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# GEOTHERMAL RESERVOIR ENGINEERING RESEARCH AT STANFORD UNIVERSITY

Third Annual Report for the Period
October 1, 1982–September 30, 1983

By
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September 1983

Work Performed Under Contract No. AT03-80SF11459

Stanford University
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# GEOTHERMAL RESERVOIR ENGINEERING RESEARCH

# AT STANFORD UNIVERSITY

THIRD ANNUAL REPORT

DOE CONTRACT NO. DE-AT03-80SF11459

FOR THE PERIOD

OCTOBER 1, 1982 THROUGH SEPTEMBER 30, 1983

Principal Investigators:

H.J. Ramey, Jr., P. Kruger, R.N. Horne, W.E. Brigham, F.G. Miller

September 1983

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

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PREFACE

The Stanford Geothermal Program was initiated under grants from the National Science Foundation in 1972 and has continued under contracts from the Energy Research and Development Administration and the subsequent Department of Energy since 1977. This publication is the Third Annual Report to the Department of Energy under Contract DE-AT03-80SF11459 which was initiated in fiscal year 1981. The report covers the period from October 1, 1982 through September 30, 1983.

The Stanford Geothermal Program conducts interdisciplinary research and training in engineering and earth sciences. The central objective of the Program is to carry out research in geothermal reservoir engineering techniques that will be useful to the geothermal industry. A parallel objective is the training of geothermal engineers and scientists for employment in the industry. The research is focused toward accelerated development of hydrothermal resources through the evalution of fluid reserves, and the forecasting of field behavior with time. Injection technology is a research area receiving special attention. The Program is geared to maintain a balance between laboratory studies and matching field applications.

Technology transfer is an integral part of the Stanford Geothermal Program. Major activities include a Geothermal Reservoir Engineering Workshop held annually in December, and weekly Seminars held throughout the academic year. The Workshop has produced a series of Proceedings that are a prominent literature source on geothermal energy. The Program publishes technical reports on all of its research projects. Research findings are also presented at conferences and published in the literature.

Geothermal reservoir engineering research at Stanford has gained considerable breadth through the Program's international cooperative projects. There are two formal research agreements with Italy and Mexico, and several colleague-to-colleague cooperative projects. These international projects provide a wide spectrum of field experience for Stanford researchers, and produce field data with which to develop and test new geothermal reservoir engineering techniques.

The successful completion of the Stanford Geothermal Program's objectives depends on significant help and support by members of federal agencies, the geothermal industry, national laboratories and University programs. These are too many to acknowledge by name. The major financial contribution to the Program is the Department of Energy through this contract. We are most grateful for this support and for the continued cooperation and help we receive from the agency staff.

Henry J. Ramey, Jr.

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## INTRODUCTION

The Stanford Geothermal Program in fiscal year 1983 was divided into nine task areas as defined in the Department of Energy contract. Tasks 1-2 were carried out within the Civil Engineering Department, Tasks 3-6, 7 and 9 within the Petroleum Engineering Department, and Task 8 within the Geophysics Department. A sub-task of Task 7 was carried out within the Civil Engineering Department. The Stanford Geothermal Program tasks are interdisciplinary research and training in engineering and earth sciences.

Task 1. Heat Extraction from Hydrothermal Reservoirs--The long-term commercial development of geothermal resources for power production will depend on optimum heat extraction from hydrothermal resources. The work in this task has involved a combination of physical and mathematical modeling of heat extraction from fractured geothermal reservoirs. Experiments have been carried out in a rechargeable laboratory reservoir with comparative testing of alternative modes of heat and fluid production. The results are leading to a useful mathematical method for early evaluation of the potential for heat extraction in newly developing geothermal resources.

Task 2. Noncondensable Gas Reservoir Engineering--Radon and other noncondensable gases in geothermal fluids can be used as natural in-situ tracers for assessing thermodynamic conditions and structural features of geothermal reservoirs. Measurements of radon mass transients have been shown to be a complementary method to pressure transient analysis in single- and two-phase geothermal reservoirs. Current work in this task aims at relating radon measurements to two-phase conditions in reservoirs through analysis of noncondensable gas partitioning during two-phase flow to the wellhead. The results should be useful for assessing the potential for thermodynamic changes during production and the effect of recharge and structural features of the reservoir on future production.

Task 3. Well Test Analysis and Bench Scale Experiments--Well test analysis offers a rapid way to perform an initial assessment of geothermal systems. Well testing includes both single-well pressure drawdown and buildup testing, and multiple-well interference testing. The development of new well testing methods continued to receive major emphasis during the year. Work in this task included projects on composite reservoirs (water injection into a vapor-dominated system or production from a steam zone in a liquid-dominated system), and slug testing in double-porosity reservoirs. The total system compressibility of reservoirs that produce under a two-phase condition was investigated. Improving understanding of the physical processes occurring in geothermal reservoirs is an important objective of the Stanford Geothermal Program. A balance between theoretical and experimental studies is sought. The goal is to develop new methods for observing reservoir behavior and to test these in the field. Bench-scale experiments are performed to determine fundamental flow characteristics of fluids and to provide a balanced university-based research. Three main pieces of equipment are involved: a large core and a small core permeameter, and BET adsorption apparatus. Work in this task included two projects on relative permeability functions: (1) using the large core apparatus and, (2) a centrifuge.

Tasks 4/5: Field Applications and Testing--The Stanford Geothermal Program takes part in several cooperative projects through both formal and informal agreements. The main objective of these agreements is the application and testing of new and proven reservoir engineering technology using nonproprietary field data and geothermal wells made available by steam field operators. Stanford has two formal cooperative agreements with foreign agencies. These are the DOE-ENEL cooperation with Italy and SGP-IIE cooperation with Mexico. The Italian work during the year dealt with the water adsorption and deliverability behavior of vapor-dominated systems. The Mexican work dealt with the production behavior of wells in liquid-dominated systems; their two-phase flow behavior and wellbore scale deposition. Cooperative work with Mexico was also carried out in Task 7 on reinjection technology. The interaction between academic research and field applications has proved valuable to geothermal reservoir engineering studies at Stanford.

Task 6: Workshop, Seminars and Technical Information--Technology transfer is the main purpose of this task. As more people become involved in the exploration, development and production of geothermal energy, the need for dissemination of reservoir engineering knowledge and information becomes greater. The annual Workshop on Geothermal Reservoir Engineering has been held at Stanford University since 1975. The Workshop is attended by more than 100 scientists and engineers actively involved in geothermal energy developments in the U.S. and worldwide. Weekly geothermal energy Seminars are held at Stanford throughout the academic year. The Seminars are open and are attended by Stanford faculty and students, and individuals from geothermal companies and institutions in the San Francisco area. The appendices to this annual report describe some of the activities of the Stanford Geothermal Program that result in interactions with the geothermal community. These occur in the form of technical reports, presentations at technical meetings, and publications in the open literature.

Tasks 7/9: Reservoir Engineering Aspects of Reinjection--The reinjection of spent geothermal fluids has rapidly become a pressing research problem in geothermal reservoir engineering. Although reinjection has the potential of maintaining reservoir pressure, world-wide experience from liquid-dominated fields indicates that rapid thermal breakthrough can occur. The cold fluid short-circuits from the injection well to production wells along high conductivity fractures. The task on reinjection concerns the flow of fluids in fractures. A powerful method for investigating such flow is the use of external tracers. Field tracer tests were carried out during the year at Klamath Falls, Oregon, and Los Azufres, Mexico.

Task 8: Monitoring of Vapor-Liquid Interfaces in Reservoirs--The study of seismic methods to detect and monitor the position of interfaces between liquid water and steam in geothermal reservoirs was studied in this task. The uses of geophysical methods in reservoir engineering to follow depletion behavior with time appear promising. This task concerns the monitoring of long-term processes during production and injection in both liquid and vapor-dominated reservoirs.

A brief discussion of specific results in each task follows.

Task 1. Heat Extraction from Hydrothermal Reservoirs

One of the major accomplishments needed by the fledgling U.S. geothermal industry is a reliable means to assess the economic potential of geothermal resource development. One of the key uncertainties is the long-term rate and longevity of heat extraction from hydrothermal resources. The threats of excessive fluid drawdown and cooling by recharge fluids still looms large in current geothermal technology. The objective of Task 1 is to develop a model for estimating the heat extraction potential from fractured hydrothermal reservoirs of geothermal energy. The ability to estimate heat extraction potential at an early stage, given only geologic information and rock thermal properties of a prospective field should reduce the uncertainty in economic analysis.

During the current contract year, several advances have been achieved in the combined program of physical and mathematical modeling of heat extraction from fractured geothermal reservoirs. Efforts were focused in three major directions: (1) analysis of physical model results with a LBL numerical code*; (2) analysis of the importance of thermal stressing in cold-water reinjection recharge of fractured hydrothermal reservoirs on thermal properties; and (3) development and improvement of the one-dimensional linear heat sweep model for external use.

The LBL numerical code for geothermal reservoir simulation is being used both for testing of the LBL numerical model and for evaluation of the heat extraction experiments carried out in the SGP large physical reservoir model. During the year difficulties in matching simulated results to observed results for the three experiments of varying production conditions have led to

*This effort is being carried out with the assistance and cooperation of Karsten Pruess (Lawrence Berkeley Laboratory, Berkeley, CA).

reevaluation of the physical properties of the reservoir formation, the experimental heat loss conditions, and the model grid requirements to simulate the temperature differential between rock and water as a function of production time. A production experiment allowing boiling to occur in the formation was run during the year to provide further evaluation of the LBL numerical simulator.

The second thrust was in the examination of the potential for changes in thermal properties in the geothermal reservoir during sustained production with cold-water recharge, and the potential effect on long-term heat transfer and energy extraction. Thermal stressing of the rock in the large physical model was completed during the year. The bottom center rock had a significant temperature/stress history during the several production runs, and its thermal and mechanical properties are being examined in comparison to a similar rock which had no stressing history.

The third activity was in the continued development of a simple 1-D linear heat sweep model for early assessment of thermal extraction potential in new geothermal fields. During the year, a User's Manual was prepared to enable developers and utility companies to examine the model output based on geologic estimates of rock size or fracture spacing. To improve the manual, a number of draft copies was sent to qualified individuals to test the manual on a prepared sample problem. On return of the critiques, the manual will be distributed to potential users. The model is being extended to include radial flow geometry.

<u>1.1 LBL Numerical Model Analysis</u>, by Stephen T. Lam, research assistant, Professor Anstein Hunsbedt, and Professor Paul Kruger

During the current year, progress was made on modeling the series of energy extraction experiments of the regularly shaped rock loading in the SGP physical model. The Lawrence Berkeley Laboratory's geothermal simulator MULKOM (Pruess, 1983) was used to simulate the temperature transients. The objectives of the modeling efforts are (1) to verify the numerical code MULKOM and the method of "multiple interacting continua" (MINC; Pruess and Narasimhan, 1982), (2) to assist in interpreting the physical model experimental data, and (3) to provide guidance for designing future one- and/or two-phase experiments.

The model geometry consisted of a one-dimensional column of disk-shaped elements to represent the pressure vessel interior and two columns of concentric ring elements to represent the steel vessel wall and the surrounding ambient boundary conditions. Additional irregularly shaped elements were used for the top and bottom portions of the vessel. Each interior element was partitioned into one-dimensional strings of 4 to 11 shell elements using the MINC method, so that energy transport between the rock, the water, the vessel and the ambient air could be simulated quantitatively (for more details, see Ramey et al., 1982). Only 1/8th of the vessel cross-section was modeled to take advantage of the physical model's radial symmetry.

Encouraging preliminary results were reported in simulating thermal sweep experiment Run 5-1 (Ramey, et al., 1982). Major discrepancies were observed at the bottom rock and water layers where temperature gradients were high. However, simulations for the other two experiments, Runs 5-2 and 5-3, using similar computer input parameters showed larger differences.

The results showed that to model the series of experiments with greater resolution, the system material properties and initial and boundary conditions must be specified with greater accuracy. It also appeared that the thermophysical properties of water were being modeled accurately in the code. Thermophysical properties of the three major pressure vessel structural components, namely the head and walls (SA 516 Gr-70 steel), the body flanges (SA 105 Gr-II steel), and the aluminum flow-distribution baffle (see Fig. 1-1, Ramey et al., 1982) were obtained from various handbooks. Rock properties used in the model were typical of granite at 121°C, with density = 2675 $kg/m^3$, porosity = 0, permeability = 0, thermal conductivity = 2.94 W/mK, and specific heat = 913 J/kgK. Uniform initial temperature and pressure were applied in all cases. Convective and conductive heat losses from the vessel system involved difficult time- and space-varying boundary conditions. An average heat loss parameter $\upsilon$ ($W/m^2K$) was derived from the cooldown test Run 5-4 for the boundary heat loss term. Finally, cold water injection into the vessel system was modeled by matching the measured inlet temperature transient for each production run.

A parametric study was performed on the key physical and computational parameters, so that maximum accuracy could be obtained at reasonable computer cost. Over 30 computer runs were made to identify the relative importance of these parameters, such as mesh size, wall thermal conduction path length, time step, heat loss parameter, and rock thermal conductivity. A reference case was selected to compare the results between cases. The reference case (for Run 5-1) had 30 layers of rock disk elements with 4 shells per element, a rock thermal conductivity of 2.94 W/mK, a maximum time step of 250 sec, a uniform conduction path length along the pressure vessel wall, and a heat loss parameter $\upsilon$ = 2.80 $W/m^2K$. This value of $\upsilon$ resulted in a good match with the system experimental cooldown curve. Computed water temperatures in the reference case were, in general, slightly higher than the corresponding measured temperatures throughout the entire production period. Table 1-1 summarizes the major effects observed in the study as a function of important parameter changes for some of the completed computer runs.

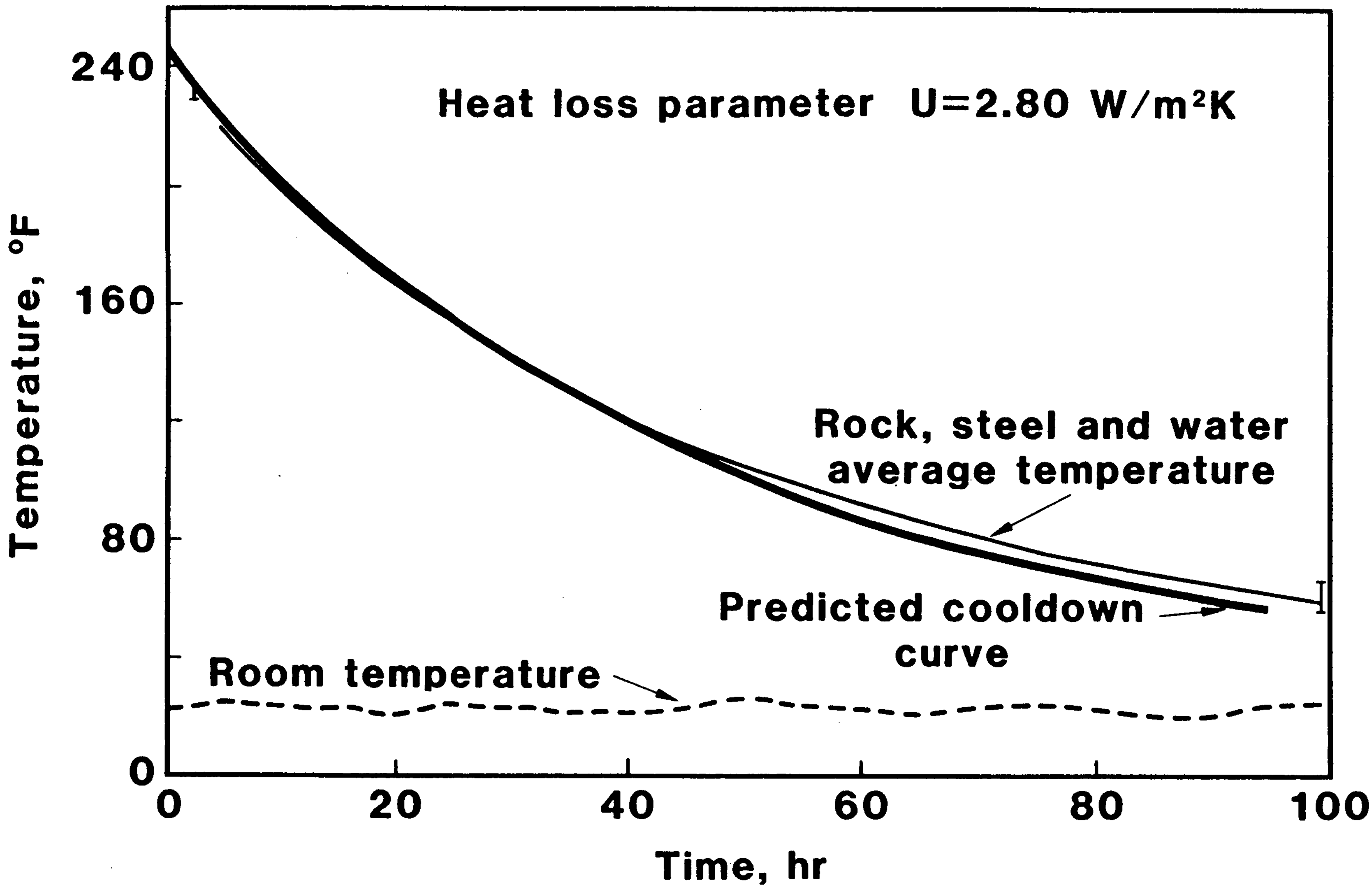



Fig. 1-1: Comparison of Measured and Predicted Vessel System Temperature for Cooldown Experiment Run 5-4.

Table 1-1

Sensitivity Study Table

| Run | Major Parameter Changed | Major Effects Observed |
|---|---|---|
| 1 | Reference case (Run 5-1) | Fair agreement with data |
| 2 | 60 layers, 4 shells/layer | Moderate change in water temp T ~ 15°C, Lowered T curve at small distance x*, Raised T curve at large x* for time $\tau \gtrsim 1$ hr |
| 3 | Half time step (maximum $\Delta\tau$ = 125 sec) | Little change in T, T curve lowered ~ 5°C |
| 4 | Finer grid of inside layers 11 shells per layer | Insignificant change[1] in T, Block center T higher ~ 1°C |
| 5a | Higher heat loss parameter $\nu$ = 3.80 W/m$^2$K | Insignificant change in T, Lowered T curves by ~ 2°C at B- and M-planes for large $\tau$ |
| 5b | Lower heat loss parameter $\nu$ = 2.20 W/m$^2$K | Little change in T, T curves raised ~ 5°C |
| 6 | Baffle conductivity = 0 | Insignificant effects |
| 7a | Shorter conduction path length near lower flange (30% of original length) | Little change, T curves lowered ~ 5°C |
| 7b | Variable conduction path length axially (20%-50%) | Lowered T curves by ~ 7°C for $\tau \gtrsim 1$ hr |
| 8 | Finer gridding near B-, M-, and T-planes (11 shells) | Insignificant change in T |
| 9a | Smaller vessel bottom volume (81.8% of original volume below flow baffle) | Little change in T ~ 3°C T curve lowered for $\tau \gtrsim 2$ hr |
| 9b | Smaller bottom volume (66.8%) | Little change in T ~ 3°C |
| 10 | Rock Conductivity k = 2.42 W/mK | Little effects |
| 11 | Combined 1, 2, 3, 7b & 9b (Run 5-1) | Improved agreement with data (see Fig. 1-2) |

1 Insignificant changes or effects means T changes less than 7°C, the estimated combined measurement and numerical uncertainties.

The maximum temperature gradient at the B-plane was observed as about 10°C/cm, in contrast to the maximum computed value of about 7°C/cm. Since a significant averaging effect occurs in MULKOM, the simulation can only be improved further by acquiring a better understanding of the physical processes and thermophysical data involved in the experimental system.

(a) MULKOM Results

The cooldown experiment Run 5-4 reported last year was reanalyzed. It appeared justified to use a lumped temperature for the vessel system (rock, water, and vessel structures) in investigating the heat loss from the system to the surroundings by natural convection, conduction, and radiation. An energy balance for the system gave a system heat loss parameter $\nu$ as a function of $\Delta T = (T_{system} - T_{\infty})$. The heat loss parameter was found to vary from 3.8 $W/m^2K$ to 2.2 $W/m^2K$, when $\Delta T$ decreased from 219°C to 35°C. The final numerical modeling of Run 5-4 was done using a heat loss parameter value of 2.8 $W/m^2K$ and 30 layers of disk block elements with 4 shells per layer element.

Fig. 1-1 shows the calculated results in comparison with observations, and the ambient temperature as functions of time. Temperature calculations were generally within the combined experimental and numerical uncertainties, but were somewhat low for long-term (~ 100 hr) behavior. Average values of the heat loss parameter were derived for various $\Delta T$ ranges from the cooldown data for application to analysis of the heat extraction experiments.

Heat extraction experiments Runs 5-1, 5-2, and 5-3 were analyzed using similar input parameters, except that a computation mesh of 60 layers was used. The values of $\nu$ used were 2.8, 3.8, and 2.2 $W/m^2K$, respectively. The maximum time steps used were 125, 30, and 250 sec, respectively. Figs. 1-2 through 1-4 show a comparison between computer results and experimental

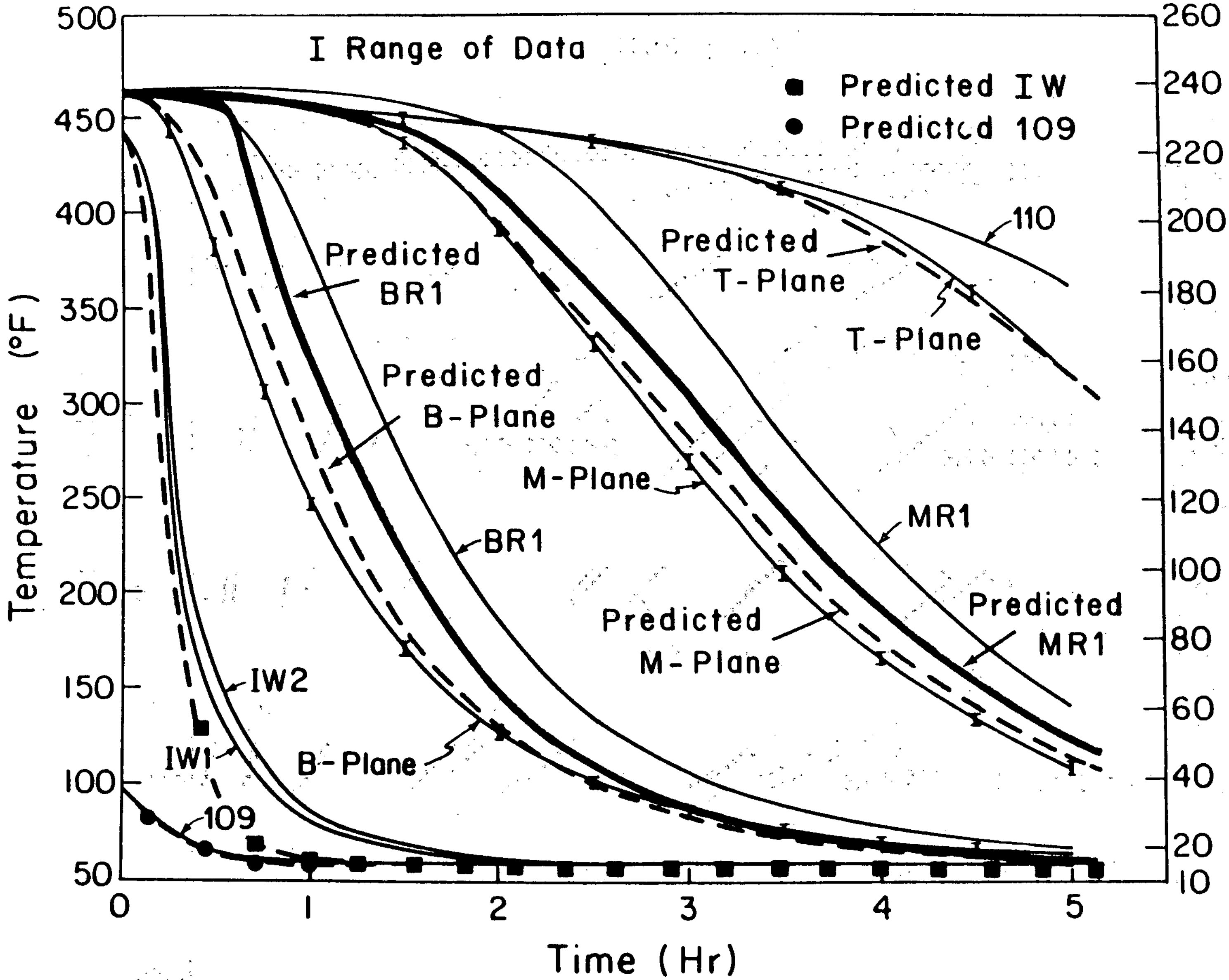



Fig. 1-2: Comparison of Measured and Predicted Water and Rock Temperatures for Heat Extraction Experiment Run 5-1.

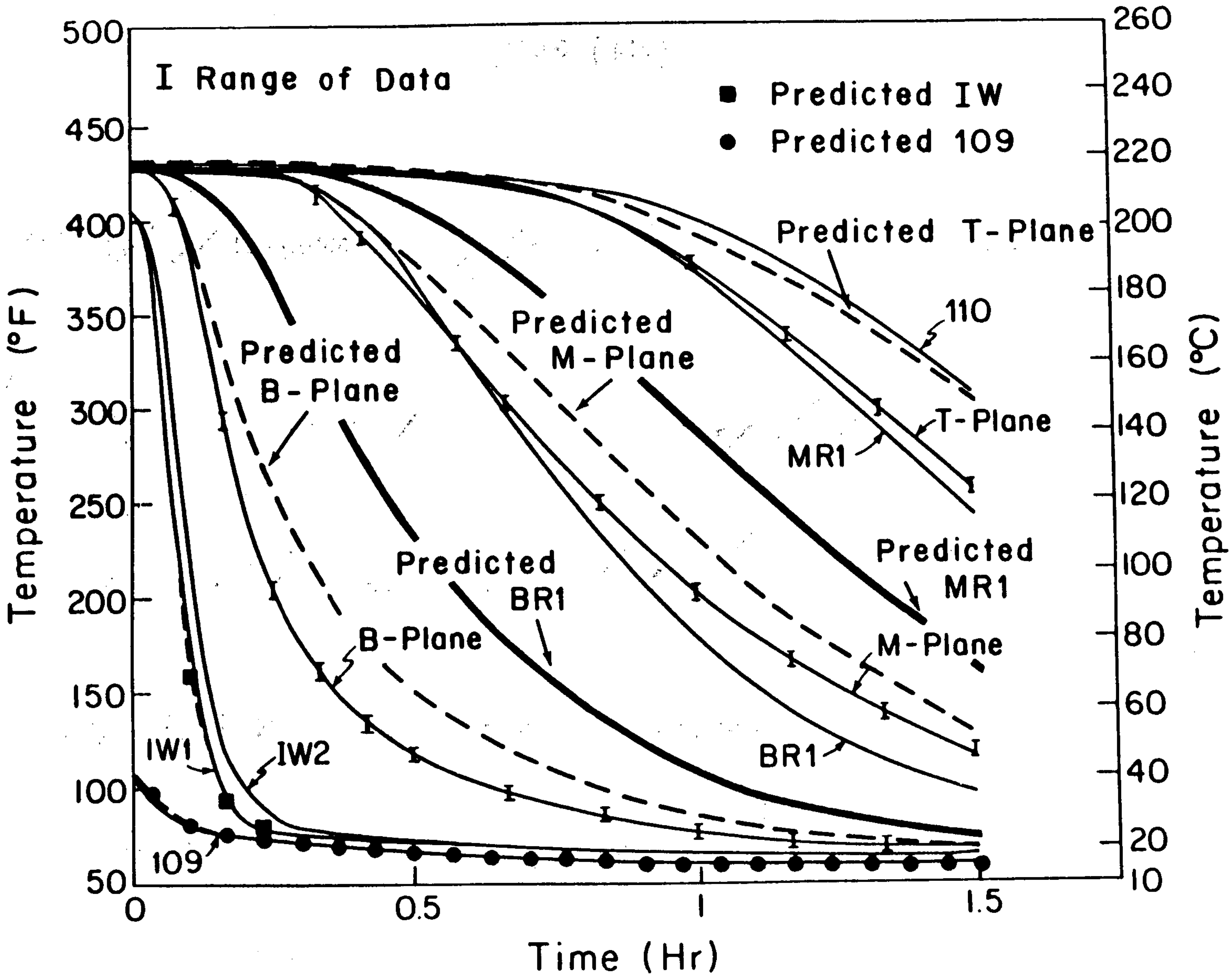



Fig. 1-3: Comparison of Measured and Predicted Water and Rock Temperatures for Heat Extraction Experiment Run 5-2.

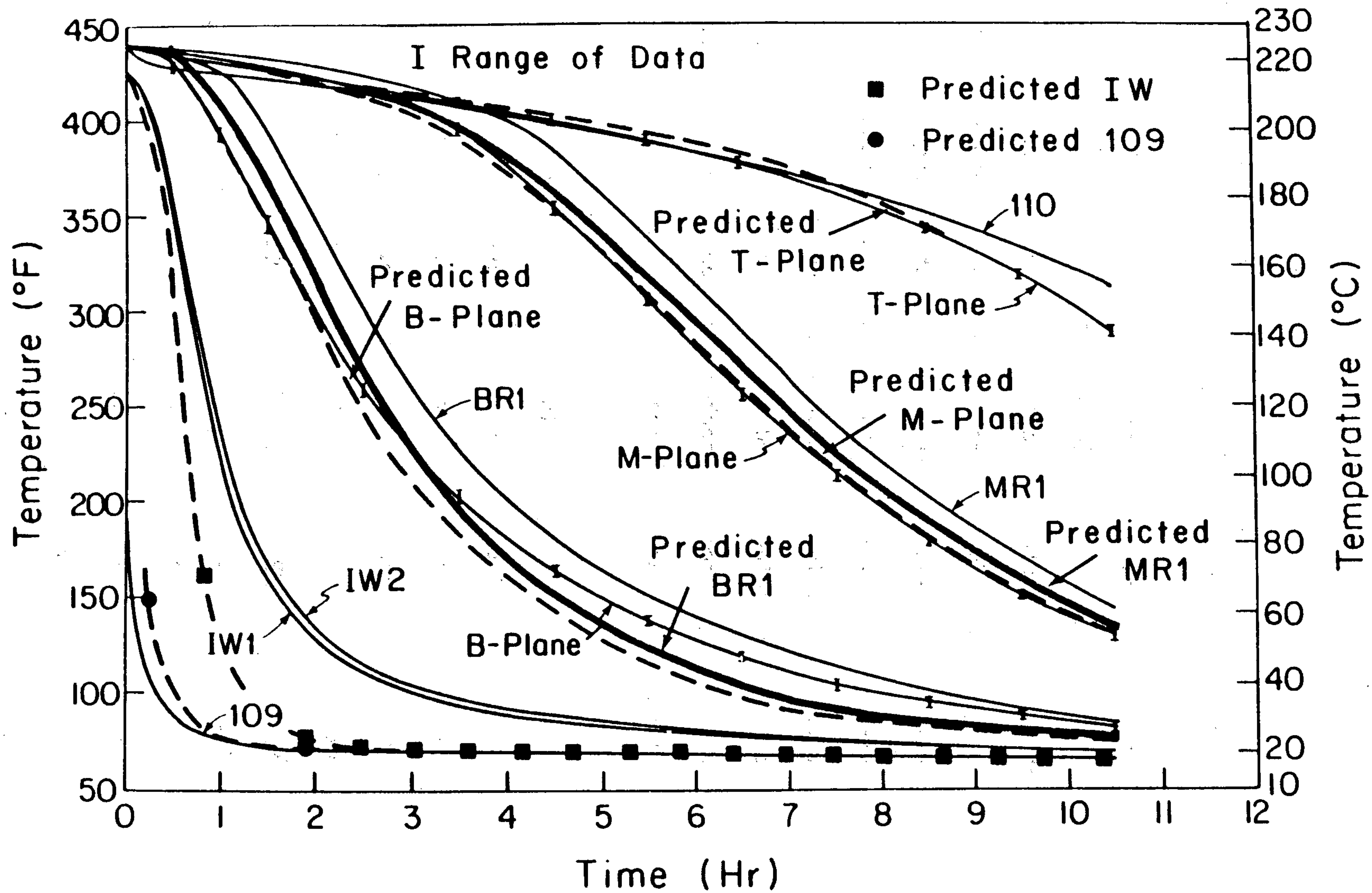



Fig. 1-4: Comparison of Measured and Predicted Water and Rock Temperatures for Heat Extraction Experiment Run 5-3.

measurements. Due to the complexity of modeling heat and fluid flows in the vessel inlet plenum (below the aluminum flow-distribution baffle), the numerically-specified recharge water temperature as recorded by thermocouple 109 resulted in a good temperature match at the I-plane for Run 5-2 (1.5-hr case) only.

Fig. 1-2 indicates a good match between measured and computed water temperatures at all axial locations (except the I-plane). The agreement was less satisfactory in the B-plane at early times. Results for Run 5-2 given in Fig. 1-3 show a good match for the I-plane, but the computed water temperature is generally higher than measured values in the other planes. Results for Run 5-3 given in Fig. 1-4 show a good match for the M- and T-planes, but the computed water temperature is lower than that measured in the B-plane. Energy loss to the surroundings played an important role in this long (10.5 hr) run. In addition, the computed rock-center temperatures for both B- and M-planes in all three runs are significantly lower than the corresponding measured values.

These comparisons led to the conclusion that some physical properties involved, and/or the modeling of the physical processes were inadequate. In particular, the previous results indicated that there could be too much heat transfer from the rock blocks to the water, possibly because the rock thermal conductivity value might be too high. This aspect was investigated further.

(b) <u>Rock to Water Temperature Difference Comparison</u>

Further investigation of the water temperature discrepancies was performed by comparing computed and measured rock-center to average water temperature differences for the B- and M-planes. The results are given in Fig. 1-5 for two different numerical model configurations. The computed rock-center to water temperature difference was less than half of the observed value for the

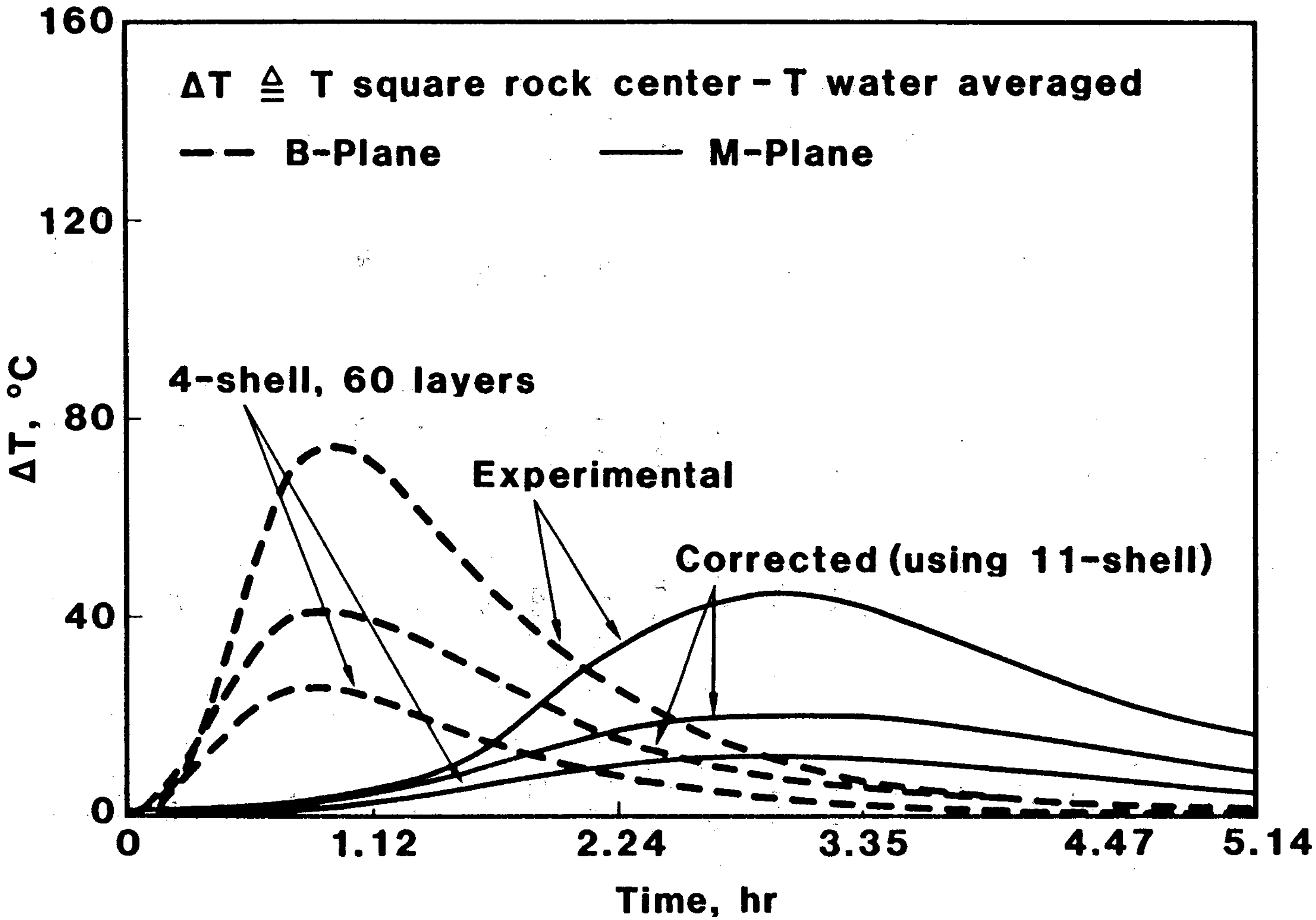



Fig. 1-5: Comparison of Measured and Predicted Rock-Center to Water Temperature Differences for Heat Extraction Experiment Run 5-1.

4-shell model. The discrepancy decreased when the number of shells per disk layer increased to 11 (see Fig. 1-5). With 11 shells per layer, the temperature of the innermost shell represented the rock center temperature, and is directly comparable to the temperature measured by the thermocouple in the rock at this location. The results in Fig. 1-5 show that computed rock-center to water temperature differences are about half of the measured values, indicating that too much heat is extracted from the rock, which in turn results in higher water temperatures. This trend was evident for Run 5-1 and was more pronounced for Run 5-2, where the rock-center to water temperature differences were much higher due to the higher production rate.

In the computer runs, the rock thermal conductivity value of 2.94 $W/m^2K$ was based on extrapolation of one thermal conductivity data point measured at 66°C for the type of granite rock (before stressing) used in the physical model experiments. This conductivity value corresponds to an average rock temperature of 121°C as indicated in Fig. 1-6. However, thermally-induced microcracks in the rock blocks can lower the thermal conductivity further. Effects of rock water saturation, thermal stressing, and elevated temperatures on thermal conductivity are being studied. It is anticipated that the conductivity for a thermally-stressed rock is lower than for an unstressed rock and that this is the main reason for the less-than-satisfactory agreement between computed and measured results. Some evidences of the stress-induced effect are given in section 1.4.

Presently, numerical modeling efforts are concentrated on:

(1) running the cooldown case (Run 5-4) with a lower rock thermal conductivity (~ 2 W/mK). For this case, a mesh configuration composed of 60 layers and 11 shells per layer near the B-, M-, and T-planes, and 4 shells for the rest of the elements will be used. The emphasis of the study will be on the resulting changes in the value of the heat loss parameter;

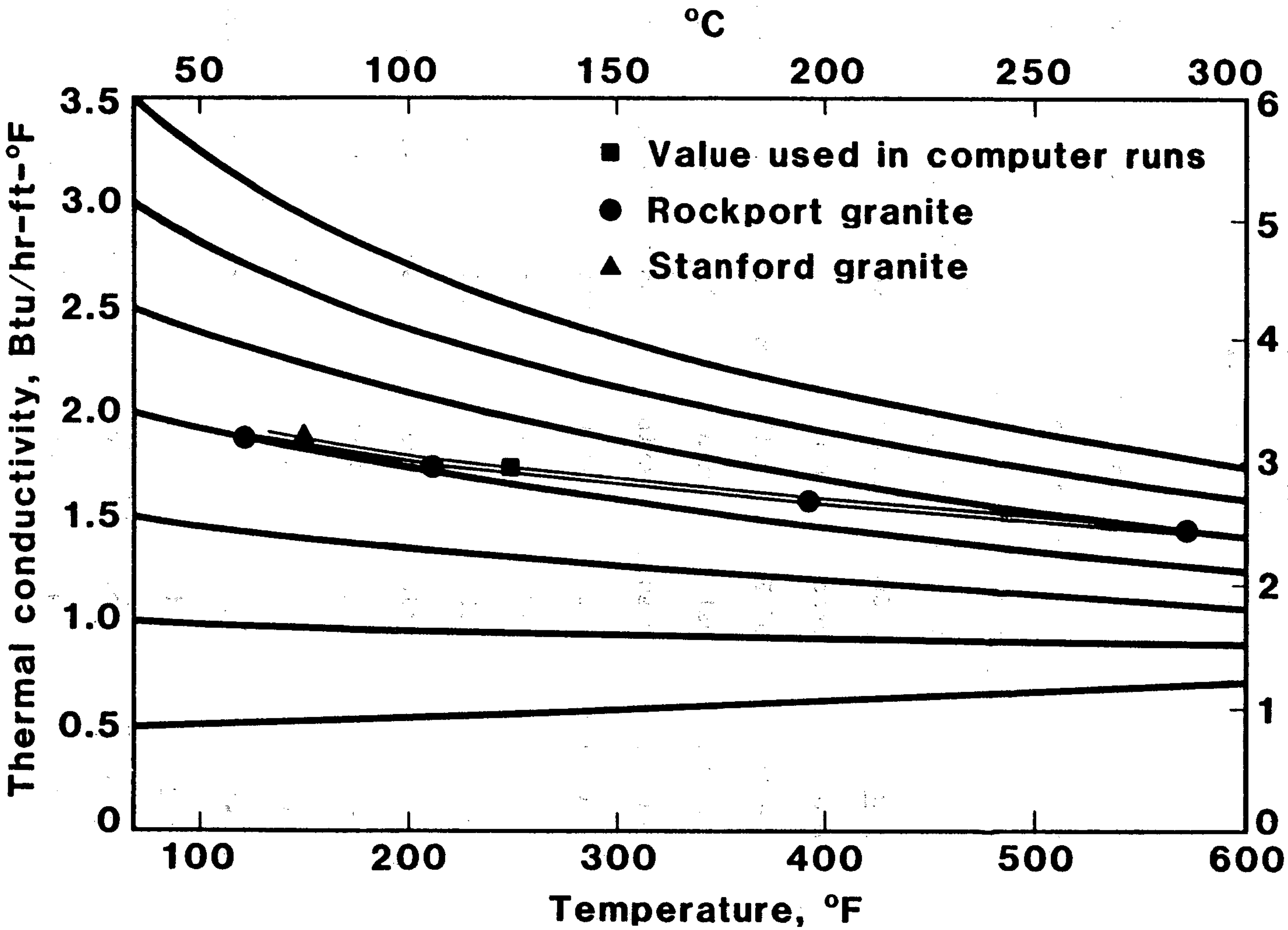



Fig. 1-6: Effect of Temperature on Rock Thermal Conductivity.

(2) rerunning the three heat sweep experiment cases with the lower conductivity value, possibly a new value of the heat loss parameter, and the modified mesh size. Measured I-plane temperatures will be used to specify the input enthalpy for some cases in order to eliminate modeling problems in the vessel inlet plenum; and

(3) studying the production performance of the physical model under different numerically-imposed boundary conditions, such as an adiabatic boundary surrounding the rock elements. The goal is to analyze the physical model performance without the heat capacity influence of the large steel shell.

1.2 Boiling Experiments by Stephen T. Lam, research assistant, Professor Anstein Hunsbedt, and Professor Paul Kruger

During the last part of FY83, a boiling experiment (Run 5-5) was conducted in the SGP physical model with the regularly-shaped granite rock loading used in the earlier sweep experiments (Runs 5-1 through 5-3). In the boiling experiment*, reservoir pressure was reduced by steam production at the top of the rock matrix resulting in boiling two-phase saturated steam conditions in large portions of the reservoir. The declining pressure and temperature conditions with production provided the necessary driving temperature difference between the rock blocks and the fluid (steam/water) to accomplish the rock energy extraction. This production mode is in contrast to the earlier heat sweep experiments where the driving rock-to-water temperature difference was generated by injecting cold water at the bottom of a compressed liquid reservoir. The main purpose of conducting the boiling experiment was to provide additional physical-model data for the LBL numerical geothermal reservoir simulator.

*Two such experiments were conducted, but the first experiment was aborted due to a failure of the temperature recorder.

A preliminary evaluation of the experimental data has been completed. The measured cumulative steam produced as a function of time in Run 5-5 is given in Fig. 1-7. The steam production rate was held approximately constant (at about 100 $lb_m$/hr) by opening the flow control valve in increments as the pressure declined during the experiment. The flow control valve was fully opened when the reservoir reached atmospheric pressure at 1.33 hr (as indicated in Fig. 1-8). The steam production rate, given in Fig. 1-7, decreased significantly at this point, and would be expected to be dominated by mass transfer from small internal rock voids. The total amount of steam produced at the end of the experiment was 139 $lb_m$ which compared favorably with an initially calculated water mass of 147 $lb_m$ based on fracture porosity of 17.3 percent. Since the rock porosity is about 1 percent, there would still be a small amount of water/steam left in the rock matrix in addition to the water present under the flow baffle (see Fig. 1-1, Ramey et al., 1982).

Comparison of measured reservoir pressure and the saturation pressure based on the measured average temperature of all water/steam thermocouples in the bottom plane (B-plane in Fig. 1-1, Ramey et al., 1982) indicates that the reservoir was saturated over most of the pressure transient. However, during the latter part of the transient, some steam superheat is indicated by the fact that the saturation pressure is above the measured pressure.

The presence of superheat in various parts of the reservoir is also indicated by the temperature measurements performed in the B-, M-, and T-planes of the reservoir. The average steam/water temperatures in these planes, denoted by $\overline{BW}$, $\overline{MW}$, and $\overline{TW}$, respectively, are given in Fig. 1-9 as functions of time. Also given are the measured rock block center temperatures in the B-plane (T/C BR1) and in the M-plane (T/C MR1) as well as the water temperature below the inlet baffle plate (T/C IW1).

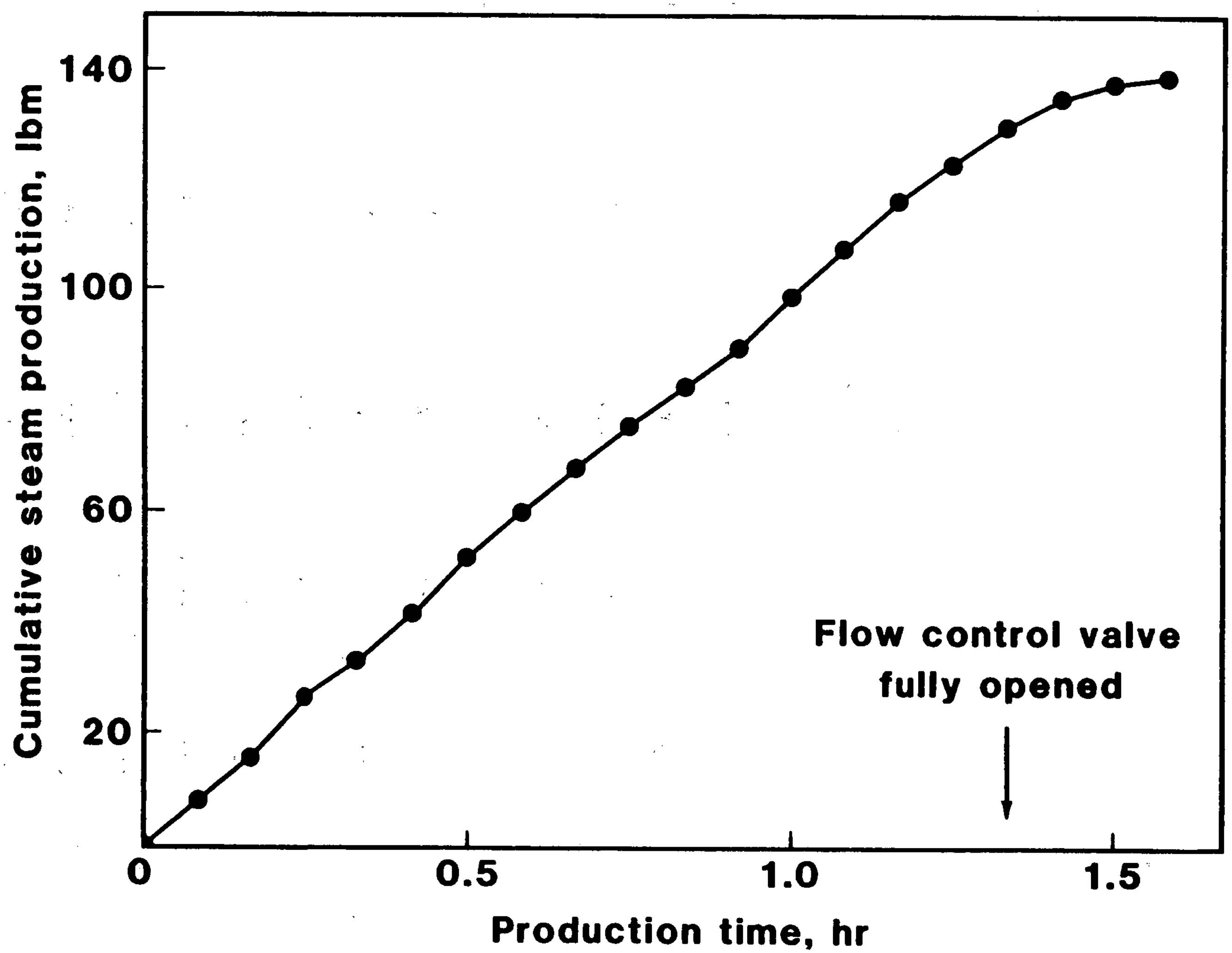



Fig. 1-7: Cumulative Steam Production as a Function of Production Time for Run 5-5.

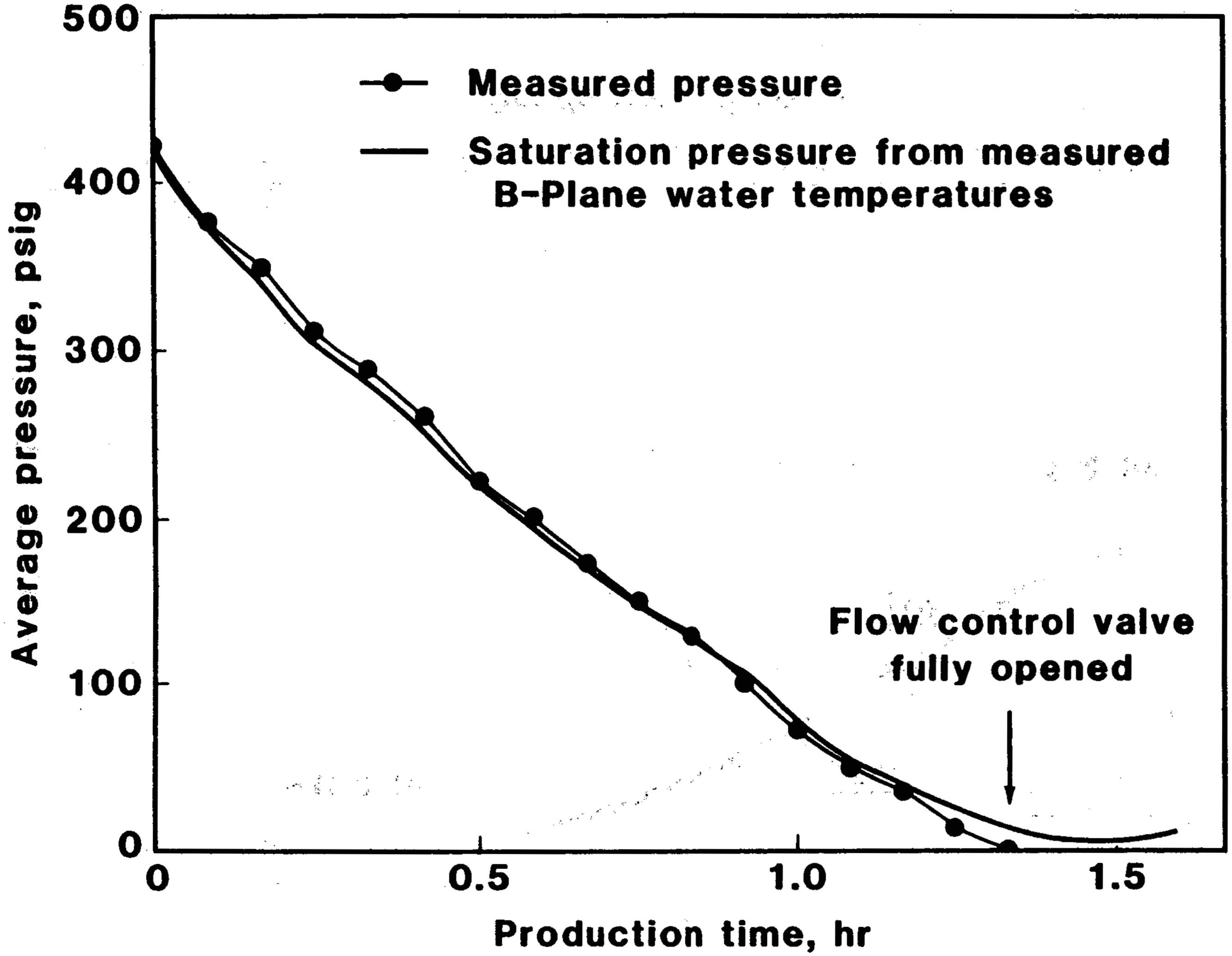



Fig. 1-8: Average Matrix Pressure as a Function of Production Time for Run 5-5.

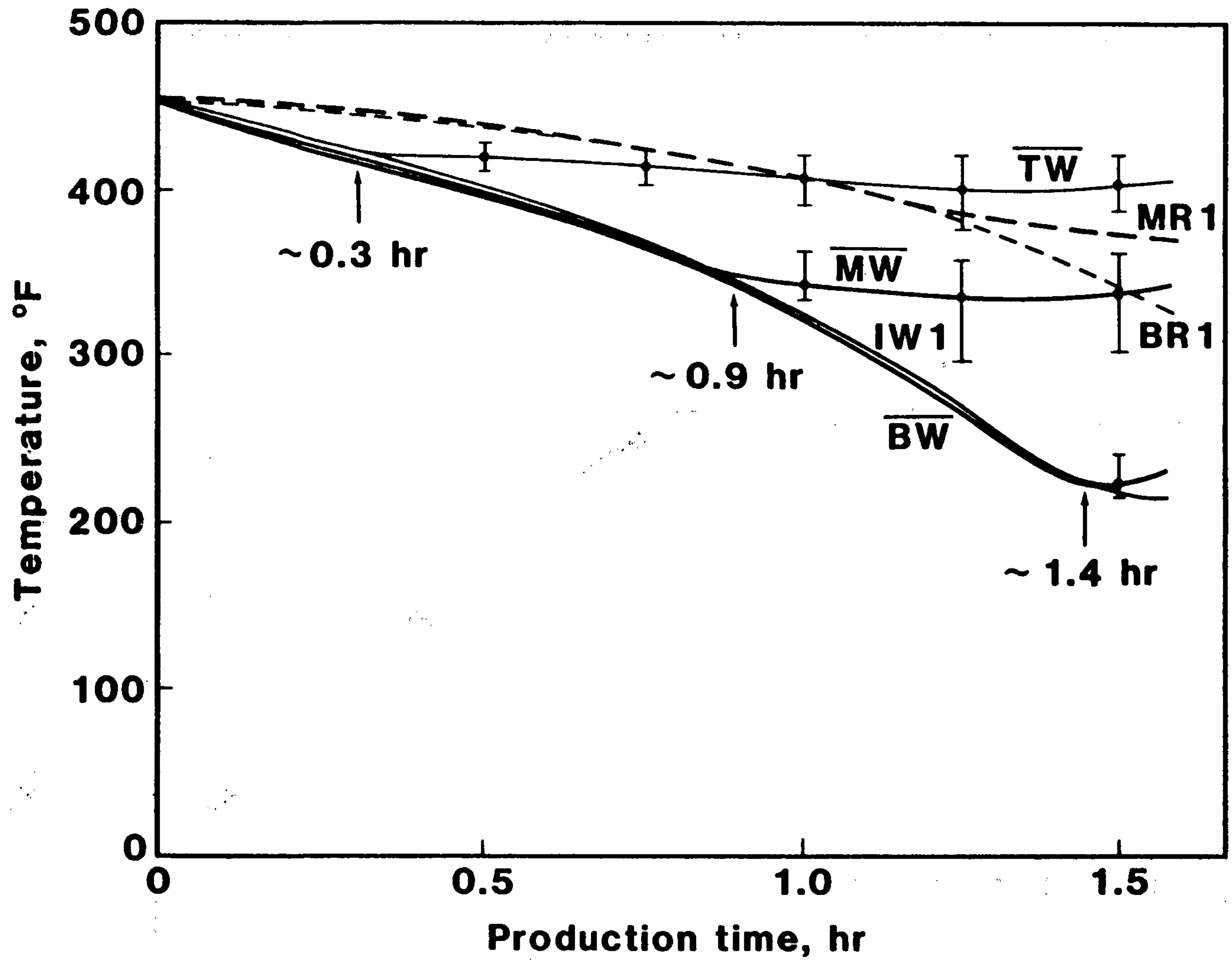



Fig. 1-9: Measured Water, Steam, and Rock Temperatures as Functions of Production Time for Run 5-5.

It is observed in Fig. 1-9 that the rate of decline in steam temperature in the T-plane decreases at about 0.3 hr and subsequently followed a generally higher temperature level. The degree of deviation from the remaining temperature curves (e.g., $\overline{MW}$ and $\overline{BW}$ representing the saturated two-phase temperature) indicates the degree of superheating of the steam that took place in this experiment. Significant temperature nonuniformities were observed in the superheated regime. This effect is indicated in Fig. 1-9 by the vertical bars; the length of the bar shows the maximum temperature difference measured in different channels. The temperature nonuniformity generally increased with time. No significant differences between temperatures measured near the steel vessel and within the rock fracture were noted. In the two-phase regime, the measured steam/water temperatures were uniform, generally within the estimated measurement uncertainty of ±5°F.

The superheating started in the M- and B-planes at about 0.9 hr and 1.4 hr, respectively, as the upper part of the two-phase regime dropped towards the bottom of the reservoir and as the water boiled. The degree of temperature nonuniformities in these planes were similar to that in the T-plane. Slight steam temperature increases were observed towards the end of the experiment in the three planes. This effect is believed to be caused by an increasing proportion of steam being driven from voids in the hot rock blocks as compared to the amount of saturated steam originating from evaporation of water in the fractures. The amount of water evaporating from the fracture spaces became negligible towards the end of the experiment when the two-phase regime had dropped to the inlet baffle level.

The rock center temperatures, MR1 and BR1, are seen from Fig. 1-9 to decrease continuously throughout the transient. However, the rate of decrease for MR1 dropped toward the end because of the decreasing steam-to-rock temperature difference and surface heat transfer coefficient. However, these effects would be expected to be partly offset by increased mass-associated energy transport when pore water is driven out of the rocks at later times.

The next step in this task is to apply the LBL reservoir simulator to the boiling problem. It is anticipated that the numerical model configuration used in the analysis of the sweep experiments can be used with little change, except for the initial temperature and the boundary conditions applied at the inlet and outlet, i.e., zero injection at the bottom and the measured production and steam enthalpy histories at the top. The emphasis of the analysis will be on the boiling portion of the transient, i.e. for times less than about 1.3 hr.

1.3 Heat Sweep Model Development, by Stephen T. Lam, research assistant, Professor Anstein Hunsbedt, and Professor Paul Kruger

(a) 1-D Linear Heat Sweep Model User's Manual

A user's manual for the one-dimensional Linear Heat Sweep Model has been completed (Hunsbedt, Lam, and Kruger, 1983). The model is designed to calculate water and rock matrix temperature distributions in fractured hydrothermal reservoirs as functions of distance from the injection point and time of production. The principal intended use of the model is to provide early estimates of energy recovery from fractured geothermal reservoirs based on early estimates of geological and heat transfer properties of the formation.

The reservoir geometry assumed for the 1-D heat sweep model is given in Fig. 1-10. Cold water is either naturally recharged or injected through a line of wells at point A and produced at the same rate through a line of wells at point B. The recharge or injection water temperature may be constant or decreasing exponentially from the initial temperature to a lower constant value. The reservoir block consists of rock fragments of unequal size and of

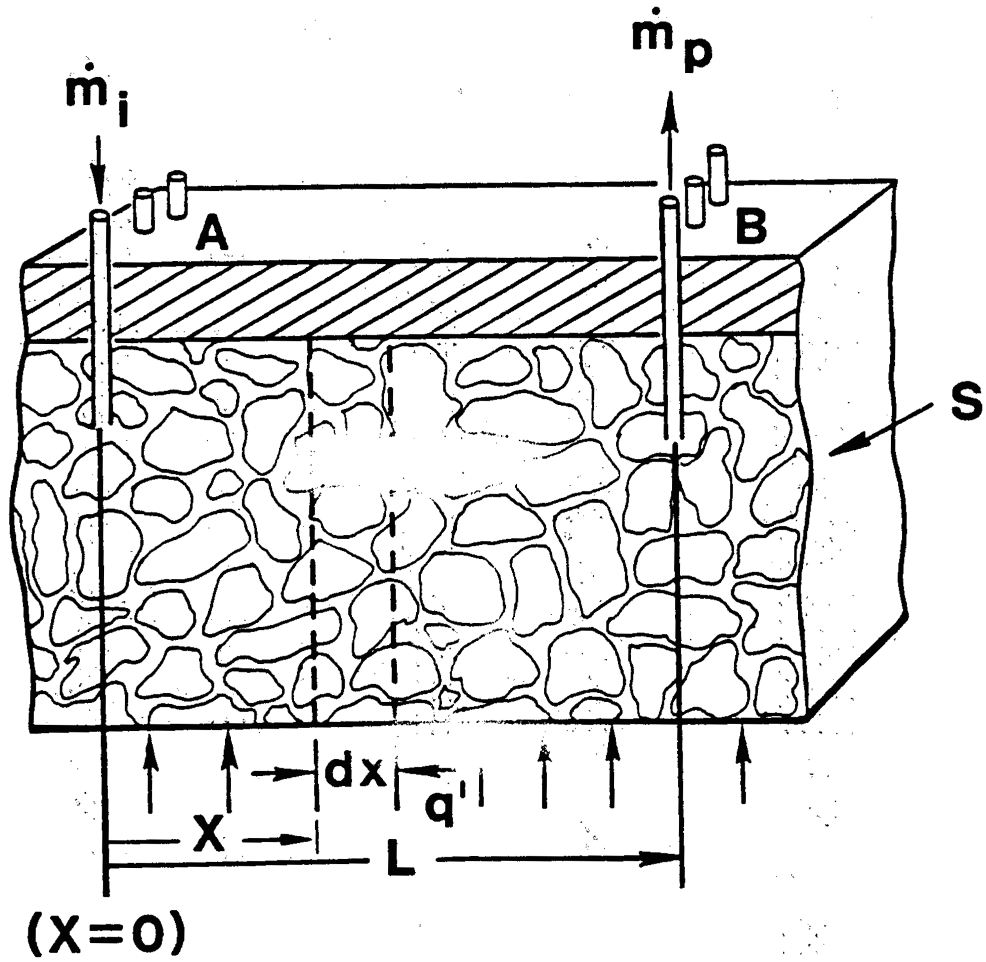



Fig. 1-10: Linear Heat Sweep Model Geometry.

irregular shape. A method was developed in which the thermal behavior of the rock collection can be represented by a single effective rock block size.

The user's manual describes the major assumptions made in the model and the mathematical basis for the model. The use of the model is illustrated with the analysis of two sample problems. The first example is the analysis of the experiment Run 5-2 conducted in the Stanford Geothermal Program's large physical model of a fractured-rock hydrothermal reservoir (Hunsbedt et al., 1982). The second example is a hypothetical reservoir having characteristics similar to those that can be expected in a hydrothermal field (e.g., the Cerro Prieto field). In each case, the manual illustrates the preparation of input data and shows how to obtain and interpret the output data.

Currently, the draft of the user's manual is undergoing external review. The reviewers were asked to use the model to analyze an additional test problem provided with the user's manual. It is hoped that this exercise will result in constructive comments by the reviewers not only on the adequacy of the manual, but also on the model limitations for practical applications.

(b) <u>1-D Radial Heat Sweep Model Development</u>

In many practical situations the dominant flow field in a geothermal reservoir is from the outside perimeter of the field towards the center where production occurs. This situation can be approximated by radial flow geometry as illustrated in Fig. 1-11 rather than the linear flow geometry shown in Fig. 1-10.

Development of the radial heat sweep model, based on enhanced capability and flexibility of the simple model approach, was initiated this year. In this model, cold water through natural recharge or by injection wells at a circular outside perimeter at A in Fig. 1-11 flows radially inward to production wells at B, where fluid is produced at the same rate as the injection

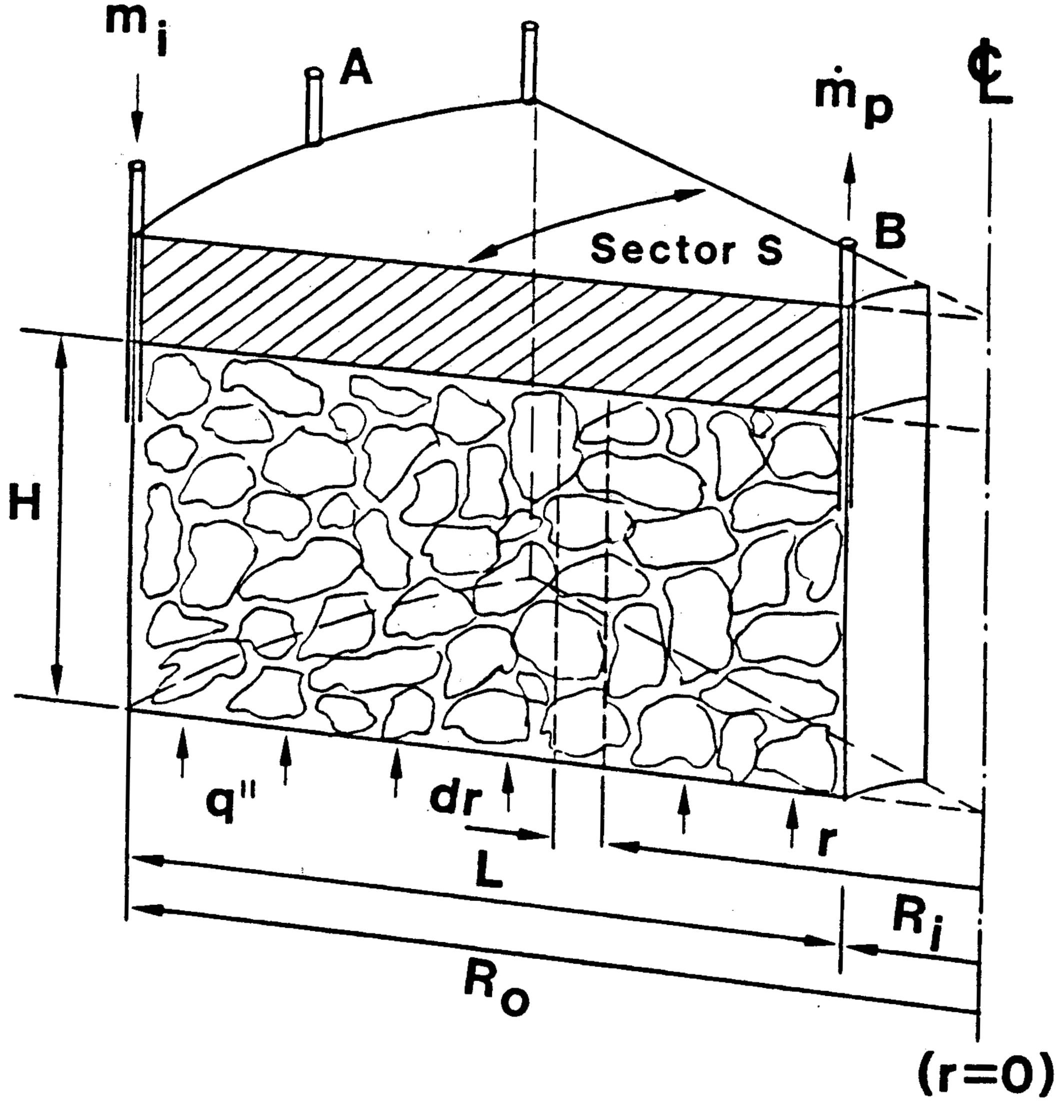



Fig. 1-11: Radial Heat Sweep Model Geometry.

rate. The model can consider a partial or full sector. Other major assumptions and capabilities are similar to those used for the linear model.

The mathematical basis for the radial model has been developed and programming of the model is expected to be completed next year. The objective is to demonstrate the use of the model for a problem similar to that used for the linear model, and to include the model in an updated user's manual. This should provide additional capabilities for users of the model.

1.4 Thermal Stressing Task, Stephen T. Lam, research assistant, Professor Drew V. Nelson, Professor Anstein Hunsbedt, and Professor Paul Kruger

Successful modeling of heat extraction from fractured hydrothermal reservoirs requires knowledge of the physical and thermal properties of geothermal rocks and how such properties might change under changing reservoir conditions. It has been postulated that tensile thermal stresses developed near the surfaces of reservoir rocks undergoing cold sweep energy extraction process may reduce rock strength, increase porosity, and reduce thermal conductivity. If such changes are significant, the heat extraction behavior of a reservoir could, in turn, be affected significantly. The objective of this task is to explore whether such property changes occur and the extent to which they are likely to be important.

Specimens for this investigation were obtained from the granite block which had been located in the bottom layer of a rectangular block loading used in the recent series of cold sweep heat extraction experiments in the SGP physical model. The bottom layer experienced the highest cooling rates and thus the largest thermal stresses during the series of experiments. In particular, the block (19.1 x 19.1 x 26.4 cm in size) was subjected to seven cycles of heating (average rate $\lesssim$ 0.1°C/min.) and cooling (maximum rate $\lesssim$ 4°C/min.) during the experiments.

Rectangular specimens (6.35 x 3.81 x 0.85 cm), as depicted in Fig. 1-12, were obtained from a vertical surface and the interior (close to the center) of the stressed block and from the surface of an unstressed block. A three-point bending test apparatus was built to determine the bending stress at fracture of the specimens.

Results of the bending tests, conducted at room temperature and with dry samples, showed that the average strength of specimens taken from the surface of the stressed block was about one-third of the average strength of specimens taken from the unstressed block. Average strength of specimens taken from near the center of the stressed block was approximately one-half of the average strength of unstressed specimens. These results are for a limited number of specimens (three from the unstressed block, and six from the stressed block) but are considered significant. An analysis of the thermal stress history experienced by the block from the SGP physical model will be undertaken to interpret the test results. Also, additional specimens are being tested to increase the database. The observed reduction in strength would definitely favor the formation and growth of thermally-driven micro-cracks in reservoirs.

The influence of thermal stressing on porosity and thermal conductivity was also investigated. Several circular specimens (3.49 cm dia., 0.79 cm thickness), as shown in Fig. 1-12, were taken from both the stressed and unstressed blocks at locations close to those from which the bending strength specimens were taken. Porosity was measured by the saturation method, and thermal conductivity was measured by R. J. Munroe, U.S.G.S. (Menlo Park, CA), using a steady-state divided-bar technique (Sass, 1971). Wet (saturated) properties were measured at room temperature. Little difference in thermal conductivity was observed between stressed and unstressed specimens; however,

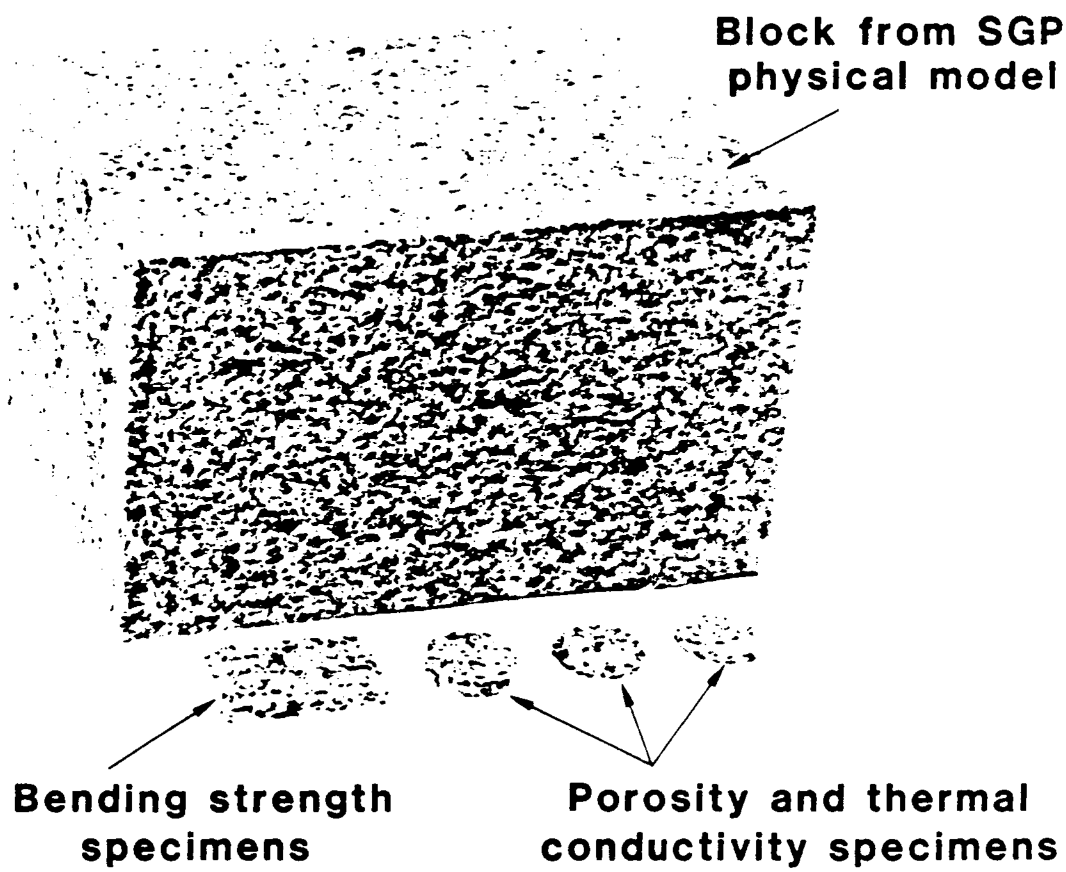



Fig. 1-12: Specimen Types Used in Property Determination Tests.

about a 20% increase in porosity was found in specimens taken from near the surface in the stressed block. In addition, tests were made with specimens of the same diameter but with thicknesses of 0.32 and 0.17 cm. These thinner specimens were closer to the surface of the thermally-stressed block and thus experienced higher average values of tensile thermal stress across their thickness than the thicker specimens. Preliminary test results have shown that the average saturated thermal conductivity of the thin stressed specimens was approximately 20% lower than that of the unstressed specimens. Porosity of the stressed specimens was again about 20% higher. The thermal conductivity of dry stressed specimens was approximately 25-30% lower than that of specimens taken from either the unstressed block or from the center of the stressed block. These results are also based on a limited number of stressed specimens (four), but appear significant since the experimental uncertainty in measurement of thermal conductivity is estimated to be 3-4%.

Current efforts are concentrated on estimating and relating the magnitude of thermal stresses experienced by the specimens to the observed changes in porosity and thermal conductivity. Sensitivity analysis is being conducted to see how the reduction in thermal conductivity is likely to affect computed reservoir heat extraction behavior. If the reduction has a significant influence, then further experiments would be performed to generate more data on changes in thermal conductivity.

## Task 2. Radon Reservoir Engineering

This annual report on Radon Reservoir Engineering summarizes the final efforts on Task 2 during the current year. The objective of the research effort was to develop wellhead radon concentration measurement as an internal tracer for the study of geothermal reservoirs. During the FY83 contract year, efforts included the following topics:

(1) completion of the third survey of the Cerro Prieto field and analysis of the acceleration of two-phase development in the reservoir;

(2) further evaluation of the regression analysis of radon concentration as a function of reservoir fluid specific volume; and

(3) analysis of transient data by numerical modeling of radon transport in geothermal reservoirs.

Measurements of radon concentration and acquisition of production data during the year were achieved at: (a) vapor-dominated fields at The Geysers, CA, Serrazzano, Italy, Los Azufres, Mexico, and Matsukawa, Japan; and (b) liquid-dominated fields at Cerro Prieto, Mexico, Wairakei, NZ, Los Azufres, Mexico, Puna, Hawaii, and Kakkonda, Japan. Data from Roosevelt Hot Springs, Utah, acquired under another program, were included in the regression analysis. During the current year, evaluation was made of the two additional parameters expected to affect the regression, namely radon emanation and formation porosity. Numerical model studies made in this fiscal year included the Los Alamos phase I tests of petrothermal resources at Fenton Hill, NM, and the short-term and long-term start-up transients at The Geysers. The latter study was presented at the Ninth Annual SGP Workshop on Geothermal Reservoir Engineering (Semprini and Kruger, 1983).

(a) Radon Observation of Two-Phase Development at Cerro Prieto, by Lewis Semprini, research assistant and Professor Paul Kruger

Three radon contour analyses have been carried out over a four-year period at the Cerro Prieto field, with large field surveys taken during 1979/80, 1982, and 1983. In these surveys, wellhead radon concentrations were evaluated with respect to production data, reservoir thermodynamic conditions, and rock mass to fluid mass ratio for radon emanation.

Results of the first two contour surveys were reported by Semprini and Kruger (1984). The data indicated significant changes in equilibrium conditions during transport within the reservoir. The contour analysis showed a decided shift over the two-year period in fluid enthalpy and wellhead radon concentration toward the northeast section of the field.

A third survey of the field, accomplished with the assistance of the CFE staff, was made in February and June of 1983. Production data for the 22 wells sampled were provided by CFE. The data were examined for evidence of a continued shift in radon concentration and fluid enthalpy over the 1-year production period in relation to the changes observed over the prior two-year period.

Data for the June, 1983 survey period are shown in Figs. 2-1 and 2-2. A remarkable increase in two-phase behavior towards the eastern part of the field, near the major NW-SE zone is evident from the contours. The acceleration of two-phase development is in the deeper eastern zone of the reservoir. Development of the two-phase zone in this area of the reservoir is also supported by enthalpy, temperature estimates, by $SiO_2$, and Na-Ca-K geothermometers.

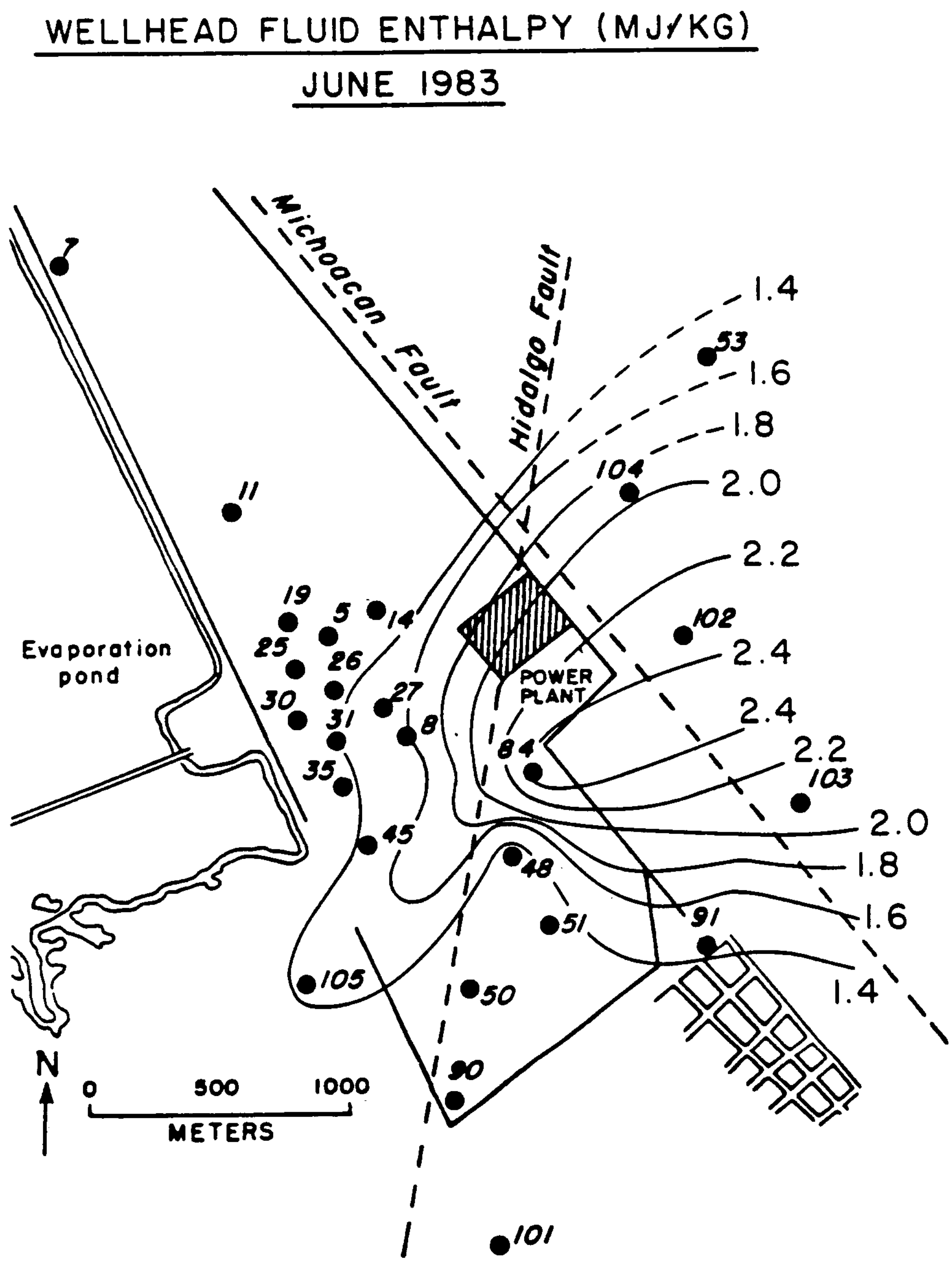



Fig. 2-1: Wellhead Fluid Enthalpy
Cerro Prieto - June 1983.

WELLHEAD RADON CONCENTRATION (NCI/KG)
JUNE 1983

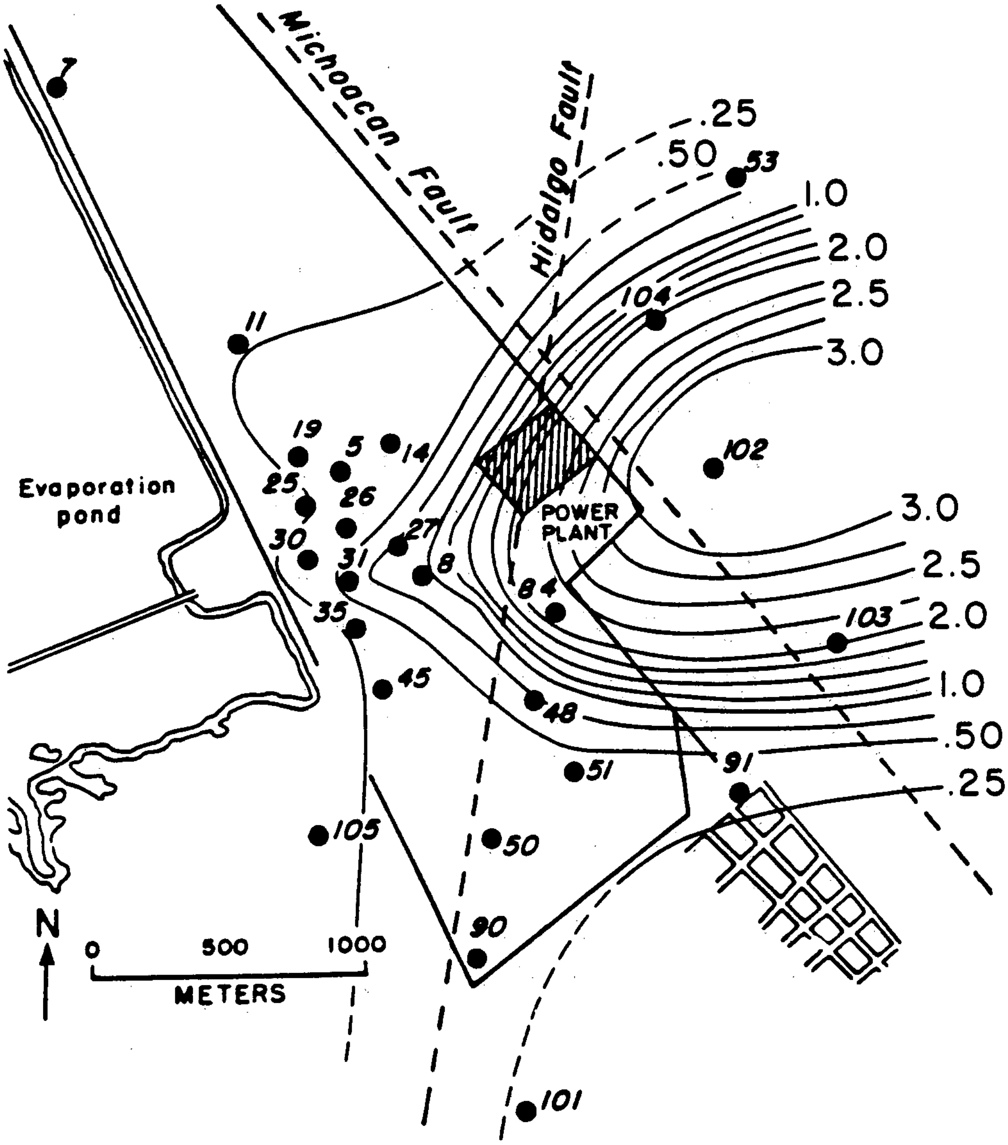



Fig. 2-2: Wellhead Radon Concentration
Cerro Prieto - June 1983.

(b) Analysis of the Los Alamos Phase I Data, by Lewis Semprini, research assistant, and Professor Paul Kruger

Radon concentration measurements were performed during Segments 2, 4, and 5 of the phase I LASL hot, dry rock resource development at Fenton Hill, NM. Analysis of Segment 2 data was reported by Kruger et al. (1978). Measurements of the Segment 4 and 5 samples were made on-site by LASL. The data were reported by Grigsby (1981) and Grigsby et al. (1983).

During the present contract year, modeling studies were carried out to examine the parameters which effect wellhead radon concentration. These include reservoir circulation volume, fluid loss rate, and changes in emanation from the reservoir formation.

Recirculation of injected fluid as the heat carrier in the LASL loop system results in a high degree of mixing in the system. The model used for the analysis assumes a completely mixed system. The transient response of radon in such a system is given by:

$$\frac{\partial}{\partial t}(V\phi C_R) = - Q_L C_R - \lambda V\phi C_R + \frac{E_m V_m}{V} + RC_m \tag{2-1}$$

where $C_R$ = radon concentration in reservoir fluid $(M/L^3)$

$C_m$ = radon concentration in make-up fluid $(M/L^3)$

$E_m$ = radon emanation in reservoir $(M/L^3T)$

$Q_L$ = water loss rate $(L^3/T)$

$R$ = water make-up rate $(L^3/T)$

$V_m$ = reservoir modal volume $(L^3)$

$V$ = total system volume $(L^3)$

$\phi$ = porosity $(L^3/L^3)$

$\lambda$ = decay constant for radon $(1/T)$

The model assumes that the fluid make-up rate, R, is equal to the fluid loss rate, $Q_L$. The emanation term is influenced by the ratio of the volume of reservoir rock $V_m$ to the volume of the entire circulation loop V, which includes the reservoir modal volume, $V_m$, plus the wellbore and surface piping volumes.

By external tracer measurements, Tester (1982) showed the system modal volume increased during the segment runs. Modal volume increased from 11.3 $m^3$ to 26.5 $m^3$ in segment 2, to 136 $m^3$ in segment 4, and from 155 $m^3$ to 187 $m^3$ during segment 5.

The model to simulate the transport of radon in geothermal reservoirs is described by Semprini (1984). The routine used to solve Eq. (2-1) involves a Runga-Kutta numerical integration scheme. Model inputs include water loss rate, initial system volume, final volume, and a constant emanation rate during the segment. The model assumed a linear increase in modal volume with time during each run segment. The modeling was conducted on a modal pore volume basis, since system porosity is not well established.

Fig. 2-3 shows the results of model simulation in comparison to field measurements for the 75-day segment 2 test. The water make-up rate is also shown in the figure. The data suggest two important time developments: (1) low radon concentration at early times (1 - 20 days), no doubt related to the high water loss rates in the system which dilute the radon concentration, and (2) increased radon concentration at later times (40 - 75 days), related to the decrease in water loss rate and increase in fracture volume with concommitant increase in reservoir emanation volume. The radon concentration results from the simulation are consistent with those expected from the modal volume measurements from the dye tracer tests.

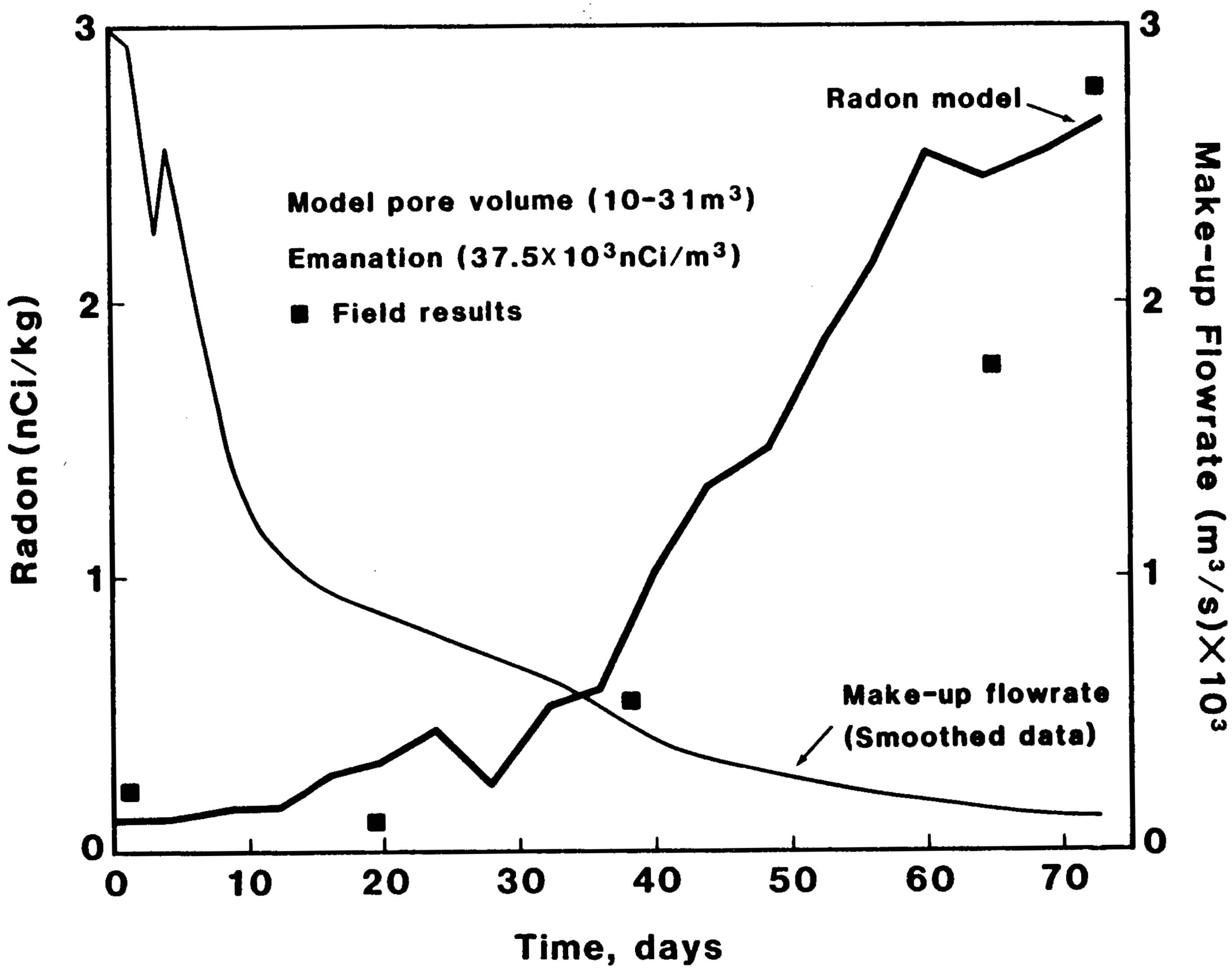



Fig. 2-3: Radon Concentration vs Time Segment 2 Test.

Fig. 2-4 shows the results of the model simulation for the first 14 days of the segment 4 test. The modal volume increased during fracturing experiments from 30 $m^3$ to 136 $m^3$. Field measurements for this segment were taken only during the initial 12 days of the test (C. Grigsby, private communication). The simulation shows the extent of dilution during the initial phase of the test. Simulation and field results are in fair agreement at later times. Based on the same emanation factor used for the segment 2 simulation, the changes in segment 4 of surface area for emanation are directly related to the increase in modal volume of the system.

Fig. 2-5 shows the results for segment 5. In this simulation, a match with observed values was achieved when the emanation rate was increased from the value of 37 nCi/$m^3$ for segments 2, and 4 to 100 nCi/$m^3$ for segment 5. Speculation of the reason for the need for this increase in emanation by a factor of three suggests that the effective area for radon emanation increased faster than the observed modal volume, implying an increase in the effective surface to volume ratio of the formation rock in the reservoir. The simulation of radon concentration, requiring an increased emanation source, suggests that enhancement of radon-diffusing fractures may have resulted from the long-term drawdowns in segments 2, 4, and 5. The agreement between model simulation and measured radon concentrations suggest that the assumption of a well-mixed circulation fluid is a good one. The analysis supports the conclusions that water loss rate is a key factor in modeling the early radon response and that the growth of the reservoir by thermal or mechanical stressing of the formation rock can be studied using radon as an in situ tracer.

(c) Simulation of Radon Transport, by Lewis Semprini, research assistant, and Professor Paul Kruger

A major effort during the present contract year was the development of a

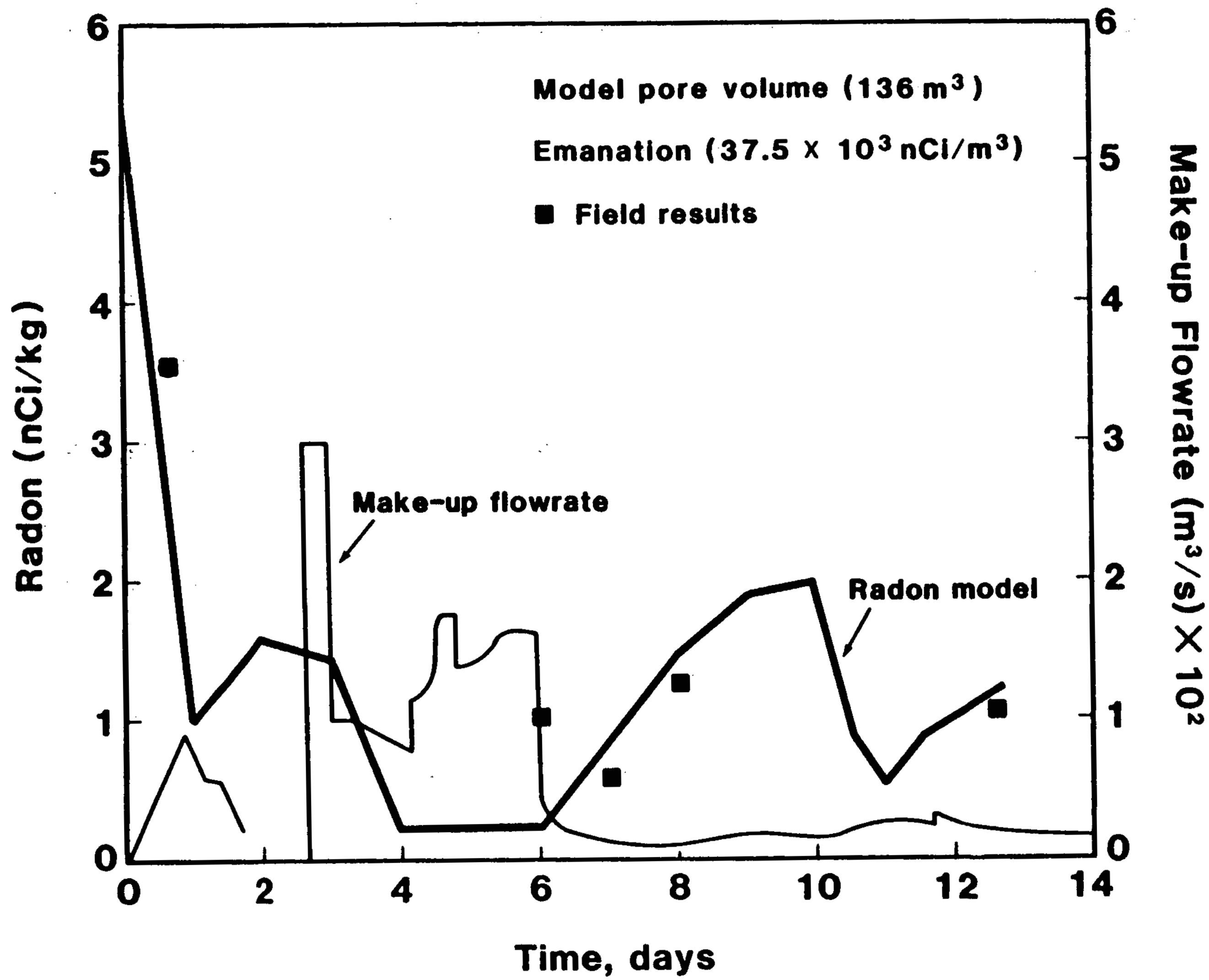



Fig. 2-4: Radon Concentration vs Time Segment 4 Test.

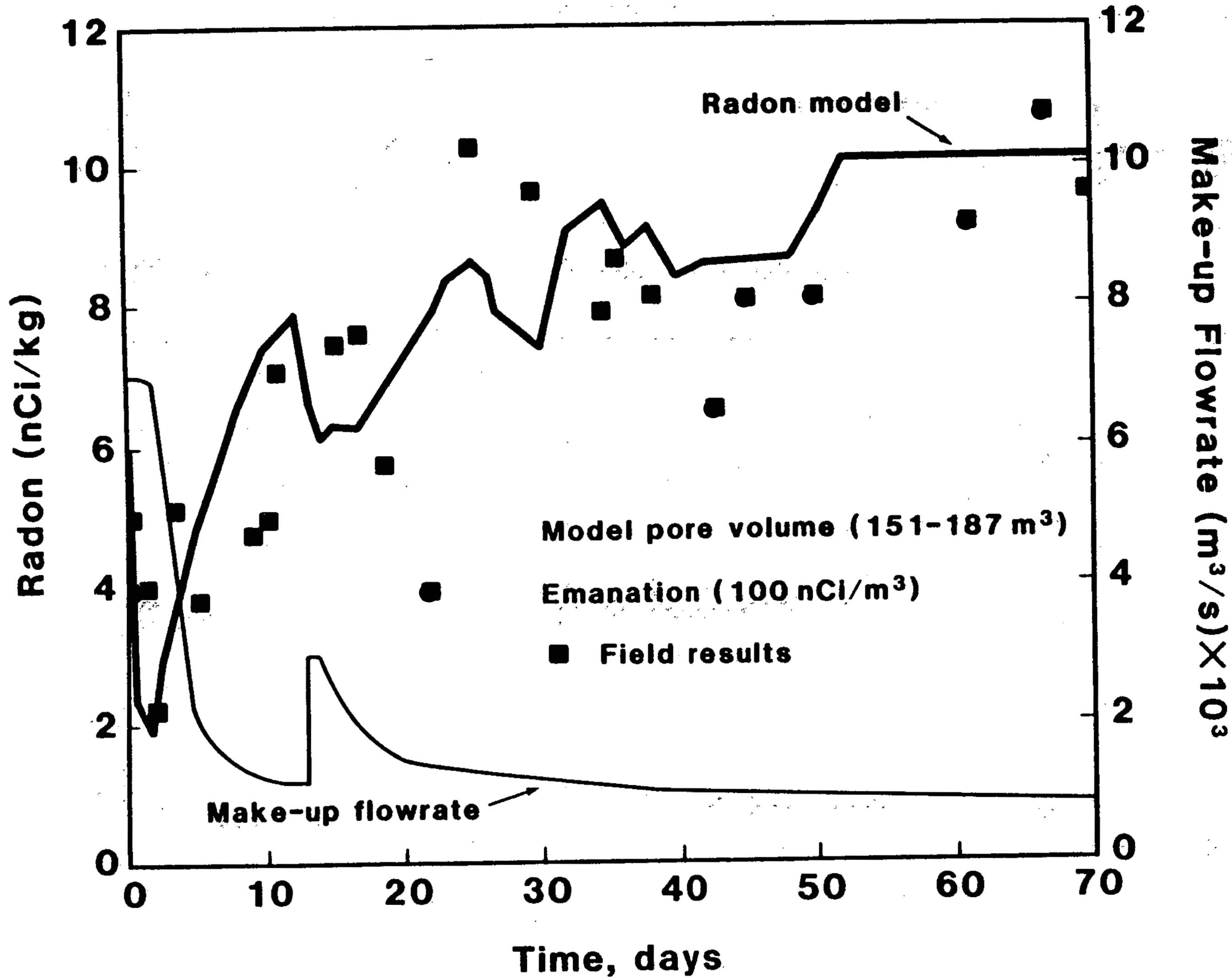



Fig. 2-5: Radon Concentration vs Time Segment 5 Test.

model of radon transport in geothermal reservoirs. Numerical simulation is a useful adjunct in the study of radon as an internal tracer of reservoir hydrodynamic and thermodynamic processes. The model was designed to simulate transient response of radon concentration in wellhead geofluid as a function of reservoir conditions. During FY83, the model was used to simulate radon concentration response during production drawdown and two flowrate transient tests carried out in earlier years at The Geysers vapor-dominated field. The results of these simulations were reported by Semprini and Kruger (1983).

The radon transport model was based on radial flow in a homogeneous reservoir in analogy to the well-test models for vapor-dominated systems as discussed by Moench and Atkinson (1978) and Moench (1980). Parameters for The Geysers' test, obtained from literature sources, are summarized in Table 2-1.

TABLE 2-1

PARAMETERS FOR NUMERICAL SIMULATION

| Formation Properties | |
|---|---|
| Porosity | $\phi = 0.10$ |
| Rock Density | $\rho_r = 2300\ kg/m^3$ |
| Rock Specific Heat | $C_r = 1000\ J/kg\ °C$ |
| Reservoir Thickness | $h = 500\ m$ |
| Matrix Permeability | $k = 1 \times 10^{-14} m^2 - 1 \times 10^{-13} m^2$ |
| Rock Radon Emanation | $E_m = 0.005 - 0.015/kg$ |
| Dispersivity | $\alpha = 1\ m$ |
| **Initial Conditions** | |
| Temperature | $T = 241°C$ |
| Liquid Saturation | $S_l = .05, .20, .50$ |
| **Production** | |
| Wellbore Radius | $r_w = 0.112\ m$ |
| Skin | $S = 4.50$ |
| Effective Wellbore Radius | $R_w' = r_w e^{-S} = 10\ m$ |
| Production Rate | 10 kg/sec - 36 kg/sec |

Fig. 2-6 shows the spatial response of pressure, saturation, mass flow, and radon concentration, with simulation outputs at 1.2, 12, and 36 days during a constant rate drawdown. The pressure response shows drawdown extending into the formation, resulting in vaporization with a gradual decrease in liquid saturation. The mass flux responds to the outward propagation of the boiling zone during exploitation, with steam (and radon) traveling to the wellbore from further in the reservoir. Radon concentration decreases near the wellbore at early drawdown time (1.2 days) by dilution from the vaporization of steam. Over the 12 day period, the radon concentration increases as the volume of steam-filled reservoir near the wellbore increases. At 36 days, the boiling zone has progressed further into the reservoir and the radon concentration continues to increase towards its saturation value.

Sensitivity analysis of this long-term drawdown was made for the parameters of permeability, saturation, and flowrate. The results, shown in Fig. 2-7, indicate a strong dependence on permeability at all times, a weak dependence on saturation, and a moderate dependence on flowrate at early times becoming smaller at later times. The dependence on permeability indicates the achievement of rapid boiling under rapid pressure response. The lack of response to saturation is surprising in that it was expected that the rate of boiling zone propagation would be influenced by the initial liquid saturation. It appears that this influence may be offset by radon enrichment through phase partitioning from liquid water to steam.

Results of the short-term drawdown tests of Stoker (1975) and Warren (1980) are shown in Figs. 2-8 and 2-9. The simulations show good agreement with observed data. In Fig. 2-8 the short-term cyclic test, the early decrease in radon concentration by dilution near the wellbore is apparent,

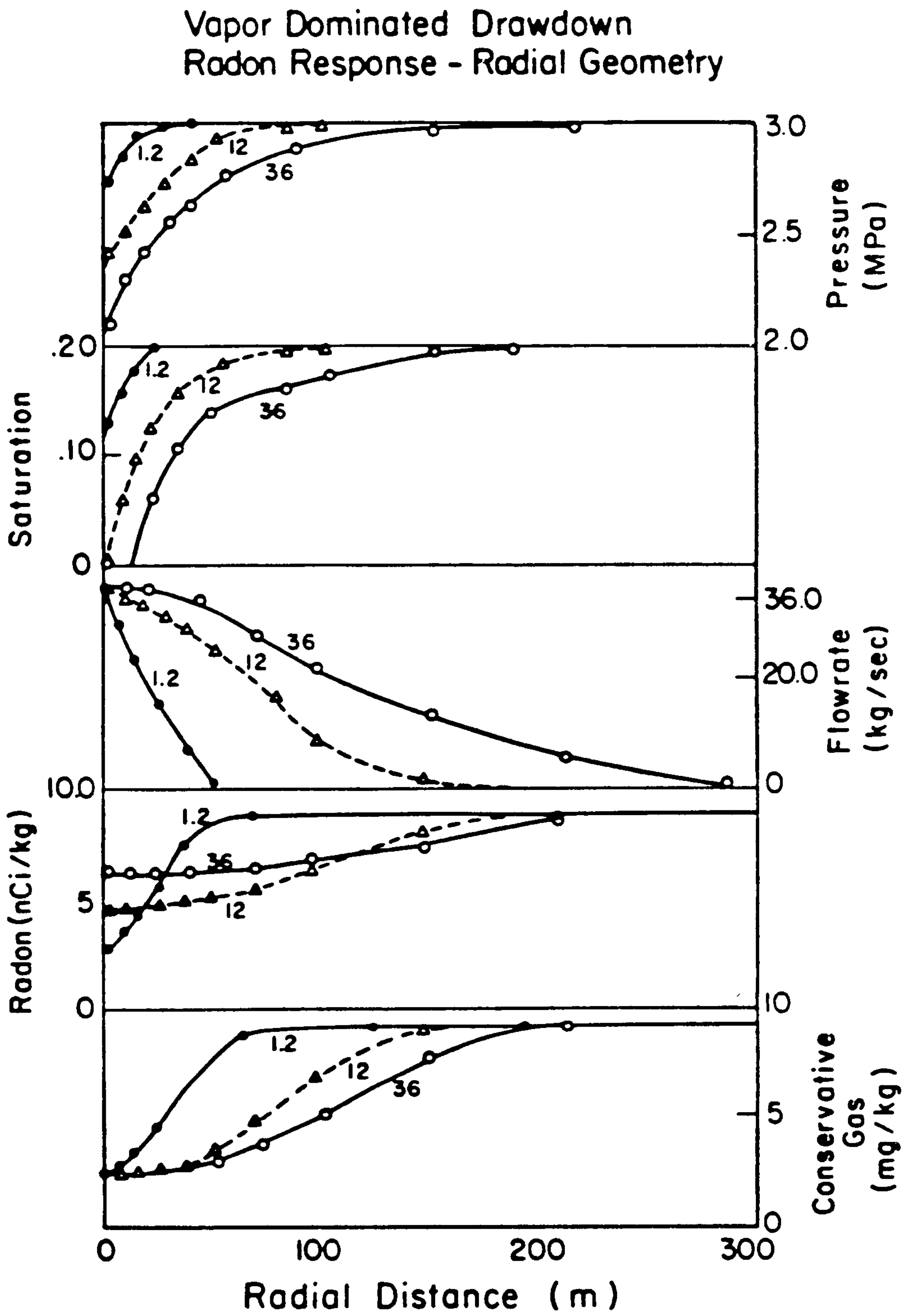



Fig. 2-6: Radon Response to Radial Drawdown in a Vapor Dominated System.

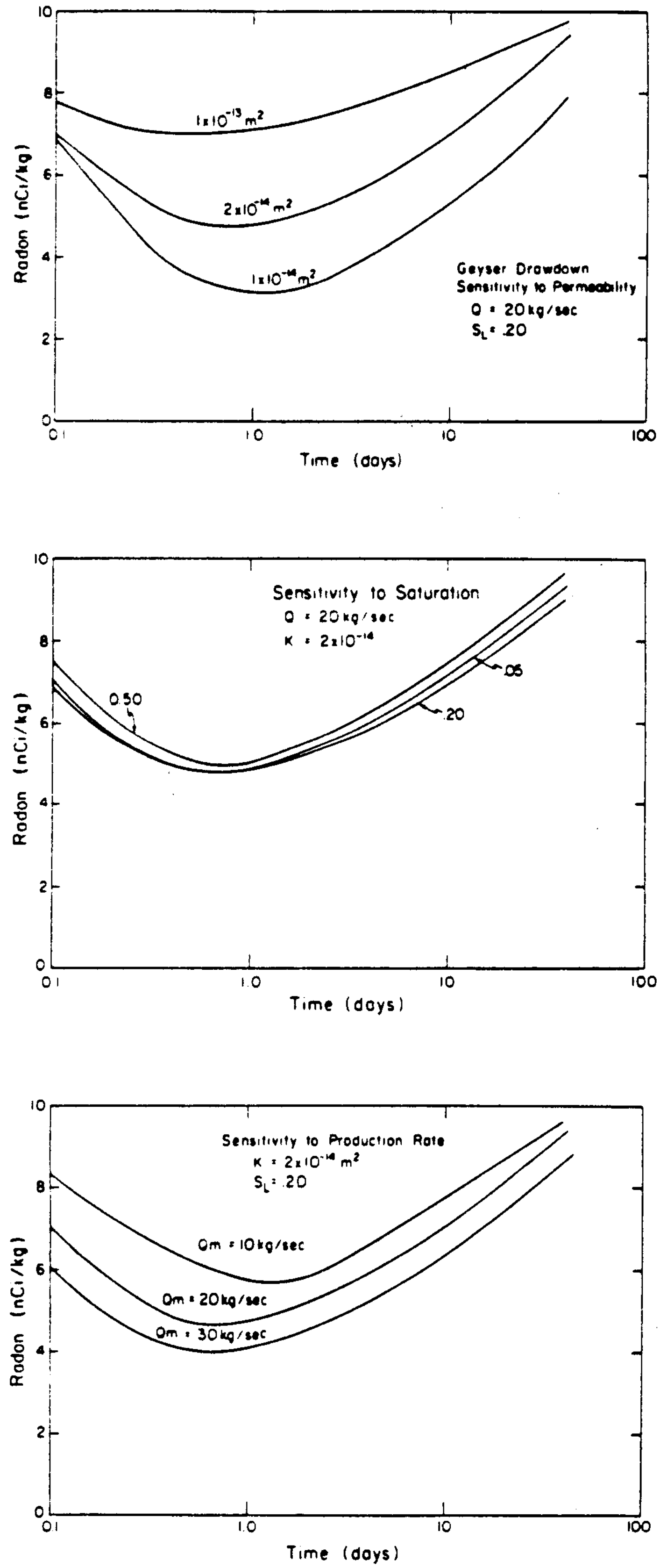



Fig. 2-7: Sensitivity Analysis of Wellbore Radon Response to Permeability, Saturation and Flowrate-Vapor Dominated Reservoir.

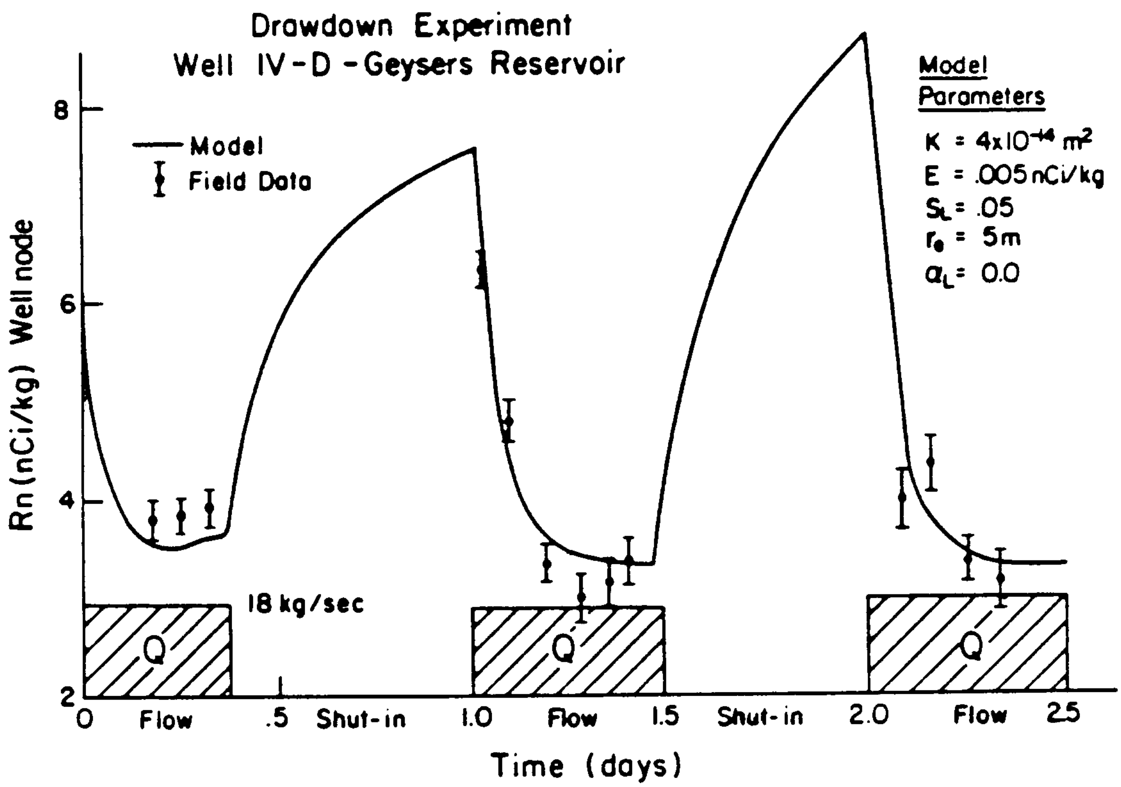



Fig. 2-8: Simulation of Cyclic Drawdown Response at the Geyser.

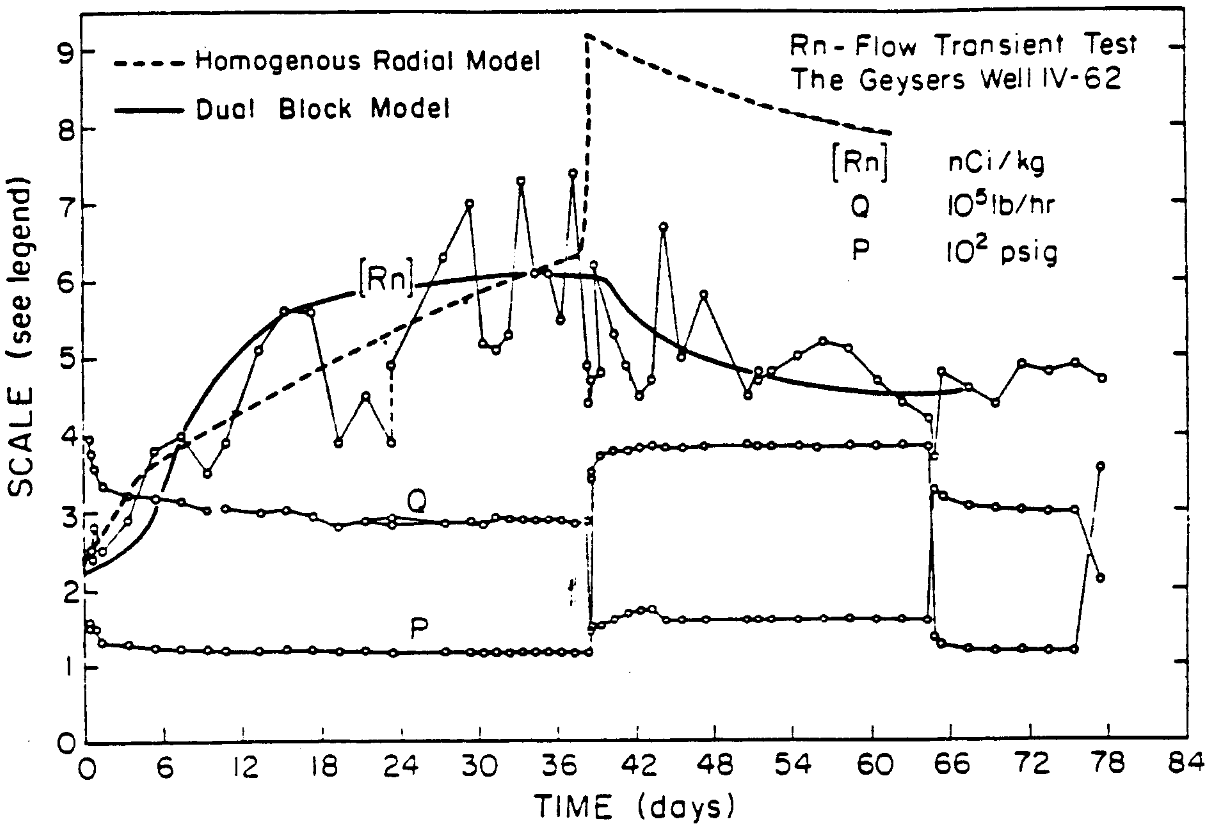



Fig. 2-9: Simulation of Long-Term Radon Drawdown Test at the Geysers.

especially in the second transient cycle when earlier wellhead sampling was achieved. The model also simulates the enrichment of radon during the shutin periods, indicative of steam condensation with pressure buildup near the well.

The 75-day flow experiment reported by Warren and Kruger (1979) had two changes in flowrate for mass transient analysis. The experimental data showed a growth in radon concentration during the first 38-day period, a transient decrease over the next 27 days at reduced flowrate, and a rise when the original flowrate was restored.

The simulation based on the homogeneous reservoir produced an acceptable fit to the observed data during the constant rate drawdown period. During the period of reduced flow, the model predicted an increase in radon concentration with pressure buildup, when a decrease was actually observed. The simulation suggested that an inhomogeneous reservoir configuration was needed to model the observed decrease in radon concentration. As a result, a two-block model was developed for this drawdown, in which three parameters were varied: (1) emanation coefficient, (2) block volume, and (3) liquid saturation. The solid line in Fig. 2-9 shows the simulation results for the two-block model. The fit was based on an emanation value in the outer block that was a factor of 10 higher than emanation in the inner fissure block, and essentially no liquid saturation in the fissure block. The former adjustment is supported from the work of Sammis et al. (1981) who observed lower emanation with increased permeability in granite cores. The small liquid saturation in the fissure block is supported from the model of Truesdell and White (1973) and simulations of Pruess and Narasimhan (1982) for steam production from fractured systems.

(d) Wellhead Radon and Reservoir Fluid Specific Volume, by Lewis Semprini, research assistant, and Professor Paul Kruger

Effort continued in the current year on the evaluation of radon as an indicator of the thermodynamic conditions in the reservoir. The dependence can be written in linear form (Semprini et al., 1982) as:

$$[Rn] = \left(\frac{E_m \rho_r}{\phi}\right) \overline{V}_f \qquad (2\text{-}2)$$

The three parameters in the coefficient involve the emanation flux of radon from rock to pore fluid, the formation density, and the reservoir porosity. Fig. 2-10 shows the results of recent data that have been added to the published distribution of radon concentration and specific volume. Values have been added for the HGP-A well in Puna, Hawaii, and the test well at the Roosevelt Hot Springs in Utah. The agreement of the new data is reasonable. Based on regression analysis assuming a constant coefficient in Eq. (2-2), the specific volume of fluid in the reservoir can be expressed as $\overline{V}_f = \alpha\,[Rn]$, and the reservoir fluid enthalpy is given by:

$$H_f = \frac{H_g - H_l}{\overline{V}_g - \overline{V}_l}\,(\alpha[Rn] - V_l) + H_l \qquad (2\text{-}3)$$

The value of $\alpha$ reported by Kruger and Semprini (1983) for data from Wairakei and Cerro Prieto two-phase reservoirs is 0.0072 $m^3$/nCi for a linear relation of zero intercept.

As additional data from other fields are added to the correlation analysis, it becomes apparent that the coefficient of Eq. (2-2) cannot be constant for all geothermal fields. The two key variables for examining specific reservoirs are the formation porosity and the emanation flux. Since it is

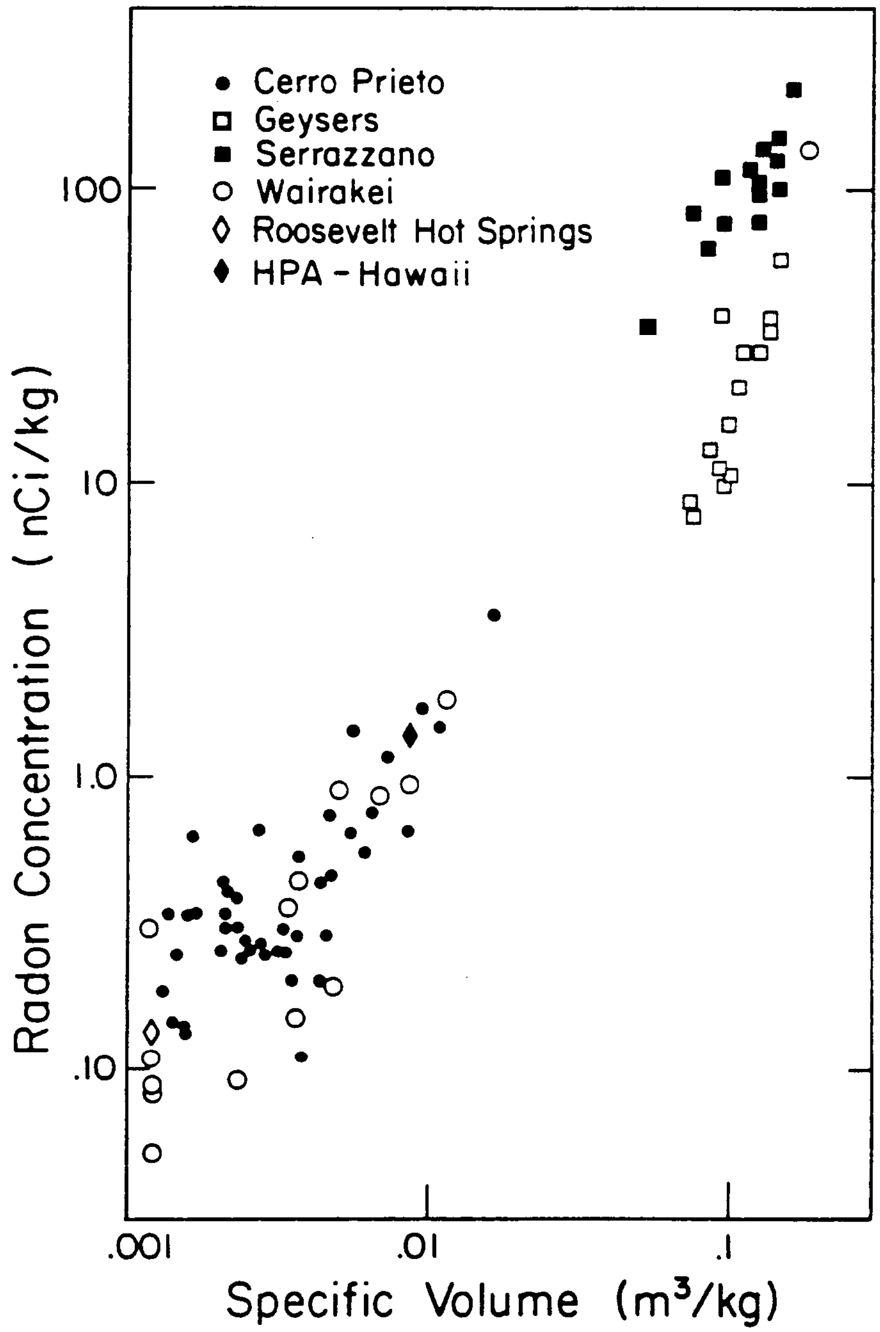



Fig. 2-10: Radon Concentration vs Specific Volume in Six Geothermal Fields One with New Data Point.

very difficult to estimate in-situ porosity, the parameter most amenable to evaluation is emanation. During the current year, cores have been obtained from the Cerro Prieto field in Mexico to augment the cores already obtained from the Serrazzano field in Italy. Emanation from the cores as a function of rock type and temperature was measured during the year in a small physical reservoir in our high-temperature air bath. Preliminary data are given in Table 2-2. The work was not completed as of the end of the contract period.

Table 2-2

EMANATION OF CERRO PRIETO CORES

| Location | Depth (m) | Rock Type | Weight (gm) | Emanation Water (20°C) | Emanation Steam (110°C) |
|---|---|---|---|---|---|
| M-5 | 1105 | Limolite | 337 | 0.024 ± .002 | 0.071 ± .0012 |
| M-11 | 1103 | Limolite | 386 | 0.029 ● .001 | ND |
| M-120 | 1980 | Sandstone | 751 | 0.0127 ± .002 | ND |
| E-2 | 1938 | Sandstone | 731 | 0.0067 ± .005 | 0.0083 ± .00015 |
| E-2 | 1941 | Shale | 448 | 0.0093 ± .0014 | 0.027 ± .0009 |

The data for the November, 1983 radon measurement at the HGP-A well in Puna, Hawaii are given in Table 2-3 together with the data from earlier measurements (Kruger et al., 1977) made before commercial operation. The earlier data were in agreement with the suggestion of Stoker and Kruger (1975) that in liquid-dominated reservoirs, in which the swept volume $V_\phi$ does not depend strongly on flowrate $Q$, the change in concentration with flowrate is expected to vary according to $(1 - e^{-\lambda V_\phi / Q})$. The new data taken under different sampling conditions after sustained production shows a significant increase in radon concentration. This data supports results from Cerro Prieto, of an increase in wellhead radon concentration as a boiling zone propagates out from the wellbore. It would have been interesting to compare the specific volume for the earlier period to the current period if the data had been available.

Table 2-3

RADON CONCENTRATIONS HGP-A WELL, HAWAII

| Sample Date | Enthalpy (kJ/kg) | Flowrate (klb/hr) | [Rn] (nCi/kg) |
|---|---|---|---|
| July, 1977 | ND* | 285±45 | 0.89±0.16 |
| " | ND* | 137±3 | 0.85±0.09 |
| July, 1982 | 1720 | 158±4 | 1.68±0.03 |
| Nov., 1983 | 1623 | 112±3 | 1.42±0.10 |

* 2-phase flow samples

In concluding this Task 2 under DOE sponsorship, it is noted that the measurement of radon for reservoir engineering purposes has become widespread in geothermal nations. Laboratories to measure radon have been constructed in several major geothermal countries, among them Italy, New Zealand, and Mexico. It is anticipated that the pioneering work in radon reservoir engineering initiated under the Stanford Geothermal Program will bear dividends in the ability to understand better the emanation and transport characteristics of geofluids in operating geothermal resources.

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

### Task 3.1 Well Test Analysis

(a) Inertia and Friction in the Flow Period of a Drill-Stem Test, by Miguel Saldana-Cortez, research assistant, and Professor H. J. Ramey, Jr.

A comprehensive report on this project was presented in the second annual report, September 1982, page 19. Consequently, little detail will be presented herein. This project was finished and report SGP-TR-69 completed. Two solution methods for drill-stem testing which include friction, inertia of liquid, and slug size (or cushion size) were developed. Linear problems were solved by Laplace transformation, and non-linear problems were solved by a finite-difference formulation which permits simulation of both the flow and shut in periods of a drill-stem test. Analysis of results provided useful criteria for estimating the relative importance of inertial and frictional wellbore effects, and removed certain assumptions made in previous studies. The computer code is included in the 351-page report on this study.

(b) Infinite Conductivity Fracture in a Naturally-Fractured Reservoir, by O.P. Houze, research assistant, Professor R. N. Horne, and Professor H. J. Ramey, Jr.

Many geothermal wells owe extraordinary productivity to the presence of one or more high-conductivity natural fractures. Because geothermal systems are also frequently fissured (two-porosity) mediums, this study was initiated to investigate the behavior of a two-porosity medium producing through a single, high-conductivity vertical fracture. Solution was obtained for pseudo-steady interporosity flow.

The Line Source solution is reviewed, and the Line Green's function for a double-porosity medium is introduced and studied. These functions are used to solve the uniform flux problem, introducing the "Fracture Source solution" and the "Fracture Green's function", which are respectively the dimensionless pressure drop and its derivative due to a constant rate production by a uniform flux fracture. The infinite conductivity case is then solved using the uniform flux results. Type-curves are presented. This project was completed, and report SGP-TR-73 presents detailed results. A paper, SPE No. 12778, will be presented at the California Regional Meeting of the Society of Petroleum Engineers in Long Beach, California, April 1984.

(c) Slug Test Data Analysis in Reservoirs with Double Porosity Behavior, by K. Mateen, research assistant, and Professor H. J. Ramey, Jr.

The slug test has become popular in testing of deep aquifers. The hydrologic expression of this test is to suddenly remove a float from a static column of water in a well and record the water level vs time thereafter. The drill-stem test is a petroleum engineering expression of the same sort of test, except the entire fluid column is removed at the start of the test. Because geothermal systems are frequently dominated by fractures, the behavior of a slug test in a fractured (double-porosity) or communicating layered system was computed. Solutions were obtained for either pseudo-steady or transient interporosity flow. The solutions were used to produce type curves for interpretation of results from field testing.

Fortunately, it was possible to produce type curves exactly like the present type curves for a slug test, but with the addition of interporosity flow lines. These new type curves appear to explain some anomalous results obtained previously with type curve matching. These curves should become of great utility in interpreting field data. A report, SGP-TR-70 was prepared, and a paper will be offered to the Society of Petroleum Engineers, paper SPE 12779.

Fig. 3-1 presents the interporosity flow curves for pseudo-steady interporosity flow, and Fig. 3-2 presents one of six new type curves for the double-porosity slug test. Full-scale type curves are being produced in two colors and will be available on request.

(d) Pressure Transient Analysis of Reservoirs with Linear or Internal Circular Boundaries, by Abraham Sageev, research assistant, and Professor Roland N. Horne

This project set out to discover what can be learned from a rate test in a well neighboring a steam cap. The economic evaluation of a geothermal resource depends upon the interpretation of pressure transient tests. Even a small local steam cap may have a significant effect on the pressure response of a nearby well. During the research, the project deepened and diversified. We examined several aspects of pressure transient analysis of a well near a circular discontinuity, which may be a steam cap in a liquid dominated system, or a liquid subregion in a steam or two-phase system. The following conclusions were reached:

Linear Boundaries

1. The distance between a production well and a linear boundary may be estimated making use of a new semilog type curve matching technique.
2. The new semilog type curve matching technique supercedes an existing double straight line analysis method.
3. The use of the method allows flow tests to be an order of magnitude shorter in duration.

Internal Circular Boundaries

4. The size of and the distance to an internal circular boundary may be

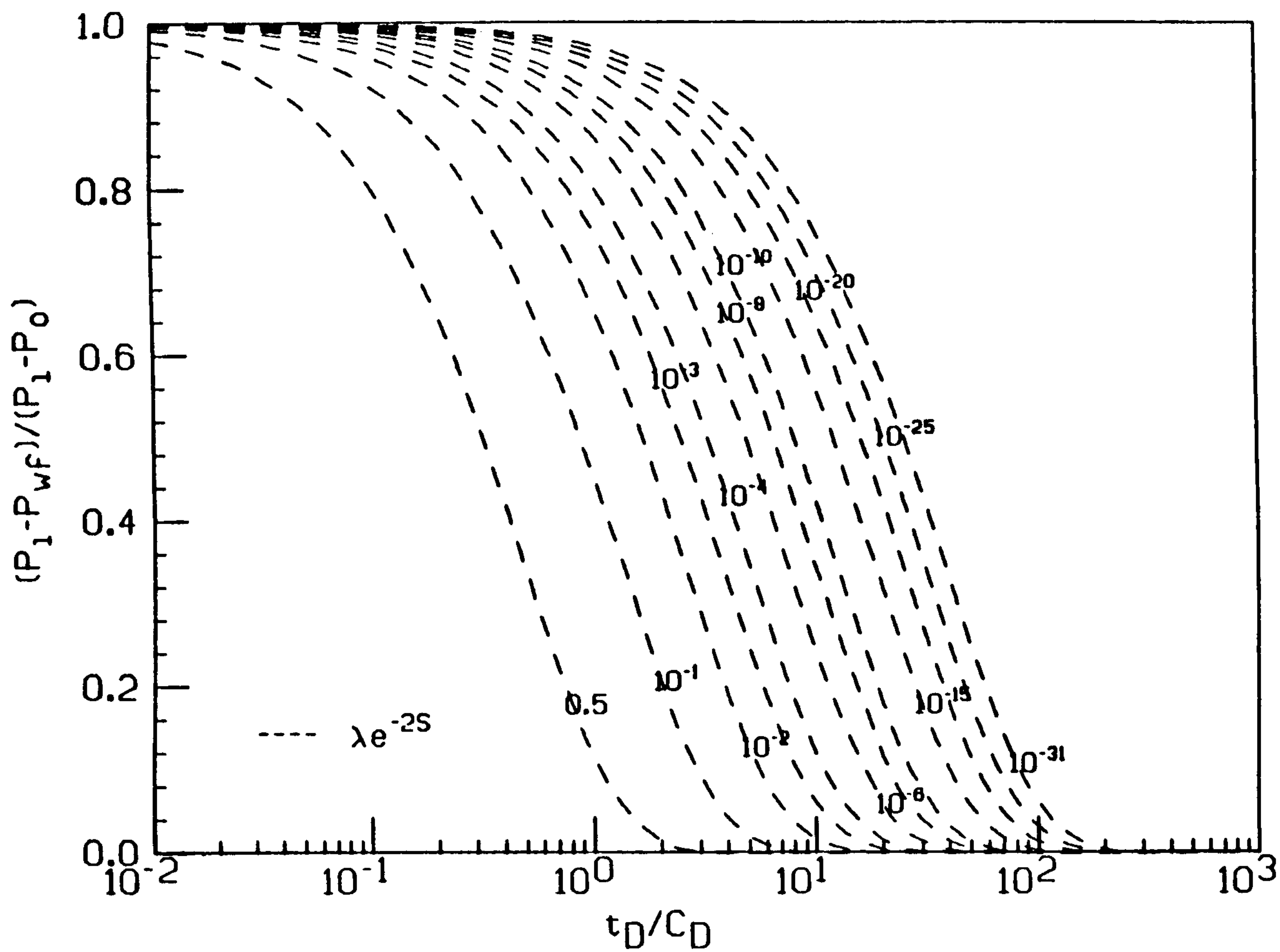



Fig. 3-1: Transition Pressure in Double Porosity Reservoir (PSS).

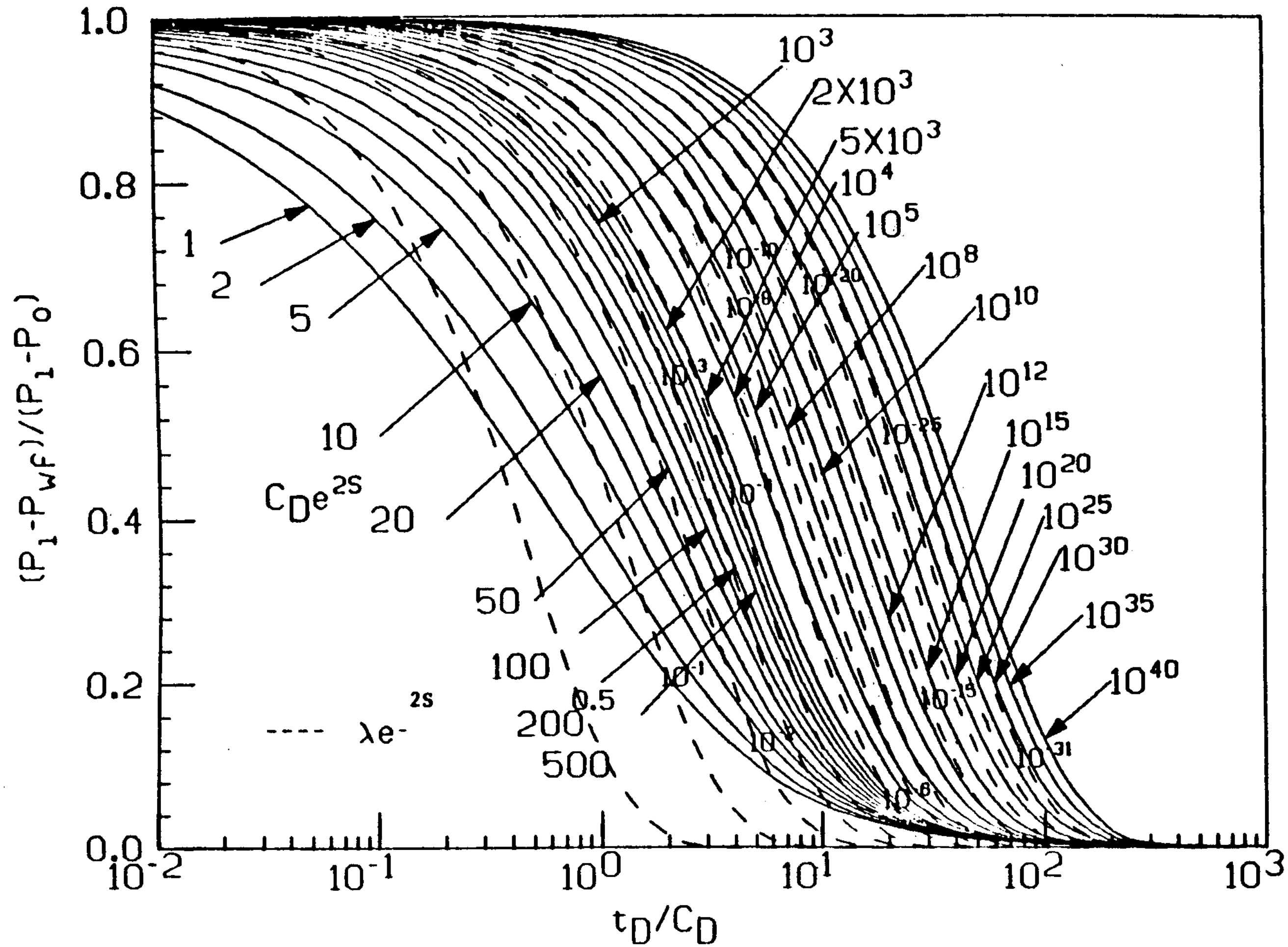



Fig. 3-2: Semi-Log Double Porosity Type Curve (PSS).

estimated using semilog type curve matching data from a production well.

5. An impermeable boundary (such as a cold water region around an injection well in a steam or two phase system) with a relative size of $F < 0.3$, cannot be detected. The variable F is the ratio of the radius of the internal boundary to the distance between the well and the center of the internal boundary.

6. A constant pressure boundary (such as a steam cap in a liquid dominated system) with a relative size of $F > 0.9$, may not be distinguished from a constant pressure linear boundary.

7. Interference testing in the presence of a steam cap (all the wells are in the liquid dominated portion of the reservoir) may lead to an erroneous approximation of the total compressibility of the system. Such tests should be handled with care, and under certain conditions, may allow the correct evaluation of reservoir properties and an approximation of the size of the steam cap.

8. The new method may be applied to interpret pressure interference between various large sections of a geothermal system.

9. The superposition method may be applied to interpret tests of wells near a semicircular boundary (such as a steam cap bounded on one side by a fault).

General

10. All semilog type curve matching may be done on a single type curve shown in Fig. 3-3. This generalized type curve can be used for approximating the distance to, and the size of both linear and circular internal boundaries.

A semi-analytic method was used to produce a semilog type curve. Most

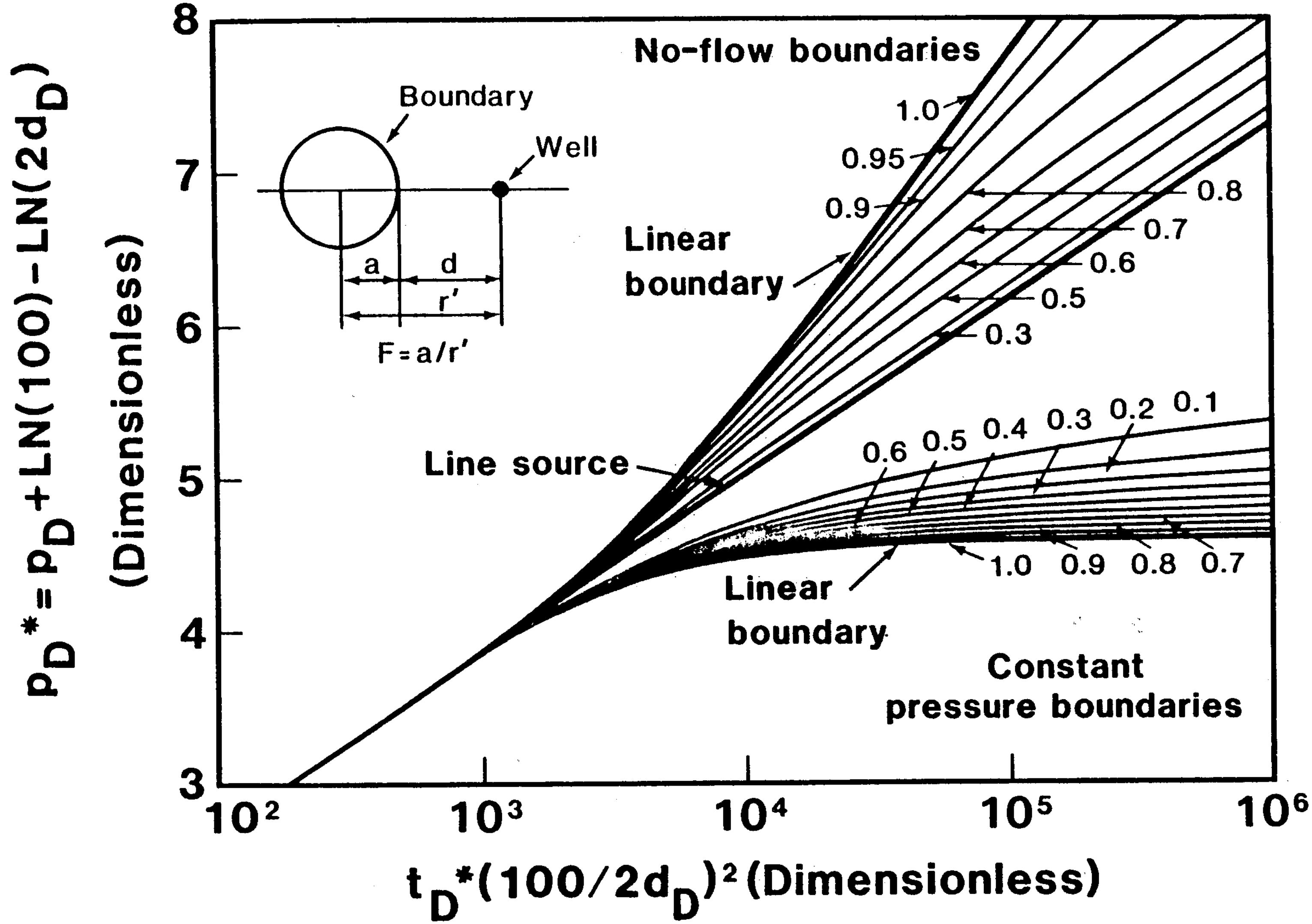



Fig. 3-3: Type Curve for Discontinuity Effects.

of the early part of 1982 was spent on the mathematical derivation of the problem, producing analytical solutions in Laplace space. These solutions are complex, and real time inversion was done by a numerical inversion technique. A detailed description of this project is presented in SGP-TR-65, and a paper, SPE 12076, has been prepared.

Research is continuing into various aspects of this pressure transient analysis topic. We are examining a type of test where one well produces at a constant pressure, and another well produces at a constant rate. This case is termed the rate-pressure model. We are examining pressure interference on a large scale, reservoir to reservoir, and well to well pressure interference in the presence of steam caps.

(e) Total System Compressibility, by Luis Macias-Chapa, research assistant, and Professor Henry J. Ramey, Jr.

Work was conducted on the implementation of a program to simulate an instantaneous vaporization, i.e., a flash process, for n components, either isothermal or adiabatic. The program combines energy and mass balances for a closed system, and solves simultaneously two equations for temperature and fractional vaporization, which also gives the mol fractions of n components in the liquid and the gas phase.

Equilibrium ratios are calculated with fugacity coefficients for the gas phase, which are calculated with the virial equation of state, that gives appropriate results for polar compounds in the pressure range under consideration (p 100 bar), and for the liquid phase are calculated with activity and fugacity coefficients. The thermodynamic properties required for the calculations are supplied by nine subroutines within the same package. The purpose of this program is to evaluate fluid compressibilities, from a fluid behavior point of view, under different thermodynamic paths.

Task 3.2 Bench Scale Experiments

(a) Effect of temperature on relative permeability, by Mark A. Miller, Craig Nunes, and B.J. Beal, research assistants, and Professor Henry J. Ramey, Jr.

A major report on this project was completed by Mark A. Miller, SGP-TR-64, during the fiscal year. This work was presented at the Annual Fall Meeting of the Society of Petroleum Engineers, San Francisco, Oct. 1983, paper SPE 12116. Dr. Miller has accepted a position as Assistant Professor of Petroleum Engineering at the University of Texas. Because the work was described in detail in last year's Annual Report, only currently planned work will be described.

Presently-planned studies include an investigation of the effect of gravity under-ride on horizontal displacements in the 2-ft long by 2-in wide core holder. Runs are planned for vertical as well as horizontal positions. This work was not included in a list of additional work in the last report because Miller identified certain problems in the last experiments completed in his program. It is still planned to study consolidated mediums.

(b) Effect of temperature level on capillary pressures by the centrifuge method, by Brian Skuse, research assistant, and Professor Henry J. Ramey, Jr.

This study was initiated to check the effect of temperature on capillary pressure-saturation measurements. A high-temperature centrifuge has been made available to the Stanford Geothermal Program by Beckman Corporation. A visiting professor, Dr. Abbas Firoozabadi, has experience with this method and is advising the project. It also appears possible to determine relative permeability information in this manner.

(c) Measurement of adsorption of fluids on rock surfaces, by Professor Henry J. Ramey, Jr.

This project is an extension of the study of C. H. Hsieh (see SGP-TR-38, and publication: "Vapor Pressure Lowering in Geothermal Systems" by C. H. Hsieh, and H. J. Ramey, Jr., Soc. Pet. Engr. J., Feb. 1983, pp 157-167.) A similar study by Herkelrath and Moench, Water Resources Research, Dec. 1983, has indicated the importance of adsorbed water on the reserves in a vapor-dominated system. It is the intention to make more measurements of adsorption with natural geothermal system cores. During the summer of 1983, F. G. Miller and H. J. Ramey visited Pisa, Italy, and have arranged for delivery of cores from Larderello for adsorption measurements. We expect to receive cores from other vapor-dominated fields for similar studies. It is also planned to repeat experiments by Herkelrath and Moench on transient flow of steam in porous media.

## TASKS 4/5: FIELD APPLICATIONS

### (a) DOE-ENEL Cooperative Research

In Stanford's First Annual Report on Geothermal Reservoir Engineering Research, issued under DOE Contract No. DE-AT03-80SF11459 for the period October 1, 1981 through September 30, 1982, the status of Stanford-ENEL cooperative reservoir engineering research is discussed in detail. This research was initiated in conformance with Project 3 of the DOE-ENEL Cooperative Agreement on geothermal energy which became effective in 1975. Stanford-ENEL joint research began officially on October 1, 1976, the effective date of the first contract awarded to Stanford by the Energy Research and Development Administration (now DOE). The Cooperative Agreement was for a period of five years. In 1980, at the end of this period, the Agreement was extended for another five years. Stanford-ENEL reservoir studies progressed remarkably well during the first part of the extension period, until 1981, when progress lagged and by 1982 practically came to a standstill, for a number of reasons. However, there was no lack of interest on the part of either the Stanford or Italian researchers who worked directly on the project.

During a Stanford visit to ENEL in April 1981, about seven topics were examined as prospects for FY'82 joint research. Because of limited technical help and funding, proposals were written and submitted to ENEL management for only two. Stanford did not learn until three months later that they had not been accepted. In an attempt to resolve whatever difficulties were delaying or preventing ENEL acceptance, further conferences were held in July 1981. A new joint project was agreed upon by the Stanford-ENEL research teams. The subject was "Tracer Experiments in the Latera Field." Stanford learned early in 1982 that it too had been disapproved. In 1982 another conference was held in Italy in an effort to prod the Stanford-ENEL program into moving forward again. No appreciable success was gained.

With little doubt ENEL management's decisions to decline new research were influenced by a number of factors. Although they were not disclosed formally to Stanford, informal discussions indicated that one of the two most important ones was ENEL's change of attitude regarding publication of Italian field data. By 1981 ENEL was beginning to consider these data as proprietary information. The second factor, which may have been related to the first, was ENEL's inability to obtain desired data on American fields, most of which are proprietary and unavailable. The remainder are scarce. Thus, ENEL faced a dilemma. If the Stanford-ENEL data exchange was not truly bilateral, and neither the Americans nor the Italians were at fault, it still could have provoked ENEL to decline proposals leading to dissemination of Italian field data.

Because of disappointing experiences and what appeared to be a cloudy future, Stanford made two recommendations intended to clear matters in its First Annual Report. The first was that the DOE-ENEL Cooperative Agreement be studied to determine whether it contained provisions which would apply to the problem of resuming joint research. The second was that a meeting of DOE and ENEL be convened to discuss possible solutions with the hope that one could be found which would be mutually acceptable to both countries. If this were not possible, it was believed that Stanford-ENEL reservoir engineering research should be formally discontinued, in a spirit of good will and understanding.

None of this came to pass, however, because ENEL in the latter part of FY'82 reversed its position and suggested further cooperative research with

Stanford. Following extensive Stanford-ENEL discussions in Pisa, Italy, in September 1983, a draft of a joint proposal was accepted by ENEL management. It was a carry-over of the proposal made in July 1981 and was entitled "Tracer Experiments in Reinjection in Liquid- and Vapor-Dominated Geothermal Fields." It also was to be a part of a program headed: "Implementation during the 1983-1985 Period of Project 3 of the DOE-ENEL Agreement on Cooperative Research and Development in Geothermal Energy." Thus, work on the new project would continue through the five-year extension period of the Agreement. It is anticipated that binational formal approval will be forthcoming early in FY'84, and that a second proposal will be prepared and submitted.

As FY'82 closed, the prospects for fruitful cooperative research in the coming year appeared to be good. Although no new cooperative work got under way in FY'82, advances were made on work already in progress.

(b) Geothermal Reservoir Evaluation Considering Fluid Adsorption and Composition, by Michael J. Economides, and Professor Frank G. Miller

Previous reservoir engineering studies of vapor-dominated geothermal reservoirs have generally been analogous to conventional model studies of natural gas reservoirs. One inconsistency in some past work has been a discrepancy between the estimated quantity of steam-in-place and the geological constraints on the estimated reservoir bulk volume.

The concept that considerable adsorbed water may exist in a vapor-dominated zone is examined in detail. Experimental and theoretical evidence of adsorption phenomena are decribed. Then, the implications of adsorption on material balance calculations and on well test analysis are determined by incorporating adsorption effects into existing models.

The resulting new methods of analysis provide a more realistic estimate of the nature and extent of the vapor-dominated zone. In particular, the new methods result in a reduction in the estimated formation thickness and suggest that fracture porosities can be underestimated using conventional models for naturally-fractured reservoirs.

In addition, the presence of noncondensable gases in the geothermal fluid has a profound effect on the thermodynamics associated with vapor-liquid equilibrium and adsorption. Noncondensable gases can cause the dew point pressure of a noncondensable gas-water mixture to be elevated as much as 80 psi or more above the vapor pressure for pure water at the reservoir temperature depending on the composition of the mixture. Hence, the presence of these gases in geothermal steam extends the pressure range where vapor adsorption phenomena are in effect. Monitoring of gas production in the produced geothermal fluids provides additional data useful in evaluating adsorption effects in the formation.

Consideration of adsorption phenomenon in reserve estimation can be of importance. This work shows that a reserve estimate based only on geologic evidence and the thermodynamic properties of steam could be as much as an order of magnitude lower than the actual mass of water present. A report on this project will be issued in the coming fiscal year.

(c) Reservoir Engineering Analysis of a Vapor-Dominated Geothermal Field, by John F. Dee, research assistant, and Professor William E. Brigham.

A model was developed to compute both reserves and deliverability from a vapor-dominated geothermal field. This study, initiated in June 1982 and completed in May 1983, is a continuation of a previous study by William E. Brigham (see report SGP-TR-72). The data used are fictitious, although their general character is similar to that seen in real fields. The purpose of this study was to show that an empirical lumped parameter model is effective in describing pressure drawdown behavior in a vapor-dominated geothermal reservoir, and to demonstrate how addition of deliverability information can be incorporated in the Brigham model.

The reservoir pressure and production data used indicate that depletion is occurring in the example reservoir unit. A reasonable assumption of the flow behavior is that there exists a zone of boiling water deep in the reservoir, which supplies steam to the producing horizon where the wells are completed. The pressure drop seen at this producing zone is a combination of depletion of the boiling water and frictional flow effects. The frictional flow drawdown is an additional transient pressure drop due to frictional losses as the steam rises through relatively tight vertical fractures.

Using these concepts, a lumped parameter model was developed describing pressure drawdown in the reservoir. Depletion of the boiling water zone is assumed to fit linearly with p/Z. The transient linear vertical flow is calculated using a lag time concept to change transient flow into equivalent steady state flow. The lag time is unknown, but a lag time of 30 months has produced a reasonable fit. Various areas within the system have experienced different drawdown behavior, and therefore, the flow rates from these areas were separated from the total flow rate and were then incorporated into separate flow and pressure drop parameters.

The deliverability problem described by these example data is a <u>reservoir</u> problem, and a sustained flow rate can only be maintained until approximately the 30th year. However, subsequent to that time, the flow rate decline will be gradual, in the neighborhood of two percent per year. This is quite similar to the behavior of several geothermal reservoirs.

Many people feel there is considerable "perched and adsorbed" liquid water in inaccessible areas within the producing horizon. As the pressure drops, this "perched" water could boil and the resulting steam would then flow toward the highly permeable channels connected to the wells. Presumably, the flow connection between the perched water and the permeable channels is tenuous. In other words, we are describing a two-porosity system. The important point is that the reservoir model developed herein fits this physical picture equally well. The resulting equations would be identical.

(d) Two-Phase Flow in Wellbores by, by Jaime Ortiz-R., research assistant, and Professor Jon S. Gudmundsson.

The application of wellbore flow models has not received much attention in the geothermal literature. Several two-phase models have been presented, but reports of their uses are few. One reason for this may be that we are not aware of the problems wellbore flow models are best applied to. The purpose of this project was to develop a computer code for two-phase wellbore flow, and then try it on a few reservoir and production engineering problems. Our long-term aim is to find new methods of analyzing output measurements of two-phase geothermal wells.

The computer code developed is based on earlier work by Fandriana et al. (1981). The new code takes about ten times less execution time and accepts a wider range of input conditions than does the Fandriana code. The new code however is limited to the use of Orkiszewski's (1967) method, while the other has several options. This method of correlating vertical upward two-phase flow was found to be the best for geothermal wells by Fandriana et al. (1981). Upadhyay et al. (1977) came to similar conclusions.

The superficial velocity of steam (gas) and liquid water in two-phase flow is defined as:

$$V_{sg} = q_g/A \quad (4\text{-}1)$$

$$V_{sf} = q_f/A \quad (4\text{-}2)$$

where $q_g$ and $q_f$ are the respective volumetric flowrates and A the cross-sectional area. The total superficial velocity is defined by:

$$V_t = V_{sg} + V_{sf} \quad (4\text{-}3)$$

$V_t$ was used by Orkiszewski (1967) to correlate data for friction losses in the slug flow regime. For $V_t \leq 10$ and $V_t > 10$ different correlations were used. We found that when going from one to the other, there was a jump in the calculated pressure gradient. This jump becomes apparent in geothermal applications, partly due to the low viscosity of water. The correlations were developed for higher viscosity flow in the oil industry. We modified the Orkiszewski (1967) method slightly and used the following relationships:

$$\Gamma = -0.065\ V_t - 0.1 \quad (4\text{-}4)$$

$$\Gamma = (0.045 \log/\mu_f) / D^{0.799} -0.709-0.162 \log V_t - 0.888 \log D \quad (4\text{-}5)$$

where $\mu_f$ is the liquid water viscosity, and D the wellbore diameter. The first expression is new, the second one is the same as in the original method. In the computer code, the $\Gamma$ value is calculated from both expressions, and the larger of the two used. This modification gave smooth pressure gradients in the slug flow regime, and satisfactory agreement with field data.

The following are some of the features of the new two-phase wellbore flow code: (1) data from wellhead or bottomhole can be used as input, (2) pressure drop and other flow parameters are calculated at equal length intervals, (3) heat transfer to or from the formation is included, (4) total pressure drop is split into friction, potential and kinetic terms, and (5) up to eight different wellbore diameters can be used in one well. The effect of noncondensable gases is not included. The wellbore code was validated against three data sets from East Mesa, Cerro Prieto and Roosevelt Hot Springs. The match between field data and calculated values was satisfactory for East Mesa and Cerro Prieto, and reasonable for Roosevelt Hot Springs.

Geothermal wells are known for their extremely high flowrates and temperatures compared to oil and gas wells. This means that downhole measurements in flowing wells are rarely attempted. By analyzing output data from geothermal wells with the aid of a wellbore simulator, new insights may be gained into the behavior of wellbore/reservoir systems. Many reservoir and production engineering problems require knowledge of downhole flowing conditions. A few of the problems have been studied concerning wellbore, and feedzone conditions. In the wellbore problem, temperature, pressure and flow regime are of interest. Examples of use would be casing design, wellbore deposition and heat transfer to or from the formation. In regard to feedzone conditions, the wellbore simulator may be used to calculate downhole conditions at the production interval to examine reservoir behavior. Examples of use would be in discharge analysis, well test analysis and decline curve analysis. Details of this work are given by Ortiz (1983).

Well deliverability in the Svartsengi field in Iceland is greatly affected by wellbore diameter. The field is liquid-dominated and highly permeable. Increasing the wellbore diameter from 9-5/8" to 13-3/8" almost doubles the cross-sectional-flow area and the output. The measured deliverability curve for well 10 (diameter 13-3/8") is shown in Fig. 4-1. The highest flowrate measured was about 1,500,000 lb/hr at 140 psia wellhead pressure. The reservoir temperature at Svartsengi is in the range of 235-

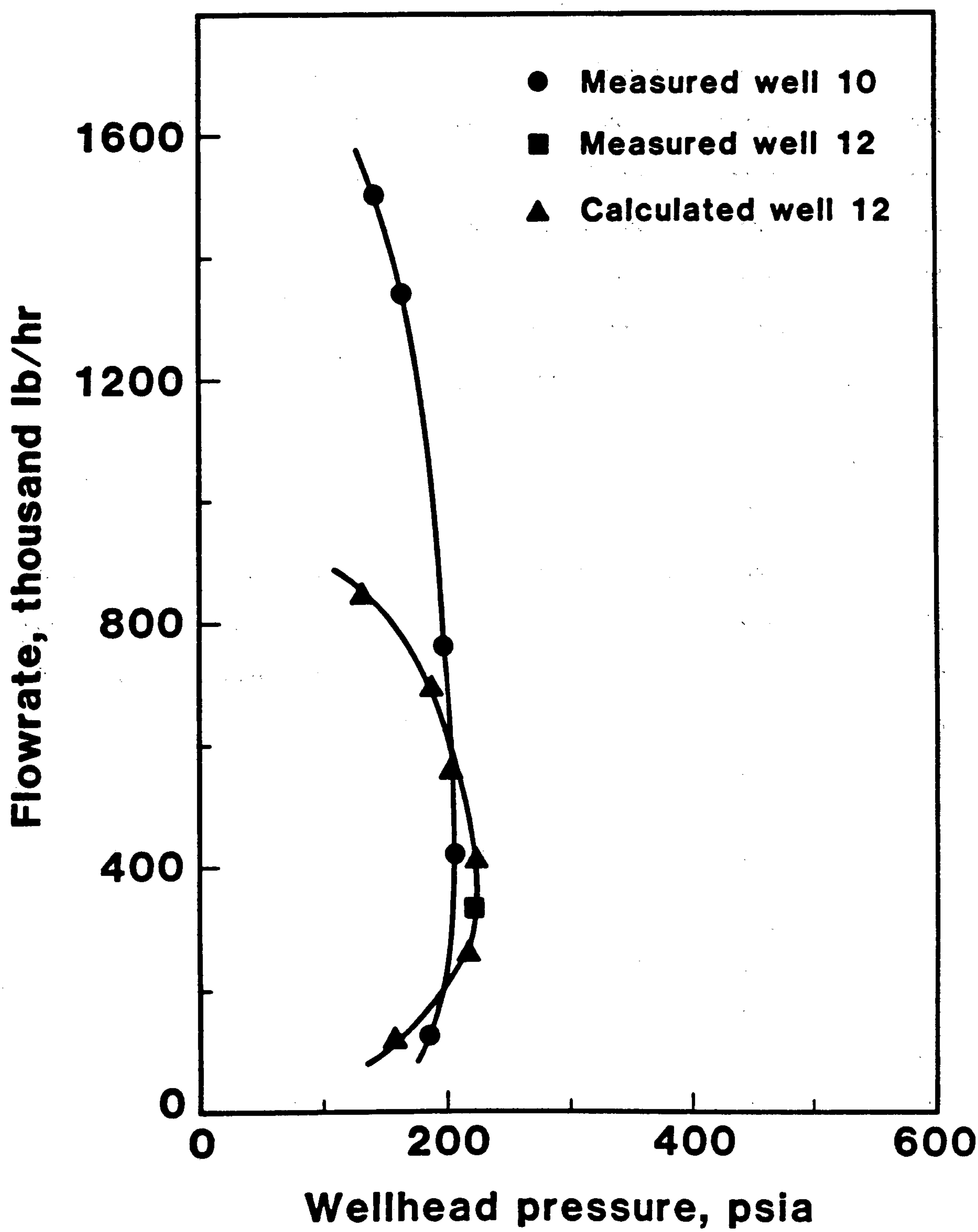


Fig. 4-1: Flowrate vs Wellhead Pressure for Svartsengi Field, Iceland.

240°C. Each of the 13-3/8" diameter wells produces enough to generate 10-15 MW of electricity.

The question of economic wellbore diameter is a major issue in geothermal engineering. Wellbore simulator results were compared to discharge measurements for large diameter wells. Most two-phase flow correlations are based on small diameter pipes and low flowrates without flashing. The simulator was used for discharge analysis of well 12 in Svartsengi, a typical 13-3/8" well. The necessary data for well 10 were not available. In discharge analysis, we use the concept of productivity index:

$$PI = \frac{W}{\bar{p} - p_{wf}} \tag{4-6}$$

where W is the total flowrate, $\bar{p}$ the static reservoir pressure, and $p_{wf}$ the flowing sandface pressure. The data available were one discharge (point) measurement and the static well pressure (and temperature) profile before discharge:

| | |
|---|---|
| Total flowrate: | 333,000 lb/hr |
| Wellhead pressure: | 220 psia |
| Fluid enthalpy: | 430 Btu/lb |
| Well depth: | 3936 ft |
| Reservoir pressure: | 1279 psia |
| Diameter 0-1991 ft: | 1.052 ft |
| Diameter 1991-3936 ft: | 1.021 ft |

The flowing sandface pressure at 3936 ft depth was computed. This resulted in a productivity index of 1456 lb/(hr-psi). Assuming that the index does not change significantly with time, the wellhead pressure was calculated at several flowrates. The results are shown in Fig. 4-1 with the one discharge measurement. The calculated curve for well 12 is similar to the measured curve for well 10, but quantitatively different at high and low flowrates. At low flows, the simulated bubble-slug flow regime becomes more important than at high flowrates. The two-phase mixture density in these flow regimes is higher than in the churn-annular regimes; hence the lower wellhead pressure. We suspect that in high velocity, large diameter, flashing-flow situations, such as geothermal wellbores, conventional flow regimes may not apply. Results from the Freon two-phase flow experiments at Brown University (Maeder et al. 1983) should help in resolving this question.

At high flowrates, above 800,000 lb/hr, the calculated flowrate is lower than that measured, as can be seen in Fig. 4-1. The simulator calculates the contribution of potential, friction and kinetic terms to the overall pressure drop up the wellbore. We have graphed the contribution of potential energy and friction to the pressure drop from the reservoir to the wellhead; kinetic losses were calculated to be negligible. The calculations were done for well 12 assuming 13-3/8" diameter to bottomhole. The results are shown in Fig. 4-2. The calculated output curve is at the left-hand side of the figure; the right-hand side represents the reservoir pressure 1279 psia. Note the "flashing" line in the middle. Fig. 4-2 demonstrates that frictional effects become important above 600,000-800,000 lb/hr flow, where calculated and measured values begin to deviate as shown in Fig 4-1. We conclude that the simulator may overestimate the contribution of friction to the total pressure drop. Or, the flashing nature of the flow may lift the mixture more strongly than expected from two-phase flow such as air/water. This demonstrates the need to continue fundamental research on vertical two-phase flashing flow, and to work with field data for comparison.

(e) Flow test Analysis, by Eduardo Granados G., research assistant,

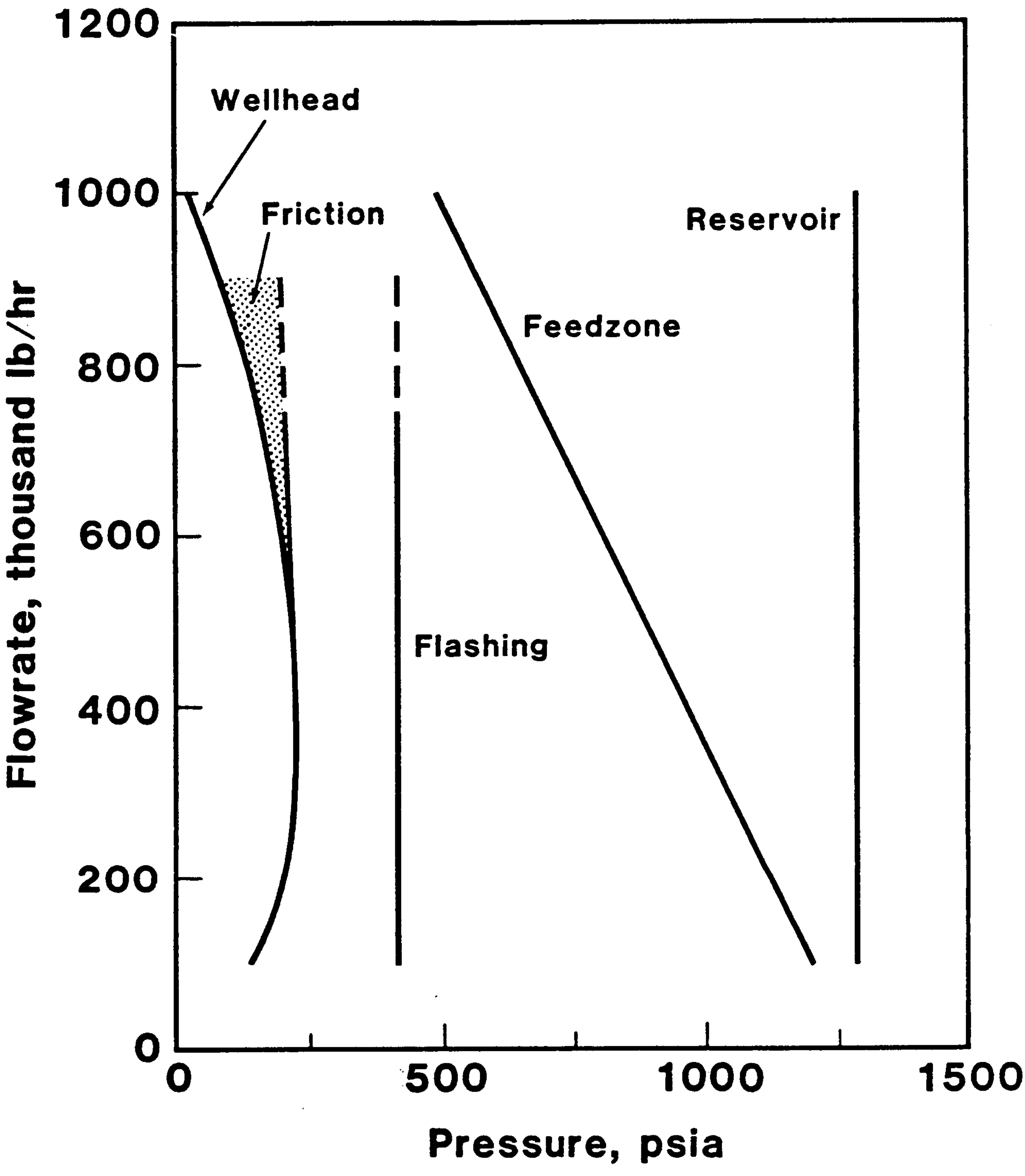



Fig. 4-2: Computed Flowrate vs Pressure for Well 12, Svartsengi Field, Iceland.

and Professor Jon S. Gudmundsson.

Extensive production data became available during the year from the Miravalles geothermal field in Costa Rica. The data are from three wells drilled about five-years ago by Instituto Costarricense de Electricidad. When these wells were first flow tested, it was discovered that they suffered serious wellbore deposition of calcium carbonate. One of the wells was cleaned after flowing first for one month and then three months. After the cleaning it was flowed for six months. We selected this well (PGM-1) for flow test analysis.

The purpose of this project is to characterize the deliverability and chemical behavior of wells suffering wellbore deposition. The first step was to analyze the production data with time. In Figs. 4-3 and 4-4 are shown the flowrate and wellhead pressure of well PGM-1 with time in the first flow test period. The well was fully open during this test. The flowrate decreased from 76 kg/s to 41 kg/s in 27 days, and the wellhead pressure declined from 8.7 kg/cm$^2$ to 3.8 kg/cm$^2$. The Miravalles reservoir is liquid dominated with temperature around 240$^{\circ}$C. After the flow test, it was confirmed by caliper logging that a typical calcium carbonate restriction had formed in the well. The other flow tests will not be shown here for brevity.

When a geothermal well is put on long-term discharge, the reservoir pressure should decrease rapidly at early times, and then change slowly. Looking at Figs. 4-3 and 4-4, we see the opposite. At early times the decrease is slow, and then it becomes more rapid. We believe that this behavior is characteristic of wellbore behavior. Similar observations have been made in New Zealand and Iceland. Calculations were made using the wellbore simulator described previously. By placing a 50-ft-long

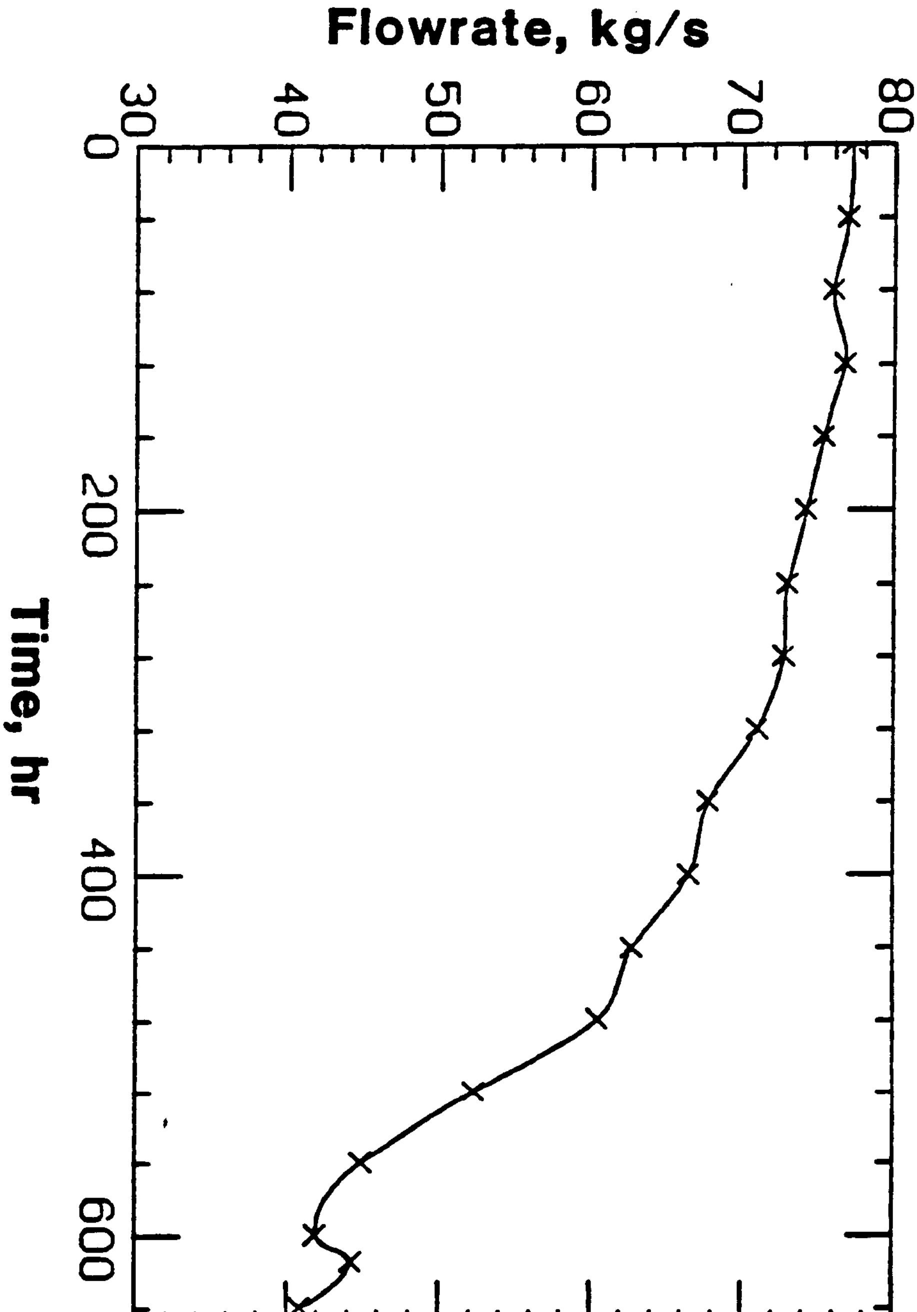



Fig. 4-3: Flowrate vs Time for Well PGM-1, Miravalles Steam Field, Costa Rica.

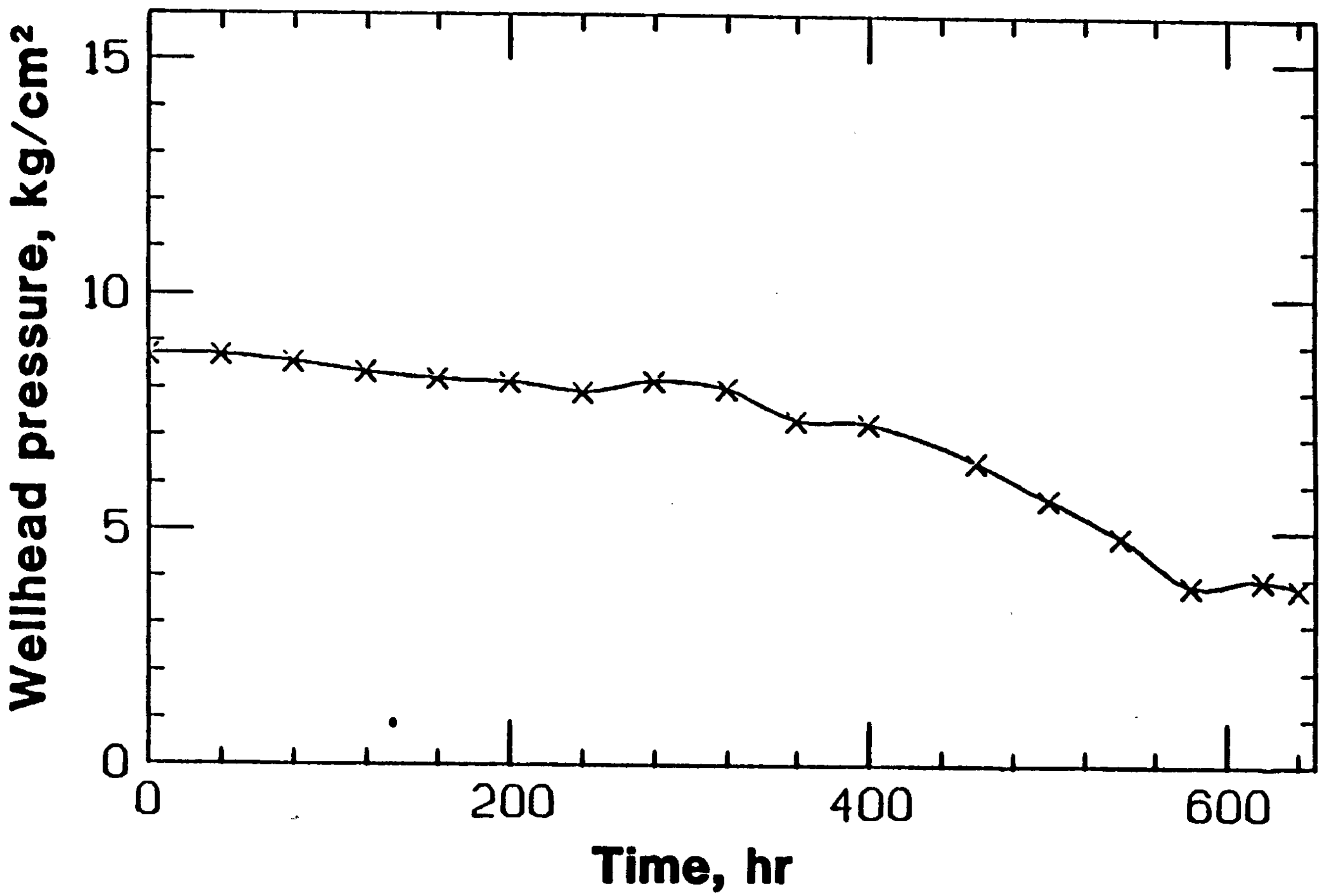



Fig. 4-4: Wellhead Pressure vs Time for Well PGM-1, Miravalles Steam Field, Costa Rica.

restriction in the wellbore where flashing occurs, and calculating the wellhead pressure at constant flowrate, we found that increasing the restriction produced a curve similar in shape to Figs. 4-3 and 4-4.

An interesting observation was that the ratio of flowrate to wellhead pressure was about the same at the start and finish of the flow test periods. Plotting the ratio W/p for the whole test gave a straight line. The ratios for the first and second flow tests are shown in Fig. 4-5. This is a new observation to the best of our knowledge.

This project is still in progress, but the following conclusions can be reached after the flow test analysis:

(1) The flow behavior of wells suffering wellbore deposition is qualitatively different from that caused by reservoir drawdown. This difference can be used for diagnostic purposes. Calcium carbonate deposition has limited effect at early times but decreases the well output rapidly at later times.

(2) It was discovered that the ratio of flowrate to wellhead pressure remained constant with time for a well suffering wellbore deposition in the Miravalles field. Again, this can be used for diagnostic purposes to differentiate between wellbore and reservoir effects on well deliverability in liquid dominated reservoirs.

(f) <u>New Field Application Projects</u>

During 1983, contacts were made with two new geothermal agencies concerning possible field application projects. H.J. Ramey visited New Zealand in May 1983 during sabbatical leave, and presented a short course on well test analysis, and reanalyzed interference data from the Broadlands Field. A brief account is presented by Grant et al., "Recent Developments in Reservoir Engineering in New Zealand," Ninth Geothermal Workshop,

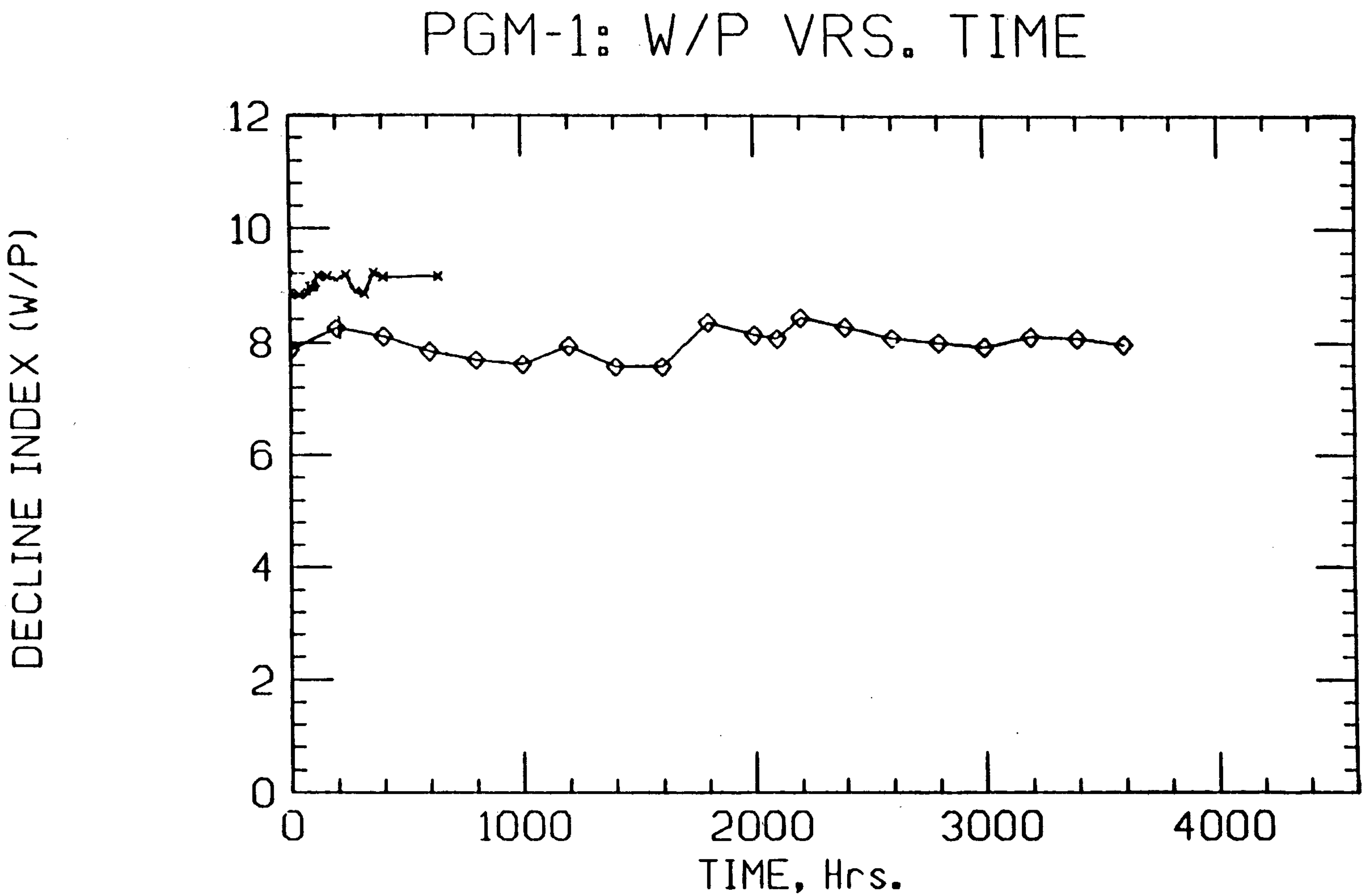



Fig. 4-5: PGM-1 -- Decline index versus time for two long term tests

Stanford, December 13-15, 1983. Recent interference tests show interesting detail, and cooperative work on well test analysis and reinjection tracer testing is under consideration. In September, 1983, H.J. Ramey visited the Middle Eastern Technical University, Ankara, Turkey. A letter outlining cooperative research in reinjection and scaling technology between METU and Stanford has been exchanged. This work should start in 1984.

TASK 6: WORKSHOP, SEMINARS AND TECHNICAL INFORMATION

The Eighth Workshop on Geothermal Reservoir Engineering was held at Stanford University December 14-16, 1982. The attendance was the highest ever with 123 participants of which 17 were from 6 foreign countries.

The purposes of the Workshop are to bring together researchers, engineers and managers involved in geothermal reservoir studies and developments, and to provide for prompt and open reporting of progress and the exchange of ideas. There were 39 technical papers presented at the Workshop, and 7 additional papers were printed in the Proceedings. The papers were presented under the categories of: Hydrothermal Systems, Field Development, Well Testing, Two-Phase Flow, Geophysics and Well Logging, Simulation, Petrothermal and Geopressured Energy, Reinjection and Reservoir Chemistry.

At the Eighth Workshop, three experts were invited to give keynote presentations. They were M.L. Sorey on "Geothermal Reservoirs in Hydrothermal Convection Systems"; A.J. Batchelor on "The Stimulation of a Hot-Dry-Rock Reservoir on the Cornubian Granite, England"; and F. D'Amore on "Fluid Geochemistry Applications in Reservoir Engineering: Vapor Dominated Systems." The keynote speakers provided the highlight of the Workshop.

Weekly seminars were held during the academic year on geothermal energy topics. In the autumn and winter quarters, the seminars were mainly given by scientists and engineers from outside Stanford University. During spring quarter the seminars covered some of the work carried out at Stanford. In previous years, the Stanford work has been presented in autumn quarter. Moving Stanford lectures to spring quarter gave students graduating a chance to present their almost-completed projects. The

Stanford Geothermal Program faculty and students are most grateful to the speakers and their organizations for their support and time.

The Geothermal Library was moved from the Petroleum Engineering Department to the Branner Library during the year. There is now a Geothermal Collection in Branner Library. All the items of the Geothermal Collection were cataloged and are now available on the computer information bank of the Engineering and Earth Sciences Schools through keyword registration. This new arrangement should be of great help to geothermal energy researchers at Stanford. Arrangements were made during the year for various geothermal reports to be sent to the Geothermal Collection. These include all DOE geothermal reports and reports from United Nations supported training programs in New Zealand and Iceland. Our aim is to have a central collection of world-wide geothermal reports and publications that are easily accessible by researchers.

The Proceedings of previous Workshops are still in great demand. They are all out of print and have been so for several years. During the year we worked on reprinting the Proceedings with author and subject indexes. These are now complete so printing the first six Proceedings in two volumes can go ahead.

The contents of the Proceedings of the Eighth Workshop on Geothermal Reservoir Engineering and the Seminar Schedule for 1982-1983 academic year are shown in the Appendix.

## TASKS 7/9: REINJECTION TECHNOLOGY

Task 7 was initiated in 1982 and Task 9 in 1983; there are several projects underway. Some of the projects are continuations of work started earlier in other parts of the program, and some are new. The main emphasis during the year was the investigation of fundamental properties and behavior of tracers under geothermal reservoir conditions. Tracer tests were initiated in May and July 1983 in Klamath Falls, and August 1984 at Los Azufres geothermal field. Details of the projects are described in the following sections.

(a) Tracer Retention in Reservoirs, by Gardner Walkup, research assistant, and Professor Roland N. Horne.

In earlier experiments, Breitenbach (1982) noted that up to 60% of a potassium iodide (KI) solution was retained in a Los Azufres andecite core at 150°C over a three-day period. This work was published in Horne and Breitenbach (1982), and the implications for tracer test interpretation were discussed by Horne, Breitenbach, and Fossum (1982) at the Eighth Stanford Geothermal Workshop in December 1982.

The aim of current activity in this project is to confirm Breitenbach's (1982) preliminary results, and to identify the mechanism of tracer retention so that tracer retention may be included in an interpretation model. The apparatus was rebuilt during the year to exclude the viton sleeve that was a potential source of extraneous KI retention. The new stainless steel core holder also will allow the apparatus to be used at higher temperatures, closer to realistic geothermal reservoir temperatures. Attaining 250°C capability proved to be a problem, however, as fluid leaks were difficult to overcome at high temperatures. After some months of experimentation, a suitable O-ring material was identified, and the apparatus was brought into use late in the year. Currently, the project is at the stage of reproducing the conditions of Breitenbach (1982), using a similar Los Azufres andecite sample. The object is to determine whether the effects observed by Breitenbach (1982) will also be observed in the new apparatus.

Other than the refabrication of the apparatus, a KI analysis system was obtained during the year so that analyses may be performed in the laboratory quicker and in a standardized manner. The equipment obtained was a Fisher Ion Specific Electrode and Ionalyzer instrument. This same instrument has also been used in field experiments at Klamath Falls and Los Azufres.

(b) Field Measurement System, by Peter Jackson, research assistant, and Professor Roland N. Horne.

As part of the proposed field experiment at Roosevelt Hot Springs, an automatic sample collection system was designed and fabricated. Although the Roosevelt test was ultimately cancelled, this automatic sampler saw over 2000 hours of use during the two tracer tests at Klamath Falls, Oregon, and the tracer test at Los Azufres, Mexico. The system consists of a microprocessor-controlled relay bank that operates 16 separate 3-way valves.

The sampler is installed at the production wellhead and receives produced fluid through a tap in the production line (at Los Azufres a mini-separator was used, at Klamath Falls none was necessary). Fluid flows continuously through all 16 valves in parallel and then to a drain. When one of the valves is activated by the timer, the flow is diverted through a short length of tube into the sample bottle. After a timed interval (set such that the bottle is filled), the valve is de-activated, and the flow again passes to the drain. In this manner, the device can collect 16 samples before being replenished with empty bottles by an attendant. This capability proved to be a considerable advantage during 24 hour/day sampling.

There are several reasons for continuous purging of sample lines. First, the purge guarantees that the fluid diverted to the sample bottle is always fresh. Second, fluid does not remain stagnant in the sample tubing which might cause scaling, corrosion or wide temperature fluctuations.

The device may also be used with 30 sample ports. Even though the timer can control only 16 relays, one relay can be used to activate one of the three-way valves to direct flow into one or other of two banks of fifteen valves. Each of the remaining fifteen relays would activate one valve from each of the two banks simultaneously. Only one of the two valves would have flow to its inlet at any given time.

Few problems were encountered with the device in field operations at Klamath Falls. However, sampler operation was unreliable at Los Azufres. The main reason was the difficulty in obtaining a stable power supply, which caused the loss of the microprocessor program and occasional extraneous or missing actuations of the valves. At both Klamath Falls and Los Azufres, the device was installed with the 16th valve controlling flow through the valve bank such that the purge operated only for several minutes before and after each sample. This setting was necessary at Klamath Falls because of limited drainage for the exhaust, and the setting was retained at Los Azufres because of the high dissolved solids concentration. At Los Azufres, this valve eventually became blocked with scale deposits, but protected the other 15 valves from similar scaling.

The device will be retained in its present form and used by the Stanford Geothermal Program in planned tracer tests. In retrospect, the device could be more usable at remote sites if it were battery powered. However, the device would lose some portability as a result. The design and operation of the sampling device is described in a report by Jackson (1983).

(c) Activable Tracers, by Professor Paul Kruger

This project has the objective of increasing the sensitivity of external tracers for reinjection testing using high-resolution activable tracers to improve breakthrough time measurement and extend the measurement period for tracer recovery. The need for extending the useful measurement period of external tracers occurs at both ends of the reinjection test. Early arrival of reinjected fluids can play a significant role in estimating long-term thermal quality of the fluids produced for energy extraction, whereas late arrival can play a significant role in the interpretation of the porosity-permeability distribution of the reservoir.

Phase I of the project has been completed. During this phase, several potential activable tracers were identified for liquid-dominated reservoirs. One noble-gas element (Kr-82) appears to be suitable for vapor-dominated reservoirs. The choices were based on favorable nuclear activation and measurement properties and low or unknown background concentrations in geothermal brines. Three alternate methods of analysis were designed, based on the availability and location of appropriate neutron-irradiation facilities. Phase II of the study is directed to establishing the necessary criteria for successful use of activable tracers in geothermal reservoirs. It includes determination of the optimum chemical form for conservation of tracer against losses by physical retardation, chemical reaction, and thermal instability, establishment of signal-to-noise ratio of the activable tracer with respect to natural background concentration in geothermal brines, and design of suitable methods for field utilization at competitive cost.

Activable tracers can utilize the advantages of high-sensitivity, high-resolution radiation measurement without the use of radioactive materials in environmentally sensitive systems. The advantages of radioactive tracers in groundwater aquifers and oil-field reservoirs is well-known (e.g., Davis, et al., 1980; Kruger, 1958; and IAEA, 1967). Radiotracers have been used in geothermal fields (e.g., Gulati, et al., 1978). The shielding problems of large-source radiotracers and the regulatory requirements for field experimentation have constrained the widespread use of radiotracers in field studies. Activable tracers offer a good compromise between retaining the advantages of high-sensitivity analysis, small tracer quantity, long test duration, and wide choice of tracer form, and the disadvantages of using highly radioactive materials in the field.

The activable tracer method combines the use of stable elements in appropriate chemical and physical form to trace a given component or fluid in a complex system with the use of activation analysis as the measurement method. Activation analysis is an established technique for chemical analysis of trace elements in terrestrial and lunar materials. It is accomplished by the irradiation of the activable tracer in samples from the system to produce a specific radionuclide, followed by the positive identification and measurement of the radiation emitted by that specific radionuclide.

The principles of radioactivation analysis are discussed by Kruger (1971). The key aspects are selection of the appropriate activable tracer, optimum nuclear reaction, and irradiation conditions to produce the radionuclide for radiation measurement. The nuclear properties of an activable tracer useful for activation analysis include the isotopic abundance in the natural element, its cross section (probability) for undergoing the selected nuclear reaction, and the radiation properties (type, energy, half life) of the produced radionuclide. During phase I of the study a computer program was written to evaluate the literature data amassed for more than 300 stable isotopes of the elements. Initial screening of the elements for suitability as a tracer in geothermal reservoirs narrowed the list of potential activable tracers to some 26 chemical elements. Selection of a suitable tracer for geothermal reservoirs requires several considerations.

First, activable tracers must meet the two fundamental requirements of all external tracers:

(1) behavior predictable and identical to the traced component, and

(2) distinguishable at times of measurement.

Activable tracers can generally be chosen and prepared to represent the component being traced, and with suitable activation and radiation measurement facilities, the tracer can be readily distinguished and measured at very small tracer concentrations.

Second, for use in geothermal fluids, major additional requirements are:

(1) elements of low background concentration and variability in the geofluid,

(2) optimum nuclear (activation) properties for the available irradiation facilities, and

(3) availability of tracer and irradiation at reasonable cost.

The background concentration should be as close as possible to the maximum sensitivity of the activation analysis. To avoid large uncertainty in measured concentration due to difference of large numbers, the variability in background concentration with time should also be small.

Suitable activable tracers have the properties of large natural isotopic abundance, or availability as enriched low-abundant isotopes, large reaction cross section, and favorable radiation properties of optimum half life for the available irradiation facilities and large branching ratio of gamma radiation for high-resolution gamma-ray spectroscopy.

The half life of the product radionuclide is an important parameter in two aspects: it determines the time parameters for the degree of radioactivity saturation in the activation step and the allowable decay period from end of irradiation to final measurement. The latter aspect is especially important in the choice of shipping a batch of samples to a remote irradiation facility or performing rapid analysis near the measurement equipment. For the first choice, a variety of large neutron-flux research reactors are available, but with significant delay in transport and monitoring of the irradiated samples before measurement. For the second choice, local activation improves the flow and cost of operations, but raises the minimum detection level to match the locally available irradiation sources.

The third consideration of a suitable activable tracer is its compatibility with the geothermal reservoir and the wellhead fluid produced, either in liquid phase or in steam phase, or in two-phase fluids. Properties of the tracer such as speciation of the element in the compound, its boiling point, and Henry's law constant become important factors. Activable tracers meeting the criteria of low background and good nuclear properties must be conservative in the hostile geothermal reservoir with its high temperature, multiple geologic pathways through various geochemical structures, and phase changes of the transporting geofluids. Suitable activation tracers must be conservative through rock-water interactions, pH changes, oxidation-reduction cycles, evaporation-condensation cycles, and adsorption-desorption processes, all at the high temperature of the reservoir.

Sensitivity calculations were made for the elements meeting the initial screening criteria. These were further evaluated with respect to: (1) the physical state of the geothermal reservoir to be tested, and (2) the irradiation facility to be used. The potential activable tracers were divided into two categories by type of geothermal reservoir: (a) solute tracers and (b) gaseous tracers. Nuclear activation data for the potential elements were obtained from several literature sources, e.g., Sher, (1974), Erdtmann (1976), and Lederer and Shirley (1978). The computer output gives the minimum detection level of each activable tracer in a geothermal fluid sample of 100 ml volume. The computer database consists of two types of parameters: changeable and fixed. The changeable parameters, chosen for the particular mode of analysis, include the minimum counting level, the decay time from irradiation to measurement, the detection system efficiency, the available neutron flux, and the irradiation time.

$A(t)$ = minimum counting level (cps)

$t$ = decay time from end of irradiation (hr)

$\epsilon$ = detector efficiency for E (c/d)

$\phi$ = neutron flux (n/cm$^2$ sec)

$T$ = irradiation time (hr)

The fixed parameters are the database of nuclear properties, which for the $i^{th}$ isotope include:

$A(i)$ = mass number

F(i) = isotopic abundance

C(i) = activation cross section (barns)

H(i) = half life of product nuclide (hr)

G(i) = gamma-ray branching ratio.

Three types of irradiation facilities were evaluated during phase I: (1) activation analysis services at a commercial activation analysis service company (e.g., General Atomics Corp.), (2) irradiation services at the nearby University of California Triga reactor at Berkeley, with radiochemical measurement at our radiation measurement laboratory, and (3) an on-line activation analysis system, designed to use a Cf-252 isotopic neutron source in a mobile trailer in the field at the well site.

Table 7-1 summarizes the activable tracer sensitivity calculations for 24 tracer elements using the University of California Triga reactor. In this calculation the changeable time parameters were set at one half life or 6 hours for $T_{1/2} < 6$ hr and 24 hours for $T_{1/2} > 24$ hrs. The neutron flux of $5 \times 10^{12}$ n/cm$^2$ sec corresponds to the multi-sample rotating lazy-Susan irradiation site.

Table 7-2 summarizes the activable tracer sensitivity calculations for the noble gases. Since most of the resulting activation products are short lived, e.g., 1.86-hr Kr-82 and 1.83-hr Ar-40, the sensitivity was calculated using an on-line Cf-252 neutron flux of $10^9$ n/cm$^2$ sec for a geofluid sample process cycle time of 12 minutes (0.2 hr). The results show that Ar-40 or Kr-82 would be the most sensitive activable tracer for steam. The additional activity from the Kr-84 isotope may enhance or interfere with the Kr-82 measurement.

Table 7-1

ACTIVABLE TRACER SENSITIVITY

Soluble Tracers
(UCB Reactor Activation)

| Tracer | | Min. Dect. Level (ng) | Min. Conc. (ng/ml) |
|---|---|---|---|
| Sc | 45 | 22216.31 | 222.163 |
| Ti | 50 | 347.588 | 3.476 |
| V | 51 | .782 | .008 |
| Mn | 55 | 2.661 | .027 |
| Co | 59 | .224 | .002 |
| Cu | 65 | 71.504 | .715 |
| Ga | 69 | 1519.095 | 15.191 |
| Br | 81 | 4.026 | .04 |
| Ru | 104 | 1455.264 | 14.553 |
| Rh | 103 | 32.691 | .327 |
| Pd | 108 | 109.843 | 1.098 |
| Ag | 107 | 31.492 | .315 |
| In | 115 | .181 | .002 |
| I | 127 | 13.104 | .131 |
| Cs | 133 | 33.419 | .334 |
| La | 139 | 2.893 | .029 |
| Eu | 151 | 33.997 | .34 |
| Dy | 164 | .764 | .008 |
| Lu | 175 | 15.124 | .151 |
| W | 186 | 1.905 | .019 |
| Ir | 193 | 106.662 | 1.067 |
| Au | 197 | 30.998 | .31 |
| Hg | 204 | 473.579 | 4.736 |
| Th | 232 | 3.675 | .037 |

Table 7-2

ACTIVABLE TRACER SENSITIVITY

Gaseous Tracers
(On-line Activation)

| Tracer | Min. Dect. Level ($\mu g$) | Min. Conc. ($\mu g/ml$) |
|---|---|---|
| Ar-40 | 76.4 | 0.76 |
| Kr-82 | 44.0 | 0.44 |
| Kr-84 | 4080 | 40.8 |
| Xe-134 | 32500 | 325 |
| Xe-136 | 11300 | 113 |

Table 7-3 shows a comparison of the more promising activable tracers in atomic number order for the three modes of radioactivation. Agreement between the University of California Triga reactor and the Commercial service standard specifications (also based on a Triga reactor) is adequate to rank the activable tracers in order of sensitivity. The major difference between the two research reactors and the on-line system is the use of short-lived activation products for the on-line system to partially make up for the factor of 5000 in neutron flux.

Table 7-4 summarizes the potential of activable tracers by maximum sensitivity for Triga reactor activation in relation to natural background data acquired for three geothermal resources of varying pH and salinity. The sensitivity data show that four elements should be considered as potential activable tracers for geothermal reservoirs: In-115, Co-59, V-51, and Dy-164.

Table 7-3

ACTIVABLE TRACER SENSITIVITIES

| | Minimum Detection Level (μg) | | |
|---|---|---|---|
| Tracer | On-Line(A) | Triga(B) | Commercial(C) |
| V-51 | 6.5 | 0.002 | 0.002 |
| Mn-55 | 8.2 | 0.006 | 0.0001 |
| Co-59 | 0.9 | 0.0006 | 0.01 |
| Br-81 | 23.1 | 0.01 | 0.003 |
| In-115 | 0.6 | 0.0005 | 0.00006 |
| I-127 | 46.3 | 0.033 | 0.002 |
| La-139 | 9.6 | 0.007 | 0.005 |
| Dy-164 | 2.4 | 0.002 | 0.00003 |
| W-186 | 6.8 | 0.005 | 0.004 |
| Au-197 | 93.1 | 0.077 | 0.0005 |
| Th-232 | 13.3 | 0.009 | 0.2 |

(A) $= 1 \times 10^9$ $n/cm^2sec$ $T_{irr} = T_{decay} = 10$ min

(B) $= 2 \times 10^{12}$ $n/cm^2sec$ $T_{irr} = T_{decay} = 6$ T 1/2 24 hr

(C) Standard Service Specifications

Table 7-4

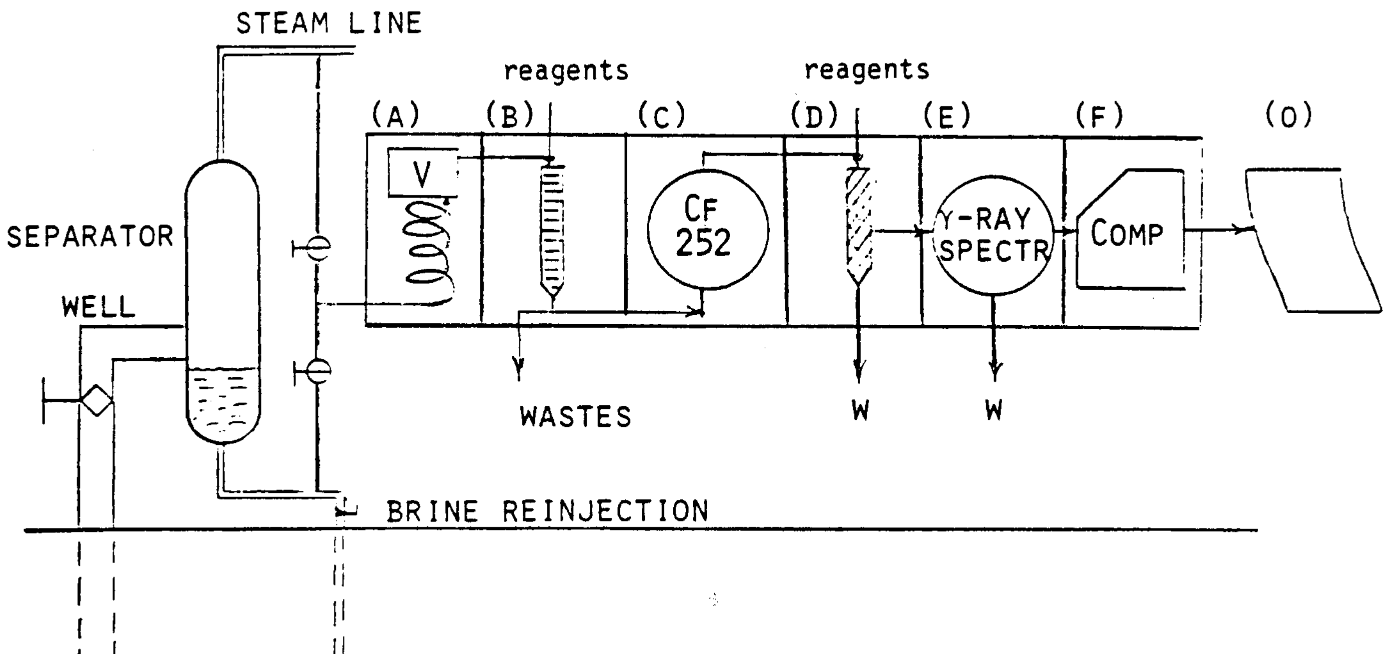
ACTIVABLE TRACER SENSITIVITY

| Tracer Nuclide | Minimum Detectable Concentration ($\mu g/l$) (UCB Rea) | (Comm Co) | | Natural Background ($\mu g/l$) Central UT | E. Mesa CA | Niland CA |
|---|---|---|---|---|---|---|
| | | | pH | 4.7 | 6.3 | 3.7 |
| | | | TDS(ppm) | 6500 | 4200 | 235000 |
| In-115 | 0.002 | 0.0006 | | NA | 0.05 | |
| Co-59 | 0.002 | 0.1 | | 0.2 | 0.05 | 0.02 |
| V-51 | 0.008 | 0.02 | | 0.15 | 0.03 | 0.5 |
| Dy-164 | 0.008 | 0.0003 | | NA | 0.001 | 0.001 |
| W-186 | 0.019 | 0.04 | | NA | 1 | 0.008 |
| Mn-55 | 0.027 | 0.001 | | 0.08 | 0.3 | 687 |
| La-139 | 0.029 | 0.05 | | NA | 0.004 | 0.7 |
| Th-232 | 0.037 | 2.0 | | NA | 0.05 | 0.001 |
| Br-81 | 0.040 | 0.02 | | 23.3 | 1.3 | 60 |
| I-127 | 0.131 | 0.02 | | 0.4 | 3.0 | 8.7 |

Efforts were initiated under Phase II of the study to design a geothermal on-line activable tracer system and a procedure for on-line activation analysis for geofluids of varying salinity and chemical composition.

A schematic drawing of a preliminary design is given in Fig. 7-1. In this system, sampling can occur from either the steam or liquid phase ports on the wellhead fluid separator. The system condenser can be set to provide 100 ml aliquots on a timed cycle of sample collection, pre-irradiation treatment, on-line neutron activation, post-irradiation separation, gamma-ray spectroscopy, and computer resolution and calculation.

The treatment procedure has been adapted from Channell and Kruger (1971) for rare earth elements as activable tracers in estuarine and bay water brines. Detection sensitivity was based on activation with the then-available 10-kW Stanford University research reactor, a maximum irradiation time of 6 hours at a thermal neutron flux of $1 \times 10^{11}$ n/cm$^2$ sec. Sensitivities for nine of the rare earth elements and six others were in the range of 0.1 to 100 ng per sample. The difficulty of working with high-salinity brines was resolved with pretreatment by chemical isolation of the rare earth elements as insoluble hydroxides. Following activation, further radiochemical isolation prepares the tracer on ion-exchange resins for gamma-ray spectroscopy. To preserve quantitative analysis, radiotracer Y-88 is added to the samples at the pretreatment step to serve as a chemical yield tracer. Studies on the persistence of rare earth elements in sea water were made for adsorption, pH effects, sediment precipitation, solubility, chelation, and biological uptake. The results were favorable, especially the persistence found with chelation with $10^{-3}$ M EDTA solution.




(A) Sample Condenser (V = 100 mL)

(B) Pre-irradiation Treatment

(C) Cf-252 Thermal Neutron Irradiator

(D) Post-irradiation Separation

(E) γ-ray Spectrometer

(F) Computer Resolution and Calculation

(O) Output: [Tr] = f(t)

Fig. 7-1: Geothermal On-Line Activable Tracer System.

Application of this procedure to geothermal samples requires refinement. Possible separation techniques for heavy metal tracers were described by Pinta (1962). In particular, he noted chelation with dithiocarbamate and filtration through membrane filters was effective for the proposed activable tracers with little retention of the alkali (Na, K, Rb) and the alkaline earth (Ca, Sr, Ba) elements.

Initial evaluation of indium as an activable tracer shows a wide range in chemical behavior with many soluble compounds, strong complex ions for ion exchange or solvent extraction as $InCl_4$, $InCl_6$ , InBr or $InF^{+2}$. Indium strongly complexes with EDTA as a possible conservative tracer in liquid-transport geothermal reservoirs. Current studies are designed to test the suitability of In, Co, V, and Dy as activable tracers in geothermal reservoirs and to determine their natural concentrations in various types of resource.

(d) Tracer Return Profile Interpretation, by Clair Jensen, research assistant, and Professor Roland N. Horne.

This project was motivated by the observation in earlier work (Horne, Breitenbach and Fossum, 1982) that tracer retention would significantly affect the return profiles. A new transfer model was developed, modifying the fracture flow model of Fossum and Horne (1982) to include the effects of diffusion of tracer into the porous matrix. The two governing equations and their solutions for this transport mechanism are:

$$R \frac{\partial C_f}{\partial t} - \frac{2D_e}{\delta} \frac{\partial C_p}{\partial y}\Big|_{y=0} + U_f \frac{\partial C_f}{\partial x} = 0 \qquad (7\text{-}1)$$

$$D_a \frac{\partial^2 C_p}{\partial y^2} = \frac{\partial C_p}{\partial t} \qquad (7\text{-}2)$$

$$C_f = \frac{E\alpha\beta}{\sqrt{\pi}(\beta t-1)^{1.5}} \exp\left[-\frac{\alpha^2}{(\beta t-1)}\right]$$

where $\alpha = (D_e \theta t_w)^{0.5}/\delta$ and $\beta = \frac{1}{t_w R}$

$C_f$ = tracer concentration in fracture

$C_p$ = tracer concentration in matrix

$D_e$ = effective diffusion coefficient

$R$ = retardation factor

$\theta$ = porosity

$t_w$ = water residence time

$\delta$ = fracture width

The model was used to interpret tracer return profiles from tests performed by the Institute of Nuclear Sciences, DSIR, New Zealand, at Wairakei geothermal field. In all instances the match was considerably better than with the Fossum (1982) model. From the model, first tracer arrival times, and the number of individual fractures (the principal conduits of fluid flow in the reservoir) joining the injector-producer wells can be estimated. If the porosity adsorption distribution coefficient, bulk porosity, and effective diffusion coefficient are known, fracture widths may be calculated.

One of the tracer return profiles was not satisfactorily matched. It may be that hydrodynamic dispersion down the length of the fracture should also to be considered in the model. Doing so, however, would require some numerical approximations in the mathematical model solution, or the use of finite-element modeling.

In addition to the tracer profile matching by the matrix diffusion model, comparisons with the fracture model utilized by Fossum and Horne (1982) have been made. One such comparison is shown in Figs. 7-2 and 7-3.

(e) Field Projects, by Professor Jon S. Gudmundsson, and Professor Roland N. Horne, and Steve Johnson, Peter Jackson, Gardner Walkup, John Gilardi, Clair Jensen, Rick Cindrick, and Margarita Quihuis, research assistants.

During the year, three tracer experiments were conducted by the Stanford Geothermal Program, two at Klamath Falls, Oregon, and one at Los Azufres in Mexico. The purpose of these tests was to obtain tracer return data under controlled conditions in order to field test the engineering analysis procedures under development in the other parts of Task 7.

The test at Los Azufres was initiated late in the year to replace the scheduled test at Roosevelt Hot Springs geothermal field in Utah, which had to be cancelled after a failure to reach contractual agreement between Stanford University and the field operator. On August 26, 1983, 2000 lbs of KI tracer were injected into Los Azufres well A-8, and production wells A-2 and A-16 were monitored continuously for tracer return. Monitoring was still underway at the end of the contract period, and the test will not be completed until the beginning of 1984. Well A-2 will remain in production until the end of November 1983, and A-16 for some months after that.

Two tracer tests were carried out in Klamath Falls, Oregon. The first in May-June and the second in July-August, 1983. These tests were done in cooperation with the Geo-Heat Center at Oregon Institute of Technology mainly, but also the U.S. Geological Survey and Lawrence Berkeley Laboratory.

The main use of geothermal energy in Klamath Falls is in space heating.

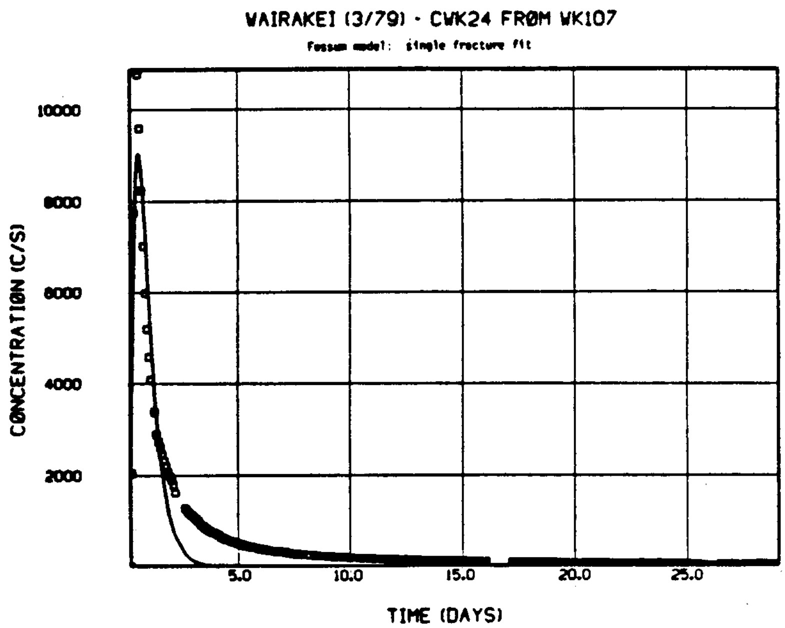



Fig. 7-2: Wairakei 24 Tracer Return Profile Match Using Fossum and Horne (1982) Model. Squares are Data, Solid Line is Model.

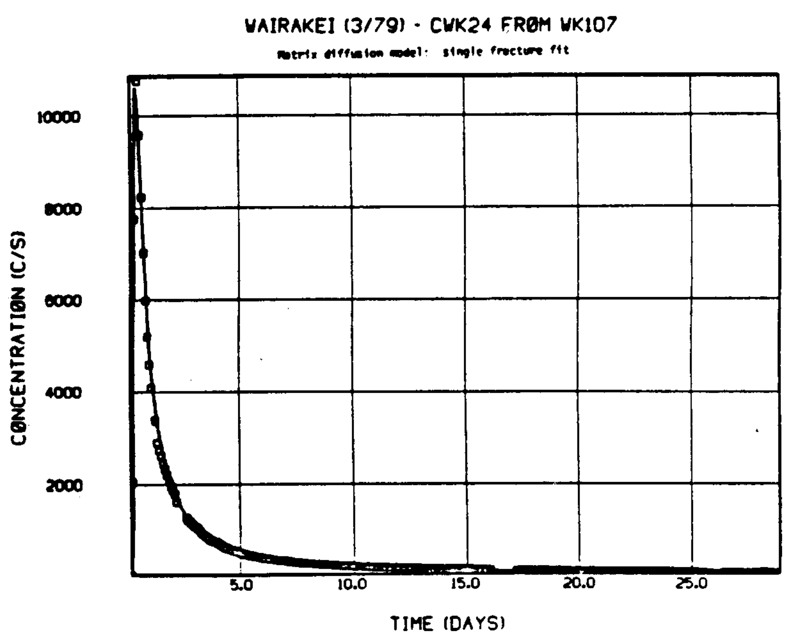



Fig. 7-3: Wairakei 24 Tracer Return Profile Match Using Jensen and Horne (1983) Model. Squares are Data, Solid Line is Model.

More than 400 wells have been drilled since about 1930. The wells range in depth from 100-2000 ft and reach temperatures of 70-230°F. Down-hole heat exchangers are used in most of the wells. There are also a few doublet systems in the city. These systems have one production well and one injection well. The two wells tend to be of similar depth and design. They are closely spaced. There are several pumped wells in Klamath Falls without injection; these have low pump rates. The first tracer test was carried out in a doublet system (no wells between producer and injector); the second test in a new pumping system with long distance injection (many wells between producer and injector). This new system was pumped at a high rate.

The first tracer test was carried out in the Klamath Union High School doublet. The producer and injector are 257 ft and 240 ft deep, respectively. The pump rate is 320 gpm, and the geothermal fluid temperature is 160°F, which is then cooled in heat exchanger to 152°F before injection. Rhodamine WT and fluorescein dyes were selected for use in the doublet tracer test. It was also decided to use potassium iodide because of its potential application in high temperature geothermal systems. The rhodamine WT and fluorescein were mixed together in 100 gallons of geothermal water; 1 lb of each material was used. It took 15 minutes to inject the dye solution into the injection well. The potassium iodide was mixed in 150 gallons of geothermal water. The amount used was 500 lb; it took 20 minutes to inject this solution.

An automatic sampling apparatus was set up at the production well. The apparatus was programmed to fill one bottle every half hour. Five other wells were sampled by hand during the tracer test. At first, samples were collected every hour, then less frequently. The other wells sampled were:

Balsiger, Creamery, Eccles, Friesen and Garrison. A fluorimeter was used to measure the dyes and an ion-selective electrode to measure the potassium iodide.

A tracer breakthrough curve shows the concentration of a tracer with time and provides a record of what happens underground when fluid flows between the wells of a doublet system, for example. The following breakthrough times were measured in the wells:

| | |
|---|---|
| Production | 2-3/4 hr |
| Creamery | 20 hr |
| Balsiger | ~100 hr |

These times are only a fraction of those expected. The tracer broke through in the production well 25-75 times faster than expected for a porous media reservoir. Tracer returns were not detected in the Friesen and Garrison wells. The fluorescein and potassium iodide breakthrough curves for the Klamath Union High School production well are shown in Figs. 7-4 and 7-5. The analysis of the data from this tracer test is still in progress. However, the following two conclusions appear warranted from the observations made so far.

(1) A disparity was found between reservoir characterization based on tracer concentration and breakthrough times. The concentrations measured indicate doublet behavior initially, and radial behavior at later times. The tracer breakthrough times were rapid and showed lower porosity-thickness values than expected, indicating fracture flow.

(2) The data indicate an important consequence for geothermal injection. While tracer returns (breakthrough time) indicate small reservoir volumes, the mixing or contact volumes appears much larger. The consequences of injecting cold fluids would appear not to be as great as indicated by tracer tests.

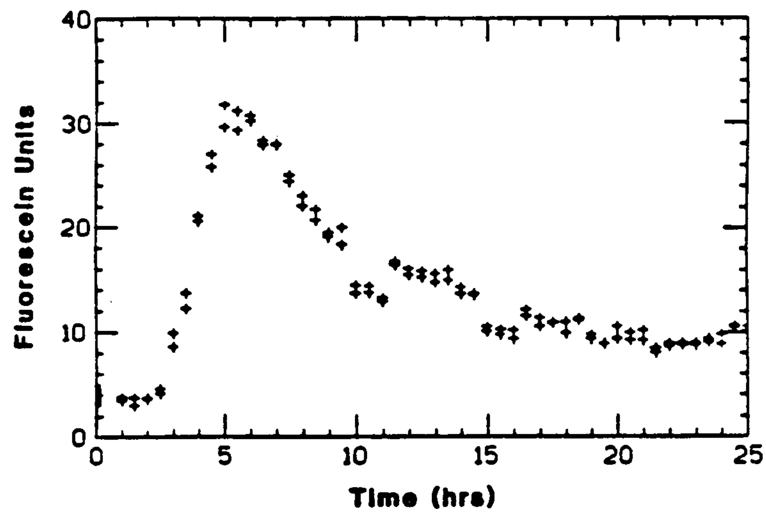



Fig. 7-4: Fluorescein Breakthrough Curve in Production Well.

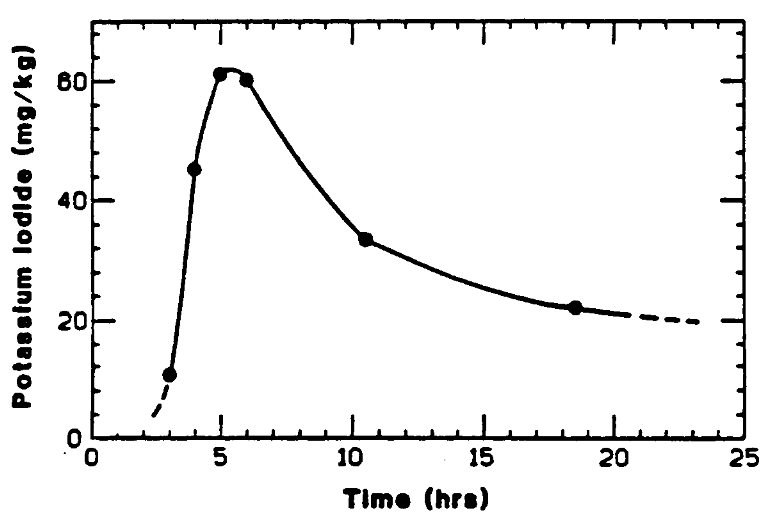



Fig. 7-5: Potassium Iodide Breakthrough Curve in Production Well.

The second tracer test was carried out in connection with a major aquifer test of the Klamath Falls resource. City well 1 was pumped about 740 gpm with the Museum well acting as the injector. These wells are spaced about 3000 ft with many wells in between; satellite injection. The City well was pumped for about one month before the injection started, the water being discharged at the surface. Pressure changes in neighboring wells were monitored closely. The purpose of the overall project was to assess the effect of long-term pumping and injection on wells with down hole heat exchangers.

Fluid injection was started the last week in July; the tracer was injected a few days later. This time, only rhodamine WT was used. In all, 50 lbs were injected. The automatic sampling apparatus was on the production well. Wells in the area of the Museum well were sampled by hand. Breakthroughs were measured in the Friesen (Laundry) and Creamery wells. The first of these is about 600 ft to the east, the other the same distance northwest. The breakthrough curves are shown in Figs. 7-6 and 7-7. The tracer broke through in 1-2 days in the Creamery well; in 16-18 days in the Laundry well. Notice the different time scales.

Figs. 7-6 and 7-7 provide an interesting comparison that ties in with the conclusions of the first Klamath Falls tracer test listed as (1) and (2) previously. The dominant fracture/fault direction in the area is northwest to southeast. The breakthrough times indicate that the injected fluid flowed along fractures to the Creamery well. The fluid flow across the fracture/fault line was much slower to the Laundry well; similar to flow in porous media. These observations are tentative since the data have not been analyzed in detail. The tracer concentrations measured in both wells are, however, similar; maximum values 5-7 units. The flowrates of

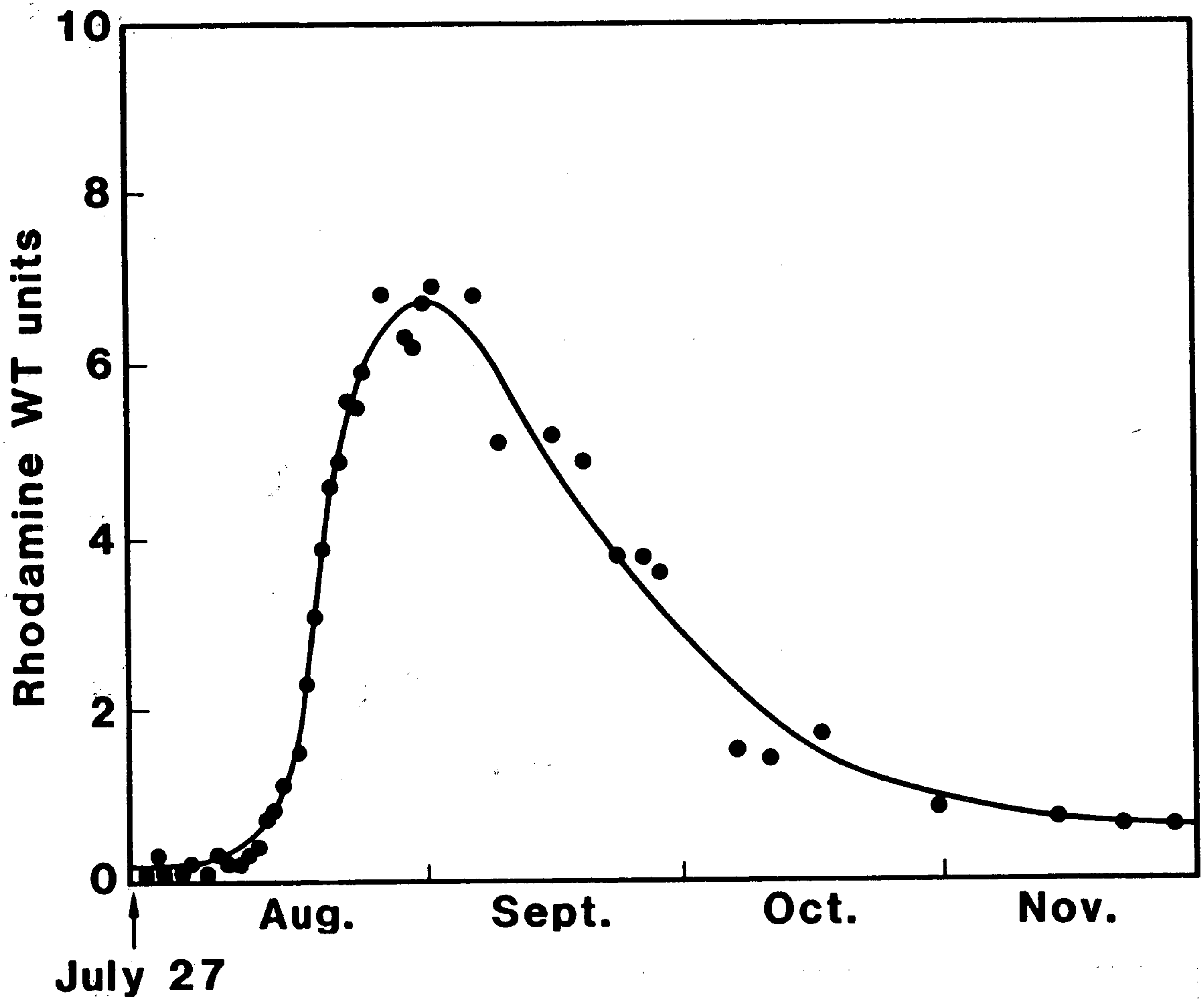



Fig. 7-6: Tracer Concentration at Laundry Well vs Time for Museum Well Injection.

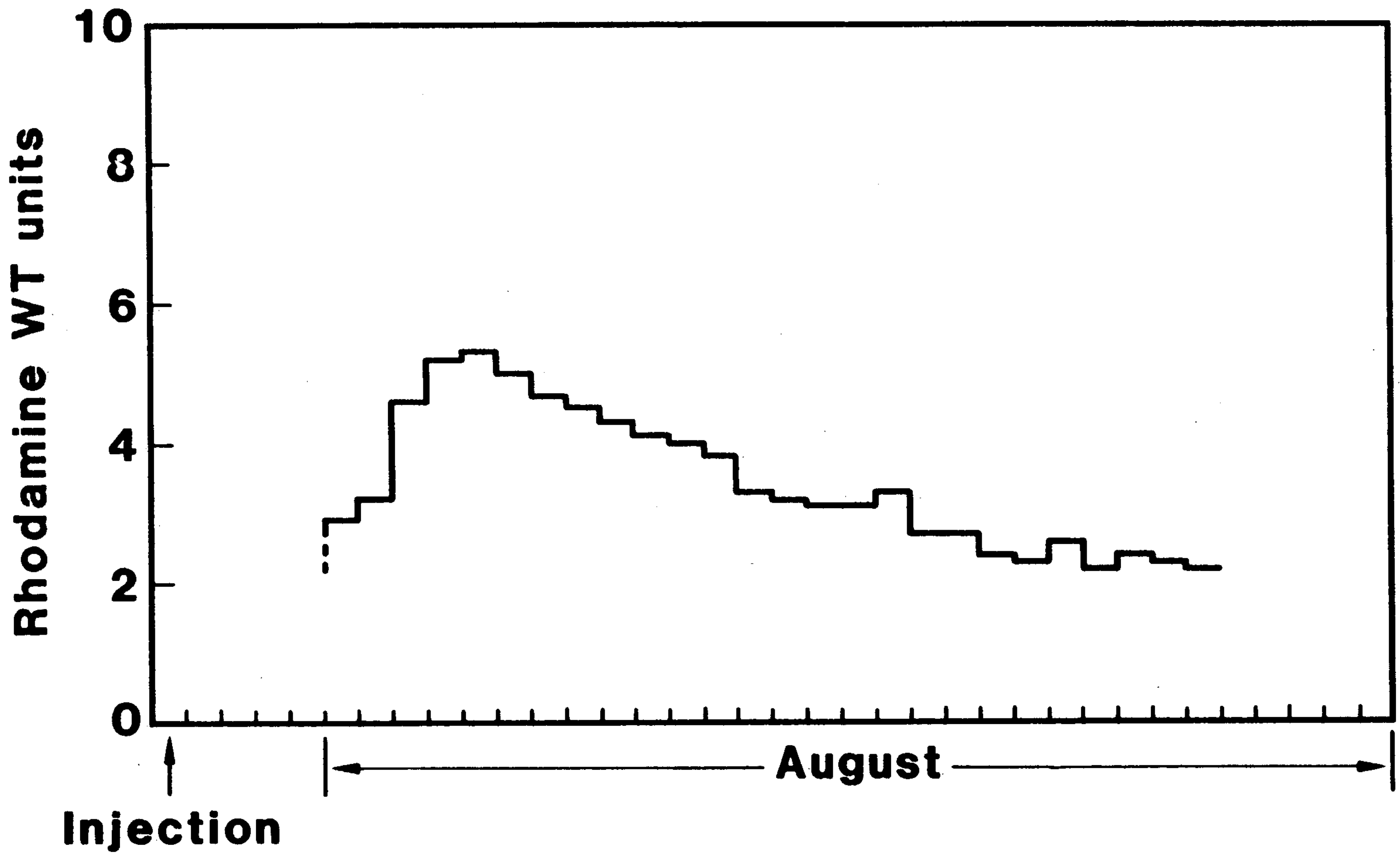



Fig. 7-7: Tracer Concentration at Creamery Well vs Time for Museum Well Injection.

the two wells were of the same magnitude. We conclude, again, that tracer concentrations from fractured systems typified by the Creamery well are similar to those expected in porous media systems, as indicated by the Laundry well results. These tentative conclusions will receive major attention in further analysis of the data.

TASK 8: SEISMIC MONITORING OF VAPOR/LIQUID INTERFACES

(a) Effect of Temperature, Pore Fluids, and Pressure on Seismic Waves in Geothermal Reservoir Rocks, by Terry Jones, research assistant, and Professor Amos N. Nur.

New measurements of seismic wave velocity and attenuation are reported in the kiloHertz frequency range to temperatures of 140°C, and confining and pore pressures to 200 bars in Berea sandstone. With increasing temperature, shear velocity and attenuation decrease at all pressures in a fully water-saturated rock. In a partially-saturated rock (Fig. 8-1), at low pressure, shear and extensional attenuation decrease with temperature increase to 130°C. Velocities first decrease, then increase with increasing temperature. The data show thermoelastic attenuation is not a significant loss mechanism under these conditions. We propose that dissipation is controlled by a viscous fluid flow mechanism, in which a sharp frequency peak in attenuation is shifted from about two kiloHertz at room temperature to about eight kiloHertz at 120°C as the pore fluid viscosity is decreased with increasing temperature. Frequency dependence is not significantly suppressed by the application of pressure. The velocity decrease is too great to be accounted for by a change of relaxation times. A non-dispersive temperature softening in shear and/or chemical effects may control the velocities. Mechanisms for attenuation of seismic waves under shallow crustal conditions which have a solid theoretical basis are evaluated in light of this data and results from other workers. Some form of wave induced fluid flow is the only mechanism which is consistent with most of the experimental evidence. A remaining problem is identifying the geometric or transport properties of the pore space which are responsible for the finely-tuned nature of the loss

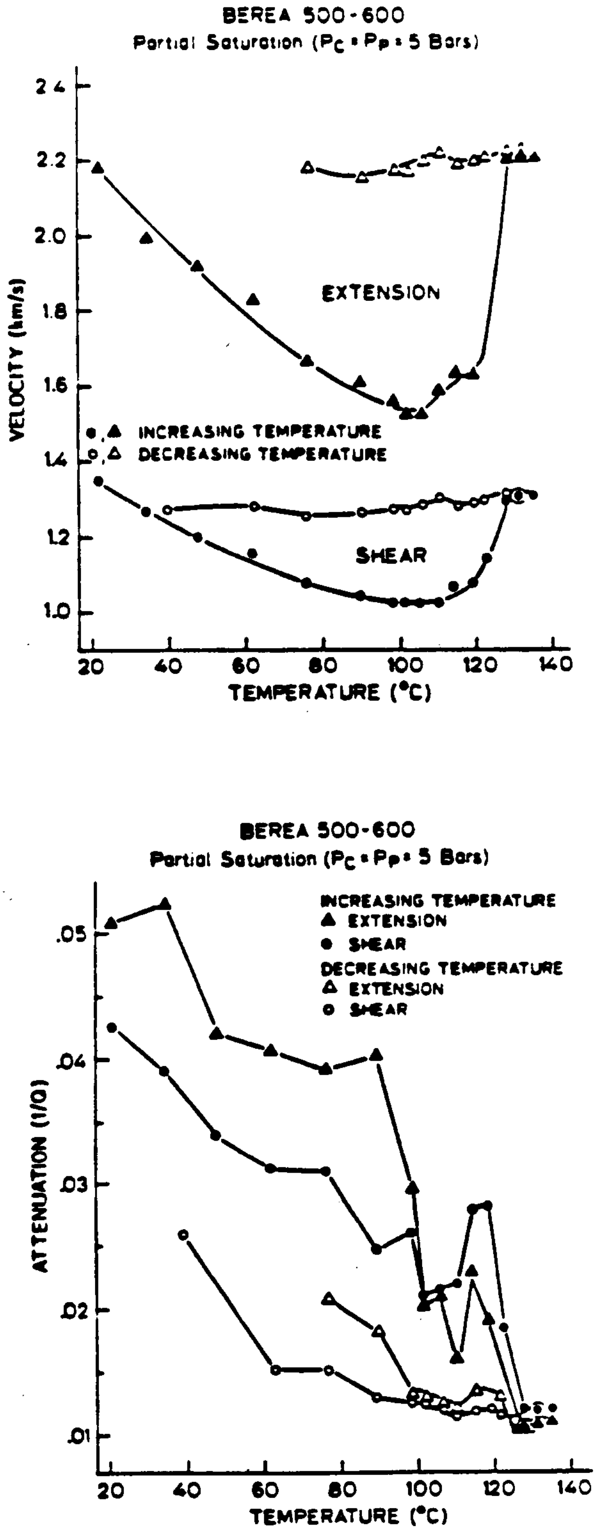



Fig. 8-1: Effect of Temperature on Extensional and Shear Velocity to 140°C. Confining and Pore Pressure were Held at 5 Bars Throughout the Experiment. Partially Saturated Berea 500-600.

mechanism. This may be related to upper and lower limits of pore aspect ratios beyond which losses are insignificant.

(b) The Seismic Signature of Zones of Elevated Pore Pressure and Temperature, by Terry Jones, research assistant, and Professor Amos N. Nur.

The distribution and pressure of a free fluid phase in the earth's crust is an important factor in the distribution of energy resources, the strength of crustal rocks, the velocity structure of the crust, and particularly in exploring for geothermal resources. In this study we have considered some models for permeability of crustal rocks, the distribution of pore pressure, and the resulting effects of pore pressure and pore fluids on seismic velocity and reflection data.

The models for seismic velocity in overpressured or steam-bearing zones show that localized pore pressure gradients may contribute strongly to velocity variations with depth, and may affect the amplitudes of reflected waves in either crystalline or sedimentary rock. (Fig. 8-2) is short lived in comparison to the existence of fluid pressures large enough to significantly affect the strength of crustal rock units. It was found that relatively independent of rock type and dimension of the pressurized zone, the effect on amplitude of reflected waves is small for t.k greater than about $10^{-9}$ or $10^{-8}$(c.g.s.). For this to be a significant effect for one million years requires a permeability of about $10^{-13}$ darcy, well below that generally observed experimentally. The same models predict a large effect on seismic waves when steam is present in the pore space. The above effects could be complicated further by compaction of sedimentary layers, fluid sources at depth due to dehydration reactions or flushing, reduction of porosity and permeability through pressure solution or scaled deposits, and permeability reduction due to ductile deformation or thermally driven

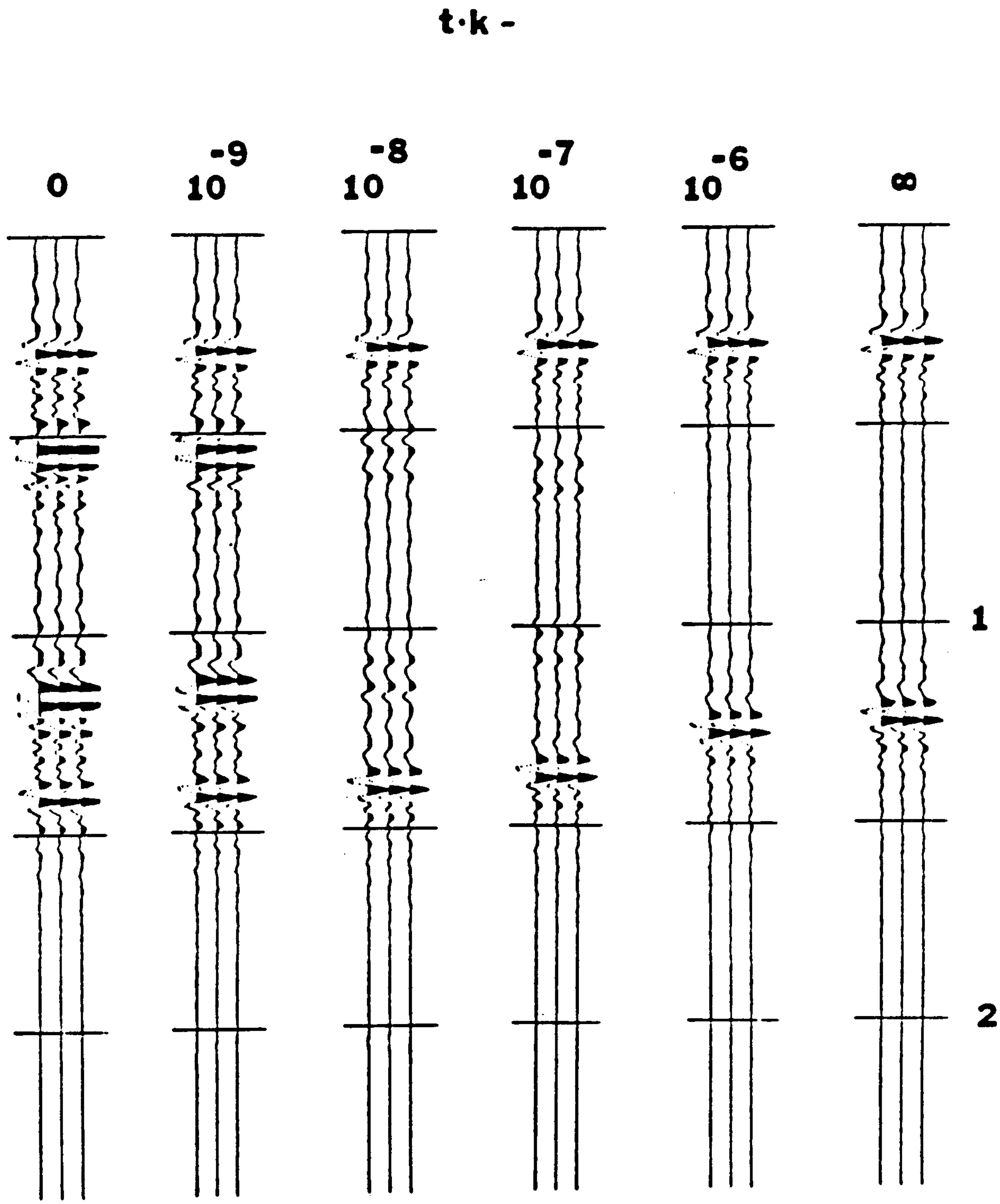
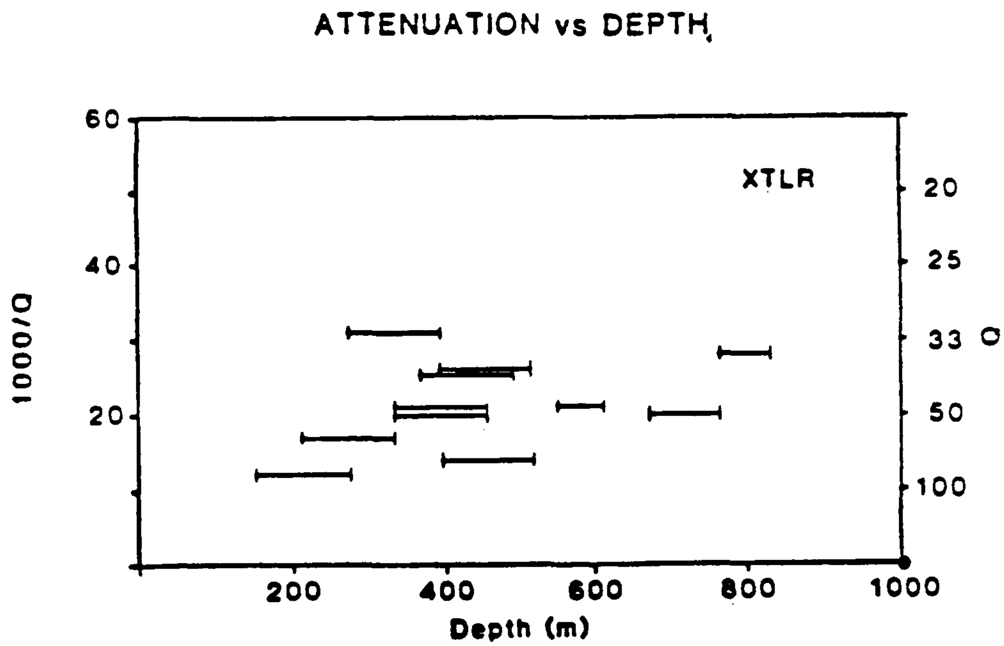



Fig. 8-2: Synthetic Seismograms Computed Over A Thick Section of Berea Sand-Stone as the Pore Pressure Decays with Normalized Time t · k, Where k is Hydraulic Permeability. The Top and Bottom Reflections are from the Top and Bottom of the Pressurized Zone.

heating rocks. The present results may show promise when applied to short time scale processes such as in draw-down of reservoirs, or the production of steam in geothermal areas.

(c) Velocities and Attenuation in East Mesa Geothermal Anomaly, by Dan Moos, research assistant, and Professor Amos N. Nur.

We have compared measurements of sonic velocity from core and borehole logs and seismic velocity from vertical seismic profiling (VSP). The relative importance of dispersion, mechanical damage at the well bore, and the effects of finite-length fractures were considered. Also, the value of the wave energy loss parameter $Q^{-1}$ was calculated from the uncorrected VSP data using two different techniques (pulse rise time and spectral ratios). The effects of intrabed multiple was calculated and the relative contributions of anelastic attenuation and scattering to the in situ measurements was estimated (Fig. 8-3).



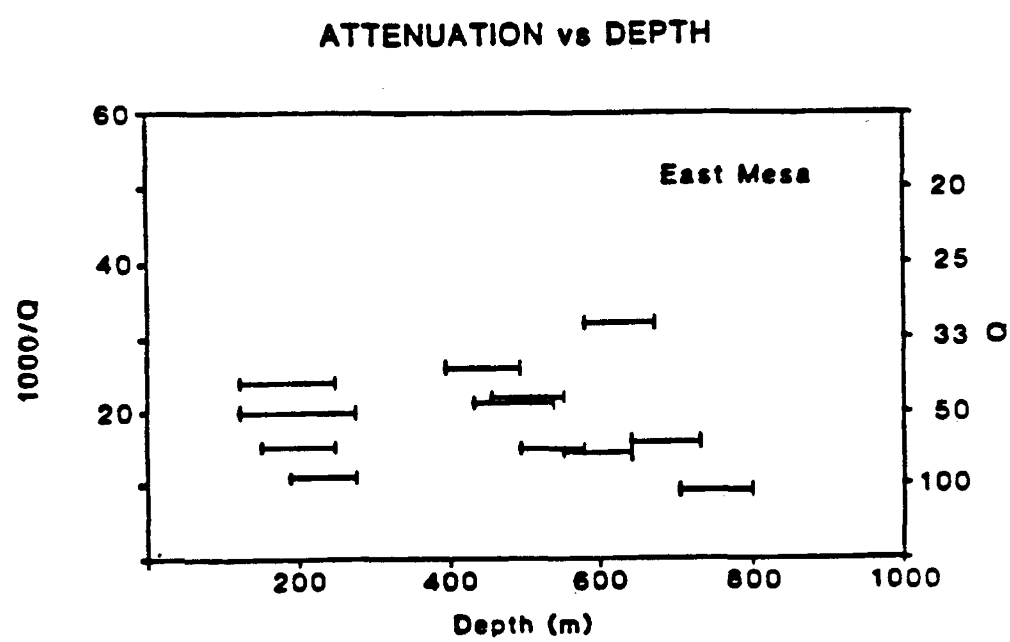




Fig. 8-3: Plots of Values of the Attenuation Factor (1000/Q) from Spectral Ratios Calculated from the VSP Data At: (a) XTLR, and (b) East Mesa Well 5-1. Only Those Receiver Pairs Whose Spectral Ratio Could Be Fitted to An Equation of the Form (3.2) were Used. The Horizontal Lines Indicate the Depth Range over which the Ratios were Calculated.

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# SEMINAR SCHEDULE

Autumn Quarter, 1982 — Room B-67, Mitchell Building — Thursdays, 1:15-2:30 p.m.

| Date | Title | Speaker |
|---|---|---|
| Oct. 7 | Organizational Meeting | Faculty and students SGP |
| Oct. 14 | No Meeting (GRC Annual Meeting) | |
| Oct. 21 | "Relative Permeability Investigations" | Mark A. Miller<br>Petroleum Engineering |
| Oct. 28 | "Low-Temperature Geothermometry" | George A. Parks<br>Applied Earth Sciences |
| Nov. 4 | "Radon Transport in Two-Phase Reservoirs | Lewis Semprini<br>Civil Engineering |
| Nov. 11 | "Silicic Volcanic Centers Supporting Geothermal Systems in the Mexican Neo-Volcanic Belt" | Gail A. Mahood<br>Geology |
| Nov. 18 | "Heat Extraction Modeling" | Stephan T. Lam<br>Mechanical Engineering |
| Nov. 25 | No Meeting (Thanksgiving) | |
| Dec. 2 | "Geophysical Monitoring of Vapor-Liquid Interfaces in Reservoirs" | Amos M. Nur<br>Geophysics |
| Dec. 9 | No Meeting (Dead Week and A.G.U. Fall Meeting) | |

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| Dec. 14 to 16 | 8th Geothermal Reservoir Engineering Workshop |

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## S E M I N A R   S C H E D U L E

Winter Quarter, 1983 — Room B-67, Mitchell Building — Thursdays, 1:15-2:30 p.m.

| Date | Title | Speaker |
|---|---|---|
| Jan. 13 | "Remote Sensing of Geothermal Resources in Japan" | Ronald J. P. Lyon<br>Applied Earth Sciences<br>Stanford University |
| Jan. 20 | "Planning Commercial Development at The Geysers" | Robert J. Membreno<br>SAI Engineers |
| Jan. 27 | "High Temperature Well Testing Instruments" | Sally M. Benson<br>Lawrence Berkeley Laboratory |
| Feb. 3 | "Geothermal Energy Development at The Geysers" | Robert Lengquist<br>Former Chief Engineer<br>Magma Thermal Power |
| Feb. 10 | "Hydraulics of the Klamath Falls Geothermal System" | Edward Sammel<br>U.S. Geological Survey |
| Feb. 17 | "Economic and Institutional Factors in the Development of Geothermal Energy" | Tsvi Meidav<br>Trans-Pacific Geothermal |
| Feb. 24 | No Meeting | |
| Mar. 3 | "High Temperature Geothermal Developments in the Basin and Range Province" | W. Richard Benoit<br>Phillips Petroleum Compa |

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# SEMINAR SCHEDULE

**Spring Quarter, 1983** | **Room 113, Mitchell Building** | **Thursdays, 1:15-2:30 p.m**

| Date | Title | Speaker |
|---|---|---|
| April 7 | Hot Dry Rock Program Update | H. Murphys, Los Alamos National Laboratory |
| April 14 | Carbonate Chemistry in Geothermal Wellbores | D. E. Michels<br>Republic Geothermal |
| April 21 | Pressure Transient Analysis of Reservoirs with Linear or Internal Circular Boundaries | A. Sageev<br>Stanford University |
| April 28 | Reinjection Testing in 1982 in Svartsengi, Iceland | J. S. Gudmundsson<br>Stanford University |
| May 5 | Production Decline Caused by Deposition in Wellbore | E. E. Granados<br>Stanford University |
| May 12 | Volcanic and Seismic Hazards in Geothermal Areas (tentative title) | C. G. Bufe<br>U.S. Geological Survey |
| May 19 | Deep Drilling into the Salton Sea Magma-Hydrothermal System | W. A. Elders, University of California, Riverside |
| May 26 | Evolution of the Geothermal System in the Lassen Volcanic National Park Area | S. Ingebritsen<br>Stanford University<br>M. L. Sorey<br>U.S. Geological Survey |

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# ON

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### PRINCIPAL INVESTIGATORS

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

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| Anstein Hunsbedt | Civil Engineering |
| Drew V. Nelson | Mechanical Engineering |

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Jaime Ortiz-Ramirez
Abraham Sageev
Brian Skuse
Miguel Saldana-Cortez
Gardner W. Walkup

#### Civil Engineering

Lewis Semprini

#### Mechanical Engineering

Stephen T. Lam

## APPENDIX B: PAPERS PRESENTED AND PUBLISHED OCTOBER 1, 1982 THROUGH SEPTEMBER 30, 1983

### Geothermal Resources Council Annual Meeting, San Diego, California, October, 1982

Interpretation of Tracer Return Profiles at Wairakei Geothermal Field Using Fracture Analysis--M. P. Fossum and R. N. Horne

Utility Industry Estimates of Geothermal Electricity--P. Kruger and V. Roberts

World Uses of Low-Temperature ( $150^{\circ}C$) Geothermal Resources in 1980--J.S. Gudmundsson and G. Palmason

### Fourth New Zealand Geothermal Workshop, Auckland, November 1982

Evaluation of Chemical Tracers for Geothermal Use--K. A. Breitenbach and R. N. Horne

### First Japan-United States Joint Seminar on Hydraulic Fracturing and Geothermal Energy, Tokyo, Japan, November 1982

Experimental Studies on Heat Extraction from Fractured Geothermal Reservoirs--P. Kruger

### Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, December 1982

Well Test Analysis for Naturally Fractured Reservoirs--G. DaPrat

Flashing Flow in Fractured Geothermal Reservoirs--A. J. Menzies, J. S. Gudmundsson and R. N. Horne

Heat Extraction Modeling of the Stanford Hydrothermal Reservoir Model--A. Hunsbedt, S. T. Lam, P. Kruger and K. Pruess

Retention of Chemical Tracers in Geothermal Reservoirs--R. N. Horne, K. A. Breitenbach and M. P. Fossum

Interpretation of Radon Concentration in the Serrazzano Zone of the Larderello Geothermal Field--L. Semprini, P. Kruger and F. D'Amore

### International Symposium on Solving Corrosion and Scaling Problems in Geothermal Systems, San Francisco, California, January 1983

Silica Deposition from Geothermal Brine at Svartsengi, Iceland--J. S. Gudmundsson

Society of Petroleum Engineers 53rd Annual California Regional Meeting, Ventura, California, March 1983

Streamtube Relative Permeability Functions for Flashing Steam-Water Flow in Fractures--J. S. Gudmundsson, A. J. Menzies and R. N. Horne

Use of Lumped Parameter Modeling for Geothermal Engineering--
L. M. Castanier and W. E. Brigham

Seventh Annual EPRI Geothermal Conference and Workshop, San Diego, California, June 1983

Radon Startup Analysis at a Roosevelt Hot Springs, Utah Geothermal Well--
Proceedings, Seventh Annual EPRI Geothermal Conference and Workshop,--
P. Kruger and L. Semprini

Energy, Vol. 8, No. 7, 491-513, 1983

Geothermal Electric Power in Iceland: Development in Perspective--
J. S. Gudmundsson

Society of Petroleum Engineers Journal, (February 1983), 157-167

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

Geophysics Research Letters, 10, 289-292, 1983

Dispersion in Tracer Flow in Fractured Geothermal Systems--R. N. Horne and
F. Rodriguez

Journal of Petroleum Technology, 35, 2127-2134, 1983

Pressure Response of a Reservoir with Spherically Discontinuous Properties
M. Onyekonwu and R. N. Horne

APPENDIX C

## 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. Casse, "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. |
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