EXPERIENCES IN HEAT EXTRACTION ESTIMATES FROM SHORT-TERM HDR GEOTHERMAL CIRCULATION TESTS

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SUMMARY-From two decades of examining the results of short-term circulation tests in some six HDR reservoirs around the world, several general ideas about heat extraction fiom geothermal resources have evolved. They focus on the concept of heat mining in analogy to the mineral extraction industry and involve estimating three commercial-decision parameters that can be estimated fiom early short-term circulation tests: (1) extractable resource content (reserves); (2) optimum extraction rate (deliverability); and (3) resource lifetime (longevity). A review of existing field data fiom the several HDR circulation tests are used to evaluate these parameters. It is concluded that sufficient confidence in the assessment of a fully stimulated HDR reservoir can be obtained during a long-term production test of the resource.

1.0 INTRODUCTION

Geothermal resources are available throughout the world in a variety of geologic forms, but only a few high-temperature hydrothermal resources at attainable depth have been commercially developed for electrical energy generation. The technology for these resources were developed primarily by the hydrogeology and petroleum engineering industries and the methodology for borehole investigations concentrated on reservoir pressure and fluid flowrate measurements. The result has been a focus on fluid extraction performance. An alternate focus could have been the technology of the mineral industries, where the commercial value of the product is evaluated in terms of in-place reserves, concentration distribution, and commercial production rate. A greater potential resource base for long-term growth of a world-wide geothermal energy industry exists for HDR-type geothermal deposits rather than for hydro-type geothermal deposits. Thus, it would be more germane to focus on the product itself, thermal energy, and express product extraction in terms of temperature distribution, size of thermal energy deposit, and the ability for a heat-carrier fluid (either in-place or circulated) to extract the thermal energy (reserves) in commercial concentration (enthalpy) at a sufficient extraction rate (deliverability) and for a sufficient period (longevity).

The relative ease of thermal extraction fiom hydrothermal resources has been accompanied by relatively low thermal energy extraction efficiency. A comparison of thermal extraction for hydrothermal and HDR geothermal resources, adapted fiom Ramey Kruger, and Raghavan (1973) is shown in Table 1. It was noted that the small extraction of energy fiom the high-quality steam-dominated reservoir was due to the essentially isothermal extraction of the steam mass without heat transfer fiom the reservoir rock. The greater thermal energy recovery fiom liquid-dominated reservoirs is due to in-reservoir boiling by heat transfer fiom the rock upon pressure reduction. Fluid recharge of producing reservoirs has increased thermal extraction efficiency in many hydrothermal resources. Continuous circulation in a HDR reservoir eventually produces all of the in-place available energy.

Table 1. Energy Recovery fiom Geothermal Reservoirs

	Steam*		Liquid' HDR**			
	Rock	Fluid	Rock	Fluid	Rock	Fluid
Mass (10^9 kg)	450	0.663	450	15.0	450	0.0
Aband. Content	–	0.134	–	0.16	–	0.0
Production (10^9 kg)						
as Steam	–	0.429	–	3.7	–	0.0
as Water	–	0.0	–	11.1	–	33.2
Avail Energy (PJ)	57.4	1.84	57.4	8.04	57.4	0.0
Recovery (%)						
Fluid Mass	–	79.7	–	98.9	–	90+
Avail Energy	–	6.3	–	43.0	–	100

*from Ramey, Kruger, and Raghavan (1973), based on reservoir of 280°C, 10% porosity, 2×10^8 m^3 volume, 1900 kJ/kg production enthalpy, and abandonment pressure of 0.8 MPa (170°C).

** from Kruger (1993) for same size reservoir with negligible fracture porosity and total production mass to produce 100 MW_{th} for 20 years.

2.0 HDR HEAT EXTRACTION

A HDR geothermal resource may be defined as a deposit of thermal energy in a massive volume of rock of sufficient heat content to support an adequate rate of heat extraction for an adequate amortization period. The available heat content, HC (J), of the resource above the abandonment temperature (the minimum useful fluid temperature) is given by

$$HC = (\rho V)\, C_p\, (To - T_a) \qquad (1)$$

where ρ = rock density (kg/m^3)
V = reservoir volume (m^3)
C_p = rock specific heat (J/kg-C)
T_o = initial formation temperature (C)
T_a = abandonment temperature (C)

The attainable extraction rate depends on two sets of factors: (1) the heat transfer properties of the rock massive and (2) the hydraulic properties within the fluid flow regime. The former is determined by the rock-type fracture network within the fluid-reaching reservoir volume which controls the rate of heat conduction to the fracture surfaces for heat transfer to the circulating fluid. The latter is determined by the connected fracture porosity and permeability distributions which control the fluid flowrate.

The rate of heat extraction may be described by a single index, the number of heat transfer units (N_{tu}) which is the ratio of two time parameters for the thermal and hydraulic properties. The thermal index is the mean-size rock-block time constant, τ, a measure of the rate with which heat from inside the rock block can be conducted to the block surfaces for heat transfer. The fluid index is the mean residence time, t_r, a measure of how long the surrounding fluid is in contact with the rock blocks. $N_{tu} = t_r/\tau$. Thus, for a given total available heat content above a given abandonment temperature, the range of N_{tu} is governed by the sustainable production flowrate at acceptable pressure and the sustainable heat transfer rate to the circulating fluid beyond the initially in-place fluid. The circulation flowrate can be varied within some range of pressure control. An optimum flowrate balances the need for maximum power output (larger flowrate) with maximum thermal extraction efficiency (smaller flowrate). The commercial quality of the resource can be evaluated by the potential for achieving an adequate sustainable power output over an adequate amortization period until the abandonment temperature is reached.

The thermal energy extracted, HE (J), is given by

$$HE = \int_{t_0}^{t_a} Q(t)\, \Delta h\, (T_i, T_f, t)\, dt \qquad (2)$$

where Q = production flowrate (kg/s)
h = fluid enthalpy (kJ/kg)
T_i = injection fluid temperature (C)
T_f = produced fluid temperature (C)

Ah is the increase in enthalpy of the produced fluid above that of the injected fluid.

In the technology development of HDR geothermal resources, a number of experiments have been carried out in several countries in the world (e.g., Kruger, *1995)* in which HDR deposits have been fracture stimulated for water circulation to determine the potential for commercial thermal energy extraction. The emphasis on these tests has been the technology for deep drilling in hard, hot rock and fracture stimulation to provide a reservoir volume for circulation of water as a heat-carrier fluid. The experimental evaluations have been to determine the resulting fluid injection rate as a function of reservoir pressure in analogy to the experience already acquired for hydrothermal resources. These evaluations are acquired by short-term flow tests where the flowrate response to pressure changes provides data on the efficacy of the stimulation method to create the reservoir. However, the commercial feasibility of the HDR resource should be evaluated from the results of long-term circulation testing at constant injection flowrate to provide reliable data for estimating three key parameters: (1) the extractable flow-accessible heat content above the system abandonment temperature (reserves); (2) the optimum heat extraction rate (deliverability) for recovery of operating costs at the sustainable power output; and (3) the resource lifetime (longevity) for amortization of the total investment.

The largest uncertainty in evaluation of a newly stimulated geothermal reservoir is the magnitude of the reservoir volume constituting the total reserves of thermal energy available for heat transfer to the circulating fluid that will eventually return to the production well within the lifetime of the resource. In pre-production testing, the potential reservoir volume can be estimated by several methods. The most common is an estimate of the most likely flow geometry around the stimulated wellbore system. Other methods have been derived from (1) a basis for limiting the volumetric envelop of microseismic events to that most likely to bound the circulating fluid contact volume within the accessible fracture network, (2) measurement of modal fluid (tracer) volume and

mean porosity of the reservoir, (3) a basis for limiting the pressure inflation response (Brown, 1991) to the fluid contact volume, and (4) evaluation of prior heat extraction history. An example of the range of such estimates is given in Robinson and Kruger (1992) compiled for the Fenton Hill HDR reservoir.

3.0 STAGES OF THE SGP 1-DHSM

The SGP 1-D Heat Sweep Model, initiated by Hunsbedt (Hunsbedt, Kruger, and London, 1978), was designed for analysis of the SGP Physical Model of a uniformly fractured-rock hydrothermal reservoir to measure heat extraction with limited geologic and thermodynamic data. The model was improved to estimate heat extraction from reservoirs of rock blocks of irregular shapes and size distributions (Kuo, Kruger, and Brigham, 1977) in terms of heat transfer from a sphere of equivalent thermal radius, for which the heat transfer equations can be solved analytically (Carslaw and Jaeger, 1973). Experimental verification of the model was shown by Hunsbedt (Hunsbedt, et al., 1979). The model results were compared to results using the MULKOM geothermal reservoir simulator (Pruess, 1983) as reported by Lam, et al. (1988). The model was further improved to provide for radial and doublet flow (Lam, 1990), non-uniform initial temperature distribution (Lam and Kruger, 1989), and zonal sector flow (Kruger and Yamaguchi, 1993).

The thermal physics of the model is summarized in Kruger (1983). For the prescribed reservoir flow regime boundaries and initial conditions, the model solves the heat transfer equations by converting them to Laplace transform equations with numerical inversion by the Stehfest (1970) algorithm. The output is the calculated temperature distribution over the linear sweep geometry and the bottom-hole fluid temperature as function of production time.

4.0 APPLICATION OF THE MODEL

The SGP 1-D Heat Sweep Model has been used for several studies of hydrothermal and HDR geothermal resources. For hydrothermal systems, the model has been used to estimate fluid sweep and percolation recharge with cooldown history matching in operating fields and scenario analysis of cold-water injection for repressuring of mature fields. For HDR geothermal systems the model is useful for analysis of heat extraction data from experimental circulation tests and for prediction of heat extraction potential from newly stimulated reservoirs prior to short-term well testing and long-term production testing. The latter type of testing is most important for commercial investment decisions in that prediction of thermal energy recovery over the useful life of the resource can be obtained continuously from early times during long-term production testing with continuously decreasing uncertainty. For a given thermal extraction rate (fluid enthalpy and potential electric power level), the total energy extractable (reserves) can be estimated by two complementary estimates of the resource longevity (time to fluid abandonment temperature). Analysis of the heat sweep can be made in two forms; as a temperature decline curve at the production well, and as a temperature cross-section through the reservoir. The resource longevity is defined as the time when the production well bottom-hole temperature falls below the abandonment temperature and as the time when the thermal frontal zone at the abandonment temperature reaches the production well.

4.1 World-Wide HDR Circulation Tests

The SGP 1-D Heat Sweep Model has been used in a majority of the HDR circulation tests carried out from the inception of the HDR geothermal program to date. A review of the status of completed tests and planned tests as of 1995 was reported by Kruger (1995). Analysis of the completed tests included the HDR program at Rosemanowes, UK (1985-1988), Fjallbacka, Sweden (1989), Fenton Hill, USA (1992-1993), and the on-going programs at Hijiori (since 1991) and Ogachi (since 1993) in Japan.

4.1.1 Rosemanowes, UK, 1985-88

The first long-term (> 1 year) circulation test was operated at the Rosemanowes Quarry in Cornwall, England from 1985 to 1988. Details of the program were described in Parker (1989). For heat extraction analysis an important aspect of the test was the continuous operation at sustained injection mean flowrate and measurement of downhole temperature. Nicol and Robinson (1990) had estimated the reservoir volume from seismic data as 5 million m^3. From the 3-year production database, Kruger (1990) obtained a match of the observed temperature decline, shown in Figure 1, based on two key parameters: the reservoir volume and the mean fracture spacing for heat transfer from the reservoir rock. The former is a parameter for the mean residence time and the latter is a parameter for the rock-block time constant. With a sensitivity for best-fit of within ± 5-10% over the modeled range, the match yielded a reservoir volume of 3.25×10^6 m^3 and mean fracture spacing of 50 m.

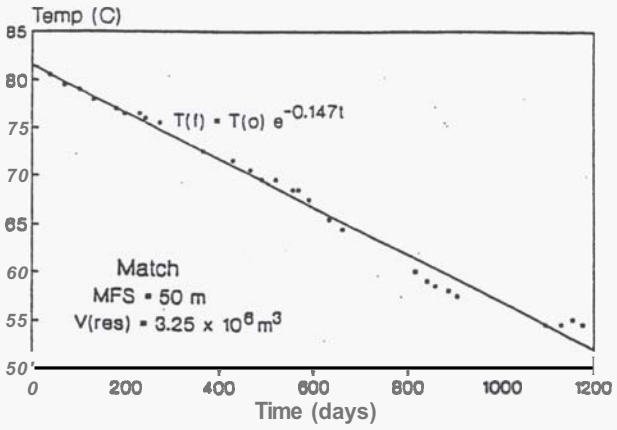


Fig.1. Match of observed cool down at Rosemanowes with simulated cooldown based on fitted reservoir volume and mean fracture spacing.

4.1.2 Fenton Hill, **NM,** USA, **1992-93**

The long-term flow test (LTFT) at Fenton **Hill** has been the most studied attempt to operate a HDR resource under near-commercial conditions, deep enough for high-temperature fluid recovery and long enough to estimate economic parameters. Details of the **LTFT** were reported by Brown **(1993)** and an analysis of the heat extraction data was given by Kruger and Robinson **(1994).** Although the project was beset by many problems over its lifetime, including failure of the available heavy-duty pumps after the initial 4-month period of the LTFT, the test continued with three additional production periods over a 14-month test period. Automatic acquisition of test data over the entire test period provided a large database of flowrate and surface injection and production temperature for heat extraction analysis. Numerical calculation of **Equ.(2)** (with **steam** table data incorporated into the program) was made for each of the **six** production segments of the test. The largest uncertainty in the estimated heat content of the stimulated reservoir was the reservoir volume. A review of the several methods used to estimate reservoir volume is given in Robinson and Kruger **(1992).** The results of the heat extraction analysis, based on a best-estimate of 6.5×10^6 m^3 for the reservoir volume indicated that the heat extracted at mean injection flowrate (constant power output) over the **14** months of circulation was **6** %. Extrapolation of the test data to the abandonment temperature yielded **an** estimated resource life-time of **15** years in good agreement with the pre-test estimates given by Robinson and Kruger **(1992).** A comparison of the heat extraction results for the two long-term circulation tests at Rosemanowes and Fenton Hill is shown in Table **2.**

Table **2.** Comparison of the Two LTFTs

	Rosemanowes **UK 1985-88**	Fenton Hill USA **1992-93**
Duration (days)	**1200**	**273**
Reservoir Depth (km)	**2.0**	**3.5**
Res. Volume (10^6 m^3)	**3.5**	**6.5**
No. of Wells	**3**	**2**
Temperature (C)		
mean initial	**82**	**240**
injection	**20**	**50**
abandonment	**50**	**150**
Heat Content (10^{15} J)	**0.24**	**1.5**
Mean Flowrate (kg/s)	**14.5**	**8.0**
Heat Extracted (PJ)	**0.29**	**0.09**
Fraction Produced	**1.20**	**0.06**

4.1.3 Hijiori and Ogachi, Japan, **1991-97**

Technology development for HDR geothermal resources for electric power generation has been active in Japan since the **1980s.** Current focus is on two experimental sites (the Hijiori and Ogachi resources) in Honshu where multi-well, multi-horizon stimulated reservoirs have been created to expand the potential for increased thermal production efficiency by maximizing the reservoir volume of connected permeability. Since **1991,** several short-term circulation tests have been carried out at the two fields to evaluate the response to the respective reservoir stimulation projects and **to** measure the pressure-flowrate reservoir characteristics. The **status** of these tests was reported by Tenma and Iwakiri **(1998)** for Hijiori and by Kitano, **Kiho,** and **Hori** (1 **999)** for Ogachi.

To assist in the evaluation of the thermal aspects of these tests in preparation for planned long-term production tests, the SGP 1-D Heat Sweep Model was used to estimate the key heat extraction parameters of the respective reservoir **as** they were studied for each of the short-term tests. From **1991** through **1996,** three circulation tests were carried out in the Hijiori reservoir and four in the Ogachi reservoir. A ***summary*** of the combined data from these tests was given in Kruger, Karasawa, Tenma, and Kitano **(2000).** Heat extraction analysis of the circulation in the multi-well, multi-horizon reservoirs required modification of the 1-D Heat Sweep Model to account for the varied production at multiple entry horizons in each production well and from one production well to another in each reservoir. The analysis method, described in Kruger and Yamaguchi **(1993),** was based on assigning the recovery fraction of the injected fluid for thermal analysis to zonal sector flow geometry in which the fluid flow is confined to a **zonal** sector of mean

thickness of each reservoir zone at a sector angle, *a,* proportional to the fluid recovery rate. The zonal sector flow is given by

$$\alpha_{i,j} = 2\pi\, Q(p_{i,j})/Q(i) \qquad (3)$$

where Q(p) = mean production flowrate (kg/s) in zonal sector well i and horizon j
Q(i) = mean injection flowrate (kg/s).

Analysis of heat sweep through the zonal sector was made in two forms: **(1)** with variation of mean fracture spacing to observe the effect of heat transfer rate fiom fractured rock to circulating fluid; and **(2)** as a temperature cross-section at constant mean fracture spacing to observe the passage of the thermal front through the sector. Examples of the output data for each form are shown in Figures 2 and **3.** The former **shows** the difference in cooldown rate in the lower zonal sectors between the two production wells in the Hijiori 31-day test in **1996** (Kruger and Tenma, **2000).** The latter shows the temperature cross-section at the lower zonal sector for the lower-impedance well. The extrapolated lifetime to the production well at abandonment temperature was **4.2** years compared to **17.1** years for the other (higher impedance) well.

A *summary* of the heat extraction results for the seven short-term circulation tests at the Hijiori and Ogachi fields is given in Table 3. The data show the variations between the two fields as well as the variations between tests at each site. The results for the two projects are used for planning of the forthcoming long-term production tests scheduled for each of the two fields.

Table 3. ***Summary*** of Results for Hijiori and Ogachi

	Hijiori			Ogachi			
	1991	1995	1996	1993	1994	1995	1996
V_r ($10^6 m^3$)	0.66	6.3	-	0.14	0.75	1.77	0.91
HC (PJ)	0.18	2.2	-	0.03	0.18	0.34	0.18
Δt (days)	90	25	31	22	151	30	10
Q(i) (kg/s)	16.7	24.7	16.7	16.7	10.8	9.7	7.8
Q(p) (kg/s)	12.8	4.8	5.2	0.28	1.01	2.01	0.84
R_{th} (MJ/s)	27.5	7.9	7.8	0.3	9.6	1.9	0.9
HE (TJ)	0.12	16.6	11.8	0.5	-	4.8	0.8
Life (yrs)	>0.7	>5.0	-	6.5	7.5	13.5	16

5.0 CONCLUSIONS

The potential for world-wide geothermal energy, besides the few natural hydrothermal systems that exist in a few endowed countries, rests in the successful utilization of hot *dry* rock geothermal resources widely available. Thus, the need is evident to accelerate the development of the technology for commercial scale HDR geothermal resources. Besides the existing problems of how to improve methods for locating potential HDR deposits from the surface, drilling efficiently into hard rock formations, and creating large volumes of permeable reservoirs, there also exists the need for pre-production estimation of the economic viability of the stimulated reservoir. Thermal recovery to date indicates encouraging results.

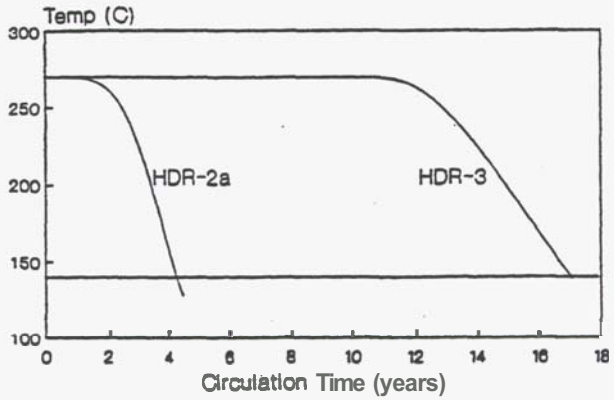


Fig.2. Temperature decline curves for the two production wells in the lower reservoir of the Hijiori 31-day circulation test of **1996** (from Kruger and Tenma, **2000).**

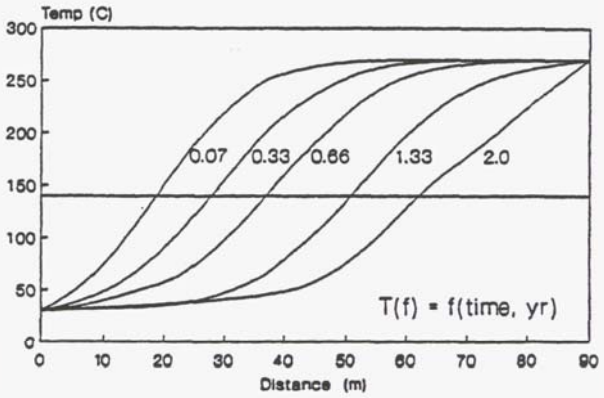


Fig.3. Temperature cross-sections as a function of time through the HDR2a lower reservoir zonal sector of the Hijiori 31-day circulation test of **1996** (fiom Kruger and Tenma, **2000).**

However, it is also apparent that improvements are needed to increase confidence in estimating the three key heat extraction parameters: (1) the reserves available in the resource; (2) the rock-block size distribution for effective heat transfer; and (3) the optimum production flowrate to obtain maximum power level with sufiicient longevity for economic recovery.

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