EVALUATION OF THE DEEP-SEATED GEOTHERMAL RESOURCES IN JAPAN

T. TOSHA[1], K. KOIDE[1], H. TOKITA[2] & T. SATO[3]

[1]Geothermal Research Centre, NEDO, Tokyo, Japan
[2]Geothermal Department, WJEC, Fukuoka, Japan
[3]Technical Department, GERD, Tokyo, Japan

SUMMARY - Stochastic analyses were conducted to estimate the reservoir parameters such as temperature, pressure, and permeability in the deep reservoirs. The validity of the stochastic analyses was examined by comparing the parameters derived from a numerical simulation with a conceptual model of the geothermal field. The resources of the deep reservoirs in several geothermal fields are estimated and summarised by comparing these with shallow reservoirs. The deep-seated geothermal resources are possible and exploitable and may increase the output of the geothermal power plants.

1. INTRODUCTION

Deep-seated geothermal resources are expected to be present at a depth of about 2,000m or deeper and may contribute to the immediate growth of geothermal power generation in Japan. The Deep-Seated Geothermal Resources Survey (DSGR) Project conducted by New Energy and Industrial Technology Development Organization (NEDO) aimed to assess deep-seated resources and evaluate the feasibility of their utilisation and exploitation. The project started in the 1992 fiscal year (FY) and was completed in 2000 FY. In the first part of the project (1992FY-1998FY), a deep exploration well, WD-1, was drilled at Kakkonda. Three studies were planned for the project. One of the studies is a detailed field survey using the exploration well to investigate three basic factors of geothermal resources: heat supply, geothermal fluid supply, and highly developed fracture systems, so that the overall geothermal system including both shallow and deep reservoirs is well described. The others are a study of drilling techniques to extremely high temperatures and pressures in deep geothermal reservoirs, and a study of deep geothermal fluid utilisation. The progress of the project has been reported (e.g. Koide et al., 1999).

In the second part of the project, the deep-seated geothermal resource in the other fields were compared with the survey results from Kakkonda and numerical simulations. In order to evaluate the resources in the deep reservoirs, reservoir parameters such as temperature, pressure and permeability are necessary. This study aims to present various estimation methods of the reservoir parameters to evaluate the resources in the deep reservoir and potentials of the deep-seated geothermal resources at several geothermal fields in Japan.

2. METHODS

Conceptual models were constructed to evaluate the resources with the reservoir parameters. We made two conceptual models one for northeast Japan and the other for Kyushu Island as they have different tectonic settings. The reservoir parameters (temperature, pressure and permeability) at the deep reservoirs were estimated using the extrapolation and the relaxation method with logging data, which had been acquired from shallow wells.

2.1 Conceptual models

The geology of Japan is complex and the geological settings in the northeast Japan and Kyushu are quite different. Northeast Japan is situated in a compressional tectonic regime, and Kyushu is situated in an extensional tectonic regime. Because of the differences, two kinds of conceptual models (model-A and model-B) are examined. Taking into account how the convection flow forms in the conceptual models, the reservoir volume and flows are essential features.

In the model-A, knowledge of the reservoir volume is essential. The horizontal area of the reservoir was calculated by the geological and geochemical data from the surface. The thickness of the reservoir was estimated by the vertical temperature profile. The temperature of 400°C was assumed as the lower boundary of the reservoir as there were no convective flow beneath this temperature based on results from Kakkonda. The upper boundary was concordant with the lower boundary of the shallow reservoir. Model-A was applied to the geothermal fields where the fracture systems are highly developed.

In the model-B, ascending fluid from the basement rocks as well as the lateral flow above the top of the basement are necessary to create stable convection in the reservoir. The supply of the flow from the basement rocks was assumed using the results of a numerical simulation on the shallow reservoir, The supply was adjusted to maintain convective flow in the reservoir, coinciding with observed well data. Model-B was applied to the geothermal fields controlled by large faults. It is hard to estimate the effective volume of the reservoir in the model-B as the permeability of the reservoir is very large compared to that in the model-A.

2.2 Estimations of temperature

Temperature was estimated by the extrapolation and relaxation methods using temperature-logging data in shallow wells. The simplest way to extrapolate the temperature profile is to calculate the temperature gradient between the surface and the bottom hole and to extrapolate it to the target depth. Another way to extrapolate temperature profiles is by using the gradient defined near the bottom. The assumption that temperature should be constant after it reaches –650 °C was applied; at hotter temperatures rocks begin partial melting. The boiling temperature of water at each depth was also used to modify the estimated temperature profiles. In model-B this method was used and the estimated temperatures were concordant with the precise analysis.

The relaxation method is one of the repetition methods used to calculate the distribution of geophysical parameters such as temperature. Tamanyu et al. (1995,1996) applied this method to the temperature data obtained from geothermal well logging and estimated deep subsurface temperature in the geothermal fields. If the subsurface temperature is in equilibrium, Laplace's equation for temperatures should be satisfied,

$$\nabla^2\phi = 0 \qquad (1)$$

where ϕ is temperature. If temperatures are rewritten using finite differences in Figure 1, the temperatures at the 6 lattice points are substituted for that at the central lattice point.

$$\phi_{(i,j,k)} = \frac{1}{6}(\phi_{(i-1,j,k)} + \phi_{(i+1,j,k)} + \phi_{(i,j-1,k)} + \phi_{(i,j+1,k)} + \phi_{(i,j,k-1)} + \phi_{(i,j,k+1)}) \qquad (2)$$

When the temperatures at the boundary of the target region are given, we can estimate the temperature at any point in the target region using the above equation.. The calculation will be terminated when the convergence is achieved to a desirable level.

$$\sum_{i,j,k} w\left|\phi^{n}_{(i,j,k)} - \phi^{n-1}_{(i,j,k)}\right| < \varepsilon \qquad (3)$$

where $\phi^{n}_{(i,j,k)}$, w, and ε stand for temperature after n-th iteration, coefficient of relaxation and conversion error, respectively. Shiga et al. (2000) showed the details of the above methods in the DSGR project.

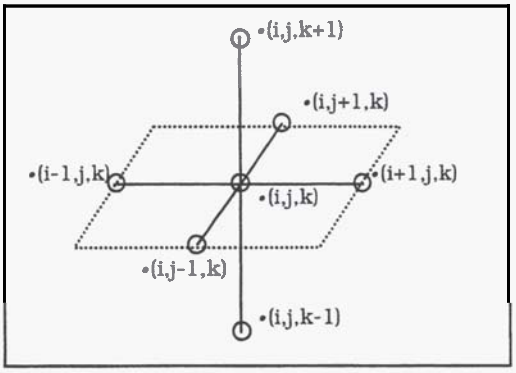

Figure 1. Three-dimensional grid for relaxation method

2.3 Estimations of permeability

Several methods were also tested for the permeability estimations in the geothermal reservoir. We at first estimated the permeability using the relationship between porosity and the depth. The porosity data were obtained by the analyses of the core samples. The permeability-thickness of the layer (kh) was also analysed by plotting kh versus depth. As the kh decreases the depth increases. A continuous relationship was applied to the logarithm plot between kh and depth.

Another method to estimate the permeability is the analysis by the ascending fluid flow. Turcotte and Schubert (1982) showed temperature distribution along the ascending fluid as follows;

$$T = T_r - (T_r - T_0)\exp(\rho \cdot C \cdot v \cdot z / \lambda) \qquad (4)$$

where T, Tr, and T_0 are temperatures at depth of z, at the reservoir, and at the surface, respectively. Symbols ρ, C, v and λ stand for density, specific heat at constant pressure, velocity of the fluid and thermal conductivity of rocks in the reservoir, respectively. Symbol z denotes the depth. The above equation can be translated to another equation;

$$\log(T_r - T) = \log(T_r - T_0) + m \cdot z \qquad (5)$$

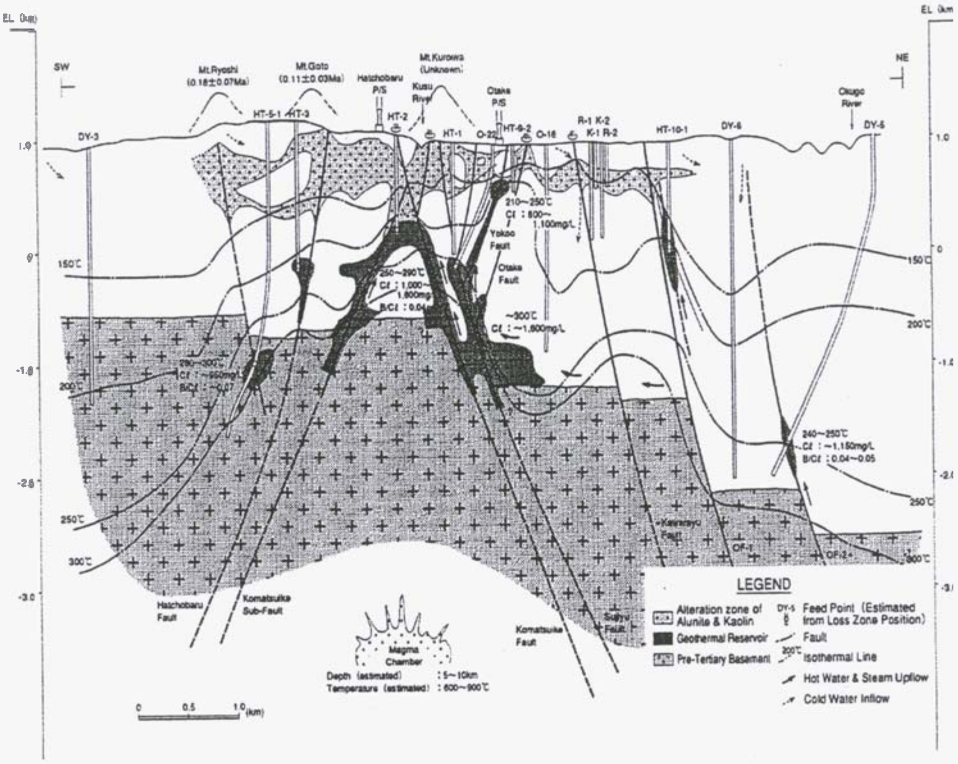

Figure 2. Conceptual model for the Otake-Hachobaru geothermal field, Kyushu Island

where $m = \log(\rho \cdot C \cdot v / \lambda)$. We can estimate the velocity of the ascending flow from the gradient of the relationship between temperatures and depth. The velocity can be translated to permeability (k) using the following equation;

$$k = \mu\, v / \Delta P \qquad (6)$$

where μ *and* ΔP are the viscosity coefficient and initial pressure gradient, respectively. Hanano and Kajiwara (1999) applied this method to the Kakkonda geothermal field and discussed the difference of the permeability between the shallow and the deep reservoirs.

3. EVALUATION OF THE ESTIMATED PARAMETERS

In order to evaluate the reservoir parameters estimated by the stochastic analyses, a precise numerical simulation was executed. The validity of the conceptual models was also examined in the simulation, where the simulator TOUGH2 (Pruess, 1991) was used with the EOS11 option. The EOS11 allows the numerical simulations up to 2000°C and 2000bar (Kissling and White, 1999).

Figure 2 shows a plan view of the grid design for the precise model in the Otake-Hachobaru geothermal field (after Momita et al., 2000). The model covers 7.8 km x 7.4 km around the geothermal field, as the wider area is necessary to obtain the precise distribution of the reservoir parameters in the reservoir. In the Uenotai geothermal field the precise numerical model covers 10 km x 12 km (Sato et al. 2000). More than 100 models were examined to establish whether convective flows were excited in the reservoir. The natural states were obtained after 10,000-1,000,0000 yrs calculation and the best model was selected judging from the difference between the calculated results and the borehole measurements.

Temperature and permeability obtained by the stochastic analyses were compared with those estimated from the numerical simulation. The simple extrapolation method, which calculates the temperature gradient from the surface and the bottoms of wells directly, gave deep reservoir temperatures that were too high. Temperature profiles were estimated using the plot for the boiling temperature versus the depth in model-B. The profiles were concordant with those calculated by the numerical simulation (Figure 3). The relaxation method was also useful to estimate the temperature distribution and the results using the method matched the simulation.

The permeability distribution inferred fiom the numerical simulation were concordant with the estimations fiom the logarithm plots between kh (permeability-thickness of layer) and depth. The analysis of the ascending fluid flow has also presented good results and were concordant with the simulation results. We applied the ascending flow analyses and the estimation using the logarithm plots to the model-A and model-B, respectively.

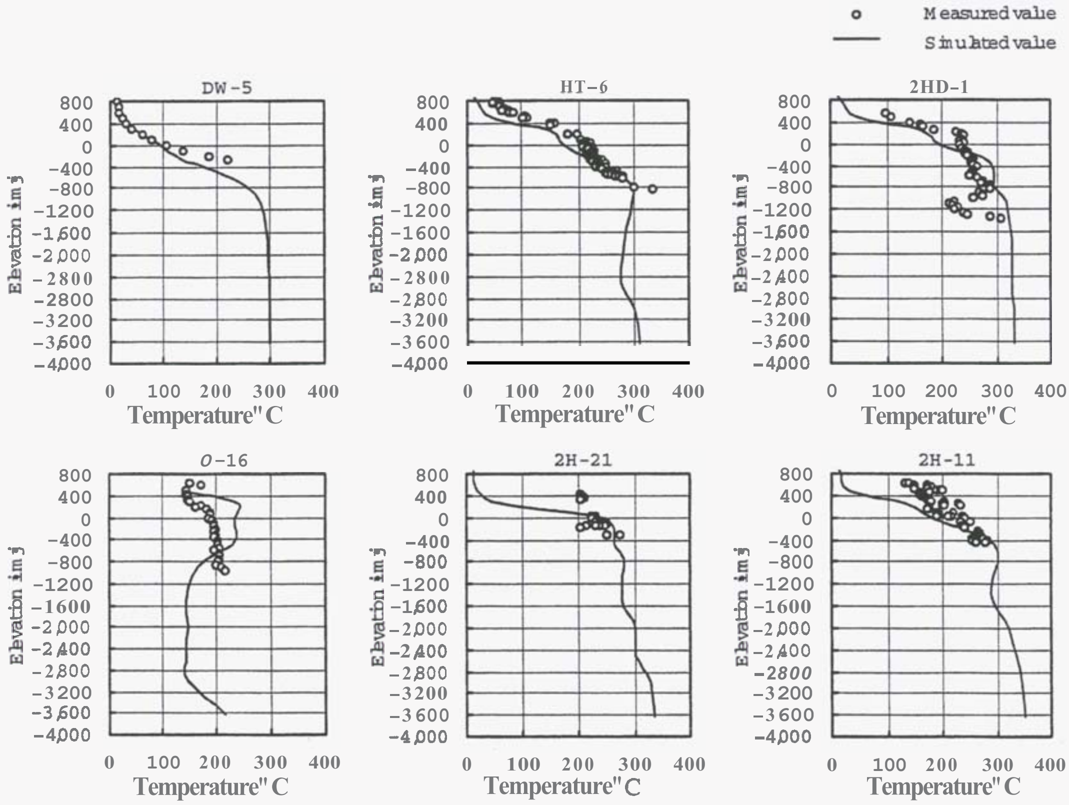

Figure 3. Comparison of measured and simulated temperature profiles for wells in the natural state

4. POTENTIAL OF THE RESERVOIR

After the reservoir parameters (temperature, permeability, and pressure) were estimated, the potential of the deep seated resources was evaluated with a simple numerical model. In conceptual model-A, the shallow reservoir, which is used by the geothermal power plant, is tentatively defined as the 0-2,000m depth interval and the deep reservoir is defined as the 2,000-4,000m depth interval. In the simple model, the deep reservoir was divided into 3 layers and the grid block size in the production zone is 250m x 250m as shown in Figure 4.

The production wells are located at a depth of 3,000m in the middle layer. The well head pressure during the production and the productivity are assumed to be 0.6MpaA and $10^{-3}m^3$/Pa/sec, respectively. The steam potential and the attenuation of the reservoir for electricity generation were computed.

Tables 1 and 2 show the estimated potential of the deep seated geothermal resources at several geothermal field in Japan. In the table, resources are presented by the index, which show the potential of the deep seated geothermal resources compared to that of the shallow geothermal resources in each geothermal field. The resources of the deep reservoir are estimated to be 1.25 times larger than those of the shallow reservoir. The total geothermal resources in the shallow and deep reservoirs in Japan are roughly estimated to be 20GW and 44GW for 30 years, respectively (MITI, 1996). The estimations in this study are relatively small because the bottom depth was truncated at 4,000m depth.

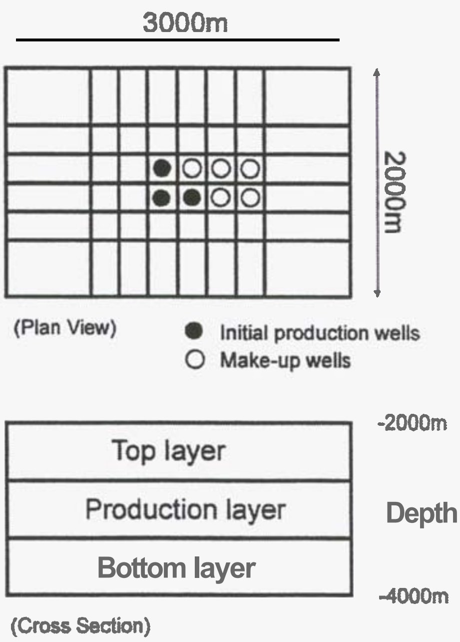

Figure 4. Simple model for evaluation of the resources

Table 1. Resources at the deep reservoir relative to those at the shallow reservoir using model-A

	Mori	Sumikawa	Uenotai	Yanaizu-Nishiyama
Resources at deep reservoir	1.0 -	1.6 -	1.4 -	1.0 -
Attenuation (%/year)	4	4	3	4

Table 2. . Resources at the deep reservoir relative to those at the shallow reservoir using model-B

	Otake	Hachobaru	Ogiri
Resources at deep reservoir	3.6 – 3.7	1.0 – 1.1	0.6 – 1.5
Attenuation (%/year)	5	5	5

Figure 5. Location map of the geothermal field studied in this paper

5. CONCLUSIONS

We have presented the possible ways to estimate the resources in the deep geothermal reservoirs and evaluated them at several geothermal fields in Japan. The reservoir parameters such as temperature, pressure and permeability in the deep layers are estimated by stochastic analysis such as the extrapolation and the relaxation methods. The stochastic methods used in the further analysis showed differences based on the conceptual models of the geothermal fields that could be evaluated by the precise numerical simulation for a range of models. For the temperature estimations, the relaxation method and the extrapolation method modified by the relationship between vapour saturation temperatures and the pressure show good agreement to the results by the simulation. The conceptual models were constructed with geological and geophysical data from the surface and from the boreholes. We have presented two conceptual models, which are used in the northeast Japan and Kyusyu regions because the tectonic settings as well as the reservoirs are different.

The deep reservoirs have 1.25 times the resource of shallow reservoirs. Deep-seated geothermal resources are possible and worth exploiting in order to increase the immediate output of geothermal power plants.

However, technology development will be required to explore and develop deep-seated geothermal resources. The exploration technology will be evaluated using the shallow wells because the regions are too deep and the exploration targets are unclear. Even when the shallow reservoir is developed, drilling is expensive. The cost of drilling deep wells is very high, and the troubles during the drilling are greater. Technology developments for exploration and cost reduction are required to encourage companies to invest in the deep-seated geothermal resources in Japan.

6. ACKNOWLEDGMENTS

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