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Hydraulic properties of the Rheingraben basement material

by *T. Hettkamp, G. Fuhrmann & F. Rummel

Institute of Geophysics, Ruhr University Bochum, Universitätsstr. 150, 44780 Bochum, Germany

ABSTRACT

The next step in the European HDR-project at Soultz-sous-Forêts, France, is the deepening of borehole GPK-2 to app. 5 km, in order to reach rock formation temperatures of app. 200 "C and to prepare a longterm circulation test at higher production temperatures. The success of **the** longterm circulation test 97JUL12 is based on the permeability increase due to earlier stimulation tests. Hydraulic flow in the granite Rheingraben basement is mainly restricted to faults and fractures, because the rock matrix permeability is low. The economy of a HDR-power-plant is controlled by the flow rate and the production temperature of the circulated water. The knowledge of the permeability of fractures under controlled laboratory conditions is therefore fundamental.

A laboratory test program in 1999 will be carried out on cylindrical ***(6*** cm diameter) and /or cubic (max. 10 cm edges) granite samples with a central hole (0.3 cm diameter). In hydraulic injections tests vertical or horizontal fractures will be induced. In consideration of different flow models (radial or straight) the fracture permeability will be determined in dependence on the pressure normal to the fracture plane and on the flow rate. In a next step the dependence of the permeability of fractures on the fracture aperture and on the fracture-surface-roughness will be investigated by shearing and/or thermal treatment of the fracture plane.

Additionally in situ hydraulic tests are planned to derive the fracture transmissivity in 5 km depth from pressure oscillation analysis. The **results of** the planned in situ and laboratory tests will be presented at the conference. In the paper the results of the earlier in situ tests in 1996 and the preliminary permeability laboratory tests mainly on intact rock samples are summarised.

KEYWORDS

Transmissivity, permeability, rock physics, Soultz-granite, HDR

1. Permeability of the Soultz-granite derived from in-situ and laboratory tests

Permeability data obtained from laboratory and in-situ measurements differ significantly for crystalline rocks. Laboratory tests of the permeability were performed on small intact rock samples and tend therefore to yield the rock matrix Permeability. On the other hand the in-situ estimations include the effect of natural and/or artificially stimulated fractures connected to the well and yield the rock mass permeability. Both the rock mass and matrix permeability depend on pressure, temperature and chemical conditions.

One of the main **tasks** of an HDR-Project at great depth is to increase the natural rock mass permeability between the circulation wells. The success of the four months circulation test in 1997 between the open hole sections of the boreholes GPK-1 (2850-3590m) and GPK-2 (3211-3876m) is based on the increase of the rock mass permeability by the earlier stimulation tests carried out in 1993, 1995 and 1996. In-situ determinations of the permeability are derived from the analysis of pressure oscillations observed during various hydraulic tests (RUMMEL et al. 1997).

In-situ rock mass permeability data are compared with laboratory results. The pressure dependence of the rock matrix permeability was investigated in laboratory tests. Additional tests on thermal treated samples and samples fractured in the direction of flow were carried out to gain more information on the rock **mass** permeability by laboratory testing.

2. In-situ permeability tests

A number of pressure oscillations were recorded during the hydraulic tests at Soultz between 1994-1996. Assuming Darcy flow conditions within the rock mass, an analytical model of a pressurized well/fracture system was developed, which relates the oscillation characteristics (damping constant and frequency) to the hydraulic transmissivity and storage capacity (WEIDLER 1996, RUMMEL & WEIDLER 1996, RUMMEL et al. 1997a). One **of** the main restrictions of the analytical model of a pressurized well/fracture system is the assumption of radial or slightly elliptic flow in a ***single*** fracture (i.e. a horizontal or a slightly inclined fracture).

An overview plot of the stimulation test 96SEP18 of borehole GPK-2 is shown in figure 1. A total volume of 27.000 m^3 of freshwater was injected in three steps with injection rates of 25, 45 and 78 l/s during the period September 18" to 25".

In order to quantify the success of the stimulation, three pressure pulse tests were carried out by injection with a rate of 31 l/s for 1, 2 and 3 minutes before and after the stimulation (figures 2 and 3). The undisturbed pressure level was about 1 bar for the pre- and about 15 bar for the post-stimulation tests, respectively. The different injection periods resulted in strongly varying pressure build-ups before (50, 67 and 75 bars) and similar pressure build-ups after the stimulation test (28, 30 and 31 bars).

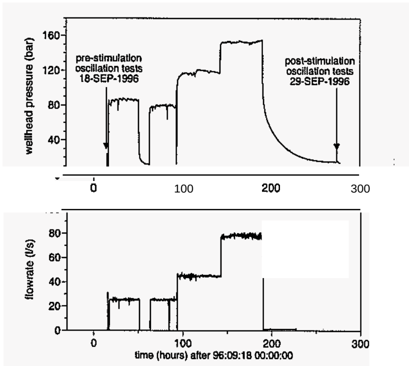

Figure 1: Stimulation test 96SEP18 in borehole GPK-2. The oscillation tests are marked with arrows.

The oscillation parameters of the pre- and after-stimulation tests were determined using a modified Prony-analysis. To calculate the transmissivity from the determined oscillation parameters some values have to be known in advance: (i) the wellbore stiffness s_w which depends on the wellbore volume and the fluid compressibility, the casing and e.g. the wellhead equipment, (ii) the storativity S of the fracture which depends on the fracture roughness, the stress field and the rock compressibility, and (iii) the effective wellbore-radius r_{eff} which depends on the wellbore-fracture cross section and takes into account the fracture inclination. The following values were assumed for the evaluation of the oscillation tests: $s_w = 10^{-7}$ Pa/m^3; $S = 10^{-10}$ m/Pa; $r_{eff} = 1$ m.

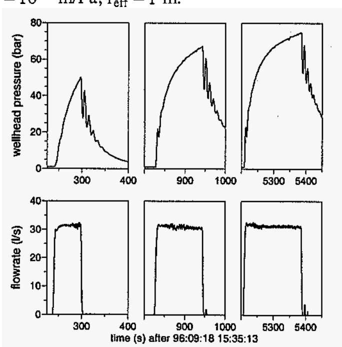

Figure 2: Pre-stimulation pressure oscillation tests (96SEP18) in borehole GPK-2.

The resulting values including data derived from earlier investigations are summarised in table **1.** Rock mass permeability values k can be estimated from the fracture transmissivities **T by**

$$k \approx \frac{T \cdot \eta}{h}$$

where **h** is the length of the openhole section **(740 m** for **GPK-1** and **665 m** for **GPK-2)** and η is the fluid viscosity **($\approx 3 \cdot 10^{-4}$ Pzs).**

Year (Experiment)	P_{whd} (bar)	T (m^3/Pa·s)	K (m^2)
GPK-1			
94 (94JUN16)	5	$0.4 \cdot 10^{-8}$	$1.6 \cdot 10^{-15}$
95 (95JUN16)	5	$0.6 \cdot 10^{-8}$	$2.4 \cdot 10^{-15}$
GPK-2			
95 (95JUN16)	140	$1.8 \cdot 10^{-8}$	$8.1 \cdot 10^{-15}$
96 (96SEP18 pre)	75	$3.3 \cdot 10^{-8}$	$1.5 \cdot 10^{-14}$
96 (96SEP18 post)	≈ 30	$1.0 \cdot 10^{-7}$	$4.5 \cdot 10^{-14}$

Table 1: Transmissivity T and permeability k derived from pressure oscillation analysis (P_{whd} = wellhead pressure)

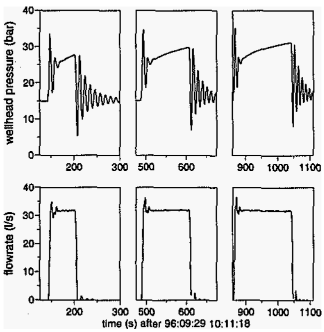

Figure 3: Post-stimulation pressure oscillation tests (96SEP18) in borehole GPK-2.

Although the post-stimulation pressure oscillation tests were carried out at significant lower wellhead pressure levels (smaller fracture width), the results demonstrate that the stimulation of GPK-2 in 1997 yields an increase of transmissivity by a factor of **3.** However, it should be noted that pressure oscillation tests yield the near-wellbore transmissivity, which may differ from values derived from long-term steady-state hydraulic tests.

A comparison of rock mass and rock matrix permeability of various HDR-projects is presented in figure **4** (WEST et al. 1975, DELISLE 1975, JUNG 1986). The rock matrix permeability determined in the laboratory is generally smaller than the rock mass permeability in crystalline rock. The difference is explained by the existence of fractures, which are in-situ the main **flow** paths.

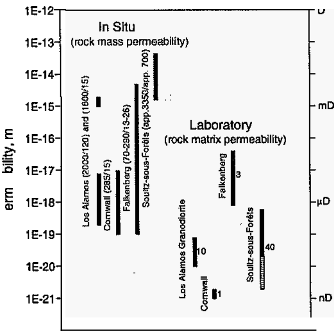

***Figure 4:** Comparison of permeability measured in-situ and in the laboratory (numbers in brackets are depth and interval length of the permeability tests in m, numbers close to the rock matrix permeability are the hydrostatic pressures of the tests in MPa)*

3. Laboratory permeability tests

Rock matrix permeability determination in laboratory is carried out by stationary flow tests and/or by the pressure pulse method on cylindrical samples of the Soultz-granite (6 cm in **length** and **3** cm in diameter). Argon was chosen as the flow medium, the direction of the gas flow was parallel to the cylindrical axis of the sample. The permeability was studied in a triaxial pressure chamber and the dependence on the differential and the confining pressure was investigated. The accuracy of the determined permeability data is ± 10%.

Permeability of the **Soultz** granite decreases half an order of magnitude during axial deformation in accordance to the initial volume reduction (figure 5). The subsequent permeability increase seems to occur after the onset of dilatancy. After failure the permeability is one order higher than the initial permeability. The fracture plane intersects only one end surface of the sample, so there is no short cut between the samples end surfaces by a fracture and a great part of the flow is dominated by the diffusion through the matrix. From laboratory tests on intact samples only a lower limit for the rock matrix permeability can be derived. Therefore, the samples were thermally treated (RUMMEL et al. 1997b) and axial fractures were induced which intersect both sample end faces. The results are summarised in figure *6*.

A model suggested by WYLLIE & ROSE (1950) simplifying the fracture system in the sample by a tube with a constant diameter and a length greater than the sample length yields the following relation between the permeability **k** and the effective pressure σ_{eff}:

$$k^{1/n} = a \cdot \log(\sigma_{eff}) + b$$

with a, b and n as fitting parameters, where $n \in [3,\infty[$.

The used model curves approximate well the measured data and are in good agreement with the observations of **WALSH** & BRACE (1984) and BERNABE (1987).

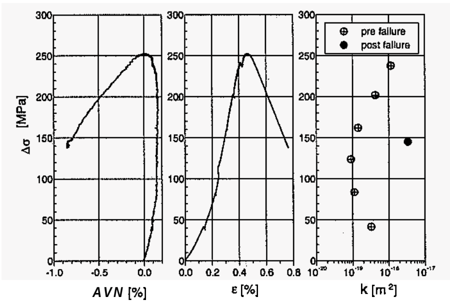

Figure 5: Permeability during a triaxial compression test. The confining pressure was 5 MPa. The differential pressure $\Delta\sigma$ is plotted against the volume change AVN (compression is positive), the axial shortening ε and the permeability k.

For the Soultz granite the confining pressure dependence of the permeability of intact and thermally treated samples can be described with an exponent $n = 6 - 7$. The permeability of the samples with a fracture in the direction of the flow connecting both end surfaces of the sample show a three order of magnitude higher permeability than the intact samples. In comparison the pressure dependence of the permeability of samples with a fracture parallel to the flow direction can be described with an exponent n=3 indicating a minor effect of pressure on permeability.

Permeability determined in laboratory tests on samples with a fracture parallel to flow direction is close to the permeability determined in-situ (figure *6)*. Therefore the determined pressure dependence of these samples is used to estimate the in situ rock mass permeability in 5 km depth. The depth profiles of the in-situ stresses yield a minimum horizontal stress of S_h = 40 MPa at **3.2** km depth (KLEE & RUMMEL **1993).** Linear extrapolation of the stress regime to 5 km depth yields a value of $S_h \approx$ 70 MPa. Assuming no variation in the composition of the rock material, neglecting the temperature dependence of the permeability and neglecting further the size effect by using the laboratory results for the pressure dependence, **a** decrease of half a decade in rock mass permeability can be expected.

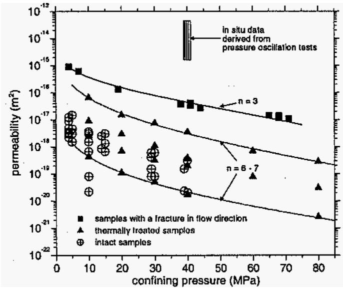

*Figure **6:** Confining pressure dependence of permeability derived from laboratory tests*

4. Summary and conclusions

The analysis **of** pressure oscillation tests yields rock mass permeability data for the near-wellbore area completing the results of steady-state injection tests for the far-field region. The results show an increase of the permeability after the stimulation in **1996** by a factor of at least **3.** Future hydraulic investigations in 1999/2000 at great depth (5 km) should incorporate pressure oscillation analysis to complete long-term steady-state tests.

Laboratory investigations on fractured granite samples under extrapolated in-situ conditions allow a prediction of rock mass permeability at 5 km depth, which will be verified by in situ tests in **1999.** Neglecting the size-effect, a decrease of rock **mass** permeability by half a decade can be expected. Further laboratory tests will concentrate on the influence of thermal cracking, shear displacement and dilation on the permeability of fractures.

Acknowledgements

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