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HEAT EXTRACTION IN FRACTURED
HYDROTHERMAL RESERVOIRS

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PREFACE

The study of heat extraction from fractured rock blocks in geothermal resources has been an ongoing part of the Stanford Geothermal Program since its inception in 1972 under a grant from the National Science Foundation. The study continued under transfer of the NSF energy programs to the newly-formed Energy Research and Development Administration, and then under the evolving Department of Energy. The study continues under new contracts with DOE administered by the Idaho Operations Office.

The role of heat extraction from fractured geothermal rock blocks is of primary importance in the development of the United States' vast array of vapor-dominated, liquid-dominated, and hot dry rock geothermal resources. Heat extraction as a thermal process affects both the rate of and total thermal recovery from commercial reservoirs and the extent of secondary thermal recovery that can be obtained from prudent reinjection of cooled brines from the primary production of the geofluids. This Final Report describes the currently-completed efforts in the heat extraction program under DOE Contract 86-SF-16482.

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I. Overview

The main objective of the Heat Extraction Project has been the development of means to estimate the thermal behavior of geothermal fluids from fractured hydrothermal resources based on production of mixed reservoir fluids from heat sweep by reinjected brine and resource fluid cooled by drawdown and infiltrating waters. Several reports and publications, listed in the concluding section of this report, resulted from the application of the SGP heat sweep model to achieve this objective.

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 Hornos, and La Primavera fields in Mexico, for the 500 t/h reinjection test for the redevelopment program at Wairakei, New Zealand, for two hot water supply recirculation systems to be developed in the USSR, and for the phase 2 test at the Hot Dry Rock project at Fenton Hill, New Mexico. Advances were also made in the cooperative studies with CFE at Los Azufres on the evaluation of the effects of early operation of small wellhead generators on the reservoirs of potentially large geothermal fields.

During the contract period, accord was reached on the scope of the two joint studies under the DOE-CFE Geothermal Agreement. For Task 4, Reservoir Engineering, the joint study is on the startup analysis of the first five years of operation for the 5-MW portable generators in the Maritara 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 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.

Also during the contract period, 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 designed and completed. The analysis of these experiments and a description of the theory of thermal stress changes on thermal conductivity in fractured geothermal systems constitutes the Ph.D. dissertation of Research Assistant Stephen T. Lam.

II. Development of the 1-D Heat Sweep Model

The 1-D Heat Sweep Model was initially developed under the Heat Extraction Project as a tool for early analysis of the potential for secondary heat recovery and its concomitant risk of thermal breakthrough of reinjected cooled brines as recharge into geothermal reservoirs under steady production. The original model, for Linear Heat Sweep, was described in the User's Manual prepared by Hunsbedt, Lam, and Kruger in 1983. 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 Ph.D. 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.

During the contract period, the 1-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 difficulty 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 1-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 1 shows a plan view of the El Chino zone with the constrained radial sweep geometry superimposed. The application of the 1-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 were prepared for presentation at the 9th annual New Zealand Geothermal Workshop in November, 1987 in conjunction with a trip to work on the Wairakei 500 t/h reinjection test heat sweep analysis.

Figure 1. Plan view of the El Chino zone of the Los Azufres geothermal field with superimposed radial flow from injection well Az-3 to production well Az-9. (from Lam and Kruger, 1987)

III. Heat Sweep Joint Studies with CFE, Mexico

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. A list of studies under the cooperative arrangements is given in Table 1.

Table 1

SGP-CFE COOPERATIVE HEAT SWEEP PROJECTS

HSP No.	Field No.	Project Zone	Injection Wells	Production Wells
0	CPI	Cerro Prieto I	influx	western line
1	LAz1	w. Tejamaniles	Az-31	Az-26
2	LAz2	e. Tejamaniles	Az-8	Az-2
3	LAz3a,b	Maritaro	Az-15	eastern line
4	LAz4	Tejamaniles	(4)	Central (15)
5	LHu1	1st Wellhead	H-5	H1, H7
6	LaP1	1st Wellhead	PR-2	PR-9
7	LAz5b	n. Tejamaniles	Az-1	Az-22
8	LAz6b	Maritaro	Az-14	Az-4
10	LAz7	El Chino	Az-3	Az-9
11	LHu2	2nd Wellhead	H-4	H-16
12	LaP2	2nd Wellhead	PR-2	PR-1

Many 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 the Input Data to the model 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. The results of the earlier joint studies have been published in recent Symposia. Currently heat sweep studies are underway at three Mexican fields at Los Humeros, Los Azufres, and La Primavera.

1. Los Humeros

Joint project HSP5, as presented at the 12th annual SGP Workshop, was completed. The project examined the potential for reinjection recharge flow from recharge well H5 individually to the two production wells H7 and H1. During the year, the results of this study were also prepared as a technical article (in Spanish) for publication in the Mexican journal Geotermia.

The joint study is focused on reinjection heat sweep for the four new portable wellhead units expected in 1988. The wells being considered for these units are listed in Table 2.

Table 2

Wells for the First Wellhead Units at Los Humeros

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

2. Los Azufres

Several 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 early in FY87 were prepared for presentation 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 2 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.

The joint studies at Los Azufres were changed markedly during FY87 to 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 lake for cooling and silica deposition before reinjection. Therefore, the studies, revised to reflect the specific objectives outlined in the Task 5 joint study for heat sweep analysis in the Los Azufres field, should be useful in determining the optimum

Figure 2. Plan view of the Maritaro zone of the Los Azufres geothermal field showing the radial sweep flow from injection well Az-15 across the arc of new production wells towards the production wells in the east and the comparison of heat sweep calculations for assumed (unbounded) linear flow widths. (from Molinar et al., 1986)

reinjection time and temperature. Table 3 shows 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 were initiated during the year's visits for the Task 5 study.

Table 3

Task 5 Heat Sweep Joint Studies

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
6b	Maritaro	Az-15	Az-4
6c	"	Az-40	Az-4
8a	"	Az-15	Az-51
8b	"	Az-40	Az-51
9	"	Az-52	Az-42
10a	"	Az-15	Az-43
10b	"	Az-40	Az-43

3. La Primavera

Heat sweep studies for the La Primavera field have been centered on the plans for the first 5-MW portable wellhead unit to be installed at well PR9 with reinjection into well PR2. The joint studies for this unit were published in the SGP 12th annual Workshop in January, 1987. Currently, plans are to examine the effects of the second 5-MW unit to be installed concurrently with Unit 1, both units should be on-line in 1988. CFE plans to manifold production from three production wells to operate the two units centrally, with combined reinjection to well PR2. The possibilities for thermal sweep or premature thermal breakthrough to one or more of the three production wells presents an interesting challenge for heat sweep analysis. Data for the new wells are being assembled by the senior staff at La Primavera for the joint study. The wells involved at summarized in Table 4.

Table 4

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

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

Although the joint studies for the La Primavera and Los Humeros initial units heat sweep analyses are not formally part of the Task 5 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.

IV. Startup Analysis of the First Five Years of Production on 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 latest 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 the beginning 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.

Figure 3 shows the divergent behavior between two of the key wells in this zone after 4.5 years of operation with additional data acquired during the current (fifth) year. Well Az-5 exhibits a steadily increasing Na-K-Ca geotemperature water arriving at the wellhead with increasing fluid enthalpy, whereas well Az-13 in the same area exhibits an increasing Na-K-Ca geotemperature, but a decreasing mean enthalpy, which with the most recent data appears to be falling quite precipitously. 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 is quite apparent.

Figure 3. Comparative Na-K-Ca geothermometer and enthalpy data and regression lines for 4.5 years of flow for wells Az-5 and Az-13 in the Maritaro zone of the Los Azufres geothermal field. (not yet published)

During the project period, the focus of the project sharpened for the joint study under Task 4 of the DOE-CFE Geothermal Agreement. 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 are being accumulated in the form of chemical data for Na, K, Ca, Cl, and SiO₂. Production data include wellhead pressure P(wh), separator pressure P(sep), liquid flowrate Q(l), 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 SiO₂ geothermometers and with the wellhead enthalpy the reservoir specific volumes are being estimated. For the Task 4 joint project, these calculations are expected to further provide 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 well-fractured geothermal resource.

V. Heat Sweep Joint Study with MWD, New Zealand

Reinjection has been proposed 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 Electricity Corp, the Ministry of Works and Development, and the Department of Scientific and Industrial Research are embarking 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 have been 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 4 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 have been made to present the results of these and the first runs with the 1-D Doublet Heat Sweep Model at the 9th 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.

VI. Heat Sweep Joint Study with LMI, Leningrad, 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 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 water to an abandonment temperature of 90 °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 1-D heat sweep model using the same input data. The results were prepared as a joint paper for the Geothermal Resources Council Annual Conference in October, 1987. The agreement between the two model was very satisfactory and it is anticipated that the cooperative efforts will continue to improve the analysis by both models.

Figure 4. Plan view of the Wairakei geothermal field showing the proposed injection zone (wells WK 61, 62, 63) and the main production area in the western borefield with superimposed radial geometry for estimating thermal breakthrough at three radii. (not yet published)

VII. 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 1-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 is under preparation for the 13th annual SGP Geothermal Workshop in January, 1988. 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 1988 or 1989.

VIII. Thermal Stress Effects on Fractured Rock Thermal Conductivity

During the contract period, the experimental phases of the study of the effects of cold-water reinjection heat sweep induced thermal stresses on the thermal conductivity of fractured reservoir rock blocks were completed. The extensive data collected are being analyzed to determine reliably measured rock thermal conductivity values and associated stress levels.

The objective of these experiments is to determine the extent of change in hydrothermal reservoir rock thermal conductivity as a result of thermal energy sweep production. The rock thermal conductivity is a critical parameter which effects reservoir thermal capacity and heat extraction rates, and thus, the produced fluid temperature and reservoir lifetime. Significant changes in thermal properties due to heat sweep needs to be accounted for in geothermal reservoir simulations.

The thermal stressing experiments were conducted in the SGP physical reservoir model with a rock loading of two right cylindrical granite blocks, both 7 inches in diameter and 21 inches long. Each block was instrumented with 11 thermocouples strategically arranged at three cross-sectional levels as shown in Figure 5. An axial core heater with temperature monitor and power control was provided to generate measurable radial temperature gradients in each block. The recorded mid-plane temperatures of the blocks were used primarily to derive rock thermal conductivity. The water and vessel shell temperatures were also monitored during the experiments for rock surrounding thermal analysis which will provide input boundary conditions for block thermal stress analysis.

The experimental procedure included three complete cycles of system heatup and thermal sweeps, and one cooldown test. A series of steady-state temperature measurements was made for each cycle during the heatup at various temperature levels ranging from 60 °F to 460 °F (subcooled), and also throughout the heat sweep transient. Both sets of data are used to derive rock thermal conductivity for pre- and post-sweep states. The experimental and analytical results should confirm the extent of changes in reservoir rock thermal conductivity over the useful lifetime of a fractured hydrothermal reservoir operated with sweep reinjection.

Figure 5. Schematic diagram of the double rock heating and cooling thermal stressing experiments in the SGP large geothermal physical model showing the location of the many thermocouples used to estimate the extent of changes in thermal conductivity.

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