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Title: SUMMARY OF RECENT FLOW TESTING OF THE FENTON HILL HDR RESERVOIR

Author(s): DONALD WEBER BROWN

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November 29, 1993

Dr. Donald W. Brown
Las Alamos National Laboratory
Earth & Environmental Sciences Div.
Los Alamos, New Mexico 87545

Re: "Flow and Fluid Volume Relationships for the Multiple Jointed Geothermal Reservoir at Fenton Hill, New Mexico " by Donald W. Brown

Dear Don:

The Program Committee of the Nineteenth Workshop on Geothermal Reservoir Engineering wishes to thank you for submitting the abstract of your proposed paper. I am pleased to inform you that this paper has been accepted for formal presentation and publication in the Workshop Proceedings.

The Nineteenth Workshop is to be **January 18-20, 1994** in the CERAS Building on the Stanford University Campus.

Your paper should be pasted-up on standard sheets (that we are supplying by separate mailing) and returned to us in camera-ready form by **January 4, 1994.** The presentation is an abbreviation of the paper and should take between fifteen and twenty minutes The written document may be up to eight pages in length. If your document is available on disk could you send us the full size pasted-up form, plus a copy of your disk, as we still hope to have a simpler method of reproduction of material. We need to determine some standards for software to accept in the future.

The sheets and instructions for format, etc. will be sent soon in a special waterproof mailer which we hope you can reuse to return the finished paper. This year we ask for your suggestions of keywords and important placenames, etc. to include in the index, to speed up our production of final volumes.

We look forward to seeing you here in January. Regular registration packets will go out in early December.

Sincerely yours,

Jean W. Cook
Program Manager

mine

SUMMARY OF RECENT FLOW TESTING OF THE FENTON HILL HDR RESERVOIR

Donald W. Brown

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

Abstract

Through May of 1993, a sequence of reservoir flow tests has been conducted at our Fenton Hill Hot Dry Rock (HDR) test site as part of the Long-Term Flow Testing (LTFT) program. This testing, which extended over an aggregate period of about 8 months, has demonstrated several significant features concerning HDR reservoirs that taken together reflect very positively on the future development of the HDR concept into a viable commercial reality.

Of most significance is the demonstrated self-regulating nature of the flow through such a reservoir. Both temperature and tracer data indicate that the flow, rather than concentrating in a few potential direct flow paths, progressively shifted towards more indirect flow paths as the test proceeded. This self-regulating mechanism may be related to the strongly temperature-dependent viscosity of water.

Measurements have shown that the reservoir flow impedance is concentrated in the near-wellbore region surrounding the production well. This situation may well be a blessing in disguise since this suggests that the distance between injection and production wells can be significantly increased, with a greatly enhanced access to fractured hot rock, without an undue impedance penalty. However, since the multiply interconnected joints within the HDR reservoir are held open by fluid pressure (pressure-propping), a higher mean reservoir pressure is the obvious path to increased productivity while still retaining the distributed nature of the flow.

Other significant observations include a very small rate of reservoir water loss that was still declining at the end of the flow testing, and a set of temperature measurements in the production well that show no significant temperature drawdown during the period of testing.

Introduction

The long-term flow testing of the Phase II Hot Dry Rock (HDR) reservoir at Fenton Hill began in early April 1992 and extended through May 1993. During this period of testing, as shown in Figure 1, there were two intervals of near-steady-state operation referred to as the first (16-week) and second (8-week) phases of the Long-Term Flow Test (LTFT). This testing was generally conducted at an injection pressure of 3960 psi (close to the pressure which would cause renewed reservoir growth) and at a production backpressure of 1400 psi. Between these two phases of the LTFT, there was a 6-week period of lower-rate flow testing referred to as the Interim Flow Test (IFT) and two months of testing in November and December of 1992 where the reservoir was operated at even higher backpressure conditions. Finally, in May of 1993, a brief series of cyclic flow tests was conducted.

What follows is a summary of the results of the recent flow testing of the Fenton Hill HDR reservoir, emphasizing the four different steady-state operating conditions that were established during the last 5 months of 1992. Then, the remainder of the paper is devoted to an extended set of conclusions that focus on the significant features of this particular HDR reservoir that have been determined during the flow testing, and their significance for the future development of the HDR concept.

Steady-State Flow Performance

Near the end of each phase of significant reservoir testing, a 1- to 8-day period of time was selected as representative of steady-state operation under each specific set of conditions. These were as follows:

(1) LTFT, first phase	July 21-29, 1992
(2) IFT	September 29, 1992
(3) 1800 psi backpressure	December 27, 1992
(4) 2200 psi backpressure	December 10, 1992
(5) LTFT, second phase	April 12-15, 1993

However, since the reservoir flow conditions existing near the end of the second phase of the LTFT were nearly identical to those near the end of the first phase of the LTFT (as discussed later), only the first four reservoir operating conditions will be considered at this point. In Table I, these four sets of pressure/flow conditions, referred to as Operating Points 1, 2, 3, and 4, correspond to the numbers in parenthesis given above.

A review of these four sets of steady-state test data shows that we operated the Fenton Hill HDR reservoir at two different surface injection pressures -- 3960 psi and 3240 psi, but at the same backpressure of 1400 psi; and at three different levels of production backpressure -- 1400 psi, 1800

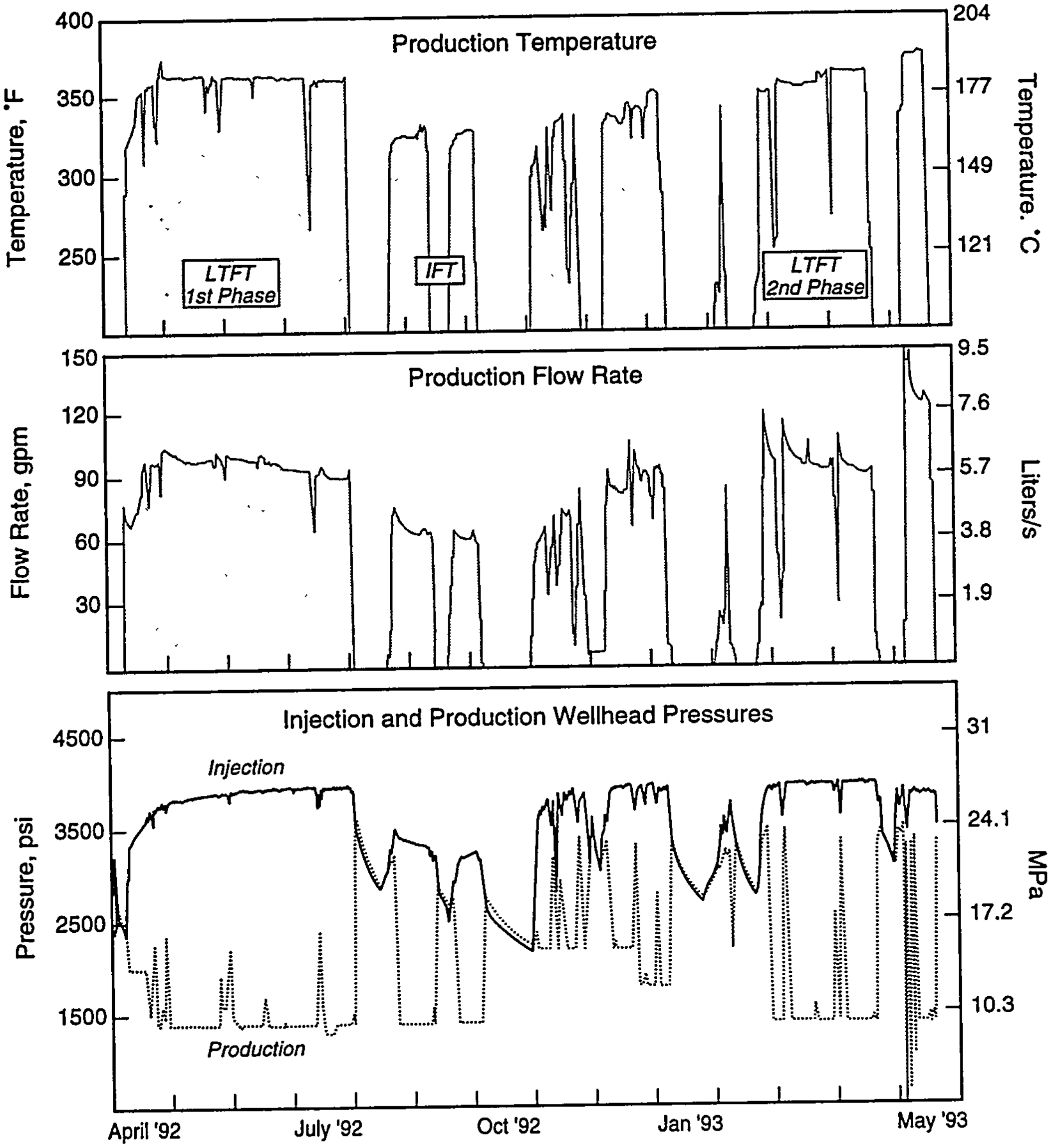

Figure 1. Fenton Hill Reservoir Operating Conditions from April 1992 to May 1993.

Table I
Steady-State Operating Conditions at Fenton Hill

Operating Point	1	2	3	4
Surface Inlet Conditions				
Pressure, psi	3958	3243	3962	3963
Flow Rate, gpm	107.1	68.8	113.1	116.2
Temperature, °C	19	18.5	17.5	17.5
Surface Outlet Conditions				
Pressure, psi	1401	1399	1798	2201
Flow Rate, gpm	89.7	61.1	90.5	84.6
Temperature, °C	183	165	183	177
Reservoir Pressure Drop				
Apparent, psi	2557	1844	2164	1762
Buoyant Drive, psi	+719	+664	+709	+686
Corrected for Buoyancy	3276	2608	2873	2448

psi and 2200 psi, but at the same injection pressure of about 3960 psi.

Point 2, representing the IFT, indicates that at about 2/3 of the LTFT injection rate (68.8 gpm vs. 107.1 gpm), the injection pressure could be maintained at only about 3240 psi, a drop of 18% from the LTFT injection pressure of 3960 psi. Points 1, 3 and 4 show that there is a broad maximum in the production flow rate between 1400 and 1800 psi, with the rate dropping by about 6.5% as the backpressure is further increased to 2200 psi. These steady-state data are currently being used to validate the coupled flow/displacement discrete-element reservoir model (GEOCRACK) being developed by Prof. Dan Swenson and his team at Kansas State University (KSU). A coupled heat transfer solution has recently been added to this finite-element model, which will be reported on in the near future.

Comparison of the Two Phases of the LTFT

Table II presents the steady-state operating data for the two phases of the LTFT shown in Figure 1.

Table II
Comparison of Reservoir Performance Between the Two Phases of the Long-Term Flow Test

Measured Performance	July 21-29, 1992	April 12-15, 1993
Injection Conditions		
Flow Rate, gpm (l/s)	107.1 (6.76)	103.0 (6.50)
Pressure, psi (MPa)	3958 (27.29)	3965 (27.34)
Production Conditions		
Flow Rate, gpm (l/s)	89.7 (5.66)	90.5 (5.71)
Backpressure, psi (MPa)	1401 (9.66)	1400 (9.65)
Temperature, °C	183	184
Peripheral Water Loss		
Rate, gpm (l/s)	12.5 (0.79)	7.3 (0.46)
Percent	11.7	7.0

Of most significance is the repeatability of the operating data between these two phases of the LTFT, separated in time by almost 9 months. Except for a reduction in the rate of water loss from 12.5 gpm to 7.3 gpm, which is reflected in a concomitant reduction in the injection flow rate, the two sets of operating data are remarkably similar. Further, it should be noted that the surface production temperature, within the accuracy of the measuring system, remained constant during this time reflecting the fact that for this limited period of flow testing, there was no drawdown in the reservoir production temperature. However, how long this situation would have continued if the long-term flow testing had not been terminated is pure conjecture in light of an unknown effective reservoir volume and joint spacing for heat transfer.

Self-Regulating Nature of the Flow Through HDR Reservoirs

The most significant observation that has been made during the recent testing at Fenton Hill is the self-regulating nature of the flow through the pressure-dilated (i.e., pressure-propped) HDR reservoir. With time, the flow tends to progressively concentrate in the more indirect flow paths at the expense of the more direct flow paths. That is, the flow tends to become more distributed with time rather than becoming more concentrated in a few direct flow paths. This observation is based on both tracer and borehole temperature data obtained during the recent long-term flow testing of the Fenton Hill reservoir.

Figure 2 shows the dye tracer response for three times during the flow testing: Early and late during the first phase of the LTFT and late during the second phase of the LTFT. As shown, the first arrival of the tracer in April 1992 took about 3-1/2 hours. The delay in tracer arrival then increased in subsequent tests to a final value of about 5

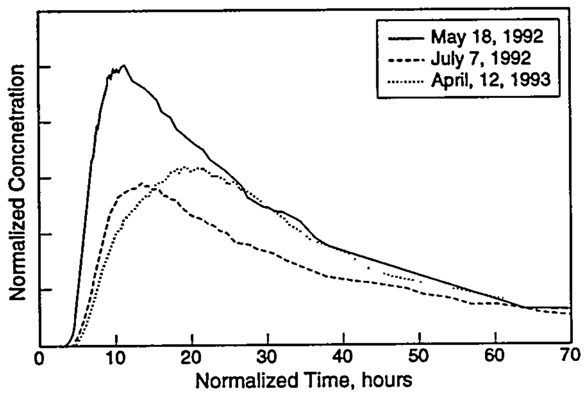

Figure 2. Recovery of Fluorescein Dye Tracer on Three Occasions During the LTFT.

hours. This suggests that the most direct flow paths were being somewhat closed off with time. A corollary observation is the peak in the tracer arrival, which was progressively delayed in time as the testing proceeded. This delay would imply that the flow was becoming more diffuse with time, with the flow tending to concentrate in the more indirect flow paths.

The production interval temperature data given in Figure 3 and Table III chart the redistribution of the flow and temperature in this part of the reservoir as the testing proceeded. The most significant change occurred in the deepest flowing joint in the production interval -- at point A -- where the temperature decreased by 3°C over a period of 8 months. However, the mixed-mean production-interval outlet temperature at point D varied only slightly, and within the error of the measuring system. The strong inference is that while the flow through Joint A was being cooled, it was also being impeded; otherwise the mixed-mean temperature at point D would have shown a corresponding cooling. Preliminary analyses by members of the KSU team would suggest that this self-regulating phenomenon is associated with the almost order-of-magnitude decrease in the viscosity of water between ambient and reservoir temperature conditions.

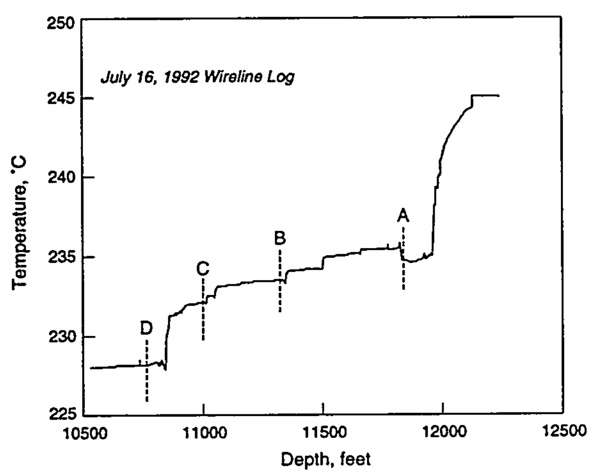

Figure 3. Temperature Profile Across the Reservoir Production Interval.

Table III
Comparison of Fluid Temperatures at Four Specific Points Across the EE-2A Production Interval

	7/16/92 Log	9/29/92 Log	3/16/93 Log
Point A (11,840 ft)	234.5°C	233.9°C	231.5°C
Point B (11,320 ft)	233.4°C	232.9°C	232.4°C
Point C (10,990 ft)	232.0°C	231.7°C	231.5°C
Point D (10,750 ft)	228.2°C	228.1°C	227.8°C

Flow Impedance Implications from Test Data and Modeling Results

Numerous shut-ins of the reservoir have shown that the flow impedance is concentrated in the vicinity of the production wellbore. For instance, Figure 4 shows the pressure response for 94 minutes following the shut-in of the injection and production flow at the end of the first phase of the LTFT. As can be seen, after 5 minutes of shut-in, the pressure had risen very markedly at the production well while the corresponding injection pressure had dropped only slightly. This pressure behavior would suggest that the reservoir flow impedance is much greater around the production well than in the body of the reservoir. It appears that the reservoir is very well manifolded to the injection well due to the cooling-induced dilation of the joints connecting the injection interval to the body of the reservoir. Numerical modeling of the reservoir by the KSU team shows that this impedance concentration may actually be to our advantage. Figure 5 shows the computed difference in the reservoir pressure profiles for wellbore separation distances of 200 m and 400 m. For only a small decrease in flow rate (from 100 gpm to 84 gpm), the accessible region of fractured hot rock is greatly increased -- probably by almost a factor of four.

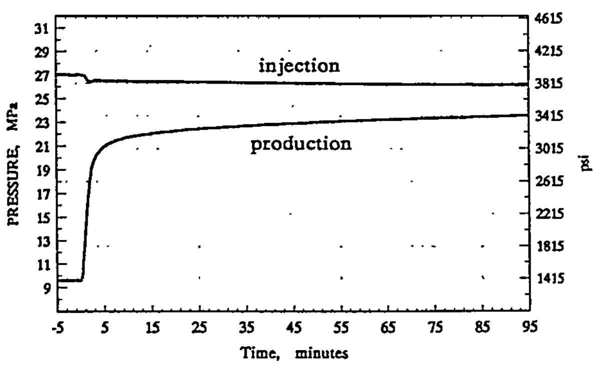

Figure 4. Wellhead Shut-in Pressure Responses.

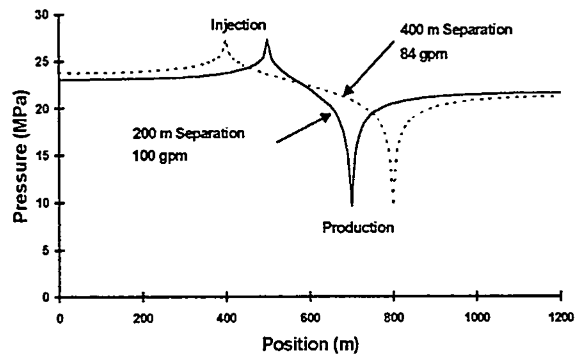

Figure 5. Pressure Profiles for Two Wellbore Spacings.