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A DOWNHOLE PUMP TEST ON A 2 KM DEEP HOT DRY ROCK GEOTHERMAL SYSTEM

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SUMMARY

During the continuing long-term circulation programme of the 2 km deep Hot Dry Rock (HDR) geothermal system at Camborne, a downhole pump was installed in the production well and used to investigate the effects of sub-hydrostatic pressure on reservoir performance. This condition is expected to occur naturally in a 6 km deep HDR reservoir.

Tracer test results showed a change in the flow distribution but no overall change in the effective circulating volume of the reservoir and this was confirmed by the unchanged thermal behaviour of the reservoir. Although the production flow rate did increase during the test the impedance was also increased and indicated that the increased effective stress acting on the joints close to the production well was causing them to close up.

INTRODUCTION

For the past eight years the Camborne School of Mines has been developing and investigating a Hot Dry Rock (HDR) geothermal system at a depth of 2 km in Cornish granite. The current system consists of three wells drilled to depths of between 2100 and 2600 m (*Figure 1*). *The main circulating reservoir* lies between Wells RH12, the injection well, and RH15, the production well. The third well, RH11, produces at a rate of only 2 to 3 l/s and is thought not to be well connected to the main reservoir.

Since 1985 the reservoir has been circulated continuously and a variety of tests have been carried out to evaluate its performance. At the end of 1986, in addition to continuing the characterisation studies of the existing reservoir, work was started on a detailed engineering assessment for the creation of a prototype commercial HDR system at a depth of 6 km in the Cornish granite.

One area of importance that was investigated was the behaviour of the system when the production well was operated under sub-hydrostatic conditions using a downhole pump (DHP). This allowed the effective stress conditions which would exist in a 6 km deep system being operated under normal circulation, to be simulated, and the performance of a reservoir with a well producing under sub-hydrostatic conditions to be investigated.

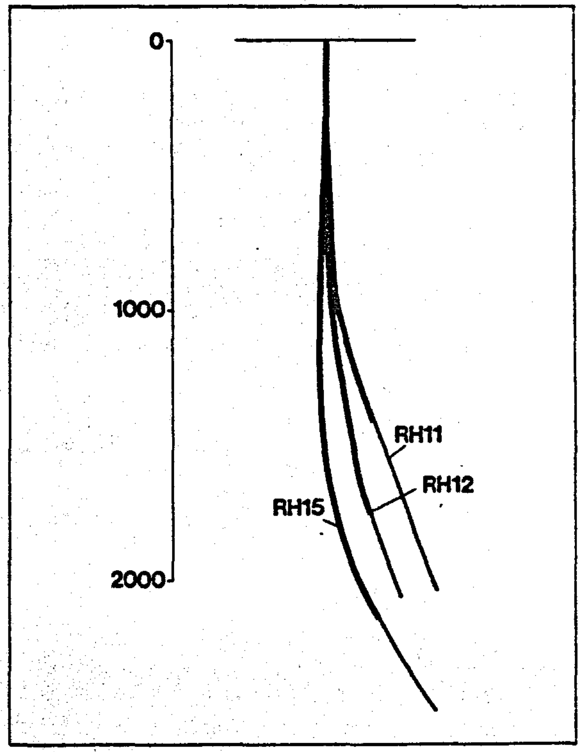

Figure 1 Well layout at the Camborne School of Mines HDR Project, Cornwall.

DESIGN

The major objective of the DHP test was to simulate partially the effective stress conditions which would be encountered when operating a deep system and to assess the effect these conditions would have on flow in the reservoir.

The effective normal stress across a vertical joint whose strike is aligned in the direction of the maximum principal stress is given by:

$$\sigma n' = \sigma h - Po$$

where: $\sigma n'$ = effective normal stress

σh = minimum principal horizontal stress

Po = hydrostatic pressure

The minimum earth stress at a depth of 6 km is predicted to be in the range 70-86 MPa. There are many uncertainties associated with this prediction as it is obtained by an extrapolation of data obtained at depths of up to 2.5 km. However, it is thought that the lower end of the stress range is the most likely (Pine and Kwakwa, 1988). If the production water is at a temperature of 220°C, the hydrostatic pressure at the bottom of the production well will be approximately 54 MPa, which is 6 MPa sub-hydrostatic, because of the lower density of the hot production water. This would be reduced to 4 MPa sub-hydrostatic if the well is pressurised to prevent the water flashing to steam in the wellbore. Therefore, the effective stress across joints orientated in the direction of the maximum principal stress at 6 km will be approximately 14 MPa. This compares with an effective stress under normal conditions of 10 MPa at a depth of 2 km.

By operating the DHP to give a drawdown head of approximately 4 MPa at a depth of 2km in the existing reservoir, it was possible to partially simulate the effective stress conditions in a 6 km deep system being operated without a DHP.

TEST PROCEDURE

The original intention was to deploy the DHP whilst the injection flow rate was 35 l/s, but this was changed when the flow rate had to be reduced to 22 l/s a few weeks before the start of the test, because the high flow rates had caused a large amount of microseismicity. As a result the test was run against a background of decreasing reservoir pressure and production flow rate.

Initially RH15 was drawn down by 4.5 MPa until a near steady state was achieved at which point two surface to surface, fluorescein tracer tests were run. The injection flow rate was then increased to 25 l/s and conditions were allowed to stabilise, so that a tracer test could be run with an unchanged drawdown on RH15. Following this the pump was put on its maximum production rate which resulted in a drawdown of 4.8 MPa and another tracer test was run. Finally, the pump was throttled back to produce a drawdown of 2.2 MPa and the last tracer test was carried out just before the pump was removed. The overall length of the experiment was 78 days.

RESULTS

HYDRAULIC DATA

Steady state data are presented in Table 1, and are those which describe the conditions under which the tracer tests were run. The changes in operating conditions during the DHP test are shown in Figure 2 along with the flow rates. The temperature data are shown in Figure 3.

DATE	08 AUG	14 SEP	06 OCT	13 OCT	23 OCT	11 NOV	13 DEC
RH12							
Wellhead pressure (MPa)	9.5	9.0	9.8	9.8	9.8	9.9	9.4
Flow rate (l/s)	21.7	21.7	25.2	25.3	25.4	25.4	22.0
RH15							
Wellhead pressure (MPa)	0.2	-4.5	-4.4	-4.6	-2.2	0.2	0.2
Flow rate (l/s)	15.2	16.4	17.9	18.3	16.8	15.5	14.9
Temperature (°C)	57.4	59.0	58.5	58.7	58.4	55.6	53.7
RH11							
Wellhead pressure (MPa)	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Flow rate (l/s)	2.4*	2.1	2.3	2.3	2.4	2.5	2.3
Temperature (°C)	52.8	50.6	51.8	51.8	52.2	52.9	51.8
+Impedance (MPa/l/s)	0.61	0.82	0.79	0.79	0.72	0.63	0.61
Overall recovery (%)	81.1	85.3	80.2	81.4	75.6	70.9	78.2
RH15/RH12 recovery	70.0	75.6	71.0	72.3	66.4	61.0	67.7

* not steady-state
\+ Impedance = pressure drop between RH12 and RH15/RH15 production flow

Table 1 Steady state conditions

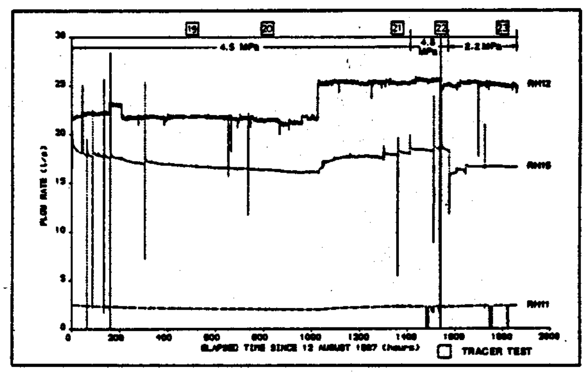

Figure 2 Flow rates, drawdown and tracer test during the downhole pump experiment.

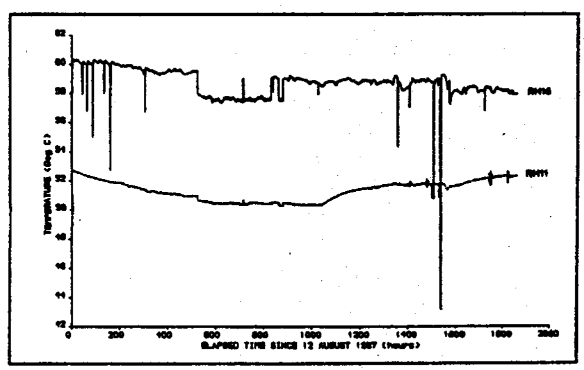

Figure 3 Wellhead temperatures during the downhole pump test.

The recovery (calculated as RH15 production flow divided by RH12 injection flow) at 21 l/s injection with a 4.5 MPa (460 m) drawdown, was 75% and was better than the recovery at the same flow rate in normal circulation, which was 69.5%.

During the period when the injection flow rate was 25 l/s, the drawdown in RH15 was initially kept at about 4.4 MPa (460 m) and then increased for a week to 4.6 MPa (480 m) before being decreased to 2.2 MPa (230 m). When the drawdown was 4.6 MPa the production flow rate was 18.3 l/s and the recovery 72%. With the drawdown reduced to 2.2 MPa, the production flow rate declined to 16.8 l/s and the recovery decreased to about 66%.

Analysis of the RH12 production logs indicated that the flow distribution before and after the pump test remained unchanged. No logging could be conducted on the production well during the test, but production logs were carried out before and after the test. These showed only small changes in percentage flow contributions from the various producing zones. The general trend of a 1°C per month thermal drawdown, which had been occurring throughout the previous year, continued during the DHP test, as confirmed in Figure 3. Note that in Figure 3 there is a sharp drop in temperature of 2°C, at 520 hours and a sharp rise of 2°C, at 840 hours. This is a result of a fault in the data acquisition system and is not a real change in temperature.

TRACER DATA

Tracer tests provided an important means of comparing the behaviour of the reservoir under normal circulating conditions with that under sub-hydrostatic conditions. A number of tracer tests, using the inert tracer sodium fluorescein, had been run throughout the circulating period prior to the test. These had been carried out during steady state conditions, and provided adequate data against which the DHP test tracer tests could be compared (CSM, 1986). The tracer tests are interpreted on the basis of plug flow in the wellbores and fractures, so that the highly dispersed nature of the tracer determined residence time distributions is attributed to variations in flow path lengths and flow rates within the reservoir.

Five tracer tests, each using 2 kg of sodium fluorescein, were conducted during the DHP test and a further two tracer tests were run after the pump had been removed. The results of the DHP tracer tests are summarised in Table 2 and an RTD curve for test no 20 is shown, along with those from the tests immediately preceding and following the DHP test, in Figure 4.

TEST NUMBER	19	20	21	22	23
Test start date	1 Sep	14 Sep	6 Oct	13 Oct	23 Oct
Test start time	09:00	09:00	09:00	09:00	09:00
Test duration (hours)	72	72	72	84	90
Tracer type	NaFl NH_4Br	NaFl	NaFl EtAc	NaFl	NaFl EtAc
Injection flow rate (l/s)	21.7	21.7	25.2	25.3	25.4
Production flow rate (l/s)	16.8	16.5	17.9	18.3	16.8
Injection pressure (MPa)	9.1	9.1	9.8	9.8	9.8
RH15 water level (m)	460	460	460	480	230
RH15/RH12 recovery (%) •	7.4	76.0	71.0	72.3	66.1
Breakthrough time (hours)	3.6	3.4	3.2	3.4	3.6
Breakthrough volume (m^3) *	81	65	69	86	81
Time to peak conc (hours)	6.2	6.4	6.0	5.6	6.2
Volume to peak conc (m^3)	375	380	387	369	375
Modal volume (m^3) *	238	243	250	232	238
Median volume (m^3) *	1917	1722	1707	1574	1488
Tracer recovery (%)	56.7	59.4	57.6	59.7	58.6

• Recovery = 15V/12I
* Wellbore volume = 137 m^3 (RH12 vol = 69 m^3; RH15 vol = 68 m^3)

Table 2 Results of tracer tests during the downhole pump test

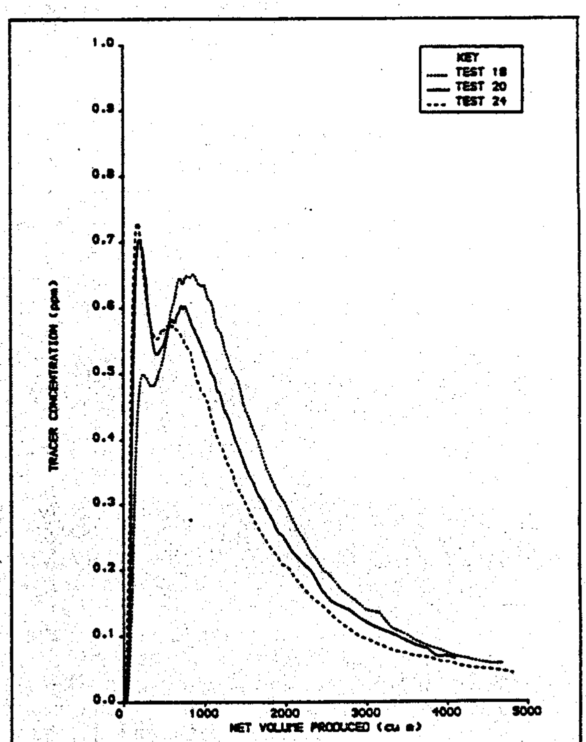

Figure 4 Inert tracer results for tests 18, 20 and 24.

DISCUSSION

HYDRAULIC AND THERMAL BEHAVIOUR

During the period when the injection flow rate was 21 l/s, the recovery declined continuously until just before the increase in injection flow to 25 l/s. It is likely that the high production flow rate in the early part of the test was in part due to the production of water that was in storage. It is most probable that the continued decline in the production flow rate was due to the area affected by joint closure, caused by the increased effective stress acting across the joints, increasing as the region influenced by the DHP gradually increased.

A very small drop in pressure (0.5 MPa) was observed at RH12 which occurred soon after the start of the test. This small pressure drop at RH12, together with the sub-hydrostatic pressure imposed by the DHP at RH15, resulted in the impedance being increased, as shown in Figure 5.

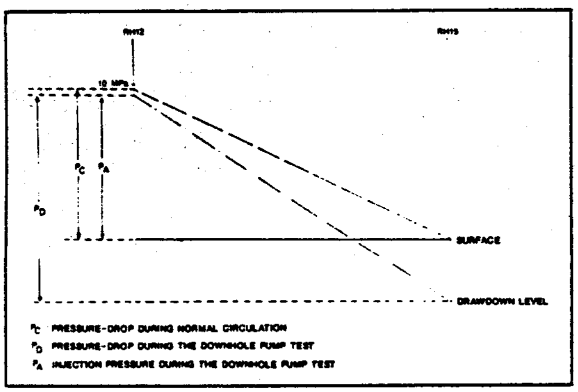

Figure 5 Comparison of pressure distribution with and without downhole pump.

In the DHP test an imposed sub-hydrostatic pressure of up to 4.6 MPa only produced a reduction in injection overpressure of 0.5 MPa (PA-PC). As the reduction in injection pressure is small compared with the drawdown, the impedance was greater using the DHP even though the production flow was generally higher than under normal circulating conditions.

Although the production flow in each stage of the test declined continuously, there was no stage during which the recovery fell below that which would be expected at the same injection flow rate in normal circulation. The improved recovery also resulted in a re-distribution of the flow in the reservoir as shown by the tracer data and discussed in the following section.

The slight increase in production temperature above that recorded immediately before the test is due to the heat given off by the pump motors. The rate of decline of the production water temperature, which had been observed for several months before the test, was unaffected by the introduction of the DHP.

Immediately following the test, the recovery fell to about 61%, which was lower than the expected value of about 68% under normal circulation conditions at an injection flow rate of 25.4 l/s. This was probably due to water going into storage and a re-adjustment of the joint apertures after the return to hydrostatic effective stress conditions. Two months after the end of the downhole pump test the recovery had returned to about 68%.

TRACERS

The effect of operating the production well under sub-hydrostatic conditions and increasing the pressure drop across the reservoir appeared to cause a major change in the flow paths as shown in the RTD curves (Figure 4). However, a change in the shape of this curve was starting to occur before the start of the DHP test with the first peak gradually becoming more prominent as the injection flow rate (and thus injection pressure) was increased during earlier experiments. It is likely that the DHP test helped to enhance this effect.

The initial peak is considered to be associated with the breakthrough flow path and the second peak with a number of other paths. Data from previous tests showed that the breakthrough feature was not dependent on pressure changes within the reservoir (CSM, 1986) and this was confirmed by the DHP test. The change in shape of the RTD curves at the start of the DHP test occurred because some of the flow paths associated with the second peak are probably pressure dependent and the reduction in hydrostatic head on the production well was sufficient to cause the near-well flow paths to close up and therefore reduce their contribution. However, the overall water recovery from the production well was higher than during normal circulation, so more fluid may have been forced through the breakthrough feature as a result of the increased pressure drop across it.

The tracer tests which had been run before the pump test were showing a general decrease in the peak concentration and an increasingly diffusive tail. This occurred as the injection flow rate was increased and had indicated that the reservoir was growing and becoming more diffuse. The shapes of the tails of the tracer tests run during the DHP experiment were similar to those of the two tests which were run immediately before and after it. The median volume, which represents the volume of the major flow paths in the reservoir, decreased during the DHP test to a level which was equivalent to that observed during earlier tests at similar production flow rates. It is suspected that this was due to the rapid decrease in injection flow rate prior to the start of the test rather than an effect of the DHP. Therefore, it is thought that there can have been no large volumetric changes as a result of operating the production well under sub-hydrostatic conditions.

The marginal change in impedance, along with the small volumetric changes seen in the tracer data, suggests that the region affected by sub-hydrostatic conditions was close to the production well.

CONCLUSIONS

The DHP test was used to simulate conditions anticipated in a 6 km deep system and, although it was not possible to run for a sufficient length of time to allow totally steady state conditions to be established, some important conclusions can be drawn.

1 The overall recovery improved during the DHP test compared with that achieved during normal circulation.

2 The continued decline in production flow rate indicates that joints were closing up as a result of the increased effective stress and, therefore, that joint apertures will be reduced when operating a system under sub-hydrostatic conditions.

3 Following as from 2 above, it is probable that the greater part of the buoyant drive caused by sub-hydrostatic conditions at the production well will be required to overcome increased resistance to flow through the paths in the region affected by the sub-hydrostatic conditions, unless these flow paths are held open using proppants placed close to the production well.

4 The tracer data indicated that there was no major change in the effective volume of the reservoir during the DHP test, although there was a change in the flow distribution of the system.

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