Hydrofrac Stress Data for the European HDR Research Project Test Site Soultz-Sous-Forets

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INTRODUCTION

In-situ stresses are key parameters in the design of a hot-dry-rock (HDR) operation for the extraction and the economic use of geothermal energy. In-situ stresses control the operation pressure to activate pre-existing fracture/joint-systems, determine the underground fluid flow paths, or influence borehole stability in un-cased borehole sections.

Besides Bad Urach/Swabian Alp (Germany) and Rosemanowes/Conwain (UK), the HDR geothermal research site at Soultz-sous-Forets/Alsace (France) with a target reservoir temperature of 175 °C at only 3.5 km depth is a possible candidate for a future European HDR-prototype. The site is located about 50 km north of Strasbourg near the western margin of the Upper Rhine Graben in the center of a well-known geothermal anomaly. The temperature is about 100 °C in the sediments at one kilometer depth and increases with about 30 °C/km in the underlying granite.

During the first project phase (1986-1990) borehole GPK-1 was drilled to a depth of 2000 m. In the granitic section between 1376 m and 2000 m depth, eight hydrofrac or injection tests were conducted [1]. These tests were characterized by several technical problems caused by using conventional packer technology in the hostile downhole environment (temperatures of up to 140 °C and high gas and salt contents of the borehole fluid). In spite of the problems, five tests yielded sufficient pressure and fracture orientation data to conduct an inversion type stress analysis as proposed by Cornet and Valette [2] and Baumgärtner [3]. The result of the computations yields the following stress profile for the depth interval between 1458 m and 2000 m:

\[
P_t = 15.1 + 0.0179 \cdot (z - 1458)
\]
\[
P_H = 24.8 + 0.0198 \cdot (z - 1458)
\]
\[
P_m = 0.024 \cdot z
\]

direction of \( P_H \): N 155° ± 3°.

Due to the limited data base of only five tests a valid extrapolation of this stress profile to reservoir depth was impossible. The determination of stresses down to reservoir depth, therefore, asked for the conduction of deeper and more reliable hydrofrac stress testing. Such tests also required the development of a new hydrofrac tool based on aluminum packers adequate to the hostile downhole environment.

ALUMINUM STRADDLE PACKER TOOL

Conceptual design

New possibilities for further stress measurements at the Soultz site occurred during project phase II (1991-1992) by drilling the second geothermal exploration borehole EPS-1 (500 m SSE of GPK-1) to 2227 m depth and by deepening borehole GPK-1 to 3590 m. Based on the drilling scheme for the open-hole sections of both boreholes, the aluminum straddle packer systems were designed for 96 mm (EPS-1) and 159 mm (GPK-1) diameter boreholes. A schematic diagram showing the essential details of the tools is shown in Fig.1. The dimensional data for the aluminum straddle packer systems are given in Table 1. The major characteristics are as follows:

The packer elements consist of pure aluminum (Al 99.5%) which allows a maximum deformation of 25% at room temperature. The wall thickness within the packer inflation section is 17 mm for the 96 mm and 24.5 mm for the 159 mm diameter borehole system. The packer diameters are designed in such a way to accommodate the borehole diameter by approximately 15% of lateral deformation and differential pressures of about 25 MPa. To a certain extent, this enables the aluminum packers to be set in irregular cross-section boreholes. However, inflation in breakouts or washouts will cause packer rupture similar to conventional packers. To guarantee sealing, the outer surface of the aluminum packers are furnished with high temperature Teflon and Viton O-rings. The soft packer elements are threaded into the injection interval part and the end-pieces, both consisting of high strength aluminum alloy (ERGAL 55).

The intelligent inner stainless steel mandrel contains high temperature Viton O-rings as sealings against the aluminum out-shell and deep borings as hydraulic connections to the packer inflation sections and the injection interval. The mandrel position inside the aluminum shell is fixed with a shear pin with a breaking force of 4 kN. This design enables to recover the steel mandrel after completion of the hydrofrac test while the outer aluminum shell remains in the borehole. The aluminum can be milled-out by adequate drilling technology.

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Table 1. Dimensions of the aluminum straddle packer tools

<table>
<thead>
<tr>
<th>tool element</th>
<th>packer material</th>
<th>injection interval material</th>
<th>end piece material</th>
<th>inner mandrel material</th>
</tr>
</thead>
<tbody>
<tr>
<td>borehole diameter</td>
<td>packer</td>
<td>injection interval</td>
<td>end piece</td>
<td>inner mandrel</td>
</tr>
<tr>
<td>mm/inch</td>
<td>Al 99.5%</td>
<td>ERGAL 55</td>
<td>ERGAL 55</td>
<td>stainless steel</td>
</tr>
<tr>
<td>OD, min. wall thickness</td>
<td>OD, ID, length</td>
<td>OD, ID, max. OD, length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>96/4</td>
<td>86</td>
<td>88</td>
<td>40</td>
<td>88</td>
</tr>
<tr>
<td>159/6 1/4</td>
<td>145</td>
<td>148</td>
<td>60</td>
<td>148</td>
</tr>
</tbody>
</table>

This unexpected low packer capacity was caused by failure of one of the inner mandrel O-ring seals. By some minor modifications the tool has considerably been improved and the present versions should allow hydrofrac tests at pressures up to 100 MPa under severe in-situ conditions.

**RESULTS OF IN-SITU HYDROFRAC TESTS**

Several hydrofrac experiments were conducted by using the new aluminum packer arrangement in the Souris boreholes EPS-1 and GFK-1. The first two tests were carried out in borehole EPS-1 at 2205 m and 2195 m depth (temperature 150 °C), the other two tests were conducted in borehole GFK-1 at 3506 m and 3315 m depth (temperature 175 °C). The test zones were selected on the basis of FMI and Caliper as well as on BHVT-logs. The logs demonstrated rather smooth open-hole boreholes with several sections well fitted for testing.

A brief description of the testing procedure is given below:

- Inflation of the aluminum packers to differential pressures of about 33 MPa.
- Activation of the push-pull valve to switch to interval pressurization.
- Pressurization of the test interval to a low pressure level above hydrostatic (3 to 5 MPa) and observation of the pressure decrease in the closed system for about 5 minutes in order to examine the test interval for open joints (permeability test).
- Injection into the test interval until a hydraulic fracture was initiated or a pre-existing fracture was opened (breakdown-cycle).
- Extension of this fracture during repeated pressurization cycles in which 15 to 40 liters of water were injected with different injection rates (2.5 to 4.5 l/min).
- Conduction of a slow-pumping test.
- Venting of the system between each of the injection cycles and observation of the pressure rebound by interruption of the back-flow during the venting phase.
- Finally, shear-off of the shear pin and recovery of the inner mandrel.

**Laboratory testing**

Prior to in-situ hydrofracturing two prototype aluminum packer tools for 96 mm diameter boreholes were tested in a borehole simulator autoclave. The first test at room temperature showed that the tools can be operated up to 91 MPa packer pressure and 81 MPa interval pressure. Packer burst occurred at a pressure of 98 MPa. In a high temperature (175 °C) / high pressure (30 MPa) test, failure occurred at 57 MPa interval pressure during packer pressurization from 66 MPa to 77 MPa.
An example for the pressure variation in the packers and the injection interval as well as the injection rate during the test at 3315 m depth is given in Fig. 2.

The major results of these experiments can be summarized as follows:

The aluminum packer technology for hydrofracturing in a hot (175 °C), gassy and geochemical aggressive downhole environment was a full success. Setting of the aluminum packers occurred at differential pressures of 20 MPa to 25 MPa, exactly as expected from the design of the new tool. Packer scaling at differential pressures up to 33 MPa was excellent as predicted from preceding autoclave tests. At the end of the tests the shear-off of the the shear pin occurred as expected from laboratory testing and the inner mandrel could easily be recovered. During the tests the downhole data recording system was in the hot environment for 5 to 6 hours. During this time, the dewar with the heat sink showed excellent performance. Finally, it should be noted that the milling of the downhole remaining aluminum shells in borehole GPK-1 to conduct post-frac FMI-logging was successful. The operation also demonstrated that the deflated aluminum shells can support large loads which opens the door for a full range of new applications (side-tracking, bridge plugs, casing packers etc.) for hostile downhole conditions.

Table 2: Pressure data and stress values derived from hydraulic fracturing tests with the aluminum straddle packer systems in the Soultz boreholes EPS-1 and GPK-1.

<table>
<thead>
<tr>
<th>depth (m)</th>
<th>$P_I$ (MPa)</th>
<th>$P_{sl}=S_h$ (MPa)</th>
<th>$S_H$ (MPa)</th>
<th>$S_r$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2195</td>
<td>29.6±0.4</td>
<td>26.6±0.1</td>
<td>50.2±0.7</td>
<td>56.0</td>
</tr>
<tr>
<td>2205</td>
<td>26.2±1.9</td>
<td>27.0±0.5</td>
<td>54.8±3.4</td>
<td>56.2</td>
</tr>
<tr>
<td>3315</td>
<td>44.2±0.8</td>
<td>45.2±0.5</td>
<td>91.3±2.3</td>
<td>84.6</td>
</tr>
<tr>
<td>3506</td>
<td>44.2±0.1</td>
<td>44.2±0.1</td>
<td>87.4±0.4</td>
<td>89.4</td>
</tr>
</tbody>
</table>

* The vertical stress $S_v$ is calculated from a mean rock density of 2.6 g/cm$^3$.

Assuming vertical fractures aligned with the direction of the acting major horizontal stress, the conventional hydrofrac hypothesis as suggested by Hubbert and Willis [4] was used to derive the minimum and maximum horizontal stresses $S_H$ and $S_{II}$:

\[ P_c = 3 \cdot S_h - S_H + P_{co} - P_o \]  
\[ P_{sl} = S_h \]  

where $P_c$ is the breakdown pressure, $P_{sl}$ is the shut-in pressure, $P_{co}$ is the hydraulic rock tensile strength and $P_o$ is the pore pressure. Eq.(1) reveals that the $S_H$ computation essentially depends on the pore pressure assumed for the rock mass tested. For the stress evaluation presented here, it is assumed that the effect of the matrix pore pressure on the stress regime is negligible due to the low porosity of the Soultz granite (usually less than 1%). Under the further assumption that the in-situ rock tensile strength $P_{co}$ can be estimated from the difference between the breakdown pressure $P_c$ and the first re-opening pressure $P_{r}$ [5], eq.(1) can be simplified as:

\[ S_H = 3 \cdot P_{sl} - P_r \]  

Using the pressure data listed in Table 2, eq.(2) and (3) yield stress magnitudes of $S_h=26.6-27.0$ MPa, $S_{II}=50.2-54.8$ MPa and $S_v=56.1$ MPa at 2200 m depth [5], $S_h=45.2$ MPa, $S_{II}=91.3$ MPa and $S_v=84.6$ MPa at 3315 m depth and $S_h=44.2$ MPa, $S_{II}=87.4$ MPa and $S_v=89.4$ MPa at 3506 m depth. This result confirms the stress profile determined for the minimum horizontal stress component $S_h$ derived from the earlier stress measurements in borehole GPK-1. The maximum horizontal stress component $S_{II}$ is higher than expected from the shallower experiments and seems to approach the level of the overburden stress $S_v$ (Fig.3). The normal faulting stress regime ($S_h < S_{II} \leq S_v$) with low $S_h$ magnitudes is typical of the tectonic situation in the...
Rhine Graben and therefore offers favourable conditions for hydraulic circulation experiments.

Although the two tests in borehole EPS-1 presently do not allow to determine the orientation of induced fractures and the processing of the post-frac FMI-log of borehole GPK-1 has not been finished yet, the observed pressure data are in accordance with previous pressure data in borehole GPK-1 which indicates a NW to NNW direction of the acting major horizontal stress. This direction is in accordance with both existing stress data for Central Europe [7] and with geological stress indicators observed at the Soultz site [8].

![Stress Diagram](image)

**Fig. 3:** Stress field at the HDR test site Soultz in relation to the hydrostatic pressure $P_{\text{hyd}}$ (fresh and salt water, temperature corrected). The vertical stress $S_v$ is calculated from a mean rock density of 2.6 g/cm$^3$.

**CONCLUSIONS**

In designing of an HDR operation for the extraction and use of geothermal energy it is necessary to have knowledge of the magnitude and the direction of in-situ stresses at the depth of the geothermal reservoir. For this purpose, hydraulic fracturing stress measurements were carried out in the Soultz research boreholes as a part of the HDR feasibility study. The hostile downhole environment (high temperature up to 175 °C, high gas and salt content of the borehole fluid) required the development of a completely new technology based on aluminum packers operated by a wireline system for zone isolation in boreholes with 96 mm and 159 mm diameters. This technology was successfully used down to 3.5 km depth.

Autoclave tests of the new tool demonstrated enormous packer capacities which enables future hydrofrac experiments under high pressure conditions at great depth.

The milling operation of the downhole remaining aluminum shells in borehole GPK-1 showed that the aluminum packers can support large loads which opens the door for a full range of new applications (side tracking, bridge plugs, casing packers etc.) for hostile downhole conditions.

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**REFERENCES**