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Electricity Production from Hot Rocks

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ABSTRACT

The European geothermal research program for the extraction of energy from Hot Dry Rocks started at Soultz-sous-Forêts in 1987. The test site is located in France on the western edge of the Rhine Graben, about 50 km north of Strasbourg near the German border. The granite basement at Soultz lies below app. 1400 m of sedimentary cover; the fracture network in the granite has been explored down to 5000 m depth, where temperatures exceed 200°C. The planned scientific pilot plant will use a total of three 5 km deep boreholes, two for production and one for re-injection.

The drilling of the 2nd production well GPK4 was finalized on 11th of April 2004. The directional well GPK4 reached a length of 5260 m and a vertical depth of 4982 m, the casing shoe is located at 4756 m measured depth. GPK4 was kicked off at 2100 m depth and the openhole section is separated by 1150 m south from the wellhead. UBI, GPIT, EMC, HNGS logs were performed in the openhole section to characterize the deep fractures in the granite.

After the deepening of the 1st production well GPK2 in 1999, the stimulation of GPK2 in 2000, the drilling of the central injection well GPK3 in 2002, the stimulation of GPK3 in 2003 and the drilling of the 2nd production well GPK4 in spring 2004 the underground work of the scientific HDR pilot plant will be finalized with the stimulation of GPK4 and a re-stimulation of GPK3 in autumn 2004. It is expected that by end of 2007 for the first time a HDR pilot plant will be able to produce around 50 MW of thermal power at temperatures above 180°C. Up to 6 MW of electricity can be produced from this heat where the net output of the power plant is expected to be in the order of 4.5 MWe.

1. INTRODUCTION

The HDR/EGS test site is located in Soultz-sous-Forêts (France) on the western edge of the Rhine Graben, some 50 km north of Strasbourg near the German border (Figure 1). The length of the Rhine Graben is about 300 km (NNE/SSW) and its average width is 40 km (E/W) limited by large-scale normal faults. In the Rhine Graben, the post Paleozoic sediments of the western European platform cover the Hercynian basement which consists of granite, gneiss and other related basement rocks. In Soultz the basement, granite, lies beneath ca. 1400 m of sedimentary rock. A number of thermal springs are located on the Rhine Graben borders in connection with the large-scale faults. Soultz is located in the heart of an intensive oil exploitation area at the beginning of the last century. The oil wells were drilled down to app. 1000 m depth. At the end of the 1960's the oil exploitation around Soultz was shut down.

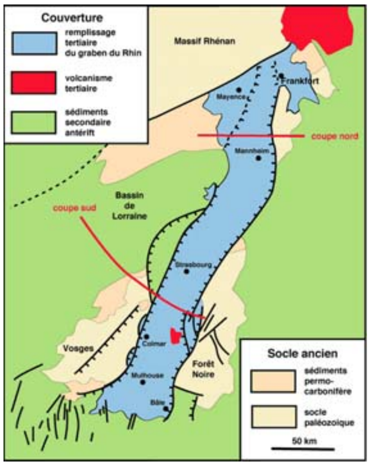

Figure 1: Geological map of the Rhine Graben (Brunet, 1998).

Since the beginning of the 90's international teams of scientists working in Soultz made a great progress on development of the HDR Technology. A first successful forced circulation test of several months duration has been performed in 1997 in the depth range of 3000 m to 3500 m. This test demonstrated the validity of the "Hot Fractured Rock" concept. It was possible to circulate continuously about 25 l/s of water, at more than 140°C, between two boreholes 450 m apart without any water losses and requiring only 250 kWe pumping power compared with a thermal output of more than 10 MW. It could be shown that such a loop can be managed virtually automatically, reliable and without any noticeable environmental impact.

Following this experience, an industrial consortium, an European Economic Interest Grouping called "GEIE Exploitation Minière de la Chaleur" ("Heat Mining"), was created combining five partners from the energy world, Electricité de France, Electricité de Strasbourg S.A. (French), ENEL S.p.A. (Italian), Pfalzwerke AG and BESTEC GmbH (German). This grouping acquired the site facilities and took over the management of the Soultz project since 2001. Since then BESTEC acts as the on site manager and operator of the EEIG "Heat Mining". Shell Int. Exploration and Production B.V. and SHELL Geothermal B.V. are associated and contributing to the project as special industrial partners. The aim of this consortium is to develop the HDR Technology to a stage at which the sub-surface heat can be used for commercial electricity production.

Under the leadership of the "GEIE Exploitation Minière de la Chaleur", since mid 2001 a scientific pilot plant is being established in Soultz. A new deeper reservoir at 5000 km depth was exploited to gain higher production temperatures and therefore a better efficiency for the power plant. The temperatures in the 5000 m deep fractured granite exceed 200°C. The scientific pilot plant will use a total of three boreholes of 5000 meters depth each, one injection and two production wells. All three wells are drilled from the same platform. The wellheads are separated by not more than 6 m. At depth, the wells are pulled apart using directional drilling. Between 4500 m to 5000 m depth, the open-hole section of the boreholes has a horizontal spacing of around 600 m. The three-borehole module (triplet) as realized in Soultz is considered to be the optimum base for a commercially viable energy generation from HFR systems. This configuration has never been field tested, but it is expected that compared to the traditional 2-well system the triplet potentially could help to multiply production by a factor of 3 or even more.

2. STRESS AND TEMPERATURE REGIME IN SOULTZ-SOUS-FORÊTS

The stress regime at Soultz was obtained by using a hydraulic fracturing test carried out in the wells GPK1 and EPS1 between 1458 m to 3506 m depth (Klee and Rummel, 1993). The maximum horizontal stress S_H is oriented N-S to NNW-SSE at Soultz and is in agreement with the data for Central Europe (Müller et al., 1992). The stress regime showed considerable low horizontal stresses, typical for the Graben tectonic and implies a cross over from a normal faulting ($S_h < S_H < S_V$) to a strike slip regime ($S_h < S_V < S_H$) in 3000 m to 4000 m depth. The stresses in Soultz are given by:

$$S_h\text{, MPa} = 15.7 + 0.0149 \cdot (z\text{, m} - 1458\text{ m})$$

$$S_H\text{, MPa} = 23.5 + 0.0337 \cdot (z\text{, m} - 1458\text{ m})$$

$$S_V\text{, MPa} = 33.1 + 0.0261 \cdot (z\text{, m} - 1377\text{ m})$$

where S_V is the vertical stress, S_H the maximum horizontal stress, S_h the minimum horizontal stress and z the depth.

The background heat flow density of the Rhine Graben is 80 mW/m² and the heat flow density exceeds 140 mW/m². Meteoric water is circulating in the Graben flanks; water penetrates the granitic basement in the East, driven by the topography of the black forest. Convective loops are developed within the faults in the Buntsandstone and the granite within the central part of the Graben. Water is forced to flow beneath the deepest part of the Graben filling and rises from great depth at Soultz to create the observed heat flow density (Pribnow and Clauser, 2002).

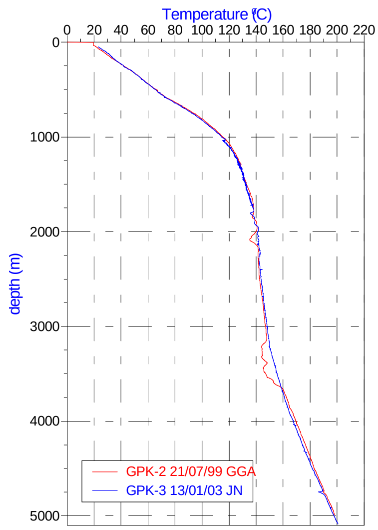

Figure 2: Temperature log in GPK2 (red), temperature log in GPK3 (blue).

The temperatures measured in the 5 km deep wells GPK2 and GPK3 in Soultz are shown in Figure 2. After the high temperature gradient within the first kilometer the temperature reaches app. 140°C between 2 km and 3 km depth and can be explained by the rising water. A normal temperature gradient of 30°/km is observed deeper than 3.8 km and 202°C are reached at 5 km depth where fluid movement is still observed. From the chemical analysis of the production tests performed in GPK2 between 2000 and 2002 an internal flow rate of the deep fluid at 5 km depth of 1 to 1.2 m³/h was determined (Sanjuan et al., 2004).

3. DRILLING AND STIMULATION OF GPK2 AND GPK3

In 1999 the well GPK2 was deepened from 3881 m to 5085 m. The open hole section of GPK2 from 4430 m to 5085 m was drilled in 8 ½”. The fluid can be injected or produced from a 7” x 9 5/8” floating casing. The trajectory of GPK2 shows a dogleg at the former bottom-hole, where the inclination shows an increase from 1° to 8° between 3870 and 3910 m and increases up to 26° in 4450 m depth. The inclination in the new bottom-hole is still 16°. The caliper log shows diameters larger than 1 m in app. 3900 m depth over a 20 m section. This ‘cave’ was the origin of the dogleg, because the used bottom-hole assemblies had no wall contact and could not guide the drill bit.

In 2000 the stimulation of the deepened well GPK2 was performed, a total volume of 23,400 m³ was injected into the openhole section of GPK2 in three steps: 31 l/s, 41 l/s and 51 l/s (Weidler et al., 2002). During the stimulation of GPK2 40,000 micro-seismic events were recorded and 14,000 of these events were located. The injectivity of the well was improved from 0.02 l/s/bar to app. 0.3 l/s/bar.

According to the orientation of the stress regime and on the base of the micro-seismic locations from the stimulation of GPK2 the trajectory of a second 5 km deep well GPK3 was defined (Figure 3). The well GPK3 will be used as the central injection well in the future scientific power plant.

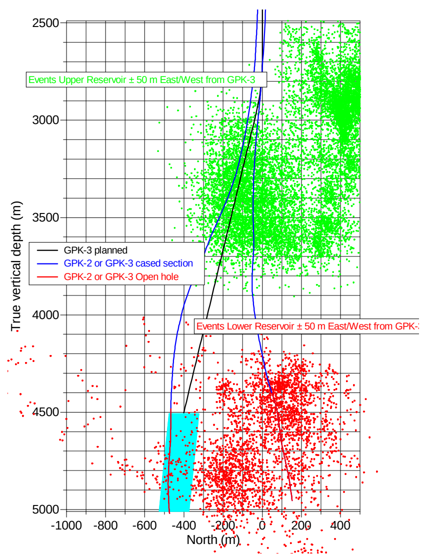

Figure 3: Vertical view of the wells GPK2 and GPK3, the cased sections are shown in blue, the open hole in red and the planned trajectory of GPK3 in black. The red dots show the micro-seismic events recorded during the stimulation of GPK2 and the green dots show micro-seismic events from earlier stimulations in the upper reservoir (50m E/W of GPK3).

In 2002, 6 m away from the wellhead of GPK2, GPK3 was drilled vertically down to app. 2700 m and then deviated southwards using a downhole motor to kick off, the angle was then maintained by rotary drilling and dropped with a pendulum assembly inside the target. The target volume of GPK3 was defined as an inclined cylinder with a diameter of 150 m and the realized well trajectory of GPK3 lies at the edge but within the already stimulated area around GPK2.

During the drilling of GPK3 total losses were observed at app. 4757 m and close to the bottom-hole at 5091 m. The performed UBI log showed a large fracture zone between 4757 m to 4761 m (Figure 4).

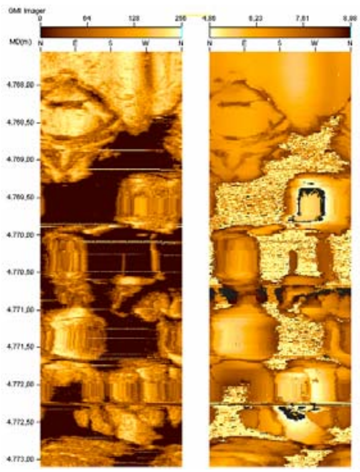

Figure 4: UBI between 4756 m and 4761 m (drillers' depth = logging depth – 12 m).

The productivity of the well GPK3 was 0.3 l/s/bar before the stimulation and shows the same value as the well GPK2 after it was stimulated. The flow distribution during the testing was dominated by the feature shown in the UBI (Figure 4); nearly 90 % of the production flow was reaching the well GPK3 in this depth.

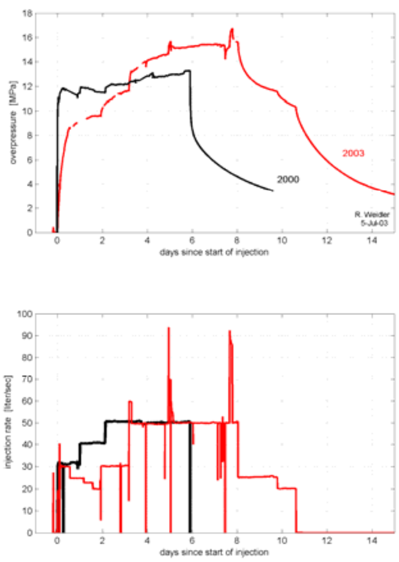

Figure 5: Injection rates and overpressures measured downhole during the stimulations of GPK2 (black) and GPK3 (red) (courtesy R. Weidler).

During the stimulation of GPK3 a total fluid volume of 34,000 m³ was injected into GPK3 at flow rates up to 95 l/s. During a dual injection phase, where fluid is injected simultaneously into both wells to improve the permeability especially in the area between the wells, 3,400 m³ of fresh water were injected additionally into GPK2. During this phase the micro-seismic locations filled the space between the two wells (Baria et al., 2004).

The overpressures needed for the stimulations in 2000 and 2003 are shown in Figure 5. Based on the prognosis derived from the stimulations in the upper reservoir and the extrapolation of the stress regime a maximum overpressure of 20 MPa was expected (Hettkamp et al., 2002). The overpressures reached only values about 13 MPa in 2000 and 17 MPa in 2003, indicating lower horizontal stresses. To verify the extrapolation of the stress field additional stress measurements in 5 km depth will be required.

The total number of micro-seismic events recorded exceeded 90,000, where 9,000 were located automatically. According to micro-seismicity the downhole heat exchanger was extended over a horizontal distance of more than 2.5 km. The total seismically activated rock volume was in the order of 2.5 km³ (Figure 6).

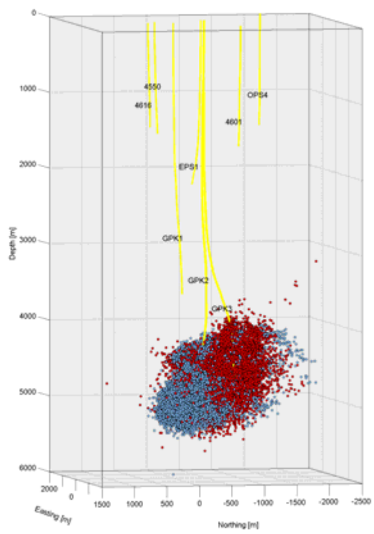

Figure 6: The deep underground at the HDR location in Soultz-sous-Forêts. The trajectories of the six seismic observation wells, 4616, 4550, 4601, EPS1, OPS4 and GPK1, the 5 km deep production well GPK2 and the injection well GPK3 are shown in yellow. Locations of the micro-seismic events occurred during the stimulation of GPK2 in 2000 are shown as blue dots and the locations of the micro-seismic events occurred during the stimulation of GPK3 in 2003 are shown as red dots.

Following this stimulation experiment, a short successful circulation test was performed between the wells GPK2 and GPK3 at a circulation rate of app. 15 l/s, using the buoyancy effect only to drive the production from GPK2 (Figure 7). At the wellhead of GPK2 a temperature of 153°C was reached after 12 days. The wellhead temperature appeared to be extremely flow rate depended. The expected final production temperature of more than 180°C will only be achieved at flow rates of 40 l/s to 50 l/s using a submersible pump and within a much longer production time.

The production from GPK2 showed a clear flow response to the injection in GPK3. Increasing the injection flow rate into GPK3 by 8 l/s resulted within 1 day in an increase of app. 1 l/s in the production flow from GPK2. The tracer test using NaNO3 showed that 7.25 days were needed for the injected fluid to flow from GPK3 to GPK2 through the new created reservoir (Sanjuan et al., 2004). This result is comparable to the breakthrough time determined for the upper reservoir during the circulation between GPK1 and GPK2 in 1997.

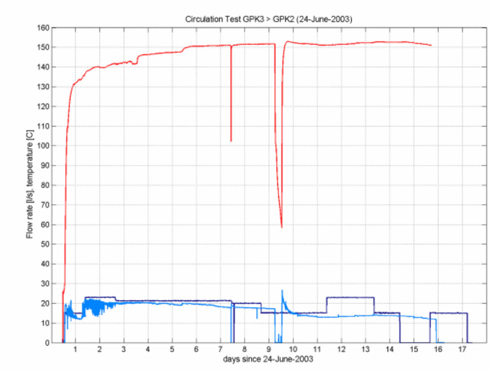

Figure 7: Production temperature (red), injection flow into GPK3 (dark blue) and production flow (light blue) during the circulation test between GPK2 and GPK3 in 2003.

During the circulation test, GPK2 showed a productivity (the suction pressure divided by the produced flow rate) in the order of app. 1 l/s/bar, which is the target productivity for the future power plant. Nevertheless, it might be that during the circulation test parts of the reservoir may have been still over-pressurized from the earlier stimulation. Therefore, injectivity values are probably underestimated while productivity values are overestimated.

4. DRILLING OF GPK4

According to the orientation of the stress regime and on the base of the micro-seismic locations from the stimulation of GPK2 in 2000 and the stimulation of GPK3 in 2003 the trajectory of the 3rd 5 km deep well GPK4 was defined. The well GPK4 will be used as the second production well in the future scientific power plant. GPK4 was drilled vertically down to 2100 m depth and then deviated southwards (azimuth 172°) using a downhole motor to kick off. The inclination was maintained afterwards by rotary drilling. The trajectory of GPK4 was continuously measured using a Measuring While Drilling tool. MWD-tool failures became rather frequent below a depth of app. 3300 m. These failures occurred mainly due to drillstring vibrations in the granite. Because of these technical problems and the time required for the subsequent trips to change the MWD-tool, the progress in depth was slower than expected. Because of the continuing problems the drilling was continued without the MWD and the well trajectory had to be measured with a multi-shot tool that was run on a wireline. Before each multi-shot measurement the well needed to be circulated clean for at least 3 hours and another 2 to 3 hours were required to run the multi-shot log. 15 multi-shot logs were performed in the 12 1/4” section. Additionally four gyro measurements were run to cross-check the results of the multi-shot and to verify the well azimuth.

Between 4707 m to 4726 m losses of up to 10 to 15 m³/h and high penetration rates at nearly no weight on the bit were observed. Within two bit runs with a long pendulum assembly (4727 m to 4910 m MD) the well trajectory was dropped to 14.3° inclination at 4893 m depth, but a strong rotation to the East was observed (142.6° azimuth at 4893 m depth). Four multi-shot surveys were performed to measure the well trajectory within the 8 ½” section. The well trajectory needed to be corrected with a downhole motor, although it was very difficult to slide and the hot MWD failed again while rotating (because of the inability to slide). In two motor runs performed between 4910 m and 4972 m the azimuth of the well rotated from 142° to 168.5° at 12.4° inclination at a depth of 4957 m. Following the motor runs a long pendulum assembly was used again to drop the inclination. On 28th of February 2004, at the end of the 31st bit run another multi-shot log was performed.

After the log the bottom-hole assembly appeared to be packed off and it was not possible to pick up the drillstring or to circulate. Two sets of holes were shot into the drill collars, one set between the reamers and one above the reamers. After the second set of shots it was possible to circulate again and to work the drill string loose. Before drilling ahead the 9 5/8” casing was set, cemented with HOZ-cement and anchored with two high temperature CuNi-packers. The casing shoe of the floating 9 5/8” casing is located at 4756 m measured depth (4489 m true vertical depth). GPK4 was finalized by drilling through the floating casing with a stiff assembly in 8 ½”. The well GPK4 reached a length of 5260 m and a vertical depth of 4982 m on 11th of April 2004 after 36 bit runs and 226 days of operations (Figure 8).

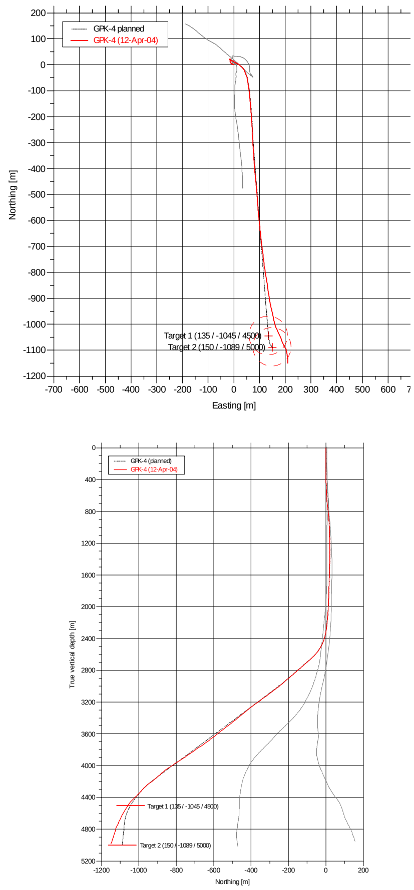

Figure 8: Plan and vertical view of the planned (black dashed), the realized (red) well trajectory of GPK4 and the well trajectories of GPK2 and GPK3 (grey).

UBI, GPIT, EMC, HNGS logs were performed successfully in the open-hole section. GPK4 was kicked off at 2100 m depth, the open-hole section is separated app. 1150 m south from the wellhead and app. 420 m of the 504 m open hole section are within the target volume.

5. CONCLUSIONS AND FUTURE PLANNING

The development of the pilot plant is divided into two stages.

The first stage (2001 – 2004) consists of accessing the resource by drilling three wells into the hot granite at depths of around 5000 m and the creation of a heat exchanger by injection of fluid under high pressure. At the end of the Soultz research project phase run by Socomine S.A. (a subsidiary of BRGM) in spring 2001, the Soultz project owned one deep well to 5000 m (GPK2), which had been successfully stimulated in the depth range between 4500 m and 5000 m in the year 2000 (end of exploration of the deep reservoir). Drilling of the 5000 m deep center injection well GPK3 was successfully completed in November 2002. The link between the two wells GPK2 and GPK3 was established by the stimulation in summer 2003. A first successful two weeks circulation experiment between these two wells was performed in July 2003 and demonstrated the satisfying communication between the wells. Drilling of the last deep well, the production well GPK4, started end of August 2003 and was successfully completed in April 2004. With the stimulation of GPK4 in autumn 2004 the underground work of the power plant construction will be finalized.

The second stage (2005 – 2007) concentrates on the characterization of the long-term behavior of the underground heat exchanger and on the installation of a power plant on surface. Both production wells GPK2 and GPK4 are supposed to produce app. 40 kg/s to 50 kg/s of fluid each at app. 180°C, while the total of 80 kg/s to 100 kg/s will be re-injected at app. 40°C into GPK3 (Figure 9). The power plant will be constructed in two steps. A small scale power production of 1.5 MWe combined with a long-term circulation followed by the expansion of the power production to 5 – 6 MWe.

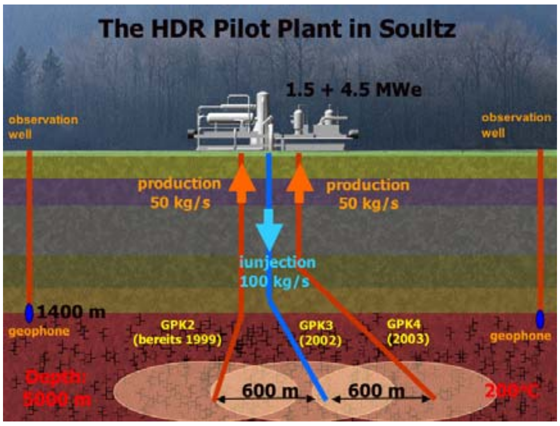

Figure 9: Schematic of the scientific "Hot Dry Rock" pilot plant at Soultz.

It can be stated that the Soultz project as a European, multi-national project appears to be on the path towards the successful completion of the first deep, man-made underground heat exchanger in the Rhine-Graben. Today, it is the most advanced project of its kind in the world.

6. FUNDING

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