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# ANALYSIS OF RECHARGE COOLDOWN AT THE WESTERN BOUNDARY OF CERRO PRIETO I GEOTHERMAL FIELD

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## INTRODUCTION

Extensive study of the Cerro Prieto geothermal' field has provided much geologic and thermodynamic data of its structurally-complex, liquid-dominated reservoir. Several of the studies investigated the resource characteristics of fluid and energy flow. An early report by Mercado (1975) showed that the heat source for the part of the reservoir under development, now called Cerro Prieto I (CPI), originated in the eastern part of the field. Subsequent studies confirmed the flow of hot water from the east. A summary of several experimental and numerical studies of fluid and energy transport in the field was given by Lippmann and Bodvarsson (1983).

The hydrogeologic model of Halfman et al. (1982) shows hot-water flow from the east divided into a shallow (alpha) aquifer at about 1200m and a deeper (beta) aquifer at about 1700m depth. A cross section along an east-west direction shows a central upflow to the two aquifers and uncertain geology beyond the western border of the field near well M-9. It also shows a fault dividing the line of border wells at M-29 from the inner wells at M-25 to the east.

The hydrogeology of the field was described by Sánchez and de la Peña (1981) as an alluvial unit from the surface to about 700 m over the production zone and a shale-sandstone unit comprising an upper, shallow (alpha) aquifer bounded below by a basement horst overlying a deeper (beta) aquifer. To date, much of the cumulative production at Cerro Prieto I has been from the alpha aquifer. Piezometric level measurements over the first 5 years of operation showed a decline in the western zone beyond the production wells.

Over the 10-year period of continuous production, a significant temperature decline has been observed along the westernmost line of wells. Several investigations of the recharge characteristics of the field have been reported. Mercado (1975) and Elders et al. (1984) indicated a flow of cold groundwater from the east. Mercado also noted that cold water was entering the reservoir from the west. In studying the expectations of field deliverability, reservoir life, and ultimate recovery of the resource, Castañeda et al. (1983) from a reservoir simulation model indicated a major degree of cold-water recharge into CPI from the west and north sides of the field. From reported chemical and thermal changes with production, Grant and O'Sullivan (1982) considered the reservoir as a leaky aquifer rather than confined, and attributed one quarter to one half of the recharge to percolation of fresh water from cooler rocks above the reservoir. From the accumulated chemical and production database, Grant, Truesdell, and Mañon (1984) suggested that the western part of the alpha aquifer was essentially unbounded and that mixing with colder water by dilution rather than by boiling is the reservoir's response to continued extraction. They suggested that local boiling occurs in most of the wells as pressure decreases but that no general vapor zone has developed.

It should be possible to estimate the cooldown history at the western border of the field. The problem of cold water recharge intrusion into the western part of the Cerro Prieto I field is of economic importance by assuming that the upper alpha aquifer at Cerro Prieto I represents a one-time source of thermal energy extractable by cold water recharge from the infiltration zone through the western surrounding formation to the westernmost line of wells. Hunsbedt, Lam, and Kruger (1983) described a 1-D linear heat sweep model for estimating energy recovery from fractured hydrothermal reservoirs based on early estimates of geological, and thermodynamic properties of the formation.

The model was designed to calculate water and rock matrix temperature distributions as functions of distance from injection site and production duration. It takes into account the temperature gradient inside large rock masses produced by long path lengths for heat conduction and small values of rock thermal conductivity when cold water flaws along the rock surfaces. The model is based on input estimates of volumetric distribution of rock blocks (e.g., mean fracture spacing) and rock heat transfer properties (Iregui, et al., 1979). The major parameters of the model are the "number of heat transfer units" and the initial distribution of the energy stored in the fluid and rock media. The "number of heat transfer units" parameter is defined as the ratio of estimated fluid residence time and the thermal response time constant for the rock block (a function of rock size and shape, thermal diffusivity, and Biot number). As the most significant parameter in the 1-D heat sweep model, it indicates the degree to which energy extraction from the reservoir is rock-heat-transfer limited or water-supply limited.

This paper presents the results of a study to evaluate the effects of cold-water recharge from the west on the long-term production characteristics of the western border wells using two 1-D sweep models. One model assumes no vertical leakage through the overlying formation and the other model assumes significant leakage from above.

## HYPOTHETICAL HEAT SWEEP OF CPI WESTERN OUTER ZONE

To evaluate the potential of the model for application to the study of cold water recharge intrusion at Cerro Prieto I, a hypothetical linear heat sweep calculation was made of the zone west of the reservoir. A significant economic parameter is the time when the temperature of the produced geofluid drops below 250°C, resulting in an inefficient heat rate for the power plants. The hypothetical study was focused to estimate this parameter. The basic premise in the study was that all of the water extracted through the westernmost line of wells at CPI originated in the western outer zone. This premise is supported somewhat by assuming that fault "L", located by Halfman et al. (1982) between wells M-29 and M-25 acts as a barrier to hot water flow from the center of the field.

The geometry of the western outer zone was estimated from published information. For the hypothetical study, it was chosen as a horizontal rectangular formation, bounded on the west by the Cerro Prieto fault zone just east of well M-6 (whose data provided the recharge water inflow temperature), on the east by fault "L" described by Balfman et al. (1982), a block width spanning the distance between wells M-43 to the north and M-35 to the south, and a uniform thickness of sandstone from wells M-6 to M-29, estimated from the published cross section of Halfman et al. (1982). The geometric, reservoir, and sandstone thermophysical data used in the model are given in Table 1.

Analysis of the heat extraction potential was made with three key input parameters: (1) the initial formation temperature, (2) the effective radius of the mean rock sizes in contact with the flowing recharge water, and (3) the effective porosity of the formation determining the mean residence time to the line of wells at the western boundary, based on production data for the 1982-83 total flow rates. Heat transfer to and from the surrounding formation by conduction was considered negligible, and for the 1-D sweep model without leakage, the upper and lower formations were considered impermeable.

The results of the calculations for the 1-D sweep model without leakage are given in Table 2. They show that the western outer zone contains a significant storage of thermal energy and with the premise that all energy production at the western line of wells is from cold-water recharge sweep, productiou at 485 t/h could continue for 20 to 50 years before cooldown to 250°C, depending on the actual distribution of the three parameters modeled. The results were sufficiently encouraging to undertake a detailed study of the observed cooldown at the western border of the Cerro Prieto I field.

## OBSERVED COOLDOWN HISTORY

To estimate how realistic the agsumptions of linear recharge sweep were, the large database of chemical and production data for the western line of wells was analyzed to obtain an "observed" cooldown history over the total production period of CPI. This history was compared to the "observed" cooldown observed in the neighboring inner line of wells on the other side of the "L" fault. The wells selected for the two lines, from north to south, were M-43, M-29, M-30, and M-35 for the border wells and M-11, M-19A, M-25, M-31, and M-26 for the inner wells. For each of these wells, available data were compiled in six-month averaged values for: (1) wellhead pressure; (2) liquid and steam flowrates; (3) wellhead enthalpy; and (4) chemical components Na, K, Ca, Mg, $SiO_2$, and Cl. The chloride values were used to delete suspicious values of the geothermometer components.

From these data the six-month averaged values were calculated for: (1) wellhead temperature and steam fraction; (2) bottom-hole temperature and steam fraction with the CFE wellbore simulator adapted from Orkiszewski (1967) which computes the pressure loss for two-phase flow in vertical pipes; and (3) reservoir temperatures, estimated by (i) constant enthalpy transport based on the geofluid in the reservoir being all liquid; (ii) Na-K-Ca geothermometers of (a) Mañon et al. (1978) (b) Fournier and Truesdell (1973), and (c) Nieva and Nieva (1982); and (iii) $SiO_2$ geothermometer of Fournier and Potter (1982).

The temperature cooldown histories of the two lines of wells are shown in Figure 1. A summary of the linear and exponential regression of the data is given in Table 3. The wellhead pressures of the border wells were kept reasonably constant at a saturation temperature of about 176°C with a correspond-

## Table 1

INPUT DATA FOR CPI HYPOTHETICAL 1-D HEAT SWEEP ANALYSIS

| | | |
|---|---|---|
| **Reservoir Geometry** | | |
| Length | | L = 1200m |
| Cross sectional area | | S = $4\times10^5$ $m^2$ |
| Porosity | | $\phi$ = 0.05 to 0.30 |
| Mean fracture spacing | | MFS = 10 to 200m |
| **Reservoir Conditions** | | |
| Initial temperature | | $T_1$ = 250 to 300°C |
| Sweep water temperature | | $T_{in}$ = 150°C |
| Production/recharge rate ('82-'83) | | Q = $4.85\times10^5$ kg/h |
| Heat transfer coefficient | | h = 1703 $W/m^2K$ |
| External heat transfer | | q' = 0 kJ/m |
| **Physical Properties** | Sandstone | Water |
| Density ($kg/m^3$) | $\rho_r$ = 2300 | $\rho_f$ = 1000 |
| Specific heat (kJ/kgK) | $C_r$ = 0.92 | $C_f$ = 4.18 |
| Thermal conductivity (W/mK) | k = 1.73 | — |

## Table 2

RESULTS OF CPI HYPOTHETICAL 1-D HEAT SWEEP
PRODUCTION OF 485 t/h FROM RECHARGE SWEEP AT 150°C

1. Variation with Initial Reservoir Temperature*

| $T_1$ (°C) | No. Heat Xfer Units | Breakthru Time to 250°C (yr) |
|---|---|---|
| 250 | 3.4 | 24.9 |
| 270 | 3.4 | 43.9 |
| 300 | 3.4 | 54.2 |

*MFS = 100m; $\phi$ = 0.20

2. Variation with Mean Fracture Spacing**

| MFS (m) | No. Heat Xfer Units | Breakthru Time to 250°C (yr) |
|---|---|---|
| 10 | 341 | 56.5 |
| 50 | 13.6 | 54.0 |
| 100 | 3.4 | 43.9 |
| 200 | 0.85 | 25.4 |

**$T_1$ = 270°C; $\phi$ = 0.20

3. Variation with Porosity (flow residence time)***

| $\phi$ (%) | No. Heat Xfrr Units | Breakthru Time to 250°C (yr) |
|---|---|---|
| 10 | 1.7 | 36.8 |
| 20 | 3.4 | 43.9 |
| 30 | 5.1 | 49.2 |

***MFS = 100m; $T_1$ = 270°C

## Table 3

TEMPERATURE COOLDOWN ANALYSIS

| | Border Wells† | | | | Inner Wells†† | | | |
|---|---|---|---|---|---|---|---|---|
| | $T_1$ (°C) | LCDR* (°C/y) | A** ($y^{-1}$) | $r^2$ | $T_1$ (°C) | LCDR (°C/y) | A ($y^{-1}$) | $r^2$ |
| Wellhead | 176 | -0.3 | -0.002 | 0.28 | 186 | -0.45 | -0.003 | 0.06 |
| Bottom hole | 270 | -3.0 | -0.012 | 0.99 | 271 | -1.57 | -0.006 | 0.63 |
| Reservoir | 295 | -2.3 | -0.008 | 0.92 | 293 | -1.0 | -0.003 | 0.69 |

† M43, M29, M30, M35
* linear cooldown rate

†† M11, M19A, M25, M31, pU6
** exponential cooldown constant

ing linear temperature cooldown rate of -0.3°C/yr. Fluctuations in production of the inner lines of wells were much greater, due to changes in discharge orifice diameter in response to sand production problems. The result appears to be a more variable temperature history. The linear regression with low correlation coefficient, $r^2$, shows saturation temperature of about 186°C with a corresponding cooldown rate of -0.45°C/yr.

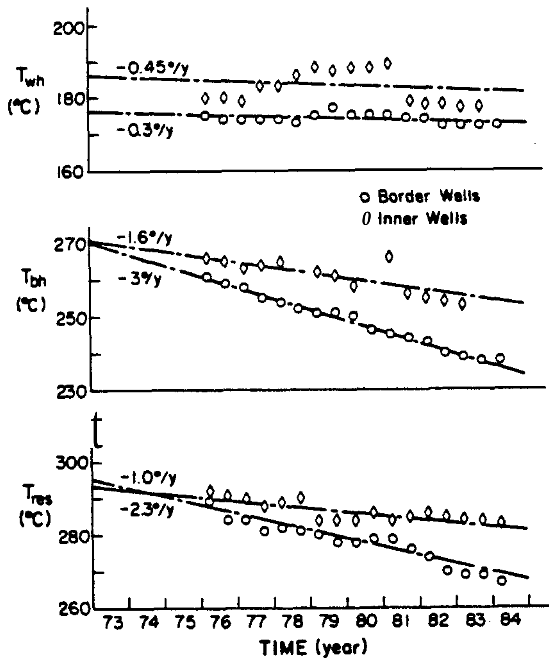


Figure 1 CPI observed wellhead, bottom-hole, and reservoir temperature histories.

The bottom-hole data for the two lines of wells show more stable conditions. Regression of the two sets of temperature cooldown data shows a common initial bottom-hole temperature of about 270°C, with a steam fraction growing steadily from about 8.8 percent in 1976 to about 10.5 percent in 1984. The mean growth rate of the steam fraction near the wellbores since commencement of sustained production is about 0.2%/yr. The bottom-hole cooldown rate in the border line of wells is about two times that of the inner line of wells. The corresponding trend in wellhead enthalpy from an initial value of 1317 kJ/kg decreases at a rate of -0.8%/yr for the border line of wells, compared to 1313 kJ/kg and -0.2%/yr respectively for the inner line of wells.

The reservoir temperatures calculated from an average of the constant enthalpy and Na-K-Ca geothermometer values show a common initial reservoir temperature of about 295°C. The linear cooldown rate for the line of border wells of -2.3°C/yr is decidedly steeper than the corresponding value for the line of inner wells of -1.0°C/yr. The data show clearly the more rapid cooldown at the border line of wells, but also the significant cooldown that has occurred at the inner line of wells.

The results of this analysis of the production and chemical data for the 11 years of steady operation suggest that multiple processes are responsible for the difference in cooldown rates from a common pre-production reservoir temperature. These may include cold-water intrusion from the western outer zone to the line of border wells, vertical cold-water percolation from above to both lines of wells, hot-water flow from the east to the inner line, and hot-water and natural groundwater flow from below to both lines of wells. The l-D linear heat sweep model has been revised to examine the role of distributed cold-water percolation from above.

## SWEEP-RECHARGE HEAT SWEEP OF CPI

Modification of the 1-D linear heat sweep model included a uniformly distributed source of cold water percolation from above, along the entire sweep path, and testing of the inversion of Laplace transformed governing equations by two alternate numerical algorithms. Vertical recharge was assumed to occur at a uniform rate, constant temperature, and insignificant vertical momentum. The recharge fluid was further assumed to mix rapidly with the horizontal sweep flow across the thickness of the semi-condined aquifer zone. At the production horiaon, adiabatic mixing occurs with the heated water recharge from the eastern source of the reservoir at the observed exponential-falling temperature of the inner line of wells. A schematic drawing of the flow geometry is given in Figure 2.

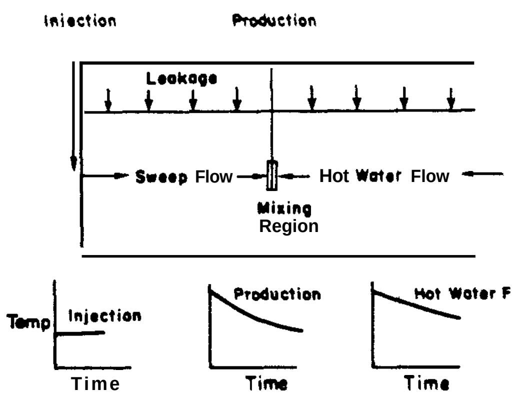


Figure 2 Schematic of the 1-D linear heat sweep model for CPI analysis.

In the sweep-recharge heat sweep process of the CPI western zone, the major parameters iacluded the percolation rate, the sweep rate, the hot-water influx, the percolation fluid temperature, and the mean fracture spacing. The parameters were systematically varied to investigate their influence on matching the simulated cooldovn history of the border line of wells with the corresponding observed cooldovn history over the 1973 to 1984 production period.

The 1-D grid imposed on the sweep zone assumes a rectangular slab geometry based on the geological analysis of Cobo. His data fixed the slab geometry as a thickness of 800 m from the bottom of a 500 m thick leaky upper cap to 1300 m at the bottom hole horizon of the production vells, a mean porosity of 18% with 45% of the formation as permeable sandstones, a path length of 1900 m from recharge to production wells, and 1000 m across the N-S line of wells normal to the flow path. The percolating recharge water temperature vas estimated by Castañeda et al. (1983) as 52°C. A summary of the input parameters to the sweep-recharge analysis is given in Table 4.

The solution of the 1-D sweep model's governing equations are based on conversion into Laplace space and the use of a numerical inversion procedure to obtain the calculated cooldown history. Prior experience with the stochastic Gaver-Stehfest algorithm (Gaver, 1966; Stehfest, 1970a.b) shoved numerical overshoot at the temperature breakthrough and tail portions of the cooldown curve. Two other numerical inversion algorithms were tested for this analysis: The Piessens-Branders algorithm (Piessens and Branders, 1971; Piessens, 1984) using generalized Laguerre polynomials and the Crump algorithm (Crump, 1976; IMSL, 1982) using Fourier series approximations. A comparison of these inversion procedures as applied to thermal sweep problems is undervay by Lam (1985).

Figure 3 shows the production temperature cooldovn simulated with the three algorithms using the same input parameters in comparison to the observed cooldovn for a period of 60 years. In this simulation, the mean residence time is 39.2 years. The results of the matched simulated and observed cooldovn curves were achieved for the distribution of component flows given in Table 5

## CONCLUSIONS

The western zone of CPI has been successfully modeled by a simple linear heat sweep model combining flows from horizontal *sweep* from an injection source near westernmost well M-6 at its observed formation temperature, uniform percolation recharge water from above at its estimated groundwater temperature, and geothermal resource fluid from the east at its observed temperature history. Three numerical inversion algorithms applied to the Laplace transformed equations of the simulation give essentially the same cooldovn history match to the observed cooldown. Extrapolation of the matched cooldown curve indicates that the fluid temperature on continuous production of the border line of wells would decrease to 250°C in approximately 52 years, indicating a substantial reservoir of available heat in the western zone of the field. The match of calculated and simulated cooldowns vas optimized to component flows of about 51±2 percent from westward sweep, 41±2 percent from percolation from above, in accord with the estimates of Grant and O'Sullivan (1982), and only 8±4 percent from the geothermal resource from the east cooling at its observed rate.

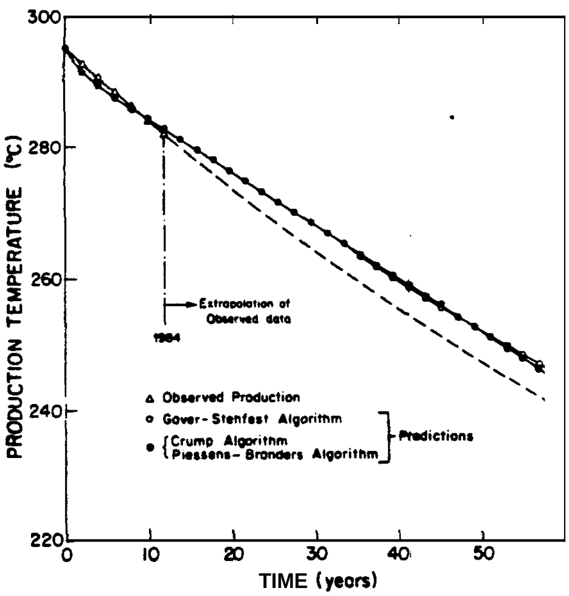


Figure 3. Comparison of simulated and observed production temperature cooldown.

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Table 4

INPUT DATA FOR CPI SWEEP RECHARGE ANALYSIS

| | | |
|---|---|---|
| **Reservoir Geometry** | | |
| Length | | $L = 1900 m$ |
| Cross sectional area | | $S = 3.6 \times 10^5 m^2$ |
| Porosity | | $\phi = 0.18$ |
| Mean fracture spacing | | MFS = 100 m |
| **Reservoir Conditions** | | |
| Initial temperature | | $T_1 = 295°C$ |
| Sweep water temperature | | $T_{in} = 150°C$ |
| Recharge water temperature | | $T_p = 52°C$ |
| Production rate ('82-'83) | | $Q = 4.85 \times 10^5$ kg/h |
| Heat transfer coefficient | | $h = 1703 W/m^2K$ |
| External heat transfer | | $q' = 0$ kJ/m |
| **Physical Properties** | Sandstone | Water |
| Density ($kg/m^3$) | $\rho_r = 2380$ | $\rho_f = 921$ |
| Specific heat (kJ/kgK) | $C_r = 0.92$ | $C_f = 4.87$ |
| Thermal conductivity (W/mK) | $k = 2.40$ | -- |

Table 5

RESULTS OF COOLDOWN HISTORY MATCH

| Component | Input Temperature (°C) | Matched Flowrate (kg/s) | Estimated Contribution (%) |
|---|---|---|---|
| Percolation | 52 | 55.2 | 41±2 |
| Sweep | 150 | 68.7 | 51±2 |
| Hot Water | $T_{in}+\Delta T e^{-\lambda t}$ (see Table 3) | 10.8 | 8±4 |