STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

SGP-TR-51

# GEOTHERMAL RESERVOIR ENGINEERING RESEARCH AT STANFORD UNIVERSITY

## FIRST ANNUAL REPORT

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# PREFACE

This publication is the first annual progress report to the Department of Energy under contract No. DE-AT03-80SF11459. It covers the period from October 1, 1980 through September 30, 1981.

The Stanford Geothermal Program was initiated by the National Science Foundation in 1972 and has continued under the Energy Research and Development Administration and the successor Department of Energy since 1975. The central objective of the program is to carry out research in geothermal reservoir engineering techniques that will be useful to the nation's geothermal industry. A parallel objective is the training of engineers for employment in the geothermal industry. The research program is geared to maintain a balance between laboratory studies of techniques and models and matching field application. By moving theory and practice along in conjunction, the theoretical and experimental laboratory studies are more pragmatically based, thereby fitting more closely the real needs of industry. The result is a rapid transfer of the benefits of these studies to field operations.

The Stanford Geothermal Program has gained greater depth through its international cooperation projects. Within the program there are specific research ties to projects in Italy and Mexico. They augment the program's U.S. projects, providing a wider spectrum of field experience and data with which to test ideas, theory and experiment. This international scientific exchange is extended through both working and conference meetings. The Stanford Geothermal Program assists further with this scientific exchange through its annual workshop on geothermal reservoir engineering.

The Stanford Geothermal Program is divided into six task areas: three major study areas for the development of practical methods and data for geothermal reservoir engineering and reservoir assessment--(1) heat extraction modeling, (2) noncondensable gas studies, (3) bench-scale models and well test analyses; the two international cooperative programs--(4) with ENEL in Italy, and (5) with IIE in Mexico; and a communication task--(6) incorporating the annual workshop, a seminar series that runs weekly throughout the academic year, and reports of the results of the research program. This annual report describes briefly the results obtained in the three major internal study areas, the established cooperative programs with ENEL and IIE, and the activities for transferring the results to the geothermal community.

Of significant help in the successful completion of the objectives of this program is the ready, and continuing, support by members of industry, various federal agencies, national laboratories, and university programs. These personnel present lectures in the weekly seminar series and participate actively in the annual workshop, both by the presentation of papers and by assistance with program organization, session chairing, and discussion. Their names are acknowledged in the preface to the Workshop Proceedings, in the report on the panel discussion at the Workshop and in the text and Appendices to this report. The major financial contributor to the program is the Department of Energy through this contract. We are grateful for this support and for the continuing cooperation we receive from the agency staff.

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# INTRODUCTION

The primary aim of the Stanford Geothermal Program is to obtain the best possible understanding of the geothermal resevoir. The effort is directed towards the development of techniques for assessing geothermal reservoirs through better interpretation of physical models, mathematical analysis, and field experimentation. Field efforts are used to test ideas and obtain real wellbore and reservoir data. Efficient utilization of geothermal resources requires an understanding of reservoir productivity and longevity, and methods to extend the life of the resources through production stimulation and increased fluid and energy extraction.

To achieve this aim, 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 mathematical models and improve our understanding of the physical and chemical mechanisms occurring in the reservoir. Another goal is to develop new methods for observing reservoir behavior and to test these in the field.

In this report, individual projects are grouped under the tasks as defined in the Department of Energy contract:

(1) Energy Extraction

(2) Noncondensable Gas Reservoir Engineering

(3) Bench-Scale Experiments and Well Test Analysis

(4) DOE-ENEL Cooperative Agreement

(5) Stanford-IIE Cooperative Agreement

(6) Workshops & Seminars.

The section on energy extraction experiments concerns the efficiency with which the in-place heat and fluids can be produced. Energy extraction considerations are of importance to the geothermal industry in decisions concerning fluid recharge and potential commercialization of liquid-dominated hydrothermal resources. The research utilizes the large Geothermal Reservoir Model, which evaluates energy extraction by alternate methods of fluid production. This year a long-term study using a regular arrangement of spaced blocks as the reservoir matrix has been started and first experimental runs carried out. This experimental study is being paralleled by matching numerical model development. Extended studies of thermal fracturing by hydrothermal stressing is included in these experiments by monitoring specific blocks in the physical model.

During the early part of this year the first phase of the two projects being carried out under the noncondensable gas reservoir engineering program were completed and written up. The second phase of each is now underway. The section on noncondensable gas reservoir engineering covers both the completed and continuing work in these two interrelated research areas: radon emanation from the rock matrix of geothermal reservoirs, and radon and ammonia variations with time and space over geothermal reservoirs. The aim of the current phase of this project is to get a better understanding of the mechanisms involved and thereby be able to use the results of the field measurements as a tool for further interpretation of reservoir behavior.

The bench-scale experiments and well test analysis section covers both experimental and theoretical studies. The small core model continues to be used for the study of temperature effects on absolute permeability. The unconsolidated sand study was completed at the beginning of this contract period. The study now is directed towards consolidated materials. A new larger coreholder for the relative permeability apparatus has been designed and constructed. Significant progress has been made on the theoretical front with other projects, relating to the location of feed zones and effects of phase changes in the reservoir near test wells. Continuing and new projects relating to interference between injection and production wells and the estimation of in-situ water saturations have been performed.

The section on the DOE-ENEL Cooperative Agreement covers two projects that are now virtually complete and are being written up. The results have been a number of important technology transfers to the U.S., such as the development of a new method to forecast steam production based on the long-time records available from the Larderello fields. Another is a method of engineering analysis to estimate fluid content in steam reservoirs. New projects are now being; started to continue to use the Larderello steam fields as an experimental laboratory to broaden our reservoir engineering technology.

Under the Stanford-IIE Cooperative Research Task, a Memorandum of Understanding between the Petroleum Engineering Department of Stanford University and the Instituto de Investigaciones Electricas on Cooperation in Geothermal Reservoir Engineering Investigation was signed. This paved the way for formally initiating the cooperative research projects that are now underway. Projects include pressure gradient analysis, tracer analysis of fractured systems, analysis of interference tests on flashing reservoirs, and lumped parameter modeling of the Cerro Prieto reservoir. Two of these projects have been successfully completed.

Task 6 of the Stanford Geothermal Program focuses on the efforts being made to communicate the results of our geothermal reservoir engineering program and the results of related research to the geothermal community, in particular through the Annual Workshop on Geothermal Reservoir Engineering and the Geothermal Seminar series.

The Appendices to this report describe some of the Stanford Geothermal Program activities that results in interactions with the geothermal community. These occur in the form of SGP Technical Reports, presentations at technical meetings and publications in the open literature.

## TASK 1. HEAT EXTRACTION FROM HYDROTHERMAL RESERVOIRS

A major facet of the Stanford Geothermal Program since its inception in 1972 has been the realization that long-term commercial development of geothermal resources for electric power production will depend on optimum heat extraction from hydrothermal reservoirs. Optimum extraction is analogous to secondary and tertiary recovery of oil from petroleum reservoirs; in the geothermal case, the resource may be either heat-transfer limited or convecting-fluid limited. The effort in the Stanford Geothermal Program has been a combination of physical and mathematical modeling of heat extraction from fractured geothermal reservoirs. Experiments have involved several rock loadings in the SGP physical model of a rechargeable hydrothermal reservoir with comparative testing of alternate modes of heat and fluid production. The results are leading to a useful mathematical means to evaluate the heat/fluid extractability in full-size geothermal resources.

During the recent preceding years, several advances have been achieved, such as the development of a simple, lumped-parameter heat extraction model to evaluate the potential for recharge-sweep production of geothermal reservoirs. This model built on the graduate student studies of Hunsbedt (SGP-TR-11) in developing the original model, Kuo (SGP-TR-16) in correlating shape factors for single, irregular-shaped rocks, Iregui (SGP-TR-31) in extending the concept of a single, equivalent radius sphere for an assembly of reservoir-shaped rocks, and Rana (SGP-TR-54) in examining the effect of thermal stressing on rock heat transfer properties. These continuous efforts have resulted in the model reported by Hunsbedt et al (1979) which examines a hydrothermal rock system with cold water reinjection using the single spherical-rock concept of "effective radius" as the heat source and "number of heat transfer units" as the heat extraction parameter.

Current efforts in the program are focused on improving the heat extraction model to remove uncertainties concerning axial heat conduction in the physical model, to calibrate the model using a rock loading of known geometric shape, and to investigate extended thermal stressing on physical and heat transfer properties. During the past year, progress was achieved in three directions: (1) completion of the regular-shaped rock loading and initiation of the calibration experiments, (2) development of a finite-element numerical model to analyze the experimental data, and (3) incorporation of a multi-stressing experiment into the SGP physical model to measure the effect of extended thermal stressing on reservoir rock heat transfer properties.

(a) Heat Extraction Experiments

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

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

The water temperature is measured at the several locations shown in Figure 1-2: at the inlet to the vessel, the I-plane just below the baffle, the B-plane half-way up the first rock layer, the M-plane half-way up the third rock layer, the T-plane at the top of the matrix, and at the vessel outlet. Temperatures are also measured at the center of four rock blocks. Three thermocouples were placed in the bottom central rock for thermal stress evaluation. Temperature measurements from the emplaced thermocouples are recorded on two multi-point recorders.

Experimental Run 5-1 has been completed using this rock matrix with

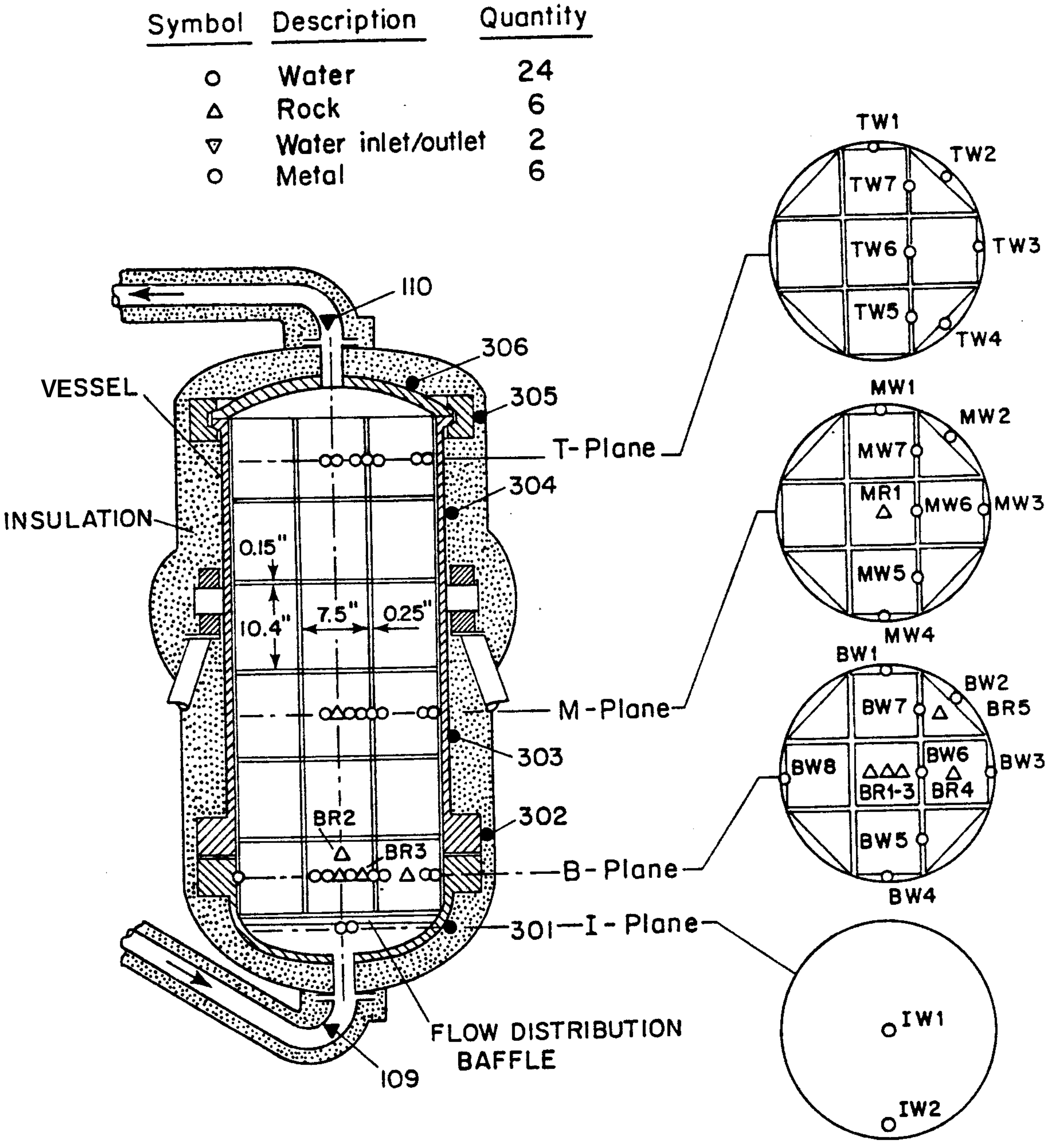

FIG. 1-1: EXPERIMENTAL ROCK MATRIX CONFIGURATION AND THERMOCOUPLE LOCATIONS

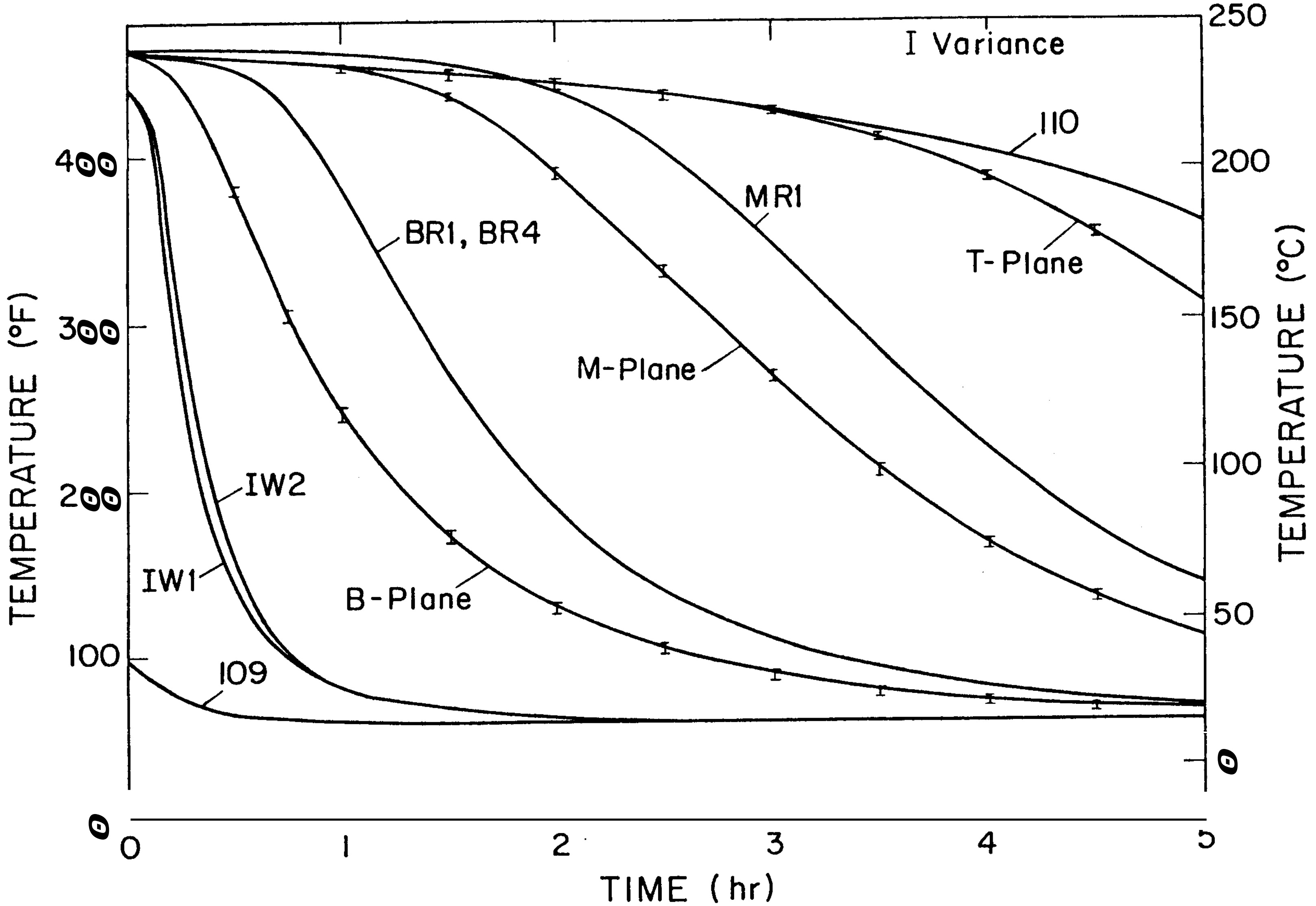

FIG. 1-2: WATER AND ROCK TEMPERATURES AS FUNCTIONS OF TIME

a water injection rate sufficient to result in almost complete cooling and energy extraction from the rock. Data for the experimental conditions and parameter values are summarized in Table 1. Data for the measured water and rock temperatures at the various thermocouple locations are given in Figure 1-2.

The results indicate that water temperature at the 1-plane is initially slightly hotter near the surface wall due to heating by the steel. The injected water approached a uniform, constant temperature of 59°F, after about one hour. The data also showed that the cross-sectional water temperatures were essentially uniform in each of the planes, with a maximum deviation of ±4°F, well within the estimated uncertainty of thermocouple temperature difference of ±5°F.

TABLE 1

Experimental Parameters for Run 5-1

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

Also given in Figure 1-2 are several representative rock center temperature transients. Comparison of these temperatures with the corresponding surrounding water temperatures showed that: maximum rock center to water temperature differences of about 100°F developed during the cooling process decreasing to smaller values toward the end of the experiment. These data indicate that the rock energy extraction was relatively complete and the energy extracted from the rock resulted in a high, constant exit water temperature.

Interpretation of the experimental data is in progress in conjunction with the analytic model development. The additional experiments planned for this rock loading await data interpretation of the current experiment as feedback. These additional experiments will provide a broad data range to evaluate optimum performance of heat transfer limited fracture geothermal reservoirs.

### (b) The Finite-Element Numerical Model

In analyzing the heat extraction data from prior experiments in the SGP physical reservoir using the one-dimensional lumped-parameter model, three major shortcomings in the model became evident: (1) axial heat conduction is not included; (2) cross-sectional flow may not be uniformly distributed in the model, and (3) the large heat capacity of the model reservoir vessel may distort the heat transfer characteristics at the model boundaries. In order to extend the use of the desired lumped-parameter model to full-size geothermal reservoirs, it is necessary to evaluate the effects of these shortcomings on the heat extraction model results. For this purpose, a finite element heat transfer model of the present regular-shaped rock loading experiments has been developed during the present contract year. In this model, individual blocks, or groups of blocks, can be represented as single elements. This approach allows less restraint on element shape compared to finite difference models. If successful in analysis of the physical model experimental data, it should provide application to full-size fractured rock geothermal reservoirs.

A flow chart of the finite element computer code is shown in Figure 1-3. The code as a general computational tool can evaluate a class of problems described by conduction or conduction-convection partial differential equations with boundary conditions consisting of specified temperature-time histories and/or specified heat flux-time histories controlled either by a direct source or by convection means. Specification of internal heat production (or loss) sources can also be included.

Some of the features of the finite-element code include: (1) free-field input of the model data; (2) automatic two- and three-dimensional block mesh generation; (3) automatic nodal renumbering to minimize the

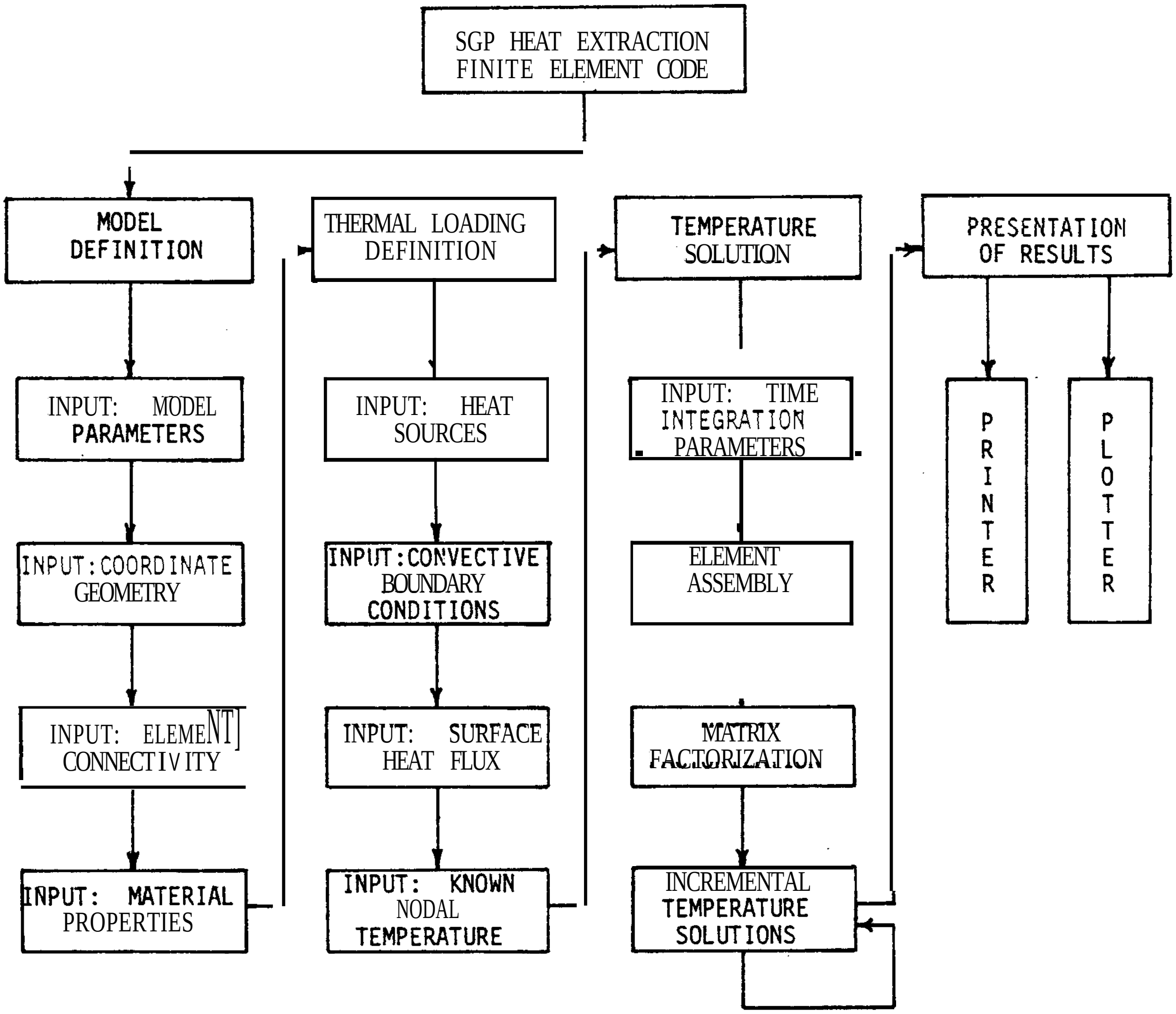

FIG. 1-3: FLOW CHART OF THE SGP HEAT EXTRACTION FINITE ELEMENT CODE

effective bandwidth; (4) line graphics presentation of the model mesh; and (5) printer and line graphics presentation of the results.

The model spatial discretization can be performed in two- or three-dimensional Cartesian coordinates or in axisymmetric cylindrical coordinates. An arbitrary number of general anisotropic material properties can be used to describe the particular reservoir being modeled. Results generated by the finite element code consist of temperature-time history curves and heat flux history curves. The data can be displayed in tables or graphically. The features of the code, including the user interactive capabilities during both the pre- and post-processing phases, make the SGP finite element code a flexible tool for advancing our understanding of heat extraction from geothermal reservoirs.

The model will be used initially to evaluate the data resulting from the current set of cold-water sweep experiments. For the current set of experiments in the SGP physical model, the loading is discretized into a set of analyst-defined rock elements, fluid elements, steel elements, and insulation elements. The element library consists of a two-dimensional, isoparametric quadrilateral element and a three-dimensional isoparametric hexahedron element. A variety of finite elements can be generated from the two generic types. Its long-term development is directed towards modeling full-size fractured geothermal reservoirs to evaluate optimum methods for energy production.

### (c) Thermal Stress Experiments

Thermal stresses are expected to produce several important changes in reservoir energy extraction behavior. One of these is the formation and growth of thermally induced cracks emanating from natural or hydraulically-imposed primary fractures in the formation. The role of thermal stress cracking on hot dry rock reservoir performance is under study at the Los Alamos Scientific Laboratory. A second important change is the alteration of mechanical and heat transfer properties of reservoir rocks under tensile thermal stresses. Changes in strength, porosity, permeability, and thermal conductivity are likely to affect rock-water heat transfer performance and the potential to induce new heat transfer areas by micro- and macro-size fractures.

Efforts under the Stanford Geothermal Program are focused on experimental evaluation of the influence of thermal stressing on rock heat transfer and mechanical properties. Prior efforts reported by Nelson et al. (1979, 1980) showed the influences of thermal stressing on the strength and porosity of granite specimens subjected to uniform heating at 450°F and face spraying with water at 70°F. The physical model for these experiments is shown in Figure 1-4. The thermal stress distribution is shown in Figure 1-5A, and its corresponding effect on bending strength in Figure 1-5B. Tensile thermal stresses were produced below the sprayed face with compressive stresses in deeper regions. A significant reduction in strength is noted in the region of tensile thermal stress. Porosity in this region also increased substantially, from 1.6% in unstressed specimens to an average value of 4.8% after five cycles of stressing. The reduction in strength and the increase in porosity both favor the formation of thermal cracks in geothermal reservoirs.

Current efforts involve a long-term thermal stressing test as part of the large block loading in the SGP physical reservoir model. The blocks in the B-plane shown in Figure 1-1 will experience the largest tensile thermal stress at the cold water recharge interface. Thermocouples, as noted in Figure 1-6, have been installed in various rock locations to obtain rock temperature-time information during the series of cold-water sweep experiments. The thermal stresses in these blocks will be computed from the spatial temperature-time histories predicted by the finite-element heat transfer model and adjusted from the observed data. Upon completion of the heat transfer experiments, several blocks of different thermal stress history will be sectioned for measurement of changes in thermal conductivity, strength, and porosity.

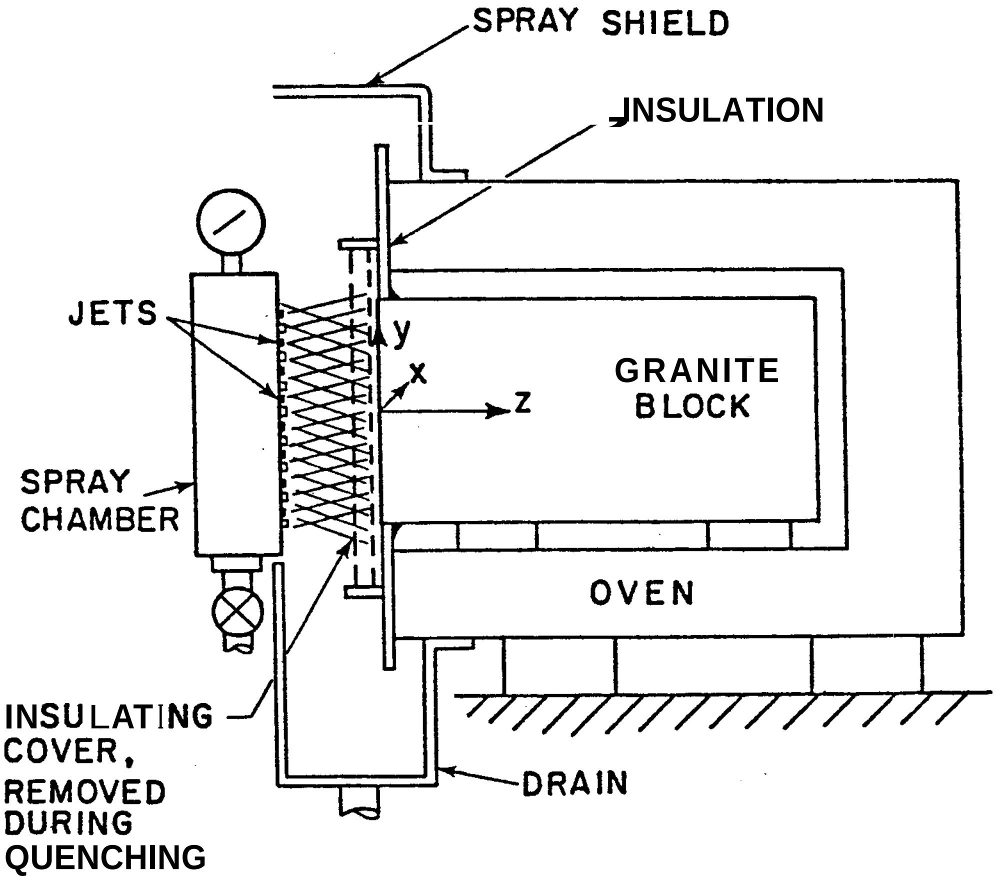

FIG. *1-4:* SCHEMATIC OF TEST RIG USED TO PRODUCE THERMAL STRESS IN GRANITE SLABS

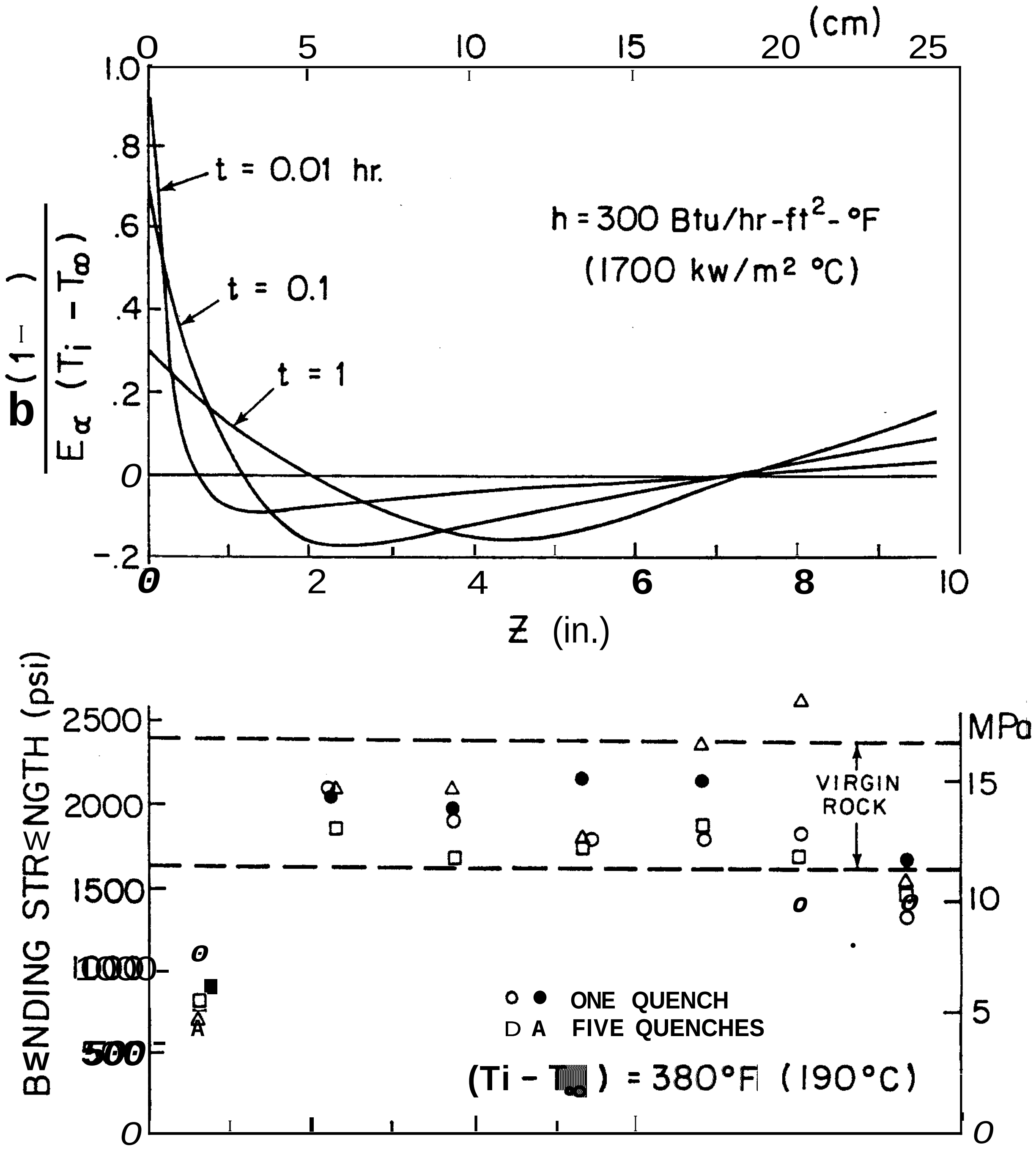

FIG. 1–5: (A) NORMALIZED THERMAL STRESS DISTRIBUTION IN A GRANITE SLAB

(B) STRENGTH OF SPECIMENS SECTIONED FROM THERMALLY-STRESSED SLABS

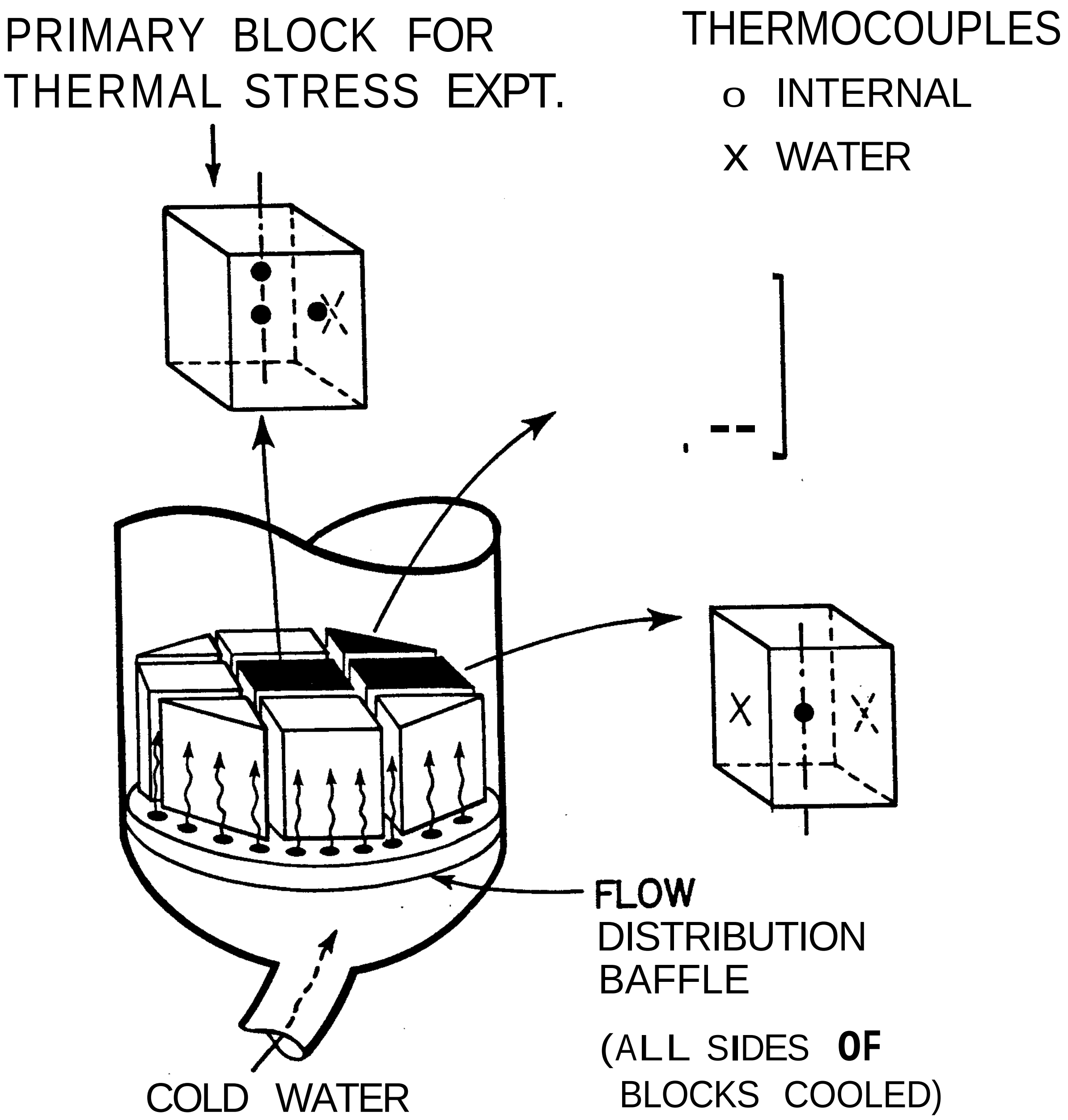

FIG. 1-6: INSTRUMENTED BLOCKS EXPERIENCING THE LARGEST THERMAL STRESSES DURING A COLD SWEEP EXPERIMENT

## TASK 2. NONCONDENSABLE GAS RESERVOIR ENGINEERING

Results in several aspects of evaluating the characteristics of geothermal reservoirs were achieved during the current year. The output from these studies resulted in an engineering thesis on the transect method, an engineering thesis on emanation studies, a paper on the Cerro Prieto field transects, and a paper at the American Geophysical Union winter meeting, reviewing the transect technique.

### (a) Reservoir Transect Analysis

A confirming transect analysis at The Geysers vapor-dominated field in California showed a remarkable dependence on noncondensable gas component concentrations on reservoir structural features. Figure 2-1 shows the gas component analytical results in relation to the reservoir structure as reported by the field operators. The data showed a general similarity of radon to ammonia concentrations across the 18-well transect, with apparent changes in gradient at the two fault boundaries and possible cross-overs in the concentration ratio at the fault locations. Analysis of the possible explanations of these observations in Lewis Semprini's thesis, in conjunction with discussions with Franco D'Amore of CNR in Italy, resulted in the hypothesis that a condensation process even in the dry-steam zone of The Geysers might be responsible for the concentration gradients observed in the two transect tests.

Another result, reported by Semprini and Kruger at the 1981 conference on Cerro Prieto, was the apparent dependence of radon concentrations on the enthalpy values across four subsections of the transect test carried out by Semprini in cooperation with CFE. Figure 2-2 shows the results for these four sub-transects of concentration and enthalpy profiles. The data for this liquid-dominated reservoir were consistent with a condensation process that would allow each of the noncondensable gas components to fractionate according to its own characteristic Henry's Law constant between the vapor and liquid phases of the brine solution in the reservoir which in turn is related to the fluids enthalpy and transport history.

The success of these transect studies in two different types of geothermal reservoir leads to the anticipation that a single

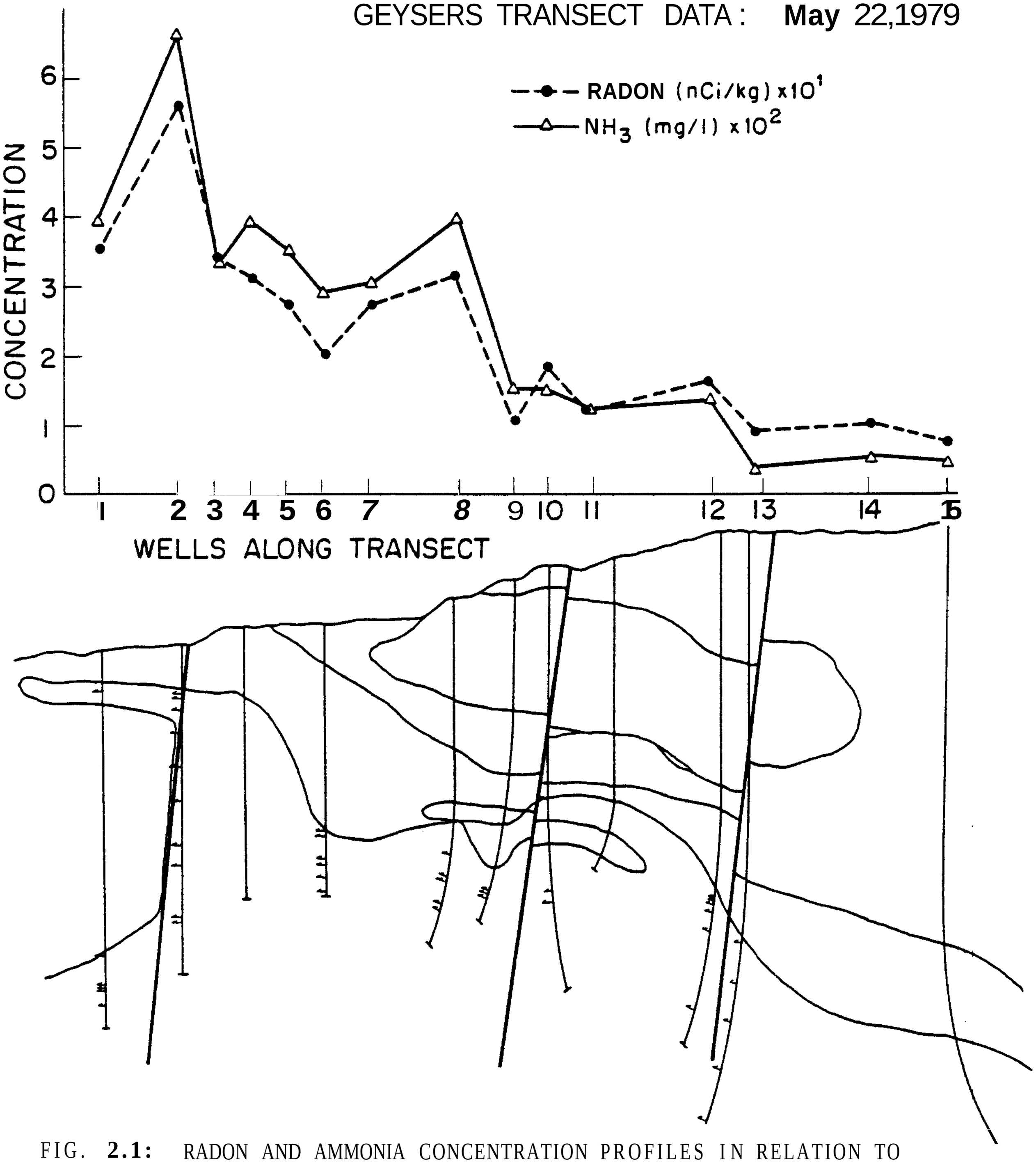

FIG. **2.1:** RADON AND AMMONIA CONCENTRATION PROFILES IN RELATION TO STRUCTURAL FEATURES OF THE, GEYSERS RESERVOIR

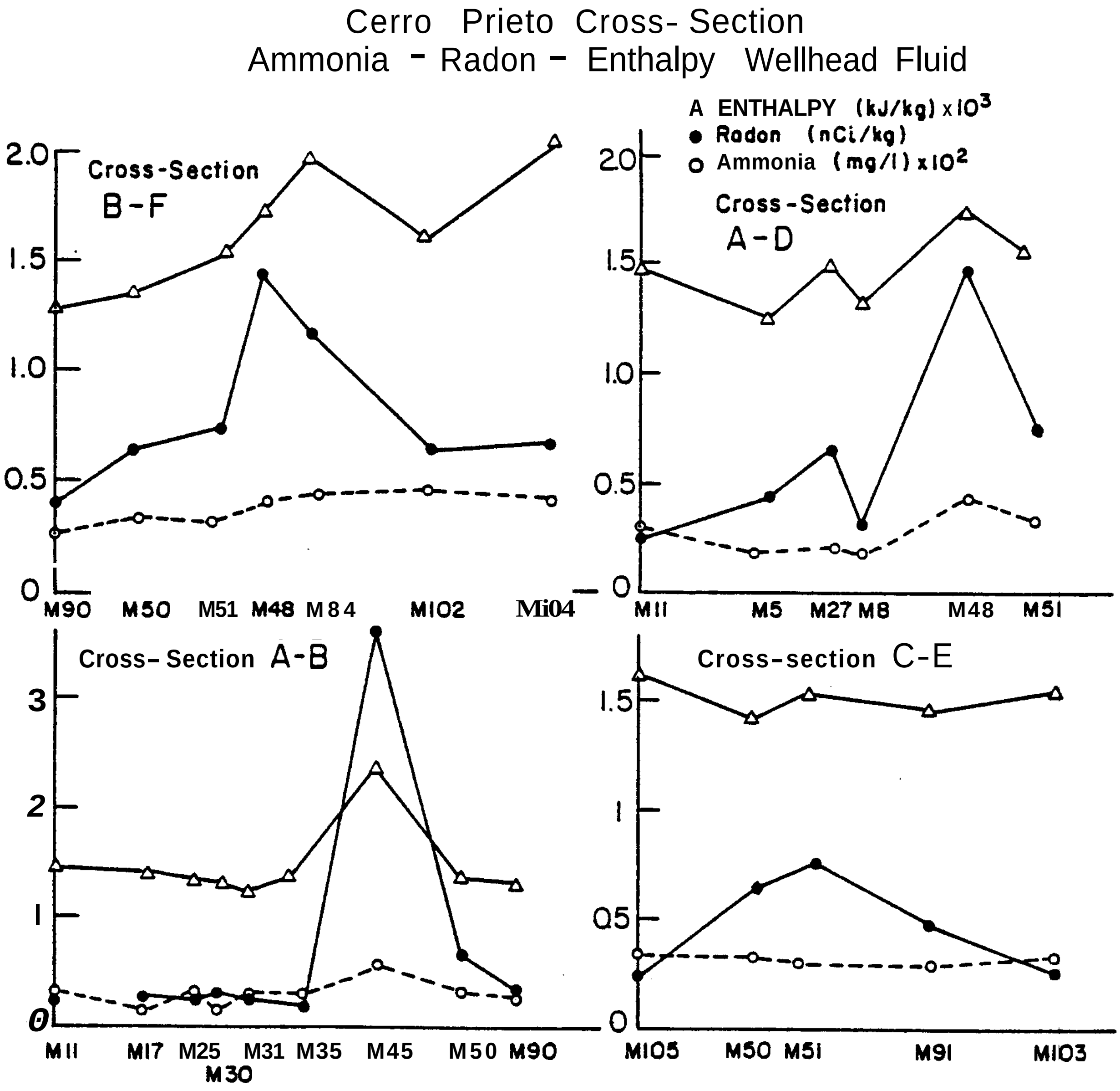

FIG. 2.2: CONCENTRATION PROFILES ALONG THE FOUR CERRO PRIETO TRANSECTS

condensation model can be developed to account for observed data at these and other geothermal fields. During the current year, a detailed examination of this possibility was developed by Lewis Semprini as a condensation simulation model, based on existing hydrodynamic models of vapor- and liquid-dominated reservoirs. The model will evaluate the partitioning (and subsequent enrichment and dilution in concentration) of key noncondensable gas components as the reservoir fluids move from source to wellhead. The research effort includes parameter choice and dimensions consistent with available hydrodynamic models and quality of reservoir data, laboratory measurement of key process parameters and partitioning coefficients of the noncondensable gas components, testing of the model under laboratory conditions, and evaluation of the model under field conditions. Two comparative tests are planned--(1) transects at Larderello, Italy (in conjunction with CNR in Italy) to examine the similarity in two vapor-dominated reservoirs; and (2) transects at Cerro Prieto (in conjunction with CFE in Mexico) to examine the similarity between vapor-dominated and liquid-dominated reservoirs. The results should be quite useful in evaluating the concept of noncondensable gas chemistry as a tool in geothermal reservoir engineering, especially in adding to the various types of corollary data being collected by others.

### (b) Emanation Studies

A second major effort in this Task has been the initiation of a two-year thesis study by Kazuichi Satomi, a visiting student supported by Nippon Steel Corporation in Japan. His research studies will continue the pioneering studies reported by Macias in evaluating the emanation source of radon in geothermal reservoirs as functions of reservoir pressure and temperature. Another important variable which Satomi is experimentally evaluating is the emanating power as a function of particle size distribution. A series of radon emanation studies is underway to add the effects of this variable onto the results of pressure and temperature effects already reported by Macias. It is anticipated that these results will be incorporated into the source terms for the noncondensable gas component condensation simulation model.

## TASK 3. BENCH-SCALE EXPERIMENTS--WELL TEST ANALYSIS

### 3.1 Bench-Scale Experiments

Several experimental studies were conducted with small cores of porous media. In general, the objective of all experiments was to determine fundamental characteristics of flow important to field reservoir engineering. There are three main pieces of equipment involved: the small core apparatus, the large core apparatus, and the vapor-pressure lowering apparatus.

(a) Absolute Permeameter, by A. Sageev, M.S. student in Petroleum Engineering, and Prof. H. J. Ramey, Jr.

An array of experiments investigating the effect of temperature on absolute permeability has been carried out throughout the last decade. These experiments covered a range of rock types, fluids, confining pressures and several other system characteristics. Out of the array of possible experiments, one configuration of rock, confining and pore pressures, and fluid was chosen for this study--i.e., distilled water flowing through unconsolidated sand cores at 2000 psig confining pressure and 200 psig pore pressure. Work done at Stanford University, primarily by Casse and Aruna (SGP-TR-3 and SGP-TR-13) indicated a decrease in permeability with an increase in temperature at these conditions. This decrease in permeability could not be explained by thermal expansion, porosity changes, or other explanations that were suggested, such as silica-water interaction. The purpose of this work was to construct an improved absolute permeameter to attempt to determine the nature of the effect.

Four major problems arose during the construction of the apparatus: (1) noise and pump pulsations affecting the tranducer's performance; (2) control of the average pore pressure with varying flowrates; (3) a calculated permeability that was flowrate dependent; and (4) plugging of the down stream needle valve. These problems were solved by:

(a) Isolating the core from airbath vibrations

(b) Changing the pump/accumulator piping arangement

(c) Using an excess flow loop to maintain constant upstream pressure

(d) Moving the pressure taps directly next to the sand face

(e) Improving the design of the core holder end plugs to assure nonconverging flow to the end of the core.

A schematic of the final apparatus is shown in Figure 3-1.

After resolving all of the problems with the permeameter design, a large number of absolute permeability measurements were made. Several sand packs were used having permeabilities of approximately 2.5 and 5.0 darcies. For each pack, measurements were made over several temperature cycles from 70°F to 300°F (20°C to 150°C). Results for several of the runs are shown in Figure 3-2.

The absolute permeability to distilled water of Ottawa silica sand was not found to be dependent upon the temperature from 70°F to 300°F. This result does not agree with much of the data in the literature. It is believed that some of the work done at Stanford University in recent years experienced mechanical problems (resolved in this work) that resulted in flowrate dependent permeability measurements which were interpreted as being temperature dependence.

One of the most important results of this study was the elimination of temperature-dependent absolute permeability as an explanation for the temperature dependence observed in two-phase relative permeabilities.

(b) Large Core Apparatus, by Morse Jeffers, M.S. student, Mark Miller, Ph.D. candidate in Petroleum Engineering, and Prof. H. J. Ramey.

This project is a continuation of several years of experimental work investigating the relative permeabilities of laboratory cores to steam and water (see Counsil, 1979, and Counsil and Ramey, 1979). Despite overcoming many difficult experimental problems, the steam/water relative permeability results have proved unsatisfying. Counsil found little effect of temperature upon gas-water relative permeabilities for a synthetic cement-sand consolidated porous medium. We now suspect the artificial "sandstone" to behave more like a limestone. Temperature sensitivity has never been evident for limestones. Other possible reasons for the differences compared to previous results in oil-water

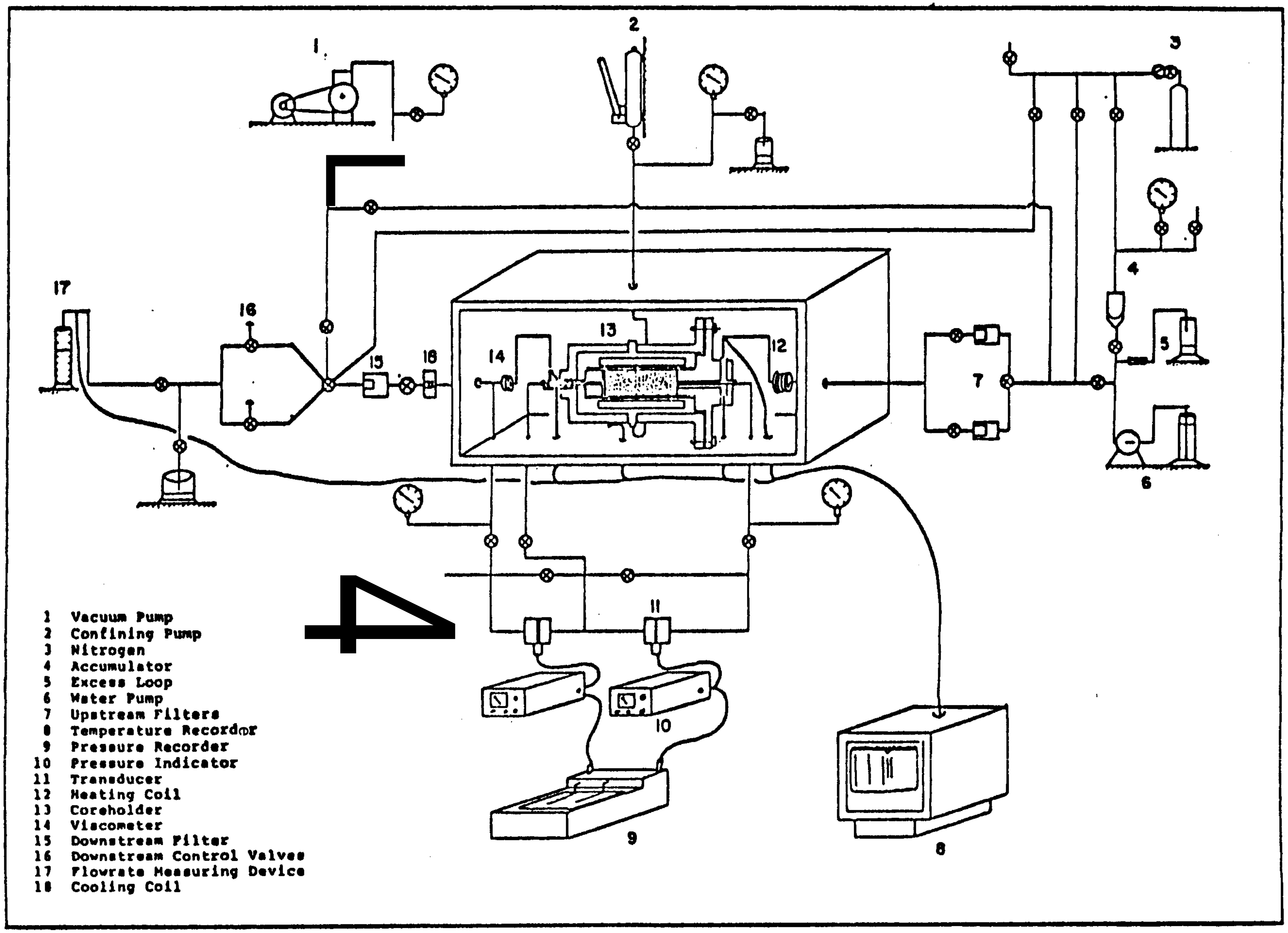

FIG. 3-1: SCHEMATIC DIAGRAM OF THE APPARATUS-WATER FLOW

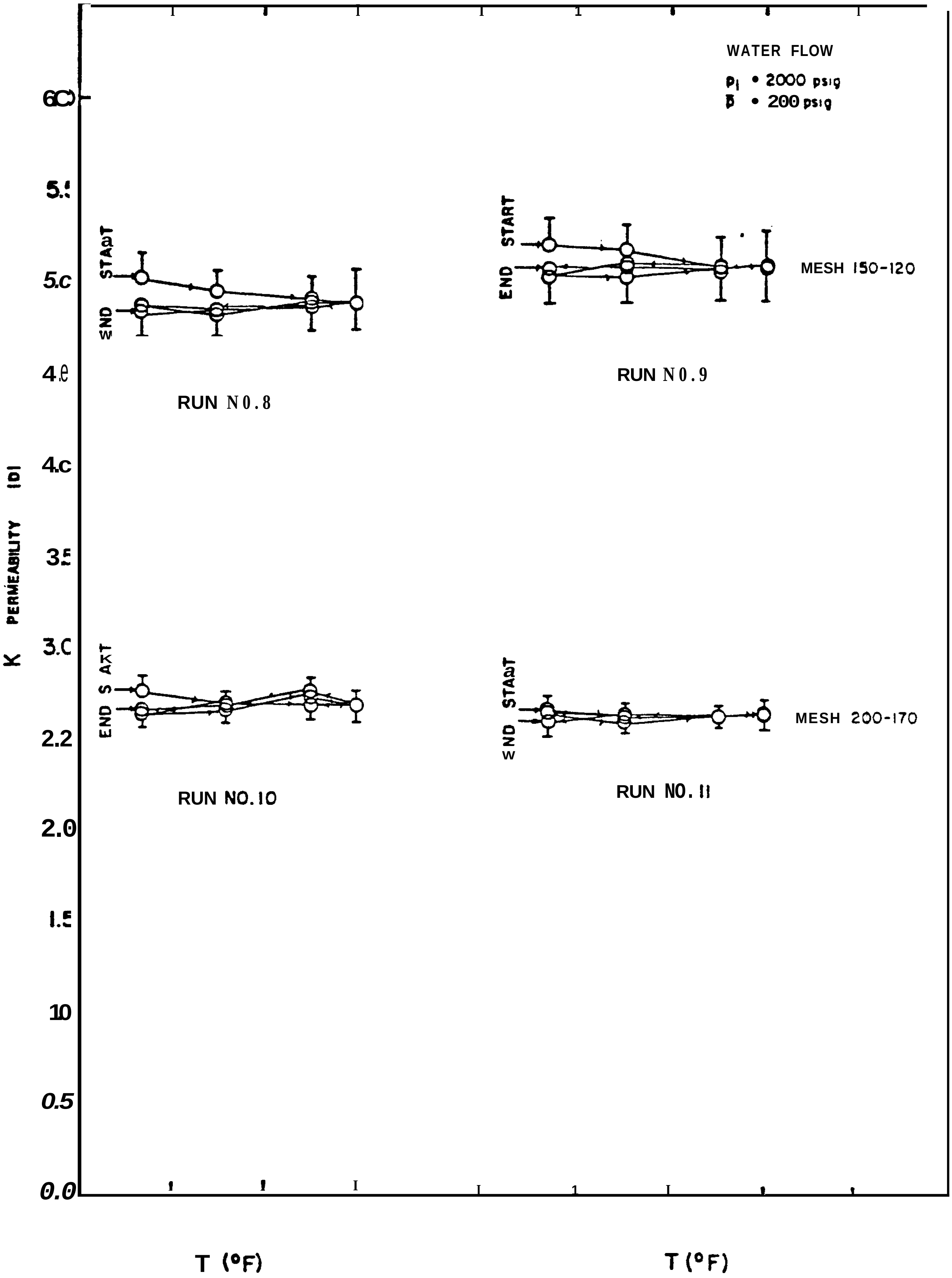

FIG. 3-2: PERMEABILITY VS. TEMPERATURE FOR RUNS 8, 9, 10 AND 11

systems include effects due to changes in viscosity, flowrate, and viscous fingering.

Our current intention is to perform experiments for the case of two immiscible liquids. To this end, the equipment has been redesigned and rebuilt. It was necessary that the apparatus be able to measure relative permeabilities of water-oil rock systems at elevated temperatures under unsteady-state conditions.

Figure 3-3 shows schematically the design of the new apparatus. The equipment will be used for a constant flowrate displacement at a given temperature. Measurements can be made of cumulative displaced liquid as a function of cumulative injection, time, and pressure drop and this information corrected for temperature effects to calculate relative permeability at elevated temperatures.

Initial runs with the apparatus have pinpointed some design problems which are currently being resolved. In addition, we are investigating an improved method of measuring produced volumes by means of an optical device that senses the refractive index change between oil and water.

Along with the laboratory measurements, work is proceeding on a mathematical microscopic network flow model of porous media to help provide a theoretical basis for observed two-phase flow behavior.

(c) Vapor Pressure Lowering, by Dr. C. H. Hsieh and Prof. H. J. **Ramey, Jr.**

This bench-scale study involves an investigation of vapor pressure lowering effects for liquid gas interfaces in the pore space of a porous medium. Because of classic work in this field, it was believed that these eifects could be attributed to capillarity; however, the results of this program indicated that the major cause of vapor pressure lowering effects in a porous medium were probably caused by adsorption-desorption phenomena. Consequently, a Brunauer-Emmett-Teller (1938) adsorption apparatus was constructed which could be operated at various temperature levels in an air bath. The mass of various gases adsorbed in several sandstones was measured over a range of temperatures. The gases used in this study included nitrogen, methane, and water vapor

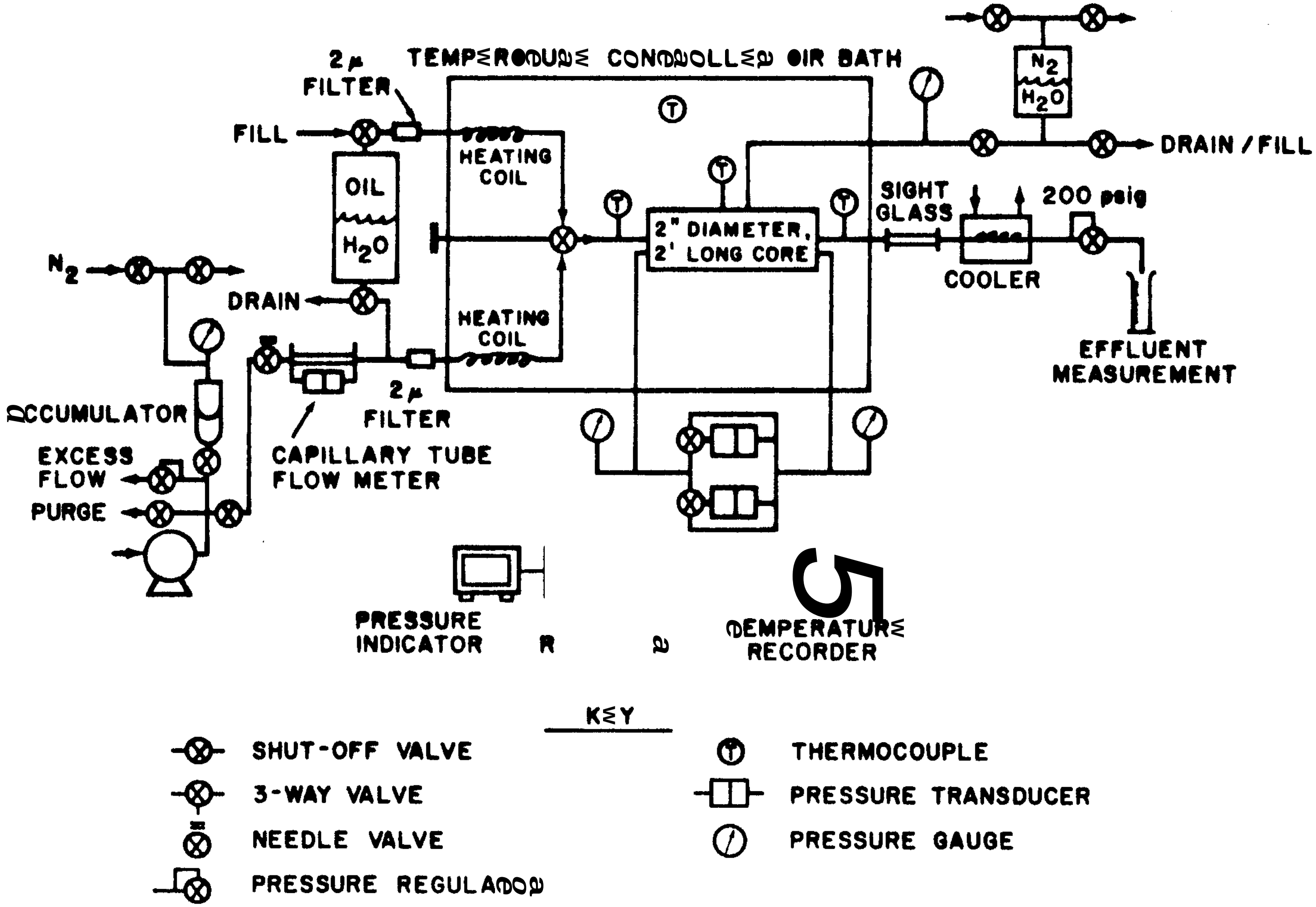

FIG. 3-3: LARGE CORE RELATIVE PERMEABILITY APPARATUS

over temperature ranges from room temperature to 300°F. Complete details of the results of this study are available in a dissertation by Hsieh (1980). Figure 3-4 shows typical results for adsorption of water vapor in a sandstone. In general, the following important observations were made. Micropore adsorption of water vapor is capable of storing a mass of water ten times as great as the mass of steam in the pore space of a porous medium. This is true at elevated temperatures, and appears to be one possible explanation for the location of the liquid water in vapor-dominated geothermal systems such as The Geysers steamfield in California and the Larderello (Italy) vapor-dominated steamfields. This observation appears to agree with conclusions reached in the radon study performed under Task 2.

The state of the adsorbed water appears to be somewhere between that of a liquid and a solid. A new dielectric constant probe designed for this equipment appears capable of measuring liquid contents for this type of adsorption. This new probe design may have application in other laboratories' experimental work.

The major effort during the past year on this project involved the completion of analysis of Dr. Hsieh's data and the dissemination of information. However, new measurements on a variety of additional cores are planned, and some extremely low permeability samples have been obtained. It is intended to obtain samples of greywacke similar to The Geysers reservoir rock material and other samples pertinent for geothermal vapor-dominated systems. A paper on this work was presented at the California Regional Meeting of the Society of Petroleum Engineers in March 1981.

### 3.2 Well Test Analysis

Well test analysis offers a rapid way to perform an initial assessment of geothermal systems. Well testing includes both pressure drawdown and buildup testing, and interference testing. Development of new well test analyses continues to receive major emphasis in the Stanford Geothermal Program. During the year, several studies were completed, and papers presented on a variety of well test analysis methods. In this contract year, particular emphasis has been placed on the analysis of fractured reservoirs, and reservoirs that produce from

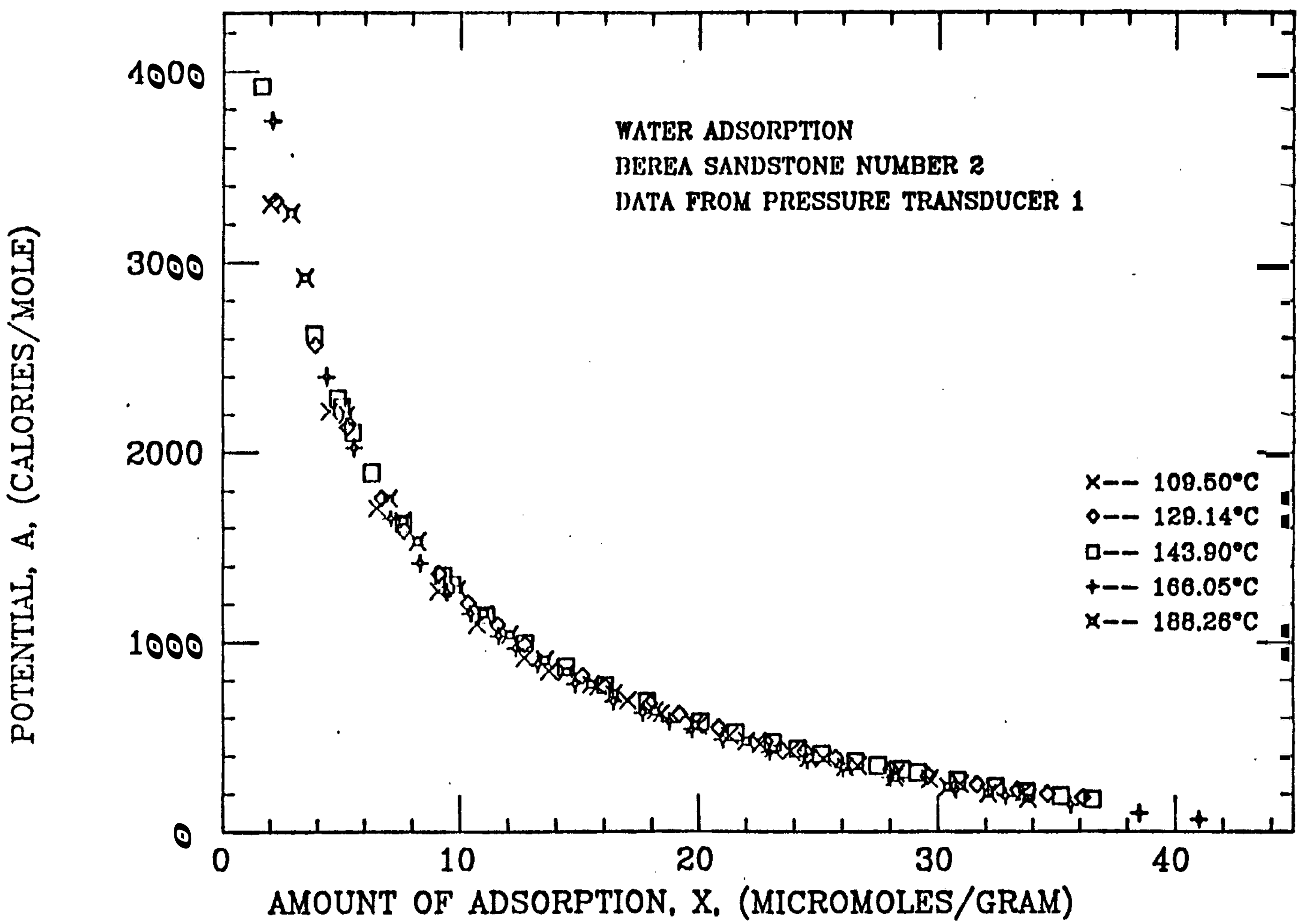

FIG. 3-4: CHARACTERISTI< < OF WATER ADSORPTION ON ROCK SAMPLE

two-phase conditions. The following summarizes some of the more important results.

(a) Analysis of Transient Pressure Tests in Flashing Reservoirs

Based on the two-region reservoir concept developed in the contract year ending September 1980, by Satman, Eggenschwiler, and Ramey (1980) and Horne, Satman and Grant (1980), a method was developed for the interpretation of well tests in reservoirs with boiling close to the well. The analysis developed methods to determine reservoir properties on both sides of the flash front as well as the volume contained within the boiling zone. As an extension of this work Prof. Horne and research assistant M. O. Onyekonwu augmented the analysis to include the case of a spherically growing flash front which is the more likely case in a fractured geothermal system. The work concluded that the volume of the flashed region can be calculated in the same manner as in the radial case. This work will be presented at the 1981 Annual Fall Meeting of the Society of Petroleum Engineers (Onyekonwu and Horne, 1981).

(b) Parallelepiped Models, by D. Ogbe and M. Economides, Ph.D. candidate in Petroleum Engineering, and Prof. R. N. Horne, Prof. F. G. Miller, and Prof. H. J. Ramey, Jr. These models have been successful in demonstrating three-dimensional boundary effects in geothermal reservoirs. Previous year's work in this area focused on a three-dimensional reservoir contained on all sides and at the top by impermeable boundaries, with a constant pressure boiling surface at the base. These models (either with a partially penetrating well or fracture) were used successfully to analyze well test data from The Geysers and the Travale-Radicondoli fields (see Economides et al., 1980). Later year's activities extended the model to include the configuration of a three-dimensional reservoir with a boiling surface at the base and a condensation surface at the top. This situation is characteristic of the Kawah Kamojang field in Indonesia, and also of some parts of The Geysers. Typical drawdowns for such a system are illustrated in Figure 3-5. The objective of this study was to produce generally useful type-curves with an emphasis on detection of the outer limits of the reservoir. It is also intended that these models be used to represent the entire drainage volume for a power plant (encompassing

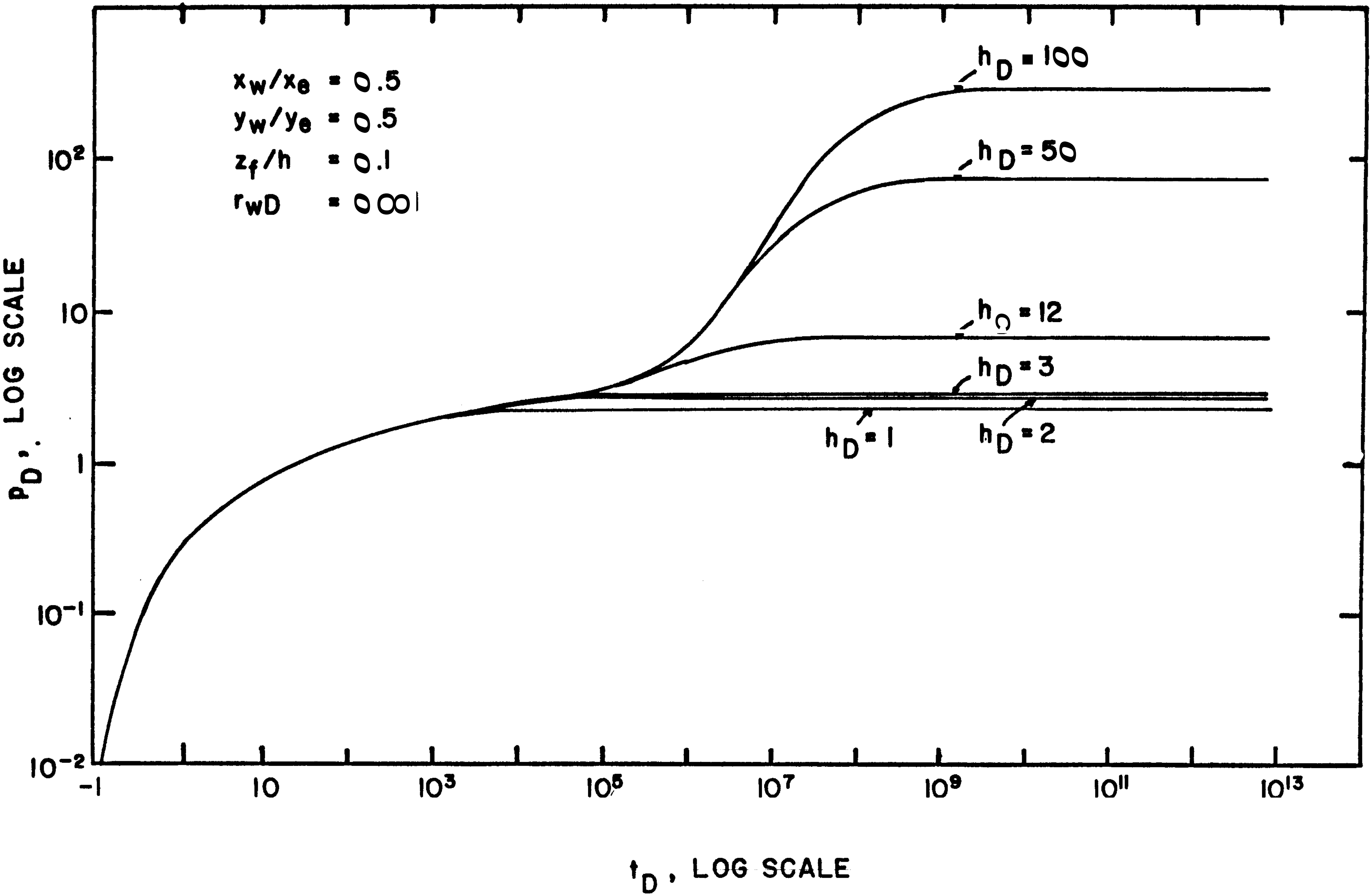

FIG. 3-5: LOG-LOG TYPE-CURVE FOR A PARALLELEPIPED MODEL

ten or more wells). This earlier work on the parallelepiped models is being organized into a treatise on the subject which will collate all the three-dimensional well test analysis methods in order that they may be more effectively used.

(c) Naturally Fractured Reservoirs, by G. Da Prat, Ph.D. Petroleum Engineering, Prof. H. Cinco-Ley, and Prof. H. J. **Ramey,** Jr.

This study presents solutions for production rate decline under constant pressure production in a naturally fractured reservoir. Solutions for dimensionless flowrate are based on the model presented by Warren and Root (1963). The model was extended previously by Mavor and Cinco-Lev (1979) to include wellbore storage and skin effect. In the present study, the model was extended to include constant producing pressure in both infinite and finite systems. Figure 3-6 shows the results obtained for a finite, no-flow outer boundary. The flowrate shows a rapid decline initially, becomes nearly constant for a period, and then a final decline in rate takes place. The new type-curves of the analytical solutions are graphed in terms of dimensionless flowrate and time ($q_D$ and $t_D$) and the two parameters $\lambda$ and $\omega$ are characteristic of the fracture/block properties. An important conclusion of this work is that a type-curve matching based only on the initial decline can lead to erroneous values for the dimensionless wellbore outer radius, $r_{eD}$, if the systems is considered homogeneous. $\lambda$ and $\omega$ should be obtained from pressure buildup analysis, and these values used to define the particular type-curve to be used in production forecasting or matching for estimation of reservoir size.

This work was completed during the year, and was presented at the 1980 SPE of AIME Annual Fall Meeting in Dallas, Taxas (Da Prat, Cinco-Ley and Ramey, 1980) and at the 1981 California Regional Meeting of the SPE in Bakersfield, California (Da Prat, Cinco-Ley, and Ramey, 1981).

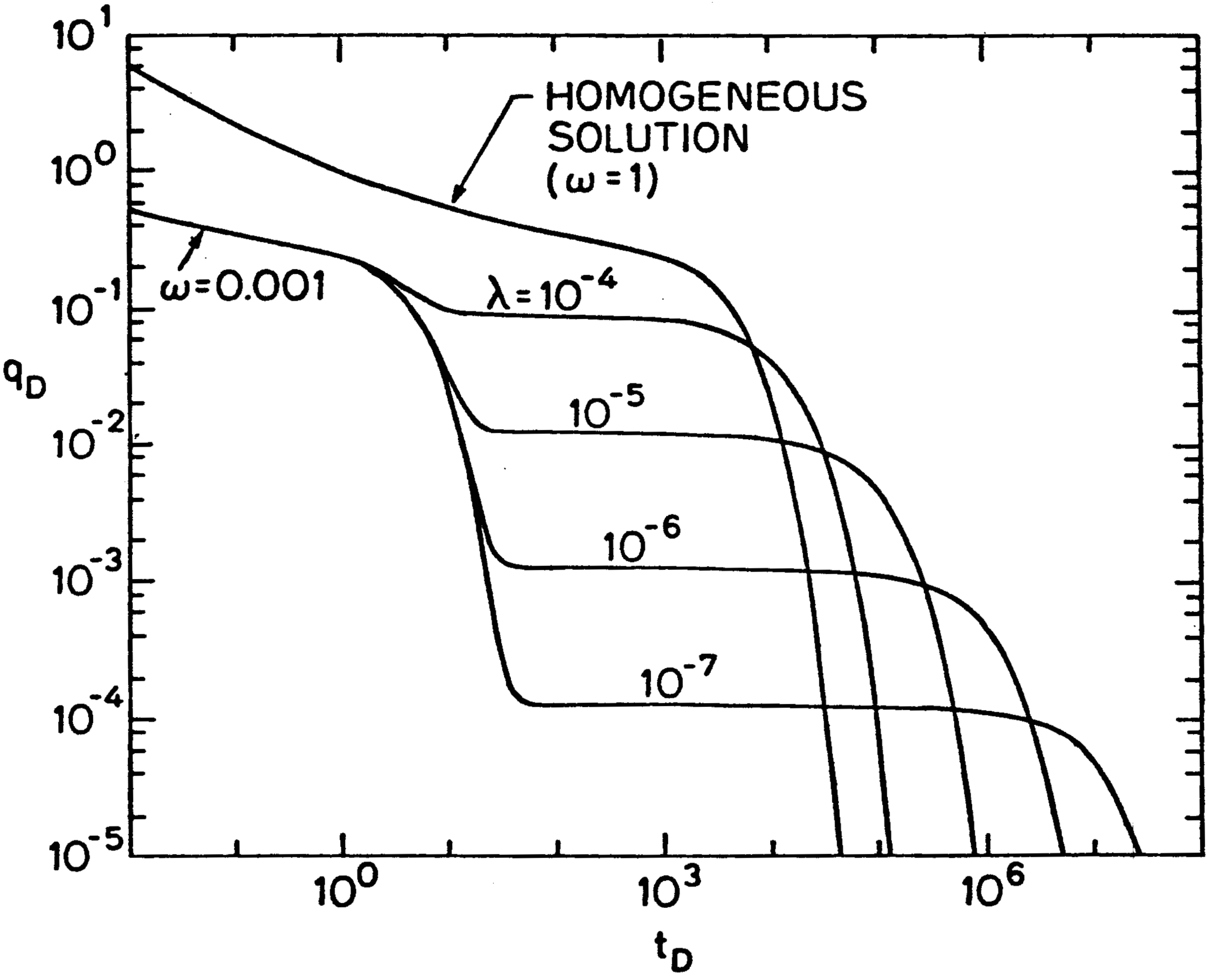

**FIG.** *3-6:* $q_D$ VS $t_D$ FOR CONSTANT **PRESSURE** PRODUCTION; **CLOSED** BOUNDARY ($r_{eD}$ = 50, **SKIN** FACTOR = 0)

## TASK 4. STANFORD-ENEL COOPERATIVE RESEARCH

With the DOE-ENEL Cooperative Agreement on geothermal energy research, first signed in 1975, our government through Stanford is using the Larderello region of geothermal steam fields in Italy as an experimental laboratory to develop new reservoir engineering technology. This work falls under Project 3 of the Agreement.

Although reservoir engineering principles have been applied for more than a half century to petroleum and groundwater systems, these principles were not applied to geothermal-fluid reservoirs until the early 1960's and thus the development of new technology is important. Reservoir engineering studies often follow established patterns. Generally the observed field performance data of a reservoir under examination are used to formulate an hypothesis regarding its nature. The hypothesis is tested in different ways using physical or mathematical models, or both. The physical laws involved in the performance of the reservoir can then be recognized so that pertinent engineering equations can be derived and solved. To establish their validity, solutions are tested by comparing them to field performance. When a test indicates that a mathematical description of a reservoir is reasonable, it is possible to study various prospective methods of field development and production and to forecast performance.

It is important, however, to have long-term field data available. In Italy we have access to field performance histories back to 1945, and we can plan, design, and implement field tests. In contrast, for field performance histories in the U.S.A. we must turn to new fields which cannot supply the information needed. This is particularly significant at a time when the geothermal industry in the U.S.A. is just beginning to gain recognition as a viable alternate source of energy. Growth is reflected in recent progress in field exploration and development, but these activities cannot relieve our dearth of reservoir engineering technology.

Thus far, reservoir engineering research done under Project 3 has resulted in a number of important transfers of technology to the U.S.A. For example, a successful new method has been developed to forecast steam production. This method was developed from studies made in the Gabbro field in Italy and applies to similar fields in the U.S.A. Work on the Gabbro field was done under DEA Task 3/9 of Project 3. In October 1980 a paper on the results was presented at the Second WE-ENEL Workshop for Cooperative Research in Geothermal Energy. Later this paper was written for publication in the Workshop Proceedings (Brigham and Neri, 1980). This research is described briefly in section 4.1 of the present report.

Another example of a transfer of technology to the U.S.A. is a method of engineering analysis developed to estimate flow patterns and fracture trends in certain geothermal steam reservoirs in which a principal producing well penetrates a vertical fracture extending part way to the "bottom" of the reservoir, hypothesized as a boiling water interface. This method was developed from well interference studies made under DEA Task 3/4 on the Travale steam field in Italy and can lead to important information on steam reserves. The method is known to apply to the East Mesa field in California and will apply to other similar fields in the U.S.A. Task DEA 3/10 was a follow-up study on the same field in which an analysis was made of the pressure-production history of Travale Well T-22 over an extended period of time. A paper on the results of this study was presented at the Second DOE-ENEL Workshop for Cooperative Research in Geothermal Energy. Later this paper too was written for publication in the Workshop Proceedings (Barelli et al., 1980). This work is described briefly in section 4.2.

Task DEA 3/5 consisted of thermodynamic studies of the Bagnore steam field. A major feature of this field is the presence of and high content of carbon dioxide. Mathematical models of the field were designed and applied. They addressed the question of its high carbon dioxide content using chemical equilibria, attempted to describe the field's history using the the thermodynamics of vapor-liquid equilibrium, and to describe the field's pressure and composition histories. The follow-up research after completion of DEA Task 3/5 was DEA Task 3/15. It has consumed the major effort of the Stanford and ENEL reservoir engineering research teams during fiscal year 1981. A progress report on DEA Task 3/15 was presented at the Second DOE-ENEL

Workshop for Cooperative Research on Geothermal Energy (Celati et al., 1980). This report as well as research done on this Task since October 1980 is described in section *4.3* below.

In contrast to many areas of geothermal energy research, results developed from reservoir engineering studies under the DOE-ENEL Cooperative Agreement can be applied immediately and put to practical use. Observing that steam production from The Geysers field in California can generate enough electricity continuously to supply a city the size of San Francisco, and that many new fields are under development, this becomes a matter of national economic importance in the U.S.A.

## *4.1* A Depletion Model for the Gabbro Zone

Task DEA 3/9 of the ENEL-DOE joint agreement is directed toward the development of simple reservoir models which will match past performance data and can be used to predict future production rates and ultimate reserves. To this end, studies were made of the pressure and production data available from the Gabbro Zone, a small producing interval north of the main producing area of the Larderello field. Production began in 1961. The reservoir pressure data clearly show a pressure trend toward Larderello which has persisted throughout the productive life of this zone.

During the past ten years the number of producing wells has remained constant and during this time both the producing rate and the Gabbro Zone pressure have declined continuously. Thus there is strong evidence that this zone is undergoing depletion. A reasonable hypothesis of the production dynamics is to assume that deep within the reservoir is a zone of boiling water which is supplying steam to the upper producing interval in which the wells are completed. Depletion of this zone can occur due to production from the Gabbro Zone and also due to flow from the Gabbro reservoir toward the main part of the Larderello field.

Further, since the deep zone seems to be connected to the producing zone by a system of relatively tight fractures an additional pressure drop will occur in the producing zone due to frictional losses as the steam flows vertically. The vertical frictional pressure drop is a transient linear flow phenomenon whose timing depends on the hydraulic diffusivity of the fracture system. Since this term is not known a priori, it has been evaluated by a trial and error procedure using the concept of a "lag time" to calculate the linear flow dynamics.

The above concepts have been successfully incorporated into a lumped-parameter reservoir model of the Gabbro Zone production history.

History matches and projections to the year 1995 were made for lag times of 30 months, 42 months, and 48 months. In spite of large differences in the parameters used, the future projections from all three cases are similar.

Figure 4.1 is typical of the three cases studied. It shows the Gabbro Zone pressure-production history match and the (p/Z) drop due to depletion, flow to Larderello, and linear flow.

## 4.2 Reservoir Engineering Studies of the Travale-Radicondoli Reservoir

Initial reservoir engineering studies of the Travale-Radicondoli steam field in the Larderello region of Italy were begun in late 1976, with the ultimate objective of estimating energy reserves. Research centered on pressure transient (well test) studies. Reasonable success was attained in studying mathematical models of the reservoir in an attempt to duplicate the pressure buildup behavior of Travale Well 22 as observed in the field. A well interference test was later designed and implemented, involving Well T-22 as the test well, and seven other nearby observation wells. Results of analysis of the test appeared to be conclusive. They indicated the direction of the main fracture in the reservoir which is penetrated by Well T-22, the steam flow pattern in the reservoir, and that the reservoir can be represented by a parallelpiped model.

Following this study, it was believed that a better concept of the Travale reservoir structure and the flow behavior of its fluids could be developed through analysis of the pressure-production history of Well T-22 over a period of two years and seven months, beginning just after construction of a power plant in 1973.

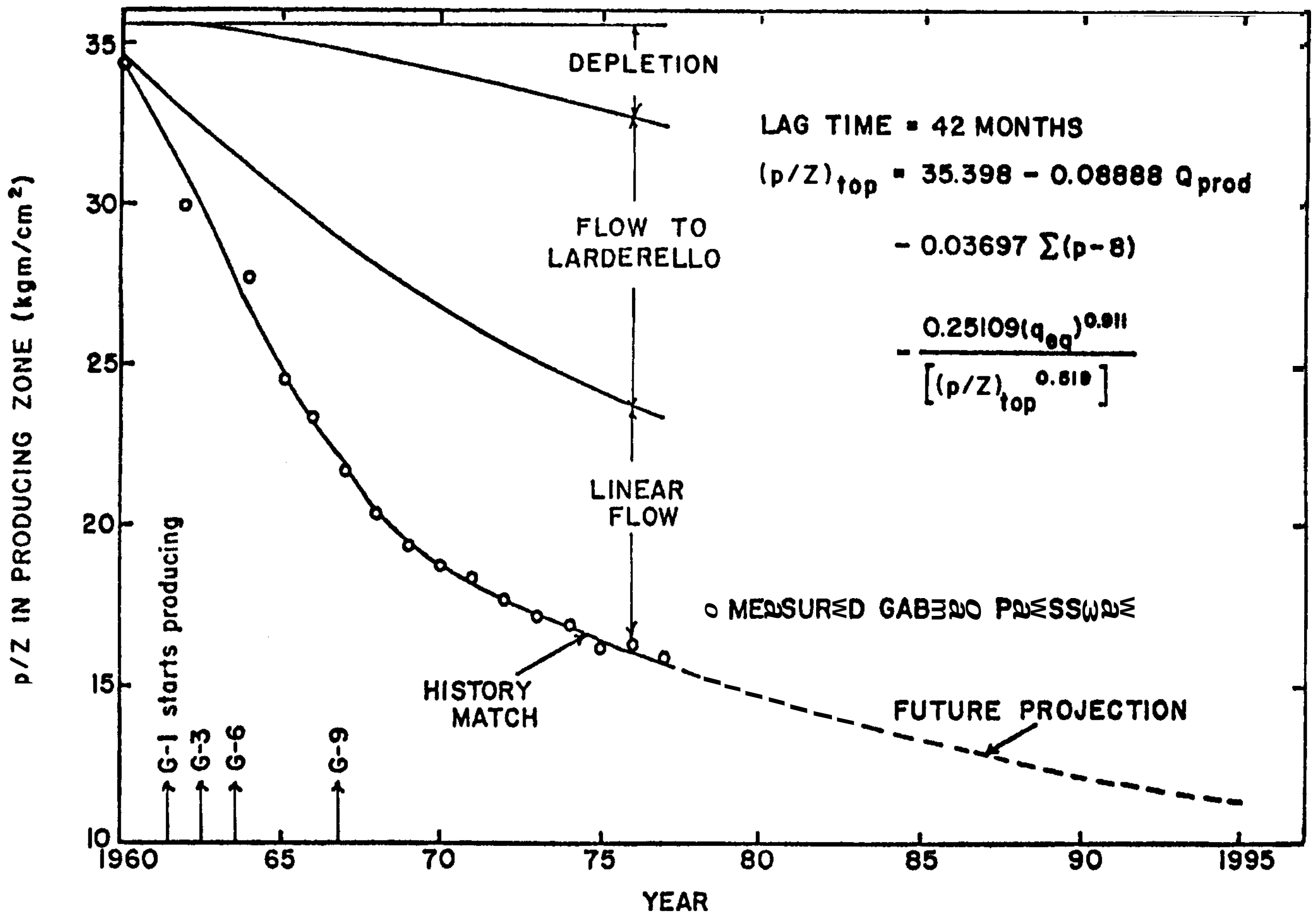

FIG. 4.1: GABBRO ZONE PRESSURE-PRODUCTION HISTORY MATCH

The data available consist of a long wellhead pressure history from July 1973 to July 1975. During this period, flow rates, wellhead temperatures, and noncondensable gas composition were recorded once a month. By means of this information, bottomhole pressures were calculated. Flow rate changes and many shut-ins took place during this period.

The bottomhole pressure history was calculated from wellhead data. Attempts were made to develop this history for idealized constant flow-rate conditions by applying the principle of superposition to the actual variable rate. Due to some uncertainties in field data, influence functions obtained through these calculations cannot be interpreted uniquely. Dimensionless pressure drop was generated with a parallelepiped model which simulates a boiling water interface at its base. Influence functions can be interpreted equally validly with a linear flow model similar to that described in an interference-test analysis reported earlier. This research contributes to the general development of reservoir engineering techniques for estimating geothermal-fluid reserves, and brings to light the limitations of existing methods and the need for new methods.

### 4.3 Study of Water Influx and Fluid Composition in the Bagnore Field

The purpose of this project, designated originally as DEA Task 3/15, was to study water influx and variations of fluid composition in the Bagnore field, which lies on the southwestern slope of the Mt. Amiata volcano, 80 kilometers southeast of Larderello, Italy.

The field is considered to consist of two regions in each of which the thermodynamic and fluid properties are considered uniform. The upper region is a fractured limestone filled with a gaseous mixture composed of steam and noncondensable gases, mainly carbon dioxide, while the lower region is a fractured limestone filled with liquid water containing dissolved carbon dioxide and minor quantities of other dissolved gases. The fluids in the two regions are assumed to be in equilibrium with each other.

After three years' production the fraction of carbon dioxide in the produced fluid stabilized at about 10%. Also during this three-year period the reservoir pressure declined from 23 atm to 7 atm. The initial reservoir temperature was estimated to be between 170°C and 180°C. The pressure in the steam phase in the reservoir was controlled primarily by the coexisting carbon dioxide. The large decrease in the carbon dioxide content of the reservoir and the corresponding decrease in its partial pressure caused a large influx of water from a surrounding aquifer. The rate of influx stabilized, however, once the carbon dioxide content and the partial pressure of the carbon dioxide stabilized.

Studies of hydrogeological data from the Bagnore field were made as a part of the work done under DEA Task 3/5. This was to develop information that could be used in studies of the thermodynamic behavior of the fluids produced. This behavior was determined by analyzing and applying a mass balance independently to the produced steam and to the noncondensable gases. Mathematical models which account for thermodynamic and chemical equilibria between the vapor, liquid and solid carbonate phases were developed and applied. This research confirmed the hypothesis that there was initially a large accumulation of noncondensable gas in the reservoir, and that it was drawn off during the early years of production. Calculated and observed production histories of noncondensable gases, mainly carbon dioxide are poorly matched, however. The sustained level of carbon dioxide, as measured in the field, suggests the presence of an unexplained source of carbon dioxide in the reservoir.

New reservoir engineering research on the Bagnore field accomplished during fiscal year 1981 consisted principally of two studies. One of these was an extension of the foregoing work on thermodynamic behavior and chemical equilibria and the other was a study of the implications of adsorption and formation fluid composition on geothermal reservoir evaluations. The first of the two studies was made by Drs. R. Celati, F. D'Amore, and G. Neri in Italy, and the second by the Stanford research team, mainly by M. J. Economides for his Ph.D. research. He has been engaged in Stanford Geothermal research for more than two years. It is anticipated that reports for publication will soon be completed on both studies. First the work will be coordinated and revised, however, through joint action of the Stanford and Italian researchers.

### 4.3.1 Thermodynamic Behavior, Chemical Equilibria, and Water Influx in the Bagnore Field

Earlier work under DEA Task 315 dealt with pure water and calcite in the initial conditions of the Bagnore field. Carbon dioxide pressure, in equilibrium conditions, was shown to be two orders of magnitude lower than the initial carbon dioxide pressure at Bagnore. In the new work the system calcite-anhydrite-dolomite-water was considered to be a more adequate geochemical model.

Chemical equations, the charge balance relation, and a suitable mass balance equation were used at the original reservoir temperature. The results of these calculations gave a carbon dioxide partial pressure lower by more than one order of magnitude than the carbon dioxide pressure observed in the field. Thus, this more complex model gave a result similar to that obtained earlier.

The geochemical model was improved after considering the roles of other chemical species in the reservoir that could affect the calculations of the partial pressure of the carbon dioxide. Added chemicals introduced in the calculations were ammonia, potassium chloride, and sodium chloride. Results of these calculations yield a carbon dioxide partial pressure close to the initial value at Bagnore, indicating that equilibrium existed in the reservoir. The computed pH was far from water neutrality, however, and indicated relative high acidity.

Other possible processes, chemical and physical, which could control chemical equilibria were considered. These processes seemed capable of explaining the initial accumulation of carbon dioxide. During development of the field, however, the wells have produced carbon dioxide along with steam at a rate of 8-10 x $10^3$ kg/hr. Thus, these processes would have to be capable of supporting this rate, but investigation and analysis has indicated that they are not capable.

One cannot conclude from this result, however, that a more comprehensive study should not be made. Such a study involving the simultaneous occurrence of the various possible mechanisms considered should shed light on the observed production of carbon dioxide.

At the present stage of this research it is felt that a chemical mechanism with an external restraint, a low pH for example, would be capable of ensuring the continuous production of carbon dioxide observed in this field.

### 4.3.2 Implications of Adsorption and Formation Fluid Composition on Geothermal Reservoir Evaluation

A comprehensive investigation has been made of the effects of adsorbed water and noncondensable gases on geothermal reservoir evaluation. For the first time material balances are developed which take into account adsorption phenomena and vapor-liquid equilibria of water-carbon dioxide systems.

In estimating reservoir longevity and productivity it is important to identify the fluid phases, quantities and forms of distribution. It has been determined experimentally and reported in the literature that geothermal rocks can hold significant quantities of water in the form of adsorbed molecular layers.

Porous media offer large surfaces for such adsorption. The quantities of water found in a reservoir defy the free state thermodynamic relationships. At pressures at which one would expect superheated vapor, a reservoir formation can store as much as ten times the amount of fluid that classical thermodyanmics allows. Conventional gas-reservoir material balance calculations and pressure transient analysis are used commonly to estimate reserves and various reservoir parameters. Yet, neglect of adsorption phenomena can result in physically impossible estimates of reservoir thicknesses, porosities or fluid distributions.

Frequently, noncondensable gases are present in a geothermal fluid. Carbon dioxide is the most prevalent compound accounting in some instances for over 95% of the gas composition. The presence of noncondensable gases because of their high vapor pressure, results in a significant shifting of the mixture boiling curve compared to the one for pure water.

In this study it is shown that the initial fluid content of a vapor-dominated geothermal reservoir can be calculated considering the presence of adsorbed water. Moreover, the effect of adsorbed water in a material-balance evaluation of reservoir depletion can be very large as compared to a similar evaluation neglecting adsorbed water.

To illustrate the contribution of adsorbed water to the shape of the material balance curve an example calculation can be made using typical parameters. For a reservoir at an initial pressure $p_i$ of 144 psia, a temperature T of 450° F, a porosity of 5.0% and a rock density $\rho_r$ of 165 $lb/ft^3$, the cumulative production versus p/Z can be calculated. The results appear in Figure 4.2. The curve representing both steam and adsorbed water indicates a much greater cumulative production for any given value of p/Z than the curve determined under the assumption that only vapor exists in the reservoir, and hence the reserves also would be much greater.

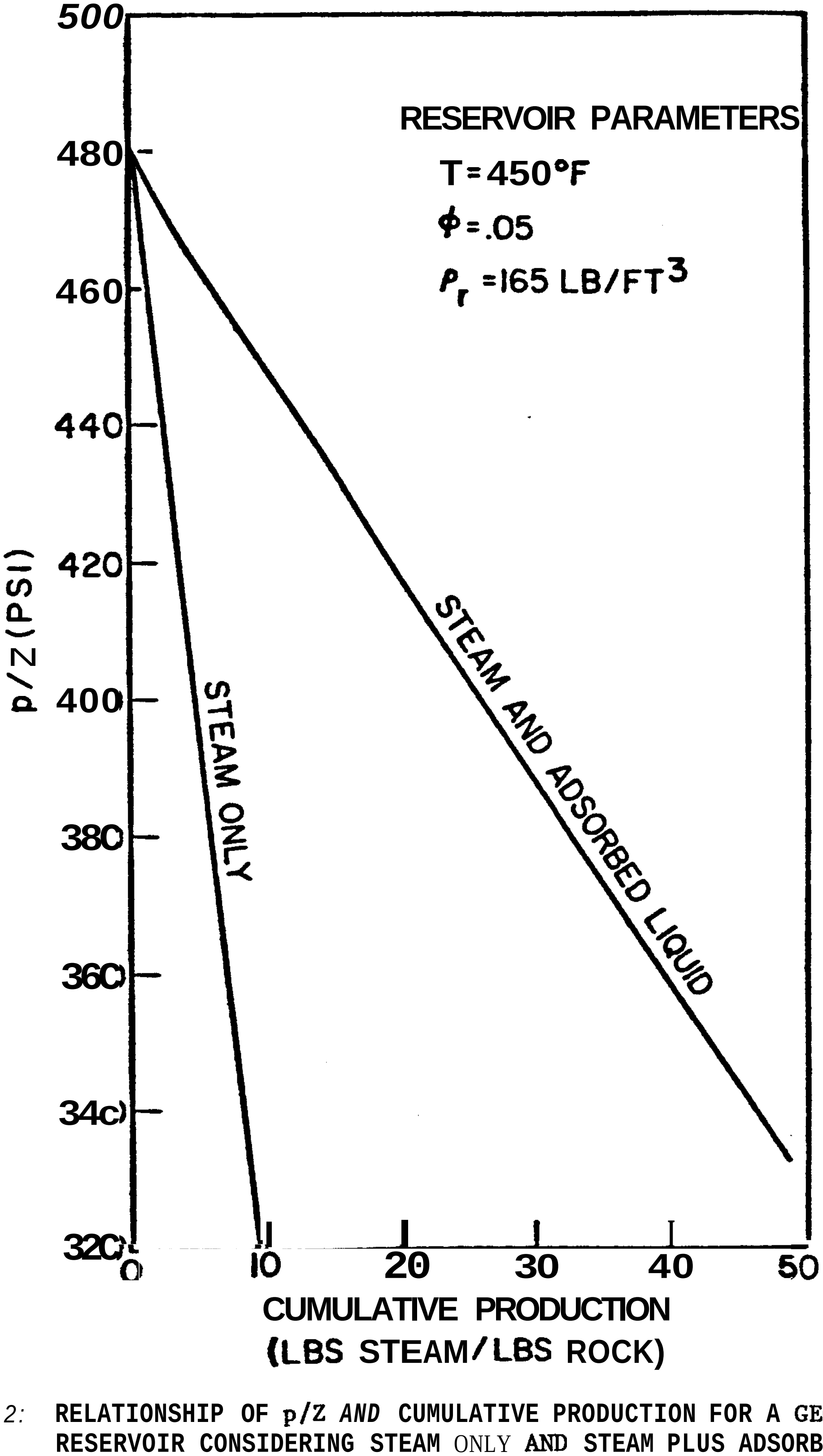

**FIG. 4-2:** RELATIONSHIP OF p/Z AND CUMULATIVE PRODUCTION FOR A GEOTHERMAL RESERVOIR CONSIDERING STEAM ONLY AND STEAM PLUS ADSORBED LIQUID

## TASK 5. STANFORD-IIE COOPERATIVE RESEARCH

Work was initiated in October 1980 on this cooperative agreement between the Department of Petroleum Engineering at Stanford University and the Instituto de Investigaciones Electricas in Mexico, to undertake joint research on geothermal energy development. Although there is considerable overlap, the program responsibilities could be broadly described as theoretical analysis and formulation by Stanford and experimental field testing by IIE. The benefits to both U.S. and Mexico stem from the development of new technology, the U.S. benefits particularly in the field testing of new procedures in a nonproprietary environment, and Mexico benefits particularly from the greater breadth of analytical skills applied in its field problems.

This work has quickly gained momentum and several projects are in progress, one having already been completed. The joint program of work was decided during a meeting attended by Professors Ramey and Miller of Stanford and Drs. Mulas and Cordoba of IIE in March 1981 in Mexico, and Stanford's progress on the various projects for the year has been as follows:

### (a) Pressure Gradient Analysis

This work was undertaken by Prof. Roland Horne of Stanford and Ing. Mario Castaneda of IIE (who was coincidentally an M.S. student at Stanford), to investigate the use of pressure gradient profiles in well analysis. The fact that geothermal wells produce from only a limited number of discrete fractures or "feed zones" often gives rise to confusing temperature and pressure logs. This is because the wells frequently are flowing from one zone to another while the measurements are made--even though the well is shut in. Interpretation of the temperature and pressure logs is then difficult unless the location of the feed zones can be determined and the internal flows recognized. Although this may often be determined by an experienced reservoir engineer, there remains considerable room for ambiguity. This work developed a method for locating the feed zones and simultaneously registering upward or downward flows by comparing the measured pressure gradient with the hydrostatic gradient calculated from a simultaneously

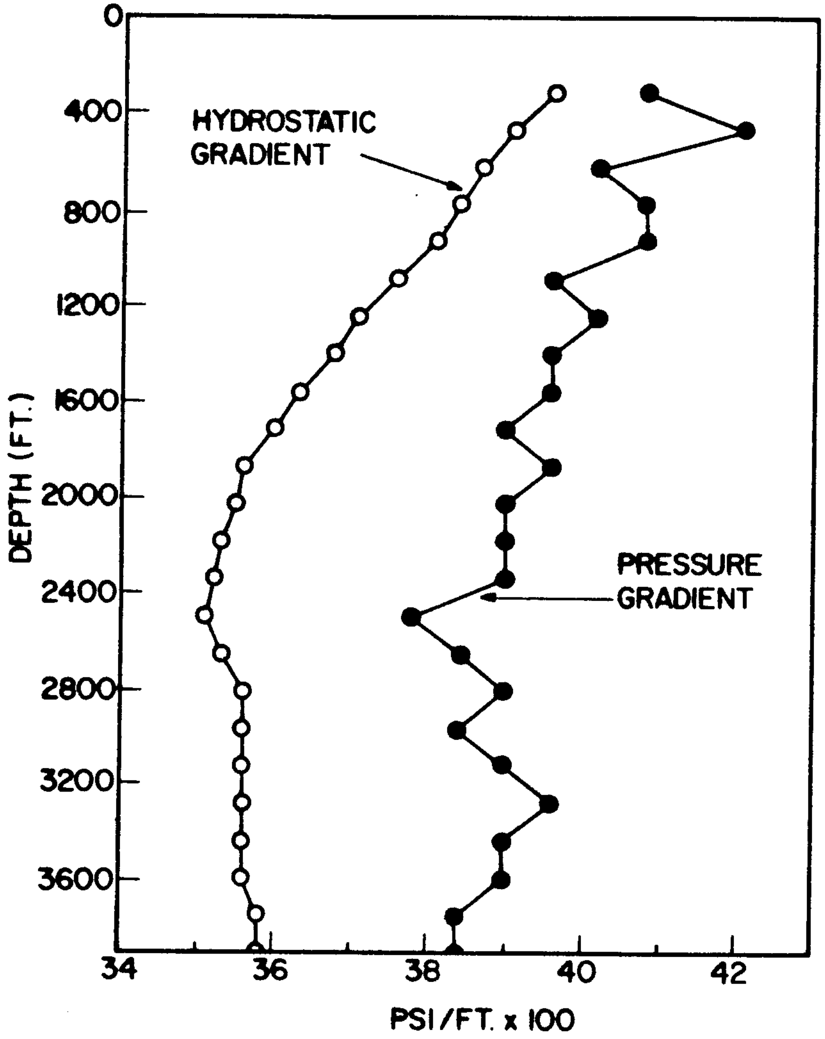

FIG. 5-1: CERRO PRIETO WELL M-9 PRESSURE PROFILES JUST AFTER RECOMPLETION JULY 2, 1975

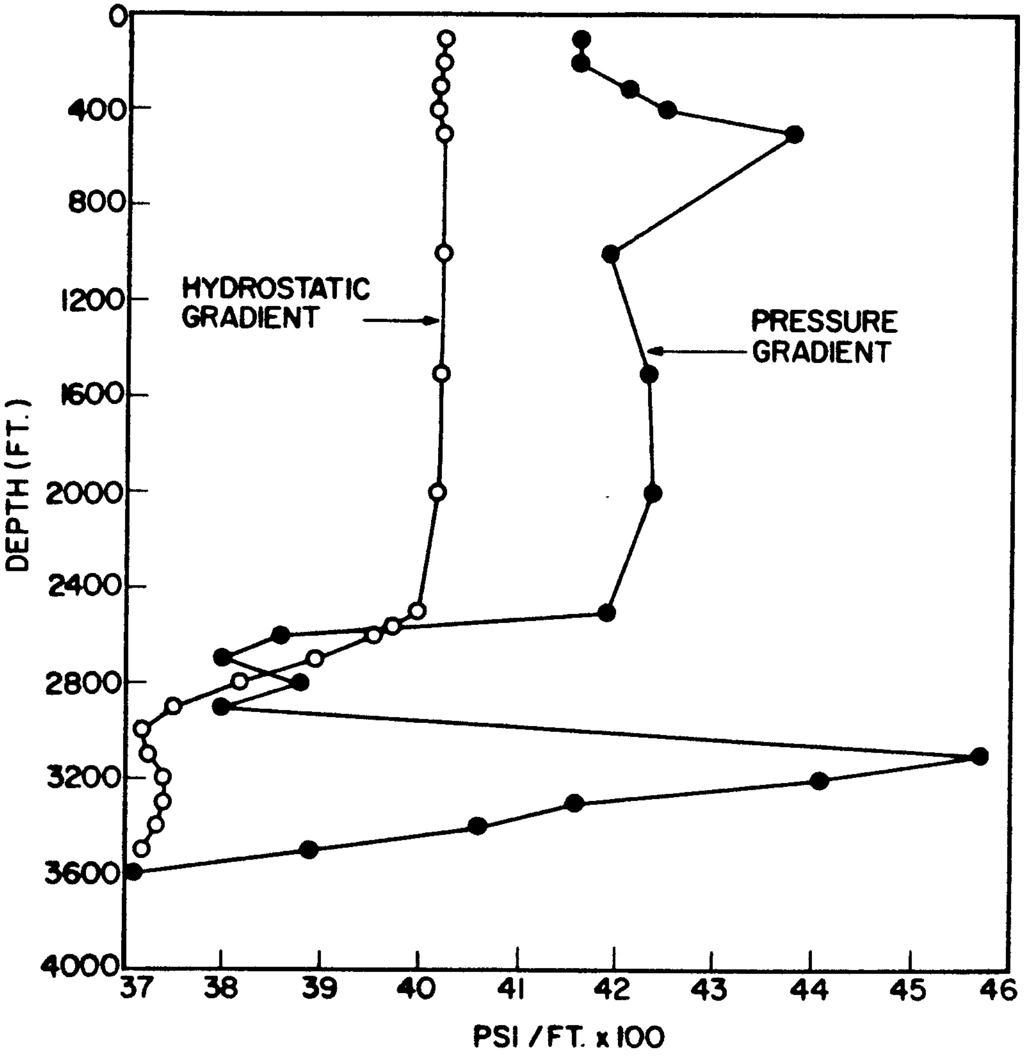

FIG. 5-2: CERRO PRIETO WELL M-9 PRESSURE GRADIENT PROFILES, OCTOBER 26, 1979

run temperature log. Demonstration of the techniques in Cerro Prieto is shown in Figures 5.1 and 5.2. Figure 5.1 shows a comparison of the two pressure gradients immediately after a recompletion of the well cemented in a gun perforated interval from 2348 to 2810 feet depth. Other than a uniform "drift" there are no distinctive differences between the profiles. Figure 5.2 shows the same well some years later after the cement in the perforations had deteriorated--in this case there is clear evidence of a superhydrostatic gradient indicating an upward flow in the well into the reopened perforations. Thus this work has demonstrated the use of simultaneous pressure and temperature logs as a crude flowmeter, which is nonetheless able to distinguish upflows and indicate feed zones in geothermal wells.

This work has been completed to a first stage. A preliminary paper is to be presented at the Geothermal Resources Council 1981 meeting (Castaneda and Horne, 1981) and a final form of the paper considering general implications of the technique will be presented at the 1981 New Zealand Geothermal Workshop (Horne & Castaneda, 1981). A technical report describing the investigation of feed zones in specific Cerro Prieto wells using the technique has been prepared as SGP-TR-47. The possibility of extending this technique to investigate the development of a measuring device is being considered as a second stage of the work.

### (b) Tracer Analysis of Fractured Systems

The benefits of performing tracer tests in geothermal reservoirs have recently (1979-1980) become evident in Japan and New Zealand field tests, although tests were performed as early as 1971 in El Salvador. Tracer testing has been practiced for many years in the oil and gas industry.

The most outstanding feature of these recent tests is that they indicate extremely rapid movement of tracers underground between reinjection and production wells, sometimes at rates up to 100 meter/hour. Rates of tracer return have also been observed to correlate with later success in reinjecting into the reservoir - slower returns indicate less fractured systems which provide fewer "short circuit" paths for injected fluid and subsequently less thermal drawdown of the field.

Other than implications of the degree of fracturing on the reinjection capabilities of a particular field, there is also the question of resource estimation. Commonly, station size is based on recovering a given percentage (for example 50%) of heat in place in the estimated volume of the reservoir. Recovery of this heat over a time scale on the order of thirty years will be dependent on the degree of fracturing. Clearly a uniformly permeable porous medium can give up a larger fraction of its stored heat than a system with high permeability fractures and intervening low permeability blocks. In the porous medium case, heat is recovered convectively while in the fracture case it is recovered conductively. A decision on the recoverable percentage of heat in place should consider the degree of fracturing.

Tracer testing may also provide information on the reservoir volume, recharge, and degree of "connectivity" between different "horizons" in the reservoir. These aspects are accessible by monitoring long-term increases in tracer concentration in the reservoir at large (i.e., the effects of dilution).

This work was therefore initiated to develop analysis techniques appropriate to fractured systems. Following a preliminary study of previous uses of tracer surveys (Horne, 1981a), the need for a concentration/time technique was identified. A plan was therefore formulated to develop such a technique and to subsequently design and implement a tracer test at Los Azufres field. Division and allocation of the work between IIE and Stanford was decided as follows:

(1) Development of analysis procedures (Stanford)

(2) Selection of the tracer (IIE - Stanford)

(3) Tracer adsorption experiments (IIE)

(4) Implementation design (Stanford - IIE)

Work on development of the analysis procedures by Prof. Horne and Ing. Rodriguez progressed at Stanford during the summer. The main conclusion reached was that molecular and Taylor dispersion in the fractures are both insignificant in comparison with turbulence. A preliminary summary of this analysis will be presented at the 1981 Geothermal Resources Council meeting (Horne, 1981b).

### (c) Analysis of Interference Tests on Flashing Reservoirs

Based on the two-region reservoir concept developed by Satman, Eggenschwiler and Ramey (1980), Horne, Satman, and Grant (1980), and Onyekonwu and Horne (1981) (performed under Task 3), it was proposed that a recent interference test at Los Azufres be analysed considering flashing in the reservoir. This will be carried out by IIE.

### (d) Lumped-Parameter Modeling of Cerro Prieto Reservoir

This study by research assistant J. Westwood and Dr. L. Castanier at Stanford extended the lumped-parameter technique used successfully in Italy by Brigham and Neri (1979) to include two-phase effects. The resulting history match provided considerable insight into the pressure and enthalpy behavior of the field and indicated, for example, that the reservoir must have become extensively two-phase to have the observed behavior. This work has been issued as a technical report SGP-TR-48, and will also be presented at the 1981 Geothermal Resources Council Annual Meeting (Westwood and Castanier, 1981).

## TASK 6. WORKSHOPS AND SEMINARS

This year the Sixth Annual Workshop on Geothermal Reservoir Engineering was held at Stanford. A total of 51 papers were offered and were categorized into eight categories--field development, geopressured systems, modeling, production engineering, well testing, reservoir physics, reservoir chemistry and risk analysis. Unfortunately not all these papers could be presented in the time available and hence some authors had to be requested to offer their papers for publication alone.

In the addition to the technical paper presentation, one half-day of the three-day meeting was set aside for a panel discussion of the numerical model intercomparison study carried out last year under a grant from DOE. This panel discussion and the intercomparison study were the subject of a separate Stanford Geothermal Program Report.

The Sixth Workshop was attended by some 105 scientists and engineers, with some 18 attending from outside the U.S.A. The workshop must thus now be regarded as a primary international meeting on geothermal reservoir engineering.

Preparations for the Seventh Workshop are now well underway with the program approaching the final planning stage. Again some authors are having to be asked to offer their papers only in written form.

During the University year, the Geothermal Seminar series continued at Stanford. During the Autumn Quarter, these seminars mainly covered the work being carried out under the Stanford Geothermal Program or by people involved in the program. During the Winter and Spring Quarters, the topic and speaker range was broadened to cover other aspects of geothermal research, mostly carried out outside of Stanford. The organizers of the Stanford Geothermal Program are most grateful to the speakers and their organizations for their support and time.

The program in the Proceedings for the Sixth Annual Workshop program on Geothermal Reservoir Engineering and a list of the seminar speakers for the three academic quarters follow.

# PROCEEDINGS OF THE SIXTH WORKSHOP
# ON
# GEOTHERMAL RESERVOIR ENGINEERING

HENRY J. RAMEY, JR., AND PAUL KRUGER
CO-PRINCIPAL INVESTIGATORS
WILLIAM E. BRIGHAM, IAN G. DONALDSON, ROLAND N. HORNE,
AND FRANK G. MILLER

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD, CALIFORNIA

DECEMBER 16-18, 1980

SPONSORED BY
THE GEOTHERMAL DIVISION OF THE DEPARTMENT OF ENERGY
UNDER STANFORD-DOE CONTRACT NO. DE-AT03-80SF11459

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STANFORD. CALIFORNIA 94305

Inquiries:
Dr. I. G. Donaldson
Petroleum Engineering Dept,
(415) 497-1218

## SEMINAR SCHEDULE

Autumn Quarter, 1980-81 Room B67, Mitchell Building Thursday, 1:15-2:30 p.m.

| Date | Topic | Speaker, |
|---|---|---|
| Oct 23 | Managing the Rotorua-Whakarewarewa Geothermal Field, Rotorua, New Zealand | I.G. Donaldson<br>S.G.P. |
| 30 | Observations on the Effects of Reinjection in Onikohe, Kakkonda, Onuma and Hatchobaru Geothermal Fields, Japan | R.N. Horne, S.G.P. |
| Nov 6 | The Miravalles Geothermal Reservoir, Costa Rica | H.J. Ramey, Jr.<br>S.G.P. |
| 13 | Recent Radon Transect Analyses in the U.S. and Mexico | L. Semprini, S.G.P. |
| 20 | Research, Entrepreneur and National Viewpoints on Geothermal Energy | P. Kruger, S.G.P. |
| Dec 4 | Progress in the Energy Extraction Study Program | A. Hunsbedt, S.G.P. |
| 11 | Temperature Effects on Absolute Permeability | B. Gobran and<br>A. Sageev, S.G.P. |

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## SEMINAR SCHEDULE

Winter Quarter, 1980-81 Room 113, Mitchell Building Thursday, 1:15-2:30 p.m.

| Date | Topic | Speaker |
|---|---|---|
| Jan 22 | Gas Chemistry of Geothermal Fields | Franco D'Amore (CNR, Italy) |
| 29 | Hot Dry Rock Geothermal Energy Systems: Reservoir Performance Characteristics--Theory vs. Practice | Jeff Tester (Chem.E. Dept., MIT) |
| Feb 5 | Optimal Extraction and Timing and/or Risk Analysis [Exact title to be announced.] | Kamal Golabi (Woodward-Clyde Consultants) |
| 12 | Krafla Geothermal Field, Iceland | Gudmundur Bodvarsson (LBL) |
| 19 | United Nations Geothermal Experiences | Jim McNitt (GeothermEx) |
| 26 | The Geologic Framework for the Yellowstone Geothermal system . | Bob Christianson (USGS) |
| Mar 5 | The 1978 Assessment of Geothermal Resources<br>Low Temperature Geothermal Resource Assessment | Patrick Muffler<br>Marshall Reed (USGS) |

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## SEMINAR SCHEDULE

Spring Quarter, 1980-81 | Room 113, Mitchell Building | Thursday, 1:15-2:30 p.m.

| Date | Topic | Speaker |
|---|---|---|
| Apr 16 | Exploratory Aspects of the Miravalles Geothermal Project, Costa Rica | Eduardo Granados (SGP) |
| 23 | Effect of Temperature and Saturation on Seismic Wave Velocity and Attenuation in Rocks | Terry Jones (Rock Physics Project, Geophysics, Stanford) |
| **30** | Design and Analysis of Two-Phase Geothermal Well Tests including Wellbore | Connie Miller (LBL) |
| **May 7** | Hydrothermal Alteration at the Geysers Steam Field | Diane Moore (USGS) |
| **14** | Geothermal Reservoir Simulation | Charles Morris (Republic Geothermal) |
| **28** | Direct Use of Geothermal Energy for Production of Fuel-Grade Ethanol | Dr. Phiet Bui (Occidental Research) |

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Barelli, A., Economides, M., Manetti, G., and Miller, F. G.: "Reservoir Engineering Studies of the Travale-Radicondoli Reservoir," to be published in the Proceedings of the Second DOE-ENEL Workshop on Cooperative Research in Geothermal Energy, held at Lawrence Berkeley Laboratory, Berkeley, California, October 20–23, 1980.

Brigham, W. E. and Neri, G.: "Preliminary Results on a Depletion Model for the Gabbro Zone," SGP–TR–40, Proceedings, 5th Stanford Workshop Geothermal Reservoir Engineering (1979), 229.

Brigham, W. E. and Neri, G.: "A Depletion Model for the Gabbro Zone (Northern Part of Larderello Field)," to be published in the Proceedings of the Second DOE-ENEL Workshop on Cooperative Research in Geothermal Energy, held at Lawrence Berkeley Laboratory, Berkeley, California, October 20–23, 1980.

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

Castaneda, M. and Horne, R. N.: "Location of Production Zones with Pressure Gradient Logging," Geothermal Resources Council Transactions, 5, 1981.

Celati, R., D'Amore, F., Economides, M. J. and Neri, G.: "Study of Water Influx and Fluid Composition in the Bagnore Field," to be published in the Proceedings of the Second DOE–ENEL Workshop on Cooperative Research in Geothermal Energy, held at Lawrence Berkeley Laboratory, Berkeley, California, October 20–23, 1980.

Counsil, J. R.: "Steam-Water Relative Permeability," Ph.D. Dissertation, Stanford University, Stanford, California, May 1979; SGP-TR-37.

Counsil, J. R. and Ramey, H. J., Jr.: "Drainage Relative Permeabilities Obtained from Steam-Water Boiling Flow and External Gas Drive Experiments," Geothermal Resources Council Transactions (1979), 3, Geothermal Resources Council (1979), 3, 141.

Da Prat, G., Cinco-Ley, H., and Ramey, H. J., Jr.: "Decline Curve Analysis Using Type-Curves for Two-Porosity Systems," Paper SPE 9292, presented at the 55th Annual Conference, SPE of AIME, Dallas, Texas, Sept. 21–24, 1980.

Da Prat, G., Ramey, H. J., Jr., and Cinco-Ley, H.: "A Method to Determine the Permeability-Thickness Product for a Naturally Fractured Reservoir," paper SPE 9906 presented at the 51st Annual California Regional Meeting SPE of AIME, Bakersfield, California, March 1981.

Economides, M. J., Ogbe, D., and Miller, F. G.: "Pressure Buildup Analysis of Geothermal Steam Wells Using a Parallelepiped Model," Paper SPE 8886, presented at the 50th Annual California Regional

Meeting, SPE of AIME, Pasadena, California, April 1980.

Horne, R. N.: "Geothermal Reinjection Experience in Japan," paper SPE 9925 presented at the 51st Annual California Regional Meeting SPE of AIME, Bakersfield, California, March (1981a); also to appear in Journal of Petroleum Technology, 1982.

Horne, R. N.: "Tracer Analysis of Fractured Geothermal Systems," Geothermal Resources Council Transactions , 5, (1981b).

Horne, R. N. and Castaneda, M.: "Location of Production Zones and Flash Points with Pressure Gradient Logging," Proceedings, 3rd Annual New Zealand Geothermal Workshop, 1981.

Horne, R. N., Satman, A., and Grant, M. A.: "Pressure Transient Analysis of Geothermal Wells with Phase Boundaries," Paper SPE 9274, presented at the Fall Meeting, SPE of AIME, Dallas, Texas, Sept. 21-24, (1980a).

Horne, R. N., Satman, A., and Grant, M. A.: "Pressure Transient Analysis of Geothermal Wells with Phase Boundaries," Proc., 2nd New Zealand Geothermal Workshop (1980b).

Hsieh, C. H.: "Vapor Pressure Lowering in Porous Media," Ph.D. Dissertation, Stanford University, Stanford, California, May 1980; SGP-TR-38.

Hunsbedt, A., Kruger, P., and London, A. L.: "Recovery of Energy from Fracture-Stimulated Geothermal Reservoirs," Journal of Petroleum Technology, August 1977.

Hunsbedt, A., Kruger, P., and London, A. L.: "Laboratory Studies of Fluid Production from Artificially Fractured Geothermal Reservoirs," Journal of Petroleum Technology, May 1978.

Hunsbedt, A., Iregui, R., Kruger, P., and London, A. L.: "Energy Recovery from Fracture-Stimulated Geothermal Reservoirs," ASME Paper 79-HT-92, August 1979.

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, April 18-20, 1979.

Nelson, D. V. and Hunsbedt, A.: "Progress in Studies of Energy Extraction from Geothermal Reservoirs," SGP-TR-40, Proceedings, Fifth Workshop Geothermal Reservoir Engineering, December 1979.

Nelson, D. V., Kruger, P. and Hunsbedt, A.: "Geothermal Energy Extraction Modeling," SGP-TR-50, Proceedings, Sixth Workshop Geothermal Reservoir Engineering, December 1980.

Onyekonwu, M. O. and Horne, R. N.: "Pressure Response of a Reservoir with Spherically Discontinuous Properties," paper SPE 10226 presented at the 1981 SPE Annual Technical Conference and Exhibition, San Antonio, Texas, Oct. 4-7, 1981.

Satman, A., Eggenschwiler, M., and Ramey, H. J., Jr.: "Interpretation of Injection Well Pressure Transient Data in Thermal Oil Recovery," Paper SPE 8907 presented at the 50th Annual California Regional Meeting, SPE of AIME, Pasadena, CA, April 9-11, 1980.

Warren, J. E. and Root, P.J.: 'The Behavior of Naturally Fractured Reservoir," SPE J. (Sept. 1963), 245-255.

Westwood, J. D. and Castanier, L. M.: "Application of a Lumped Parameter Model to the Cerro Prieto Geothermal Field," Geothermal Resources Council, Transactions, 5 (1981).

# APPENDIX A: PARTICIPANTS IN 'ME STANFORD GEOTHERMAL PROGRAM

## PRINCIPAL INVESTIGATORS:

| | |
|---|---|
| William E. Brigham | Petroleum Engineering |
| Roland N. Horne | Petroleum Engineering |
| Paul Kruger | Civil Engineering |
| Frank G. Miller | Petroleum Engineering |
| Henry J. Ramey, Jr. | Petroleum Engineering |

## PROGRAM MANAGER:

| | |
|---|---|
| Ian Donaldson | Petroleum Engineering |

## ASSOCIATED FACULTY:

| | |
|---|---|
| Heber Cinco-Ley | Petroleum Engineering |
| Anstein Hunsbedt | Civil Engineering |
| Drew V. Nelson | Mechanical Engineering |

## RESEARCH ASSOCIATES:

Susan Brown
Louis Castanier
Lyle W. Swenson, Jr.

## STUDENT RESEARCH ASSISTANTS

### Petroleum Engineering

Morse Jeffers
Mark Miller
Abraham Sageev
Mario Castaneda
Chih-Hang Hsieh
Giovanni Da Prat
Fernando Rodriguez
Miguel Saldana-Cortez
Winifred Ho
Luis Macias-Chapa
John Moody
Brian Gobran
Kenneth Breitenbach
Rafael Lerner
Michael Economides
John Walsh
John Westwood
Michael Onyekonwu
Kwaku Temeng
Knut Aarstad
Olga Malito

### Civil Engineering

Kazuichi Satomi
Lewis Semprini

### Mechanical Engineering

Rajiv Rana

## APPENDIX B: VISITING PARTICIPANT

This year our Program Manager was Dr. Ian Donaldson. Dr. Donaldson has been involved in geothermal reservoir research since 1955, and is currently Head, Applied Mechanics Section, Physics 6 Engineering Laboratory, Department of Scientific & Industrial Research in New Zealand. He was in the United States for the year on a Fulbright-Hayes Award.

As well as participating in the program as program manager, by direct involvement in the research program, and by giving the graduate level course in Geothermal Reservoir Engineering in the Petroleum Engineering course, Dr. Donaldson contributed to the program through his own research efforts and his writings. His contribution to the program through presentation or publication during his stay at Stanford include:

"Heat Extraction from Geothermal Reservoirs" in Geothermal Systems: Principles and Case Histories, L. Rybach and L. J. P. Muffler (eds.), Wiley, 1981.

"Heat and Mass Circulation in Geothermal Systems," Annual Reviews in Earth and Planetary Sciences, 10 (in press).

"Geothermal Energy Resources Can also be Tourist Resources: Lessons from Wairakei and Rotorua-Whakarewarewa, New Zealand," Proc. 6th Workshop on Geothermal Reservoir Engineering, Stanford University, Dec. 16-18, 1980, pp. 41-48.

"The Development of Conceptual Model of the Rotorua-Whakarewarewa Geothermal Reservoir, New Zealand," SPE 9923, presented at the 1981 SPE California Regional Meeting at Bakersfield, CA, Mar. 25-26, 1981, (Proc., pp. 401-407). (with M. A. Grant).

"Some Possible Restraints on Geothermal Development in New Zealand," presented at the EPRI Geothermal Conference, San Diego, CA, June 23-25, 1981.

"Non-Static Reservoirs: The Natural State of the Geothermal Reservoir" (with M. A. Grant and P. F. Bixley), SPE 10314, to be presented at the 56th Annual Fall Technical Conference of SPE, San Antonio, Texas, Oct. 5-7, 1981. (with M. A. Grant and P. F. Bixley)

"Internal Flows in Geothermal Wells; Their Identification and Effect on the Wellbore Pressure and Temperature Profiles," SPE 10317, to be presented at the 56th Annual Fall Technical Conference of SPE, San Antonio, Texas, Oct. 5-7, 1981. (with M. A. Grant and P. F. Bixley)

As his major project while at Stanford, Dr. Donaldson has been working on a book on Geothermal Reservoir Engineering, with New Zealand co-authors Dr. M. A. Grant and Mr. P. F. Bixley. By doing much of his writing at Stanford, Dr. Donaldson was able to ensure that geothermal reservoir engineering work carried out at Stanford and in other parts of the United States was fairly represented. The manuscript should be in the hands of the publishers, Academic Press, by January, 1982.

## APPENDIX C: PAPERS PRESENTED AND PUBLISHED OCTOBER 1. 1980 THROUGH SEPTEMBER 30, 1981

### Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Dec. 16-18, 1980

Geothermal Energy Resources Can also Be Tourist Resources: Lessons from Wairakei and Rotorua-Whakarewarewa, New Zealand - I. G. Donaldson

Well Test Analysis Research - H. J. Ramey, Jr., R. N. Horne, F. G. Miller, and W. E. Brigham

Geothermal Energy Extraction Modeling - D. V. Nelson, P. Kruger, and A. Hunsbedt

Determination of TDS in Geothermal Systems by Well-Log Analysis - S. L. Brown, B. D. Gobran, and S. K. Sanyal

The Effect of Temperature on the Absolute Permeability to Distilled Water on Unconsolidated Sand Cores - A. Sageev, B. D. Gobran, W. E. Brigham, and H. J. Ramey, Jr.

Radon Transect Studies in Vapor- and Liquid-Dominated Geothermal Reservoirs - L. Semprini and P. Kruger

### 1980 New Zealand Geothermal Workshop, University of Auckland, New Zealand, Nov. 3-5, 1980

Pressure Transient Analysis of Geothermal Wells with Phase Boundaries - R. N. Horne, A. Satman, and M. A. Grant

### 2nd Workshop for Cooperative Research in Geothermal Enerpy, USDOE/ENEL, Oct. 20-23, 1980, Lawrence Berkeley Laboratory

A Depletion Model for the Gabbro Zone (Northern Part of Larderello Field) - W. E. Brigham and G. Neri

Reservoir Engineering Studies of the Travale-Radicondoli Reservoir - A. Barelli, M. J. Economides, G. Manetti, and F. G. Miller

Study of Water Influx and Fluid Composition in the Bagnore Field - R. Celati, F. D'Amore, M. J. Economides, and G. Neri

### 51st Annual SPE California Regional Meeting, March 25-27, 1981, Bakersfield, California (Society of Petroleum Engineers of AIME)

Pressure and Temperature Dependent Properties of the Rock-Fluid Systems in Petroleum and Geothermal Formations, SPE Paper 9919 - C. A. Ehlig-Economides and M. J. Economides, University of Alaska

The Development of a Conceptual Model of the Rotorua-Whakarewarewa Geothermal Reservoir, New Zealand, SPE Paper 9923 - I. G. Donaldson and M. A. Grant

Geothermal Reinjection Experience in Japan, SPE Paper 9925 - R. N. Horne (to appear in Journal of Petroleum Technology)

Vapor Pressure Lowering in Geothermal Systems, SPE Paper 9926 - C. H. Hsieh and H. J. Ramey, Jr.

<u>Third Symposium on the Cerro Prieto Geothermal Field, Baja, CA, Mexico, San Francisco. California. March. 1981</u>

Radon and Ammonia Transects Across the Cerro Prieto Geothermal Field - L. Semprini and P. Kruger

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## APPENDIX D: 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

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|---|---|
| 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." |
| 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. |

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| 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 #1673500, September 1979. |
| SGP-TR-36 | Christine A. Ehlig-Economides, "Well Test Analysis for Wells Produced at a Constant Pressure," June 1979. |
| SGP-TR-37 | John R. Counsil, "Steam-Water Relative Permeability," May 1979. |
| SGP-TR-38 | Chih-Hang Hsieh, "Vapor Pressure Lowering in Porous Media," August 1980, Ph.D. Dissertation. |
| SGP-TR-39 | Kiyoshi Shinohara, "A Study of Inertial Effect in the Wellbore in Pressure Transient Well Testing," April 1980. |
| SGP-TR-40 * | "Proceedings: Fifth Workshop on Geothermal Reservoir Engineering," December 12-14, 1979. (Henry J. Ramey, Jr., and Paul Kruger, Editors) |
| SGP-TR-41 | Kern H. Guppy, "Non-Darcy Flow in Wells with a Finite Conductivity Vertical Fracture," Spring 1980. |
| SGP-TR-42 | Proceedings, Special Panel on Geothermal Model Intercomparison Study, at the Sixth Workshop on Geothermal Reservoir Engineering, Dec. 17, 1980. |
| SGP-TR-43 | Abraham Sageev, "The Design and Construction of an Absolute Permeameter to Measure the Effect of Elevated Temperature on the Absolute Permeability to Distilled Water of Unconsolidated Sand Cores," Dec. 1980 (M.S. Report). |
| SGP-TR-44 | Hasan Y. Al-Yousef, "Limitations of the $\Delta p/q$ Approximation in the Analysis of Pressure Drawdown Interference with Variable Flow Rate," June 1979 (M.S. Report). |
| SGP-TR-45 | Henry J. Ramey, Jr., and Paul Kruger, "Stimulation and Reservoir Engineering of Geothermal Resources," Third Annual Report to U.S. Dept. of Energy, Sept. 1980. |
| SGP-TR-46 | Lewis Semprini and Paul Kruger, "Radon and Ammonia Transects in Geothermal Reservoirs," September 1981. |
| SGP-TR-47 | Mario Castaneda, "Feed Zones in Geothermal Wellbores," March 1981. |
| SGP-TR-48 | John D. Westwood and Louis M. Castanier, "The Application of Lumped Parameter Modeling to Cerro Prieto Geothermal Field," June 1981. |
| SGP-TR-50 | Benry J. Ramey, Jr., and Paul Kruger, Editors, "Proceedings, Sixth Workshop on Geothermal Reservoir Engineering," Dec. 16-18, 1980, |
| SGP-TR-51 | Henry J. Ramey, Jr., and Paul Kruger, Geothermal Reservoir Engineering Research at Stanford University, First Annual Report, DOE Contract No. DE-AT03-80SF11459, September 1981. (Period: 10-1-80 - 9-30-81) |
| SGP-TR-54 | Rajiv Rana and Drew Nelson, "Exploratory Study of the Effect of Thermal Stressing on Granite Strength and Porosity," Dec. 1981. |
| SGP-TR-55 | Paul Kruger and Henry J. Ramey, Jr., editors, "Proceedings; Seventh Workshop on Geothermal Reservoir Engineering, Dec. 15-17, 1981." |

* out of print