SGP-TR-121

- Heat Extraction Project -
Geothermal Reservoir Engineering Research at Stanford

Principal Investigator:
Paul Kruger

January, 1989

Fourth Annual Report
Department of Energy Contract Number
DE-AS07-84ID12529
For the Period
January 1, 1988 through December 1, 1988

Stanford Geothermal Program
Interdisciplinary Research in
Engineering and Earth Sciences
STANFORD UNIVERSITY
Stanford, California

TABLE OF CONTENTS

PREFACE

The Stanford Geothermal Program was initiated under a grant from the National Science Foundation in 1972 and has continued since then under contracts from the Energy Research and Development Administration and its successor agency, the U.S. Department of Energy.

The Stanford Geothermal Program combines interdisciplinary research and training in engineering and earth sciences. The Program is designed to maintain a balance between fundamental, applied, and field-data matching applications. The principal objective of the Program is to carry out research on geothermal reservoir engineering techniques useful to the geothermal industry in the United States. A parallel objective is to train qeothermal engineers and scientists for employment in the industry. The research is focused toward accelerated development of hydrothermal resources through the evaluation of resource thermal conteint and quality, fluid reserves, and the forecasting of reservoir behavior under potential production and recharge practices of reservoir management. The Heat Extraction Project for evaluation of thermal properties of fractured geothermal resources and forecasted effects of reinjection recharge into operating reservoirs is an important element of the Stanford Geothermal Program.

This publication is the Fourth Annual Report to the Idaho Office of the Department of Energy. Prior annual reports of the Heat Extraction Project were included in the Annual Reports of the prime Contract, DE-AS03 84ID12529. The Third Annual Report, SGP-TR-114, was issued in February, 1988 [1].

The successful execution of the Heat Extraction Project's objectives depends on the help and support of many individuals in the Department of Energy, the geothermal industry, national laboratories, and universities. Special acknowledgement is due to Dr. John E. Mock of the Department of Energy for his continued support of this project and to Engineer Rafael Molinar of the Mexican Federal Energy Commission for his extended cooperation in coordinating the efforts of the staffs at the Los Azufres, La Primavera, and Los Humeros geothermal fields under the SGP-CFE and DOE-CFE Geothermal Agreements.

Paul Kruger
January 1989

SECTION 1. OVERVIEW

The main objective of the SGP Heat Extraction Project is to provide a means for estimating the thermal behavior of geothermal fluids produced from fractured hydrothermal resources. The methods are based on estimated thermal properties of the reservoir components, reservoir management planning of production and reinjection, and the mixing of reservoir fluids: geothermal resource fluid cooled by drawdown and infiltrating groundwater, and reinjected recharge heated by sweep flow through the reservoir formation. Several reports and publications, listed in Appendix A, describe the development of the analytical methods which were part of five Engineer and PhD dissertations, and the results from many applications of the methods to achieve the project objectives.

During FY88, the Heat Extraction Project made major advances in the development of the 1-D Heat Sweep Model and its application in geothermal fields in several countries. Heat sweep joint studies are underway for reinjection evaluation at the Los Azufres, Los Humeros, and La Primavera fields in Mexico under the DOE-CFE Geothermal Agreement. The location of these three geothermal fields in relation to Mexico City is shown in Figure 1. The timing of these studies is especially important because the development at each of these fields is at the stage when decisions must be made on the selection on brine disposal wells at each of the production zones.

Also during the year, the initial estimates of thermal effects by heat sweep under the joint studies with the New Zealand Ministry of Works and Development were provided for the 500 t/h reinjection test to the newly-formed Electricorp redevelopment program at Wairakei, New Zealand. The Electricorp group has taken over the reduced program and the temperature cooldown data is expected at the conclusion of the test.

A broad cooperative program was initiated with the Leningrad Mining Institute in Leningrad, USSR on the development of hot water supply recirculation systems to be developed in the USSR, the first of which is scheduled for the Zakarpate Oblast in western Ukraine in 1989. On the basis of an invited two-month visit to the Leningrad Mining Institute in the spring of 1989, a possible paper resulting from the joint efforts on the Zakarpate field has been offered for the Camborne School of Mines' International Conference on Hot, Dry Rock Resources, in Cornwall, England, June, 1989. Cooperative efforts are also being carried out for the phase 2 test at the Hot,Dry Rock project at Fenton Hill, New Mexico. During FY88, a joint study on the comparison of thermal decline during the long-term flow test, estimated by the LANL and SGP models, were published by B. Robinson (LANL) and P. Kruger (SGI?) at the Thirteenth SGP Geothermal Workshop in January, 1988 [2].

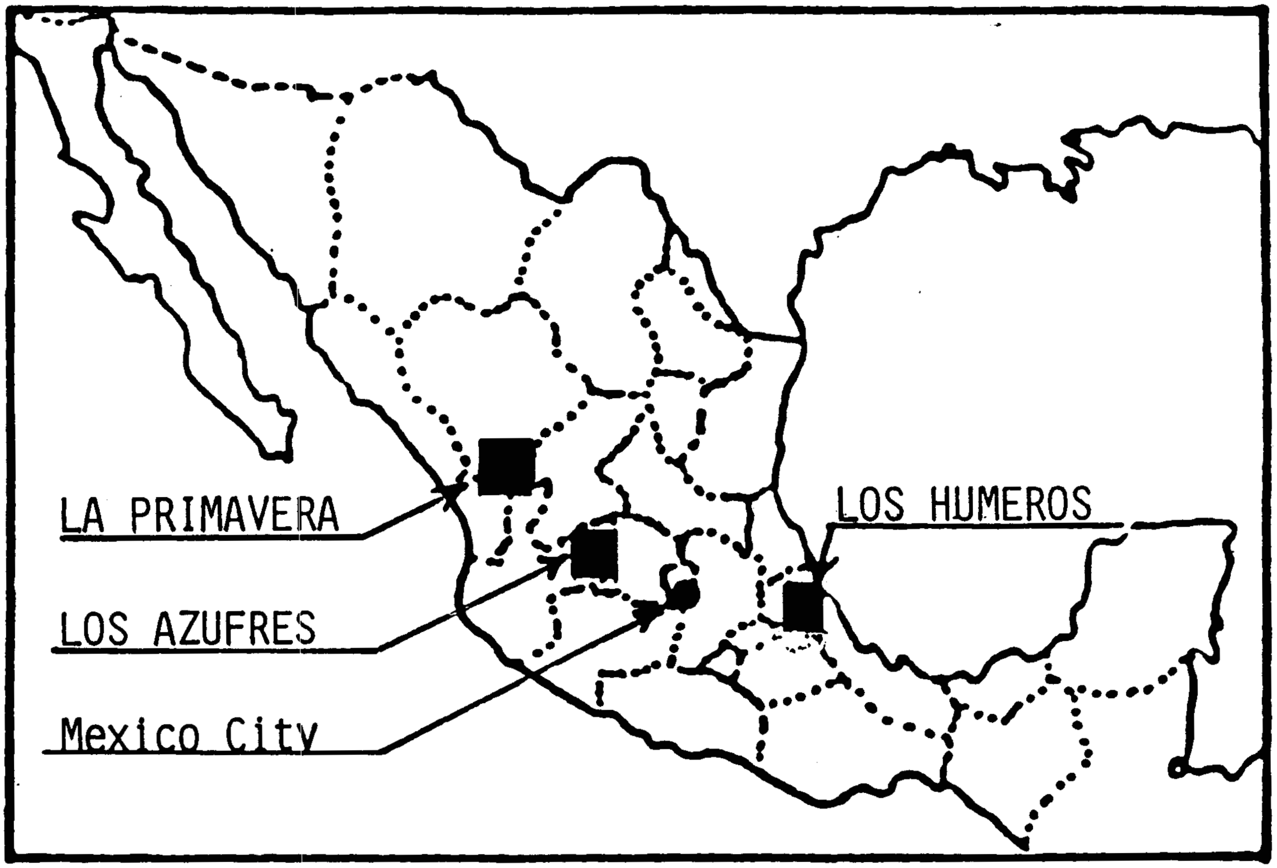


Figure 1. Map of Mexico showing the three new developing geothermal fields on the neo-volcanic belt across Mexico in relation to Mexico City.

Another main effort of the Heat Extraction Project is the early evaluation of thermal drawdown by small wellhead electrical generating units on potentially large geothermal resources. Such evaluations is of use in the planning for larger central power plant units. Advances were made in the long-term cooperative studies at Los Azufres, now also included under the DOE-CFE Geothermal Agreement, on the evaluation of the effects of the first five years of operation of the CFE 5-MW wellhead generators on the reservoirs of the thermally different Maritaro and Tejamaniles zones of the large Los Azufres geothermal field.

During FY88, Final Drafts were completed for the two joint studies to be presented at the Final Symposium under the existing 3-year DOE-CFE Geothermal Agreement. For Task 4, Reservoir Engineering, the joint study [3] focused on the startup analysis of the first five years of operation for the 5-MW portable generators in the two-phase Maritaro zone of the Los Azufres field. The study should assist in determining the extent of thermal drawdown over the lifetime of the local reservoir units and in evaluating observed changes in thermodynamic properties of the reservoir and long-term production characteristics. For Task 5, Reinjection, the joint study [4] on heat sweep in the three different zones of Los Azufres should assist in analysis of thermal breakthrough potential for alternate choices of injection wells and the heat extraction effects of partial reinjection into these three zones.

For the analysis of thermal stressing effects on long-term thermal behavior of fractured hydrothermal reservoirs, the laboratory experiments in the SGP physical reservoir model to examine the effects of thermal stress by reinjection cooling on the thermal conductivity of reservoir fractured rock blocks were completed by PhD candidate Steven Lam. The SGP Physical Reservoir Model completed its useful life during FY88 and is in the process of decommissioning. The data acquired by Research Asst. Lam is in the process of analysis and comparison with theoretical predictions for completion of a PhD dissertation to be completed in FY89.

SECTION 2. DEVELOPMENT OF THE 1-D HEAT SWEEP MODEL

The 1-D Heat Sweep Model was developed under the Heat Extraction Project as a tool for early analysis of the thermal effects of reinjected cooled brines as recharge into geothermal reservoirs under steady production. Evaluation is required for prudent reservoir management in selection and operation of recharge wells, contrasting the concomitant potential benefit for secondary heat recovery (in addition to the primary benefits of waste brine disposal and reservoir pressure maintenance) and the potential risk of premature thermal breakthrough of the cooled reinjection recharge. The original model, the 1-D Linear Heat Sweep, was described in the User's Manual prepared by Hunsbedt, Lam, and Kruger in 1983 [5]. The physical basis for heat transfer from fractured rock to reinjected fluid during sweep flow in hydrothermal reservoirs has been described in earlier project reports. The model was simplified in one flow dimension in terms of the Number of Heat Transfer Units parameter, which expresses the ratio of the residence time of the reinjected sweep fluid to the time constant of the fractured rock block distribution as an equivalent rock block sphere for heat transfer for which the solution is known analytically. A large number of heat transfer units implies a reservoir that is heat transfer rate limited, whereas a low number indicates a reservoir that is fluid flow limited.

The 1-D :Linear Heat Sweep Model was improved by Graduate Student Stephen Lam as part of his PhD thesis to allow for other types of injected recharge flow and for mixing of sweep fluid with reservoir fluid near the production well for production flow that is only partially reinjected. The model was then able to handle reinjection flow in linear or radial geometry between single and lines of injection and production wells either by heat sweep alone or by mixing with sweep flow with percolation recharge from above and/or hot water flow from the reservoir resource below declining in temperature at a constant exponential cooldown rate. Other improvements included evaluation of several Laplace transform inversion methods to optimize the accuracy of the output cooldown curves and compilation of the heat sweep source code as a microcomputer version for use in field applications.

In FY87, the l-D Heat Sweep Model was further advanced to include doublet flow from a pair of injection-production wells. The doublet flow geometry is especially useful in new geothermal zones where only exploratory production wells are available and flow boundaries, such as faults, are not sufficiently identified. The initial difficulty encountered in using doublet flow geometry in a one-dimensional model is its intrinsic two-dimensional behavior. The approach taken to accomplish the reduction in dimensionality was division of the total flow field into a large number of linear channels and the method of multi-channel integration of the one-dimensional linear heat sweeps over the domain of the two-dimensional flow. For a sufficiently large number of flow channels (e.g., N > 80), the crescent flow channels between expanding streamlines can be expressed as equivalent rectangles having the same heat transfer surface and mean fluid velocity. With the mean channel length and mean fluid velocity in each channel, the heat transfer between fluid and reservoir rock is modeled as a 1-D linear heat sweep in each channel. Summing of the N channel cooldown data in an array of residence time intervals provides the time dependent cooldown curve for the total flow at the production well. If the reinjection rate is only part of the production rate, mixing of the sweep fluid with reservoir resource fluid at the appropriate cooldown rate is also modeled.

The first application of the l-D Doublet Heat Sweep Model was made for the El Chino zone of the Los Azufres geothermal field. This zone is between the steam reservoir in the Tejamaniles (south) zone and the two-phase reservoir in the Maritaro (north) zone. One production well (Az-9) and one potential reinjection well (Az-3) have been drilled in this zone. CFE has decided to locate one of the four new 5-MW wellhead units at well Az-9 and reinject at Az-3. Figure 2 shows a plan view of the El Chino zone with the constrained radial sweep geometry superimposed. The application of the l-D Doublet Heat Sweep Model allows a comparison with the linear and radial models evaluating the differences for flow potentially bounded by the El Chino and Laguna faults. The results of this study [6] was presented at the 9th annual New Zealand Geothermal Workshop in November, 198'7 in conjunction with a trip to report on the Wairakei 500 t/h reinjection test heat sweep analysis.

During FY88, it was apparent that the assumption of an infinite uniform temperature for the doublet flow model was unacceptable. For a uniform initial reservoir temperature, infinite in geometry for doublet flow, the heat content available above a useful abandonment temperature increases rapidly with increasing crescent number. The result is a very long cooldown time to the abandonment temperature relative to those obtained with the uniform temperature in the bounded flow geometry inherent in the linear and radial flow models. An improvement in the l-D Doublet Heat Sweep Model was achieved by limiting the formation volume of the reservoir at mean initial temperature to a defined geometry. Unfortunately, little temperature distribution data exist in the new geothermal fields covered under the current joint projects. In this fiscal year, efforts were initiated to acquire temperature data, and an initial temperature cross section was prepared by the CFE staff at the La Primavera field. To obtain early insight on the effect of bounded temperature distribution on doublet recharge return flow geometry, an exercise was carried out for several potential initial temperature distributions at the La Primavera field and El Chino zone of the Los Azufres field. These are illustrated in Figure 3. The output temperature distribution as a function of crescent number is shown in Figure 4. Crescent number 25 corresponds to one well-axis radius, crescent number 31 corresponds to the 170 C abandonment temperature at the La Primavera field, and crescent number 50 corresponds to the furthermost crescent in the external temperature regime of 145 C. The results of the study were prepared for presentation by Lam and Kruger (1989) at the Fourteenth Annual Stanford Geothermal Workshop, scheduled for January, 1989 [7].

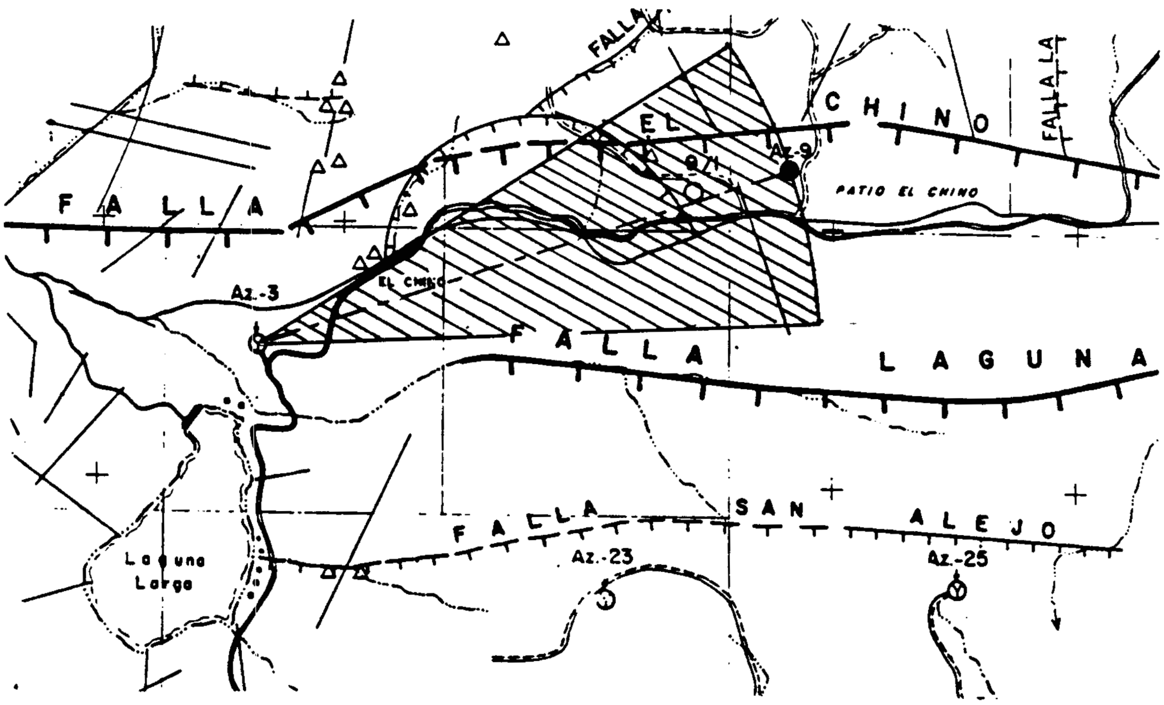


Figure 2. The El Chino zone of the Los Azufres geothermal field in relation to the major faults as estimated by the CFE geologic staff.

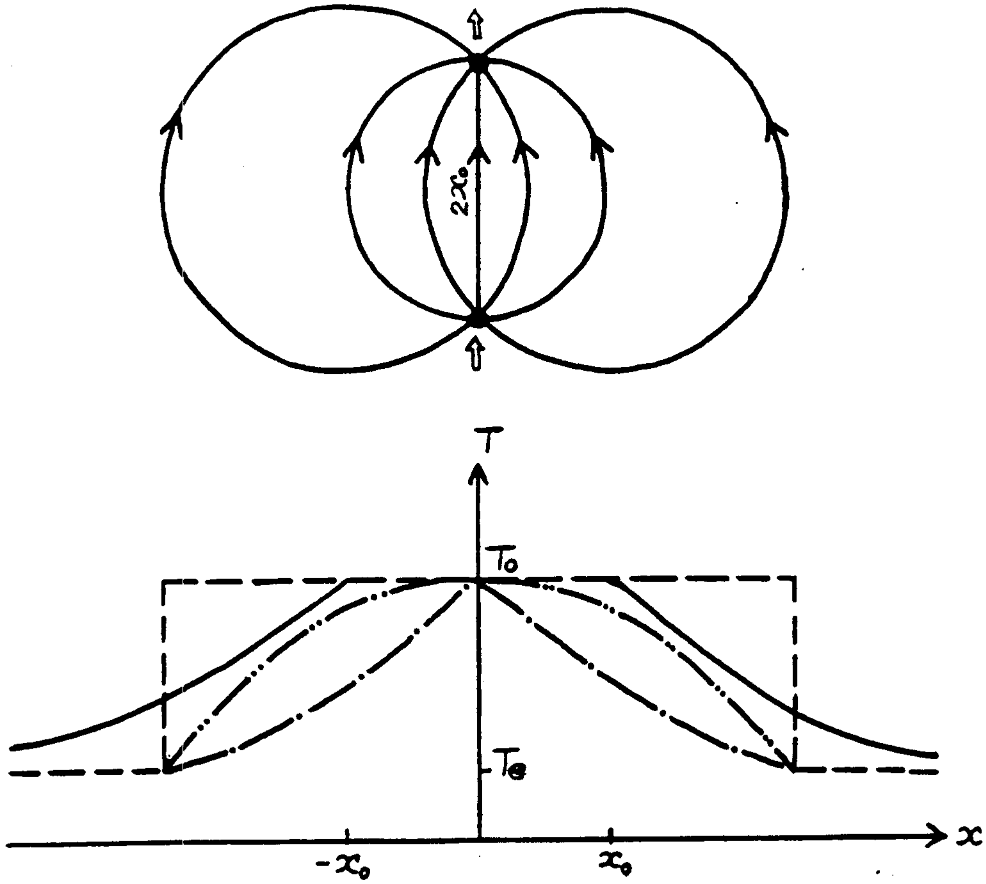


Figure 3. Temperature distributions for doublet flow simulations: (a) doublet flow as a series of crescents bounded by streamlines; (b) circular, step, normal, and exponential temperature distributions.

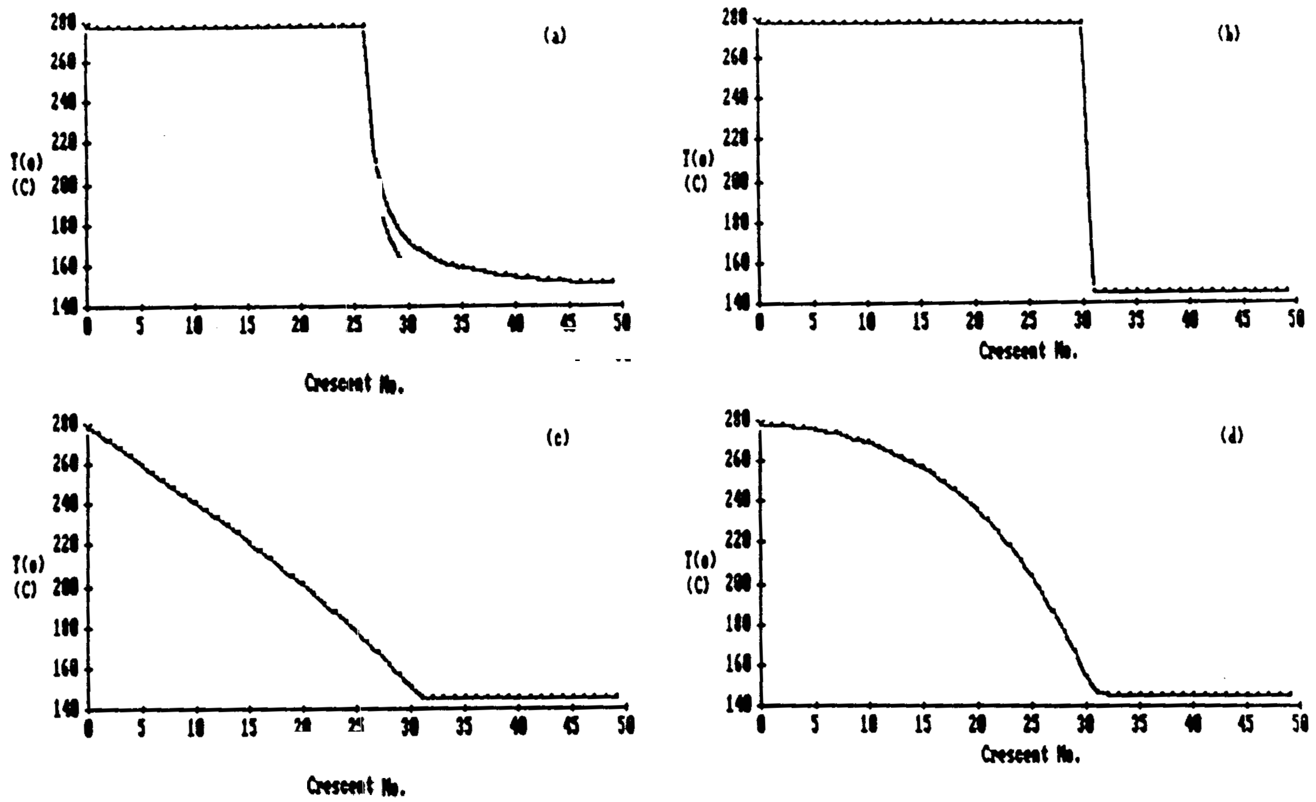


Figure 4. Temperature distribution output from the simulations for the La Primavera and El Chino doublet studies: (a) circular reservoir with external decreasing temperature to abandonment temperature; (b) step function to given crescent number; (c) exponential decline; and (d) normal distribution. For scale, crescent no. 25 is at 1 well-axis radius, crescent 50 is at 23 well-axis radii.

SECTION 3. DOE–CFE HEAT SWEEP PROJECT

The 1-D Heat Sweep Model has been in continuous application in cooperation with CFE in Mexico since its first use in matching the observed cooldown along the western border of the Cerro Prieto I upper reservoir, published in 1985 [8]. A review of the several SGP-CFE joint studies in heat sweep analysis at the four Mexican geothermal fields was presented at the first CFE Symposium on (GeothermalReservoir Engineering [9]. A list of the joint studies under the cooperative arrangements is given in Table 1.

Table 1

SGP-CFE COOPERATIVE HEAT SWEEP STUDIES

Study No.	Project Zone	Injection Wells	Production Wells	Status*
CPI	Cerro Prieto I	influx	western line	P
LAz1	W. Tejamaniles	Az-31	Az-26	+
LAz2	e. Tejamaniles	Az-8	Az-2	R
LAz3a,b	Maritaro	Az-15	eastern line	P
LAz4	Tejamaniles	(4)	Central (15)	U
LHu1	1st Wellhead	H-5	H-1, H-7	P
LaP1	1st Wellhead	PR-2	PR-9	P
LAz5b	n. Tejamaniles	Az-1	Az-22	+
LAz6b	Maritaro	Az-15	Az-4	P
LAz7	El Chino	Az-3	Az-9	P,+
LHu2	2nd Wellhead	H-4	H-16	P
LaP2	2nd Wellhead	PR-2	PR-1,8,9	P
LAz8a	Maritaro Unit7	Az-15	Az-4	+
LAz8b	Maritaro Unit7	Az-40	Az-4	+
LAz9a	Maritaro Unit8	Az-15	Az-51	+
LAz9b	Maritaro Unit8	Az-40	Az-51	+
LAz10	Maritaro Unit9	Az-52	Az-42	+
LAz11a	Maritaro Unit10	Az-15	Az-43	+
LAz1113	Maritaro Unit10	Az-40	Az-43	+

*Status: P=published; R=reported to CFE; U=underway;
+ = studies included under the DOE-CFE Geothermal Agreement.

During FY88, reunions were held with the senior staffs of the respective fields to review the results from prior visits, evaluate the current output data, and incorporate the most recent production, chemical, and reservoir data and changes in plans for the development of the field. A major advantage that has already resulted from the joint application of the Heat Sweep Model has been the preparation of field staff generated estimation of the reservoir and production conditions as Input Data for the simulations runs. In most cases, the compilation of the required reservoir, structural, and thermal data for the study has required cooperative estimation among the senior staff of each field. Results of the joint studies completed before the DOE-CFE tasks were underway have been published in several Symposia.

Heat sweep studies underway during FY88 at the three Mexican fields include Los Humeros and La Primavera under the SGP geothermal agreement and the 10 case studies for the three zones of the Los Azufres field under the DOE-CFE geothermal agreement. Progress, including presentation of results, was achieved for each field.

A. Los Humeros

Joint project HSP5, as presented at the 12th annual SGP Workshop [10], was completed. The project examined the potential for reinjection recharge flow from recharge well H5 individually to the two production wells H7 and H1. The radial flow geometry used for these two well pairs is shown in Figure 5. The results of the study were prepared as a technical article (in Spanish) and published in the Mexican journal, Geotermia, Volume 3 (1987) [11]. In FY88, the joint study was re-focused on reinjection heat sweep for the four new portable wellhead units expected in 1989-90. The wells being considered for these units are listed in Table 2. This study is currently underway, and the preliminary results are scheduled for review between the co-principal investigators in the Winter of 1989.

Table 2

Wells for the First Wellhead Units at Los Humeros

5-MW Unit	Production Wells	Injection Well
1	H9	H5
2	H16 (+H17)	H5
3	H7 (+H8)	H5
4	H12 (+H6)	H2

B. Los Azufres

During FY88, studies were completed for the several well pairs listed in Table 1, including thermal breakthrough estimates at the new well pairs in both the Tejamaniles and Maritaro zones. The studies completed in FY87 were prepared for presentation [12] at the 8th New Zealand Geothermal Workshop in conjunction with the trip to initiate the joint study on the Wairakei 500 t/h reinjection test. One of the interesting applications in the Maritaro zone is shown in Figure 6, covering the radial sweep from the proposed reinjection well Az-15 towards the producing area at the right, but passing through the reservoir zone of three newly completed production wells. The comparison of the 55 degree heat sweep across the arc of the three wells with the earlier estimates for linear sweep with unknown, but assumed values for the unbound sweep width.

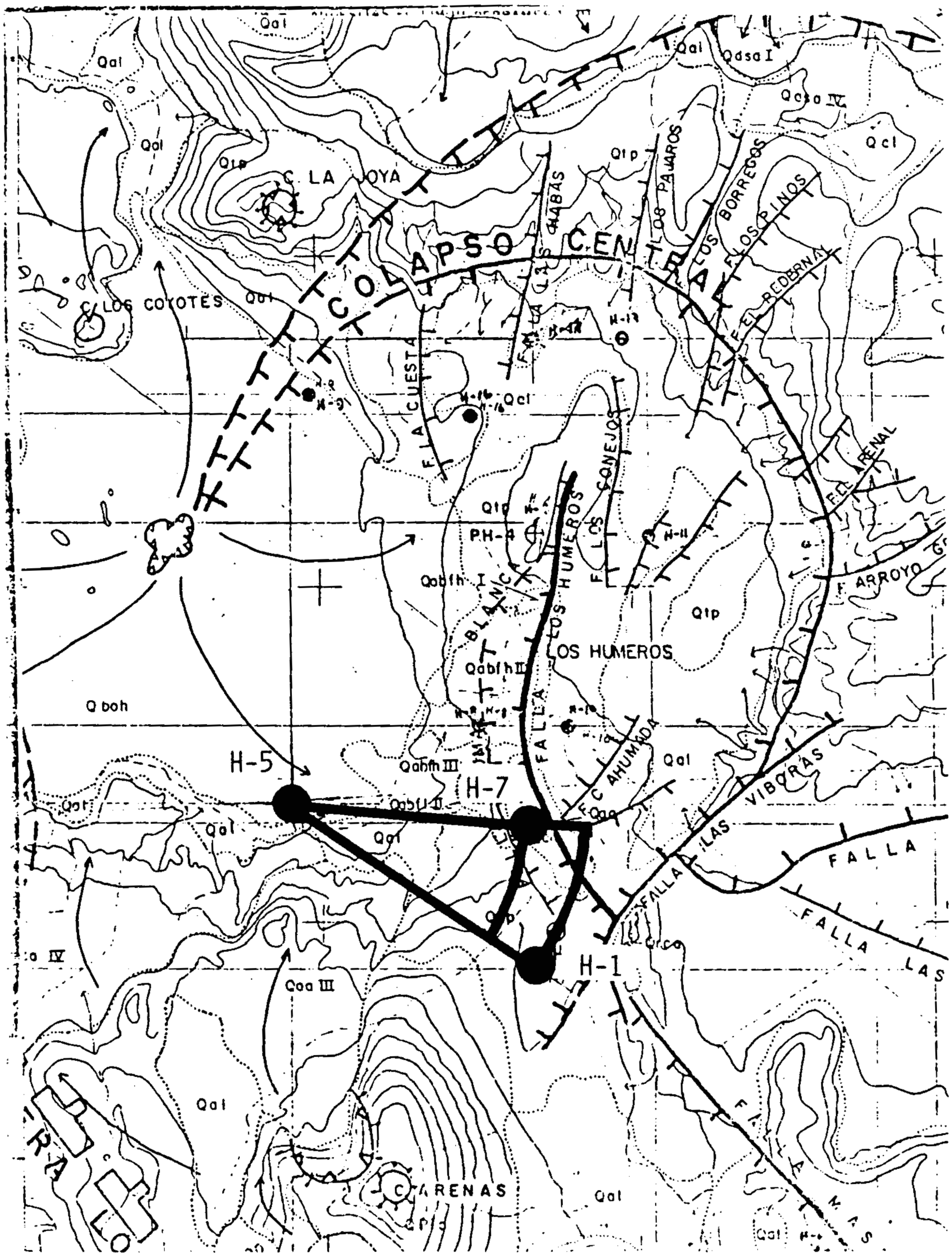


Figure 5. Radial flow geometry used for the initial reinjection recharge studied at the Los Humeros geothermal field.

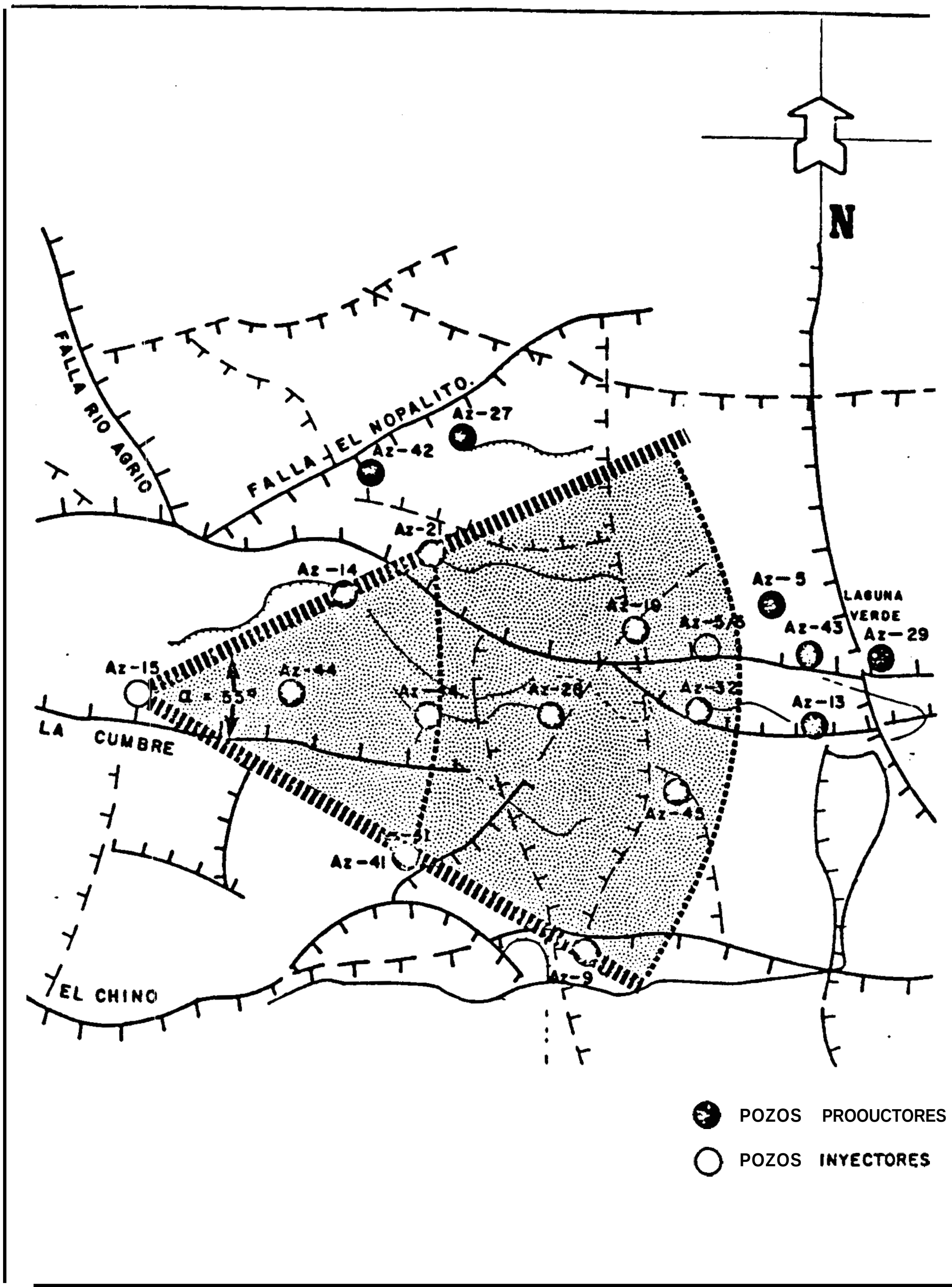


Figure 6. Radial flow heat-sweep analysis of the potential for early thermal breakthrough at the arc of newly drilled wells from recharge return flow to the production wells at the eastern part of the Maritaro zone.

The joint studies at Los Azufres during FY88 reflect the change in philosophy of CFE to change to plastic (polyethylene) surface tubing, which costs less but has a lower maximum allowable fluid temperature for the recharge lines. CFE is evaluating the option of using the nearby Laguna Verde lake for cooling and silica deposition before reinjection. Therefore, the studies, revised to reflect the specific objectives outlined in the DOE-CFE Task 5.1 joint study for heat sweep analysis in the Los Azufres field, should be useful in determining the optimum reinjection time and temperature. Table 3 summarizes the 10 heat sweep analyses chosen for the Task 5 joint study in the three production zones of Los Azufres. Compilation of the input data sets was completed during the year's visits for the Task 5 study and the first draft of the final report for presentation at the DOE-CFE Final Symposium was exchanged with the CFE co-authors. Simulations were run for varying return flow geometries with appropriate dispersion flow angles and for uniform doublet flow. Studies were also made of the sensitivity of choice of mean fracture spacing, resource fluid cooldown rate, and reinjection fluid temperature for various storage times and cooling treatments. The results indicate the possibility of premature cooldown in some production wells near designated reinjection wells which will accept a large flowrate from brine and condensate reinjection from several other wells. In other cases, a clear potential benefit of significantly enhanced thermal energy recovery is noted.

Table 3

Task 5.1 Heat Sweep Joint Studies [4]

HSP Study LAz-No.	Production Zone	Injection Wells	Production Wells
1c	Tejamaniles	Az-31	Az-26
5c	"	Az-1	Az-22
7b	El Chino	Az-3	Az-9
8a	Maritaro	Az-15	Az-4
8b	"	Az-40	Az-4
9a	"	Az-15	Az-51
9b	"	Az-40	Az-51
10	"	Az-52	Az-42
lla	"	Az-15	Az-43
llb	"	Az-40	Az-43

C. La Primavera

Heat sweep studies for the La Primavera field in FY87 were centered on the plans for the first 5-MW portable wellhead unit planned to be installed at well PR9 with reinjection into existing well PR2. The joint studies for this unit were published in the SGP 12th annual Workshop in January, 1987 [10]. During FY88, the joint project was adjusted to examine the effects of a second 5-MW unit to be installed concurrently with Unit 1. Steam for the two wells are expected to be supplied from three existing production wells, PR9, PR1, and PR8, as noted in Table 4. Both 5-MW Units are expected to be on-line in 1989-90. CFE plans to manifold production from the three production wells to operate the two units centrally, with combined reinjection to well PR2.

Table 4

Proposed Wells for the Manifold Steam Supply to the First *Two* 5-MW Units at La Primavera

Injection Well	Production Wells
	H-9
H-2	H-8
	H-1

Although the joint studies of reinjection recharge heat sweep for the La Primavera (and Los Humeros) initial generating-Unit wells are not formally part of the DOE-CFE Task 5.1 Reinjection joint study with the staff at Los Azufres and CFE Headquarters, the mutual benefit derived from these studies assists in the interpretation of the Los Azufres heat sweep data. The possibilities for thermal sweep or premature thermal breakthrough to one or more of the three production wells at La Primavera presents an interesting challenge for heat sweep analysis. Data for the new wells was assembled by the senior staff at La Primavera for the joint study. A composite three-dimensional cross section, shown in Figure 7, was prepared by Engr. Roberto Maciel of the La Primavera staff. The results of the expected cooldown at the three production wells were presented at the 1988 Geothermal Resources Council Annual Meeting (in English) [13], published in Geotermia (in Spanish) [14], and presented at the Ninth Convention of the Mexican Geological Society (in Spanish) [15].

During FY88, it was indicated that reinjection well PR2 may not have sufficient injection rate capacity to accept the total recharge fluid from the liquid leg of the separators and turbine condensate. Plans are underway to design a dedicated additional well solely for reinjection purposes (the first such well in Mexico). As a result, a modification of the flow regime will necessitate a re-analysis of the potential for premature cooldown, especially for the production well closest to the new planned injection well. It is planned to initiate heat sweep analysis joint studies for this case in the Winter, 1989 visit when plans for the additional reinjection well are firmed.

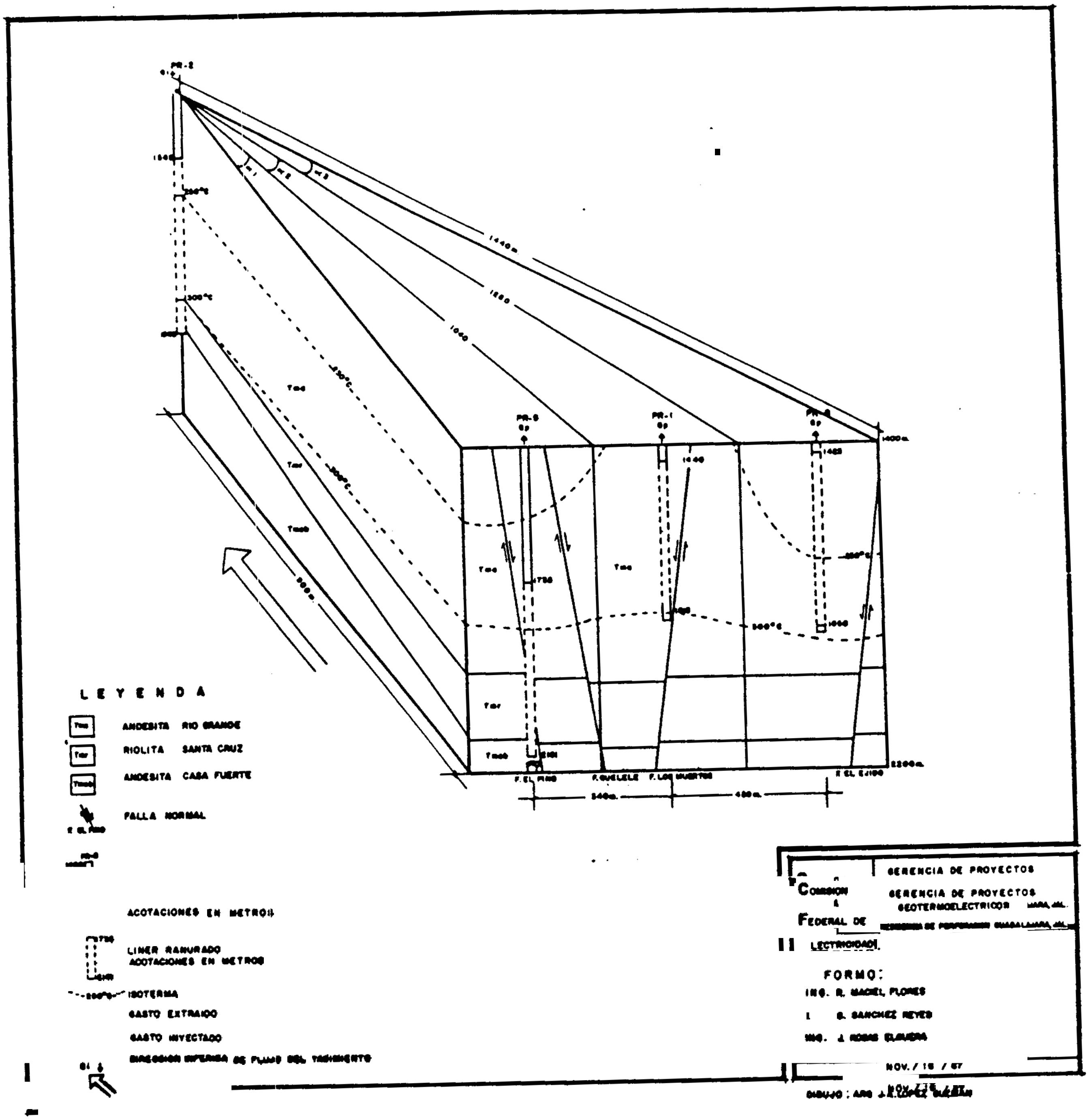


Figure 7. Three-dimensional cross section of the La Primavera ɔrs, field, showing the small-angle direct return flow sectors, the reinjection-production horizon and the estimated .ls initial temperature distribution for the production wells selected for the first two 5-MW portable generators.

SECTION 4. DOE-CFE LOS AZUFRES WELL STARTUP PROJECT

A. Startup Analysis of the First Five Years of Production in the Maritaro Zone Reservoir

The response of the Los Azufres geothermal field to the onset of continuous production from the original five wells to supply the five 5-MW wellhead units has been examined in previous annual reports. Publications were prepared after 2, 2.5, and 4 years of operation. The last report, with analysis of the first four years of production were, was given at the SGP 12th annual Workshop in January, 1987. The accumulation of the many production, chemical, and reservoir data has allowed a detailed examination of the effects of the cumulative production on the thermal drawdown of the reservoir. An important aspect of this analysis is the thermal history of the produced water, especially in the two-phase Maritaro zone, where geothermometer temperature data allows the estimation of reservoir specific volumes for the chemical components.

An interim evaluation after 4.5 years of operation with additional data acquired during the fifth year of operation continued the startup analysis. For example, well Az-5 exhibited a steadily increasing Na-K-Ca geotemperature water arriving at the wellhead with increasing fluid enthalpy, whereas well Az-13 in the same area exhibited an increasing Na-K-Ca geotemperature, but a deceasing mean enthalpy, which with the most recent data appears to be falling quite precipitously. The trends of these data are shown in Figure 8. The significance of this drop is under study and one possible reason for it is the closing of well Az-19 which previously exhibited a sharp drop in wellhead fluid temperature and enthalpy caused by an influx of cold water through a break in the casing. The need to analyze these phenomena before serious problems in the Maritaro zone results is quite apparent.

During FY88, the major effort on the joint study under Task 4.2 of the DOIE-CFE Geothermal Agreement was the compilation and analysis of the cumulative data from the first five years of continuous operation. In continuation of the joint study on thermal drawdown effects, the general objective remains to observe the thermodynamic changes in the reservoir and to evaluate the extent of changes observable by operation of small wellhead units in potentially large geothermal fields. Data for the first five years of production were accumulated in the form of chemical data for Na, K, Ca, Cl, and SiO_2. Production data include wellhead pressure P(wh), separator pressure P(sep), liquid flowrate Q(1), vapor flowrate Q(v), noncondensable gas flowrate Q(g), and wellhead enthalpy (H). From these data, calculated mean values are compiled for the Na-K-Ca and Si02 geothermometers and with the wellhead enthalpy the reservoir specific volumes are being estimated. For the Task 4.2 joint project, these calculations were the basis for analysis of the relationship between wellhead concentration and reservoir specific volume and the extent of hemispherical thermal drawdown for production wells acting as just-penetrating into a fully-fractured geothermal resource. A first draft [3] of the joint paper for the Final Symposium of the DOE-CFE Geothermal Agreement

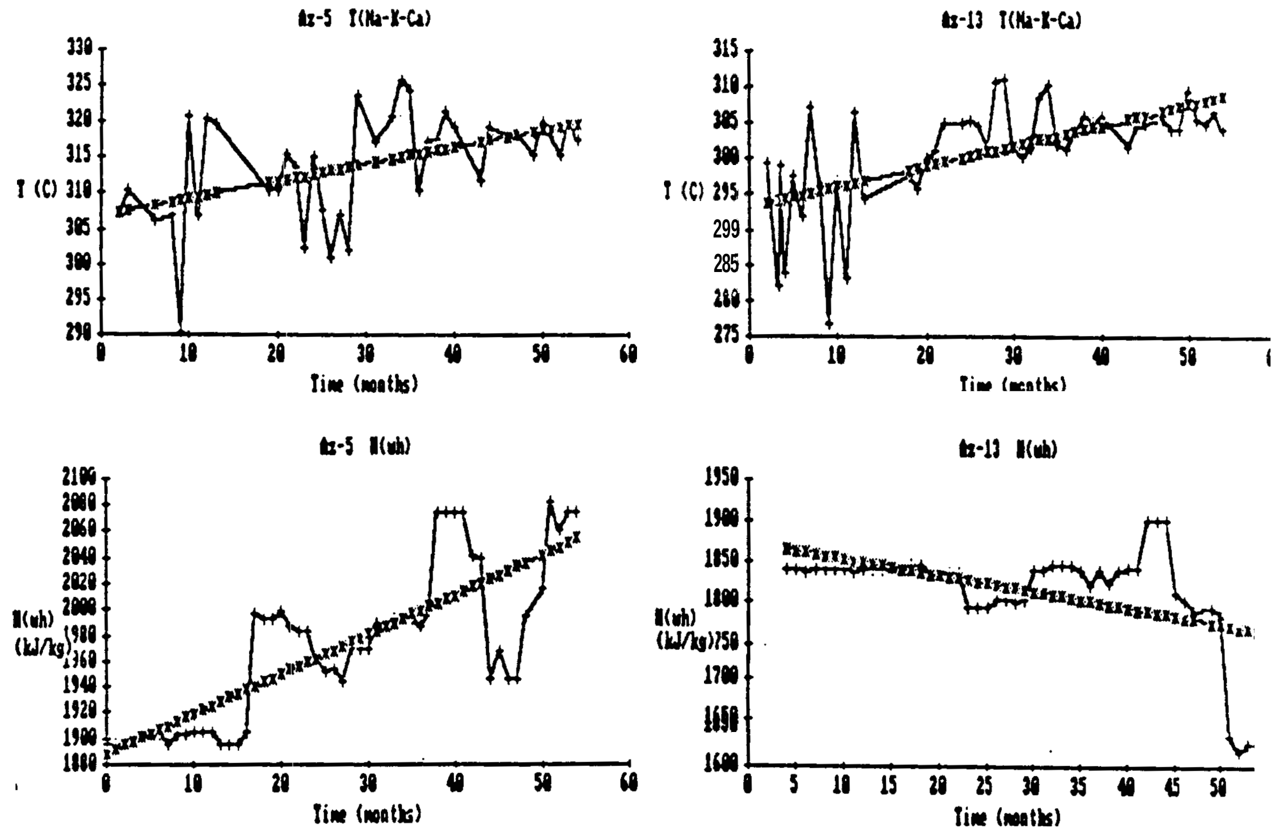


Figure 8. Monthly wellhead fluid temperature and enthalpy for the first five years of production at wells Az-5 and Az-13 with superimposed trend lines.

for April, 1989 was prepared and exchanged with the CFE co-authors.

B. Planning for the Renewed DOE-CFE Geothermal Agreement

During FY88, several planning sessions were held with the operating staff of the three neo-volcanic geothermal fields to develop start-up analysis programs for reservoir management objectives. A joint proposal was generated for each field individually for the DOE-CFE renewed Geothermal Agreement. The title of each joint study is Chemical Reservoir Engineering at the respective field and the co-principle investigators are listed below:

1. Los Humeros: P. Kruger (SGP)
P. Sanchez (CFE Gerencia)
M. Medina and J. Lopez (Los Humeros)

2. Los Azufres: P. Kruger (SGP)
P. Sanchez (CFE Gerencia)
J. Ortiz, M. Gallardo, and C. Miranda (LAz)

3. La Primavera P. Kruger (SGP)
P. Sanchez (CFE Gerencia)
R. Maciel, C. Lucio, and S. Villa (La Pr)

The general objectives of the two new fields, Los Humeros and La Primavera are to define an adequate brine sampling program and to initiate an evaluation of observable changes in chemical and physical parameters under steady production and to interpret the changes by statistical and flow models based on geothermometex and enthalpy analyses. The existing joint program at Los Azufres was amended to continue the startup analysis of the original wellhead unit wells and to add new startup analysis of the wells that will be receiving the new units expected in 1989.

A joint study was initiated in FY88 to examine the problems associated with the collection of brine samples at the discharge weir following pressure reduction and cooling at the silencer. The preparation of brine for reinjection in this manner results in four potential problems in measuring chemical concentrations and brine flow rates:

(1) reduction in pressure
(2) reduction in brine temperature
(3) loss of water due to flashing in the silencer
(4) introduction of atmospheric oxygen.

An experimental program was designed to examine the extent of these potential sources of error. The results will be published as a joint study by P. Kruger (SGP) and M. Gallardo (LAz): "Comparison of Sampling Locations for Chemical Analysis at the Los Azufres Geothermal Field" for publication and presentation at the 15th SGP Workshop at Stanford, and by Gallardo and Kruger: "Comparacion de Sitios de Mostrear para Analisis Chimica en el Campo de Los Azufres" in the CFE Journal, Geotermia, 1990.

SECTION 5. OTHER JOINT STUDIES

A. Heat Sweep Joint Study with MWD. New Zealand

Reinjection was proposed in 1987 as a solution at the mature Wairakei geothermal field where the power station's output has fallen significantly over the past few years. The New Zealand group comprising the Ministry of Electricity, the Ministry of Works and Development, and the Department of Scientific and Industrial Research embarked on a test program to redevelop the Wairakei geothermal field. The proposed reinjection program noted two significant benefits of reinjection; first, a solution to the waste disposal problem that has become acute during this period, and second, the prospect of repressuring the main Eastern Borefield to stimulate increased production. During the visit to Wairakei in FY87 it became clear that a third benefit might accrue from reinjection, namely secondary heat recovery by heat sweep of the repressuring recharge. Accordingly, a modest heat sweep analysis project was initiated to participate in the forthcoming 500 t/h reinjection test scheduled for early in FY88.

Based on the best assumed data compiled during the visit, a set of three case studies was completed, in which cooldown estimates have been made for linear and radial heat sweep from the injection site in the smaller western borefield to the edges and center of the main eastern borefield. Figure 9 shows the plan view of the injection and production borefields and the initial radial sweep geometry chosen to estimate the possible thermal breakthrough at three radii over a 21 degree recharge sweep covering the whole eastern borefield. These early estimates have been forwarded to the MWD for advance planning of the test. Plans were made to present the results of these and the first runs with the l-D Doublet Heat Sweep Model at the 10th New Zealand Geothermal Workshop in conjunction with the visit to Wairakei to revise the input data with the most recent group estimates of the test and reservoir parameters. In FY88, a reorganization in the new Electricorp resulted in a reduction in the scope of the reinjection test, and the measurement program was limited solely to project personnel. It is expected that the thermal data will be released at the conclusion of the test at which time a comparison of test results with forecasts made by the l-D Heat Sweep Model will be of interest in validating the model for thermal sweep in similar reservoir repressuring tests.

B. Heat Sweep Joint Study with LMI, Leninarad. USSR

During the Fulbright Lectureship visit to the Stanford Geothermal Program in the Spring Quarter of 1987, Prof. Yuri D. Dyadkin of the Leningrad Mining Institute offered the PE269 course in Geothermal Technology in which he reviewed the plans for geothermal energy development in the USSR. He published an article in the May, 1987 issue of the Geothermal Resources Council Bulletin [16] describing the initiation of two closed geothermal circulation systems in petrogeothermal areas as part of the USSR national program to provide hot water supplies to remote towns and villages. As a result of these exercises, a joint analysis was undertaken to examine the lifetime of hydrofractured reservoirs in providing large flowrates of 100+ C

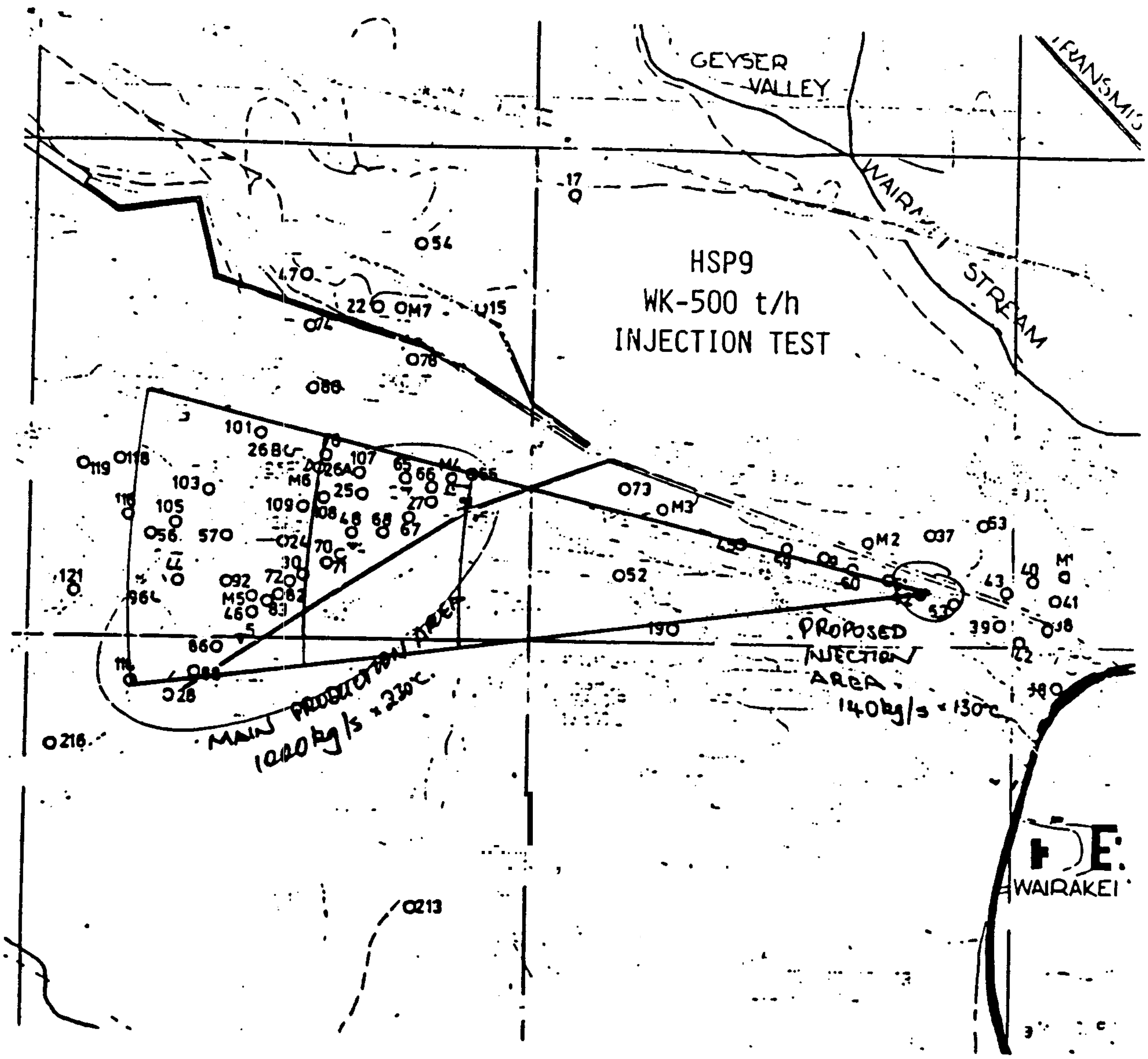


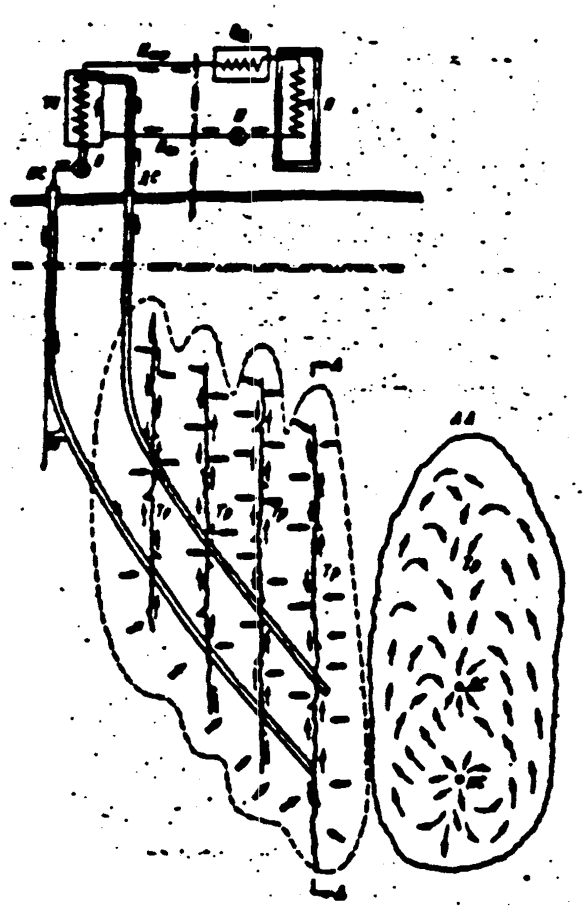
Figure 9. The Wairakei geothermal field showing the planned injection wells for 500 t/h injection test and the direct recharge return flow angle assumed for worst-case heat-sweep analysis of premature thermal breakthrough.

artificially circulated water to an abandonment temperature of 90-100 C with recharge water of 30 C. The case study for the hot water supply was a comparison of the calculations made with the LMI heat extraction model developed from basic principles of heat transfer from oblate slabs of parallel hydrofractured rock using heat transfer coefficients derived from simulations and regression analysis of Soviet oil and gas well experience and the SGP l-D heat sweep model using the same input data. The flow geometries for the two models are shown in Figure 10. The results were prepared as a joint paper for the Geothermal Resources Council Annual Conference in October, 1987 [17]. The agreement between the two model was very satisfactory.

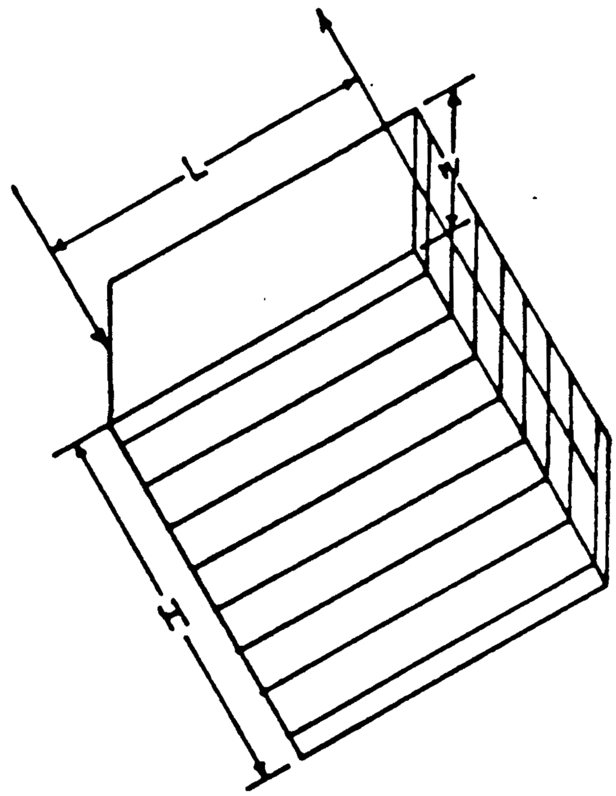
During FY88, communications continued with the Leningrad Mining Institute for the execution of a cooperative agreement with the Stanford Geothermal Program for joint efforts in low-temperature petrothermal resources noted by USSR authors to be abundant throughout the Soviet Union. Arrangements for a visit by the principal investigator of the Heat Extraction Project for two months was completed in FY88. The visit is expected to be in the Spring of 1989. One of the projects expected to be included in the joint study is the experimental hydrofractured resource in the Zakarpate Oblast in the Russkie Komarovtsy. A possible joint paper [18] on these studies was suggested to the Camborne School of Mines for their 1989 International Symposium of Hot, Dry Rock Technology.

C. Heat Sweep Joint Study with LANL, New Mexico

A similar comparative study was initiated during FY87 with B. Robinson of LANL to compare simple models for estimating cooldown history in the Fenton Hill hydrofractured Hot,Dry Rock reservoir for the phase 2 experiment of thermal drawdown. The LANL model is based on convolution of observed tracer response curves, for which a network of flow paths connected in parallel with a consistent set of fracture apertures and flowrates chosen for the measured tracer residence time distribution. Heat transfer within each path is calculated with a model similar to the SGP l-D Heat Sweep Model. The overall production fluid temperature is the mixed outlet temperature from the individual paths. A joint paper describing the analysis of the predicted heat transfer behavior in the current Phase II HDR reservoir at Fenton Hill by both models was given at the 13th annual SGP Geothermal Workshop in January, 1988 [2]. Sensitivity analysis is underway to identify the key parameters on the expected cooldown. The validity of the results will be tested during the 1-2 year heat extraction experiment scheduled to start in 1989-90.



(a)



(b)

Figure 10. Flow geometries for the LMI and The SGP heat sweep models.

SECTION 6. THERMAL STRESS ANALYSIS

The study of thermal stress effects on fractured rock thermal conductivity was continued during FY88. The thermal stress experiments, by Research Asst. Steven Lam, conducted in the large SGP physical reservoir model with a fractured rock loading of two cylindrical granite blocks were completed in FY87. The objective of these experiments was to determine the extent of changes in thermal conductivity of fractured reservoir rocks due to reinjection of cooled geothermal brines with subsequent sweep induced thermal stress cracking over the useful lifetime of the reservoir. The experiments consisted of thermally stressing the system (rocks, water, and pressure vessel) over three cycles of heatup, several intermittent partial cooldowns of the system, and a cold-water heat sweep, and at the end, a final long-term cooldown to room temperature. In each cycle, the heatup process was carried out very slowly and stops were made at various system temperatures to conduct thermal conductivity measurements using radial temperature gradients generated in the rock core with core axial heaters. Core cooldown tests were conducted at several system temperatures before the heat sweep process was initiated at an initial temperature of 232 C. After the three heat sweep cycles, the final system cooldown was initiated from a temperature of 221 C to 20 C.

The extensive physical measurement system of the SGP reservoir model was used to acquire recorded temperature data for each of the three thermal cycles, consisting of: (1) transient rock temperatures when the core axial heaters were turned on at the several system temperature levels; (2) steady-state rock temperatures with the axial heaters on and the cores at thermal equilibrium with the total system at each temperature level; (3) transient natural cooldown temperatures initiated intermittently during the system heatup process; and (4) transient cooldown temperatures during cold-water heat sweep cooling. System temperatures were also recorded for the complete system cooldown test. These temperature data are needed to derive rock thermal conductivity values for the pre- and post-sweep states and as a function of the number of sweeps.

The temperature data have been compiled and organized in FY88 for analysis with both steady and transient thermal models of the cylindrical rock blocks. Table 5 lists the several thermal models being used to interpret the experimental data from the three thermal stressing cycles and the final long-term natural cooldown test (LTCD).

Table 5
Thermal Models for Data Reduction of the Cylindrical Block Thermal Stress Experiments

	Process at Each Temperature Level			
Cycle No.	Heatup Transient	Heatup Steady-State	Cooldown Transient	Sweep Transient
1	1-D	1-D	2-D	2-D
2	1-D	1-D	2-D	2-D
3	1-D	1-D	2-D	2-D
LTCD	1-D		2-D	

REFERENCES

[1] Reservoir and Injection Technology: Geothermal Reservoir Engineering Research at Stanford, Third Annual Report, SGP-TR-114, Stanford University, February, 1988.

[2] Robinson, B.A. and P. Kruger, A Comparison of Two Heat Transfer Models for Estimating Thermal Drawdown in Hot Dry Rock Reservoirs, Proceedings, 13th SGP Geothermal Workshop, TR-113, 113-120, 1988.

[3] Kruger, P., P. Sanchez, and J. Ortiz, Startup Analysis of Wellhead Unit Production Wells, Proceedings, Final Symposium, DOE-CFE Geothermal Agreement, April, 1989.

[4] Kruger, P. and A. Aragon, Heat Sweep Analysis, Proceedinss, Final Symposium, DOE-CFE Geothermal Agreement, April, 1989.

[5] Hunsbedt, A., S. Lam, and P. Kruger, User's Manual for the 1D Linear Heat Sweep Model, Stanford University Technical Report No. SGP-TR-75, August, 1983 (in Revision).

[6] Lam, S. and P. Kruger, l-D Doublet Heat Sweep Model, Proceedinss, 9th New Zealand Geothermal Workshop, November, 1987.

[7] Lam, S. and P. Kruger, Doublet Heat Sweep Model with Bounded Initial Temperature Distribution, Proceedings, 14th SGP Geothermal Workshop, TR-120, January, 1989.

[8] Kruger, P., S. Lam, A. Hunsbedt, C. Esquer, R. Marquez, L. Hernandez, and J. Cobo, Analysis of Recharge Cooldown at the Western Boundary of Cerro Prieto I Geothermal Field, Proceedinss, 10th Workshop on Geothermal Reservoir Engineering, Stanford University Technical Report No. **SGP-TR-84**, 73-78, January, 1985.

[9] Kruger, P., The Role of Heat Sweep in Reinjection of Cooled Geothermal Fluids, Geotermia 4, No.1, 247-253, (1988).

[10] Kruger, P., S. Lam, R. Molinar, and A. Aragon, Heat Sweep Analysis of Thermal Breakthrough at Los Humeros and La Primavera Fields, Mexico, Proceedinss, 12th Workshop on Geothermal Reservoir Engineering, Stanford University Technical Report No. SGP-TR-109, 97-102, January, 1987.

[11] Aragon, A. and P. Kruger, Uso del Modelo de Barrido Termico en el Campo Geotermico de Los Humeros, Puebla, Geotermia 3, No.3, 263-273 (1987).

[12] Molinar, ,R., A. Aragon, P. Kruger, and S. Lam, One-Dimensional Heat Sweep and Fluid Mixing at the Los Azufres Geothermal Field, Proceedings, 8th New Zealand Geothermal Workshop, November, 1986.

[13] Kruger, P., A. Aragon, R. Maciel, C. Lucio, and S. Villa, Preproduction Simulation of Thermal Decline at the La Primavera First 5-MW Wellhead Units, Transactions, Geothermal Resources Council, **12, 475-480, (1988)**.

[14] Kruger, P., A. Aragon, R. Maciel, C. Lucio, and S. Villa, Simulacion de la Declinacion Termico Antes de la Produccion con Unidades de 5-MWe en el Campo Geotermico de La Primavera, Jalisco, Geotermia 4, **No.3, 195-210, (1988)**.

[15] Maciel, R., P. Kruger, A. Aragon, C. Lucio, and S. Villa, Estudio del Declinamiento Termico en el Yacimiento del Campo Geotermico de La Primavera, Usando Datos de Preproduccion, Proceedinss, IX Convention of the Mexican Geological Society, October, **1988**.

[16] Dyadkin, Yu., Engineering Problems and Possible Stages of Geothermal Resource Development in the Soviet Union, Geothermal Resources Council Bulletin, **3-8**, May, **1987**.

[17] Dyadkin, Yu. and P. Kruger, Estimates of Thermal Cooldown in Fractured Petrogeothermal Resources, Transactions, Geothermal Resources Council, October, **1987**.

[18] Dyadkin, Yu. and P. Kruger, Heat Extraction from Low-Temperature Fractured Petrothermal Resources, Proceedinss, International Conference on HDR Geothermal Energy, Cornwall, England, June, **1989** (in preparation).

Appendix A

(1) Reports and Publications Prepared in FY87-88

Aragon, A. and P. Kruger, Uso del Modelo de Barrido Termico en el Campo Geotermico de Los Humeros, Puebla, Geotermia 3, N0.3, 263-273 (1987).

Dyadkin, Y. and P. Kruger, Estimates of Thermal Cooldown in Fractured Petrogeothermal Resources, Transactions, Geothermal Resources Council, October, 1987.

Kruger, P., S. Lam, R. Molinar, and A. Aragon, Heat Sweep Analysis of Thermal Breakthrough at Los Humeros and La Primavera Fields, Mexico, Proceedinss, 12th Workshop on Geothermal Reservoir Engineering, Stanford University Technical Report No. SGP-TR-109, 97-102, January, 1987.

Kruger, P., J. Ortiz, C. Miranda, and M. Gallardo, Response of the Los Azufres Geothermal Field to Four Years of 25 MW Wellhead Generation, Proceedinss, 12th Workshop on Geothermal Reservoir Engineering, Stanford University Technical Report No. SGP-TR-109, 181-187, January, 1987.

Kruger, P., The Role of Heat Sweep in Reinjection of Cooled Geothermal Fluids, Geotermia 4, No.1, 247-253, (1988).

Kruger, P., A. Aragon, R. Maciel, C. Lucio, and S. Villa, Preproduction Simulation of Thermal Decline at the La Primavera First 5-MW Wellhead Units, Transactions, Geothermal Resources Council, 12, 475-480, (1988).

Kruger, P., A. Aragon, R. Maciel, C. Lucio, and S. Villa, Simulacion de la Declinacion Termico Antes de la Produccion con Unidades de 5MWe en el Campo Geotermico de La Primavera, Jalisco, **Geotermia 4**, No.3, 195-210, (1988).

Lam, S.T., The Effect of Heat-Sweep Induced Thermal Stress on Reservoir Rock Thermal Conductivity, Ph.D. Thesis, Stanford University, 1989 (in preparation).

Lam, S., A. Hunsbedt, P. Kruger, and K. Pruess, Analysis of the Stanford Geothermal Reservoir Model Experiment Using the LBL Reservoir Simulator, Geothermics 17, 595-605 (1988).

Lam, S. and P. Kruger, 1-D Doublet Heat Sweep Model, Proceedinqs, 9th New Zealand Geothermal Workshop, November, 1988.

Molinar, R.,,A. Aragon, P. Kruger, and S. Lam, One-Dimensional Heat Sweep and Fluid Mixing at the Los Azufres Geothermal Field, Proceedings, 8th New Zealand Geothermal Workshop, November, 1986.

Robinson, B.A. and P. Kruger, A Comparison of Two Heat Transfer Models for Estimating Thermal Drawdown in Hot Dry Rock Reservoirs, Proceedinus, 13th SGP Geothermal Workshop, TR-113, 113-120, 1988.

(2) Prior Background Reports and Publications

Hunsbedt, A., R. Iregui, P. Kruger, and A.L. London, Energy Recovery from Fracture-Simulated Geothermal Reservoirs, Proceedings, ASME/AIChE Heat Transfer Conference, Paper 79-HT-92, 1979.

Hunsbedt, A., S. Lam, and P. Kruger, User's Manual for the 1D Linear Heat Sweep Model, Stanford University Technical Report No. SGP-TR-75, August, 1983 (in Revision).

Hunsbedt, A., S. Lam, P. Kruger, and K. Pruess, Heat Extraction Modeling of the Stanford Reservoir Model, Proceedings, 8th Workshop on Geothermal Reservoir Engineering, Stanford University Technical Report No. SGP-TR-60, 255-260, December, 1982.

Kruger, P., Experimental Studies on Heat Extraction from Fractured Geothermal Reservoirs, in S. Nemat-Nasser, H. Abe, and S. Hirakawa, eds, Hydraulic Fracturing and Geothermal Energy, 373-397 (M. Nijhoff, The Hague, 1983).

Kruger, P., S. Lam, A. Hunsbedt, C. Esquer, R. Marquez, L. Hernandez, and J. Cobo, Analysis of Recharge Cooldown at the Western Boundary of Cerro Prieto I Geothermal Field, Proceedings, 10th Workshop on Geothermal Reservoir Engineering, Stanford University Technical Report No. SGP-TR-84, 73-78, January, 1985.

Kruger, P., L. Semprini, S. Verma, R. Barragan, R. Molinar, A. Aragon, J. Ortiz, C. Miranda, A. Garfias, and M. Gallardo, Initial Chemical and Reservoir Conditions at Los Azufres Wellhead Power Plant Startup, Proceedings, 10th Workshop on Geothermal Reservoir Engineering, Stanford University Technical Report No. SGP-TR-84, 219-226, January, 1985.

Kruger, P., L. Semprini, D. Nieva, S. Verma, R. Barragon, R. Molinar, A. Aragon, J. Ortiz, C. Miranda, A. Garfias, and M. Gallardo, Analysis of Reservoir Conditions during Production Startup at the Los Azufres Geothermal Field, Transactio —, Geothermal Resources Council 9, 527-532, August, 1985.

Kruger, P., Application of the SGP 1-D Linear Heat Sweep Model, Proceedings, 7th New Zealand Geothermal Workshop, 45-48, November, 1985.

Kuo, M.C.T., P. Kruger, and W.E. Brigham, Shape-Factor Correlations for Transient Heat Conduction from Irregular-Shaped Rock Fragments to Surrounding Fluid, Proceedings, AIChE-ASME Heat Transfer Conference, Paper 77-HT-54, 1977.