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Development of Energy Supply Systems Using Abandoned Deep Wells

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ABSTRACT

Abandoned deep geothermal and oil/gas wells have enormous potential for the supply of energy to the neighboring communities if converted to a ground heat exchanger (GHE). Since the well re-completion costs are significantly cheaper than those of drilling new wells, the energy supply system could be a highly cost-effective choice. In this study, field tests and numerical simulation studies were performed to demonstrate the effectiveness of the energy supply systems using abandoned deep wells.

An abandoned geothermal well of 635m deep was converted to a GHE in Akita Prefecture, Japan, to supply heated water to be mixed with geothermal steams for producing hot spring water. With the circulation of river water through the GHE, the well currently supplies over 100kWt of heat stably without any outside power supply. A numerical model with the consideration of forced convection by groundwater flow was developed to simulate the past heat extraction performance and to improve the well designs and the operation strategies. The simulation results showed good agreement with the measured heat extraction performance, while the use of low thermally conductive inner pipes was proposed to enhance the heat extraction rate.

A conversion plan of a depleted gas well of 2637m deep in Niigata Prefecture, Japan, was developed with the use of the same simulation model. The numerical simulation showed that the well could supply over 150kWt of heat with a water circulation rate of 400L/min. The numerical simulation also suggested that the use of low thermally conductive inner pipe is important to maximize the heat extraction rate.

1. INTRODUCTION

In Japan, a large number of deep wells are abandoned after deletion in geothermal fields and oil/gas fields. If the bottom hole temperatures of these wells are sufficiently high, we could reuse these wells to supply energy for snow meting, space heating or hot water supply with the use of ground heat exchangers (GHEs). The advantages of the systems are i) low initial cost with the use of exiting wells, ii) no emission of CO_2, iii) low operation and maintenance costs. In this paper, field tests and numerical simulations are conducted to design and develop cost-effective and environmentally friendly energy supply systems using abandoned deep wells.

Researches have been made to develop optimum conversion plans of abandoned deep wells to GHEs. Morita (2001) proposed utilization plans of abandoned deep wells in Poland using downhole coaxial heat exchanges (DCHE). Kohl et al. (2002) conducted a numerical simulation study using a finite-element model to revive abandoned deep wells in Switzerland. In the above studies, however, field tests were not carried out to demonstrate the long-term heat extraction capacity of the energy supply systems.

In this study, optimum well design and operation strategies for an energy supply system using abandoned deep wells are investigated through field tests and numerical simulations. Section 2 briefly describes the numerical simulation model developed for the performance prediction of deep GHEs with the consideration of groundwater effects. In Section 3, the results of a long-term heat extraction test in Akita Prefecture, Japan, is presented. The GHE performances will be interpreted using the numerical simulation model. In Section 4, an energy supply plan using a depleted gas well in Niigata Prefecture, Japan, is developed using the numerical simulation model. Optimum circulation rates are investigated in terms of pump power and heat extraction rates.

2. NUMERICAL MODELING

The numerical model assumes a coaxial GHE completed with steel outer pipes and steal or plastic inner pipes for circulating heat medium (water). The heat medium is circulated from tubing side to annulus side. A 3D numerical simulation model was developed using finite difference method to simulate the heat extraction behavior from the GHE and the temperature distribution in the formation. The governing equation in the 3D model is given as Equation (1). Convective heat transfer by fluid movement is considered in Equation (1) as well as heat conduction.

$$\rho_e C_{pe}\frac{\partial T}{\partial t} + \rho_{ew} C_{pw}\left(U_x \frac{\partial T}{\partial x} + U_y \frac{\partial T}{\partial y} + U_z \frac{\partial T}{\partial z}\right) = \lambda_e\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \dot{q} \qquad (1)$$

where ρ, C_p, T, U, λ, $\dot{q}$ are the density, the specific heat, the temperature, the fluid velocity in the formation, the thermal conductivity and the heat flow rate per volume, respectively. Subscripts e and w denotes effective and water, respectively.

The heat transfer in pipes is expressed using a energy conservation equation as shown in Equation (2).

$$\rho_w C_{pw}\frac{\partial T}{\partial t} = -\rho_w C_{pw} u \frac{\partial T}{\partial z} + \dot{q} \qquad (2)$$

where u is the fluid velocity in pipes. Heat transfer rate from the formation to the heat medium is calculated using Equation (3).

$$\dot{q} = \frac{hA\Delta T}{V_p} \qquad (3)$$

where A, ΔT, V_p are the surface area of pipe, temperature difference between fluid and formation and volume of pipes, respectively. Heat transfer coefficient h is evaluated using the Nusselt numbers of the fluid in the pipes. In the simulation models, Equations (1) and (2) are discretized with finite difference method. The temperature distribution in the formation and heat extraction rate from the well are sequentially calculated by solving the above equations using ADI method (Smith, 1975).

3. UTILIZATION OF A GEOTHERMAL WELL

3.1 Description of well

In October 2002, an abandoned geothermal well (hereafter called Well-A) located in Akita Prefecture, Japan (Figure 1), was converted to a GHE. Originally, the well was drilled as a steam producer in 1986 to supply steam for producing hot water by mixing the steam with river water. Since 1991, however, the well had been closed because of depletion. The geological column of the well is shown in Figure 2. The groundwater level in the well is –60m below the surface. The annual average ambient temperature at the well location is estimated to be 6°C. The formation temperature in October 2002 was 145°C, 195°C and 218°C at –100m, -300m and –500m, respectively. The GHE was completed with two sets stainless pipes, one for outer pipes and another as inner pipes as shown in Figure 2, to prevent possible corrosion problems with the use of corrosive river water as the heat medium. The water is circulated from tubing side to annulus side. Since the river water has a potential head, hydrostatic head enables an electricity-free circulation of heat medium.

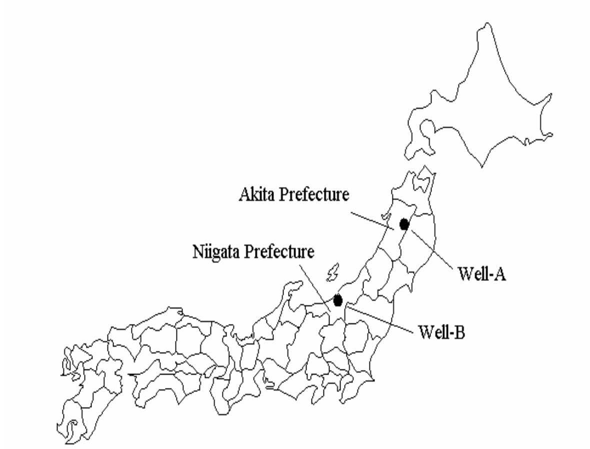

Figure 1: Location of Research Area

Figure 3 shows the history of well inlet/outlet temperatures, circulation rates and heat extraction rates from the completion of the GHE in October 2002 to Jan. 2004. Before Oct. 2003, circulation rates were unstable owing to a problem in water intake systems. With the modification of the system in October 2003, circulation rate has increase by 70% and became stable. The heated water is further mixed with geothermal steam from other wells to produce hot water to be supplied to neighboring hotels and houses for balneology.

The heat extraction rate showed an increase of 10% during the six month from Nov. 2002 to Apr. 2003. The reasons of the increase have not been clearly identified yet. One possible interpretation is the generation of free convection in the formation accelerated by the circulation of cold water in the borehole drilled in a steam-dominated geothermal reservoir. Inaccurate measurement of circulation rate would be another possible reason. After Apr. 2003, heat extraction rates stabilized at 100kWt – 110kWt.

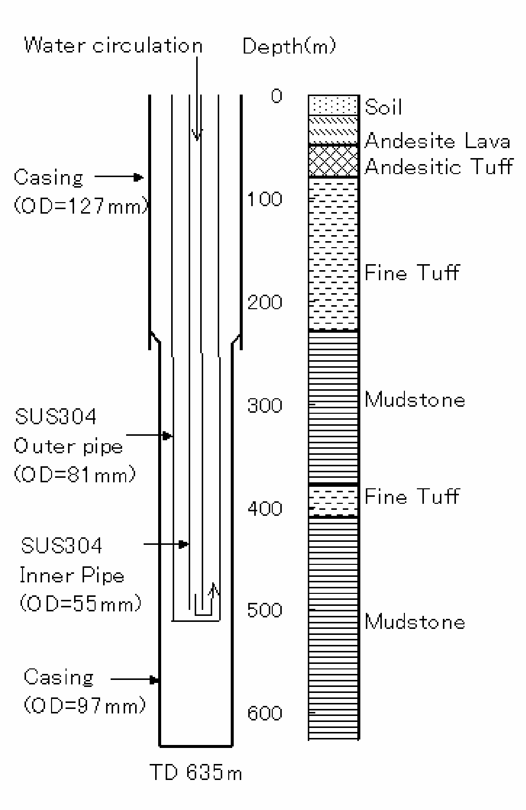

Figure 2: Well drawing & geological column of Well-A

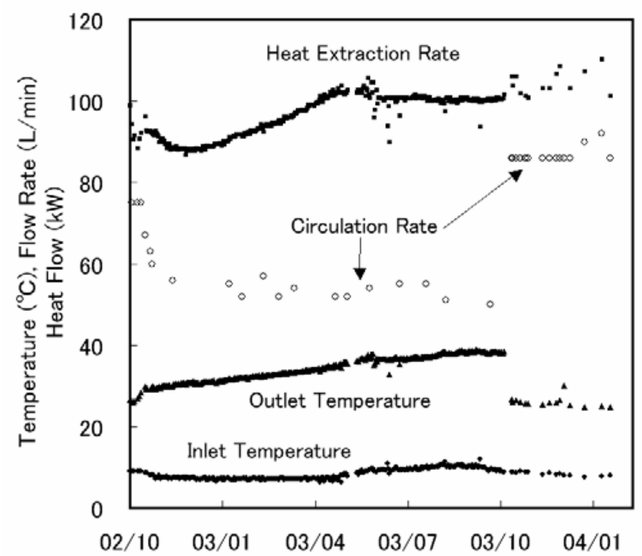

Figure 3: History of heat extraction in Well-A

3.2 History matching and case studies

We constructed a 3D numerical simulation model for Well-A to interpret the heat extraction performance and to develop optimum future operational plans. Since the performances between Nov. 2002 and Apr. 2003 have not been fully understood as mentioned above, the well performance between Oct. 2003 and Jan. 2004 was matched well using the simulation model.

The 3D model has 11 x 11 x 30 grids in X, Y and Z directions, respectively. The grid size in the vicinity of the GHE is 0.5m, which increases gradually as approaching the outer boundary of the model. The size of the model is 30m x 30m x 600m in X, Y and Z directions, respectively. The GHE is located in the center of the model. The thermal conductivity of formation was determined as 2.0W/(mK) based on laboratory test results of core samples (NEDO, 1992). Considering the stable heat extraction performance, we assumed a forced convection of groundwater in the formation. With trial and errors, best fittings were obtained as shown in Figure 4 with a horizontal groundwater velocity of 1.0m/day. The figure shows that the developed 3D model simulated the heat extraction performance reasonably well.

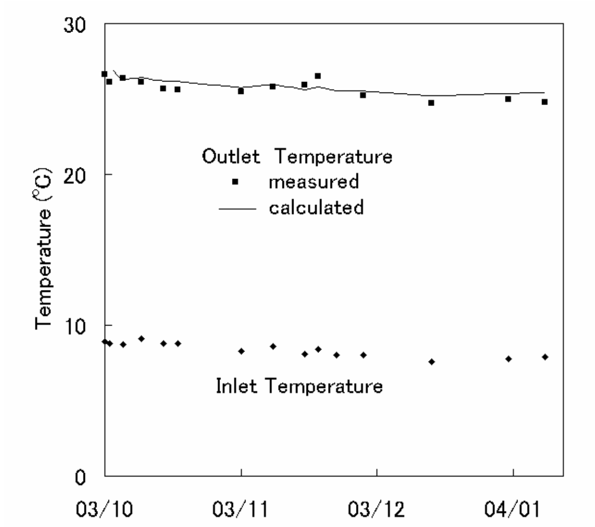

Figure 4: History matching result of Well-A

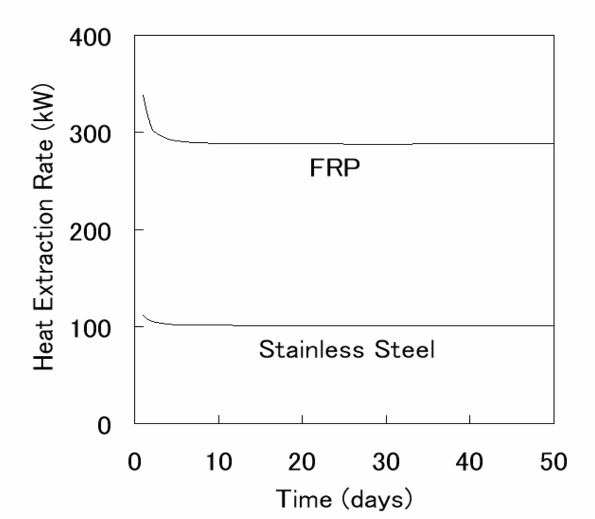

Figure 5: Effect of thermal conductivity of inner pipe materials on heat extraction (Well-A)

Using the simulation model, we investigated the effects of thermal conductivity of inner pipes on heat extraction rates. The heat extraction performances using stainless pipes (λ=16.0W/(mK)) and fiber reinforced plastic (FRP) pipes (λ=0.17W/(mK)) were predicted for 50days as shown in Figure 5. Well inlet temperatures and water circulation rates were set to be 10°C and 85L/min., respectively. Figure 5 shows that the stabilized heat exchange rate would be increased by three times with the use of FRP pipes as inner pipes. Replacement of inner pipes, therefore, should be considered in the next well workover operations to effectively extract the geothermal energy from Well-A.

4. UTILIZATION OF A GAS PRODUCTION WELL

4.1 Well Information

Japan is not rich in oil and gas resources. In northern Japan, however, there are a large number of abandoned oil and gas wells close to or in the midst of populous areas, especially in Niigata and Akita Prefectures. Since these areas require significant amount of energy for snow melting and space heating in winters, the use of these abandoned wells for energy supply would greatly contribute to the conservation of energy and environmental protection.

In this study, we selected a gas well (hereafter called Well-B) in Niigata Prefecture, Japan (Figure 1) for predicting the heat extraction performance from existing oil/gas wells. Well-B was drilled in 1971 for gas production, but has been suspended since 1984 because of the depletion of the gas reservoir. The total depth of the well is 2637m. The geological column of the well is shown in Figure-6. Annual average ambient temperature from 1979 to 2000 at the well location is 13°C. The formation temperatures are 79°C and 105°C at -1905m and -2637m, respectively.

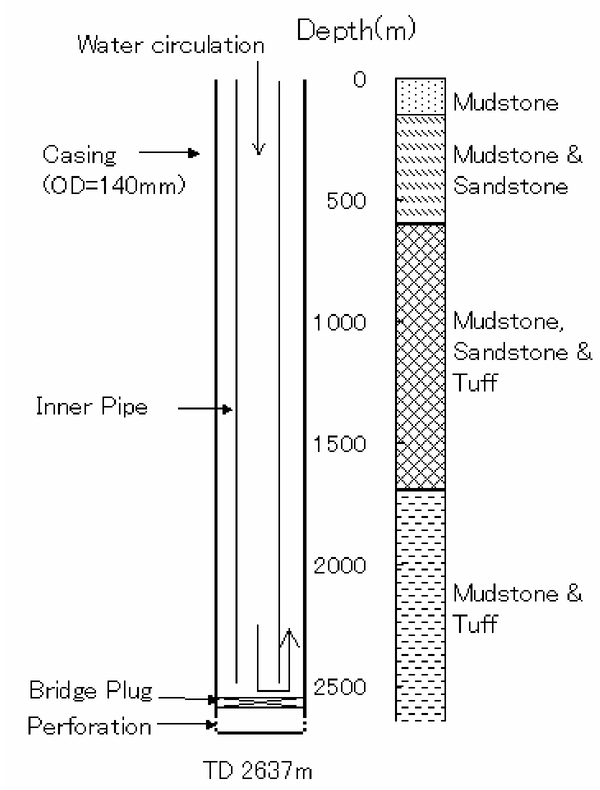

Figure 6: Proposed well design & geological column of Well-B

To convert the well to a GHE, existing perforations between -2580m and TD needs to be isolated to use the existing casing as outer pipes for circulation. To enable this, we planned to set a bridge plug at -2500m and then run tubing pipes as inner pipes for circulation down to the depth just above the bridge plug. The proposed well completion design is shown in Figure 6.

4.2 Case Studies

We constructed a 3D simulation model to predict the heat extraction performance from Well-B. The 3D model has 17 x 17 x 28 grids in X, Y and Z directions, respectively. The grid size in the vicinity of the GHE is 0.5m, which increases gradually as approaching the outer boundary of the model.

The size of the model is 440m x 440m x 2800m in X, Y and Z directions, respectively. In the simulation runs, well inlet temperature and circulation rate of heat medium were set at 10°C and 400L/min., respectively. The thermal conductivity of formation was determined as 1.5W/(mK) using typical values for mudstones (Japan Society of Thermophysical Properties, 1990). The convection effect of groundwater was not included in the model since no information of groundwater is available.

As was discussed in Section 3, thermal conductivity of the inner pipe would strongly affect the heat extraction rates in deep GHEs. Here, we predict the heat extraction performance of Well-B using different λ values for inner pipes. Figure 7 compares the heat extraction rate using FRP pipes or steel pipes (λ=38.6W/(mK)) as inner pipes. The figure shows again that heat extraction rates increase with the use of low λ inner pipes, though the difference in heat extraction rate between the two materials is not as large as in Well-A.

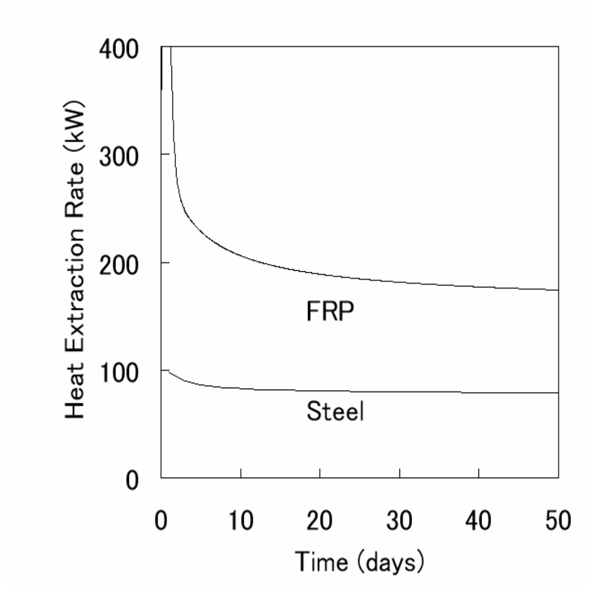

Figure 7: Effect of thermal conductivity of inner pipe materials on heat extraction (Well-B)

To clarify the reasons of the difference in heat extraction rates, the depth-temperature profiles of heat medium at 50 days are compared in Figure 8. With the use of high λ inner pipes, the temperature of heat medium increases to 42°C at the bottom of the well because of the large heat transfer rate between the tubing and the annulus side. On the other hand, the heat medium significantly cools down while ascending in the annulus because of the heat loss from the annulus side to the tubing side. When using FRP, the fluid temperature shows little increase in the tubing. In the annulus side, however, the temperature of heat medium shows an increase since little heat is lost to the tubing side resulting in a larger heat extraction rate than the case with steel pipes.

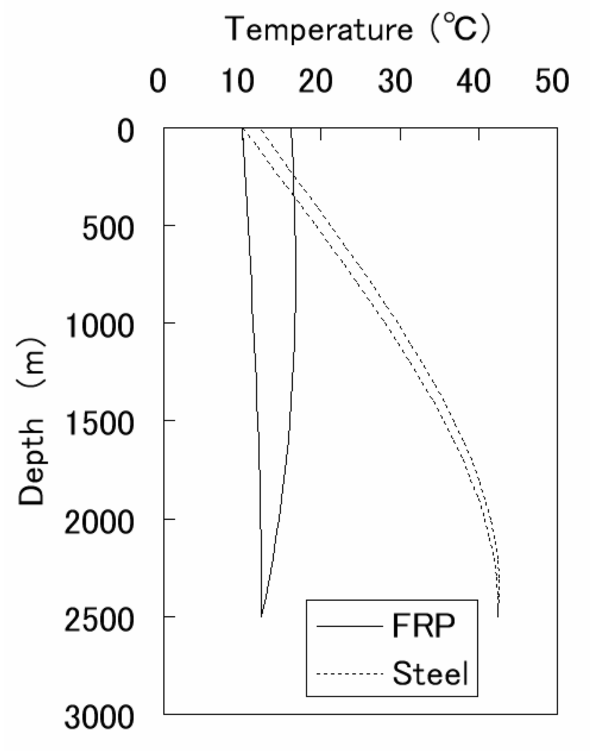

Figure 8: Temperature Profiles at 50 days (Well-B)

Next, we investigated the effect of circulation rates on heat exchange rate. As inner pipe materials, we used only FRP pipes based on the above sensitivity studies. Figure 9 shows the calculated the heat extraction performance for 50 days with different circulation rates, 100L/min, 200L/min, 400L/min and 600L/min. Heat extraction rates increased with the increase of circulation rates. The rate of increase, however, became smaller when circulation rate exceeded 400L/min because the heat supply from formation by heat conduction is limited.

The net thermal output from the GHE is obtained by subtracting the power input for circulation from the heat extraction rate from the formation. Figure 10 shows the relationship between circulation rates and heat extraction rates (circle), pumping power (square) and net thermal output (triangle). Pumping power is nearly zero when circulation rate is small because the fluid in the annulus is warmer than the fluid in the tubing, which provides the hydrostatic head to assist fluid circulation. With the increase in circulation rates, required pumping power steeply increases since the friction loss in the tubing and annulus is roughly proportional to the second power of circulation rates. Since heat extraction rates increases with the increase in circulation rates as well as pumping powers, there exists an optimum circulation rate as indicated in Figure 10, which maximize the net thermal output. Figure 10 shows that the optimum circulation rate is 300-400L/min, which gives a net thermal output of 150kWt. If the heat is supplied for snow melting around the well location, it would be sufficient to cover approximately 1000m^2 of land, though Niigata prefecture is one of the most snowy areas in Japan.

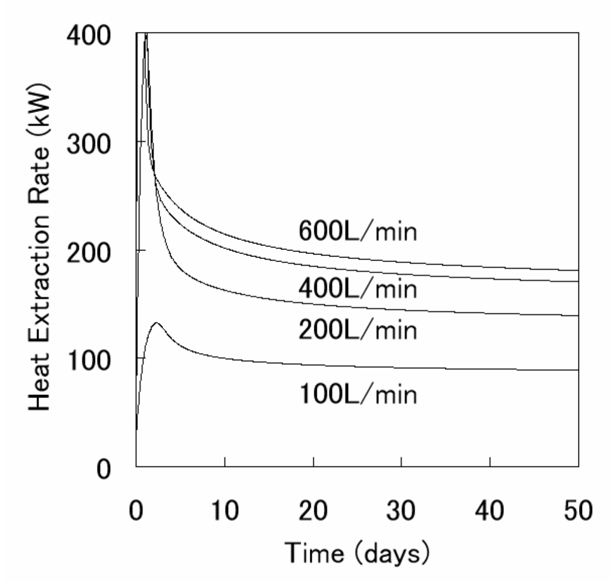

Figure 9: Effect of circulation rate on heat extraction (Well-B)

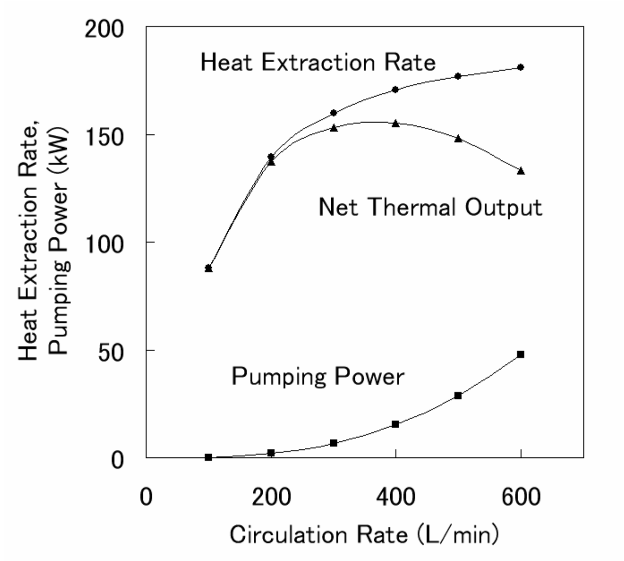

Figure 10: Circulation rate vs. net thermal output (Well-B)

The above calculations used a simulation period of 50 days to predict the short-term performance of Well-B. Since the primary heat transfer mechanism would be heat conduction in Well-B, the long-term heat extraction performance should also be predicted when planning the conversion of the well to a DHE. Figure 11 shows the heat extraction performance of 5years with a circulation rate of 300L/min. Considering that the extracted energy from Well-B is mainly spent on snow melting and space heating in winters, 90days' heat extraction period and 275 days' shut-in period are assumed in a operation of 1 year.

At the end of each year's operation, heat extraction rates show a decline of nearly 25% from the beginning of 90days' operation, which should be reflected in the operation plan of each year. On the other hand, the annual decline in heat extraction rate is negligible since the geothermal energy supplied from the surrounding formations recovers the formation temperatures during the shut-in period of 275days. The final heat extraction rate in each year's operation showed a decline of only 0.5% even after 5 years' operation.

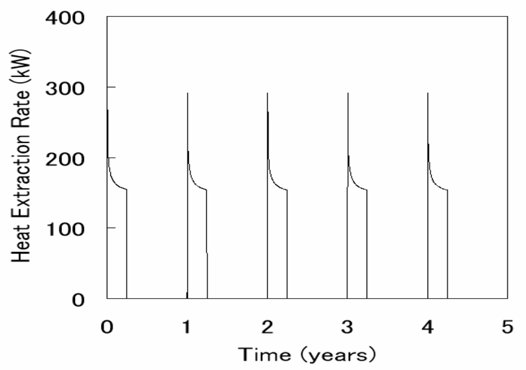

Figure 11: Long-term heat extraction performance of Well-B

5. CONCLUSIONS

Field tests and numerical simulations were conducted to develop optimum well designs and operation strategies for using abandoned deep wells as ground heat exchangers.

A field test, conducted in Akita Prefecture, Japan, showed that abandoned geothermal well can output over 100kWt of heat with no power input from outside. Simulation studies showed the possibility of significantly increasing the thermal output with the use of low thermal conductivity (λ) materials for inner pipes.

Simulation calculations on an abandoned gas well of 2637m deep in Niigata Prefecture, Japan, confirmed the advantage of using low λ materials for inner pipes. From the calculated net thermal output, optimum circulation rate of heat medium, which maximize the net thermal output, was estimated to be 300-400L/min.

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REFERENCES

Kohl, T., R. Brenni and W. Eugster (2002) System performance of a deep borehole heat exchanger, *Geothermics*, v.31, p.687-708.

Morita, K. (2001) One possible way to utilize abandoned deep wells -the application of the DCHE-, *Technika Poszukiwan Geologicznych Geosynoptyka i Geotermia*, p.129-148.

Smith, G.D. (1975) *Numerical solution of partial differential equations*, Oxford University Press, 179p.

Japan Society of Thermophysical Properties (1990) *Thermophysical Properties Handbook*, Yokendo, 489p.

NEDO (1992) Report of geothermal development promotion survey, Tazawako-tobu, p.721-722