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PROGRESS REPORT ON THE LONG-TERM FLOW TESTING OF THE HDR RESERVOIR AT FENTON HILL, NEW MEXICO

Donald W. Brown and Robert DuTeau

Los Alamos National Laboratory
Earth and Environmental Sciences Division
Los Alamos, New Mexico 87545

Abstract

Through mid-December 1992, long-term flow testing of the Phase II Hot Dry Rock (HDR) reservoir at Fenton Hill, NM has been conducted for an aggregate of 24 weeks at near-optimum aseismic injection conditions. This period of flow testing, which began on April 9, 1992, included several reservoir shut-ins due to equipment problems and an intervening lower-injection-rate Interim Flow Test lasting about 6 weeks.

With the exceptions noted above, the majority of the flow testing for that period was conducted at an average injection rate of 7.2 l/s and at pressures up to 27.3 MPa. However, this high level of injection pressure has not produced any discernible reservoir microseismicity, indicating that we have been operating the reservoir at pressures below the threshold for fracture extension. The permeation loss from the boundaries of the reservoir at these elevated pressures has averaged about 0.7 l/s, a very low rate of water loss considering the very large volume of fractured rock (about 16×10^6 m^3) comprising the pressure-stimulated reservoir region.

Temperature logging across the 350-m production interval, centered at a depth of about 3500 m, indicates that there has been no measurable drop in the mixed-mean reservoir production temperature at the top of this interval since the time of our first temperature log in mid July.

Most recently, we have conducted additional intermittent reservoir testing at higher levels of production backpressure during a period of reservoir pressure maintenance using a high-capacity rental triplex mud pump.

Introduction

The present Phase II HDR reservoir at Fenton Hill represents the successful creation and operation of a second, deeper and hotter engineered geothermal system for mining the earth's heat at this site in northern New Mexico. The smaller and shallower Phase I reservoir was flow tested during the period from 1978 to 1980, with the longest flow test lasting over 9 months (Dash et al., 1981).

The primary objective of the present long-term flow testing of the Phase II reservoir is to demonstrate a sustainable level of heat production for a sufficient period of time -- at least for one to two years. The initial phase of this testing began on April 9, 1992 and lasted 16 weeks. Unfortunately, failures of both primary injection pumps caused a premature, but temporary, end to high-injection-pressure flow testing on July 31. This period of testing has previously been referred to as the Long-Term Flow Test (LTFT), and will be so referred to in this paper.

Reservoir flow testing was then continued at a lower rate of 4.3 l/s (68 gpm) for the 6-week period from August 20 to October 2. This period of lower-injection-pressure flow testing, referred to as the Interim Flow Test (IFT), ended when a "terminal" failure occurred to the smaller backup pump. Following the end of the IFT, a used triplex mud pump was leased on a temporary basis to maintain reservoir pressure and to allow a modicum of flow testing until a more suitable replacement pump was located.

There were several ancillary technical objectives for the subsequent flow testing that have been accomplished since the end of the 16-week LTFT on July 31. These objectives focus on the measurement of the reservoir flow performance at other (than LTFT) injection and production pressure levels, and are critical to our overall understanding of how an engineered geothermal system actually performs under a variety of operating conditions. With this knowledge, we will be able to engineer changes in the flow behavior of this specific HDR reservoir in the future to considerably enhance its productivity, as well as to improve the design of future HDR systems.

Reservoir Performance During the LTFT

During 16 weeks of continuous flow testing, the surface injection pressure was maintained at levels up to about 27.3 MPa (3960 psi). This maximum pressure produced no discernible microseismicity indicating stable, nonextensional reservoir operation. That the reservoir was not extending during this period of time is supported by the low and slightly declining rate of reservoir water loss.

Figures 1 and 2 show the surface injection and production pressures and the corresponding injection and production flow rates during the LTFT. As shown in Figure 1, the injection pressure was gradually increased to 27.3 MPa (3960 psi) and then maintained at this level, while the production backpressure was generally maintained at 9.3 MPa (1400 psi). The actual control variables for this phase of flow testing were injection flow rate and production backpressure, the latter being controlled by an automated pressure-regulating system. As shown in Figure 2, both the injection and production flow rates declined by about 10 percent during the LTFT. Tracer evidence indicates that this flow-rate decline resulted from a gradual redistribution of reservoir flow away from the more direct flow paths (Rodrigues et al., 1993).

Figure 1. LTFT Wellhead Pressures

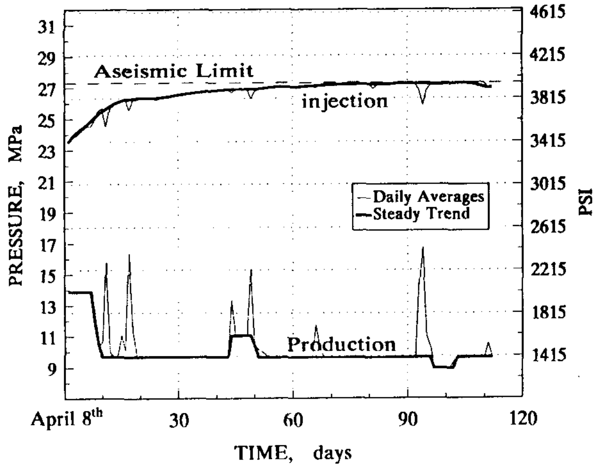


Figure 2. LTFT Flow Rates

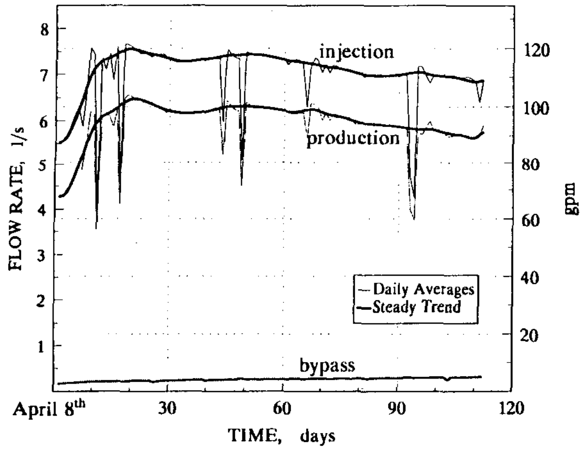
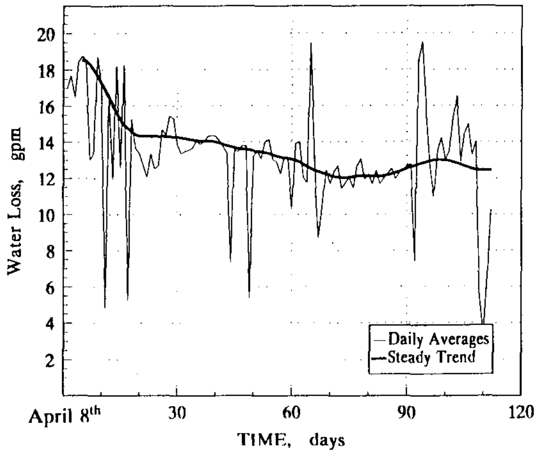


Figure 3 shows the apparent rate of reservoir water loss during the LTFT. This loss is the observed difference between the 24-hour mean injection and production flow rates, corrected for the small (about 0.3 l/s) annular casing bypass flow from the reservoir occurring at the injection well.

Figure 3. LTFT Water Loss

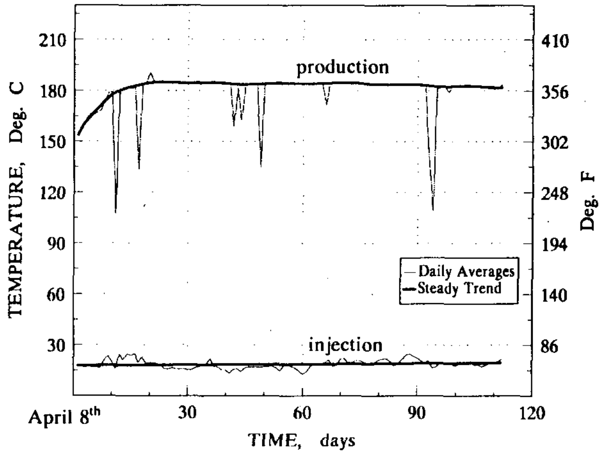


However, this calculated loss rate has not been corrected for the approximately 0.1 l/s of "loss" actually resulting from additional fluid storage within the reservoir due to the continued cooling-induced contraction of the rock blocks near the reservoir entrance region and the accompanying joint dilation (Rodrigues et al., 1993).

As can be seen in Figure 3, the rate of water loss declines quite rapidly during the initial transient period, and then more slowly during the remainder of the test. In contrast, the injection pressure, and therefore the pressure on that part of the reservoir boundary away from the production well where the majority of the diffusional water loss occurs, was rising or constant. (The slight rise in the water loss rate beyond day 90 was caused by the protracted reservoir shutin at about that time, as shown in Figure 2.) The inference is that the reservoir boundary was stable, and that the diffusional portion of the reservoir water loss rate was slowly declining with time as has been observed during previous static reservoir pressure testing (Brown, 1992).

The variation of the surface production temperature and the corresponding thermal power during the LTFT are given in Figures 4a and 4b. As shown, the production temperature first increased as equilibrium was approached, and then very slowly decreased. The slow decline in temperature was undoubtedly due the falloff in production flow rate as shown in Figure 2, and the concomitant increase in the heat loss, per unit flow rate, from the production wellbore to the surrounding rock. As a point of reference, during the 30-day flow test of the Phase II reservoir in mid-1986 (Dash, 1989), the production temperature rose to above 190°C at a flow rate of about 13.9 l/s (220 gpm), giving another example of the dependence of production temperature on flow rate.

Figure 4a. LTFT Wellhead Temperatures



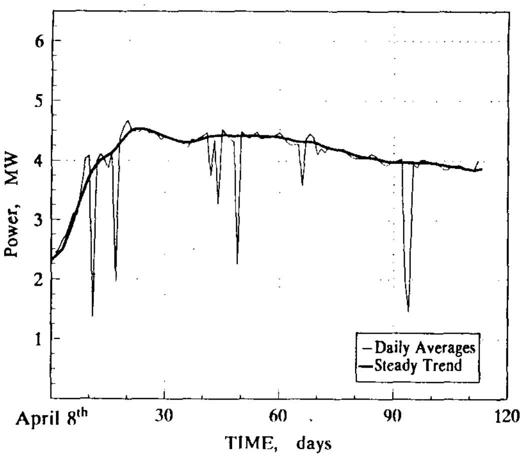


Figure 4b. LTFT Thermal Power

Interim Flow Test

During the 6-week period from August 20 to October 1, referred to as the IFT, reservoir flow testing continued at a lower injection rate of about 4.3 l/s (68 gpm) using a smaller-capacity reserve pump. Also included in this 6-week period was a 1-week reservoir shut-in for necessary pump repairs.

Figure 5 shows the injection and production pressure profiles during the IFT, while the injection and production flow rate profiles are shown in Figure 6. The period of reservoir shut-in is apparent. After establishing steady-state flow conditions near the beginning of the IFT, the injection pressure slowly leveled out at about 22.2 MPa (3220 psi) at an injection rate of 4.3 l/s (68 gpm). Following the shut-in, the injection pressure more rapidly stabilized, but again at a level of 22.2 MPa.

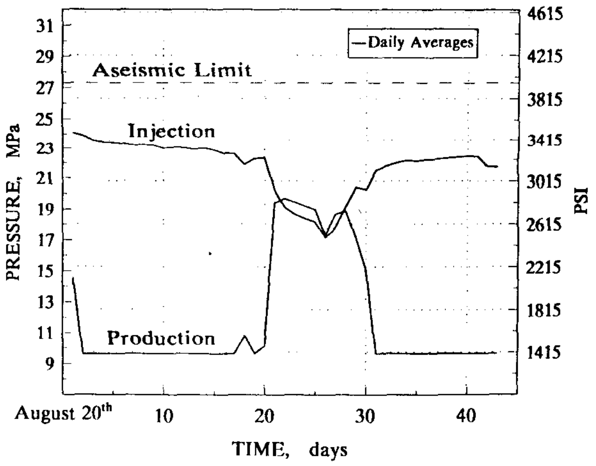


Figure 5. IFT Wellhead Pressures

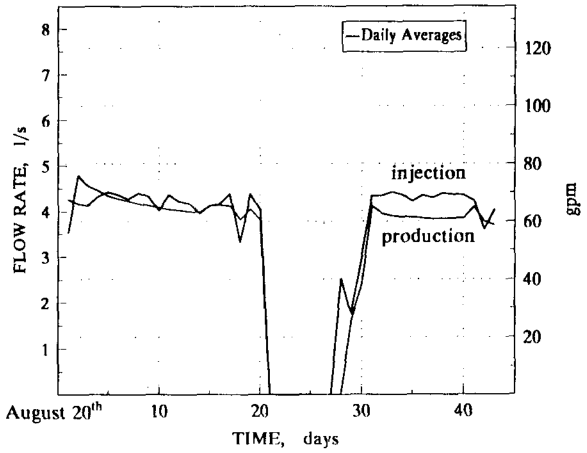


Figure 6. IFT Flow Rates

The production temperature variation during the IFT is shown in Figure 7. It is apparent that the 3-week reservoir shut-in following 16 weeks of circulation during the LTFT did not cause a significant perturbation in the temperature field surrounding the production well, since it required only a few days of flow to re-establish a steady-state production temperature at the lower value of about 165°C. This would indicate that the rock surrounding the production wellbore had been considerably heated during the LTFT.

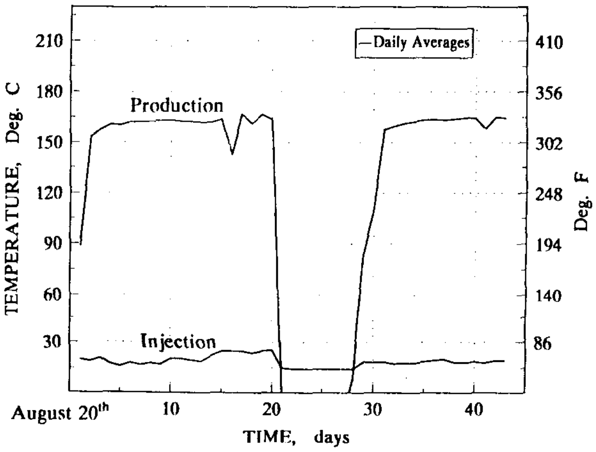


Figure 7. IFT Wellhead Temperatures

Table I compares the principal reservoir performance data for the LTFT and the IFT. It should be noted that these two flow tests were performed at the same production backpressure level of 9.65 MPa (1400 psi), thus providing a direct measure of the effect of reduced injection pressure on reservoir flow at a constant production backpressure. These data have been essential in validating the GEOCRACK discrete-element reservoir flow/deformation model being developed at Kansas State University (Swenson and Beikmann, 1992).

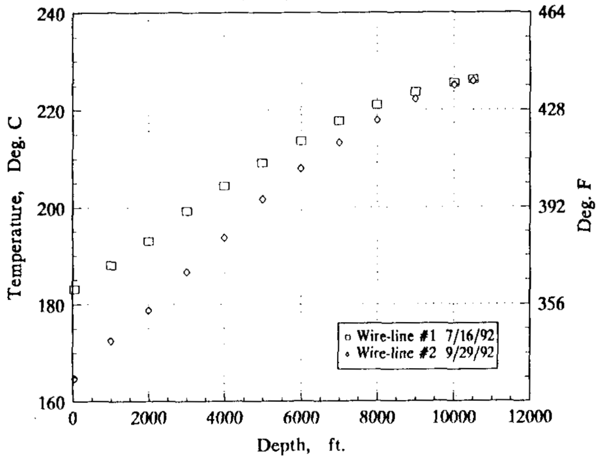
Table I. Reservoir Performance During the LTFT and the IFT Showing the Variation in Flow Rate as a Function of Injection Pressure

Test	LTFT	IFT
Measured Performance	7/21-29/92	9/29/92
Injection Conditions		
Flow Rate, l/s (gpm)	6.76 (107.1)	4.34 (68.8)
Pressure, MPa (psi)	27.29 (3958)	22.36 (3243)
Production Conditions		
Flow Rate, l/s (gpm)	5.66 (89.7)	3.85 (61.1)
Backpressure, MPa (psi)	9.66 (1401)	9.65 (1399)
Temperature, °C	183	165
Water Loss		
Rate, l/s (gpm)	0.79 (12.5)	0.23 (3.6)
Percent	11.7	5.2

Two observations can be made from the data presented in Table I. First, a 22% increase in the injection pressure between the IFT and the LTFT results in a much larger 56% increase in the injection rate. This shows the strong nonlinear relationship between joint flow and pressure in the body of the reservoir. Second, the rate of peripheral water loss through the microcrack fabric of the rock mass surrounding the HDR reservoir region was markedly decreased by reducing the injection pressure from 27.3 MPa (3960 psi) to 22.4 MPa (3250 psi). The water loss data shows, for matrix flow in this case, the strong nonlinear dependency of permeation outflow on the mean pressure level between the reservoir boundary and the far-field.

Figure 8 shows the wire-line-measured wellbore temperature profiles for corresponding times near the end of the LTFT and the IFT. Even though the surface production temperature for the IFT shows a significant decline from that for the LTFT due to the reduction in flow rate, the corresponding mixed-mean reservoir outlet temperatures at a depth of 3200 m (10,500 ft) indicate no measurable decline. Since the mixed-mean reservoir outlet temperature at 3.85 l/s (61 gpm) should have been about 2°C lower than that at 5.66 l/s (90 gpm) for the same set of distributed wellbore fracture entrances due to additional heat loss as the produced fluid flowed upward through the production interval, one can conclude that the reservoir has experienced no net cooldown between the times of these two temperature surveys.

Figure 8. Production Wellbore Temperature Surveys at 5.82 l/s (7/16) and 3.91 l/s (9/29)



Recent Flow Testing at Higher Backpressures

Following a month of reservoir shut-in, a leased positive-displacement mud pump was brought on line in early November 1992. While re-inflating the reservoir and establishing steady-state flow conditions in November, the pump operated for only a total of 20 days as materials and maintenance issues related to its operation were being addressed. During December, however, with newly designed pump plungers and liners, the pump operated on a near-continuous basis, and we were able to establish two higher-backpressure production flow conditions as shown in Table II.

Table II. Reservoir Flow Performance Under Conditions of Higher Backpressure (15.2 MPa and 12.4 MPa)

Measured Performance	12/10/92	12/27/92
Injection Conditions		
Flow Rate, l/s (gpm)	7.33 (116.2)	7.14 (113.1)
Pressure, MPa (psi)	27.32 (3963)	27.32 (3962)
Production Conditions		
Flow Rate, l/s (gpm)	5.34 (84.6)	5.71 (90.5)
Backpressure, MPa (psi)	15.18 (2201)	12.40 (1798)
Temperature, °C	177.1	182.8

The production data given in Tables I and II indicate that there is a broad maximum in the production flow rate as a function of backpressure, with only a 5% falloff in flow rate as the backpressure is increased from 12.4 MPa (1800 psi) to 15.2 MPa (2200 psi). This would suggest that the decrease in the driving pressure difference across the reservoir, as the backpressure is increased, is about balanced by the decrease in reservoir flow impedance with increasing backpressure. The overall subject of reservoir flow impedance is discussed in a companion paper (DuTeau and Brown, 1993).

Conclusions

To date, long-term flow testing of the Phase II reservoir at Fenton Hill under stable, aseismic conditions has shown no thermal drawdown for an aggregate flow testing period of about 6.3 months. This conclusion is based on both surface production temperature measurements and temperature logs (Refer to Figure 8 and Tables I and II).

During the initial 16-week LTFT, which was conducted at injection pressures up to 27.3 MPa (3960 psi), the production backpressure was generally maintained at 9.65 MPa (1400 psi). The resulting mean production flow rate was 5.8 l/s (92 gpm) at a temperature of 184°C. The mean thermal power production was 4.0 MW, but the actual power level declined by about 10% during the LTFT due to a gradually decreasing production flow rate. This decreasing flow rate in turn reflected a gradual redistribution of flow within the reservoir, away from more direct paths and toward more indirect paths. For the LTFT, the apparent water loss rate averaged about 0.8 l/s (12.5 gpm), of which 0.1 l/s (16%) was actually being stored within the fractured reservoir in thermally dilated joints near the injection interval, and possibly to some extent in new fracture flow paths.

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