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An Exploitation Model and Performance Predictions for the Ahuachapan Geothermal Field, El Salvador

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ABSTRACT

The Ahuachapan geothermal field in El Salvador has been producing electrical power since 1975. The field currently produces at only about 50 percent of the installed capacity of 95MW$_e$. The reasons for this low power production include a large reservoir pressure drawdown and limited drilling of make-up wells.

The focus of our study is to develop means for increasing the power production over the next 30 years. One possible option is to devise an injection scheme to decrease the pressure decline and increase the energy recovery from the reservoir. Another possibility is to drill step-out wells to increase the size of the wellfield. To determine the effects of injection and expanded production, a three-dimensional numerical model of the field has been developed.

The model was used to predict the responses of the existing wells and proposed development wells. Also, the the overall reservoir response to various exploitation and injection scenarios was investigated. The results indicate that the geothermal system can produce at a level of 95 MW$_e$ for about 20 years. However, the system can produce up to 75 MW$_e$ for a 30 year period with the drilling of about 20 new production wells and significant reinjection.

INTRODUCTION

The Ahuachapan geothermal field in El Salvador (Fig. 1) has been producing electrical power since 1975. The field produces approximately 50 MW$_e$, far below the installed capacity of 95 MW$_e$. Currently, there are 14 wells on-line with an average spacing of approximately 250 m. A limited injection program operated from 1975–1982; no injection has occurred since that time. This study investigates the possibility of significantly increasing the power generation at the Ahuachapan field over the next 20 to 30 years. Some of the questions of interest are:

(i) Will injection increase the power production at Ahuachapan?

(ii) What is the best location for injection wells and what percentage of the produced fluids should be injected?

(iii) Where should new production wells be located and how many wells are required for the next 30 years?

(iv) What is the highest power production level that can be economically maintained over a 30 year period?

To address these questions, a complex three-dimensional numerical model of the field has been developed. This model is based on all of the available data, which were analyzed by Aunzo *et al.*, (1989). The results of this comprehensive study, which included a geologic model, reservoir data analysis, a conceptual model and a natural state model, were incorporated into the 3-D model. The model was then calibrated against production data,

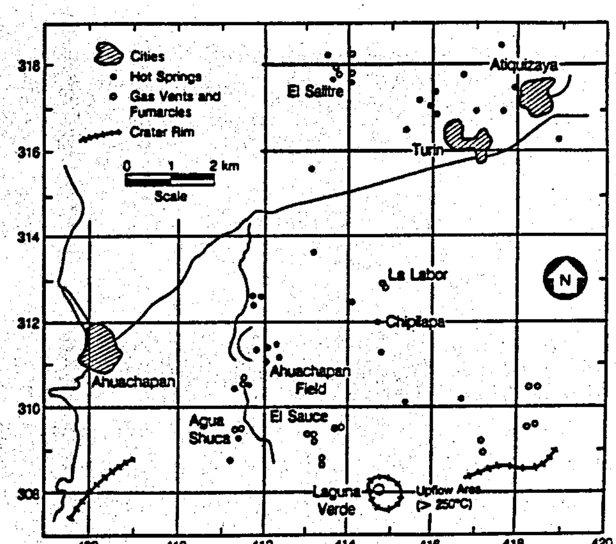

Figure 1. Map of the Ahuachapan area.

which include the reservoir pressure decline and flow rates and enthalpies from all of the wells during the period 1975–1989. The calibration (history match) involved numerous iterations in which reservoir parameters were adjusted until a satisfactory match was obtained between calculated and observed production data.

Once the history match was obtained, the model was used to predict the responses of the existing and hypothetical additional production (development) wells, and investigate the overall reservoir response to various exploitation and injection scenarios. These scenarios were evaluated based upon the total production rate, the pressure decline, returns of injected fluids and economic viability (Ripperda *et al.*, 1989).

THREE-DIMENSIONAL NUMERICAL MODEL

The geothermal reservoir at Ahuachapan is found below about 400 masl and is associated with the Ahuachapan Andesites and Older Agglomerates (Fig. 2). The caprock is formed by a mostly impermeable layer between the Ahuachapan Andesites and Young Agglomerates. Barriers to flow are believed to exist north and west of the present wellfield. The wellfield and the primary surface fault traces are shown in Fig. 3. The northern barrier is indicated by the much lower temperatures found in wells AH-11 and AH-12. The western barrier is inferred from the pressure and temperature data from wells AH-17, AH-8, and AH-15. The initial temperatures in wells AH-17 and AH-8 are on the order of 220°C, while the temperature in AH-15 is about 120°C. Well AH-15 is located only several hundred meters west of AH-17 and AH-8.

The present wellfield is located in a horst structure that has about 50 m of uplift. This shallow structure allowed a two-phase zone to develop over most of the region between wells AH-23 and AH-17 before exploitation. North and west of the horst, much cooler liquid was initially found. The hottest temperatures reported at Ahuachapan were in well AH-14, east of the wellfield. Wells AH-18 and AH-32, which are south of the uplifted region, are also hotter than most of the other wells, but the reservoir is deeper here and these wells did not penetrate a shallow two-phase zone.

Because of the complex thermodynamic and geologic conditions at Ahuachapan, it was decided that a fully three-dimensional model of the field was necessary. The important components of the model include the design of the grid, the rock and fluid properties, the initial conditions, and the boundary conditions.

A grid with four horizontal layers was developed. A multi-layered model was necessary because most of the wells have multiple feedzones. A relatively shallow two-phase zone provides a significant fraction of the produced fluids. Also, much of the fluid recharging the system flows through a deep rock unit, the Older Agglomerates (Aunzo *et al.*, 1989).

A map of the Ahuachapan area, including the field and surface thermal manifestations is shown in Fig. 1. An areal view of a single layer of the grid is shown in Fig. 4. The grid extends from the El Salitre hot springs in the north to a location about two kilometers south of the Laguna Verde volcano (Fig. 1).

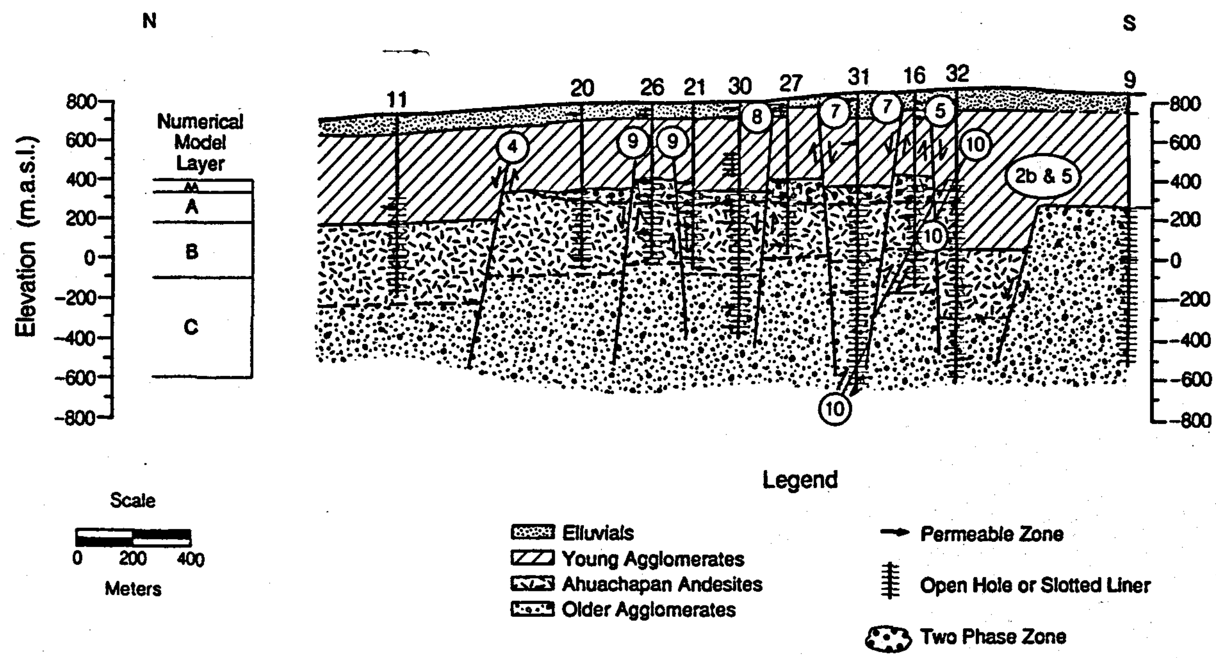

Figure 2. Cross-section of the Ahuachapan reservoir, running north to south.

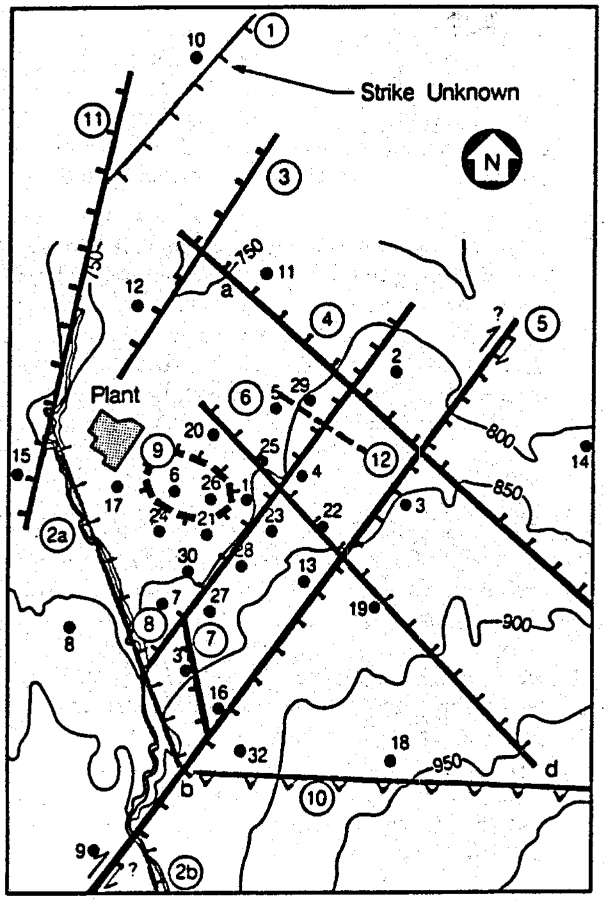

Figure 3. Locations of the wells and projections of the faults to the surface.

The north-south dimension of the grid is 14.5 km, the width is 8 km, and the thickness is 1 km. The AA, A, and B layers (Fig. 2) comprise the Ahuachapan Andesites, and are assigned thicknesses of 30 m, 150 m, and 250 m respectively. The C layer represents the Older Agglomerates and is assigned a thickness of 550 m. Closed boundary conditions were assigned along the east, west and north edges of the grid. An infinite boundary condition was imposed south of the field to provide hot fluid recharge to the system. An infinite boundary condition was also assigned in the northwest corner of the grid to account for the cooler groundwater influx that has been inferred to occur during exploitation (Aunzo *et al.*, 1989).

The pressure throughout the reservoir prior to 1975 was about 48 bars at an elevation of 75 masl. This depth corresponds to the middle of the B layer in the simulation model. The temperatures at this depth ranged from nearly 250°C around wells AH-32 and AH-18 in the southern region of the reservoir to about 140°C in well AH-12 just north of the reservoir. The temperatures in the reservoir increase from north to south and from west to east. This is consistent with the hot recharge coming from the southeast and cooler boundaries located north and west of the reservoir.

HISTORY MATCHING

The primary data used for the history match of the Ahuachapan wells were the flow rate, flowing enthalpy and static pressure data. The flow rate and enthalpy data were compiled from monthly Comision Ejecutiva Hidroelectrica del Rio Lempa (CEL) production records and the pressure data were taken from shut-in pressure logs. Fluid production from the field began on August 27, 1968, when well AH-1 was flowed for the first time. Fluid extraction increased in the following years as new wells were completed and flow tested. Large scale exploitation started in June 1975, when the first 30 MW_e generator went on line. A second 30 MW_e unit went on line in July 1976 and a third one (35 MW_e) in November 1980.

The numerical simulator MULKOM (Pruess, 1983) was used in the modeling. Numerous iterations were necessary to obtain reasonable matches with the observed well flow rates, enthalpies and pressures. The parameters

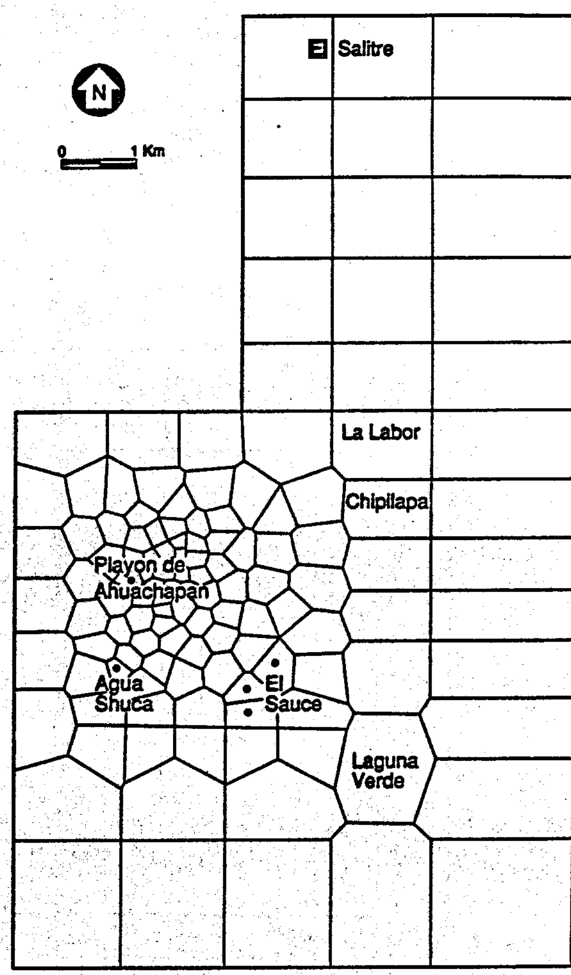

Figure 4. Areal view of the numerical grid, including the locations of several surface manifestations.

that were adjusted during the iteration process were:

(1) productivity indices

(2) permeabilities

(3) porosities

Although the effects of these parameters are coupled, each of them affects the flow rates and enthalpies in a different way. The productivity index most strongly controls the flow rate at relatively early times; consequently, this parameter was used to fix the initial rate from a well. The permeability primarily affects the flow rate decline with time, but also affects the enthalpy transients. The porosity has very little effect on the flow rate, but has a relatively strong effect on the enthalpy (Bodvarsson *et al.*, 1984).

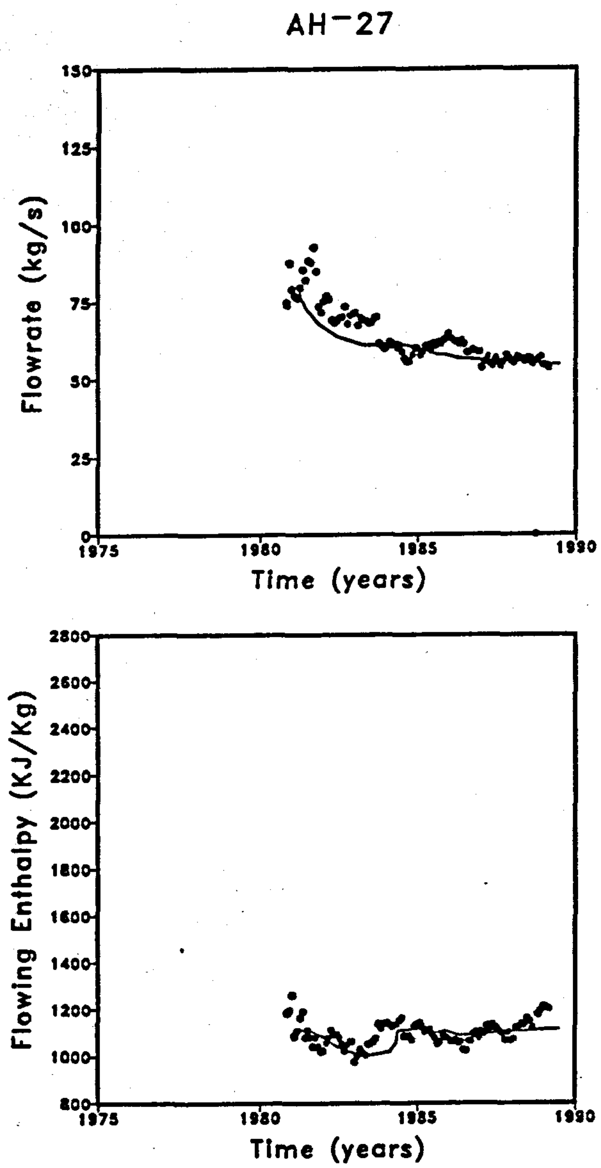

Figure 5. Comparison between computed (solid line) and observed flow rates and enthalpies for well AH-27.

A sample history match for well AH-27 is shown in Fig. 5. Both the flow rate decline and the enthalpy transients match very well. For almost all wells there is good agreement with the late time data, and in most cases the calculated and observed flow rates and enthalpies agree well over the entire exploitation period.

The average permeability within the wellfield is estimated to be 100 md. There are several high permeability flow paths, generally associated with fault zones, where the permeability ranges up to one darcy (Fig. 6). Without these high permeability zones, the computed pressure drop within the reservoir is too large. These zones are also needed to channel the hot recharge fluid to match the enthalpy behavior of the high enthalpy wells.

The permeability in the vapor cap is estimated to range between 1.0 and 1.5 darcies, which is much higher than the average values for the lower layers. However, because the vapor cap is so thin (30 m) its transmissivity (permeability-thickness) is comparable to those of the other layers (around 30 Dm). The high permeabilities in the vapor cap are necessary to support the high production rates from high enthalpy wells such as AH-6, AH-17, and AH-26. With lower permeabilities, the steam mobility is too low because of low steam density, and the reservoir pressures in the well elements draw down too quickly.

From the enthalpy transient matches, the porosities in the two-phase zone are estimated to vary between 10

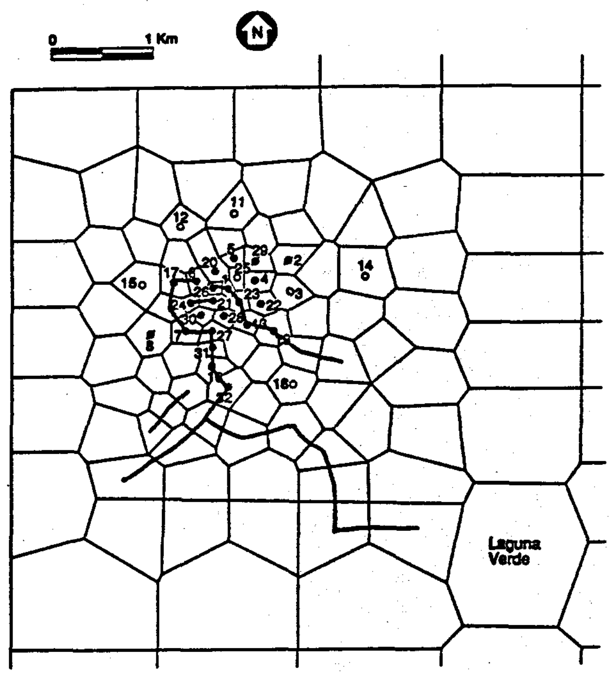

Figure 6. Locations of the high permeability flow paths in the B layer (dark lines).

and 20 percent. The porosities in the liquid layers could not be estimated and were assigned a value of 10 percent based upon the data from Larios, (1983).

A contour map of the pressure distribution in the B layer at the end of the history match (1989) is shown in Fig. 7. The reservoir pressure has declined by about 16 bars. The pressure decline is much more pronounced at the northern edge of the field than at the southern edge. This is to be expected, given that the fluid recharging the system enters from the south.

FIELD PERFORMANCE PREDICTIONS

On the basis of the production history match a model was developed which can be used to predict the response of the reservoir and individual wells to various exploitation schemes. The primary interest at Ahuachapan is to determine the maximum electrical power generation levels that can be economically maintained over a suitable time period. Numerous cases were considered ranging from letting the field continue in its present state (i.e., decreasing rate of fluid production) to drilling enough wells to bring the power generation up to the full 95 MW_e capacity. In each case, the effects of injection were investigated.

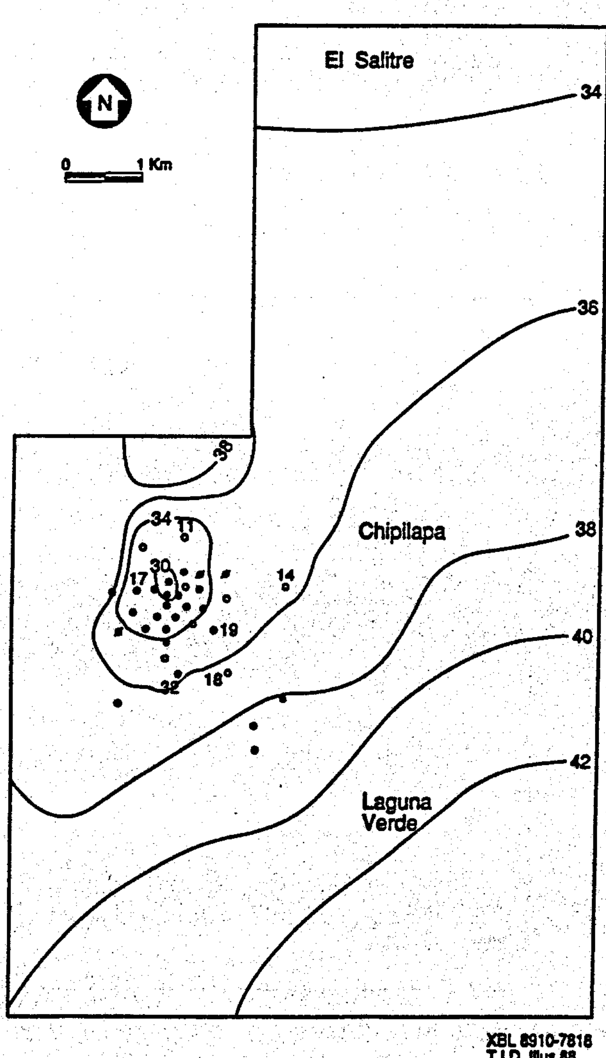

Figure 7. Calculated pressure distribution (bars) in the B layer in the year 1989.

The best area for injection appears to be northeast of the current wellfield (Fig. 8). There are barriers to flow directly north and west of the field and there is cooler groundwater beyond these barriers. Also, the hot fluid recharge originates south and southeast of the field. Thus, injection in the northeast helps decrease the cold water recharge, while having a minimal impact on the hot fluid recharge. A constant injection temperature of 150°C was assumed for all cases except for those with generation levels of 95 MW_e, which used an injection temperature of 100°C. The targeted area for expansion is primarily southeast of the current wellfield, closest to the hot fluid recharge.

Figure 9 summarizes the well drilling requirements for several of the test cases. These cases maintain the electrical power production at the specified level by adding new wells when needed. It can be seen that five new wells will be needed to maintain power production at 50 MW_e until the year 2020 without any injection. If 60 percent of the produced fluids are injected back into the reservoir, then four new wells will be required. This relatively small number of wells is not too surprising, since the current flow rate decline is extremely low for most of the wells at Ahuachapan (see for example Fig. 5).

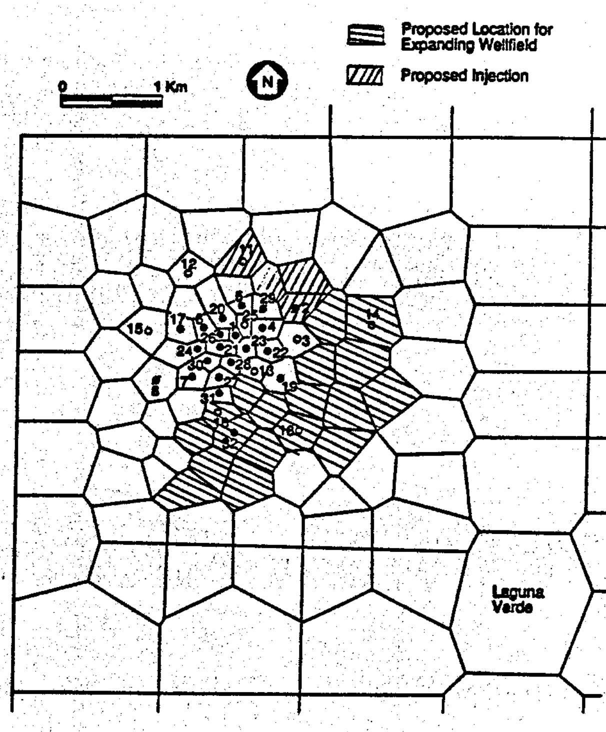

Figure 8. Locations of the proposed new development and injection areas.

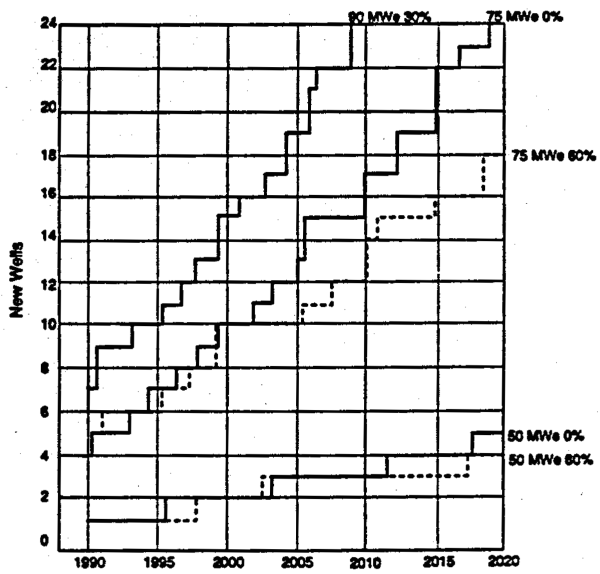

Figure 9. Time table for additional production wells required for several of the development options.

Increasing the power generation output to 75 MW_e requires a much larger number of new wells, both initially, and over the 30 year projection period. The effects of injection are much more apparent with higher extraction rates. Without injection, 24 new wells will be required to maintain 75 MW_e power generation. However, only 18 new production wells will be necessary if 60 percent of the produced fluids are reinjected.

The results of the numerical simulations indicate that the field cannot maintain 95 MW_e power production for 30 years, even with injection. Because generating 95 MW_e requires the high and low pressure turbines, only 30 percent of the produced fluids are available for reinjection when the power plants are producing at full capacity. From Fig. 9 it can be seen that 24 new wells will be required in the first 20 years. From then on, the well spacing for the expanded production area falls below 300 m and the productivity of any new well is very low. The production level was allowed to decline naturally with time after 20 years. The computed power production was 70 MW_e in the year 2020.

An interesting alternative is to drill no new production wells and just let the production rate decline with time. The power generation for this case, with and without injection, is shown in Fig. 10. Injection increases the final power production level by about 15 percent.

For all cases with injection, there is a decline in the average enthalpy of the produced fluids. But this is countered by the strong effect injection has on decreasing the reservoir pressure decline. An important concern about injection is the amount of cooling caused by the injected fluids. The modeling results show that the

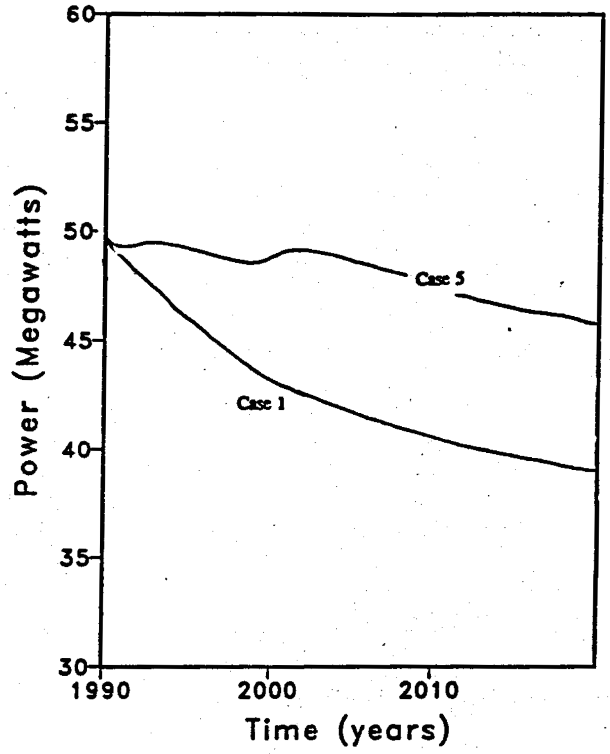

Figure 10. Power generation versus time for the no development option with 60% injection (case 5) and without injection (case 1).

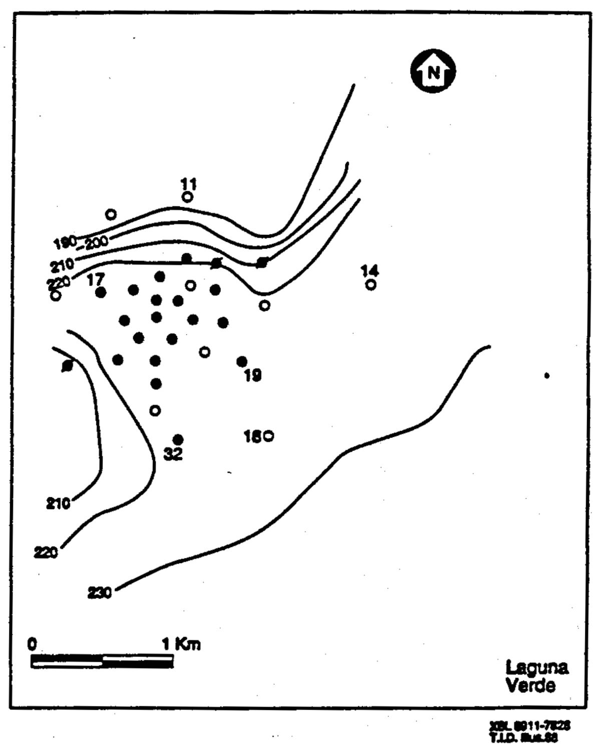

Figure 11. Temperature distribution in the B layer for the case with 75 MW_e power production and 60 percent injection.

cooled zone is confined to the northeastern corner of the field (Fig. 11). The temperature throughout most of the field remains between 220 and 230°C after 30 years of injection (and production). It must be noted that our model is a porous medium representation and might underestimate the lateral extent of cooling in a fractured reservoir.

SUMMARY

A three-dimensional numerical model of the Ahuachapan geothermal field has been developed. This model was designed on the basis of all available data from the field. It was calibrated against 15 years of reservoir pressure measurements and individual production rates and flowing enthalpies from 16 wells.

The model corroborates the location of barriers to flow identified in the conceptual flow model by Aunzo *et al.* (1989). Some cold water recharge (in the range of 30 to 60 kg/s) enters the field from the north and from the southwest. It was necessary to include several of the faults identified in the conceptual flow model as highly conductive flow paths in the model.

The model was utilized to investigate the effects of different injection scenarios and to determine the level of power generation that can be sustained for 30 years. Injection significantly decreases the reservoir pressure decline, with only a small effect on the temperatures throughout most of the reservoir. The injection wells should be located northeast of the current wellfield.

An optimum spacing for the new production wells appears to be approximately 350 m. The best location for the new production wells appears to be southeast of the current field.

The modeling results indicate that the reservoir can support 50 MW_e for 30 years with only several make-up wells. The reservoir can support 75 MW_e for 30 years with about 20 new wells. An electrical power output level of 95 MW_e can be maintained for only about 20 years. A production level of 75 MW_e with 60 percent reinjection of the produced fluids appears to be the best option.

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