

## A ROUGH ESTIMATION OF DEEP GEOTHERMAL POTENTIALS OF THE HOHI AND OGIRI AREAS, JAPAN WITH SIMPLIFIED NUMERICAL MODEL

H. Tokita<sup>1</sup>, M. Momita<sup>1</sup>, K. Matsuda<sup>1</sup>, H. Takagi<sup>1</sup>, T. Tosha<sup>2</sup>, and K. Koide<sup>2</sup>

<sup>1</sup>West Japan Engineering Consultants, Inc., Fukuoka 810-0004, Japan

<sup>2</sup>New Energy and Industrial Technology Development Organization, Tokyo 170-6028, Japan

### ABSTRACT

*As a study-project of NEDO to assess deep-seated geothermal potential in Japan, a method was developed to roughly estimate deep potential by using a simplified numerical model, in which stochastic methods were examined to define deep reservoir parameters such as pressure, temperature and permeability. The Hohi and Ogiri areas, which represent fault-controlled hydrothermal systems, were selected as study areas in Kyushu in fiscal 1999 and 2000, respectively. Deep reservoir parameters estimated by extrapolating the existing shallower parameters to the depth of prospective deeper reservoirs was evaluated in comparison with the results of reservoir simulation, conducted to represent the hydrothermal convection in the study area. The results showed that the deep temperature could be extrapolated by applying a logarithmic approximation, because a fault-controlled hydrothermal system has a tendency to form a temperature profile that is similar to the saturation temperature curve and is reflecting the dominant hydrothermal convection. Simulated results obtained by using the simplified numerical models indicated that the deep reservoirs below the existing development fields have almost the same potential as those of the existing Otake-Hatchobaru (122.5 MWe) and Ogiri (30 MWe) power stations located in the respective study areas.*

### 1.0 INTRODUCTION

The New Energy and Industrial Technology Development Organization (NEDO), which is a special agency of the Japanese Government, has endeavoured to prepare general-purpose guidelines for the development of Deep-seated Geothermal Resources (DSGR). NEDO carried out this project from fiscal 1992 to 1998 with Kakkonda field in Tohoku as a study area. The

Kakkonda field has representative reservoirs, which are controlled by intrusive rocks and network-fractures. In Kakkonda a deep exploratory well of 3729 m, the deepest geothermal well in Japan, was drilled. Based on findings from the Kakkonda study, guidelines for the survey, drilling, and production of DSGR were prepared (Tosha et al., 2001). Furthermore, in order to consider reservoirs, which are mainly controlled by fault distributions, the project was extended until fiscal 2000 selecting the Hohi and Ogiri areas in Kyushu and other two locations in Tohoku as study areas for the fault-controlled system. In general, there is a difference between the reservoir in Kyushu, which is dominated by fault distribution, and that in Tohoku which is dominated by a network of fractures. Otake (12.5 MWe) and Hatchobaru (110 MWe) power plants are located in the Hohi study area, and Ogiri power plant (30 MWe) in the Ogiri study area. As this additional study excluded the drilling of a deep exploratory well like that in the Kakkonda field, a reservoir simulation was conducted instead to predict deep reservoir parameters based on the simulated hydrothermal convection. Moreover, for the purpose of developing a method to assess deep resource potential without drilling a deep well, resource assessment was attempted by using a simplified numerical model, in which a stochastic method was applied to define the representative deep reservoir parameters. Taking into account the additional findings from these model studies, the general-purpose guidelines for the development of DSGR were revised and supplemented. In this paper, the rough estimation of deep resource potentials of the Hohi and Ogiri areas with a simplified numerical model are introduced.

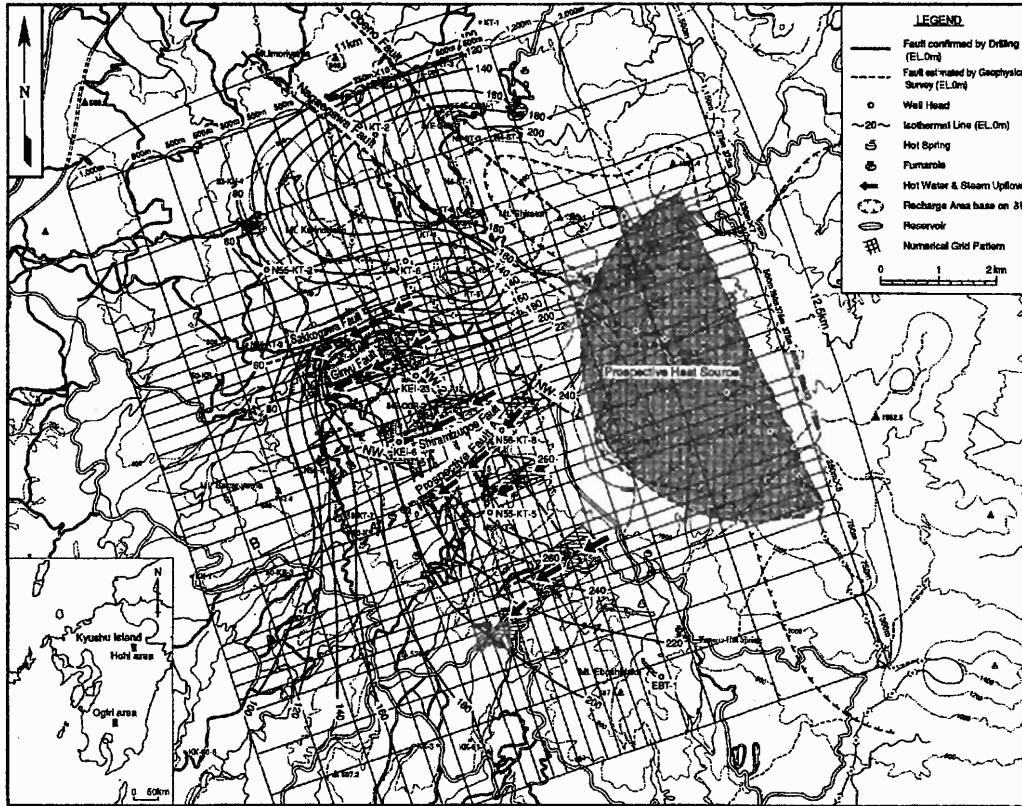


Figure 1. The plain view of a conceptual model with numerical grid pattern of the Ogiri area.

## 2.0 SIMULATED HYDROTHERMAL CONVECTION

### 2.1 The Hoho area

Several isotope indices such as B/Cl, As/Cl, and  $^{87}\text{Sr}/^{86}\text{Sr}$  suggest that the deep geothermal fluids ascend through the Tertiary Hoho volcanic rocks and Usa group which overlie the granitic basement (Momita et al., 2000). Based on the conceptual model, we constructed a three-dimensional numerical reservoir model that covers  $57.7 \text{ km}^2$  ( $7.8 \times 7.4 \text{ km}$ ) centered at the Otake-Hatchobaru geothermal fields. In the vertical direction, the top and bottom of the numerical model correspond to elevations of about 1100 m ASL and 4000m BSL, respectively. Consequently the thickness of the model is 5100m and total number of the grid blocks is about 8000.

In order to clarify the hydrothermal convection in this area, a natural state simulation was conducted using the simulator TOUGH2 (Pruess, 1991). The conceptual model suggests that the Hoho area should have two kinds of fluid

recharges. One is an upflow of high temperature fluids of  $350 \text{ }^\circ\text{C}$  from the greater depth around Mt. Kuroiwa that is a prospective heat source, and another is a lateral flow from the direction of the southeast and the northeast boundaries of the numerical model. Simulated results also indicated that the high temperature fluids ascending from the granitic basement rocks should be supplied to the Otake-Hatchobaru geothermal fields, comprising less than 30% of the total, while more than 70% of the fluids are supplied to the fields by the lateral flow above the granitic basement rocks. This relatively small proportion of deep water from the basement rocks is in agreement with the conceptual model, which predicts that the majority of the deep fluids should be supplied through the Tertiary Hoho volcanic rocks and Usa group rather than the granitic basement rocks.

### 2.2 The Ogiri area

Figure 1 shows the plain view of a conceptual model with numerical grid pattern of the Ogiri study area. The reservoirs in the Ogiri area are

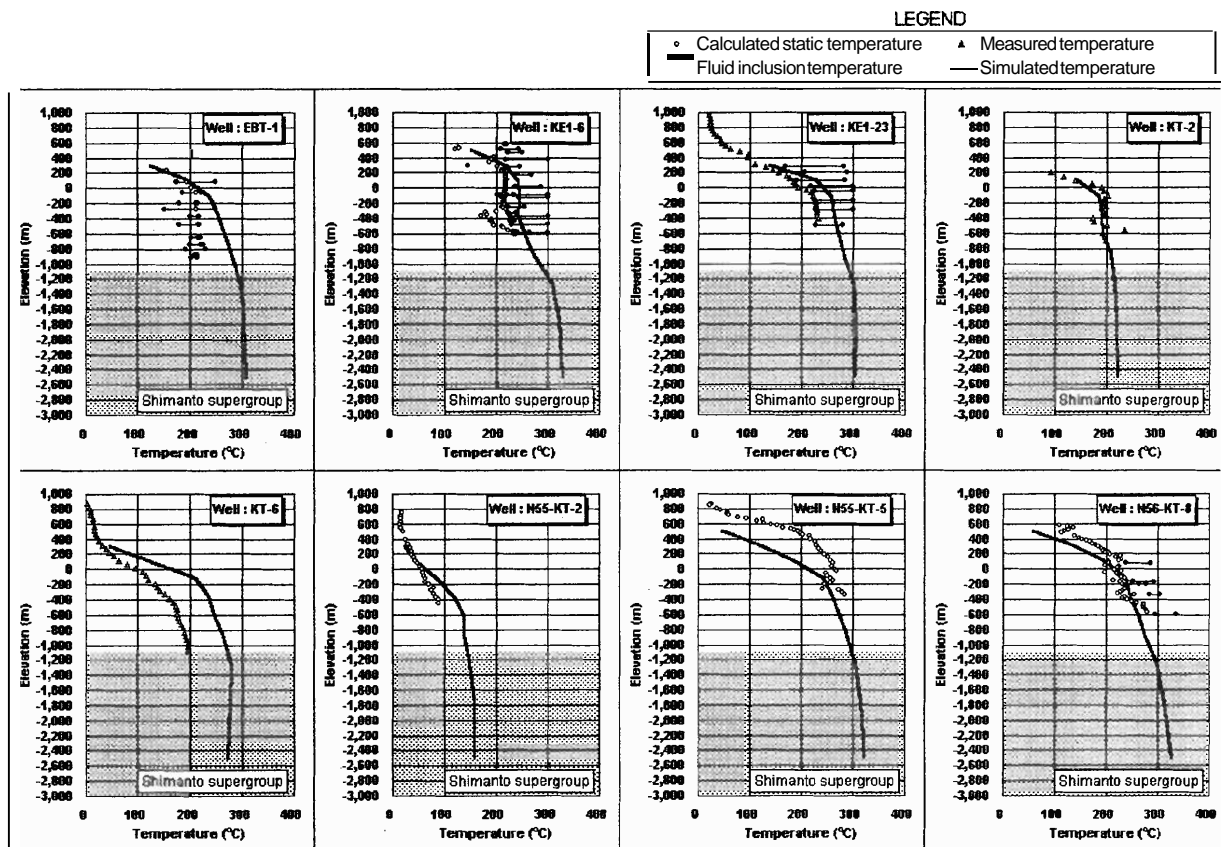


Figure 2. The simulated temperature profiles of wells with measured data in the Ogiri area.

mainly controlled by NE-SW and NW-SE trending faults, which play the role of dominant fluid paths. It is considered that the NE-SW trending faults are particularly related to the formation of the reservoirs in this area. The high temperature fluids are considered to ascend from the sedimentary basement rocks of the Shimanto supergroup. Considering that the molecule ratio of B/Cl in the thermal waters in this area is high and almost constant, the fluids are likely stored and heated in the marine sediments. A three-dimensional numerical reservoir model, which covers a wide area of about 138 km<sup>2</sup> (11x12.5 km), was constructed to represent hydrothermal convections in Ogiri. In the vertical direction, the model has a thickness of 4000m from a height of 1000 m ASL to a depth of 3000 m BSL, and was divided into 13 layers depending on the geological structure. The total number of grid blocks is about 5300. Mass recharge of the high temperature fluids of 350 °C was assumed to be 171.9 kg/s from the bottom layer at the prospective upflow zones, which are located in the east of the area. On the other hand, it was assumed that 10 or 20% of

the rainfall in this area should permeate to the subsurface of the model, appearing as cold anomalies at the shallower depths, which were observed by exploratory wells in the northern area. Setting the cold mass sources of 15 °C to be 50.2 kg/s at all of the ground surface blocks represented the permeation of the rainfall.

Figure 2 shows the simulated temperature profiles of wells with measured data in Ogiri, suggesting the presence of a dominant ascending fluid flow from the depths. Compared with the Hohi area, the Ogiri area is distinctive in having no dominant lateral flow. In the Hohi area, in which the majority of the fluids are supplied by lateral flow rather than ascending flow from the basement rocks, a higher temperature is locally distinguished at shallower depth in the region where lateral flow is especially dominant. On the other hand, the temperature in the Ogiri area smoothly increases with depth, reflecting the dominant ascending flow from the sedimentary basement rocks, and it eventually shows such a profile that is similar to the saturation temperature curve.

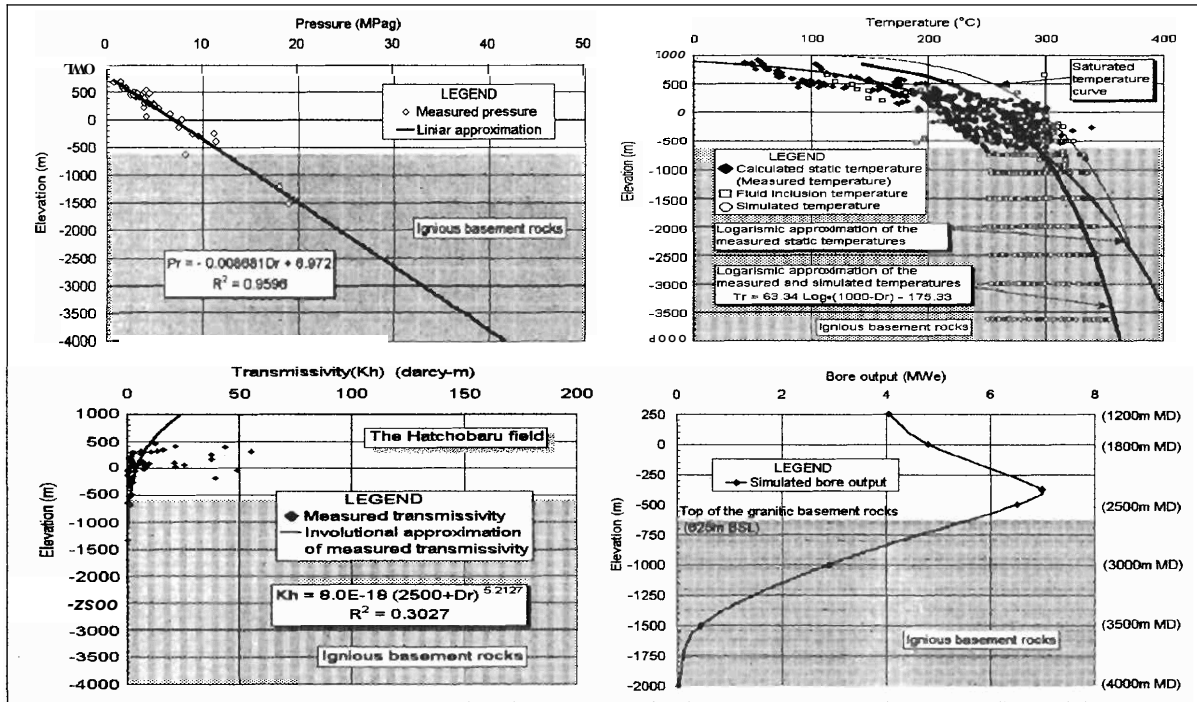


Figure 3. The relationships between elevations and reservoir pressure, temperature, transmissivity and simulated bore output in the Hoho area.

The simulated temperature distribution reflects the ascension of high temperature fluids of 350 °C through the faults of dominant permeability from the sedimentary basement rocks in the east, and their expansion to the west with decreasing temperature due to dilution by contaminating cold water such as the permeated rainfall and river water.

### 3.0 SIMPLIFIED NUMERICAL MODEL

#### 3.1 The Hoho Area

Stochastic methods were applied to estimate deep parameters. Three geothermal fields, Otake, Hatchobaru, and Sensui fields are located in this area. Figure 3 shows the relationships between elevations and reservoir pressure, temperature, transmissivity (kh) and simulated bore output in the Hoho area. Not only existing measured data but also simulated results have been used. The following approximation equations were obtained to represent the above relationships.

$$Pr = -0.008681Dr + 6.972 \quad (1)$$

$$Tr = 63.34 \text{ Log}_e(1000-Dr) - 175.33 \quad (2)$$

$$Kh = 8.0E-18 (2500+Dr)^{5.2127} \quad (3)$$

where: Pr = pressure (Mpa-g)  
 Tr = temperature (°C)  
 Dr = elevation (m)  
 kh = transmissivity (darcy-m)

A linear equation is available for approximating the pressure profile, while a logarithmic and involutional approximate equation should be applied to estimate deep temperature and transmissivity, respectively. The reliability of the deep temperature estimated using the approximation equations was verified by comparing it with the simulated deep temperature. The simulated temperature distribution indicates that the condition of the deep reservoirs should be liquid-phase, and the temperature profile is similar to the saturation temperature curve, reflecting the dominant hydrothermal convection, which is controlled by fault distributions with high permeability. Accordingly, the deep temperature extrapolated from the shallower measured data should be revised so as not to go beyond the saturation temperature, as long as the deep reservoirs are considered to be liquid-phase. The relationship between the exploitation depth and representative bore output was calculated using a wellbore simulator, which was originally developed by the Kyushu University, Japan (Itoi

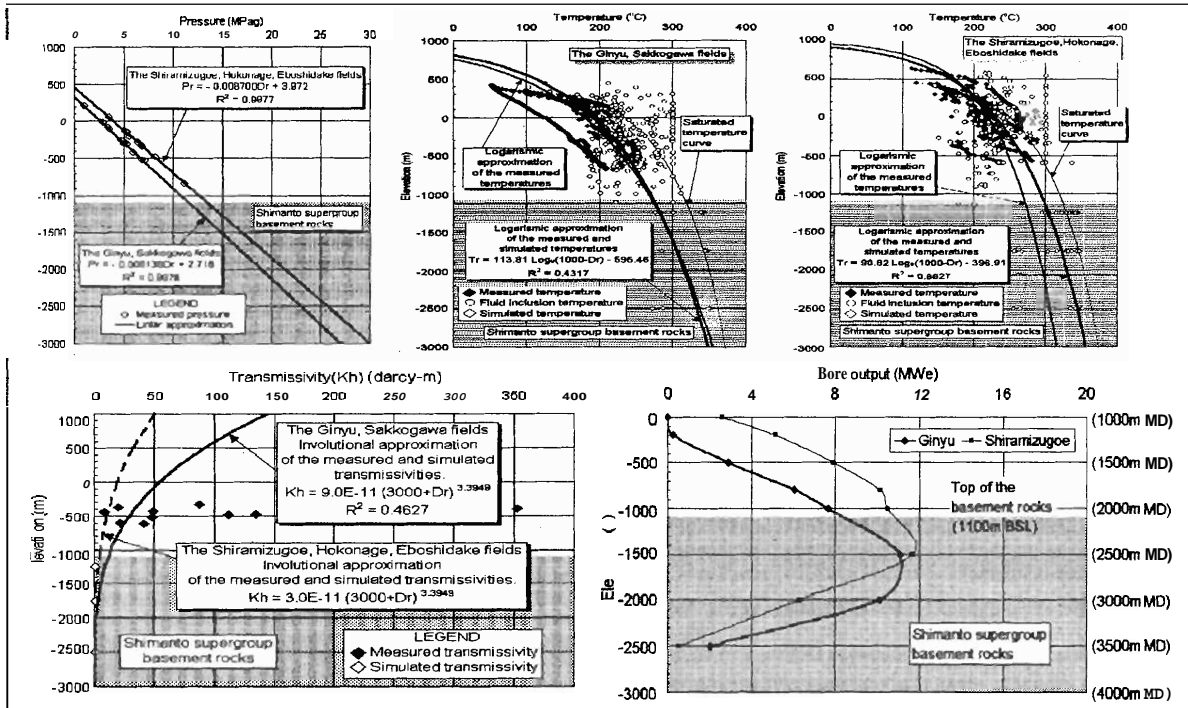


Figure 4. The relationships between elevations and reservoir pressure, temperature, transmissivity and simulated bore output in the Ogiri area

et al, 1983), and then modified and named WELLFLOW by Tokita. As shown in Figure 3, simulated bore output indicates that it would increase with the exploitation depth until it reaches the granitic basement rocks, and this is reflected in the increase of reservoir pressure and temperature. However, it would decrease within the granitic basement rocks due to the very poor permeability. Consequently, an average bore output is maximized as 7 MWe at a depth of around 350 m BSL (2300 m MD) above the granitic basement rocks.

### 3.2 The Ogiri Area

Similar calculations were conducted in the Ogiri area. The results are shown in Figure 4. The approximation equations to estimate deep parameters are as follows:

area north of the Ginyu fault

$$Pr = -0.008138Dr + 2.716 \quad (4)$$

$$Tr = 113.81 \text{Log}_e(1000-Dr) - 595.46 \quad (5)$$

$$Kh = 9.0E-11 (3000+Dr)^{3.3949} \quad (6)$$

area south of the Ginyu fault

$$Pr = -0.008700Dr + 3.972 \quad (7)$$

$$Tr = 90.82 \text{Log}_e(1000-Dr) - 396.91 \quad (8)$$

$$Kh = 3.0E-11 (3000+Dr)^{3.3949} \quad (9)$$

The Ogiri area can be divided into two areas in terms of hydrological structure, because the water levels are quite different in the northern and southern areas divided by the Ginyu fault. Two geothermal fields, Ginyu and Sakkougawa are in the northern area, while the other three fields, Siramizugoe, Hokonage, and Eboshidake are in the southern area. The permeability in the southern area was assumed to be one-third of that in northern area based on the very limited data. A linear approximation is applied to the pressure profile, while a logarithmic and involutional approximation is applied to the temperature and transmissivity profiles, respectively. The relationship between the exploitation depth and representative bore output shows that the average power outputs are maximized as about 11 MWe at a depth of 1700 m BSL (2700 m MD) in the northern area, and 12 MWe at a depth of 1500 m BSL (2500 m MD) in the southern area, respectively. These exploitation depths are inside of the sedimentary basement rocks, as shown in Figure 4. It is thought that transmissivity significantly affects the bore output at the deeper depths. We should notice that only the transmissivity would be getting smaller with the depth, in contrast with the reservoir pressure and temperature, which increases.

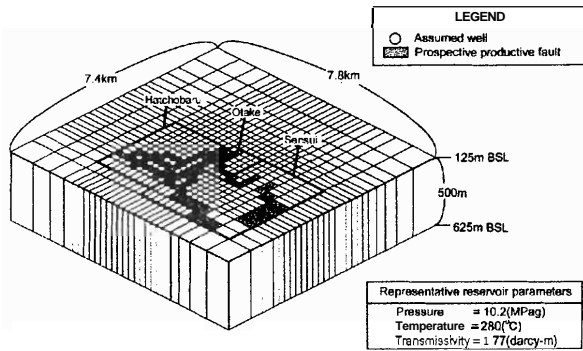


Figure 5. A simplified numerical model of the deep reservoirs in the Hoho area.

## 4.0 DEEP RESOURCE POTENTIAL

### 4.1 The Hoho Area

Based on the bore output analysis, it was assumed that deep reservoirs in the Hoho area are formed along dominant faults above the granitic basement rocks. In order to assess the deep resource potential, we constructed a simplified numerical model that has a single layer covering 57.7 km<sup>2</sup> with the thickness of 500 m (125 m to 625 m BSL), as shown in Figure 5. Representative reservoir pressure, temperature and transmissivity were input into the model as 10.2 MPa, 280°C and 1.77 darcy-m, respectively, taking account of the relationship between elevation and reservoir parameters in this area. An open condition of constant pressure/temperature was assumed for the lateral boundaries of both the eastern and southern sides. A dosed condition was

assumed for other lateral boundaries and top boundary. Regarding the bottom boundary, either a constant pressure/temperature condition or constant mass source condition was assumed only for the prospective upflow zones, and to the other zones a closed condition was assumed. The constant mass source of 280°C was applied to a depth of 375 m below the bottom of the model. The mass flow rate was assumed to be 307 kg/s, which was the summation of 11 kg/s, 70 kg/s, and 226 kg/s in the Otake, Hatchobaru and Sensui fields, respectively.

In order to evaluate deep resource potential, a tentative development scenario was adopted, in which assumed production wells were distributed, regardless of the constraints of the national park and constructible drilling sites, at intervals of 200 m along the prospective productive faults where a reservoir temperature of more than 250°C can be expected. The sustainable resource potential was studied by supposing the wells to be producing simultaneously. The simulated total power outputs declined with time and stabilized within 30 years at 45-46 MWe in Otake, 105-120 MWe in Hatchobaru, and 170-240 MWe in the Sensui field as shown in Figure 6, which were considered as the individual sustainable resource potentials. The deep resource potential of the Hatchobaru field was estimated to be almost the same as that in the exploited depths of 1000 to 2000 m MD. Compared with the results of stored heat analysis conducted using the same reservoir properties, the resource potentials obtained with the simplified numerical models were equivalent to 5.9-11.5

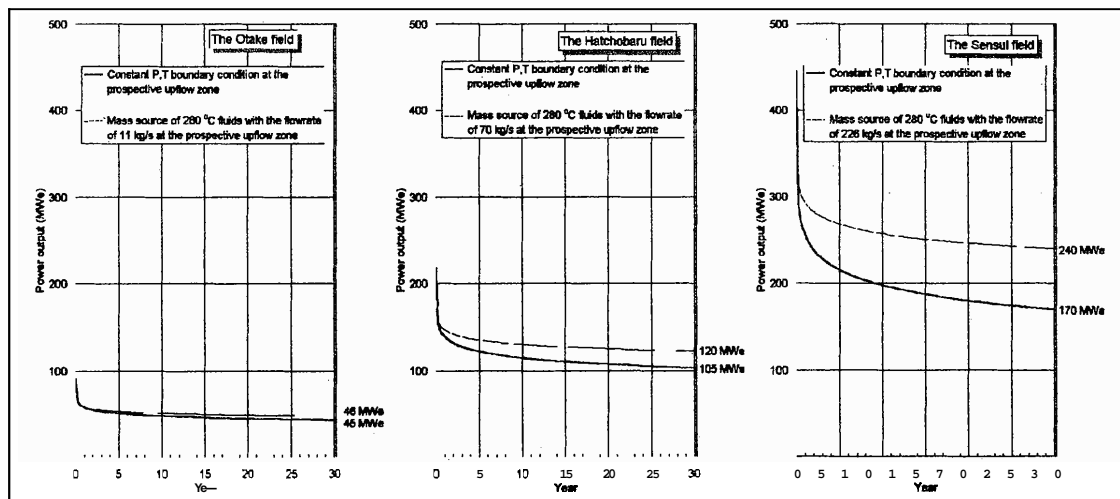


Figure 6. The changes of power outputs with time predicted by a simplified numerical model of the Hoho area.

times the most likely resource potentials from the stored heat analysis, as shown in Table 1. The resource potential of a simplified numerical model would be larger than that of a stored heat analysis because the simplified numerical model considers the mass recharge that is provided by the conditions of constant mass source or constant pressure/temperature at the prospective upflow zones.

Table 1. Deep Resource Potentials in the Hoho area.

Field	Simplified Simulation	Stored Heat Analysis
Otake	45-46 MWe	4 MWe
Hatchobaru	105-120 MWe	16 MWe
Sensui	170-240 MWe	29 MWe
Total	320-406 MWe	49 MWe

## 4.2 The Ogiri Area

Taking account of the depth at which a maximum bore output of 11 to 12 MWe can be expected, we constructed a simplified numerical model of the Ogiri area, which covers 138 km<sup>2</sup> with a thickness of 1000 m (1000 to 2000m BSL). Considering that this area can be divided into two regions in terms of hydrological structure, a couple of reservoir parameters were applied to the simplified numerical model. In the northern area, 14.9 MPa, 295 °C, and 5.45 darcy-m were applied as a representative reservoir pressure, temperature and transmissivity, respectively. The values were 17.1 MPa, 314 °C and 1.82 darcy-m in the southern area. An open condition with constant pressure/temperature was assumed for only to the eastern lateral boundary, while a closed condition was assumed for the other lateral boundaries except the prospective upflow zones at the bottom layer of the model. For the upflow zones, we applied either a constant pressure/temperature condition or constant mass source, which supplies high temperature water of 350°C at 171.9kg/s in total from 500 m below the bottom layer. Assumed production wells were distributed at intervals of 200m along the prospective productive faults, in which the temperature can be expected to be 250 °C or more.

As a result of supposing the wells to be producing simultaneously, the simulated power outputs declined with time and stabilized within 30 years at 36-66 MWe in Sakkogawa, 18-45

MWe in Ginyu, 57-138 MWe in Shiramizugoe, 18-69 MWe in Hokonage, and 42-111 MWe in the Eboshidake field, depending on the conditions assumed for the prospective upflow zones in the model. These stabilized power potentials are considered to be the individual sustainable resource potentials. The deep resource potential of the Ginyu field was equivalent to 60 to 160% of the exploited power potential of the 30 MWe Ogiri power plant. Compared with the resource assessment using a stored heat method with the same reservoir properties as this model, the simulated resource potentials of the simplified numerical models were equivalent to 0.5-3.6 times the most likely resource potentials from the stored heat analysis, as shown in Table 2. The simulated power potential estimated with a simplified numerical model appears to be highly sensitive to the recharge conditions such as constant pressure/temperature, and/or constant mass source.

Table 2. Deep Resource Potentials in the Ogiri area.

Field	Simplified Simulation	Stored Heat Analysis
Sakkogawa	36-66 MWe	20 MWe
Ginyu	10-45 MWe	28 MWe
Shiramizugoe	57-138 MWe	61 MWe
Hokonage	18-69 MWe	36 MWe
Eboshidake	42-111 MWe	30 MWe
Total	171-426 MWe	175 MWe

## 5.8 CONCLUSIONS

As an element of the project for DSGR of NEDO, a method to roughly estimate deep resource potential with a simplified numerical model using a stochastic method was devised and tested in the Hoho and Ogiri study areas, Kyushu, Japan. The following findings were obtained:

- 1) In a hydrothermal convection system controlled by faults with the high permeability, reservoir temperature increases with depth, reflecting the dominant ascending flow from the deep, and it eventually shows a profile that is similar to the saturation temperature curve.
- 2) Transmissivity (kh) remarkably affects the bore output at the deeper depth, reflecting

the fact that it becomes smaller with depth. Using the involutorial approximation equation can represent the transmissivity profile. Based on the representative reservoir pressure, temperature, and transmissivity profiles, the average bore output is expected to be a maximum of 7 MWe at the depth of 2300 m in Hohi and 11-12 MWe at 2500-2700 m in the Ogiri area.

- 3) The sustainable resource potentials of both the Hohi and Ogiri areas are estimated by using simplified numerical models. The deep resource potential of the Hatchobaru field in the Hohi area was evaluated as 110-120 MWe, which is almost the same as that of exploited depths, and that of the Ginyu field in the Ogiri area as 18-45 MWe, depending on the conditions assumed for the prospective upflow zones.
- 4) The resource potential suggested by a simplified numerical model would usually be larger than that indicated by a stored heat analysis due to mass recharge, which is provided by the conditions of constant mass source and/or constant pressure/temperature. The mass recharge assumption will highly affect the resource potential indicated by a simplified numerical model.

## ACKNOWLEDGMENTS

We would to thank to the staff of Kyushu Electric Power Company Co., Nittetsu Kagoshima Geothermal Company LTD., NEDO and Industrial Integrated Laboratory for their cooperation in providing data, technical advice and also in giving permission for the publication this paper.

## REFERENCES

- Itoi, R., Fukuda, M., Sekoguchi, K., and Iwaki, T. (1983). Theoretical study on steam and water flow rates from geothermal production wells. *Journal of the Geothermal Research Society of Japan*, vd. 5, no. 4, 235-248.
- Momita, M., Tokita, H., Matsuda, K., Takagi, H., Soeda, Y., Toshi, T. and Koide, K. (2000). Deep geothermal structure and hydrothermal system in the Otake-Hatchobaru geothermal field, Japan. *Proceedings of 22<sup>nd</sup> NZ Geothermal Workshop 2000*, 257-262.
- Pruess, K. (1991). TOUGH2 - A general-purpose numerical simulator for multiphase fluid and heat flow. Report LBL-29400, UC-251.
- Toshi, T., Koide, K., Tokita, H., and Sato, T. (2001). Evaluation of the deep-seated geothermal resources in Japan. *Proceedings of 23<sup>rd</sup> NZ Geothermal Workshop 2001*, 225-230.