HEAT EXTRACTION FROM HDR GEOTHERMAL RESERVOIRS

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ABSTRACT

Commercial development of HDR geothermal resources requires estimates of extractable heat content and potential for optimum heat extraction rate and production lifetime under given reservoir structure and fluid circulation conditions. Major parameters in evaluation of prospective resources are the volume (heat content) of the heat extractable reservoir, the fracture distribution that governs the hydraulic regime (mean residence time), and the mean fracture spacing of rock-block size distribution that governs the rate of heat transfer (thermal conduction time). The relationship of the fluid residence time and the rock block thermal conduction time determines the production temperature decline curve under steady production. The total heat extracted is the integral product of the production flowrate and the increased enthalpy of the circulated fluid. These data can be examined from long-term flow tests of the few active and planned HDR reservoirs in the world.

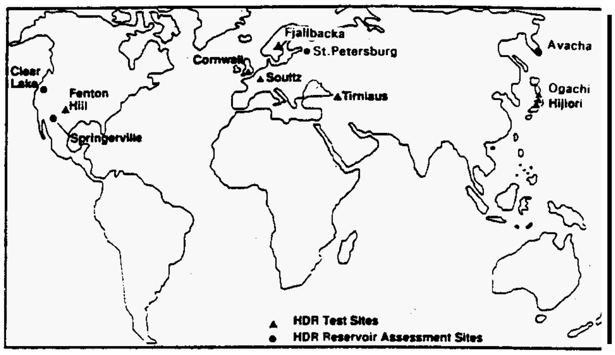

Fig. 1 Location of worldwide HDR rescarch sites.

INTRODUCTION

Geothermal heat mining may be defined as the extraction of useful energy at suitable temperature from deposits of heat located throughout the Earths crust. Where sufficient water is not naturally available as a heat-carrier tluid in hot dry rock (HDR) resources, engineered circulation systems must be created for heat extraction. Several experimental projects are underway in many countries to develop technology for commercial mining of HDR geothermal deposits.

HDR technology development includes design studies, well drilling and fracture stimulation to create geothermal reservoirs. Well testing is performed to determine reservoir flow characteristics. Long-term flow tests are carried out to estimate economic parameters, which include:
(1) estimation of stimulated flow-accessible reservoir volume and available heat content above a given application-specific minimum temperature; and
(2) evaluation of the data to design an optimum extraction strategy.

In recent years, five heat-extraction circulation tests have been carried out in four countries. This review examines the heat-extraction data acquired from these tests relative to reservoir rock volume, temperatures, well multiplicity, available heat content, and flowrate, and summarizes the data on extent of heat extracted.

HDR GEOTHERMAL HEAT EXTRACTION

In evaluation of the commercial potential of a stimulated HDR geothermal reservoir, three parameters must be sufficiently estimated for investment decisions:
(1) available heat content of the reservoir
(2) optimum thermal extraction rate
(3) total heat extracted.

The available hcat content, HC, (J) of a given stimulated HDR reservoir, as noted in Kruger (1993), is given by

$$HC = (\rho V_r)\, C_p\, (T_o - T_a) \qquad (1)$$

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

The thermal extraction rate for a specific reservoir depends on two sets of reservoir characteristics: (1) the heat transfer properties of the reservoir and (2) the flow regime for heat transfer. The heat transfer properties are determined by the rock-type fracture network which controls the rate of conductive heat transfer to the rock-block surfaces. The flow regime is determined by the connected fracture porosity and permeability distributions. 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 thermal extraction rate over a given amortization period until the abandonment temperature is reached.

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

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

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

Δh is the increase in enthalpy of the circulated fluid above that of the injected fluid. The fraction of available heat content produced is the ratio

$$FP = HE/HC \quad (3)$$

COMPLETED HDR CIRCULATION TESTS

Several HDR geothermal development projects were included in the review of international programs reported in the Geothermal Hot Line (CA Resources Agency, 1991). A more detailed description of the international programs in HDR technology development was given by Duchane (1991). These two reports listed some 11 project sites in *6* countries. Five of the projects have resulted in completed circulation tests; others are underway or under study. Summaries of the heat extraction aspects of these programs which are of significant interest *in* the development of HDR technology were given by Kruger (1994a,b).

The data in Table 1 summarizes the heat extraction experience accumulated for the five completed HDR circulation tests in four of the countries with HDR programs. The data show a rather large spread in engineering design, reservoir characteristics, and test duration. In each case, studies were made to examine the thermal behavior of the test, involving estimates of reservoir volume, thermal properties, and thermodynamic conditions. Several additional studies are underway to evaluate the heat extraction efficiency, based on estimated heat content of the reservoir and heat extracted during the test. These aspects of the five tests follow.

(1) Rosemanowes, UK, 1985-88

The first long-term flow test in a HDR geothermal reservoir was operated for more than 3 years at the Rosemanowes Quarry in Comwall, England, from 1985 to 1988. Descriptions of the test were given by Parker (1989a,b). An important aspect of the test was the continuous operation at sustained mean flowrate and measurement of downhole temperature. With detailed seismic mapping and tracer testing, it has been possible to estimate the reservoir heat content and heat extracted. Nicol and Robinson (1990) estimated the reservoir volume from seismic data as **5** million m^3. From the production database provided by Nicol (D. Nicol, private communication, 1989), Kruger (1990) obtained a match of the observed temperature decline over the 3-year production period based on parameters of 3.25×10^6 m^3 reservoir volume and 50 m mean fracture spacing for heat transfer from the reservoir rock. By Equ.(2), with enthalpy assumed to decline exponentially similar to the temperature decline (Kruger and Robinson, 1994), the fraction produced was estimated as 120 %, indicating the possibility of thermal recharge over the 3-year production period, equivalent to a reservoir volume of 3.9×10^6 m^3. However, with the computer program prepared by Robinson to calculate the heat extracted from the Fenton Hill LTFT, and the large short-period database provided by Nicol, the integral of Equ.(2) yielded a fraction produced of 98 %. The question of long-term conductive heat recharge of HDR reservoirs remains unanswered.

(2) Fjallbacka, Sweden, 1989

A circulation test was carried out for 35 days with continuous injection at the Fjallbacka site in western Sweden to investigate the hydraulic performance of the reservoir. A description of the test was given by Eliasson, Sundquist, and Wallroth (1990). From the detailed microseismic data obtained from the test, Wallroth (private communication, 1994) estimated a seismic-active volume of 30×10^6 m^3. For the thermal properties of the monzogranitic formation, the estimated available heat content was about 0.42 PJ. Although continuous downhole temperature measurement was attempted, the probe failed after 9 days of circulation and further thermal data were not available. However, the 9 days of temperature data show a smooth rise towards the initial reservoir temperature, and perhaps further examination of the heat extraction data could provide a better estimate of the heat-content volume for comparison with the estimated seismic-response volume.

(3) Hijiori, Japan, 1991

The Hijiori 90-day circulation test is unique in being the only multi-production well test run for a sufficient period to observe temperature cooldown at multiple production horizons in the stimulated reservoir. A description of the test was given by Yamaguchi, et al (1992). The test was run with accumulation of a large database of production conditions. Several abrupt changes in flowrate due to multiple test objectives were made during the 90-day test. In spite of these perturbations, sufficient temperature data were collected at each well to allow a reasonable evaluation of the heat content and heat extraction. An analysis of the thermal drawdown was reported by Kruger and Yamaguchi (1993) based on modeling the flow regime as zonal sectors with proportional fractions of the constant injection flowrate. From matching of observed downhole temperature cooldown in the major flow zone in each production well, it was possible to estimate the heat extracted from these zones. With the further assumption that the major zones were representative of the other zones, the total heat extracted provided an estimate of the heat content of the reservoir and thus the reservoir volume.

(4) Fenton Hill, USA, 1992-93

The long-term flow test (LTFT) at Fenton Hill may be considered to be the closest attempt to operate a HDR resource under near-commercial conditions, deep enough for high-temperature recovery, and long enough to estimate economic parameters. A description of the LTFT was reported by Brown (1993) and an analysis of the heat extracted was given by Kruger and Robinson (1994). Although the test was beset by pump failures after the initial 4-month period of operation, the test continued with three additional production periods over a 14-month test period. The automatic acquisition of test data during the entire test period provided a large data base of flowrate and surface injection and production temperatures for the estimation of heat extracted. A numerical calculation of the heat extracted using Equ.(2) (with steam table data incorporated into the program) was made for each of the six production segments of the test. The resulting fraction produced for the 14-months of the test duration was *6 %*. Extrapolation of the test data to the abandonment temperature yielded an estimated resource life-time of 15 years that agreed well with the pre-test estimates given by Robinson and Kruger (1992).

(5) Ogachi, Japan, 1993

The Ogachi HDR project is being conducted by the Central Research Institute of the Electric Power Industry (CRIEPI) in conjunction with several electric power companies in Japan. **A** preliminary circulation test was run in Oct-Nov 1993 for 20 days to evaluate the reservoir. A description of the test was reported by Kitano, Hori, and Motojima (1993). The results are being used to design a 6-month circulation test scheduled for 1994, on the way to a long-term 100 kW power test in 1995.

Table 1
Completed Circulation Tests

	Rosemanowes UK 1985-88	Fjallbacka Sweden 1989	Hijiori Japan 1991	Fenton Hill US 1992-3	Ogachi Japan 1993
Duration (days)	**1200**	**35**	90	**273**	**20**
Depth to Res. (km)	**2.0**	**0.5**	**1.8**	**3.5**	**1.0**
Res. Volume ($10^6 m^3$)	**3.5**	**29**	**0.7**	**6.5**	**1.3**
Number of Wells	**3**	**2**	**4**	**2**	**2**
Reservoir Temp. (C)					
mean initial	**82**	**15**	**240**	**240**	**200**
injection	**20**	**8**	55	**50**	n/a
abandonment	**50**	**8**	150	**150**	**140**
Heat Content(10^{15}J)	**0.240**	**0.42**	**0.18**	**1.5**	**0.22**
Flowrate (kg/s)	**13.6**	**1.3**	**12.8**	**8.0**	**n/a**
Heat Extracted (PJ)	**0.236**	n/a	**0.12**	**0.09**	n/a
Fraction Produced	**0.98**	tbd	**0.67**	0.06	tbd

POTENTIAL CIRCULATION TESTS

Table **2** lists some of the HDR projects by site that may have circulation tests in the near future. These projects are in a wide range of development from initial design to test preparation.

The Soultz-sous-Forets project in France near the border with Germany is the front-runner of the sites under study by the European Community as a scientific prototype for designing a commercial HDR system. The basic criteria for the European HDR demonstration plant, given by Baria, et al **(1992),** are a rock temperature of **175** °C, maximum thermal drawdown of 1 % per year, and a flowrate of **15 l/s** (perhaps, **up** to **30 l/s)** through the heat exchange area of the reservoir. Drilling is underway to increase the current reservoir depth from about **2.0-2.2 km,** where the rock temperature is about **150 °C** to a depth of about **3.5** km to the design temperature of **175** °C. **An** economic analysis by Smolka and Kappelmeyer **(1991)** was based on a heat extraction model which calculates production temperature with time as functions of total fracture heat exchange area, distance between fractures, and production flowrate.

The Hijiori site in Japan was extended in **1993-94** to a depth of **2300** m (Yamaguchi, et al, **1993)** in preparation for creating a deeper reservoir and conducting a long-term circulation test starting in **1995** or **1996.** Analysis of the potential for heat content and extraction strategy is underway.

The Ogachi site in Japan is under study for conducting a circulation test between the two wells for a period of 6 months in **1994** (Kitano, et al, **1993)** in anticipation of a new project by CRIEPI and the electric power companies for constructing a 100 kW pilot plant in **1995.**

The Tirniauz HDR project near Mt. Elbrus in Russia was designed as a commercial hot-water supply for extending the mining season of the sponsoring tungsten-molybdenum mining company. The first hydrofracturing test of the site was carried out in February, 1991. Details of the hydrofracturing experiment were translated by Kruger **(1992).** The project is currently in abeyance pending political resolution of negotiations with the local autonomous republic.

A HDR project was initiated in Saint Petersburg, Russia as a municipal hot-water supply in **1993** (Y. Dyadkin, private communication, **1993)** to augment the current supply. It is reported that the first exploratory drilling commenced in **1994.**

An important step for HDR technology development in the United States is the initiation of a second U.S. Site suitable for demonstrating the economic viability of HDR geothermal resources for electric power generation. A second site most likely would be in the more resource rich western States, but a demonstration of HDR utilization as a national resource could also be carried out in the more populated eastern States as the technology improves.

CONCLUSIONS

The total of world experience in development of geothermal HDR technology as derived from long-term flow testing has been summarized in this brief report. The question remains: what has been learned from these five short- to long-term flow tests? In addition to the need for further technology development, which includes such problems as (1) how to locate and evaluate potential deep HDR deposits from the surface, **(2)** how to drill efficiently into hard rock formations, and **(3)** how to create and complete stimulated reservoirs, need also exists for

Table **2**
Potential HDR Circulation Tests

HDR Site	Project Description	Date
Soultz, France	European Comm. Scientific Prototype	??
Hijiori, Japan	Deeper Reservoir; Longer Test	**1995**
Ogachi, Japan	100 kW Demo; CRIEPI + Utilities	**1996+**
Tirniauz, Russia	Commercial Hot-Water Supply	??
St.Petersburg, Russia	Municipal Hot-Water Supply	??
Second U.S. Site	Commercial Size Demonstration	??

pre-production estimation of the economic viability of the stimulated reservoir. Reliable means are needed to evaluate the potential for thermal energy extraction before and during flow testing of the reservoir. The data accumulated to date from the five completed flow tests show encouraging results. It is apparent that further testing is needed to increase confidence in estimating the three key heat extraction parameters: (1) the size of the heat-extractable reservoir; (2) the fractured-block size distribution for available heat transfer rate, and (3) the optimum production flowrate to obtain the best power level with efficient heat cxtraction. It is also apparent that long-term flow testing should be camed out at constant flowrate, at least long enough for the key heat extraction parameters of the reservoir to be sufficiently determined. The experience to datc also shows that simple heat extraction models are sufficient for verification of reservoir potential.

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