

HEAT EXTRACTED FROM THE LONG TERM FLOW TEST IN THE FENTON HILL HDR RESERVOIR

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ABSTRACT

A long-term flow test was carried out in the Fenton Hill HDR Phase-2 reservoir for 14 months during 1992-1993 to examine the potential for supplying thermal energy at a sustained rate as a commercial demonstration of HDR technology. The test was accomplished in several segments with changes in mean flowrate due to pumping conditions. Pre-test estimates of the extractable heat content above a minimum useful temperature were based on physical evidence of the size of the Fenton Hill reservoir. A numerical model was used to estimate the extent of heat extracted during the individual flow segments from the database of measured production data during the test. For a reservoir volume of $6.5 \times 10^6 \text{ m}^3$, the total heat content above a minimum temperature of 150°C was $1.5 \times 10^{15} \text{ J}$. For the total test period at the three sustained mean flowrates, the integrated heat extracted was $0.088 \times 10^{15} \text{ J}$, with no discernable temperature decline of the produced fluid. The fraction of energy extracted above the abandonment temperature was 5.9%. On the basis of a constant thermal energy extraction rate, the lifetime of the reservoir (without reservoir growth) to the abandonment temperature would be 13.3 years, in good agreement with the pre-test estimate of 15.0 years for the given reservoir volume.

INTRODUCTION

Successful development of geothermal energy as an important contribution to world energy supply, beyond the few easily utilized hydrothermal systems, depends on improved technology for efficient heat extraction from a natural variety of subsurface concentrations of thermal energy deposited in accessible volumes of rock formations over a wide range of useful temperature and containing a range of in-place heat-carrier fluid, from HDR (none) to hydrothermal (abundant) systems.

Engineering experience is needed to attain successful development of heat extraction technology. It is also important to acquire reliable means to evaluate the potential for thermal energy extraction at an early stage in the development of prospective resources for commercial utilization. The key uncertainties of HDR geothermal

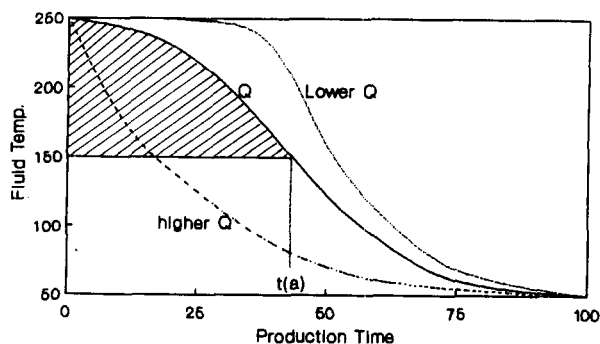


Fig.1 Relationship of fraction produced (shaded area) above a given abandonment temperature to the production flowrate (from Kruger, 1993).

resources for heat extraction include:

- (1) fractured rock volume available for heat transfer to the circulating fluid that determines the total accessible heat content;
- (2) distribution of rock-block sizes and fracture flowpaths that determine the optimum heat extraction rate;
- (3) production flowrate strategy for sustainable deliverability at sufficient power level and longevity to provide commercial incentive for development.

Figure 1, from Kruger (1993), notes the relationship for a reservoir of given thermal properties between production flowrate, Q , and thermal energy extraction, the area under the cooldown curve. The difficult management decision on balancing maximum power output (higher Q for greater current income) and maximum thermal extraction efficiency (lower Q for greater total return) over a longer amortization period also requires knowledge of these key parameters. In both cases, the parameters need to be evaluated with sufficient confidence for investment and management decisions.

Experiments to establish technical means to provide reliable estimates of the key parameters are available in the form of long-term constant-flowrate reservoir testing. Long term signifies a period sufficient to estimate the available heat content above the application minimum temperature and the range of heat extraction rate - lifetime

relations for optimum reservoir management. Only a few such experiments have been performed throughout the world; they include the 3-year circulation test at Rosemanowes, Cornwall, England, the 90-day circulation test at Hijiori, Honshu, Japan, and, now, the 14-month long-term flow test (LTFT) at Fenton Hill, New Mexico, USA.

The three-year circulation test at Rosemanowes was carried out as part of the U.K. HDR program described by Symons (1991) to evaluate the potential for electric power generation in the United Kingdom from the vast thermal energy stored in the Cornwall granitic formations. A description of the test was given by Parker (1989). It ran for over 1220 days in which the temperature decline was measured from an initial reservoir temperature of 80°C to an abandonment temperature of 52°C. From production data supplied by the test operators (Nicol, private communication, 1989), Kruger (1990) was able to match the observed exponential cooldown over the three-year period by fitting of reservoir volume and mean fracture spacing (MFS) parameters for heat transfer. The match reservoir volume of $3.25 \times 10^6 \text{ m}^3$ was in agreement with the volume of $5 \times 10^6 \text{ m}^3$ estimated by Nicol and Robinson (1990) from tracer and seismic measurements. The MFS was indicative of the uniform flow conditions for heat transfer for the mean production flowrate.

The 90-day circulation test at Hijiori was the first (and thus far, only) multi-production (three) well test in the world. The test was described by Yamaguchi, et al. (1992). It was run with three major events for different objectives, (1) an initial sharp increase in flowrate to examine the potential for increasing reservoir size, (2) with two of the three wells shut in for two weeks in succession to test the individual production wells, and (3) at constant injection rate to evaluate reservoir performance.

The Hijiori test was run with accumulation of extensive diagnostic data and frequent downhole logs to describe the flow geometries and downhole temperature history. The measurements identified a number of entry zones into each well. An analysis of the observed cooldown data was reported by Kruger and Yamaguchi (1993) based on allocation of the constant injection flowrate among the multiple entry zones of the three production wells, adjusted for observed water loss. The cooldown simulations by zonal sectors provided an estimate of the sector volumes and the corresponding heat content. Analysis of the test was made difficult by the early flowrate excursion and the two-week shut-ins. The experience, however, will be useful in execution of the deepened Hijiori reservoir which will be used for a longer flow test.

The 14-month LTFT at Fenton Hill was carried out as part of the HDR technology development program at the Los Alamos National Laboratory since the early 1970's. The latest test was run in the Phase II part of the program, designed to demonstrate, at a sub-commercial scale, the

feasibility of extracting heat from a HDR geothermal reservoir.

This paper reviews the heat extraction results obtained for the long-term flow test (LTFT) at Fenton Hill. A numerical method was used to integrate the continuous flowrate and temperature data collected during the several segments of the test to obtain the amount of heat extracted from the reservoir in relation to the calculated reservoir heat content. In addition, review is given of the corresponding estimates for the Rosemanowes and Hijiori circulation tests by analytical means.

THE FENTON HILL LONG-TERM FLOW TEST

The Long-Term Flow Test (LTFT) at Fenton Hill in 1992-3 culminates over 20 years of experimental development of the technology for HDR geothermal energy resource utilization. The objectives for the LTFT were guided by both the need to continue development of the technology for optimum energy extraction and the need to operate the reservoir at constant production to demonstrate its long-term viability as a significant source of power. These conflicting objectives resulted in a test designed to operate at a reduced power extraction level to prevent seismic activity and growth of fracture volume in the reservoir.

A description of the Fenton Hill HDR Reservoir and plans for the LTFT was reported by Brown (1993). After a series of hydraulic fracturing experiments and redrilling of the wellbores, the surface plant was constructed and the test was initiated in April 1992. The surface equipment and data acquisition and control system were designed to provide a detailed record of the operating conditions with maximum automation. In addition, numerous tracer tests and geochemical analyses were carried out to monitor the behavior of the system during long-term operation. Although the plan for the test was to accomplish steady-state power production for a period of one year or longer, circulation through the reservoir was achieved for only eight months, due to mechanical pump failure and exhaustion of project funding. Nonetheless, significant performance information was obtained, including data on the thermal behavior of the system.

A summary of the experimental details of the LTFT was given by Brown (1993). The production period for the test is conveniently divided into a number of segments of quasi-steady state conditions, based on the history of the pump failures and replacements. A summary of the segment chronology is given in Table 1, and a summary of the production conditions is shown in Figure 2, derived from Brown (1993).

The production history of the LTFT has been divided into four periods. The first segment (LTFT Phase I) was one of steady-state operation from test startup on 9 April 1992 until it ended abruptly on 31 July when the fluid injection

Table 1
Chronology of Fenton Hill Production Periods

Period No.	Production Segment Name	Production Dates (1992-93)	Mean Flowrate (kg/s)
1	Pre-LTFT	Jan - Mar	6.3
2	LTFT Phase I	9Apr - 31Jul	6.0
3	IFT Phase I	20Aug - 2Oct	4.1
4	IFT Phase II	Nov - Dec	5.4
5	LTFT Phase II	22Feb - 17Apr	6.0
6	Post-LTFT	Apr - May	7.7

pumps failed. The test was then operated as an Interim Flow Test, first as IFT Phase I at lower flowrates with a back-up injection pump from 20 August through 2 October and then as IFT Phase II during the months of November and December with a leased pump more suitable for long-term operation. These two IFT phases allowed testing of reservoir flow behavior at two different production well pressures. The fourth segment of the Test (LTFT Phase II) commenced on 22 February 1993 with a new centrifugal pump capable of flowrates similar to the original LTFT conditions and continued until 17 April when the test was abandoned. One additional period of operation (post-LTFT) was carried out to examine the performance of the reservoir in response to short, planned shut-ins of the production wellbore.

The thermal performance of the reservoir was very stable after short-term transients observed at the startup of each segment. The temperature in the production well at the depth of the highest fracture entrance remained constant at 228 °C throughout the entire test period. Thermal cooldown of the produced fluid was not observed, although changes throughout the reservoir region were observed from a series of temperature logs.

The produced fluid temperature measured continuously at the surface varied with flowrate and time since startup for each segment. Calculation of 'continuous' down-hole temperature was accomplished with the wellbore heat transmission model of Ramey (1962). The data exhibited a sharp transient during the first few days of operation as the rock around the well was heated. The process approaches a quasi-steady state, flowrate dependent heat loss at longer times. Under the LTFT segment conditions, a temperature decline of 40 to 50 °C was observed over the wellbore depth to the surface. At higher flowrates, the temperature drop was smaller. A similar effect was observed in the injection well, where heatup of the injected fluid occurred rather than cooldown.

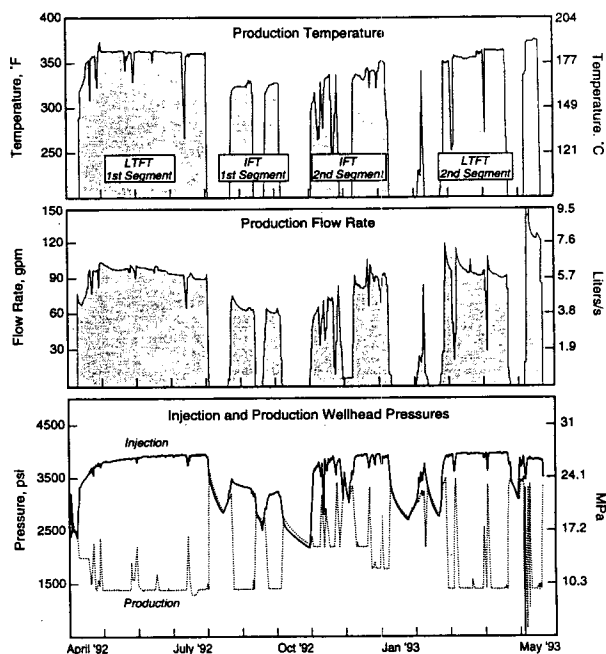


Fig.2 Production history of the Long-Term Flow Test at Fenton Hill, 1992-93 (from Brown, 1993).

HEAT EXTRACTION FROM HDR RESERVOIRS

A HDR geothermal reservoir may be considered as the rock volume above some minimum utilization temperature that can be stimulated to provide adequate surface area for heat transfer to a circulating fluid (Kruger, 1993). The available heat content, HC, (J), of the useful reservoir volume with temperature above a minimum application temperature is given by

$$HC = (\rho V) C_p (T_o - T_a) \quad (1)$$

where V = reservoir volume (m^3)
 ρ = rock density (kg/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 energy extracted, HE, (J), through production time, t , is given by

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

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

$\Delta h(T_i, T_f)$ is the increase in enthalpy of the produced fluid above the enthalpy of the injected fluid. For an amortization period in which the temperature difference ($T_o - T_s$) is small compared to the temperature difference ($T_o - T_i$), the heat extracted can be approximated from the parameter mean values as

$$HE = \bar{Q} \bar{\Delta h} \Delta t \quad (3)$$

The fraction of thermal energy produced, FP, is the ratio

$$FP = HE/HC \quad (4)$$

HEAT EXTRACTED FROM THE LTFT RESERVOIR

Calculation of the heat extracted from the six test segments listed in Table 1 were carried out with a computer program to numerically integrate Equ.2 with the database acquired for the LTFT. The input to the program were the measured inlet and outlet temperatures and production flowrate at discreet times during the test. After filtering out data points that represent spurious noise in the data, the program integrates the data using Euler's method. To compute the enthalpy of the fluid at the inlet and outlet temperature, steam table enthalpy data were fit using the quotient of rational polynomial expressions involving pressure and temperature to powers up to 3, after Zyvoloski and Dash (1991). The enthalpy computed in this way are accurate to within 0.062 %. The pressure, an independent variable of secondary importance compared to temperature, was assumed constant at 37.5 MPa, the approximate value at downhole conditions. The program was verified against a fictitious example problem of changing flowrate and declining temperature, and the program yielded results that agreed with a manual calculation using the steam tables to within 2 %. Reservoir properties for the heat extraction calculations are listed in Table 2.

Table 3 shows the results of the calculations of the heat extracted from the reservoir during each segment of the circulation tests. Also included are the cumulative heat extracted up until the end of each segment, as well as the percent of the total available heat content, based on an abandonment temperature of 150 °C and a reservoir volume of $6.45 \times 10^6 \text{ m}^3$ (Robinson and Kruger, 1992).

The two circulation test segments with the largest heat extraction are phases I and II of the LTFT. The other 4 test periods contributed relatively little to the total heat extracted. For all six segments, the total heat extracted was only 5.9% of the available heat content. It is, therefore, not surprising that within the uncertainty of temperature measurement in the series of downhole temperature logs taken during the test period, there was no decline in the produced fluid temperature.

Table 2
Heat Extraction Parameters for the LTFT

Parameter	Value
Reservoir Volume	$6.45 \times 10^6 \text{ m}^3$
Init. Reserv. Temp	228 °C
Abandonment Temp	150 °C
Rock Density	2700 kg/m ³
Rock Specific Heat	954 J/kgC

The small fraction of the available heat content removed during the LTFT confirms that Phase II reservoir at Fenton Hill is a large geothermal resource. Continued testing of the reservoir could apparently be operated in the future without serious thermal degradation, at least initially. On the basis of a constant thermal energy extraction rate, the lifetime of the reservoir to the abandonment temperature (even without reservoir growth) would be 13.3 years, in good agreement with the pre-test estimate of 15.0 years (in Robinson and Kruger, 1992) for the given reservoir volume.

The differences in the heat extracted from the reservoir and the heat recovered at the surface shown in Table 3 are quite small. The temperature loss as fluid travels up the production well is roughly 50 °C, which approximately balances the temperature gain of fluid travelling down the injection well. Thus, the computations for heat extracted from surface data (where temperature measurements are much easier to make) provide a fairly accurate estimate of the amount of heat extracted from the reservoir. However, the lower temperature of the production fluid at the surface compared to downhole results in a poorer electric conversion efficiency. Heat losses would decline at higher flow rates, and completion of the wellbore with insulating materials could further reduce wellbore heat loss.

HEAT EXTRACTED FROM OTHER TESTS

The results of estimated heat extracted from the Fenton Hill reservoir can be compared to the results from the Rosemanowes and Hijiori circulation tests.

Rosemanowes

Estimates of heat extraction were obtained both analytically and numerically. The analytical estimate was based on the observed exponential temperature decline (Kruger, 1990) over the 3-year circulation test. For the fitted equation

$$T_f = T_o e^{-k(T)t} \quad (5)$$

Table 3
Heat Extraction from the Fenton Hill Reservoir

Prodn Period No.	Heat Extraction Reservoir		Heat Extraction at Surface		Cumulative HE Reservoir		Cumulative HE at Surface	
	(TJ)	(%)	(TJ)	(%)	(TJ)	(%)	(TJ)	(%)
1	6.12	0.41	5.17	0.35	6.12	0.41	5.17	0.35
2	38.0	2.54	38.5	2.57	44.1	2.95	43.7	2.92
3	8.59	0.57	6.92	0.46	52.7	3.52	50.6	3.38
4	9.43	0.63	7.99	0.53	62.1	4.15	58.6	3.91
5	20.0	1.34	18.0	1.20	82.1	5.49	76.6	5.11
6	6.17	0.41	5.97	0.40	88.3	5.90	82.6	5.51

it was assumed that the fluid enthalpy difference also declined exponentially with decline constant, $k(h)$. For Rosemanowes test conditions of $T_o=82^\circ\text{C}$ ($h=342.2\text{kJ/kg}$), $T_s=50^\circ\text{C}$ ($h=221.9\text{kJ/kg}$), and $T_i=20.3^\circ\text{C}$ ($h=85.2\text{kJ/kg}$) at mean $Q=14.5\text{kg/s}$, the value of $k(h)$ was obtained from

$$\Delta h = \Delta h(o) e^{-k(h)t} \quad (6)$$

and the heat extracted was obtained by substitution of Δh into Equ.(2). The heat content of the reservoir from Equ.(1) was 2.40×10^{14} J. The heat extracted was 2.88×10^{14} J, with a fraction produced of 120 %. For a $FP=1.00$, the corresponding reservoir volume could be $V_r = 3.90 \times 10^6 \text{ m}^3$ in lieu of the matched reservoir volume, $V_r = 3.25 \times 10^6 \text{ m}^3$. Other sources of discrepancy could be a mean flowrate of 12.1 kg/s in lieu of 14.5 kg/s or heat transfer in both the injection and production wells.

The numerical estimate for heat extracted was made with the Fenton Hill model modified for the Rosemanowes data provided by CSMA (Nicol, private communication, 1989). For the same conditions as the analytical estimate, the integrated daily product of recorded production flowrate and injection and production temperatures yielded a heat extracted of 2.36×10^{14} J, with a fraction produced of 98.0%.

Hijiori

Thermal analysis of the Hijiori 90-day circulation test (Kruger and Yamaguchi, 1993) was made with a model in which the constant flow was divided into a number of zonal sector flows based on individual well production and logged depth of feed fractures. The largest flow zonal sector for each of the three production wells was evaluated to obtain the closest fit to the observed cooldown curve. The simulation results for the three zonal sectors showed a mean fracture spacing around 15-20 m for heat transfer, and the fractions produced for the geometric zonal sectors ranged from 129 to 266 %. An example was zonal sector 4 in well 1, where the fraction produced was 236 % for a sector of dimensions: $R = 41 \text{ m}$ and $Z = 13 \text{ m}$. For the

simulation run with $FP = 67 \%$ for the best match to the observed cooldown, the adjusted equal-aspect-ratio dimensions were: $R = 62 \text{ m}$ and $Z = 20 \text{ m}$. If it is further assumed that this sector is representative of the whole reservoir, then the total heat extracted can be estimated from the ratio of sector flow to total injection flow, adjusted for the water lost from the production total. The data also allowed for an estimate of the reservoir volume and heat content.

CONCLUSIONS

The results of the calculations of heat extracted from the LTFT at Fenton Hill, augmented by the results observed at the Rosemanowes and Hijiori sites, provide confidence that estimates of commercial quality of prospective HDR geothermal resources can be obtained from early results of circulation testing in the stimulated reservoir. The main parameters that require early evaluation are the extent of flow-connected volume created by the stimulations, the size distribution of the heat providing rock blocks, and a optimum production rate strategy that provides sufficient return over a sufficiently long amortization period.

Over the 14-month production period of the LTFT, both the small calculated fraction produced of the estimated reservoir heat content and the observed constant downhole production temperature imply that the conservatively calculated reservoir volume was sufficiently large to sustain constant production for about 15 years to the given abandonment temperature of 150°C for application as steam for electric power generation. The prospect of further reservoir stimulation to increase the reservoir size during long-term production and to recover the non-produced injected fluid needs to be technically explored in the Fenton Hill reservoir.

The results of the other two circulation tests support the basis for estimating heat extraction. Although the Rosemanowes reservoir was sufficiently large for long-term operation, the small initial temperature at reservoir depth was too small for electric power generation, but

could serve as a hot-water supply. The agreement with calculated heat extraction by the numerical model and the approximating analytical model shows the ability to plan such an application. The results of the Hijiori test show a rapid extraction in a highly fractured small reservoir, but it provides engineering data for design of the deeper reservoir planned for further technical development.

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