NUMERICAL MODELING OF THE HIGH-TEMPERATURE TWO-PHASE RESERVOIR AT UENOTAI GEOTHERMAL FIELD, AKITA PREFECTURE, JAPAN

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ABSTRACT

A three-dimensional, integrated finite-difference numerical model was developed to forecast the behavior of the geothermal reservoir supplying a 27.5 *MW* development at Uenotai in Japan. The model was calibrated in two stages: (1) by matching the initial-state temperature distribution of the field; and (2) by matching enthalpy and flow rate transient histories from a number of wells. Reservoir behavior was forecasted under various production/injection scenarios. The results obtained from these forecasts indicate that the reservoir can provide enough steam for the 27.5 MW power plant for 30 years with the drilling of two additional make-up production wells.

1. INTRODUCTION

The Uenotai geothermal field, located in Akita Prefecture in the northern part of Honshu Island, was developed by Akita Geothermal Energy Company (AGECO), a subsidiary of Dowa Mining Company. Dowa's exploration of the geothermal field began in 1971; to date, more than 55 slim and large diameter wells have been drilled by AGECO, Dowa, and various agencies of the Government of Japan.

Numerous studies of the Uenotai geothermal field have been conducted over the years, including Robertson-Tait *et al.*, (1990), Antunez *et al.,* (1990), Menzies *et al.*, (1990) and others. The numerical simulation presented in this study, based on the conceptual hydrogeological model developed by Robertson-Tait *et al.,* (1990), was carried out in an effort to (a) verify the conceptual model of the Uenotai geothermal system, and (b) confirm that the reservoir can support the 27.5 *MW* development.

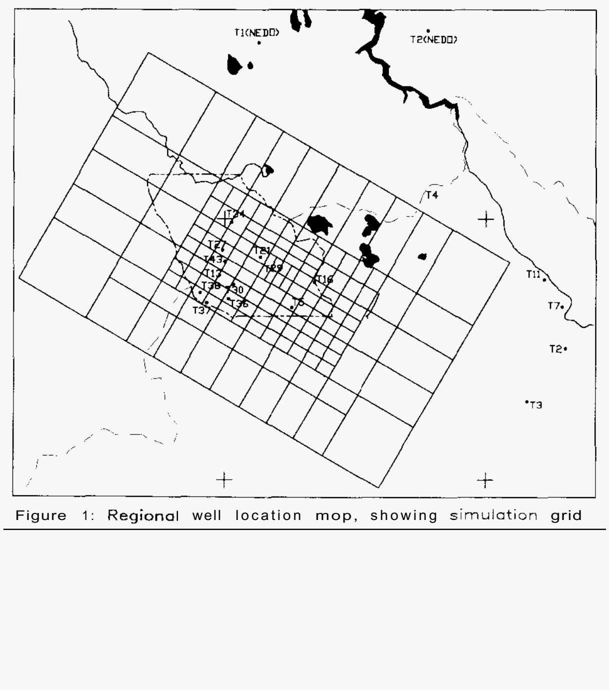

Figure 1: Regional well location map, showing simulation grid

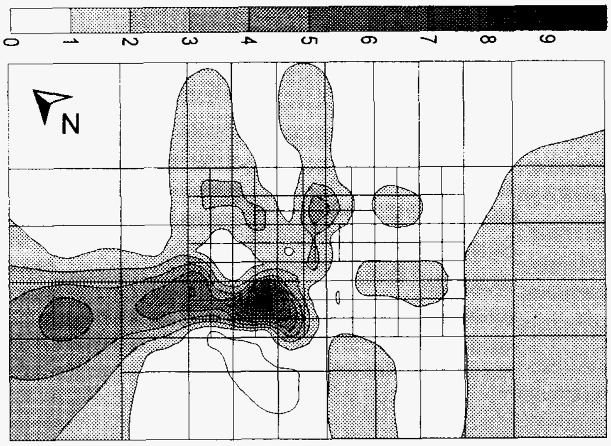

Figure 2: Horizontal permeability distribution (milli-Darcy) at 300 m, msl

2. DESCRIPTION OF THE NUMERICAL MODEL

The numerical simulation model for the Uenotai field was oriented in a NW-SE direction, with the center of the simulation grid coinciding with AGECO's leasehold (Figure 1). The model encompasses a total area of 40 km^2 (with dimensions 8 km in the NW-SE direction by 5 km in the SW-NE direction); as such, it considers a much larger area than the developed leasehold. The larger area was required to ensure a reasonable representation of the overall geological framework of the geothermal system and to reduce the effects of boundary conditions on the simulation model.

Vertically, the model extends from an average topographic surface, of +600 m msl (mean sea level), to -1,400 m msl. The overall thickness of 2,000 m is subdivided into four layers. The first layer has a thickness of 800 m, and the remaining three are each 400 m thick. A total of 557 elements were used in the model. The grid layout was coarse at the boundaries and refined in the central production and injection area, enabling the AGECO wells to be accurately located. Of the 557 elements, six are used as boundary blocks to define heat and mass inflow and outflow from the model. The boundary blocks include:

- two attached to the bottom layer, providing conductive heat flux to the model from below;
- one attached to the side of the bottom layer near the SE comer to supply heat and mass recharge; and
- two attached to the NE and NW sides of the top layer to allow fluid discharge to nearby hot springs subsurface flow of thermal water to the Minase basin.

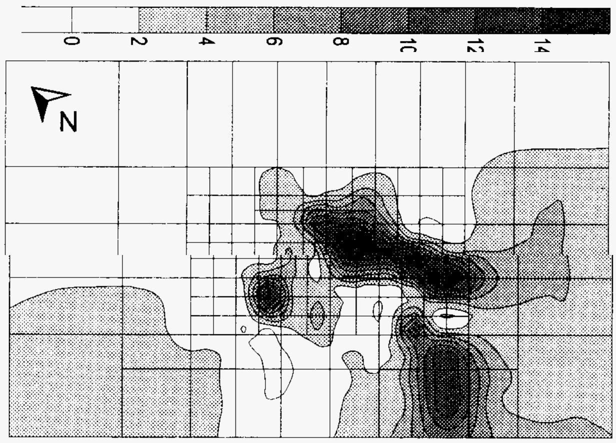

Figure 3: Horizontal permeability distribution (milli-Darcy) at -400 m. msl

3. INITIAL STATE MODEL RESULTS

Heat and mass throughput are required in geothermal systems to maintain thermodynamic conditions within the reservoir. As mentioned above, the Uenotai model includes one recharge source and two discharge sinks. Adjustments were made to heat and mass flux and thermodynamic conditions in these boundary blocks in order to match the subsurface temperature data. After many iterations, it was found that an inflow rate of 10 kg/s (36 tons/hour) was required into layer **4;** the inflowing fluid is two-phase at a source temperature of 367°C. The discharge from the model is split into two sinks located in the ***NW*** and **NE** sides of layer 1, with discharge flow rates of 8 kg/s (28.8 tons/hour) and 2 kg/s (7.2 tons/hour), respectively. The discharge to the ***NW*** represents local hot spring discharges; the **NE** discharge is introduced to match the temperature contours in the area south of the Minase basin.

The permeability distribution used in the final model was the result of numerous simulation **runs** where permeabilities of the rock types were varied until reasonable matches were obtained to the measured temperature distributions at various levels. Figures 2 and 3 show the horizontal permeability distributions used for the first two layers in the model. The rock types used in the model have relatively low horizontal permeabilities, varying from 0.015 milli-Darcy to 15 milli-Darcy. The vertical permeabilities are also relatively low, with a maximum value of *5* milli-Darcy. These values are consistent with the results from the analysis of the well test data described by Menzies ***et** al.* (1990), which showed that the intrinsic permeability of the Uenotai geothermal field is low compared with most geothermal fields.

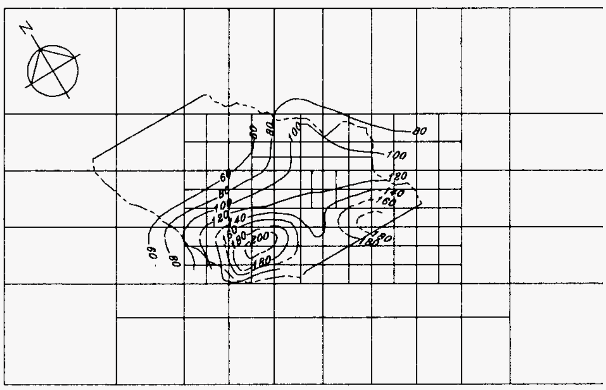

Figure 4 Measured temperature contours at +300m msl, Uenotai geothermal field.

The calculated temperatures in layer 1 (Figure *5),* which corresponds to **an** elevation of +300 m msl, are in good agreement with the observed data shown in Figure **4.** As mentioned above, a total discharge of about 10 kg/s was needed to maintain the calculated temperature distribution in layer 1, with 8 kgls flowing to the ***NW,*** approximating the flow from hot springs in the ***NW*** comer of the leasehold. The temperatures in layer 1 range from 60°C to 200°C, with two high temperature domes in both the measured and calculated data. Figure 7 shows the calculated temperatures in layer 2 , which range from 180°C to 320°C, and they are in good agreement with the contours based on measured data at -400 m msl (Figure 6). Calculated temperatures from the last two layers also agree well with measured data.

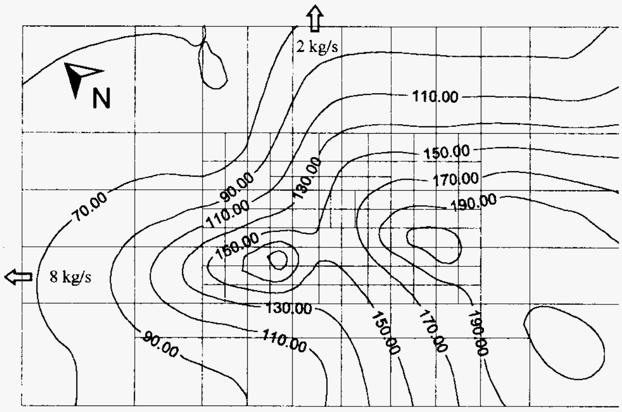

Figure 5: Initial state model temperature ("C) distribution at 300 m, msl

Calculated steam saturation distributions obtained from the model show that slightly two-phase geothermal fluid enters the reservoir through the **SE** comer of the leasehold. Near the production zone of the reservoir, the maximum steam saturation is approximately 50% with the highest values located near the **SE** comer of the lease, as shown on figure 8. Overall, the reservoir is mostly single-phase, saturated liquid with **a** small two-phase area existing in the **SE** comer of the leasehold.

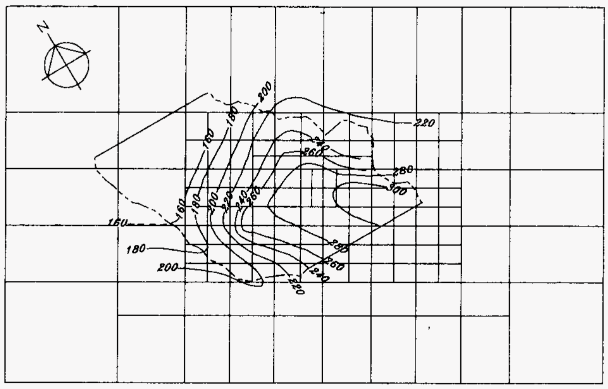

Figure 6: Measured temperature contours at —400m msl, Uenotai geothermal field.

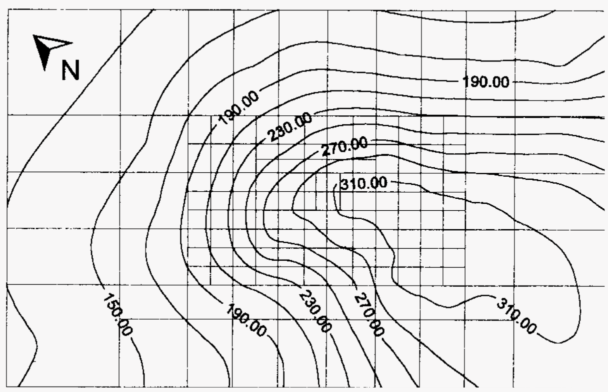

Figure 7 Initial state model temperature ("C) distribution at -400 m, msl

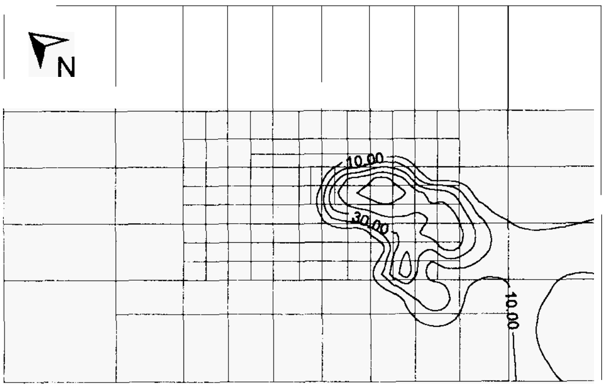

Figure **8: Initial** state model **steam** saturation (%) distribution at -400 m, msl

The results from the initial state model of the Uenotai geothermal system show that after many trial-and-error iterations, a final quantitative model has been derived that satisfactorily matches the initial state of the reservoir using plausible values of permeability and fluid recharge and discharge rates. This model remained stable after a simulated time of a few tens of thousands of years. We therefore believe that the initial state model provides a reasonable representation of the overall geothermal system and provides a valid basis for production history matching and exploitation modeling.

4. WELL TEST MATCHING USING NUMERICAL SIMULATION

Well test data collected during the 1988 flow test have provided both qualitative and quantitative information on reservoir parameters in the Uenotai geothermal field. The data can also be used in the numerical simulation modeling as a way of further verifying or calibrating the initial state model presented above. In this context, the data of most interest are downhole pressure measurements in observation or active wells and enthalpy transients measured in production wells during flow. The aim of well test matching using numerical simulation is to match as closely as possible the measured pressure, flow rate and enthalpy transients. In practice, however, it is not always possible to obtain close matches due to a number of factors, including:

1. Geothermal wells normally produce from multiple **feed** zones, and data are often unavailable for production flow rates or enthalpies from individual zones. Due to this lack of data, it is assumed in simulation modeling that production is occurring from only one layer of the model. Therefore, the output of the simulation model reflects an average condition over the depth range of the assumed production zone.

2. **In** the Uenotai geothermal field, some of the wells tested during 1988 produced fluid from casing breaks **or** leaks at liner laps. Such fluid inflows affect the discharge enthalpy, and the enthalpy measured at the surface may not reflect the true fluid enthalpy at the point of inflow from the geothermal reservoir.

Measured temperatures provide the most reliable calibration criteria for the initial-state modeling. Permeabilities in the x, y and z directions are the main variables used to match the measured temperatures. Once a match is obtained, it is assumed that the model represents the permeability distribution reasonably well. The initial-state match is not very sensitive to storage terms such as porosity. Therefore, well test or production matching provides a way of checking that the storage terms in the model are reasonable. However, well test or production data may be affected by conditions in a relatively small area of the reservoir, and the resulting changes in porosity or permeability may not necessarily apply to the total simulation model. Therefore, in matching well test or production data, it may be necessary to make changes to hydraulic parameters in the immediate area of the active or observation wells.

Within each grid block containing an active well, four concentric cylinders were placed around the well location with the innermost cylinder approximating the wellbore itself. The concentric cylinders provide a transition from the circular wellbore to the rectangular grid blocks that make up the majority of the simulation grid. These cylindrical blocks improve the accuracy of the calculations close to the wells and are also useful for simulating a "damaged" (positive skin factor) or "stimulated" (negative **skin** factor) well. The improved accuracy is particularly important when trying to match enthalpy transients.

Once the above subdivisions were made to the grid blocks, downhole pressure data from the observation wells and enthalpy transients from the production wells were matched by trial-and-error, modifying the initial-state model as required. This process required a significant number of runs of the simulation model.

5. MATCHING THE 1988 FLOW TEST DATA

The two main parameters from the 1988 multiple well flow test that have been used to calibrate the Uenotai geothermal reservoir model are the measured total flow rate and enthalpy from the production wells. **In** using the model to match the discharge characteristics of the individual wells, flow into the well is allowed from all "open" layers. The flow rates are not prescribed but are calculated using the "deliverability" option available in the simulation code. With this option, the well flow rates are calculated based upon the productivity index **(PI)** of the well, the fluid mobility in the vicinity of the well and the pressure at the feed zone. This is expressed mathematically as:

$$q = \sum_{\beta = liquid, vapor} \frac{k_{r\beta}}{\mu_\beta} \rho_\beta \, PI \, (p_b - p_{wb}) \tag{1}$$

where q = flow rate
$k_{r\beta}$ = relative permeability of the β phase;
μ_β = dynamic viscosity of the β phase;
ρ_β = density of the β phase;
p_b = pressure in the well grid block, and;
p_{wb} = flowing wellbore pressure.

The flowing wellbore pressures **(p_{wb})** for the production wells are estimated from the pressure surveys conducted under flowing conditions. The PI is not known but is adjusted along with the permeability and porosity until the calculated flow rate and enthalpy transients match the measured data. **In** general, PI affects the initial flow rate, permeability affects the **final** flow rate, and porosity **is** responsible for the rate and magnitude of the increase in discharge enthalpy.

5.1 Well T-46

T-46 started flowing on 16 September 1988 and was shut-in on 19 December 1988. The flow rate from this well remained reasonably constant throughout the test at **30** tons/hour while the enthalpy, which was initially 540 kcal/kg, increased slowly until the well was producing steam near the end of the test. Observed and calculated data are presented in Figure 9.

A good match was obtained to the measured flow rates from the well, and there was reasonable agreement between measured and calculated enthalpy. The calculated enthalpy trend shows a more rapid rise than the measured data at the start of the test, but is close to the average measured enthalpy for the duration of the test.

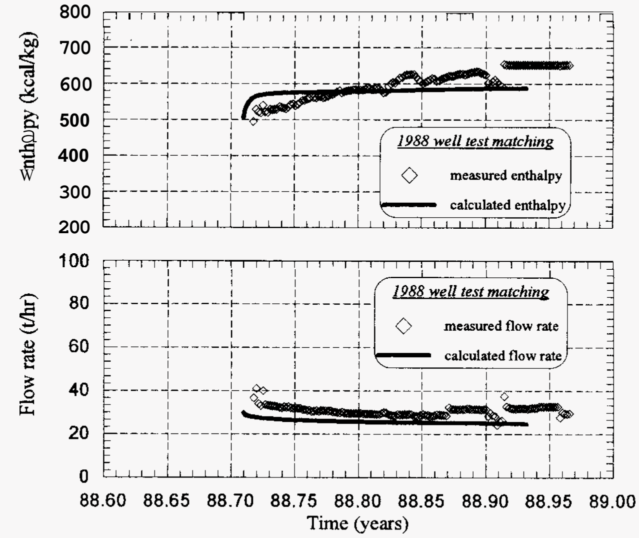

Figure 9: Numerical simulation flow rate and enthalpy match - well T46

T-45 and T-51 showed positive reactions to the flow test. These results are consistent with the measured data, further suggesting that the model provides a reasonable representation of subsurface conditions in the Uenotai geothermal reservoir.

Figure 11 shows the measured and calculated pressure responses of observation well T-45 to production from T-52 and T-53. The plot shows that although the model simulates pressure changes in response to well T-52 at the correct times, it has not been possible to obtain a good match to the shape of the measured response. However, the fact that the calculated response is not significantly affected by T-53 production indicates that the model permeability distribution is reasonable in this area of the field.

The calculated and measured pressure responses in well T-51 are shown in Figure 12. As with well T-45, this well is also mainly affected by T-52 production; the model results also show this. However, as with T-45, it has not been possible to obtain a good match to the shape of the pressure change in the observation well. The difference in response suggests that the porosity used in the model may be too low in this area, reducing the attenuation in the calculated response.

The results of matching the flow test data from the Uenotai project area are considered to be reasonable, as most of the flow rate and enthalpy data of production wells have been satisfactorily matched. The matches to the measured observation well data from the 1992-1993 test show that the model construction is reasonable in terms of permeability distribution; however, it may have been possible to obtain improved matches by using a higher porosity in the vicinity of wells T-45, T-51 and T-52.

5.2 Well T-50

Well T-50 started flowing on 14 September 1988 and was shut-in on 10 December 1988. Initially, the discharge enthalpy rose to near-steam conditions and then dropped to about 430 kcal/kg after about 13 days of flow (Figure 10). The enthalpy later rose again and then decreased to a final value of 410 kcal/kg at the end of the test. Over the same period, the flow rate gradually decreased from an initial rate of 30 tons/hour to a stabilized rate of about 12 tons/hour near the end of the test. As shown in Figure 11, excellent agreement was obtained between the measured and calculated data using the deliverability option.

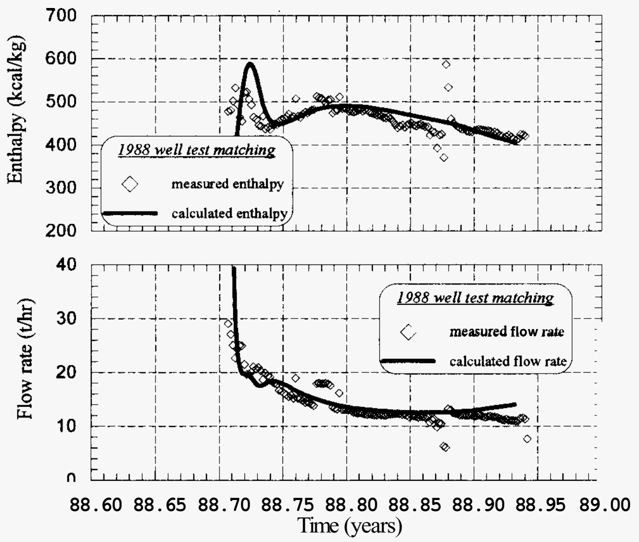

Figure 10: Numerical simulation flow rate and enthalpy match - well T50

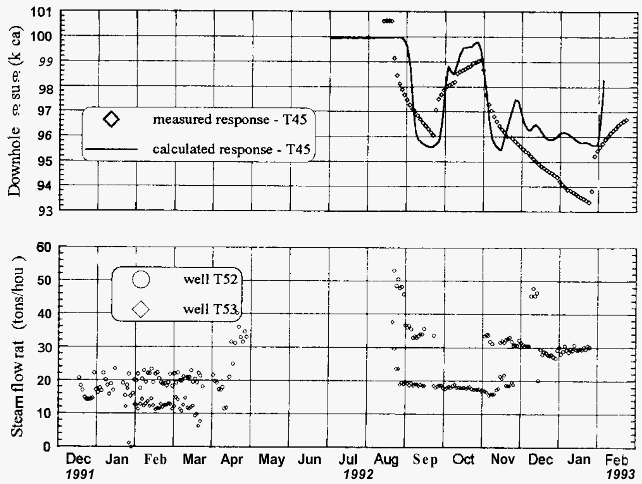

Figure 11: Matching of observation well pressure data using numerical model, Well T45

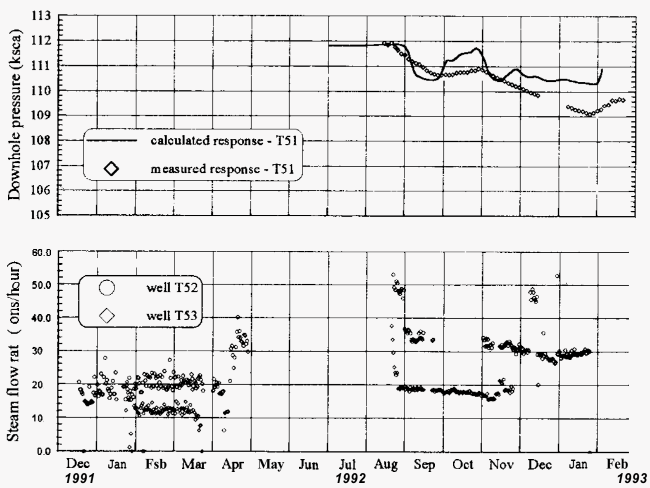

Figure 12: Matching of observation well pressure data using numerical model, Well T51

6. MATCHING THE 1992-1993 INTERFERENCE TEST DATA

Additional data were obtained to further calibrate the numerical model when two new production wells, T-52 and T-53, were tested in 1992-93. As part of the testing, downhole pressures were monitored in nine observation wells at various times.

To simulate the responses in the observation wells, the actual flow rates from wells T-52 and T-53 were input into the model, which was run for the duration of the test. The pressure responses calculated in the wellblocks containing the nine observation wells were then compared to the measured data. In the model, only wells

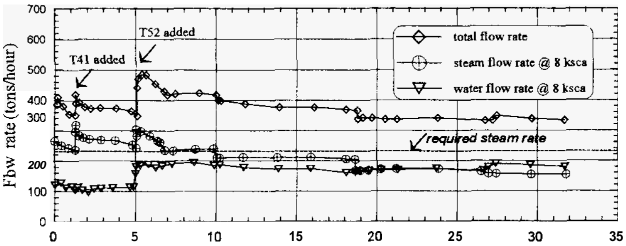

Figure 13: Numerical simulation flow rates **forecast** - scenario 1, Uenotai Field

7. FORECASTING RESERVOIR BEHAVIOR

After calibration by initial-state modeling and well test matching, the simulation model can be used to forecast the overall behavior of the reservoir under any assumed productiodinjection scenario. The ability of the simulator to forecast future behavior accurately is determined by the amount and quality of the data used in the calibration. Therefore, models of this type are generally updated during the life of the project as more production data become available.

The numerical simulation forecast presented in this report is based on steam supply from seven active production wells and two standby wells. Separated water is disposed of using several available injection wells in the leasehold. Based on this exploitation scheme, the model was set up and run for 30 years, and the resulting forecasts of flow rate and enthalpy are shown on Figure 13.

Figure 13 shows the overall steam production rate calculated for the forecast run. The results suggest that the seven active wells are adequate to provide the required steam for the initial power plant start-up. However, it is estimated that one standby well will be required after 1.3 years of production and the other remaining standby well will need to be added after five years. Using this arrangement, the forecast run results show that the wells should be capable of providing enough steam for the 27.5 MW power development for at least 10 years. Thereafter, the model predicts that the steam flow rate will fall below the required flow rate of 230 tons/hour to approximately 205 tons/hour until year 18 and then to approximately 160 tons/hour. This suggests that a make-up well will be required by year 10 and at least one further make-up well will be needed beyond that to maintain the required steam supply.

8. CONCLUSIONS

a. The results from the initial state model of the Uenotai geothermal system show that the initial state of the reservoir has been satisfactorily matched. Thus it is believed that the model provides a reasonable representation of the overall geothermal system and supplies a valid basis for history matching and exploitation modelings.

b. The results from the well test data matching indicate that the numerical model has been reasonably well-calibrated against available data. Minor differences between calculated and measured data for a few wells can be reconciled by further refining the model.

c. Based upon the results from the forecast run, it was found that the currently available nine production wells are capable of providing steam for the 27.5 *MW* power development for at least ten years. Thereafter, the model suggests that two additional make-up wells will be needed to maintain the steam rate required for the 27.5 MW power plant.

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