PROCEEDINGS, Eighteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 26-28, 1993
SGP-TR-145

THERMAL DRAWDOWN ANALYSIS OF THE HIJIORI HDR 90-DAY CIRCULATION TEST

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ABSTRACT

The Hijiori 90-day circulation test is unique in the development of HDR technology in that it was the first (and thus far the only) multi-production well test run for a sufficient production period to obtain observed cooldown curves at multiple production horizons in the stimulated reservoir volume. The experimental data have been analyzed by the SGP 1-D linear heat sweep model to examine the extent of thermal cooldown in this relatively small, multi-well, multi-zone reservoir. Although changes in production flow were carried out in specific wells at specific times during the 90 days of circulation, matching of the observed cooldown curves in conjunction with the structural and temperature logging data allows estimation of the reservoir volume and the mean fracture spacing between rock blocks for heat extraction during the 90-day test.

INTRODUCTION

In 1991, a 90-day circulation test was conducted at the Hijiori geothermal site in Japan (Yamaguchi, 1992) as part of the New Energy and Industrial Technology Development Organization (NEDO) program for the development of HDR technology. It was the first multi-well, multi-production zone circulation test in a HDR reservoir during which extensive diagnostic data were accumulated. In addition, from frequent downhole logging, production fluid temperature histories were measured at the respective feed zones of each production well. These data provide a unique opportunity to examine thermal drawdown in a fractured HDR reservoir under sustained production. They also allow study of two major problems existing in assessing economic feasibility of long-term thermal energy extraction from deposits of high-temperature rock formations, namely: (1) the size of the reservoir available for heat transfer (the total extractable heat content), and (2) the mean size of the rock blocks in the formation which are in contact with circulating fluid (the heat transfer capacity for a given production flowrate).

Fig. 1. Location of the Hijiori HDR test site in northern Honshu.

The Hijiori test is the second of two existing HDR circulation tests which provide data for matching an observed cooldown history with simulated cooldown based on models of reservoir geometry and production flow. The first example of thermal drawdown matching in a sustained HDR circulation test was reported by Kruger (1990) for the shallow (2-km) Rosemanowes experimental HDR reservoir in Cornwall, England. The 3-year continuous production history and observed fluid temperature cooldown were provided by Nicol (1989). An estimate of the reservoir volume, made from tracer tests (Nicol and Robinson, 1990) and an ellipsoid envelope around the swarm of microseismic locations observed during the hydraulic stimulation of the reservoir (Parker, 1989) indicated a reservoir volume of about 5 x 10^6 m^3. The observed cooldown could not be matched for that volume for any value of rock block mean fracture spacing. A match was obtained for the set of reservoir volume of 3.25 x 10^6 m^3 and a mean fracture spacing of 50 m. The model was extended to a proposed deeper (6-km) reservoir in the same formation (Kruger, Hicks, and Willis-Richards, 1992) to evaluate the energy extraction capability for a commercial-size system.

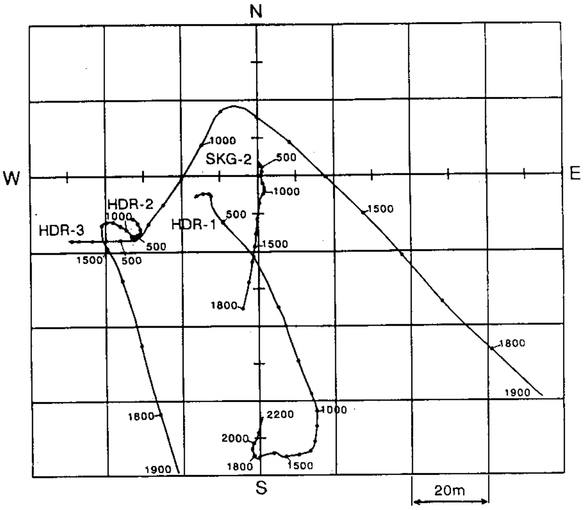

Fig. 2. Plan view of the 4-well system at the Hijiori HDR test site.

Analysis of the observed thermal drawdown for the shallow Rosemanowes reservoir was much simpler than for the Hijiori reservoir in that the experiment was run at constant production rate as a two-well doublet system (one injection well - one production well) over a long period of time (3 years). In contrast, the Hijiori experiment was run as a four-well system (one injection well - three production wells) at constant injection rate over a short period of time (90 days), but with an early brief excursion in flowrate to test enhanced stimulation and occasional shutin of two of the wells to test the third well. However, with the detailed data acquired by the Hijiori staff over the lifetime of the system, analysis of the observed cooldowns at the main feed zones in the three production wells reveals much insight on the volume and mean fracture spacing distributions in the reservoir.

THE HIJIORI 90-DAY CIRCULATION TEST

The Hijiori geothermal site is located in northern Honshu as noted in Figure 1. It has been a site for development of HDR technology since 1985 (Yamaguchi, 1992). In 1986, hydraulic fracturing studies were initiated in well SKG-2. Two wells, HDR-1 and HDR-2 were subsequently drilled, each with short (2 weeks to 1 month) circulation tests to characterize the results of the stimulation. In 1991, following creation of well HDR-3, a 3-month circulation test was carried out to test the reservoir.

A plan view of the Hijiori HDR test site is shown in Figure 2. The horizontal distances from the bottom hole of injection well SKG-2 to the main production zones of the three wells were 41 m for HDR-1, 38 m for HDR-2, and 80 m for HDR-3. A general synopsis of the 90-day test is given in Table 1. The test was run from August 6 through November 3. The injection flowrate was kept essentially constant at 1 ton/min (16.7 kg/s) except for two early excursions for enhanced stimulation. Following the first 23 days of circulation, single well production tests were conducted for about 5 days each, in order. The result of the two 5-day shutins of each well was a perturbation in the constant-flowrate cooldown curves for the production wells. During the test, frequent (weekly) logs were run downhole to measure pressure, temperature, and flowrate (PTS) in each production well (Miyairi, et al, 1992).

Table 1
Parameters of the Hijiori 90-Day Test*

Parameter	Value
Production Wells	HDR-1,2,3
Injection Well	SKG-2
Injection Flowrate	16.7 kg/s
Injection Pressure	3 MPa
Injection Temperature	55 °C
Production Temperature	160-190 °C
Pumping Duration	90 days
Fluid Recovery	77 %
Thermal Output	8 MW

*from Yamaguchi (1992).

A schematic view of the wellbore geometry at depths 1500-1900 m is shown in Figure 3. It was noted (NEDO, 1992) that each of the three production wells had multiple feed zones. From the frequent PTS downhole surveys, the depth and interval of each feed zone was estimated for each production well. Figure 4 shows the multiple feed zones inferred from the data and confirmed after the test with a borehole televiewer. For each well a feed fraction was defined as the ratio of production flowrate to the total flowrate for that well. A summary of the production flow distribution is given in Table 2.

The results of the 90-day test were reported by Yamaguchi (1992) and Yamaguchi, et al, (1992). The history of injected fluid recovery showed the effects of the two stimulation efforts at the early part of the 90-day test. Initial recoveries were less than 60 % and following the two stimulations, water recovery increased to nearly 80 %. The mean value of water loss over the test period was 23.1 %. Figure 5 shows the observed fluid temperature history at the main production interval at depths about 1750-1780 m. The fluid temperature of well HDR-1, with the smallest flowrate, reached a surface temperature of 190 °C and was still increasing at the end of the test. In contrast, wells HDR-2 and HDR-3, with larger fractional flowrates, exhibited measurable cooldown with decline to temperatures of 145 °C and 165 °C, respectively, at the end of the test.

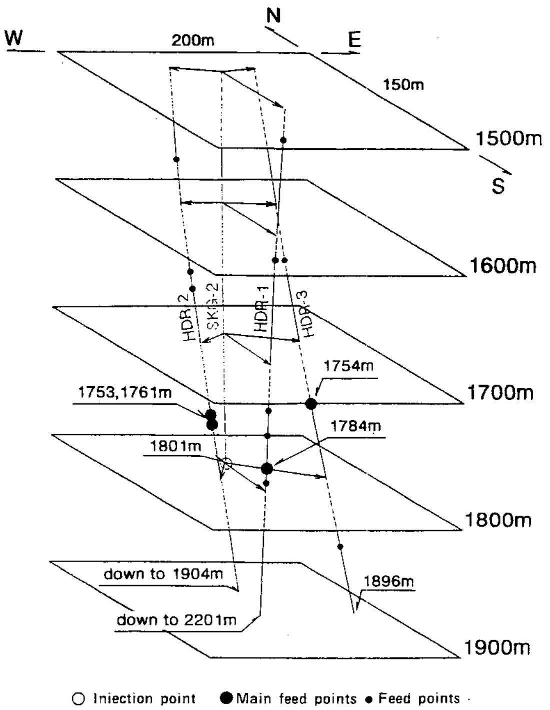

Fig. 3. Schematic view of injection well SKG-2 and production wells HDR-1, 2, and 3 for the 90-day circulation test.

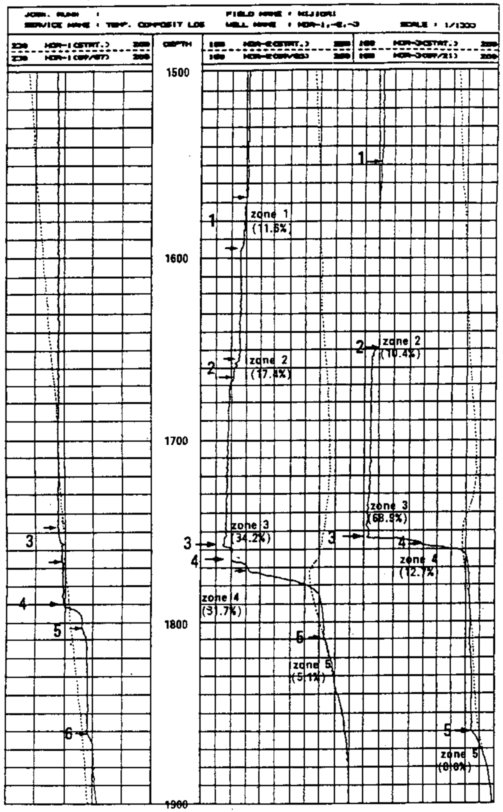

Fig. 4. Temperature profiles obtained for the three production wells showing the indicated zonal thicknesses for the feed zones relative to the injection depth at 1801 m (from Miyairi, et al, 1992).

Table 2
Production Flow Distribution*

Well	Designated Main Feed Zone (m)	Production Interval (m)	Feed Fraction (%)
HDR-1	1790	1530	15
		1628-1767	30
		1790-1803	55
		1860	
HDR-2	1753-1775	1564-1594	11.6
		1654-1668	17.4
		1753-1759	34.2
		1766-1775	31.7
		1810	5.1
HDR-3	1754	1550	0.0
		1649	10.4
		1754	68.9
		1759	12.7
		1861	8.0

*from Yamaguchi, et al (1992).

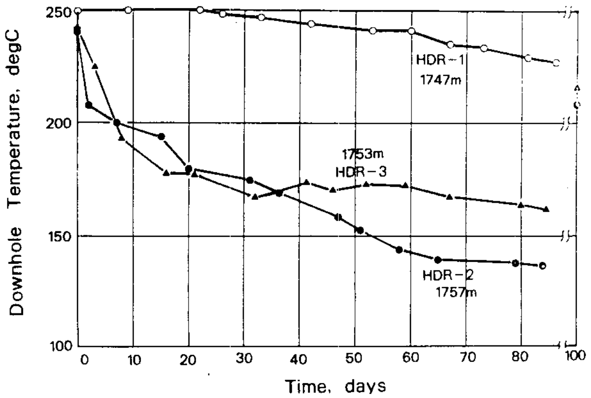

Fig. 5. Fluid temperature histories for the main production zone at depths about 1750-1780 m calculated from downhole logs.

THE SGP 1-D HEAT-SWEEP MODEL

The SGP 1-D Heat Sweep Model was developed experimentally by Hunsbedt, et al (1978) to simulate heat extraction in fractured reservoirs with fluid reinjection or circulation. The model is based on heat transfer properties of regular-shaped rock blocks surrounded by circulating heat-carrier fluid. Kuo, et al (1977) showed from experimental measurements that heat transfer properties of irregular-shaped rock blocks can be successfully approximated as spherical-shaped rocks of equivalent radius for which the heat transfer equations can be solved analytically (Carslaw and Jaeger, 1973). Iregui (in Hunsbedt, et al, 1979) showed that a distribution of varying size and shape rock blocks could be effectively modeled for heat transfer by a single mean size spherical rock with mean equivalent radius.

The governing equations describing heat transfer from the equivalent spherical rock blocks to the circulating fluid under linear heat sweep are given in Hunsbedt, et al (1983). The solution for prescribed linear sweep boundaries and initial conditions is obtained by conversion to Laplace transform equations with numerical inversion by the Stehfest (1970) algorithm. Two major model parameters are the effective reservoir volume and the mean fracture spacing.

For the Hijiori flow regime, with injected fluid partitioned between water loss, three production wells, and multiple feed zones in each well, one-dimensional heat sweep was difficult to define. In prior applications of the model to two-well systems, 1-D linear flow geometry was developed for rectangular, radial, and doublet flows.

To model the heat sweep in the Hijiori experiment from one injection well to three production wells with multiple feed zones and significant water loss, a conceptual model was adopted in which the injection flow was divided into a set of independent flows for each production well and each feed zone. Figure 6a shows the model of the Hijiori zonal flow distribution including water loss and radial flow to the production wells proportional to the flow recovery measured for each zonal thickness. Figure 6b shows the simplified zonal sector flow geometry for the 1-D radial flow heat sweep model.

Table 3 lists the resulting calculated zonal sector flowrates, Q(i,j), where i is the production well number and j is the feed zone number, adjusted for constant water loss of 23.1 %. Testing of the conceptual model was made for the observed cooldowns given in Figure 5. The set of input data for these cases is given in Table 4. Constants in the data set for the zonal sector simulations included injection temperature, porosity, well diameter, and thermal properties of the sector rock blocks.

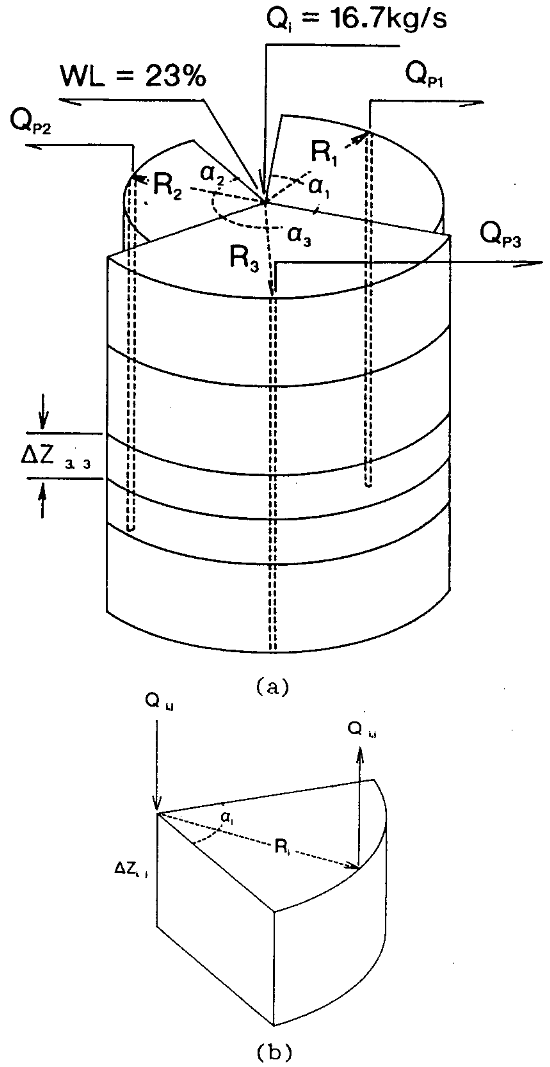

Fig. 6. (a) Conceptual model of the Hijiori zonal flow distribution; (b) radial flow model for each individual zonal sector.

Table 3
Sector Sweep Flowrates
Injection Flowrate = 16.7 kg/s
Production Flowrates

WL = 0.231

	j = zonal fraction			Q(i,j) kg/s i = well fraction		
zone	for HDR well:			1	2	3
j	1	2	3	0.138	0.299	0.332
1	0.15	0.116	--	0.346	0.578	0
2	w/3	0.174	0.104	--	0.867	0.576
3	0.30	0.342	0.689	0.691	1.71	3.81
4	0.55	0.317	0.127	1.27	1.58	0.703
5	w/4	0.051	0.080	--	0.254	0.443

Table 4
Input Data for the Simulations
Heat Sweep Zonal Data

Constants:
T_r = 55 °C R_i = 0.01 m
porosity = 0.01 Thermal Data

Main Zone Data:

	HDR-2,Z3	HDR-3,Z3	HDR-1,Z4
Temp (init) °C	240.6	240.6	252
Q(i,j) kg/s	1.71	3.81	1.27
Thickness m	5	5	13
Radius m	38	80	41
Flow Angle (°)	140	155	65

Several characteristics of the zonal sectors can be estimated from the data in Table 4: the rock block volume, $V=(\alpha/360)\pi Z R^2$; the maximum MFS as a cubic block with no intrinsic permeability, $MFS=V^{1/3}$; the equivalent radius as a sphere for heat transfer with equal surface to volume ratio, $R_{eq}=(3V/4\pi)^{1/3}$; and the initial heat content above a given abandonment temperature, $HC=\rho V C_v(T_i-T_a)$. Table 5 lists these characteristics for the three test zonal sectors for an abandonment temperature of 150 °C.

Table 5
Calculated Zonal Sector Characteristics

	HDR-2,Z3	HDR-3,Z3	HDR-1,Z4
Volume ($10^3 m^3$)	8.82	43.3	12.4
MFS(cubic) (m)	20.7	35.1	23.1
R_{eq}(sphere)(m)	12.8	21.8	14.4
HC (10^{12} J)	2.16	10.6	3.41

SIMULATIONS

The first case examined was the third zone of well HDR-2, where the accumulated data seemed to offer the most definitive input data for sector flow at the feed level of 1754 m. Figure 7 shows the simulation results for the data given in Table 4. Although the observed cooldown curve shows the excursion in bottom-hole temperature due to the two one-week shutins of the well after day 23, two trends are clear: (1) the initial cooldown proceeds with MFS consistent with the dimensions estimated in Table 5; and (2) all of the family of MFS cooldown curves show an area for heat extraction less than the heat extraction indicated by the observed cooldown curve. For the given thermal properties, it is evident that the estimated volume of zonal sector HDR-2,Z3 is too small. Figures 8a and 8b show the effect of doubling the volume, Z changed to 2Z, and quadrupling the volume, R changed to 2R. In the first case, the initial cooldown follows a MFS of 20 m, but the total heat extracted is still too small; in the second case, the initial cooldown follows a MFS greater than 25 m, but the full curve shows a better fit. The excursion in temperature over the critical early period makes it difficult to distinguish between these two alternate cases. The sector volume probably falls between these two values, with some degree of doublet flow accounting for a greater sector radius that the direct linear distance between the two wells.

Figure 9 shows the results for zonal sector HDR-3,Z3 for the data given in Table 4. Here again the observed cooldown follows an initial cooldown simulated by MFS of about 20 m, but the

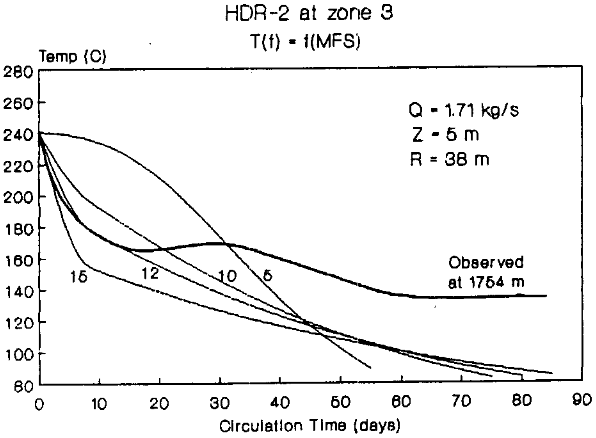

Fig. 7. Simulated cooldown curves of bottom-hole fluid temperature as a function of mean fracture spacing for zonal sector HDR-2,Z3 for the initial estimated dimensions.

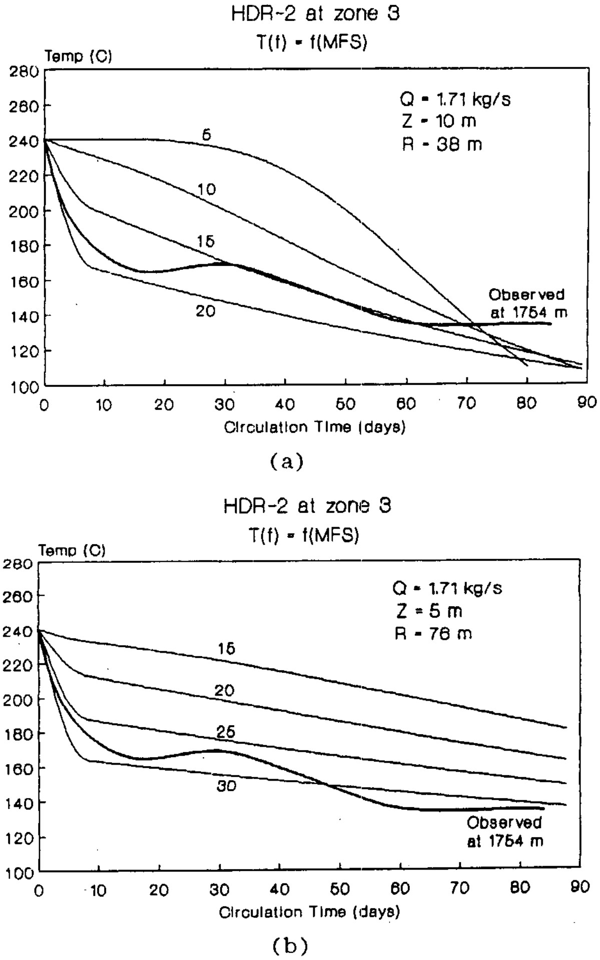

Fig. 8. Simulated cooldown curves for HDR-2,Z3 with (a) twice the zonal thickness (2Vo) and (b) twice the zonal radius (4Vo).

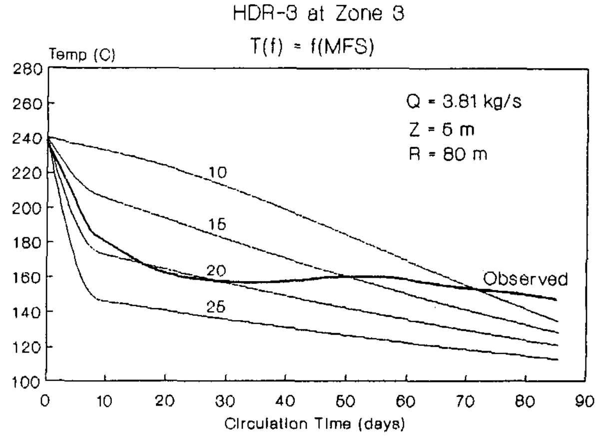

Fig. 9. Simulated cooldown curves of bottom-hole fluid temperature as a function of mean fracture spacing for zonal sector HDR-3,Z3 for the initial estimated dimensions.

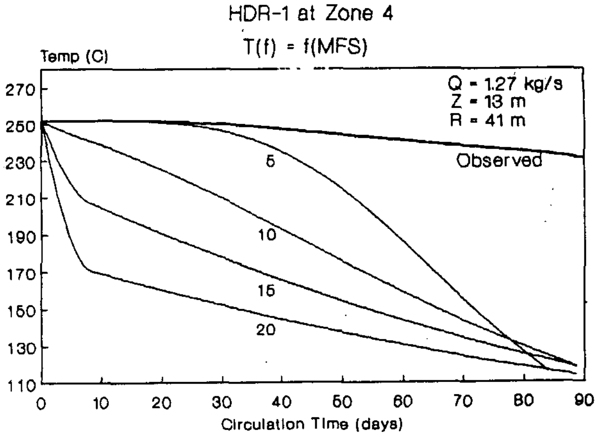

Fig.10. Simulated cooldown curves of bottom-hole fluid temperature as a function of mean fracture spacing for zonal sector HDR-1,Z4 for the initial estimated dimensions.

longer-period temperature excursion on ten days of well shutin prevents greater definition of the unperturbed cooldown. However, here again, the trend does indicates a zonal sector volume greater than that initially estimated.

The observed cooldown for zonal sector HDR-1,Z4 in Figure 5 indicates a more classical S-shaped cooldown curve (or a very long perturbation period on shutin) and greater effort to match it is underway. Figure 10 shows the simulations for the data set in Table 4. The observed cooldown follows a small MFS, but the heat extraction area is much larger than the simulated curves for all MFS. Figure 11 shows the results of the analysis to match both the volume of the zonal sector and its mean fracture spacing with the constraint of maintaining a constant aspect ratio (0.3171) of thickness, Z = 13 m, to radius, R = 41 m. The figure shows the progression of simulated cooldowns for varying MFS with increased volume, from 2Vo to 5Vo, where Vo = 12,400 m^3 (Table 5). It is clear, even for the short 90-day test, that for volume 2Vo, the observed cooldown will have an area greater than the curves for all MFS and that for 5Vo, the observed cooldown will fall below the curves for maximum MFS. Even with the excursion in temperature during the shutin periods, the best fit appears to be for a volume between 3Vo and 4Vo with MFS between 13 and 17 m. The corresponding dimensions of the zonal sector would be a thickness of 19-21 m and a mean flow radius of 59-65 m, The larger flow radius is consistent with the larger radius apparent for zonal sectors HDR-2,Z3 and HDR-3,Z3, where the major part of the injected flow was recovered.

DISCUSSION

The thermal analysis of the 90-day Hijiori test points out several interesting aspects with respect to the extent of heat extraction from the reservoir. First, it is apparent that the test itself can hardly be called a long-term flow test; it is essentially a time-connected string of experiments with several, conflicting objectives: to stimulate fracture growth with flow surges, to evaluate behavior of individual wells on shutin of the other wells, and to test heat extraction from the reservoir. Second, following the early experiments, the test was not run sufficiently long at constant flowrate to overcome the shutin perturbations and establish cooldown trends. In spite of these perturbations, the detailed downhole observations were sufficient to narrow the range of the two key parameters of a HDR reservoir for heat extraction, the volume of rock and MFS accounting for the observed cooldown.

Table 6 shows the extent to which the heat-sweep simulations with the available thermal drawdown data can indicate the range of reservoir heat content and heat extraction parameters. The estimates of reservoir rock block volume and mean fracture spacing were obtained for a constant aspect ratio of zonal sector thickness to radius as estimated from pressure, temperature, spinner logs. Other dimensions for the same volume could have been used. The heat extracted was calculated from

$$HE = \int_{t_o}^{t_a} Q(t)\Delta h(T_r - T_i, t)\, dt$$

where $\Delta h(T_r - T_i)$ is the increase in enthalpy of the produced fluid above the enthalpy of the injected

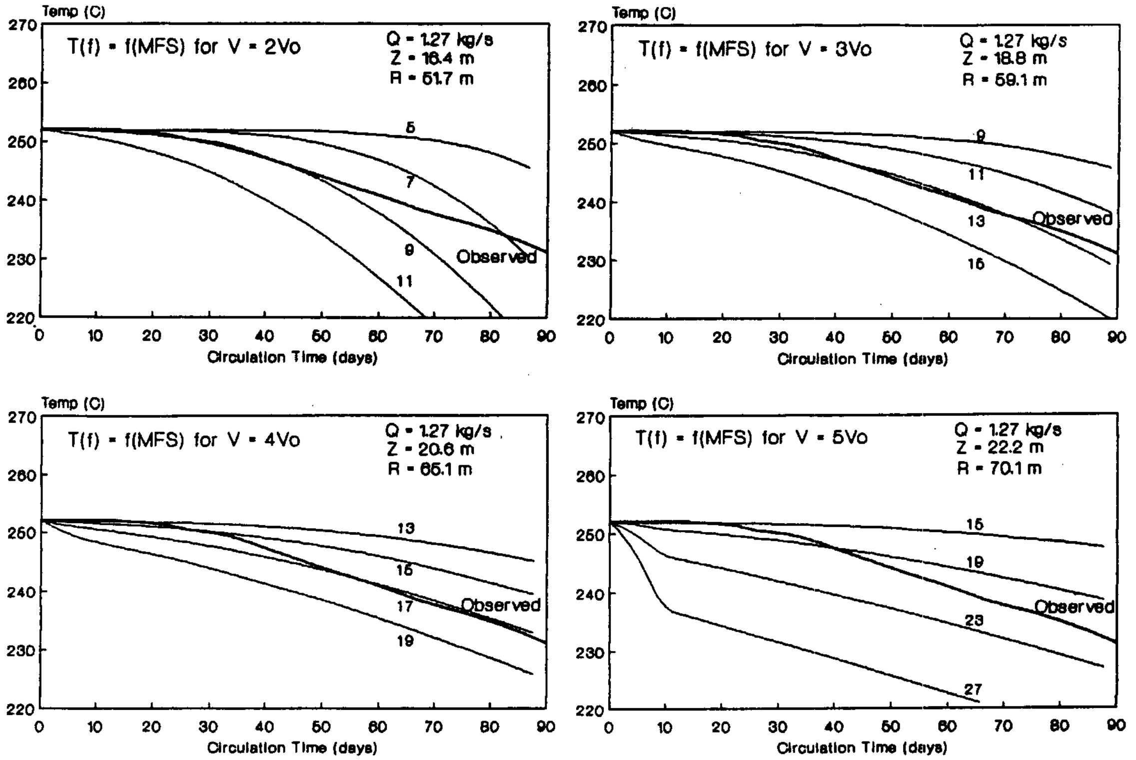

Fig. 11. Simulated cooldown curves for HDR-1, Z4 for the progression of zonal sector volume from 2Vo to 5Vo.

Table 6
Simulation Results

Zonal Sector	Sector Dimensions Z (m)	R (m)	V ($10^3 m^3$)	Mean Fr.Sp (m)	Heat Content (10^{12}J)	Heat Extracted (10^{12}J)	Fraction Produced (%)
HDR-2, Z3	5+	38+	>9	15-30	>2.16	5.75	266
HDR-3, Z3	5+	80+	>40	15-20	>10.6	13.7	129
HDR-1, Z4	19-21	59-65	36-50	13-17	>3.41	8.05	236
			for 3.5Vo		11.9		67

fluid. For $T_a >> T_i$, the heat extracted can be approximated from mean parameters as

$$HE = \bar{Q}\,\bar{\Delta h}\,\Delta t$$

The fraction produced is the ratio HE/HC.

The fractions produced for the three well sectors, shown in Table 6, were based on initial estimated dimensions of the sectors. They range from 129 to 266 %, again indicating that the actual sector size (and heat content) is much larger. For example, for sector HDR-1, Z4, with sector dimensions of 20 m thickness and 62 m radius (3.5Vo), the heat content would be 11.9 x 10^{12} J and the fraction produced at T_a = 150 °C would be 67 %. The 1-D heat sweep simulation for these dimensions gives a fraction produced of 77 %. Considering the large uncertainty in the cooldown data, these values are in good agreement. For these dimensions of sector HDR-1, Z4, the simulation estimates a lifetime to the abandonment temperature of 150 °C of 0.67 years.

One further uncertainty is noted which affects the definition of observed cooldowns noted for the zonal flows. The observed temperature of the downhole fluid in HDR-3, Z3, for example, is the temperature of the mixed fluid from zones, 5, 4, and 3 as it passes the PTS log. Thus, the temperature shown for HDR-3, Z3 is actually an estimate calculated from the logging data. This is also true for HDR-2,Z3. However, for HDR-1, where spinner logging was not possible because of the well casing, the data shown are the actual measured temperature of the produced fluid at zone 4. In view of the compounding problem of the temperature excursions during the shutins, the extent of uncertainty of the observed cooldown curves due to mixed production fluid are difficult to estimate.

CONCLUSIONS

Several conclusions can be inferred from the thermal analysis of the Hijiori 90-day flow test, primary among them is the apparent need to run flow tests for both sufficient time and at constant flowrate to establish a clearly defined cooldown history. The thermal analysis indicates that the feed zones deduced from the PTS logs are representative of the rock-block dimensions for heat extraction and that the observed cooldown curves can be approximately modeled with mean fracture spacing for equivalent cubic or spherical dimensions. Another primary conclusion is the that in spite of the many problems associated with the data as a 'long-term' flow test, it is possible to estimate the approximate size of the Hijiori reservoir as it was constituted during the 90-day test period. If it is assumed that the approximate fraction recovered for sector HDR-1,Z4 is representative of the whole reservoir, then the total heat extracted would be $Q_p/Q_s \times HE_s$, where the total production flowrate, $Q_p = Q_i (1-WL) =$ 12.8 kg/s. The total heat extracted would be $(12.8/1.27) \times 11.9\times10^{12}$ J $= 1.2\times10^{14}$ J. For a recovery fraction of 0.67 (Table 6), the available heat content of the reservoir above the abandonment temperature of 150 °C would be 1.8×10^{14} J and the volume of the reservoir would be 6.6×10^{5} m^3.

The uncertainty in reservoir size and available heat content caused by the water loss of 23 % remains. If "available", the reservoir volume would be 8.7×10^{5} m^3 and the heat content would be 2.3×10^{14} J. Whether this difference in available heat is actually 'lost' or 'stored' needs to be determined.

For the multi-purpose test at Hijiori, the zonal sector model does permit at least a cursory evaluation of the sector rock-block dimensions, the extractable heat content for a given application abandonment temperature, and an idea of the lifetime expectancy for a given circulation flowrate. These data should be of great value in planning the next (deeper) phase of the Hijiori test facility in the near future.

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