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NUMERICAL MODELING OF THE MT. APO GEOTHERMAL RESERVOIR

by

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ABSTRACT

A three-dimensional numerical model was developed to forecast the behavior of the Mt. Apo Geothermal Reservoir supplying steam to two plants with a total installed capacity of 102 MWe. The numerical model currently running in TETRAD consists of 1122 blocks. The model was calibrated initially by matching the pre-exploitation state of the reservoir, followed by matching the production histories of nine wells supplying steam to the first 52 MWe plant. The obtained natural state gave good matches to the measured temperatures and pressure and represented the major features of the field. History matching runs closely match the discharge history of the field. Forecasting runs were made under the present development strategy of the field. Forecasting results indicated that the current available production wells are capable of providing steam for the two plants for at least five years.

INTRODUCTION

The Mt. Apo Geothermal Field is located in the south-eastern part of the island of Mindanao, Philippines. Commercial exploitation of the field commenced in March 1997 with the commissioning of the 52 MWe condensing turbine. An additional 50 MWe double flash unit power plant is set for commissioning in June 1999 thus increasing the total installed capacity of the field to 102 MWe.

The geothermal field features major geologic structures that influence the hydrological activity of the system (Figure 1). The main hot upflow is in the south-eastern part of the field beneath the Sandawa Collapse. This hot upflow, with temperatures greater than 300 °C, was diverted horizontally towards the northwest. The various NW-SE trending faults in the Marbel Corridor served as the flowpaths of the fluid. In the natural state there exists a steam zone at shallow levels beneath the Sandawa Collapse that extends above the outflowing fluid in the Marbel Corridor. The outflowing fluid is then diverted towards the north, past well APO-2D, upon encountering an impermeable sector in the cold Matingao Block. They then discharged to the surface through the chloride springs of Imba, Marbel and Sisiman.

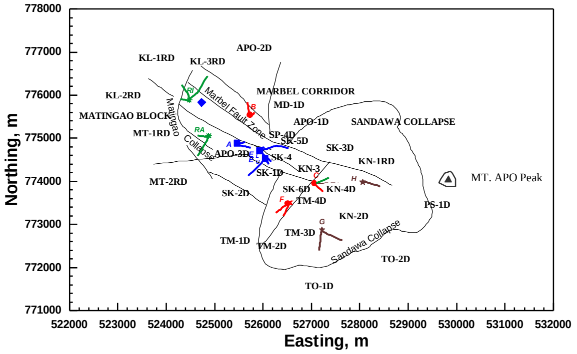

Figure 1. The Mt. Apo Geothermal Field.

Mt. Apo geothermal field is developed in two stages. The first stage, the Mindanao 1 Geothermal Production Field (M1GPF), was commissioned last March 1997. The nine production wells of M1GPF are situated in the Marbel Corridor and are supplying steam to a 52 MWe power plant. By June 1999, the 50 MWe power plant of the Mindanao 2 Geothermal Production Field (M2GPF) will be commissioned. The steam for the second production stage will come from six wells in the Sandawa sector, two wells in from Marbel Corridor, and steam from the secondary flash of brine from M1GPF wells.

There are six injection wells for brine disposal. Five injection wells dedicated for M1GPF are situated in the Matingao Block. One injection well situated in Sandawa Collapse is dedicated for the six production wells of M2GPF located in Sandawa sector.

RESERVOIR PERFORMANCE

Large scale production of the Mt. Apo Geothermal Reservoir begun after the commissioning of the M1GPF Fluid Collection and Disposal System (FCDS) in October, 1996.

During the early stages of operation of the field mass extraction was apparently being extracted from the steam cap and the two-phase zones of the reservoir. The average enthalpy indicated an increasing trend during the first year of exploitation. With production coming from the shallow steam cap and two-phase zone the available steam is more than enough to meet the plant requirements despite the formation of calcite in two of the production wells (Figure 2). Reservoir pressure drawdown is very minimal, a drop of 0.50 MPa relative to the baseline value.

By the second year of commercial operation last March 1998, the production field was already experiencing a reduction in steam availability of the production wells because of two contributing factors: (a) calcite formation in two production wells and (b) declining enthalpy. Five production wells exhibited declining enthalpies which are apparently due to the depletion of the steam cap. The apparent depletion of the steam cap is best observed in a shallow well SK-1D (719 m VD), which is originally a steam well but is now discharging a steady and increasing flow of saturated liquid. The pressure drawdown in the steam cap induces the inflow of reservoir fluids into the well as exemplified by the same reservoir chloride found in other wells.

The reduction in outputs of the four deep wells (SK-2D, SK-3D, SK-5D and SK-6D) is also attributable to the steam cap depletion. These wells which also intersected the steam and two-phase zone, initially discharged relatively higher enthalpy fluids, particularly during the first year of exploitation of M1GPF. By the fourth quarter of 1998, these four were already discharging liquid-saturated fluids, indicating the dominance of the liquid-feed zones in their discharges

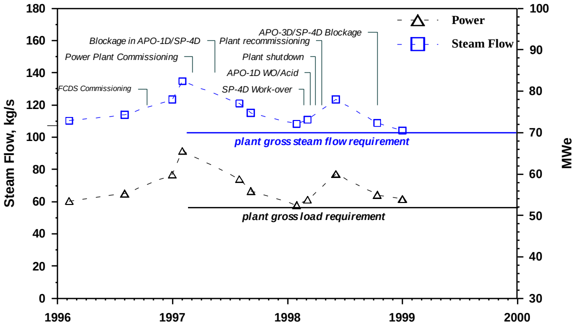

Figure 2. M1GPF output trends.

DESCRIPTION OF THE MODEL

The objectives of the three-dimensional modeling are to match the subsurface temperatures and to reproduce all the significant features of the conceptual model. Further calibrations were made by matching the two-year production history of M1GPF. Production modeling would then forecast the likely behavior of the reservoir under exploitation.

The numerical simulation model of the Mt. Apo field considered a total area of 60 km^2 (Figure 3). The model was oriented in the NW-SE direction, roughly parallel to the Marbel Fault Zone.

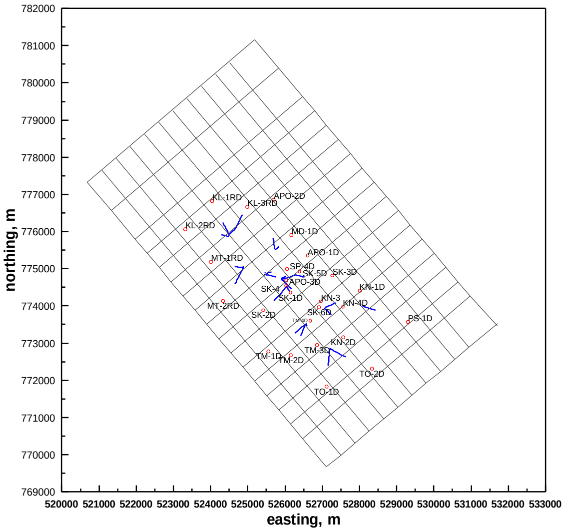

Figure 3. Plan view of the three-dimensional model.

The model vertically extends from an average topographic surface of +1250 m msl (mean sea level) to -1500 m msl. It is divided into six layers: the first layer has a thickness of 300 m; the next four layers are 400 m thick each; and the last layer is 750 m thick. A total of 1122 blocks were used in the model.

To match the major features of the reservoir, aquifers were attached on several blocks to define the boundary conditions of the model. These features include the low temperatures in the impermeable sector of the cold Matingao Block, the major outflow past well APO-2D, the chloride springs of Imba, Marbel, and Sisiman, and the upflow source beneath Sandawa Collapse. The upflow source fluid was simulated by the ten injection wells in the bottom layer.

Initial block permeabilities were assigned based on the injectivity index and production capacity of the wells. For blocks with no well test data, a background permeability was assumed. The rock porosity was considered to be a function of permeability, based on the assumption that the rock matrix has very low porosity.

The model was developed on the TETRAD reservoir simulator.

The model was calibrated in two stages, first by matching the natural state of the reservoir and second by matching the production history of the field.

NATURAL STATE MODELING RESULTS

For the natural state matching, adjustments were made to the heat and mass flux and the thermodynamic conditions of the boundary blocks. Simulation results suggest that the upflowing source fluid has a rate of 190 tons per hour (53 kg/s) at a temperature of 320 °C.

The permeability distribution in the model was constantly adjusted until the calculated temperatures reasonably matched the measured temperatures. Horizontal permeabilities of the final model range from 0.50 md to 35 md while vertical permeabilities range from 0.001 md to 1.5 md.

The temperature contour in layer 3, which corresponds to an elevation of +350 m msl, is plotted in Figure 4. The pattern of the model contour agrees closely with the actual contour. Figure 5 compares the calculated and measured temperature profiles of two wells located in the upflow and outflow sectors of the field. In both sectors of the field the temperature matches are generally good.

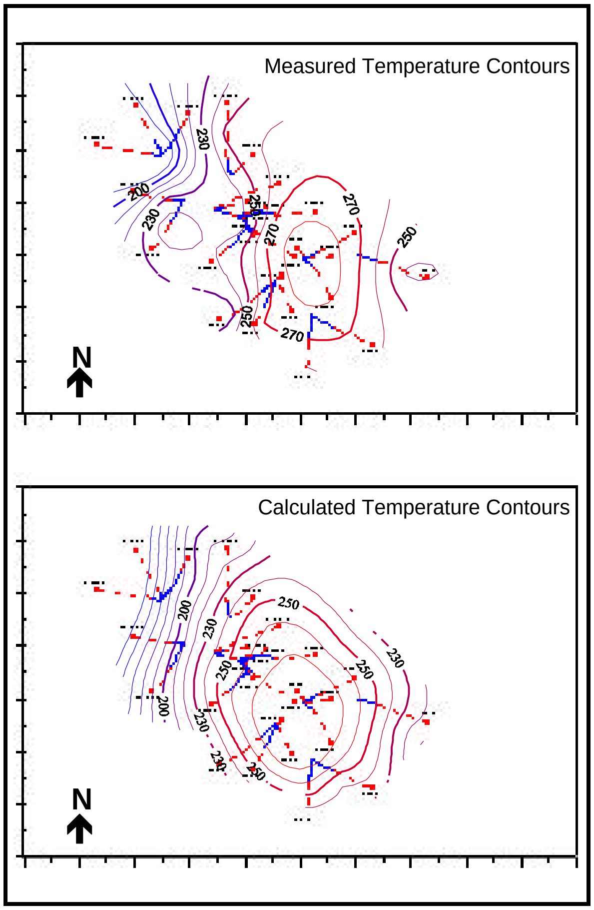

Figure 4. Measured and simulated temperature (°C) distribution at + 350 m msl.

The calculated vapor saturation distribution on certain blocks in layers 2 and 3 is not high enough to give a steam discharge as observed in wells SK-1D, TM-3D and TM-4D. The low vapor saturation obtained is due to the relatively large block (500 m by 500 m by 400 m) assigned to these wells. The maximum steam saturation obtained is approximately 30%. In general, however, the two-phase condition achieved in the model closely coincides with the extent of the two-phase zone of the conceptual model.

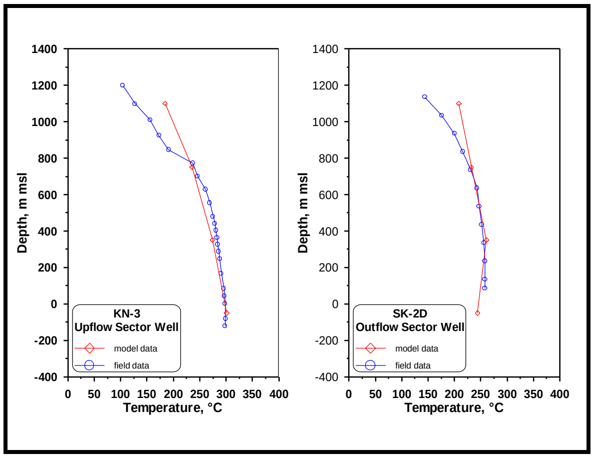

Figure 5. Temperature vs. Depth profiles.

HISTORY MATCHING

The resulting initial state model was further calibrated by matching the discharge histories of the nine production wells of M1GPF. The permeability structures and porosity were also further adjusted. The model results were compared with the actual production enthalpy and the measured pressure decline.

After several adjustments were made on the model, a reasonable match to the measured data was achieved. The rock porosities used in the final model range from 2 to 7 %.

Achieving the initial high discharge enthalpy of the steam well SK-1D prove to be difficult despite the adjustments made on the rock porosity. As mentioned earlier, this is attributable to the large block size that initially had a lower vapor saturation value. However, the enthalpy trend of SK-1D in the model coincided with the actual enthalpy trend decreasing through time (Figure 6).

For low enthalpy wells such as APO-1D the calculated discharge enthalpy closely matches the measured enthalpy values (Figure 6).

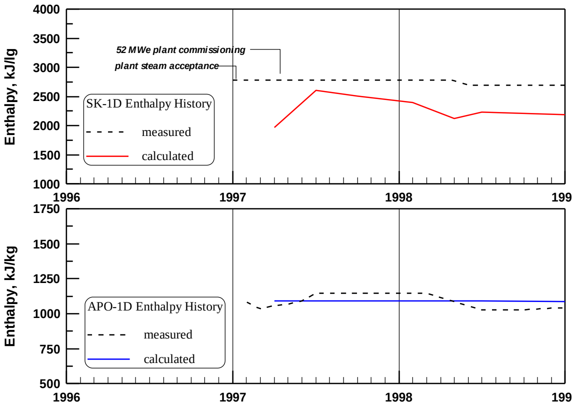

Figure 6. Enthalpy history of SK-1D and APO-1D.

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Figure 7 compares the actual field enthalpy with the simulated field enthalpy. The model result shows close agreement between the calculated enthalpy and the measured enthalpy particularly in the later period. Aside from this, the field enthalpy trend of the model is in agreement with the declining trend of the actual field production enthalpy.

Figure 7 also shows the simulated pressure response compared with the actual pressure decline. Again the model pressure response reasonably matched the actual pressure response.

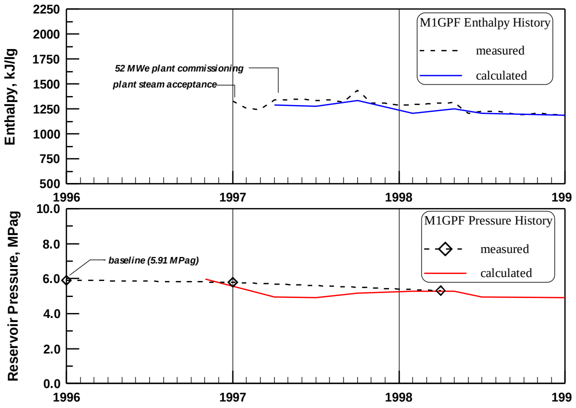

Figure 7. Field enthalpy and pressure history of M1GPF.

FORECASTING RUN RESULTS

After successfully completing history matching, the simulation model was used to forecast the future reservoir performance under the present development scheme for the Mt. Apo field: load increase from 52 MWe to 102 MWe by June 1999. The forecasting run was based on the steam supply from the available 17 production wells and from the 44.6 tons per hour flashed steam supplied by the 900 tons per hour of separated water from M1GPF wells. The separated water is disposed in six injection wells. The forecasting run covered a period of 20 years.

Results of the forecasting run suggest that the 17 production wells are capable of providing the required steam of the two plants at least up to the fifth year of the field's commercial operation (Figure 8). By year 6, overall steam production from the 17 wells will fall below the required 750 tons per hour to approximately 700 ton per hour. This suggests that a make-up well will be required by year 6 to meet the needs of the power plant.

As for the required 900 tons per hour of separated water flow for the second flash, the nine M1GPF wells are enough to supply the requirements of the flash plant for over a period of 20 years.

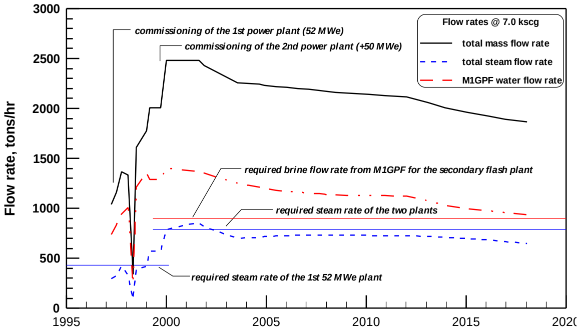

Figure 8. Fieldwide forecast of production flow rates.

CONCLUSIONS

The natural state modeling of the Mt. Apo reservoir reasonably matches the conceptual model of the field. Thus, the obtained model provides a good representation of the field which can be reasonably used for history matching and predicting the response of the field to exploitation.

The model was calibrated against the available production data with reasonable matches being obtained to the flowing enthalpy and to the reservoir pressure response. After successfully calibrating the model, it was used to predict the future field behavior. Results indicate that the 17 available production wells are capable of providing steam for the two power plants up to fifth year of commercial operation of the field. This suggests that a make-up well will be required by year 6 to meet the total plant load requirements.

Though the model has a reasonable match the actual field conditions, some aspects in the model has to be improved. Examples of these are the vapor saturation at the two-phase blocks in the model are to be increased and the temperatures in the first layer in the model are to be reduced. The model can be further improved by (a) assigning aquifers in the top layer to simulated the regional flow of groundwater across the field; this could lower temperatures in the upper layer; (b) add "psuedo-wells" to simulated steam loss to the surface; for better matching of the steam cap and two-phase zone, and further refinement of the grid-block system of the model.

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