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THE GEOTHERMAL ANALOG OF PUMPED STORAGE FOR ELECTRICAL DEMAND LOAD FOLLOWING

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ABSTRACT

A 6-day cyclic Load-Following Experiment, conducted in July 1995 at the Los Alamos National Laboratory's Fenton Hill Hot Dry Rock (HDR) test site in north-central New Mexico, has verified that an HDR geothermal reservoir has the capability for a significant, and very rapid, increase in thermal power output upon demand. The objective of the Load-Following Experiment was to study the behavior of the Fenton Hill HDR reservoir in a high-production-backpressure (2200 psi) baseload operating condition when there was superimposed a demand for significantly increased power production for a 4-hour period each day. In practice, this enhanced production -- an increase of about 65% -- was accomplished by a programmed decrease in the production well backpressure over 4 hours, from an initial value of 2200 psi down to about 500 psi. This rapid depressurization of the wellbore during the period of enhanced production resulted in the draining of a portion of the fluid stored in the pressure-dilated joints surrounding the production well. These joints were then gradually reinflated during the following 20-hour period of high-backpressure baseload operation. In essence, the HDR reservoir was acting as a fluid capacitor, being discharged for 4 hours and then slowly recharged during the subsequent 20 hours of baseload operation.

In this mode of operation, there would be no increase required in the reservoir size or number of wells (the *in situ* capital investment) for a significant amount of peaking power production for a few hours each day. Therefore, one of the advantages of geothermal load following over other utility options such as pumped storage or compressed air storage is that the HDR power plant would be operated during off-peak hours in a baseload mode, with an augmented return on investment compared to these other peaking systems which would normally not be operated during off-peak periods. Of course, the surface power plant and the geofluid reinjection pumps would need to be sized for the peak rate of thermal energy production, adding somewhat to the overall HDR system capital costs when compared to a simple baseload power plant design.

INTRODUCTION

The concept of Hot Dry Rock (HDR) geothermal energy, which has been under development by the Los Alamos National Laboratory (LANL) for the past 25 years, has been discussed extensively in the literature (see for example Duchane, 1995a and 1995b). This renewable-energy concept, the engineering feasibility of which has been demonstrated in a sequence of long-term flow tests beginning in 1992, is based on the development of a man-made geothermal reservoir in a previously impermeable region of deep, hot, crystalline rock, by the application of hydraulic pressure. The depth, temperature, size, and operating pressures of the resulting fractured HDR reservoir are under the developer's control, not the whims of Mother Nature. Therefore, the worldwide HDR resource is much more widely available than the limited occurrences of natural hydrothermal resources with temperatures suitable for electric power generation.

The HDR geothermal reservoir at LANL's Fenton Hill HDR test site was most recently flow tested for a 9-week period from May through July of 1995 (Brown, 1995). Near the end of this period, following 18 days of steady-state testing at a backpressure of 2200 psi, a 6-day series of cyclic flow tests was performed. For a period of 4 hours each day, the production flow rate was dramatically increased by a programmed reduction in the surface backpressure at the production well. Collectively, this series of cyclic flow tests is referred to as the Load-Following Experiment (LFE), with the objective of studying the behavior of an HDR reservoir under a simulated demand for enhanced power production for a period of 4 hours each day.

This cyclic testing followed a previous, shorter, 3-day cyclic test of the Fenton Hill reservoir in May 1993, at the end of the Long-Term Flow Test (LTFT) (Brown, 1994). At that time, 3 daily flow surges were performed to gain an understanding of how an HDR reservoir behaves during cyclic production. For that testing, the reservoir was produced for 16 hours at a very low flow and a very high backpressure, and then for 8 hours at a very high flow and a low backpressure (Brown and DuTeau, 1995). During the 1993 cyclic testing, the pressure at the injection well was maintained at about 3960 psi by injection at a controlled, but variable, rate. The most striking feature of the 1993 cyclic production tests was the degree of enhanced production flow that was obtained for a period of 8 hours each day -- an average of about 145 gpm compared to a previous steady-state level of 90 gpm near the end of the LTFT in April 1993, for very similar injection conditions. Funding limitations prevented further experimental investigation of this enhanced flow phenomenon until the summer of 1995.

FLUID STORAGE IN PRESSURIZED JOINTS NEAR THE PRODUCTION WELL

Based on the results of extensive transient and steady-state flow and pressure testing over the past 10 years, it is apparent that the HDR reservoir at Fenton Hill is comprised of a sparse, multiply interconnected set of joints in a very large volume of hot crystalline rock. The ratio of fluid to rock volume is of the order of 10^{-4}. Within the body of the HDR reservoir, fluid is stored primarily in dilated joints which are mostly jacked open by fluid pressures that are well above the least principal earth stress. Therefore, the major part of the reservoir fluid storage arises from the elastic compression of the rock blocks between pressurized joints.

The pressure gradient across the body of the reservoir, from the inlet to near the outlet, is reasonably gradual. However, within the 50-foot ± region surrounding the production wellbore, the pressure gradient steepens markedly as the pressure drops to the level of the imposed pressure in the wellbore (imposed by the backpressure regulating valve at the surface). As a result, the joints are progressively more tightly closed by the earth stresses as the flow converges toward the pressure sink represented by the

production wellbore. This near-wellbore pressure gradient for the production well can be inferred from the set of transient shut-in pressure recovery profiles shown in Figure 1 (DuTeau and Brown, 1993).

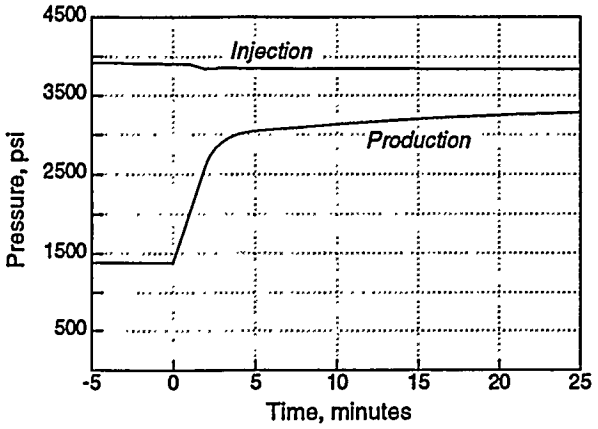

Figure 1. Transient Shut-in Pressure Profiles for the Injection and Production Wells.

When the production well was suddenly shut-in, the pressure measured at the surface (a direct measure of the downhole reservoir outlet pressure) rose from 1400 to 3000 psi in less than 3 minutes, indicating that this high pressure level existed in the joint network very close to the production interval.

Conversely, when the production well backpressure is suddenly *decreased* from an elevated level of 2200 psi, this steep pressure gradient-region rapidly extends radially further into the body of the reservoir, effectively depressurizing and draining a significant zone of fractured rock surrounding the production wellbore. After 4 hours of continuous low-backpressure operation (following upon a longer period of high-backpressure operation), this zone of depressurized joints probably extends radially outward one to two hundred feet from the production wellbore.

THE JULY 1995 LOAD-FOLLOWING EXPERIMENT

Starting on July 3, 1995, the Fenton Hill HDR reservoir was again tested in a cyclic production mode, but now in a much more controlled fashion than the preliminary testing done in May 1993. This series of cyclic tests was begun from a well-established steady-state, high-backpressure operating condition that had been maintained for the previous 18 days (Brown, 1996). The operating data for the precursor steady-state reservoir flow test are given in Table I.

Table I
1995 STEADY-STATE RESERVOIR PERFORMANCE AT A BACKPRESSURE OF 2200 PSI

Dates Measured:	June 27-29, 1995
Injection Conditions	
Flow Rate, gpm	124.2
Pressure, psi	3960
Production Conditions	
Flow Rate, gpm	99.0
Backpressure, psi	2200
Temperature, °C	183

Figure 2 shows the profiles of production pressure, and injection and production flow rates for the entire 6 cycles of the LFE. As is

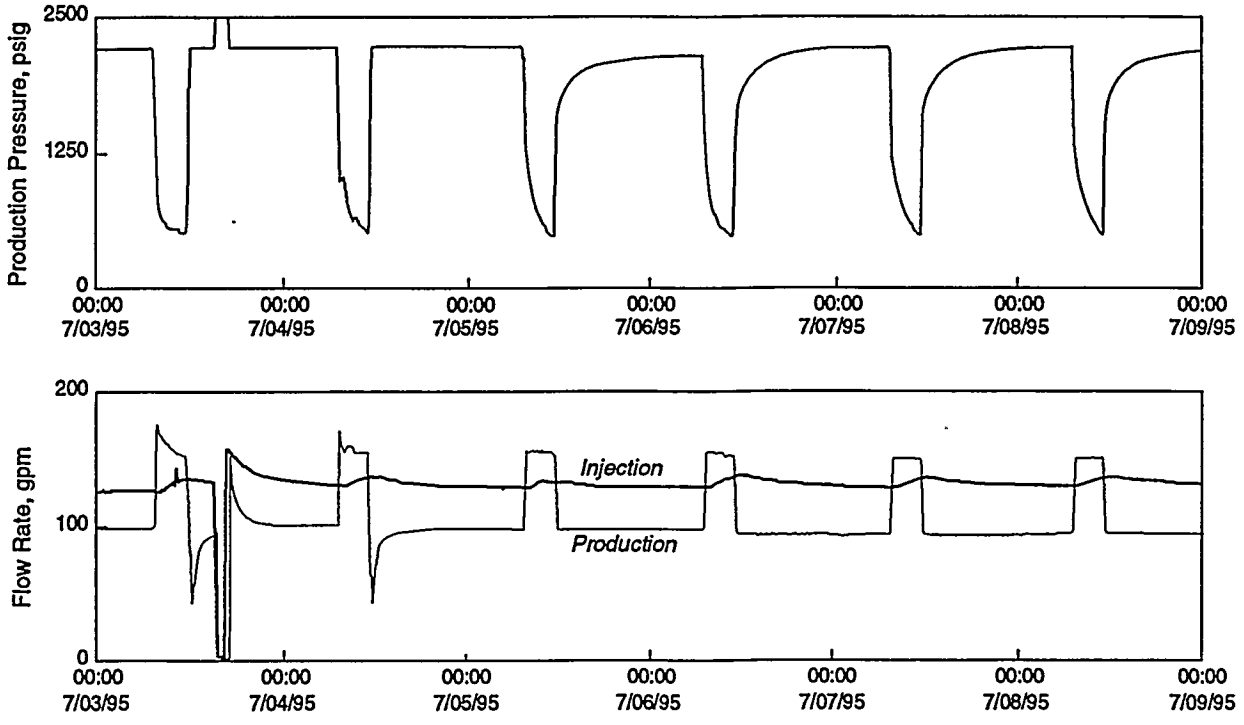

Figure 2. The Six Day Cyclic Load-Following Experiment in July 1995.

obvious from this figure, reservoir operation during the first cycle, which was run in pressure control, was a learning experience. The control system on the injection well worked adequately until the 4-hour pulsed flow period was over, and then human error produced an unscheduled shutdown of both the injection pump and production system. The second cycle, on July 4, was also run in pressure control, but with much better results. The last 4 cycles were run in flow control after the appropriate rates for the baseload and peaking flows had been determined from the pressure control experiments.

LAST TWO CYCLES OF THE LOAD-FOLLOWING EXPERIMENT

Figure 3 shows expanded-scale profiles for the last two cycles of the LFE. In flow control, the production well backpressure was continually and automatically adjusted by the control system to alternately maintain two essentially constant, but significantly different, production flow rates for these two 24-hour periods.

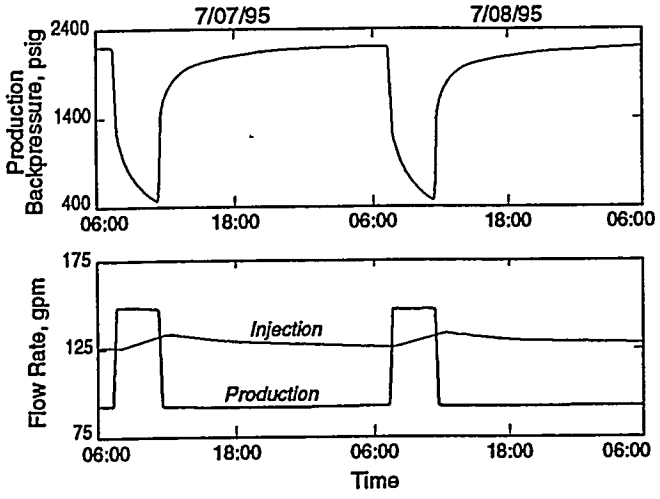

Figure 3. Last Two Cycles of the Load-Following Experiment.

Table II presents the reservoir performance data for the sixth cycle of the LFE.

Table II
RESERVOIR PERFORMANCE RESULTS FOR THE SIXTH CYCLE OF THE LOAD-FOLLOWING EXPERIMENT

Averages	4-hr Peaking	20-hr Baseload	24-hr Overall
Injection Flow, gpm	129.3	129.6	129.6
Production Conditions			
Flow Rate, gpm	146.6	92.4	101.6
Temperature, °C	188.7	182.9	183.9
Thermal Power, MW	6.12	3.72	4.11

As shown in Table II, the actual mean flow rates for the sixth cycle were 146.6 gpm for 4 hours at a production temperature of 189°C, followed by 92.4 gpm for the subsequent 20 hours at a production temperature of 183°C. The peaking flow rate for the sixth cycle indicates a production flow enhancement of 59% over the baseload level of 92.4 gpm. When the higher temperature of the produced fluid is factored in, the corresponding increase in thermal power during the 4-hour enhanced production period was 65% over the baseload level of 3.72 MW. The time required to increase the reservoir power output from the baseload to the peaking rate was about 2 minutes.

The average production flow rate for the last 24-hour cycle was 101.6 gpm, 3.9% greater that the steady-state level of 97.2 gpm existing on the morning of July 3, just prior to beginning the 6-day LFE. Similarly, the mean production temperature was 183.9°C, up slightly from the 182.7°C level existing on July 3. These average flow and temperature levels during cyclic operation show that there was also a meaningful overall enhancement in reservoir performance, due to the cyclic operation of the reservoir *per se*, when compared to preexisting steady-state levels at a constant backpressure of 2200 psi. During the 1995 testing, this enhancement due to cyclic operation was almost enough to compensate for the previously measured steady-state flow decrease resulting from an increase in backpressure from 1400 to 2200 psi, and the accompanying decrease in reservoir driving pressure drop (see Figure 4).

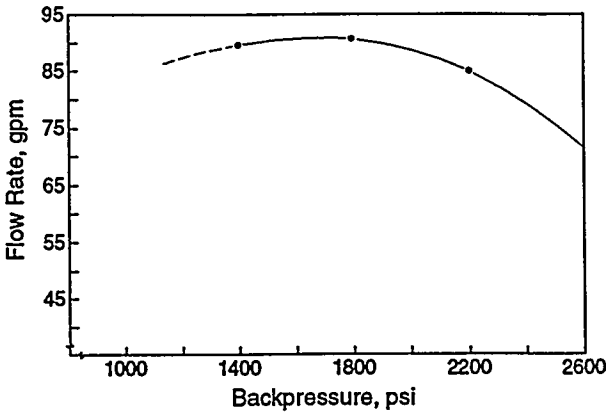

Figure 4. The Variation of Production Flow Rate with Backpressure for an Injection Pressure Level of 3960 psi, as Measured During the LTFT.

The production temperature profile for the sixth cycle of the LFE is shown in Figure 5. During the 4 hours of enhanced production, the production temperature increased from 181.6°C to 192.1°C, for a net temperature change of 10.5°C (19°F). This small change in temperature during the daily

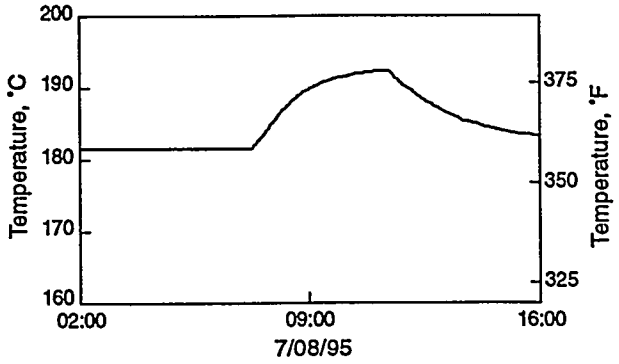

Figure 5. The Production Temperature Profile for the Sixth Cycle of the Load-Following Experiment.

cycle of peaking power production should have a minimal effect on the integrity of the production casing and surface piping. In operations at Fenton Hill extending over the past 10 years, the production wellbore has been repeatedly cycled from full production temperature down to the geothermal gradient with apparently no adverse effects.

Although we were able to achieve a power augmentation of 65% for a period of 4 hours each day during the LFE, there appear to be several engineering approaches that could increase this peaking factor even more. For instance, for the LFE testing, we operated the reservoir at an injection pressure level significantly below that required to extend the open joint-network at the periphery of the existing reservoir region. If the ambient pressure level of the HDR reservoir were to be increased to the maximum allowable pressure without reservoir growth, this would correspondingly increase the fluid storage in the pressure-dilated joints surrounding the production well, providing additional drainage volume for the transient periods of surging flow. In addition, since the properties of the fluid in an HDR reservoir are under our control, the composition of the fluid could be altered to allow a continued pressure drawdown below 500 psi, down almost to the vapor pressure of the production fluid (180 psi at 190°C). To implement this strategy at our Fenton Hill HDR site, it would be necessary to add an appropriate amount of ammonia to the circulating water to prevent the evolution of the dissolved CO_2 known to be present.

CONCLUSIONS

A unique new method for operating an HDR reservoir to produce both baseload and peaking power has been experimentally demonstrated. In initial tests of this concept, an enhanced thermal power output of 65% for a period of 4 hours each day was obtained. This enhanced power output was obtained from a level of baseload operation that was within only a few percent of the previously determined optimum steady-state operating conditions. The principal objection to cycling the production from any geothermal reservoir has been the temperature cycling induced in the production wellbore. However, in this present method of surging the production flow, the temperature excursions were limited to only about 19°F. The demonstration of this load-following capability could greatly increase interest in HDR geothermal systems by electric utilities because providing for surges in electric power demand is one of their major concerns at present.

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