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APPLICATION OF A LUMPED PARAMETER MODEL TO THE CERRO PRIETO GEOTHERMAL FIELD

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Abstract In this paper, a lumped parameter mathematical model for hot water geothermal reservoirs is developed and applied to the Cerro Prieto geothermal field in Mexico.

The production and pressure histories of Cerro Prieto were assembled from field data. A computer program was then used to perform sensitivity studies on reservoir size, porosity, aquifer recharge, and temperature of recharge fluid. Two types of depletion schemes were investigated; in the first, the reservoir remains essentially one-phase liquid, and in the second, the reservoir becomes two-phase at a point early in its history. A satisfactory match of the history of the field has been obtained. This paper shows the usefulness of a lumped parameter model in clarifying the basic behavior of a hot water geothermal system and in giving focus to more complex two- and three-dimensional modeling efforts. The results obtained specifically for the Cerro Prieto field will also be of value to the scientists and engineers studying this reservoir.

Introduction Typically, a geothermal power plant must have a lifetime of thirty years to be economic. Because of the large increments of investment necessary at each successive stage of development, it is especially important to be able to forecast the future performance of a field from existing knowledge. Geothermal reservoir models attempt to serve this predictive function. In the beginning of the life of a field, when relatively little is known, the simplest models, which require the least amount of information, are appropriate. Later, as more information is accumulated about the geologic, geochemical, hydrodynamic, and thermodynamic characteristics of the field, these models may be refined and a better understanding of the resource achieved. One of the simplest types of mathematical models is the so-called "lumped parameter" model. The purpose of this kind of simulator is to match average reservoir behavior. The reservoir is treated as a homogeneous body, whose characteristics change as quantities of mass and energy enter and exit. The value of a particular parameter throughout the model reservoir is the average value of that parameter in the real system.

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In this paper, a lumped parameter approach to geothermal modeling is investigated. The amount of data required is minimal compared to finite-difference models. The Cerro Prieto geothermal field in Mexico was the subject of the modeling study; the lumped parameter model is most appropriate here since the field is still "young," having entered its eighth year of commercial production.

Some examples of lumped parameter models can be found in the literature. Whiting and Ramey (8) first used this concept in 1969 to model the Wairakei reservoir in New Zealand. Brigham and Morrow (2) in 1974 developed three models appropriate for closed, vapor-dominated reservoirs. In 1979 Brigham and Neri (3) modeled the Gabbro zone of the Larderello field. Castanier, Sanyal, and Brigham *(4)* included heat transfer in the recharge region to simulate the behavior of the East Mesa reservoir.

To date, there have been no lumped parameter studies of the Cerro Prieto field similar to those reviewed above. However, a few preliminary simulation efforts have been made. In 1978, Lippmann, Bodvarsson, et al. (6), formulated a simplified three-dimensional, finite-difference model of the reservoir. In 1979, Lippmann and Goyal presented the results of two three-dimensional, finite-difference, hydrogeologic models of Cerro Prieto (7). Liguori (5) in 1979 used a simplified finite-difference reservoir model coupled to a wellbore model.

The Cerro Prieto Field The Cerro Prieto field is located about 30 km south of Mexicali, Mexico. This study is concerned with modeling the area of the field shown in Fig. 1, which supplies Units 1 and 2 and which has been in production since 1973. The wells have a perforated interval of 100-200 m at an average depth of 1200-1300 m. However, because of the complex interbedding, it is not obvious what the thickness of the reservoir is in this area. Porosity ranges from .15 to .35 in sand or sandstone, but is lower in shales. Various estimates of the permeabilities range from 40 to 100 md. The temperature of most wells in the Unit 1 and 2 area is about 300°C. Non-condensable gases, predominantly CO_2 and H_2S, are present in sufficient quantity to affect both the compressibility and the phase behavior.

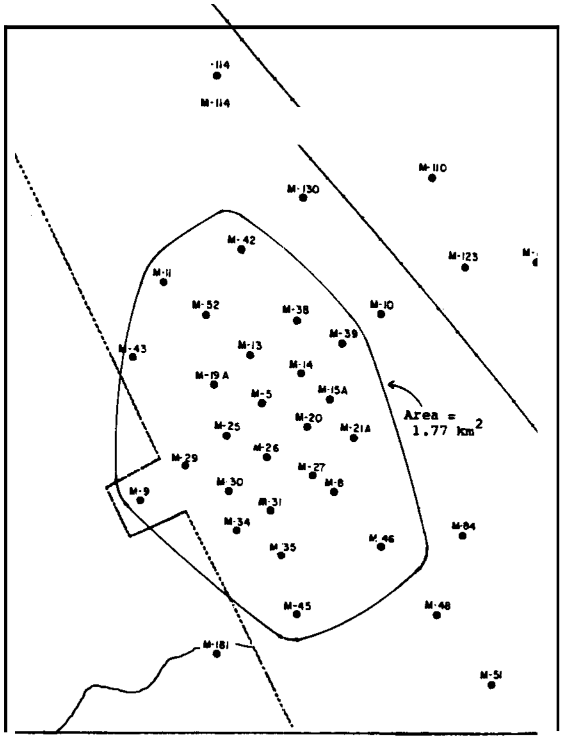

Fig. 1: The Units 1 and 2 Production Area

In the lumped parameter model, reservoir and fluid properties are considered to be uniform throughout. During a time step, quantities of mass and heat enter and exit, changing the reservoir from its initial state to its final state. The model in this paper neglects conductive heat transfer and convective movement of mass and heat across reservoir boundaries. For a complete description of the model, please see references *4* and 8.

Data Analysis Modeling requires two general types of data: field properties and field history. Some field properties such as reservoir area, rock matrix compressibility, density and heat capacity are known well. Others, such as thickness, porosity, and fluid compressibility of the production zone as well as geometry, permeability, and temperature of the recharge aquifer are not known accurately.

The history of reservoir behavior is deduced from logging, geochemical, and well production data. The model requires the history of mass flowrate, specific enthalpy of produced fluid, average reservoir pressure, and average reservoir temperature.

The history of average pressure in the production zone was developed from a set of isobaric maps which were presented by Bermejo, et al. (1) Using the four maps in their paper, the average pressure was determined in the production zone during 1973, 1975, 1977, and 1979. These four points are the basis for the curve of observed pressure history which is drawn for reference in Fig. 2.

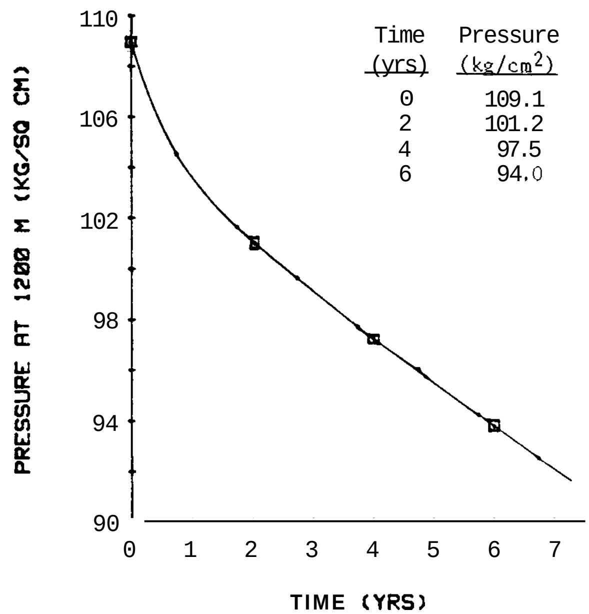

Fig. 2: History of Average Field Pressure

The initial temperature in the production zone is calculated from the enthalpies of the producing wells in 1973. The enthalpy should correspond to that of liquid water because the steep decline in pressure during this period indicates that the reservoir fluid was essentially one-phase liquid. After neglecting the cold wells M-9, M-34, and M-39, and M-29 because they were producing from a cold shallow zone during this time, the average liquid enthalpy was calculated to be 316 kcal/kg. This enthalpy corresponds to an initial temperature of 296°C. It is generally believed that the temperature has declined steadily at a rate of 1-3°C per year to about 285°C in 1979.

If the reservoir is uniformly two-phase, then the pressure and temperature must follow the saturation line. Unfortunately, the vapor pressure curve is not certain because of the effects of water salinity, non-condensable gases, and capillarity in the pore space. With this in mind, it is more appropriate to determine the position of the saturation curve empirically.

After examining the enthalpy and pressure histories, it was decided that if the reservoir flashed at all (in the sense of a lumped parameter model), it flashed sometime around the beginning of 1974. It is at this time that the initial steep decline in pressure due to liquid decompression perhaps levels out somewhat because of the growth of two-phase conditions. The fluid enthalpy also rises above the average enthalpy of liquid water at the initial temperature. The specification of two-phase conditions starting at the beginning of 1974 determines the initial point on the "pseudo" vapor pressure curve as 104.7 kg/cm^3 and 296°C. The rest of the curve is constructed according to the shape of the actual vapor pressure line for water. The rate of temperature decrease, which is dictated by the rate of average pressure decline, matches the observed rate (Fig. 3).

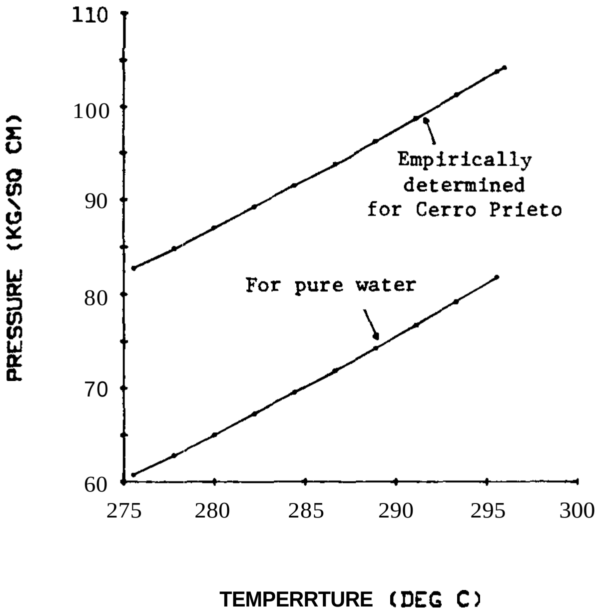

Fig. 3: Vapor Pressure Curves

History Matching In the simulation of a two-phase scenario for the reservoir, the behavior outlined above was assumed. As an alternative for comparison purposes, the reservoir was also modeled as a one-phase system with a large compressibility.

Various sensitivity studies were performed under each depletion scheme in order to investigate the effect: of varying reservoir parameters.

Several factors were considered in obtaining a satisfactory match of the history at Cerro Prieto. On the basis of the sensitivity studies, it was felt that a two-phase scheme would offer the best chance of matching the pressure behavior.

Figure 4 shows the results of history matching. The match is quite good over the entire 7.5 year period. The parameters used in obtaining this match are realistic except for aquifer size. The thickness of the production zone is 380 m; the porosity is 22%; and the recharge temperature is 260°C. However, the cross-sectional area of the aquifer is 18 x 10^6 m^2, which is about 3.5 times the total surface area of the production zone. The strength of the recharge indicates that a radial or spherical influx may be closer to actual conditions. In any case, the results in this report with a linear recharge system indicate that strong recharge is occurring at Cerro Prieto. One additional possibility is bottom water influx into the reservoir. This would explain the behavior shown by the pressure and enthalpy

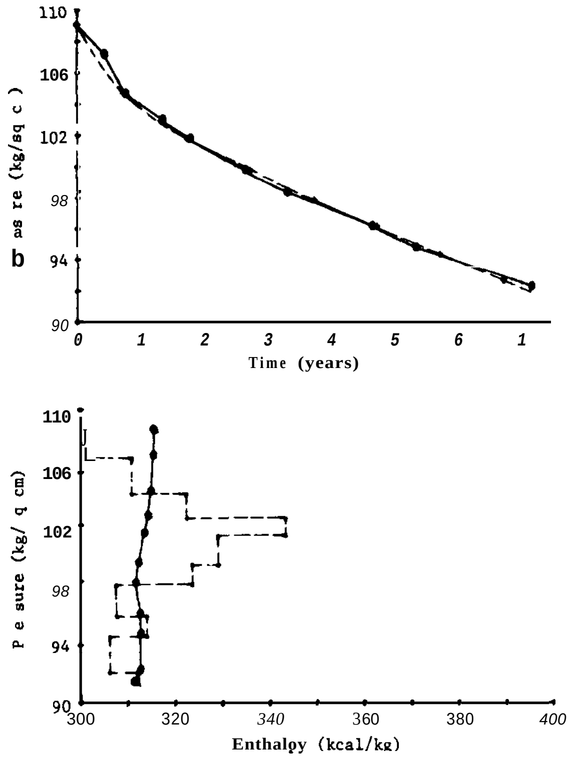

Fig. 4: History Match

observations. As shown by the results of the sensitivity studies presented later, a satisfactory match of the reservoir by a one-phase scheme is impossible. A two-phase scheme presents a sharp decline in pressure until the reservoir reaches the pseudo-vapor pressure curve. It then flashes and the pressure decline rate decreases while the enthalpy in the reservoir rises. In order to match both the pressure and the produced-enthalpy curves, it is necessary to assume a large aquifer recharge. At the same time, this would slow the pressure decline rate at the beginning of production and then lower the enthalpy at the end by reducing the steam quality into the reservoir.

A sensitivity study on the temperature of recharge water showed that raising the temperature of fluid influx would cause the pressure decline to be more gradual. Decreasing the reservoir thickness would counteract this effect, and would cause the enthalpy rise to be slower. In order to obtain agreement with the enthalpy history, a large aquifer would be necessary to provide a cool mass of recharge water. As the volume of the production zone became smaller relative to the cold aquifer, the decline in pressure along the saturation line would increase. Figure 5 shows an example of a sensitivity study in which the temperature of the recharge water is varied, assuming a two-phase depletion scenario. In this case, the size of the aquifer was too small to match either the pressure or the enthalpy observed.

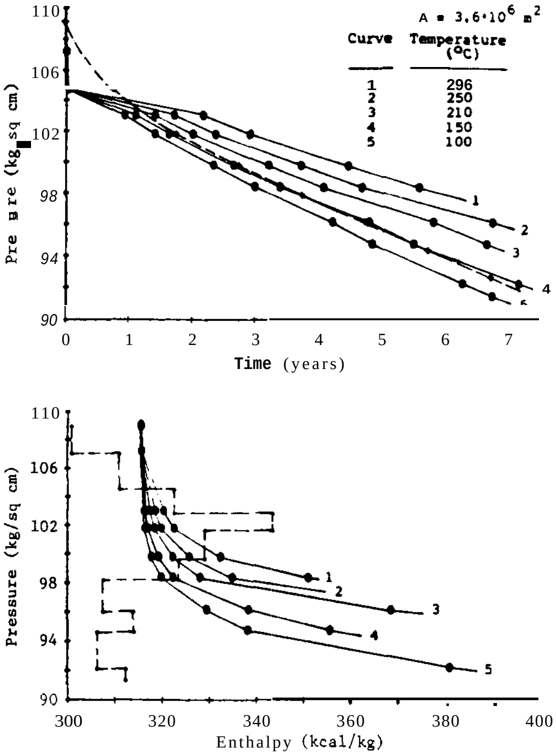

Fig. 5: Sensitivity Study of Temperature of Recharge Fluid (Two-Phase)

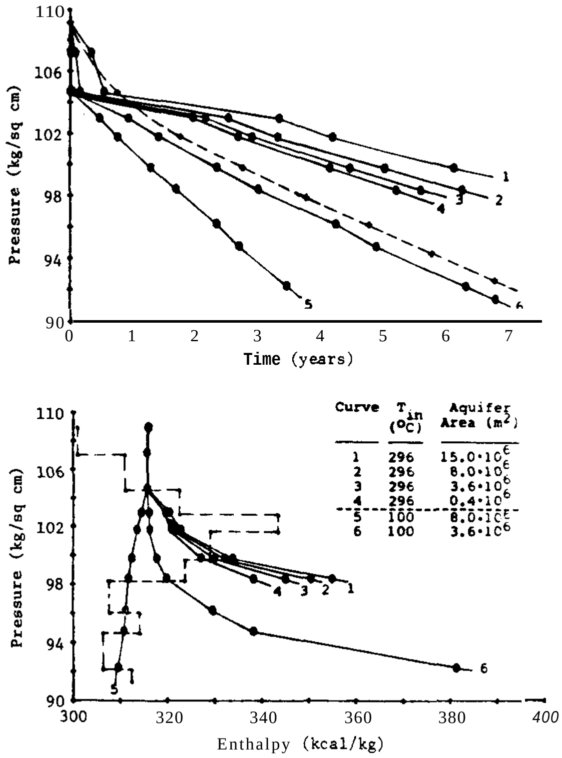

Fig. 6: Sensitivity Study of Aquifer Size (Two-Phase)

Figure 6 shows the effect of a change in aquifer size.

An additional point to address in this work is the sensitivity of the model to the location of the arbitrary zones; particularly, the intermediate zone extent may effect the validity of the results.

Figure 7 shows the drop in pressure and the rate of rise of produced enthalpy when the length of the intermediate zone increases. Geological data and temperature surveys must be used carefully in order to input this parameter properly.

Due to the complex faulting and difficult geology of Cerro Prieto, the thickness of the producing interval is difficult to estimate. In Fig. 8, we varied this parameter from 250 to 750 m. The best history match was obtained for a thickness of 380 m. The porosity was changed from .15 to .25. As can be expected, the model is not very sensitive to this parameter, because the total heat content in the reservoir is not very dependent on the porosity.

The history match obtained here is not unique. Other matches, which were not as good, were possible for a smaller reservoir and a warmer and stronger recharge. A temperature of 260°C is the minimum for which it is possible to get good enthalpy and pressure matches. Below this temperature, a smaller aquifer must be

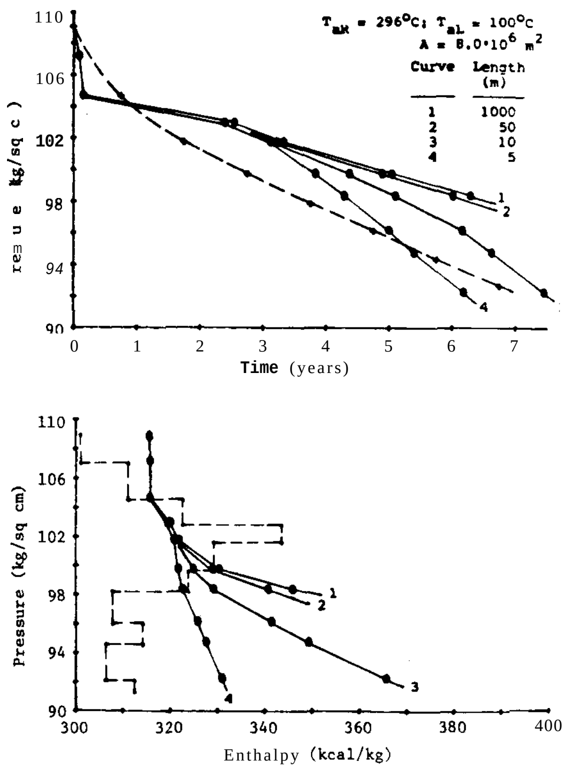

Fig. 7: Sensitivity Study of Length of Thermal Zone (Two-Phase)

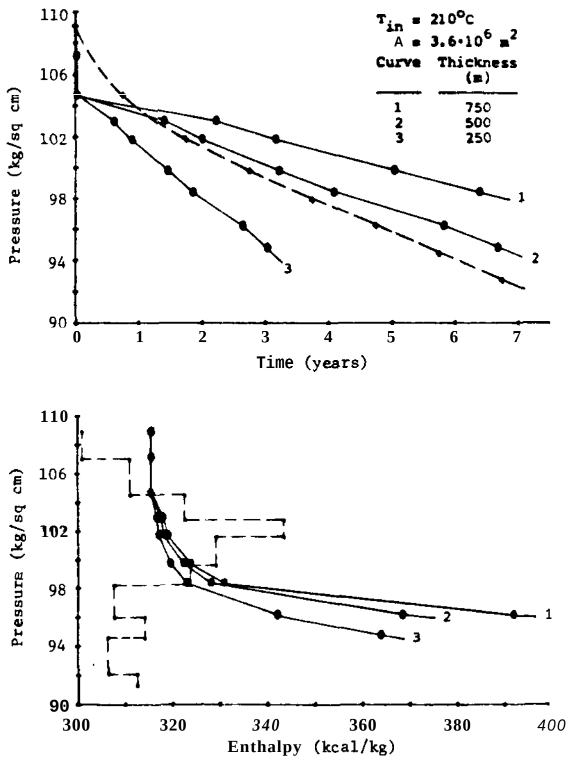

Fig. 8: Sensitivity Study of Reservoir Thickness (Two-Phase)

specified to reproduce the pressure trend, but the enthalpy becomes too high because the reservoir mass is depleted too rapidly. Above this temperature, it is possible to obtain simultaneous pressure and enthalpy matches, but the discrepancy between aquifer size and reservoir volume becomes larger.

The history match has been extrapolated out to a 30-year lifetime. A flowrate of 2000 tons/hr is assumed, and the produced enthalpy is approximately equal to the enthalpy of the reservoir fluid. No attempt is made to account for the effect of production in other areas of the field. After thirty years, the pressure has declined to 67 kg/cm^2, the temperature to 256°C, and the reservoir fluid is 5% quality steam with an enthalpy of 286 kcal/kg.

Conclusions Although the information that was required for the lumped parameter model of Cerro Prieto Units 1 and 2 is minimal compared to distributed parameter models, considerable judgment was still necessary to formulate a consistent set of data from the diverse and sometimes conflicting sources that are available. However, the simple nature of the lumped parameter approach allows rapid insight into relationships between physical reservoir characteristics and production behavior. The following conclusions may be drawn:

1) A depletion scheme in which the production zone becomes two-phase early in its history best fits observed behavior at Cerro Prieto.

2) A potent aquifer recharge has prevented the enthalpy of the fluid in the reservoir from rising in response to high rates of production from a relatively small volume. The geometry of the recharge system is probably radial or spherical, rather than linear.

3) The temperature of the recharge water is about 260°C. If the temperature is below 260°C in the model, then either the pressure decline is too steep or the enthalpy in the reservoir increases. If the temperature is above 260°C, the history matches are not as good, and the reservoir description becomes less physically realistic.

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