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LONG-TERM TESTING OF GEOTHERMAL WELLS IN THE COSO HOT SPRINGS KGRA

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ABSTRACT

Three wells have been drilled by the Los Angeles Department of Water and Power at the Coso Hot Springs KGRA. A long-term flow test was conducted involving one producing well (well 43-7), one injector (well 88-1), and two observation wells (well 66-6 and California Energy Co's well 71A-7).

This paper presents the equipment and techniques involved and the results from the long-term test conducted between December 1985 and February 1986.

INTRODUCTION

A long-term flow test was conducted in the Coso Hot Springs KGRA, California, during the period December 1985 to March 1986. The flow test involved wells 43-7, 88-1 and 66-6 on the leases of Los Angeles Department of Water and Power (LADWP) and well 71A-7 on the leasehold of California Energy Company (CEC). The well locations are shown on figure 1.

The long-term flow test involved flowing LADWP 43-7 through a 10-inch pipeline to a vertical flash cyclonic separator. The water and steam phases were metered separately and then recombined before being discharged to the atmosphere through an atmospheric separator/muffler. The separated waste water was allowed to cool in a settling pond to precipitate the majority of the dissolved silica and then pumped to LADWP 88-1 where the water was first filtered and then injected back into the reservoir. Wells LADWP 66-6 and CEC 71A-7 were used to monitor for any interference effects caused by production from LADWP 43-7 or injection to LADWP 88-1. Downhole pressures were also monitored in both the production and injection wells.

The production well, LADWP 43-7, was completed on February 28, 1985 to a total depth of 2,976 feet. The well profile, including casing shoe depths and fluid entries recorded during air drilling, is shown in figure 2. The well was flow tested for a period of 37 hours during March 1 and 2, 1985 and was found to produce 5.5 MW (mass flow = 390,000 lbs/hr; enthalpy = 490 BTU/lb) at a wellhead pressure of 130 psia. The well encountered a maximum reservoir temperature of 468°F (figure 3) which has a corresponding saturation enthalpy of 450 BTU/lb; hence the well was producing some free steam from the reservoir.

After the short-term test, the well was shut-in until the start of the long-term test.

TEST EQUIPMENT

The equipment involved in the long-term flow test can be divided into 3 main components:

(1) well production metering system,
(2) water injection metering system, and
(3) downhole pressure monitoring system.

The well production metering system was used to measure the wellhead pressure and determine the production rate, enthalpy and chemical charateristics of the produced steam and water from LADWP 43-7. The two-phase fluid produced at the well was conducted through a 10-inch pipe to a vertical flash cyclonic separator rated for 175 psi at 371°F. After separation, the water and steam phases were metered separately and remixed downstream of the separator control valves. The mixture was then conducted through a 12-inch pipe to an atmospheric separator/muffler which served the purpose of reducing the noise level at the exhaust.

The separated waste water was collected in a setting pond and then pumped through a 6-inch aluminum pipeline to the injection well, LADWP 88-1. Both direct reading and recording equipment were used to monitor the injection rate. Injection water temperature and wellhead pressure (vacuum) were also monitored at LADWP 88-1. A double body filtering unit with a capacity of 1000 gpm utilizing 28 filtering elements (20 microns) was installed before the liquid inlet to LADWP 88-1.

The downhole pressure monitoring equipment for each well included a stainless steel pressure chamber attached to 0.125 inch O.D.

stainless steel capillary tubing. The surface end of the capillary tubing was connected to a Paroscientific quartz pressure transducer. Any change in downhole pressure would be transmitted to the transducer by helium gas contained in the chamber and the tubing. The transducer signals were amplified and sent via a multiple conductor cable to a central data logger equipped with a portable computer. Pressure transducers were also used to monitor the wellhead presure of LADWP 43-7 and to monitor atmospheric pressure. Wellhead and ambient temperature were also recorded.

TEST SCHEDULE

Well LADWP 43-7 was stimulated to flow on December 11, 1985 after compressing the well with air to approximately 350 psig and allowing the well to heat up for 24 hours. The flow was then bypassed to the separator and the well continued to flow until February 27, 1986 when it died due to hole collapse. During the last month of the test, sudden changes in the flowing parameters and downhole presssure were noted on 2 occasions, accompanied by drops in flow rate and enthalpy.

After the well died, monitoring of downhole pressures in the observation wells continued until March 28, 1986.

ANALYSIS OF TEST DATA

Well LADWP 43-7 Flow Data

Figure 4 presents plots of the downhole pressure data, production rate and total fluid enthalpy as functions of time for well LADWP 43-7. The data covers the time period 70 to 160 days, based on September 27, 1985, as the starting data. The zero time was chosen as it coincided with the start of monitoring of downhole pressures in the wells. Several important observations can be made based on the flow metering data and downhole pressure data collected from well LADWP 43-7:

1. The well produced a small amount of free steam during most of the flow period, with the downhole steam quality declining from about 3% at the start of the flow test to nearly 0% after day 137 (that is, after 61 days of flow). Under static conditions, the reservoir is at saturation condition but has no free steam.

2. The well's flow characteristics changed abruptly on days 119-120 (24-25 January 1986), as evidenced by sharp reductions in both wellhead and downhole pressures and mass flow rate. The enthalpy also showed a slight rise, but the change is not as significant as noted in the other parameters. This abrupt change was believed to be caused by a sudden fill-up of the lower part of the well by rock debris.

3. The well characteristics continued to deteriorate after the first abrupt change. This deterioration is believed to result from continued fill-up of the well with rock debris.

Table 1 summarizes the observed characteristics of well LADWP 43-7 after it stabilized (and before it deteriorated because of hole fill-up).

Drawdown Data

The downhole pressure data from well LADWP 43-7 were analyzed using a mathematical model based on the line source solution for radial flow in a homogenous and isotopic porous medium of uniform-thickness with pressure-independent rock and fluid properties, small pressure gradients and negligible gravity forces. As we are analyzing the response in the producing well, it is also necessary to include the skin factor of the well in the calculations.

The line source solution is generally only applicable when the active well is producing at a constant flow rate. However, by using the principle of superposition in time, it is possible to account for a variable flow rate history.

The procedure used in the model calculations was to input the measured production schedule (figure 4) and the pressure behavior of the well was then calculated as a function of time for a series of reservoir and well characteristics input to the model: specific volume of the reservoir fluid; wellbore diameter and skin factor; reservoir flow capacity (kh) and storage capacity; reservoir temperature and initial pressure; initial static water level in the well; concentration of dissolved solids and gases in the reservoir fluid; etc. Reservoir properties were assumed to be isotropic.

The calculated pressure behavior was then compared with the observed pressure behavior. If the two agreed within a chosen tolerance, the test data for the well were assumed to be "matched"; that is, the assumed model with the chosen parameters was supposed to be "calibrated".

If the calculated and observed pressure behaviors did not match, one or more of the flow capacity, storage capacity or skin factor were changed and the pressure behavior recalculated. This trial-and-error process was continued until the calculated pressure behavior matched with the observed within the chosen tolerance. Although it is theoretically possible that this process may not give a unique solution, in practice it is generally found that the overall shape of such a measured pressure response can only be matched by a unique set of parameters.

For well LADWP 43-7, attempts were made to match the measured response as outlined in the above discussion. However, it was found that the downhole pressure was not responding to production as expected; the pressure was dropping as the flow rate decreased from 90 to 116 days instead of rising as would be predicted by the above model. This suggested that the response could not be adequately matched by assuming that the input parameters remained constant.

It was decided to match the measured response in well LADWP 43-7 by assuming the reservoir flow capacity and storage capacity had the same values as calculated from the short term flow test in March 1985 (kh = 8000 md·ft, S=0.004 ft/psi, S=0.004 ft/psi) and by allowing the skin factor to vary as a function of time. The resulting match to the measured data is shown in figure 5 while the calculated variation in apparent skin factor is shown in figure 6. The apparent skin factor history provides a method of illustrating the changes in well performance with time.

The plot in figure 6 shows that the well initially had an apparent skin factor of approximately -3.5. The skin factor increased gradually from -3.5 to -2.6 by day 120 (25 January 1986) when the sharp deterioration in well characteristics was noted as discussed before. This gradual increase may have been due to changes in apparent flow capacity caused by two phase conditions in the reservoir but the change is not considered to be particularly significant. After day 120, the skin factor jumped from -2.6 to -0.8 within 3 days implying a significant deterioration in well characteristics. The skin factor remained reasonably stable until day 140 (14 February 1986), when it began increasing rapidly again. The well had reached an apparent skin factor of 2.6 on day 153, just before the well stopped flowing.

Observation and Injection Well Data

From a preliminary analysis of the observation and injection well data, we have concluded the following:

1. The downhole pressure in well LADWP 66-6 did not respond when well LADWP 43-7 started producing but started to rise once injection began to well LADWP 88-1. Similarly, the pressures began to fall as soon as injection to well LADWP 88-1 was stopped. It is therefore concluded that well LADWP 66-6 was only responding to injection in well LADWP 88-1 and not to production from well LADWP 43-7.

2. Considering that well LADWP 66-6 is responding to injection even though it is closer to the production well LADWP 43-7 than the injection well LADWP 88-1, and that both wells LADWP 88-1 and LADWP 66-6 have deeper casing and deeper production zones than does well LADWP 43-7, we conclude that wells LADWP 88-1 and LADWP 66-6 are communicating through a deeper part of the reservoir than the level from which LADWP 43-7 is producing.

3. The downhole pressure in well LADWP 88-1 declined considerably during the test even though the injection rate remained nearly constant. This implies that the well was improving in injectivity, possibly due to cleaning up of existing fractures and/or opening up of new fractures.

4. Well CEC 71A-7 had a very "noisy" pressure response, when compared to the response measured in well LADWP 66-6. This is believed to be due to the well being on bleed during the test.

The pressure response of well LADWP 66-6 was analyzed using the mathematical model described above, assuming that the well was responding to injection to well LADWP 88-1. In this case, the response in an observation well was being matched and hence it was not necessary to know the skin factor. With observation well data, it is also possible to directly calculate both the flow capacity and the storage capacity.

Figure 7 shows the match obtained between the observed (continuous line) and calculated (small squares) pressure responses at well LADWP 66-6. The match is excellent, the difference between the calculated and observed pressure values being always less than the resolution of the pressure data obtained. The reservoir flow capacity required to obtain the match was 108,000 md·ft, indicating that the "lower" reservoir with which LADWP 66-6 communicates has a very good flow capacity. The storage capacity value required to match the pressure data of LADWP 66-6 was 0.0012 ft/psi. Assuming typical values of 10^{-5} psi^{-1} for total reservoir compressibility and 0.05 to 0.10 for porosity, this storativity value implies a reservoir thickness of 1,200 to 2,400 feet. This range of reservoir thickness appears reasonable.

The value of flow capacity calculated from the analysis of the interference response of well LADWP 66-6 is an order of magnitude higher than the values calculated from short term flow test data for wells LADWP 43-7 (March 1985) and LADWP 66-6 (June 1985). This difference between parameters calculated from single well tests and interference tests has been seen in a number of geothermal fields. It is believed, however, that the parameters calculated from interference data better reflect how the reservoir will respond to exploitation.

It is believed that well CEC 71A-7 did not respond to the discharge of well LADWP 43-7 and the pressure variations can be satisfactorily explained by leaks in the capillary tubing and the bleeding of the well. A possible reason for the lack of response is the high compressibility of the two-phase steam/water mixture which is known to exist around well CEC 71A-7. Fluid with high compressibility acts like a barrier to pressure transients.

The pressure response of well LADWP 88-1 was also analyzed using the same approach as used for LADWP 43-7 and LADWP 66-6. As with well LADWP 43-7, it was found that the measured pressure response could not be adequately matched if it was assumed that the reservoir parameters remained constant during the test. It was noted that the measured pressures were declining at a faster rate after 120 days than would be expected by the drop in injection rate caused by the hole collapse in well LADWP 43-7.

The decline in pressure noted in well LADWP 88-1 may have been caused by:

1. reservoir pressure drawdown related to the discharge of well LADWP 43-7; or
2. improvement in the injectivity of well LADWP 88-1.

The most likely explanation is the improvement in injectivity of well LADWP 88-1. If the change was due to interference from well LADWP 43-7, it would have started to occur nearer the start of the flow test.

To model the improvement in injectivity, the skin factor was allowed to vary as a function of time. For practical purposes it is found that the skin factor generally falls within the range from -8 to 20 for the vast majority of geothermal wells. The possible range of skin factor values therefore provided a constraint on the value of flow capacity that could be used in the model. The storage capacity used in the model was assumed to be the same as calculated from the pressure response measured in well LADWP 66-6 (0.0012 psi/ft).

After numerous trials it was found that a flow capacity of 50,000 md·ft gave a good match to the measured pressure response, with calculated skin factors remaining within the required range. The match to the observed pressure response is shown in figure 8. Figure 9 shows the calculated skin factor history as a function of time. The well had a high apparent well damage (skin factor of 16) until day 120, after which the general trend shows the skin factor gradually dropping until it reached -8 at the end of the test. These changes in skin factor are believed to indicate that the well showed improved injectivity either due to clean up of drill cuttings or opening of more fractures due to the thermal shock of cold water injection.

CONCLUSIONS

In summary, it can be concluded that the long-term test program has been quite successful in assessing the LADWP wells and the reservoir. The following important information relating to the development aspects of the field were learned from the test:

1. Well LADWP 43-7 has a sustained capacity of approximately 4 MW at a wellhead pressure of 80 psia.
2. The test indicated that there are probably two different production levels in the reservoir. The shallower level, in the depth range 2,000 to 3,000 feet, is tapped by LADWP 43-7, while the deeper level (below 3,500 feet) is tapped by wells LADWP 88-1 and LADWP 66-6.
3. The lower level is believed to be a better exploration target because it is probably the source of fluid for the upper level and it has a higher reservoir pressure. Although wells LADWP 88-1 and LADWP 66-6 proved to be cooler and therefore less productive than LADWP 43-7, the upflow zone appears to underlie most of the LADWP leasehold. Therefore, hotter deeper production may be discovered on the LADWP leasehold in the future.
4. The test clearly indicated that the production wells should be lined with slotted liner to prevent accumulation of rock debris in the well.

Table 1 Stabilized Characteristics of Well LADWP 43-7

Flowing wellhead pressure = 126.35 psia

Total mass flow rate = 295,000 lbs/hour

Wellhead steam quality = 16.4%

Enthalpy of total fluid = 460 BTU/lb

Static reservoir pressure = 541 psia

Static reservoir temperature = 470°F

Reservoir steam saturation at static condition = 0%

Flowing downhole pressure = 225.37 psia

Flowing downhole temperature = 392°F

Downhole steam quality = 0.8%

Productivity Index = 0.012 MW per psi

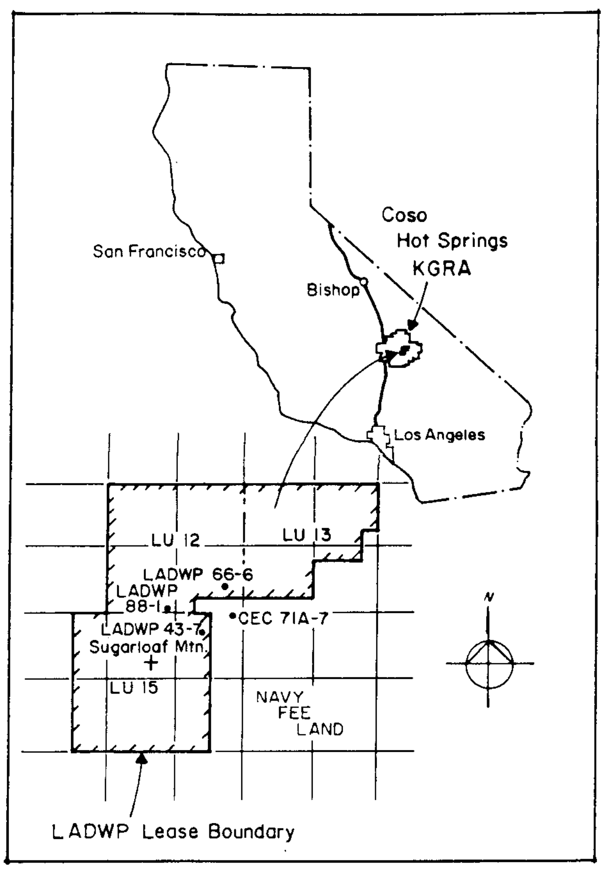

Figure 1. Location Map

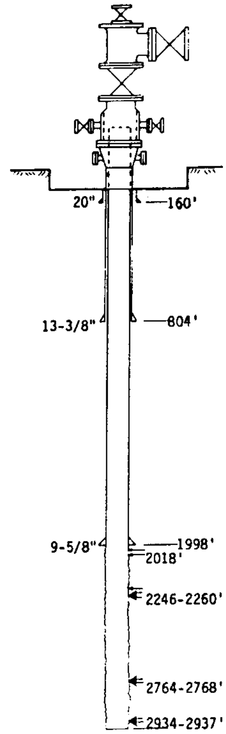

Figure 2: Well 43-7 Drilling Breaks

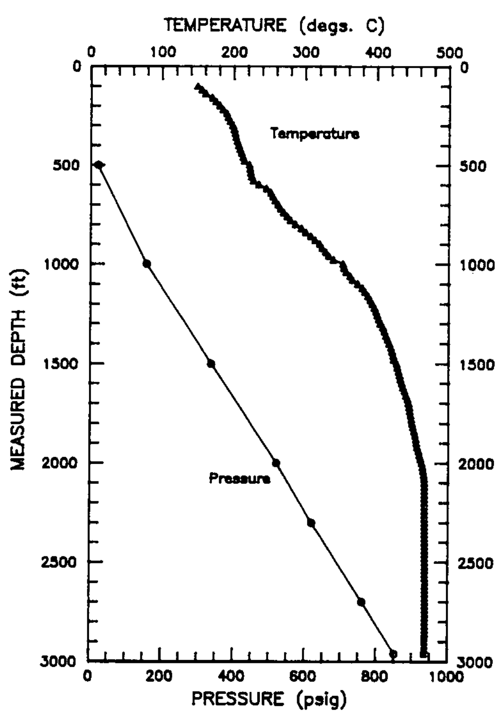

Figure 3: Downhole Surveys, Well 43–7

Figure 4: Downhole Pressure, Flow rate and Enthalpy Data, Well 43-7

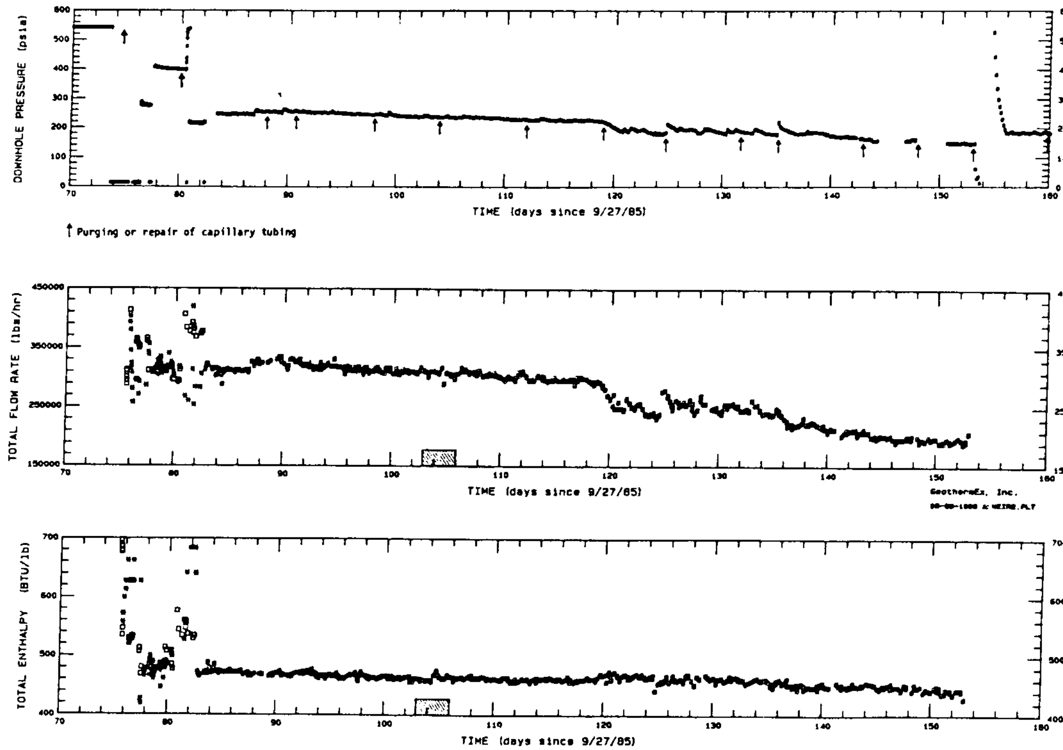

Figure 5: Drawdown Data Analysis, Well 43-7

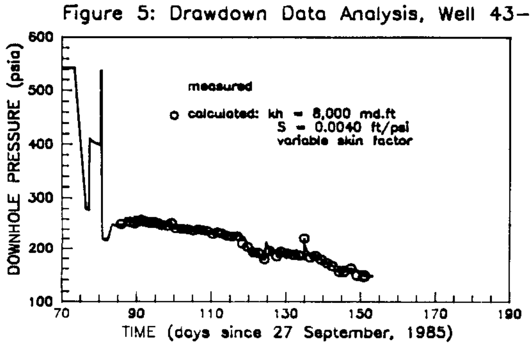

Figure 6: Calculated Skin Factor, Well 43-7

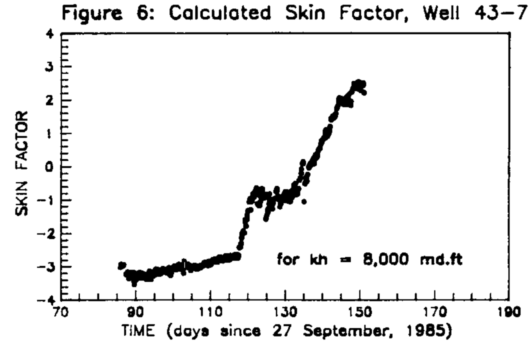

Figure 7: Interference Test Data, Well 66-6

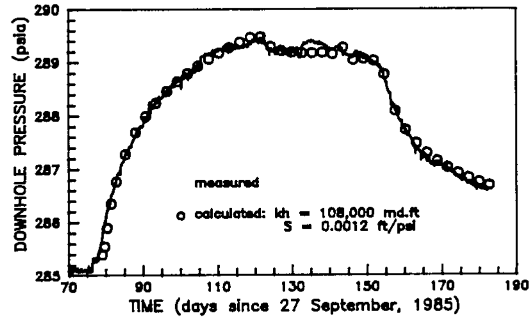

Figure 8: Injection Data Analysis, Well 88-1

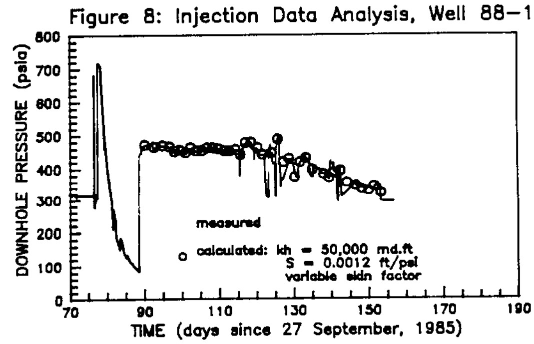

Figure 9: Calculated Skin Factor, Well 88-1