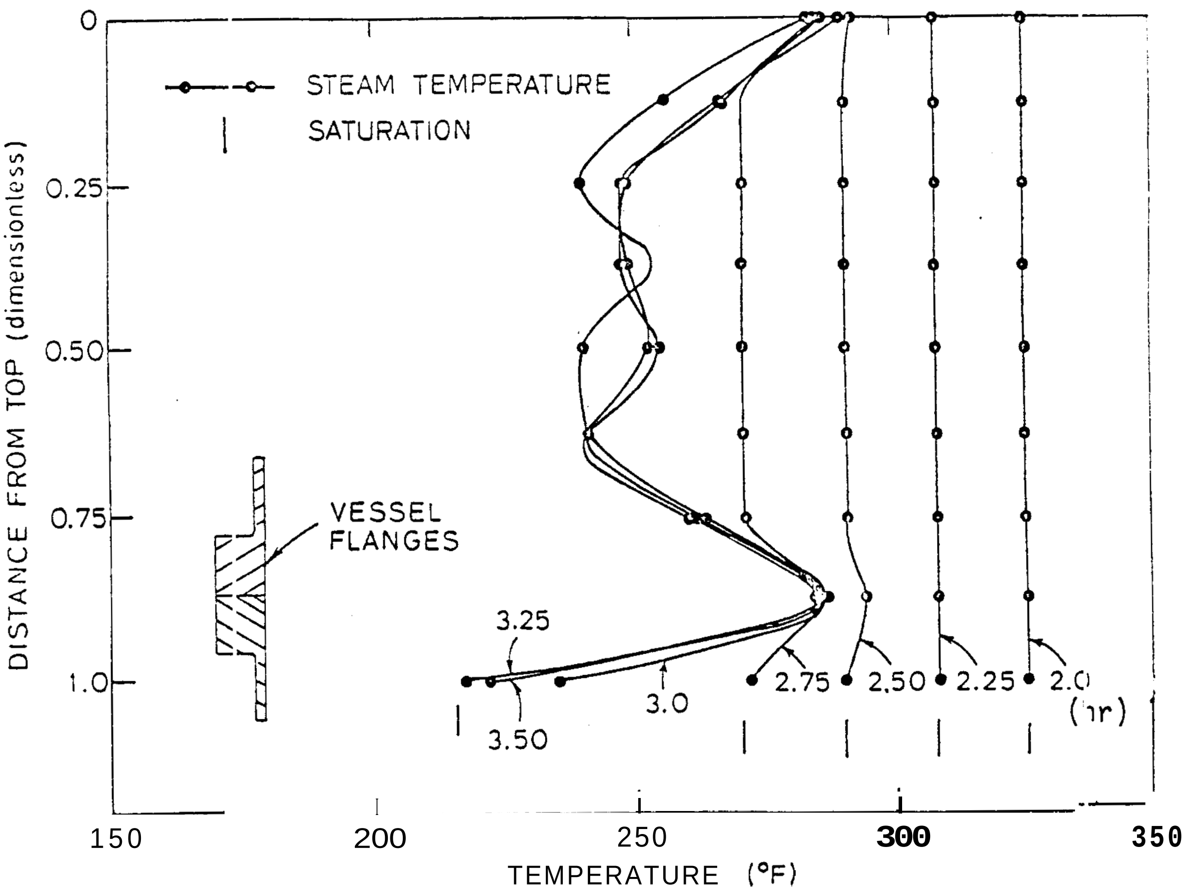


FIG. 1-2: WATER-STEAM TEMPERATURE DISTRIBUTION FOR EXPERIMENT 4-2

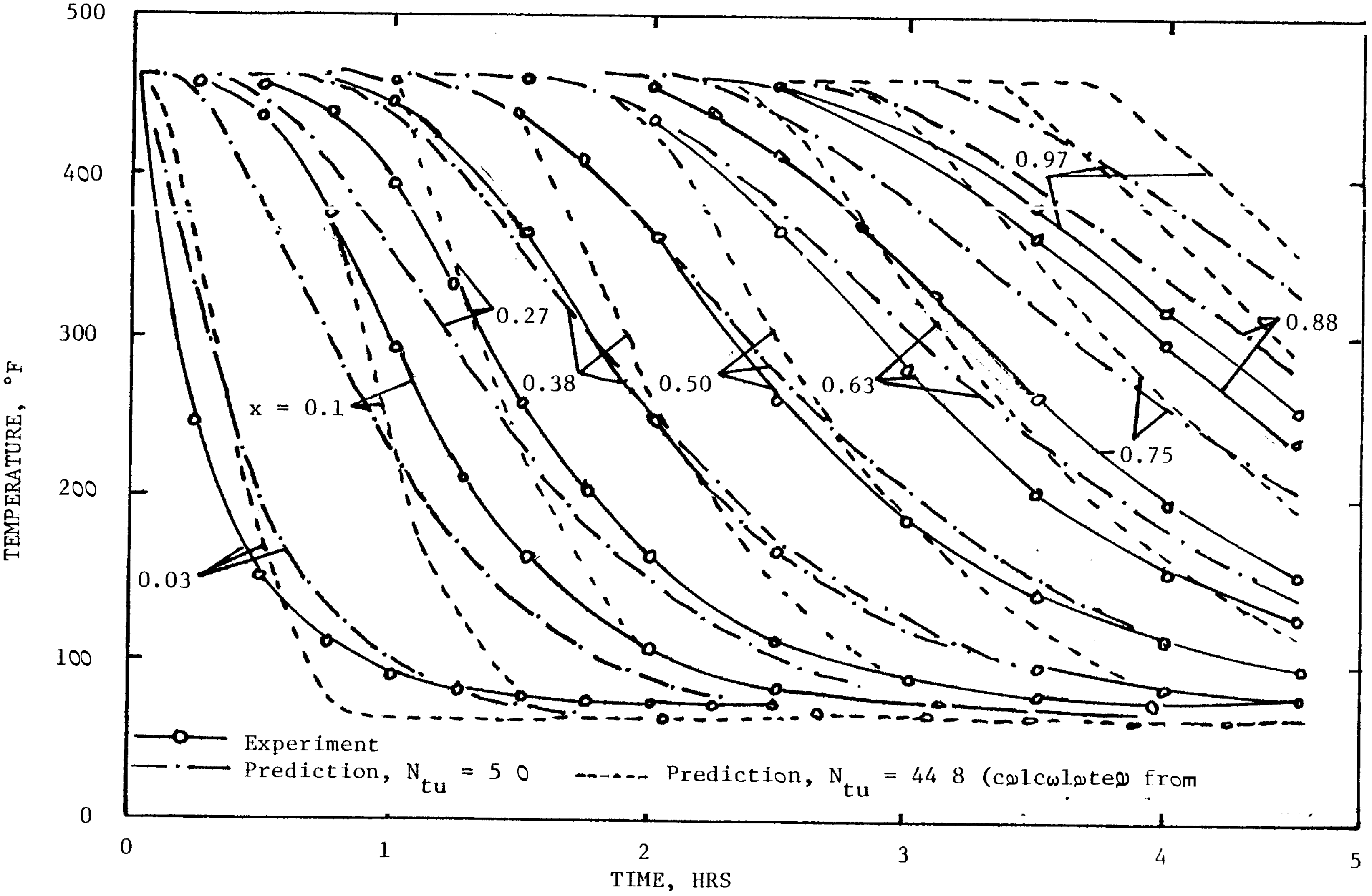


FIG. 1-3: COMPARISON OF MEASURED AND PREDICTED WATER TEMPERATURES AT VARIOUS ELEVATIONS FOR RUN 4-3

The comparison in Fig. 1.3 shows that the water temperature-time curves computed using the experimental value of number of heat transfer units (N_{tu} = 44.5) are steeper than the experimental curves at all elevations. This trend was also noted to a lesser degree in earlier experiments, as reported by Iregui et al. (1978), and by Hunsbedt et al. (1979). A parametric study was performed to determine what value of N_{tu} would more closely match the data. A value of N_{tu} = 5 gave results which were in good agreement with experiments, as indicated in Fig. 1.3.

The comparison shows that either the model results are in error or that the measured temperature data (measured along the model centerline) are not representative of the reservoir as a whole. Indications are that there are significant cross-sectional temperature variations in the reservoir caused mainly by heating from the vessel wall andbynon-uniform flow in the rock matrix. This is inconsistent with the one-dimensional analysis method used in the computation. There may also be errors in the model results, particularly in the way the thermal capacity of the vessel is lumped with the rock. These questions will be explored furtfer during future efforts.

Sweep energy extraction experiments are planned in which reservoir conditions will result in lower N_{tu} values. The rock sizes and the injection/production rates will be increased. These experiments are needed to verify the theoretical model of Iregui et al. under conditions wherein the reservoir is considered to be heat transfer limited (N_{tu} less than 10). The experiments conducted to date have been for conditions wherein the reservoir is not heat transfer limited (N_{tu} greater than 30). A more thorough packing of the sand in the void space will also be attenpted to assure a more uniform flow distribution in the rock matrix and avoid "channeling effects" suspected in the current rock/sand system.

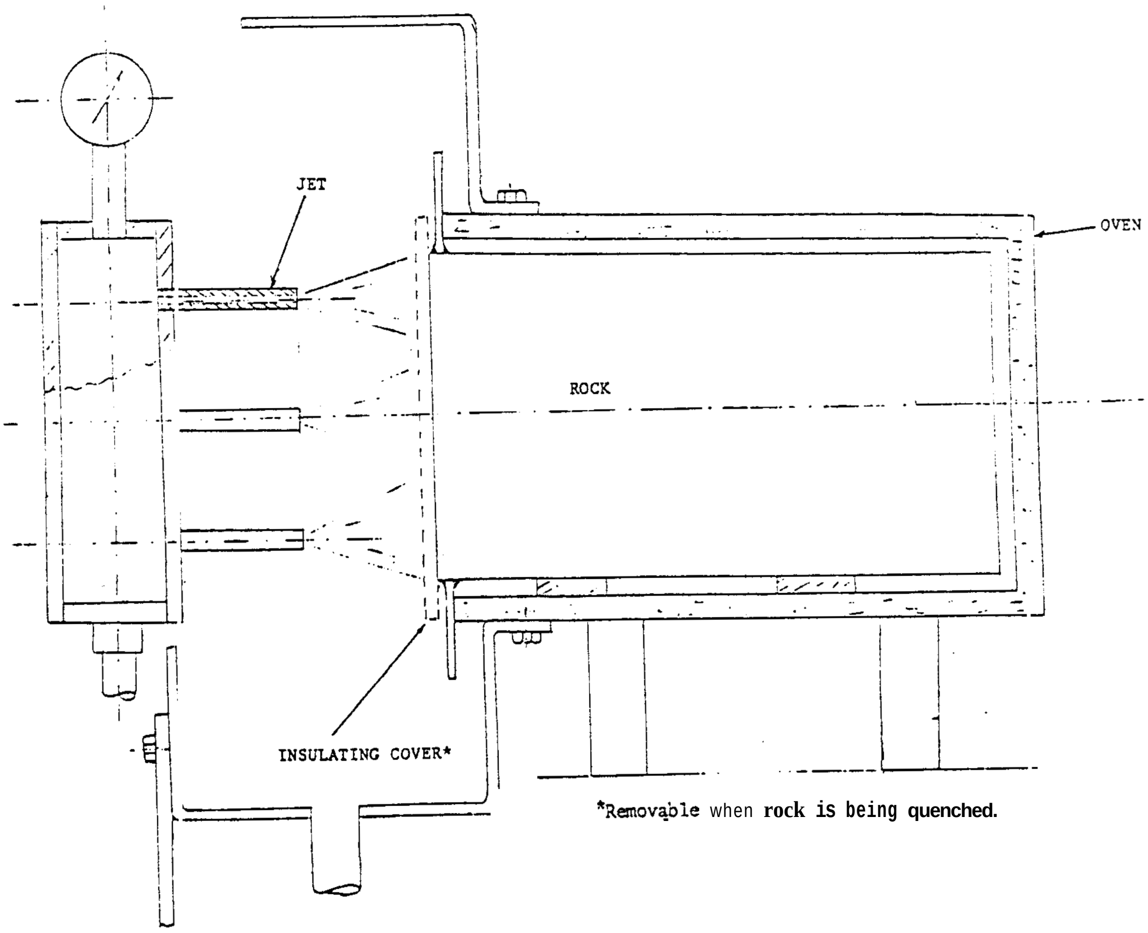
The possibility of extending the theoretical model to include the uneven heat transfer from the walls will also be considered. Computation of the average rock temperature will be included in the theoretical model.

The Large Reservoir Model is currently being prepared for the next experiments planned for the fall quarter. During part of this year, while A. Hunsbedt was on leave in England, the model was used by Rogers Engineering Company to conduct experiments on a downhole wellbore gecthermal heat exchanger. The results of these experiments will be reported separately.

(b) Thermal Fracturing Experiments, by R. Rana, Engineer's Degree Candidate in Mechanical Engineering, and Prof. D. Nelson.

Analytical studies suggest that the thermal stresses produced by water circulating in a geothermal reservoir are likely to initiate and propagate cracks in the rock. Such thermally induced cracks will augment the power extracted from a reservoir if they cause a significant increase in effective heat transfer and flow areas. Thus it is important to: (a) determine the conditions under which such cracking will occur and to determine whether these conditions are compatible with the expected operating conditions of reservoirs, and (b) investigate the extent to which energy extraction can be enhanced by cracking.

In order to perform a preliminary small-scale study of item (a), an experimental apparatus was designed and assembled during the reporting period. The main component is an air bath in which granite blocks are heated to uniform temperatures characteristic of geothermal reservoirs. To induce thermal stresses, the "exposed" rock face shown in Fig. 1-4 is sprayed with



*Removable when rock is being quenched.

FIG. 1-4: SCHEMATIC DIAGRAM OF THE APPARATUS FOR THE THERMAL FRACTURING EXPERIMENT water from multiple jets. (The face is insulated prior to the test to minimize initial temperature differences.) The spray system has been designed to allow the surface heat transfer coefficient to be controlled. Also, the cooling water temperature level can be controlled. Surface heat transfer coefficients and water-to-rock temperature differences representative of reservoir conditions are planned for the experiments.

The rock specimens are instrumented with thermocouples so that the time-temperature history can be monitored. Results are compared with an analytic solution for the transient heat transfer and thermal stress behavior of the rock specimens. Conditions under which thermal stress cracking occurs and the correspondence to reservoir operating conditions are being investigated.

Initial quenching experiments were performed on a 5 in. rock cube. Holes were drilled into the specimen from the side, and thermocouples inserted with high temperature cement. The rock was heated slowly to a uniform temperature of 400°F. The front face of the rock was then quenched. Figure 1.5 shows a typical measured temperature-time history at various thermocouple locations in the rock for a surface heat transfer coefficient of approximately 300 Btu/(hr-ft^2-°F). No cracking was observed on the quenched surface. However, subsequent experiments with the same rock specimen (under the same conditions) revealed sudden large fluctuations in temperature at the thermocouple location nearest the quenched face, indicating the possibility of thermal stress fracturing originating from the thermocouple hole. It was determined after the test that the thermocouple at that location was operating properly. The possible cracking of the thermocouple cement and/or rock itself is currently being examined. Because of the difficulty detecting and measuring internal cracking, further experiments are underway with

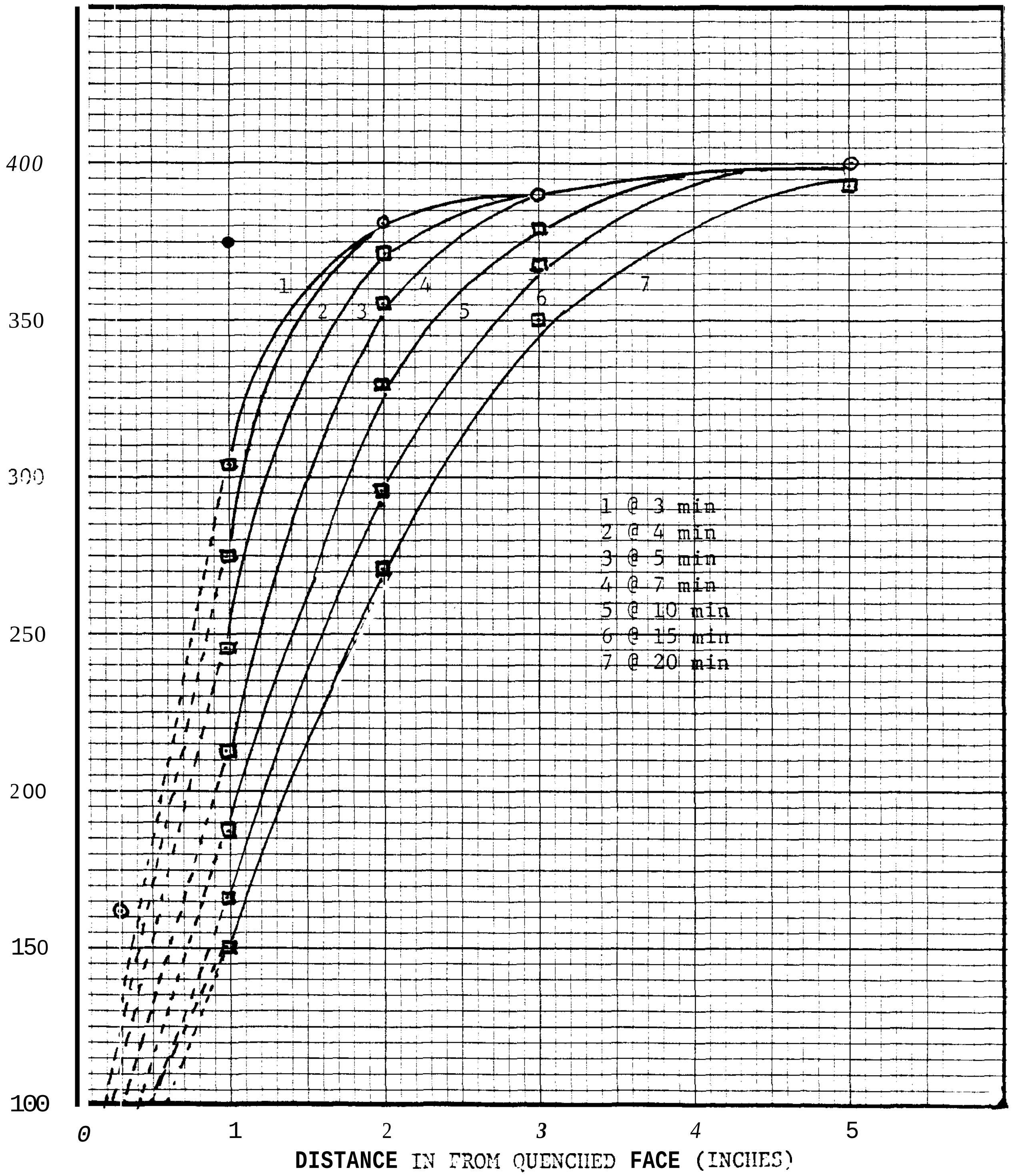


FIG. 1-5: TYPICAL MEASURED TEMPERATURE-TIME HISTORY IN QUENCHED GRANITE ROCK

1/4 in. thick specimens (other dimensions remain 5" x 5") to facilitate detection. These experiments are intended to determine thermal stress criteria for crack formation and crack growth (from preexisting flaws, if necessary). They are scheduled for completion by the end of 1979. If the results of these preliminary tests appear promising, a larger-scale experiment utilizing the Stanford Geothermal Program reservoir model will be designed. This experiment would investigate enhancement of energy extraction by thermal fracturing.

(c) Lumped-Parameter Two-Phase Flow Model, by L. Castanier, Visiting Post-Doctoral Scholar.

Whiting and Ramey (1969) proposed a lumped-parameter model which considered the reservoir to be a "black box," characterized by its volume, porosity, pressure, temperature, and fluid contents, which considers the production histories of mass and energy. The results given by the model were in good agreement with the early production history of the Wairakai reservoir in New Zealand. Brigham and Morrow (1974) proposed two lumped-parameter models which allowed for homogeneous or separate distributions of the two fluid phases (liquid and vapor) in the reservoir. However, only the case of dry steam production was considered. These models were used to demonstrate the influence of porosity on reservoir behavior.

Results from the Castanier experiments (1978, 79a) did not match any of the existing models. Hence a new mathematical model was developed. Equations describing local reservoir behavior were integrated over the total reservoir volume, assuming a succession of thermodynamic equilibrium states. Excellent agreement was found between the model and experimental results. Figures 1-6 and 1-7 depict comparisons between the experimental

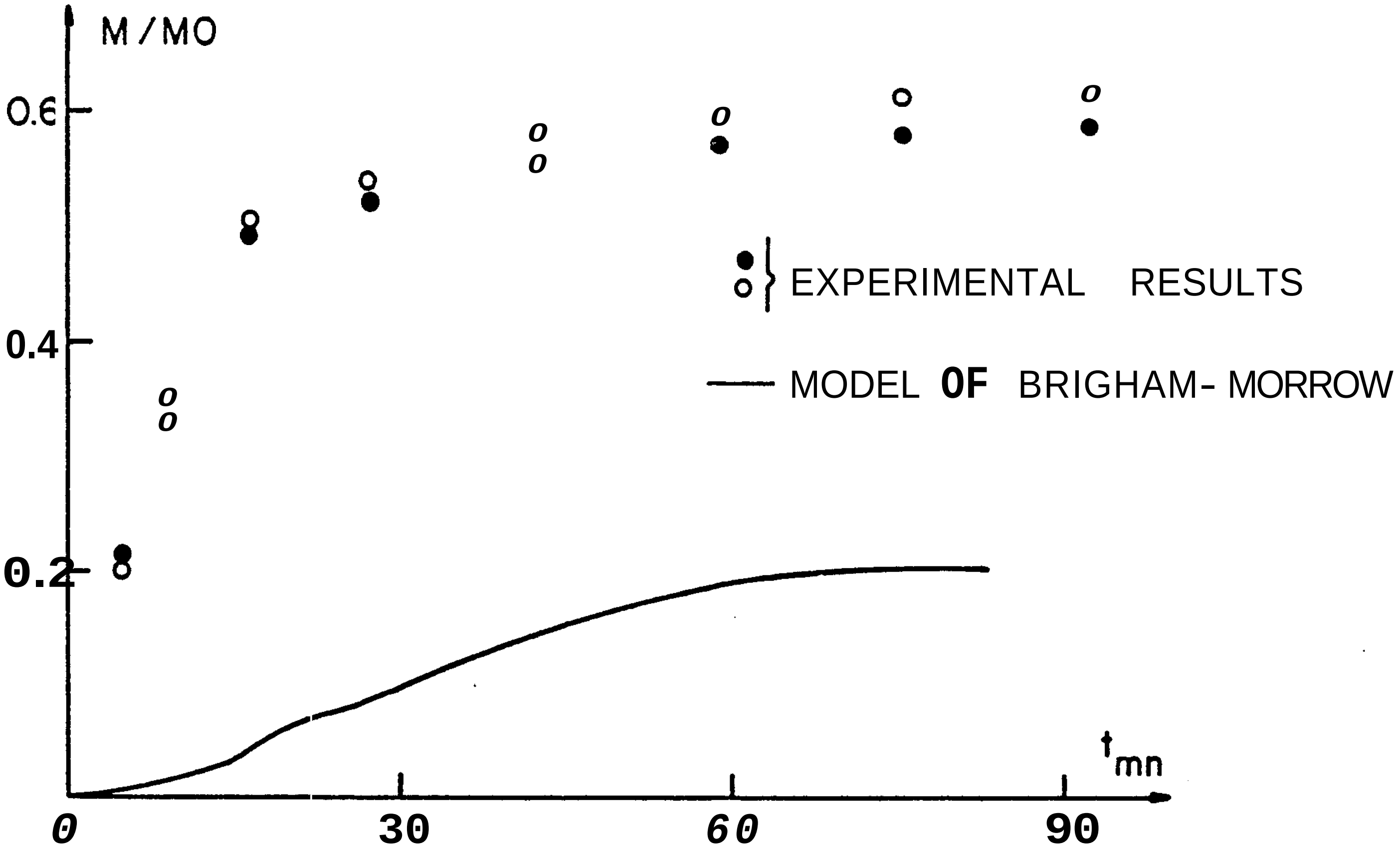


FIG. 1-6: MODEL OF BRIGHAM AND MORROW

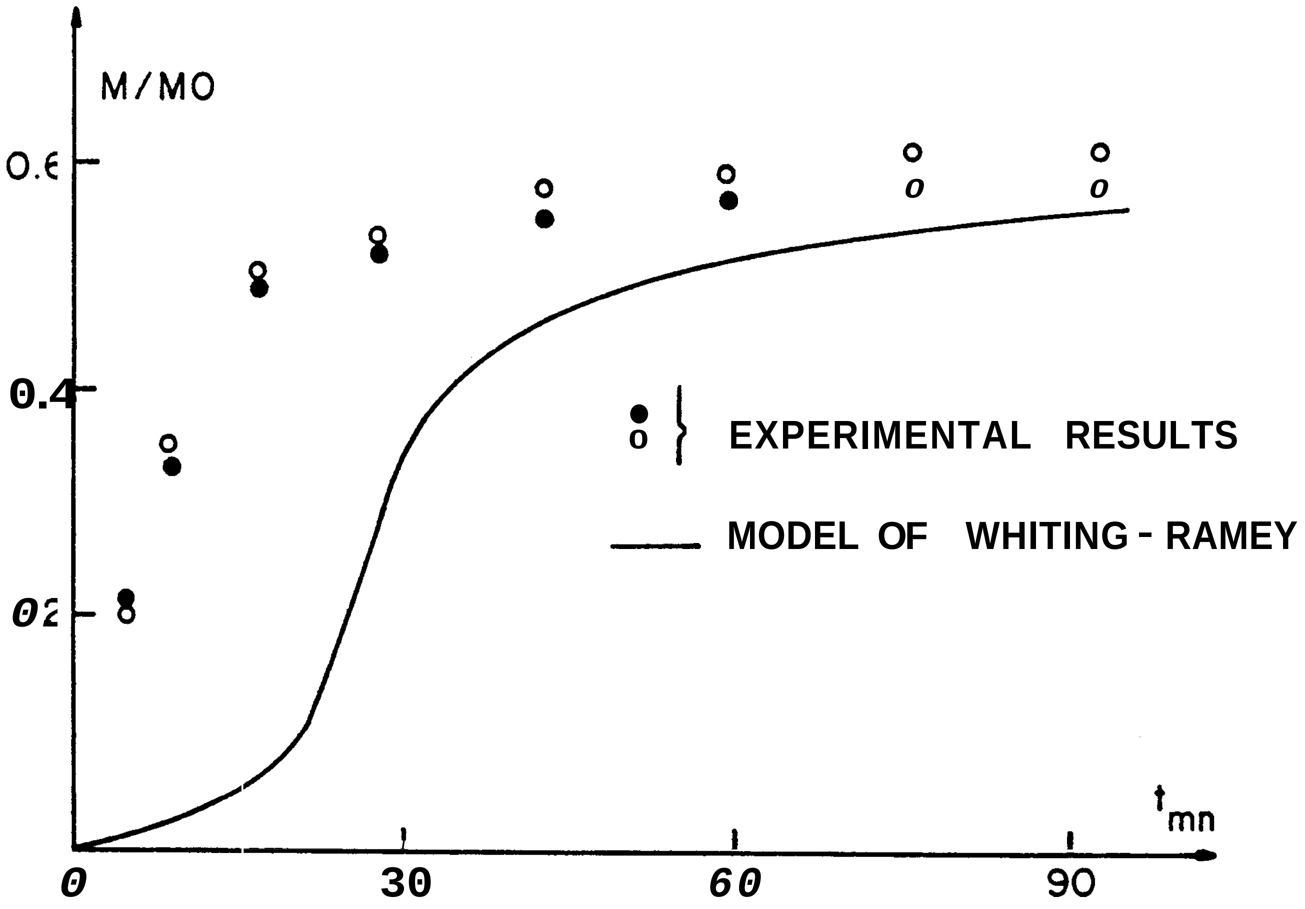


FIG. 1-7: MODEL **OF WHITING** AND RAMEY data and the models by Brigham and Morrow and Whiting and Ramey. Figure 1-8 shows comparisons of data from several experiments with the new lumped-parameter model. The details of the mathematical model are given in Castanier (1979b).

Future work will involve testing the model with data from experiments using the Large Reservoir Model.

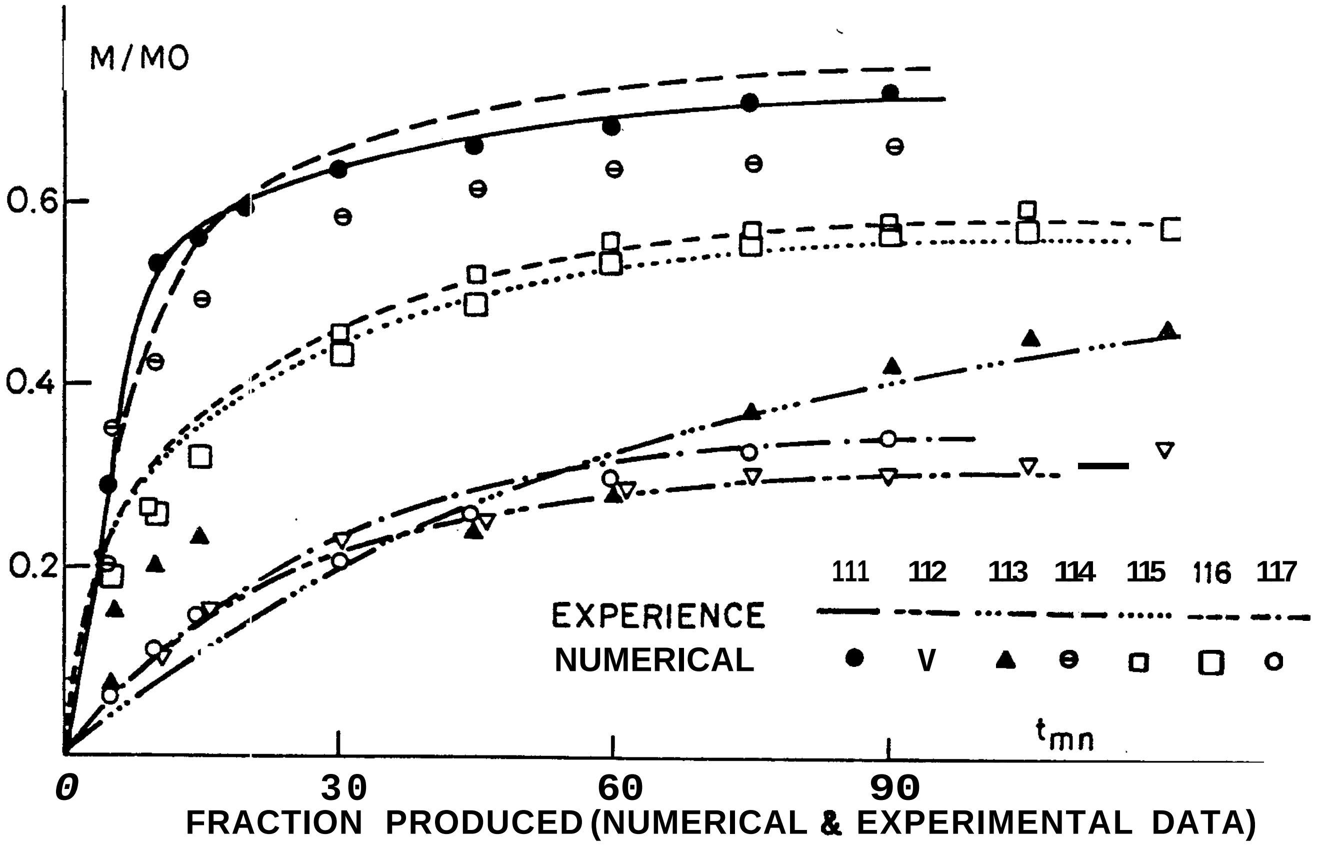


FIG. 1-8: COWARISON OF DATA FROM SEVERAL EXPERIMENTS USING THE LUMPED-PARAMETER MODEL.

2. BENCH-SCALE FLOW MODELS

In an earlier section of this report, experiments on energy extraction are detailed; later we discuss studies on well test analysis, which is concerned with reservoir fluid production. The results of these studies can be better interpreted through the basic understanding gained by use of bench-scale flow models. This section discusses the experimental effort on these bench-scale models.

Results indicated in the report on effects of temperature level on absolute permeability suggest that certain properties are unique to water and the particular flow medium. Other reports in this section deal with steam-water relative permeability measurements and the mechanisms of water vapor pressure lowering in a porous medium. Results from these experiments suggest areas for further research, which are indicated in each of the progress reports. In the last report in this section, an additional model is proposed for the observation of vapor bubble formation in a porous medium.

(a) Absolute Permeability, by C. Ehlig-Economides, Ph.D. Petroleum Engineer, A. Danesh, Visiting Professor from Abadan Institute of Technology, Iran, B. Gobran, M.S. Petroleum Engineer, and Prof. H. J. Ramey, Jr.

Several experimental studies have demonstrated temperature level effects on absolute permeability (Greenberg et al., 1968; Cassé, 1976). In this continuing study by the Stanford Geothermal Program, experiments have been designed to verify the temperature level effects and to define the mechanisms involved.

A study by Danesh et al. (1978) was concentrated on isolating certain physical parameters in the hope of determining the influence of these parameters on the absolute permeability variations with temperature. A schematic diagram of the experimental apparatus is shown in Fig. 2-1. The core materials used in this study were Ottawa sand (80-100 mesh) and stainless steel (80-100 and 100-120 mesh). Additional experiments are planned using 80-100 mesh amorphous quartz, limestone, and calcite. By preparing each unconsclidated sample in the same way, individual effects of the different materials may surface. The fluids used were filtered, deionized water and Chevron White Oil No. 3.

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. 2-2. Unlike the results reported by Aruna (1976), 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. 2-3.

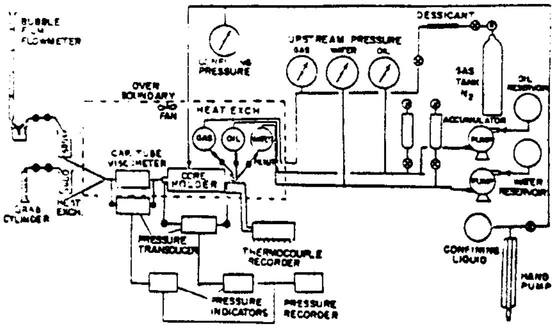


FIG. 2-1: SCHEMATIC DIAGRAM OF APPARATUS

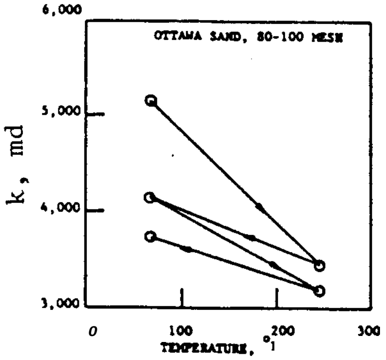


FIG. 2-2 : WATER PERMEABILITY VS TEMPERATURE, OTTAWA *SAND*

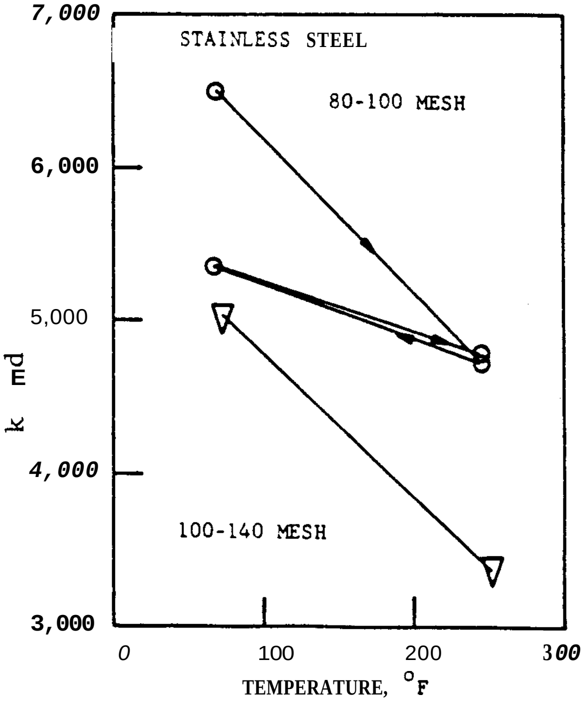


FIG. 2-3: WATER PERMEABILITY VS TEMPERATURE, STAINLESS STEEL

Finally, oil was flowed through an 80-100 mesh stainless steel core. These results are indicated in Fig. *2-4.* 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.

Results indicated that the absolute permeability of porous media may depend significantly on the flowing liquid. The permeabilities of unconsolidated sample:; of 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.

Verification of the preceding conclusions requires further study. B. Gobran is continuing the research on this project.

(b) Steam-Water Relative Permeability, by J. Counsil, Ph.D. Petroleum Engineer, and Prof. H. J. Ramey, Jr.

Steam and liquid relative permeabilities, expressed as a function of liquid saturation, are required in numerical models used to calculate mass and energy recovery from two-phase geothermal reservoirs. Currently, modified Corey-type equations are used because adequate techniques for determining proper steam-water relative permeabilities are still under development.

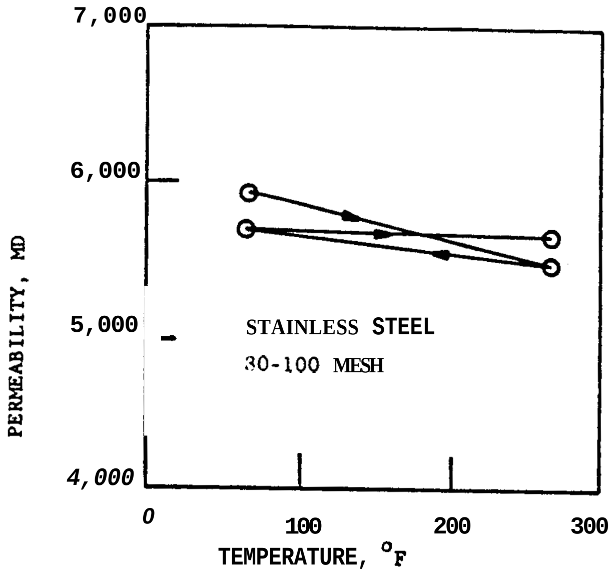


FIG. *2-4:* **OIL** PERMEABILITY VS TEMPERATURE, STAINLESS STEEL

For convenience, relative permeabilities are often expressed as equations. The purpose of this work was to determine steam-water relative permeabilities experimentally. The bench-scale model shown schematically in Fig. 2-5 was used for the experiments.

Two types of flow experiments were performed: internal drive steam-water flow and external drive nitrogen-water flow. It was determined from these experiments that gas relative permeability values at high water saturations for boiling nonisothermal flow are lower than gas relative permeabilities for the external gas-drive methods for isothermal flow. This result may be caused by the different positions occupied by gas within the porous media for the two processes. The water relative permeability curves are higher at high water saturations for the external gas drives than for the boiling or internal drives. Relative permeabilities determined from one of the internal drive steam-water flow experiments are shown in Fig. 2-6. Results from several experimental nitrogen-water drainage relative permeability determinations are shown in Fig. 2-7.

In all of these experiments, the capacitance probe reported by C. Chen (1976) was used to measure the water saturations. The apparent accuracy of the water saturation measurements using the capacitance probe calibration curves is about ±10% of the pore volume. The experiments were performed on synthetic cores. A complete report on all aspects of this work is contained in Counsil (1979).

Future experiments using natural sandstone cores are planned. The effect of the confining pressure on the experimental results should also be investigated.

(c) Vapor Pressure Lowering, by C. H. Hsieh, Ph.D. Candidate, Petroleum Engineering, and Prof. H. J. Ramey, Jr.

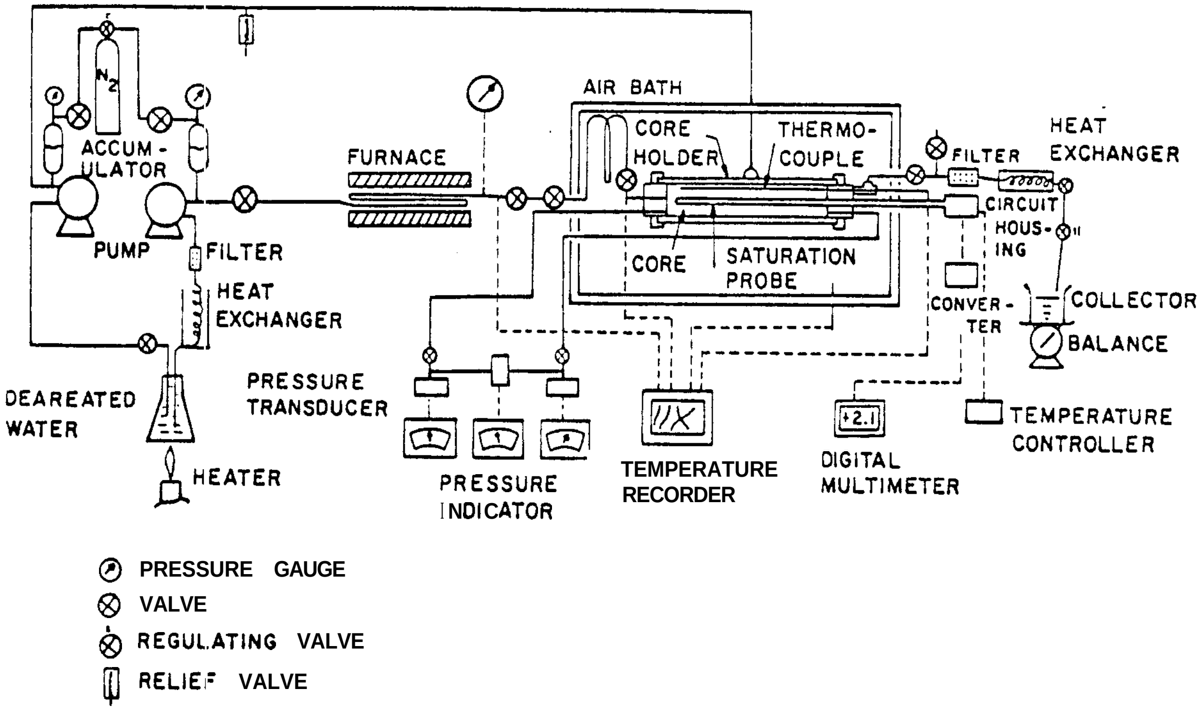


FIG. 2-5: SCHEMATIC DIAGRAM OF NONISOTHERMAL STEAM-WATER FLOW APPARATUS

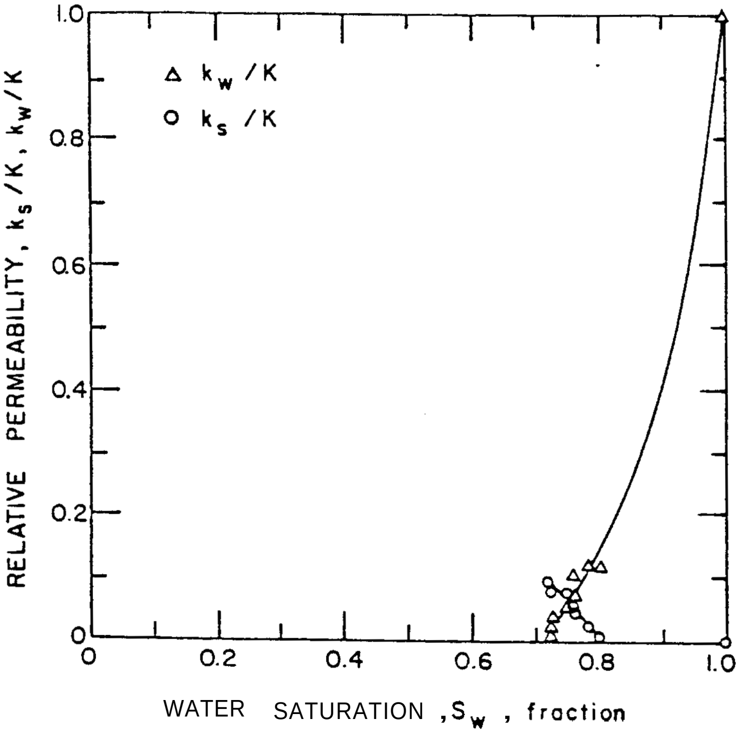


FIG. 2-6: STEAM-WATER RELATIVE PERMEABILITY VS WATER SATURATION FOR HIGH FLOW RATE, RUN SW3

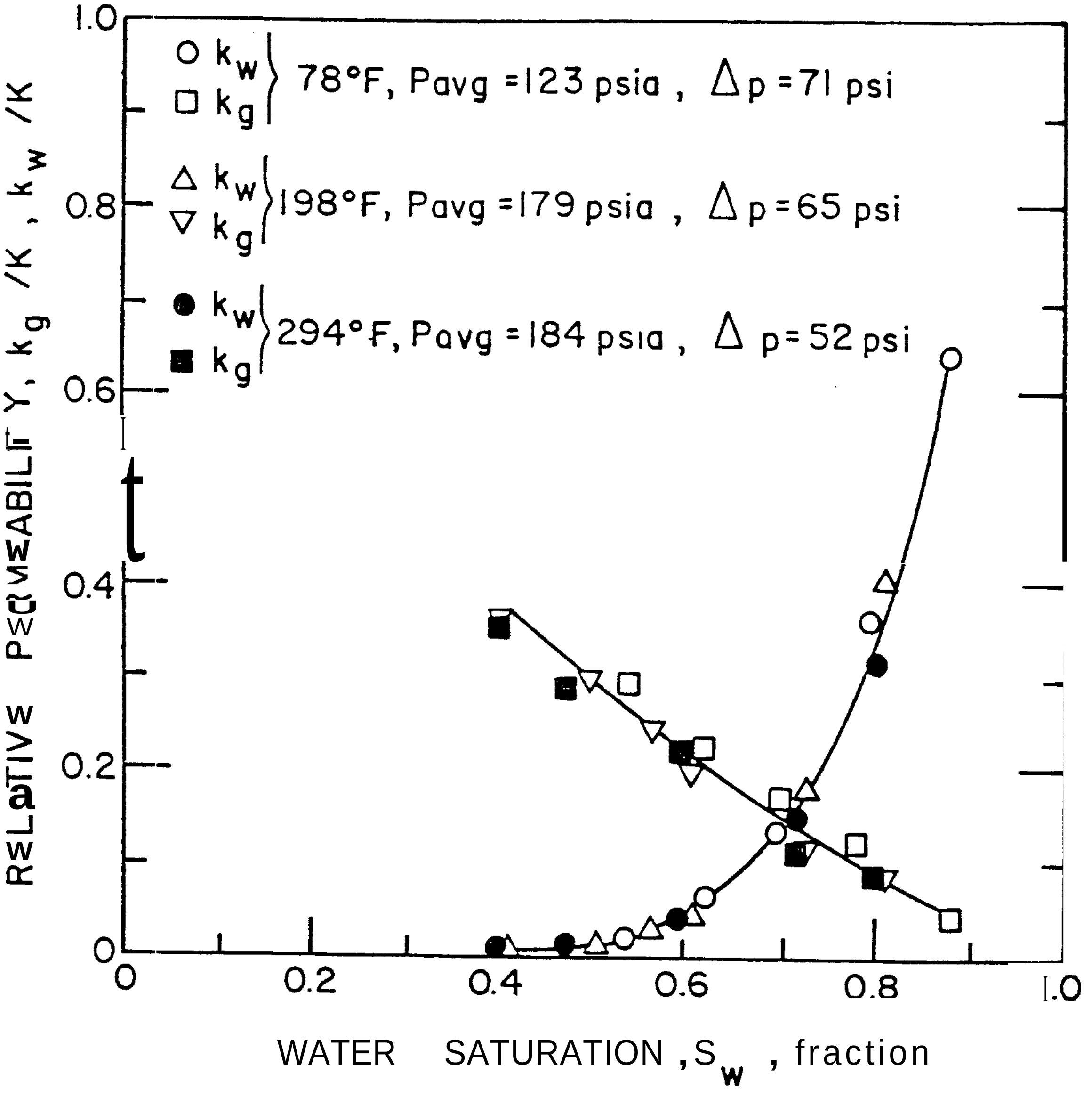


FIG. 2-7: GAS-WATER DRAINAGE RELATIVE PERMEABILITY VS WATER SATURATION FOR SEVERAL TEMPERATURES

The phenomenon of vapor pressure lowering was demonstrated by Chicoine et al. in 1977. Results reported at that time showed that the saturated vapor pressure of water in a consolidated sandstone core may be lowered by as much as 1.5 psia at temperatures between 200°F and 290°F. Recent experiments designed to determine the adsorption of water molecules on the grain surfaces of the porous medium indicate that this is a likely mechanism for vapor pressure lowering. This phenomenon is of considerable importance to geothermal resource assessment because it indicates that additional water may exist under reservoir pressure and temperature conditions which would otherwise indicate the presence of dry steam only. Experimental results on Berea sandstone cores show that as much as eight times the mass of water vapor contained in the pore space may be adsorbed on the surface of the rock. Considerably greater masses of adsorped water have been measured for natural reservoir samples. Two types of adsorption experiments have been conducted in this study: adsorption of noncondensable gases, and water vapor adsorption.

The apparatus for determining the adsorption of noncondensable gases is shown in Fig. 2-8. The procedure is the following. Initially, the entire system is evacuated with Valve C to the sample holder closed. The sample holder is held in a vacuum while gas is allowed to come to equilibrium at room temperature and a given pressure in the gas expansion chamber (Valves A and B closed). Then Valve C is closed and Valve B is opened, allowing the gas to flow into the sample holder, which is submerged in a constant temperature bath. The resulting pressure change is measured with the pressure transducer. The volume of gas that flowed into the sample holder is determined through the use of the ideal gas equation (for low pressures), by van der Waals' equation, and subtraction of the known

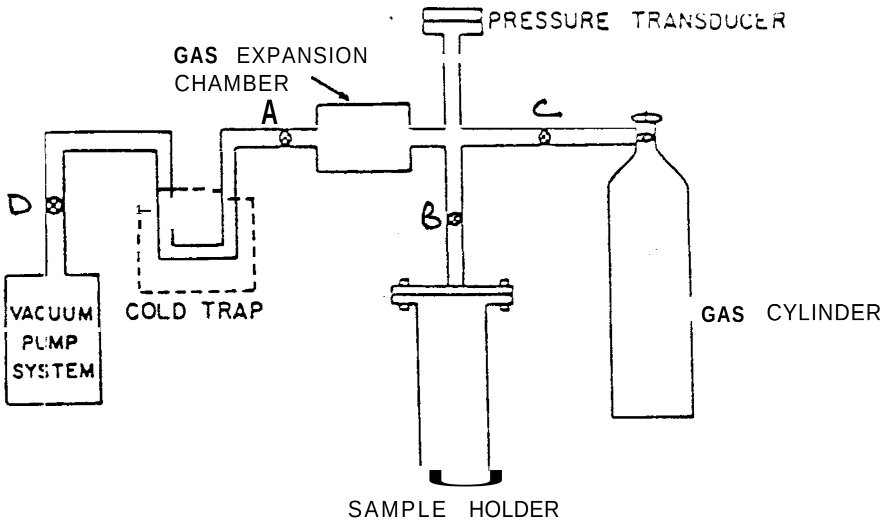


FIG. 2-8: BET CELL USED TO DETERMINE ROCK SURFACE AREA

volume associated with the gas expansion chamber. For helium, the volume of gas measuxed in the sample is equal to the void volume of the sample, and the sample porosity can be determined. For other noncondensable gases, significant volumes of gas are adsorbed to the grain surfaces. Thus, if porosity were measured using both helium and nitrogen, the porosity determined using nitrogen would be about 2 to 3% higher than the actual porosity measured using helium. The extra 2 to 3% of the void volume is the volume of adsorbed gas. Thus, by measuring the void space using helium, this volume can be subtracted from measurements of the volume of nitrogen flowed into the sample holder to determine the volume of nitrogen adsorbed as a function of the temperature of the bath and the final pressure. Results of such an experiment are shown in Fig. 2-9.

A high temperature apparatus is required for analysis of water vapor adsorption. This apparatus is shown in Fig. 2-10. The procedure is roughly the same for water, but frequent difficulties with equipment failures resulted from elevated temperatures.

Nonetheless, for a number of temperatures, data similar to the results shown in Fig. 2-11 were recorded.

Using the BET equation (Brunauer, Emmett, and Teller, 1938), the volume of fluid required for monolayer adsorption was determined for experiments with both water and nitrogen. Then, by multiplying by the volume occupied by the water or nitrogen molecules, the surface area of the grains in the samples was determined. The values determined for several samples which were run using both nitrogen and water showed excellent agreement. Thus the results using the two different experimental apparatus were consistent.

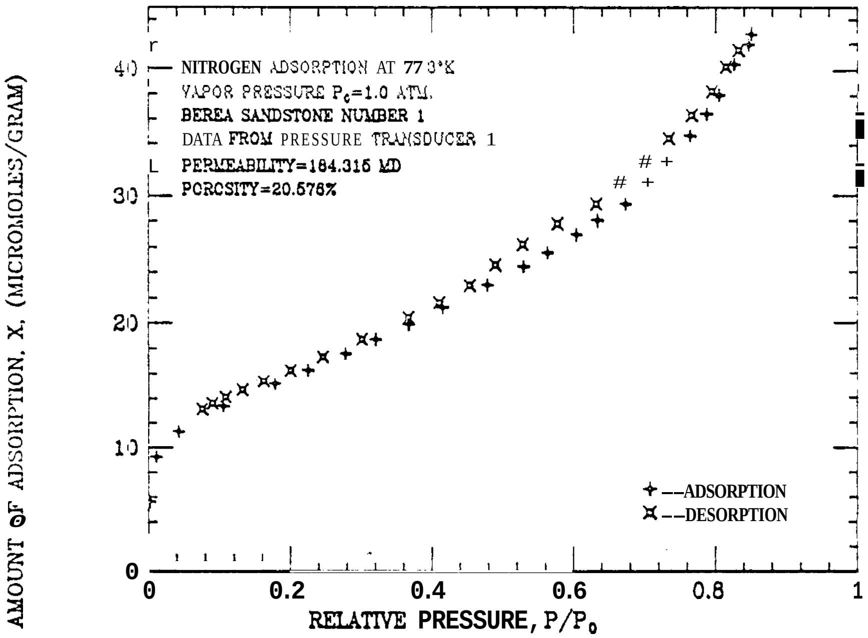


FIG. 2-9: ADSORPTION ISOTHERM OF NITROGEN AT 77.3°K

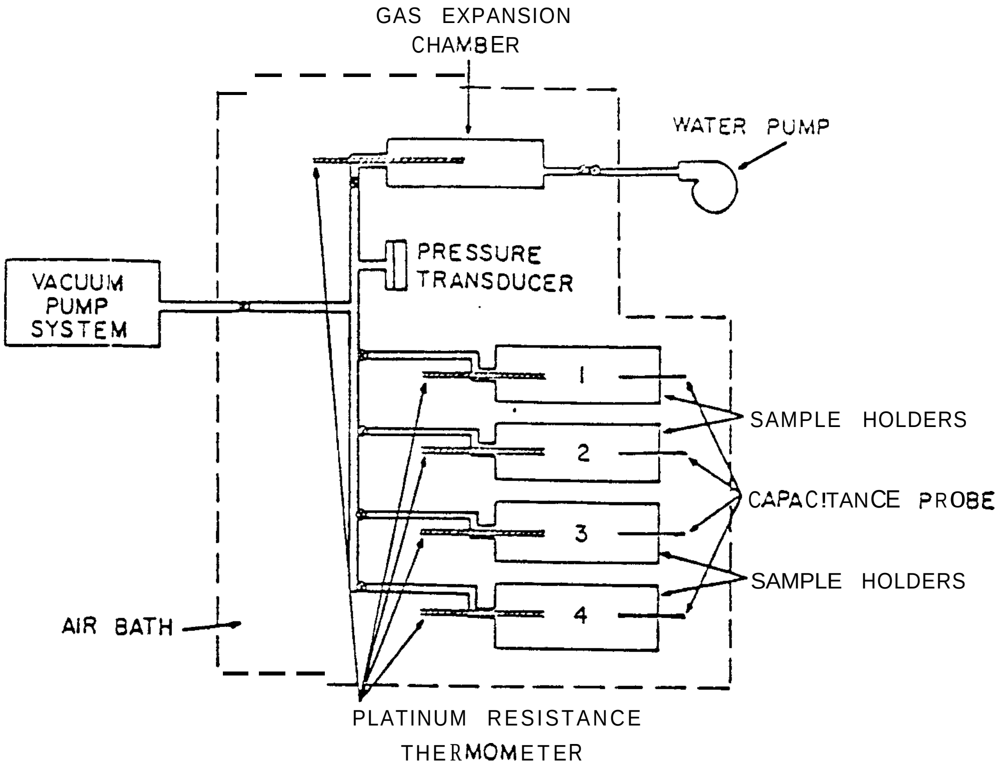


FIG. 2-10: APPARATUS USED TO DETERMINE WATER ADSORPTION AND VAPOR PRESSURE LOWERING

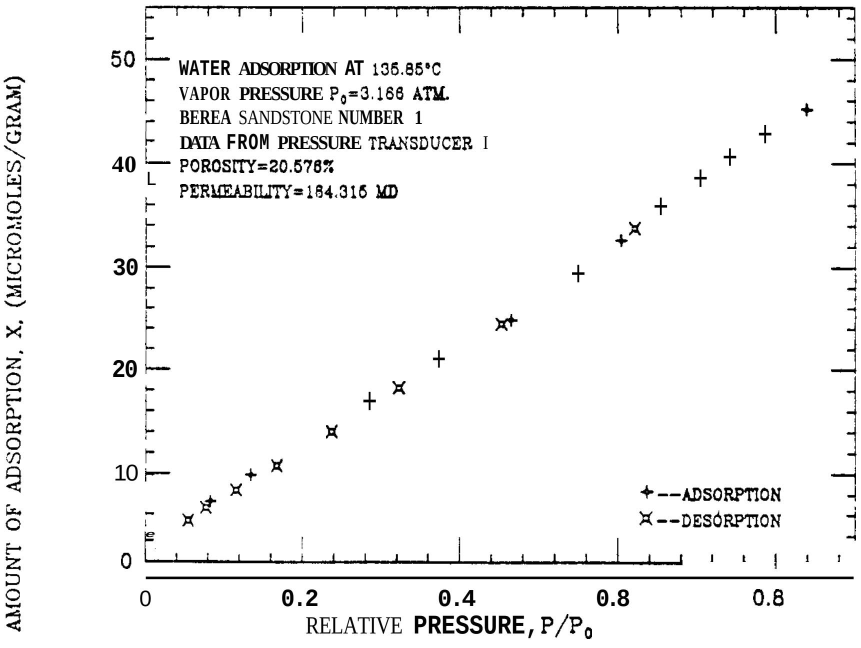


FIG. 2-11: WATER ADSORPTION VS RELATIVE PRESSURE FOR A BEREA SANDSTONE

The general trends in the data were qualitatively the same for different temperatures. Thus it appears that the adsorption phenomena is not temperature sensitive.

Additional studies are proposed using samples other than the Berea sandstone and unconsolidated sand packs used in the past.

(d) Vapor Bubble Formation, by L. Castanier, Visiting Post-Doctoral Scholar.

An experimental study of vapor bubble formation and growth is proposed for next year. A mathematical analysis of vapor bubble growth in a porous medium was developed by S. G. Bankoff (1969). Despite his assuming a negligible latent heat of vaporization for water, his approach yielded interesting results. In particular, he derived a relationship for the diameter of the bubble as a function of time. Rubin and Schweitzer (1972) considered the problem of vaporization or condensation accompanying flow with a temperature gradient parallel to the flow direction. These studies have never been verified experimentally.

Studies of the in-situ vaporization will include the following:

- a mathematical analysis of the results of Bankoff and Rubin and Schweitzer for the case of steam bubble growth,
- construction of an experimental apparatus for simulation of this phenomenon which considers all thermodynamic processes influencing the vapor bubble formation, and
- a comparison between the experimental and theoretical results.

3. RADON TRACER TECHNIQUES

Great strides were made during the year in the utilization of radon tracer techniques to examine a wide variety of geothermal resource types. In addition to the use of radon transient analysis as a promising complementary technique to pressure transient analysis in evaluation of geothermal reservoirs, three other applications were initiated: (1) radioactive/stable tracer ratios, in which ammonia and boron concentrations were compared to radon concentrations, (2) reservoir transect analysis, in which a line of wells along a cross-section of the reservoir was sampled simultaneously to examine the time properties of circulation in the reservoir, and (3) source term experiments, in which the emanating power of radon was measured as a function of five key reservoir parameters.

The following is a review of the general features of radon as a geothermal reservoir tracer, the many producing tests made during the year, and the achievements in the three dew applications.

Stoker and Kruger (1975) showed that ^{222}Rn, a n turally occurring radioactive gas formed from decay of radium present in all geothermal formation rocks., serves as an internal tracer of geothermal fluids in producing geothermal reservoirs. Since radon is produced essentially "forever" in the reservoir, but decays with a characteristic 3.83 day half-life when separated from the parent radium in the rock, it introduces a "time element" in geothermal reservoir tracer studies. This property of radon contrasts sharply with the stable gas components of geothermal fluids, such as CO_2, NH_3, H_2S, and δ(180).

Radon concentration is measured in samples taken at the wellhead of producing geothermal wells. The concentration depends on two sets of parameters, one set relating to the initial concentration of radon in the reservoir pore fluid and the other set to the transport properties of the fluid from the rock pores to the wellhead.

The concentration of radon in pore fluid depends on the radium concentration and distribution in the formation rock, the conditions for emanation and diffusion into the pore fluids, and the density of the pore fluid. These conditions in turn are dependent on the thermodynamic properties of the reservoir. The transport conditions depend on the hydrodynamic properties of the reservoir. Summaries of radon research results follow.

(a) Radon Transient Analysis, by G. Warren and L. Semprini, Engineer's Degree Candidates in Civil Engineering, and Prof. P. Kruger.

Several radon transient experiments were carried out during the reporting period, representing a significant acceleration of this part of the program. The experiments relate the observed changes in wellhead radon concentration to rapid changes in flowrate in wells where production flow had been established. The results of the early experiments were given in the First Annual Report, **SGP-TR-28** (Kruger and Ramey, 1978). During the current period, radon tests were performed at the following geothermal reservoirs, listed below by resource type:

- Vapor-Dominated Systems
    - The Geysers, California
    - Serrazzano, Tuscany, Italy

- Liquid-Dominated Systems

  Mammoth Lakes, California
  Pohoiki, Hawaii
  Raft River, Idaho
  Wairakei, New Zealand
  Cerro Prieto, Baja California, Mexico
  Los Azufres, Michoacan, Mexico

- Petrothermal System

  Fenton Hill, Los Alamos, New Mexico

The experimental results of these tests were initially reported as individual communications with the respective field operators, and subsequently reported in the literature following the evaluation of the results. Recent publications include a summary of the transient tests in the SGP Annual Workshops (SGP-TR-25 and TR-30), and the Society of Petroleum Engineers geothermal meeting (Kruger and Warren, 1979). An overview of these results is summarized in this report.

- Vapor-Dominated Systems

Radon transient tests were conducted at The Geysers California in November 1978, and at the Serrazzano steam field, Italy, in November 1976 and August 1978. The second transient test at the Serrazzano field was run with the cooperation of the ENEL Italy staff.

In the first test at the Grottitana well, Serrazzano field (November 1976), the radon concentration was linearly dependent on flowrate over the experimental flowrate change. The ratio of radon concentration to flowrate was 7.33 ± 0.76 (nCi/kg)/(t/hr) in the Q range of 7.5 to 11.8 t/hr. The radon concentration decreased rapidly following the change in flowrate (see Table 3-1).

The results of the second test confirmed these results, and also showed an interesting difference when the flowrate change was extended. These results are shown in Fig. 3-1. The reduction in flow was carried out in

TABLE 3-1: RADON TRANSIENT TESTS, GROTTITANA, ITALY

Test Dates	[Rn]/Q Ratio	Q Range (t/hr)
Nov - Dec 1976	7.33 ± 0.76	7.5 - 11.8
Aug - Sept 1978	7.8 ± 0.3	8.1 - 11.3
	11.5 ± 0.6	4.6 - 5.0

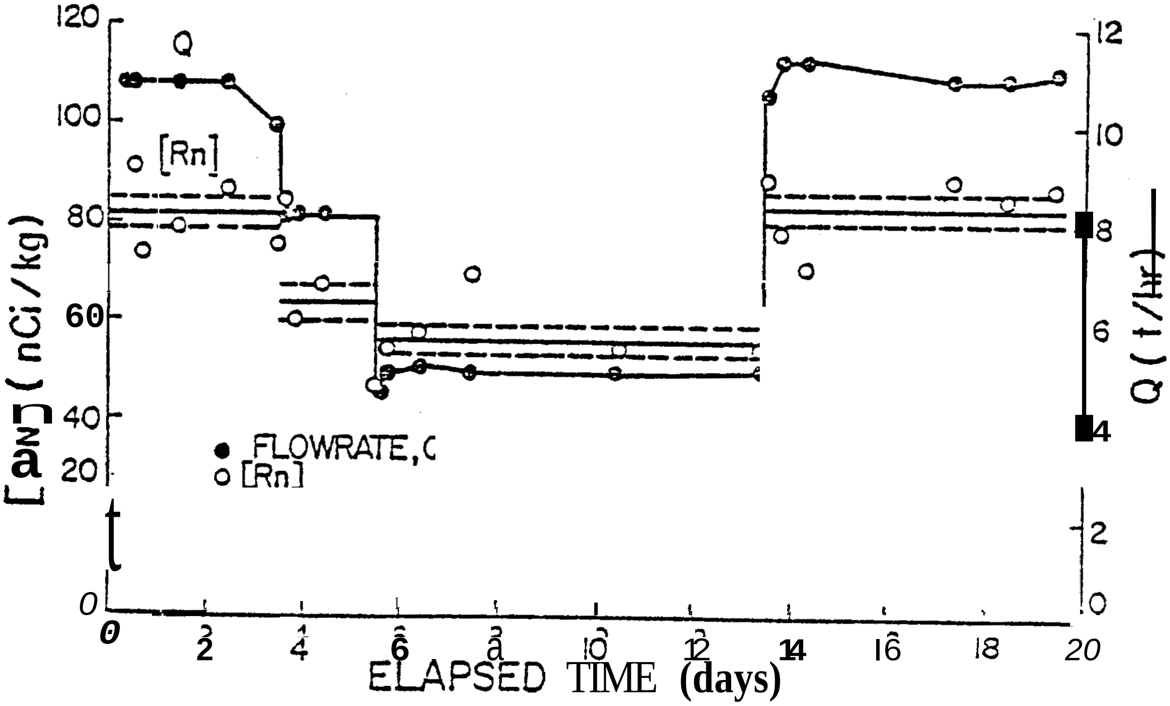


FIG. 3-1: RADON DATA, GROTTITANA WELL, ITALY

two steps, from 11.3 t/hr to 8.1 t/hr, and later to 5 t/hr. The first reduction in flowrate reproduced the observations of the first test: the radon concentration dropped rapidly with the reduction in flowrate, but was again linear, having a [Rn] to Q ratio of 7.8 (nCi/kg)/(t/hr) within the flow range of 8.1 to 11.3 t/hr.

The second reduction to 5 t/hr also showed a rapid radon transient of less than one day; however, the radon concentration was not linear with flowrate. The radon to flowrate ratio ([Rn]/Q) was 11.5 (nCi/kg)/(t/hr) at this low flowrate.

Kruger and Warren (1979) concluded that the rapid decrease in radon concentration of less than 1 day observed in the two tests cannot be ascribed to radioactive decay alone. The results of the second test, which included a nonlinear flowrate dependence at larger flowrate changes, support the conclusion that mechanisms other than decay are responsible for the radon behavior in the Grottitana well. The possibility exists of incorrect flowrate measurement at the very low flowrates. This will be examined in future transient experiments. Changes in emanation of radon with changes in the thermodynamic properties of the reservoir may also be responsible for the observed radon transients. Bench-scale radon emanation studies currently underway at Stanford will help in the interpretation of the results from the two transient tests.

The transient test at The Geysers (November 1978) was conducted to study the changes in radon concentration during a rapid change in flowrate in one well in a field of several producing wells. The objective of this test was to verify the previous observation of interference of radon transport over a producing area. In an earlier transient test in a different area of The Geysers field, Kruger and Warren (1979) showed that the radon concentration was independent of flowrate. The results were attributed to well interference phenomena, where the change in flowrate in one well of many tapping a common reservoir would not significantly alter the total transient time from the source to the wellhead. Thus little change in radon concentration should be caused by radioactive decay.

Well V-A, the site of the November 1978 test, was previously used for a transient test when the well was the only producing well in a shut-in field. Kruger, Stoker, and Umaña (1977) found the radon concentration to be linearly dependent on flowrate, having a [Rn]/Q ratio of 0.75 (nCi/kg)/(t/hr) in a flowrate range of 110 t/hr to 220 t/hr.

Table 3-2 shows the average results for high and low flowrate from the November 1978 test. The average radon concentration was 23.2 ± 2.2 nCi/kg at the average high flowrate of 110,300 lbs/hr. The average radon concentration at the average low flowrate of 56,500 lbs/hr was 22.3 ± 4.7 nCi/kg. The radon concentration was thus observed as remaining unchanged at the high and low flowrates. The agreement of transient test results from the two different areas of The Geysers steam field supports the concept of well interference between wells in close proximity in a producing area. This would 're particularly true for a reservoir model where steam leaving a boiling front migrates upward through a series of interconnected fractures.

TABLE 3-2: SUMMARY OF RESULTS, WELL V-A, November 1978

	Mean Q (klb/hr)	Mean [Rn] (nCi/kg)	Mean Ratio [Rn]/Q
Full Flowrate	110.3	23.2 ± 2.2	0.21
Reduced Flowrate	56.5	22.3 ± 4.7	0.39

- Liquid-Dominated Systems

Radon transient tests were conducted at several liquid-dominated reservoirs in the past year. The first was a short-term test on the undeveloped steam flashing geothermal reservoir at Pohoiki, Hawaii. A second test was a three-week test conducted at the Cerro Prieto field in Mexico as a joint project between the Coordinadora Ejecutiva de Cerro Prieto of the Comision Federal de Electricidad and the Stanford Geothermal Program. Other studies were initiated at Raft River, Idaho, Casa Diablo, California, and Wairakei, New Zealand.

Kruger, Warren, and Honeyman (1977) indicated the use of radon transient analysis as a tool for geothermal reservoir engineering. The model of flowrate dependence (Stoker and Kruger, 1975) for liquid-dominated reservoirs with confined horizontal flow through a large reservoir where the parent radium is homogeneously distributed throughout the reservoir is given by:

$$Rn = \frac{E}{\phi}\left[1 - \exp\left(- \frac{\lambda\phi\pi h}{Q}\,({r_e}^2 - {r_w}^2)\right)\right]$$

where E is the emanating power, and λ is the decay constant. Other symbols have their usual meaning.

The radon concentration to flowrate relation in this model has a factor $(1 - e^{-\lambda V\phi/Q})$.. When realistic values of these variables are substituted into the above equation, the radon concentration appears to be independent of flowrate except at very high flowrates (e.g., 100,000 gal/min).

The first radon transient test at Pohoiki, Hawaii (run in July 1977), consisted of flowing the HGP-A well 4 hours: 2 hours at the maximum flowrate and 2 hours at the minimum flowrate. The second test (July 1978) consisted of flowing the well intermittently for a period of 13 hours over a two-day period.

The comparison of results for these two short tests is shown in Table 3-3. In both tests the radon concentration is shown to be independent of flowrate, in agreement with the liquid-dominated reservoir model. However, in both tests it was apparent that the data might not be indicative of the radon behavior with long-term production of the well. Verification of the radon dependence on flowrate will require a much longer flow period, which is planned for the testing period when new equipment is installed at Well HGP-A.

TABLE 3-3: RADON TRANSIENT TESTS, POHOIKI, HAWAII

Date	Orifice (inches)	$\bar{Q}$ (klb/hr)	$[\overline{Rn}]$ (nCi/kg)	$[\overline{Rn}]/Q$ $\left(\frac{pCi/kg}{mt/hr}\right)$
July 1977	8	286	0.89	1.41
	1-3/4	137	0.85	2.82
July 1978	8	201	1.22	2.76
	2	121	1.20	4.50

Another useful aspect of radon measurements at HGP-A noted in Table 3-3 is the change in ratio of radon concentration to flowrate. Over the one-year period between tests, during which very little production occurred, the mean flowrate at full flow decreased from 286 klb/hr to 201 klb/hr, while the radon increased from 0.89 nCi/kg to 1.22 nCi/kg. Similar changes occurred at the low flowrate.

The increase in the ratio of [Rn]/Q is consistent with the increases observed in a new well at The Geysers in an area of the steam field which had not yet undergone extensive production. Kruger and Warren (1979) postulated that this increase in radon concentration per unit flowrate may be caused by the presence of liquid water near the wellbore of a new well that boils out as production continues. In this case the increase in radon concentration could be attributed to the replacement of water by less dense steam, thus increasing the volume of rock emanating radon into the equivalent weight of fluid. Using a "grab" sample taken during early flow testing of the HGP-A well in January 1977 of 0.059 nCi/kg at a flowrate of 70 tons/hr, and the two later test results, Fig. *3-2* shows the expected value of radon concentration to flowrate ratio with the onset of production.

The results from the two short transient tests at Well HGP-A in Pohoiki, Hawaii, indicated a need for a long-term transient test on a liquid-dominated field. In January and February of 1979, a three-week transient test was run on Well M-11 at the Cerro Prieto geothermal field in Cerro Prieto, Baja California, Mexico. The 25-day radon transient experiment consisted of taking samples of the steam phase from a cyclone separator at full flow and again at reduced flow conditions. In addition to the transient test, two radon mass balances were made around the cyclone separator system to evaluate the partitioning of radon between the steam and liquid phases. Samples were also taken directly at the wellhead to compare the radon concentration obtained by the direct sampling of the two-phase fluid to the concentration determined by mass balance measurements.

Results from the mass balance measurements around the cyclone separator are shown in Table *3-4.* The mass balance at the high flowrate showed radon

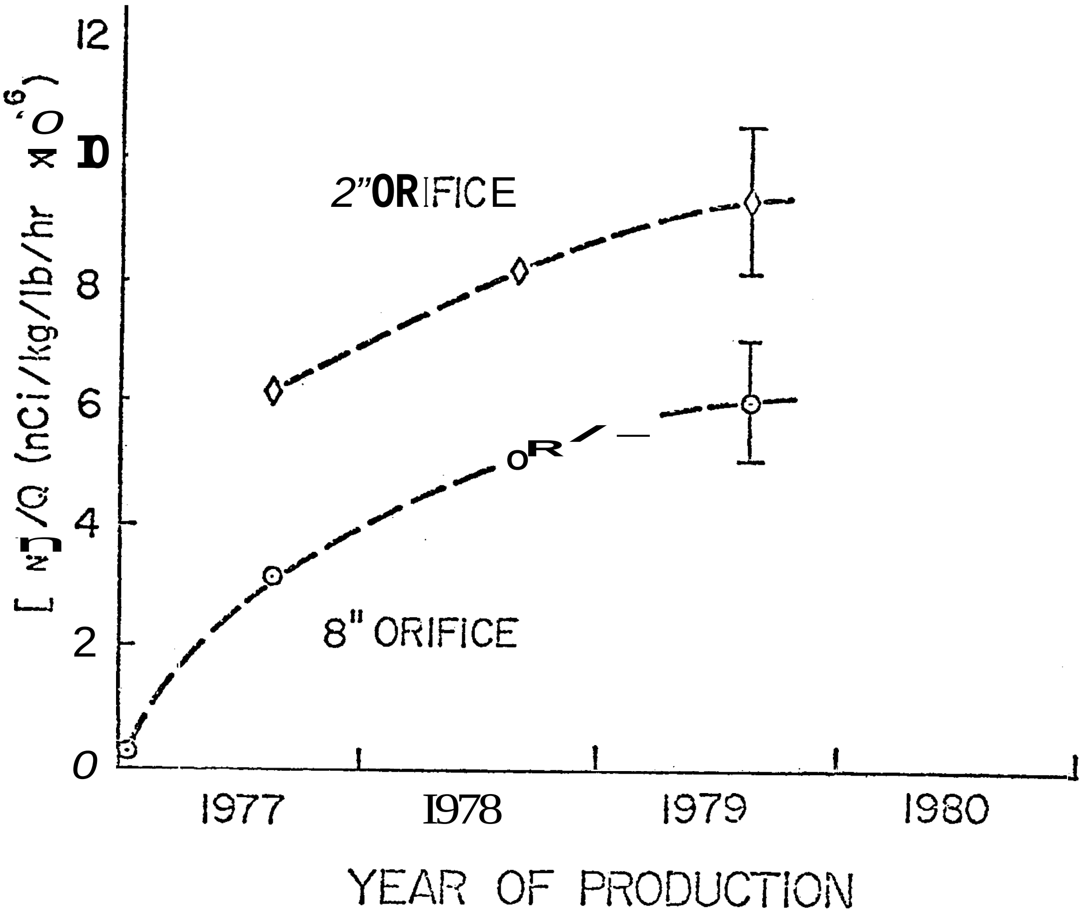


FIG. 3-2: RADON CONCENTRATION PER UNIT FLOWRATE HISTORY WITH EXTRAPOLATED VALUES FOR FUTURE PRODUCTION

partitions 95% into the steam phase after cyclone separation. The radon concentration at the wellhead calculated from the mass balance was 0.19 nCi/kg. The radon concentration measured from direct sampling of the two-phase fluid at the wellhead was 2.79 nCi/kg. The higher radon concentration obtained by direct sampling at the wellhead indicates that enrichment of noncondensible gases occurs when sampling the two-phase flow. Thus the mass balance approach is a much more quantitative method of measuring wellhead radon concentration. The steam sample from the second mass balance was lost during radon analysis. The mass balance is thus incomplete.

TABLE 3-4: MASS BALANCE OF RADON ACROSS CYCLONE SEPARATION, WELL M-11

Date	Location	Flowrate (t/hr)	[Rn] (nCi/kg)	[Rn] Fraction (%)
1/12/79	water	41.26	0.013	5
	steam	16.21	0.65	95
	wellhead			
	(calculated)	(57.47)	(0.192)	(100)
	measured		2.79	
1/30/79	water	27.20	0.014	(5)
	steam	11.15	lost	(95)
	wellhead			
	(calculated)	(38.35)	NA	(100)
	measured		6.26	

The radium content in the condensate of Well M-11 (Table 3-5) was measured by the double extraction technique. The radon produced from radium contained in the fluid was 0.0035 ± 0.0003 nCi/kg. This represents less than 2% of the total radon found in the geothermal fluid.

TABLE 3-5: RADIUM CONTENT IN CONDENSATE, WELL M-11

Date	$[Rn]_f$ (nCi/kg)	$[Rn]_i$ (nCi/kg)	$[Rn]_{wh}$ (nCi/kg)	$[Ra]_{wh}$ (%)
1/12/79	0.0037	0.013	(0.192)	1.9
1/30/79	0.0032	0.014	NA	---

Results of the transient test are summarized in Table 3-6.

TABLE 3-6: SUMMARY OF RESULTS, RADON TRANSIENT TEST, WELL M-11

Location	Mean Q (t/hr)	Mean [Rn] (nCi/kg)	[Rn]Q (nCi/hr x 10^4)
Steam from Separator			
Before Transient	16.1 ± 0.3	0.80 ± 0.13	1.29 ± 0.21
During Transient	10.5 ± 1.0	0.84 ± 0.40	0.88 ± 0.43
After Transient	16.5 ± 0.3	0.86 ± 0.13	1.42 ± 0.22
Wellhead			
Before Transient	57.2 ± 0.8	0.23 ± 0.04	1.32 ± 0.23
During Transient	39.7 ± 0.3	0.23 ± 0.11	0.91 ± 0.44
After Transient	56.0 ± 0.9	0.27 ± 0.04	1.51 ± 0.23

The average radon concentration was independent of flowrate, with a total average wellhead concentration of 0.23 nCi/kg at high and low flowrates. However, the radon concentration did vary from sample to sample, and, under reduced flow conditions, resulted in a large standard deviation of ±50%. The large fluctuations in radon concentration suggest a pulsing release of radon, which might be caused by the opening and closing of fractures caused by the rapid change in reservoir pressure or by anisotropic reservoir permeability.

Noncondensable gas analyses were performed at Cerro Prieto by the CFE staff during the transient test. Results of these analyses are shown in Table 3-7.

TABLE 3-7: NONCONDENSIBLE GAS ANALYSIS, WELL M-11

Date	Transient Time (days)	QS (t/hr)	$[CO_2]$ (ppt,wt)	$[H_2S]$ (ppt,wt)	[Gas] (wt %)
1/15/79	3.9	15.54	14.5	2.61	0.89
1/17/79	5.9	16.63	16.8	2.53	0.82
1/18/79					0.85
1/19/79	7.9	11.28	19.3	2.07	
1/30/79	18.9	11.15	17.2	2.24	0.87
1/31/79	20.3	16.50	14.8	2.13	
2/1/79	21.0	16.92	12.2	2.90	
1/6/79	26.1	15.10	13.1	2.09	

The date. for the noncondensable gas components CO_2 and H_2S in the steam phase also show variability. The CO_2 concentration increased approximately 20% at the low flowrate, suggesting a CO_2 source closer than the radon to the wellbore. The H_2S decreased by approximately 15% at the low flowrate. Changes in the gas composition suggest that changes in other chemical components as well as radon be examined in future transient well tests.

In August 1978, samples were collected from two wells at the Raft River field in Idaho. The results of these analyses are given in Table 3-8. The radon concentration was 0.87 nCi/kg in Well 1, operating at normal flow, and 0.012 nCi/kg in Well 2, operating at bleed flowrate. The single data value for Well 1 indicates a higher mean radon concentration compared to the mean value of 0.3 nCi/kg in liquid-dominated systems, such as the Imperial Valley, but about the same as observed at Pohoiki, Hawaii, which is a steam flashing liquid system. The lower concentration in Well 2 may have resulted from: (1) the decay of radon in and around the wellbore during the shut-in period, and (2) the decay of radon during the long transient time from the reservoir to the wellhead while operating under bleed flow conditions.

TABLE 3-8: RADON TEST RESULTS, RAFT RIVER, IDAHO, AUGUST **31, 1978**

Well	Time	P_{wh} (psig)	T_{wh} (°F)	Flowrate (gpm)	Radon (nCi/kg)
1	12:00 N	155.2	271.5	176	0.87
2	13:10	100.0	234.0	bleed	0.012

A radon test was run at the Casa Diablo field at Mammoth Lakes, California, to measure the radon concentration during early production operations in a liquid-dominated geothermal field. The isolated well at Casa Diablo was interesting to study because the fluid is pumped to the wellhead to keep it from flashing. Thus a comparison could be made to systems already studied wherein flashing in the well was allowed to take place.

The results of the three-week test (Table 3-9) are similar to those of the Cerro Prieto test. The steady-state radon concentration of 0.35 nCi/kg agrees with the average value of 0.25 nCi/kg observed at Cerro Prieto. Using the double radon measurement method, it was noted that 99% of the radon contained in the fluid resulted from radon emanation rather than from dissolved radium.

The consistent radon concentration in liquid-dominated systems studied thus far seems to indicate that the radial flow model of Stoker and Kruger (1975) for a confined aquifer of homogeneous radium distribution is valid for liquid-dominated systems.

TABLE 3-9: **RADON** TEST RESULTS, CASA DIABLO WELL, MAMMOTH LAKES, CALIFORNIA

Date	Time (PST)	Q_1 (gpm)	P_{wh} (psig)	T_{wh} (°F)	[Rn] (nCi/kg)
6/13/79	1915	79	198	328	0.37
6/13/79	1930	79	194	328	0.37
6/20/79	2000	79	194	325	0.35
6/28/79	1100	75	199	330	0.30
7/5/79	1000	65	207	316	2.29

Radium Content in the Condensate:

Date	$[Rn]_f$	$[Rn]_{wh}$	$[Rn]_f/[Rn]_{wh}$ (%)
6/13/79	.0030	0.370	0.8

(b) Radioactive/Stable Tracer Ratios

The ability to study other chemical tracers in geothermal reservoirs as well as radon during both transient and cross-sectional analysis is important in gaining a better assessment of geothermal reservoirs. A study was conducted to determine reliable methods to sample and analyze boron, ammonia, chloride, and noncondensable gases, and to improve the radon measurement methods. The study showed that it was feasible to measure the concentration of these chemicals without increased difficulties in field collection techniques, and still be able to complete the chemical analysis at Stanford.

The new collection method involves the condensation of steam in a double-stage condensation process (Nehring and Truesdell, 1977). The two-stage process enables effective cooling, which is required for proper chemical sampling.

In the prior method, radon samples were collected in 4.7 liter, evacuated steel cylinders. Using the new method of sampling, the total condensed steam fraction is taken into the evacuated steel cylinders. The steam condensate and noncondensable gasesarecollecteduntil 1 atm of pressure is reached in the container. The total amount of condensed steam collected depends on the noncondensable gas content and the final pressure in the steel cylinder. The radon content is measured using the Stoker and Kruger method (1975). The noncondensable gas content of the steam can be determined by pressure measurements.

- Ammonia

The total steam sample (both condensate and noncondensable) is collected in a bottle containing enough hydrochloric acid to lower the pH of the condensate to pH < 2, thus insuring that all the ammonia is present as ammonium ion (NH_4^+). The ammonia content in the steam is determined by analyzing the ammonium concentration of the condensate using the Kjeldahl distillation method, and by acidimetric titration of the distillate, as described in Standard Methods for the Examination of Water and Waste Water (1975).

- Boron and Chloride

The steam condensate is collected in a separate bottle. Condensate temperatures below 40°C are maintained during collection to insure proper collection. The boron content in the steam is determined using the Carmine methcd. The chloride content is determined by the Mercuric Nitrate method, also described in Standard Methods for the Examination of Water and Waste Water (1975).

- Results of Method Improvement Tests

A method improvement experiment was run at a producing well at The Geysers in March 1979 to test the new methods for sampling radon and other chemical components of interest. Samples for radon were also collected using the prior method of direct collection of steam into the evacuated steel cylinders. Results of the experiment (Table 3-10) reveal that the new method of sampling the steam for radon yields better reproducibility. A standard deviation of ±1% was obtained for the three samples collected using the new method, while a ±8% standard deviation was observed for the prior method of collection, consistent with prior results. The improvement using the total condensation method results from the larger quantity of sample which can be collected over a longer period of time.

TABLE 3-10: RADON SAMPLING PROCEDURE RESULTS, THE GEYSERS, 3/22/79

	Prior Method (Direct Sampling)				Revised Method (Steam Condensation)			
Sample	Time (PST)	Duration (min)	Condensate (g)	[Rn] (nCi/kg)	Time (PST)	Daraticn (min)	Condensate (g)	[Rn] (nCi/kg)
1	1230	1	89.3	33.3	1312	4	494	30.4
2	1310	1	105.7	30.7	1322	6	625	31.0
3	1452	1	105.4	37.2	1330	10	1010	31.2
Mean [Rn]			33.7 ± 2.7					30.9f0.3

CHEMICAL ANALYSIS RESULTS

Sample	Time (PST)	Ammonia (mg/l)	Boron (mg/l)	Chloride (mg/l)
1	1312	287	18.4	239
2	1322	316	16.5	221
3	1330	307	18.0	lost
Mean		303 ± 12	17.6 f 0.8	230 ± 9

The ammonia, boron, and chloride content of the steam was found to be in the concentration range that could be measured using the methods discussed earlier. The methods yielded reproducible results having a standard deviation of ±4%.

The standards method revealed that other chemical components in the steam did not interfere with the chemical analysis of ammonia, boron, and chloride.

Work was started on developing a method fordirect field measurement of radon without the need to return samples to the laboratory. The method involves direct sampling of the noncondensable gas content into Lucas scintillation cells, as described by D'Amore (1975). This work was conducted as part of the March methods test.

After condensation of the steam, the condensate and noncondensable gases were separated and the gas-steam ratio was measured using the method described by Christoffersen et al. (1975). Noncondensable gas samples were collected in 250 ml evacuated gas sample containers. At the Stanford laboratory, the gas samples were transferred directly to the Lucas cells for counting, after passing through a sampling train where H_2S gas was removed in an icdine scrubbing trap and residue water vapor was removed in a $CaSO_4$ trap.

The results of the direct field method of radon measurement are shown in Table 3-11, The radon in the total steam was calculated from the gas-steam ratio and from the activity of radon in the 125 ml Lucas cell.

This preliminary work demonstrated that radon can be measured directly in the field by sampling the noncondensable gases directly into Lucas cells. With appropriate precleaning, the method appears to be reproducible; the three samples tested to date have a standard deviation of ±5%. The gas samples taken directly into the Lucas cellshadan activity lower than the gas sample analyzed by the normal radon procedure, This lower activity probably results from CO_2 in the noncondensable gases lowering the counting efficiency of the scintillation cells. This effect must be considered in field measurement when noncondensable gases are collected. directlyinto Lucas cells. Further effort on this improvement should result in a mobile radon measurement system for field use,

TABLE 3-11: DIRECT MEASUREMENT OF RADON IN WELLHEAD GASES

Sample	Size (ml)	Rn (nCi)	$[Rn]_{gas}$ (nCi/l)	$[Rn]_{steam}$ (nCi/kg)
1	125	0.280	2.24	18.6
2	125	0.306	2.45	20.4
3	125	0.280	2.24	18.6
Mean				19.2
Radon Measurement with Laboratory Separation				
4	280	1.165	4.16	34.3

Gas-Steam Ratio: 8 l/kg

Efficiency Ratio of the Two Methods: $\frac{\text{direct}}{\text{separation}} = \frac{19.2}{34.3} = 56\%$

(c) Reservoir Transient Analysis

The use of cross-sectional measurements of radon concentration across a geothermal field may be a feasible method of studying fluid migration patterns and fluid age distribution in the field. Efforts were initiated during the current year to use radon and the other natural tracers to study such behavior. The wellhead concentration of radon depends on the type of reservoir emanation site, described by Kruger and Warren (1979). These include: (1) hydrothermally deposited radium close to the wellbore, (2) radium in a boiling liquid below a steam interface, and (3) radium present in the pathway from the source to the wellhead. A combination of transect analysis and transient test may help in determining which sources are prevalent.

The cross-sectional analysis of the Wairakei steam field in New Zealand was begun as a joint project between Prof. Roland Horne, Auckland University, New Zealand, and the Stanford Geothermal Program. The results from the first seven wells sampled at Wairakei are shown in Table 3-12. The radon concentration is in the steam phase after the cyclone separation process.

TABLE 3-12: SUMMARY, NEW ZEALAND RADON ANALYSIS

Wairakei Well	Date	Pressure (bars)	Flowrate (t/hr)	Condensate (g)	[Rn] (nCi/kg)
46	5/4/79	5	14.8	76.2	4.24
83	5/4/79	10	21.0	100.6	2.46
72	5/4/79	11	42.5	121.8	6.93
30	5/4/79	10.2	19.5	150.0	0.847
71	5/4/79	10	35.5	105.7	0.953
86	3/7/79	4.5	14.5	60.5	3.38
80	3/7/79	6.0	27.0	64.1	139.00

These preliminary results indicate variation in radon concentration in the reservoir, which may be caused by the effects of steam migration. Earlier studies by Belin (1959) suggest that hydrothermal alteration of radium may be responsible for these variations in concentration, which could explain the high concentration of 139 nCi/kg observed in Well 80.

At present, ten more wells in the transect are being sampled at Wairakei. In addition to radon measurement, the ammonia, boron, and chloride content of the fluids will be determined.

A transect analysis of fifteen steam wells was made at The Geysers, California, in May 1979. The new condensation collection method was used to collect samples for radon, boron, ammonia, and chloride analysis. The results from this test are currently being evaluated.

(d) Radon Emanation Studies, by L. Macias-Chapa, Engineer's Degree Candidate in Civil Engineering, and Prof. P. Kruger.

Construction of the physical model for establishing the parameters affecting radon emanation in geothermal reservoirs was completed during the current year. A schematic diagram of the model is given in Fig. 3-3. The system is designed to measure radon emanation as a function of five geothermal reservoir parameters: (1) rock type, (2) rock size distribution, (3) pore fluid density, (4) pressure, and (5) temperature.

Initial experiments are underway with a first rock loading of uniform size graywacke rock. Prior measurements were made with the reservoirs empty to obtain background measurements of radon emanation from the steel reservoirs. Data for these measurements and the graywacke loading are given in Table 3-13. The data show an uneven distribution of radium contamination in commercial steel. The graywacke rock loading shows sufficient radon emanation at room temperature to ensure successful measurements at the elevated pressure and temperature experiments.

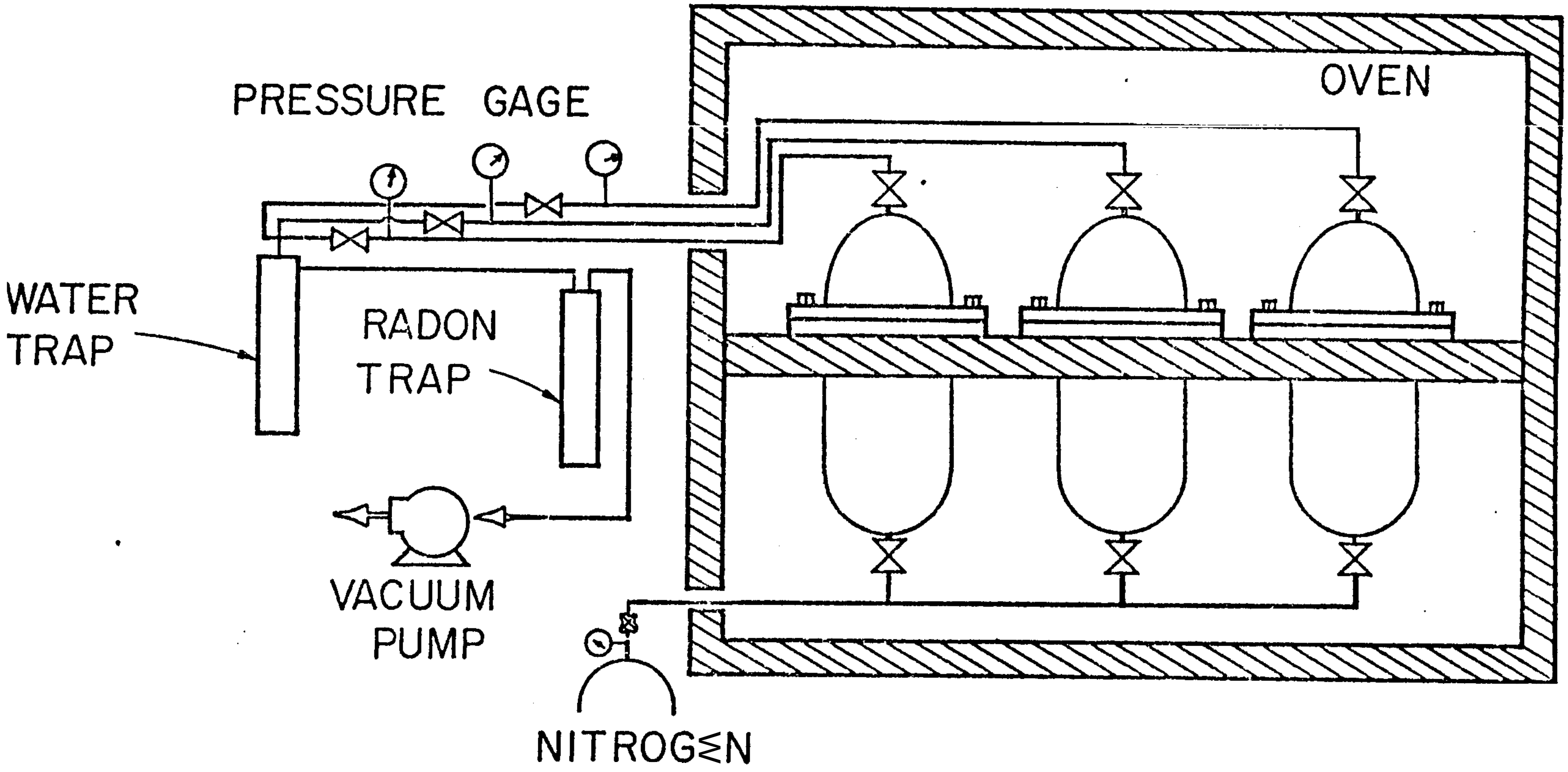


FIG. 3-3: RADON EMANATION SYSTEM

TABLE 3-13: CALIBRATION OF THE RADON EMANATION MODEL

Characteristics of the Model	
Geothermal Oven	
Inside Capacity:	1.2 x 0.61 x 0.91 m
Temperature Range:	Room to 343°C
Reservoirs	
Volume:	13.5 liters
Height:	51 cm
Outside Diameter:	20 cm
Rock Loading	
Material	Graywacke
Size:	0.6 to 1.8 cm average diameter
Porosity:	54%
Permeability:	Infinite
Pore Fluid	
Material:	Nitrogen
Radon Background of the Model	
Saturation Concentration at Full Volume:	
Reservoir Unit 1:	5 pCi/1
Reservoir Unit 2:	0.3 pCi/1
Reservoir Unit 3:	0.3 pCi/1
Calibration of Collection Efficiency from NBS Radium Standard	
Collection Sweep Efficiency:	60%

The set of experiments currently underway consists of groups of three simultaneous runs at a fixed temperature in the large geothermal airbath (oven) with a different pressure in each reservoir. The experiments will be repeated at increased temperatures to give the pressure and temperature gradients for emanation for each pore fluid. The set of pore fluids for the current rock loading is: (1) nitrogen as a nonpolar gaseous fluid for calibration, (2) superheated steam, and (3) liquid water. Current data are being prepared for a poster-session presentation at the 1979 Annual Meeting of the Geothermal Resources Council.

4. WELL TEST ANALYSIS

The behavior of a reservoir is usually monitored by observing changes in the reservoir temperature and pressure, and in the reservoir fluid composition with production of fluids. Many of the techniques for gaining information about a geothermal reservoir can be derived from standard engineering practices for both oil-and-gas and groundwater reservoirs. The methods of well test analysis have been an important tool for estimating reservoir extent and forecasting the potential fluid reserves and producing rates.

Certain assumptions, such as single-phase flow, isothermal conditions, and system idealities, are involved in many conventional well test analysis methods. To the extent that these assumptions are not limiting, the same methods may be applied for geothermal wells. Most of the results reported in this section may be applied generally. Such studies include the work on earth-tide effects, multilayered systems, interference testing, constant pressure testing, slug test DST analysis, and the transient pressure behavior in naturally fractured reservoirs. For use specifically in geothermal reservoirs, results are reported on steam-water relative permeability and the parallelepiped model, Some additional studies are planned for future research. These are discussed in the last part of this section.

(a) Earth Tide Effects, by P. Arditty, Engineer's Degree, Petroleum Engineering, and Prof. H. J. Ramey, Jr.

The gravitational attraction between the sun, moon, and earth induces a radial deformation of the earth which results in visually observable oceanic tides. The same mechanism also generates a state of stress on the surface of the earth which has been referred to as earth tides. Pressure transients caused by earth tides are of small amplitude: however, these transients are of sufficfent magnitude to cause water level variations in open wells and pits, and several investigators have indicated that a relationship exists between the amplitude of the response of an open well system and the characteristics of the formation and the fluid contained therein.

Arditty et al. (1978) modified the equations derived by Bodvarsson (1970) for an open well in a finite closed reservoir to apply to a shut-in well with the borehole completely filled with formation fluid. Only one phase is flowing in the reservoir, and the reservoir is confined and infinite in radial extent. The expression for pressure induced by an applied tectonic pressure, p_c, is given by:

$$p = p_{SD}\left(1 - \frac{ae^{n(a-r)}}{r\left[1+\frac{B}{i\omega}\left(\frac{1}{a}+n\right)\right]}\right) \tag{4-1}$$

with:

$$p_a = p_{SD}\left(1 - \frac{1}{1+\frac{B}{i\omega a}(na+1)}\right) \tag{4-2}$$

where $B = 4k/c_f\mu\ell$, $n^2 = i\omega/d$, ω = oscillation frequency, d = diffusivity $k/\phi\mu c$, a = wellbore radius, and r = radial distance from the well. The static pressure, p_{SD}, $= p_c(4G_m c_f - c_m)/(3+4G_m c_f)$, where p_c is an applied tectonic pressure, G_m is the rock matrix shear modulus, c_f is fluid compressibility, and c_m is matrix compressibility. The amplitude of the relative response, p_a/p_{SD}, is:

$$R_e(p_a/p_{SD}) \cong R_e\left(\frac{4k/i\omega\mu a\ell c_f}{1+\frac{4k}{i\omega\mu a\ell c_f}}\right) \qquad (4\text{-}3)$$

The critical frequency, ω_C, for which the response amplitude exhibits an abrupt decrease, is defined by:

$$\omega_c = \frac{4k}{\mu a\ell c_f} \qquad (4\text{-}4)$$

Tides are classified according to length of period, T: long period tides (T = 16 days); diurnal tides (T = 1 day), semidiurnal tides (T = 1/2 day); and terdiurnal tides (T = 1/3 day). If $\omega_c/2\pi >> 2$, then the critical frequency exceeds both the diurnal and semidiurnal frequencies, and $A_D/A_{SD} \approx 1$, where A_D and A_{SD} are the diurnal and semidiurnal amplitudes of the earth tide effect. If $1 < \omega_c/2\pi < 2$, then $1.25 < A_D/A_{SD} < 2$. If $\omega_c/2\pi << 1$, both amplitudes will be small, and undetectable. Thus, the ratio of the two amplitudes determines limits on the value of ω_c, which in turn gives an approximation for $k/\mu c_f$, since a and ℓ are known. If ω_c is computed from $k/\mu c_f$, an explanation for existence or nonexistence of tidal effects is provided.

A graph of amplitude versus period for a typical sandstone reservoir containing gas is shown in Fig. 4-1. From these results we would expect the diurnal tide amplitude to exceed the semidiurnal tide amplitude, and both should be detectable.

Figure 4-2 shows raw data from a fluid test. Figure 4-3 shows the data in Fig. 4-2 modified to show relative pressure variations. Spectral analysis using Fast Fourier Transforms provides the results shown in Fig. 4-4. The two small peaks in amplitude are caused by diurnal and semidiurnal tide effects. The reader is referred to Arditty et al. (1978) for more detail.

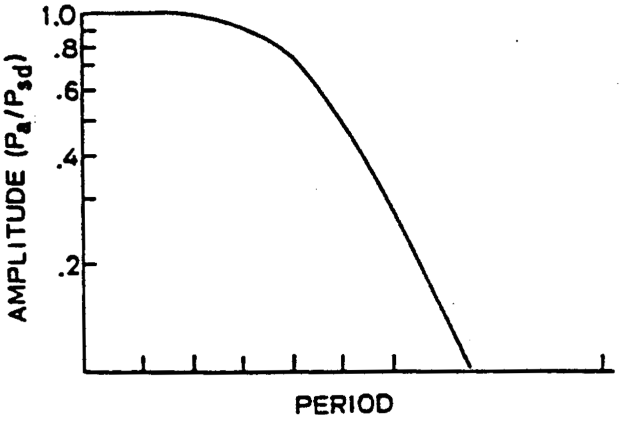


FIG. 4-1: RESPONSE (p_a/p_{SD}) OF A CLOSED-WELL RESERVOIR SYSTEM FOR A SANDSTONE CONTAINING GAS

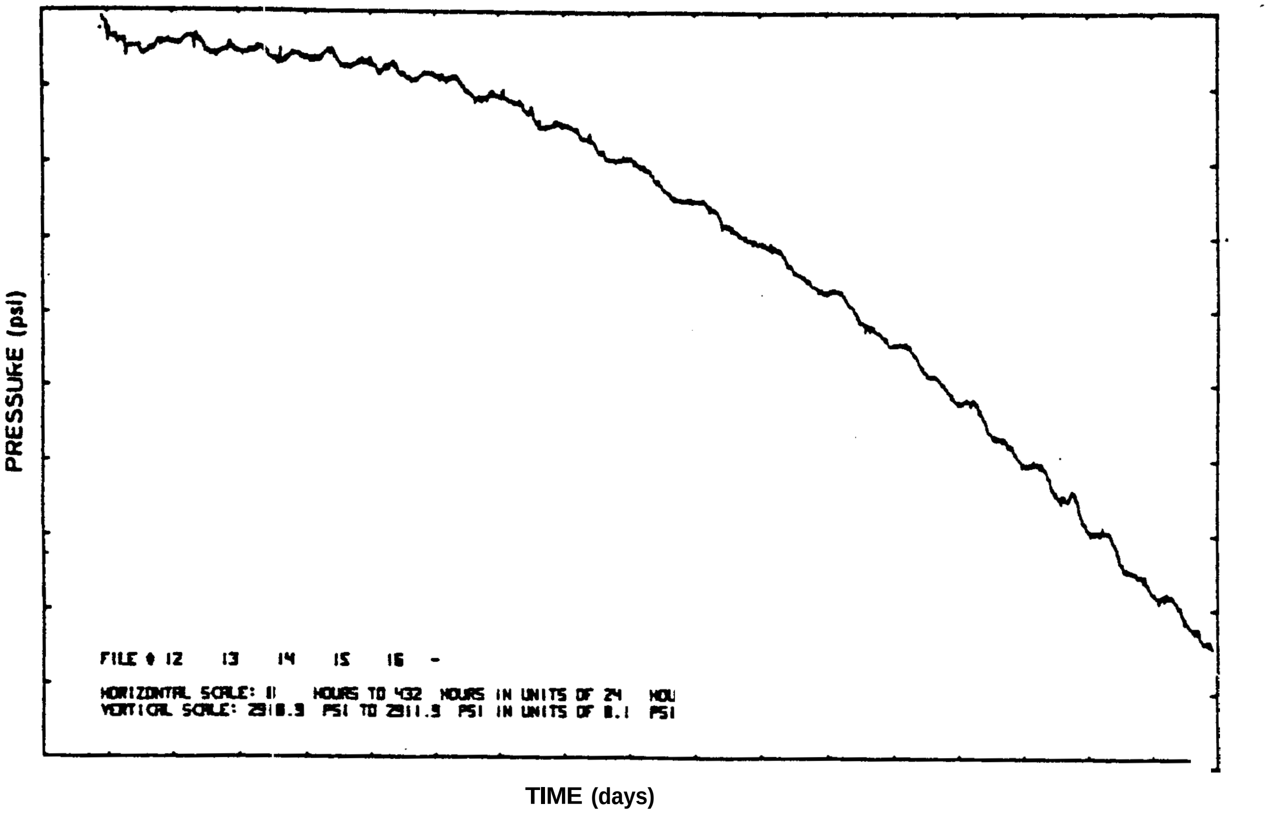


FIG. 4-2: INITIAL DATA FOR THE "A" FIELD

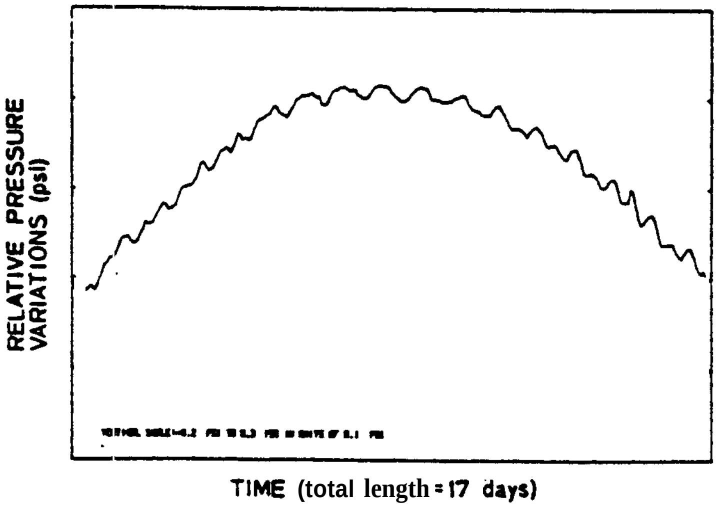


FIG. 4-3: MODIFIED DATA FOR THE "A" FIELD

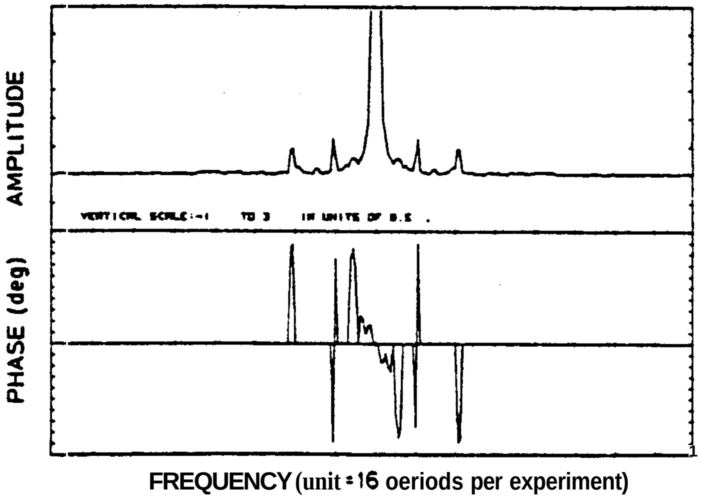


FIG. 4-4: SPECTRUM ANALYSIS BY FFT FOR "A" FIELD

(b) Multilayered Systems, by S. Tariq, Ph.D. Petroleum Engineer, and Prof. H. J. Ramey, Jr.

A mathematical model was derived by S. Tariq (1977) and Tariq and Ramey (1978) to satisfy the following conditions for a multilayered reservoir: each layer is horizontal and circular, homogeneous and isotropic, and bounded by impermeable formations at the top, bottom, and at the external drainage radius. Each layer has constant porosity and permeability, and uniform thickness, but the drainage radius may be different for different layers. The fluid in each layer has small and constant compressibility. Initial reservoir pressure is the same for each layer; and instantaneous sandface pressure is identical for all layers. Pressure gradients are small, and gravity effects are negligible. The total production rate, q, is constant, but the production rate for each layer may vary in time. The model for n layers is specified by the following equations:

$$\frac{\partial^2 p_j}{\partial r^2} + \frac{1}{r}\frac{\partial p_j}{\partial r} = \frac{\phi_j \mu_j c_j}{k_j}\frac{\partial p_j}{\partial t}; \quad p_j(r,t) = p_i - p_j(r,t), \quad r \varepsilon [r_{wj}, r_{ej}] \tag{4-5}$$

$$p_j(r,0) = 0 \tag{4-6}$$

$$\frac{\partial p_j}{\partial r}(r_{ej},t) = 0 \tag{4-7}$$

$$p_{wf}(t) = p_j(r_w,t) - S_j\left(r\frac{\partial p_j}{\partial r}\right)_{r_w} \tag{4-8}$$

$$q = C\frac{\quad}{\partial t} + \sum_{j=1}^{n} q_j(t)$$

$$= C\frac{dp_{wf}}{dt} - 2\pi\sum_{j=1}^{n}\left(\frac{kh}{\mu}\right)_j\left(r\frac{\partial p_j}{\partial r}\right)_{r_{wj}} \tag{4-9}$$

where $j = 1, 2, \ldots, n$; s_j = skin factor for each layer; and C = wellbore storage constant, cc/atm.

The system of equations is solved in Laplace space. The resulting solution is then numerically inverted using the algorithm by Stehfest (1970).

A thorough analysis of drawdown data generated for different types of layered systems was conducted. The cases investigated included layers having different perneabilities, thicknesses, radii, and skin effects. Log-log type-curves for analysis of multilayered systems were developed, and techniques for analyzing two-layered systems using semilog graphs of pressure versus time were described. The reader is referred to Tariq and Ramey (1978) and Tariq (1977).

(c) Interference Testing, by H. Sandal, Engineer's Degree, Petroleum Engineer, and Prof. H. J. Ramey, Jr.

As more sensitive pressure gauges have become available, interference testing--that is, observation of the pressure changes at a shut-in well resulting from a nearby producing well--has become feasible. Interference testing has the advantage of investigating more reservoir volume than a single-well test. For a producing well with large wellbore storage and skin effects, the combined effects of the storage and skin is to prolong the time needed for the sandface flowrate to become equal to the surface flowrate. Since the sandface flowrate is not constant during this time period, conventional interference testing, which assumes a constant rate, is not valid.

The mathematical model used in this study by Sandal et al. (1978) assumes the flow is radial, the medium is infinite, homogeneous, and isotropic with constant porosity and permeability, the single-phase fluid is slightly compressible with constant viscosity, pressure gradients are small, and wellbore storage and skin are constant. The equations which represent this system are the following:

$$\frac{\partial^2 p_D}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial p_D}{\partial r_D} = \frac{\partial p_D}{\partial t_D} \; ; \; p_D = p_D(r_D,t_D), \; r_D > 1, \; t_D > 0 \qquad (4\text{-}10)$$

$$p_D(r_D,0) = 0 \; ; \; r_D > 1 \qquad (4\text{-}11)$$

$$C_D \frac{\partial p_{wD}}{\partial t_D} - \left.\frac{\partial p_D}{\partial r_D}\right|_{r_D=1} = 1 \; ; \; t_D > 0 \qquad (4\text{-}12)$$

$$p_{wD} = p_D - S \left.\frac{\partial p_D}{\partial r_D}\right|_{r_D=1} \; ; \; t_D > 0 \qquad (4\text{-}13)$$

$$\lim_{r_D \to \infty} p_D(r_D, t_D) = 0 \; ; \; t_D > 0 \qquad (4\text{-}14)$$

where p_D, r_D, t_D, and C_D are dimensionless pressure drop, radius, time, and storage, respectively. p_{wD} is the pressure drop inside the wellbore, and S is the wellbore skin factor.

The equations are solved in Laplace space. The resulting Laplace space solution is numerically inverted using the Stehfest algorithm (1970).

Results were compared with the study by Garcia-Rivera and Raghavan (1970), which was based on the superposition of a series of line source solutions combined with sandface flowrates obtained for a finite radius well (Ramey and Agarwal, 1972, and Ramey, Agarwal, and Martin, 1975). The comparison indicated that for low values of the effective wellbore radius,

C_De^{2s}, the G'arcia-Rivera and Raghavan study may be in error. Figure 4-5 shows the close agreement between the two solutions for large values of C_De^{2s}. Figure 4-6 shows an example of differences between the two solutions.

(d) Steam/Water Relative Permeability, by R. Horne, Visiting Professor, Petroleum Engineering, K. Shinohara, Ph.D. Candidate in Petroleum Engineering, and Prof. H. J. Ramey, Jr.

Using production data from the Wairakei field, Horne (1978) and Shinohara (1978) demonstrated that steam/water relative permeability curves can be generated from field data. The method of analysis was suggested by Grant (1977), but improvements were made on the production data. Specifically, assuming negligible wellbore heat loss, steam and water discharges at the sandface were back-calculated from the surface values. The wellbore heat loss was less than 1% on the wells tested because they had been flowing for a long period of time at high .rates. Total discharge values were divided by the wellhead pressure in order to filter out changes in discharge due only to pressure depletion in the reservoir. Thus changes in discharge due only to relative permeability effects were isolated. The actual downhole temperature was used to determine fluid densities, viscosities, and enthalpies. Finally, flowing water saturation was determined from the back-calculated sandface steam and water discharges. They did not consider the immobile fluid in the reservoir.

Relative permeabilities were computed from equations for Darcy's law and the flowing enthalpy:

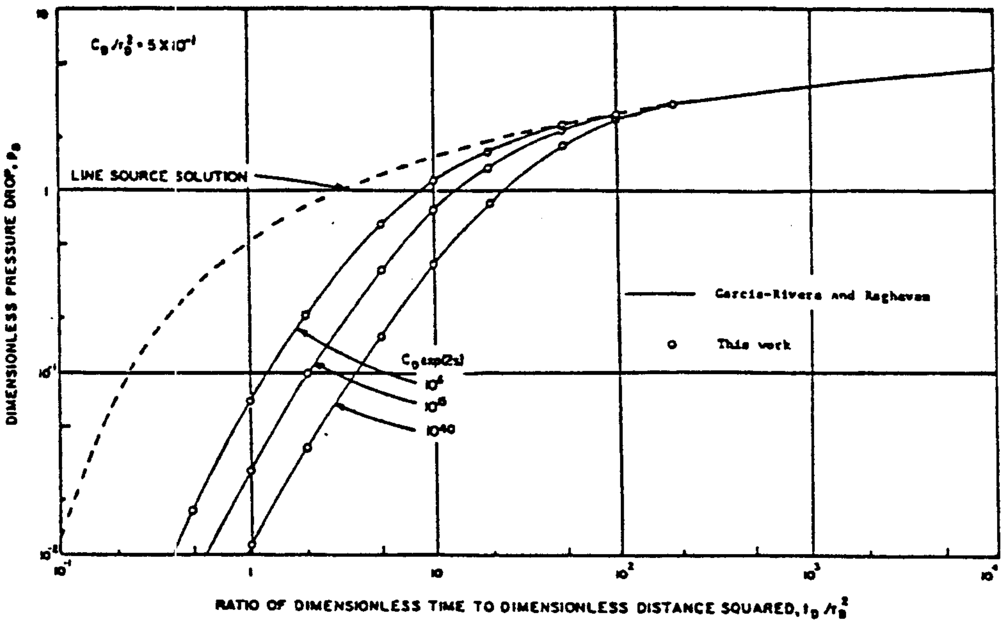


FIG. 4-5: COEPARISON OF RESULTS OF THIS STUDY WITH THE GARCIA-RIVERA AND RAGHAVAN STUDY

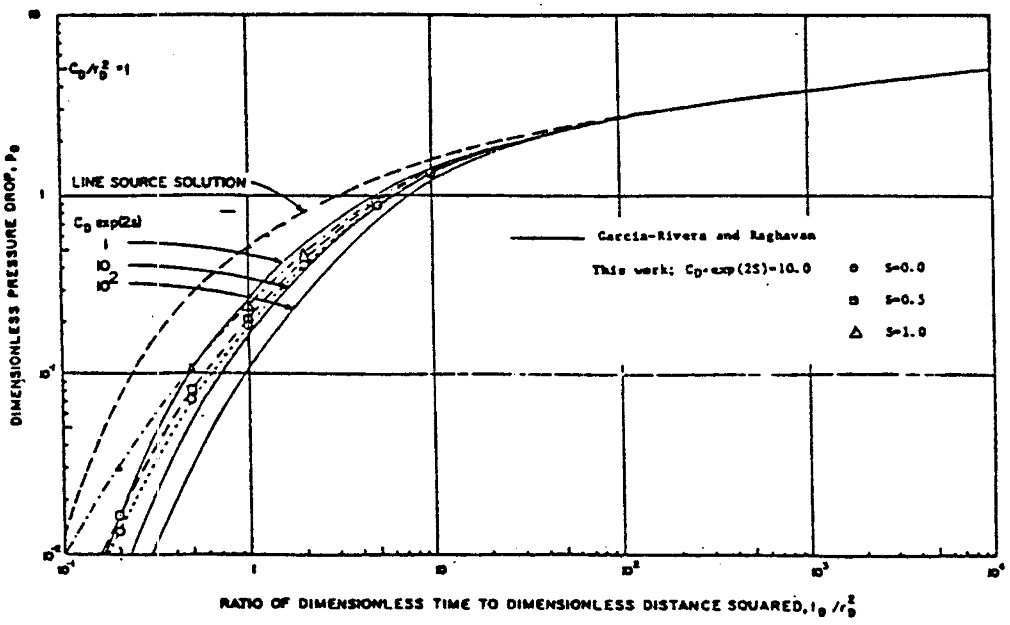


FIG. 4-6: COMPARISON OF RESULTS OF THIS STUDY WITH THE GARCIA-RIVERA AND RAGHAVAN STUDY

$$q_w = -\rho_w \frac{k}{\mu_w} F_w(S_w)\ A\ p' \qquad (4-15)$$

$$q_s = -\rho_s \frac{k}{\mu_s} F_s(S_w)\ A\ p' \qquad (4-16)$$

$$h = \frac{\rho_w h_w F_w(S_w)/\mu_w + \rho_s h_s F_s(S_w)/\mu_s}{\rho_w F_w(S_w)/\mu_w + \rho_s F_s(S_w)/\mu_s} \qquad (4-17)$$

where q is the discharge rate, ρ is the one-phase fluid density, μ is the viscosity, A is the flow area, p is the pressure gradient, F is the relative permeability, S_w is the flowing water saturation, and subscripts s and w refer to the steam and water phases. Figure 4-7 shows the resulting permeability curves.

Future improvements on this method will include incorporation of wellbore heat loss in the calculation of fractional flow, and the use of irreducible water saturations estimated from results of experimental studies in the Stanford Geothermal Program.

(e) Constant Pressure Testing, by C. Ehlig-Economides, Ph.D. Petroleum Engineer, and Prof. H. J. Ramey, Jr.

Although the conditions which result in constant pressure flow often exist for geothermal production and injection wells, the methods for analyzing the resulting rate transients and pressure buildup for such wells have been incomplete or nonexistent. The objective of this work is to review the existing methods of analysis and to contribute new solutions where needed in order to produce a comprehensive well test analysis package for wells produced at constant pressure. The work is near completion, and a technical report will be published. Other publications of results from this project are given by Ehlig-Economides and Ramey (April and June 1979).

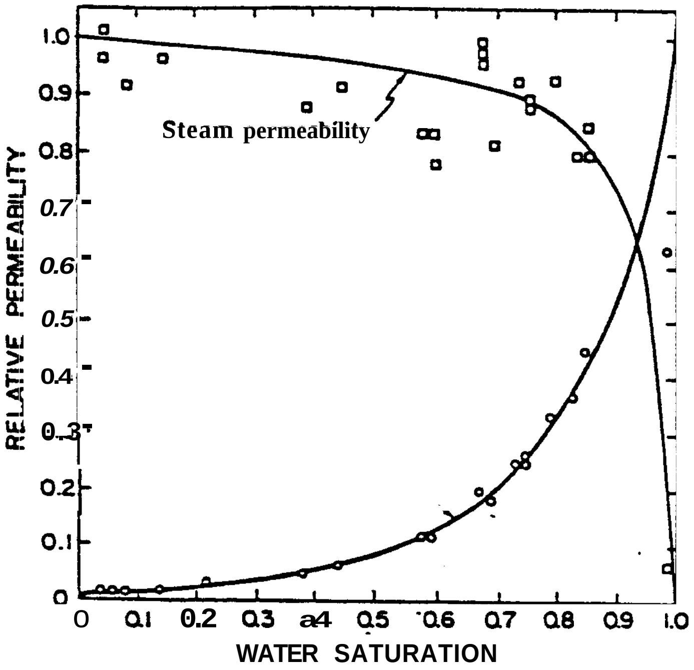


FIG. 4-7: STEAM-WATER RELATIVE PERMEABILITIES FROM WAIRAKEI WELL DATA

The methods provided in this work are summarized by the following:

- Determination of k and @e^{-2s} by type-curve matching with a graph of log q_D versus log t for the infinite system.
- Determination of k and s from the semilog straight line in a graph of 1/q versus log t.
- Determination of reservoir area and approximate shape from a graph of log q versus t after the onset of exponential decline.
- Analysis of transient rates when the wellhead pressure is constant.
- Determination of k and @e^{-2s} from an interference test by type-curve matching with a graph of log p versus log t_D/r_D^2 for the infinite system.
- Determination of C_D, s, and x_f for fractures penetrated by the wellbore, and other inner boundary effects, by type-curve matching of early pressure buildup data with conventional pressure transient solutions.
- Horner buildup analysis for wells produced at constant pressure.
- Analogous methods for the Matthews, Brons, and Hazebroek determination of static reservoir pressure.

(f) The Parallelepiped Model, by T. Schultz, M.S. Candidate in Petroleum Engineering, Prof. H. Cinco-Ley, and Prof. H. J. Ramey, Jr.

Recent well test data from both The Geysers and the Travale-Radicondoli fields suggest that the parallelepiped model, shown schematically in Fig. 4-8, may be an appropriate approximation for both geothermal reservoirs. Through the use of source functions, Green's functions, and the Neumann product method described by Gringarten and Ramey (1973), solutions are readily available for a number of related problems. The model assumes three-dimensional flow in a reservoir bounded by impermeable and/or constant pressure boundaries with a well located at any point in the reservoir. The well may be fully or partially penetrated through the reservoir

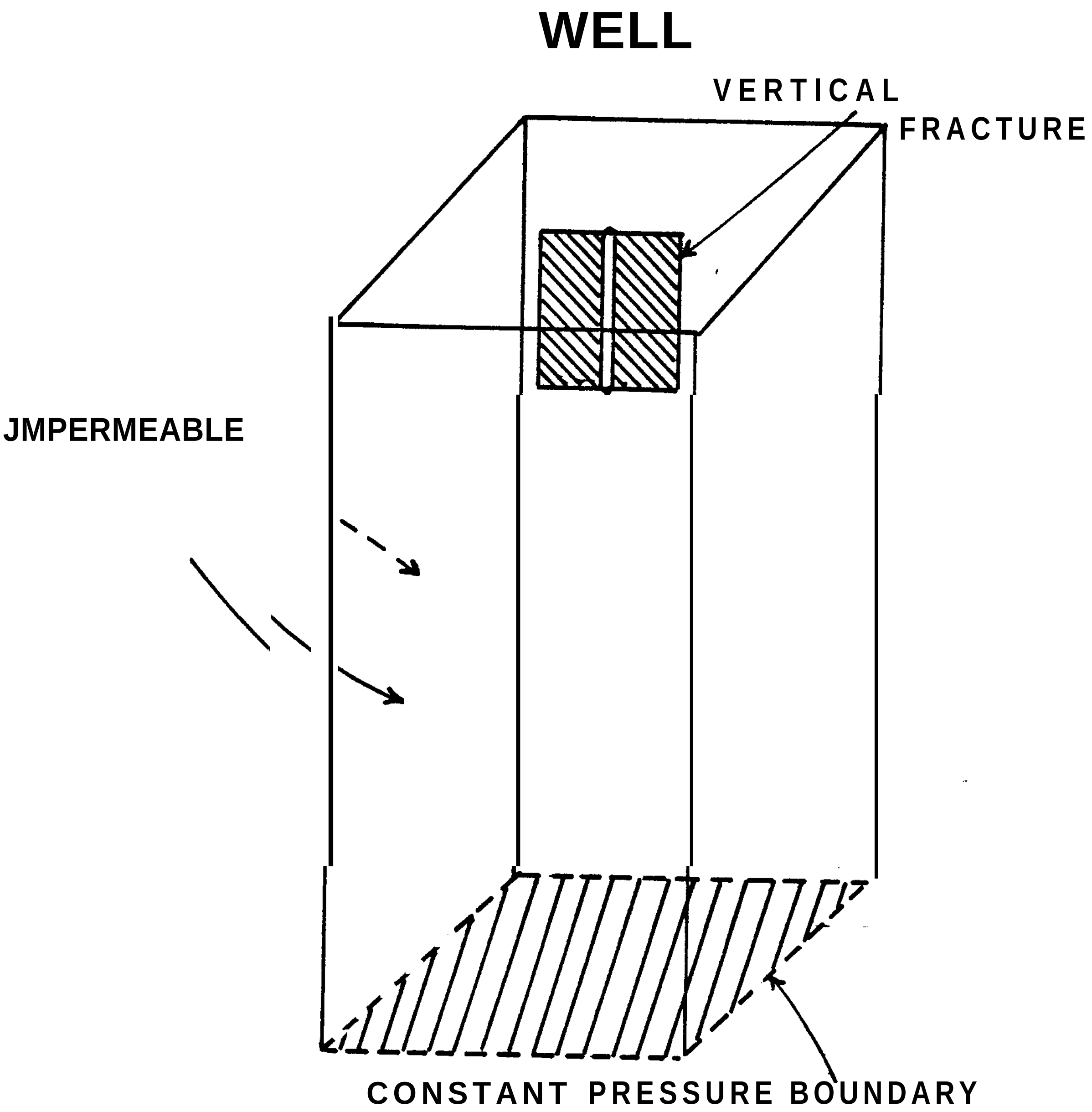


FIG. 4-8: PXRALLELEPIPED MODEL FOR A WELL INTERSECTED BY A PARTIALLY PENETRATING VERTICAL FRACTURE

thickness and may intersect a horizontal or a vertical fracture. The analytical solutions in the form of infinite sums and integrals are integrated by computer.

The objective of this study is to produce generally useful type-curves with a focus on detection of the postulated boiling front at the base of the reservoir, or a source which has a similar behavior. The boiling front constitutes a constant pressure boundary if the reservoir may be assumed to be isothermal. This work will directly augment field studies.

(g) "Slug Test" DST Analysis, by K. Shinohara, Ph.D. Candidate in Petroleum Engineering, and Prof. H. J. Ramey, Jr.

The solutions for the slug test (decreasing flow rate) drill stem test (DST), including wellbore storage and the skin effect, were presented by Ramey et al. in 1975. In field data from slug test DSTs, an initial period of constant flowrate can often be observed. Thus a new model which includes the initial constant flowrate 'for a slug test was developed. Type-curves were graphed which were then matched with field data. Two examples of the quality of the match between actual data and a slug test type-curve are shown in Fig. 4-9. The slug test type-curves can be applied to both the flow period and the pressure buildup after the initial shut-in in the DST. A special feature of the new type-curves is that they may be used to estimate the initial formation pressure from the initial cleanup flow pressure buildup data.

In deep high rate wells, the inertia and momentum of the fluid moving in the wellbore become important. Most available pressure transient solutions neglect these phenomena. Sometimes the inertia effect can cause oscillation of the fluid level in the wellbore. An approximate method

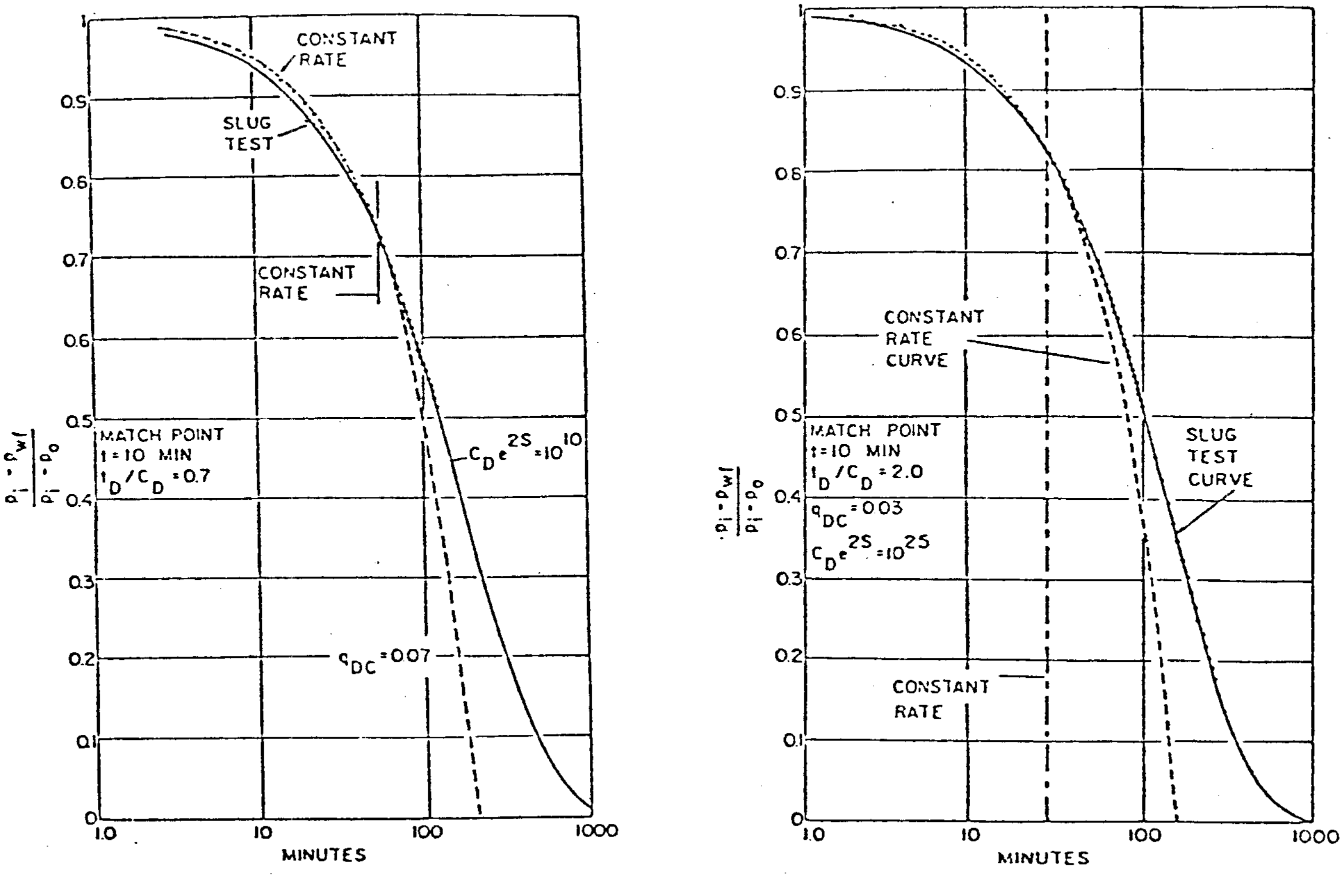


FIG. 4-9: FIELD DATA MATCHED WITH SLUG TEST AND CONSTANT RATE TYPE-CURVES

using an exponentially damped fluctuation was presented by van der Kamp in 1976. However, this method cannot be applied to the early time pressure behavior, which is often of interest. A complete solution for this problem was found and the resulting type-curves were graphed and matched with field examples. Figure 4-10 shows some of the new solutions. The parameter x_D represents the fractional liquid level rise following the sudden removal of the liquid from a static wellbore. This acts like opening a bottomhole valve in a DST when there is air in the drill pipe, The parameter a is:

$$\alpha = \frac{L}{g}\left(\frac{k}{\phi\mu c_t r_w^2}\right)^2$$

where L is the **well** depth and g is the acceleration of gravity. Other **symbols** have their usual meaning. The term α is a new parameter which considers momentum or inertia of fluid in the wellbore. A value $\alpha = 0$ is the usual slug test. When α reaches values of 10^5 or more, the results differ greatly from the slug test. Oscillations occur when α is 10 or more. Both the skin effect and wellbore storage affect the results significantly.

This theory can also be applied to closed-chamber DSTs and water injection falloff tests. These results will be published in **SPE** 8208, by Shinohara and Ramey (1979).

Further work is planned during the coming year on inertial effects. Also proposed for future work is a bench-scale model experiment to simulate the slug test wellbore conditions.

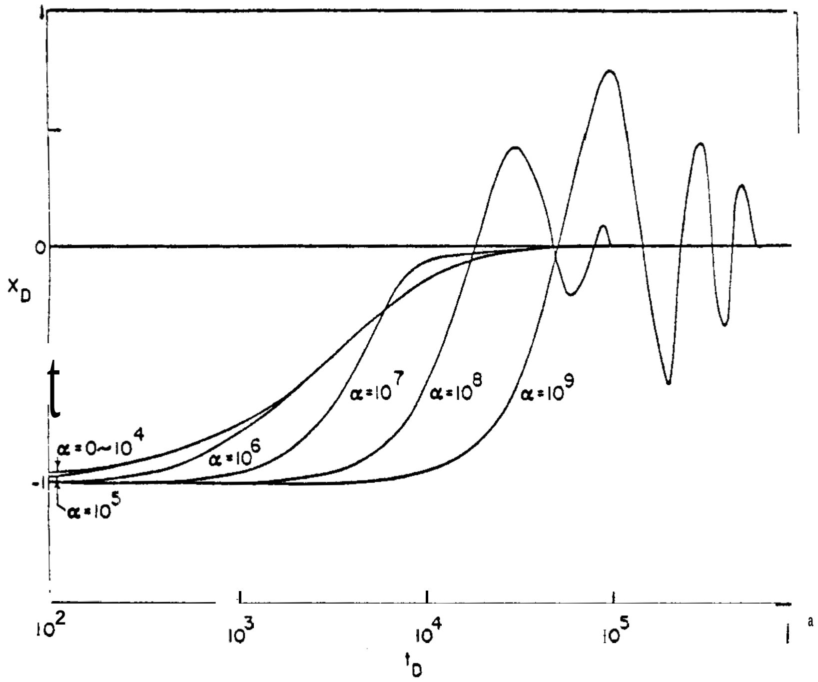


FIG. 4-10: LIQUID LEVEL VS **TIME FOR** THE UNDAMPED SLUG **TEST**

(h) Naturally Fractured Reservoirs, by M. Mavor, M.S. Degree, Petroleum Engineering, Prof. H. Cinco-Ley, and Prof. H. J. Ramey, Jr.

This study considers a horizontal radial reservoir initially at uniform pressure with impermeable upper and lower boundaries. The system was treated as a continuum with the fracture network superimposed on the primary porosity. This idealization resulted in two pressures, matrix and fracture, at each location in space. The primary porosity contained the majority of the fluid stored in the reservoir, while all flow through the reservoir to a fully penetrating well was confined to the secondary system. The fracture permeability was assumed to be constant and to exceed the constant matrix permeability by at least one order of magnitude. The rock compressibility of each system was constant and independent of the pressure in the opposite system. Darcy flow was assumed. The single-phase fluid had constant viscosity and a constant compressibility of small magnitude. The fluid density at any point in space was the same value in the matrix as in the fractures. Figure 4-11 shows a schematic representation of fractured media.

This study was an extension of the work of Warren and Root (1963) to include wellbore storage and damage, and the transient rate response for a constant producing pressure in an infinite system. Type-curves of the analytical solutions were graphed in terms of the following dimensionless parameters:

$$p_D = \frac{kh(p_i - p)}{141.2 qB\mu} \qquad (4-18)$$

$$t_D = \frac{.000264\, k_f t}{(\phi_m c_m + \phi_f c_f)\mu r_w^2} \qquad (4-19)$$

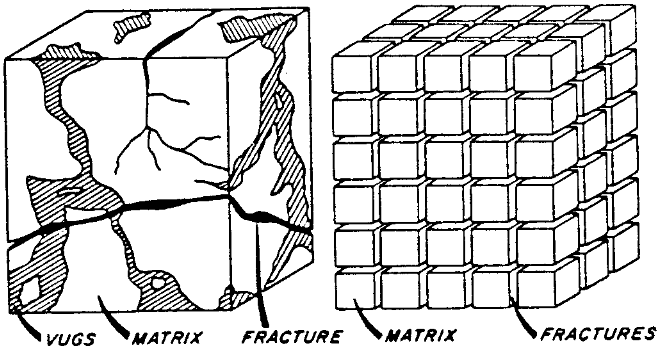


FIG. 4-11: SCHEMATIC ILLUSTRATION OF A NATURALLY FRACTURED RESERVOIR AND ITS IDEALIZATION. AFTER WARREN AND ROOT.

$$\lambda = \frac{\alpha k_m}{k_f} r_w^2 \qquad (4-20)$$

$$w = \frac{\phi_f c_f}{\phi_m c_m + \phi_f c_f} \qquad (4-21)$$

$$C_D = \frac{C}{2\pi\phi c_t h r_w^2} \qquad (4-22)$$

where k_f and k_m are fracture and matrix permeabilities, respectively, $\phi_f c_f$ and $\phi_m c_m$ are fracture and matrix porosity-compressibility products, respectively, and a is the interporosity shape factor.

The Warren and Root model indicated the characteristic two-slope behavior of the graph of p_D versus log t_D, as shown in Fig. 4-12. However, results of this work indicated that the early time behavior may be dominated by storage effects, as shown in Fig. 4-13. The storage effect can mask the two-slope semilog behavior, as shown in Fig. 4-14. Late time behavior in a closed, naturally fractured reservoir exhibits pseudosteady-state behavior, as shown in Fig. 4-15.

Some results for constant pressure production were also provided. In particular, the reciprocal of the flowrate when graphed as a function of log time also shows the two-slope behavior.

Future Studies

Although well test analysis studies have produced many papers and reports, additional work is contemplated on many of the studies described in this report because almost every problem solution seems to produce several other important and related problems. The work on inertial effects for high rate movement of liquids in a wellbore appear especially productive, and will continue during the coming year. This work has broad

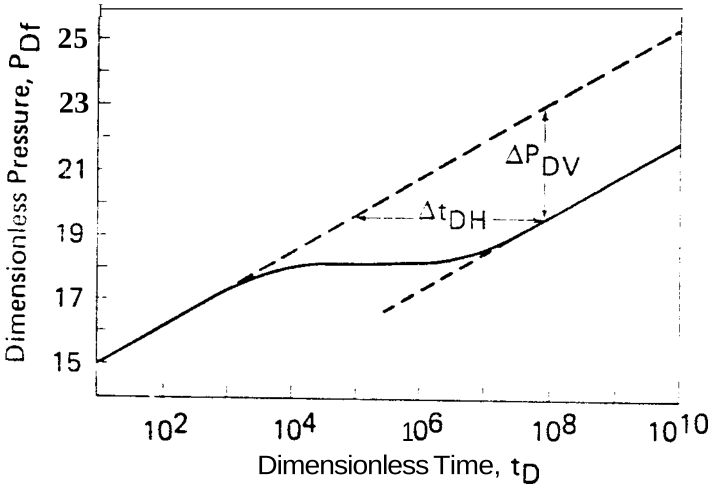


FIG. 4-12: DIMENSIONLESS PRESSURE VS DIMENSIONLESS TIME,
W = 1-3, λ = 10-7, S = 10

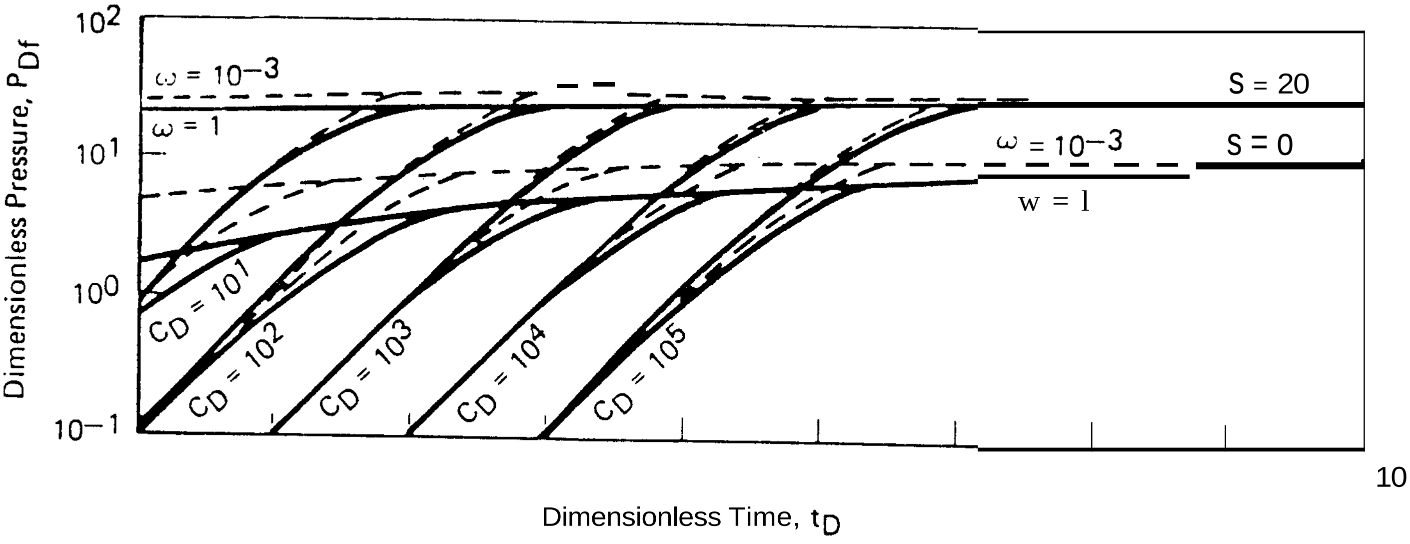


FIG. 4-13: EFFECTS OF WELLBORE STORAGE AND SKIN; INFINITE NATURALLY FRACTURED RESERVOIR, $\lambda = 10^{-9}$

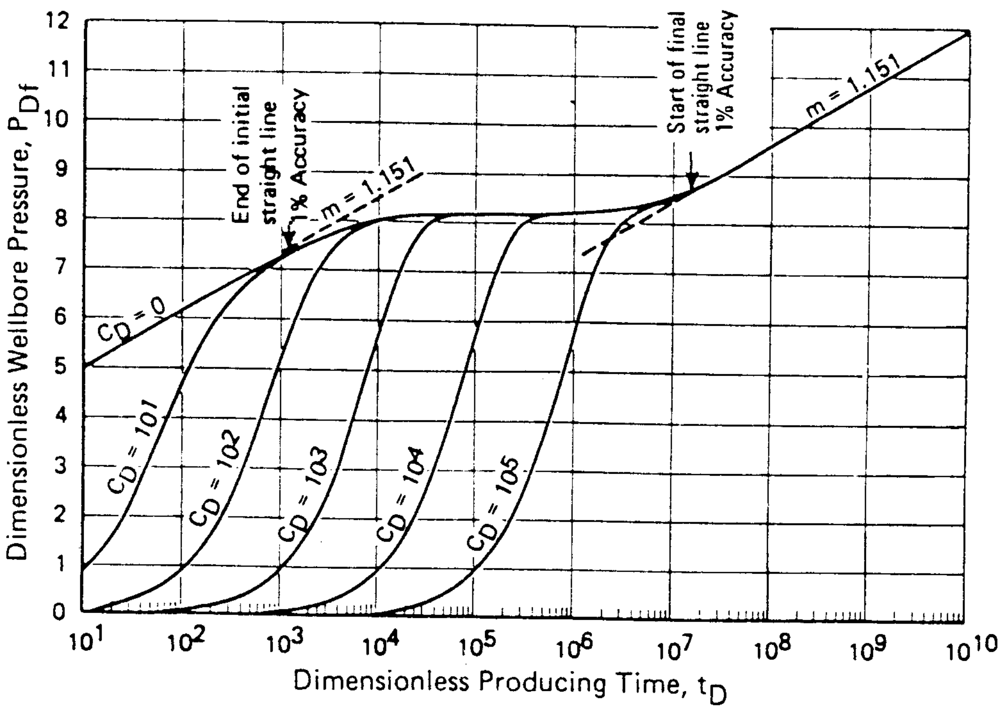


FIG. 4-14: NATURALLY FRACTURED RESERVOIR DRAWDOWN BEHAVIOR WITH STORAGE; $w = 10^{-3}$, $\lambda = 10^{-7}$

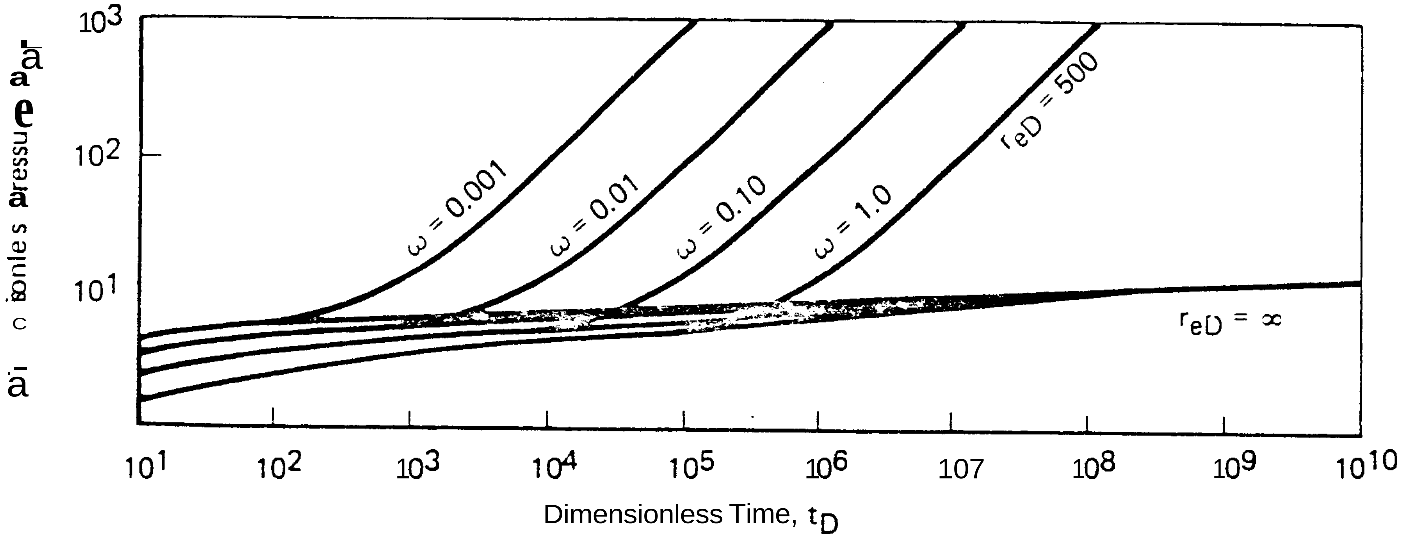


FIG. *4-15a:* CLOSED, NATURALLY FRACTURED RESERVOIR BEHAVIOR, $A = 10^{-9}$

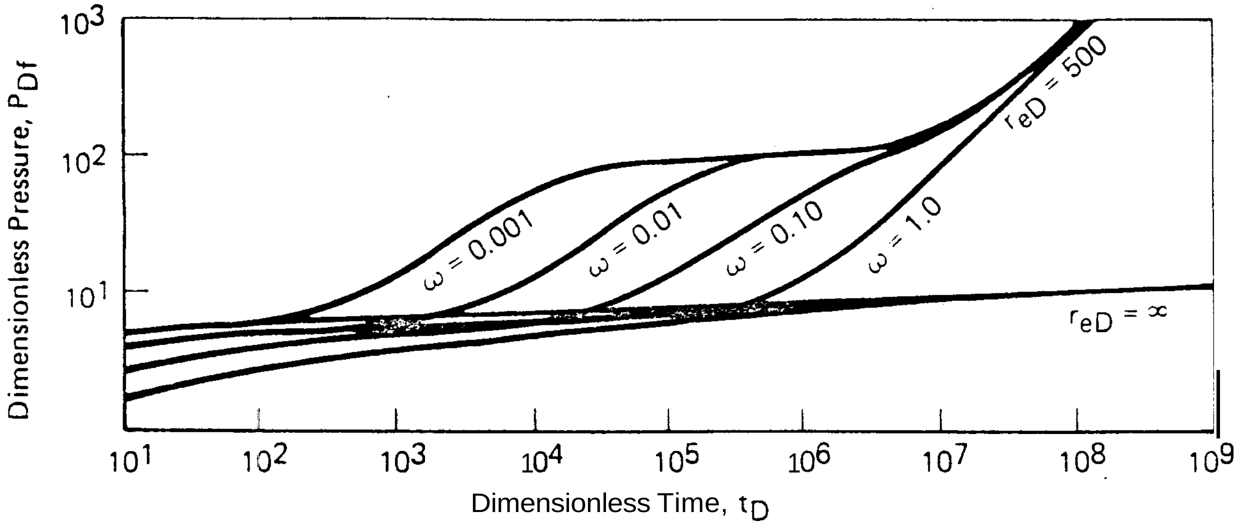


FIG. 4-15b: CLOSED, NATURALLY FRACTURED RESERVOIR BEHAVIOR, $A = 10^{-7}$

implications for all types of fluid production, and is particularly important for drill stem testing. Work on fractured systems, the parallelepiped models, and constant pressure testing will also continue. New work on composite systems involving changes in fluid phase and permeability in the areal sense is planned for the coming year; it will be applied to handling well test data in systems involving steam bubbles in liquid-dominated systems. Finally, continued work on determination of relative permeability from test data is also intended.

It is expected that Prof. R. N. Horne will rejoin our staff during 1979-80.

5. CONCLUSIONS AND RECOMMENDATIONS

The Stanford Geothermal Program offers a diverse and intensive program of research in geothermal reservoir engineering. In this section each of the four major areas of study are examined from the viewpoint of the overall program. Conclusions are offered, as well as plans for future areas of research.

In the area of well test analysis, each of the project reports summarized a published paper. Many additional well test studies were conducted at Stanford without the aid of outside financial support. These efforts include the work by H. Cinco-Ley and H. J. Ramey on a well test analysis package which will incorporate most of the existing well test analysis methods with user-interactive computer programs for automatic history matching, automatic-type curve matching, and reservoir simulation. Naturally, geothermal well test analysis will benefit from this related study. Other studies proposed for next year were described in the last report in Section 4 of this document. There is intense interest in application of the results of these studies to geothermal field data. Practical applications to date include four commercial geothermal fields and a number of other geothermal research field tests on new, potentially commercial activities. Graduates of this program are highly sought as employees by energy companies and laboratories.

The energy extraction studies now include two major components: the Large Reservoir Model and the bench-scale model for simulation of thermal stress fracturing. These models provide fundamental information about the conditions which promote increased energy extraction and natural reservoir stimulation. This research will continue in the direction indicated in the progress reports. A technical report is planned for publication next fall on the recent experiments on the Large Reservoir Model.

Much of the research on the bench-scale flow models is ready or nearly ready for publication in technical reports. The experimental steam-water relative permeability results suggest that the generalized relative permeability curves for gas/oil or water/oil systems may not be directly applicable for geothermal fluid systems. The study on vapor pressure lowering yields conclusive evidence that adsorption is the primary mechanism for that phenomenon, and may be a major source of steam for vapor-dominated systems. It is planned that new members of the Stanford Geothermal Program staff will continue work on these projects in the fall. An additional project is proposed to examine the growth and propagation of vapor bubbles in porous media.

Considerable work was done in the past year in the area of radon transient analysis. A number of new radon field tests were conducted; results of those tests are summarized herein. The radon emanation bench-scale model has been constructed and is operational. The feasibility study on the use of boron and ammonia as tracers is in progress. Evidence of the usefulness of radon as a natural reservoir tracer is now in hand. Additional field tests are planned for next year to further correlate the radon transient responses to different reservoir conditions. The bench-scale radon emanation model will aid in verifying the local behavior of radon transport through the porous medium.

In addition to the primary research responsibilities, the Stanford Geothermal Program aids dissemination of information to the geothermal industry at large through its sponsored meetings and through outside meeting attendance and advising by participants in the Stanford program. Travel and meeting attendance during this reporting period is indicated in Appendix D. Program-sponsored meetings include the weekly Geothermal Seminar and the Annual Geothermal Reservoir Engineering Workshop. The programs for these meetings are found in Appendix E. In addition, the Stanford Geothermal Program was pleased to host 37 visiting Japanese geothermal managers and technical personnel for an afternoon meeting including a seminar describing our research program and a tour of the laboratory facilities. Many other visitors to Stanford toured the geothermal laboratories during the year. Active cooperation with other research efforts at national laboratories, industrial laboratories, and other universities continued to be a major thrust of the Stanford Geothermal Program, and we expect this policy to continue to benefit a mature research effort.

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.

Arditty, P.C.: "The Earth Tide Effects on Petroleum Reservoirs, Preliminary Study," Engineer's Degree Thesis, Stanford University Petroleum Engineering Department, 1978.

Arditty, P.C., Nur, A.T., and Ramey, H.J., Jr.: "Response of a Closed Well-Reservoir System to Stress Induced by Earth Tides," Paper SPE 7484, presented at the 53rd Annual Fall Meeting, SPE of AIME, Houston, Texas, Oct. 1978.

Aruna, M.: "The Effects of Temperature and Pressure on Absolute Permeability of Limestone,'' Ph.D. Dissertation, Stanford University Petroleum Engineering Department, 1976.

Bankoff, S.G.: "Growth of a Vapor Bubble in Porous Media," Congress A.I.R.H., Haifa, Israel, 1969.

Belin, R.E.: "Radon in New Zealand Geothermal Regions," Geochimica et Cosmochimica Acta (1959), 16, 181-189.

Bodvarsson, G.: "Confined Fluid as Strain Meters," J. Geoph. Res. (1970), 75, No. 14, 2711.

Brigham, W., and Morrow, B.: "P/Z Behavior for Geothermal Steam Reservoirs, Paper SPE 4899, presented at the 44th Annual California Regional Meeting, SPE of AIME, San Francisco, California, Apr. 4-5, 1974.

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

Casse, F.J.: "The Effect of Temperature and Confining Pressure on Fluid Flow Properties of Consolidated Rocks," Ph.D. Dissertation, Stanford University Petroleum Engineering Department, 1974.

Castanier, L.: "Etude Experimentale du Changement of Phase en Milieu Poreux," These de Docteur-Ingenieur, Institut National Polytechnique de Toulouse, France, July 1978.

Castanier, L., and Bories, S.: "Experimental Results from a Bench-Scale Model for Phase Change Study by In-Situ Vaporization in Porous Media," Paper SPE 8002, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, April 18-20, 1979(a). Work done at E.N.S.E.E.I.H.T., Toulouse, France.

Castanier, L.: "A Lumped-Parameter Numerical Model of a Two-Phase Geothermal Reservoir," unpublished manuscript, June 1979(b).

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, SPE of AIME, Denver, Colorado, Oct. 1977.

Chen, Hsiu-Kuo: "Measurement of Water Content of Porous Media Under Geothermal System Conditions," SGP-TR-15, August 1976.

Christoffersen, D., Wheatley, R., and Baur, J.: Proc., First Workshop on Sampling Geothermal Effluents, Las Vegas, Oct. 1975.

Counsil, J.R.: "Steam-Water Relative Permeability," Ph.D. Dissertation, Stanford University Petroleum Engineering Department, May 1979.

D'Amore, F.: "Radon-222 Survey in Larderello Geothermal Field, Italy," Geothermics (1975), 4.

Danesh, A., Ehlig-Economides, C., and Ramey, H.J., Jr.: "The Effect of Temperature Level on Absolute Permeability of Unconsolidated Silica and Stainless Steel," Trans., Geothermal Resources Council (1978), 2, 137-139.

Ehlig-Economides, C., and Ramey, H.J., Jr.: "Pressure Buildup for Wells Produced at a Constant Pressure," Paper SPE 7985, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979(a).

Ehlig-Economides, C., and Ramey, H.J., Jr.: "Transient Rate Decline Analysis for Wells Produced at Constant Pressure," Paper SPE 8387, to be presented at the 54th Annual Technical conference and Exhibition, SPE of AIME, Las Vegas, Nevada, Sept. 23-26, 1979(b)

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, SPE of AIME, Bakersfield, California, Apr. 1977,

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

Gringarten, A.C., and Ramey, H.J., Jr.: "The Use of Source and Green's Functions in the Solution of Unsteady Flow Problems in Reservoirs," Soc. Pet. Eng. J. (Oct. 1973), 285-296; Trans., AIME, 255.

Horne, R.N., and Ramey, H.J., Jr.: "Steam/Water Relative Permeabilities from Production Data," Trans., Geothermal Resources Council (July 1978), 2, 291-293.

Hunsbedt, A., Iregui, R., Kruger, P., and London, A.L.: "Energy Recovery from Fracture-Stimulated Geothermal Reservoirs," ASME Paper No. 79-HT-92, presented at the ASME/AIChE National Heat Transfer Conference, San Diego, August 6-8, 1979.

Iregui, R., Hunsbedt, A., Kruger, P., and London, A.L.: "Analysis of Heat Transfer and Energy Recovery in Fractured Geothermal Reservoirs," SGP-TR-31, June 1978.

Kruger, P., and Ramey, H.J., Jr.: "Stimulation and Reservoir Engineering of Geothermal Resources," SGP-TR-28, First Annual Report to U.S. Department of Energy, Apr. 1978.

Kruger, P., Stoker, A., and Umana, A.: "Radon in Geothermal Reservoir Engineering," Geothermics (1977), 5, 13-19.

Kruger, P., and Warren, G.: "Radon Transients in Vapor-Dominated Geotherma Reservoirs," Paper SPE 8000, presented at the 1979 California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

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

Mavor, M.J., and Cinco-Ley, H.: "Transient Pressure Behavior of Naturally Fractured Reservoirs," Paper SPE 7977, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

Nehring, N., and Truesdell, A.: "Collection of Chemical, Isotope and Gas Samples from Geothermal Wells," Proc., Second Workshop on Sampling Geothermal Effluents, Las Vegas, Feb. 1977.

Proceedings, Third Workshop on Geothermal Reservoir Engineering, December 14-16, 1977, SGP-TR-25.

Proceedings, Fourth Workshop on Geothermal Reservoir Engineering, December 13-15, 1978, SGP-TR-30.

Ramey, H.J., Jr., and Agarwal, R.G.: "Annulus Unloading Rates and Wellbore Storage," Soc. Pet. Eng. J. (Oct. 1972), 453-462.

Ramey, H.J., Jr., Agarwal, R.G., and Martin, I.: "Analysis of 'Slug Test' or DST Flow Period Data," J. Can. Pet. Tech. (July-Sept. 1975), 37-47.

Rubin, A., and Schweitzer, S.: "Heat Transfer in Porous Media with Phase Change," Int. J. Heat and Mass Transfer (1972), 15, 43-60.

Sandal, H.J.: "Interference Testing with Skin and Storage," Engineer's Degree Thesis, Stanford University Petroleum Engineering Department, 1978.

Sandal, H.J., Horne, R.N., Ramey, H.J., Jr., and Williamson, J.W.: "Interference Testing with Wellbore Storage and Skin Effect at the Produced Well," Paper SPE 7454, presented at the 53rd Annual Fall Meeting, SPE of AIME, Houston, Texas, Oct. 1978.

Shinohara, K.: "Calculation and Use of Steam/Water Relative Permeabilities in Geothermal Reservoirs," M.S. Report, Stanford University Petroleum Engineering Department, 1978.

Shinohara, K., and Ramey, H.J., Jr.: "Analysis of 'Slug Test' DST Flow Period Data with Critical Flow," Paper SPE 7981, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

Shinohara, K., and Ramey, H.J., Jr.: "Slug Test Data Analysis, Including the Inertia Effect of the Fluid in the Wellbore," Paper SPE 8208, to be presented at the 54th Annual Fall Meeting, SPE of AIME, Las Vegas, Nevada, Sept. 23-26, 1979.

<u>Standard Methods for the Examination of Water and Wastewater</u>, 14th Ed., American Public Health Assoc.: Washington, D.C., 1975.

Stehfest, H.: "Numerical Inversion of Laplace Transforms," <u>Communications of the ACM</u> (Jan. 1970), <u>13</u>, No. 1, Algorithm 368.

Stoker, A., and Kruger, P.: "Radon Measurements in Geothermal Systems," Second United Nations Symposium on the Use and Development of Geothermal Energy, San Francisco, 1975.

Tariq, S.M.: "A Study of the Behavior of Layered Reservoirs with Wellbore Storage and Skin Effect," Ph.D. Dissertation, Stanford University Petroleum Engineering Department, 1977.

Tariq, S.M., and Ramey, H.J., Jr.: "Drawdown Behavior of a Well with Storage and Skin Effect Communicating with Layers of Different Radii and Other Characteristics," Paper SPE 7453, presented at the 53rd Annual Fall Meeting, SPE of AIME, Houston, Texas, Oct. 1978.

van der Kamp, G.: "Determining Aquifer Transmissivity by Means of Well Response Tests: The Underdamped Case," <u>Water Resources Research</u> (Feb. 1976).

Warren, J.E., and Root, P.J.: "The Behavior of Naturally Fractured Reservoirs," <u>Soc. Per. Eng. J</u>. (Sept. 1963), 245-255.

Whiting, R.L., and Ramey, H.J., Jr.: "Application of Material Energy Balances to Geothermal Steam Production," <u>J. Pet. Tech</u>. (1969), 893-900.

APPENDIX A

PARTICIPANTS IN THE STANFORD GEOTHERMAL PROGRAM

PRINCIPAL INVESTIGATORS

Paul Kruger	Civil Engineering
Henry J. Ramey, Jr.	Petroleum Engineering

PROGRAM MANAGER

Christine Ehlig-Economides	Petroleum Engineering

ASSOCIATED FACULTY

William Brigham	Petroleum Engineering
Heber Cinco-Ley	Petroleum Engineering
George Homsy	Chemical Engineering
A. Louis London	Mechanical Engineering
Frank Miller	Petroleum Engineering
Subir Sanyal	Petroleum Engineering
Drew Nelson	Mechanical Engineering
Roland Horne	Mechanical Engineering, Univ. of Auckland, N.Z.

RESEARCH ASSOCIATE

Anstein Hunsbedt	Civil Engineering

POST-DOCTORAL SCHOLAR

Louis Castanier	Petroleum Engineering

RESEARCH ASSISTANTS

Petroleum Engineering

John Counsil
Christine Ehlig-Economides
Brian Gobran
Chih-Hang Hsieh
Toby Schultz
Kiyoshi Shinohara

Mechanical Engineering

Rajiv Rana

Civil Engineering

Luis Macias-Chapa
Lewis Semprini
Gary Warren
Mike Wigley
Dave Woodruff

APPENDIX B

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY

STANFORD. CALIFORNIA 94305

TECHNICAL REPORTS

SGP-TR-1 *	Paul Kruger and Henry J. Ramey, Jr., "Stimulation and Reservoir Engineering of Geothermal Resources," Progress Report No. 3, June 1974.
SGP-TR-2 *	Norio Arihara, "A Study of Non-isothermal and Two-phase Flow Through Consolidated Sandstones," November 1974.
SGP-TR-3 *	Francis J. Cassé, "The Effect of Temperature and Confining Pressure on Fluid Flow Properties of Consolidated Rocks," November 1974.
SGP-TR-4 *	Alan K. Stoker and Paul Kruger, "Radon Measurements in Geothermal Systems," January 1975.
SGP-TR-5 *	Paul Kruger and Henry J. Ramey, Jr., "Stimulation of Geothermal Aquifers," Progress Report No. 1, March 1973.
SGP-TR-6	Henry J. Ramey, Jr., William E. Brigham, Hsiu-Kuo Chen, Paul G. Atkinson, and Norio Arihara, "Thermodynamic and Hydrodynamic Properties of Hydrothermal Systems," April 1974.
SGP-TR-7 *	Anstein Hunsbedt, Paul Kruger, and Alexander L. London, "A Laboratory Model of Stimulated Geothermal Reservoirs," February 1975.
SGP-TR-8 *	Henry J. Ramey, Jr., and A. Louis London, "Stimulation and Reservoir Engineering of Geothermal Resources," Progress Report No. 4, August 1975.
SGP-TR-9	Paul Kruger, "Geothermal Energy Development," November 1975.
SGP-TR-10 *	Ming-Ching Tom Kuo, Paul Kruger, and William E. Brigham, "Heat and Mass Transfer in Porous Rock Fragments," December 1975.
SGP-TR-11	Anstein Hunsbedt, Paul Kruger, and A. L. London, Laboratory Studies of Stimulated Geothermal Reservoirs," December 1975.
SGP-TR-12	Paul Kruger and Henry J. Ramey, Jr., editors, "Geothermal Reservoir Engineering," Proceedings, Workshop on Geothermal Reservoir Engineering, Stanford University, December 1975.
SGP-TR-13	Muhammadu Aruna, "The Effects of Temperature and Pressure on Absolute Permeability of Sandstones," May 1976.
SGP-TR-14	Paul G. Atkinson, "Mathematical Modelling of Single-phase Nonisothermal Fluid Flow through Porous Media," May 1976.
SGP-TR-15	Hsiu-Kuo Chen, "Measurement of Water Content of Porous Media Under Geothermal System Conditions," August 1976.
SGP-TR-16	Ming-Ching Tom Kuo, Paul Kruger, and William E. Brigham, "Shape Factor Correlations for Transient Heat Conduction from Irregular Shaped Rock Fragments to Surrounding Fluid," August 1976.

*Out of Print

TECHNICAL REPORTS

SGP-TR-17	Stephen D. Chicoine, "A Physical Model of a Geothermal System--Its Design and Construction and Its Application to Reservoir Engineering," June 1975.
SGP-TR-18	Paul G. Atkinson, "Numerical Simulation of Two-phase Boiling Flow in a Linear Horizontal Porous Medium," December 1975.
SGP-TR-19	Roger P. Denlinger, "An Evaluation of the Capacitance Probe As a Technique for Determining Liquid Saturations In Laboratory Flow Experiments," June 4 1975.
SGP-TR-20	Summaries: Second Workshop on Geothermal Reservoir Engineering, December 1-3, 1976.
SGP-TR-21	Paul Kruger and Henry J. Ramey, Jr., Final Report to National Science Foundation." 1977.
SGP-TR-22	Gary Warren, "Radon in Vapor-Dominated Geothermal Reservoirs," December 1978.
SGP-TR-23	Chih-Hang Hsieh, "Progress Report on Experiments on Water Vapor Pressure Lowering Relating to Capillarity and Adsorption-Desorption," November 1977.
SGP-TR-24	Syed M. Tariq, "A Study of the Behavior of Layered Reservoirs with Wellbore Storage and Skin Effect," December 1977.
SGP-TR-25	Proceedings: Third Workshop on Geothermal Reservoir Engineering, December 14-16, 1977.
SGP-TR-26	Leslie S. Mannon and Paul G. Atkinson, "The Real Gas Pseudo-Pressure for Geothermal Steam," September 1977.
SGP-TR-27	Paul Kruger and Lewis Semprini, "Radon Data--Phase I Test, Los Alamos Scientific Laboratory, LASL Hot Dry Rock Project, January 27-April 12, 1978."
SGP-TR-28	Paul Kruger and Henry J. Ramey, Jr., "Stimulation and Reservoir Engineering of Geothermal Resources," First Annual Report to U.S. Department of Energy, April 1978.
SGP-TR-29	Kiyoshi Shinohara, "Calculation and Use of Steam/Water Relative Permeabilities in Geothermal Reservoirs," June 1978.
SGP-TR-30	Proceedings: Fourth Workshop on Geothermal Reservoir Engineering, December 13-15, 1978.
SGP-TR-31	Roberto Iregui, Anstein Hunsbedt, Paul Kruger, and Alexander L. London, "Analysis of the Heat Transfer Limitations on the Energy Recovery from Geothermal Reservoirs," June 1978.
SGP-TR-32	Paul Kruger and Henry J. Ramey, Jr., Stanford Geothermal Program Progress Report No. 7 to the U.S. Department of Energy for the Period October 1, 1978 to December 31, 1978.
SGP-TR-33	Paul Kruger, Lewis Semprini, Gail Cederberg, and Luis Macias, "Recent Radon Transient Experiments," December 1978.
SGP-TR-34	Patricia Arditty, "The Earth Tide Effects on Petroleum Reservoirs; Preliminary Study," May 1978.

TECHNICAL REPORTS

SGP-TR-35 Paul Kruger and Henry J. Ramey, Jr., "Stimulation and Reservoir Engineering of Geothermal Resources," Second Annual Report to U. S. Department of Energy/LBL. DOE-LBL 81673500, September 1979.

APPENDIX C

PUBLICATIONS AND TECHNICAL PRESENTATIONS

Arditty, P.C., Nur, A.M., and Ramey, H.J., Jr.: "Response of a Closed Well-Reservoir System to Stress Induced by Earth Tides," Paper SPE 7484, presented at the 53rd Annual Meeting, SPE of AIME, Houston, Texas, Oct. 1-3, 1978.

Castanier, L., and Bories, S.: "Experimental Results from a Bench-Scale Model for Phase Change Study by In-Situ Vaporization in Porous Media," Paper SPE 8002, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979. Work done at E.N.S.E.E.I.H.T., Toulouse, France.

Chen, H.K., Counsil, J.R., and Ramey, H.J., Jr.: "Experimental Steam-Water Relative Permeability Curves," Trans., Geothermal Resources Council (1978), 2, 103-104.

Cinco-Ley, H., and F. Samaniego-V.: "Evaluacion de un Fracturamiento Hidraulico por Medio de Pruebas de Presiones," presented at the First Panamerican Petroleum Congress, Mexico City, March 1979.

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

Danesh, A., Ehlig-Economides, C., and Ramey, H.J., Jr.: "The Effect of Temperature Level on Absolute Permeability of Unconsolidated Silica and Stainless Steel," Trans., Geothermal Resources Council (1978), 2, 137-139.

Ehlig-Economides, C., and Ramey, H.J., Jr.: "Pressure Buildup for Wells Produced at a Constant Pressure," Paper SPE 7985, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

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

Horne, R.N., and Ramey, H.J., Jr.: "Steam/Water Relative Permeabilities from Production Data," Trans., Geothermal Resources Council (1978), 2, 291-293.

Hsieh, C.H., and Ramey, H.J., Jr.: "An Inspection of Experimental Data on Vapor Pressure Lowering in Porous Media," Trans., Geothermal Resources Council (1978), 2, 295-296.

APPENDIX C, continued

Hunsbedt, A., Iregui, R., Kruger, P., and London, A.L.: "Energy Recovery from Fracture-Stimulated Geothermal Reservoirs," presented at the 18th ASME-AIChE National Heat Transfer Conference, San Diego, California, Aug. 5-8, 1979.

Hunsbedt, A., and Kruger, P.: "Energy Extraction Experiments in the SGP Reservoir Model," Trans., Geothermal Resources Council (1978), 2, 299-301.

Iregui, R.: "Analysis of the Heat Transfer Limitations on the Energy Recovery from Geothermal Reservoirs," Engineer's Degree Thesis, Stanford University, June 1978.

Iregui, R., Hunsbedt, A., Kruger, P., and London, A.L.: "Analysis of Heat Transfer and Energy Recovery in Fractured Geothermal Reservoirs," SGP-TR-31, June 1978.

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

Kruger, P.: "Radon in Geothermal Reservoir Engineering," Trans., Geothermal Resources Council (1978), 2, 383-385.

Kruger, P., and Ramey, H.J., Jr.: First Annual Report to U.S. Department of Energy, SGP-TR-28, Apr. 1978.

Kruger, P., and Roberts, V.: "Utility Estimates of Geothermal Electricity Generating Capacity," Trans., Geothermal Resources Council (1978), 2, 379-382.

Mavor, M.J., and Cinco-Ley, H.: "Transient Pressure Behavior of Naturally Fractured Reservoirs," Paper SPE 7977, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

Miller, F.G., Cinco, H., Ramey, H.J., Jr., and Kucuk, F.: "Reservoir Engineering Aspects of Fluid Recharge and Heat Transfer in Geothermal Reservoirs," Trans., Geothermal Resources Council (1978), 2, 449-452.

Ramey, H.J., Jr.: "Hand Computer Program for James' Lip Pressure Steam Flow Rate," Trans., Geothermal Resources Council (1978), 2, 555-557.

Ramey, H.J., Jr.: "The Well Loss Function and the Skin Effect: A Review," presented at the Symposium on Recent Trends in Hydrogeology, Feb. 8, 1979, honoring Paul Witherspoon; to be published in Geological Society of America.

APPENDIX C, continued

Ramey, H.J., Jr.: "A Review of Pressure Transient Analysis," presented at the First Panamerican Petroleum Congress, Mexico City, March 1979.

Sandal, H.J., Horne, R.N., Ramey, H.J., Jr., and Williamson, J.W.: "Interference Testing with Wellbore Storage and Skin Effect at the Produced Well," Paper SPE 7454, presented at the 53rd Annual Meeting, SPE of AIME, Houston, Texas, Oct. 1-3, 1978.

Shinohara, K., and Ramey, H.J., Jr.: "Analysis of 'Slug Test' DST Flow Period Data with Critical Flow," Paper SPE 7981, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

Tariq, S.M., and Ramey, H.J., Jr.: "Drawdown Behavior of a Well with Storage and Skin Effect Communicating with Layers of Different Radii and Other Characteristics,'' Paper SPE 7453, presented at the 53rd Annual Meeting, SPE of AIME, Houston, Texas, Oct. 1-3, 1978.

Warren, G.J., and Kruger, P.: "Radon in Vapor-Dominated Geothermal Reservoirs," Paper SPE 8000, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

APPENDIX D

TRAVEL AND TECHNICAL MEETING ATTENDANCE

Geothermal Resource Council 2nd Annual Meeting, Hilo, Hawaii, July 25-27, 1978.

Brigham, W.E.
Cinco, H.
Counsil, J.R.
Ehlig-Economides, C.
Hsieh, C.H.
Kruger, P.
Miller, F.G.
Sanyal, S.

Grottitana Well Site, Italy, August 1978.

Kruger, P.

49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

Castanier, L.
Cinco-L., H.
Counsil, J.
Ehlig-Economides, C.
Kruger, P.
Miller, F.G.
Ramey, H.J., Jr.
Shinohara, K.

First Panamerican Petroleum Congress, Mexico City, March 19-22, 1979.

Cinco-L., H.
Ramey, H.J., Jr.

Symposium on Recent Trends in Hydrogeology, Lawrence Berkeley Laboratory, February 1979.

Castanier, L.
Cinco-L., H.
Kruger, P.
Ramey, H.J., Jr.

Annual Fall Meeting, Society of Petroleum Engineers, Denver, Colorado, October 1978.

Brigham, W.E.
Castanier, L.
Counsil, J.
Miller, F.G.
Cinco-L., H.

APPENDIX E

SGP SPONSORED MEETINGS

The Stanford Geothermal Program sponsored regular weekly seminars and the 4th Annual Geothermal Reservoir Engineering Workshop in December 1978. A list of the weekly seminars and the program of the Annual Workshop is given in the following. In addition, many visitors to Stanford were provided tours of the laboratory during the year. The most important such event was a visit by a large delegation from the Japanese Geothermal Energy Development Center in the spring. A copy of the news release concerning this event is also presented in the following.

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD. CALIFORNIA 94305

SEMINAR SCHEDULE

AUTUMN QUARTER, 1978 TH 1:15 RM. 113 MITCHELL

DATE	TOPIC	SPEAKER
OCT 12	UTILIZATION OF A NATURAL PHENOMENON, THE EARTH TIDES, FOR THE STUDY OF HYDROCARBON RESERVOIRS	PATRICIA ARDITTY PET. ENGR.
OCT 19	CASE STUDIES OF GEOTHERMAL WELL LOGS FROM FOUR GEOTHERMAL FIELDS	SUEIR SANYAL PET. ENGR.
OCT 26	BENCH SCALE MODEL OF STEAM-WATER FLOW IN POROUS MEDIA	LOUIS CASTANIER PET. ENGR.
NOV 2	RADON TRANSIENT ANALYSIS	GARY WARREN CIVIL ENGR.
NOV 9	INTRODUCTION TO GEOTHERMAL RESERVOIR SIMULATION (EVALUATION OF EXISTING METHODOLOGY)	GEORGE PINDER CIVIL ENGR. (PRINCETON U.)
NOV 16	STEAM-WATER RELATIVE PERMEABILITY	JOHN COUNSIL PET. ENGR.
NOV 30	TECHNIQUES FOR ANALYSIS OF PRESSURE TRANSIENT DATA WITH VARIABLE FLOW RATE	MICHAEL ECONOMIDES PET. ENGR.
DEC 7	TRANSIENT RATE AND PRESSURE SOLUTIONS FOR PRODUCTION AT CONSTANT WELLBORE PRESSURE	CHRISTINE EHLIG-ECONOMIDES PET, ENGR.

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

SEMINAR SCHEDULE

WINTER QUARTER 1979 ROOM B67 MITCHELL BUILDING THURSDAYS 1:15-2:30 PM

DATE	TOPIC	SPEAKER
JAN. 18	STABILITY AND SPACING OF COOLING CRACKS IN ROCK	Z. BAZANT NORTHWESTERN UNIVERSITY
25	GAMMA RAY ADSORPTION FOR MEASUREMENT OF LIQUID SATURATION	L. CASTANIER ENSEEIHT, FRANCE
FEB. 1	BROADLAMIS--A FRACTURE-DOMINATED GEOTHERMAL FIELD?	R. HORNE, UNIVERSITY OF AUCKLAND, NEW ZEALAND
8	[NO SEMINAR - HYDROGEOLOGY SYMPOSIUM AT LBL, BERKELEY]	
15	LABORATORY INVESTIGATIONS OF STEAM FLOW IN POROUS MATERIALS AT USGS	W. HERKELRATH USGS, MENLO PARK
22	GAS COMPOSITION OF LARDERELLO GEOTHERMAL FIELD, ITALY	F. D'AMORE, ITALIAN RESEARCH NATIONAL COUNCIL
MAR. 1	DESIGN CONSIDERATIONS IN STEAM PIPELINE CONTROL	G. FRYE, AMINOIL; and R. 'LENGQUIST, formerly THERMAL POWER CO., UNION OIL CO., RET.

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

SEMINAR SCHEDULE

Spring Quarter, 1979   Rm B67 Mitchell Building   Thurs 1:15 - 2:30 pm

Date	Topic	Speaker
Apr 26	Gravity and Seismic Studies for The Geysers Steam Field	R. Dinlinger U.S.G.S.
May 3	Petrologic Aspects of Geothermal Reservoirs	W. Elders U.C. Riverside
May 10*	A Numerical Approach to Modeling Wells That Intercept Fractures	T.N. Narasimhan LBL
May 17	Stimulation Techniques for an Analysis of Hot Dry Rock Geothermal Systems: Recent Developments	J.W. Tester LASL
May 24	Use of LANDSAT Digital Data for Location of Hydrothermal Alteration and Geothermal Resources	A. Prelat, R.J.P. Lyon, W. Kowalick, Stanford U.
May 31	Evidence of Steam Depletion at The Geysers Geothermal Field	C. Strobel Union Oil

* Time changed to 3:30 p.m.

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

FOURTH ANNUAL WORKSHOP ON GEOTHERMAL RESERVOIR ENGINEERING

STANFORD UNIVERSITY
DECEMBER 13 - 15, 1978

FINAL PROGRAM

WEDNESDAY, DECEMBER 13, 1978

0800 REGISTRATION, TRESIDDER UNION, UPSTAIRS LOBBY

0900 SESSION I - Overviews Chairman: H. J. Ramey, Jr., Stanford University

Marshall Reed (DGE), "Recent Developments in the DGE Program"

H. Alonso E. (LBL), B. Dominguez A. (CFE), M. J. Lippmann (LBL), A. Mañon M. (CFE), R. E. Schroeder (LBL), and P. A. Witherspoon (CFE), "Recent Activities at the Cerro Prieto Field"

J. Howard, J. E. Noble, W. J. Schwarz, & A. N. Graf (LBL), "Progress Report on the DOE/DGE/LBL Reservoir Engineering and Subsidence Programs"

I. Donaldson (DSIR), "Geothermal Reservoir Engineering Research in New Zealand: A Simplistic Model and the Wairakei Geothermal Reservoir"

1200 LUNCH, Tresidder Union, Main Lounge (Room 281)

1315-1500 SESSION II - Reservoir Physics Chairman: Robert Christiansen (USGS)

J. Martin (Chevron), "The Replacement of Geothermal Reservoir Brine as a Means of Reducing Solids Precipitation and Scale Formation"

D. Lockner, D. Bartz, and J. D. Byerlee (USGS-Menlo Park), "Permeability Changes during Flow of Water through Granite Subjected to a Temperature Gradient"

W. N. Herkelrath and A. F. Moench (USGS-Menlo Park), "Laboratory Investigations of Steam Pressure Transient Behavior in Porous Materials"

J. Counsil, C. Ehlig-Economides, A. Danesh, C. Hsieh, H. J. Ramey, Jr., and P. Kruger (SG), "Bench Scale Experiments in the Stanford Geothermal Project"

L. M. Castanier and S. Bories (E.N.S.E.E.I.H.T., France), "An Experimental Study of the Phase Change by in-Situ Vaporization in Porous Medium"

1520-1700 SESSION III - Well Testing ana Formation Evaluation Chairman: Stephen Lipman (Union Oil)

A. Truesdell, G. Frye (Aminoil), and M. Nathenson (USGS-Menlo Park), "Downhole Measurements and Fluid Chemistry of a Castle Rock Steam Well, The Geysers, Lake County, California"

C. J. Strobel (Union Oil), "Formation Plugging While Testing a Steam Well at The Geysers"

A. Moench (USGS-Menlo Park), "The Effect of Thermal Conduction upon Pressure Drawdown and Buildup in Fissured, Vapor-Dominated Geothermal Reservoirs''

C. Goranson, R. Schroeder and J. Haney (LBL), "Evaluation of Geothermal Exploratory Well CGEH-1, Coso Hot Springs, China Lake, California"

D. Kihara (Univ. of Hawaii), "Locating the Producing Layers in HGP-A"

R. Horne, R. O. Gale, and M. A. Grant (Univ. of Auckland and DSIR), "Results from Well Testing in the Broadlands Geothermal Field, New Zealand"

<u>THURSDAY, DECEMBER 14, 1978</u>

0800-1010 SESSION III (continued): Chairman: George Frye (Aminoil

G. Bodvarsson (Oregon State Univ.), "Mechanism of Reservoir Testing"

G. Bodvarsson and E. Zais, "A Field Example of Free Surface Testing"

A. Barelli, W. E. Brigham, H. Cinco, M. Economides, F. G. Miller, H. J. Ramey, Jr. and A. Schultz (SG?), "Pressure Drawdown Analyses for the Travale 22 Well"

M. Saltuklaroglu (Electroconsult) and J. Rivera-Rodriguez (CFE), "Injection Testing in Geothermal Wells"

C. Ehlig-Economides (SGP), "Recent Developments in Well Test Analysis in the Stanford Geothermal Program"

1050-1200 P. Kruger, L. Semprini, G. Cederberg, and L. Macias (SGP), "Recent Radon Transient Experiments"

P. Cheng and M. Karmarkar (Univ. of Hawaii), "An Evaluation of James' Empirical Formulae for the Determination of Two-Phase Flow Characteristics in Geothermal Well Testing"

E. Tansev (Chevron Resources), "Evaluation of a Geothermal Well, Logging, DST and Pit Test"

1215 LUNCH, Tresidder Main Lounge (Room 281)

1330-1500 <u>SESSION IV - Field Development</u> Chairman: John Howard (LBL)

J. Pritchett (Systems, Science & Software), "Reservoir Engineering Data: Wairakei Geothermal Field, New Zealand"

J. Rudisil (Thermal Power), "Recent Reservoir Engineering Developments at Brady Hot Springs, Nevada"

P. Messer and V. F. de las Alas (Union Oil/Philippine Geothermal), "The Bulalo Geothermal Reservoir Makiling-Banahao Area, Philippines"

S. Hirakawa (Univ. of Tokyo), "System Approach to Geothermal Field Development"

1520-1700 <u>PANEL SESSION - Geochemistry</u> Moderator: Mohinder Gulati (Union Oil)

Panelists: W. Elders (UC-Riverside) J. Pritchett (S^3)

M. Reed (Chevron) A. Truesdell (USGS)

1800 RECEPTION (No-Host Cocktails) and BANQUET - Faculty Club

Speaker: Dr. Robert W. Rex, President, Republic Geothermal, Inc.

on "Credibility of Geothermal Reservoir Engineering Calculations"

FRIDAY, DECEMBER 15, 1978

0830-1000 SESSION V - Stimulation Chairman: James Barkman (Republic Geothermal)

H. Murphy (LASL), "Heat Extraction Performance and Modeling"

C. O. Grigsby and J. W. Tester (WSL), "Flow Characteristics and Geochemistry"

J. N. Albright (LASL), "Reservoir Characterization Using Acoustics Techniques"

M. S. Ayatollahi (LBL), Stress and Flow in Fractured Porous Media"

Z. D. Bazant (Northwestern Univ.), "Spacing and Width of Cooling Cracks in Rock''

1020-1200 SESSION VI - Modelling Chairman: Erdal Tansev (Chevron)

G, Randall and R. F. Harrison (TerraTek), "An Annotated Research Bibliography for Geothermal Reservoir Engineering"

T. Li, J. W. Mercer, and C. R. Faust (USGS-Reston), "Simulation of Geothermal Reservoirs including Changes in Porosity and Permeability due to Silica-Water Reactions"

S. Garg (Systems, Science & Software), "Preliminary Assessment of the Production and Subsidence Behavior of the Brazoria County Geopressure Geothermal Prospect"

C. D. Voss and G. F. Pinder (Princeton), "The Achilles' Heel of Geothermal Reservoir Simulators"

O. Weres, A. Yu, and L. Tsao (LBL), "Predicting the Precipitation of Amorphous Silica from Geothermal Brines"

1215 LUNCH, Tresidder Main Lounge

1330-1600 SESSION VI - Modelling (continued) Chairman: Erdal Tansev (Chevron)

K. P. Goyal and D. R. Kassoy (LBL), "Heat and Mass Transfer Studies of the East Mesa Anomaly"

K. Preuss (LBL), "Studies of Two-Phase Flow in Geothermal Reservoirs with the Simulator Shaft78"

Y. W. Tsang and C. F. Tsang (LBL), "An Analytic Study of Geothermal Reservoir Pressure Response to Cold Water Reinjection"

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD CALIFORNIA 94305

Reply to:

PRESS RELEASE May 15, 1979

A large delegation of Japanese technical and managerial personnel visited the facilities of the Stanford Geothermal Program. The stop here was part of a "study mission" through the U.S. and Mexico with the ultimate purpose of technology transfer in the utilization of geothermal energy. The mission was organized by the Japan Geothermal Energy Development Center (JGEC), a group affiliated with the Ministry of International Trade and Industry. The visitors included several top executives of Japanese corporations and high level technical people.

Prof. Paul Kruger of the Civil Engineering Department and Co-Principal Investigator of the Stanford Geothermal Program analyzed to the visitors several of the major aspects of the research work done here. Michael Economides of the Petroleum Engineering Department made an overview presentation of the bilateral research effort between the Italian Electrical Energy Authority (ENEL) and Stanford's Petroleum Engineering Department. Finally, Prof. Roland Horne, of the University of Auckland, New

Zealand talked about the geothermal efforts in his institution.

Following the presentations, the visitors toured the research facilities escorted by the Geothermal Program Manager, Christine Ehlig-Economides and other Stanford personnel.