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HEAT EXTRACTION FROM THE OGACHI HDR GEOTHERMAL RESOURCE

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ABSTRACT

Heat extraction from the Ogachi geothermal resource has been carried out in four test periods following creation of the two-layered stimulated HDR reservoir at depths of about 720 and 1000 m. The tests consist of a 20-day hydraulic communication test in 1993, a 151-day circulation test in 1994, a 30-day test in 1995, and 10-days of production in the summer testing of 1997. The heat extracted from each of these tests has been calculated and the cumulated heat extracted has been estimated in relation to the estimated total heat content of the reservoir.

INTRODUCTION

The development of HDR technology for electric power generation in Japan by the Central Research Institute of Electric Power Industry (CRIEPI) since 1985 has focused on the Ogachi experimental facility in northern Honshu (Kitano, Hori, and Motojima, 1993). The reservoir consists of an injection-production well pair separated by about 90m, intersecting hydraulicly-stimulated fractures at 720 and 1000 m depth. A description of the reservoir re-stimulation in 1994, just prior to the 151-day circulation test, was given by Kitano, Hori, and Kaieda (1996). Four circulation tests with fluid production have been carried out in the Ogachi reservoir to date: (1) 20 days in 1993, (2) 151 days in 1994, (3) 30 days in 1995, and (4) 10 days in 1997. Most of the focus on these tests were to determine the hydraulic connectivity and flow condttions in the reservoir. The 30-day circulation test in 1995 was conducted to obtain reservoir data for planning a series of flow tests in 1997 of the two individual reservoir layers. To assist in evaluating these tests, CRIEPI organized a computational project for comparison of modeling forecasts with measured test data. The heat extraction calculations for the planned tests with the SGP heat extraction model are included in this paper.

An important aspect of HDR technology is assessment of total heat extraction from a stimulated reservoir of finite size and initial mean resource temperature. These determine the total heat content in the reservoir available to the circulating fluid. For steady, long-term circulation at constant fluid production rate, the lifetime of the reservoir cooled to a given abandonment temperature can be estimated. For a series of short-term circulation testing, especially at varying flowrate, it is important to estimate the heat extracted from each test to account for the total energy extracted over the lifetime of the resource. For this purpose, estimates of the cumulative heat extraction from the four tests have been made using the simple, one-dimensional SGP radial heat sweep model (Hunsbedt, Lam, and Kruger, 1983). The calculation of heat extracted from the Ogachi reservoir was based on the zonal sector flow model described in Kruger and Yamamoto (1995) for the 1994 151-day circulation test. The reservoir volume available for heat extraction is given by

$$V_r = (\alpha/360)\pi R^2 \Delta Z \qquad (1)$$

where $a = 360\, Q(p)/Q(i)$
$Q(p)$ = mean production flowrate (kg/s)
$Q(i)$ = mean injection flowrate (kgls)
R = mean sector radius (m)
ΔZ = mean sector thickness (m)

The zonal sector heat content available above an abandonment temperature for the electricity conversion system installed is given by

$$HC = (\rho V_r)\, C_p\, (T_o - T_a) \qquad (2)$$

where ρ = mean rock density (kg/m^3)
C_p = rock specific heat capacity (kJ/kg°C)
T_o = mean initial sector temperature ("C)
T_a = abandonment temperature (°C)

The cumulative heat extracted during the circulation test is given by

$$\mathbf{HE} = \int_{t_o}^{t_a} Q(t)\, \Delta h(T_i, T_f, t)dt \qquad (3)$$

where Q = production flowrate (kg/s)
Ah = increase in fluid enthalpy (kJ/kg)
T_i = injected fluid temperature (°C)
T_f = produced fluid temperature (°C).

The fraction of available heat content produced is the ratio

$$FP = \mathbf{HEMC} \qquad (4)$$

HEAT EXTRACTION FROM PRIOR TESTS

(1) 20-Dav Test of 1993

The first hydraulic communication test following completion of the two-layer stimulated reservoir was a 20-day test in 1993. A description of this test was given by Yamamoto, Fujimitsu, and Motojima (1995). The test was used to measure transmissivity and coefficient of storage. The hydraulic communication results were not considered satisfactory. especially the production flowrate which slowly reached a value of about 30 Ymin after a cumulative injection volume of about 29,000 m^3. At an average injection rate of about 1000 Ymin, the production fraction was of the order of 3 percent. Thus, for an average production rate of **15** Ymin over 20 days of flow from a reservoir with mean initial temperature of 230 'C, the total heat extracted was about 0.39 x 10^{12} J.

(2) 151-Dav Test of 1994

The first long-term flow test was carried out in 1994 10 days after a stimulation of the production well with injection of 3,100 tons of cold water to increase the fraction of water recovery. ***An*** analysis of the thermal aspects of this test was given by Kruger and Yamamoto (1995). From the extensive test data collected, it was noted that about 90 days were needed to reheat the production well zone to initial conditions. During the final 60 days, the mean downhole temperature was 214°C at 730 m and 231 C at 1080 m. For the total test, the mean circulation parameters were an injection flowrate of 10.8 kg/s at pressure of 0.6 MPa and a production flowrate of 1.01 kg/s. **Based** on the mean flowrate data, the thermal analysis was carried out for a zonal sector flow geometry with flow angle given from Equ.(1) as a = 33.7'. The resulting reservoir parameters for the thermal analysis were an estimated reservoir volume of 7.5x10^5 m^3 at a mean sector temperature of 230°C with estimated available heat content of 1.8x10^{14} J (180 TJ) above an abandonment temperature of 140°C.

The thermal extraction analysis was made with the SGP 1-D radial heat sweep model (Hunsbedt, Lam, and Kruger, 1983) in two forms:

(1) varying the mean fracture spacing (MFS) to observe the effect of heat transfer rate from the reservoir rock blocks to the circulating fluid;

(2) calculating temperature cross-sections at fixed MFS **to** observe thermal front passage through the sector.

The results for the mean fracture spacing showed that 40 m was an upper limit to the practical range of the time constant for heat conduction inside the rock blocks to their surface. All sizes smaller than 40 m could provide sufficient heat conduction rate to maintain the observed production flowrate at the initial reservoir temperature. The cross-sectional temperature results showed that the thermal front at the abandonment temperature had moved only about 19 m away from the injection well. The estimated lifetime of the zonal sector was 7.3 years. Integration of the heat extraction rate over the 151 days of circulation indicated that the total heat extracted was about 9.6 TJ. For the estimated zonal sector heat content of 180 TJ, the fraction of heat produced was 5.3 %. Thus, at the observed production flowrate, the 1994 circulation test could have continued for about 7.7 years, consistent with the 7.3 years of lifetime estimated from the temperature cross-sections.

1995 CIRCULATION TEST

The objective of the 1995 circulation test was to obtain sufficient reservoir information to plan a series of flow tests in 1997 of the two individual stimulated layers of the reservoir. The large database of pressure and flowrate during the 30 days of circulation was obtained on disk from CRIEPI. The thermal analysis was conducted in four steps. First, the database on flowrate with varying time steps was reduced to a uniform set of 6-hourly averages and these were integrated in spreadsheet form to obtain mean injection and production flowrate. Second, the 6-hourly production flows were integrated with the mean 6-hourly enthalpy increases by Equ.3, also in spreadsheet form, to obtain the mean heat extraction rate and the total heat extracted during the circulation period. Third, the mean flowrates were used in the zonal sector flow geometry model to calculate the expected cooldown curve for constant production rate.

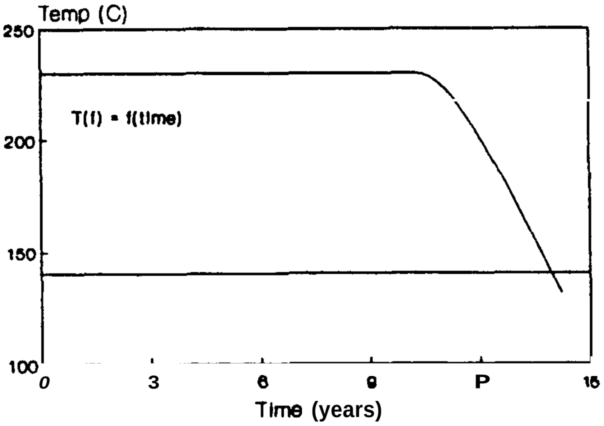

Fig.1. Simulated bottom-hole fluid temperature from the 1995 30-day test at constant production rate.

Fourth, cross-sectional temperature profiles were prepared to estimate the lifetime to abandonment temperature.

The results of the analysis confirmed the expected increase in heat extraction based on the observed increase in production flowrate. The mean production rate was 2.01 kg/s for a mean injection rate of 9.69 kgls, representing a recovery of 20.7 Yo. The production recovery in the 1994 151-day test was 9.4 Yo. Spreadsheet integration of Q(p)Δh over the 30 days of circulation yielded a mean thermal production rate of 1.85 MJ/s for a total heat extraction of **4.8** TJ.

The simulated **cooldown** for constant production flowrate, shown in Figure 1, indicates a potential extraction period of about 10 years at the initial reservoir temperature, and a total lifetime to the selected abandonment temperature of about 13.9 years. The **cross-sectional** temperature profiles are shown in Figure 2. The value of r^2/t at the abandonment temperature for the 2.28-year profile was 600 m^2/yr. Extrapolating this gradient to the production well yielded a reservoir lifetime of 13.2 years to reach the abandonment temperature, in good agreement with the value of 13.9 years obtained from the temperature decline curve in Figure 1.

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The [illegible] of [illegible] 1997 test was **a better** understanding of the hydraulic [illegible] of th[illegible] two-layered [illegible] **by** [illegible] 'individual reservoir **circulation** [illegible]. The tests included injection of water into the **upper** reservoir with the **lower** one plugged [illegible] 1) [illegible] injection [illegible] th[illegible] lower reservoir with th[illegible] [illegible] one [illegible] (Case 2).

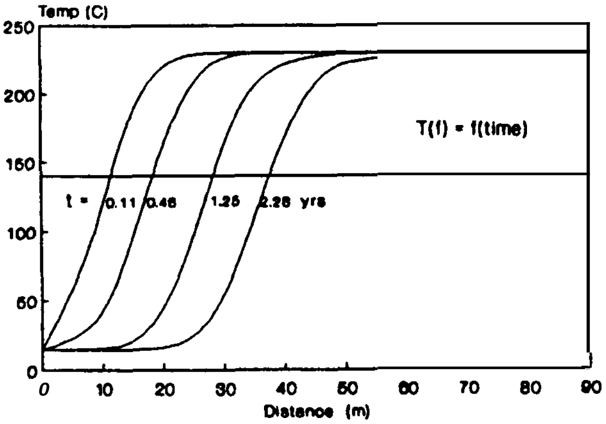

Fig.2. Temperature cross-sections through the zonal sector as a function of time.

It was planned at CRIEPI to evaluate these tests in two ways:

(1) a 'round-robin' computational project for pre-test comparison of the simulated results from models **run by** many participants using a supplied set of input data;

(2) analysis of the field data following the flow **tests** for the two layers.

(1) Computational Results for the 1997 Test

For the computational project in this ***study,*** the zonal sector flow **geometry** was designed for the two *cases* from the CRIEPI-supplied cutaway view of the reservoir showing the injection and production points (from Yamamoto, Fujimitsu, and **Ohnishi,** 1995). The Case 1 sector was **based** on gravity flow from the upper layer and the Case 2 sector was based on upflow from the lower layer, adjusted for the relative production yields of 30 % from the upper layer and 70 % from the lower layer. In each case, the planned production flowrate was set at 25 %, resulting in a flow angle of ***a*** = 137 **degrees. A** summary of the input parameters used in the SGP model is given in Table 1.

Table **1**
input Parameters for the Computation

Parameter	case1	case2
Flowrate		
Q(i) (kg/s)	8.33	8.33
Q(p) (kg/s)	2.08	2.08
Sector Geomeby		
Radius (m)	77	90
ΔZ (m)	340	87
Angle (deg)	137	137
Temperature (°C)	220	230

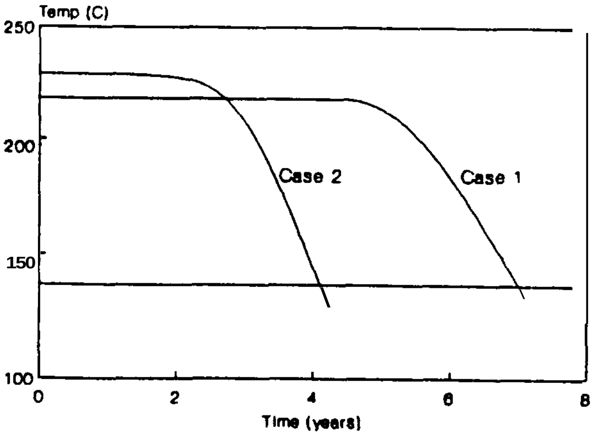

Fig.3. Simulated bottom-hole fluid temperature for the 'round-robin' computational project.

Figures 3 shows the expected bottom-hole fluid temperature cooldown for the two cases. Case 1 with the larger effective reservoir volume shows a lifetime to abandonment temperature of about 7.1 years compared to Case 2 which shows a lifetime of about 4.1 years, both at 25 % production recovery. The comparison of the two lifetimes is affected somewhat by the 10°C difference in mean initial sector temperature. The area under the curves is proportional to the respective heat extracted. Figure 4 shows the temperature cross-sections for Case 1. Extrapolation of the r^2/t gradient at the abandonment temperature from the profile at 3 years to the production well gives a lifetime of 7.3 years. Figure 5 shows the temperature cross-sections for Case 2. The extrapolated lifetime is 3.9 years. The results from the two simulation techniques for resource lifetime. at constant production rate, are proportional to the estimated zonal sector reservoir volume and heat content. A summary of the computational project results is given in Table 2.

Table 2
Summary of Pre-Test Computational Results

Parameter	Case 1	Case2
Reservoir		
Volume (10^6 m^3)	0.30	0.17
Heat Content (TJ)	51.3	33.6
Lifetime		
Cooldown to t(a) (y)	7.1	4.1
T(a) front to well (y)	7.3	3.9

The results of the 'round-robin' computation of the Ogachi reservoir by the other participants were distributed by CRIEPI (private communication, October 1997). It was noted that the 1997 test could not be conducted as planned. The actual circulation test consisted of simultaneous circulation in both the upper and lower layers instead of the 'individual circulation tests'.

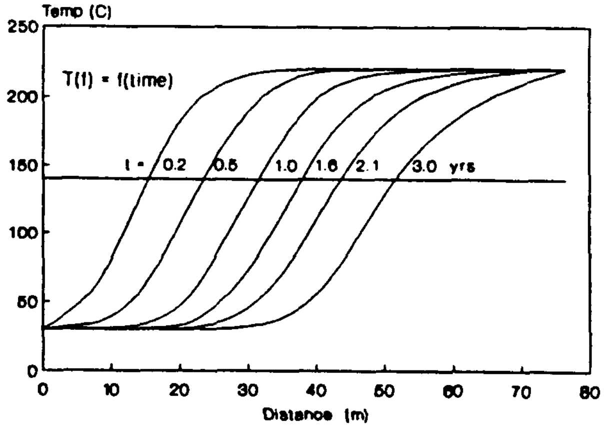

Fig.4. Temperature cross-sections for Case 1 of the 'round-robin' computational project.

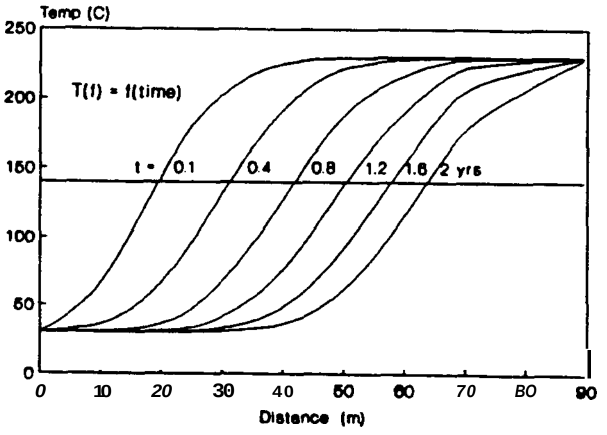

Fig.5. Temperature cross-sections for Case 2 of the 'round-robin' computational project.

(2) Thermal Analysis of the 1997 Test

The actual field test at Ogachi in 1997 was a series of circulations made in four segments over a period of about 38 days. Significant production was achieved only during the fourth segment of 10 days. Thus, in accounting for the cumulative thermal energy extracted from the production well, only this fourth segment was analyzed. Reduction of the test database for flowrate in 4-hour increments was carried out similarly to the reduction of the 1995 test database in 6-hour increments. The resulting mean injection flowrate was 7.81 kg/s and the mean production flowrate was 0.84 kg/s. The recovery fraction was 10.7 %, about the same as the value in the 1994 151-day circulation test.

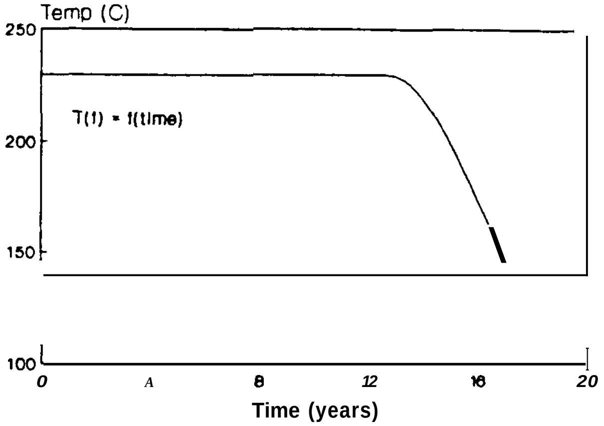

Fig.6. Simulated bottom-hole fluid temperature from the 1997 10-day test at constant production rate.

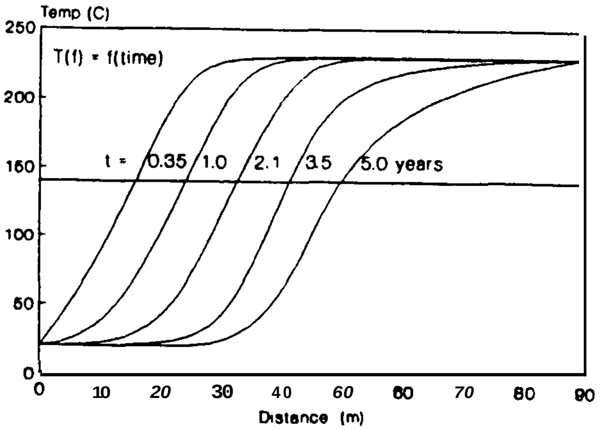

Fig.7. Temperature cross-sections through the zonal sector as a function of time for the 1997 test.

Based on the mean flowrates, the zonal sector angle for this circulation test was α = **38.5** degrees, essentially the same as the angle used for the 151-day 1994 circulation test. The corresponding sector volume was 9.1×10^5 m^3 and at mean sector temperature of 230 °C, the available heat content was 176 TJ.

Figure 6 shows the bottom-hole temperature cooldown curve and Figure 7 shows the temperature cross-sectional temperature profiles though the sector from *0.35* to *5* years of circulation at constant production rate. From Figure 6, the lifetime to the abandonment temperature is 16.6 years at the production flowrate of 0.84 kg/s. From Figure 7, the lifetime extrapolated from the value of r^2/t at 5 years is 16.2 years. The heat extracted during the 10-days of circulation was 0.8 TJ at a mean heat extraction rate of 0.90 MJ/s.

DISCUSSION

With four circulation tests carried out over 5 years of field experimentation at Ogachi, there has not been a long-enough circulation test at constant injection-production flowrate to establish a good database for estimating the thermal capacity and deliverability of the reservoir as it was created in 1992-94. A major uncertainty results from the small recovery fractions observed in each of the four tests. The short testing duration does not yield information on whether the small recovery is due to large water losses from the reservoir (probably not recoverable) or due to a large storage capacity away from the direct flow paths between the wells (probably recoverable over the resource lifetime). Nevertheless, sufficient data has been acquired to approximate the thermal aspects of reservoir as it currently exists. The model used for the thermal analysis accounts for the small fluid recovery by adjusting the fraction of the a full radial reservoir to a sector that corresponds to the mean production flowrate with respect to the mean injection flowrate. Another major uncertainty is the effective thickness of the reservoir with respect to horizontal flow and the effect of gravity. The model uses a mean thickness estimated from the geometry of the injection horizons and the production feed points. provided by CRIEPI from their logging data. With these two approximations, the model effectively calculates the heat extraction rate from the zonal sector for a given continuous production rate. This latter consideration is very important in the thermal evaluation of a prospective HDR resource. Furthermore, the deliverability (thermal extraction rate) and longevity (lifetime to abandonment temperature) must be convincingly determined before an extensive investment is made in a full-size commercial HDR geothermal resource.

A summary of the thermal analyses of the four short circulation tests is given in Table 3. The mean injection and production flowrates over the duration of each test determined the sector volume for heat transfer to the circulating fluid and the available heat content above the abandonment temperature. The duration-weighted means over the 4 tests provide a useful basis for planning of future tests under the same reservoir characteristics. Integrations of the production flowrate-increased enthalpy data show the range of heat extraction rates over the varying mean production rates. The weighted value of 0.86 MJ/s is consistent with the value for the 1994 151-day test based on the closeness of the mean fluid recovery rates.

Table 3
Summary of the Heat Extraction Results

Test Year	Duration (days)	Mean Injection Rate (kg/s)	Mean Production Rate (kg/s)	Mean Heat Extraction Rate (MJ/s)	Heat Extracted (TJ)	Extrapolated Lifetime to T_a (Years)
1993	20	17.0	0.25	0.22	0.4	–
1994	151	10.8	1.01	0.74	9.6	7.3-7.7
1995	30	9.7	2.01	1.85	4.8	13.2-13.9
1997	10	7.8	0.84	0.90	0.8	16.2-16.6
Duration-Weighted Means		11.1	1.07	0.86		
Total Heat Extracted (TJ)					15.6	

The total heat extracted over the four tests periods is 15.6 TJ. Based on the estimated available heat content of the zonal sector for the longest test, the 1994 151-day test, of 180 TJ, the minimum heat extracted from the reservoir sector is 8.7 %. This value is based on the assumption that all of the injected fluid is in storage somewhere in the resource and has not carried away any heat from the sector volume.

The two methods of extrapolation of heat extraction on continuous production at the mean rate agree sufficiently well. The lifetimes range from about 7.5 years for conditions of the 1994 151-day test, and 13.5 years for the larger fluid recovery fraction of the 1995 30-day test to 16.4 years for the 1997 10-day test. The range is partially explained by the change in reservoir flow geometry and corresponding variation in available heat content. But other factors probably play an important role. These could be evaluated only with a sufficiently-long circulation test.

ACKNOWLEDGMENTS

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