PROCEEDINGS, Thirty-Fourth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 9-11, 2009
SGP-TR-187

OVERVIEW OF THE CURRENT ACTIVITIES OF THE EUROPEAN EGS SOULTZ PROJECT: FROM EXPLORATION TO ELECTRICITY PRODUCTION

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ABSTRACT

This paper reports a multinational approach to develop an Enhanced Geothermal System reservoir (EGS) in Europe. The pilot site is located at the French-German border in Soultz-sous-Forêts, France. Over two decades research and development have been carried out with French, German and Swiss governmental and European funding. The on-going Soultz project is now very close to the end of the pilot plant phase (2009). Then, a geothermal power plant constructing phase started in 2007 with the building of an ORC (Organic Rankine Cycle) plant having a net power capacity of 1,5MWe. Surface equipments (turbine, air cooling system, heat exchanger) as well as two different types of down-hole pumps were installed respectively on surface and in the production wells. Finally, we present the main milestones about the EGS reservoir and the on-going activities about this experimental power plant.

INTRODUCTION

The Soultz EGS project has been running for more than 20 years by taking into account the deep-seated geology including fluid geochemistry, the temperature field and the hydraulic properties of the deep crystalline basement penetrated by several deep exploration and geothermal wells. Initiated by a French-German team (Gérard et Kappelmeyer, 1987), it has been a European project with a significant Swiss contribution mainly supported by public funding between 1987 and 1995 and co-funded by industry from 1996 to 2009. After an early phase of exploration by drilling at shallow depth (2 km), the Soultz project obtained convincing results between 1991 and 1997. A 4 month circulation test was successfully achieved between 2 wells in the upper fractured granite reservoir at 3.5 km. Based on these encouraging results, 3 deviated wells were drilled down to 5 km depth between 1999 and 2004 for reaching down-hole temperatures of 200°C. Geothermal water is pumped from the production wells (GPK2, GPK4) and re-injected at lower temperature into the injection well GPK3 (Figure 1).

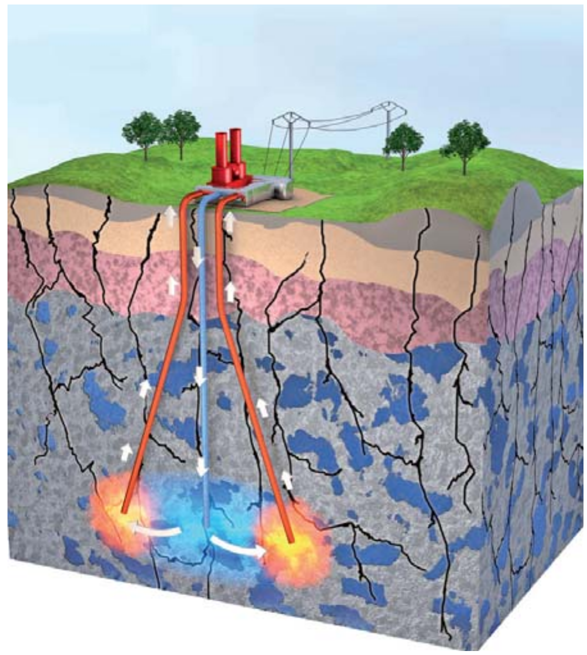


Figure 1: The Soultz geothermal triplet. Geothermal fluid is pumped by down-hole pumps from 2 lateral production wells (in red), delivering the geothermal energy to a binary power plant on surface. Cooled water is re-injected in the fractured granite by a central injection well (in blue).

On a horizontal view, the 3 deep deviated wells are roughly aligned with the N170°E orientation which is the main orientation of both the main fracture network and present-day principal maximal horizontal stress (Figure 2). The geothermal wells were hydraulically and chemically stimulated between 2000 and 2007 in order to enhance the low initial permeability of the lower reservoir. A 5 month circulation test was carried out in 2005 between the well triplet showing similar results than in 1997 in terms of hydraulics. In both cases, about 30% fluid mass recovery was obtained at the production wells highlighting the open nature of the reservoir (Gérard et al., 2006). However, the limited recovered mass was continuously compensated by native brine supply that insures the in situ observed global fluid balance and indicates direct connections with a deep geothermal reservoir (Sanjuan et al., 2006).

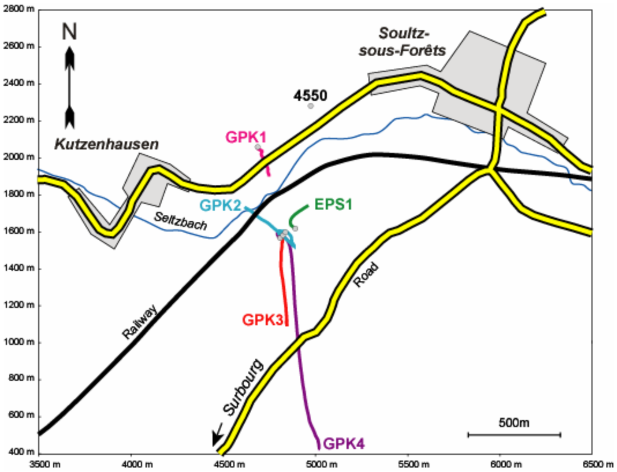


Figure 2. Local map view of the Soultz site between Kutzenhausen and Soultz. 4550 is a seismic well. GPK1 and EPS1 are former exploration wells.

On surface, the 3 wells are drilled from the same geothermal platform. The horizontal distance between the wells is 6 m long only whereas at the bottom hole, the distance between each production well and the re-injection well is about 700 m length (Figure 2). GPK1 is an old geothermal well that could be used for re-injection well if needed. All the wells are cased between surface and about 4.5 km depth offering an open-hole section of about 500 m length in each geothermal well (Figure 3).

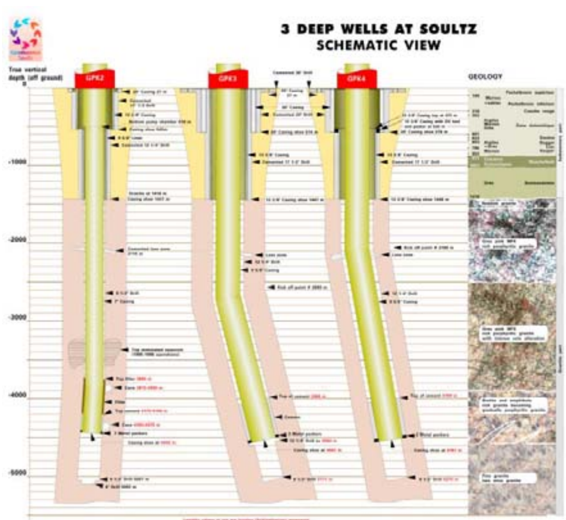


Figure 3. Schematic completion of the 3 deep geothermal wells at Soultz and corresponding geological units.

Between 2007 and 2008, a geothermal power plant has been built and is currently in its testing phase and commissioning. Therefore, this paper summarizes the main scientific achievements about the Soultz reservoir and presents the first results, issues and challenges about this new geothermal power plant.

MAIN SCIENTIFIC RESULTS DURING EXPLORATION AND RESERVOIR DEVELOPMENT

Introduction

A lot of high quality datasets data have been collected, interpreted and numerically modeled by various teams in Europe (Baumgaertner et al, 1998, Baria et al., 1999, Gérard et al., 2006) in order to understand the hydro-thermo-mechanical and geochemical behavior of a deep crystalline basement dedicated to various hydraulic experiments (injection, production, hydraulic stimulation, chemical stimulation, inter-well circulation). Exploration and reconnaissance of the crystalline rocks were mainly based on drilling data (cuttings, cores, well logging, borehole image logs, vertical seismic profiling, geochemical fluid monitoring, temperature, hydraulics, stress field, induced seismicity, ...) collected from the top basement (1.4 to 2 km), into the upper reservoir (3.5 km) and into the lower reservoir (5 km).

Geology and Fluid Geochemistry

During the exploration phase and the creation of the upper reservoir (<3.5 km depth), the reconnaissance by vertical drilling showed that the geothermal target was reached at about 1.4 km depth and corresponds to Paleozoic granites highly fractured from micro-cracks to fault scales (Figure 4). In terms of petrography, two different granite units were encountered: a grey porphyritic monzo-granite and a grey fine grained two-mica granite. Some altered cataclastic shear zones showed a low natural permeability characterized by the occurrence of brines and were defined as Hydrothermally Fractured and Altered Zones (HAFZ) indicating both high fracture density and strong hydrothermal alteration (Genter et Traineau, 1992). Due to the natural fluid circulations within fractures, there are both a strong dissolution of the primary minerals (biotite, plagioclase) and a significant deposition of some altered minerals such as clay minerals (illite, tosudite), calcite, secondary quartz and sulfides.
The geochemical composition of the deep native geothermal fluids was obtained from deep wells and provided some relevant information on the nature, origin, circulation and deep temperature of these fluids (Pauwels et al., 1993; Aquilina et al., 1997; Sanjuan et al., 2009). Geothermal fluids indicate similar chemical and isotopic compositions (NaCl

brine with a pH value close to 5), and a high salinity with 100 g/l. Geothermometer studies suggest that the native geothermal brine and associated gases (predominant CO_2) are equilibrated with a mineralogical assemblage at temperatures close to 220-240°C. From a tracer test carried out between 2000 and 2002 in GPK2, the natural flow of the native geothermal brine was estimated at about 1 m^3/h (Sanjuan et al., 2006).

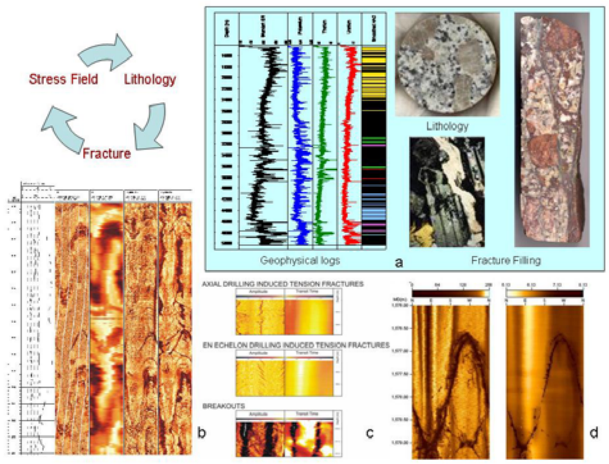


Figure 4. Main geological investigations carried out from well data at Soultz: lithology and hydrothermal alteration from spectral gamma ray and core studies (a), fracture geometry and in-situ stress field conditions (b, c, d).

Hydraulics and Microseismicity

Hydraulic tests conducted on HAFZs have shown natural transmissibilities from zero to 10^{-11} m^3. In the granite rock mass, the transmissibility is 10^{-16} to 10^{-17} m^3 (Evans et al., 2008). The highest permeable zone corresponds to a major HAFZ observed at about 2120 m depth in GPK2 well which induced total mud losses during drilling operations. Its natural transmissibility was estimated to about 1.1 10^{-11} m^3.

The three deep wells were first subjected to hydraulic stimulations, which resulted in an improvement of the productivity index of GPK2 and GPK4 ~20 times more than initially and of GPK3 ~1.5 times (Nami et al., 2008). Natural productivities or injectivities cover a wide range of values between 0.02 and 0.20 $L.s^{-1}.bar^{-1}$. Lowest values characterize production wells, GPK2 and GPK4, whereas the highest natural value was measured in the injection well GPK3. The impact of the hydraulic stimulation in GPK2 is significant although its initial natural productivity is low. The chemical post treatment represents a relative increasing of 20% only (Table 1). The impact of the hydraulic stimulation in GPK4 is moderate although its initial productivity is very low. The chemical post treatment represents a relative increasing of 60% (Nami et al., 2008).

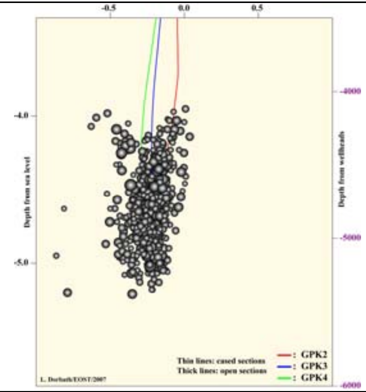
Well	Initial productivity/ injectivity values	After hydraulic stimulation	After chemical stimulation
GPK2	4%	76%	20%
GPK3	53%	32%	15%
GPK4	2%	38%	60%

Table 1. Relative normalized productivity/injectivity percentage values for the 3 deep Soultz wells from Nami et al. (2008).

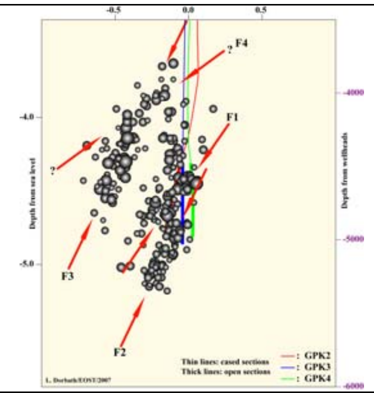
Hydraulic stimulations generated micro-seismic activity which was interpreted recently in terms of major structures in order to try to link event location with fault organization (Dorbath et al., 2009). The stimulation of GPK2 in 2000 induced more than 700 seismic events with a magnitude greater than 1.0 which were recorded by the surface seismic network (Figure 5). The seismicity describes a dense, homogeneous cloud, without any apparent large-scale fault. The injectivity has been increased by a factor 20. The stimulation of GPK3 induced only about 250 events with a magnitude greater than 1.0 but with a greater proportion of large events, up to 2.9. This 2.9 magnitude event was the largest event ever recorded at Soultz. It occurred during a shut in period and was felt by the local population. The hypocenters form clear structures identified as large faults. The injectivity of the GPK3 well, which was already high before the stimulation, remained nearly unchanged. The stimulation of GPK4 produced only 128 events having a magnitude higher than 1. The high clustering of the events suggests that the seismicity occurred principally on a single fault zone striking approximately NS and highly dipping to the west (Figure 5).

Fracture Zone Organization at Depth

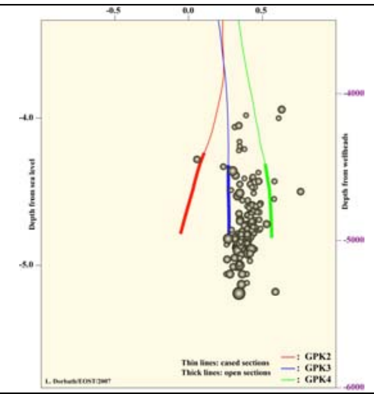
The major fracture zones encountered around the Soultz wells were interpreted based on borehole image logs, microseismic structures and Vertical Seismic Profiling (VSP) structures (Dezayes et al., 2009; Dorbath et al., 2009; Place et al., 2007). They were interpreted and presented in a 3D model using the gOcad software platform (Sausse et al., 2009). A large-scale fault, plotted in red in Figure 6, crosses GPK3 at 4770 m MD (Measured Depth). This fault supported 70% of the flow and was clearly visible on the borehole acoustic image logs. Moreover, it concentrates the microseismic activity and a simple extrapolation of this fault intersects GPK2 at about 3900 m MD. At that depth, a casing restriction is known and a casing leak is suspected (Nami et al., 2008). This feature corresponds to a huge cave interpreted as a HAFZ detected during drilling operation. This fault was also extended towards GPK1 well at around 3.5 km depth. At that depth, a permeable fracture zone is also well-known from drilling operation. However, due to its high dipping value, this large-scale fault does not intersect GPK4 (Figure 5). The fault plane is located around 90 m below the bottom of the hole.



The 2000 stimulation of GPK2



The 2003 stimulation of GPK3



The 2004 and 2005 stimulations of GPK4

Figure 5. Hydraulic stimulations in the Soultz wells. Seismic clouds of (M>1) events are plotted on nearly N-S cross-sections from Dorbath et al., 2009.

The geometry of this large-scale fault is consistent with the hydraulic results obtained during the circulation test done in 2005 (Gérard et al., 2006, Cuenot et al., 2006; Sanjuan et al., 2006). From tracer data and flow rate data, we observed that the connection between GPK3 and GPK2 was relatively good (direct link) whereas that between GPK3 and GPK4 was quite tight (no direct link). This large-scale fault geometry is therefore a good candidate for explaining the circulation test results.

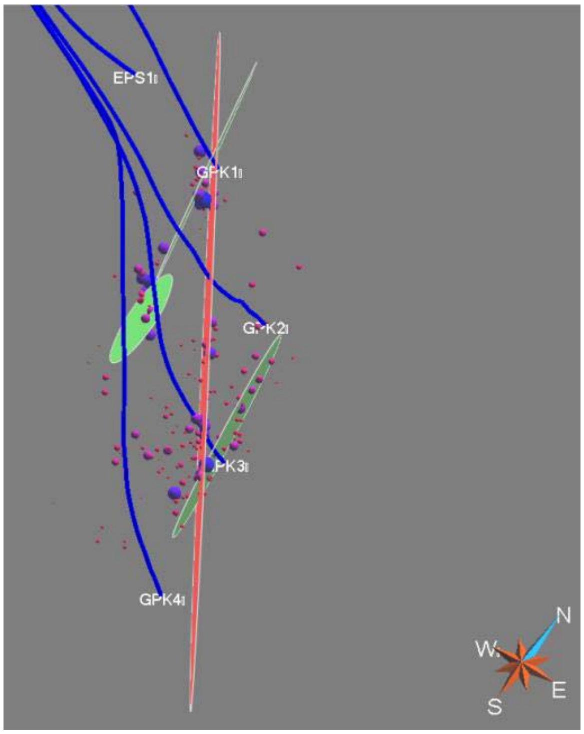


Figure 6. Examples of major 3D planar structures derived from borehole data (red) and microseismicity (green). Well trajectories are plotted in blue from Sausse et al., 2009.

THE SOULTZ POWER PLANT

Introduction

According to the hydraulic results of the circulation test done in 2005, and the improvement of the hydraulic performances of the three existing deep wells, it was decided to build a geothermal power plant. The chosen heat-power conversion scheme is the Organic Rankine Cycle (ORC). Thus, a first 1.5 MWe ORC unit was designed and ordered to a European consortium made of Cryostar, France and Turboden, Italy (Figure 7). The different components of the power plant have been installed and power production of the first geothermal KWh was achieved on June 2008. However, to reach a significant fluid production, it is necessary to install down-hole production pumps, because the artesian production is not sufficient. Thus, two types of production pumps were deployed and tested in the wells: a Line Shaft Pump (LSP) and a Electro-Submersible Pump (ESP).

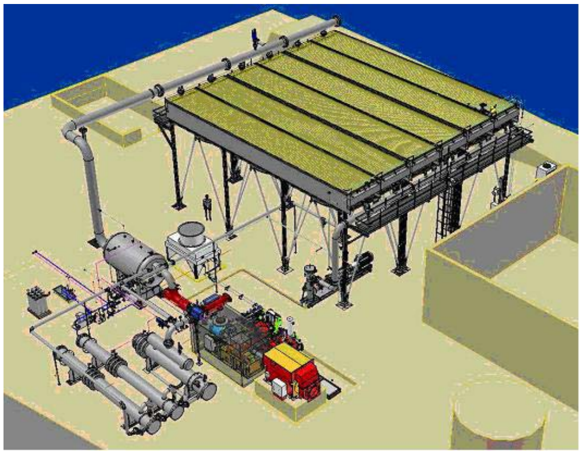


Figure 7. The Soultz ORC unit designed by Cryostar and Turboden.

Down-hole production pumps

Line Shaft Pump in GPK2

The LSP itself is in the well, the motor is at surface and the connection is done through a line shaft (Figure 8). The main advantage is to avoid installing the motor in hot brine, but the possible installation depth is limited and there are mechanical risks with the line shaft, which has to be perfectly aligned. The LSP has been supplied by Icelandic Geothermal Engineering Ltd (IGE). The length of the shaft is 345 m. The shaft (40 mm diameter) is put in an enclosing tube (3” internal diameter) with bearings every 1.5 m. The enclosing tube is set by means of centralisers in the middle of the LSP production column (6” internal diameter) which is put into the 9 5/8” casing. The pump itself is from Floway, USA and made of 17 different stages of 20 cm (3.4 m length). The LSP flow rate can be modulated until 40l/s with a Variable Speed Drive. The maximum rotation speed is 3000 rpm at 50 Hz. The surface motor is vertical. Metallurgy is cast iron and injection of corrosion inhibitor can be done at the pump intake by mean of coiled tubing which has been installed. Shaft lubrication is made with fresh water injected from surface in the enclosing tube.

The pump has been installed at 350 m depth into GPK2, which presents good verticality and is the best producer. Due to hydraulic drawdown, the maximum flow rate expected with the LSP installed at 350 m is 35 l/s. During summer 2008, between 07th July and 17th August, after six weeks of geothermal production (25 l/s, 155°C), we observed some scaling problem within the lubrication part of the shaft. The fresh water used for lubricating the shaft was too mineralized and some carbonate deposits (calcite, aragonite) precipitated. Then, a poor lubrication occurred and the first axis of the shaft broke. Between mid August and November 2008, both the shaft and the pump were fully dismantled, analyzed and a demineralization water system has been set up. The LSP pump has been re-installed at 250 m depth in GPK2 and works properly.

Figure 8. The 3 well-heads on the geothermal platform with GPK4 (left), GPK3 (middle) and GPK2 with the external black motor of the LSP (right).

Electro-Submersible Pump in GPK4

With the ESP, both the pump and its motor are installed into the GPK4 well at 500 m depth. The maximum expected flow rate from GPK4 equipped with ESP is 25 l/s but the pump is designed to a maximum flow rate of 40 l/s. The ESP has been delivered by Reda/Schlumberger. Due to the expected maximum temperature (185°C) and salty composition of the brine, specific design and noble metallurgy have been used. The electrical motor is beneath the pump and connected to this one through a seal section which compensates oil expansion and metallic dilatation. The motor is cooled by the pumped geothermal brine and internal oil temperature can reach 260°C. A fiber optic cable has been deployed with the EPS pump and allows monitoring the motor temperature and gives down-hole information about the geothermal draw-down in the well.

In parallel to the re-installation of LSP in GPK2 at 250m depth, the first production tests from GPK4 with the ESP with an expected target of 25 l/s started on mid November 2008. After some days of production, GPK4 production decreased to 12.5 l/s at 152°C and the geothermal water was re-injected in GPK3 at 50°C. LSP started again and GPK2 flow-rate has been stabilized at 17.5 l/s for a temperature of around 158°C. Both flows coming from GPK2 and GPK4 have been re-injected under full automatism in GPK3 at 30 l/s. The ORC commissioning started for these geothermal conditions at around 155°C. GPK3 well-head pressure will be maintained around 70-80 bars for re-injection. It was the first time that the triplet was operational for a while with the two producers equipped with production pumps.

Figure 9. The GPK4 well with the ESP pump deployed inside.

The ORC Geothermal Plant

As the purpose of the project is first to demonstrate the feasibility of power production, a binary system utilizing an organic working fluid called an Organic Rankine Cycle (ORC) technology has been chosen. Due to the high salinity of the geothermal brine, the geothermal fluid cannot be vaporized directly into the turbine. Then, we used a secondary circuit which involves a low boiling point organic working fluid (isobutane). As there is no easily accessible shallow aquifer around the geothermal site, an air-cooling system was required for the power plant, which also limits the impact on environment. It consists in a 9-fans system. The turbine is radial and operates at around 13000 rpm. The generator is asynchronous and is running at around 1500 rpm (Figure 10). The generator shall deliver 11 kV and the produced power will be injected into the 20 kV local power network. The expected net efficiency of the ORC unit is 11.4%. Geothermal water may be cooled down to 80-90°C in the heat exchangers of the binary unit. After this cooling, the entire geothermal water flow rate is re-circulated in the reservoir. The system is built so that the production coming from one or two wells can easily be used to feed the power production loop (Figure 11). On surface, the pressure in the geothermal loop is maintained at 20 bars in order to avoid mineral precipitations. Locally, in the filtering system, we observed some scaling corresponding to barite, celestine, iron oxides, galena and calcite mainly. In order to investigate corrosion and scaling, an innovative corrosion pilot was set up on the geothermal loop in surface and tested for the first time between September 2008 and February 2009 (Baticci, 2009). Different kinds of steel are investigated for corrosion in the geothermal conditions of re-injection (20bars, <80°C).

Figure 10. The ORC part of the Soultz power plant. On left, the heat exchanger. On right the generator and the air cooling system.

Figure 11. The Soultz geothermal power plant: in the back, the ORC power unit; in the middle, the 3 geothermal wells; in the front, the cooled geothermal loop.

CONCLUSIONS AND PERSPECTIVES

At Soultz, the drilling of several deep wells in crystalline rocks has yielded fundamental insights into the geology, nature of fracturing, fluid geochemistry, temperature and hydraulic properties of deep crystalline basement. A geothermal ORC plant has been built with a net capacity of 1,5MWe and is still in its testing and commissioning phase. A negotiation with the French government is under discussion because the feed-in tariff in France is about 12c€ per KWh. The target for the future should be to reach the level of Germany which is 24c€ per KWh for power plants having a net power below 10MWe. This target could be reached by mid 2009 in France. A three years scientific and technical monitoring of the power plant has been starting on January 2009 and will be focused on the reservoir evolution as well as on the different technologies used (pumps, exchanger, corrosion).

ACKNOWLEDGEMENTS

This work was done in the framework of the European EGS Pilot Plant project which is supported by the European Commission, BMU and Forschungszentrum Jülich (Germany), ADEME (France), the Swiss Federal Office of Energy (OFEN) and by a consortium of French and German industrial members (EDF, EnBW, ES, Pfalzwerke, Evonik). The authors also thank the Soultz geothermal team and the Working Group members.

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