PROCEEDINGS, Twenty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 2000
SGP-TR-165

HEAT EXTRACTION ANALYSIS OF THE 1996 HIJIORI 31-DAY CIRCULATION TEST

Paul Kruger and Norio Tenma

Stanford Geothermal Program
Stanford University
Stanford, CA, 94305, USA
kruger@cive.stanford.edu

GeoEnergy Division
Nat'l. Inst. Resources & Environment
Tsukuba, Ibaraki, Japan
tenma@nire.go.jp

ABSTRACT

Evaluation of the Hijiori HDR geothermal resource continued in 1996 with a 31-day flow-enhancement circulation test to characterize the improvement in connectivity of the two production wells. In this last of a series of short-term circulation tests to improve reservoir performance, analysis of the thermal energy extracted was added to the accumulated data from previous tests to predict the thermal energy production capability in a planned long-term circulation test. In contrast to prior short-term circulation tests, the injection flowrate was maintained essentially constant over the 31-day period. The test consisted of two production periods, the first for 23 days to stimulate flow to production well HDR-3 (with well HDR-2a shut-in), and the second for 8 days with flow to production wells HDR-2a and HDR-3. For analysis of thermal energy extracted, the test data for both production periods were treated as flow through independent zonal sectors similar to the technique used for the prior Hijiori short-term circulation tests. The thermal output was estimated by the two heat-sweep methods of calculated temperature cooldown at the production well and calculated thermal-front velocity at abandonment temperature from temperature cross-sections across each zonal sector. The two methods provide estimates of thermal energy extracted from the two zonal sectors during the circulation periods and the reservoir lifetime to the selected abandonment temperature.

INTRODUCTION

The Hijiori HDR geothermal resource in northern Japan has been under investigation by NEDO since 1985 to determine the feasability of hot dry rock power generation in Japan. The project has undergone several stages in development from 1991 when the first (shallow) reservoir was formed and 1992 when a second (deep) reservoir was initiated to create a larger-scale and higher-temperature resource.

Since then through 1995, the two layer system was improved to increase production and in 1996 the connectivity from injection well (HDR-1) to the two production wells (HDR-2a and HDR-3) was tested. In the reservoir development period, three short-term circulation tests were carried out: (1) 90 days in 1991; (2) 25 days in 1995; and (3) 31 days in 1996. A cross-section of the system is shown in Figure 1.

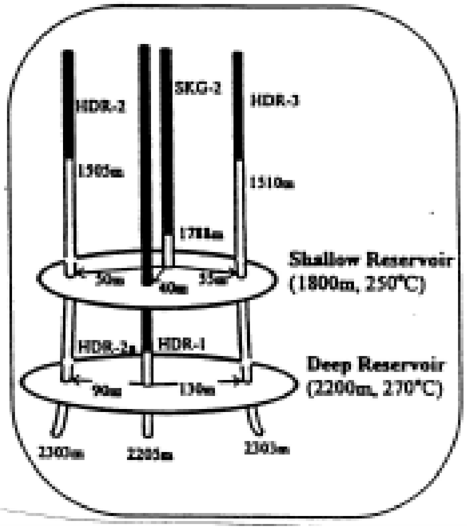

Figure.1. Cross-section of the Hijiori HDR reservoir (from Tenma and Iwakiri, 1998).

Although the primary objective of these short-term circulation tests was to obtain engineering data about the reservoir, an additional benefit of the tests is the accumulation of a heat-extraction database useful in the long-term assessment of the commercial feasibility of HDR resources. Analysis of heat extraction from the 1991 test was given in Kruger and Yamaguchi (1993) and from the 1995 test in Kruger, Sato, and Shinohara (1996). Heat-extraction analysis of the 1996 31-day circulation test adds to the cumulative database. The analysis also is of interest in examining heat extraction in a short-term test with change in production from one well to production from two wells.

HEAT EXTRACTION MODEL

One major uncertainty in assessment of a potential HDR resource is the thermal reserves above a technology determined abandonment temperature available for commercial extraction. The thermal reserves depend on the effectiveness of the reservoir stimulation which determines the range of production flowrate. The production flowrate determines the ratio of mean fluid residence time to mean thermal conduction time in the fractured rock blocks. This ratio (Kruger, 1983) is a function of the mean fracture spacing for fluid flow, which determines the rate of heat transfer to the rock-block surfaces.

In analysis of thermal extraction in short-term flow tests, two parameters are evaluated, (1) the total heat extracted during the test flow period and (2) the fraction of the available heat content of the reservoir. The first parameter is obtained from the experimental data by integration of the product of the unit time flowrate and the enthalpy acquired by the circulating fluid over the total circulating time. The second parameter is estimated from the reservoir volume providing heat to the circulating fluid, multiplied by the mean rock density, rock specific heat, and the mean temperature drawdown given by the difference of the mean initial reservoir temperature and the selected application abandonment temperature. These parameters are described in several prior thermal extraction studies, for example, Kruger (1995).

The SGP 1-D Heat Sweep Model was created by Hunsbedt (Hunsbedt, Kruger, and London, 1978) for the Stanford physical model of a uniformly fractured hydrothermal reservoir. The model was improved to estimate heat extraction from rock blocks of irregular shape and size distribution (Kuo. Kruger, and Brigham, 1977) as heat transfer from spheres of equivalent thermal radius for which the the heat transfer equations can be solved analytically (Carslaw and Jaeger, 1973). The model was compared to the MULKOM geothermal reservoir simulator of Pruess (1983) and the results were given in Lam, et al., (1988). The model was further improved to provide for radial and doublet flow (Lam and Kruger, 1989), and zonal sector flow (Kruger and Yamaguchi, 1993).

Modeling of zonal sector flow is useful in multi-well, multi-horizon reservoirs, such as Hijiori, where both the injection and production wells have multiple entry intervals. In this method, thermal extraction is estimated from recovery fractions of the injected fluid by confining fluid flow to zonal sectors in which the sector flow angle is proportional to the fluid recovery fraction for the estimated thickness of the reservoir. The zonal sector angle (α) is given by $360[Q(p)/Q(i)]$ in degrees. Analysis of heat sweep can be made in two forms, as a temperature decline curve, and as a temperature cross-section. These analyses provide estimates of resource longevity as the time when the production well bottom-hole temperature decline curve falls below the abandonment temperature and as the time when the thermal frontal zone at the abandonment temperature reaches the production well.

The 1996 HIJIORI 31-Day Circulation Test

The 31-day test in the Hijiori reservoir was run in the summer of 1996 as a series of eight test segments within the flow enhancement program described in NEDO (1996). A listing of the test segments is given in Table 1.

Table 1
Segments of the Hijiori 1996 Circulation Test

Date	Operation	Q(l/m)	P(MPa)
10 Aug	1st step-rate injection	4.2-30.0	1.8-10
10-16	flow to HDR-3 only	16.6	8.7
16-22	back-pressure stimulation	16.6	8.2
22-25	comparative P production	16.6	8.0
25-30	comparative P production	16.6	7.6
30-02 Sep	comparative P production	16.6	7.5
02-08	flow to HDR-3 and 2a	16.6	7.4
09	2nd step-rate injection	4.2-30.0	2.1-7.4

The several components of the test, for heat extraction analysis, neglecting the step-rate tests before and after circulation, include a constant injection flowrate under several changes in injection pressure, and a change in flow regime at the change from flow to one production well (HDR-3) to two production wells (HDR-3 and HDR-2a). Both of these operations affected the internal flow patterns (and thus the effective zonal sector volumes), thus adding much uncertainty to the lifetime estimates.

Heat Extraction

The circulation test database supplied by NEDO was reduced in spreadsheet format into delta t (dt) units of constant injection and production flowrate, with a largest dt of 24 hours. The database flowrate (in m^3/m) was converted into mass flowrate (in kg/s) with wellhead injection fluid temperature and steam-table density. The mean flowrate over the circulation period was calculated as the total mass flow divided by the total flow time.

The heat extraction calculations were also made by spreadsheet using dt for each period of constant production rate and the steam-table enthalpy at the interpolated bottom-hole temperature from the several logs taken during the test from which the enthalpy of the injected water was subtracted. The integral of $Q\Delta hdt$ was the heat extracted which divided by the total production time yielded the mean heat extraction rate. Table 2 lists a summary of the heat extraction results.

Table 2: Heat Extraction Data for the 1996 Hijiori Test

Mean Value for	HDR-3	HDR-2a
Injection Flowrate from HDR-1 (kg/s)	16.61	16.61
Production Flowrate (kg/s)	3.39	5.36
Mass Recovery Fraction (%)	20.4	32.3
Enthalpy Increase (kJ/kg)	981	842
Heat Extraction Rate (MW)	3.31	4.49
Total Heat Extracted (TJ)	8.84	2.98

Reservoir Heat Sweep

The second part of the thermal analysis requires an estimate of the reservoir volume available for heat transfer to the circulating fluid. For the 1996 Hijiori flow enhancement test, the estimate of reservoir configuration was adopted from the change in flow conditions for the test segments given in Table 1. The heat extraction period was divided into three zonal sector heat sweeps: (1) for HDR-3, from 10 August to 2 September, when HDR-2a was shut; (2) for HDR-3, from 2 to 8 September, and (3) for HDR-2a from 2 to 8 September, when both wells HDR-3 and HDR-2a were open. The flow regime for the one-production well period is sketched in Figure 2 and the flow regime for the two-production well period is sketched in Figure 3.

The change in flow regime is noted from the data of NEDO (1966) for the entry horizons in injection well HDR-1 at the beginning of the test on 10 August and at the end of the test on 9 September, listed in Table 3. with the entry flow data for the two production wells.

The very complicated flow regime between the upper and lower horizons of the Hijiori reservoir was discussed by Hyodo, Shinohara, and Takasugi (1996) as direct flow from the deep reservoir at HDR-1 to the shallow reservoir. They suggested two possible flow regimes: either up the cement annulus around HDR-1 or directly through the reservoir, neither of which has been determined. The latter flow regime was assumed by Kruger, Sato, and Shinohara (1996) in the heat extraction analysis of the 1995 Hijiori circulation test. The analysis for the 1996 circulation test is even more complicated as noted in Figures 2 and 3. The one-production well period suggests that flow from the lower reservoir went up through the shut-in well HDR2a, and up through the annulus at HDR-1 during the two-well production period.

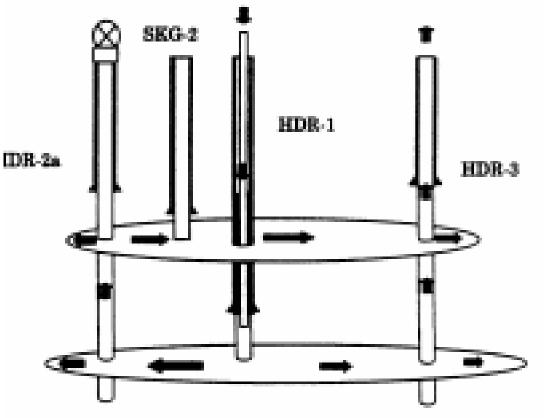

Fig.2 Sketch of the flow pattern in the one-production well test from 10 Aug to 2 Sep 1996.

Another factor in the selection of the zonal sector flow geometry is the unknown amount of fluid storage remaining from previous circulation tests. Potential fluid storage, termed ‘water loss’ in early HDR experiments, was estimated from the cumulative injection and production data in the upper horizon of the Hijiori system through 1991 as approximately 82,000 m^3. This is about the same volume as the total fluid injected in the 1995 circulation test (51,500 m^3) and the 1996 test (41,000 m^3) into the lower reservoir. Thus in this short-term flow test with large change in flow regime, it is possible that the fluid produced from the upper horizon at HDR-3 was stored fluid from previous tests.

Table 3: Fractional (%) Flow Measurements

Horizon	HDR-1		HDR-2a		HDR-3			
(m)	8/10	9/9	8/14-29	9/4	8/21	8/24	9/1	9/5
Upper								
1550					21	32		
1649-75				7	21	23	62	70
1757-82				45	11	7		
Lower								
1930					8	12		
2002-35				4	31	14	16	23
2108				6				
2165-76	10	60	100	38				
2182-90	50	25			8	13	22	7
2193-04	50	15						

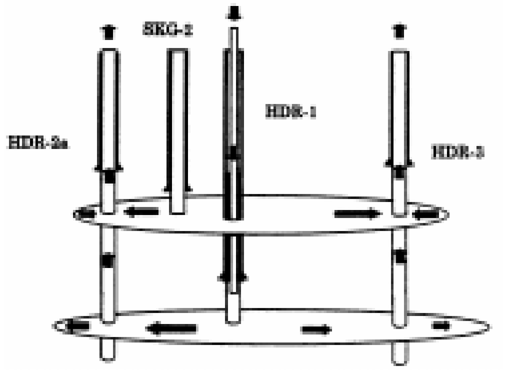

Fig.3 Sketch of the flow pattern in the two-production well test from 2 Sep to 8 Sep 1996.

With these great uncertainties in the flow regime, the heat-sweep analysis was carried out in two ways:

(1) (for the first part of HDR-3 production) with the assumption of complete mixing in the total reservoir volume by the four paths of upflow in the HDR-1 annulus, upflow in the closed production well HDR-2a, direct flow from the lower horizon to the upper horizon, and upper production solely from stored water; and

(2) (for the two-well production) with the assumption of production solely from the lower horizon as a two zonal sector flow.

The flow geometry for the HDR-3 first flow period was selected as a truncated elliptic cone with dimensions obtained from the flow entry levels. The total sector was HDR-3 (1) heat extraction modeled as a right circular cylinder of equivalent radius for the same reservoir volume for the sector mean thickness. The values for the two lower zonal sectors were obtained from Figure 1 and Table 3. A summary of the sector data used for the heat-sweep calculations is listed in Table 4.

The results of the heat-sweep calculations are shown in Figures 4 to 8. Figure 4 shows a sequence of cooldowns in the total reservoir produced from well HDR-3 as a function of the production flowrate. At the measured mean flowrate, the production well would receive fluid above 140C for 60 years. Estimates were made for production flowrate reaching 50% and 100% of the injection flowrate as the reservoir became fully saturated. These are shown in Figure 4 as 8.3 and 16.6 kg/s respectfully. Figure 5 shows the temperature decline curve for the two lower zonal sectors. The smaller zonal sector volume and greater flowrate for HDR-2a results in a faster cooldown compared to the larger volume and smaller flowrate for HDR-3 during the two-well flow period.

Table 4: Heat-Sweep Model Data

	Zonal Sector (Flow Period)		
	HDR-3 (1)	HDR-2a (2)	HDR-3 (2)
R-bar (m)	89	90	130
ΔZ (m)	400	134	260
Q(p) (kg/s)	3.37	2.57	1.03
Angle (°)	360	56	22
Temp(i) (C)	260	270	270
Temp(a) (C)	140	140	140
Calculated			
V(res) (10^6 m^3)	10.0	0.17	0.27
HC (10^{15} J)	3.24	0.060	0.095

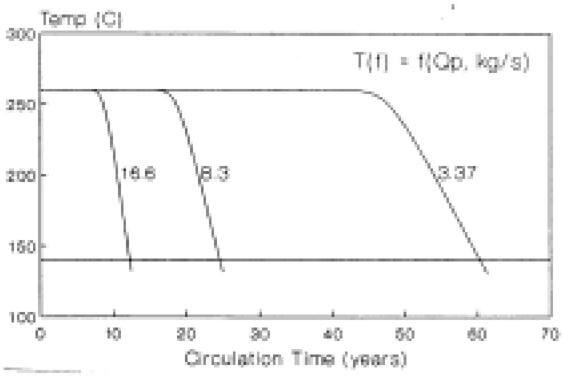

Fig.4. Temperature decline curves for HDR-3 (1) as a function of production flowrate.

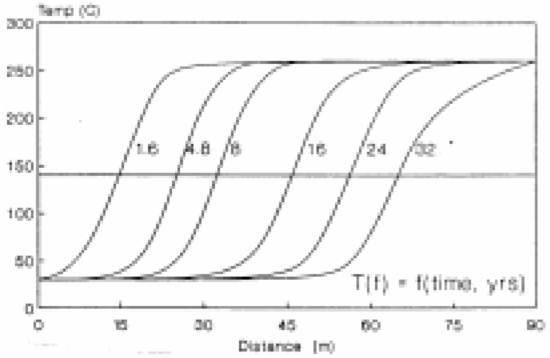

Fig. 5. Temperature decline curves for HDR-2a and HDR-3 in the lower reservoir zonal sectors at the production flowrate.

Figure 6 shows the progress of the thermal front traversing the equivalent-volume reservoir for flow though well HDR-3 only, based on the first period production conditions. The flux velocity at the 140C abandonment temperature line declines as a function of r^2/t (in m^2/y) for estimation of the lifetime to T_a. The temperature cross-sections for the two lower zonal sectors are shown in Figures 7 and 8. A summary of the lifetime estimates from the heat-sweep calculations is given in Table 5.

Table 5: Results of the Heat-Sweep Calculations

	Zonal Sector (Flow Period)		
	HDR-3 (1)	HDR-2a (2)	HDR-3 (2)
Temp Decline			
10% drop time	50.2	2.6	13.3
time to T_a (yr)	60.4	4.3	17.0
for Qp = ½ Qi	24.5		
for Qp = Qi	12.2		
Sector Heat Sweep			
flux vel. at T_a (m^2/y)	131	1920	990
time to well (yr)	60.4	4.2	17.1

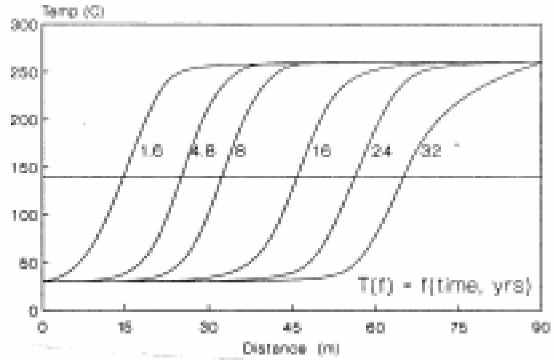

Fig.6. Temperature cross-sections through the HDR-3 total reservoir sector as a function of time at the production flowrate.

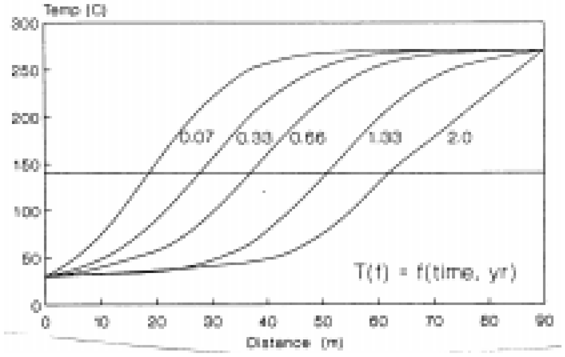

Fig.7. Temperature cross-sections through the HDR-2a lower reservoir zonal sector as a function of time.

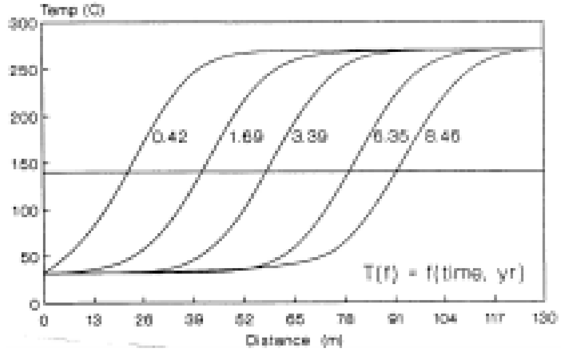

Fig.8. Temperature cross-sections through the HDR-3 lower reservoir zonal sector as a function of time.

DISCUSSION

In view of the great uncertainties in flow regime during this 31-day circulation test, the estimates of heat extracted, estimated temperature decline rate, and longevity to reaching abandonment temperature are within reasonable limits. The values obtained can be compared to those reported by Kruger, Sato, and Shinohara (1996) for the 25-day circulation test in 1995. With the same injection flowrate of 16.6 kg/s and both production wells open, the distribution in fractional flow between the upper and lower reservoirs was about the same. Thus it can be inferred that the flow regime for the 1995 test was the same as that shown in Figure 3 for the two-production well period. The production flowrate was 5.41 kg/s for HDR-2 in 1995 and 5.36 kg/s for HDR-2a in 1996. The flowrate for HDR-3 was 3.80 kg/s in 1995 and 3.39 in 1996. However, since the assumed reservoir flow geometry for heat sweep in the 1995 test was a large truncated zonal sector over both horizons of the reservoir, the estimated reservoir volume and heat content was much greater than that assumed in the 1996 test. The estimated reservoir volume in the 1995 test was about $20x10^6$ m^3, based on a sector volume of $6.3x10^6$ m^3 for wells HDR-2 and HDR-3. The reservoir volume of $10x10^6$ m^3 estimated for the flow geometry for HDR-3 in the first period of the 1996 test may be considered to be in agreement with the 1995 test. Thus, it may be inferred that the 'actual' reservoir volume of the Hijiori system is somewhere between 10 and 20 million m^3 with a total heat content between 3.2 and 7.0 PJ.

The estimates of longevity from the thermal front temperature cross-sections also require distinction between the 1995 and 1996 tests. At the low flowrate of 3.37 kg/s through the reservoir for production from HDR-3 only, the heat content would supply bottom-hole fluid above the abandonment temperature for a period of about 60 years, but at a mean power level of only 3.3 MW_{th}. It was noted for the 1995 test that at the mean flowrate for HDR-2 and HDR-3, the power output was 8 MW_{th}, estimated to last for more than 5 years. The values for the 1996 test are in agreement. The two lower reservoir zonal sectors would provide 4.5 MW_{th} for 4.2 years from HDR-2a and 3.4 MW_{th} for 17 years from HDR-3.

In conclusion, the observation given in Kruger, Sato, and Shinohara (1996) that although short-term flow tests for resource characterization can provide valuable information about the potential for thermal power extraction, a long-term production test at constant flowrate for at least one year is necessary to characterize the real heat extraction capacity of the Hijiori resource, can be repeated here.

REFERENCES

Carslaw, H.S. and Jaeger, J.C. (1973). *Conduction of Heat in Solids*, 2nd Edition, Oxford University Press.

Hunsbedt, A., Kruger, P. and London, A.L. (1978). "Energy Extraction from a Laboratory Model Fractured Geothermal Reservoir", *J.Petro.Tech.* 30,(5) pp.712-718.

Hyodo, M., Shinohara, N., and Takasugi, S. (1996). "An HDR System Hydraulics Model and Analysis of the 1995 Preliminary Circulation Test at the Hijiori HDR Site of the NEDO Project, Japan", *Proceedings*, 3rd International HDR Forum, Santa Fe, NM, May 1996, pp.23-24.

Kruger, P. (1983), "Experimental Studies on Heat Extraction from Fractured Geothermal Reservoirs", in S. Nemat-Nasser, H. Abe, and S. Hirakawa, eds, *Hydraulic Fracturing and Geothermal Energy*, Martinus Nijhoff Pub., Hague, pp. 373-397.

Kruger, P. (1995). "Heat Extraction from HDR Geothermal Reservoirs", *Proceedings*, IGA World Geothermal Congress, Florence, Italy, pp. 2517-2520.

Kruger, P., and Yamaguchi, T. (1993), "Thermal Drawdown Analysis of the 90-day Circulation Test", 18th Stanford Workshop on Geothermal Reservoir Eugineering, SGP-TR-145, 111-118.

Kruger, P., Sato, Y. and Shinohara, N. (1996), "Energy Extraction Analysis of the 1995 Hijiori 25-day Circulation Test", Geoth.Res.Counc.Trans. **20**, 457-463.

Kuo, M.C.T., Kruger, P. and Brigham, W.E. (1977). "Shape-factor Correlations for Transient Heat Conduction from Irregular-shaped Rock Fragments to Surrounding Fluid", AIChE-ASME Heat Transfer Conference, Paper 77-HT-54.

Lam, S.T., Hunsbedt, A, Kruger, P. and Pruess, K. (1988). "Analysis of the Stanford Geothermal Reservoir Model Experiment Using the LBL Reservoir Simulator", *Geothermics*, 17, 595-605.

Lam, S.T. and Kruger, P. (1989). "Doublet Heat Sweep Model with Bounded Initial Temperature Distribution", 14th Stanford Workshop on Geothermal Reservoir Engineering, SGP-TR-122, 249-256.

NEDO (1996). "FY 1996 Summary of Hot Dry Rock Geothermal Power Project", Geothermal Energy Technology Department, NEDO, Japan.

Pruess, K. (1983). "Development of the General Purpose Simulator MULKOM, Annual Report 1982, LBL-15500.

Tenma, N. and Iwakiri, S. (1998). "Program of the Preparatory Period for a Long-Term Circulation Test on the Hijiori HDR Project", *Proceedings*, 4th International HDR Forum, Strasbourg, 28-30 Sep 1998.