PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

STATUS OT THE SOULTZ GEOTHERMAL PROJECT DURING EXPLOITATION BETWEEN 2010 AND 2012

Genter Albert[1], Cuenot Nicolas[1], Goerke Xavier[1], Melchert Bernd[2], Sanjuan Bernard[3], Scheiber Julia[1]

[1]GEIE Exploitation Minière de la Chaleur
Route de Soultz, Kutzenhausen, Bas-Rhin, 67250, France
[2]BGR, Stilleweg 2, 30655 Hannover, Germany
[3]BRGM, Geothermal Division, 3 Av. Guillemin, 45060 Orléans cedex 2, France
e-mail: genter@soultz.net

ABSTRACT

A three-year research program (2010-2012) associated with the geothermal exploitation of the Soultz-sous-Forêts power plant is on-going with a scientific and technical monitoring. Several hydraulic circulation tests have been performed that involve one production well, GPK-2 and two reinjection wells, GPK-1 and GPK-3 (Figure 1): a long term circulation for about 11 months in 2010, and two short term circulation tests in 2011.
During the 2010 exploitation, geothermal fluid discharge from GPK-2 reached a volume of about 500 000 m^3 by producing at 18L/s for a temperature of 164°C. A tracer test was conducted and showed the good connection between GPK-3 and GPK-2. In 2010, more than 400 induced micro-seismic events of low magnitude occurred. Geochemical monitoring of the fluid discharged from GPK-2 indicates that the chemical composition of this fluid becomes closer to that of the native geothermal brine (NGB) because only 4-8% of injected freshwater between May and October 2010 and 1-4% in February 2011 remain in the production fluid.
In 2011, geothermal fluid discharge from GPK-2 reached a volume of about 300 000 m^3 by producing at 24L/s for a temperature of 159°C. The strategy was to increase the reinjection flow rate in GPK-1 and simultaneously minimize it in GPK-3 in order to decrease reinjection pressure. Induced seismic activity was very low with only 5 micro-earthquakes in 2011. The observed improvement of well productivity is interpreted as a self-cleaning of the fracture network during geothermal production.
In parallel, many research works have been carried out for characterizing scaling (sulfate, sulfide) and the natural radioactivity derived from natural brines circulating within a deep fractured granite reservoir. Such scaling is preferentially located in the cold part of the geothermal installations (reinjection side). On-site corrosion study on several kinds of materials indicates a corrosion rate of about 0.2mm/year at re-injection conditions. Down-hole pump technology was also tested in various geothermal conditions during exploitation. In April 2011, occurrences of cuttings (granite particles) at high flow rate, generated abrasion of the production pump reinforcing its damaging. In October 2011, significant vibrations during high rate pumping were observed and interpreted as the main cause of pump destruction. Gross thermal power was relatively stable during production whereas the gross electrical power was quite variable.
Environmental nuisances such as noise, vibration, seismic activity, and natural radioactivity have to be carefully investigated in order to evaluate their impact on the local population and then on public acceptance.

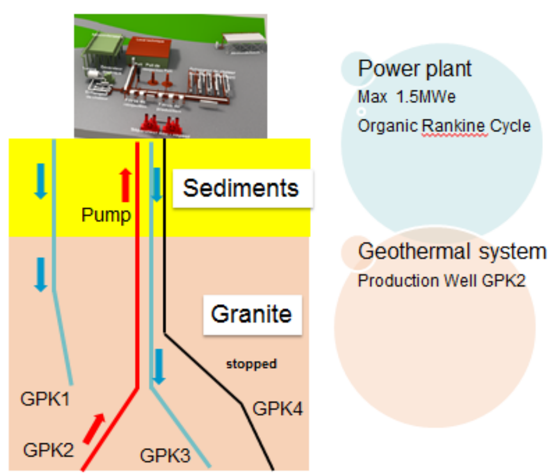

Figure 1: The Soultz power plant and the deep deviated well system. A down-hole pump is deployed in GPK-2 at 260 m depth.

INTRODUCTION

The German-French geothermal project located at Soultz-sous-Forêts is the first EGS (Enhanced Geothermal System) demonstration site producing electricity in France inland. The geothermal site, located 50 km NE of Strasbourg within the Upper Rhine Graben, corresponds to a binary power plant

(ORC: Organic Rankine Cycle) with maximal installed net capacity of 1.5MWe (Figure 1).
Several deep geothermal wells penetrated a hidden fractured granite located in this Tertiary graben. For the sub-surface, a quite comprehensive review of basic Soultz foundations is presented in Genter et al. (2010a).
The main results which are compiled hereafter are related to a three-year research program dealing with the scientific and technical monitoring of the power plant during geothermal exploitation between 2010 and 2012. A German-French scientific and technical team is operating on site in order to monitor, observe, measure and manage the geothermal activity and the power plant. In addition to on-site operations, many scientific and technical partners from Germany, France and Switzerland are involved for conducting research activity.
This program is organized around three main topics such as reservoir performance, power plant technology and environmental nuisances related to geothermal exploitation (Figure 2).

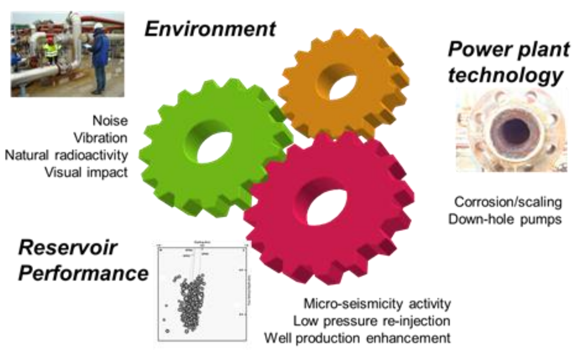

Figure 2: Reservoir performance, power plant technology and environmental issues represent the three main on-going research topics for the Soultz geothermal project.

Reservoir studies mainly correspond to a comprehensive surface geothermal monitoring during exploitation such as hydraulic studies (temperature, pressure, flow rate, tracer tests), induced micro-seismic activity, and a physico-chemical monitoring of discharged fluid. Technology includes surface and sub-surface geothermal equipment (filtering system, heat exchanger, production pumps) which have been tested and evaluated during geothermal circulation, as well as on-site corrosion and scaling study. Finally, a series of environmental studies including noise measurement, and natural radioactivity analysis is conducted during exploitation. In parallel, many scientific teams are conducting their own research about various modeling works (Baillieux et al., 2011, Dezayes et al., 2011, Gentier et al., 2011) and reservoir studies from geophysics (Calò et al., 2011, Place et al., 2011). Thus, in parallel to electricity production, major results related to this on-going scientific and technical monitoring of the power plant during exploitation are presented.

RESERVOIR MONITORING

Hydraulic Circulation In 2010

The 2010 circulation test began in November 2009 after a maintenance period and lasted until October 2011. Pressure, temperature, flow rate and production pump parameters (frequency, torque) are systematically recorded on the plant.
The hydraulic data are presented on Figure 3. The curves shown here are not very precise, as we experienced several problems with the data acquisition system, causing a loss of data. The hydraulic regime was very stable all along the test and around 500 000 m^3 of fluid circulated. Production from GPK-2 was performed at an almost constant rate of 18 L/s. Note that on Figure 3, the production flowrate seems to be higher than 20 L/s. This is a wrong value, inasmuch as a technical problem was detected on the flowmeter, leading to an overestimation of the flowrate. The injection into GPK-3 was done at an initial flowrate of about 17 L/s, and then decreased to 15 L/s, when a part of the produced fluid was injected into GPK-1 (flowrate: <2 L/s). GPK-2 wellhead pressure was kept at 18 bar, while GPK-3 wellhead pressure was maintained with an injection pump to about 50 bar, then 40 bar when reinjection was performed also into GPK-1. GPK-3 pressure kept slightly increasing until the end of the test.

Hydraulic Circulation Early 2011

The earliest 2011 circulation test began in January 2011 after a maintenance period and lasted until April 2011. About 165 000 m^3 of geothermal fluid circulated between January and April 2011.
A renovated pump was deployed in GPK-2 at 260 m depth in November 2010. By comparison with the 2010 circulation test, it was decided to maintain the geothermal production with GPK-2 and to reinject much more flow in GPK-1 than in GPK-3. In 2011, about 13l/s and 9l/s were reinjected in GPK-1 and GPK-3 respectively without any reinjection pump. This means that the maximum GPK-3 well-head pressure never exceeded 20 bar in 2011, in comparison to 50 bar in 2010 (Figure 3, Figure 4).
From January to mid-February 2011, the production flow rate from GPK-2 was around 18 L/s with a LSP-frequency of 35 Hz. Flow meter issue observed in 2010 was solved. Later, the pump frequency was lifted up stepwise to ~40 Hz to gain an increase in production flow rate of 3 L/s of up to ~21.5 L/s at the end of February 2011 (Figure 4). In March, the LSP-frequency was further increased up to ~46 Hz and the production flow rate rose up to ~26 L/s.

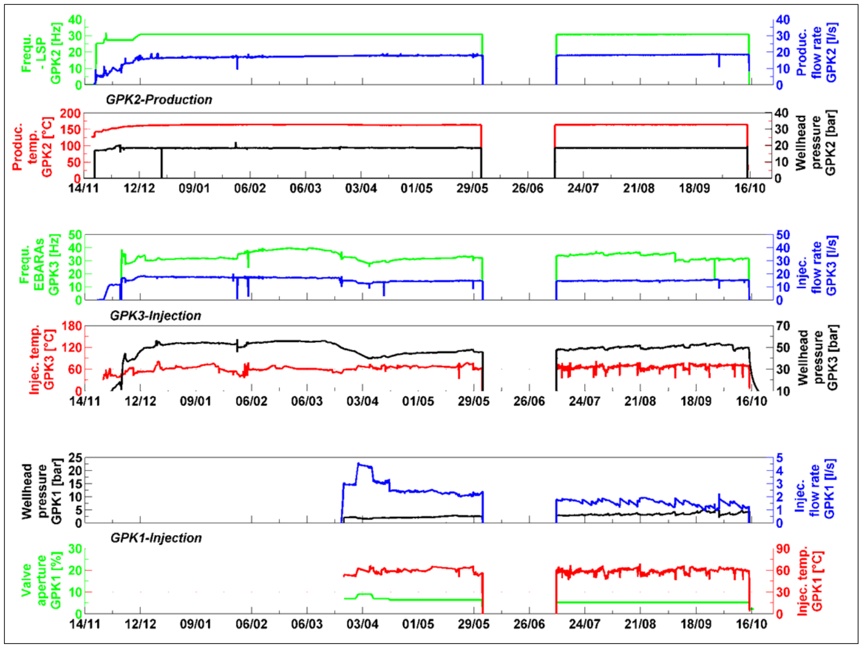

Figure 3: Overview of flow rates (blue), wellhead pressures (black) and temperatures (red) for the Soultz wells GPK-1, GPK-2, and GPK-3 during hydraulic circulation from November 2009 to October 2010. Also shown in green are the frequencies of the production and injection pump (Ebara pump for GPK-3) and the aperture of the valve for re-injection into GPK-1.

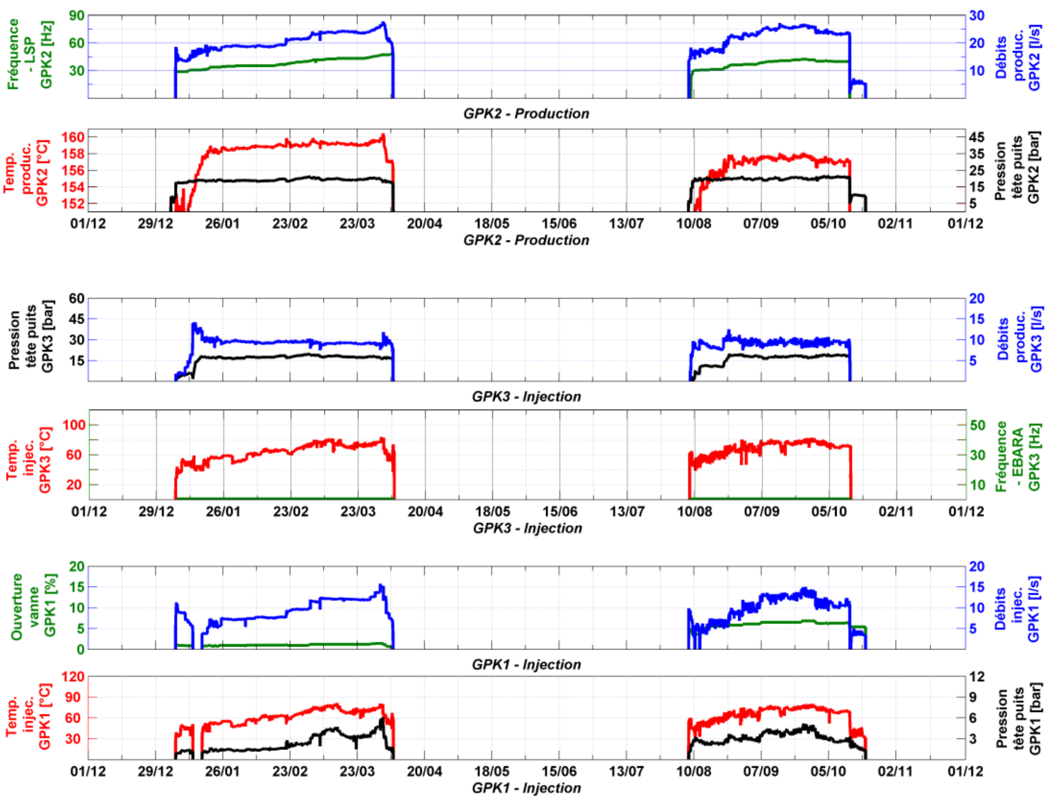

Figure 4: Overview of flow rates (blue), wellhead pressures (black) and temperatures (red) for the Soultz wells GPK-1, GPK-2, and GPK-3 during hydraulic circulation in 2011. Also shown in green are the frequencies of the production pump and injection pump (Ebara pump for GPK-3) and the aperture of the valve for re-injection into GPK-1.

The produced fluid temperature of GPK-2 rose continuously from 158.7°C at the beginning of February to 159.5°C at the end of March. The injection flow rate into GPK-3 was kept more or less constant between ~9 L/s during both months at a corresponding stable wellhead pressure from 18.5 to 20 bar. The injection flow rate into GPK-1 was kept constant between 7.2 to 7.7 L/s in February. Then, the increased produced flow rate was additionally re-injected by gravity only into GPK-1, so that the injection flow rate rose up to ~13 L/s at the end of March. The wellhead pressure in GPK-1 was around 1.5 bar at a injection rate of ca. 7.5 L/s and increased up to ~4.8 bar at 13.5 L/s injection flow rate. The relative high value of the well-head pressure in GPK-1 is mainly due to free gas derived from the brine.

Hydraulic Circulation Late 2011

About 135 000 m^3 of geothermal fluid circulated between August and mid-October 2011. The geothermal installation was restarted after a stop due to the failure of the LSP in April 2011. A new pump was deployed in GPK-2 at 265 m depth in July 2011. By comparison with the early 2011 circulation test, the same hydraulic strategy was applied. It was decided to maintain the geothermal production with GPK-2 and to reinject much more flow in GPK-1 than in GPK-3. In 2011, the maximum well-head pressure never exceeded 20 bar in GPK-3, in comparison to 50 bar in 2010. The same orders of magnitude for flow rate and well-head pressure were applied for this second hydraulic test of 2011. However, for the discharge temperature at the well-head of GPK-2, an overall decrease of more than 1°C has been observed when comparing October 2011 and April 2011.

From August 08th to 22nd, the production flow rate was around 17 L/s with a LSP-frequency of ~30 Hz (Figure 4). The well-head pressure on surface was around 20 bar and was regulated by both the outlet pressure of GPK-2 and an automatic regulating valve controlling GPK-1 reinjection. During this period, the output temperature of GPK-2 increase from 152 to 156°C. Reinjection flow rate was lower 8 L/s for both GPK-1 and GPK-3 (Figure 4).

Then, after August 22nd, pump frequency was lifted up stepwise over ~40 Hz to gain an increase in production flow rate of up to ~26 L/s from mid to end of September (Figure 4). In a first step, pump frequency was increased to 35 Hz till 05th September and in a second step, to 42 Hz by the 29th of September 2011. From this date, LSP-frequency was reduced to around 40 Hz to minimize the observed vibrations on the LSP-pump, with a corresponding production flow rate of ~23 L/s.

The injection flow rate into GPK-1 was constantly increased from 5 L/s in August of up to 13 L/s in mid-September and from end of September to mid-October the re-injection rate was around 10 L/s with a corresponding wellhead pressure between 3 and 5 bar (Figure 4). In GPK-3 the reinjection flow rate was around 7 L/s in August and was then kept constant at around 10 L/s for the rest of the circulation phase with a constant wellhead pressure of ~16 bar, as well.

It is noticeable to observe the evolution of the geothermal fluid temperature discharged from GPK-2 during this hydraulic test. Firstly, during the two first weeks of production with low LSP-frequency (<30 Hz), temperature slowly increased from 152 to 156°C. Secondly, by pump frequency increase up to 42 Hz, production temperature increases but never exceeds 158°C probably in relation with a re-injection of up to 13 L/s into GPK-1. As soon as the LSP-frequency is reduced from 42 to 40 Hz on September 30 due to vibrations, the resulting production flow rate is reduced from 26 to 23 L/s. In perfect time correlation, the production temperature dropped from about half degree with flow rate reduction (Figure 4).

In comparison with the circulation phase between January and April 2011, production temperature dropped from another 1°C. Compared to hydraulic conditions observed in 2010 with a production temperature of 165°C and a limited injection flow rate of less than ~2 L/s in GPK-1, fluid temperature in GPK-2 decreased from about 6°C in 2011.

Hydraulic Performance During Circulation

It was not possible to measure the water level in GPK-2 during 2010 due to technical issue. Thus, neither productivity of GPK-2 nor injectivity of GPK-3 and GPK-1 were calculated. In 2011, a technical improvement in GPK-2 allows measuring water level and then deriving hydraulic performance.

Between the two successive hydraulic tests done in January-April and August-October 2011, a significant increase of the productivity of GPK-2 was observed with values ranging from 1.2 to 1.9 L/s/bar. This significant improvement of the well performance could be explained by a significant self-cleaning of GPK-2 well in general and better connections between this production well and the deep heat exchanger or the reservoir in particular. Increasing flow rate in GPK-2 resulted in the lifting up of 200 kg of cuttings from January to April 2011 and 50 kg of cuttings from August to October 2011. The well improvement fits with the cumulative cutting volume lifted up at surface during pumping. The high cutting quantity removed from the well in 2011, improves the well performance in term of productivity.

GPK-2 well which was deepened in 1999 accumulated a great quantity of crushed rocks (cuttings) within fractures and faults porosity. As the well was probably not sufficiently cleaned at the end of the drilling operations, cuttings stuck within the fracture porous network. In 2010, even with more than 10 months of continuous circulation at 18L/s, no cuttings were observed within the filtering system. In 2011, the dual effect of increasing the pumping rate to 23L/s (March) and 26 L/s (September) combined with a significant reinjection volume in GPK-1 tends to favor the lifting up of cuttings to the surface. The fact that the output temperature of GPK-2 decreased of more than 1°C between April and October is also an indirect argument in favor for a good hydraulic connection between GPK-1 and GPK-2.

Between the two successive hydraulics tests done in January-April and August-October 2011, there was no real improvement of GPK-3 injectivity and values were rather stable below 0.40 L/s/bar. This relative stability could indicate the absence of mineral precipitations in the reservoir.

For GPK-1, estimated injectivity values are larger than 2 L/s/bar.

Tracer tests from GPK-3 to GPK-2

In order to check the hydraulic connection between GPK-2 and GPK-3, a new tracer test has been done. It started in May 2010 during the longest fluid circulation test ever carried out at Soultz (323 uninterrupted days). The fluid production flow-rate was about 18 L/s and the fluid injection flow-rates were 15 L/s (for GPK-3) and 3 L/s (for GPK-1), respectively. As for previous tracer tests (Sanjuan et al., 2006), an organic compound from the naphthalene sulfonate family such as 1,3,5-nts was used because of its properties of quasi-ideal tracer. This compound is inexpensive, environmentally safe, highly soluble in water (200 g/L), non-adsorptive and non-interactive with rocks and minerals of the fractures, thermally stable up to 340°C (Rose et al., 2000), detectable at low concentrations (down to 0.25 μg/L) and absent from natural geothermal fluids.

An amount of 200 kg of 1,3,5-nts was dissolved in a tank of 1 m^3 of freshwater before being injected into the well GPK-3 on May 4, 2010 (Sanjuan, 2011).

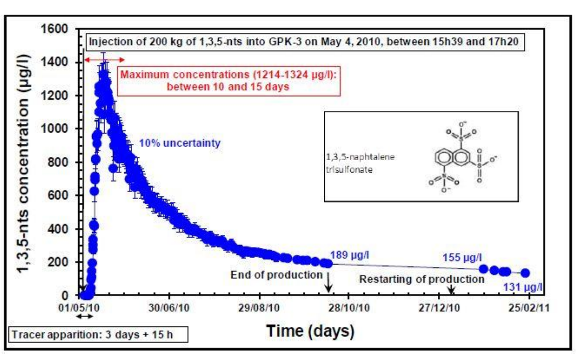

Figure 5: Restitution curve of the 1,3,5-nts tracer injected into the well GPK-3 in 2010 (Sanjuan, 2011).

Tracer data obtained from the GPK-2 fluid are presented in Figure 5. As for previous tests, they show a typical response of the behavior of a tracer injected in a fractured medium. The first appearance of 1,3,5-nts in the GPK-2 fluid occurs 87 hours (3,6 days) after tracer injection. The maximum 1,3,5-nts concentration is observed between 240 h and 360 h (10 and 15 days), after tracer injection. The maximum linear fluid velocity and the mean apparent velocity were estimated at 7.9 m/h and 2.3 m/h respectively (Sanjuan, 2011). These values are close to those determined in 1997 and 2005 (Sanjuan et al., 2006). Up to now, only simple calculations were considered for this tracer test but similar modelling works as those done in Gentier et al. (2011) are being carried out for a better interpretation of these data The minimal connected porous volume derived from this tracer test was estimated to be close to1.5 $10^6 m^3$.

Seismic Monitoring

A detailed analysis of the seismic monitoring of the Soultz site during circulation for 2010 has been extensively presented (Cuenot et al., 2011a).

Seismic monitoring in 2010

Only a few events occurred during the first 3 months after the beginning of the test. Then, about 400 microseismic events were detected during the circulation. The highest activity was observed during the first phase of the test, when reinjection was performed into GPK-3 only. Once a part of the geothermal fluid was reinjected into GPK-1, making GPK-3 wellhead pressure decreasing, the microseismic activity remained at a low level (between 0 and 5 events per day). Only near the end of the test, the activity seemed to increase a bit, maybe in relation to the continuous rise of GPK-3 injection pressure. A small activity had remained for 15 days after the end of the test. Magnitudes are in the range -0.3 to 2.3. 25 earthquakes reached a magnitude equal or larger than 1. Among them, 7 were above magnitude 1.8 and 4 reached magnitude higher than 2. All the earthquakes of magnitude larger than 1.8 occurred during the first phase of the test, that is before the beginning of injection into GPK-1 (Cuenot et al., 2011a).

In term of location, as for previous hydraulic tests, the same zones concentrate the seismicity: in the area on the West/South-West of GPK-3, events are located at depths between 4.9 and 5.3 km; in the area between GPK-2 and GPK-3, hypocenters are located a bit deeper and in the northern part of GPK-2 where the larger events (M>2) are located. As already observed in the previous tests, no seismicity is located around GPK-4, which was not used here, and around GPK-1, into which reinjection took place at a low flowrate.

Seismic monitoring in 2011

Contrary to what was observed during the 2010 circulation, very few microearthquakes occurred in 2011: only 4 during the circulation of January-April

2011 and only 1 during the circulation of August-October 2011.

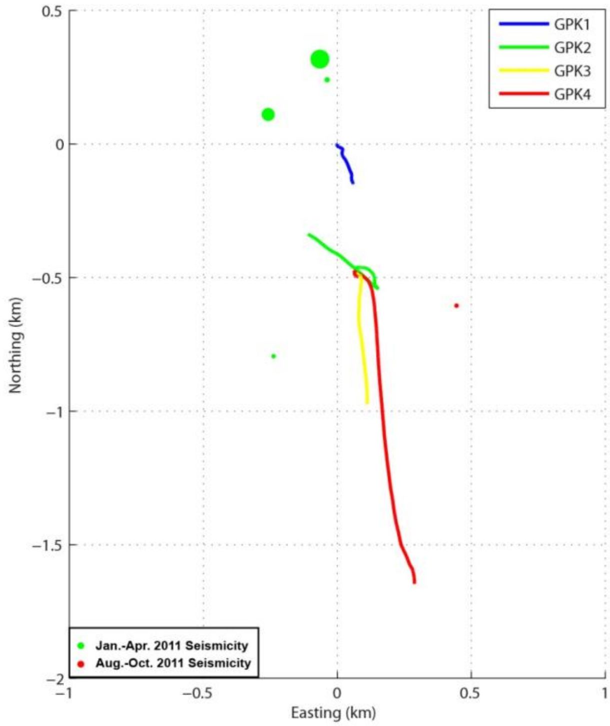

Figure 5: Plane view of location of microseismic activity observed in 2011 during geothermal circulation. Diameters of circles are proportional to magnitude.

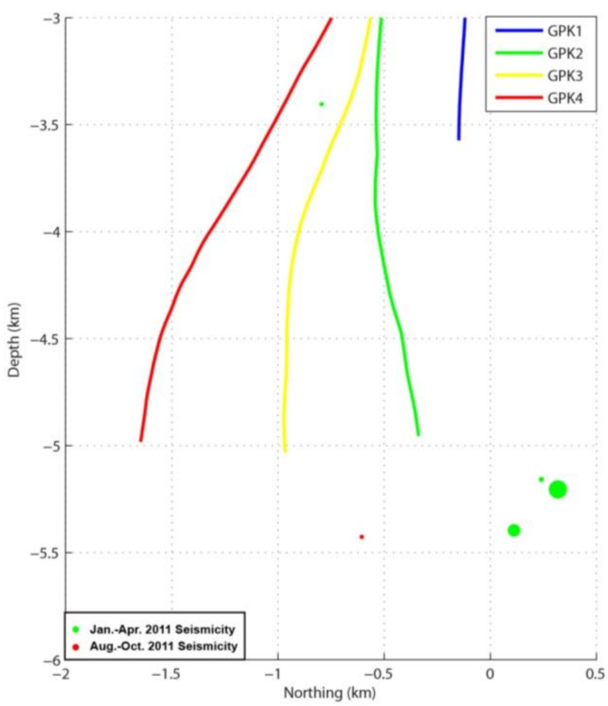

Figure 6: N-S vertical cross-section of the microseismic event locations at depth.

During the early 2011 circulation, only one event occurred during the circulation period itself; the three others took place after the stop of the pump, that is, during the shut in period. The largest earthquake reached a magnitude of 1.7. Another was of magnitude 1.3. Both were not felt by the population. In October 2011, the microseismic event occurred during the circulation time.

The activity was greatly reduced as compared to last year: in 2010, around 400 microearthquakes occurred over 11 months of continuous circulation (Cuenot et al., 2011a). Moreover, in 2011, no earthquakes reached a magnitude higher than 2, compared to 4 events in 2010. This behaviour may be explained by the reinjection strategy: since 2009, the borehole GPK-1 has been more and more used to reinject a part of the geothermal fluid so that the reinjection has been shared between GPK-1 and GPK-3. In 2011, a larger proportion of the fluid has been reinjected into GPK-1, allowing to reinject into GPK-3 without the use of pump. The consequence of this strategy is a lower injection pressure, which led to a minimum microseismic activity, both in number and magnitude.

Figure 5 and Figure 6 show the location of the 5 microseismic events, in planar view and North-South vertical cross-section respectively. 3 events from the first tests (including the largest ones) are located in a zone on the North of GPK-2 bottom hole at great depth. This zone was already active during the previous circulation experiments and already hosted the largest events. The event occurred during the second test is located rather deep on the East of GPK-2-GPK-3 inter-well area. The last one, which was the first occurred in 2011, exhibits an unexpected location: its depth is very shallow (3.4 km). Thus we could have expected that this event would be located in the vicinity of GPK-1, because its depth corresponds to the depth of GPK-1; but on Figure 5, it is clearly located on the West of GPK-2-GPK-3 inter-well region, thus, far from GPK-1 bottom hole.

Fluid Monitoring During Exploitation

The knowledge of the chemical composition of the fluids discharged from GPK-2 and re-injected into GPK-3, and GPK-1, as well as of its evolution during the geothermal circulation was useful to (1) characterize the water-rock interaction processes with temperature changes, (2) estimate the possible risks of mineral scaling and consequently, to take measures to avoid these scales and (3) determine the volume of natural brine mixed with injected waters.

Geochemical monitoring of the geothermal fluid at production and reinjection was done during the fluid circulation tests carried out in 2010 and 2011.

Fluid characterization at production

On-site geochemical fluid studies were carried out at production during circulation (Sanjuan, 2011).

Determination of conductivity, pH, alcalinity, chloride, and silica concentrations were conducted in the GEIE field laboratory.

Punctual geothermal fluid samples (geothermal water and associated incondensable gases) were collected on-site for a more detailed geochemical and isotopic characterization (major species, trace elements, stable isotopes) in the BRGM laboratories. The geochemical monitoring of the discharged water shows an evolution of its chemical and isotopic composition toward that of the NGB (Sanjuan, 2011).

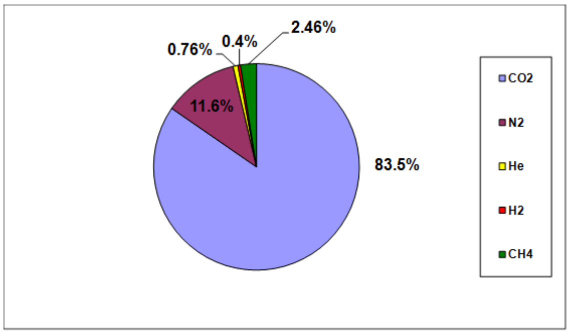

Figure 7: Chemical composition for gas sample collected from the well GPK-2 using the GEIE EMC cyclonic micro-separator (Sanjuan et al., 2011).

About 92-96% of NGB were estimated in the water discharged from GPK-2 between May and October 2010 and 96-99% of NGB in February 2011. The Gas-Liquid Ratio (GLR) and the chemical composition of the associated incondensable gases were very different from those previously determined (Sanjuan et al., 2010). The GLR measured in February 2011 using a phase micro-separator indicates a value of 104% in volume (Sanjuan, 2011) and the chemical composition of the corresponding gas sample in which CO_2 is dominating (Figure 7) is probably the most representative.

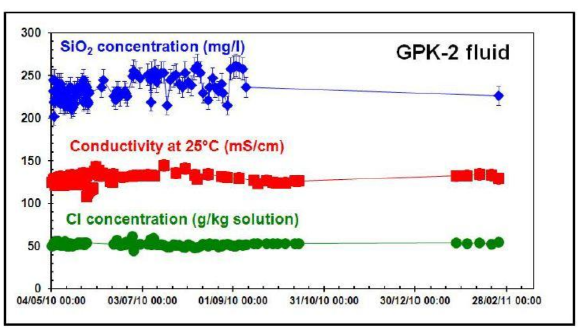

Figure 8: Physico-chemical parameters (SiO_2, Conductivity, Chloride content) of the geothermal fluid sampled at GPK-2 from May 2010 to February 2011 (Sanjuan, 2011).

From August to October 2011, Cl and SiO_2 concentration, pH, conductivity and alcalinity remained constant and very close to the values observed in 2010 and early 2011 (Figure 8). As shown in this figure, the conductivity and Cl concentration values are progressively increasing to 135 mS at 25°C and 53 g/kg respectively. The pH, alkalinity and SiO_2 concentration values are more variable: for example, from 1.48 to 3.48 meq/l for alkalinity and 215 to 260 mg/l for SiO_2 concentration.

Fluid characterization at reinjection

A continuous physico-chemical monitoring of the fluid circulating in the deep heat exchanger, integrating continuous measurements of temperature, conductivity, pH and Eh was performed in the Low Temperature Skid (LTS), located just before fluid injection into the GPK-3 well-head (Figure 9).

In the fluid stream at 20 bar and temperature of 70˚C, pH which is close to 4.7-4.8, is slightly lower than pH in the brine after sampling and degassing of CO_2 in the geothermal fluid. Eh measurements are strongly related to the flow parameters (pressure, temperature, stagnant conditions) of the power plant. Under stagnant conditions, the Eh increases immediately; in constant flow conditions, the Eh measurements can reach a value of -390 mV, which corresponds to a final value close to -215 mV, if the potential of the reference electrode is eliminated.

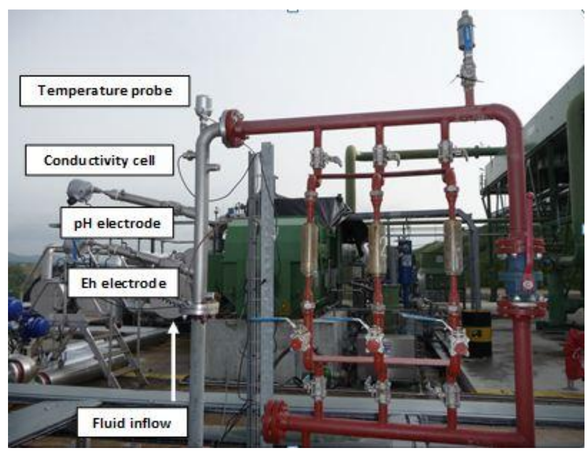

Figure 9: Low Temperature corrosion Skid (LTS) installed at reinjection conditions equipped with physico-chemical probes.

SUB-SURFACE TECHNOLOGY

On-Site Corrosion Monitoring

On-site corrosion experiments are conducted with a Low Temperature Skid (LTS), located between the heat exchanger and the reinjection well GPK-3 (70°C, 20 bars). The skid is equipped with three separated chambers (Figure 9) for the exposure of metal coupons under in-situ conditions (Baticci et al., 2010). This LTS was designed, installed and tested from 2008. Corrosion resistance, corrosion rate by mass loss and specific corrosion behavior like pitting or uniform corrosion are currently investigated. On-site short term (4 weeks) and long term experiments (several months) are conducted in cooperation with our scientific partners (Mundhenk et Huttenloch., 2011, Mundhenk et al., 2011). Several kinds of materials with mild and high alloyed steels are currently tested. Main results of the on-site experiments for iron steels show a corrosion rate of 0.2 mm per year.

In order to investigate corrosion in high temperature conditions, a construction of a High Temperature Skid (HTS) has been designed and is under construction (Sontot, 2010). This equipment will be located between GPK-2 and the filter at the production side. Various steels and coatings will be tested.

Scaling Studies

The cooling of a highly saline geothermal brine (100g/L) could generate scaling within the surface installations. During exploitation, scaling has been sampled for a whole geochemical and mineralogical characterization. They correspond to black deposits and are preferably located within the ORC heat exchangers, the geothermal pipes, and the filtering system at reinjection side (Figure 10). They correspond mainly to sulfates such as celestine-barite ((Ba, Sr) SO_4) and sulfides such as galena (PbS).

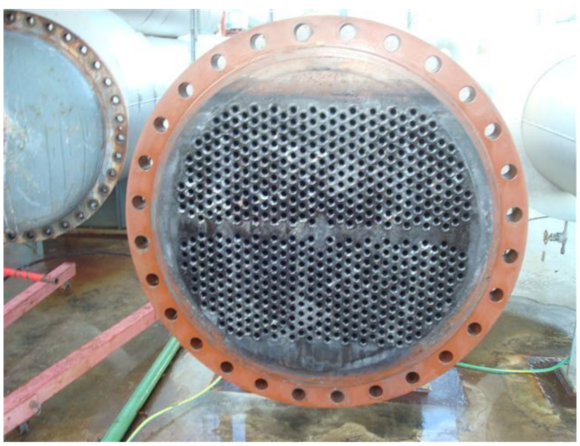

Figure 10: Black scaling observed within the heat exchanger during exploitation.

As those minerals are able to trap radionuclides (barium can exchange with radium) and thus generate some wastes, research work for the application of an inhibitor system for scale avoidance has been launched. It includes the selection of an appropriate crystalline inhibitor for sulfates which started with laboratory test with some specific chemicals chosen for their potential of scale inhibition in the geothermal fluid (Scheiber et al., 2012).

Down-Hole Pump Technology: LSP

Results from 2010 circulation test

From November 2009 to October 2010, the down-hole pump, LSP, deployed at 260 m in GPK-2 well, ran continuously at stable flow regime of 18 L/s with a rotation speed of 30 Hz. After 323 days of normal operating, LSP was pulled out. It showed a good mechanical status with no damage related to cavitation, erosion or corrosion. A piece of the hydraulic part of the pump that was treated with boron, do not exhibit any significant traces of corrosion. Before redeploying the pump in the well and in order to protect its hydraulic part from corrosion, several pieces were treated with a special metal treatment with boron. After the technical stop of October 2010, the LSP has been dismantled, inspected and repaired.

Results from 2011 circulation tests

As a repaired LSP pump was deployed in GPK-2 at 260 m depth in December 2010, production restarted in January. Until mid-February 2011, the production flow rate was around 18 l/s with a LSP-frequency of 35 Hz. Later, the pump frequency was lifted up stepwise to ~40 Hz to gain an increase in production flow rate of 3 l/s of up to ~21.5 l/s at the end of February 2011. In March, the LSP-frequency was further increased up to ~46 Hz and the production flow rate rose up to ~26 l/s. At the beginning of March, a strong increase of lifted up cuttings with the geothermal fluid was observed due to the increasing production flow rate (> 23 l/s). As a consequence, heat exchangers and filters were partly stuck with cuttings and had to be cleaned frequently.

Figure 11: Status of the LSP pump after the pull operation of April 2011. Picture of the hydraulic part of the pump.

In April 2011, LSP failed, provoking a general stop of the geothermal circulation and then of the power production. Occurrences of cuttings (crushed granite) which appeared when the flow rate was higher than 23l/s, had two negative effects on the geothermal installation: first, they generated a significant abrasion of the LSP, reinforcing its damaging (Figure 11) and second, they stuck the filtering system at production. Then, the pump system was dismantled and a new one has been deployed in GPK-2 at 265 m in July 2011.

After the reinstallation of the pump, the reactivation of the well GPK-2 and the restart of the pump on the 8th of August 2011, the pump had been running during 2.5 month at high flow conditions. The aim of this test was to evaluate the behavior of the pump at a high flow and also to reach the necessary conditions for a normal start of the ORC system. On the 13th of October, the LSP pump had to be stopped due to a major leak on the system. This leak was caused by the destruction of one lubrication string of the pump. This destruction was caused by the rubbing between the lubrication string and the centralizer. After the dismantling of the pump, such damage has been observed all along the pump. High speed could generate high vibrations level which can provoke pump destruction.

LSP vibration analysis

Vibrations on the pump have been measured continuously based on 5 sensors installed on the GPK-2 well-head. Evolution of both LSP rotation speed and vibration rate versus time of one sensor located on the LSP motor is presented on Figure 12.

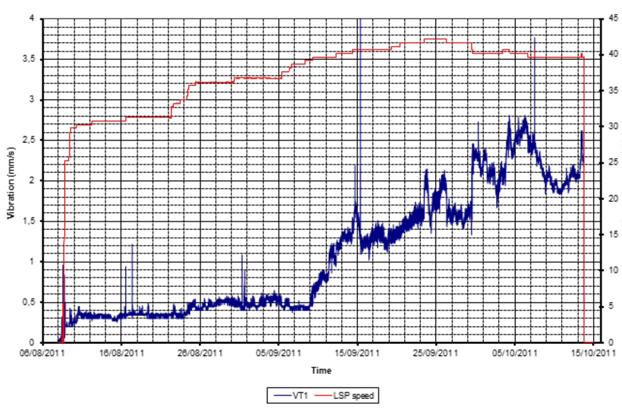

Figure 12: Pump vibrations (mm/s in blue) and LSP rotation speed (Hz in red) versus time measured on the GPK-2 well-head.

From beginning of August to the 09th of September, vibrations are not significant and always below 0.6 mm/s with a LSP maximum rotation speed of 39 Hz. During this first phase, each increase of rotation is associated with a small increase of vibration (Figure 12). Between the 09th and 15th of September, as soon as the rotation speed is higher than 39 Hz and reaches 41 Hz, vibrations jump drastically from 0.5 to 1.6 mm/s. The same behavior is observed later till the 26th of September when a vibration rate of 2 mm/s is measured for a maximum speed of 42.5 Hz. Later, the rotation was progressively decreased below 40 Hz but vibrations continue to grow with a maximum value of 2.8 mm/s (Figure 12). This tendency indicates an irreversible damaging of the whole production system which provokes the destruction of the lubrication string evidenced by a vapor leak.

Thermal Power And Electrical Power

In 2010, the new French feed-in tariff at 20€ct per kWh was not yet available. Thus, only thermal and electrical power data from late 2011 are presented hereafter. The ORC-unit was restarted on September 1st and was stopped together with the shut-down of the LSP-pump on October 13th (Figure 13). The mean electrical gross power was around 500 kW and was significantly influenced by ambient temperature conditions of daily cycles which showed high thermal amplitude between day and night in September 2011. The highest observed gross power was 655 kWe for a thermal power of 8474 kW on September 21st. Surprisingly, the gross thermal power was relatively stable during the whole period whereas the gross electrical power was quite variable with a rather stable geothermal installation consumption (Figure 13). During this period, among the 400 kWe of self-power consumption, about 25% are induced by the LSP motor.

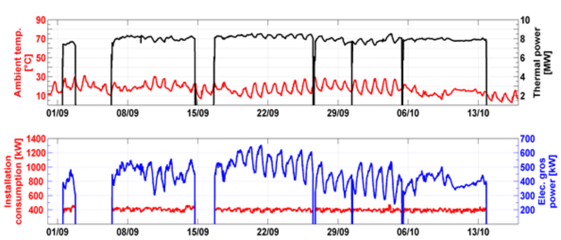

Figure 13: Thermal output of the Soultz plant in MWth and ambient air temperature versus time (above). Gross electrical power and self-consumption in kWe produced by the power plant versus time (below).

From the 1st to 21st of September, expected gross electrical power was roughly increasing in correlation with production flowrate increase. However, from the 21st of September to the 06th of October, gross electrical power decreased much more than the thermal power. This low efficiency of the plant could not be explained by the simple flow rate reduction from 26 to 23 l/s only but by the occurrence of two main factors: first, some permanent working fluid losses due to untightened flanges on the ORC induced degraded cycle efficiency and secondly, ambient temperature conditions were abnormally high during this period. During this unusual warm period, the daily ambient temperature variations ranging from 10°C during the night to 30°C during

the day, had a serious impact on the gross electrical power production of over 200 kWe (Figure 13).
From the 06th to the 13th of October, although the production flow rate was lower (26 to 23 l/s), both thermal and electrical gross powers were better in average than the days before. This observation could be explained by colder and flatten ambient temperature conditions due to intense rainfalls (Figure 13). Moreover, the relative better efficiency observed during this period was also partly due to some technical improvements of the plant regulation system done by the manufacturer.
During the ORC operating in September 2011, a mean electrical net power of 100 kW has been produced.

ENVIRONMENTAL STUDIES

Geothermal energy such as EGS is a rather new technology in Central Europe which can induce some environmental nuisances such as noise, vibration, seismic activity, natural radioactivity and visual impact. Those nuisances have to be carefully investigated in order to evaluate their impact on the local population and then on public acceptance. One of the main clues for maximizing public acceptance is to be open and transparent as far as possible by explaining regularly through various media, the main geothermal results and the potential nuisances associated with. Those results are presented to a large audience from local population, to politicians, schools and universities as well as to geothermal industry.
The main nuisances investigated were noise, seismic activity and natural radioactivity;

Noise

In operation, the power plant generates some noise mainly related to the electrical production part of the plant. The noise is mainly attributed to the expansion of gas inside the turbine and to the rotation of the 9 fans of the air-cooling system. The turbine itself is already installed inside a shelter.
Two complaint letters from local inhabitants about the nuisance caused by the noise were received. The mayors of the surroundings cities were also informed about the complaints. Consequently, a noise study has been planned and launched: measurements have been taken when the power plant was not operating, to define the “normal” noise level. Local inhabitants and several delegates of the municipal council including the mayor have been informed about the ongoing study. A joint visit was organized on site including a power plan visit. Following this visit, an article has been published in 2011 within the local Newspaper for informing the local population.

Seismic Nuisances

Based on the new reinjection strategy used in 2011 (no reinjection pump), the micro-seismic activity was very low because only 5 events were detected during the two consecutive hydraulic circulation tests. After the failure of the LSP pump early April, 3 micro-events were detected but no felt. Those events are clearly related to the sharp stop of the production pump. None of those events was felt by the local population. By comparison with 2010, more than 400 events were induced but the reinjection overpressure was higher than 45 bars. In 2011, the reinjection overpressure was regulated by the production pump, the LSP, which was operating with less than 20 bars. Thus, this strategy was very successful because it minimized the hydro-mechanical effects on the reservoir (very low seismic activity).

Radioprotection

The Soultz power plant operates with a geothermal fluid circulating within a fractured crystalline reservoir (Genter et al., 2010b). Thus, as this granite contains natural radioactive isotopes, monitoring of natural radioactivity on the geothermal site has been carried out during exploitation, following the request of ASN (French National Agency for Nuclear Safety) that recommended to follow precisely the evolution of natural radioactivity within the geothermal installation. The first goal of this study is to ensure the protection of workers against potential radiations.
Thus, eight measurement campaigns have been carried out since 2009 to observe and characterize the natural radioactivity evolution during hydraulic circulation tests, both on GPK-2 and GPK-1 surface installation (Cuenot et al., 2011b). As the goal is mainly radioprotection, the measured parameter is the dose rate, expressed in micro-Sievert per hour (µSv/h). Two kinds of measurements are performed: “contact” (1 cm from the installation) and “ambient” (1 m away from the installation) measurements.
Around 350 “contact” and 50 “ambient” measurements were regularly sampled both on GPK-1 and GPK-2 platforms. For all measurement campaigns, the results show a general increase of the dose rates with the circulation volume and the highest values were found mostly on the reinjection line, where the temperature is lower (~70°C). This indicates a correlation between the observed radioactivity and the scaling processes inside the installation: some newly formed minerals are able to trap radionuclides.
For the last campaign from October 2011, the average dose rate ambient value and contact value measured on GPK-2 platform are about 0.45 µSv/h and 2 µSv/h respectively. The highest value was 10 µSv/h.

Generally, there is a correlation between the increase of dose rate values and the cumulative volume of fluid having circulated inside the installations.

CONCLUSION

Because Soultz is the first EGS geothermal power plant in France, many challenges have been outlined, new scientific and technical expertise is raising and will benefit to the French-German consortium for transferring the results to some new geothermal projects through the Upper Rhine Valley. The scientific and technical program for 2012 is to produce from GPK-2 well and reinject simultaneously the geothermal brine in GPK-1, GPK-3, and GPK-4 wells.

ACKNOWLEDGMENTS

This work was done in the framework of a German-French project which is supported by BMU/BGR and Forschungszentrum Jülich (Germany), ADEME (France), and by a consortium of French and German industrial members (EDF, EnBW, ES, Pfalzwerke, Steag). The authors would also thank the technical team of the GEIE for the management of every circulation tests.

REFERENCES

Baillieux P., Schill E. and Dezayes Ch. (2011), "3D structural regional model of the EGS Soultz site (Northern Upper Rhine Graben, France): insights and perspectives", Proceedings, 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA.

Baticci F., Genter A., Huttenloch P. and Zorn R. (2010), "Corrosion and scaling detection in the Soultz EGS power plant, Upper Rhine Graben, France", World Geothermal Congress, WGC2010, Bali, Indonesia, April 2010.

Calò M., Dorbath C., Cornet F.H. and Cuenot N. (2011), "Large-scale aseismic motion identified through 4-D P-wave tomography", *Geophysical Journal International*, **186**, 1295-1314.

Cuenot N., Frogneux M., Dorbath C. and Calo' M. (2011a), "Induced microseismic activity during recent circulation tests at the EGS site of Soultz-sous-Forêts (France)", Proceedings, 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA.

Cuenot N., Goerke X., Guery B., Bruzac S., Sontot O., Meneust P., Maquet J. and Vidal J. (2011b), "Evolution of the natural radioactivity within the Soultz geothermal installation" Soultz geothermal conference, 5 & 6 October 2011, Conference Volume, p. 19.

Dezayes Ch., Beccaletto L., Oliviero G., Baillieux P., Capar L. and Schill E. (2011), "3-D visualization of a fractured geothermal field: the example of the EGS Soultz site (Northern Upper Rhine Graben, France)", Proceedings, 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA.

Genter A., Evans K.F., Cuenot N., Fritsch D. and Sanjuan B. (2010a), "Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of Enhanced Geothermal Systems (EGS)", *Geoscience*, **342**, 502-516.

Genter A., Goerke X., Graff J.J, Cuenot N., Krall G., Schindler M. and Ravier G. (2010b), "Current status of the EGS Soultz geothermal project (France)", World Geothermal Congress, WGC2010, Bali, Indonesia, April 2010.

Gentier S., Rachez X., Peter-Borie M., Blaisonneau A. and Sanjuan B. (2011), "Transport and flow modeling of the deep geothermal exchanger between wells at Soultz-sous-Forêts (France)", GRC2011, Annual Meeting, October 23-26, San Diego, USA.

Mundhenk N. and Huttenloch P. (2011), "Corrosion in geothermal brine environments in the Upper Rhine Graben", Soultz geothermal conference, 5 & 6 October 2011, Conference Volume, pp. 54-55.

Mundhenk N., Huttenloch P., Zorn R., Steger H. and Kohl Th. (2011), "Metal corrosion under impact of geothermal brines in the Upper Rhine Graben, Germany", Low Carbon Earth Summit 2011, Dalian, China, p. 729.

Place J., Sausse J., Diraison D., Géraud Y., Naville Ch. and Marthelot J.-M. (2011), "3D mapping of permeable structures affecting a deep granite basement from isotropic 3C VSP data", *Geophysical Journal International*, **186**, 245-263.

Rose P.E., Benoit W.R., Lee S.G., Tandia B.K. and Kilbourn P.M. (2000), "Testing the naphthalene sulfonates as geothermal tracers at Dixie Valley, Ohaaki, and Awibengkok", Proceedings, 25th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA.

Sanjuan B., (2011), "Soultz EGS pilot plant exploitation - Phase III: Scientific program about on-site operations of geochemical monitoring and tracing (2010-2013)", First yearly progress report BRGM/RP-59902-FR, 92 pp.

Sanjuan B., Brach M., Béchu E., Jean-Prost V., Bruzac S. and Sontot O., (2011), « On site Soultz-sous-Forêts (France) research works carried out between March 2010 and February 2011: geochemical monitoring and tracing operations", Soultz geothermal conference, 5 & 6 October 2011, Conference Volume, pp. 17-18.

Sanjuan B., Millot R., Dezayes Ch. and Brach M. (2010), "Main characteristics of the deep geothermal brine (5 km) at Soultz-sous-Forêts (France) determined using geochemical and tracer test data", *Geoscience*, **342**, 546-559.

Sanjuan B., Pinault J-L, Rose P., Gérard A., Brach M., Braibant G., Crouzet C., Foucher J-C, Gautier A. and Touzelet S. (2006), "Tracer testing of the geothermal heat exchanger at Soultz-sous-Forêts (France) between 2000 and 2005", *Geothermics*, **35**, 5-6, 622-653.

Scheiber J., Nitschke F., Seibt A., and Genter A. (2012), "Geochemical and mineralogical monitoring of the geothermal power plant in Soultz-sous-Forêts (France)", Proceedings, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA.

Sontot O. (2010), « Dimensionnement d'un skid de corrosion haute température et pression et suivi géochimique des fluides lors du test de traçage initié en mai 2010 sur le site géothermique de Soultz-sous-Forêts (Alsace, France) », Internal GEIE EMC – INSA Toulouse report, 48 pp.