STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305

SGP-TR-89

GEOTHERMAL RESERVOIR ENGINEERING RESEARCH
AT STANFORD UNIVERSITY

FOURTH ANNUAL REPORT

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PRINCIPAL INVESTIGATORS:

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SEPTEMBER 1984

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PREFACE

The Stanford Geothermal Program was initiated under grants from the National Science Foundation in 1972 and continued under contracts from the Energy Research and Development Administration and the subsequent Department of Energy since 1977. This publication is the Fourth 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, 1983 through September 30, 1984.

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 evaluation 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 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, 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 research agreements with Italy, Mexico, New Zealand, and Turkey. 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.
Paul Kruger
Roland N. Horne
William E. Brigham
Frank G. Miller
Jon S. Gudmundsson

1. INTRODUCTION

The Stanford Geothermal Program in fiscal year 1983 was divided into several task areas, as defined in the Department of Energy contract No. DE-AT03-80SF11459. Four of the task areas were carried out within the Petroleum Engineering Department, and one each within the Civil Engineering and Geology Departments. The task areas reflect the interdisciplinary nature of Stanford's geothermal research and training in the fields of engineering and earth sciences.

Reservoir definition research at Stanford consists of 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 area included a project on multiphase compressibility, including the the thermal content of the rock. Several projects on double-porosity systems were completed, and work was done on relative-permeability. **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.

Heat extraction from rock will determine the long-term response of geothermal reservoir$ to development. The work in this task area 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.

International cooperative research at Stanford has field applications as its focus. Several formal and informal cooperative projects were active during the year. The main objective of Stanford's cooperative research 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 world-wide. Stanford has two formal cooperative agreements with foreign agencies. These are the DOE-ENEL cooperation with Italy, and IIE-SGP cooperation with Mexico. The Italian work duing the year dealt with adsorption of water on reservoir cores, and the planning of tracer surveys. The Mexican work dealt with an injection and tracer test in the Los Azufres fields. Through informal agreements with colleagues in Iceland, field and well data from the liquid-dominated Svartsengi field was used in several projects. The interaction between academic research and field applications has proved valuable to the research and training program.

Reinjection of spent geothermal fluids has rapidly become a pressing research problem in 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. A powerful method for investigating such flow is the use of external tracers. Data from Stanford's two field tests, Los Azufres and Klamath Falls, were used in projects during the year.

Geochemistry has become an important component of not **only** the exploration of geothermal resources, but also the monitoring of fluid changes during development. A further important use is the study of mineralogy of cores and cuttings, to better define the flow of fluids within the reservoir in its natural state. Work of this nature aids in reservoir evaluation and modeling. A project to make available a number of proven geochemical codes was carried out during the year. The codes were installed on the Geology Department's computer and are now available to Stanford geothermal researchers.

An annual Workshop of Geothermal Reservoir Engineering has been held at Stanford since 1975. It **is** attended by 120-130 geothermal engineers, scientists, and developers from around the world. Weekly seminars on geothermal energy matters are held at Stanford throughout the academic year.

2. RESERVOIR DEFINITION

2.1 Multiphase and Multicomponent Compressibility

L. Macias-Chapa and H.J. Ramey, Jr.

Total system compressibility plays an important role in the interpretation of well test analysis. Accurate information on the total effective fluid compressibility is necessary for the possible isolation of formation compressibility from interference testing in subsiding systems.

Adiabatic and isothermal compressibility and production compressibility were computed with a thermodynamic model for single and multicomponent systems. The model consists of an energy balance, including a rock component, and a mass balance. It has thermodynamic relationships for enthalpy and equilibrium ratios using the virial equation of state. calculations consisted of modeling a flash process, either adiabatically or isothermally, and calculating fluid compressibilities for H_2O, $H_2O - CO_2$, and various hydrocarbon systems. The production compressibility was computed for gas production, and for production based on relative permeability relationships for a one-component system.

Non-condensible gas content of discharged fluid for a steam-dominated geothermal system was studied with the thermodynamic model. An initial increase in the non-condensible gas concentration was observed, followed by a stabilization period, and finally a decline in the non-condensible gas concentration, behavior that resembles actual field results, Study of the behavior of non-condensible gases in produced geothermal fluids is important for planning turbine design.

Total isothermal compressibility is defined as the fractional volume change of the fluid content of a porous medium per unit change in pressure, and it is a term that appears in the solution of all problems on isothermal transient flow of fluids in a porous medium. Recently, it has been reported (Grant, 1978) that the total system compressibility for systems where a change of phase and production are involved is usually higher than the compressibility of the gaseous phase at the same conditions. Evaluation of total system effective compressibility for multiphase systems for different production modes is the purpose of this study.

Runs were made to compute the two-phase compressibility for a single-component water system, and multicomponent systems: $H_2O - CO_2$, $C_1 - C_3$, $nC_4 - iC_4 - C_5 - C_{10}$, $C_1 - C_7$ and $C_1 - C_7 + H_2O$. Production runs were made for gas production, and production according to relative permeability- saturation relationships. Typical results of steam production runs are shown in Fig. 2.1.

Usually, results showed a two-phase compressibility higher than gas compressibility fob similar conditions, and a production compressibility larger than either the two-phase compressibility or the gas-phase compressibility, under the same conditions. The two-phase compressibility results tend to corroborate **an** observation that a two-phase system has the effective density of the liquid phase, but the compressibility of a gas. Production compressibility is large because of a reduction in the amount of liquid in the system because of the effects of vaporization and production enhanced by the effect of heat available from rock in the system.

In the design of turbines for geothermal field electric production, it is necessary to have an estimate of the noncondensible gas content of the produced geothermal steam. **A** thermodynamic compositional model can give information on the noncondensible gas behavior for a given system of interest. Runs were made with a system simulating a vapor-dominated geothermal field with two components: $H_2O - CO_2$. See Fig. 2.2 for example. Results indicated an increase in the concentration of carbon dioxide in the produced fluid, followed by a stabilization period, and finally an eventual decline in the produced CO_2 concentration, behavior that resembles field results, Pruess et al. (1985).

2.2 Decline Curve Analysis in Double Porosity Infinite Systems

A. Sageev and H. J. Ramey, Jr.

A transient pressure analysis method was developed for analyzing the rate decline of a constant pressure well producing in an infinite double-porosity reservoir, with and without wellbore **skin.** This analysis method may be used to interpret well test rate data, and to com-

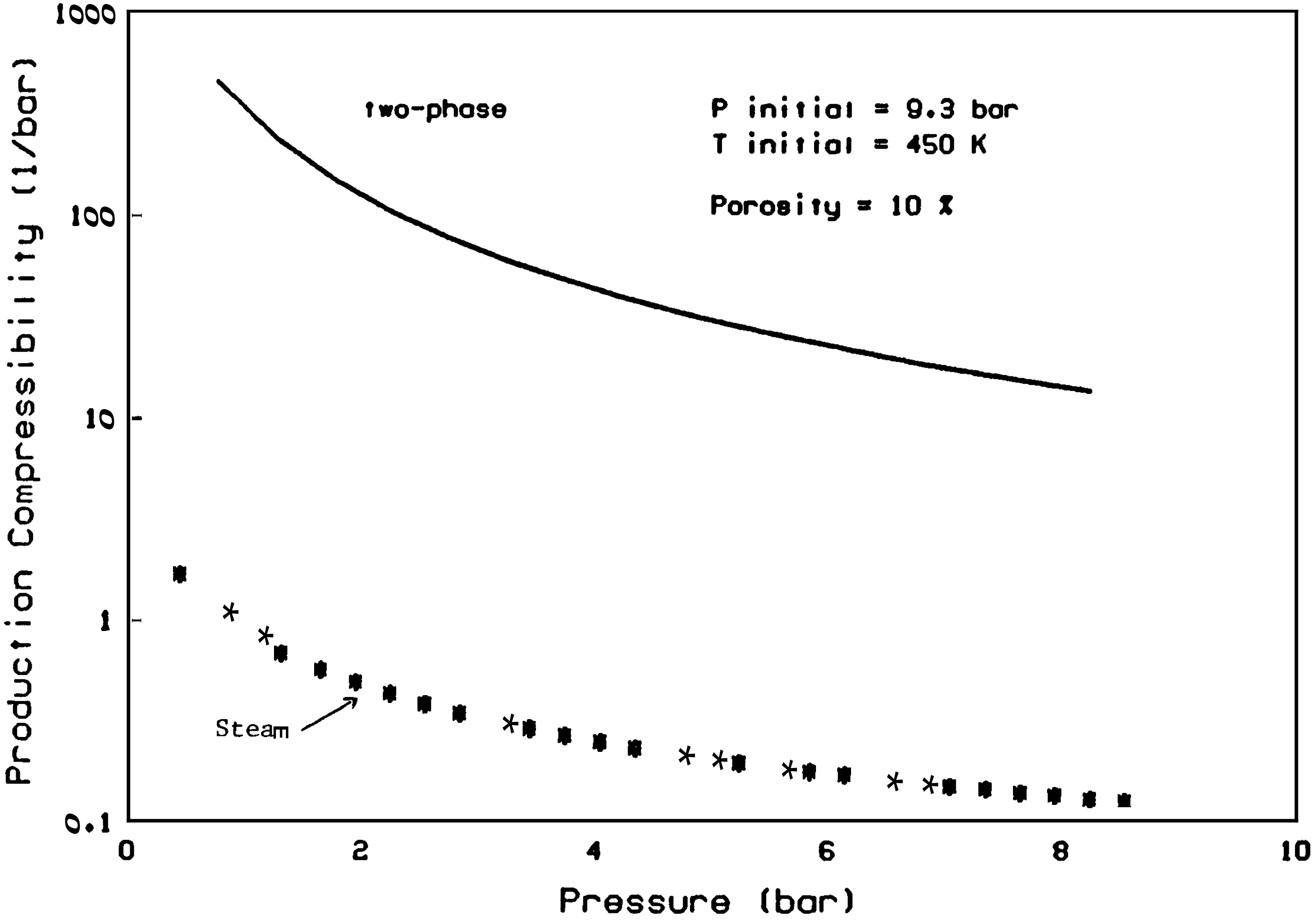


Figure 2-1: Steam production compressibility versus pressure, water system No. 16

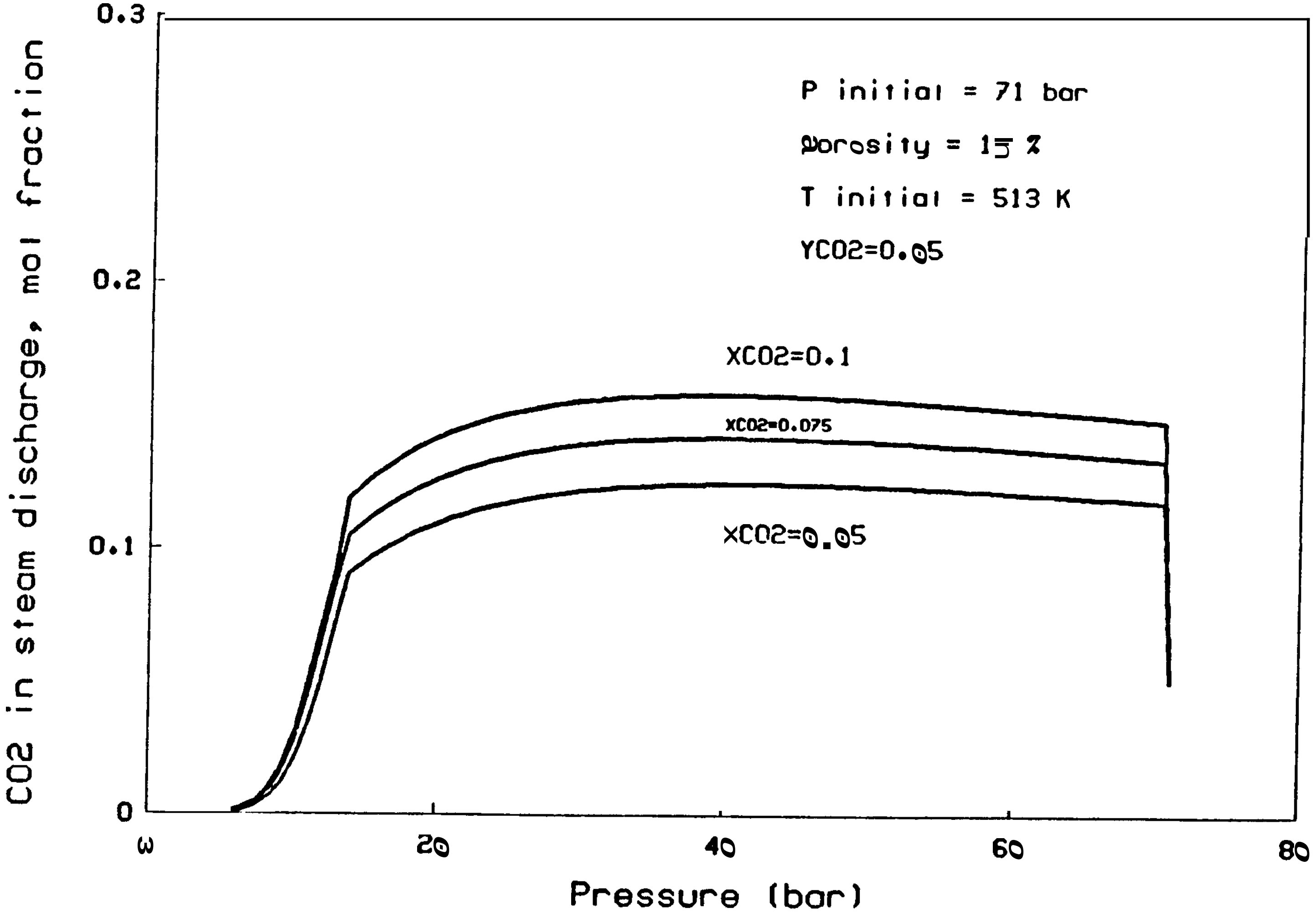


Figure Z-2: CO_2 discharge mol fraction versus pressure for a simulacion of a vapor dominated geothermal field with gas production pute the rate behavior of an infinitely acting reservoir that is produced at constant pressure.

In a double porosity-system, there are two main parameters that describe the behavior of pressure and rate as a function of time: h and ω. The first parameter, h, describes the interporosity flow, and the second parameter, w describes the relative fracture storativity.

In a double-porosity system, with pseudo-steady state interporosity flow, the initial infinite-acting rate decline, representing only the fracture system, is followed by a constant rate flow period. The length **of this** constant rate flow period is controlled by the parameter ω. The beginning of this period is controlled by the interporosity flow parameter, λ. Following this constant rate period, the rate resumes an infinite homogeneous decline, representing the total system, fractures and matrix. The parameters h and w may be estimated from a log-log match of rate data to the type curve (see Fig. **2.3).**

The presence of wellbore skin sets un upper limit on the flow rate at the well, which is analogous to the film coefficient studied in heat transfer. Hence, the early time rate response may yield a match on the log-log type curve estimating the value of skin.

2.3 Linear Boundary Detection Using Buildup Tests

G. Fox and **A.** Sageev

We have been working on linear boundary detection using transient pressure analysis for the past three years. This last year we concentrated on the detection of linear boundaries using buildup tests. Several type curves were developed for three different methods **of** analysis.

In the log-log total time method, the pressure data are matched to a type curve, where **the** time scale includes the drawdown and the shutin flow periods. Two log-log type curves were generated, one for no-flow and one for constant pressure linear boundaries. Here, the matching parameters are the dimensionless production time, and the distance to the linear boundary.

The second method of analysis is the Horner method. Here, the time axis is the defined as the total elapsed time form the **start** of the drawdown over the shutin time, and the pressure scale **is** dimensionless. In order to use this type curve, an initial match of the drawdown data

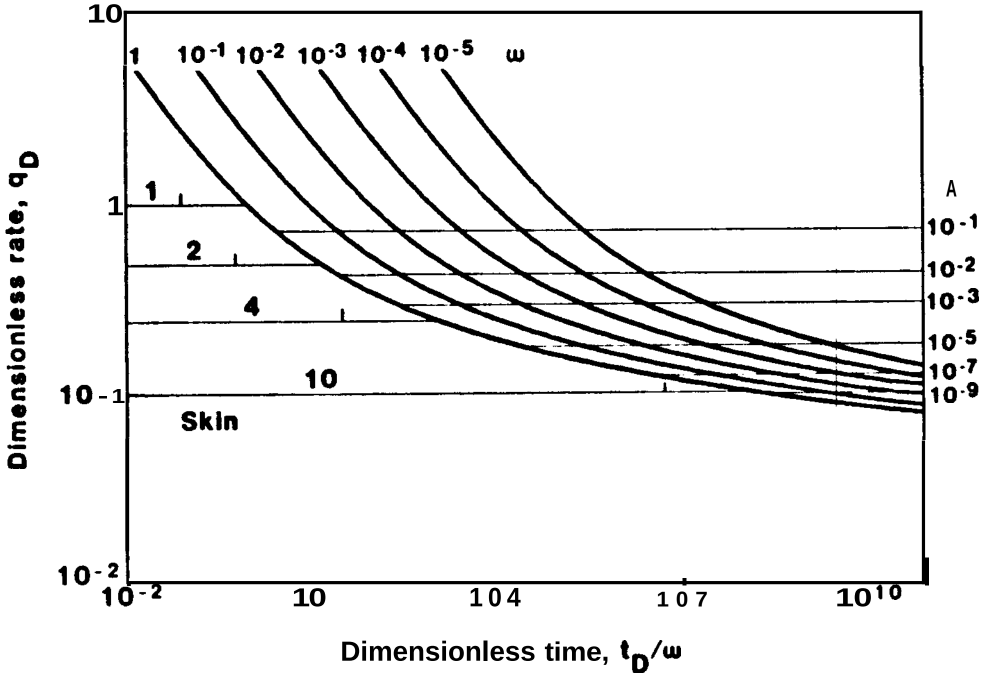


Figure 2-3: Log-log type curve for infinite double-porosity systems with and without wellbore skin

to the line source solution must be obtained, so that the actual pressures may be converted to a dimensionless form.

The third method of analysis requires a graph of the data in a semilog fashion, where the time scale includes the drawdown and the buildup flow periods. The pressures must be converted to a dimensionless form before using the semilog type curve (see Fig. 2.4). **A** match of the drawdown and the buildup flow periods to the semilog type curve yields a direct estimate of the distance between the well and the linear boundary.

2.4 Rate-Pressure Doublet Model

A. Sageev, R.N. Horne and H. J. Ramey, Jr.

In this task we examined pressure and rate interference between a well producing at **a** constant rate, and a well producing at a constant pressure. This pressure transient analysis method may be applied to an isolated two-spot pattern encountered during pilot testing or to a geothermal field where reinjection **is** implemented. Such a configuration may be superposed in space to yield any number of constant rate wells around a constant pressure well. An isolated five-spot pattern with a constant pressure injector is considered. On **a** larger scale, the model may be applied to the interpretation of pressure interference between communicating constant rate and constant pressure reservoirs.

The behavior of three time-dependent parameters may be calculated using the model: the pressure response of the constant rate well, the injection/production rate, and the cumulative injection/production **of** the constant pressure well. The solutions for the rate-pressure model were derived as a particular case of a production configuration in which a constant rate line source well produces near a constant pressure finite radius boundary. The pressure and rate Laplace solutions were derived and inverted numerically. Fig. 2.5 presents a semilog type curve for the rate-pressure model. The relative diameters of the two wells had a significant effect on the rate and pressure responses.

Although the late time steady state behaviors of the rate and pressure wells are identical

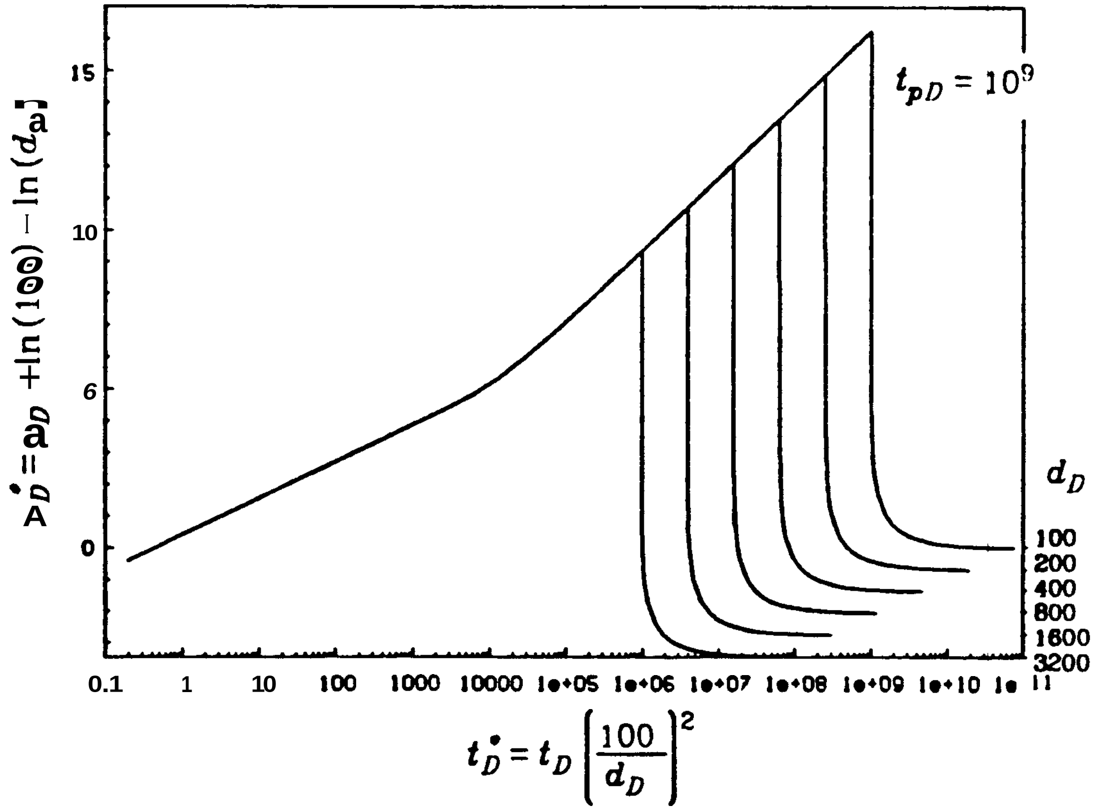


Figure 2-4: Semilog type curve for detection of no-flow linear boundaries using buildup tests

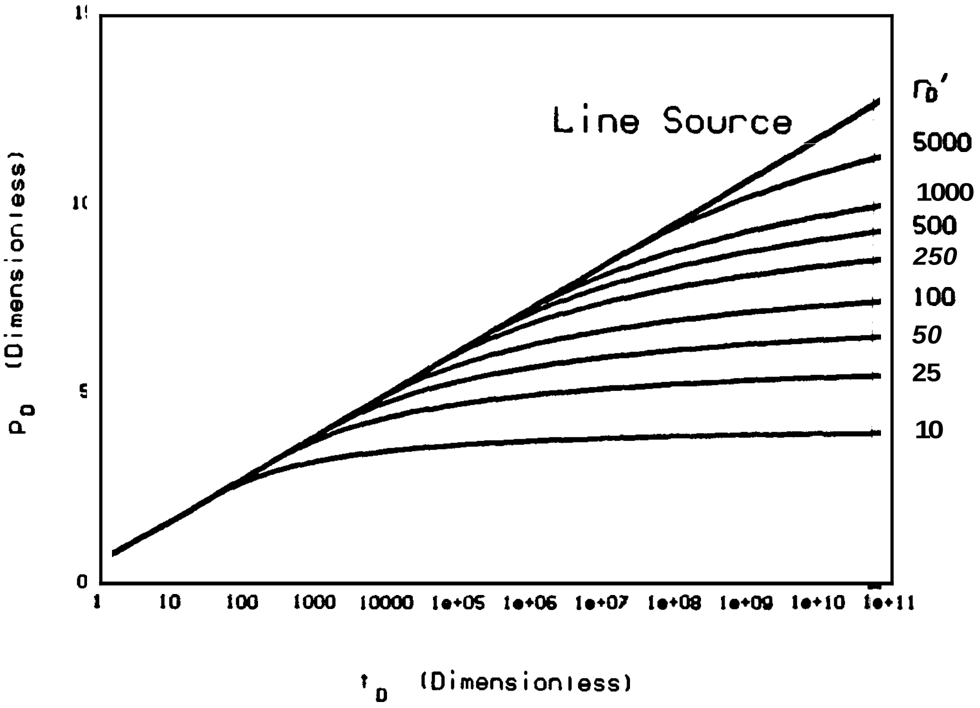


Figure 2-5: Semilog type curve for a rate-pressure doublet model

to those of a pair of line source-sink wells, the transient pressure behaviors are different. In the case of a large, isolated five-spot pattern, the interference effects of the constant rate wells may be detected before the constant pressure center well causes the pattern to approach a steady state condition. A two-well production system with a constant rate well and a constant pressure well has been approximated in the past by superposition in space of two wells. The rate-pressure model offers a practical and rigorous method for interpreting the pressure and rate responses of such production systems.

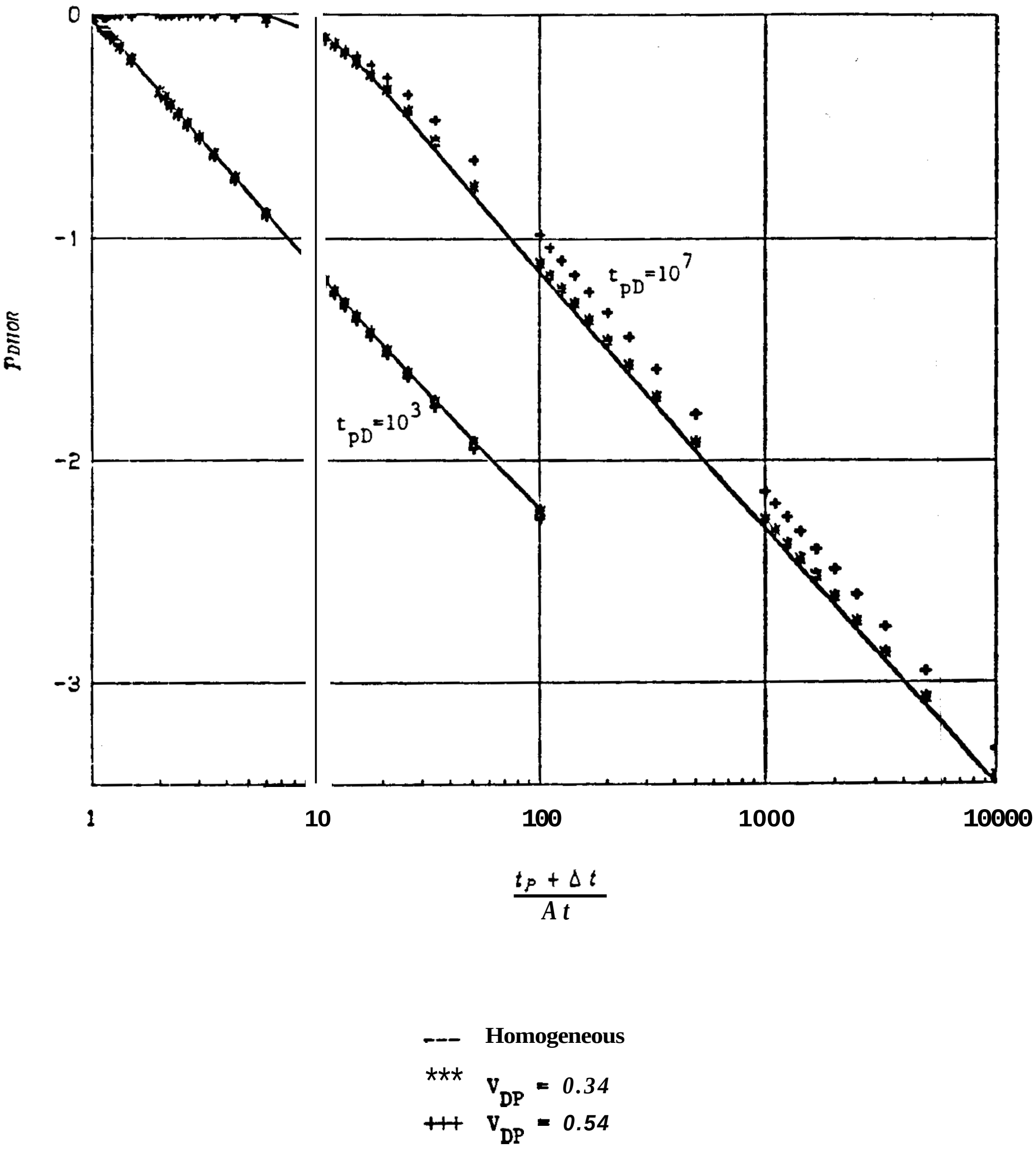
2.5 Pressure Transient and Tracer Concentration-Time Data for Layered Reservoirs Under Injection

S. Mishra and Henry J. Ramey, Jr.

This study compares pressure transient and tracer concentration-time data for layered reservoirs with non-communicating strata in developed production-injectidn patterns. A mathematical model was used to simulate drawdown and buildup responses for a hypothetical stratified system (Fig. *2.6).* The tracer test response was generated using the model of Abbaszadeh-Dehghani and Brigham (1982). The tracer concentration-time data show sensitivity to both the degree of stratification and the nature of permeability distribution (Fig. 2.7), whereas the pressure data is essentially insensitive.

Pressure buildup response **is** seen similar to that for a homogeneous system with a constant-presswe outer boundary. See Fig. **2.6.** This contrasts with buildup behavior in layered systems with a closed outer boundary, where differential depletion between layers leads to a flattening of buildup pressure before the final pressure **rise,** or the ***humping*** generally believed diagnostic of non-communicating layered systems. A major finding of this study is that ***humps*** will not occur in the constant- pressure outer boundary case - the fluid injection case. There is no differential depletion between layers for this case.

This work confirms that well-to-well tracer tests will contain information about reservoir heterogeneities that **is** not usually apparent **from** conventional pressure transient tests.



V_{DP} is Dykstra-Parsons permeability variation for a log - normal distribution

Figure 2-6: Effect of producing time and permeability contrast on buildup behavior

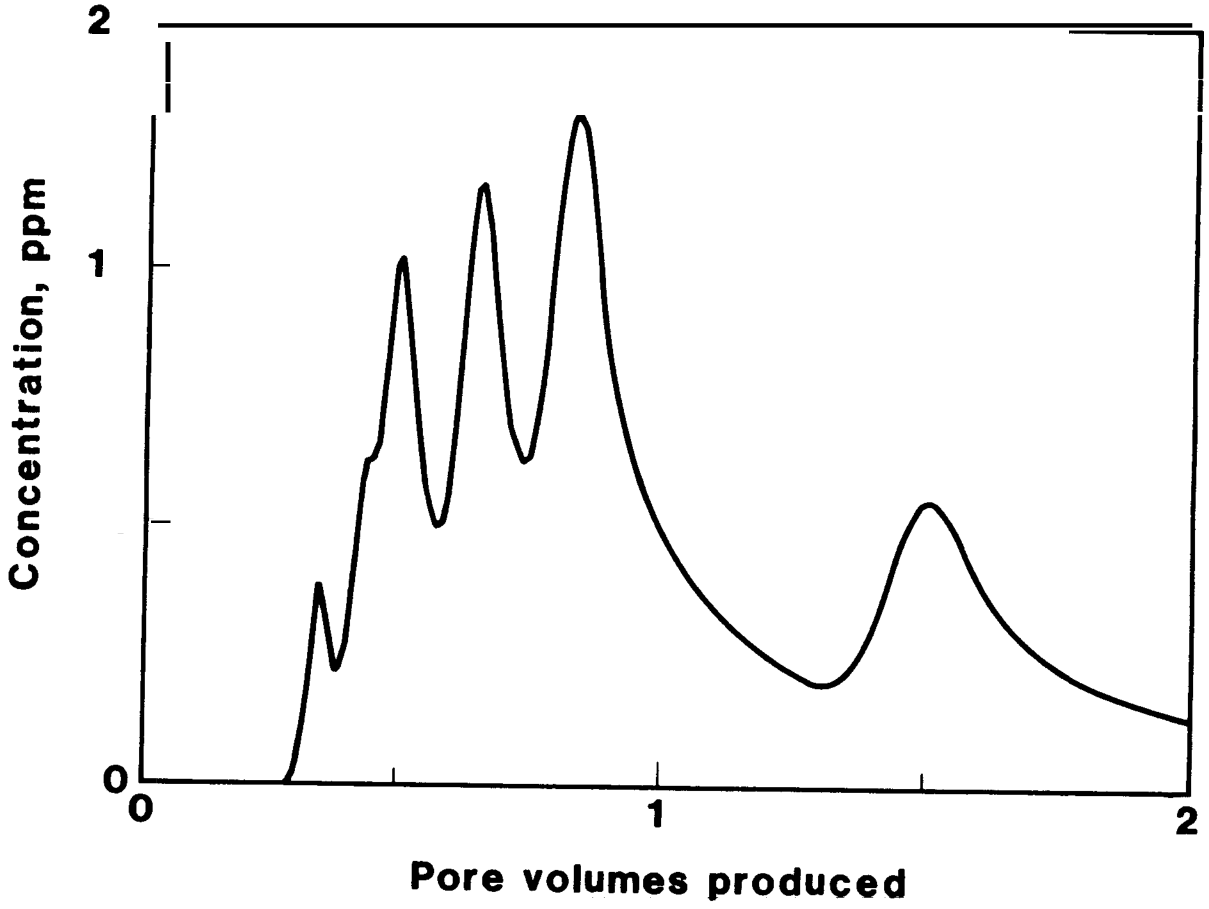


Figure 2-7: Tracer breakthrough curve, 6-layer system Dykstra-Parsons permeability variation of $V_{DP} = 0.34$

2.6 Velocity and Gravity Effects in Relative Permeability Measurements

B.J. Beal, C.S. Nunes and H.J. Ramey, Jr.

There have been several studies on the effects of gravity and flowrate on laboratory relative permeability measurements. Most of these studies have concentrated on the effect of these parameters on the flooding front. Miller's (1983) data showed that the influence of of these and other variables are not well understood. This study found that the calculated reaovery at breakthrough was different from the observed recovery at breakthrough. The calculated recovery at breakthrough was based on theory derived from Buckley-Leverett pistoh-like displacement. This study attempted to determine how gravity or core positioning and flowrate of the displacing fluid might be used to achieve a stable flooding front.

Miller (1983) explored the effect of temperature on relative permeability and found that relative: permeability remained unaffected by temperature. His approadh was to use a simple, well-known porous media and fluid system to determine the effect of elevated temperatures on relative permeability. His experiments were conducted using a dynamic displacement relative permeameter. Miller modified the apparatus from the original design and constructed by Jeifers (1981). Though **his** results were reproducible, Miller saw a water breakthrough consistently earlier than that predicted by Buckley-Leverett theory.

It is thought that, due to the size of the core used (2 in. in diameter, 24 in. in length), that gravity may have had an effect on the front such that a Buckley-Ldverett displacement through the core was not attained. In **this** case, the equations used by Miller to predict actual breakthrough would then not apply. To test **this** hypothesis, an unconsolidated core was first prepared in the same manner in which Miller prepared his. Then a series of runs, both with the core in a horizontal position and in a vertical position, was conducted. Assuming all else constant, any difference in results between the two **runs** could be attributed to some type of gravity effect on the front in the horizontal core.

The rate of fluid flow through the core was another variable that could potentially have an effect on th: displacing front during a flood. **A** flow rate of high velocity might have rendered capillary forces at the front negligible, but could induce an instability in the front (viscous fingering). With the core in the vertical position, the velocity was varied to study the effect **of** this variable.

The apparatus used in **this** study was the same as that used by Miller. The only modification to the apparatus was the construction of a vertical core holder. The only change in the procedure used by Miller was that this study was conducted at room temperature only. Since early breakthrough was observed at all temperatures, room temperature was selected for ease.

The data observed in **this** investigation were analyzed by the software developed by Miller based on the techniques of Welge (1952) and Johnson, Bossler, and Naumann (1959). Details on the apparatus, procedure, and data analysis are given in the report. This study found that gravity **had** no significant effect on the difference between calculated and observed recovery at breakthrough. It also observed that an increase in flowrate would increase the flooding front nstabilities. Therefore as flowrate decreased the calculated and observed breakthrough approach a single value. See SGP-TR-82.

3. HEAT EXTRACTION

During the year the application of the 1-D Linear Heat Sweep Model was initiated in cooperative programs with CFE at Cerro Prieto in Mexicali and at Los Azufres in Michoacan, Mexico. Both of these studies are being carried out with the assistance of R. Molinar and the reservoir engineering staff at CFE headquarters for geothermal development at Morelia, Mexico. The projects were based on implementation of the procedures given in SGP-TR-75, Hunsbedt et al. (1984), the User's Manual for the 1-D Linear Heat Sweep Model issued in preliminary form in April, 1984.

The joint effort with K. Pruess of LBL to use the MULKOM/MINC geothermal simulator on the thermal drawdown data acquired from the Stanford Geothermal Reservoir Model reservoir model studies is nearing completion. Efforts were also focused on the unresolved problem of the role of thermal stress on the long-term heat-transfer properties of hydrothermal rock formations. Progress in each of these projects is discussed in this report.

3.1 Cooperative Research

S. Lam and P. Kruger

During FY84, the first application of the 1-D Linear Heat Sweep Model was initiated as a joint project with the reservoir engineering staffs at Cerro Prieto in Mexicali and Los Azufres in Michoacan, through the coordination of the reservoir engineering staff at Morelia, Mexico.

The first of these two projects was the analysis of heat sweep through the western boundary of the original Cerro Prieto I field. After several planning discussions, it was agreed to carry out the analysis in a series of phases: (1) a hypothetical study of the western zone based on available published data to estimate the magnitude of thermal energy in place and to show the feasibility of conducting a temperature decline analysis; (2) analysis of the chemical and physical data since initiation of electrical energy production to obtain the relative cooldown history along, the western border line of wells and to compare this cooldown history to that observed at the next inner line of wells closer to the reservoir hot water; and (3) to estimate the longevity of heat sweep from the western zone of CPI in relation to production of hot water from the east and possible cold-water vertical percolation from above as postulated by Grant and Sullivan (1982).

The hypothetical study was completed in the summer of 1984. The results, based on a reservoir geometry patterned after Halfman et al. (1982) and using component temperature6 from literature models, indicated that sufficient thermal energy was available from the western zone of the field to produce fluids with temperature above the commercial threshold of 250C for at least 40 to 80 years. The key parameters were temperature drawdown, heat transfer properties, and formation effective porosity.

On the basis of further discussions with the geology staff at Cerro Prieto, a more detailed analysis of the reservoir flow geometry was completed. The chemical history of 10 wells selected for the study was used to calculate the Na-K-Ca and Si02 geothermometers for thermal drawdown history. The 1-D Linear Heat Sweep Model was further develbped to include distributed vertical cold-water recharge. Current efforts are to match the observed cooldown histories at the westernmost line of wells with that calculated as a mixture of heat sweep from the west at the observed cooler temperature, vertical percolation of colder water from above, and reservoir hot water from the east at the cooldown temperature rate calculated from the geothermometer data. Current plans are to present the first discussions of these analyses at the **SGP** weekly seminar in October, 1984 at the start of FY 85 and prepare a joidt paper for the 10th **SGP** Workshop in January, 1985.

The second joint project is to prepare the data for heat sweep analysis at Los Azufres. Plans for FY84 were to initiate the project by collating many available physical and chemical data acquired for diverse objectives into a description of the initial conditions at the five wells designated for the five 5 **MWe** wellhead generators. This effort was authorized by R. Reyes, coordinator of the Los Azufres field and in conjunction with R. Molinar, head of reservoir engineering studies. All of the chemical and production data are being compiled for analysis of reservoir temperatures. The analysis is planned to be described in a paper for the 10th SGP

Workshop in January, 1985.

A second project was initiated to use the 1-D Linear Heat Sweep Model in conjunction with the study of A. Razo, head of geologic studies at CFE headquarters in Morelia, to examine the sweep path between two pairs of injection-production wells in the south zone of Los Azufres. Plan!; were made to initiate these studies with the transfer of the User's Manual and microcomputer programs to the Morelia staff with follow-up joint analysis in the Spring of 1985.

3.2 Heat Sweep Modeling

S. Lam and A. Hunsbedt

During FY 84, efforts in heat extraction modeling covered two paths: (1) an analysis of the data obtained from the heat sweep experiments performed in the Stanford Geothermal Reservoir Model using the LBL geothermal simulator, and (2) improvements to the 1-D Linear Heat Sweep Model with regard to other geometries and inversion procedures for the Laplace-transformed equations used in the model.

Initial analysis of the experimental data obtained in the physical reservoir model was made with the 1-D Linear Heat Sweep Model designed to estimate potential heat extraction from a fractured hydrothermal reservoir based on estimated reservoir geologic and rock thermal properties. Results of the 1-D Linear Heat Sweep Model for the physical model data were in reasonable agreement with the observed results, Hunsbedt et al. (1982). However, the 1-D model could not adequately account for the effect of the steel vessel and associated heat loss to the surroundings. Arrangements were made with the Lawrence Berkeley Laboratory to test their geothermal reservoir simulator on the physical model data. The objectives were to provide insight into the detailed physical processes occurring in the relatively complex physical system, and to provide feedback to LBL on the capability of the simulator to model a complex physical system.

Results of the efforts were obtained in several stages. Initial results using the physical model input data indicated satisfactory agreement with experimental results Hunsbedt et al. (1982). However, it was evident that improvements were possible. It was also evident that the LBL simulator was not designed to model many of the complex features of the physical reservoir system such as the pressure vessel structure, associated heat losses, and the thermal mixing region in the system inlet. More detailed material property data and external heat loss characteristics were obviously required to improve the simulation. As a result, the scope of the modeling task was increased significantly. The second stage of cooperation involved performing additional experiments in the physical reservoir model to determine system heat loss characteristics. Measurements were made to obtain rock thermal conductivity Lata. The LBL numerical model was refined and a number of parametric studies involving physical and numerical model parameters were carried out. During the course of the study, more than 40 complete and many partial computer model runs were made to evaluate the influence of the many system parameters.

Results of the second stage of study indicated that the two parameters having the greatest influence on numerical model results were the system boundary conditions and the material properties, particularly the rock thermal conductivity. A good match between simulation and measurements for the heat loss experiment was achieved and modeling and parameter uncertainties associated with the boundary were substantially reduced. However, adequate modeling of the inlet region could not be achieved for all flow conditions. This was not unexpected since the LBL simulator was not designed to include the necessary natural convection and thermal mixing processes. Consequently, a third stage in the cooperative study was the successful modeling runs using specified rock matrix inlet temperatures based on measurements.

The magnitude of rock thermal conductivity was also shown to have significant influence on the simulated temperature results. Based on initial conductivity measurements at the University of California, Berkeley, and more specific measurements conducted at the U.S. Geological Survey, Menlo Park, an adequate thermal conductivity relationship with temperature was obtained. With this relationship, simulated and measured rock-center temperatures were well matched indicating that the numerical formulation for rock heat transfer under steep temperature gradient conditions **is** sound.

An example of the agreement between simulation and measurements is given in Fig. 3.1. The comparison is quite good in all regions of the model. Further details of the parametric studies will be given later. The results also show that the predicted water and rock axial temperature gradients matched the measured steep temperature gradients near the rock matrix inlet. The combined steep axial and lateral rock temperature gradients in the physical model are extreme conditions that will not usually be found in geothermal reservoirs.

The overall conclusion of this work **is** that the **LBL** simulator does an excellent job of predicting the relevant physical processes in the Stanford Geothermal Reservoir Model experiments for extreme thermal gradient conditions and for a system with very complex boundary conditions. The analysis demonstrated the importance of specifying relevant parameters accurately to provide adequate modeling for the important physical processes. The modeling effort has providedl significant understanding of the physical processes and their numerical modeling. No additional work in this area is planned.

During FY **84** the User's Manual for the 1-D Linear Heat Sweep Model was issued in preliminary form to initiate the potential for its application in newly-developed geothermal fields. The need for several potential improvements had already become evident: **(1)** the need to remove the physical reservoir model example as not germane to real reservoir problems; (2) the need to include more general flow geometries such **as** radial and doublet flows; and **(3)** the need to improve the inversion algorithm for the Laplace-transformed equations for the overshoot before the breakthrough time and the undershoot to the final sweep fluid tempera. ture.

During the year, the development of radial flow capability in the model was completed, It is planned to test this geometry with a radial flow problem **as** phase **2** of the Cerro Prieto **I** field study in FY 85. Two inversion algorithms were obtained from the literature which appear to be promising for the heat sweep model. The currently used algorithm is a combination of

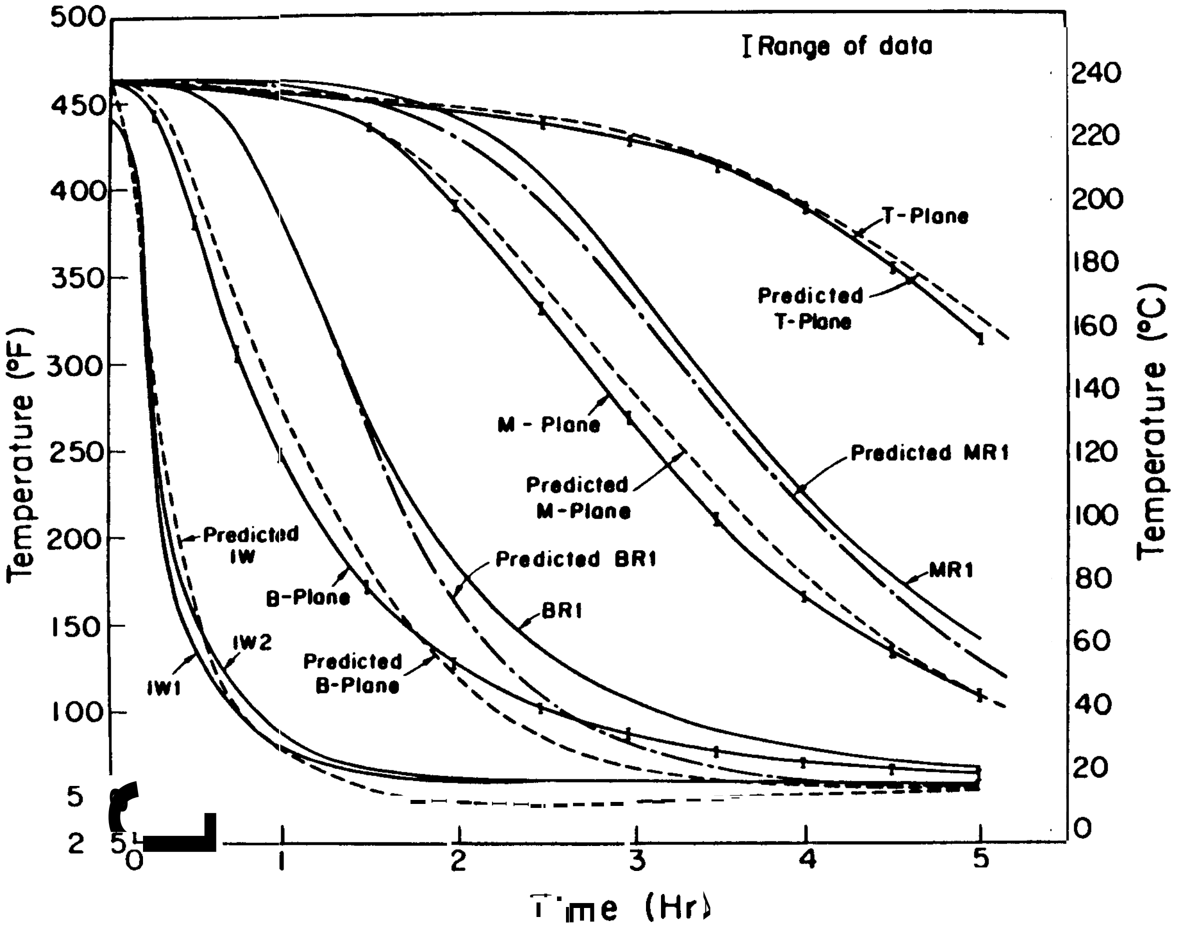


Figure 3-1: Comparison of predicted and measured rock and water temperatures for Experiment 5-1

Gaver (1966) and Stehfest (1970) which is widely used in geothermal and petroleum engineering. The two alternatives to be tested are those of Crump (1976) based on Fourier series approximations, and Piessens-Branders (1971) based on generalized Laguerre polynomials. It is anticipated that one or more of these three inversion algorithms will be discussed in the next revision to the User's Manual to be published in **FY** 85.

3.3 Thermal Stress Effects

S. Lam and D.V. Nelson

Research is continuing on the investigation of the effect of thermal stressing on rock mechanical and heat-transfer properties in cold-water sweep of liquid-dominated, fractured hydrothermal reservoirs (or hot dry rock). The objective **is** to examine the potential for changes in reservoir rock thermal properties under tensile thermal stress and the influence on long-term reservoir energy extraction.

The reservoir can be thermally modeled as a set of interconnected cracks which behave as geothermal fluid paths and heat-exchange surfaces. Cold-water sweep experiments conducted to simulate reservoir sweep production using a regular block loading in the Stanford Geothermal Reservoir Model were completed and described in detail in last year's annual report, Measurements of mechanical and thermal properties of the bottom-center block which experienced the most severe temperature/stress history during the experiments were also reported in last year's annual report. Recent results and currently planned work are described here.

Dry rectangular specimens obtained from a vertical surface and the interior near the stressed block geometric center, and from the surface of an unstressed block, Were tested for flexural strength using a static three-point bending apparatus. Disk-shaped rock specimens sectioned from similar block locations were tested for changes in porosity using the saturation method. Thermal conductivity measurement using a steady-state Birch-type divided-bar apparatus was carried **out** with the assistance of the U. S. Geological Survey's labaratory in Menlo Park, CA. Table **3.1** summarizes the observed rock strength, porosity, and conductivity of

Table 3.1

MECHANICAL AND THERMAL PROPERTIES

Granite Specimen at Room Temperature	Saturated			Dry (w/o contact fluid)
	Bending Strength (psi)	Porosity (% volume)	Thermal Conductivity (W/mK)	Thermal Conductivity (W/mK)
Unstressed [face)	1972±142	1.1±0.1	3.09±0.11	2.45
No. of spec.	(11)	(9)	(9)	(1)
Stressed [face]	1326±386	1.2±0.1	3.04f0.14	1.87±0.34
No. of spec.	(12)	(14)	(14)	(4)
Stressed [center]	1074±144	1.1fO.1	3.19±0.08	2.35
No. of spec.	(7)	(7)	(7)	(1)

Note: The standard deviation is based on (N) specimens. Overall uncertainty in strength is ±5%, porosity ± 1%, and conductivity ±4%.

both stressed (after seven thermal cycles of slow heating and rapid cooling) and unstressed granite specimens.

The data show a reduction in rock strength after thermal stressing, and with rise in porosity. In general, thinner specimens closer to the stressed face show higher porosity, lower conductivity, and lower strength. A simple estimate of the block tensile stress magnitude was made using a one-dimensional unsteady thermal and stress formulation derived by Rana (1984). The results indicate that, for the fastest sweep experimental run (average cotemperature differential of 150C, the calculated maximum transient surface tensile stress exceeds the theoretical granite uniaxial strength by an order of magnitude. These data favor the premise that cold sweep processes tend to enhance micro- and/or macro-size fracture density. However, there is no observable alternation in rock bulk density nor generation of any macro-size cracks, and the stressed block center measurements given in Table 3.1 are not readily explicable.

The impact of rock thermal conductivity on sweep flow thermal breakthrough was also assessed using the 1-D Linear Heat Sweep Model. Preliminary results indicated that a hypothetical 40% reduction in *dry* rock thermal conductivity can cause a **2-1/2** ydar reduction in breakthrough time if the defined breakthrough temperature is 80% of the initial reservoir (production) temperature of 550F. The production temperature after 15 years was reduced by 75 degree F.

Future efforts will include the design of a more definitive test for the conductivity (and diffusivity) change under thermal stressing. For example, the planned experiment could use a cylindrical specimen in the physical model and analyze test data with a more rigorous mathematical thermal and stress transient model. In addition, a 3-D approximate temperature/stress analysis of the previously stressed rectangular block will be performed, Development of a temperature-dependent thermal property model will also be initiated if deemed worthwhile, based on the results of the future thermal conductivity experiments.

4. FIELD APPLICATIONS

4.1 Cooperative Agreements

During the year, the Stanford Geothermal Program has had cooperative research relationships with the Instituto de Investigaciones Electricas (IIE) in Mexico, ENEL in Italy, Ministry of Works and Development (MWD) in New Zealand, and Middle East Technical University (METU) in Turkey. The first two cooperative agreements have been in force for some time, and the second two were new in the current year. For the most part, these cooperative programs are used as a means of field testing procedures developed either at Stanford or in cooperation with the other party. The individual tasks that have been undertaken are described in the sections of this report to which they pertain (for example, a tracer test parformed at Los Azufres is described in Section *5* as part of the discussion on Injection Technology). During the current year, a number of additional projects were initiated between Stanford and its international partners. These will mostly be active during the coming year. Included in these are tracer tests at Latera field in Italy and in Broadlands in New Zealand, core analysis of Lartdarello cores for adsorption effects, and verification of tracer interpretation methods using two-dimensional flow models at METU. Stanford joined in providing design background information for the two tracer tests, which are scheduled for December 1984 (Latera) and July 1985 (Broadlands).

4.2 Depletion Modeling of Liquid-Dominated Geothermal Reservoirs

G. Olsen and **J.S.** Gudmundsson

Geothermal and hydrocarbon reservoirs are in many respect similar, and **yet** different. In **this** project we examined one of their similarities, the recharge or influx of water from surrounding aquifers.

Several options are available in modeling aquifers surrounding geothermal reservoirs. The geometry can be radial or linear, they can produce at constant rate or constant pressure into the reservoir, and their outside boundary can be closed, at constant pressure, or at infinite distance. In **this** project we used the Schilthuis (1936), Fetkovitch (1971), and Hurst (1958) water influx methods, which can be described as steady, pseudo-steady, and unsteady state, respectively.

Water influx methods are available for most reservoir configurations and conditions. These methods are based on the van Everdingen and Hurst (1949) studies for radial and linear aquifers and they involve the use of superposition for each time step. The Hurst (1958) water influx method is a simplified version of the more general method.

In the Schilthuis (1936) method the influx is steady state. The pressure at the outside boundary of the aquifer is constant, and the rate of influx may be expressed as:

$$w_e = K(p_i - p) \tag{4.1}$$

where p_i is the initial reservoir-aquifer boundary pressure, and p the boundary pressure with time. K is the influx constant.

In the Fetkovitch (1971) method the water influx is pseudo-steady state. The outside boundary of the aquifer is closed, so the aquifer is finite. For the method to apply, we assume pseudo-steady state to be reached more rapidly than the matching or predicting time step. For each time step the average pressure in the reservoir is held constant while the aquifer pressure is allowed to decrease. The Fetkovitch method is based on the concept of constant productivity index J. The influx rate is given by the relationship:

$$w_e = J(p_i - p)\exp(-\frac{Jp_it}{W_{ei}}) \tag{4.2}$$

where W_{ei} is defined as the initial amount of encroachable water, and represents the maximum possible expansion of the finite aquifer. In the Fetkovitch method, the reservoir-aquifer boundary pressure p **is** taken as the average of each time step, thus eliminating the need for superposition.

The Hurst (1958) simplified water influx method derives from the general solutions of van Everdingen **and** Hurst (1949) which take the form:

$$W_e = BW_D(t_D)\Delta p \tag{4.3}$$

where B is the influx constant, and W_D and t_D the dimensionless cumulative water influx function and time, respectively. The three variables depend on the aquifer geometry.

We assumed that our liquid-dominated geothermal reservoir is analogous to a hydrocarbon reservoir above the bubble point pressure. In this case the compressibility of the reservoir and aquifer may be considered as constants. Hurst was able to simplify the solution of the general water influx theory by defining the ratio:

$$\lambda = \frac{c_e \rho_e}{c \rho l} \tag{4.4}$$

The numerator refers to aquifer properties and the denominator the reservoir. The length l is that of a linear reservoir. Hurst presented two limiting cases: (1) λ very large, and (2) λ very small. In the first case the aquifer dominates the pressure response, in the latter the reservoir. We are interested in the case when λ has an intermediate value.

The Svartsengi geothermal field production data was matched using the Schilthuis, the Fetkovitch, and the Hurst simplified methods. In the matches, the reservoir-aquifer system was assumed to be linear.

Results of the Schilthuis steady state model match is shown in Fig. 4.1. The match is observed to be best for the early part of the data. The quality of the match was not affected by whether we assumed the reservoir to be confined or unconfined. However, the physical parameters derived from a match depend greatly on the reservoir production mechanism chosen. The same argument applies to the Fetkovitch pseudo-steady state method.

In the Fetkovitch water influx method we obtained the history match by trial and error. The best match is shown in Fig. **4.2.** The match results in a straighter line than that exhibited by the reservoir, and overpredicts the draw-down at late time.

The history match obtained when using the Hurst simplified water influx method is shown in Fig. **4.3,** assuming an infinite linear aquifer. The optimum λ value for the Svartsengi field we found $\lambda = 1.3\times10^{-4}\ \mathrm{m}^{-1}$. To estimate the length l of the reservoir, we need values for the compressibility-density product for the reservoir and aquifer. If they are equal, our results suggest that the reservoir length is 7.7 km. If the reservoir compressibility-density product is twice that of the aquifer, then the reservoir length is 3.8 km. Similarly, we need the appropriate aquifer values for viscosity, density, and permeability to estimate the cross-sectional area A, If the respective values are assumed $110\text{x}10^{-6}$ $Pa{\cdot}s$, 1000 kg/m^3, and 1000 mD ($\approx 1.0\text{x}10^{-12}$ m^2), and taking the reservoir fluid density as 850 kg/m^3, the area becomes $A = 3.6\text{x}10^6$ m^2. For an aquifer thickness h of 1500-2500 m, the aquifer width b becomes 1440-2400 m. If the aquifer permeability is taken as 100 mD, the area increases ten-times, and the aquifer width also increases. In the absence of correct reservoir-aquifer properties, the model cannot provide specific information about reservoir size. The same applies to any other model, of course.

The main objective was to study the use of water influx methods in geothermal reservoit evaluation. We found that the steady state Schilthuis method gave a reasonable match, but reacted too strongly to rate changes. This leads us to believe that transient time effects are important. Although not shown here, the method suggested that the reservoir-aquifer system is linear. When matching the production data to a radial aquifer, we found that the encroachment angle was only a few degrees. The pseudo-steady state Fetkovitch method also gave a reasonable match. However, the model response to rate changes was weak; almost like an unconfined model without recharge. This indicated that assuming a finite aquifer was not appropriate.

The Hurst simplified unsteady state method gave the best match of the models tried. This demonstrated that the use of water influx models is appropriate in geothermal reservoir engineering. Their primary purpose is to match and predict the draw-down in the reservoir with continued fluid production. See Fig 4.4 for example. A secondary purpose is to provide information about the geometry and size of the reservoir-aquifer system. In this second endeavor, it becomes important to obtain reliable physical properties, and to draw on exploration data and interpretations; for example, resistivity measurements.

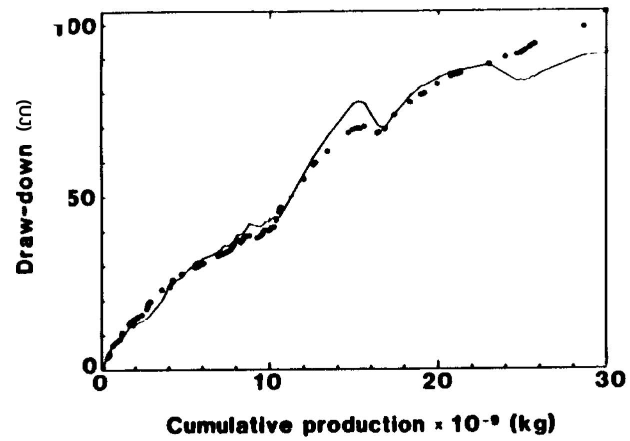


Figure 4-1: Schilthuis steady-state match

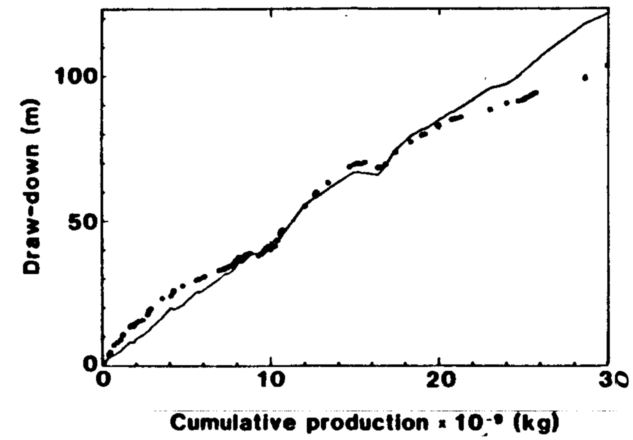


Figure 4-2: Fetkovitch pseudosteady-state match

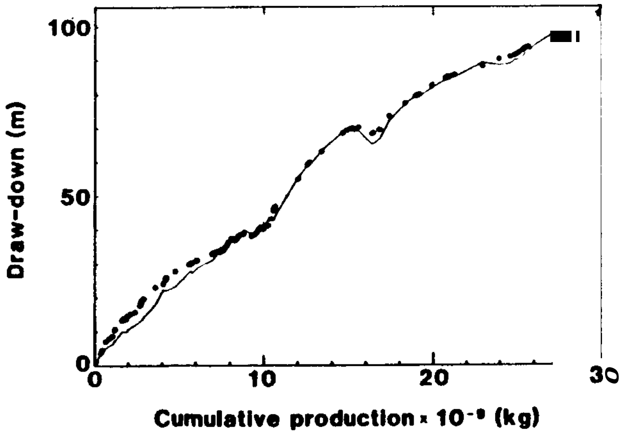


Figure 4-3: Hurst (simplified) unsteady-state match

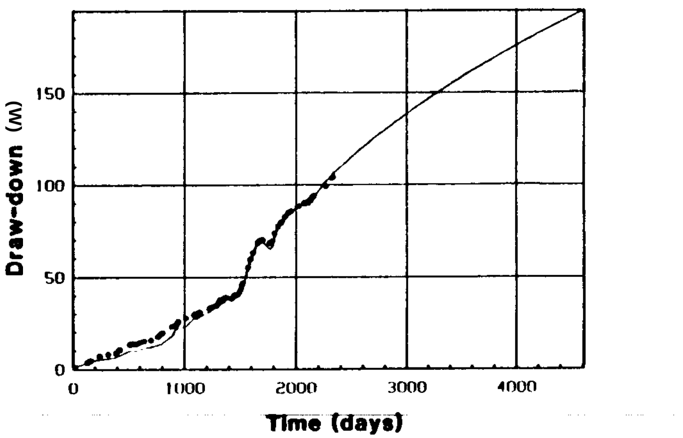


Figure 4-4: Drawdown with time in Svartsengi. Hurst (simplified) unsteady-state match and prediction for 300

4 3 Discharge Analysis Method for Two-Phase Geothermal Wells

J.S. Gudmundsson

Discharge analysis is the determination **of** steam-water flowrate versus wellhead pressure for geothermal wells. The method makes it possible to construct the discharge, output, dr deliverability curve for two-phase wells that start flashing in the wellbore. It is based on common downhole measurements and one output test that gives the total flowrate and enthalpy for some wellhead pressure.

The discharge analysis method is based on three key elements. The first is having a wellbore simulator for two-phase geothermal wells. This makes it possible to Calculate downhole flowing pressures corresponding to measured wellhead conditions. The simulator must have the capability to start the calculations from either the wellhead or bottom-hble conditions.

The second key element is the concept of productivity index:

$$P.I. = \frac{w}{\bar{p} - p_{wf}} \tag{4.5}$$

where w represents the total wellbore flowrate and $\bar{p}$ and p_{wf} the average reservdir pressure and bottom-hole flowing pressure, respectively. **As** used in **this** paper, the productivity index is assumed to stay constant with flowrate. The wells are assumed to have reached steady flowrate when measured. The analysis refers to the well discharge characteristics at the time of the output measurement used in the calculations.

The third key element is knowing the pressure at the depth of the pivot point. The pivot point pressure represents the static reservoir pressure at the main feedzone of the well, denoted by $\bar{p}$. To obtain the pivot point pressure, at least two pressure surveys must be made in the well during warm-up. The pivot point depth is the **only** point in the well where the pressure remains constant during warm-up. In wells with one major feedzone, the pivot point and the feedzone are at the same depth. In wells with two major feedzones, the pivot point will be located between the feedzones according to the lever rule.

The following data are required in the discharge analysis method:

(a) One output (discharge) measurement giving total flowrate, wellhead pressure, and total mixture enthalpy. The fluid chemistry should also be included to obtain the liquid density and the amount of non-condensable gases.

(b) Two pressure profiles in the static well during warm-up to determine the pivot point that represents the average reservoir pressure at that depth.

(c) Well and casing design for depth, diameter, and roughness.

The following calculations are carried out in the discharge analysis method using a wellbore simulator:

(a) Starting from the wellhead, calculate the flowing pressure profile down to the depth of the pivot point. This gives p_{wf}, the flowing wellbore pressure at well bottom.

(b) Calculate the productivity index using the measured flowrate w and the pressure values $\bar{p}$ and p_{wf} already obtained.

(c) Using the productivity index determined, calculate the flowing wellbore pressure for some new flowrate.

(d) Starting from the depth of the pivot point and using the new wellbore flawing pressure, calculate the pressure (and temperature) profile to the wellhead. This gives a new wellhead pressure.

By repeating steps (c) and (d) of the calculations, it becomes possible to determine the wellhead pressure at different flowrates, and to construct a deliverability curve.

When two-phase geothermal wells are discharged, it will take some time for them to reach stable output values. In many situations it will not be possible to discharge the wells for a long enough time to determine the output at different wellhead pressures. Even if it were possible, it would involve extra time and cost. Although state-of-the-art wellbore simulators may not give the correct down-hole flowing pressures, they can nevertheless be used. The rea+ son for this is that errors involved in calculations from the wellhead and down to the pivot point depth are likely to be compensated for when calculating in the other direction when determining the wellhead pressure for a new flowrate.

Output data from well 12 in the Svartsengi field in Iceland was used to illustrate the discharge analysis method. The pivot point pressure (average reservoir pressure $\bar{p}$) was determined as 1279 psia at 3936 ft depth. The casing inside diameter was 1.0521 ft, and the open hole diameter 1.0208 ft. The casing roughness was assumed that of commercial steel, and the open hole roughness the same as concrete. The total flowrate was measured as 830,000 lb/hr at 220 psia wellhead pressure and the mixture enthalpy as 429 Btu/lb.

Using the Stanford wellbore simulator, the flowing pressure at the pivot point was calculated p_{wf} = 1050 psia. For the given flowrate w (lb/hr) and average reservoir pressure $\bar{p}$, the productivity index was determined P.I. = 1456 lb/hr.psi. The wellhead pressure was then calculated for a range of flowrates. The results are shown in Fig. **4.5,** with the one output measurement value used in the analysis. Also shown is the measured deliverability curve of well 10 in the Svartsengi field.

4.4 Deuterium in Geothermal Systems

R.B. Cindrich and **J.S.** Gudmundsson

The deuterium content of water has become an important tracer in mapping hydrological flows and in determining recharge for geothermal systems. In most cases, the technique is easy to apply and is usually consistent with other geochemical methods. There are, however, instances where the methods give diverging results. An example of this is the depletion in the deuterium content of some geothermal brines below levels that can be accounted for by meteoric feed.

In this project, the evolution of stable isotope methods was examined with particular emphasis on fractionation processes active within geothermal systems. Models and theories which reconcile anomalies between geochemical and isotope analyses were developed and discussed. The geothermal systems of the Reykjanes Peninsula in southwestern Iceland, specifically Reykjanes and Svartsengi, were used for this investigation. The brines of the two systems

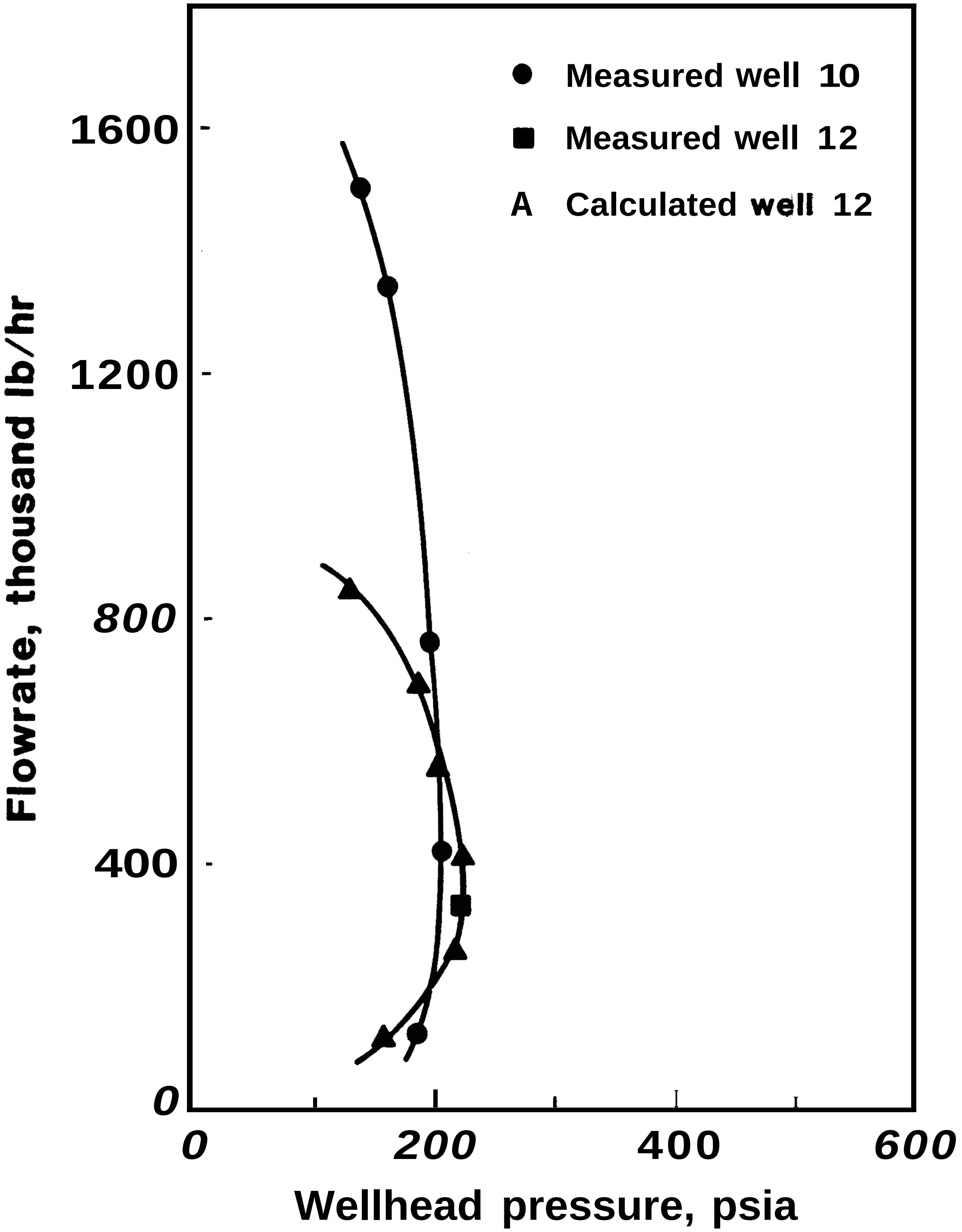


Figure 4-5: Calculated deliverability curve of well 12 and measured values of well 10

have identical deuterium concentrations, yet differ in salinity. The existence of mineral-brine equilibria that could affect the deuterium levels in these systems was examined. As a result, questions were raised concerning the application of deuterium analyses were alteration processes have changed the hydrogen isotope composition of the host rocks. It was concluded that caution should be exercised in interpreting analyses of brines evolved from high-temperature geothermal systems.

Hydrothermal alteration is a type of metamorphism involving recrystalization of a parent rock to new minerals which are more stable under changed conditions. Several factors influence the formation of alteration minerals and these may vary in importance from field to field. The main factors are: (a) temperature, (b) pressure, (c) rock type, (d) permeability, (e) fluid composition, and (f) the duration of hydrothermal activity. Despite the diversity of geology in geothermal systems around the world, a group of only 50 minerals are common to a number of systems. For example, quartz, smectites, chlorites, anhydrite, calcite, wairakite and epidote are a few of the minerals formed in both the Imperial Valley of California and in the high temperature areas of Iceland. The host rocks of the Icelandic fields are primarily basalt while those of the Imperial Valley are sedimentary. Host-rock types influence alteration processes mainly by controlling permeability. The initial composition of the rock has little effect on the alteration products above about 280°C. Alteration can seldom be achieved with very low water-rock ratios. Access of fluids to the host rock, along with temperature are the most important variables in determining the rate and extent of alteration. The water to rock ratio, defined as the total mass of water that has passed through the system, integrated through time and divided by the total mass of altered rock in the system, is often determined through examination of the alteration products.

Considerable laboratory work has been performed to establish values for clay mineral-water fractionation constants. The main thrust of these investigations was to clarify sedimentary processes. Most experiments were carried out at temperatures far below those applicable to geothermal systems. In almost all cases studied, no large-scale hydrogen or oxygen isotope exchanges were found to occur. All evidence indicates that isotope equilibrium is established at the time of clay formation, and that little to no fractionation occurs after this except in the disintegration and recrystalization of the clay structures. O'Neil and Kharaka (1976) performed fractionation experiments at temperature of 100°C. They found only minor isotope exchange, even after periods as long as *two* years. D/H exchanges of 8-23 percent could be expected to occur in clay-seawater systems at ambient seawater temperatures only after the passage of 2 to *3* million years. Clay-water interactions are responsible for buffering deuterium in the brines at Reykjanes and Svartsengi, only if new clays are formed as alteration products. It is doubtful that alteration has preceded as rapidly or to the extent necessary to effect brine deuterium levels.

Graham and Sheppard (1980) measured hydrogen isotope fractionation factors between epidote and a number of solutions varying in salinity, from pure water to seawater. Fractionation constants were determined over a temperature range of 250 to 550^{o}C. The aim of this work was to determine the isotope compositions of brine from the deuterium concentrations of the rock in fossil geothermal systems. The results show that increasing salinity decreases the effective deuterium fractionation in the epidote-brine system. The fractionation of deuterium was reduced by 12 permil for seawater relative to pure water for similar initial isotopic compositions. The fractionation values from these experiments were then applied to epidote and fluid samples from the Reykjanes and Svartsengi systems. Both Reykjanes and Svartsengi epidotes record the presence of a significant deep- source non-seawater contribution to the brine. The deuterium values of the epidotes are consistent with formation and equilibratioh in a brine *of* δD=-23. For water *to* rock ratios greater than 10 the epidote deuterium levels are set by the brine.

Three mechanisms were evaluated in this project by which deuterium levels at Reykjanes may have been depressed. Each would maintain salinity in the brine at levels similar to seawater. These mechanisms are: (1) mixture of seawater with meteoric water which has acquired salinity in its flow through volcanic sediments and/or recirculation of flashed fluids, (2) mixture of meteoric water and seawater with magmatic water of low deuterium and oxygen-18 concentrations, and (3) equilibration of the brine with alteration minerals.

The recharge characteristics of geothermal systems will be more complex than the simple case of tracing groundwater flows. The nature of geothermal systems with heat derived from deep-seated magmas; fractures and fissures associated with volcanic activity; convective flows; and other factors contributing to the disruption of the geologic column and the formation of conduits between otherwise isolated layers. Combined with uncertainties regarding the possible consequences of mineral-brine equilibria at critical pressures and temperatures, a more general question must be asked. What conclusions can realistically be drawn from appraisal of the deuterium levels of a geothermal brine?

There are no indications from the minerals found in drill cuttings that the alteration process can depress deuterium levels. However, there proves to be a lack of data. More research should be carried out involving alteration processes at high temperatures and pressures. Critical solutions may reverse trends found at near surface conditions. Similarities between deuterium levels in brines at Svartsengi, Reykjanes and Shimagamo indicate that deep alteration processes involving saline solutions could depress and buffer deuterium levels.

5. INJECTION TECHNOLOGY

The injection technology project has focussed on the study and use of tracers as a means to interpret fracture path structure in geothermal reservoirs. We have examined the tracers themselves in an attempt to improve the accuracy and resolution of the tests, add we have studied means by which the results of these tests can be interpreted. In order to appropriately propose transport models to use in the interpretive techniques, we have also undertaken two experimental programs to investigate the fundamental properties of tracer flow in geothermal systems.

The transport of tracers through geothermal reservoirs is primarily through fractures, and the understanding of the flow mechanisms is a key step before interpretive adalysis of tracer returns is possible. Two principal mechanisms have been studied by the Stanfbrd Geothermal Program, tracer dispersion within the fracture, and tracer diffusion into the rock mamx. An experimental study of tracer dispersion has recently verified our earlier theoretical derivation for one-dimensional transport. The theoretical and experimental studies of tracer retention mechanisms have suggested a method for the interpretation of tracer return histories, and have shown remarkable correspondence with field test measurements.

The principal goal of the injection technology project is the development df techniques to forecast thermal breakthrough. Using interpretation of tracer test return profiles, it should be possible to infer the effective apertures of the principal fractures in a geothdrmal reservoir. Once the effective aperture has been estimated, it is possible to obtain an estimate of the thermal breakthrough time from Fig. 5.1, which is from the heat transport investigation of Pruess and Bodvarsson (1984). This figure requires the measurement of the tracer breakthrough time, and uses the estimated effective fracture aperture to infer thermal breakthrough time.

Starting with the work of Fossum and Horne (1982), it was found that a purely dispersiva model was able to match Wairakei tracer test data with reasonable accuracy, but at least two model flow paths were necessary to achieve the match. Thus new models have been formulated to improve the degree of correspondence with observed data. Two new models ate described

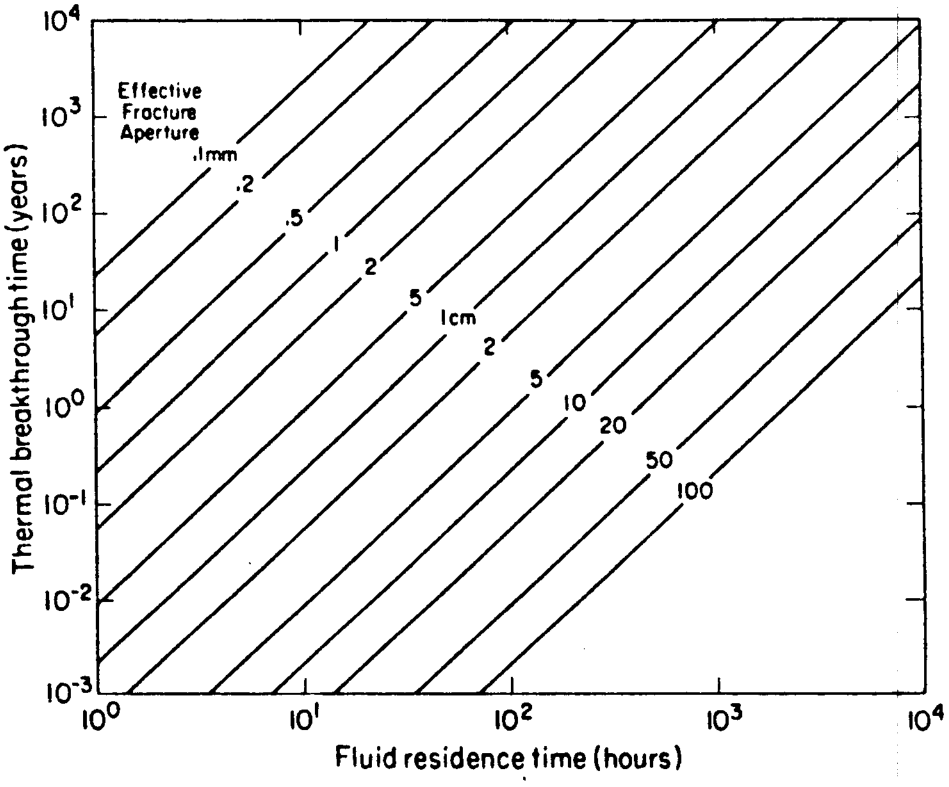


Figure 5–1: Thermal breakthrough tine as a function of fluid residence time and effective fracture aperture (from Pruess and Bodvarsson, 1984)

here, the first by Jensen and Horne (1983) and the second by Walkup (1984), both using additional tracer loss terms that were not included by Fossum and Home (1982). These two models both demonstrate good matches to the field data with only a single model flows path. However the fracture aperture is difficult to estimate from the Jensen and Horne (1983) model, since it is linked with other unknown parameters. Fortunately, adding a second dimension, as in the Walkup (1984) model, allows these parameters to be separated.

Aside from the tracer profile interpretation work, the Stanford Geothermbl Program has also recently completed the design and construction of an experimental apparatus to directly examine the tracer transport in fractures (Gilardi, 1984). The first batch of experiments have proven the applicability of the effective fracture dispersivity derived theoretically by Horne and Rodriguez (1983) in earlier work at Stanford.

5.1 Tracer Profile Interpretation

G.W. Walkup, Jr. and R.N. Horne

The Jensen and Horne (1983) model for tracer transport in fractures is based on results of experimentation by Neretnieks (1980). The model assumes "diffusion" of tracer into the rock matrix surrounding the fracture. This "diffusion" could be actual molecular diffusion, or effective diffusion due to adsorption or chemical reaction. The effect of the diffusion is a retardation of the tracer, giving rise to the long "tails" in the return profiles, that are difficult to match with the Fossum and Home (1982) model. The final tracer concentration in the matrix diffusion model is given by:

$$C = \frac{E\alpha_1\alpha_2}{\sqrt{\pi}\,(\alpha_2 t-1)^{1.5}} \exp\left[-\frac{\alpha_1^2}{(\alpha_2 t-1)})\right] \qquad (5.1)$$

where:

$$\alpha_1 = \left[D_e\,\phi\,t_w\right]^{0.5}/\delta \qquad (5.2)$$

$$\text{and } \alpha_2 = \frac{1}{t_w R} \qquad (5.3)$$

The return tracer concentration is therefore a function of time t, fluid residence time t_w , effective diffusion coefficient D_e , effective porosity ϕ , retardation factor R, and fracture aperture *6* . The parameters are grouped into the two unknowns α_1 and α_2 , which are easily found by a non-linear regression match to field data. Unfortunately, since D_e and ϕ are not measurable parameters, *6* cannot be calculated directly from knowledge of α_1 . Therefore, even though the model fits field data much better than the Fossum and Horne (1982) model, (see Figs. 5.2 and 5.3), **it** is not possible to estimate the parameter of greatest interest. The good match does however indicate that the physical mechanism embodied in the model **is** a good representation of the actual tracer transport.

With the experience gained with the Jensen and Home (1984) model, a third model was developed in an attempt to decouple the unknowns. Walkup (1984) determined that the coupling was a result of the "lumping" of parameters into the "effective" diffusion coefficient and porosity by the assumption of one-dimensional flow. Walkup (1984) therefore developed a two-dimensional model, shown in **Fig. 5.4,** in which the lateral diffusion is specifically included rather than "lumped into effective parameters. The solution for the exit tracer concentration **is** only obtainable in a space which is Laplace transformed in both distance and time. **The** analytical solution is:

$$C_1^p = \frac{C_o}{s\,(\,p + s\beta R)} - \left[\frac{z\alpha C_o}{s(p + s\beta R)}\right] \frac{e^{-my_D} + e^{-my_D}}{(1-\alpha)M(e^m - 3^{-m}) + z\alpha(e^m + e^{-m})} \tag{5.4}$$

where

s = Laplace operator for transforming t

p = Laplace operator for transforming x

$$z = \left[\frac{P_e(1-\beta)R_s}{\alpha}\right]^{1/2}$$

$$m = \left[\frac{p + s\beta R}{P_e}\right]^{1/2}$$

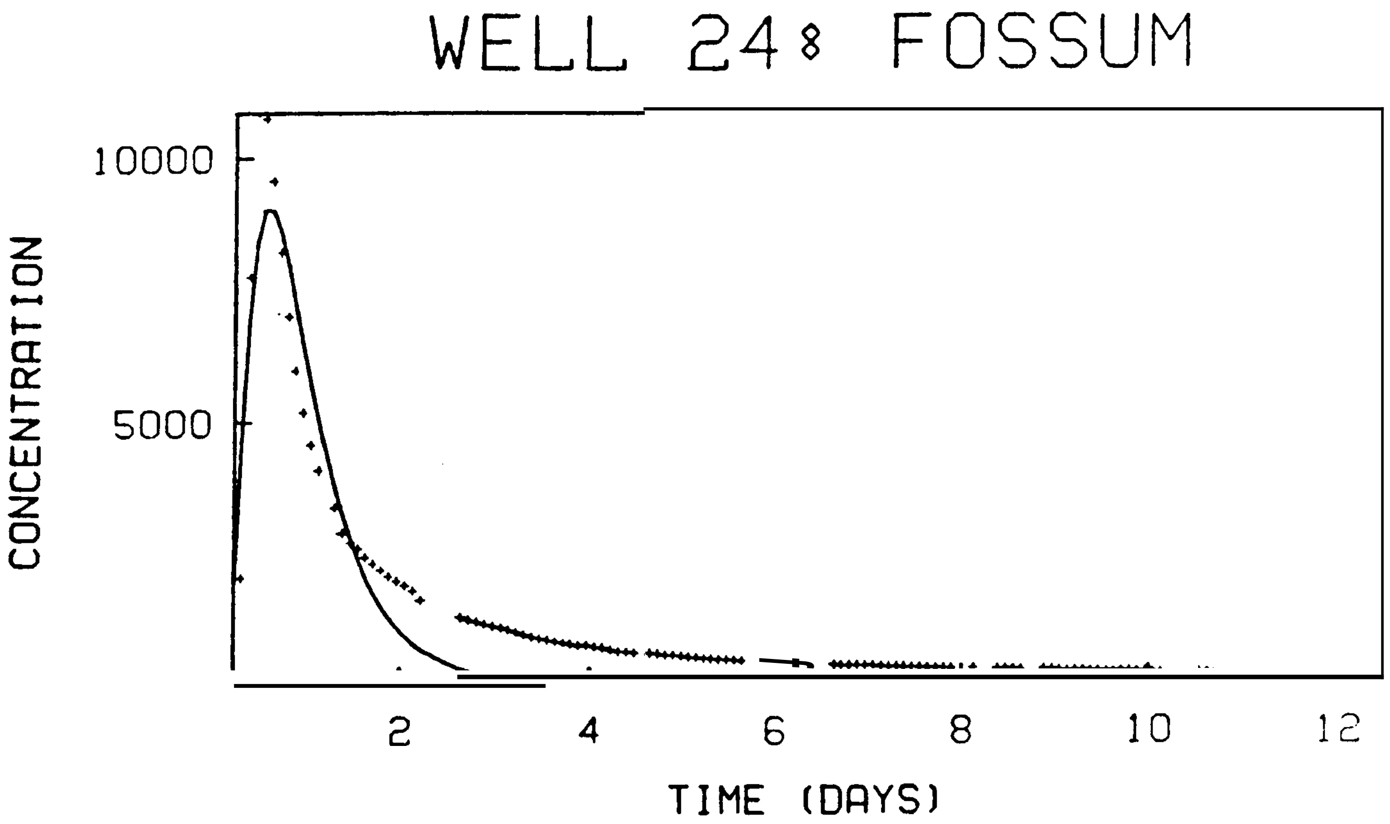


Figure 5-2: Well #24 fit with Fossum's model

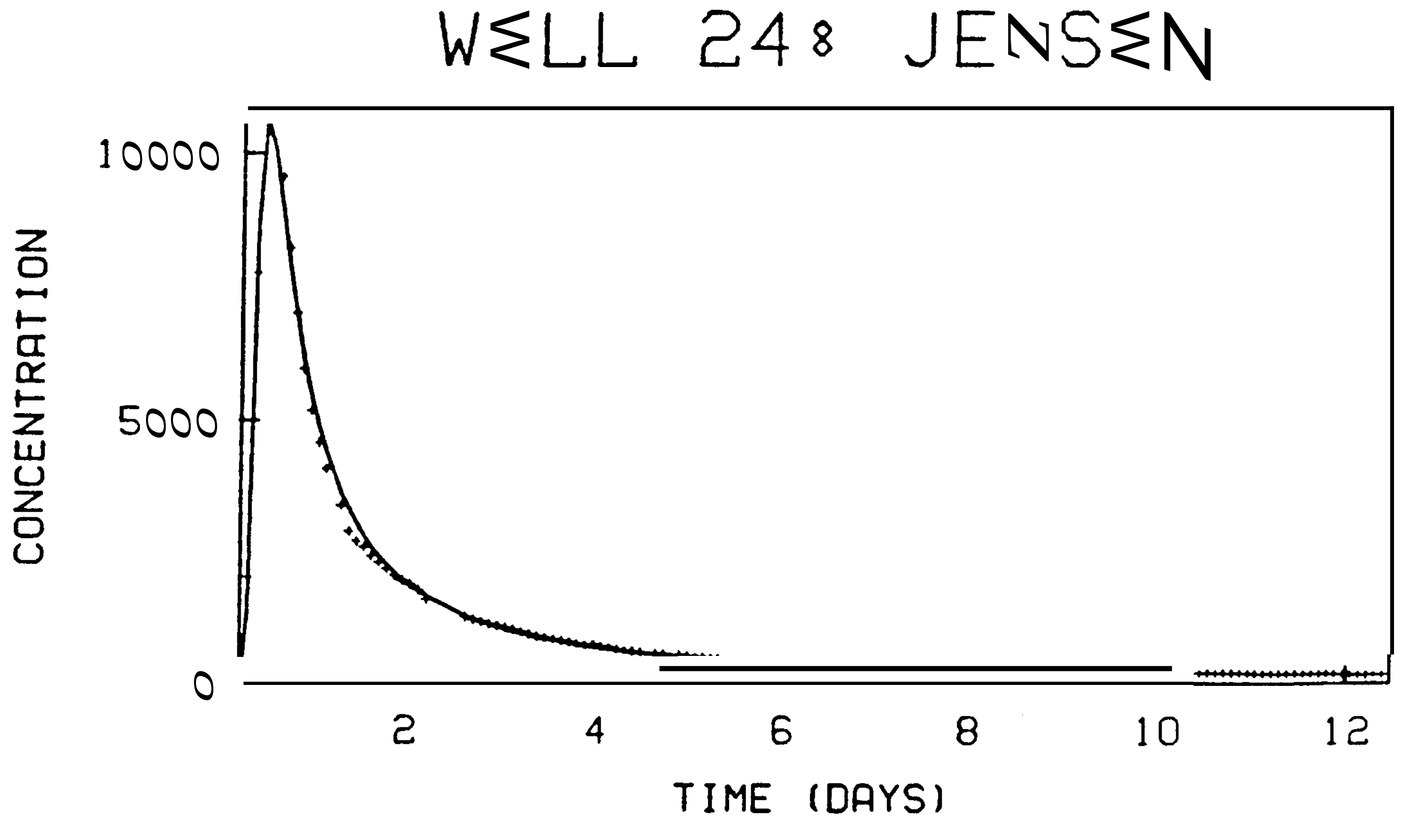


Figure 5-3: Well #103 fit with Fossum's model

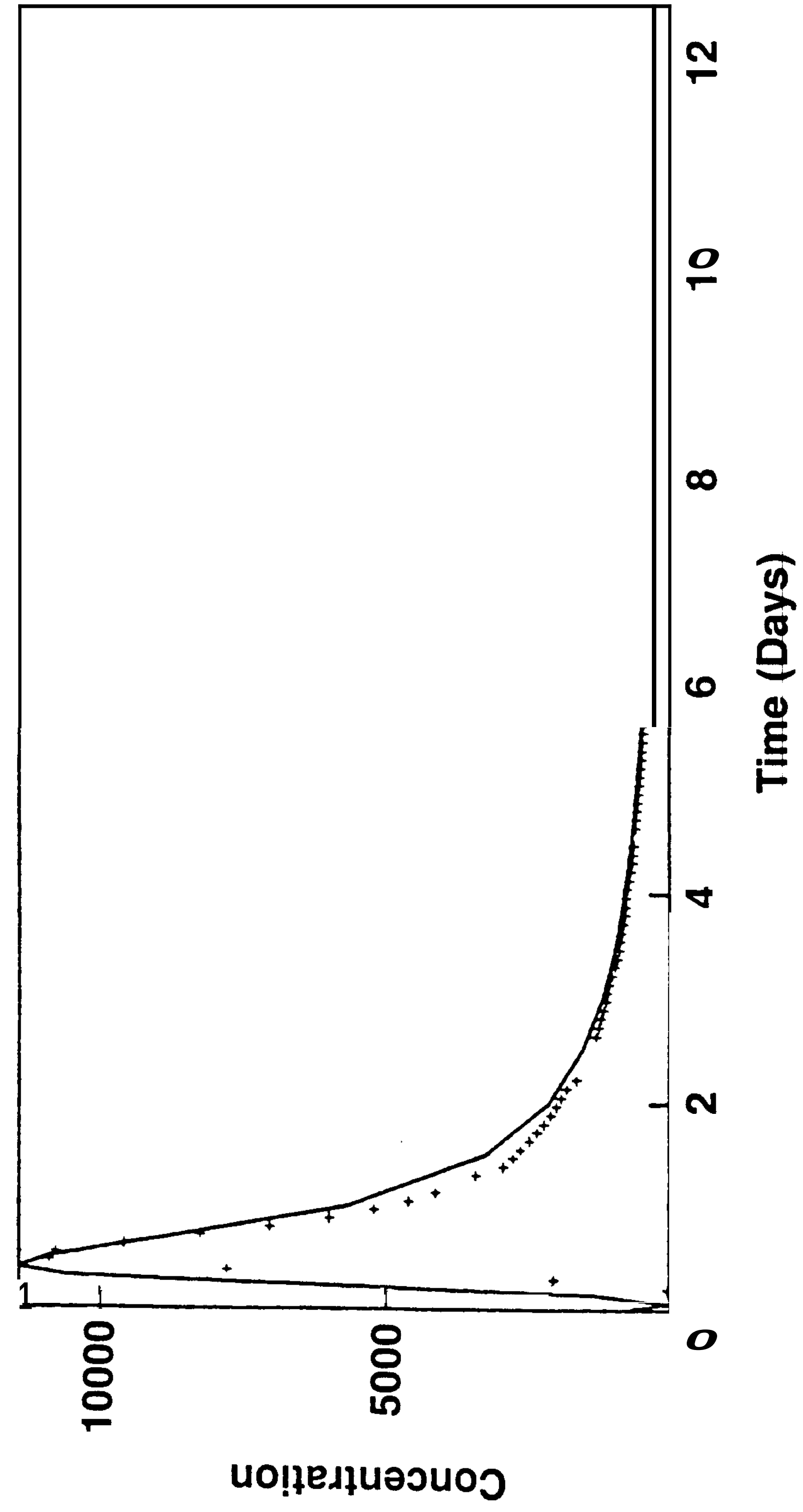


Figure 5-4: Well #24 2-D model

Table 5.1 - BEST FIT VALUES

WELL #	x_D	Pe	β	R	α
24	1.55E05	0.201	0.502	2.01E-06	0.0021
103	5.01E04	0.200	0.450	2.00E-05	0.110
121	9.71E04	0.170	0 500	3.44E-05	0.004

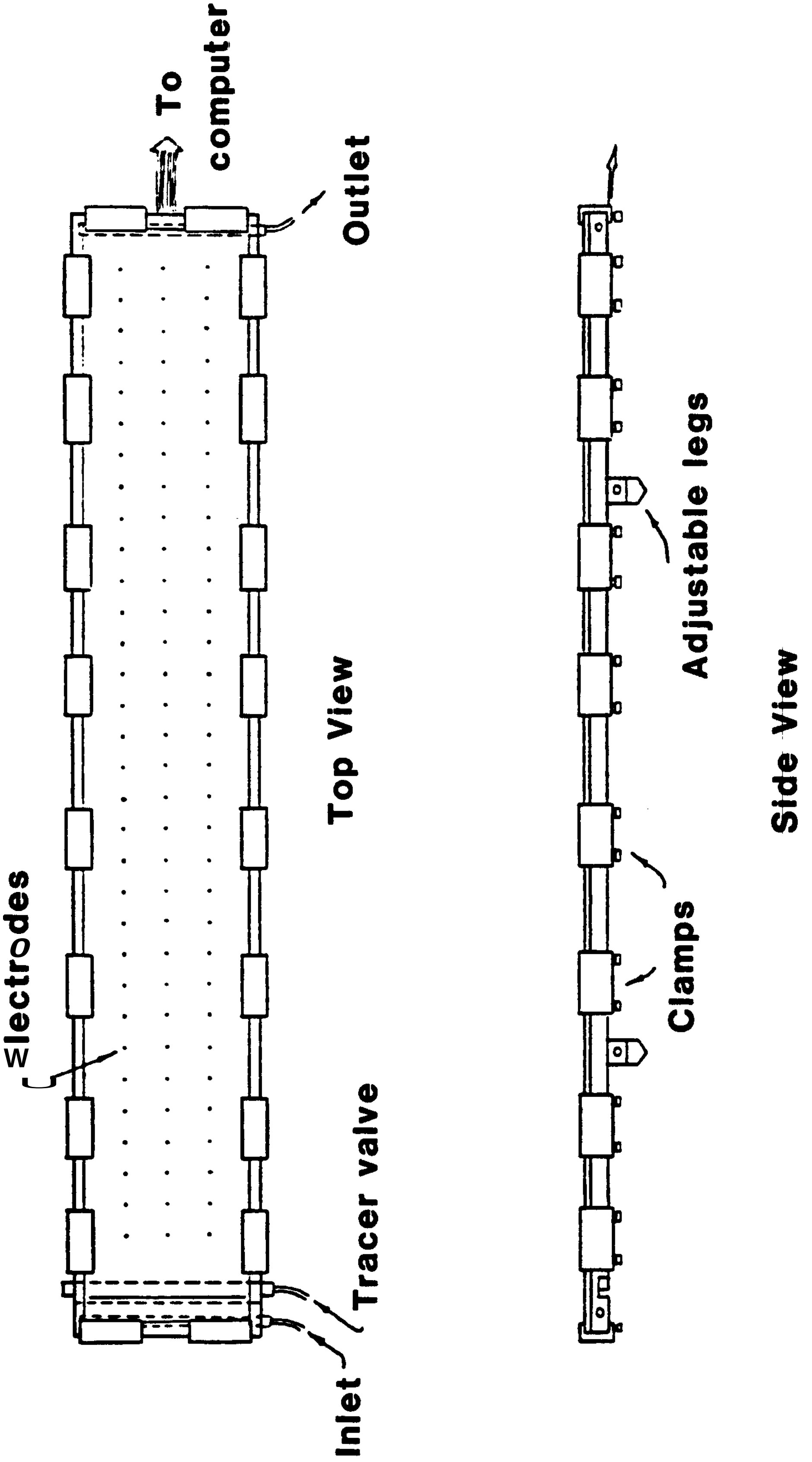
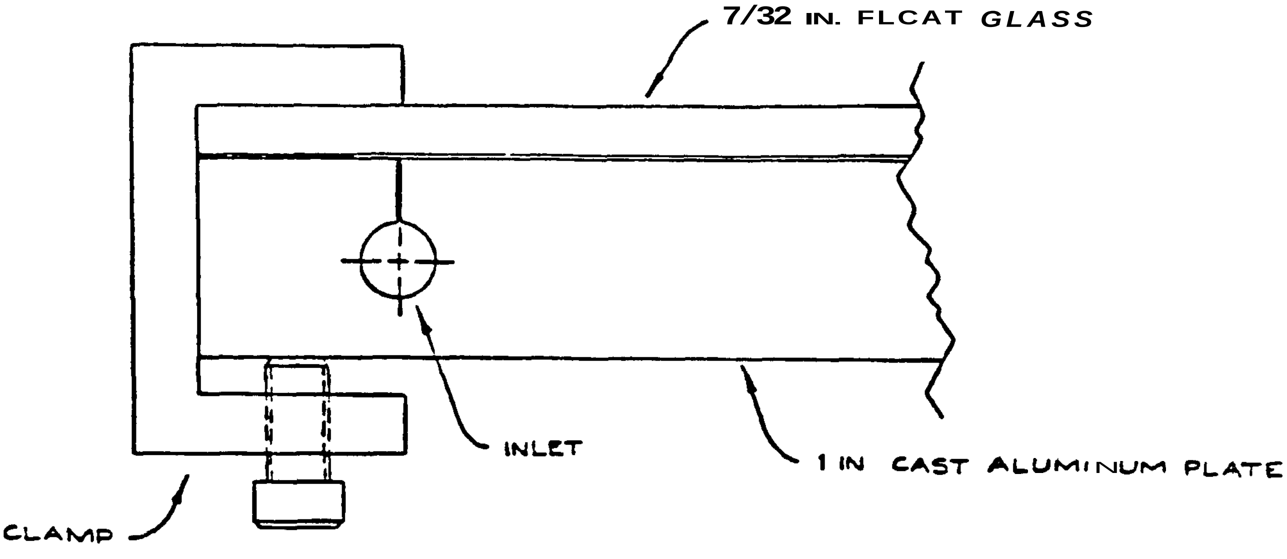
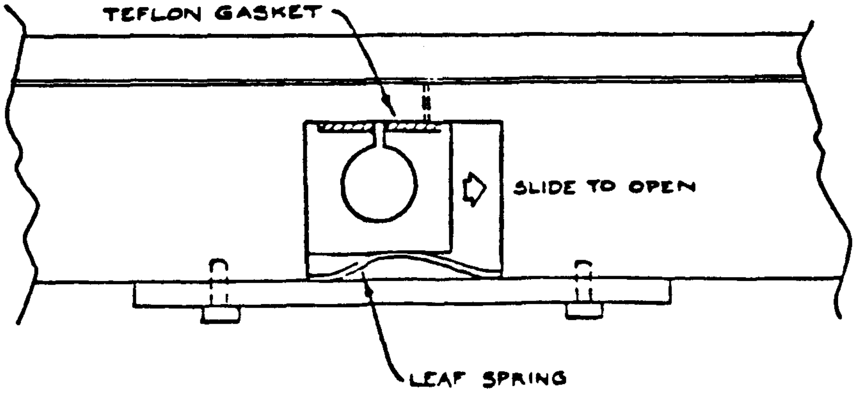


Figure 5-5: Hele-Shaw Cell

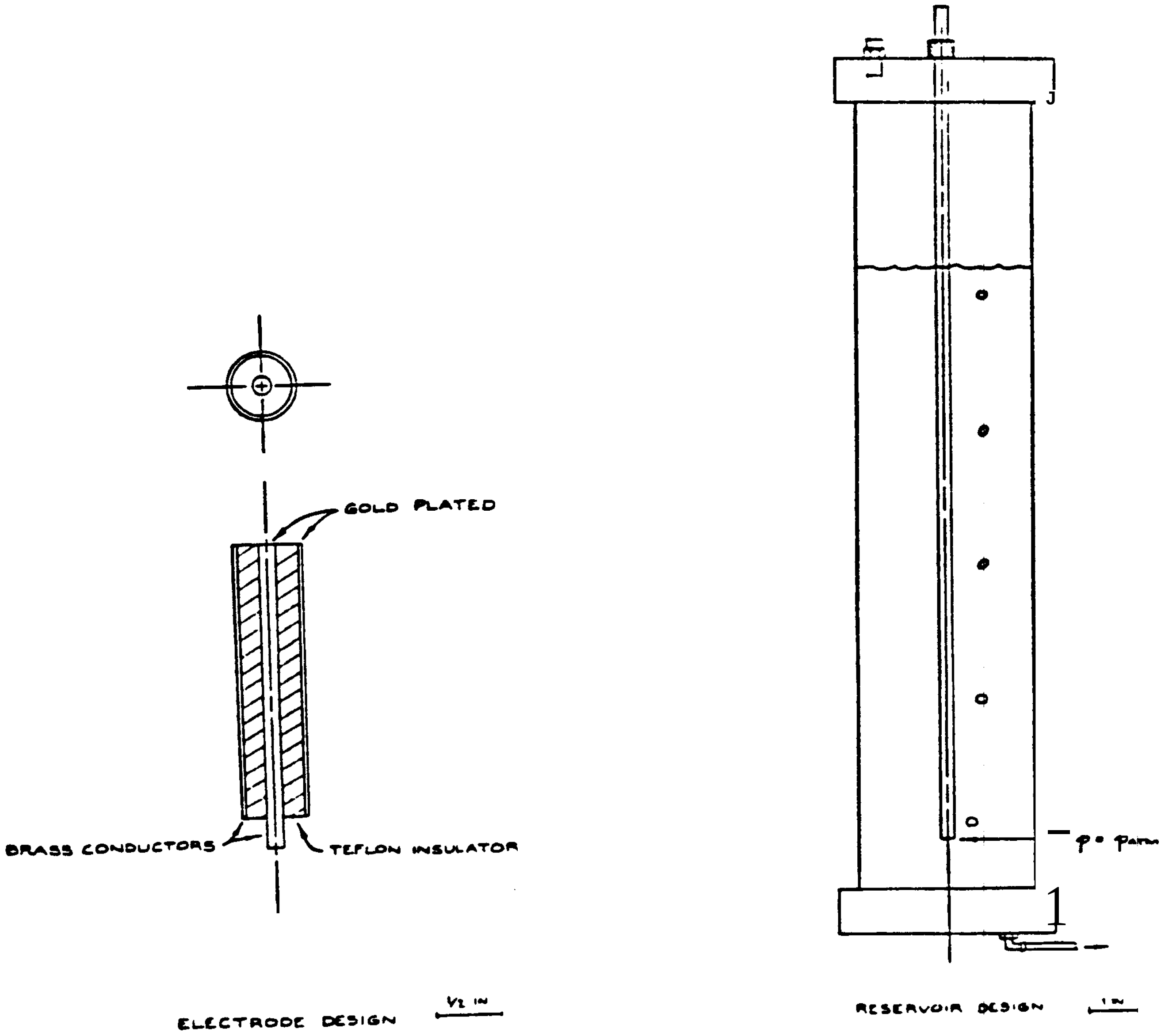


DETAIL VIEW



TRACER VALVE

Figure 5-6: Detail views of experimental apparatus



ELECTRODE DESIGN

RESERVOIR DESIGN

Figure 5-7: Design of electrodes and constant head reservoir

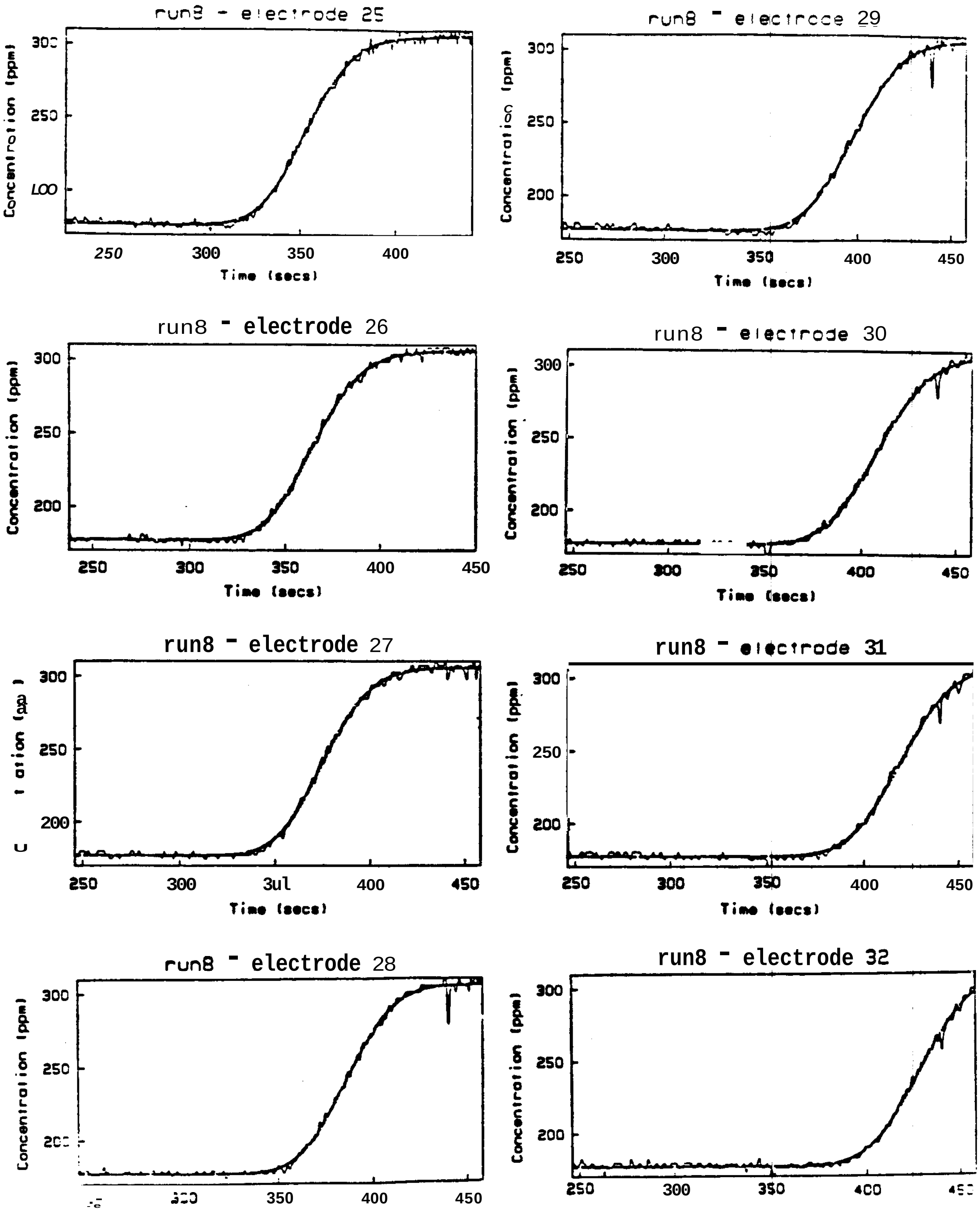


Figure 5-8: Typical concentration/time profiles, downstream end of plate

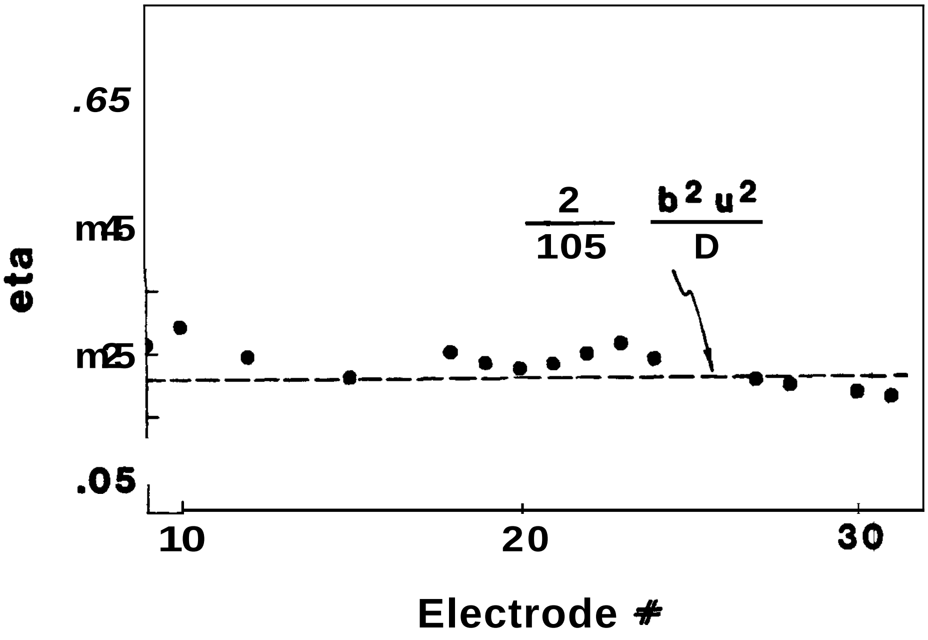


Figure 5-9: Comparison of estimated and calculated dispersivity. Run 3

within the near **future.** This is due to the identification of the diffusion model as an appropriate tracer mechanism, and the discovery that two-dimensional analysis results in a separation of the fracture aperture among the estimated parameters. It now remains to examine the effects of real parameters not included in the models, for example fracture tortuosity and wall roughness. These will be investigated using the new fracture transport experimental apparatus. If possible, we also intend to attempt to simplify the two-dimensional diffusion model in order to obtain field test matching without such a large investment in computer time.

5.3 Activable Tracers

C. Crysicopoulos and **P.** Kruger

The objective of the activable tracer project is the development of a tracer method with maximum sensitivity for measuring the early breakthrough time of reinjected geothermal brine at production wells and for extending the period of tracer recovery to increase the sensitivity for characterizing the flow processes. The advantages of external tracer tests for these purposes were described in the 1983 annual report. The analysis for optimization of external tracers based on a literature survey on the chemical composition of geothermal effluents was conducted, and four activable tracers identified in the 1983 annual report as candidate tracers for field application were, indium (In), dysprosium (Dy), vanadium (V), and cobalt (Co). The criteria used for selection of suitable activable tracers were: (a) **a** background doncentration in geothermal fluids as close as possible to the minimum detectable amount of tracer by available detection systems, (b) large neutron activation cross sections, (c) large natural isotopic abundance, (d) appropriate gamma radiation of the product radionuclide for measurement by gamma-ray spectrometry, and (e) optimum half life of the product radionuclide.

It was noted that a major consideration of an external tracer is its conservation in the reinjected geothermal brine. The external tracer must be compatible with the chemistry of the geothermal fluid. The tracer should not be lost in the reservoir by physical adsorption, **by** chemisorption reactions, by ion exchange with the rock minerals, or by any other process. Also, it must be detectable in wellhead fluid after transport through a high-temperature reservoir. The tracer should not be susceptible to thermal degradation or phase changes during its **transport.** Because anionic solute species tend to be more conservative **than** cationic species, chelation of the candidate tracers may be necessary to ensure chemical stability. Each of the four candidate tracers form strong chelate water soluble complexes with ethylenediaminetetraacetic acid (EDTA) and nitrilotriacetic acid **(NTA).** EDTA complexds appear to be stronger, but their thermal stability may be lower. Since thermal stability data on EDTA **and NTA** complexes of the selected activable tracers are not available in the literature, **this** information is being obtained experimentally.

During the current year calibration of the Stanford Linear Accelerator Center (SLAC) ^{252}Cf neutron irradiation source was completed. The facility is being used fot our procedure development. The **^{252}Cf is** encapsulated in a helium atmosphere and it is assumed to decay with an effective half-life of ***2.646*** years. The effective **^{252}Cf** content was calculated from its neutron emission rate and is given in equivalent weight units assuming 2.311×10^6 neutrons per second per microgram of **^{252}Cf.** The thermal neutron flux was calibrated with gold foils provided by SLAC. The measured flux of 2.74×10^6 thermal n/cm^{2}sec is considered adequate for procedure development, but it is not adequate for tracer background determination. For natural background measurements, it **is** planned to use the Triga research reactor at the University of California in Berkeley. However, the long time delay from end of irradiation to start of counting may require choice of other (n,γ) reactions of the candidate elements.

Sensitivity calculations for twenty-four possible activable tracers using the University of California Triga reactor were listed in the prior annual report. The four most promising activable tracers and their sensitivity calculations based on a 10-minute irradiatiod in the SLAC ^{252}Cf facility and 10-minute delay time to measurement are shown in Table 5.2. A minimum value of **A** = 180 cpm at the measurement time was set as **an** additional sensitivity requirement. This arbitrary counting rate value is high enough to permit efficient detection of the 'y-ray of interest. Indium is considered to be the most promising of the four potential activable tracers, because of its unique combination of good detection sensitivity and relatively high energy of

Table 5–2

Laboratory Sensitivity for the Activable Tracers

(^{252}Cf Source Activation)

TARGET NUCLIDE **				
Element	Conc.*	Isotope	f	$\sigma_{(n,\gamma)}$
V	< 0.005	^{51}V	0.997	4.88
Co	< 0.06	^{59}Co	1.000	19
In	< 0.1	^{115}In	0.957	70
Dy	< 2	^{164}Dy	0.281	900

PRODUCT NUCLIDE **				
Isotope	$T_{1/2}$	Major-γ	ε	Sensitivity***
^{52}V	3.75m	1.434	2.15	36.37
^{60m}Co	10.47m	0.059	1.73	1.32
^{116m}In	54.12m	1.294	2.93	1.03
^{165}Dy	2.33h	0.095	12.38	0.21

* Concentrations (ppm) in geothermal fluids, from Cosner and Apps (1978). Values are in micrograms per liter and they are neither exact not representative of every geothermal fluid.

** The nuclear data have been adapted from Lederer and Shirlep (1978). f = isotopic abundance; $\sigma_{(n,\gamma)}$ = thermal neutron cross section (barns); ε = over-all counting efficiency (d/c).

*** Minimum weight (mg) of the element necessary to obtain 180 cpm after la-minute irradiation in a thermal neutron dux of 2.7×10^6 n/cm^2-sec end 10-minute delay time till measurement.

major γ-ray emission. High energy γ- rays are preferred when interfering radionuclides with low γ-ray energy are present because their Compton scattering contribution to the tracer full-energy peak is negligible. However, the counting efficiency decreases with increasing γ-ray energy.

Studies were made of the correction factors necessary to relate the counting rate (A) obtained from the multichannel analyzer, to concentrations of tracer in the sample. These include the background count rate obtained with the absence of tracer, the variation of counting efficiency with gamma ray energy, the sample volume and its geometric position in the well. The measured data for these corrections are shown in Figure 5.10.

Geothermal effluents contain major constituents whose activation would lead to high levels of radiation or to generation of radionuclides with gamma radiation perturbing the instrumental determination of the product nuclide. Therefore, a preconcentration of the tracer element is necessary prior to neutron activation. In our study, rapid ion exchange separation procedures with a Chelex-100 (50-100 mesh) cation exchange resin, followed by the modified hydroxide precipitation technique proposed by Behrens et al. (1977) and Drabaek (1982) have been selected for the tracer preconcentration step. The procedure of tracer preconcentration analysis is schematically represented by the flow chart of Figure 5.11.

During the current year, experiments have been designed for the determination of thermal stability of **EDTA** and NTA complexes of indium (In), dysprosium (Dy), vanadium **(V), and** cobalt (Co) as geothermal reservoir tracers. The relationship between thermal degradation and temperature as well as the lowest temperature at which decomposition of the metal chelates proceeds at a significant rate is obtained through batch experiments. Aqueous solutions of each metal chelate will be tested for degradation products throughout the temperature range of 25° - 300°C. The sample solutions can be placed into sealed glass ampoules enclosed within a pressure vessel. Water added to the reaction vessel will provide a heat transfer medium and will equalize the pressure within the reaction vessel. The amount of degradated tracer will be determined by neutron activation after a hydroxide gel precipitation.

Figure 5-10

Calibrations for the Gamma-Ray Scintillation Detector

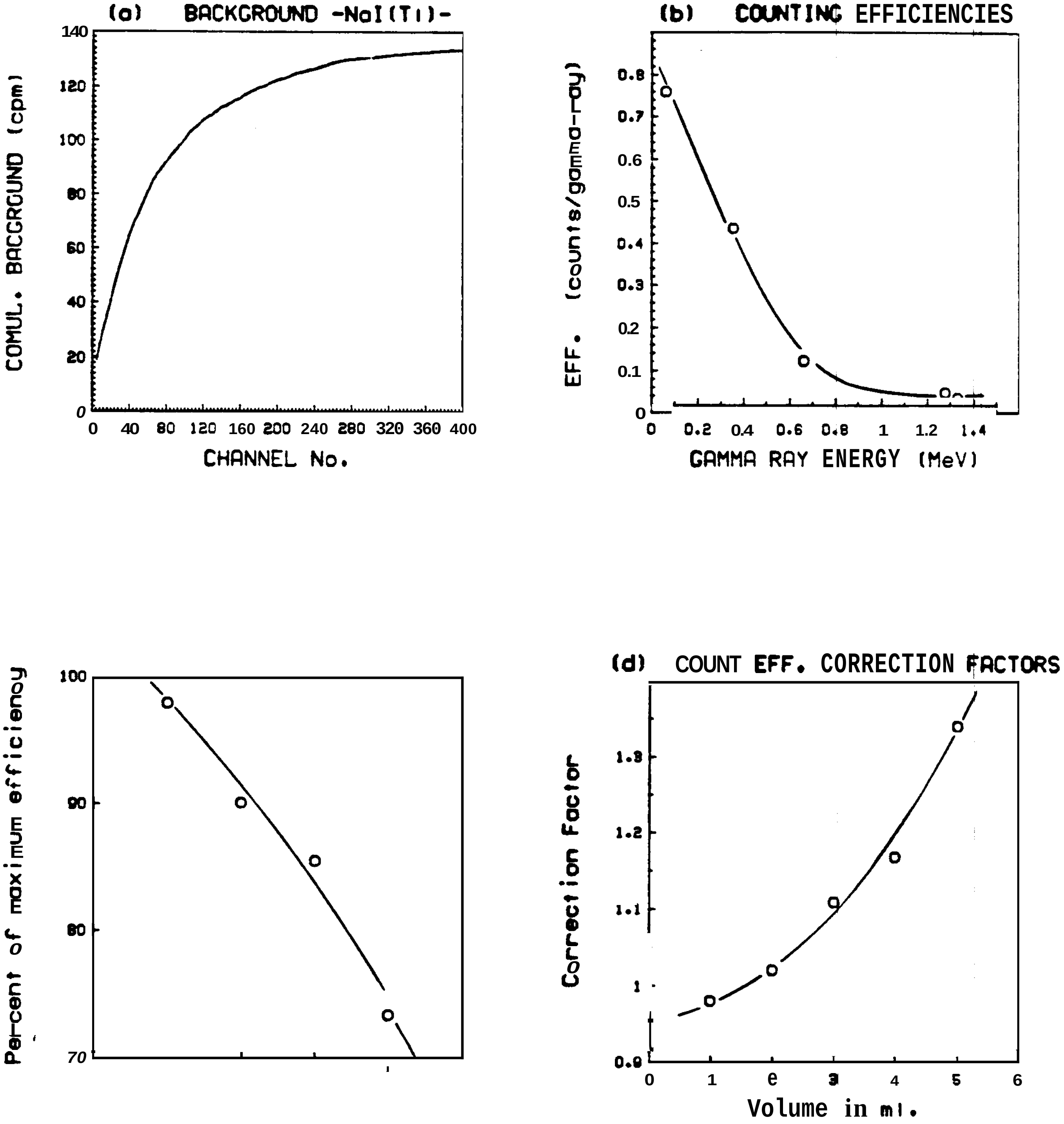
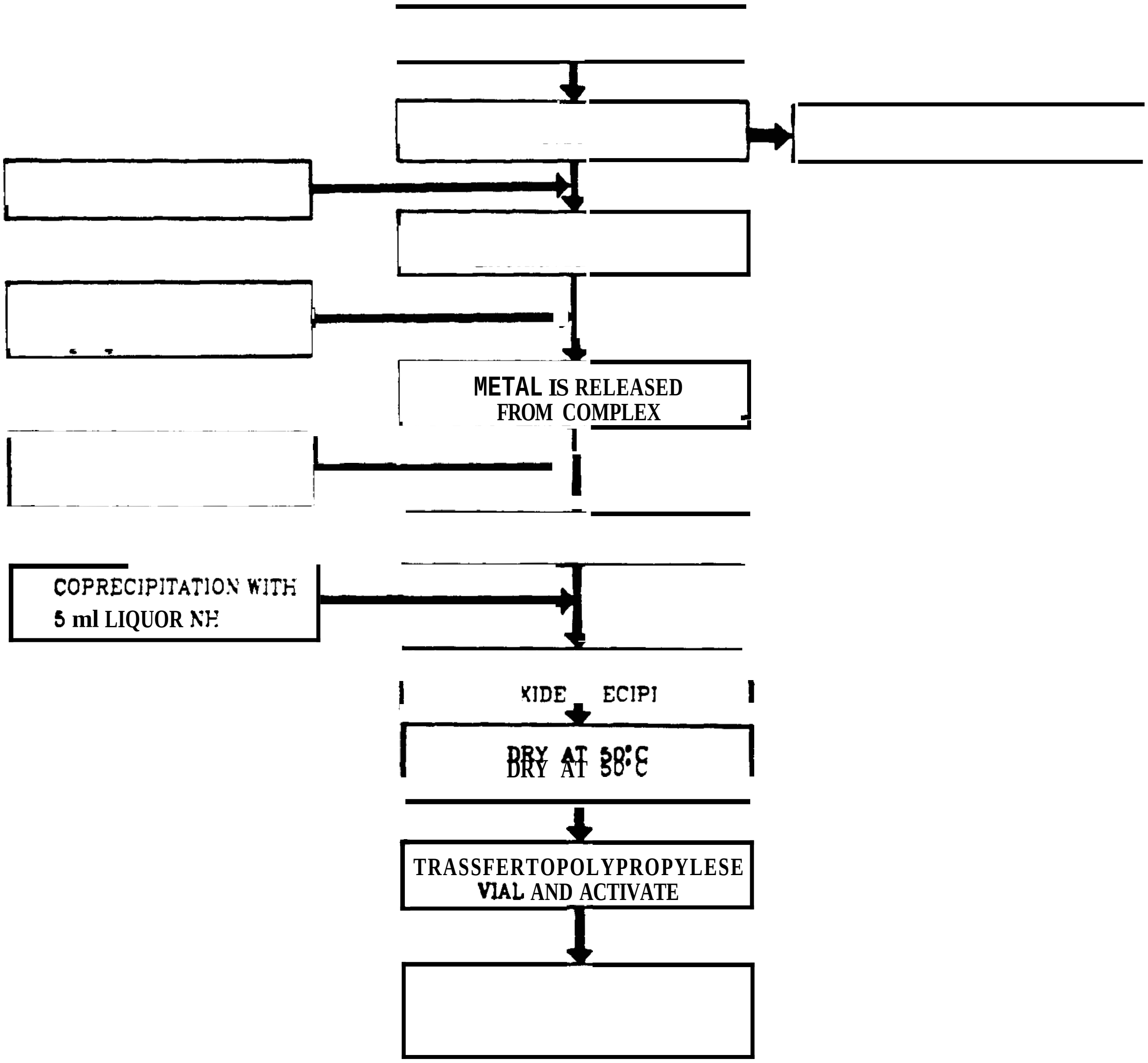


Figure 5-11

Separation Scheme for the Analysis of Activable Tracers



In addition, sample solutions of the chelated tracers will be investigated for the effect of temperature on tracer adsorption in reservoir rock. Porous and fractured rocks will be tested in one of our high temperature air bath facilities. The experiment consists of flowing a complexed tracer in saline solution through a rock core under reservoir pressure and temperature and following the elution concentration history by activation with the SLAC neutron source.

Testing of the preconcentration step will be achieved in conjunction with the determination of the natural background of the four candidate tracer elements in geofluid brines from one or more geothermal fields of varying total dissolved solids and reservoir temperature. These data should be adequate to resolve the feasibility question of a rapid on-site activation, measurement system for reinjection studies in the field.

5.4 Los Azufres Field Experiment

R.N. Home

From August 1983 until January 1984, the Stanford Geothermal Program conducted **a** tracer test at Los Azufres geothermal field in Mexico in cooperation with the Instituto de Investigaciones Electricas and Commission Federale di Electricidad. In August 1983, 2000 lbs of potassium iodide tracer were injected into well A-8, and wells A-2 and A-16 were monitored for the return of the iodide as well as for any other change in chemical species. Well A-8 lies at the western edge of the central section of the field, and wells A-2 and A-16 lie in a straight line east from A-8. Thus the configuration was the ideal "two-well doublet" that Stanford had been seeking for some time as a means to field test the tracer profile interpretation methods that we have developed.

Stanford's automatic sampler was installed at the wellhead of well A-2, but performed unreliably due to the variability of the power supply. After a few weeks of operation, both wells were sampled by hand. The ion-specific electrode also performed unreliably in the field, although it worked well when brought back to the laboratory. For some time during the analysis of the samples, we had some difficulty finding agreement between the different iodide detection methods used. Finally, a series of samples was sent out to an outside laboratory for ion chromatographic analysis, and a constant iodide concentration of around 0.23 ppm was determined throughout the test. No iodide was found in either producing well.

Although the experiment was unsuccessful in providing the desired data, it proved to be useful in several aspects. First, the test was designed to produce 20 times background increases in iodide concentration at the producing wells, and the fact that no iodide was found leads to an indication that there is no tracer path between the injector and the two producers. This has been found previously in other fields which subsequently did have rapid breakthrough when full-scale production was initiated. Thus we have established a base case for the evaluation of changes to tracer breakthrough patterns that might occur when Los Azufres enters production. Second, we were able to pinpoint several difficulties with the sampling and analysis of iodide samples in a remote field location. Although we have no immediate plans to repeat such a test, the experience gained will be of value to the geothermal community in designing future tracer operations in the field.

5.5 Tracer and Model Testing in Klamath Falls

S.E. Johnson and **J.S.** Gudmundsson

Two tracer tests were carried out in Klamath Falls, Oregon, in cooperation with the **U.S.** Geological Survey, Lawrence Berkeley Laboratory, and the Geo-Heat Center. The purpose of the tests was to obtain data which would lead to information about the reservoir, and to test the applicability of current tracer flow models. Along with a porous media modtl, two models developed by Stanford researchers to analyze fractured geothermal systems were used. Tracer flow through fractures **as** a function of time and various nonlinear parameters were found using a curve-fitting technique.

The tracer tests have already been described in two papers by Gudmundsson et al. (1983) and Gudmundsson (1984), and will not be repeated here; the modeling work will be presented here. Three models were investigated: (1) doublet flow in a porous media, (2) single fracture flow, and (3) single fracture flow model with retention.

The homogeneous porous media model was presented by Klett et al. (1981). The model is based on streamline potential in a doublet system. Using this model gives information about dispersion of tracer through the reservoir.

The next level of complexity was to assume fracture flow. Based on a mathematical model developed by Horne and Rodriques (1983), taking into account the dispersion of traced during flow through a fracture, Fossum (1982), used a planar fracture flow mbdel to analyze field data collected in Wairakei, New Zealand. Another level of complexity was added by Jensen (1983), who included the effect of retention to the fracture model.

The Jensen's and Fossum's models do not distinguish between different dispersion mechanisms. The main difference between the porous model and the fracture flow models is that the fracture flow models represent flow along only one or two of the infinite number of streamlines contained in the porous model. As more fractures are added, the solution approaches that of the porous media model. Stated differently, the porous media model represents1 a flow model with an infinite number of fractures. Thus, the fracture models ark a limited case of the porous model.

Parameters in the porous media model were changed by trial and error to achieve the best match, shown in Fig. 5.12 for the Friesen well. For details see Gudmundsson (1984) and Johnson (1984). The porous model was found not to match the data adequately, the largest error being before the first tracer breakthrough. The match of the fracture model to the Friesen data is shown in Fig. 5.13. The model accurately predicts the breakthrough and slope of concentration to peak values. This fit is superior to both the porous media model and the fracture flow model with retention. The match of the fracture flow model with retention is shown in Fig. 5.14. This model is low in relation to the peak concentrations. Also, the retention term has too great an effect at late times.

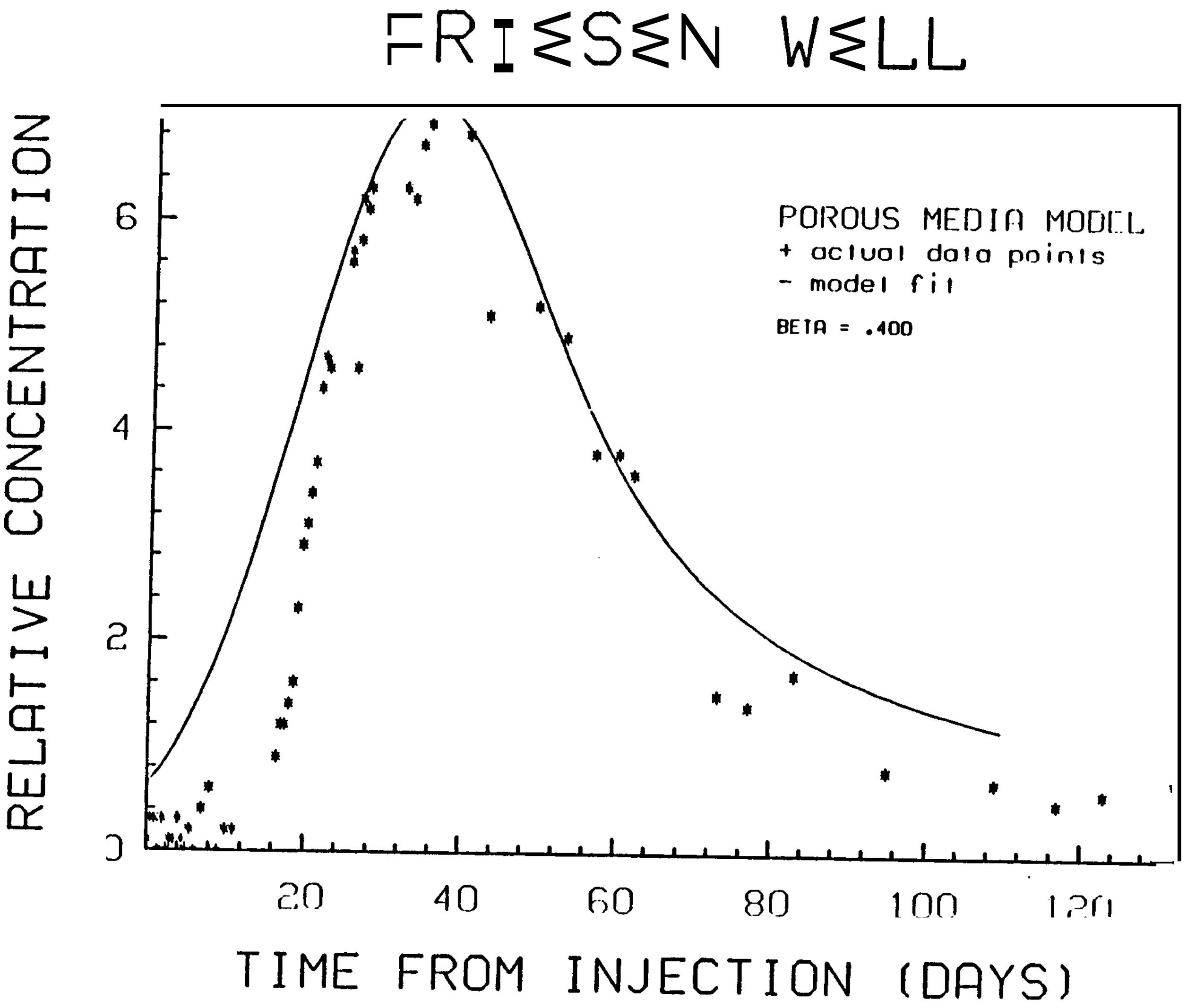


Figure 5-12: Friesen well porous model match district test

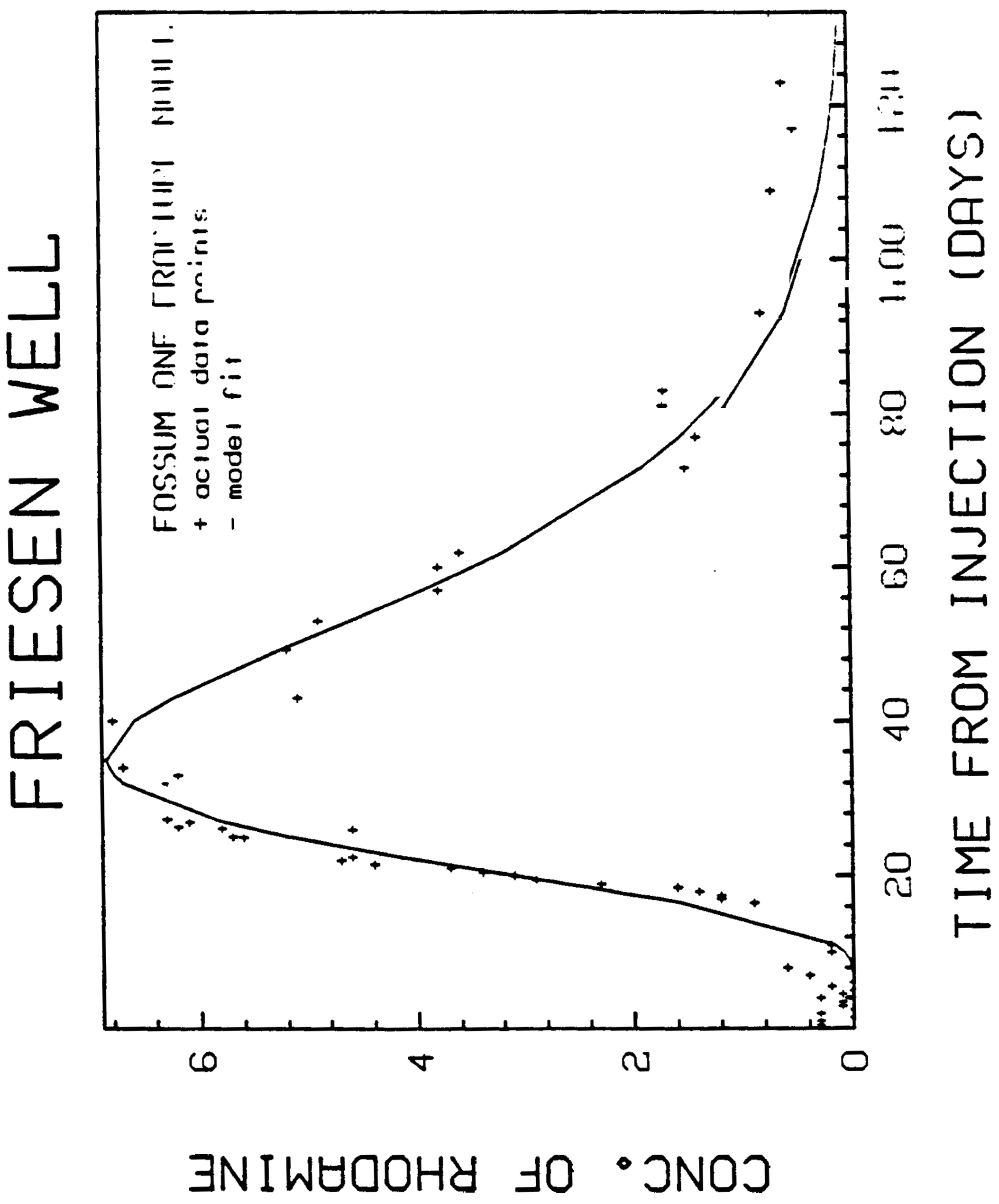


Figure 5-13: Friesen well single flow path model match district test

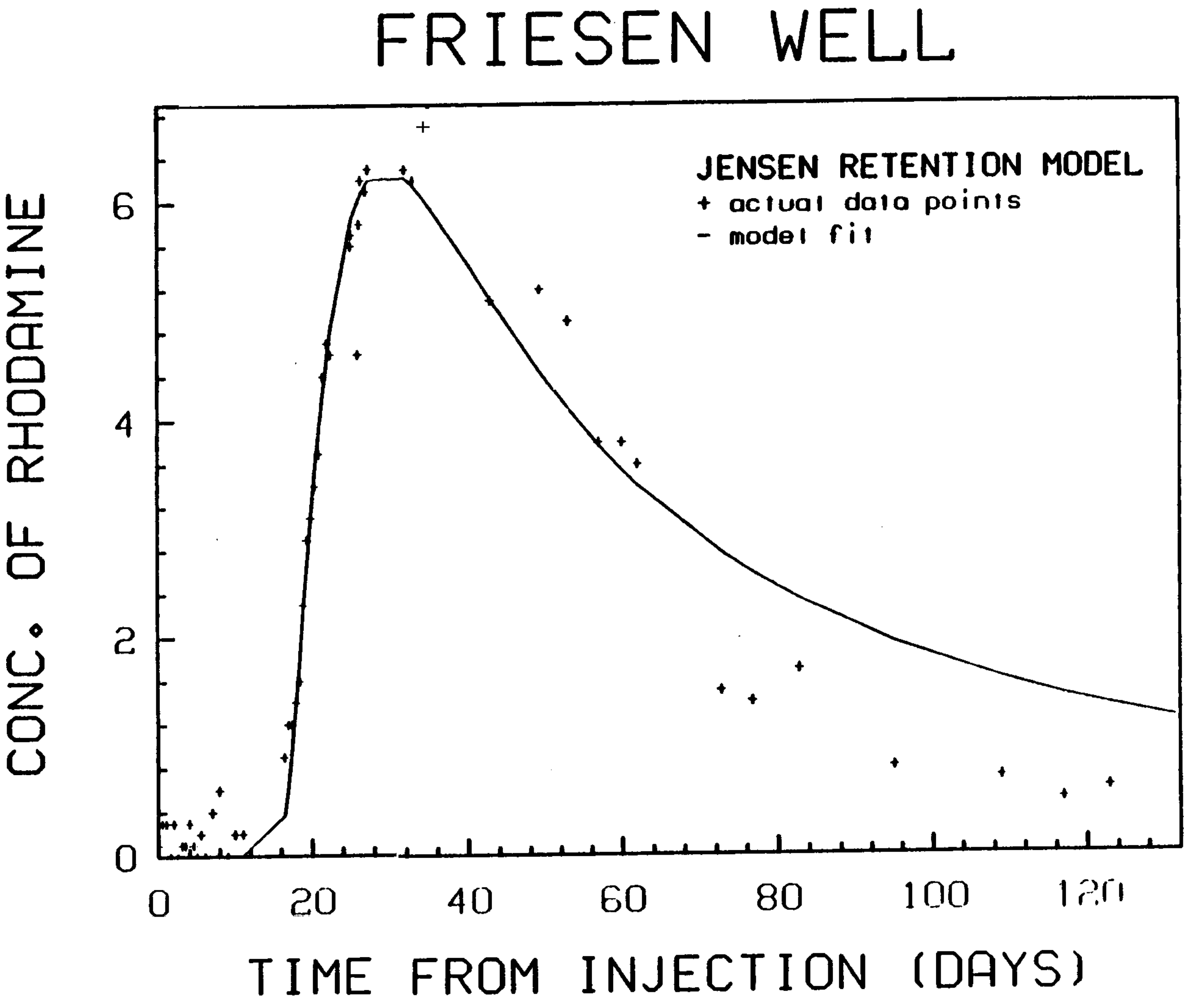


Figure 5-14: Friesen well retention model match district test

6. EARTH SCIENCES

D.K. Bird

Efficient assessment and management of thermal energy production from active geothermal systems requires reliable evaluation of chemical reactions between geothermal reservoir fluids and their geologic environment during the natural and production states of the system. Thermodynamic analysis of reactions between geothermal reservoir fluids and the matrix rock of the reservoir can provide useful information on evaluating solute and mineralogic geothermometers and the expected changes in porosity of the system during production or reinjection as a consequence of chemical mass transfer. Between September 1983 and September 1984 we have succeeded in bringing online and documenting a number of geochemical codes at Stanford that are necessary for evaluating chemical processes in geothermal systems. This coincided with the purchase and installation of a **VAX** 11/750 operating on 4.2bsd **UNIX** and serving the Departments of Geology and Applied **Earth** Sciences.

A number of geochemical programs were obtained from outside laboratories and implemented on the Department of Geology/ **AES VAX** 111750. This year attention was focused on the following codes:

SUPCRT (H. C. Helgeson, Berkeley): Thermodynamic properties for minerals, gases, ions, water and reactions thereof at elevated temperatures and pressures.

EQ3NR (T. Wolery, Lawrence Livermore Laboratories): Computation of aquilibriuni distribution of species in aqueous electrolyte solutions, including heterogeneous equilibrium, along the saturation surface for H_20.

EQ6 (T. Wolery**,** Lawrence Livermore Laboratories): Irreversible mass transfer among aqueous solutions and minerals along the saturation surface for H_20.

FINDX (G. Flowers, Tulane University): Composition of $H_20–CO_2$ fluid in equilibrium with a given mineral assemblage.

FINDX (T. Bowers version, C.I.T.): Composition of $H_20–CO_2–NaCl$ fluid in equilibrium with a given mineral assemblage.

EQUILAS (G. Flowers, Tulane University): Gibbs free energy minimization for a given bulk rock composition.

RKMIX (G. Flowers, Tulane University): Calculations of non-ideality in the H_2O-CO_2 system.

FUGCO (T. Bowers, C.I.T) : Calculates fugacity coefficients in the system H_2O-CO_2-NaCl.

DENFIND (T. Bowers, C.I.T.): Calculates pressure and temperature corresponding to density isochores for H_2O-CO_2-NaCl fluids.

WATER (G. Flowers, Tulane University): Calculates thermodynamic, transport, and electrostatic properties of H_2O to high pressures and temperatures.

Interactive file generators were written to help users write input files for SUPCRT and EQ3NR. A similar program will be written to generate input for EQ6. The following have been written to supplement the geochemical program library:

SUSORT : Sorting of SUPCRT output for orthogonal plotting

PYX : Modification of Papike's pyroxene recalculation program

CALCQ : Calc-Silicate recalculation and manipulation program.

Three levels of documentation for these codes have been developed. Level 1 consists of a summary for each program, written in the style of the standard UNIX programmer's manual, and provides a quick reference of what is available **and** how it is accessed. Level 2 consists of online interactive helpfiles and Level 3 consists of more in depth articles about the programs, their applications, and their limitations.

During the past year these geochemical codes were used to evaluate chemical reactions between reservoir fluids and minerals in several active and fossil geothermal systems. In the Cerro Prieto geothermal system we have calculated the compositional relations between geothermal fluids and metasomatic mineral zones throughout the reservoir (Schiffman et al., 1984;

Bird et al., 1984). The results of these calculations were used to evaluate the conditions of fluid flow within the reservoir and to postulate the nature of the magmatic heat source (Elders et al., 1984). In addition, we have used these codes to investigate the zoning of calc-silicate mineral assemblages in geothermal systems worldwide (Bird et al., 1984). During the year the codes were also used extensively by students in the School of Earth Sciences. Supcrt was used as a teaching tool for two classes, and EQ3NR and EQ6 was used for research by students in the geochemical and ore deposits programs.

7. TECHNOLOGY TRANSFER

The Ninth Workshop on Geothermal Reservoir Engineering was held at Stanford University on December 13-15, 1983. The attendance was similar to previous years with 123 registered participants of which 22 represented 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. A record number of technical papers (about 60) were submitted for presentation at the Workshop. It was therefore decided to ham several parallel sessions to accommodate most of the papers. This format proved unpopular and will not be repeated. Many of the participants felt that the Workshop lost some of its unique qualities by having parallel sessions. There were 58 technical presentations at the Workshop, of which 4 were not made available for publication. Several authods submitted papers not presented at the Workshop.

The theme of the 1983 Workshop was "field developments world-wide." This theme was addressed by encouraging participants to submit field development papers, and by inviting several international authorities to give presentations at the Workshop. Field developments in at least twelve countries were reported: China, El Salvador, France, Greece, Iceland, Italy, Japan, Kenya, Mexico, New Zealand, the Philippines, and the United States.

Weekly seminars were held during the academic year on geothermal energy topics. Id autumn and winter quarters most of the seminars were given by engineers and scientists from outside Stanford University. During spring quarter, however, all of the seminars were given by some of the students working of geothermal research projects. This gave students graduating in June a chance to present their almost-completed projects.

The contents of the Proceedings of the Ninth Workshop of Geothermal Reservoir Engineering, and the Seminar Schedules for the 1983-1984 academic year are shown in Appendices A and B.

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SEMINAR SCREDULE

Autumn Quarter 1983	Room B-67, Mitchell Building	Thursdays,, 1:15-2:30 p.m.
Date	Title	Speaker
Sept. 29	Organizational Meeting	SGP Faculty
Oct. 6	No Meeting (SPE Annual)	
13	Activable Tracers in Geothermal Reservoirs	Paul Kruger Stanford University
20	Klamath Falls Tracer Tests	Jon S. Gudmundsson Stanford University
27	No Meeting (GRC Annual)	
Nov. 3	Geothermal Exploration and Geochemistry of Thermal Waters in the Andes of Northern Argentina	Chris Klein GeothermEx
10	Steam and Gas Flow in Geothermal Reservoirs	Bill Herkplrath U.S. Geological Survey
17	Modeling the Natural State of Geothermal Systems in the Salton Trough	Marcelo Lippmann Lawrence Berkeley Lab.
24	No Meeting (Thanksgiving)	
Dec. 1	Acid Cleanout and Stimulation of Geothermal Wellbores	Tom Turnet Phillips Petroleum Company
8	No Meeting (Dead Week)	

Dec. 13-15 Ninth Workshop on Geothermal Reservoir Engineering

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SEMINAR SCEEDULE

Winter Quarter 1984 — Room B-67, Mitchell Building — Thursdays, 1:15-2:30 p.m.

Date	Title	Speaker
Jan. 12	Current Research Projects	Faculty and students SGP
Jan. 19	How Big The Geysers?	Bob Greider Geoth. Resources Int'l.
Jan. 26	Geothermal Resources for Direct Use in Lake County	Gerald Niimi ThermaSource
Feb. 2	Localization and Evolution through Tertiary Time of High-Temperature Geothermal Systems	Don White U.S.G.S.
Feb. 9	Magma's Activities in East Mesa and Niland	Tom Hinrichs Magma Power
Feb. 16	Tracking Injected Fluids with Geophysical Methods	Paul Kassameyer Lawrence Livermore Lab.
Feb. 23	Temperature Logging: Anomalous Fluid Motions and Instabilities	Tom Urban U.S.G.S
Mar. 1	Aminoil's Operating at The Geysers	John Counsil Aminoil USA
Mar. 8	Salton Sea 10 MW plant Performance Review	Phil Messer Union Oil
Mar. 15	No Meeting (Dead Week)	

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD.CALIFORNIA 94305

Jon S. Gudmundsson
Petroleum Engr. Dept.
Mitchell Bldg., Room 360
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SEMINAR SCHEDULE

Spring Quarter, 1984	Room 124, Noble Building	Thursdays, 1:15-2:30 p.m.
Date	**Title**	**Speaker**
April 26	Multi-Component Compressibility in Geothermal Reservoirs	Luis Macias Petroleum Engineering
May 3	Thermal Stressing of Rocks in Cold Water Sweep	Steve Lam Mechanical Engineering
May 10	Reservoir Thermodynamic Conditions from Radon Concentration	Lew Semprini Civil Engineering
May 17	Linear Boundary Detection Using Pressure Buildup	Glenn Fox Petroleum Engineering
May 24	Gravity Effects in Relative Permeability Measurements	Barry Beal and Craig Nunes Petroleum Engineering
May 31	Doublet Tracer Testing Analysis	Steve Johnson Petroleum Engineering

APPENDIX B: Table of Contents Proceedings Ninth **Workshop**

STANFORD GEOTHERMAL PROGRAM
STANFORD UNIVERSITY
STANFORD CALIFORNIA 94305

SGP-TR-74

PROCEEDINGS OF THE NINTH WORKSHOP
ON
GEOTHERMAL RESERVOIR ENGINEERING

Stanford University

Stanford, California

December 13-15, 1983

SPONSORED BY

THE GEOTHERMAL AND HYDROPOWER TECHNOLOGIES DIVISION

OF THE DEPARTMENT OF ENERGY

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APPENDIX C: PARTICIPANTS IN THE STANFORD GEOTHERMAL PROGRAM 1984-85

Principal Investigators

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

Program Manager

Jon S. Gudmundsson	Petroleum Engineering

Associated Faculty

Dennis K. Bird	Geology
Anstein Hunsbedt	Civil Engineering
Drew V. Nelson	Mechanical Engineering
Abraham Sageev	Petroleum Engineering

Student Research Assistants

Yathrib Al-Riyami
Barry J. Beal
Costas Chrysikopoulos
Mary E. Eipper
Glenn A. Fox
John R. Gilardi
Stephen E. Johnson
Stephen T. Lam
Luis Macias-Chapa
John Marcou
Craig S. Nunes
Gudmund Olsen
Jeffi-ey F. Simmons
Carlos Tavares
Gardner W. Walkup

APPENDIX D: PAPERS PRESENTED AND PUBLISHED OCTOBER 1, 1983 THROUGH SEPTEMBER 30,1984

Geothermal Resources Council Annual Meeting, Portland, Oregon, October, 1983

Injection Testing in 1982 at the Svartsengi High-Temperature Field in Iceland--J.S. Gudmundsson

Geothermal Soil Heating in Iceland--J.S. Gudmundsson

Drawdown Pressure Transient Analysis of Well Near a Steam Cap--A Sageev and R.N. Horne

Society of Petroleum Engineers Annual Technical Conference, San Francisco, October 1983

Temperature Effects on Oil/Water Relative Permeabilities of Sands--M.A. Miller and H.J. Ramey, Jr.

The Fenske Conservation Method for Pressure Transient Solutions with Storage--R.N. Horne

Automated Type Curve Matching in Well Test Analysis Using LaPlace Space Determination of Parameter Gradients--A.J. Rosa and R.N. Horne

Fifth New Zealand Geothermal Workshop, Auckland, November, 1983

Choked Flow in Fractured Geothermal Reservoirs–A.J. Menzies, **J.S.** Gudmundsson and R.N. Horne

Ninth Workshop on Geothermal Reservoir Engineering, December 1983

Slug Test Data Analysis in Reservoirs with Double Porosity Behavior--K. Mateen and H.J. Ramey, Jr.

Analysing Spinner Measurements from Well Tests Using Computerized Interpretation Techniques-R.N. Horne, A. Guillot and A. Rosa

Simulation of Radon Transport in Geothermal Reservoirs--L. Semprini and P. Kruger

Mamx Diffusion and Its Effect on the Modeling of Tracer Returns from the Fractured Geotherma Reservoir at Wairakei, New Zealand--C.L. Jensen and R.N. Horne

Doublet Tracer Testing in Klamath Falls, Oregon--J.S. Gudmundsson, **S.E.** Johnson, R.N. Horne, P.B Jackson and G.G. Culver

Society **of** Petroleum Engineers California Regional Meeting, Long Beach, 1984

Infinite Conductivity Vertical Fracture in a Reservoir with Double Porosity--0.P. Houze, R.N. Horn and H.J. **Ramey,** Jr.

Two-Phase Flow and Calcite Deposition in Geothermal Wells--J.S. Gudmundsson, J. Ortiz R. and E.E. Granados

Partially Penetrating Fractures: Pressure Transient Analysis of an Infinite Conductivity Fracture--F. Rodriguez, R.N. Home and H. Cinco-Ley

Geothermal Reservoir Evaluation Considering Fluid Adsorption and Composition--M.J. Economides and F.G. Miller

Slug Test Data Analysis in Reservoirs with Double Porosity Behavior--K. Mateen and H.J. Ramey, Jr,

Economic Commission, Florence, May **1984**

Eighth Annual Geothermal Conference and Workshop, EPRI, August **1984**

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

Geothermics, Vol. **13,** No. **1/2, 103-115, 1984**

Relationship of Radon Correlation to Spatial and Temporal Variations of Reservoir Thermodynami Conditions in the Cerro Prieto Geothermal Field--L. Semprini and P. Kruger

Analysis and Interpretation of Data Obtained in Tests of the Geothermal Aquifer at Klamath Fall Oregon, USGS Water Resources Investigations Report **84-4216, 1984**

Interwell Tracer Testing in Klamath Falls--J.S. Gudmundsson

Geo-Heat Center Bulletin, 8, **1983**

Geothermal in Iceland: It's Only Natural--J.S. Gudmundsson

Geothermal Resources Council Annual Meeting, Reno, Nevada, August, **1984**

Discharge Analysis Method for Two-Phase Geothermal Wells--J.S. Gudmundsson