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MAINTAINING THE RATED POWER OUTPUT OF THE HATCHOBARU GEOTHERMAL FIELD THROUGH AN INTEGRATED RESERVOIR MANAGEMENT

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ABSTRACT

In order to maintain the rated power output of a geothermal power plant, it is required to keep reservoir pressure and temperature constant. This is however difficult because both parameters usually change due to the interference between wells and to the breakthrough of reinjected water into production zones. Reservoir monitoring and numerical simulation are therefore indispensable to keep track of the actual operation condition of the reservoir and to forecast the tendency of future changes in its properties. In fact it is only through reservoir simulation that it is possible to analyze different scenarios to efficiently maintain the rated power output, and to optimize the position of drilling targets and the operation of production and reinjection wells. The first step is to construct a precise numerical model that satisfactorily explains the tendency of the past and present variations of pressure, temperature, and fluid behavior. Then, following steps are addressed to predict future changes of power output by coupling reservoir and wellbore simulators. The results of analyzing different exploitation schemes can provide the optimum well position that will prevent overproduction and/or cooling of production zones.

An integrated reservoir management based on reservoir monitoring techniques and reservoir simulation has been conducted to maintain the rated power output of 110 MW at the Hatchobaru geothermal power plant which is located in northern part of Kyushu Island, Japan. The potential of the reservoirs in Hatchobaru has been studied by means of numerical simulation. A three-dimensional reservoir model was constructed and progressively updated. Now, it is capable of reproducing changes in pressure, temperature, gravity and tracers behavior simultaneously, which are recorded during the reservoir monitoring and periodical well tests. Numerical simulation showed that the reservoirs in Hatchobaru are capable of sustaining power facilities of the capacity around 120 MW. Therefore, the present exploitation is equivalent to the 92% of this power potential. However, in the case of no future make-up drilling, the power output is predicted to drop to 80 MW within 5 years. It was disclosed that the reason for this is the current overexploitation of one of the main productive faults. A scenario to maintain the rated power output was devised. This scenario permitted the optimization of future production and reinjection targets taking into consideration the power potentials of each productive fault. In this paper, studies of optimizing the scenario of power maintenance in the Hatchobaru geothermal power plant are introduced.

1. INTRODUCTION

The Unit No.1 (55 MW) of the Hatchobaru geothermal power plant started commercial operation in 1977 and Unit No.2 (55 MW) in 1990. The combined total rated power output of both units is 110 MW. The reservoirs are of the water-dominated type and have been tapped at depths between 1000 m and 1800 m. The reservoirs are controlled by 5 main productive faults namely: Komatsuike Fault, Komatsuike-sub Fault, NE3 Fault, NE4 Fault and Hatchobaru Fault. The total mass rate being extracted from the reservoirs using 26 production wells is around 560 kg/sec and the total mass rate being reinjected back into the reservoir using 10 reinjection wells is around 280 kg/sec. The turbine inlet pressure of Units No.1 and No.2 is 0.6 MPa.a and 0.7 MPa.a, respectively. Depending on the pressure loss between wellheads and turbine, the wellhead pressure of production wells in average is 0.8 MPa.a.

Both units are operated for a total reinjection of waste water at about 90 degrees C and at atmospheric pressure. The reinjection strategy adopted is to separate the production and reinjection zones so that the northern part of the field is used for reinjection and the southern part for production. However, a partial return of the reinjected hot water to the production zones has been experienced and corroborated by tracer testing and by monitoring of the Cl concentration. This breakthrough of cold water has caused a drop of reservoir temperature and consequently, the productivity of some wells has gradually been reduced (Mimura et al., 1995). In order to measure the changes in the reservoir pressure and temperature, downhole monitoring using a capillary tubing system has been continuously conducted since 1998 at several observation wells. Monitoring of gravity changes has also being carried out since 1990 on 46 benchmarks covering most of the Hatchobaru exploitation area of around 2 km^2. Gravity measurements are carried out every three months using a Sintrex CG-3 gravimeter (Tagomori et al., 1997). The changes of reservoir temperature and their distribution all over the area are estimated by applying the silica, Na-K, and Na-K-Ca geo-thermometers and the results of chemical analysis of discharged fluids sampled in production wells every six months. In addition, tracer tests have been periodically carried out to investigate the return rate of reinjected water to production zones. The information derived from reservoir monitoring and tracer tests has been important to refine the numerical model of the reservoirs.

2. SCENARIO OF POWER RECOVERY

2.1 Tendency of Power Decline

The power output rapidly declined from 110 MW to 70 MW within 4 years soon after the commissioning of Unit No.2. Results of pressure monitoring have indicated that a complicated change in pressure usually occurs due to interference among wells. The pressure drawdown of more than 0.5 Mpa in the production zones for Unit No.2, detected soon after this Unit commenced commercial operation, propagated to the reinjection zones allocated to this unit. The reservoir pressure decline also affected by 0.4 MPa the production zones for Unit No.1, and propagated into its corresponding reinjection zones. This cause and effect relationship showed that the pressure fronts were able to propagate to reinjection zones located as far as 1km from the production zones of Unit No.2. The conclusion of reservoir simulation conducted using TOUGH2 (Pruess, 1991) was that an average pressure reduction of 0.9 MPa in the production zones for Unit No.2 and of 0.5-0.7 MPa in those allocated to Unit No.1 occurred within three years due to an increase of the mass extraction from 420 kg/sec to 560 kg/sec (Kawazoe and Tokita, 1993). Although the reservoir temperature already decreased as a consequence of the reinjection since Unit No.1 commissioned its operation, the tendency of decreasing the reservoir temperature was also accelerated after the commissioning of Unit No.2 due to the increased return of reinjected water to the production zones of both units, No.1 and No.2. Results of tracer tests indicate that the reinjected water partially returns to the production zones through faults, and that the rapid return from some reinjection wells is the cause for the steep power decline (Tokita et al., 1995). The countermeasure to this problem was to relocate the reinjection zones far away from production zones to prevent their cooling.

2.2 Verification of the Scenario of Power Recovery

Fig.1 shows results of calibration by matching the monitored changes in reservoir pressure, temperature, gravity, and the tracer behavior to simulator's outputs. Simulated gravity change at each gravity measurement point can be obtained by converting the simulated total change of fluid density, which is integrated from the surface to bottom blocks of the model, into a gravity value. The tracer concentration of each block of the model can be calculated using the following equation.

$$Ct = \frac{Mt}{Mrt} \times Xrt$$

where
Ct: Simulated tracer concentration of each block
Mt: Mass of injected tracer
Mrt: Mass of reinjected water including tracer
Xrt: Simulated mass fraction of reinjected water including tracer of each block

As shown in this figure, partial success in satisfactorily matching results with monitoring data of pressure, temperature, gravity changes and tracer behavior was obtained. However more work is required because not all of the grid blocks with measured data have yet reached an acceptable match. Currently endeavors are being addressed to complete a more representative numerical model through progressive refinements. Fig.2 shows the prediction of the scenario for power recovery. In this figure, the actual variations of power output are presented together with the simulated values for comparison. To accomplish the prediction of this scenario and to bring the power output back to 110 MW, three activities were necessary. One was to maintain a distance of more than 500 m between production and reinjection zones, which might be difficult to accomplish due to the limited exploitation area of around 2 km^2 in Hatchobaru. The second was to stop reinjection operation at well 2HR-2 because its reinjected water rapidly returns to the production zones of Unit No.1 and causes a cooling of fluids at the northern part of Komatsuike-sub Fault, one of most productive faults. The third activity was the drilling of a total of six to seven make-up wells within five years. Based on these requirements, in 1992, most of the reinjection targets were actually moved at least 500 m from the production zones toward the north of the power station. The reinjection operation at well 2HR-2 was also suspended. The positive effect of relocating reinjection targets was corroborated by the reservoir monitoring data, showing a recovery in the silica temperature and a decrease in the Cl concentrations. The temperature monitored at observation well H-7, located near the reinjection zones, shows that its recovery rate is 0.9□ per year from the time the main reinjection zones were relocated. Furthermore, the results of tracer tests, conducted after the relocation of main reinjection zones, indicate that maximum tracer concentration in produced fluids has been kept below 10 ppb. This concentration is quite a low compared to the concentration of several tens or hundreds of ppb recorded before the relocation. When the additional six wells were completed and incorporated to the steam gathering system in 1997, the power output was successfully brought back to 110 MW. As shown in Fig.2, the simulated recovery of power output matches in general terms, the actual recovery. This validates the reliability of the numerical model and confirms the practical utilization of numerical simulation as an indispensable tool for reservoir management (Tokita and Haruguchi, 1998).

3. SCENARIO OF POWER MAINTENANCE

3.1 Prediction of Power Output without Make-up Wells

Forecast simulations were carried out to predict the change of power output and to make sure that the rated power output of 110 MW could be maintained in the future without drilling make-up wells. However, the predicted power output declined to around 80 MW within eight years (Fig.3). Fig.4 shows the predicted change of power output per tapped productive fault.

It is worth noticing that only the power output from the NE3 Fault alone showed a remarkable decline from 43 MW to around 24 MW before attaining stabilization, while that for other productive faults showed almost stable performance or a slight decline. Thus, it is inferred that the sustainable power potential of the NE3 Fault is around 24 MW and that currently it is being 19 MW overexploited due to the concentration of wells tapping this fault (Tokita and Haruguchi, 1998). It will be therefore, necessary to drill make-up production wells to maintain the rated power output in the future. This drilling should be done during the time in which the NE3 Fault declines towards its sustainable production condition.

3.2 Power Potential of Total and Each Productive Fault

In order to devise an optimized scenario for maintaining the rated power output by drilling make-up wells, the knowledge of the sustainable power potential of each productive faults is necessary. This potential was estimated in a similar way as it was applied for the NE3 Fault. As far as the Komatsuike-sub Fault and Hatchobaru Fault are concerned, almost stable or slight overproduction conditions are currently present. This conclusion comes from the remarkable interference effects among the wells tapping these faults. The sustainable power output of the Komatsuike and NE4 Faults is unknown. This potential was studied considering three tentative scenarios in which, respectively, a total of 17, 26 and 31 make-up wells are supposed to produce simultaneously from these faults. Both, number of wells and distance between bottom holes of them (100-200 m) were taken regardless of the number of wells that could be drilled from existing drilling pads. The simulated total power output temporally reached 190-265 MW depending on the number of assumed make-up wells, however, as shown in Fig.5 in all of the three scenarios a power decline is experienced as time passes by until it stabilizes at around 120 MW. These results indicate that the sustainable power potential of the Hatchobaru reservoirs would be approximately 120 MW. It is also shown that it will be possible to maintain the rated power output of 110 MW if the targets for production make-up wells are selected in such way so as not to overproduce the faults beyond their sustainable power potential. The sustainable power potential of each of these productive faults ranges from 13 to 52 MW. The sustainable potential of the Komatsuike and NE4 Faults is estimated in 52 MW and 15 MW respectively.

3.3 Scenario of Power Maintenance Based on the Optimized Well Allocation

Fig.6 shows the optimum target zones for production make-up wells, and Fig.7 shows the predicted power output based on the above scenario of optimized production make-up wells. The result suggests that in order to maintain the rated power output it is necessary to compensate the power decline in the NE3 Fault while it reaches its sustainable power output of 24 MW by the year 2003. To do this compensation a total of three make-up wells have to be drilled in a period of three years targeting the optimum locations mentioned in the previous section. According to this scenario, the power output will be 110 MW again by the year 2003. Consequently, all of the productive faults are expected to attain almost sustainable conditions within their own power potentials, and then the total power output will naturally come to nearly steady conditions as shown in Fig.7 The reservoir simulation indicates that the rated power output can be maintained with few make-up wells after the year 2003.

The case studies also dealt with the optimum location of reinjection targets. This location should be effective not only to prevent production zones from cooling but also to sustain the reservoir pressure in the production zones. This is not a straightforward task because it represents the balance between two competing conditions: one is to keep enough distance between reinjection and production zones to prevent breakthrough of reinjected water and the other requires to shorten this distance to sustain the reservoir pressure. Thus, the task was to find the appropriate distance between production and reinjection zones within the limited area of 2 km^2 of the Hatchobaru power plant site. To search for this distance four alternative reinjection zones were tested, namely: A-zone, B-zone, C-zone and D-zone (Fig.6). In order to choose the best reinjection zone among these four alternatives, we simulated each of them to compare the resulting changes in power output assuming that all the reinjection wells were concentrated in the A-zone, B-zone, C-zone, and the D-zone, respectively. As shown in Fig.8, the results suggest that the most effective reinjection zone would be the A-zone, which is the farthest from the production zones. This result enhances the need of keeping as much distance as possible between production and reinjection zones within the exploitation areas of limited size in order to maintain the power output more effectively. In practice based upon these results, most of the reinjection targets have been relocated in the optimum A-zone as much as possible. The forecasted power output considering the relocation of reinjection targets resulted similar to that of the scenario for the A-zone.

Fig.9 shows the simulated distribution of tracer concentration after 20 days since tracer injected into the well 2HR-9, which is one of the main reinjection wells, located in the A-zone along the Komatsuike Fault. The reinjection rate in this well is 90kg/sec, and the reinjection depth is 1,340 m. This depth is relatively deep compared to that of other reinjection wells, because it was necessary to reach the target located as far away as possible from the production zones. The simulated tracer behavior indicates that the reinjected water migrates to deep levels by flowing fault paths. Accordingly, it is expected that there is a threat of affecting deeper production zones by reinjecting into deep zones. However, the detected concentration of tracer return was less than several ppb suggesting a limited breakthrough of reinjected water into the deep reservoir. Although the tendency of invading of reinjected water to deep production zones has still continued in spite of the relocation of the reinjection targets, the silica temperature indicates that the temperature of reinjected water has increased during its flow along fault paths at deep levels.

Fig.10 shows simulated temperature distributions and the simulated expansion of reinjected water for years 1984, 1991, 1998 and 2005. It is possible to appreciate in this figure that the expansion of reinjected water front drastically accelerates after the commissioning of Unit No.2 in 1990, and that by 1998 the extent of this propagation has expanded compared to that in 1991.

Although the propagation of reinjected water front will be still persistent in the future at deep levels, the cooling effects are believed to be smaller than that when reinjection was conducted at shallower levels. This is because there is a positive effect of temperature increase of reinjected water migrating towards production zones at deep levels, which is actually corroborated by the monitored silica temperature.

4. CONCLUSIONS

1) In order to maintain the rated power output of the geothermal power plant, it is highly recommended to conduct an integrated reservoir management consisting of two main group of activities; monitoring of reservoir properties and numerical simulation. The first group of activities will serve to construct a reliable numerical model satisfying all observed physical and chemical changes in the reservoir. Succeeding in the construction of such reliable model, it will be possible not only to analyze all sort of appropriate scenarios based on more precise prediction of the power output but also disclose the optimum location of production and reinjection wells.

2) For the Hatchobaru geothermal field, this integrated reservoir management has been carried out. Monitoring of reservoir properties such as pressure, temperature, gravity, chemical characteristics of discharged fluid and tracer behavior has been conducted. Three dimensional reservoir simulations were carried out to disclose the best scenario for recovering and maintaining the power output. We actually succeeded in recovering the power output from a declined value of 70MW, which occurred after the Unit No. 2 had commissioned the operation, to the rated power output of 110 MW. This recovery was the result of adopting the best scenario resulting from the analysis, through reservoir simulation of different case studies.

3) The power output is however predicted to gradually decline because the NE3 Fault is considered to be currently overexploited. The reservoir simulation indicates that the sustainable power potential of the NE3 Fault is around 24 MW, while it is now being exploited at 43 MW. With time the total power output is predicted to decline until the production from the NE3 Fault attains its sustainable value. Other productive faults in the Hatchobaru geothermal field resulted to be producing within their sustainable power potentials.

4) Defining a predicted sustainable power potential of a fault as that obtained by reservoir simulation, for the productive faults in the Hatchobaru geothermal field, this potential is estimated to be in the range of 11 to 55 MW. The total power potential of the Hatchobaru reservoirs can be therefore estimated to be around 120 MW. It implies that it is possible to maintain the rated power output of 110 MW if the location of production and reinjection wells is optimized based upon the sustainable power potential of each productive fault.

5) Results of case studies provided the optimized targets of make-up production wells so as not to overexploit the productive faults beyond their sustainable power potential. In addition the results enhanced the need to take as much distance as possible between reinjection and production zones to prevent production zones from cooling.

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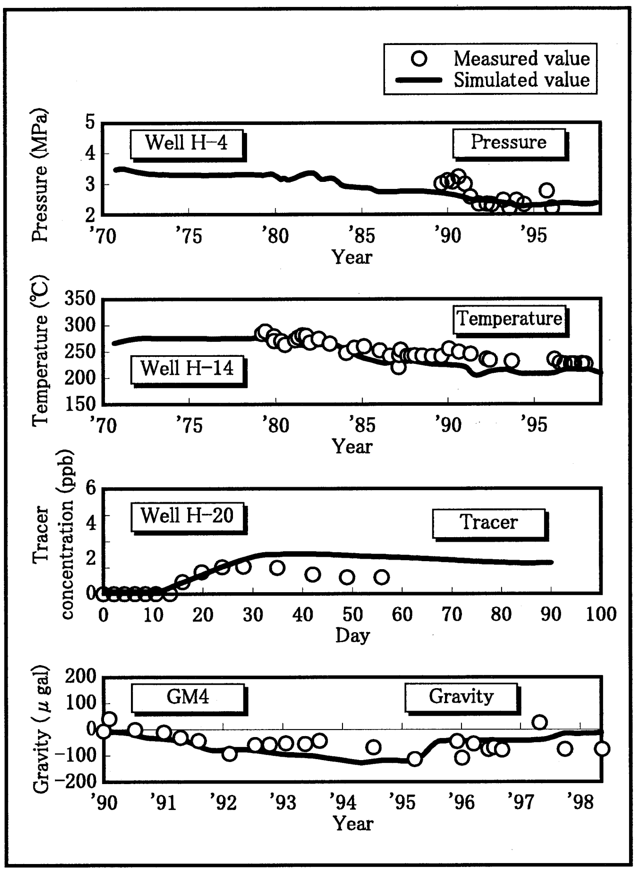

Figure 1 History matchings with reservoir monitoring data

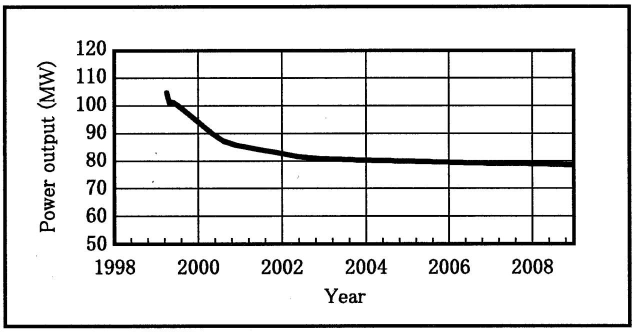

Figure 3 Predicted future decline of power output without make-up wells

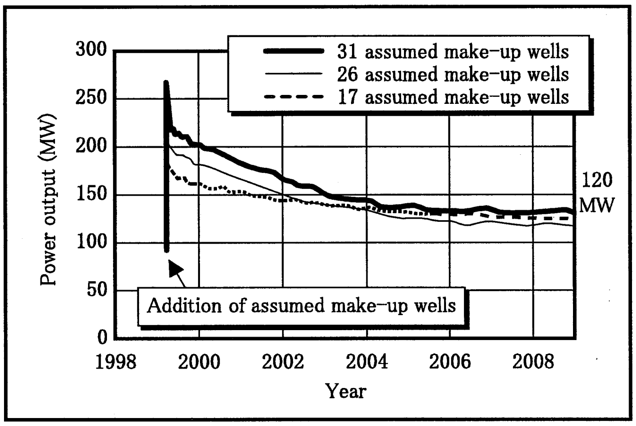

Figure 5 Case studies for evaluating power potential of the Hatchobaru reservoirs

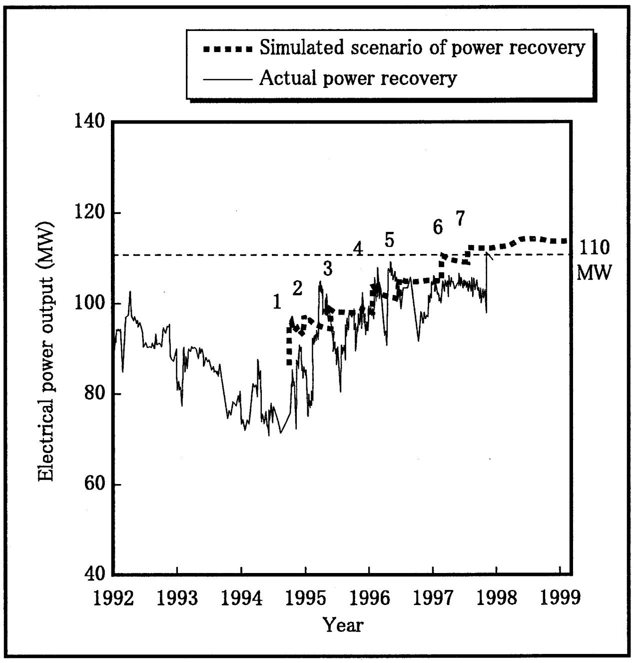

Figure 2 Comparison between simulated scenario of power recovery and the actual one

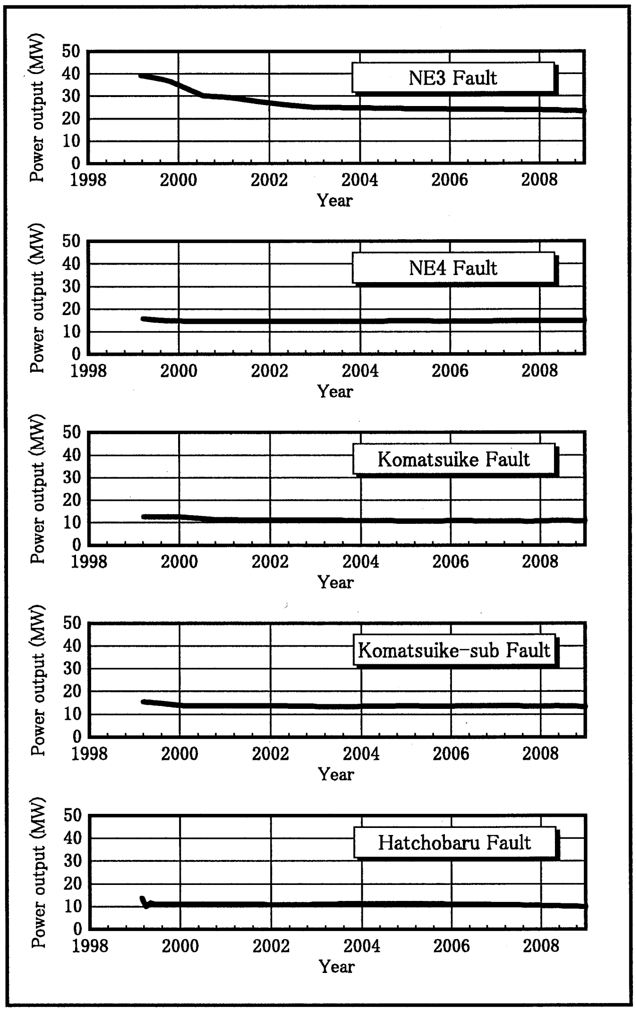

Figure 4 Predicted future decline of power output of each productive fault without make-up wells

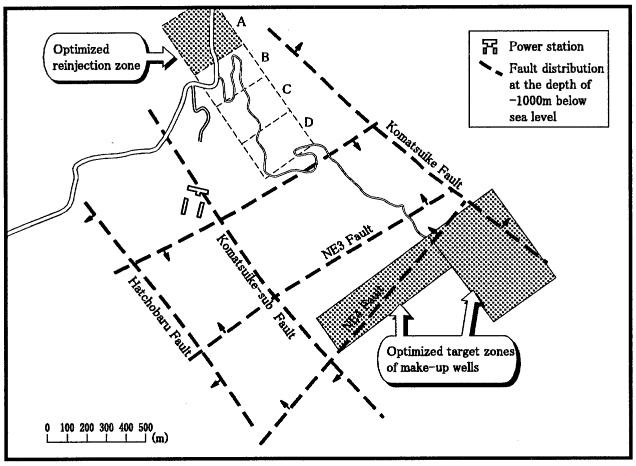

Figure 6 Optimized target zones of make-up wells and optimized reinjection zone

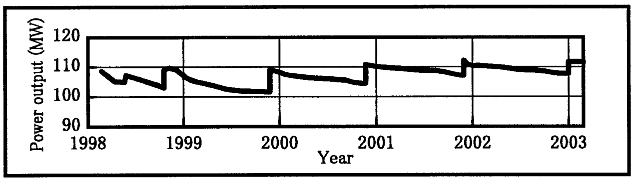

Figure 7 Predicted power output based on the scenario of optimized make-up wells

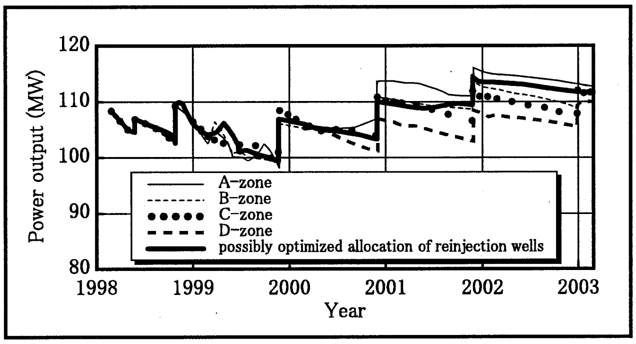

Figure 8 Case studies for optimizing reinjection zone

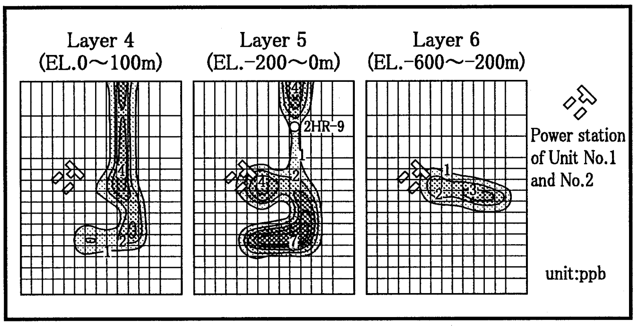

Figure 9 Simulated distributions of tracer concentration after 20 days since tracer injected into the well 2HR-9

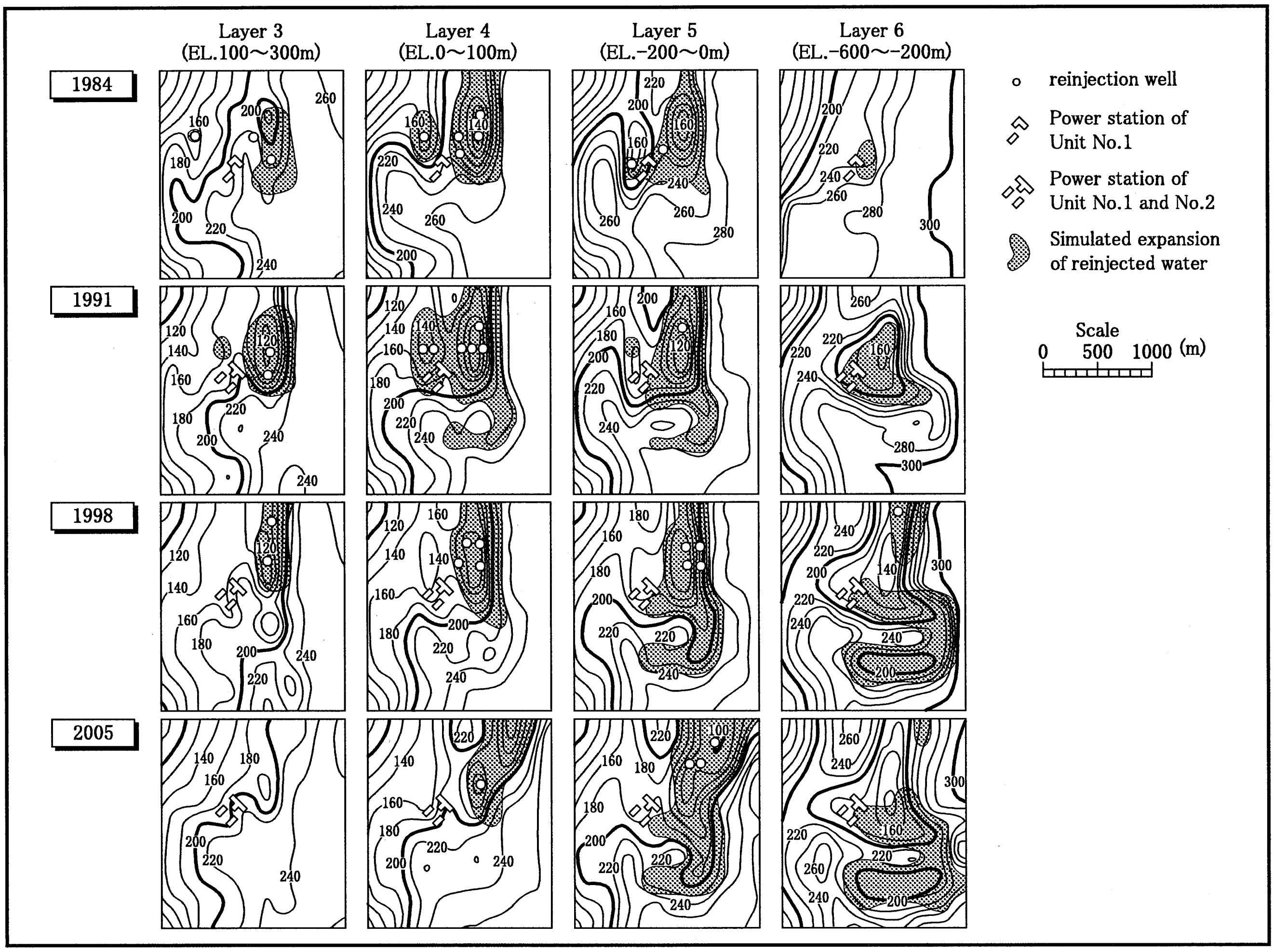

Figure 10 Simulated temperature distributions with simulated expansions of reinjected water in 1984, 1991, 1998, and 2005