EVALUATION OF HYDRAULIC TESTS AT SOULTZ-SOUS-FORETS, EUROPEAN HDR-SITE

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ABSTRACT

Two massive hydraulic fracturing tests were performed in the 3600 m deep borehole GPK1 in low permeable granite at rock temperatures up to 160 °C. A large (> 1 km^2) NW-SE trending vertical fracture system was created by injecting 45,000 m^3 of water. The fracture system was found to be connected to a natural reservoir of hot brine (nearby fault or fracture zone). This hydraulic link can contribute considerably to the production flow in a ti-ture HDR circulation loop but carries also the risk of high fluid losses if the loop is operated at elavated pressure.

1. INTRODUCTION

Hydraulic in-itu investigations at Soultz-sous-Forets in the Upper Rhine Valley are carried out since 1988. During the first phase of the project (1988 - 1991) the upper part of the crystalline basement (1400 m - 2000 m) was investigated (Kappelmeyer et al., 1991). Though the hydraulic and hydro-mechanical conditions in the 2000 m deep pilot borehole GPK1 were quite favourable (Jung, 1991, 1992) this part of the granite was abandoned since the rock temperature of 140°C (Schellschmidt and Schulz, 1991) was considered as too low for a later HDR demonstration project. In the Winter of 1992193 GPK1 was deepened to 3590 m. At that depth the temperature reached 160 °C (Garnish et al., 1994). which is still not satisfactory. Nevertheless an extensive hydraulic program was conducted in order to gain information on the hydro-mechanical conditions in this deeper part of the granite, that showed the same tectonic characteristics as the upper part (Genter et al., 1991, Tenzer et al., 1991). and to find out to what extent the results obtained so far can be generalized.

2. SITE AND TEST FACILITIES

Soultz is located in the northern part of the Upper Rhine Valley about 50 km north of Strassbourg, France. The test site is 6 km east of the western margin of this active graben on a horst structure where the crystalline basement is found at a depth of 1400 m. Five boreholes were drilled at the site: the central borehole GPK1 (3590 m), exploration borehole EPS1 (2200 m deep, 400 m SW of GPK1), and 3 seismic observation holes (1500 m deep, 500 m to 1500 m distant from GPKI). The latter were equipped with cemented-in geophons for seimo-acoustic fracture monitoring. The site has water storing facilities for 25 000 m^3 of water, permanently installed high pressure pumps (2000 KW, 35 MPa, 60 l/s), and 2 logging winches. A workover rig was installed at GPK1 during part of the test program

3. HYDRAULIC TESTS AND RESULTS

The hydraulic test program consisted of 3 test sequences: pre-fracturing hydraulic investigations to determine the natural hydraulic conditions in the deeper part of the granite, hydraulic

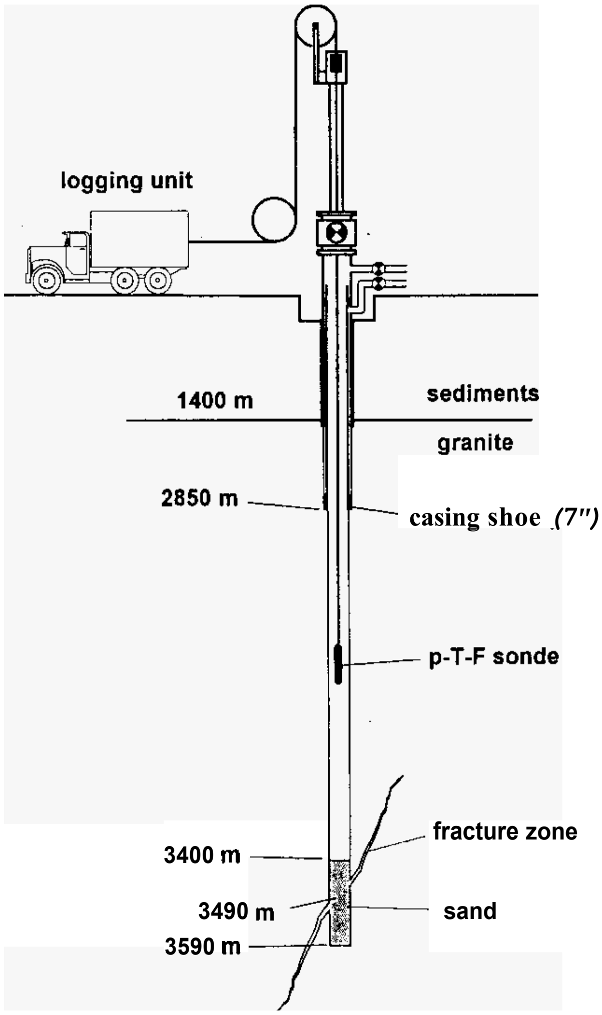

Figure 1. Scheme of the borehole arrangement during the stimulation tests. For test 93SEP01 the bottom part of GPK1 was filled with sand in order to prevent the stimulation of the fracture zone at 3490 m. For test 93OCT11 the sand plug was removed.

fracturing tests, and post-fracturing hydraulic tests for determining the hydraulic properties of the stimulated fracture systems All tests were performed in the openhole section of GPK1 (2850 m - 3590 m)

5.1 Pre-fracturing hydraulic tests

Several lowrate injection, venting, and production tests were performed in GPK1 with the following objectives. to recover and analyze formation fluid, to determine the overall hydraulic characteristics of the open hole section, and to locate the most conductive fractures by thermal and spinner flowmeter measurements

About 300 m^3 of formation fluid with a chemical composition similar to that found in the upper part of the granite and in the overlaying Buntsandstein (Pauwels et al., 1991) could be produced by using a downhole pump. A sodium chloride content of about 100 g/l and a density of 1069 kg/m^3 was determined for this fluid.

The static wellhead pressure was 0 15 MPa when the borehole was filled with formation fluid compared to a static wellhead pressure of 0.25 MPa (lung, 1991) for the upper part of the granite (1400 -2000 m). A production flowrate of about 0.5 lis was achieved at a drawdown of about 1 MPa. This corresponds to a specific yield of C = G.5 l/(s*MPa). It should be mentioned however that a step injection test at flowrates between 0.2 l/s and 1 l/s yielded a quadratic relationship between flowrate and injection pressure thus indicating turbulent flow. The specific yield and the injectivity is therefore decreasing with increasing flowrate.

Spinner and thermal flowmeter measurements during injection showed that more than 90 % of the flow lefr the borehole at 3480 m - 3490 m. According to acoustic televiewer and FMI measurements the borehole is intersected here by a fracture zone containing widely open fractures. This fracture zone had been detected previously during the drilling as it caused substantial losses of drilling fluid and had partly been plugged at that time by injecting a mixture of bentonite and nutshells.The test results indicate that the internal conductivity ofthis fracture zone is very high over an area io the order of 02 - 2 km^2 but is much lower beyond this area. It seems to be connected to a constant pressure outer boundary

3.2 Stimulation tests

Two successful openhole stimulation tests were performed in 1993 besides two less successful packer tests, whose results will not be presented here. The first openhole test (93SEP01) was aimed to stimulate the openhole section above the major fracture zone, whereas in the second test (93OCT11) the fracture zone itselfwas stimulated.

Test 93SEP01

Prior to the test the bottom pan of GPK1 including the major fracture zone at 3480 - 3485 m was sanded off.This limited the test interval to 2850 - 3400 m (s. Fig.1). Injection started on 1 September and ended an 17 September. During this time 25300 m^3 of water were injected in 12 injection periods at flowrates between 0.15 Vs and 36 Vs. Injection was followed by a I-day shut-in and a 2-days venting period during which 1200 m^3 of fluid were recovered. Seismo-acoustic and pressure monitoring in the seismic observation holes and in borehole EPS1 continued throughout the test. Flow and temperature logs were run during each injection period, during shut-in and venting

The injection pressure observed during the 12 injection periods increased significantly with increasing flowrate for low flowrates (0.15 l/s to 0.6 l/s), moderately for medium flow-rates (1.2 l/s to 12 l/s), and remained constant at 10 MPa for high flowrates (18 lis to 36 l/s) (s. Fig.2) The comparatively high injection pressure of 5 MPa for the lowermost flowratc (0.15 l/s) indicates that the test interval was tight prior to stimulation An injectivity of

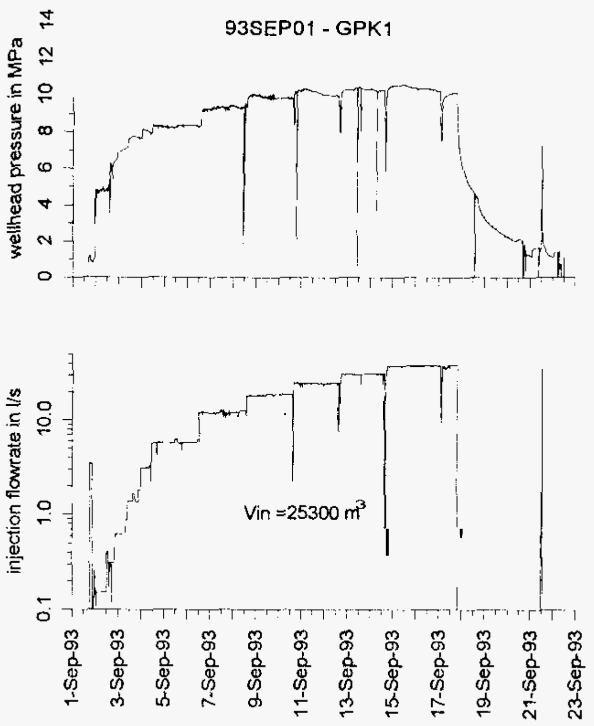

Figure 2. Records of the wellhead pressure and the injection flowrate during stimulation test 93SEP01.

C = 0.05 l/(s·MPa) can be determined for this stage. Assuming radial flaw this yields an apparent transmissibility of 0.014 D·m or an apparent permeability of 25 µD for the 550 m long openhole section.

The spinner logs performed during injection yielded 4 major outlets in the intervals 2850 - 2900 m, 3090 - 3100 m, 3230 - 3240 m, and 3320 - 3325 m. The dominance of the uppermost outlet became mare and more pronounced during the test. Finally this outlet absorbed more than 60 % ofthe flow.

Induced seismicity started at a rather low flowrate of 0.3 l/s and a wellhead pressure of 6 MPa The rate of seismo-acoustic events increased proponional to the flowrate during the subsequent injection periods and decreased gradually during shut-in and venting. About 17000 seismic events were recorded and their sources located. The spatial distribution of the seismic sources indicates NW-SE and preferably upward fracture growth. At the end of stimulation the sources ofinduced seismicity covered a volume of 1200 m x 1000 m x 400 m (height x length x width). The orientation ofthe fracture system of 150 ° agrees with the direction of the fractures induced in the upper part of the granite at 2000 m (Beauce et al , 1991) but is about 20 ° offthe direction ofthe maximum horizontal stress of 170 ° as derived from drilling induced fractures (Baumganner and Rummel, 1991; Tenzer et al., 1991).

Test 93OCT11

This test was aimed to stimulate the natural fracture zone at 3480 m - 3490 m. As a packer test for this purpose failed it was decided to stimulate the fracture zone by a high rate openhole injection test. In order to do so the sand was removed from GPK1 and injection into the openhale was started on 11 October. The flowrate was kept constant at 40 l/s for the first 4 days and was increased to 50 l/s at the last day ofinjection (Fig.3). The borehole was then shut-in for 2 days and vented afterwards. Several flow and temperature logs were performed during injection, shut-in and venting. Seismo-acoustic monitoring and pressure recording in the seismic observation holes and in EPS1 continued throughout the test. The total injected volume was 19300 m^3. About 650 m^3 were recovered during venting.

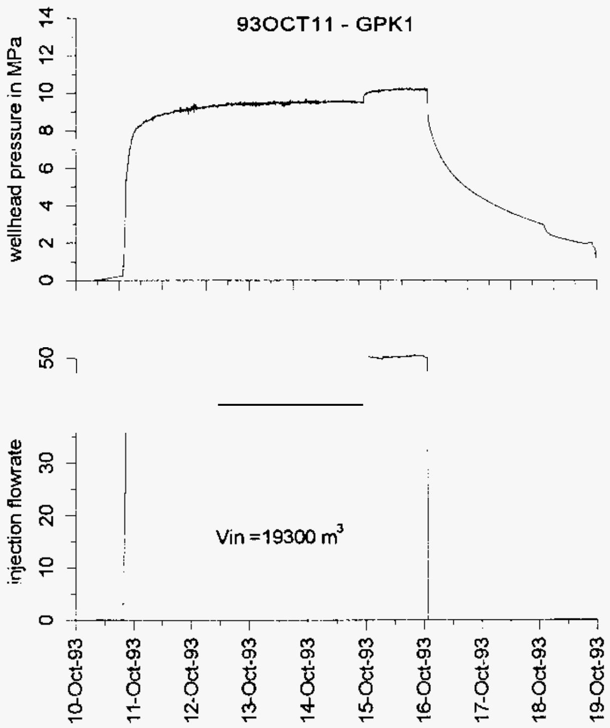

Figure 3. Records of the wellhead pressure and the injection flowrate during stimulation test 93OCT11

The main objective of the test, -stimulation of the fracture zone at 3480 - 3485 m -, could be achieved even though most of the injected flow was absorbed by the upper fracture system stimulated during the previous test. According to the flow logs about 10 % of the injected flow or a total volume of 2000 m^3 was flowing into the natural fracture zone during the test. Interestingly the steady state injection pressure of 9.5 MPa observed during the 40 l/s injection period was significantly lower than the final injection pressure of 10 MPa in experiment 93SEP01 though the net flowate for the upper part of the borehole (36 l/s) was the same for both tests. Only after increasing the flowrate to 50 l/s the injection pressure raised to about 10 MPa.

About 1700 seismic events were recorded during the test. The majority of these events originated from the fracture zone intersecting the borehole at 3480 - 3485 m. Only during the 50 l/s injection period a substantial part of the events was coming from the upper fracture system. The shape of the region of induced seismicity related to the lower fracture zone indicates a NW-SE striking fracture system covering a rock volume of 500 m x 600 m x *250* m (height x length x width).

3.3 Post-fracturing hydraulic tests

In 1994, eight months after the stimulation tests, a production test (94JUN16) and an injection test (94JUL04) were performed in order to determine the hydraulic characteristics of the stimulated fracture system.

Production test 94JUN16

The production scheme for this test is shown in Fig. 4. The steam and the noncondensible gasses were separated from the fluid before it was cooled down to about 35 °C in a tube type heat exchanger. The cooled fluid was sent through a flowmeter, buffered in a mud pool, pumped to borehole EPSI, and reinjected here

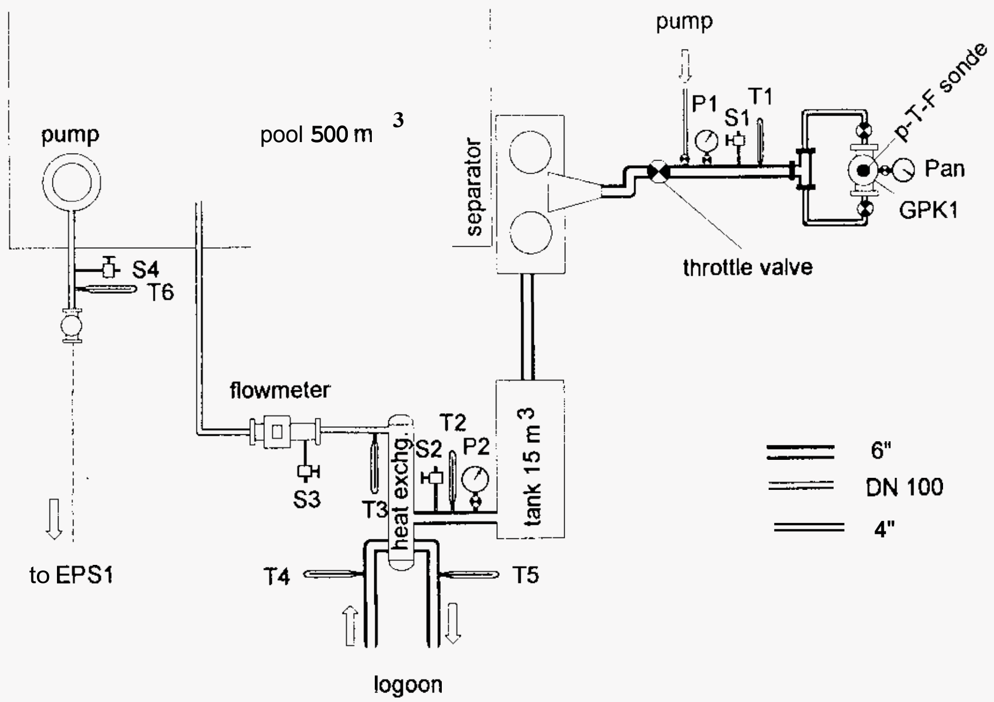

Figure 4. Scheme of the production cycle at borehole GPK1 used for the production test 94JUN16

in the openhale section extending from **2000 - 2230 m.** The produced fluid was continuously sampled and its chemical composition analyzed.

To initiate production at the highest possible rate 100 m^3 of freshwater were injected into GPKl prior to the test thus creating an artesian wellhead pressure of 1.6 MPa. During the test production was maintained solely by the artesian pressure and buoyancy effects. Production was started on 16 June by fully opening the throttle valve. Due to limitations of the reinjection capacities at EPSl the production flow had to he throttled to about 5 l/s after one day. Production at this flowrate continued for 7.5 days During this time the reinjection capacities at EPSl were improved and unthrottled production was re-staned on 25 June. After 3.5 days, as it became certain that the production flow was restricted by scaling, production was stopped and the borehole shut-in for 3 days. Several flaw and temperature logs were run during the tests in order to detect the main inlets in the openhole section of GPKl. Between the logs the same sonde was used for downhole pressure and temperature monitoring.

A total of 6200 m^3 of fluid were produced during the test. The test records as shown in Fig. 5 show that a maximum flowrate of 18 Us was achieved at the beginning of the test far unthrottled conditions. This reduced to ahout 11 l/s after one day for a constant pressure drawdown of i MPa. The flowrate was still declining when the production flow had to he throttled so that the long term production flowrate for unthrottled conditions could not be determined. The following throttled flow period demonstrates however that quasi steady state conditions are achieved after about 2 days. It can therefore be concluded that the flowate for unthrottled conditions would have stabilized at about 10 l/s. The final flow period was influenced by scaling in the surface production line. Due to this scaling a substantial flow resistance had built up in the production flowline resulting in a higher downhole pressure and a lower production flowrate as during the first flow period. Despite this disturbance the flow and pressure record of this period supports the conclusion that the long term production flowrate for unthrottled conditions would be in the order of 10 l/s This is about 20 times more than was achieved by downhole pumping during the pre-stimulation tests (for a similar pressure drawdown).

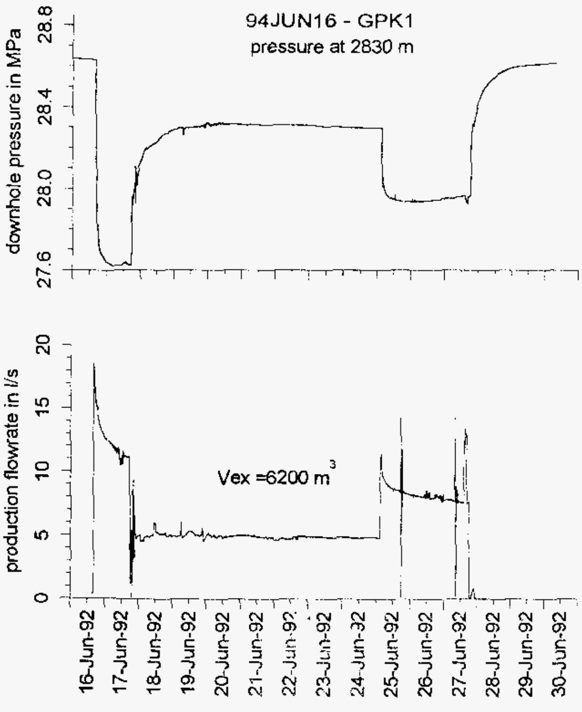

Figure 5. Records of the production flowrate [liquid phase) and the downhole pressure of the production test 94JUN16. Production was maintained by the artesian pressure and bucyancy effects.

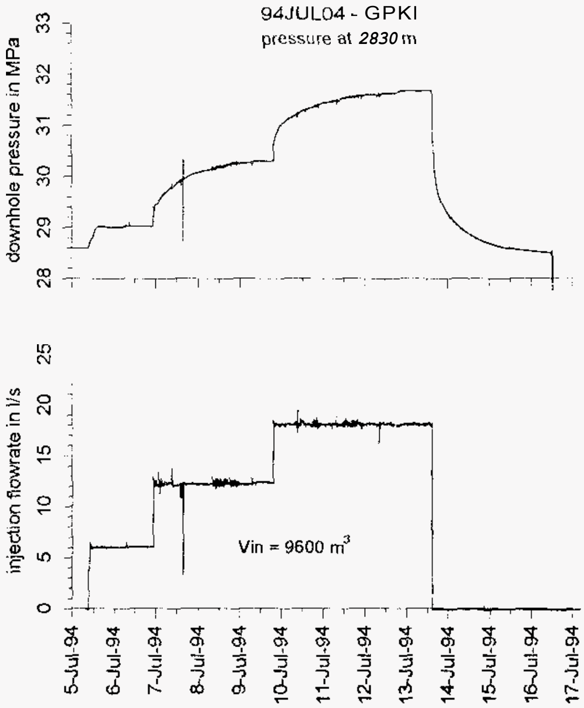

Figure 6 Records of the injection tlowrate and the downhole pressure of test 94JUL04

The density of the produced fluid increased during the first 3 days of production from 1,055 kg/m^3 to 1,06 kg/m^3 and stabilized afterwards at this value. As the density of the formation fluid is 1,069 kg/m^3 one can conclude that the produced fluid contained only about 15 % of Freshwater remaining From the stimulation tests This is surprizing since only a small fraction of the volume injected during the stimulation tests had been produced so far This indicates the presence of a large natural reservoir.

Iniection test

This test was intended to determine the injectivity of the stimulated fracture System and the long term fluid losses at different pressure levels. Care was taken that the pressure remained below the critical pressure for shearing 9600 m^3 of water were injected at flowrates of 6 l/s, 12 Us, and 18 l/s During each injection period the flowrate was kept constant until quasi steady state conditions were reached At the end the borehole was shut-in for 3 days and the pressure decline monitored. Several flow and temperature logs were performed in GPKl in order to detect the main outlets.

The records of the flowrate and the downhole pressure as shown in Fig 6 demonstrate. that the fracture can accept injection flowrates up to at least 20 l/s at a pressure level definetely below the critical pressure for shearing or jacking. This shows, that the fracture system retained a high hydraulic conductivity after stimulation even though no proppants were added to the frac-fluid. Several days were required during each injection period to reach steady state conditions. The length of the transient period obviously increased with increasing flowrate

In Fig. 7 a Homer Plat of the shut-in period is displayed. It shows that the pressure decay follows a semi-logarithmic line for about one day but is bending into a curve with a much smaller slope later and is approaching the static formation pressure after about 3 days. This indicates that the fracture is connected to a constant pressure boundary or to a region of much higher transmissibility.

In Fig. 8 the pressure difference (difference between the steady state pressure and the static formation pressure) for production and injection is plotted as a function of the flowrate. There is no linear relationship between the pressure difference and the flowrate. Instead the data can be fitted by a parabolic curve, which means that the pressure difference is proponional to the square of the flowrate. We have therefore to assume, that there is turbulent flow in the flowpath connecting the borehole and the constant pressure boundary. This turbulence is not restricted to the well-bore fracture intersections, since there is only a small instantaneous pressure change visible in the pressure records when the flowrate was changed or afler shut-in (s. Fig. 6). The same was already observed during the pre-stimulation tests and during the hydraulic tests in the upper part of the granite (lung, 1991) and can possibly be explained by asuming, that the flow is restricted to narrow channels within the fracture system.

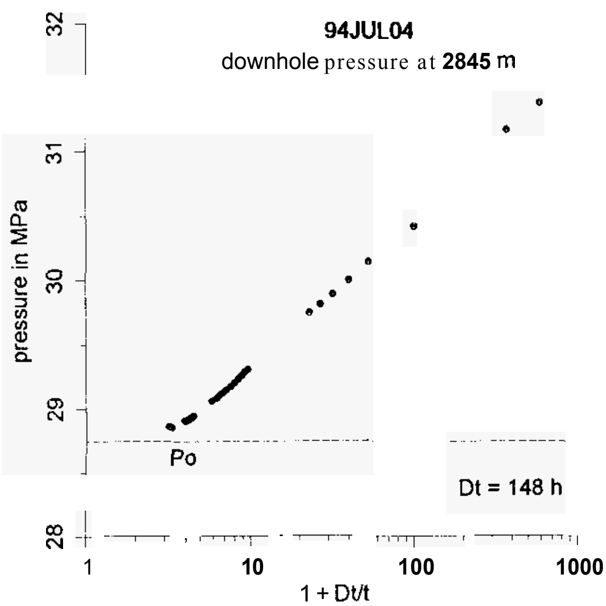

Figure 7. Homer plot of the pressure decline during the shut-in period of test 94JUL04.

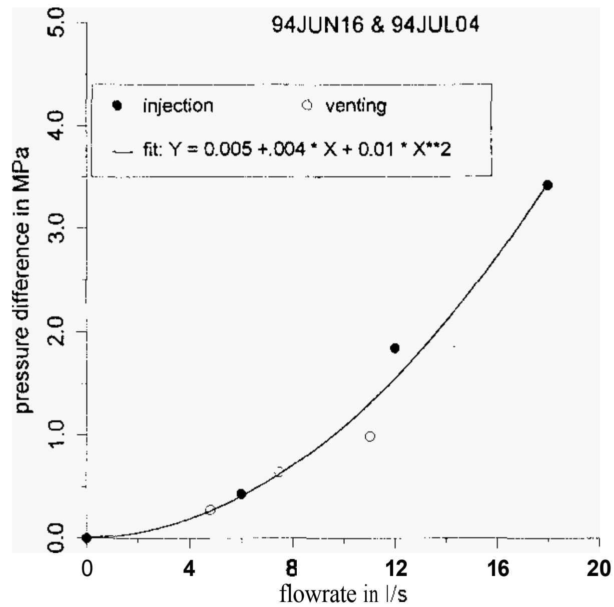

Figure 8. Pressure difference (difference between steady state pressure and static pressure) as a function of the flowrate.

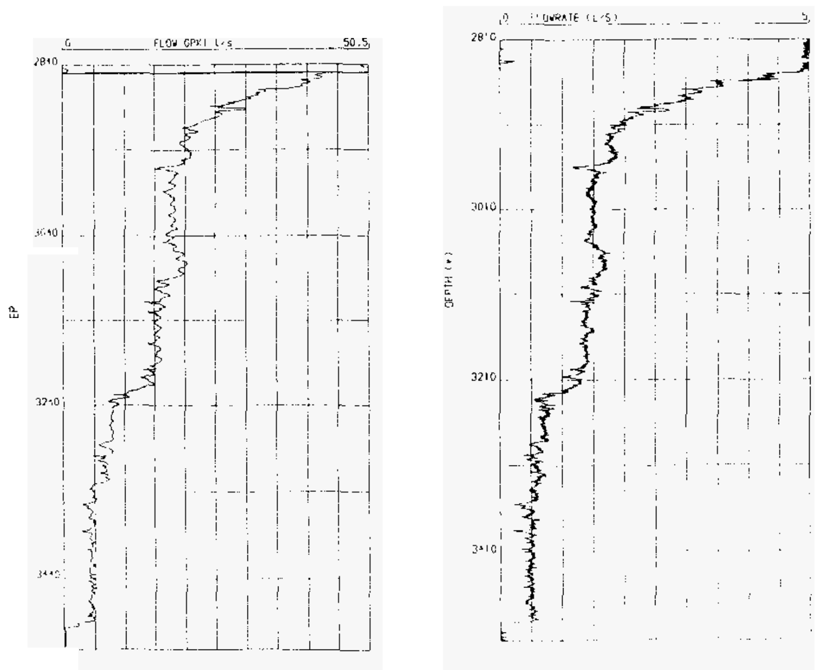

Figure 9. Records of spinner flow measurements during stimulation (test 93OCT11) and during post-fracturing production (94JUN 16).

3.4 Results of spinner flow measurements

The most interesting result of these measurements is the fact that the flowlogs recorded during stimulation and subsequent production were almost identical (s. Fig.9). The flowlogs show that about 60 % of the fluid lei? or entered the borehole at 2850 - 2900 m, 10 % at 3090 - 3100 m, 15 % at 3230 - 3240 m, 5 % at 3320 - 3340 m, and 10 % at 3580 - 3590 m. Only the contribution of the fracture at 3090 - 3100 m was slightly less during production than during stimulation From this we can conclude that the stimulation process creates flowpathes (toward the constant pressure boundary) whose permanent productivity is proportional to the flowrate consumed by each flowpath during stimulation. In fact a linear relationship is observed as is demonstrated in Fig. 10. In this graph the permanent production flowrates achieved after stimulation are plotted against the flowrate applied during stimulation. The graph contains all values obtained so far in the different sections of borehole GPK1 and includes also the data obtained in the upper part ofthe granite. The data can well be fitted by a straight line. The graph shows that the production flowrates (for a pressure difference *of* I MPa maintained by the artesian pressure and bouyancy effects) is about 20 % of the injection flowrate applied

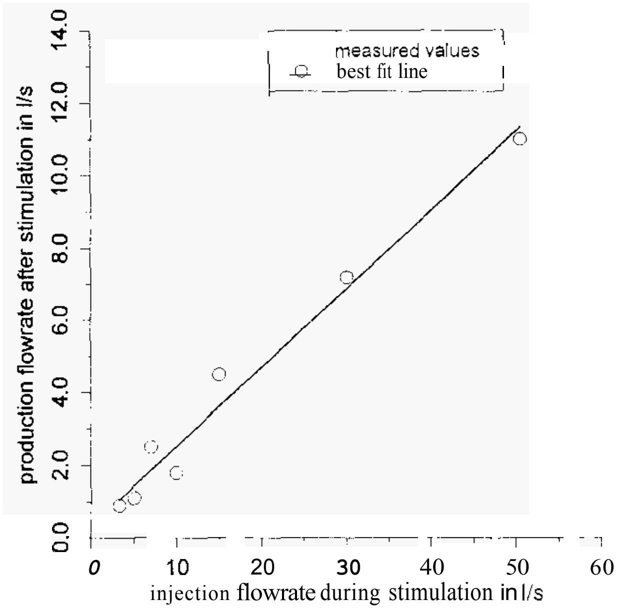

Figure 10. Post-fracturing production flowrates from all stimulated borehole sections of GPK1 as a function of the flowrate applied during stimulation. Data from hydraulic tests performed in 1988, 1991, 1993, and 1994 in the upper and the lower pan of the granite.

during stimulation This result is encouraging if one asks for production only. If one is asking for circulation between two or more boreholes the result is ambivalent since it carries the risk of high fluid losses if such a system is operated at elavated pressure. This problem may ofcourse be solved by using downhole pumps at the production side.

4. CONCLUSIONS

The test results have shown that fracture systems sufficiently large for a HDR-pilot system can be created in the crystalline basement at Soultz by injecting large quantities of water at moderate to high flowrates. The preferred direction of fracture propagation is NW-SE, which is about 20 $^{\circ}$ offthe direction ofthe maximum horizontal stress.

The fractures stimulated with water retained a high permanent transmissibility after deflation. Expensive fracturing operations using vicous fluids and proppants can therefore be avoided.

The productivity of the borehole which was 0.5 l/(s*MPa) prior to stimulation was increased by a factor of 20 to about 10 l/(s*MPa) by the fracturing tests. The productivity ofthe individual fractures, that were stimulated, proved to be linearly related to the injection flowrate applied during stimulation. The production flowrate achieved far a pressure drawdown of I MPa were about 20 % of the injection flowrate applied during stimulation, It seems likely that production flowrates of 30 l/s or more could be achieved if higher injection flowrates are applied during stimulation or if more fractures are stimulated. This applies even mare if a second borehole is drilled into the stimulated fracture system, as is planned for the Winter 1994195, and if fluid is re-injected there.

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