STANFORD GEOTHERMAL PROGRAM
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STIMULATION AND RESERVOIR ENGINEERING OF GEOTHERMAL RESOURCES

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PREFACE

This publication is the third annual progress report under the Department of Energy contract DOE-LBL-167-3500 with the Lawrence Berkeley Laboratory. It covers the period from October 1, 1979 through September 30, 1980.

The Stanford Geothermal Program was initiated by the National Science Foundation in 1972 and continued under the Energy Research and Development Administration (now DOE) after 1975. The central objective continues to be research in geothermal reservoir engineering techniques aimed at stimulating the development of a commercial geothermal industry in the United States. A parallel objective is the training of engineers for employment in the geothermal industry. A third objective of the Stanford Geothermal Program is to maintain a balance between laboratory studies of the geothermal resource and field experiments. This guarantees a balance between advancing the understanding of geothermal resource extraction, and the rapid transfer of the results of the studies to field operations of the industry.

The Stanford Geothermal Program contains four major study areas for developing practical methods and data for geothermal reservoir engineering and reservoir assessment: (1) energy extraction, (2) bench-scale flow experiments, (3) reservoir tracer techniques, and (4) well test analysis. In addition, the Program maintains an effort to bring the results of the research to the geothermal community in the form of technical reports, a weekly geothermal seminar throughout the academic year, and an international annual workshop in geothermal reservoir engineering. This annual report describes the results obtained in the four areas of geothermal reservoir engineering, and 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 support by members of industry, various federal agencies, national laboratories, and university programs. These personnel present lectures in the weekly seminar and annual geothermal workshop, and serve in program selection and in other ways important to the program. The names are too numerous to cite here. However, listings may be found in the preface of the Workshop Proceedings and in the Appendices of this report. Of course, a major contributor is the Department of Energy through the Lawrence Berkeley Laboratory.

Henry J. Ramey, Jr. and Paul Kruger

TABLE OF CONTENTS

INTRODUCTION

The research effort of the Stanford Geothermal Program is focused on geothermal reservoir engineering. The major objective of the program is to develop techniques for assessing geothermal reservoirs through better interpretation of physical models, mathematical analysis, and field experiments to obtain 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 accomplish this objective, a balance is maintained between laboratory studies and field applications. One goal is to develop the mathematical description of observed reservoir behavior. Physical models are used to calibrate mathematical models by an 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 them in the field.

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

(1) Energy Extraction
(2) Bench-Scale Flow Experiments
(3) Radon and Noncondensible Tracer Techniques
(4) Well Test Analysis

The section on energy extraction experiments concerns the efficiency with which the in-place heat and fluids can be produced. Energy extraction considerations are of importance to the geothermal industry in decisions concerning liquid recharge and potential commercialization of liquid-dominated hydrothermal resources. The research on the large Geothermal Reservoir Model which evaluates energy extraction by a method of fluid production is important in these considerations. Initial experiments on thermal fracturing by hydrothermal stressing have been completed. The development of a model useful for assessing the heat extraction potential of hydrothermal resources has progressed to a satisfactory point where a lumped-parameter model of energy extraction based on rock size distribution with two-phase flow can be examined.

The section on bench-scale flow experiments covers the results of three models used to examine the properties of flow through porous media at elevated temperatures and pressures. A small core model was used to study the effect of temperature level on absolute permeability, a second larger core model equipped with a capacitance probe for determining water and steam saturation in a porous medium was used to measure steam-water relative permeability, and a third model was operated to determine the mechanisms of vapor pressure lowering in porous media. Important findings were made in all studies during the year.

The section on radon tracer techniques describes the efforts to test several geothermal reservoirs by both transient and transect test procedures. The results of radon flow transients in the vapor-dominated reservoirs at The Geysers, California; Serrazzano, Italy; and in several liquid-dominated reservoirs were reported at several symposia. Further measurements at the fields at Wairakei, New Zealand; and at Los Azufres and Cerro Prieto, Mexico, were completed. Analysis of the first radon evaluation of reservoir performance was completed in the Phase I test of the LASL Hot Dry Rock

Program. The results of the first transect analyses of experiments at Cerro Prieto, Wairakei, and The Geysers were reported. To satisfy the need for multi-tracer evaluation of geothermal reservoirs, comparison of the ammonia-to-radon ratios were included in the transect studies. The first phase of the bench-scale experiments to define the source term as a function of reservoir parameters was completed.

The section on well test analysis describes several new developments: analysis of well test data for wells produced at constant pressure, parallelepiped models, slug test DST analysis, pressure transient behavior in naturally fractured reservoirs, temperature-induced wellbore storage effects, phase boundary effects on reinjection and boiling in production, and wellbore cycling.

The research conducted over the past year has produced several important results, some of which are being examined in continuing studies. In the final section of this report, conclusions are offered along with recommendations for areas of future research which may lead to improvements in the development of new geothermal resources.

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

1. ENERGY EXTRACTION

Energy extraction research concerned two main areas: numerical modeling of extraction experiments and thermal stress cracking experiments. Progress in both studies is reported.

(a) Energy Extraction Modeling, by John Sullivan, Research Assistant, and Anstein Hunsbedt, Consulting Assistant Professor.

An analytic model for the linear flow of water in a fractured geothermal reservoir system, referred to as the linear sweep model, was described by Iregui et al. (1978) and described by Hunsbedt et al. (1979). This one-dimensional model may be used to compute the water temperature as a function of time and space in the idealized geothermal system pictured in Figure 1-1. In the model cold water enters the formation through a series of injection wells at point A, and flows horizontally to a series of production wells at point B. The injection and production flowrates are steady, and the permeability of the formation is such that the flow is uniform. The reservoir pressure prevents boiling in the formation. The rock size distribution is assumed to be independent of the distance X between the injection and production wells. Heating from the surrounding rock media is included by a constant external. heat transfer.

The solution to the partial differential equation developed in the model was obtained using a Laplace transformation technique combined with a numerical inversion algorithm (Stehfest, 1970). A comparison of analytic and experimental data obtained from the SGP Large Reservoir Model pictured in Figure 1-2 was also presented by Iregui et al. and Hunsbedt et al. Further comparisons were given in the Proceedings of the Fifth Workshop on

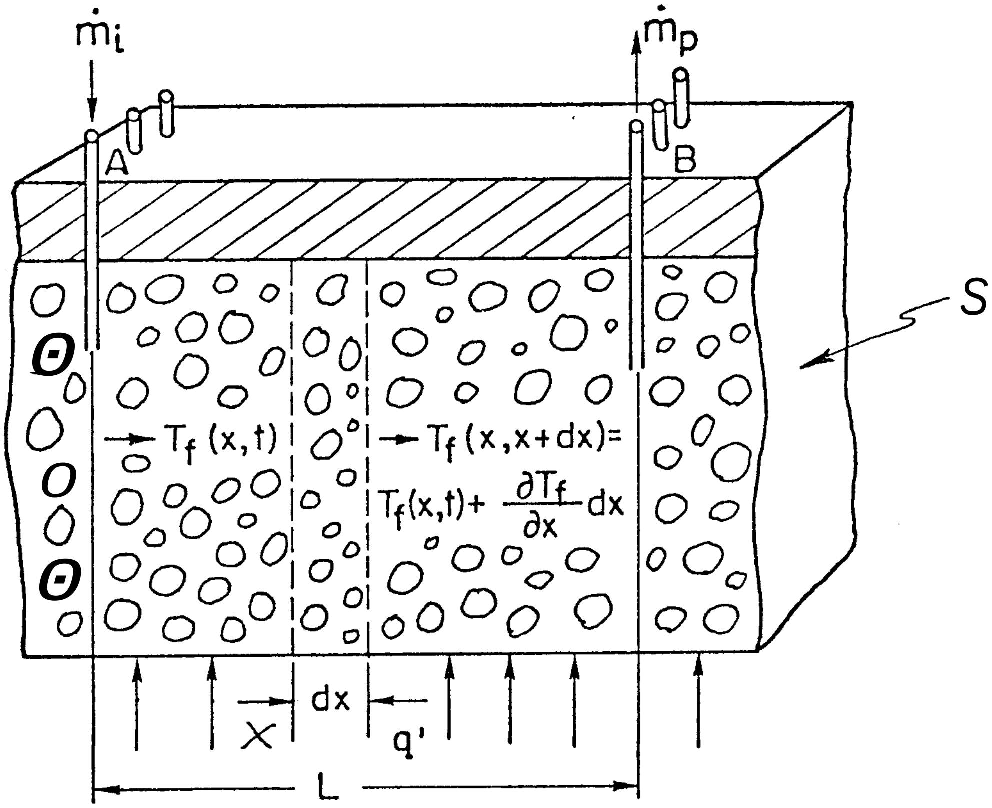
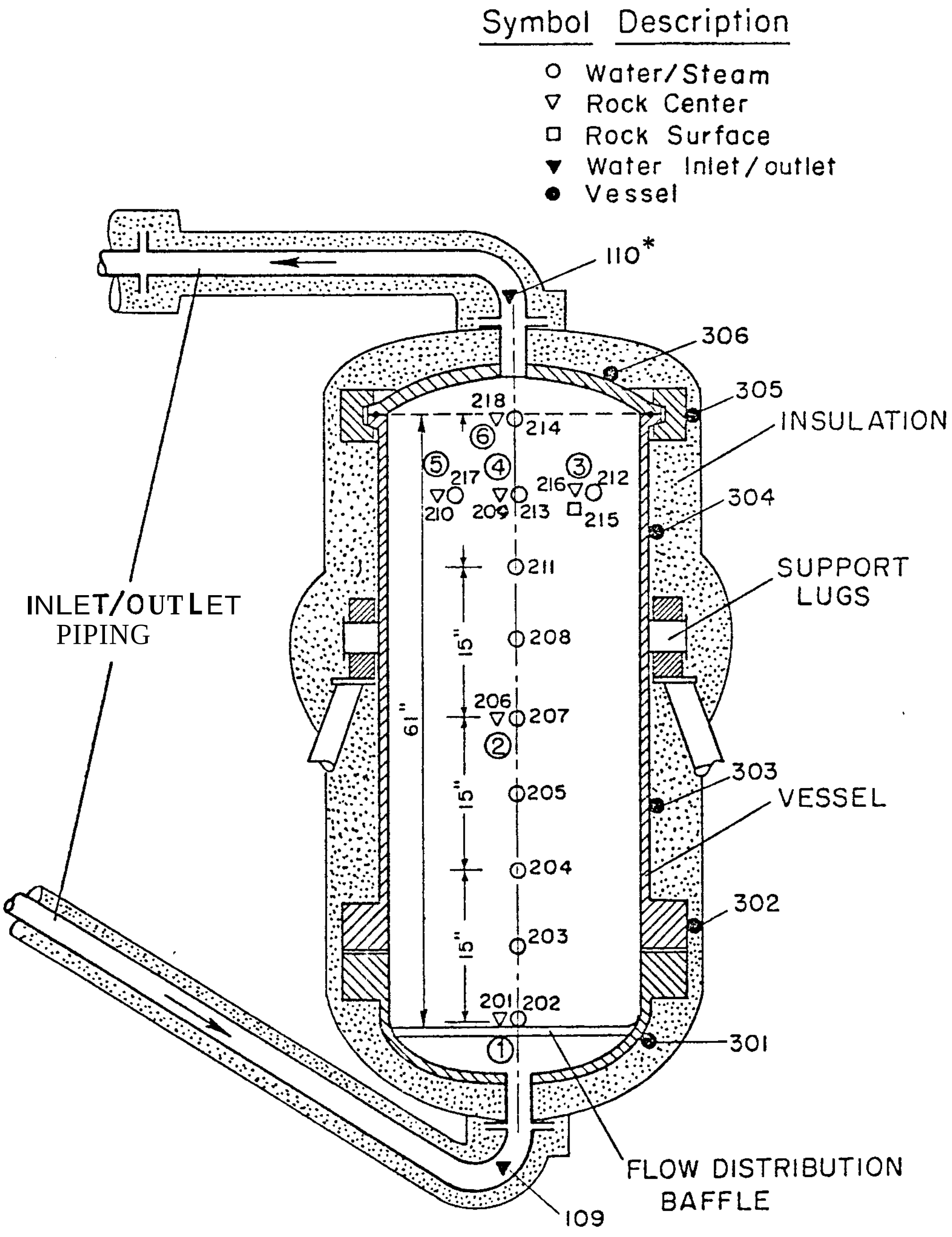


FIG. 1-1: LINEAR SWEEP MODEL



* **Thermocouple reference numbers**

① Rock **number 1**

FIG. 1-2: THERMOCOUPLE MAP OF LARGE RESERVOIR MODEL

Geothermal Reservoir Engineering for the most recent experiment conducted for the experimental conditions listed in Table 1-1. The comparison of observed water temperatures to linear sweep model results obtained by the Laplace transformation/numerical inversion solution showed considerable disagreement at some points in the reservoir. Figure 1-3 shows the experimental and computed water temperatures as functions of time at various points in the physical model. The slopes of the computed temperature curves are generally greater than the experimental data suggest. This difference has been studied extensively during this year.

Another solution for the linear sweep model was obtained using a finite difference numerical technique to check the adequacy of the Laplace transform inversion method. Comparison of results from the numerical solution, also given in Figure 1-3, shows poor agreement with the Laplace inversion solution. Although neither solution is sufficiently reliable at this time, it is believed that the finite difference solution may be better, based on extensive parametric studies involving varying time step and mesh size.

The observation that the computed temperature versus time curves are generally steeper than the experimental curves led to further examination of the behavior of the physical system and the model assumptions. The tempesature-time characteristic of the water entering the model follows an exponential, rather than a step change assumed in the mathematical model. This was deduced from the steel temperatures measured at the lower parts of the vessel by thermocouples 301 and 302 in Figure 1-2. These temperatures and the measured inlet water temperature are given in Figure 1-4. The actual water temperature entering the flow distribution baffle was not measured, but is believed to be only slightly lower than the steel temperature measured by thermocouple 301.

TABLE 1-1: SUMMARY OF INPUT PARAMETERS TO LINEAR SWEEP MODEL FOR EXPERIMENT 4-3 AND PROPOSED NEW EXPERIMENT

Experimental Conditions	Symbol/Equation	Experiment 4-3	Proposed Experiment	Units
Initial Reservoir Temperature	T_1	460	4[illegible]0	°F
Recharge Water Temperature	T_{in}	[illegible]0	[illegible]0	°F
Production/Recharge Rate	in	197 6	25-300	lb_m/hr
Reservoir Conditions				
Porosity	ϕ	0.21	0.13	fr bulk vol
Cross-Sectional Area	A_{x-s}	3.27	3.27	ft^2
Length	L	5.08	5.08	ft
Equivalent Rock Radius	R_e	0.105	0.284	ft
External Heat Transfer	q'	1.811	0	Btu/hr-ft
Physical Properties				
Mean Water Density	ρ_f	[illegible]8.5	58.5	lb_m/ft^3
Mean Rock Density	ρ_r	1[illegible]4.8	164.8	lb_m/ft^3
Mean Water Specific Heat	c_f	1.0	1.0	$Btu/(lb_m-°F)$
Mean Rock Specific Heat	c_r	0.218	0.218	$Btu/(lb_m-°F)$
Rock Surface Heat Transfer Coefficient	h	300	300	$Btu/(hr-ft^2-°F)$
Rock Thermal Conductivity	k	1.4	1.4	$Btu/(hr-ft^2-°F)$
Rock Thermal Diffusivity	α	0.039	0.039	ft^2/hr
Steel Vessel "Density"	ρ_m	2[illegible]6.8	206.8	lb_m/ft^3
Steel Vessel Specific Heat	C_m	0.117	0.117	$Btu/(lb_m-°F)$

TABLE 1-1, continued

Derived Quantities	Symbol/Equation	Experiment	Proposed Experiment	Units
Rock Capacitance Ratio	$c_r^* = \rho_r c_r/\rho_f c_f$	0.61[illegible]	0.614	dimensionless
Steel Capacitance Ratio	$c_m^* = \rho_m c_m/\rho_f c_f$	0.523	0.523	dimensionless
Combined Rock/Steel	$c^* = c_r^* + c_m^*$	1.1[illegible]	1.1[illegible]	dimensionless
Modified Storage Ratio	$\gamma = \varphi/c^*(1-\varphi)$	0.23	0.131	dimensionless
Superficial Flow Velocity	$\omega_f = \dot{m}/\rho_f A_{x-s}$	1.03	0.131-1.57	ft/sec
Pore Flow Velocity	$\omega = v_f/\varphi$	4.92	1.01-12.06	ft/sec
Water Residence Time	$t_{re} = L/\omega$	1.03	0.035-0.421	hr
Rock Biot Number	$N_{Bi} = hR_e/k$	22.5	60.9	dimensionless
Effective Time Constant	$T_c = \frac{R_e^2}{3\alpha}(0.2 + 1/N_{Bi})$	0.023	0.149	hr
Number of Heat Transfer Units	$N_{tu} = t_{re}/t_c$	[illegible]4.8	2.83-34	dimensionless
External Heat Transfer	$q^* = q'L/\dot{m}\ c_f(T_1-T_{in})$	0.026	0	dimensionless

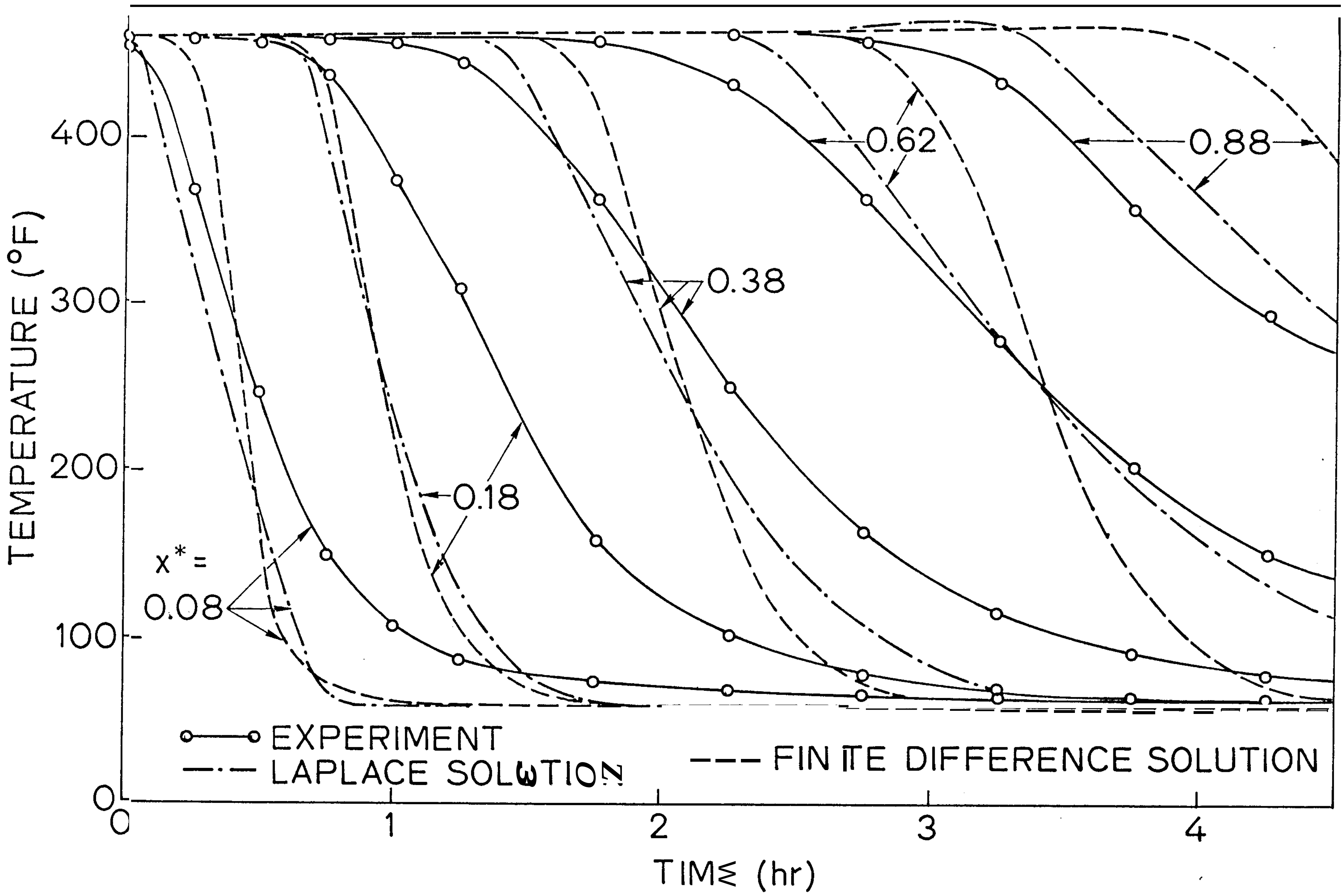


FIG. 1-3: COMPARISON OF EXPERIMENTAL AND PREDICTED RESERVOIR TEMPERATURES

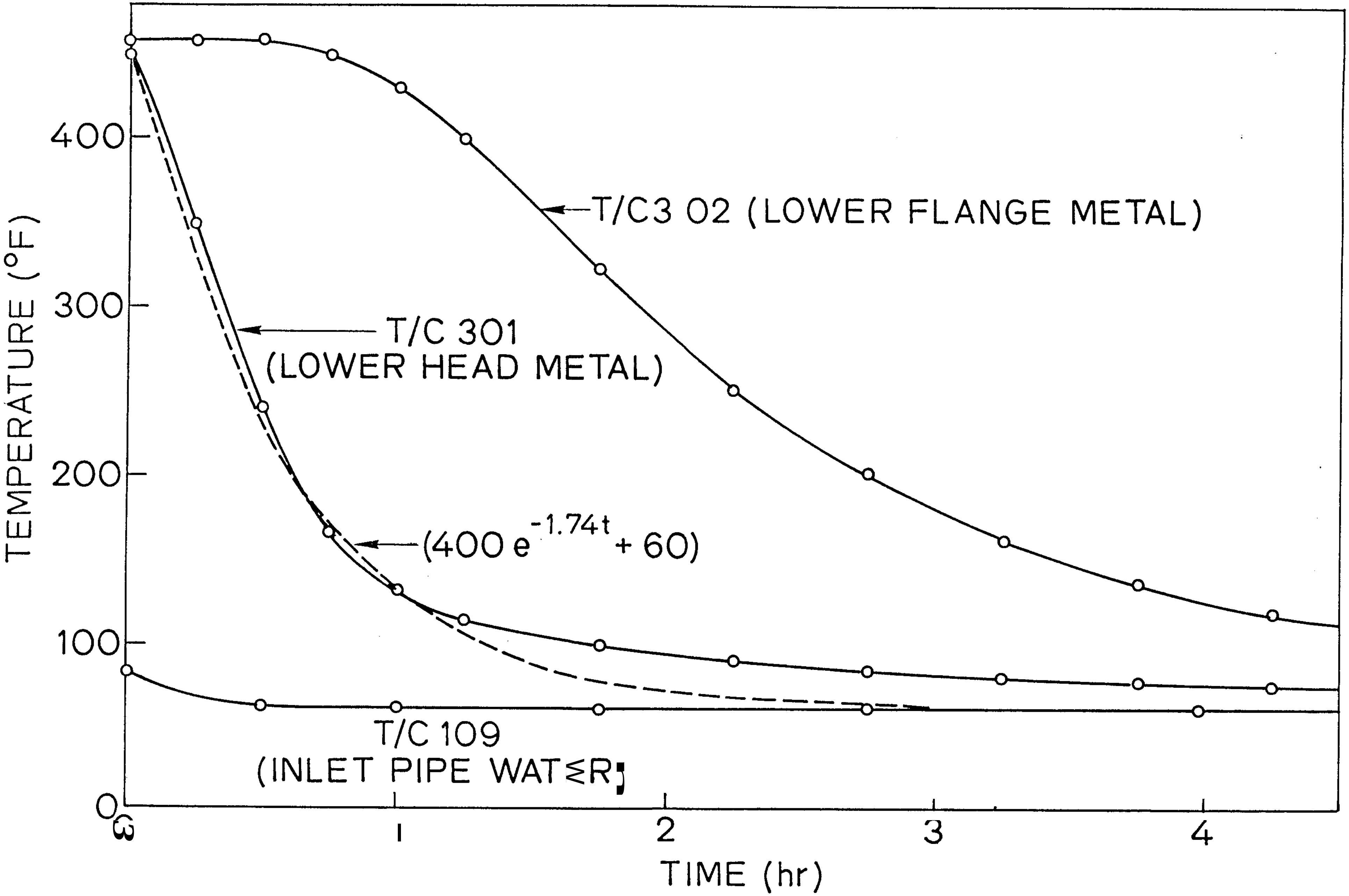


FIG. 1-4: ENTERING WATER AND MODEL TEMPERATURES AT THERMOCOUPLES 301 AND 302 VS TIME FOR THE LARGE RESERVOIR MODEL

The effect of an exponential water inlet temperature change, with a time constant of 0.57 hr, on the water temperature curves is illustrated in Figure 1-5. This figure shows that the slope of the curves computed by the Laplace transform inversion solution modified to include an exponential inlet condition is similar the the experimental results. This is encouraging. However, there is a time lag that cannot be explained at this time. Part of this problem may be related to axial heat conduction in the rock/water matrix, and heat transfer from the steel vessel. The latter effect is modeled by a constant heat transfer term in the present linear sweep model.

The effect of axial conduction in the rock/water matrix was investigated using a second finite difference numerical model. Results of this comparison is given in Figure 1-6 and shows that axial convection reduces the slope of the curves. The time lag also appears to be reduced. The effects of axial conduction and the exponential water inlet condition, together, are therefore expected to give computed results which agree well with the experimental data. However, a significant effort will be required to improve the model by including features of the physical system that are currently not modeled. One such feature is the transient behavior of the steel vessel.

The inclusion of axial conduction in the model provided an independent check on the accuracy of the two finite element solutions. The latest solution matches the earlier finite difference solution for the special case of very low axial conductance. Thus, it appears that the finite difference solutions may be more accurate than the Laplace transform solution. It is anticipated that this problem will be further studied because the Laplace transform solution is simpler to apply.

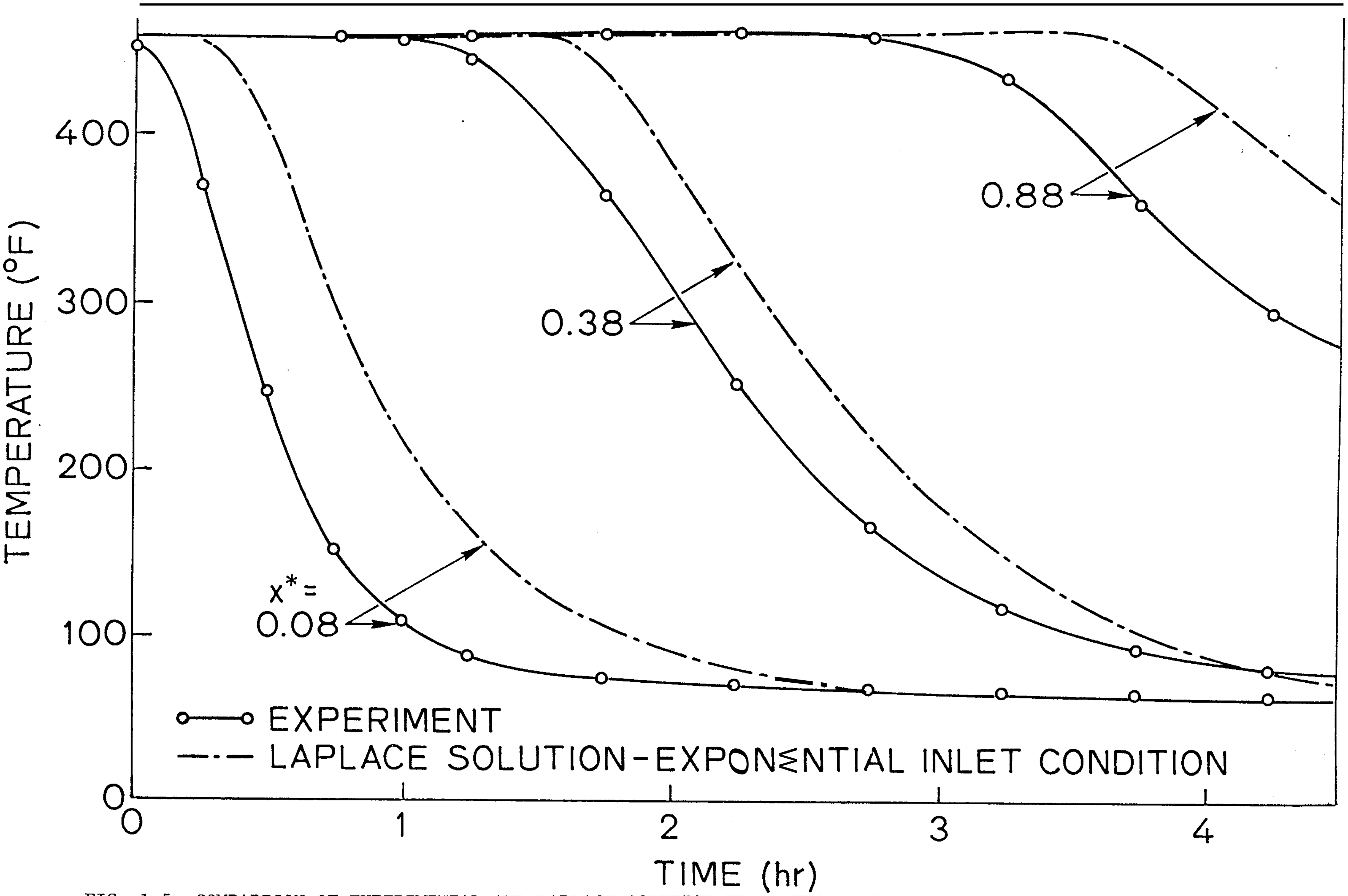


FIG. 1-5: COMPARISON OF EXPERIMENTAL AND LAPLACE SOLUTION WITH EXPONENTIAL INLET BOUNDARY CONDITION

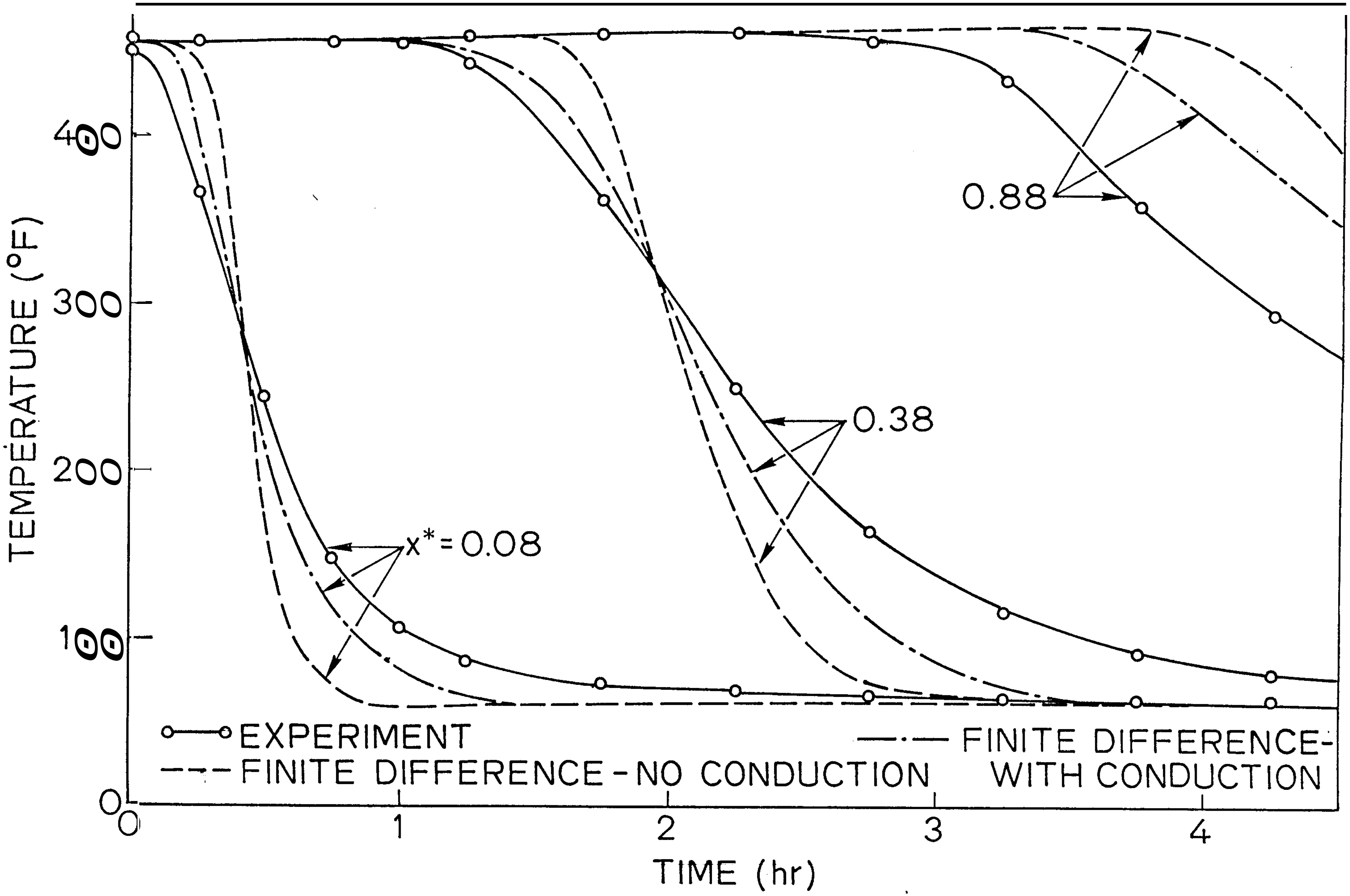


FIG. 1-6: COMPARISON OF EXPERIMENTAL AND FINITE DIFFERENCE SOLUTION WITH AND WITHOUT AXIAL HEAT CONDUCTION

The results of these comparisons show that the mathematical modeling of the laboratory system needs further improvement. The long-term objectives of the heat transfer efforts are to model the behavior of large-scale systems such as shown in Figure 1-1. Therefore, the two types of uncertainty in the present linear sweep model are being studied. One concerns modeling heat transfer from the steel vessel which releases an amount of energy comparable to that from the rock. The other is modeling heat transfer from the different fragments composing the simulated geothermal system. The objective of previous experiments was to determine whether the one-lump rock heat transfer model using in the linear sweep model was adequate. To do this, it is necessary to model the heat transfer from the vessel accurately so that the "wall effect" can be eliminated as an uncertainty. Current work on this project is proceeding along two paths: one involves additional experiments, and the other involves more detailed analytic models.

Preparation is underway to conduct experiments in the large reservoir model using regularly shaped granite blocks as shown in Figure 1-7. The use of regular sized rocks should allow a detailed modeling of the rock heat transfer which can be compared totheone-lump parameter approach previously used for rocks of distributed size and shape. It also permits evaluation of a large range of the number of heat transfer units parameter. Thus, it is anticipated that values of heat transfer units as low as 3.0 can be achieved in the present experimental system, which is well into the "heat transfer limited" region. The expected experimental conditions for the planned experiments are given in Table 1-1. A larger number of thermocouples will be introduced into the rock and water matrix to provide a larger number of temperature measurements, including the water inlet temperature distribution, and to provide cross-sectional temperature gradients

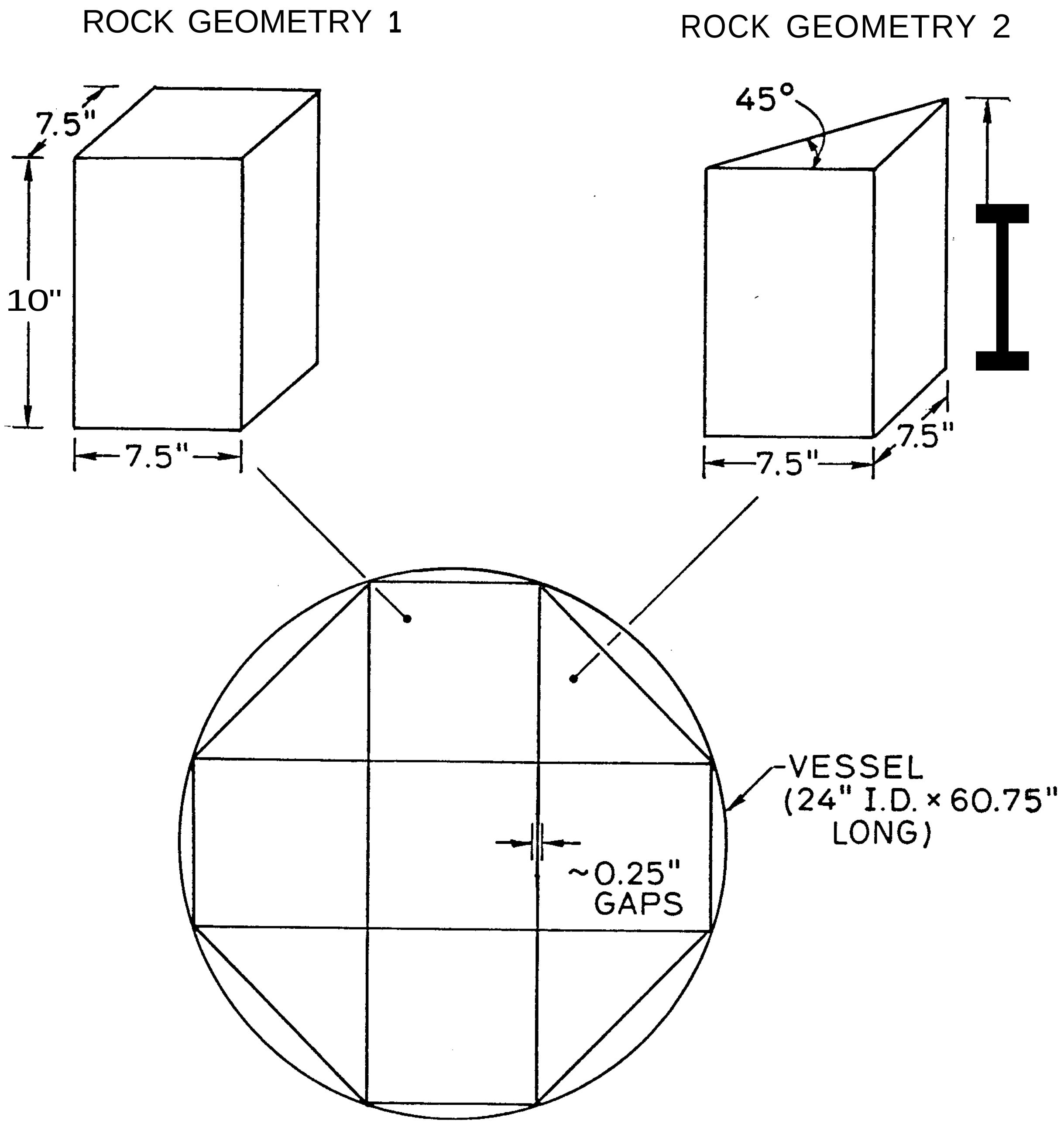


FIG. 1-7: ROCK LOADING CONFIGURATION

to be used in the planned two-dimensional analysis of the heat transfer. This analysis will be with improved mathematical models of the laboratory system, using the finite element method. Emphasis is on accurate modeling of the various elements of the steel vessel such as the heavy flanges. The modeling techniques will also be adapted to large scale geothermal systems. The initial goal of these models will be to consider the wall effect and to gain confidence in the use of the one-lump rock heat transfer model over the appropriate range of number of heat transfer units. Results of these studies will be compared to results from the current linear sweep model based on the Laplace transform solution. Improvement in the solution technique may provide a simple and convenient tool for assessing heat transfer performance of fractured geothermal systems. As these goals are achieved, the modeling method will be used to compute the heat transfer performance of large-scale fractured hydrothermal systems, such as the Baca field in New Mexico and the Los Alamos fracturing experiment at the Site 2 location.

(b) Thermal Stress Cracking Experiments, by R. Rana, Engineer's Degree Candidate in Mechanical Engineering and Professor Drew Nelson.

In fractured rock hydrothermal reservoirs, water circulation induces tensile thermal stresses in a layer below the cooled rock surface. Murphy (1978) showed analytically that these stresses have the potential to create self-driven cracks of sufficient depth and aperture to enhance energy extraction and prolong production life. Such stresses may also be generated by reinjection of fluids into naturally fractured hydrothermal reservoirs. Aside from the potential of producing self-driven cracks, thermal stressing may also influence both the mechanical and thermal properties of the rock. Changes in these properties can, in turn, affect the thermal cracking process itself and the heat transfer characteristics of rocks (even without self-driven cracks). During the past year, an exploratory study was conducted to investigate the effects of thermal stressing on rock strength and porosity experimentally.

To produce thermal stress, granite slabs (2-1/2" x 10" x 1/4") were first slowly heated (at rates of less than 2°F/min) to a temperature of 450°F in the modified air bath shown schematically in Figure 1-8. The slabs were maintained at elevated temperature for several hours to assure uniformity of temperature, which was confirmed by thermocouple readings taken at various locations inside one of the slabs. To induce thermal stress, the "exposed" face shown in Figure 1-8 was then sprayed with 70°F water from numerous small jets. This face was insulated until just before quenching to minimize initial, undesired temperature gradients.

To estimate thermal stress due to quenching, one-dimensional heat flow in the length direction of the slab was assumed. The transient

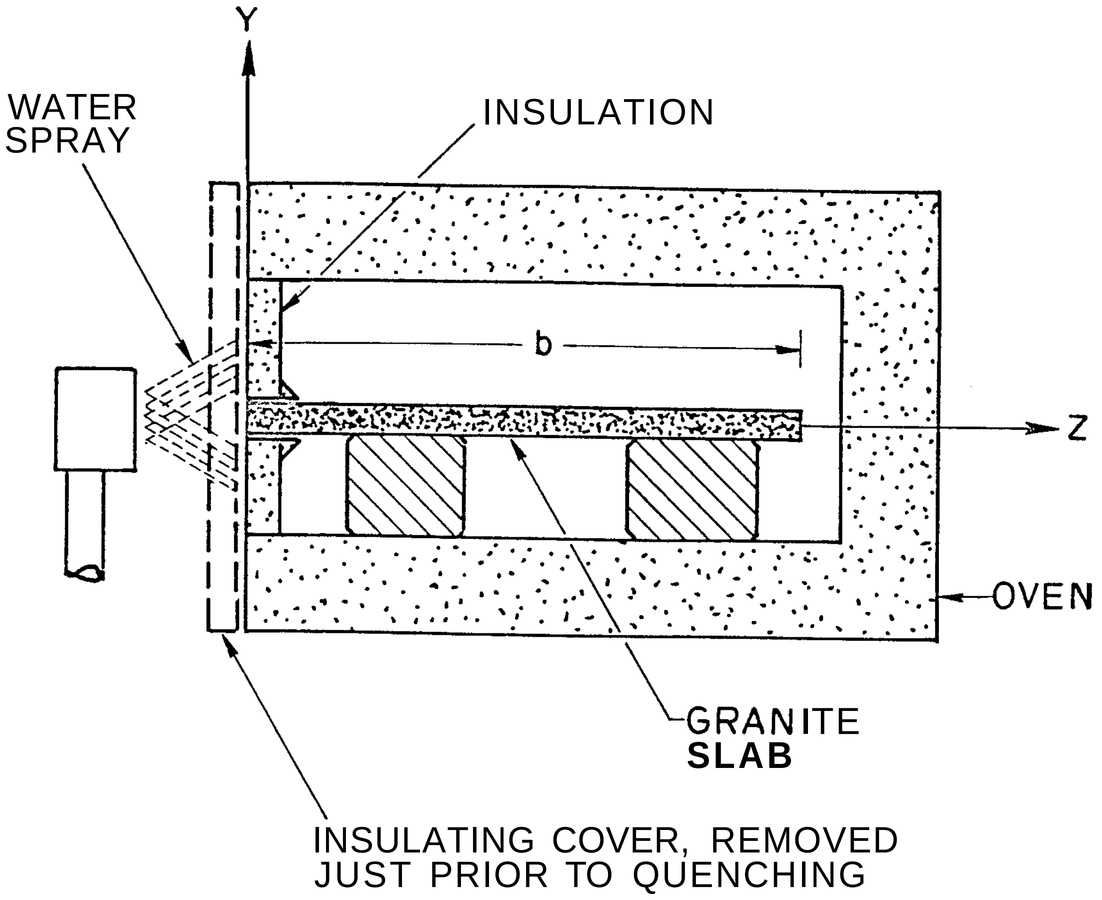


FIG. 1-8: THERMAL STRESS EQUIPMENT

temperature distribution $T(z,t)$ was estimated (Özisik, 1968) from the following closed-form solution for a slab of finite thickness with insulated sides:

$$\theta = \frac{T_i - T(z,t)}{T - T_\infty} = 1 - \operatorname{erf}\left(\frac{z}{2\sqrt{dt}}\right) - \left[\exp\left(\frac{hz}{k} + \frac{h^2 dt}{k^2}\right)\right]$$

$$\cdot \left[1 - \operatorname{erf}\left(\frac{z}{2\sqrt{dt}} + \sqrt{\frac{h^2 dt}{k^2}}\right)\right] \qquad (1\text{-}1)$$

where:

θ = normalized temperature

T_i = initial slab temperature

T_∞ = water temperature

z = distance inward from quenched face

t = time

k = thermal conductivity

d = thermal diffusivity

h = surface heat transfer coefficient between water and rock

To estimate h for the given quenching condition, $T(z,t)$ was measured along the centerline of several slabs with thermocouples cemented in place at the ends of holes drilled in from the side. Comparison of measured $T(z,t)$ with that based on Equation 1-1 indicated $h \simeq 300$ Btu/hr-ft^2-°F). This estimate was confirmed by the measured cooling of a copper block heated to 450°F and quenched with the same spray system.

Assuming linear elastic, isotropic and homogeneous behavior (Johns, 1965), the thermal stresses due to quenching were estimated from:

$$\sigma = \frac{\sigma(1-\nu)}{E\alpha} = \theta - \frac{2}{b^2}(2b-3z)\int_0^b \theta\, dz - \frac{6}{b^3}(2z-b)\int_0^b \theta z dz \qquad (1\text{-}2)$$

where:

σ^* = normalized stress (same in x and y directions of Fig. 1-8)

E = modulus of elasticity

α = coefficient of thermal expansion

ν = Poisson's ratio

b = length of block

θ = normalized temperature defined in Equation **(1-1)**

The T(z,t) behavior determined from Equation **1-1** was substituted into Equation 1-2 , and numerical integration performed to obtain σ^*. The estimated normalized thermal stress as a function of time and position along the slab centerline is shown in Fig. 1-9.

Sierra-white granite (obtained from the Raymond, California, quarry) was used in all tests. For the given quenching conditions, no large-scale cracking was observed, but none was really expected because of the small specimen size, and the freedom of the slab to contract upon cooling.

To investigate possible changes in strength due to thermal stressing, the blocks were cut into smaller rectangular specimens (1-1/2" x 3" x 0.3") and loaded to fracture in three-point bending. Based on eight specimens from an unquenched block, the mean elastically-calculated bending stress at the fracture was 1830 psi, with a coefficient of variation of 15%. The bending strength of specimens taken from various positions along the length of quenched slabs is shown in Fig. 1-10, along with the strengths of specimens taken from slabs which had been subjected to five cycles of

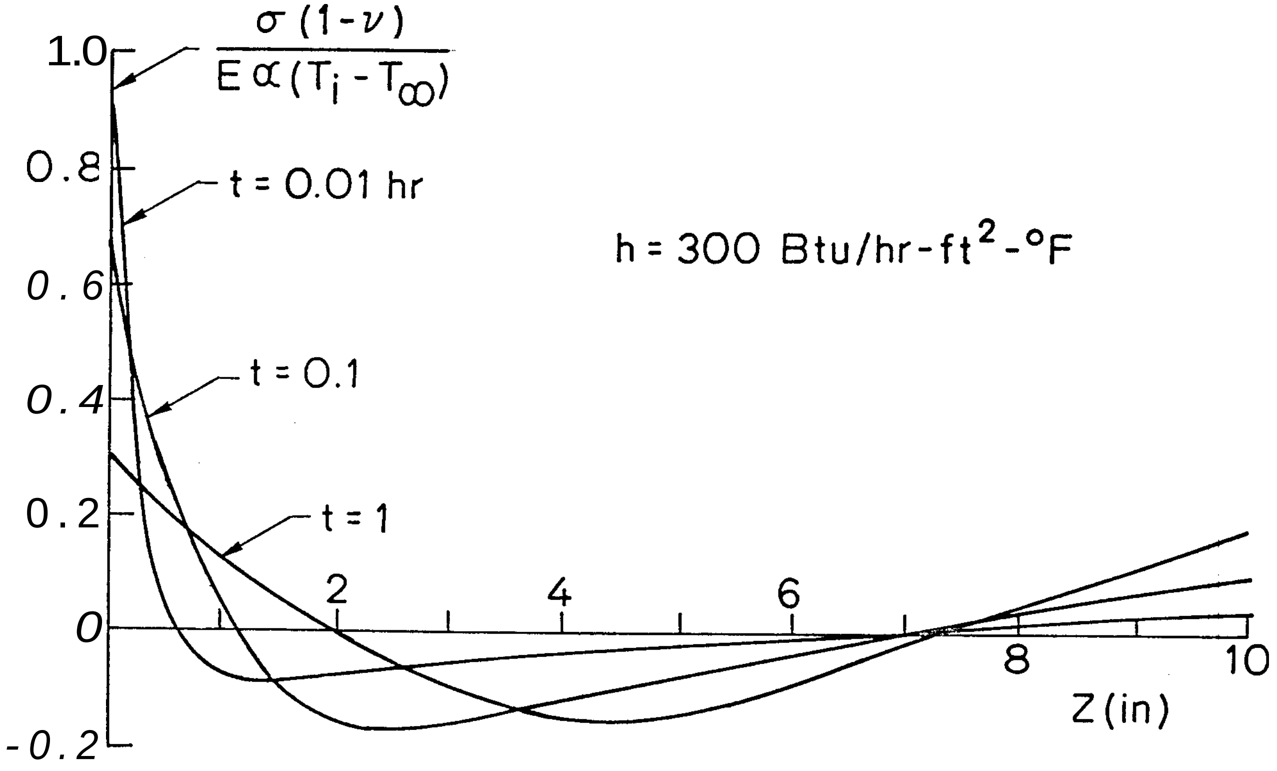


FIG. 1-9: ESTIMATED THERMAL STRESS DISTRIBUTION IN GRANITE BLOCK

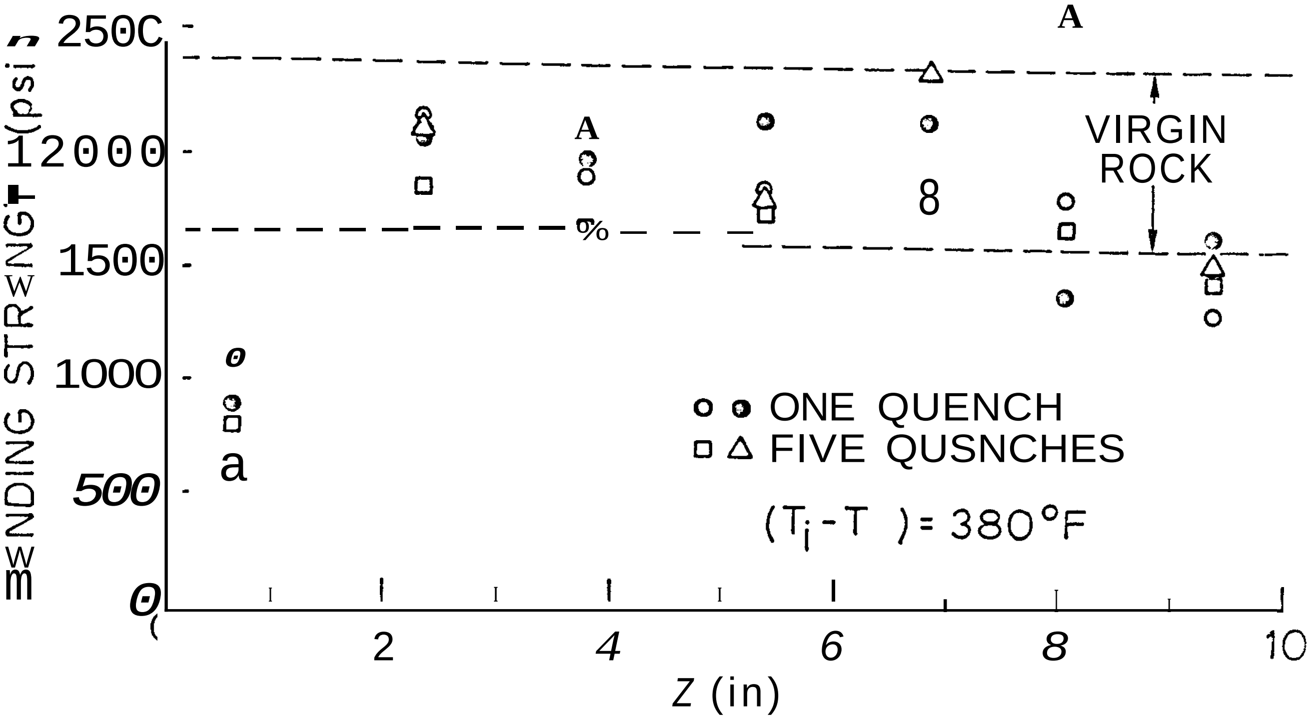


FIG. 1-10: BENDING STRENGTH OF SPECINENS TAKEN FROM BLOCK

quenching. There is a significant reduction in strength in those specimens taken from regions of compressive thermal stress. Also, the loss of strength is apparently not caused by heating alone (to 450°F). It may be due to microcracking caused by tensile thermal stress. Dye penetrant was applied to one face of some of the specimens after bend testing. Although it was found that this does not provide a satisfactory way of observing microcracking, it was noted that in unquenched specimens, the dye either did not seep through to the other side or did so very slowly. In specimens which had experienced tensile thermal stress, the dye penetrated quickly, indicating a likely increase in porosity and permeability.

Porosity measurements were made on the same specimens used in the bend tests. The saturation method was used. The average porosity of unquenched specimens was 1.6%, while the average for specimens experiencing one and five applications of tensile thermal stress was 3.8 and 4.8%, respectively. The increase in porosity is consistent with the belief that microcracking occurred in regions of tensile thermal stress.

The above results were obtained from tests conducted at atmospheric pressure. Ideally, tests should be conducted under simulated tectonic stresses. Nevertheless, the observed reduction in rock strength and increase in porosity caused by tensile thermal stressing is encouraging in terms of favoring the formation and growth of large thermal cracks in reservoirs. It also seems plausible that tensile thermal stress may alter rock heat transfer behavior by changing thermal properties (e.g., conductivity) in those regions near the surface where such stresses are significant. Further tests to investigate this phenomena would be desirable. The results would be useful in augmenting the heat extraction model being developed for large size hydrothermal reservoirs to include changes in in heat transfer properties due to thermal stresses under reinjection over the production lifetime of the reservoir.

2.0 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. These experiments have been collected as "bench-scale experiments." 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, Ramona Rolle, and Renee Rolle, M.S. candidates in Petroleum Engineering, and Prof. H. J. Ramey, Jr.

Most of the efforts during the year were devoted to the rebuilding and recalibration of the apparatus. This equipment has been in continuous use for years. Both the coreholder and piping had to be replaced, and placed in a new air bath. The rebuilding of the apparatus was also useful in that it allowed substitution of a redesigned coreholder and some new instrumentation. Recently, eight test runs were conducted, during which several problems were identified and corrected. The results of these test runs are presented, and the subsequent technical improvements are summarized.

At present, the apparatus is being used to measure absolute permeability of silica sand to distilled water. It is anticipated that further mechanical improvements will be made in order to attain a greater reproducibility of results.

As a check on the newly assembled equipment, some permeability measurements were made at various temperatures. In a typical run, summarized in

Fig. 2-1, the confining pressure was 2000 psig, the average pore pressure was 200 psig, and the temperature was varied over a range of 70°F to 300°F.

In general, there was no strong effect of temperature on the absolute permeability to water. The observations made during the run were as follows:

a. The initial room temperature permeability was around 4880 md.

b. After one cycle, the room temperature permeability dropped by 150 md. This lower value was also evident after the second heating cycle.

c. During the first heating, the permeability remained constant up to 250°F.

d. In both cycles, the 250°F and 300°F permeabilities were the same.

e. The second heating cycle did not show significant hysteresis.

f. The measured values ranged from about 2% to 3%.

g. The calculated errors ranged from about 6% to 10%.

Some earlier test runs indicated a few of the same trends, although there were technical problems (e.g., flowrate dependence) which were identified and corrected.

The sand used was Ottawa silica sand single mesh 150-120. The fluid was distilled water, flowing at a rate ranging from 200 cc/hr to 900 cc/hr at room conditions.

After the first test runs, the equipment was improved in order to get a better monitoring of the temperature distribution and the pressure differential, and also to achieve a laminar linear flow with minimal end effects. Changes were made one at a time, with a test run made after each change. This allowed the evaluation of each problem. For example, the

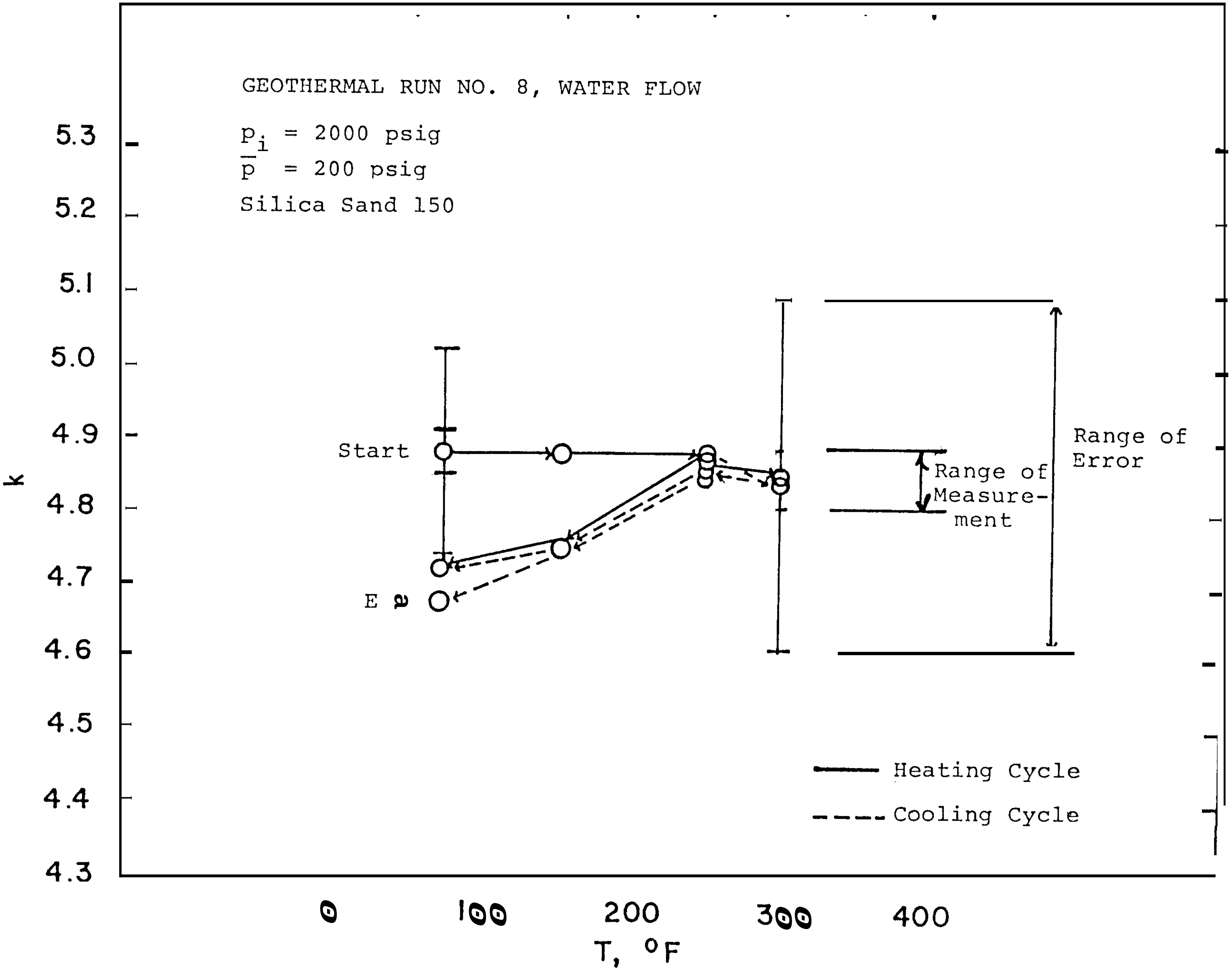


FIG. 2-3: PERMEABILITY VS TEMPERATURE

apparent permeability increased by 30% after working the core plugs to a better design. This indicated that there had been serious end effects which had caused most of the dependence of the permeability on the flowrate. Other improvements made were:

a. pressure tap location,

b. temperature control. and monitoring, and

c. flowrate control.

The behavior of the apparatus is now satisfactory. A report on this work will be completed soon by Sageev. Some additional improvements may be carried out in the near future to make a more reliable system. However, the main undertaking of current work will be the actual use of the new system in both absolute and relative permeability determinations as functions of temperature level and confining pressure. This apparatus can be operated at much higher pressure levels than the large core apparatus.

(b) Large Core Apparatus, by Morse Jeffers and Mark Miller, Engineer's Degree candidates, F. Rodriguez, Ph.D. candidate in Petroleum Engineering, and Prof. H. J. Ramey, Jr.

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. In order to investigate the effect of the rock matrix type, it was decided to perform runs with natural sandstones. Our intention is to perform experiments for the case of two immiscible liquids. To this end, the equipment has been redesigned and rebuilt. The requirements for the new apparatus were two-fold. First, it was necessary that the apparatus be able to measure relative permeabilities of water-oil-consolidated rock systems at elevated temperatures under unsteady-state conditions. Second, it was considered desirable to investigate dependence of relative permeability on fluid distribution and/or flow direction. In order to do this, flow in either direction of the core is required.

Figure 2-2 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 at room temperature, and this information corrected for temperature effects to derive an appropriate method of relative permeability calculation at elevated temperatures.

The apparatus is currently undergoing test and calibration, consisting of the following:

a. air bath calibration (because of the poor insulation of the air bath, temperature has been found to be a function of room temperature),

b. calibration of the dead volumes in the system, and

c. metering system calibration.

A consolidated sandcore with $\phi = 39\%$, length = 69 cm, and diameter = 5.08 cm has been prepared and mounted in the apparatus for testing purposes.

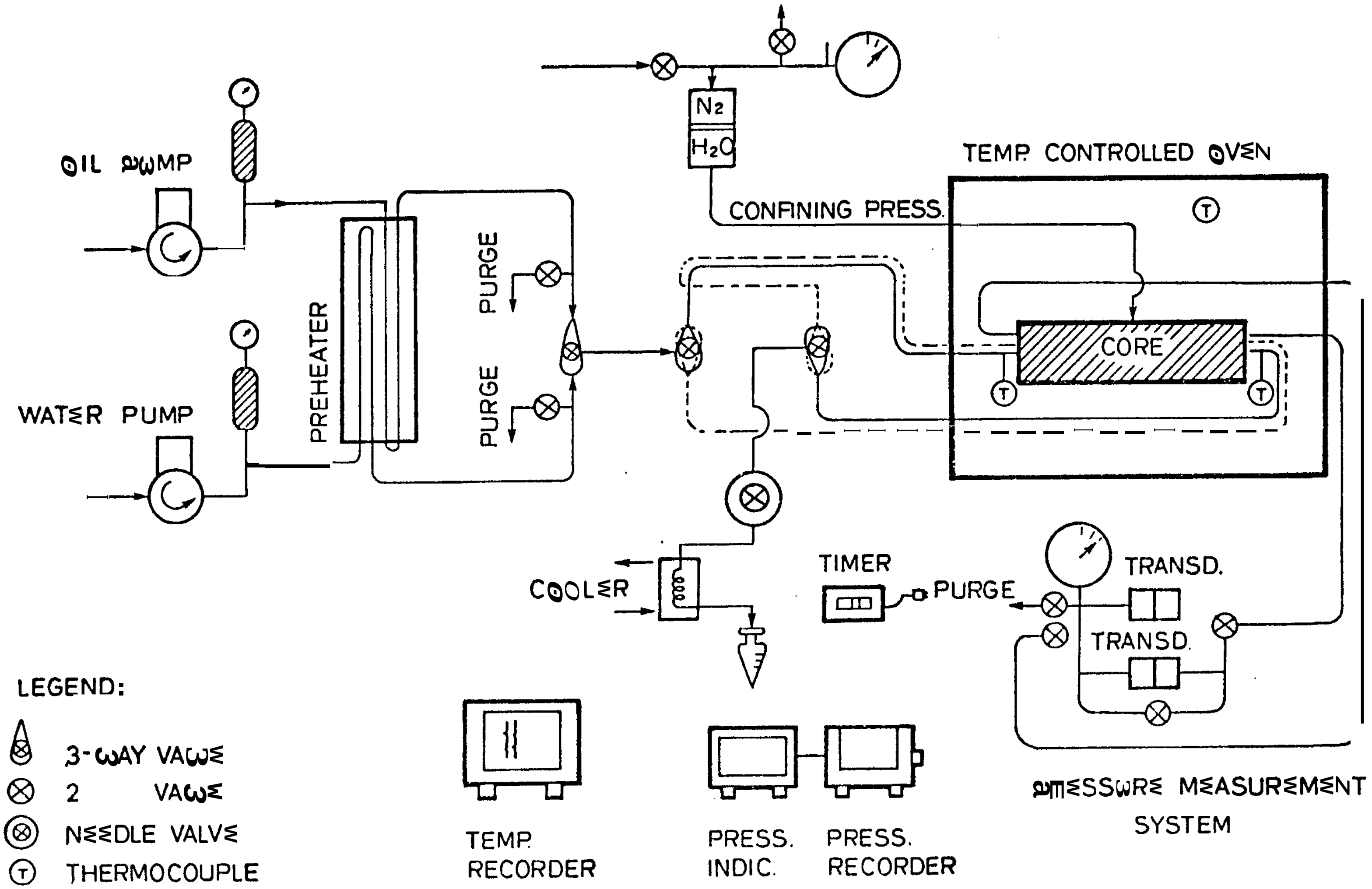


FIG. 2-2: LARGE CORE APPARATUS

(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 effects 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 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 2-3 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 during the year on the radon study cited in Section 3 of this report.

The state of the adsorbed water appears to be somewhere between that of a liquid and a solid. A new dialectric constant probe designed for

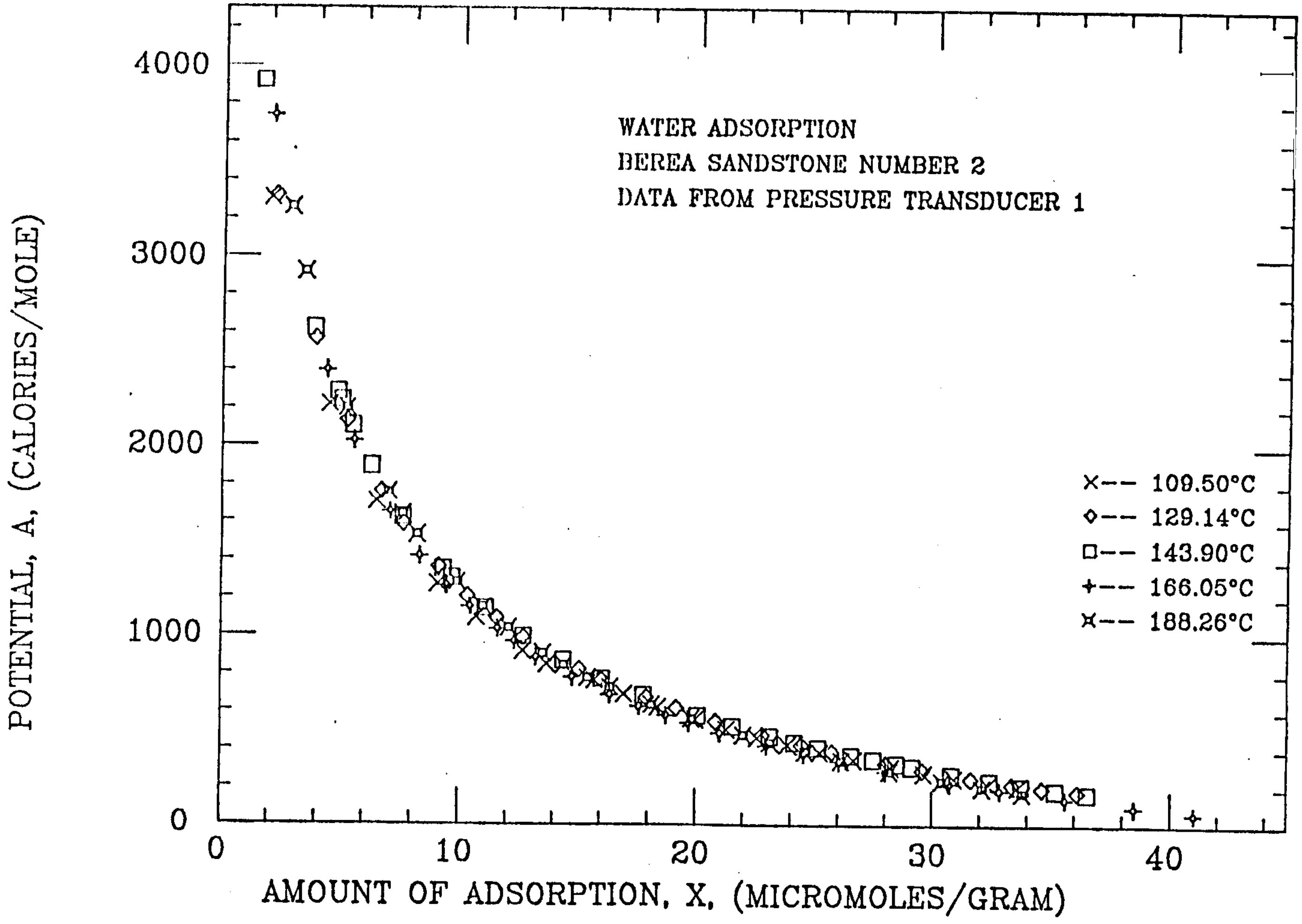


FIG. 2-3: CHARACTERISTIC CURVE OF WATER ADSORPTION ON ROCK SAMPLE

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 involves the completion of analysis of Dr. Hsieh's data and his dissertation. However, new measurements on a variety of additional cores were planned, and some extremely low permeability samples were 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 has been offered for inclusion at the California Regional Meeting of the Society of Petroleum Engineers in March 1381.

3. RADON TRACER TECHNIQUES

During the current year, three major research studies were completed. These were all aimed in different ways at establishing the value of radon as an internal tracer in geothermal reservoirs. The work carried out has been, or will shortly be, presented as dissertations. These studies related to (1) radon transients in vapor-dominated reservoirs, (2) radon transect analysis, and (3) radon emanation studies. Two advances arising from the studies were the improvement of wellhead sampling techniques to reduce the sampling and concentration standard error to less than ± 3%, and the use of ammonia analysis of the well fluid to complement the radon analyses. An important encouragement to this program has been the growing adoption of radon measurements for geothermal reservoir evaluation by other laboratories. To date radon studies are carried out at the Lawrence Berkeley Laboratories (H. Wollenberg), Los Alamos Scientific Laboratory (J. Grigsby), New Mexico Institute of Mining and Technology (M. Wilkening) in the U.S., and in Italy (F. D'Amore), New Zealand (N. Whitehead), Mexico (D. Nievas), and Japan (K. Satomi).

Radon studies in the Stanford Geothermal Program fall into three categories, each complementing the other two in our efforts to learn more about the movement of fluid in geothermal reservoirs. Transient analysis (the change in radon content with time) in the fluid discharging from a single well is useful in deducing general properties of a reservoir, during pressure transient analysis, a standard technique for measuring such properties as the porosity and the permeability-thickness. With the assumption that radon is conserved with the steam in the transport to the wellhead, concentration changes with changes in flowrate (or pressure) are also useful in examining reservoir properties. A review of this technique was given by Warren and Kruger (1979).

Radon transect analysis, described by Semprini and Kruger (1980), gives us the radon concentration gradient along a line of geothermal wells that span the structural features of a reservoir. The relationship of the concentration of radon, with a half life of 3.8 days, to the concentration of ammonia, a stable gas, has been determined for several transects.

The third group of studies was to evaluate the dependence of radon concentration at the wellhead on the emanation characteristics of the reservoir. Initial studies of emanation as a function of reservoir temperature, pressure, and pore fluid were reported by Macias, Semprini, and Kruger (1980).

(a) Radon Transient Analysis, by Gary Warren, Research Assistant, and Paul Kruger.

Gary Warren completed his Engineer Degree dissertation with a review of the status of radon transient measurements in vapor-dominated geothermal reservoirs. Radon transient experiments had been run at The Geysers in California and at Larderello in Italy. Combining the work of Stoker and Kruger (1975) and D'Amore et al. (1978), Warren developed a conical flow model based on radon flow from a horizontal boiling front at constant flux. This gives, at the wellbore,

$$N = \int_0^{H \tan \theta} 2\pi x R e^{-\lambda t_r} dx \qquad (3\text{-}1)$$

where N = number of radon atoms reaching wellbore per unit time

R = radon flux across the boiling front (atoms/m2sec)

θ = angle of conic slice in the reservoir (from the well axis)

H = depth of the steam reservoir (m)

t_r = travel time from boiling front to wellhead, given for Darcy flow as

$$t_r = \frac{H^2 \sec^2\theta}{\frac{3K}{\mu}\Delta p} \qquad (3\text{-}2)$$

The radon concentration at the wellhead is given by

$$C_F = \frac{2\pi RL}{\rho A} \exp\left\{-\frac{\lambda H^2}{K/\mu\ \Delta p}\right\} \qquad (3\text{-}3)$$

where L = average distance for the pressure gradient consistent with the pressure drop Δp actual flow rate

Δp = pressure difference between boiling front and wellbore (atm)

K = reservoir permeability (darcy)

μ = steam viscosity (cps)

A = cross sectional area of reservoir at boiling point (m^2)

However, radon is also emanated in the steam zone of the reservoir, and this additional flow to the wellhead is given by

$$N = 2\pi E \int_{r_w}^{H}\int_{0}^{\theta} h^2 \sec^2\theta \tan\theta \left| \exp\left(-\frac{\lambda h 3\sec^3\theta}{3v_o r_o^2}\right)\right] d\theta dh \qquad (3\text{-}4)$$

where r_w is the wellbore radius defining the upper limit of the reservoir.

For Darcy flow, the wellhead concentration of radon from the steam zone is

$$C_r = \frac{2}{3}\frac{\pi E}{\rho}\left[\frac{LH}{A}\ln\frac{H}{r_w} - \frac{\lambda}{Q} H^3\sec^3\theta\right] \tag{3-5}$$

The total radon concentration at the wellhead is thus

$$C_T = C_F + C_r \tag{3-6}$$

Several tests have been run over the past few years to evaluate the information attainable from radon–mass transient analysis. A summary of these tests is given in Table 3–1. An analysis of four tests in vapor-dominated reservoirs was reported by Warren and Kruger (1979). The results of the first of these tests has been reported earlier. A transient of 12±3 days was observed following the scheduled change in flowrate. However, a period of seismic activity occurred just before the flowrate change. This made the analysis of the transiept somewhat uncertain, in that a least squares fit to the concentration data could be made by starting the transient from the mean value before flowrate change or extrapolating the curve backwards to the time of flowrate change. These two exponential curves resulted in half periods which bracketed the decay constant for ^{222}Rn. However the uncertainty introduced cannot rule out other processes, such as mixing, as contributing to the observed transient. Unfortunately, because of altered conditions at this part of The Geysers field, the experiment cannot be repeated.

The first of two experiments at the Grottitana well at Larderello, Italy confirmed the linear dependence of [Rn] on flowrate, but with a

TABLE 3-1: SUMMARY OF RADON TRANSIENT EXPERIMENTS

Location	No. of Wells	Conditions	Observations
		Vapor-Dominated	
The Geysers	1	Rapid change in flowrate (i.e. rapid ΔQ)	Proportional transient with period ~ 12±3 days
Larderello	1	Isolated well, rapid AQ	Proportional transient with period ~ 0.5±0.5 days
The Geysers	2	10-flowing well field, AQ in one well Monitoring in second well	No change in [Rn] in either well
The Geysers	1	Two ΔQ's in well in nonproducing field	Transient build-up during constant Q with changes with AQ
Larderello	1	Isolated well, two AQ	Proportional transient in first AQ, nonproportional transient in second AQ
		Liquid-Dominated	
Puma	1	Short-term tests in one well at two flowrates	No change in [Rn] over the two short test periods
		Petrothermal	
Fenton Hill		Recirculation of injected fluid in fracture system	Buildup of [Rn] over period of applied pressure

AQ = Change in flow rate.

much shorter transient period of ~ 0.5±0.5 days, The data for this test are shown in Fig. 3-1. Since the effective transient constant is greater than 0.7 day^{-1}, much larger than the radioactive decay constant of $\lambda = 0.18\ \text{day}^{-1}$, a process other than radioactive decay must be responsible for the observed transient. Such processes might be changes in emanating power with pressure changes in the formation and changes in fluid density with changes in thermodynamic state. The second test at Grottitana showed both a linear and non-linear change in radon concentration with the two changes in flowrate. The data are shown in Fig. 3-2. The first change reproduced adequately the data in the first test, but a second change in flowrate resulted in a lower, but nonlinear change in radon concentration. The data are illustrated in Fig. 3-2 (Kruger, Cederberg, and Semprini, 1978). A summary of all the Grottitana data is given in Table 3-2.

TABLE 3-2: RADON TRANSIENT TESTS AT GROTTITANA, ITALY

Test No.	Flowrate Range Q(t/hr)	Mean Radon-Flowrate Ratio [Rn]/Q
1	7.5- 11.8	7.33 ± 0.76
2	8.1- 11.3	7.8 ± 0.3
2	4.6- 5.0	11.5 ± 0.6

The processes that could account for the observed nonlinear relation include (1) increased reservoir pressure at lower flowrates, resulting in increased emanation in fractured rock, (2) nonlinear emanation from the boiling front, (3) condensation of steam under subcooled transit .to the wells, and (4) incorrect flowrate measurements at the very low flowrates. Plans are underway to run a third transient test at Grottitana with monitoring in a nearby well.

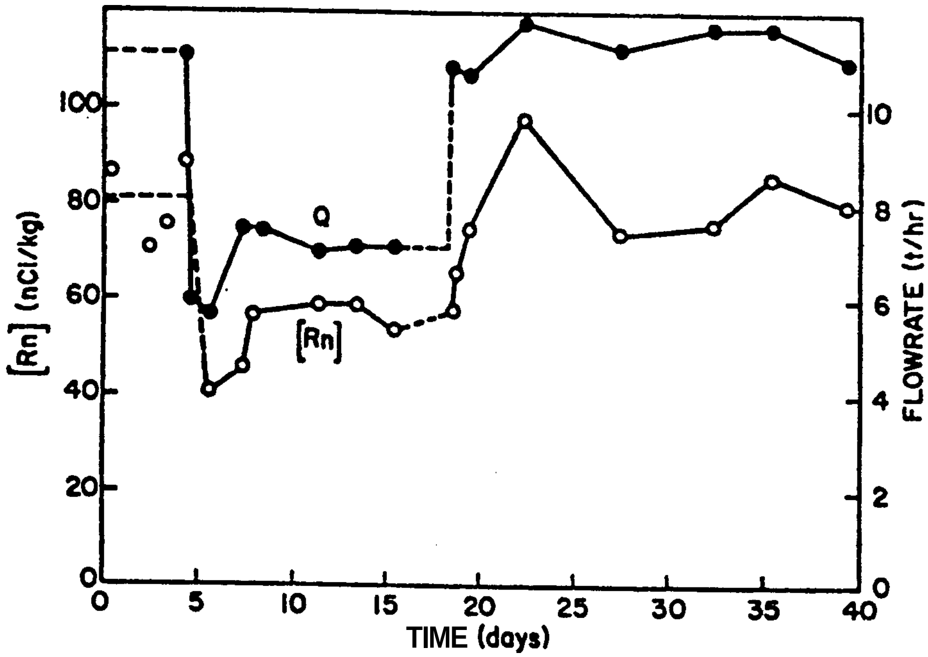


FIG. 3-1: RADON TRANSIENT DATA; GROTTITANA, SERRAZZANO, ITALY

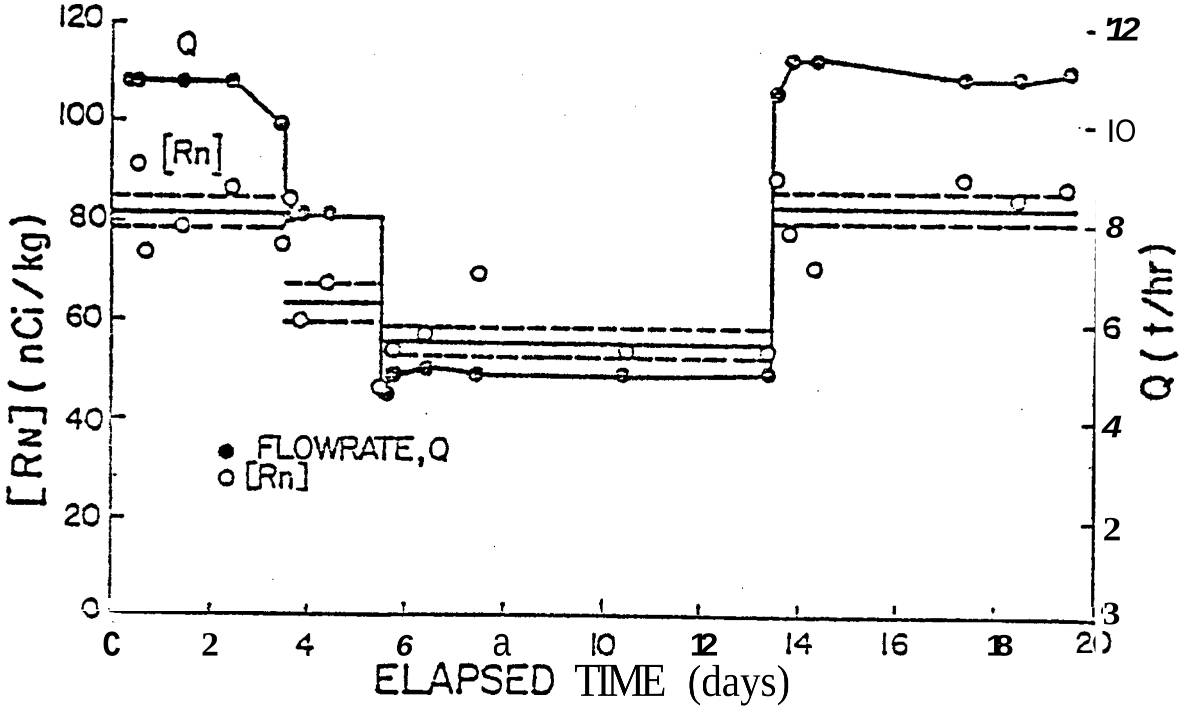


FIG. 3-2: RADON DATA; GROTTITANA WELL, ITALY

The two additional tests at different areas of The Geysers provided interesting observations. The first was carried out in a newer area when one of two twin generators was under repair and the operators were able to reduce flow in one of the ten wells feeding the second generator. Radon concentrations were monitored in two wells and two flowrate changes were carried out in one of the wells. The results, as shown in Fig. 3-3, Warren and Kruger (1979), showed a constant radon concentration in both wells over the total period of flowrate changes. These observations suggest two alternatives: (1) that the steam source was common to all ten wells that supply steam to the operating unit (thus a 50% change in flowrate in one well might be expected to produce only a 5% change in the overall radon concentration, a change too small to observe); or (2) that the difference in mean concentration between the two wells might be due to local variations in radium content or emanating power, or to a partitioning of flow through the multiple-fractured formation resulting in a distribution of transit times to the individual wells. These data suggested the use of transect analysis to see if a distribution of steam age exists across the reservoir.

The last test was an extended test of a well in a new production zone where the power plants had not yet been installed. Flow commenced for a long test during which the flowrate stabilized over a two-week period. Sampling at this established flowrate was carried out for three weeks, through a reduction in flowrate and then for two further weeks at full flow. These samples showed an increase in radon concentration with cyclic fluctuations (Fig. 3-4). A least squares fit through the cycle averaged data for this period of the test showed an exponential increase of the form:

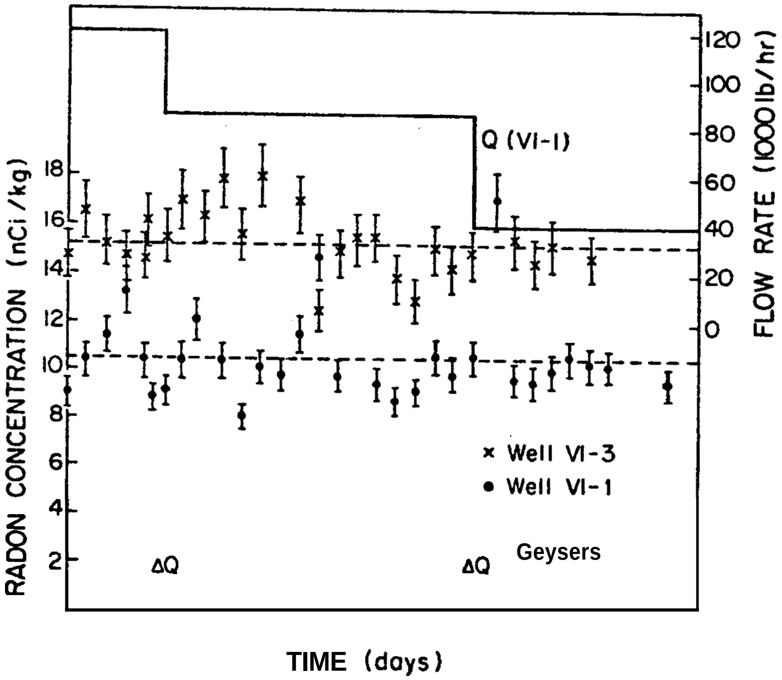


FIG. 3-3: RADON TRANSIENT DATA, WELLS VI-1 AND VI-3, THE GEYSERS, CALIFORNIA. WELL VI-3 FLOWRATE CONSTANT AT 235 klb/hr.

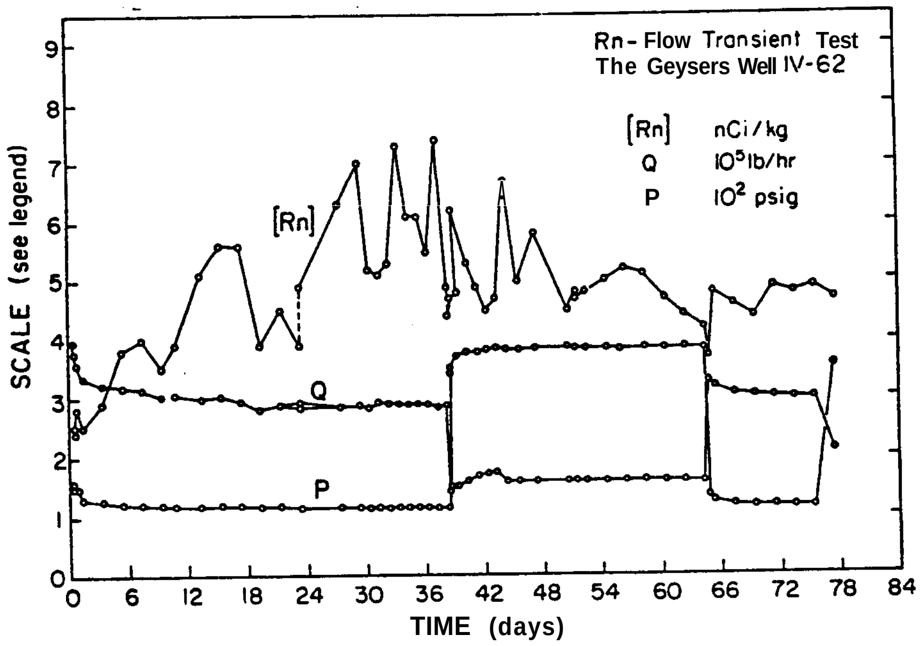


FIG. 3-4: RADON TRANSIENT DATA, WELL IV-62, THE GEYSERS, CALIFORNIA

$$C = 2.4 + 3.8\,[1 - e^{-0.062t}] \qquad (3\text{-}7)$$

with C in nCi/kg and t in days (Fig. 3-5). Following the flowrate change of 50% on day 38 at the end of that period, the mean radon concentration decreased by 14%, a significant decrease considering the general trend of increase with sustained fluid production. On return of flowrate to full value, the radon concentration again began to increase. Warren and Kruger (1979) noted several models which might account for the observed data. This test underscored the need to obtain radon measurements early in the production history of new wells. The emanation of radon is expected to increase at constant production if the steam production at early times depletes the nearby pore volume of liquid water and the boiling front moves sufficiently far into the reservoir to have full mixing. Although it is difficult to obtain flowrate reduction during normal on-line production of fluid for electricity generation, sufficient opportunities occur in U.S. fields and abroad to continue the development of a radon transient analysis method. At some future opportune time, a joint pressure transient and mass transient analysis should be carried out to compare the information obtained by pressure response and mass flow response *to* changes in wellhead flow rates.

(b) Radon Transect Analysis, by Lewis Semprini, Research Assistant, and Paul Kruger.

During the current year, Lewis Semprini completed the laboratory work on radon transect experiments at three geothermal fields: the vapor-dominated field at The Geysers, California, and at the liquid dominated fields at Wairakei, New Zealand and Cerro Prieto, Mexico. The objective

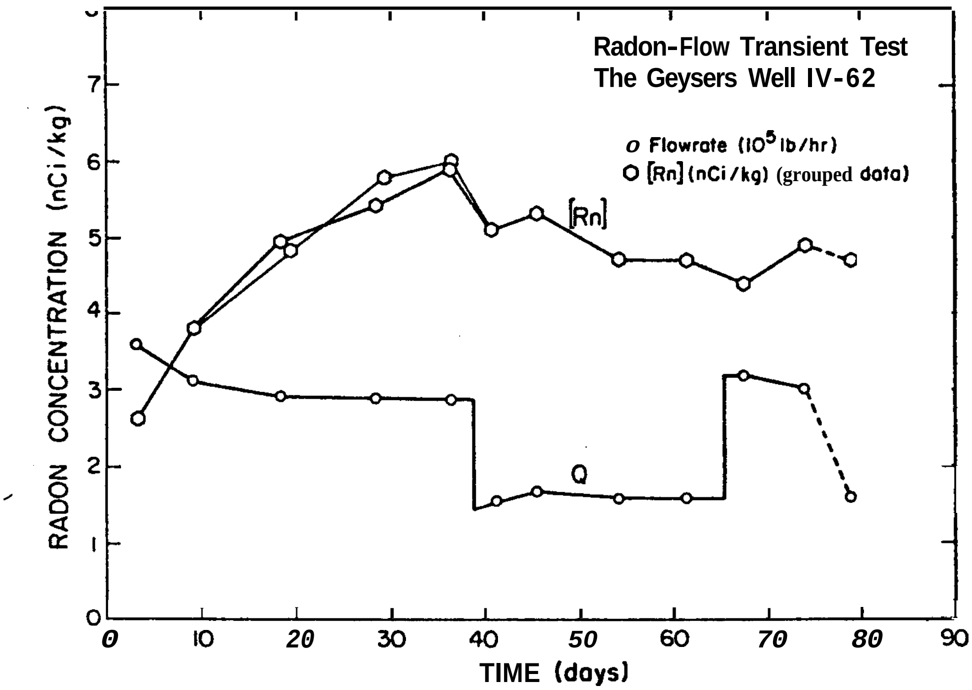


FIG. 3-5: RADON TRANSIENT DATA, WELL IV-62, GROUPED ANALYSIS

of the radon transect analysis is to examine the concentration gradients of radon and other noncondensable gas components in the geofluid along a line of wells intersecting significant structural features in the reservoir. The purpose is to provide temporal information on the flow regime across the reservoir. If the concentrations are not time dependent, they indicate changes in the source of both steam and radon emanation. To determine if observed variations in radon concentration are related to transport rather than to radioactive decay, measurements are also made of ammonia in the same samples. Ammonia is a "stable" gas component in the noncondensable gases. Details of the method and sampling procedures are described by Semprini and Kruger (1980).

Radon transects have been run in the older producing zone at The Geysers in 1978 and 1979. The results of these two tests are given in Fig. 3-6; the gradients in radon concentration show a similar trend of decreasing concentration along the transect. In the latter test, the ratio of radon to ammonia, shown in Fig. 3-7, indicates a linear correlation between the two gases and suggests that these two have a similar source in the reservoir and undergo similar transport processes. Fig. 3-8, which amplifies the initial sharp gradient on the left, shows the data in relation to the reservoir cross-section published by Lipman, et al. (1977). A discussion of the possible processes consistent with the observed data are given by Semprini and Kruger (1980).

A transect experiment was conducted at Wairakei, New Zealand, where a large difference in radon concentration had been measured in wells across the major Wairakei and other faults. As a result, a number of our steel bottles were shipped to Wairakei to obtain samples along transects parallel and normal to the major fault. The results of this test are given in

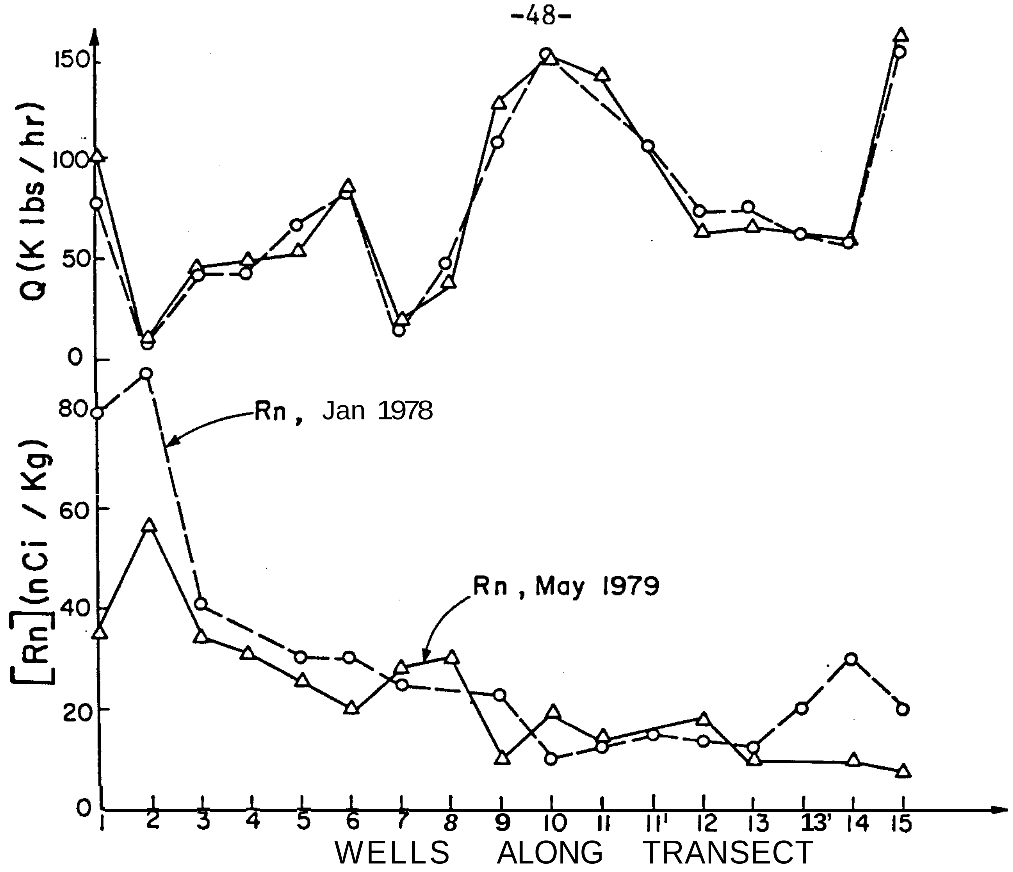


FIG. 3-6: RADON TRANSECTS ACROSS THE OLDER PRODUCING ZONE OF THE GEYSERS FIELD

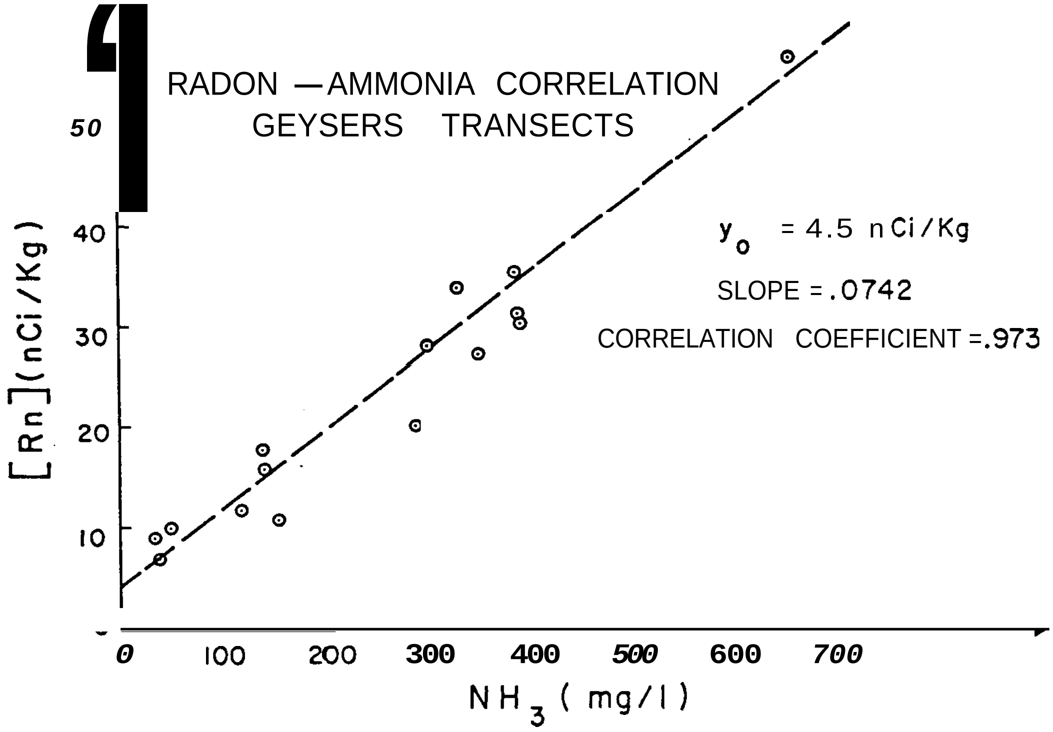


FIG. 3-7: THE RADON-AMONNIA CORRELATION FOR THE 1979 TRANSECT ACROSS THE GNSERS FIELD

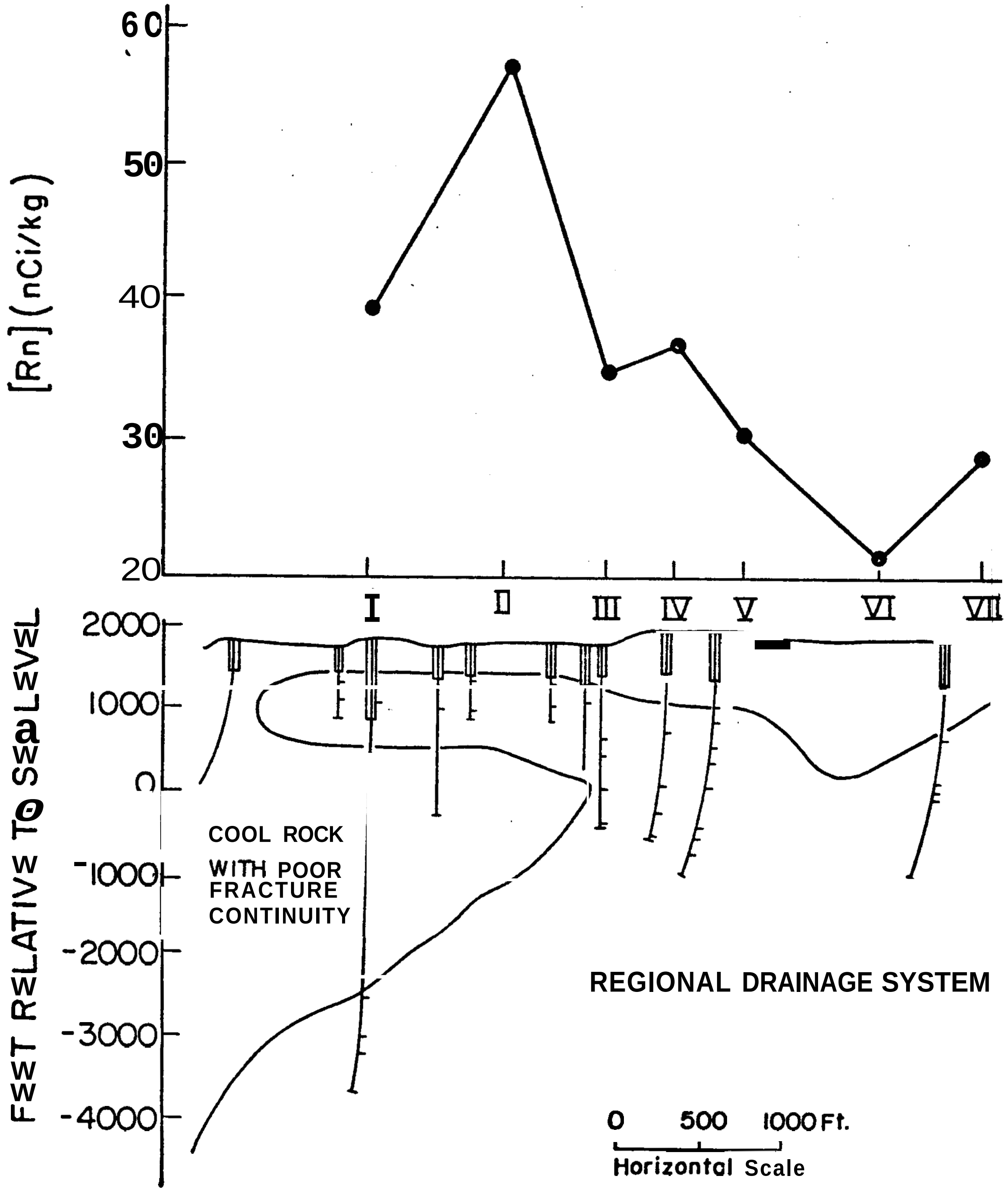


FIG. 3-8: THE MATCH BETWEEN THE RADON CONCENTRATION AND THE LOCAL GEOLOGY IN A SECTION OF THE GEYSERS

Table 33. Horne and Kruger (1979) suggested that the radon concentration may be correlated with fluid enthalpy based on the mixed fluid nature at Wairakei; a lower liquid-aquifer and an upper steam zone. The equilibrium concentration noted for a vapor-dominated system can be modified for a geothermal fluid of steam saturation, χ, as

$$C_T = \chi \frac{\quad}{\rho_V} + (1-\chi) \frac{Em\rho_f}{\rho_L} \tag{3-8}$$

where χ, ρ_V refer to the saturation and density of the vapor phase and $(1-\chi)$, ρ_L refer to the liquid phase. The correlation of the transect data are given in Fig. 3-9. A discussion of these data are given by Semprini and Kruger (1980).

The transect study at Cerro Prieto was conducted as a joint project with the Coordinadora Ejecutiva de Cerro Prieto of the Comisión Federal de Electricidad of Mexico. Results from the two transect experiments conducted in October 1979 and March 1980 are given in Tables 3-4 and 3-5. The wellhead radon concentration ranged from 0.16 to 3.60 nCi/kg in the 21 wells tested; the ammonia concentration ranged from 17.6 to 59.3 mg/1, based on mass balance at the cyclone separators. Radon and ammonia in the water phase were estimated with empirical partition coefficients from mass balance measurements at several cyclone separators in the field.

The location of wells along each of the transects is shown in Fig. 3-10. The corresponding ammonia, radon and enthalpy content along the four transect lines are shown in Fig. 3-11. The results show high content of all three components in wells M45, M48, M84 which are producing two-phase fluids of high vapor content in the central southern area of the field.

TABLE 3-3: RESULTS OF TRANSECT EXPERIMENTS AT WAIRAKEI, NEW ZEALAND

Date	Well	Pressure (sep)	Flowrate (steam)	Flowrate* (liquid)	Enthalpy** (WH)	Rn (vapor)	Rn (WH)	NH_3 (vapor)	NH_3 (WH)
		(bar)	(t/hr)	(t/hr)	(kJ/kg)	(nCi/kg)	(nCi/kg)	(mg/l)	(mg/l)
3/79	8[illegible]	[illegible] 5	1[illegible] 5	37	1209	3 38	0.94	ND	ND
5/79	[illegible]6	.0	14.8	5[illegible]	102[illegible]	[illegible].2[illegible]	0 91	ND	ND
5/79	83	10.0	21 0	14[illegible]	1009	2.4[illegible]	0 31	ND	ND
5/79	72	11 0	[illegible]2 5	122	1300	[illegible] 93	1 79	ND	ND
4/79	30	10 2	19 5	147	982	0.84	0.09	ND	ND
5/79	71	10	35 4	331	95[illegible]	0 94	0.09	ND	ND
8/79	70	9 0	303	8[illegible]	1098	4 00	0 88	[illegible] 7	1 9
8/79	[illegible]8	3 2	7.0	26	1033	2.0[illegible]	0.[illegible]	[illegible].0	1.4
8/79	67	9.0	2[illegible].0	107	979	.60	0.11	4.1	1.4
8/79	27	9.0	27	144	1037	1.01	0[illegible]5	11 1	2.9
8/79	81	9 0	7 4	5[illegible]	98[illegible]	0.41	0.04	3	1 1
8/79	45	9 2	28.0	191	1003	0 72	0.09	3	13
8/79	108	.0	ND	ND	1023	1 [illegible]0	0[illegible]	4.1	1.2
8/79	76	8.5	25.0	173	989	2.69	0.34	3.3	1.0
3/79	[illegible]0	6.0	27.0	0	2800	139	139	ND	ND
8/79	80	[illegible] 0	ND	0	2800	135	135	5.0	5.0

*Liquid flowrates calculated from enthalpy data

**Enthalpy data obtained from The Department of Scientific and Industrial Research, Wellington, New Zealand

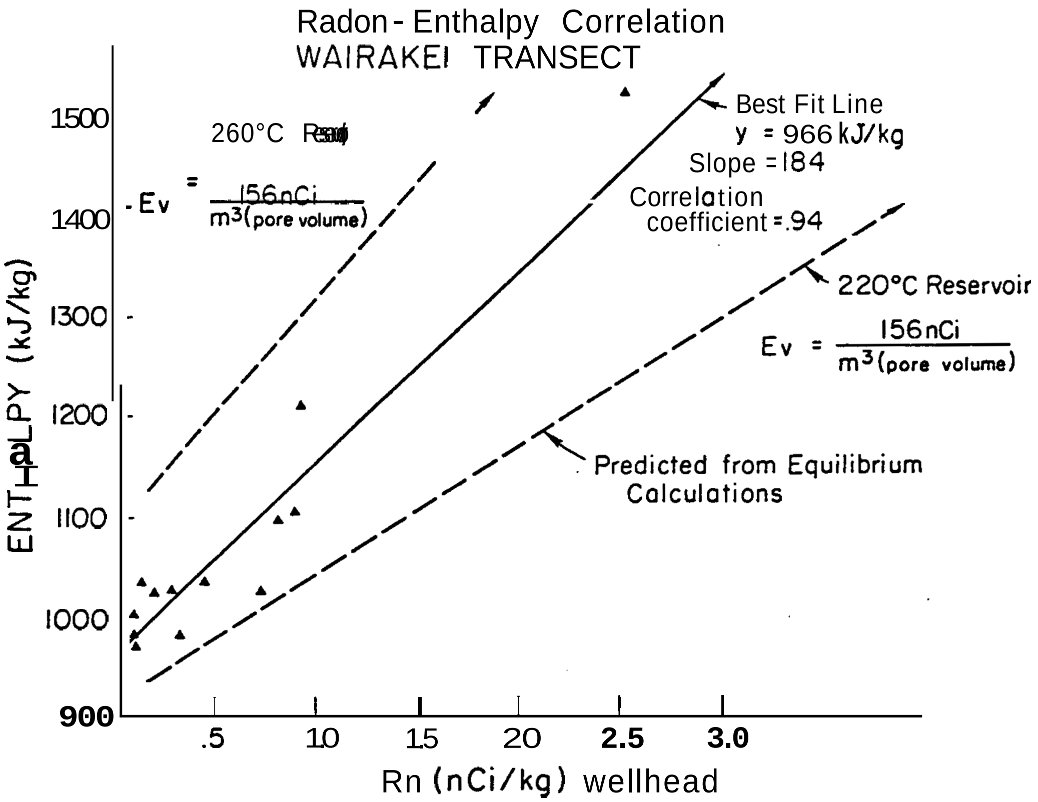


FIG. 3-9: THE RADON-ENTHALPY CORRELATION FOR WAIRAKEI, NEW ZEALAND

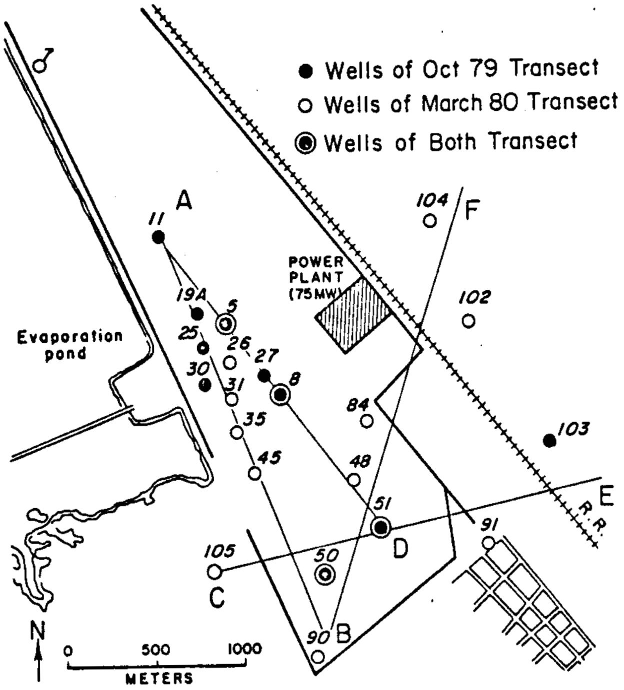


FIG. 3-10: LOCATION OF WELLS AND CROSS-SECTIONS OF THE CERRO PRIETO TRANSECT TESTS

TABLE 3-6: CERRO PRIETO TRANSECT, OCTOBER 1979

Well No.	P_{WH}* (psig)	P_{sep} (psig)	Enthalpy (kJ/kg)	Q_s (vapor) (t/hr)	Q_L (liquid) (t/hr)	Rn (vapor) (nCi/kg)	Rn (WH) (nCi/kg)	NH_3 (vapor) (mg/l)	NH_3 (WH) (mg/l)
M-11	93	92.5	1606	16.7	28.5	0.[illegible]3	0.214	[illegible]5.[illegible]	28.9
M-19A	100	97.5	1372	55.0	166.8	0.79	0.253	65.4	19.2
M-5	102	91[illegible]	1230	31.5	92.4	1.46	0.370	68.1	17[illegible]
M-23	225	9[illegible].0	1306	37.1	91.6	.96	.271	75.5	31.
M-8	100	92.0	1306	36.4	83.4	0.97	0.283	60.2	1[illegible].0
M-27	92	92.0	1625	25.5	67.4	1.85	0.667	66.1	20.7
M-30	110	96.0	1302	6[illegible].7	123.[illegible]	1.[illegible]7	0.307	67.7	18.8
M-[illegible]1	121	118.0	1569	97.3	142.3	1.[illegible]7	.759	35.	17.
M-103	8[illegible]7	127.0	156[illegible]	117.0	183.7	0.63	0.24[illegible]	67.6	32.5
M-50	123	108.0	1600	83.9	172.0	0.4	0.1[illegible]	69.3	29

* All data from the field operation report for October 1979 of the Comision Federal De Electricidad, Coordinadora Ejectiva De Cerro Prieto, B. C.

TABLE 3-5: CERRO PRIETO TRANSECT, MARCH 1980

Well No.	P_{WH}* (psig)	P_{sep} (psig)	Enthalpy (kJ/kg)	Q_s (vapor) ((t/hr)	Q_L (liquid) (t/hr)	Rn (vapor) (nCi/kg)	Rn (WH) (nCi/kg)	NH_3 (vapor) (mg/l)	NH_3 (liquid) (mg/l)	NH_3 (WH) (mg/l)	$K = \frac{[NH_3]steam}{[NH_3]liquid}$
⊳5	105	9∃ 5	1300	∃1 ∃	77 1	1 3ʒ	0 ∃9	78	ND	∃ɒ∃	ND
⊳2≤	⊂05	96	12≤Z	⊂1.⊂	11∃ ≤	0.99	0.2≤	71	10.1	2≤ ⊂	ʒ.0
M-∃1	100	97 ʒ	12∃1	31	91 2	1 01	0 Z≤	72	8·ɔ	Z⊂.5	8 ≤
M-∃ʒ	130	95 5	1∃≤0	≤3 1	136 ∃	0.≤Z	ɒ20	63	ND	26.5	ND
M-⊂ʒ	101	100 ʒ	23≤0	2⊂	6 1	⊂.ʒ0	3.60	71	11	59.3	6.
M-8⊂	108	100	19≤7	≤2.5	⊂0 1	1 8ʒ	1 13	65	12.3	⊂⊂.4	ʒ ∃
M-91	110	108	1398	79 5	158.9	0 ⊂⊂	0 1ʒ	ʒ∃	П	Zʒ.6	ND
M-10ʒ	1∃≤	12∃	1≤07	7ʒ 7	10∃.4	0 ⊂8	0 20	≤0	11 ɛ	∃2.0	5 2
M-48	125	110	17⊂1	6ʒ 8	≤7 ⊂	Z·ɔ9	1 ⊂3	71	ND	40 ʒ	ND
M-90	109	108	1298	⊂7 9	1Z⊂ 6	1 ∃7	0 ∃8	65	9 7	2ʒ 1	7
M-ʒ0	129	110	13⊂8	81 ∃	188 ≤	2.0≤	0 ≤2	80		3∃ 1	ND
M-51	11ɔ	115	1528	91.3	1⊂⊂ Z	1 92	0 7⊂	≤8	10.4	32 ʒ	6 ʒ
M-102	90	89	1645	Z8.5	∃3 9	1 ∃6	0 ≤2	88	12.0	⊂≤ 7	ɔ ∃
M-104	110	106	2057	31.6	91.2	2 58	0.≤≤	106	18.0	⊂0	5
M-8	92.5	92	1365	19.8	42.1	0.92	ɒ29	8ʒ	11.0	3⊂ ʒ	7 7

*Well data from the field operations report for March 1980 of the Comision Federal De Electricidad, Coordinadora Ejectiva De Cerro Prieto, B.C.

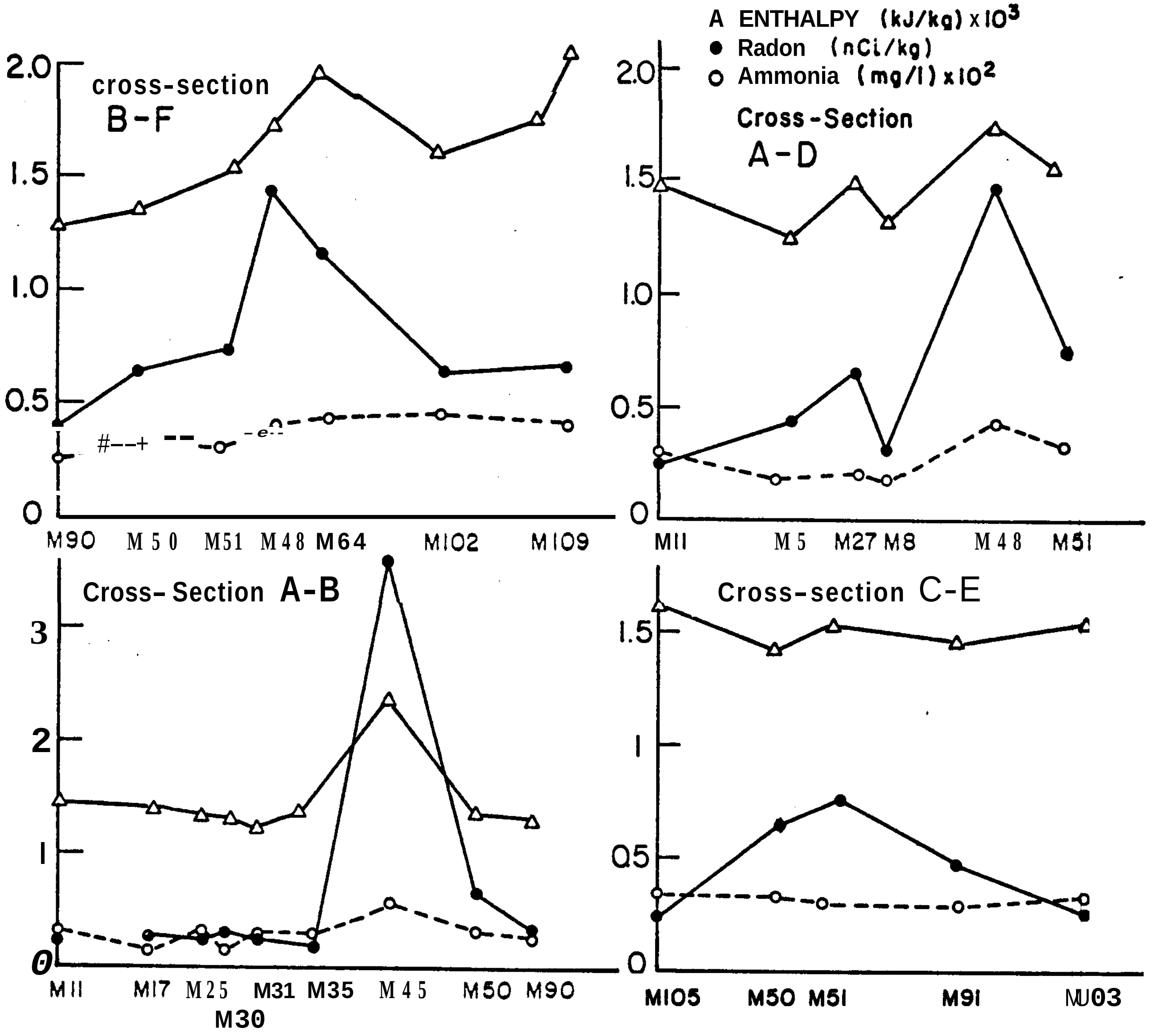


FIG. 3-11: CERRO PRIETO CROSS-SECTION; AMMONIA - RADON - ENTHALPY WELLHEAD FLUID

Production from the northern section of the field was primarily liquid with lower (and more uniform) enthalpy, radon and ammonia content.

The radon-enthalpy correlation at Cerro Prieto is shown in Fig. 3-12. The linear correlation is not as good as the one observed in the Wairakei experiment (Semprini and Kruger, 1980). The correlation, however, does indicate the radon concentration is dependent on two-phase conditions in the reservoir. Several processes that could lead to these observed variations from a linear correlation of radon and enthalpy are being evaluated. Among them are (1) lack of radioactive equilibrium in the two-phase fluids after phase separation, and (2) changes in fluid density due to variations in reservoir temperature along the various flow paths.

The results from the radon transect experiments at Wairakei and Cerro Prieto indicate that two-phase flow in hot water systems can be studied using radon. Future radon transect and transient experiments in these and other developed hot water systems will aid in studying two-phase flow in greater detail.

(c) Radon Emanation Studies, by Luis Macias-Chapa, Research Assistant and Paul Kruger.

During the current year, Luis Macias completed a series of measurements of radon emanation in a 3-unit physical model of a fractured geothermal reservoir. In this model the closed nature of the system allows radon buildup without fluid transport until the system is swept out for radiochemical analysis. A cross-section of the model in the large volume, high temperature air bath is shown in Fig. 3-13.

The emanating power of radon from rock is dependent on several rock-fluid properties, notably the rock type (structure and radium content),

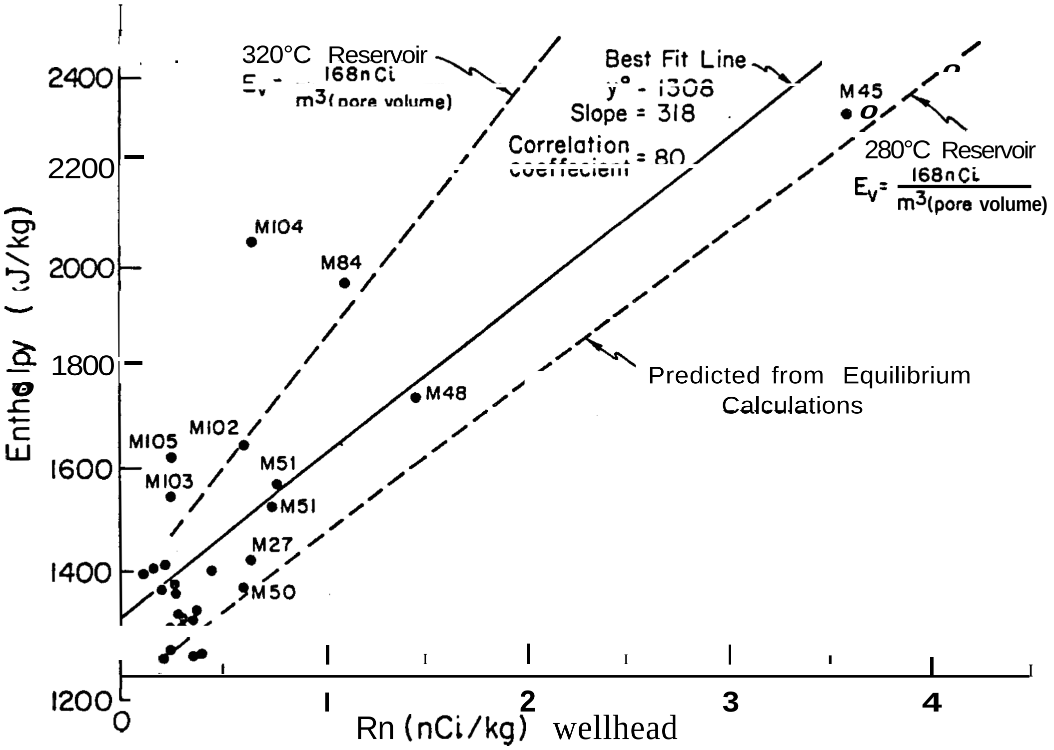


FIG. 3-12: CORRELATION OF RADON AND ENTHALPY FOR CERRO PRIETO TRANSECTS

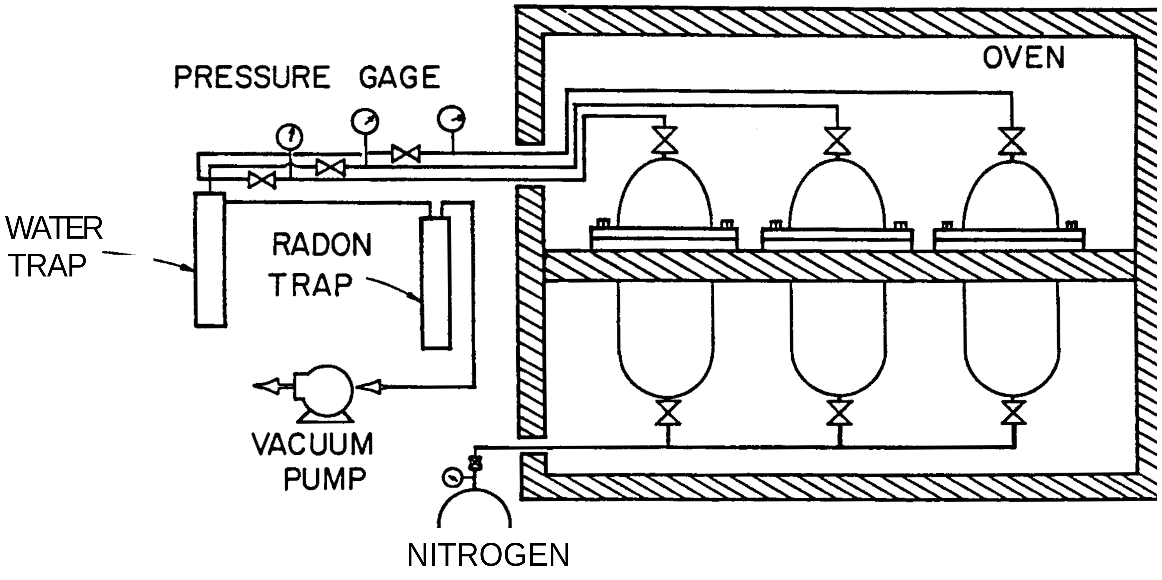


FIG. 3-13: RADON EMANATION SYSTEM

the rock size (radon recoil and diffusion), the pore fluid type (density and saturation), and the thermodynamic variables of pressure and temperature.

For his experiments Macias fixed the first two named variables by selecting a greywacke rock, representative of the rock in The Geysers area, and a rock size compatible with the model scale. The variables were thus reduced to temperature, pressure and pore fluid, and for the latter he used a noncondensable gas (nitrogen), water, and steam.

Results for all the experiments, illustrated in Fig. 3-14, suggest a mechanism for radon emanation which depends on the presence of liquid water in the pore spaces. Thus for dry nitrogen and liquid water, the results show little variation of emanation with pressure and an increase with the changes in temperature. The steam result, in contrast, shows an increase in emanation with pressure. The early nitrogen result (Fig. 3-14a) also shows a similar increase along with a marked drop in emanation in the 279°C test. Radon emanation is dependent on the density of the pore fluid and may be expected to be low for superheated steam and dry nitrogen pore fluids. If water is present, however, then the emanation would be greater.

These results are particularly interesting in light of the work recently carried out by Hsieh (1980) on water absorption. Hsieh's work indicated that liquid water may be absorbed in micropores in a porous medium under superheated steam conditions. The radon results fit in with this conclusion. A preliminary report covering early results was presented by Macias, Semprini and Kruger (1980). A full discussion of the study and the results will be available shortly (L. Macias, Engineering Thesis).

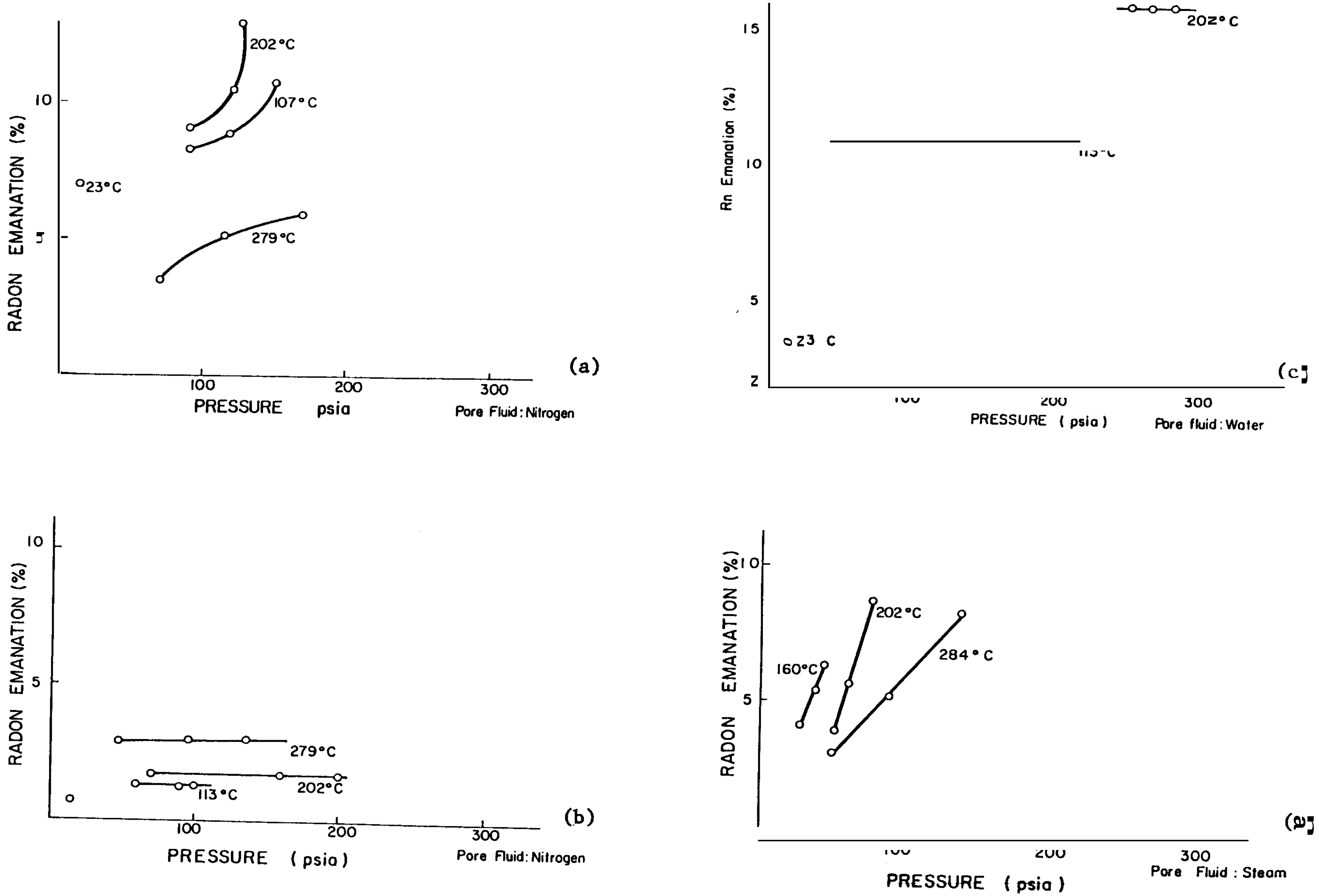


FIG. 3-14: EXPERIMENTAL RESULTS OF RADON EMANATION AS A FUNCTION OF PRESSURE AND TEMPERATURE

4.0 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, quite a few studies were completed, and reports and papers presented on a variety of well test analysis methods. The following summarizes some of the more important results.

(a) Constant Pressure Testing, by Dr. C. Ehlig-Economides and Prof. H.J. Ramey, Jr.

Although the conditions which result in constant pressure flow often exist for geothermal production and injection wells, the methods for analyzing the resulting rate transients and pressure buildup for such wells have been incomplete or nonexistent. The objective of this work was to review the existing methods of analysis and to contribute new solutions where needed in order to produce a comprehensive well test analysis package for wells produced at constant pressure. The work was completed during the year, and a technical report, SGP-TR-36, has been published. Other publications of results from this project are given by Ehlig-Economides and Ramey (April, June, November 1979).

The methods described in this work are:

- Determination of permeability and skin effect by type-curve matching with a graph of log rate vs log flow time for an infinite system.

- Determination of permeability and skin effect from a semilog straight line on a graph of reciprocal rate vs log of flow time.

- Determination of reservoir volume and approximate shape from a graph of log rate vs flow time after the onset of exponential decline.

- Analysis of transient rates when the wellhead pressure is constant.

- Determination of permeability and skin effect from an interference test by type-curve matching with a graph of log pressure drop vs log flow time for an infinite system.

- Determination of wellbore storage, skin effect, and fracture half-length for fractures penetrated by a wellbore, and other inner boundary effects, by type-curve matching of early pressure buildup data with conventional pressure transient solutions.

- Horner buildup analysis for wells produced at constant pressure.

- Analogous methods for the Matthews, Brons, and Hazebroek determination of static reservoir pressure.

(b) Parallelepiped Models, by D. Ogbe and M. Economides, Ph.D. Candidates 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. Last 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). This 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 Fig. 4-1. The objective of this study is 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 ten or more wells).

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

The solutions for the slug test (decreasing flowrate) drill stem test (DST), including wellbore storage and skin effect, were presented by Ramey et al. in 1975. In field data from slug test DSTs, an initial period of constant flowrate can often be observed. A new model which includes the initial constant flowrate for a slug test was developed. Type-curves were graphed which were then matched with field data. Two examples of the quality of the match between actual data and a slug test type-curve are shown in Fig. 4-2. The slug test type-curves can be applied to both the flow period and the pressure buildup after a short initial shut-in in a DST. A special feature of the new type-curves is that they may be used to estimate the initial formation pressure from the initial cleanup flow pressure buildup data even when the flow is so short that a Horner buildup graph is not possible (see Shinohara and Ramey, 1979).

In deep, high-rate wells, the inertia and momentum of the liquid moving in the wellbore become important. Most available pressure transient solutions neglect these phenomena. Sometimes the inertia effect can cause

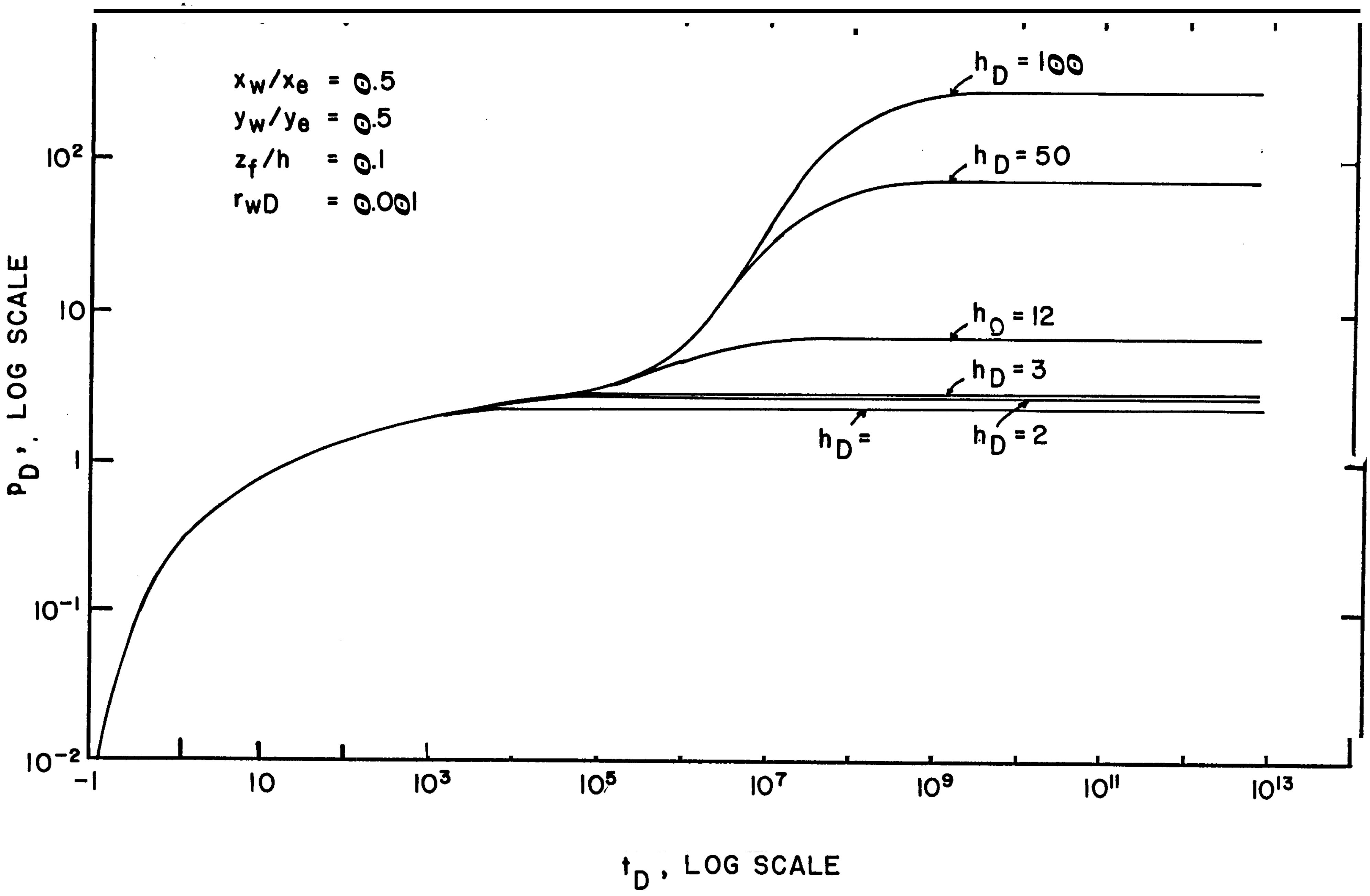


FIG. 4-1: LOG-LOG TYPE-CURVE FOR A PARALLELEPIPED MODEL

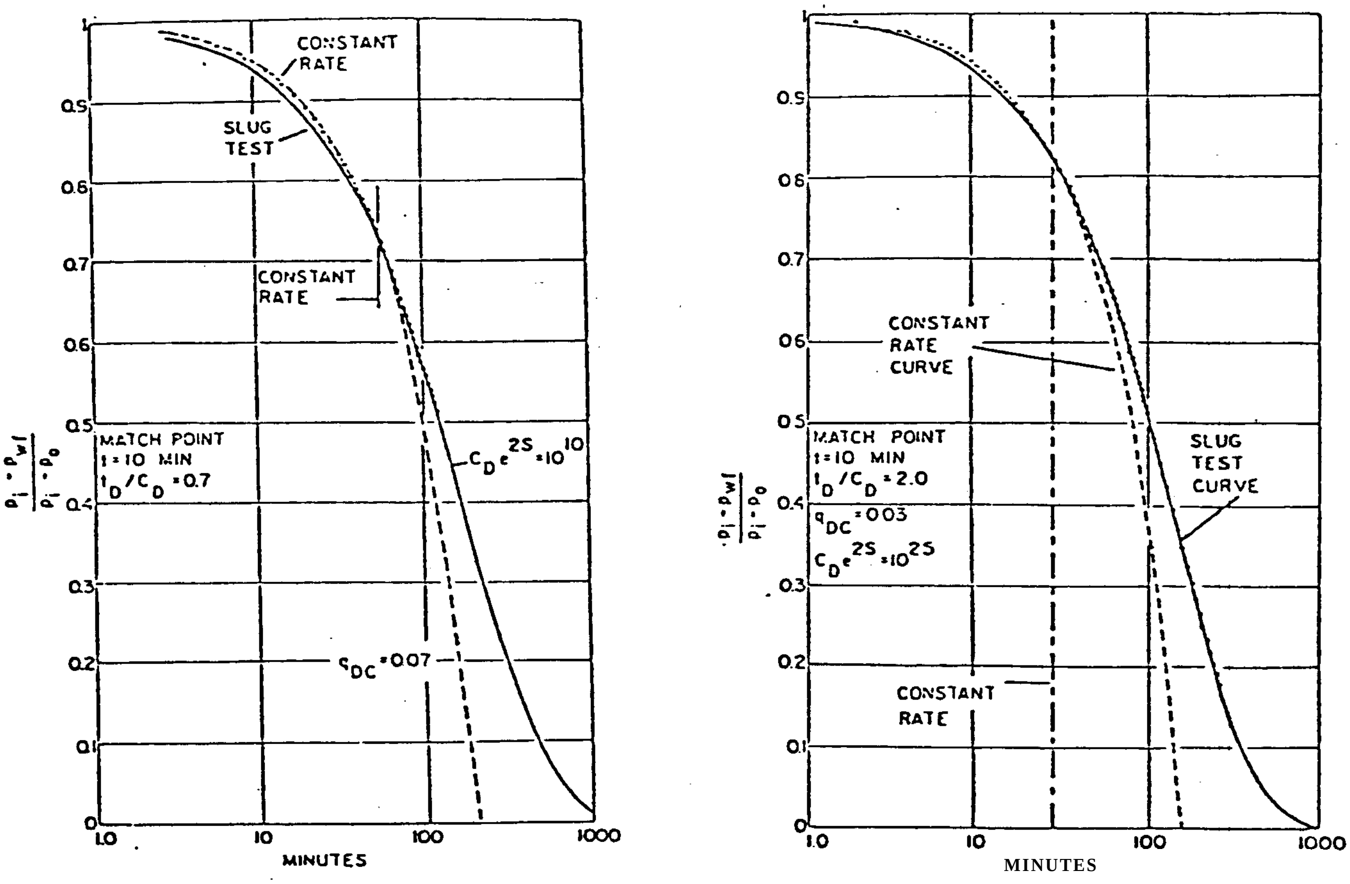


FIG. 4-2: FIELD DATA MATCHED WITH SLUG TEST AND CONSTANT RATE TYPE-CURVES

oscillation of the liquid level in the wellbore. An approximate method using an exponentially damped fluctuation was presented by van der Kamp in 1976. However, this method cannot be applied to the early time pressure behavior, which is often of interest. A complete analytical solution for this problem was found, and the resulting type-curves were graphed and matched with field examples. Figure 4-3 shows some of the new solutions. The parameter x_D represents the fractional liquid level rise following the sudden removal of the liquid from a static wellbore. This acts like opening a bottomhole valve in a DST when there is air in the drill pipe. The parameter a^2 is:

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

where L is the well depth and g is the acceleration of gravity. Other symbols have their usual meaning. The term a^2 is a new parameter which considers momentum or inertia of fluid in the wellbore. A value $a^2 = 0$ is the usual slug test. When a^2 reaches values of 10^5 or more, the results differ greatly from the slug test. Oscillations occur when $\alpha^2 = 10$ or more. Both the skin effect and wellbore storage affect the results significantly.

This theory can also be applied to closed-chamber DSTs and water injection falloff tests. These results were published by Shinohara and Ramey (1979, 1980), and also as SGP-TR-39, Shinohara (April 1980).

(d) <u>Analysis of Wells with Phase Boundaries</u>, by Profs. R.N. Horne, A. Satman, and H.J. Ramey, Jr.

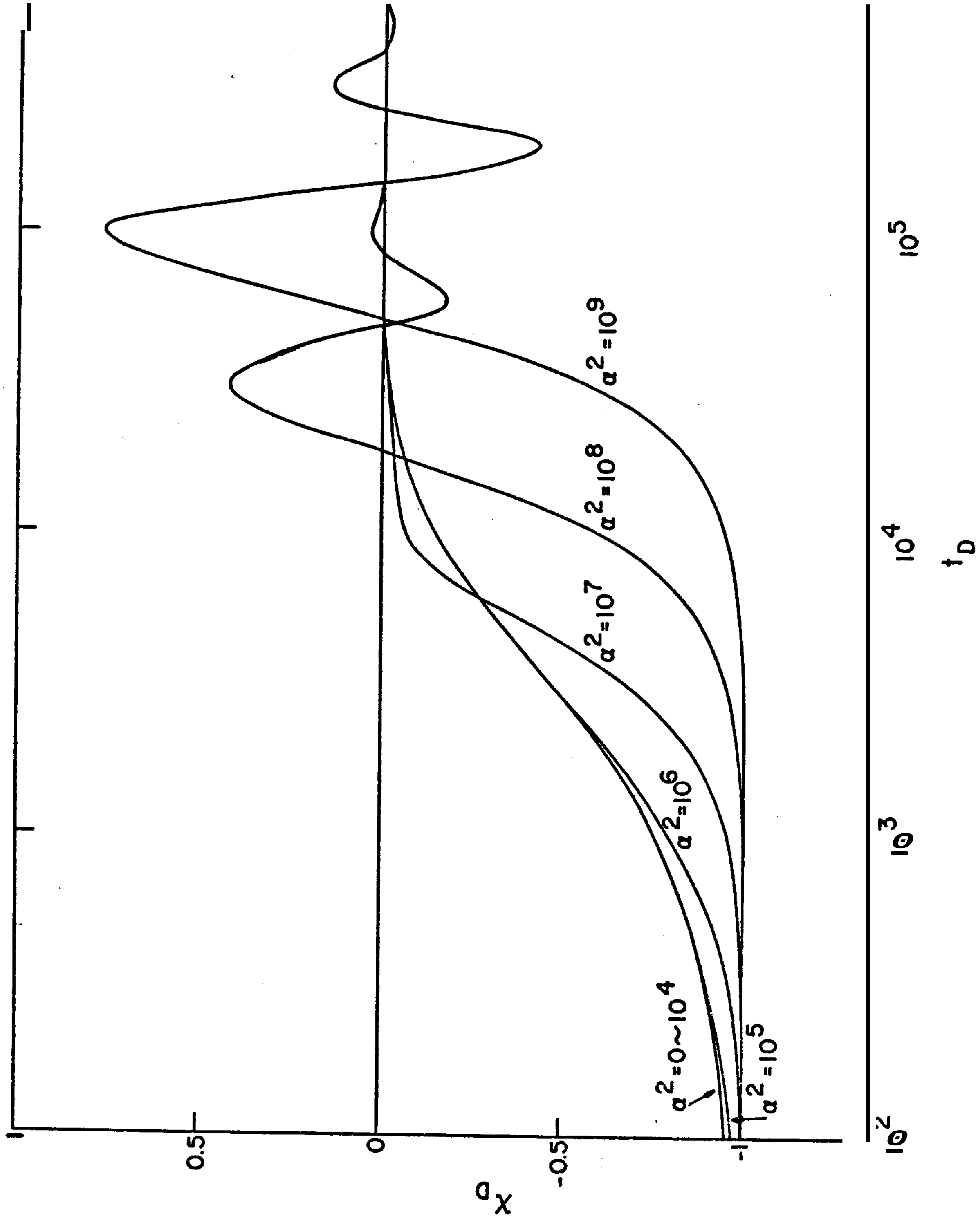


FIG. C-3: UNDAMPED SLUG TEST (Shinohara, Apr. 1980)

The analysis of pressure tests in geothermal reservoirs is often complicated by two-phase effects. This work investigated the effect of a phase boundary at a constant radial distance from the well, produced, for example, by the flashing of a water reservoir during production or by the injection of water into a steam or two-phase reservoir. This configuration may be recognized from a time shift in the buildup (or falloff) semilog straight line. In some cases, the distance to the phase boundary can be estimated by graphing the transition pressure response against time on Cartesian coordinates. Field data (provided by Malcolm Grant of the DSIR) from the Broadlands geothermal field in New Zealand confirmed the applicability of the technique and demonstrated that the injected volume (which is known) may be used with the buildup data to calculate porosity and "swept" volume.

The analysis also indicates the possibility of determining compressibility and permeability contrasts across the phase boundary. This enables estimation of the reservoir porosity and relative permeabilities in the two-phase region. In a few cases, wellbore storage effects can disguise the pressure response and make parameter determination difficult.

It was concluded that:

a. In a reservoir with a radial discontinuity, the mobility ratio may be determined from the relative slopes of the early and long-time semilog straight lines, as in Fig. 4-4.

b. In cases where the hydraulic diffusivity is also discontinuous, the early and long-time semilog straight lines are removed from one another by a distance dependent on the diffusivity ratio (as in Fig. 4-5). This distance may be indeterminable if a mobility ratio also exists.

c. In the case of an infinite reservoir, the position of the discontinuity does not affect the determination of the mobility or diffusivity

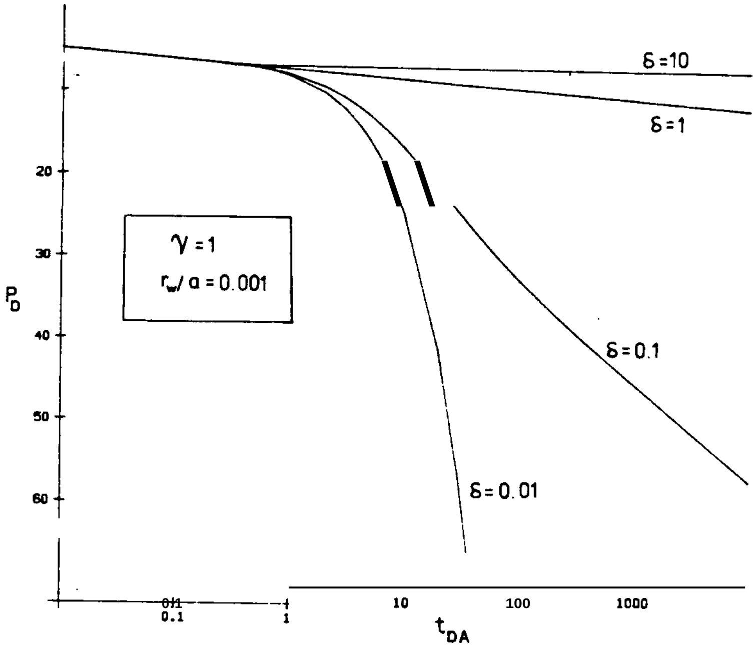


FIG. 4-4: PRESSURE DRAWDOWN RESPONSE AS A FUNCTION OF MOBILITY RATIO. DIFFUSIVITY RATIO 1.

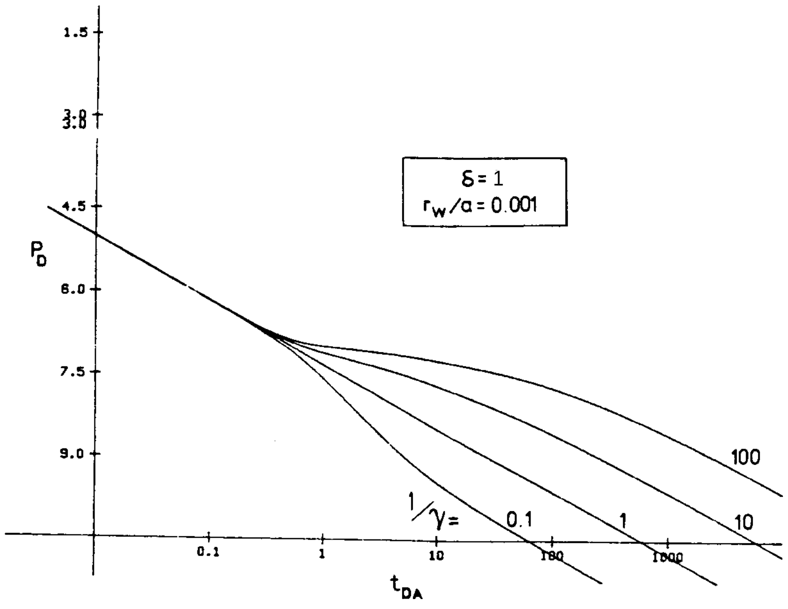


FIG. 4-5: PRESSURE DRAWDOWN RESPONSE AS A FUNCTION OF DIFFUSIVITY RATIO. MOBILITY RATIO 1.

ratios since the pressure response is geometrically similar for physically realistic times.

d. In the case of a finite system, the interception of a boundary may occur before the appearance of the semilog outer region response, in which case the analysis will not be possible.

e. At the end of the first semilog straight line there may exist a period of pseudosteady-state flow that permits the direct calculation of the volume of reservoir "inside" the phase boundary.

Figure 4-6 shows an injection falloff in Broadlands well number BR26 which proved accessible to the new method of analysis.

This work was presented by Horne and Satman (1980), and Horne, Satman, and Grant (1980a). As an informal cooperative program with the New Zealand Department of Scientific and Industrial Research, it will also be presented at the 1980 New Zealand Geothermal Workshop in November 1980, as Horne, Satman, and Grant (1980b).

(e) Internal Well Flows, by M. Castaneda-Oliveras, M.S. Candidate in Petroleum Engineering, and Prof. R.N. Horne.

Experience in analysis of temperature and pressure profiles in geothermal wells has indicated that flow frequently occurs from one production (interval) level to another--even though the well may be shut in at the wellhead. This flow occurs because pressure gradients in the reservoir are frequently greater than hydrostatic, while those in the well are restricted to be hydrostatic unless the fluid is moving. The resulting pressure imbalance causes the well to flow from one level (interval) to another. The recognition of these flows has been the subject of study by Grant (1979) based on a number of observations, including temperature

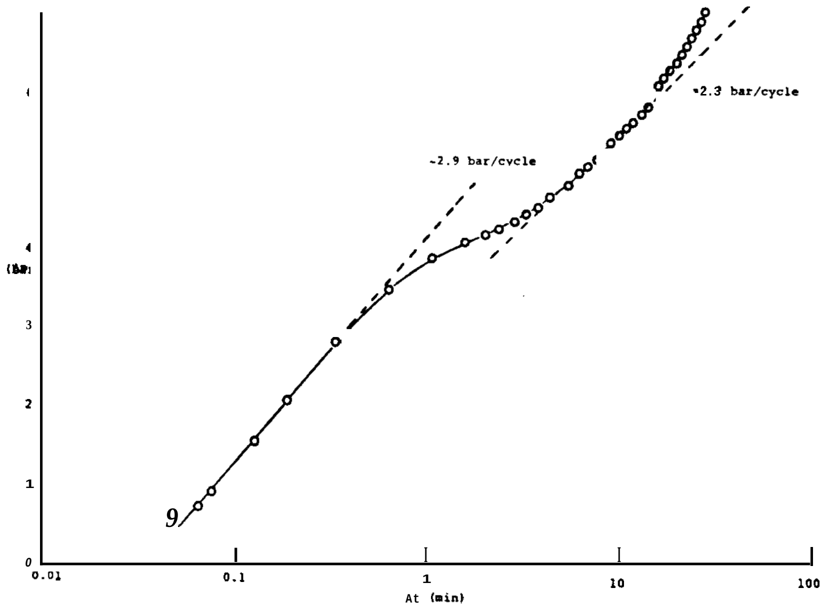


FIG. 4-6: PROJECTION FALLOFF TEST ON WELL BR26. SEMILOG COORDINATES.

profiles during heatup, injection, etc. The present study investigated the difference between the observed pressure gradient in a shut-in well, and the inferred hydrostatic pressure gradient calculated using the simultaneously measured temperature.

Analyzing a shut-in temperature/pressure log from well M-9 at Cerro Prieto, it was determined that internal flow occurred below a depth of 2500 feet since the observed well pressure gradient changed sharply from hydrostatic at this depth (see Fig. *4-7).* This well proved to be an excellent demonstration of the method because it is actually perforated at this depth; thus confirming the conclusion of the pressure gradient comparison.

Further tests using different Cerro Prieto wells are in progress. It is .anticipated that the method may be useful for the one-step recognition of producing levels and internal flows, and may even be able to detect other perturbations such as casing leaks. The rapid evaluation of internal flows is of importance in the correct interpretation of all other pressure tests, and should be considered a first step in any pressure test.

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

This study presents solutions for declining production rates 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-Ley (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 *4-8* shows the

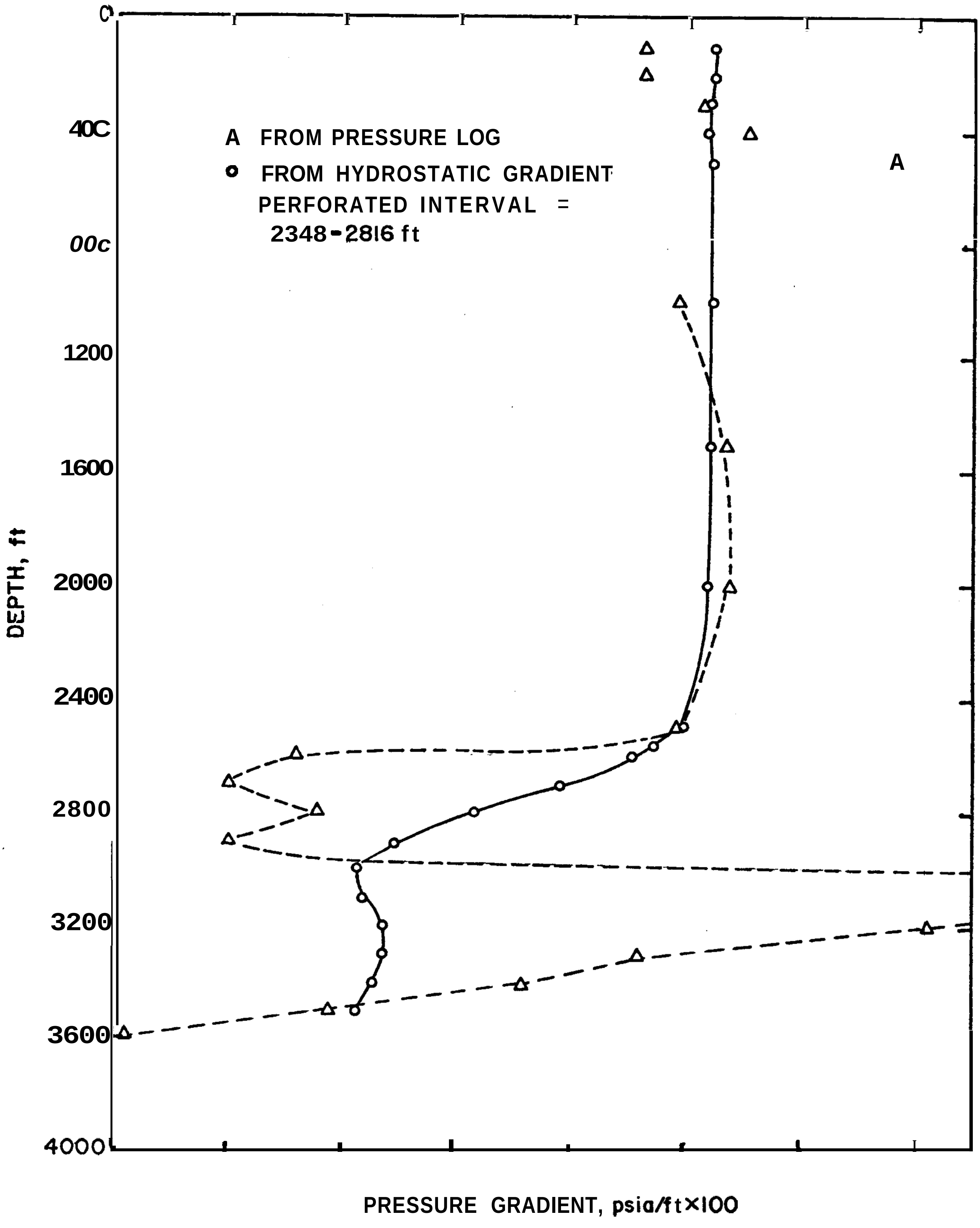


FIG. 4-7: PRESSURE VS DEPTH FOR WELL M-9, CERRO PRIETO, MEXICO

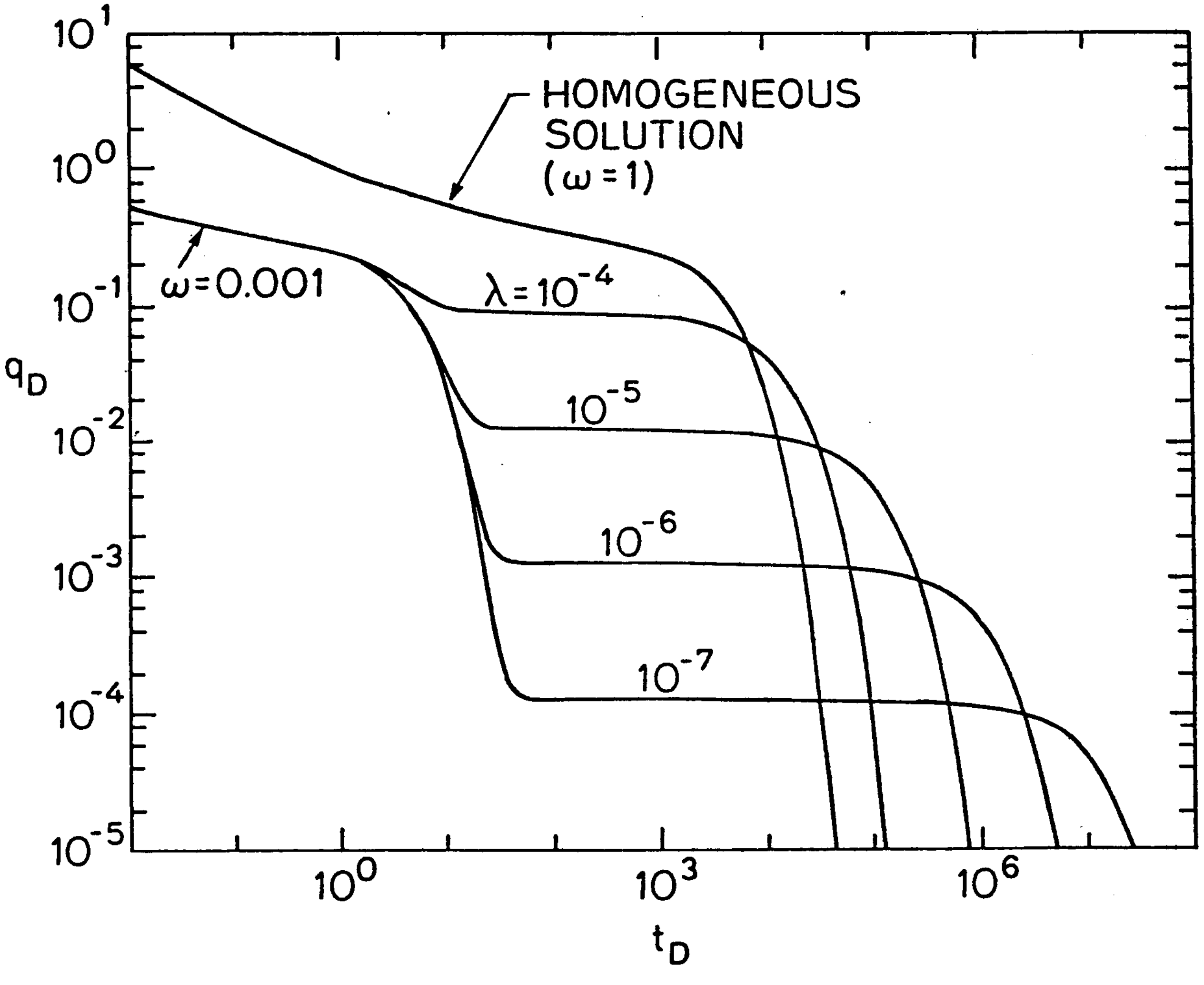


FIG. **4-8:** q_D VS t_D FOR CONSTANT PRESSURE PRODUCTION; CLOSED BOUNDARY (r_{eD} = 50, SKIN FACTOR = 0) results obtained for a finite, no-flow outer boundary. The flowrate shows a rapid decline initially, becomes nearly constant for a period, and then a final decline in rate takes place. The new type-curves of the analytical solutions are graphed in terms of the following dimensionless parameters:

$$q_D = \frac{141.2\ qB\mu}{k_f h(p_i - p_{wf})}$$

$$t_D = \frac{2.637\text{x}10^{-4}\ k_f t}{[(\phi vC)_f + (\phi vC)_m]\mu r_w^2}$$

$$\lambda = \alpha \frac{k_m}{k_f} r_w^2$$

$$\omega = \frac{(\phi vC)_f}{(\phi vC)_m + (\phi vC)_f}$$

where k_f and k_m are fracture and matrix permeabilities, respectively, $\phi_f C_f$ and $\phi_m C_m$ are fracture and matrix porosity-compressibility products, respectively, and a is the interporosity shape factor. The two parameters λ and ω are then new governing dimensionless groups, and the remaining symbols have their standard SPE interpretation.

Figures 4-9 and 4-10 show the solution for a homogeneous system compared to a fractured reservoir. 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 system is considered homogeneous. λ and ω 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

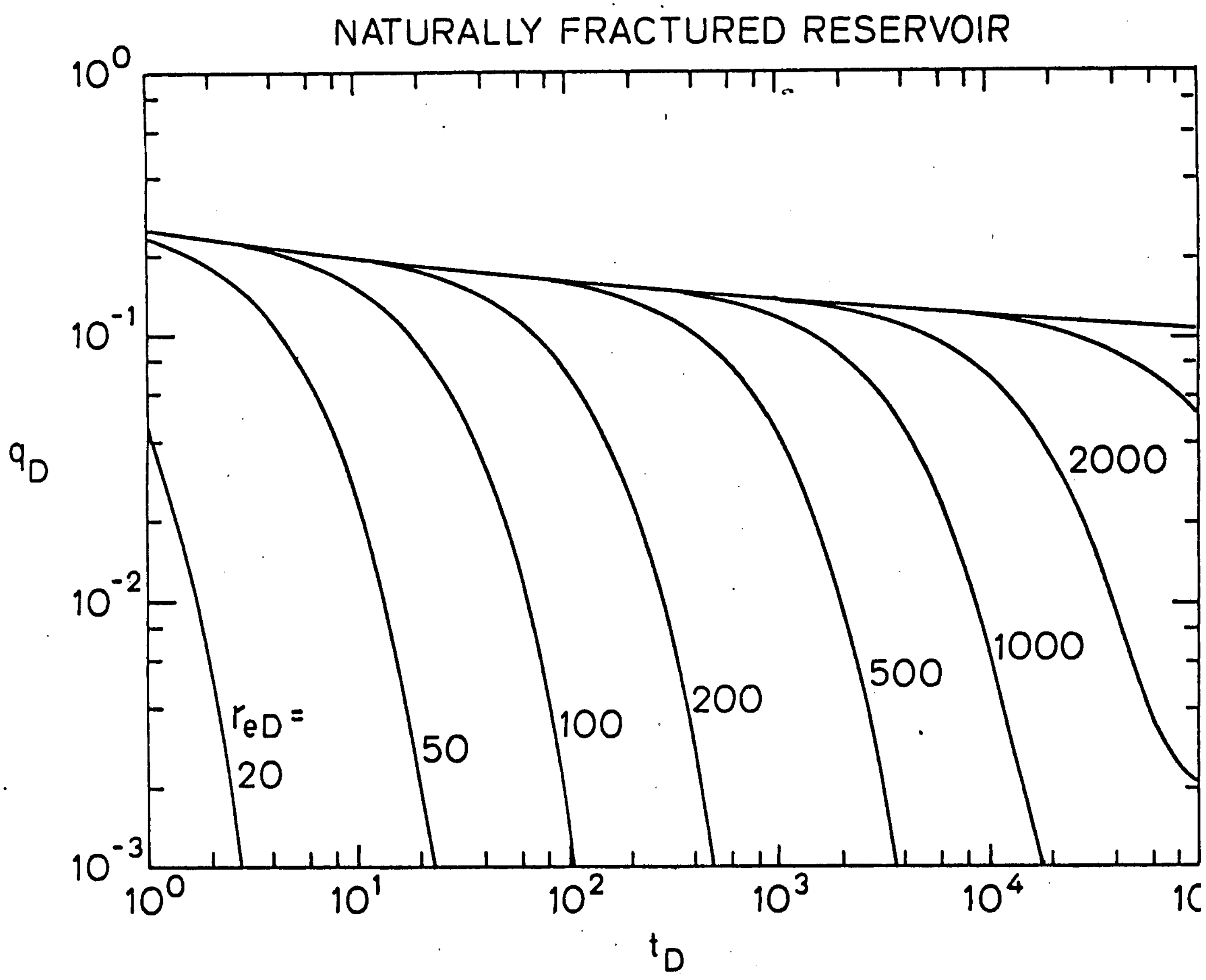


FIG. 4-9: q_D VS t_D FOR CONSTANT PRESSURE PRODUCTION ($\omega = 0.001$, $\lambda = 10^{-9}$, AND SKIN FACTOR = 0)

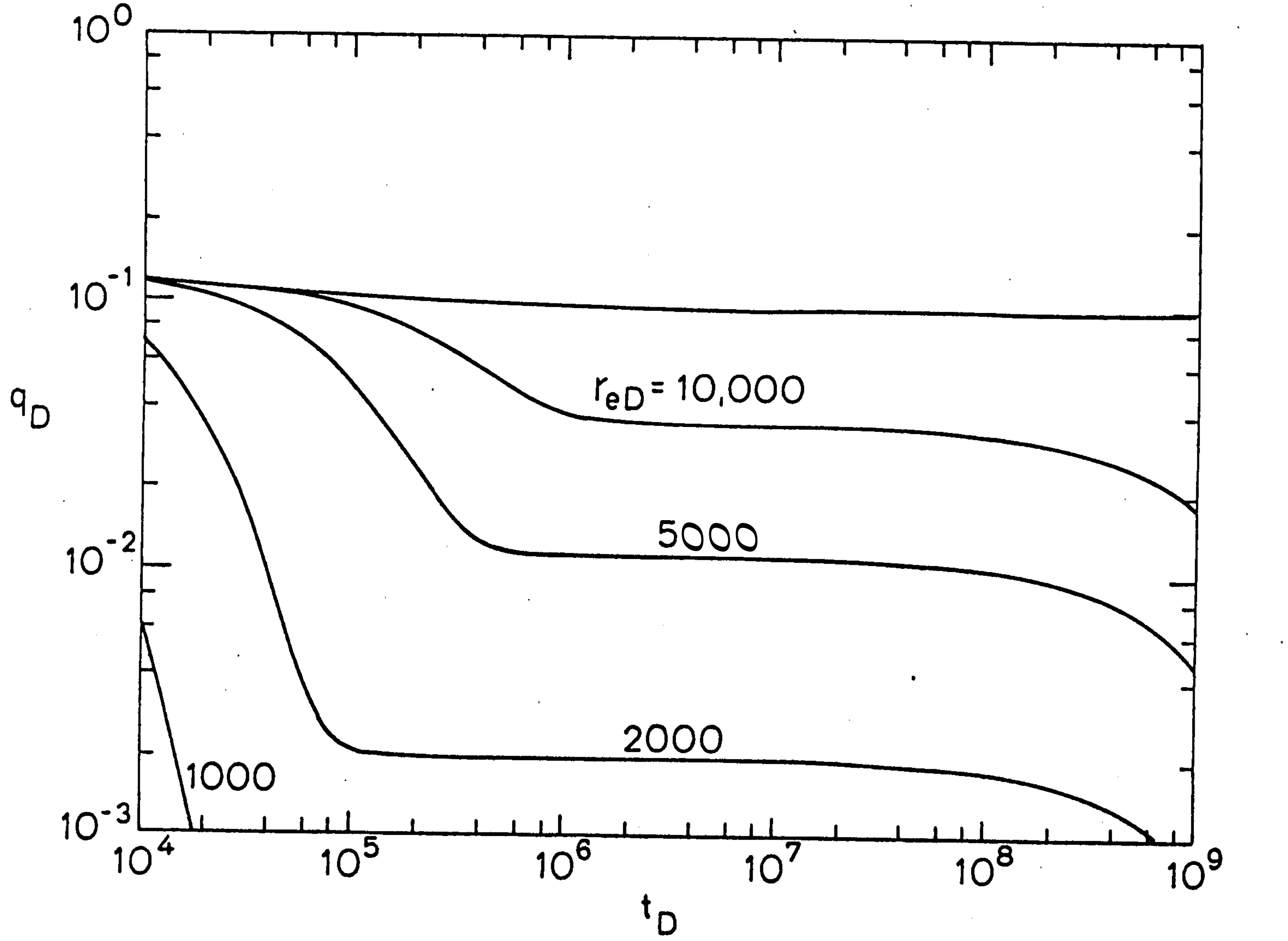


FIG. 4-10: q_D VS t_D FOR CONSTANT PRESSURE PRODUCTION ($\omega = 0.001$, $\lambda = 10^{-9}$, AND SKIN FACTOR = 0)

estimation of reservoir size. Figures 4-11 and 4-12 show another type-curve illustrating the long period of constant flowrate for large r_{eD}'s. Knowing λ and ω, some information about reservoir geometry such as the apparent matrix block dimensions and fracture storativity can be obtained from a type-curve matching.

Portions of this work were presented at the SPE of AIME Annual Fall Meeting in Dallas, Texas, 1980 (Da Prat, Cinco-Ley, and Ramey, 1980). Work will continue in this area.

(g) Temperature-Induced Wellbore Storage Effects, by U. Araktingi, M.S. in Petroleum Engineering, and Prof. H.J. Ramey, Jr.

Wellbore storage is usually attributed to pressure changes occurring in the well. This study found that wellbore storage is also affected by heat transmission and the resulting temperature changes that result from flow in the well. The inner boundary condition for solution of the diffusivity equation for a single-phase well in an infinite radial reservoir was stated so as to include a wellbore storage term depending on temperature changes. Using Laplace transform methods, an exact solution describing the pressure behavior of the fluid in the system was sought. However, due to the form of the term describing temperature changes in the wellbore, it was not to find a simple solution form. Nonetheless, the problem was prepared for solution using numerical inversion. Two-phase systems were also considered, and the inner boundary condition describing such a situation was also derived. Several examples of two-phase systems were described wherein the importance of temperature changes was apparent. An M.S. report was completed by Araktingi (1980). Further work is planned on this important class of problems.

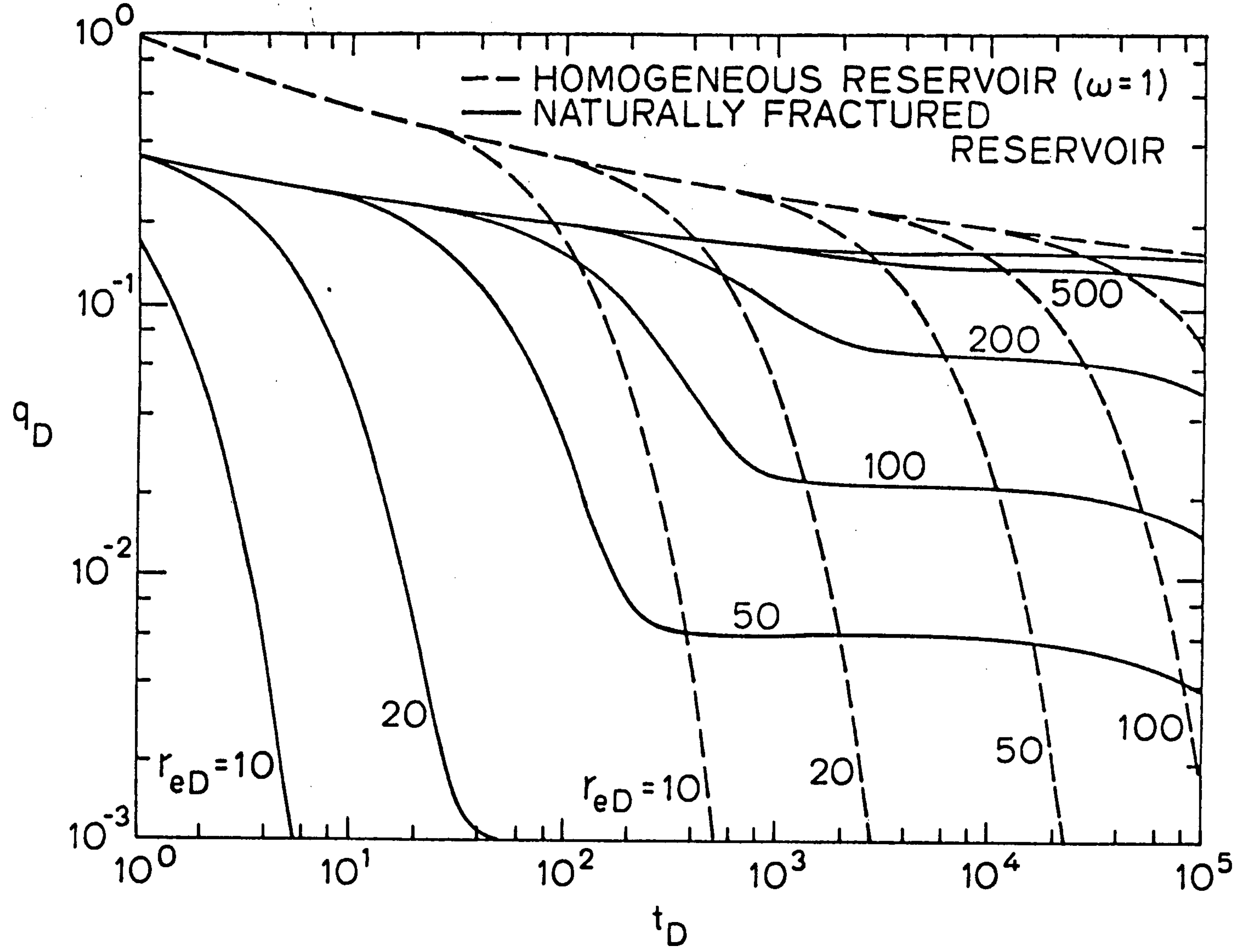


FIG C-11: q_D VS t_D FOR CONSTANT PRESSURE PRODUCTION (ω = 0.01, λ = 5x10^{-6}, AND SKIN FACTOR = 0)

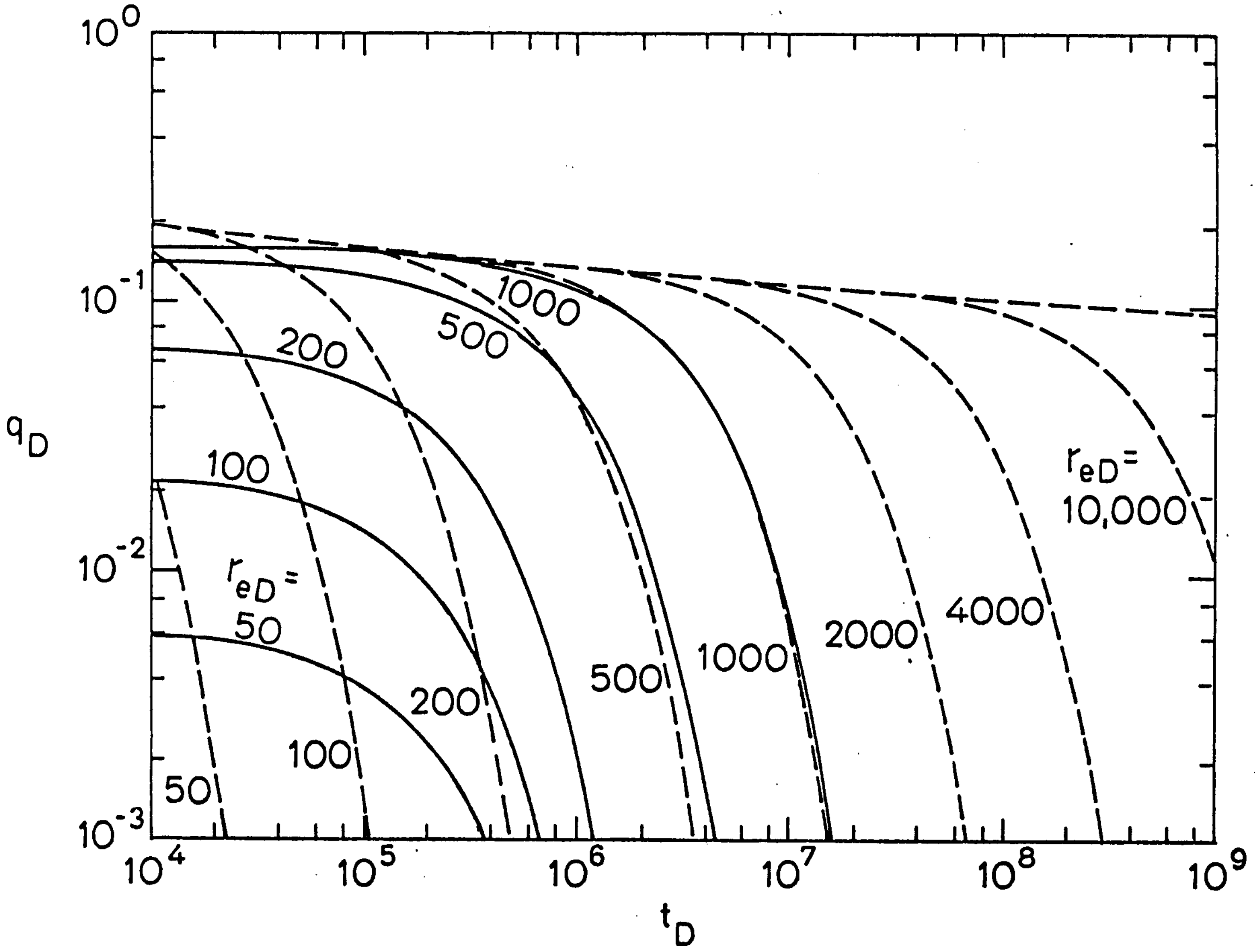


FIG. 4-12: q_D VS t_D FOR CONSTANT PRESSURE PRODUCTION (ω = 0.01, λ = 5x10^{-6}, A SKIN FACTOR = 0)

In addition to the preceding, many other field applications of well test analysis were conducted and reported during the year. Tests were performed and analyzed in the Ching-Shui Field, Taiwan (see Ramey and Kruger, eds., 1979), a new type-curve for interference testing was reported by **Ramey** (3rd LBL Well Testing Workshop, 1980), and planning and analysis of preliminary well tests in the Miravalles Field, Costa Rica, were completed (Ramey, November 1980) during July 1980.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This year was probably the most productive and surprising in the history of the Stanford Geothermal Program. Dr. Hsieh's measurements of the water adsorbed in the micropores of consolidated porous media indicated that a major source of the fluid produced from vapor-dominated geothermal systems could be adsorbed water. His observations lend credence to a theory proposed by Don White and Pat Muffler, and provided additional evidence to the gravitational field changes observed by Denlinger, Isherwood, and Kovach (1979). Furthermore, observations by Macias and Kruger concerning the radon emanating characteristics of the formation and their dependecce on pore liquid also support the view that it is necessary that an adsorbed liquid phase be present in vapor-dominated geothermal systems. Thus two separate parts of the Stanford Geothermal Program suddenly focused on the major problem of production of geothermal steam from vapor-dominated systems: where is the liquid phase? An obvious recommendation is that both works be continued for the coming year to further verify the conclusion suddenly evident during the past year.

A key feature of the Stanford Geothermal Program has been a focus of attention on the behavior of fractured systems. Almost every presently commercially developed geothermal system and proposed geothermal system depends on the existence of fractures. In some cases, the fractures are natural and in others they are induced by such techniques as hydraulic fracturing. Efforts on energy extraction in well test analysis have been aimed in this direction. Perhaps the most important results from this year's effort on fractured systems lie in the area of well test analysis.

Studies on the behavior of reservoir models containing either natural or hydraulically-induced fractures have been significant during this year. Perhaps the most surprising result, however, came from studies of naturally fractured reservoirs. Frequently these systems are produced at essentially constant pressure, and declining rate-time results are observed. Analytic calculations have indicated that for many of these systems, the rate will eventually stabilize and hold at nearly constant rate for decades of time.

A second important result in the study of fractured systems has been the steady development of the one-lump model of heat extraction based on the heat transfer from an equivalent sphere concept developed successively by Hunsbedt, Kuo, and Iregui. The natural continuation is to continue the analytical means for rapid evaluation of commercial resources while improving the experimental data base for the model. Analysis will be attempted in one or more large-scale systems.

Many other surprising results from well test analysis were found during the year. A major new area of study was discovered in an investigation of well inertia and momentum effects for testing of high rate producing wells. Other surprising results were found for analysis of wells with phase boundaries in the near well regions. Problems of this type include the boiling of a hot geothermal liquid while flowing toward a well. Other problems are concerned with reinjection of cold water condensate into a geothermal system. It appears that the pressure-time data of such well tests include information heretofore unsuspected. The most important of this information concerns the volume of the near well region.

The research efforts involving radon as an in-situ tracer blossomed during the current year. Three engineering theses were developed, involving the use of radon transient analysis for reservoir characterization, transect analysis for reservoir structural and flow properties, and emanation studies for evaluating release mechanisms of chemical components with the produced geo fluids. Another important realization was the large number of laboratories adapting radon measurement techniques for their specific purposes. Future efforts should consider not only the in-situ radon as a tracer, but its relation to other released components and its relation as a mass transient tracer to pressure transient behavior under well flow-rate changes and long-term production.

Another important area for study concerning well test analysis concerns internal well flows from one interval to another, and temperature-induced wellbore storage effects. It was discovered that geothermal well temperature depth profile is frequently affected to an extraordinary degree by flow from one interval to another. Another major effect concerns wellbore storage effects caused by temperature changes due to heat transmission. Both studies constitute the new areas for investigation. Work conducted during the year perhaps reveals more problems than were solved.

From the preceding, it is clear that many problems have been solved during the last year, and many other problems identified. The main emphasis of the Stanford Geothermal Program will continue to be research focused directly towards supporting the development of field operations. It is recommended that all existing programs continue throughout the coming year with modifications discussed.

One of the most important aspects of the Stanford University Geothermal Program may only be inferred from the preceding. A large number of researchers are involved in the various aspects of the program discussed in this report. Since the Stanford Geothermal Program is the second largest research effort in the petroleum engineering department, the impact of this program on the students graduating from Stanford is not easily assessed. Many students who enter our program intending to follow gas and oil production become intrigued by geothermal production, and enter the geothermal industry upon graduation. In addition, visiting scholars from geothermal operations throughout the world have been invited to Stanford to attend graduate courses in geothermal reservoir engineering. In recent years, visiting scholars from France, the Soviet Union, Taiwan, Italy, and Mexico have attended this program. During the coming year, inquiries have been received from candidates from The People's Republic of China and Costa Rica. One of the most important products of the Stanford Geothermal Program is that it continues to train engineers entering the geothermal industry worldwide. Stanford University graduates are district engineers for all of the Union Oil Geothermal operations internationally. We feel that the very best mode of technology transfer is via trained engineers who carry the technology to the industry. We are pleased that the staff of engineer Research Associates on the Stanford Geothermal Program for the 1980-81 academic are the most talented that we have used throughout the history of this program.

There are many other important aspects to this program not evident in the preceding. One of the most important parts of the Stanford Geothermal Program is the annual December Workshop on Geothermal Reservoir Engineering. The fifth annual meeting was held in December 1979, and the Proceedings issued shortly thereafter. The Sixth Annual Workshop on Geothermal Reservoir Engineering will be held at Stanford in December 1980. This meeting is regularly attended by approximately 100 members of the international geothermal community. The Proceedings of this meeting have become one of the primary technical documents of geothermal reservoir engineering. In addition, a geothermal seminar is held weekly throughout the academic year. The program for the 1979-80 academic year is listed in the appendix. Speakers from both within and beyond the the Stanford Geothermal Program present seminars during this program, and the seminars are widely attended by members of the geothermal community in the California area.

It is pleasant to see the international geothermal energy industry growing, and we look forward to making our contribution to this effort during the coming years.

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Ehlig-Economides, C., and Ramey, H.J., Jr.: "Constant Pressure Testing for Geothermal Wells," Proc., New Zealand Geothermal Workshop, Auckland, New Zealand (Nov. 1979c), 255.

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

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Ramey, H.J., Jr.: "The Miravalles Geothermal Reservoir, Costa Rica," Stanford Geothermal Program Seminar, November 6, 1980.

Ramey, H.J., Jr., Agarwal, R.G., and Martin, I.: "Analysis of 'Slug Test' or DST Flow Period Data," J. Can. Pet. Tech. (July-Sept. 1975), 1-11.

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APPENDIX A: PARTICIPANTS IN THE STANFORD GEOTHERMAL PROGRAM

PRINCIPAL INVESTIGATORS:

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

PROGRAM MANAGERS:

Christine Ehlig-Economides	Petroleum Engineering
Ian Donaldson (Sept. 1980)	Petroleum Engineering

ASSOCIATED FACULTY:

William E. Brigham	Petroleum Engineering
Heber Cinco-Ley	University of Mexico
George M. Homsy	Chemical Engineering
Roland N. Horne	Petroleum Engineering
Anstein Hunsbedt	Civil Engineering
A. Louis London	Mechanical Engineering
Frank G. Miller	Petroleum Engineering
Drew Nelson	Mechanical Engineering
Subir Sanyal	Petroleum Engineering
Abdurrahman Satman	Petroleum Engineering

RESEARCH ASSISTANTS:

Petroleum Engineering

Morse Jeffers
Mark Miller
Ramona Rolle
Renne Rolle
Abraham Sageev
Kiyoshi Shinohara
Mario Castaneda
Chih-Hang Hsieh
Giovanni Da Prat
Fernando Rodriguez
Udo Araktingi

Civil Engineering

Luis Macias-Chapa
Kazuichi Satomi
Lewis Semprini

Mechanical Engineering

John Sullivan
Rajiv Rana

APPENDIX B: 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.

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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 Relatfve 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," 1979.
SGP-TR-39	Kiyoshi Shinohara, "A Study of Inertial Effect in the Wellbore in Pressure Transient Well Testing," 1980.
SGP-TR-40	Proceedings: Fifth Workshop on Geothermal Reservoir Engineering, December 12-14, 1979.
SGP-TR-41	Kern H. Guppy, "Non-Darcy Flow in Wells with a Finite Conductivity Vertical Fracture," Spring 1980.

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Warren, G.J.: "Radon Transients in Vapor-Dominated Geothermal Reservoirs," Engineer's Thesis, Department of Civil Engineering, Stanford University, Stanford, California, 1979.

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

APPENDIX D: TRAVEL AND TECHNICAL MEETING ATTENDANCE

Geothermal Resources Council Annual Meeting, Reno, Nevada, Sept. 1979.

Baza, J.
Castanier, L.
Ehlig-Economides, C.
Macias, L.
Roux, B.
Sanyal, S.K.
Satman, A.

Annual Fall Meeting, Society of Petroleum Engineers, Las Vegas, Nevada, Sept. 1979.

Brigham, W.E.
Castanier, L.
Ehlig-Economides, C.
Marsden, S.S.
Miller, F.G.
Ramey, H.J., Jr.
Sanyal, S.K.
Satman, A.

1979 New Zealand Geothermal Workshop, Auckland, New Zealand, Oct. 1979.

Ehlig-Economides, C.

Well Testing Symposium, Lawrence Berkeley Laboratory, Mar. 1980.

Brigham, W.E.
Castanier, L.
Horne, R.N.
Miller, F.G.
Ramey, H.J., Jr.
Sanyal, S.K.

50th Annual California Regional Meeting, Society of Petroleum Engineers, Pasadena, California, Apr. 1980.

Brigham, W.E.
Ehlig-Economides, C.
Gobran, B.
Horne, R.N.
Ramey, H.J., Jr.
Roux, B.
Sanyal, S.
Semprini, L.

Field Visits to Cerro Prieto Field, Mexico (various dates)

Castaneda, M.
Horne, R.N.
Miller, F.G.
Ramey, H.J., Jr.
Semprini, L.

Electric Power Research Institute Geothermal Conference, Monterey, California, June 1980.

Horne, R.N.
Kruger, P.
Semprini, L.

ASME-AIChE Heat Transfer Meeting, Orlando, Florida, July 1980.

Horne, R.N.

Geothermal Resources Council Annual Meeting, Salt Lake City, Utah, September 1980.

Castanier, L.	Kruger, P.
Horne, R.N.	Miller, F.G.

APPENDIX E: SGP SPONSORED MEETINGS

FIFTH ANNUAL WORKSHOP ON GEOTHERMAL RESERVOIR ENGINEERING

STANFORD UNIVERSITY

DECEMBER 12-14, 1979

PROGRAM

WEDNESDAY, DECEMBER 12 1979

0800 REGISTRATION, TRESIDDER UNION, Upstairs Lobby

0900 SESSION I - OVERVIEW Chairman: Paul Kruger (Stanford Geothermal Program)

R. A. Gray - Department of Energy

J. H. Howard and W. J. Schwarz - Lawrence Berkeley Laboratory

H. J. Ramey, Jr. - Stanford Geothermal Program

V. Roberts - Electric Power Research Institute

1030 Coffee

1040 SESSION 11 - PRESSURE TRANSIENT ANALYSIS Chairmen: Frank G. Miller (SGP) and Manuel Nathenson (USGS)

D. Goldman and D. M. Callan (EG&G Idaho, Inc.), "Testing and Reservoir Parameters in Geothermal Wells at Raft River, Idaho"

U. Ahmed, K. M. Wolgemuth, A. S. Abou-Sayed, A. H. Jones (Terra Tek), "Injection Capability of the Raft River Geothermal Site"

* P. F. Bixley (MWD, N.Z.) and M. A. Grant (DSIR, N.Z.), "Reinjection Testing at Broadlands"

M. Saltuklaroglu (ELC, Italy), "Interference Effect of Producing Wells on Observation Wells in a Geothermal Field"

M. Saltuklaroglu (ELC), "Use of Observation Well Data in Determining Optimum Well Spacing and Recharge in a Geothermal Field (Cerro Prieto)"

1200 **LUNCH,** TRESIDDER UNION, Main Lounge (Room 281)

1320 SESSION 11, continued,

C.R.Y. Chang (CPC, Taiwan) and H. J. Ramey, Jr. (SGP), "Well Interfarence Test in Chingshui Geothermal Field"

* G. Bodvarsson (Oregon State Univ.), "Capacitive Perturbations in Well Interference Testing"

* Will not be presented.

M. J. Economides and E. L. Fehlberg (Shell), "Two Short-Time Buildup Test Analyses for Shell's Geysers Well D-6, a Year Apart"

A. F. Moench (USGS) and G. Neri (ENEL), "Analysis of Gabbro 1--Steam Pressure Buildup Test"

K. Y. Shen and C.R.Y. Chang (CPC, Taiwan), "Pressure Buildup Tests of Well CPC-CS-4T, Chinshui Geothermal Field"

H. N. Fisher and J. W. Tester (LASL), "An Analysis of the Pressure Transient Testing of a Man-Made Fractured Geothermal Reservoir"

1500 Coffee

1520 R. F. Harrison and C. K. Blair (Terra Tek) and D. S. Chapman (Univ, of Utah), "Development and Testing of a Small Moderate Temperature Geothermal system"

J. Hanson (LLL), "Tidal Pressure Response Well Testing at the Salton Sea Geothermal Field, California, and Raft River, Idaho"

M. J. Economides (Shell), "Shut-In and Flowing Bottom Hole Pressure Calculation for Geothermal Steam Wells"

M.C.T. **Kuo** (Occidental), "A Portable Geothermal Well Testing System"

1730-1830 Hosted Cocktails, FACULTY CLUB, The Red Lounge

THURSDAY, DECEMBER 13, 1979

0830 SESSION III - MODELING Chairmen: John H. Howard (LBL) and Subir K. Sanyal (SGP)

G. Antonelli and P. E. Liguori (ELC), "A Power Plant Oriented Geothermal Simulation Model"

J. W. Pritchett (SSS), "A Semi-Analytic Description of Two-Phase Flow near Production Wells in Hydrothermal and Geopressured Reservoirs"

K. Pruess and R. C. Schroeder (LBL), "Geothermal Reservoir Simulations with SHAFT79"

G. F. Pinder and L. Abriola (Princeton Univ.), "Block Response to Beinjection in a Fractured Geothermal Reservoir"

0950 Coffee

1015 S. K. Sanyal and S. Brown (SGP), L. Fandriana (Amoco), and S. Juprasert (LBL), "Sensitivity Study of Variables Affecting Fluid Flow in Geothermal Wells"

E. J. Zais (Zais and Assoc.), "A Technical Analysis of Geothermal Production Data by Decline Curve Methods"

T. D. Riney (SSS), "A Preliminary Model of the East Mesa Hydrothermal System"

M. L. Sorey (USGS) and L. F. Fradkin (DSIR, New Zealand), "Validation and Comparison of Different Models of the Wairakei Geothermal Reservoir"

1200 LUNCH, TRESIDDER UNION, Main Lounge (Room 281)

1320 SESSION III, continued

T. N. Narasimhan and K. P. Goyal (LBL), "A Preliminary Simulation of Land Subsidence at the Wairakei Geothermal Field in New Zealand"

W. E. Brigham (SGP) and G. Neri (ENEL), "Preliminary Results on a Depletion Model for the Gabbro Zone (Northern Part of Larderello Field)"

1420. Coffee

1500 PANEL DISCUSSION: Geothermal Reservoir Models--Simulation vs. Reality

Discussants: W. E. Brigham (SGP), C. W. Morris (Republic Geothermal), G. F. Pinder (Princeton Univ.), Karsten Pruess (LBL), M. L. Sorey (USGS)

* I. Donaldson (DSIR) and M. L. Sorey (USGS), "The Best Uses of Numerical Simulators"

1800 RECEPTION (Hosted Cocktails) and BANQUET - FACULTY CLUB

FRIDAY, DECEMBER 14, 1979

0820 SESSION IV - FIELD DEVELOPMENT Chairman: George A. Frye (Aminoil)

H. Alonso E., B. Dominguez A., R. Molinar C. (CFE), M. J. Lippmann, R. E. Schroeder, and P. A. Witherspoon (LBL), "Update of Reservoir Engineering Activities at Cerro Prieto"

P. Atkinson and M. S. Gulati (Union Geothermal), "Status Report on Geothermal Development in the Valles Caldera, New Mexico"

* M. A. Grant (DSIR), "Interpretation of Downhole Measurements at Baca"

S. C. Chiang, J. J. Lin, C.R.Y. Chang, and T. M. Wu (CPC, Taiwan), "A Preliminary Study of the Chingshui Geothermal Area, I-Lan, Taiwan"

P. H. Messer (Philippines Geothermal, Inc.), "Injection Performance in the Bulalo Geothermal Field, Makiling-Banahao Area, Philippines"

A. Truesdell (USGS), "Aquifer Boiling May Be Normal in Exploited High-Temperature Geothermal Systems"

1000 Coffee

1020 SESSION V - RESERVOIR PHYSICS

H. Ucok, I. Ershaghi (USC), G. R. Olhoeft (USGS), and L. L. Handy (USC), "Resistivity of Brine Saturated Rock Samples at Elevated Temperatures"

D. V. Nelson and A. Hunsbedt (SGP), "Progress in Studies of Energy Extraction from Geothermal Reservoirs"

P. Kruger, L. Macias C., and L. Semprini (SGP), "Radon Transect and Emanation Studies"

* N. E. Whitehead (DSIR), "Radon 22 Measurements at Wairakei, Broadlands and Ngawha"

MOVIE: "GEOTHERMAL ENERGY" - Union Oil Company of California

1200 LUNCH, TRESIDDER UNION, Main Lounge (Room 281)

1320 SESSION VI - PRODUCTION ENGINEERING Chairman: William E. Brigham (SGP)

S. K. Sanyal (SGP), L. Wells, and R. E. Bickham (SSS), "Fracture Detection from Geothermal Well Logs"

P. Cheng and M. Karmarkar (Univ. of Hawaii), "The Application of Two-Phase Critical Flow Models for the Determination of Geothermal Wellbore Discharge Characteristics"

* Will not be presented.

G. Bodvarsson (Oregon State Univ.), "Elastomechanical Phenomena and the Fluid Conductivity of Deep Geothermal Reservoirs and Source Regions"

C. Y. Chiang and C.R.Y. Chang (CPC, Taiwan), "Application of the Horner Method to the Estimation of Static Reservoir Temperature during Drilling Operations"

B. Roux and S. K. Sanyal (SGP), "Improved Approach to Estimating True Reservoir Temperature from Transient Temperature Data"

* R. James (DSIR), "Reinjection Strategy"

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* Will not be presented.

STANFORD GEOTHERMAL PROGRAM
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SEMINAR SCHEDULE

AUTUMN QUARTER 1979 ROOM 113 MITCHELL BUILDING THURSDAYS 1:15-2:30 p.m.

Date	Topic	Speaker
Oct. 11	Organizational Meeting	H. J. Ramey
Oct. 18	A Depletion Model for the Gabbro Zone, Larderello, Italy	W. E. Brigham
Oct. 25	Fracture Detection from Geothermal Well Logs	S. K. Sanyal
Nov. 1	Laboratory and Field Studies of Radon Transport	L. Macias, L. Semprini
Nov. 8	Calculation of Performance of Steam Wells	J. R. Baza
Nov. 15	An Improved Method for Estimating True Reservoir Temperature from Transient Temperature Data	B. P. Roux
Nov. 29	Application of Unsteady State Overall Heat Transfer Coefficient Concept to Geothermal Injection Wells	A. Satman
Dec. 7	A Review of the New Zealand Geothermal Conference	C. A. Ehlig-Economides

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SEMINAR SCHEDULE

Winter Quarter 1979/80
Room B67, Mitchell Building
Thursdays, 1:15 to 2:30 pm

DATE	TOPIC	SPEAKER
JAN. 24	GEOTHERMAL EXPLORATION AND WELL TESTING IN TAIWAN	CARL CHANG, CHINESE PETROLEUM CORP.
JAN. 31	RADIOISOTOPE AND STABLE ISOTOPE TRACER STUDIES AT THE WAIRAKEI GEOTHERMAL FIELD, NEW ZEALAND	ROLAND HORNE, STANFORD UNIVERSITY
FEB. 7	A PRELIMINARY SIMULATION OF LAND SUBSIDENCE AT THE WAIRAKEI GEOTHERMAL FIELD, NEW ZEALAND	T.N. NARASIMHAN, LBL
FEB. 14	STATUS OF THE ENEL GEOTHERMAL PROGRAM AND A REPORT ON THE RECENT TRIP TO ITALY	MICHAEL ECONOMIDES, F. G. MILLER,. STANFORD UNIVERSITY
FEB. 21	A SEMI-ANALYTIC DESCRIPTION OF TWO-PHASE FLOW NEAR PRODUCTION WELLS IN HYDROTHERMAL AND GEOPRESSURED RESERVOIRS	J.W. PRITCHBTT, SYSTMS, SCIENCE, AND SOFTWARE
FEB. 28	RISK ASSESSMENT MODELING FOR GEOTHERMAL DEVELOPMENT	K. GOLABI, WOODWARD & CLYDE CONSULTANTS
MAR. 7	MODELING HYDROTHERMAL SYSTEMS IN THE BASIN AND RANGE PROVINCE	MIKE SOREY, U.S.G.S.

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Reply to:
Dr. C. Ehlig-Economides
Petroleum Engineering Department

SEMINAR SCHEDULE

Spring Quarter, 1980 Room B67 Mitchell Building Thursday 1:15-2:30

Date	Topic	Speaker
Apr 17	Injection Capability at the Raft River Geothermal Site	A. Abou-Sayed Terra Tek, Inc.
Apr 24	The Tiwi Geothermal Reservoir, Philippines	P. Messer Union Geothermal
May 1	Nonlinear Analysis of Two-Phase Geothermal Well Tests	Mike O'Sullivan U. of Auckland, N.Z.
May 8	Chemical Changes in Cerro Prieto Reservoir Fluids due to Exploitation	Al Truesdell U.S.G.S.
May 15	Geothermal Reserve Evaluation	Jack Howard U.S.G.S.
May 22	Review of Magma Power Company's East Mesa Geothermal Binary Electric Generating Plant	Tom Hinrichs Magma Power
May 29	Assessment of Low Temperature Geothermal Resources of the U.S.	Marshall Reed U.S.G.S.