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PRODUCTIVITY FOR GPK2 AND GPK4, INJECTIVITY FOR GPK3 DERIVED FROM CIRCULATION TEST 05JUL11

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ABSTRACT

Using the data from the circulation test 05jul11 an apparent injectivity index for GPK3 and the productivity index for GPK2 and GPK4 have been calculated. Especially the calculation of the needed downhole overpressure as a function of the wellhead data is a critical task. It was carried out that at the circulation scheme of 15 l/s injection at GPK3 and production of 13 l/s from GPK2 and 2 l/s from GPK4 the indices are around 8 l/s/MPa for GPK2 and 2-3 l/s/MPa for GPK3 and GPK4. Taking into account the hydraulic influence of producing or injecting boreholes to each other a "single-borehole" injectivity or productivity index can be estimated. These values are smaller than the apparent indices given above. But it must be clearly emphasised that the interpretation of any kind of productivity and injectivity indices of a multi-well system with respect to its future productivity must be done with cautiousness.

INTRODUCTION

The measurement of downhole pressure, p_{dh}, and temperature, T_{dh}, under injection or production conditions in deep boreholes is often a risky operation. Most problems can be created from high temperature levels, uncertain depth location and further disturbances that tend to influence the accuracy of measurements. Using the new borehole simulator HEX-B a quality control of the measured data can be performed (Mégel et al, 2005). HEX-B allows to calculate downhole pressure, p_{dh}, and temperature, T_{dh}, from measured temperature T_{wh}, pressure p_{wh}, NaCl-molality and flow rate at the wellhead. Most reliable results are obtained when initial pressure, temperature and density conditions in the borehole are known and a model calibration can be performed.

The injection or production characteristics of a borehole can be expressed by the injectivity index, II, or productivity index, PI. If properly measured - or properly corrected for borehole effects - the ratio between the flow rate and the pressure change at reservoir depth characterizes in a single well configuration the downhole transmissivity. These indices can only used as a linear relationship between flow rate and pressure response when the following conditions are given:

- no hydraulic boundaries
- steady-state flow regime reached
- Darcy flow
- single borehole test

In a fractured system additional nonlinear hydraulic behaviour can be due to turbulent effects and elastic behaviour of fracture apertures. At long-term additional processes like thermo-elasticity and chemical dissolution/precipitation contribute to a change in the injectivity and productivity of the wells.

In a multi-well test situation like at the circulation test 05JUL11 in Soultz none of the conditions given above are fulfilled. Therefore productivity and injectivity indices are only apparent and should be interpreted carefully. Nevertheless the development of these indices may characterizes the reservoir behaviour for a given combination of injection and production rates and can be useful to interpret test results and make them comparable. The time series of different flow rates provides an indication of the hydraulic interaction in the fractured rock matrix at larger distance from the borehole.

The injectivity and productivity indices have been calculated for the long-term circulation test 05JUL11. Some downhole data have been acquired during this test, which have been used for calibration. The general aim was the characterisation of the reservoir created at the end of Phase 2 in mid 2005. Specifically two tasks have been focused:

1. Determination of the values of PI or II for each borehole to characterize the near borehole transmissivity under the given flow regime
2. Characterisation of the hydraulic behaviour of the larger reservoir

DATA OF THE CIRCULATION TEST 05JUL11

The circulation test 05JUL11 was started in 2005 at July 11th and lasted 160 days. Flow was only produced by buoyancy in GPK2 and GPK4 and re-injected in GPK3. The wellhead data from GPK2, GPK3 and GPK4 measured during the circulation test have been prepared to use them as input values for the pT-profile simulator HEX-B. Especially the values for density have been transformed to NaCl-molality.

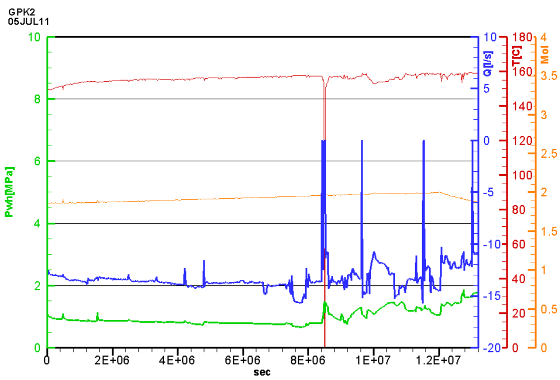

Fig. 1: Wellhead data GPK2, including the calculated NaCl-molality of the produced fluid

The produced flow from GPK2 was produced constantly at ~12 l/s at the beginning of the test increasing up to 14 l/s. Towards the end of the circulation test a decreasing tendency can be identified (Fig. 1). The measured temperature curve starts to oscillate after major interruptions of flow rate ($t > 8x10^6$sec). These oscillations also are present at the wellhead pressure data.

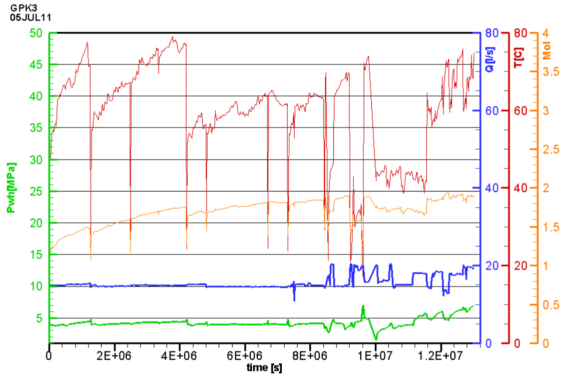

Fig. 2 Wellhead data GPK3, including the calculated NaCl-molality of the injected fluid

In GPK3 the produced fluid from GPK2 and GPK4 was re-injected at approximately 15 l/s (Fig. 2) during the first 90 days of the test. Afterwards temporarily increased injection rates have been applied. The reinjected fluid was cooled down to a range between 50 and ~70°C. Individual variations in reinjection temperature manifest as secondary peaks in the wellhead pressure data.

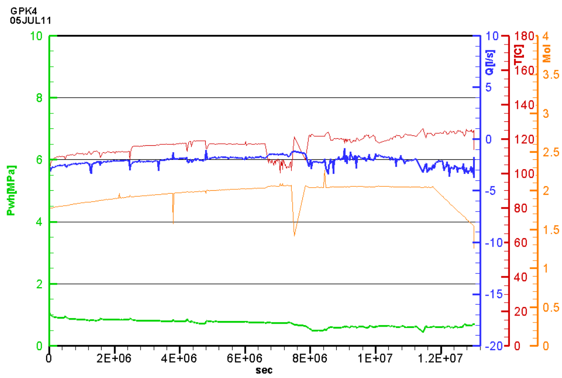

Fig. 3 Wellhead data GPK4, including the calculated NaCl-molality of the produced fluid

It is obvious from a comparison of the two production boreholes that GPK4 has a much lower productivity. Fig. 3 indicates that the produced flow was at roughly 2-3 l/s. The lower flow rate is also visible by much lower production temperatures: here, the rock mass has more time to cool down the temperature of the fluid column than in GPK2 (GPK4: ~115°C; GPK2: ~160°C).

HEX-B MODELS

For the calculation of the pT-profile in the borehole using the borehole simulator HEX-B (Mégel et al, 2005) the initial p, T, NaCl-molality conditions in the borehole, the geometry of the borehole and the rock mass properties have to be taken into account. It is assumed that the reservoir pressure is in equilibrium at the start of the circulation test. Therefore, at identical true vertical depth TVD the pressure in the open hole section of each borehole is assumed to have the same value. An initial pressure of 45.4 MPa at 4500 m TVD was identified to be most reliable in all three boreholes. The thermal borehole parameters have been calibrated with temperature values, available either as time series measured at the wellhead of the production wells GPK2 and GPK4 or as logging data measured at distinct depths in GPK3 and GPK4 about $5x10^6$ s after the circulation test has started.

Model GPK2

The thermal borehole model for GPK2 was calibrated only with the produced wellhead temperature. An initial temperature profile and a constant NaCl-molality of 1.9 in the borehole was assumed.

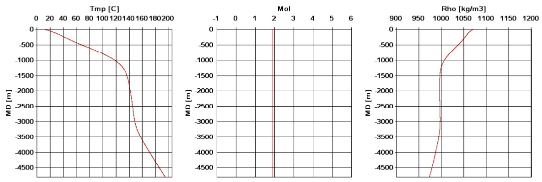

Fig. 4 Initial temperature, NaCl-molality and the corresponding fluid density in GPK2.

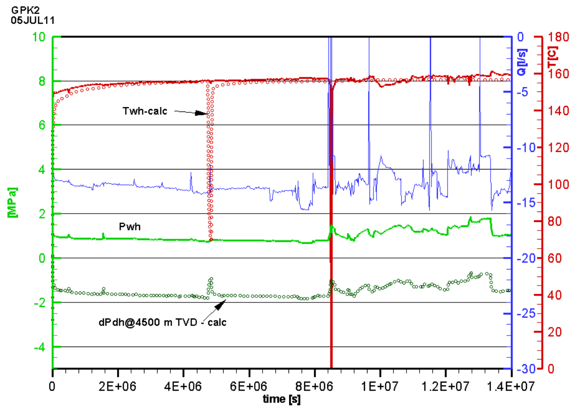

Fig. 5 Calculated production temperature (red circles) and pressure change at 4500 m TVD depth (green circles) in GPK2. Negative flow rate represents production.

As indicated in Fig. 5 the measured and the simulated T_{wh} curve coincide nicely throughout the test duration. The downhole pressure is approximately ~1.8 MPa below hydrostatic pressure level. It is roughly 2.5-3 MPa below the wellhead pressure.

Model GPK3

The borehole model for GPK3 was calibrated using logged temperatures about $5x10^6$ s after the test started. The unusual deviation of the temperature between 1700 m and 2200 m MD could only be fitted under the assumption of a zone with a very high heat exchange. At this depth a well-known fracture zone indicates a high possibility of advective thermal transport. This effect was accounted for applying a thermal conductivity of 15 W/m/K in this zone instead of the originally used homogeneous thermal rock model for GPK3.

Fig. 6 indicates the successful calibration procedure. The temperature model corresponds nearly perfectly to the measured values. The calculated downhole pressure difference at 4500 m TVD corresponds nearly to the measured wellhead pressure data at the start of the test. During the test the downhole pressure difference exceeds the wellhead pressure by about 1 MPa. This represents the effect of the increasing molality of the injected fluid and the cooling of the borehole. At larger flow rates this difference will tend to become even larger due to a more pronounced decrease of the fluid temperature.

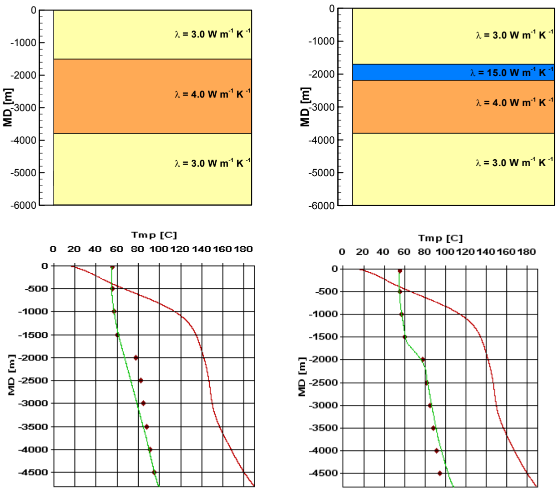

Fig. 6 Left: originally used rock model for GPK3, right: calibrated rock model for GPK3. Red dots indicate measured temperature values at distinct depths

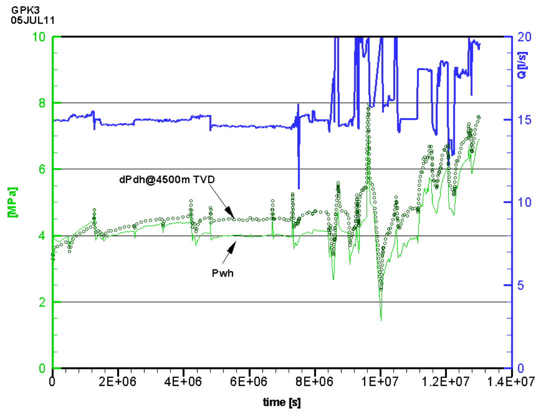

Fig. 7 Calculated pressure change at 4500 m TVD depth (green circles) in GPK3.

Model GPK4

The borehole model for GPK4 was calibrated using both, the produced wellhead temperature and the temperatures logged about $5x10^6$ s after the test started.

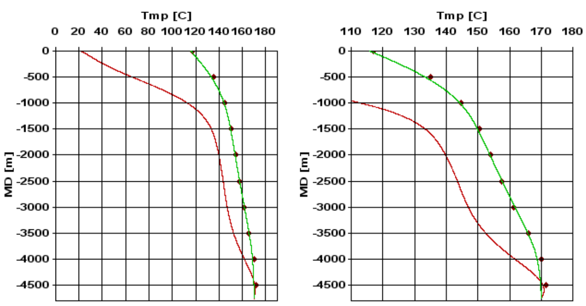

Fig. 8 Calibrated temperature in GPK4. Red dots indicate the measured temperature values at distinct depths, the red line indicate the initial temperature profile, the green line indicate the temperature profile 5 10^6 s after the test started.

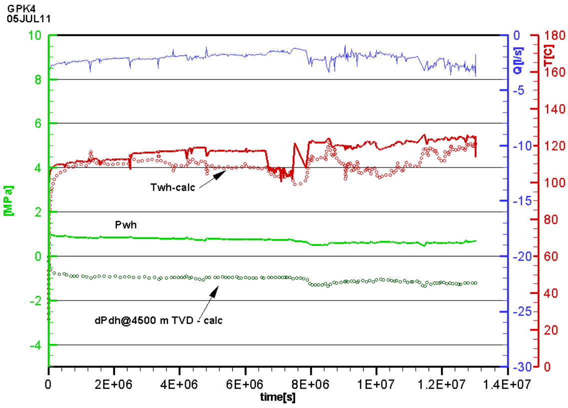

Fig. 9 Calculated production temperature (red circles) and pressure change at 4500 m TVD depth (green circles) in GPK4. The negative flow rate stands for production.

Generally, the measured T_{wh} curve was well matched by simulation. Except after the major interruptions a slightly increasing deviation is found. This may be due to non-linear effects such as non-constant downhole temperature. Throughout all simulations a constant value is assumed for all boreholes. The sensitivity of this parameter is estimated below.

Sensitivity of reservoir temperature to production temperature

The accuracy of the calculation of fluid temperature entering at reservoir depth into the well using the wellhead data is a critical task. The slower the fluid moves in the well the more dominates the heat exchange with the surrounding rock mass compared with the entrance temperature of the fluid into the well. Therefore the determination of the entrance temperature at reservoir depth is especially difficult at GPK4 (Fig. 10). With the significantly higher production rates at GPK2 more accurate conclusions to the entrance temperature of the fluid are possible with the wellhead data.

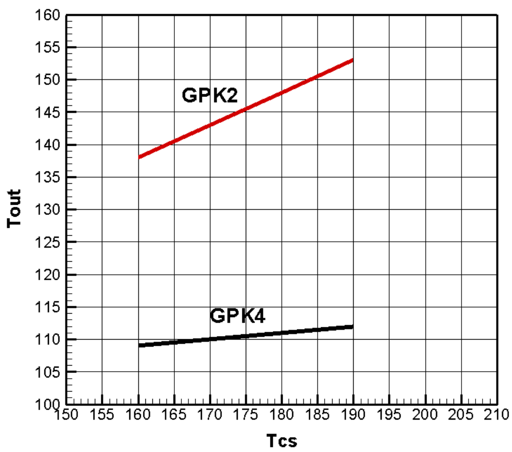

Fig. 10 Calculated production temperature as a function of the entrance temperature at reservoir depth (around 4500 m TVD) for GPK2 (calculated with 11 l/s) and GPK4 (calculated with 3 l/s).

CALCULATED PRESSURES AT 4500 M TVD

To make the downhole pressures in the boreholes comparable to each other, all values have been calculated for a depth of 4500 m TVD.

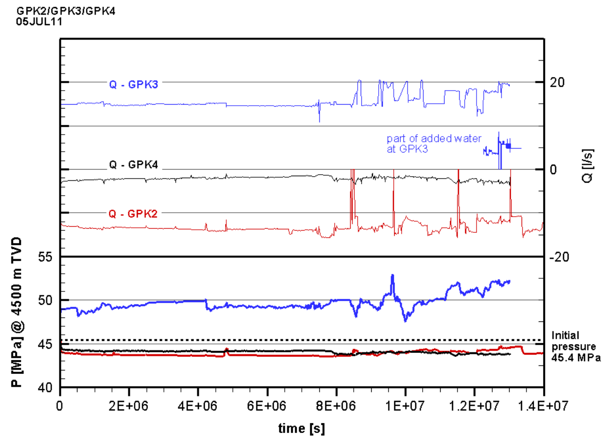

Fig. 11 Calculated pressure at 4500 m TVD depth (bottom) in GPK2, GPK3 and GPK4. Indicated also the flow rates (top); negative flow rate represents production.

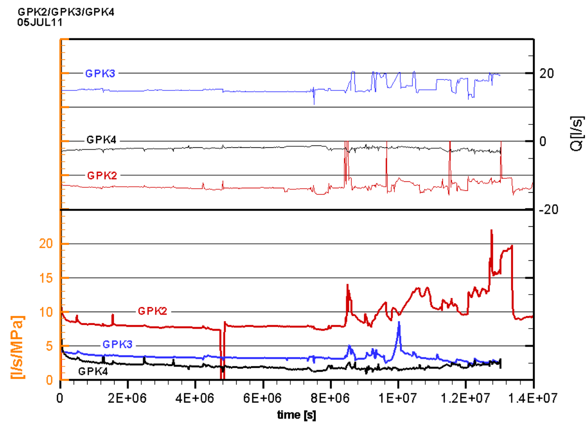

Fig. 12 Calculated apparent injectivity/productivity index (bottom) for GPK2, GPK3 and GPK4. Indicated also the flow rates (top); negative flow rate represents production.

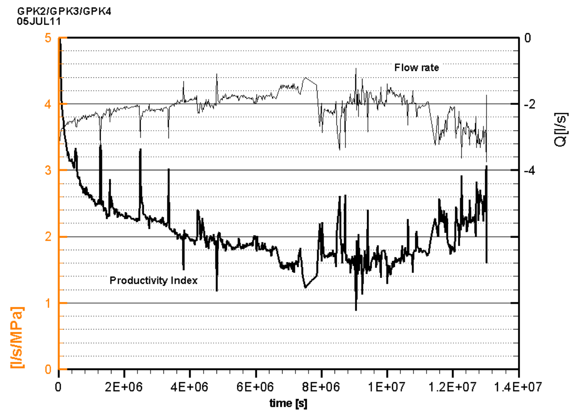

Fig. 13 Apparent productivity index and flow rate for GPK4. Negative flow rate represents production.

APPARENT AND "SINGLE-WELL" INJECTIVITY AND PRODUCTIVITY INDICES

The apparent Injectivity/Producivity Index, II_{app} and PI_{app}, is here defined as the ratio between the flow rate Q and the difference between the actual pressure $P_{4500TVD,eq}$ and the initial pressure $P_{4500TVD,0}$ at a given depth, here 4500 m TVD:

$$PI_{app} = II_{app} = \frac{Q}{P_{4500\,TVD,eq} - P_{4500\,TVD,0}} \quad \text{[l/s/MPa]}$$

The values are taken at a time when an equilibrium in pressure and flow is reached. In the case of the circulation test, the time t = $6x10^6$ s after the start of the test has been selected. The results show clearly that the difference in the apparent productivity/injectivity index between the boreholes is significant (Tab. 1).

Tab. 1 Apparent injectivity/productivity indices $6\ 10^6$ s after the circulation test started

	GPK2	GPK3	GPK4
PI_{app} /II_{app} [l/s/MPa]	7.5	3.2	2.1

An increase of the injection rate at GPK3 after about $8.5\ 10^6$ s resulted clearly in an increase of the apparent productivity index PI_{app} at GPK2 and GPK4 (Fig. 12). At GPK2 this increase is due to the increasing downhole pressure as a combined result of the slight reduction of flow rate and the pressure effect of the increased injection rate at GPK3 (Fig. 12). At GPK4 the increase of PI_{app} is the effect of the increased production rate not resulting in a linear change of the negative downhole overpressure (Fig. 13). At GPK3 the nonlinear behaviour of II_{app} due to the increase of injection rate is significantly smaller and only of temporary character since the downhole overpressure is very much higher than the negative overpressure values at GPK2 and GPK4 (Fig. 12).

It becomes clear that the apparent productivity and injectivity indices as defined above are parameters to be interpreted cautiously using multi-well test data.

The apparent indices PI_{app} and II_{app} use the initial pressure $P_{4500TVD,0}$ as base for the calculation of the overpressures. To obtain more a single-well parameter derived from the data of multi-well test 05JUL11 the initial pressure $P_{4500TVD,0}$ should be corrected at each borehole by the pressure influence $P_{4500TVD,i}$ of the other wells. This leads us to the following formulation of a "single-well" injectivity and productivity index [l/s/MPa] for the production and injection at a single-well system only:

$$PI_s = II_s = \frac{Q}{\left(P_{4500\,TVD,eq} - P_{4500\,TVD,0}\right) + \left(P_{4500\,TVD,0} - P_{4500\,TVD,i}\right)}$$

Using an estimate for $P_{4500TCD,i}$ during the circulation test 05JUL11 at Soultz, values for PI_s/II_s can be estimated which are generally lower than the apparent indices PI_{app} and II_{app} (Tab. 2).

Tab. 2 "Single-well" injectivity/productivity indices for single-well production/injection, calculated with the values $6\ 10^6$ s after the circulation test started

	GPK2	GPK3	GPK4
$P_{4500TVD,i}$ [MPa]	-1	+1	0
PI_s /II_s [l/s/MPa]	5	2.8	2.1

REMARKS

It must be clearly emphasised that all hereby presented definitions for the productivity and injectivity indices, especially the parameters PI_s and II_s, characterise only the production or injection into one borehole alone under the assumptions given in the introduction. The reservoir at Soultz is strongly inhomogeneous with respect to the permeability, fracture distribution and the hydraulic boundaries. All indices of PI and II provide therefore more hints about the hydraulic conductivity distribution in the reservoir than directly applicable values for the calculation of production capabilities. It must be considered that with the low flow rates used during the circulation test 05JUL11 only small pressure differences below 2 MPa have occurred. A minor variation of a sensitive parameter to pressure may change the index value significantly.

REFERENCES

Mégel T., Kohl T., Gérard A., Rybach L., Hopkirk R. (2005), Downhole Pressures Derived from Wellhead Measurements during Hydraulic Experiments, Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005