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NUMERICAL MODELING OF THE INITIAL STATE AND MATCHING OF WELL TEST DATA FROM THE ZUNIL GEOTHERMAL FIELD, GUATEMALA

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ABSTRACT

A significant amount of geoscientific and reservoir engineering data have been collected from the Zunil geothermal field since 1973. The data have been used to define a conceptual model for the field which has formed the basis for the construction of a three dimensional numerical simulation model. The numerical model has successfully matched both the initial state of the reservoir, as indicated by subsurface temperature and pressure distributions within the presently drilled area, and available well test data. The well test data include short and long term discharge tests and a comprehensive pressure interference test. Calibration of the model will continue during 1991 when the results from drilling and testing of three additional deep wells are available. The model will then be used to study various long term production scenarios for the proposed 15 MW power development.

INTRODUCTION

The Zunil geothermal field is located near the city of Quetzaltenango, Guatemala; approximately 200 km west of Guatemala City (Figure 1). Exploration and development of the field has been ongoing since 1973 when the Instituto Nacional de Electrificación (INDE) began a surface exploration program to define the regional geothermal system in the Zunil area. The Japan International Cooperation Agency (JICA) provided assistance during this phase of the project. In 1976 an exploration drilling program commenced which involved the drilling of 11 slim thermal gradient holes to verify and expand the data base generated from surface exploration. The exploration program successfully delineated an area of approximately 4 km^2 on the east slope of the Cerro Quemado complex which appeared to be favorable for geothermal development.

With the success of the slim hole drilling program, six large diameter wells (ZCQ-1 to 6) were drilled by INDE during 1980-81 with the assistance of Electroconsult (ELC). The wells were completed at depths ranging from 812 to 1,310 m and encountered temperatures of up to 288°C. Testing and evaluation of the six large diameter wells continued from 1981 through 1989 and included short and long term discharge tests and a comprehensive pressure interference test. The locations of the six large diameter wells and a number of the slim holes are shown in Figure 2.

Figure 1. Location of Zunil geothermal field

In 1987, INDE signed a contract with Cordón y Mérida Ings., MK Ferguson Co. and MK Engineers, Inc. (CyM-MKE) to develop and engineer a 15 MW power plant at the Zunil geothermal field. As part of the contract, further well testing and geoscientific studies were undertaken. These studies included an integrated well testing program conducted during 1989 (Menzies *et al.*, 1990) which included flowing the four available production wells (ZCQ-3, 4, 5 and 6) and monitoring of pressure interference data. The geoscientific studies are summarized in Foley *et al.* (1990) and Adams *et al.* (1990).

The data collected from the Zunil geothermal field have been used to define a conceptual model of the system which has formed the basis for the construction of a three dimensional numerical model. The measured subsurface temperature and pressure distributions, well test data and pressure interference data have been used to calibrate the numerical model.

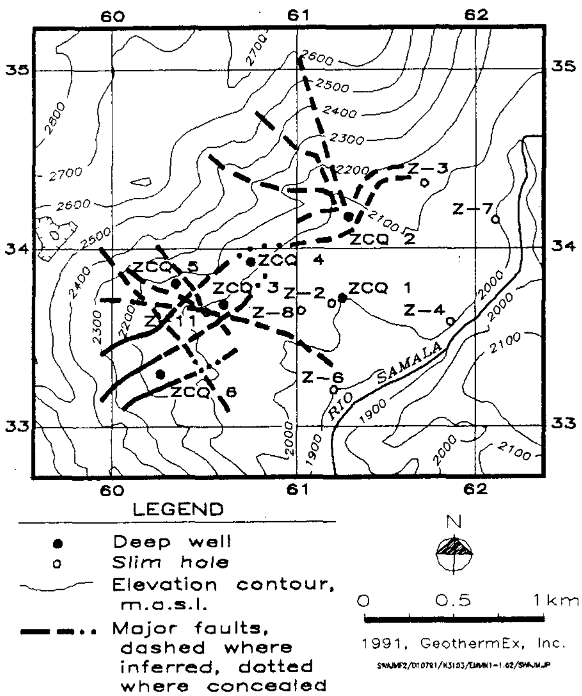

Figure 2. Well locations and major structural features

In this paper, the basic characteristics of the geothermal system are described along with the construction of the numerical model. Results from the model, including matches to the downhole temperature and pressure data and well test data are also discussed.

THE ZUNIL GEOTHERMAL FIELD

The wells drilled to date within the Zunil geothermal field have encountered features typical of many high temperature geothermal fields, for example Tongonan, Philippines (Whittome and Smith, 1979):

- A "cap" consisting of relatively low permeability rocks in which steam from the geothermal system mixes with groundwater. The rocks within the cap are mainly altered lava flows and breccias that range from dacite to andesite in composition and dacite ash-flow tuffs. Secondary mineralization is characterized by clay minerals.

- A high temperature reservoir located beneath the cap, in the vicinity of the granodioritic basement (Figure 3). The secondary mineralization within the reservoir is characterized by high temperature minerals such as epidote, quartz, chlorite and pyrite.

- A thick outflow plume which extends from the ZCQ wells, SE to the Rio Samala (Figure 2).

To help visualize the major features of the geothermal system, subsurface temperature contour maps are presented at 1,200 m msl (Figure 4) and 1,800 m msl (Figure 5). The highest temperatures encountered to date are to the W, in the vicinity of ZCQ-5 and 6. Both wells encounter temperatures of approximately 290°C below 1,200 m msl. This area is the major upflow area for the geothermal system.

The temperature contour map at 1,200 m msl (Figure 4) indicates the major direction of subsurface flow is ENE, through ZCQ-2. This is consistent with the major structural trends (Figure 2) which show that ZCQ-2 is located within the NE-SW fault trend. The relatively low thermal gradient between ZCQ-3 and 2 suggests that additional upflow is occurring within the fault zone in this area.

Temperature profiles in wells ZCQ-3, 5 and 6 are close to the "boiling-point-for-depth" curve, indicating that the maximum subsurface temperatures are controlled by local reservoir pressure. The measured pressure at 1,200 m msl (Figure 6) in ZCQ-6 (75 ksc.g) is significantly higher than in ZCQ-3 or 5 (64 to 67 ksc.g), suggesting that the lower temperatures in ZCQ-3 and 5 may be associated with lower pressures rather than being a function of distance from the upflow zone.

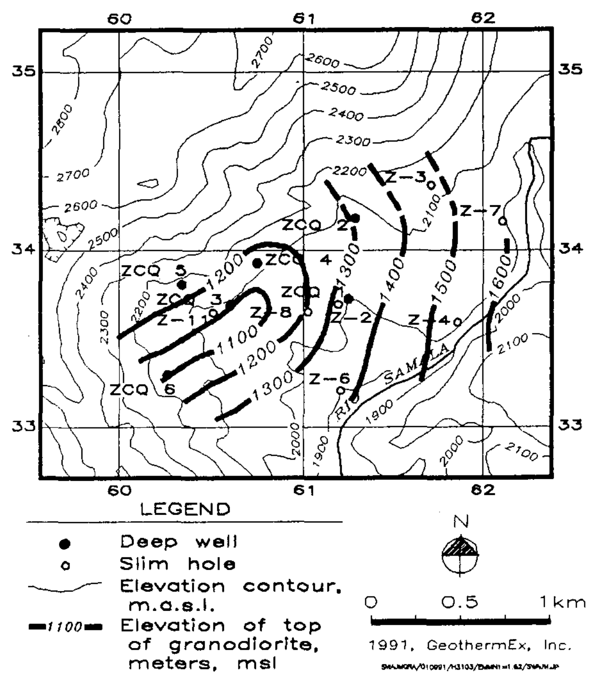

Figure 3. Contour map showing top of granodiorite

The high pressure gradient between ZCQ-6 and the rest of the deep wells is unusual in geothermal systems and indicates the presence of a low permeability area to the E of ZCQ-6. This is consistent with the results from the interference testing conducted in 1989 (Menzies *et al.*, 1990) which showed little or no pressure response in ZCQ-6 when ZCQ-3 or 4 were flowing. The low reservoir permeability may be associated with the fault intersections (Figure 2) that occur to the E of ZCQ-6.

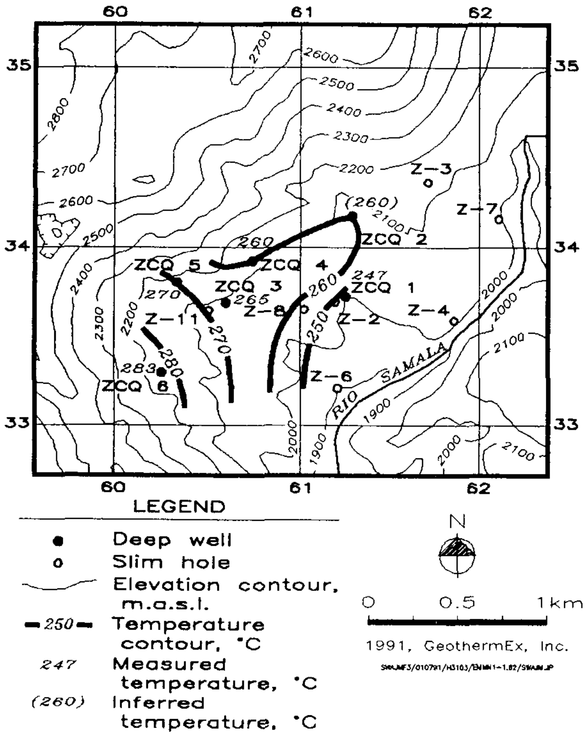

Figure 4. Temperature contour map at 1,200 m msl

At 1,800 m msl (Figure 5), the major direction of outflow shifts to the SE, through ZCQ-1 and Z-4. This outflow is controlled by the top of the granodiorite basement (Figure 3), which rises towards the SE and outcrops approximately 2.5 km to the E (Bethancourt and Dominco, 1982). Surface thermal manifestations occur within the Rio Samala valley (Figure 2); the majority being bicarbonate or acid-sulfate springs associated with steam heated ground waters. However, spring z-20, located near slim hole Z-4 (Figure 2), discharges Na-Cl water which can be related to the deep geothermal fluid.

WELL TEST DATA

Since the ZCQ wells were completed in 1980-81, a number of short and long term discharge tests have been conducted to determine well production characteristics. An interference test was also conducted during 1989 as part of an integrated well test program which involved discharging wells ZCQ-3, 4, 5 and 6 and injection to ZCQ-2. Analysis of the data from the 1989 test are presented in Menzies *et al.* (1990). Table 1 summarizes the well discharge

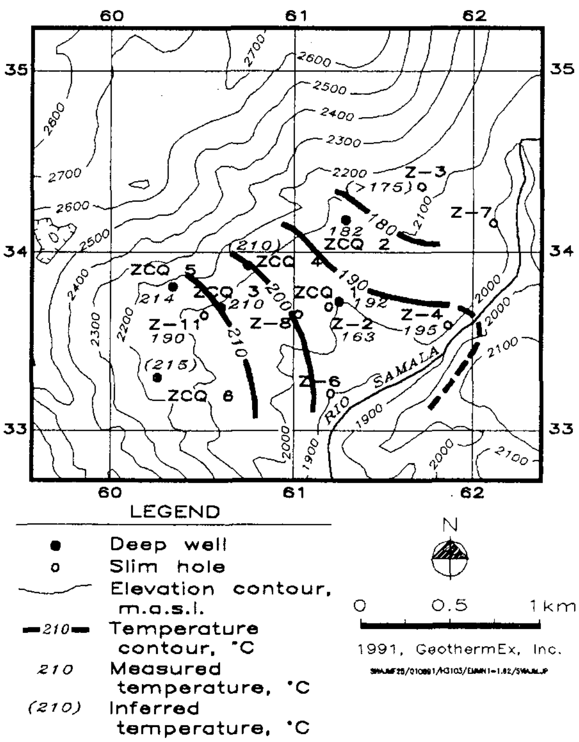

Figure 5. Temperature contour map at 1,800 m msl

characteristics based on the results from the 1989 flow tests.

The ZCQ wells were all drilled to the granodiorite basement. Well ZCQ-1 was completed deep within the basement; however it encountered no permeability and went through a temperature inversion after drilling into the basement. The other five wells encountered permeability at or near the basement contact while ZCQ-4 and 5 also encountered permeability within the overlying volcanics. The estimated thickness of the permeable zone at the basement contact is approximately 50 m (Bethancourt and Dominco, 1982).

Downhole survey and geochemical data suggest that wells ZCQ-3 and 6 produce predominantly from the contact zone and the discharge fluid is closest in chemical composition to the postulated parent fluid (Adams *et al.*, 1990). Their discharge enthalpies of 310 to 360 kcal/kg (Table 1) are higher than for single phase water at measured downhole temperatures. Either the discharge fluid is flashing in the reservoir or there is a small contribution from a two-phase or steam zone within the volcanics. Downhole surveys show that two-phase fluid is entering the wells under flowing conditions.

Well ZCQ-5 produces dry or superheated steam from the contact zone, even though the reservoir fluid is single phase water. Production of steam under these conditions indicates that the contact zone in the vicinity

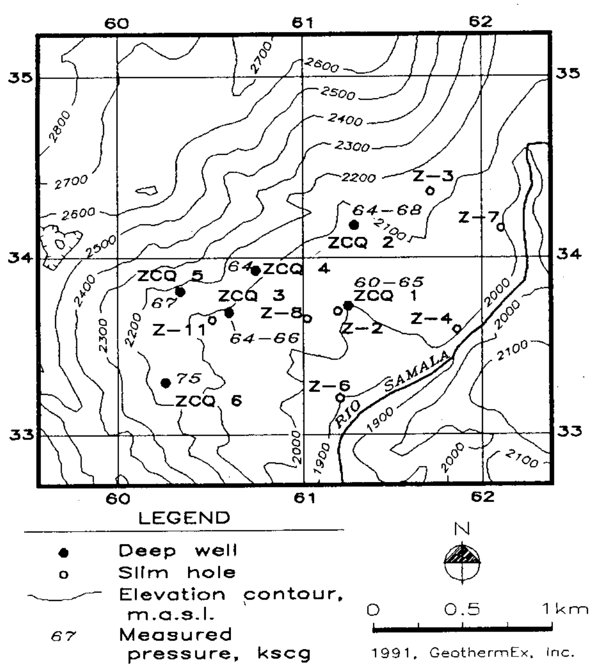

Figure 6. Pressure measurements at 1,200 m msl

of ZCQ-5 has very low permeability. The discharge from ZCQ-5 is also affected by cycling, suggesting the influence of additional permeable zone(s). Geochemical data (Michels, 1990) suggest these secondary zone(s) allow shallow, cooler fluid to enter the wellbore near the casing shoe.

Table 1: Power Capacities of Zunil Wells

Well	Wellhead pressure (ksca)	Mass flow rate (tons/hr)	Discharge enthalpy (cals/gm)	Power capacity (MW)
ZCQ-3*	9.0	105	340	4.8
ZCQ-3**	9.0	120	310	4.6
ZCQ-3***	7.0	80	360	4.1
ZCQ-4	7.0	50	600	5.7
ZCQ-5	10.0	33	580	3.5
ZCQ-6	8.0	50	360	2.5

* data from short term test (February 1989)
** data from start of long term test (March 1989)
*** data from end of long term test (July 1989)

Well ZCQ-4 produces high enthalpy fluid (550 to 600 kcal/kg) from the volcanics. It also has some permeability near the contact which causes significant cycling to occur in the well discharge. The discharge from the deeper permeable zones is apparent from downhole pressure data (Menzies *et al.*, 1990) and from spinner surveys (Dennis and VanEeckhout, 1990).

Well ZCQ-2 also encountered permeability at the contact zone but was found to be non-commercial when discharged. The well is presently designated as an injection well and was used successfully for this purpose during the 1989 well test program (Menzies *et al.*, 1990). Based on the 1989 test results, it is estimated that the well can accept at least 100 tons/hr of injection water.

The interference test conducted during 1989 showed that wells ZCQ-1, 3 and 4 are in good hydraulic communication but respond only weakly to injection in ZCQ-2. Wells ZCQ-5 and 6 did not respond significantly to the discharges of ZCQ-3 or 4 but the response in ZCQ-5 may have been affected by pressure changes associated with its own short term discharge. The lack of response in ZCQ-6 is consistent with the measured pressure data which suggest that a low permeability area exists between ZCQ-6 and the rest of the field.

The calculated reservoir transmissivities from analytical modeling of the interference responses and from pressure buildup data vary from 1,600 md.m to 8,500 md.m which are typical values for high temperature geothermal systems. The calculated storativities range from 0.01 to 0.024 m/ksc, suggesting the presence of two-phase conditions in the reservoir.

NUMERICAL MODEL DEVELOPMENT

A numerical model of the Zunil geothermal field was developed based on the conceptual model described above. The model is orientated in a SW-NE direction (Figure 7) and covers a total area of 8.06 km^2; 3.1 km in the SW-NE direction and 2.6 km in the SE-NW direction. The model consists of four layers and extends from the topographical surface (1,900 to 2,700 m msl) down to sea level.

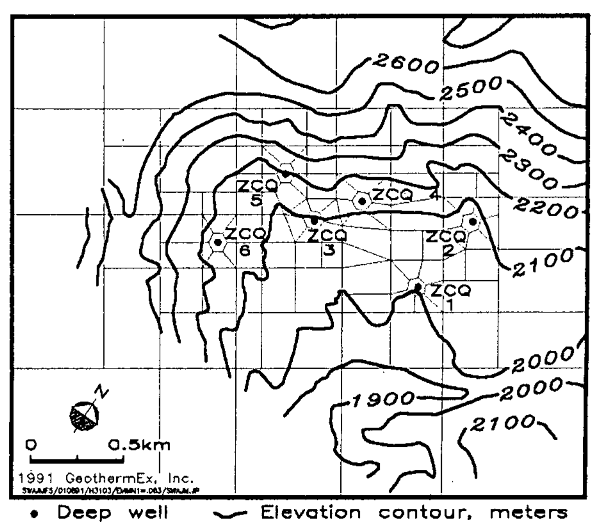

Figure 7. Grid block layout with well locations

Layer 1 extends from the topographical surface to 1,500 m msl and has a constant node level at 1,600 m msl. This layer is located within the volcanics and includes the major production zone for ZCQ-4 and the outflow plume to the SE through ZCQ-1.

Layer 2 extends from 1,500 m msl to 1,000 m msl with the node level set at 1,200 m msl. This layer includes the contact zone between the granodiorite basement and the overlying volcanics which is the major source of present production as well as providing the injection zone in ZCQ-2. Subsurface outflow through ZCQ-2 occurs in this layer.

Layers 3 (1,000 m msl to 500 m msl) and 4 (500 m msl to sea level) are located within the granodiorite with node levels of 750 m msl and 250 m msl, respectively. At the present time, the only information available from these layers is temperature data from ZCQ-1 which was drilled to 695 m msl. However, the present ZD drilling program is designed to investigate deeper production (down to 200 m msl) and layers 3 and 4 have been included in the model for the purpose of modeling the ZD well results.

Boundary layers are used in the model to provide heat and mass inflow from depth and to model the heat sink provided by the atmosphere (1 ksc.a and 20°C). For both boundaries, very large volume blocks are used to ensure that the boundary conditions remain constant during the simulation process.

Each of the four main layers contain 114 grid blocks (Figure 7) and the total number of grid blocks used, including boundary blocks, is 459. The grid blocks are of irregular shape to improve reservoir definition in the vicinity of the production wells and to allow reasonable conformity to the fault trends and the shape of the granodiorite surface.

The computer program used for the modeling employs the "integral-finite-difference" (IFD) method to calculate the fully coupled flows of water and heat within the model. The IFD formulation also allows the use of irregular grid blocks which increases the flexibility of the model. The code was originally developed at Lawrence Berkeley Laboratory under U.S. Department of Energy funding and has been improved by GeothermEx for commercial use.

INITIAL STATE MODELING

In the initial state modeling, the main upflow zone is located to the NW of ZCQ-6. The fluid rises and then flows horizontally above the granodiorite in layers 1 and 2 to the ENE and SE. The hot upflow is initiated by setting the outflow rates in layers 1 and 2 and the model run until steady state conditions are obtained. The calculated temperature and pressure distributions are then compared with the measured data. If they do not agree, changes in outflow rate, source temperature, source pressure and permeability distribution are made and the simulation run is repeated. This process continues until a reasonable match is obtained.

To obtain a reasonable match to the initial state, a secondary upflow zone was required in the vicinity of ZCQ-4 and 2 in order to maintain the relatively low temperature gradient in this region (Figure 4). The locations of the upflow zones are shown in Figure 8.

After many iterations, steady state conditions were reached where the calculated temperature and pressure distributions were in good agreement with the measured data on the three layers for which measured data are available. The final model required outflow to the ENE in layer 2 of 7 tons/hr and outflow to the SE in layer 1 of 47 tons/hr. The outflow fluid is mainly provided by the upflow zone in the vicinity of ZCQ-6 (Figure 8), with a source temperature of 300°C at sea level.

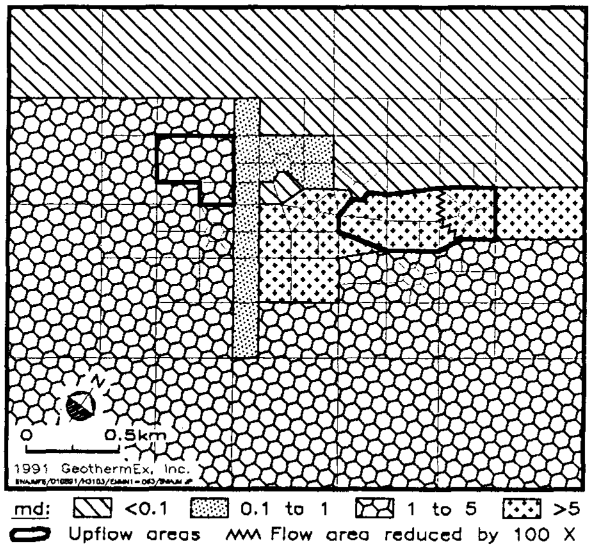

Figure 8. Permeability distribution in layer 2

The results for layer 2, including the permeability distribution, calculated temperature contours and calculated pressure contours are shown in Figures 8 to 10. The permeabilities used in layer 2 (Figure 8) range from 0.01 md up to 5.5 md. For the layer thickness of 500 m, these permeabilities correspond to transmissivities of 5 md.m to 2,750 md.m. The higher value is the same order of magnitude as the results from the analysis of the interference test data.

The very low permeabilities in layer 2 are mainly used to the NW where no data is presently available. The highest permeabilities define the flow conduit from ZCQ-3 through to ZCQ-2. Lower permeabilities are required to the SE to improve the match to measured temperatures in ZCQ-1 (Figure 9) and also between ZCQ-6 and 3 to match the high measured pressure gradient (Figure 10).

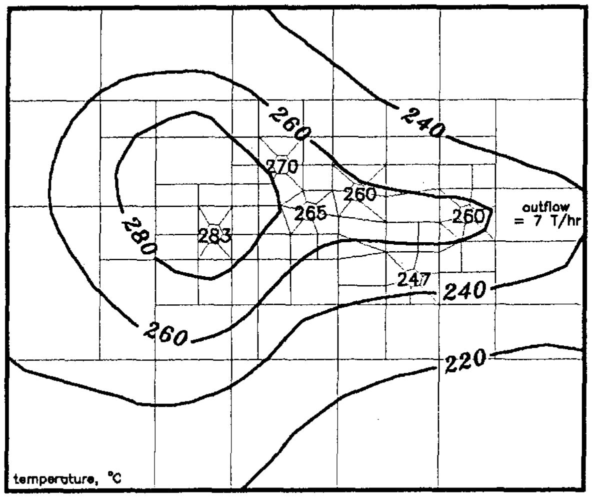

Figure 9. Comparison of calculated and measured temperature data, layer 2

In layer 1, a good match was obtained to the measured temperature data at 1,600 m msl (Figure 11), with a similar range of permeabilities to those used in layer 2. However, it was necessary to use a significantly higher outflow rate (47 tons/hr) to sustain the required temperatures. Two-phase conditions are also widespread in layer 1 (Figure 11), indicating that the calculated temperatures are functions of pressure; hence, if the temperature match is reasonable then the pressure distribution must also be reasonably correct. The presence of two-phase conditions is consistent with well data and the indications of steam in surface thermal manifestations.

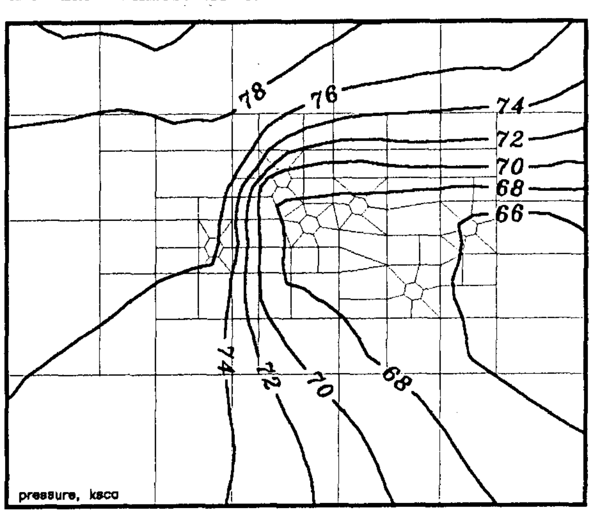

Figure 10. Calculated pressure contours, layer 2

In layers 3 and 4 the permeability has been set to 0.01 md away from the two upflow areas. This is an assumption at the present time due to the lack of data. However, a good match has been obtained to the measured temperature in layer 3 from ZCQ-1. The permeability distribution will probably be modified by the results from the drilling and testing of the ZD wells. Within the upflow zones, the permeabilities are higher; to the N of ZCQ-6, the permeability is 4 md and between ZCQ-4 and 2, the permeability is 0.5 md.

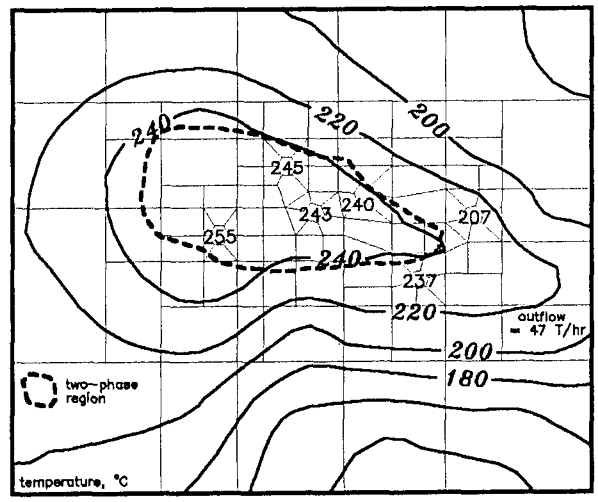

Figure 11. Comparison of calculated and measured temperature data, layer 1

MATCHING WELL TEST DATA

After successful completion of the initial state matching, the model was used to analyze the available well test data collected during the 1989 integrated well test and from long term flow test data collected during various periods from 1981 to 1986.

With the existence of two-phase conditions within the model, it is necessary to define "relative" permeability functions which control the relative flow of steam and water between grid blocks. Various functions were tried during the matching process but the Grant relative permeability functions gave the best results. These functions are based, in part, on analysis of field data from Wairakei, New Zealand (Grant, 1977) and the Corey relative permeability functions used in petroleum reservoir simulation. Residual water saturation of 0.3 and zero residual steam saturation were used in the modeling.

After a large number of runs, reasonable matches were obtained to both the 1989 test data and the earlier long term flow test data. During this process, it was necessary to modify the permeability and porosity distributions used in the initial state model. The model was rerun to steady state conditions to check that the match to the initial state had not been changed significantly. A model was finally obtained that provided a reasonable match to both the well test data and to the initial state.

Interference Test Data

Figure 12 presents the matches to the pressure interference data from wells ZCQ-1, 4 and 6. The data were collected during the discharges of ZCQ-3 and 4 and injection to ZCQ-2. Figure 12 shows that it was possible to obtain reasonable matches to the overall pressure changes, including the weak response to injection to ZCQ-2.

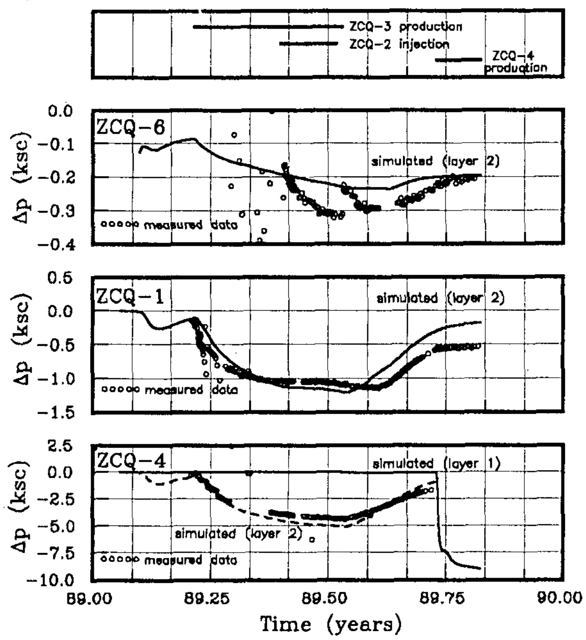

Figure 12. Comparison of calculated and measured observation well pressure responses

The data from ZCQ-1 proved difficult to match due to the significant delay in the recovery response. The reason for the delay is not well understood and is not consistent with the very fast response to the discharge of ZCQ-3. It was also not possible to obtain a satisfactory match to the flattening in the pressure response that occurred when ZCQ-4 was discharged. Well ZCQ-4 produces mainly from layer 1 in the model which is cased off in ZCQ-1. Further layers would probably be required in the model to improve the calculated response.

The final match to the ZCQ-1 data is based on the well being located in a low permeability region surrounded by higher permeability; possibly suggesting that the well was damaged during drilling. If other geometries were considered, such as more extensive zones of higher or lower permeability, the calculated pressure response was either too large or was delayed. The magnitude of the pressure response was also very sensitive to porosities in layer 1; higher porosity improved the match but affected the long term production enthalpy of ZCQ-4 while lower porosities caused excessive pressure drop in ZCQ-1.

To match the pressure response in ZCQ-4, it was necessary to locate the well in a low permeability region of layer 2 (Figure 8). This is consistent with the low productivity of the contact zone in ZCQ-4 and allowed a very good match to be obtained.

For matching the weak pressure responses in both ZCQ-1 and 4 to injection in ZCQ-2, it was necessary to reduce the effective flow area in the vicinity of ZCQ-2 by 100 times (Figure 8). This worked very well and did not change the initial state model significantly.

The successful match to the measured pressure response in ZCQ-6 (Figure 12) required the inclusion of a low permeability area (Figure 8) between ZCQ-6 and 3, with a permeability of 0.15 md.

Discharge Test Data

In using the model to match the discharge characteristics of individual wells, the "deliverability" option was used. With this option, the well flow rates are not specified but are calculated based on the productivity index (PI) of the well, fluid mobility in the vicinity of the well and the pressure difference at the feedzone:

$$q = \sum_{\beta = liquid,vapor} \frac{k_{r\beta}}{\mu_\beta} \rho_\beta PI(p_b - p_{wb})$$

The wellbore pressure (p_{wf}) is specified based on measured data from downhole pressure surveys. The PI is adjusted, along with permeability and porosity, until the model results match both the measured flow rate and enthalpy transients. Circular grid blocks are used in the vicinity of the active wells to improve the radial flow approximation within the model.

Successful matches were obtained to the discharge data from the four ZCQ wells using the above option; examples from ZCQ-3 and 4 are presented here. Figures 13 and 14 present matches to discharge data collected in 1989 and 1983-84 from well ZCQ-3 while Figures 15 and 16 present similar results for ZCQ-4 from 1989 and 1982.

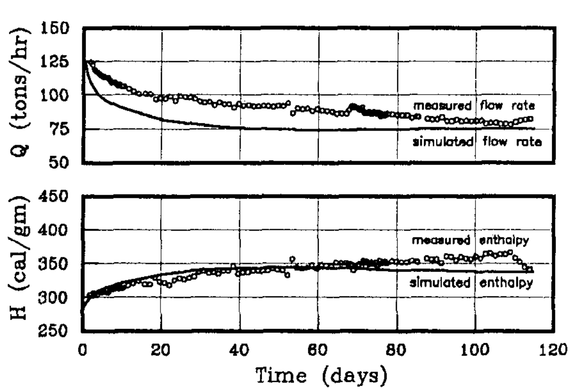

Figure 13. Matching of flow rate and enthalpy data from 1989 flow test, Well ZCQ-3

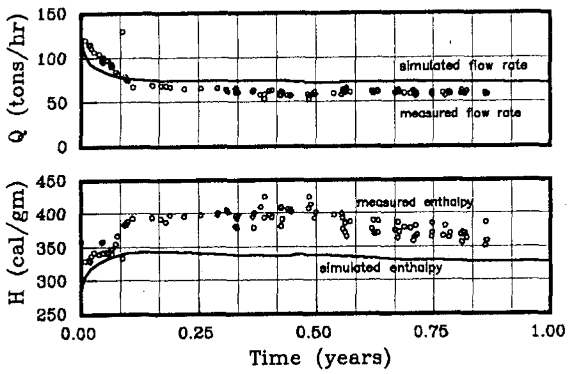

Figure 14. Matching of flow rate and enthalpy data from 1983-84 flow test, Well ZCQ-3

To obtain the matches to the measured data in ZCQ-3, it was necessary to use a very low effective porosity (0.3%) in the high permeability region of layer 2 (Figure 8). This corresponds to a porosity-thickness of 1.5 m, which is very low and indicates the reservoir has limited storage capacity; consistent with the approximate thickness of the contact zone, which is estimated to be 50 m. With this porosity, the model gives a good match to the initial enthalpy rise but calculates a higher initial flow rate decline. Overall, the matches are considered to be reasonable although the calculated enthalpy does not rise as high as the measured data over the long term.

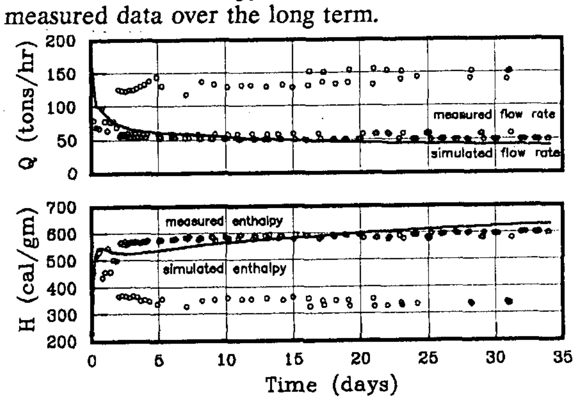

Figure 15. Matching of flow rate and enthalpy data from 1989 flow test, Well ZCQ-4

For ZCQ-4, production was assumed to occur from both layers 1 and 2 although the contribution from layer 2 is small due to the low permeability. A very good match was obtained to the 1989 data by using a porosity of 2% in layer 1. However, to match the long term data collected in 1982, it was necessary to reduce porosity in the outer blocks to 0.2% to maintain the high enthalpy. The results suggest that a lower porosity and/or permeability is probably required as the simulated flow rate remains higher than the measured data after approximately 0.25 years. However, as mentioned above, the lower porosity causes problems in matching the 1989 pressure interference response in ZCQ-1.

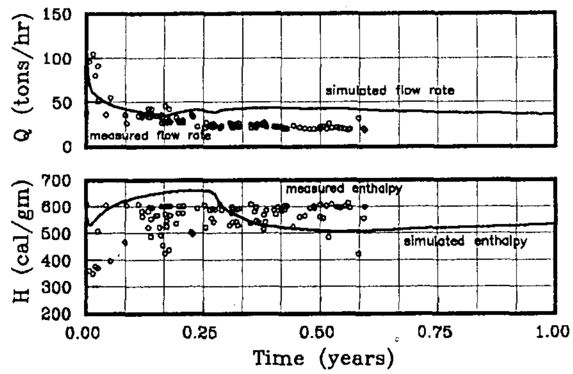

Figure 16. Matching of flow rate and enthalpy data from 1982 flow test, Well ZCQ-4

CONCLUSIONS

A three dimensional numerical model of the Zunil geothermal field has been successfully developed and calibrated against subsurface temperature and pressure data and well test data.

Matching of the initial state indicates that hot fluid rises in the vicinity of ZCQ-6 and flows both to the ENE and SE. A secondary upflow zone exists between ZCQ-3 and 2 which maintains the very low thermal gradient noted from well data. Reservoir permeabilities ranging from 0.01 md to 10 md and a natural flow through the system on the order of 50 tons/hr are required to match the subsurface temperature and pressure distributions.

Successful matches have been obtained to the available well test data, including flow test data and pressure interference data. The results indicate very low effective porosities (0.2 to 0.3%), indicating that the reservoir has a very low storage capacity.

Further calibration of the model will be undertaken when the ZD wells, which are presently being drilled, are completed and tested. These wells will provide much needed data on the deeper levels of the geothermal system. The model will then be used to predict field performance under a number of production scenarios associated with the proposed 15 MW development.

ACKNOWLEDGEMENTS

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