ENGINE- G*eothermal lighthouse projects in Europe*

Information gathered during the ENGINE co-ordination action (ENhanced Geothermal Innovative Network for Europe)
http://engine.brgm.fr/
Last update April 2008

Project Name: EGS PILOT PLANT called Soultz project
Project Leader [Companies]: EEIG Heat Mining
Contact Person: Albert GENTER
Web-site: www.soultz.net
Country: France
Location: Soultz-sous-Forêts, Bas-Rhin, Alsace

Types of resource [High/Low Enthalpy / EGS etc.]: EGS
Main on-site operators [Drilling, Simulation, Monitoring, Power plant etc.]: **Drilling, stimulation, power plant, Seismic monitoring, corrosion monitoring**
Number of wells [w. Total Depth pr. well]: **5 wells (2230, 3600, 5000, 5000, 5000m)**
Type of wells [Exploration, Production, Injection]: 1 exploration, 2 production, 2 injection
Well configuration [Single well, Doublet, Triplet]: Triplet and 2 exploration wells
Distance between well at Depth [Horiz. Dist at Depth]: 650 m
Temperature at Total Depth [Single well, Doublet, Triplet]: 200°C
Combination with other energy sources [Biomass, Biogas plants etc.]: no
Geothermal co-operation [Heat, Electricity etc.]: Electricity

Geothermal potential [MW at Date]: 1,5 MWe (planned in the coming weeks)
Expected Installed capacity [MW/*time* at Date]:
Expected Running capacity [MW/*time* at Date]:

Short description of ***Exploration History*** ***(Limit this section; no more than 200 words):***

Possible keywords:

- Objective of project Demonstrate the production of electricity based on fractured crystalline rocks
- Important dates : 2000 to 2005, drilling of 3 deep wells at 5 km depth
- 2005; 6 month circulation test between the 3 wells
- 2000 to 2007 hydraulic and chemical stimulations
- 2007 to 2008: building an ORC power plant

- Main geological context [stratigraphy, sedimentary fms, volcanism, granite intrusions, faults, graben etc..] Hidden Paleozoic granite covered by 1,5 km of Mesozoic and Cenozoic sediments, Upper Rhine Graben (normal faulting)

- Project funding Europe, Ademe (French agency for Energy and Environment), BMU (German Ministry of Environment), Industrial partners (EDF, ES, Pfalzwerke, EnbW, Evonik)
- Distribution network Electricité de Strasbourg (ES)

Reservoir Characteristics ***(Limit this section; no more than 200 words):***

Possible keywords:

- Type of reservoir [fractured, porous or both] fractured reservoir
- Hosted lithology/rock/mineralogy/fluids [composition] granite
- Fracture system : Normal faults oriented mainly N170°E (high dip >80°)
- Stress field Extensional stress field, Maximum horizontal stress is oriented N170°E
- Temperature range or temperature profile : Temperature profiles gave 200°C at 5km
- Simulation types [hydraulic, thermal, chemical] : hydraulic and chemical stimulation
- Main reservoir characteristics [porosity, (natural) permeability etc.] low natural permeability
- Connectivity between wells : Productivity Index: 0,5 to 0,8 l/s/bar
Injectivity Index: 0,4 l/s/bar
- Occurrence of natural brines : 100 g/L
- Flow rate : <1m3/h
- Storage capacity :

Exploitation ***(Limit this section; no more than 200 words):***

Possible keywords:

- Type of exploitation/power plant [ORG, Kalina cycle, single flush etc.] ORC
- Type of secondary fluid [ammoniac etc.] isobutane
- Production quail ability [day/year] not done till now
- Cooling system [water, air] Air cooling system
- Injection fluid [water, salty water etc.] salty water, cooled geothermal water

- Need for special tools [pumps, turbine etc.] down-hole pumps (Line Shaft Pump, Electro Submersible Pump), turbine with radial flow
- Development/improvement of methods (chemical frac. etc..) hydraulic/chemical stimulation
- Monitoring and optimising of field/area using computer models : not done till now
- Assessment of environmental impact : monitoring of microseismicity, noise evaluation

ORC power plant with isobutene (working fluid)
Radial turbine
Air cooling system
Geothermal water is produced and reinjected
Corrosion/scaling studies

On-going or future works planes ***(Limit this section; no more than 200 words):***

Possible keywords:

- Next important event [major hydraulic test, new geophysical measurements etc.]
- Future plans ? e.g.:
    - New wells
    - Optimizing of existing.. or building new power plants..
    - Implementation of new tools..
    - Implementation of new methods..
    - .. new exploration phase..

A Line shaft pump (LSP) will be installed in GPK2 well at 350 m depth

A Electro-Submersible Pump (ESP) will be installed in GPK4

The geothermal power plant is under constructing

Tracer experiments between the injection well and the production wells

Corrosion/scaling studies in the surface geothermal loop

ENGINE partners involved in the Project:

- Use list of partners (No.1–31) from ENGINE Web-site http://engine.brgm.fr/partners.asp

BRGM, GeoWatt, DHMA (ETH Zurich, CREGE, Polydynamics Zurich), Mesy, CNRS, IFE, GGA, BGR

Main References *(no more than 5 references):*

BARIA R., R. JUNG, T. TISCHNER, J. NICHOLLS, S. MICHELET, B. SANJUAN, N. SOMA, H. ASANUMA, B. DYER, J. GARNISH (2006), "Creation of an HDR/EGS reservoir at 5000 m depth at the European HDR project", in Proc. 31st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 30-February 1, 2006.

CHARLETY J., CUENOT N., DORBATH C., DORBATH L., (2006). Tomographic study of the seismic velocity at the Soultz-sous-Forets EGS/HDR site. Geothermics 35, 532–543.

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GÉRARD A., GENTER A., KOHL T., LUTZ Ph., ROSE P., RUMMEL F., (2006). The deep EGS ("Enhanced Geothermal Systems") project at Soultz-sous-Forêts (Alsace, France), Geothermics, Vol. 35, 473-483.

The European EGS project at Soultz-sous-Forêts: from extensive exploration to power production

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***Abstract*-- The European EGS project of Soultz-sous-Forêts (France) which was first investigated in 1987 is aimed at producing power by the extraction of the heat stored in deep, fractured crystalline rocks. Extensive research and development contributed to get a better understanding of the geothermal reservoir: large-scale hydrothermal circulation occurs within a network of large permeable faults developed within a Tertiary graben. 3 deep wells have been drilled down to 5 km depth, where a rock temperature of 200°C was reached. At the bottom depth, the horizontal distance between the producing wells is over 1.3 km length, knowing that the injection well is located in the middle. Several hydraulic and chemical stimulations were performed and combined in order to reactivate the system of fractures, which are often sealed by natural hydrothermal deposits. This led to improvement of injectivity and productivity of the wells. After a successful 5-months circulation test done in 2005, we are now building a pilot power plant. Two types of production pumps will be tested for this purpose and a first ORC conversion module of 1.5 MWe will be installed and tested in the beginning of 2008. If the results are promising, a second module should be later installed.**

***Index Terms*—Crystalline rocks, deep wells, Enhanced Geothermal Systems (EGS), geothermal energy, Organic Rankine Cycle (ORC), permeable fractures, stimulation.**

I. Introduction

THE European EGS (Enhanced Geothermal Systems) project located in Soultz-sous-Forêts, Alsace, France started in 1987 from the will of the European Commission to develop new sources for power production. The aim of the project is to produce electricity from the heat stored in deep, fractured crystalline rocks. As the geological conditions are very specific, that means that there is no evidence of thermal activity on surface compared to other conventional high enthalpy geothermal sites, the project has needed extensive research and development. The main objectives of the research were a better characterization of the underground geothermal reservoir and a better understanding of the hydrothermal circulation, leading to an optimization of the access to the hot water resource. This corresponds to the first phase of the project, during which 3 deep boreholes were drilled to a depth of 5 km. The second (and current) phase of the project consists in the building of a pilot power plant. A first demonstration module of 1.5 MWe is being installed, as well as all surface facilities. The chosen heat-power conversion scheme is the Organic Rankine Cycle (ORC). This conversion module should be tested in the beginning of 2008 in order to get an estimate of the sustainability of the system, which is mainly linked to the long-term stability of the temperature of the produced water. The produced power should be injected into the French power network.

This project is supported by public funding from the European Commission, ADEME (French agency for environment and energy), BMU (German ministry of environment) and private funding from EDF and Electricité de Strasbourg (France), Pfalzwerke AG, EnBW AG and Evonik Industries AG (Germany).

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II. Geothermal Settings

Soultz-sous-Forêts is located in the northeastern part of France in the northern part of the upper Rhine Graben (Figure 1). This site was chosen because of the observation of a large thermal anomaly in the region and because of a good knowledge of the shallow geology, which was due to former oil exploitation.

A. Geological Settings

The site is located within a Tertiary graben. The shallow geology (0 to 1400 m depth) consists in sedimentary layers, overlaying the crystalline basement, which is made of altered and fractured granitic rocks which are older than 330 My [1] and then not related to the present-day thermal anomaly. The geothermal reservoir, into which the boreholes are drilled, is developed within the crystalline rock at a depth between 4 and 5 km.

B. Temperature Settings

The temperature profile from the surface down to 5 km depth is presented on figure 2. It was recorded in the 3 deep boreholes with downhole measurements. The geothermal gradient exhibits an irregular shape: around 10°C/100 m in the first 1000 m, then a decrease to 1.5°C/100 m to 2500 m depth and then 3°C/ 100 m to 5 km depth (maximum depth for measurements) [2] [3]. The shape of the gradient is related to the presence of convective cells and fluid circulation within the granite basement [4][5][6].

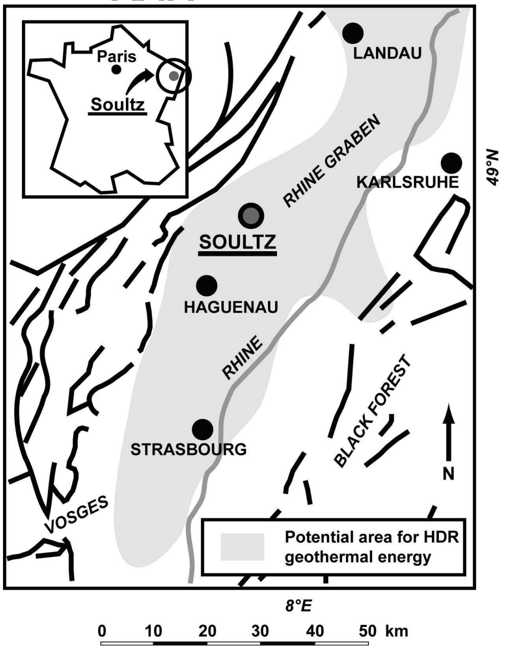

Fig. 1. Location of the geothermal site of Soultz-sous-Forêts. The zone with the highest thermal anomaly is presented in grey color.

C. *Fracture Network*

It has been observed that the underground water circulation is driven by the network of permeable fractures. Extensive research has been made to characterize the properties of the fractures. Geophysical borehole measurements, coring and cuttings analysis showed that fractures, which show a low permeability are almost oriented in a North-South direction and dip sharply [7]. Moreover it appears that most of the fractures are sealed by hydrothermal deposits, mainly, calcite, silica and clays, which decrease the global permeability of the system.

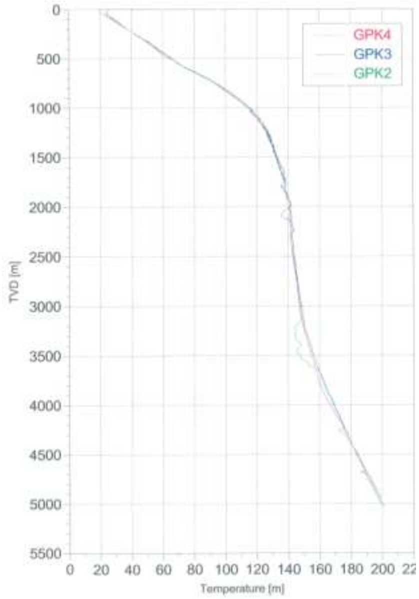

Fig. 2. Temperature profile from the surface to 5 km depth in each well.

The concept of Enhanced Geothermal System comes from this observation. As the overall permeability of the system is not high enough to ensure good hydraulic performances, it is necessary to improve the medium, that is, to reactivate the circulation system by reopening the fractures and establish a connected permeable network. This could be done through either hydraulic or chemical treatments, called "stimulation", and described below.

III. Access to the Water Resource

5 deep boreholes were drilled at the geothermal site into the granitic basement. One is 3600 m deep, one is 2200 m deep and the three others reach 5000 m depth. All have been at least once stimulated to improve their connection to the fractures network.

A. *The Deep Boreholes*

Figure 3 describes the trajectory of the deep boreholes.

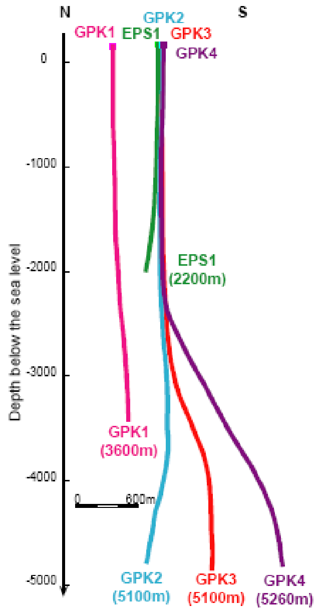

Fig. 3. North-South cross-section of the trajectory of the deep boreholes at Soultz. In brackets is the measured or logging depth [8].

EPS1 (in green) is 2200 m deep (measured depth). This well was cored from 930 m depth to bottom and is currently used as seismic observation borehole. GPK1 (in magenta) is 3600 m deep and was the first drilled well. GPK2 (in blue), GPK3 (in red) and GPK4 (in purple) reach a depth of around 5 km and form the geothermal triplet. GPK2 and GPK4 are set as production boreholes and GPK3 is used to re-inject the cooled water, once its calories have been collected. The wellheads of the GPK-2, -3 and -4 are only 6 m far apart from each other, while there is a distance of roughly 650 m between each bottom hole: this allows the water to circulate on rather long pathways in contact with hot rocks, so that it could be reheated before being pumped again. Such requirements implied that the boreholes' trajectories have to be deviated from the vertical. For instance, the trajectory of GPK4, which is the most deviated, makes an angle of around 30° with vertical.

B. Improvement of the Hydraulic Parameters of the System

Two kinds of experiment were tested at Soultz to enhance the hydraulic performance of the geothermal system. The "classical" treatment is the hydraulic stimulation. More recently we also tried to perform chemical stimulations.

1) Hydraulic Stimulations:

Hydraulic stimulations consist in injecting large volume of water (several thousands of cubic meters) at high flow rates (generally, more than 40 l/s), in order to increase the downhole pore pressure, which tends to induce shearing along the fractures planes [9]. This mechanism can help creating permeability within the fracture plane, as the sealing deposits are removed, and also at connecting permeable fractures between them.

After each drilling operation, a hydraulic stimulation was performed in order to:

- improve the connection of the borehole to the network of fractures, that is, increase the permeability of the fractures, which are intersected by the borehole or which are present in the vicinity of the borehole,
- try to improve also the permeability of fractures, which extend far from the borehole.

The direct consequence of hydraulic stimulation is induced microseismicity. On one hand, this could have a negative impact on the population, as some of the earthquakes of larger magnitude (generally higher than 2) can be felt in the surroundings, but on the other hand, induced microseismicity is a mean to monitor the effectiveness of the treatment. The analysis of the extension and the density of the "microseismic clouds" (Figure 4) can give insights about permeability improvement within the geothermal reservoir. Figure 4 summarizes the microseismicity induced during all stimulation tests, which were performed at Soultz, and recorded with a seismic network, installed in observation boreholes [13][14][15]. More than 10000 seismic events can be recorded in each test. The stimulated volume is around 2 km long, 0.5 km wide and 1 km thick. The highest density of microseismic events is observed in the vicinity of the bottom holes, meaning that hydraulic stimulations are mostly effective in that area.

2) Chemical Stimulations:

As the hydraulic performance of the boreholes were not at the required level after all hydraulic stimulations, so that further improvement was necessary, and taking into account that we had to limit the seismic activity, we performed several chemical stimulations. The goal is to try to dissolve the hydrothermal deposits sealing the fractures. Therefore a small proportion of chemicals is added to the injected water. Basic chemical stimulations with diluted HCl were performed in the three wells.

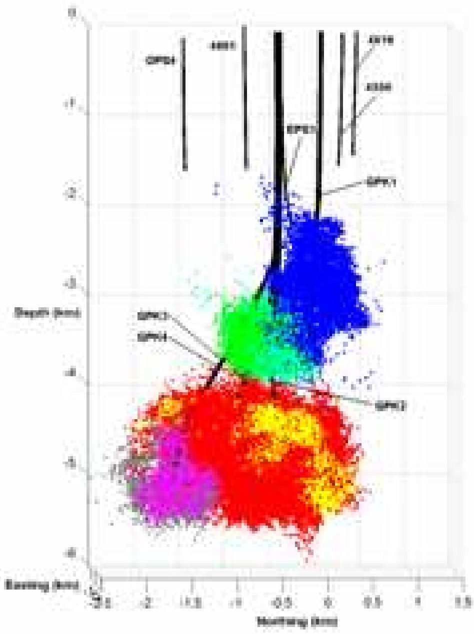

Fig. 4. Microseismic activity induced during stimulation tests. In dark blue, 1993 GPK1 stimulation; in cyan, 1995 GPK2 stimulation; in green, 1996 GPK2 stimulation; in yellow, 2000 GPK2 stimulation; in red, 2003 GPK3 stimulation; in magenta, 2004 GPK4 stimulation; in grey, 2005 GPK4 stimulation. The upper clouds correspond to the development of the former shallow reservoir (3000-3800 m depth) and the lower clouds show the actual reservoir around 5 km depth.

A one-year program was defined in order to select diverse products according to the targets, which are specific known minerals. The program of chemical stimulation was as follows [10]:

- RMA (Regular Mud Acid); the mixture is composed of HCl and HF. The target was minerals like clays, feldspars and micas.

- Chelatants (NTA, nitrilotriacetic acid); the goal was to dissolve calcite.

- OCA (Organic Clay Acid), required for high temperature medium with high clay content. It is composed of citric acid ($C_6H_8O_7$), HF, HBF_4 and NH_4Cl (Schlumberger catalogue). It has a retarding effect, which allows the chemicals to act deeper in the fractures.

It was specially designed for GPK4, as this borehole exhibits a poor productivity index after hydraulic stimulations and the OCA was also performed in GPK3.

3) Results:

After all hydraulic and chemical stimulation tests, improvements of hydraulic performances of the boreholes have been made.

- GPK2: The initial productivity value, before any stimulation was estimated between 0.01 and 0.03 l/s/bar [16]. After all stimulation tests, the productivity was increased to around 0.8 l/s/bar; this value was estimated during a circulation test and is close to the expected goal of 1 l/s/bar.

- GPK3: An initial productivity value of around 0.3 l/s/bar was calculated [17]. After hydraulic and HCl stimulation, this value remained almost unchanged at 0.35 l/s/bar. It rose up to 0.39 l/s/bar after the OCA stimulation.

- GPK4: After 2 hydraulic stimulation tests, the productivity index increased from an initial value of 0.01 l/s/bar to 0.2 l/s/bar [17]. Figure 5 shows the improvements done through the program of chemical stimulations [11]. The reached and stable value is around 0.5 l/s/bar). The data were recorded during various production tests.

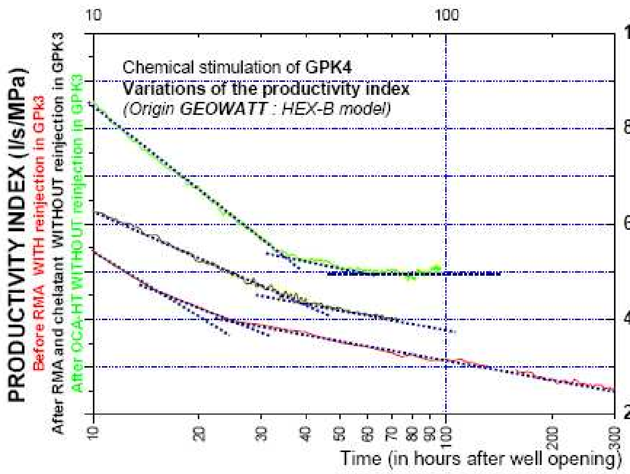

Fig. 5. Evolution of the productivity index after chemical stimulations.

Even though the productivity index of GPK3 and GPK4 do not reach the expected value, it was decided to continue with the building of the power plant and perform the next circulation test with a power output. It is nevertheless expected that productivity and injectivity should increase during circulation, as rock debris and scales, which could plug the access to the rock formation, could be little by little removed by filtering.

IV. POWER PRODUCTION

Based on the above exploration and developments, it was decided to test a first conversion module of 1.5 MWe. The different components of the power plant are installed by the end of 2007 and power production should begin in March 2008.

A. Basic Principles and Objectives

Figure 6 presents the basic concept of the geothermal pilot plant as it is expected to run. If a production flow rate of 70-100 l/s is reached, corresponding to a thermal power output of roughly 50 MW, the power plant could deliver around 5 MW of electrical power. To reach this goal, it is necessary to install production pumps into the boreholes, because the artesian production flow rates are not sufficient.

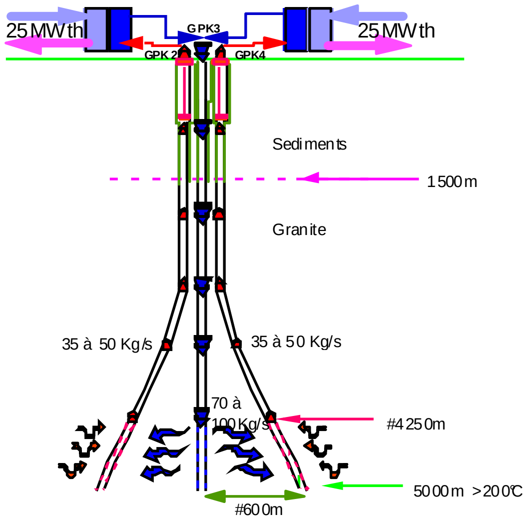

Fig. 6. Principle of the geothermal power plant developed at Soultz.

B. Production pumps

2 types of production pumps will be tested, to see if further improvements of the pumping technologies have to be made, regarding the specific conditions of the EGS projects: high temperature and a geothermal fluid, which is corrosive brine containing rocks cuttings. The test will also give insights about the real capacity of the system in term of flow rate, as it is difficult to extrapolate the flow rate obtained under artesian conditions to pumping conditions.

- Line Shaft Pump (LSP, Figure 7): the pump itself is in the well, the motor is at surface and the connection is done through a line shaft. 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. Issues related to corrosion and lubrication of the shaft should also be carefully studied. The pump should be installed at 350 m depth into GPK2, which presents good verticality and is the best producer.

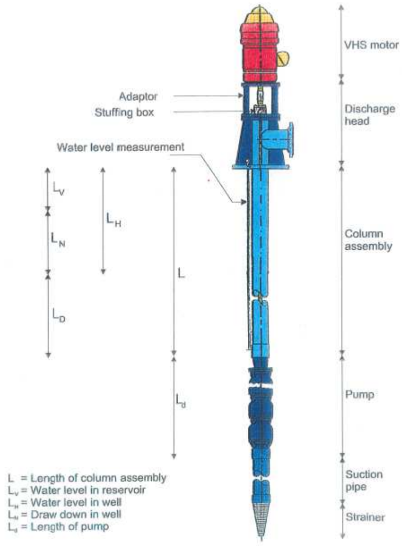

Fig. 7. Scheme of the LSP pump (IGE Ltd, Iceland)

- Electro-Submersible Pump (ESP, Figure 8): both the pump and its motor are installed into the well at any required depth (no depth limitation). The technology is well-known for standard conditions, but the problem is to adapt the pump to geothermal conditions: high operating temperature, metallurgy and resistance to corrosion require a specific design. The ESP technology has been adapted from oil industry SAGD (Steam Assisted Gravity Drainage) where the ESP can operate up to 218°C. The pump should be installed at 500 m depth in GPK4, which is the lower productive well.

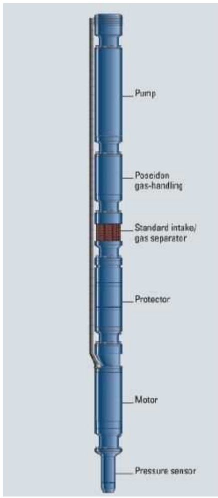

Fig. 8. Scheme of the ESP pump (Reda/Schlumberger)

C. Conversion Cycle

Due to the quality of the geothermal brine (high salt content and corrosive compounds), it cannot be vaporized and thus cannot feed directly the turbine. The produced heat shall be transferred to a secondary circuit which involves a low boiling point working fluid. This is the principle of binary cycles. Two kinds of binary cycles were studied for the case of the Soultz-sous-Forêts project: Organic Rankine Cycle (ORC) and Kalina Cycle. Even though Kalina cycle has in theory a higher efficiency, the technology is far more complex than ORC cycles with very few working references around the world. As the purpose of the project is first to demonstrate the feasibility of power production with such a system, the ORC technology has been preferred.

1) The ORC Conversion Scheme:

Figure 9 presents the principle of the ORC conversion technology.

In that frame, the geothermal fluid (expected temperature: 175°C-185°C) enters a first heat exchanger (Vaporizer), transfers the heat to the working fluid, which is transformed into its steam phase to feed the turbine.

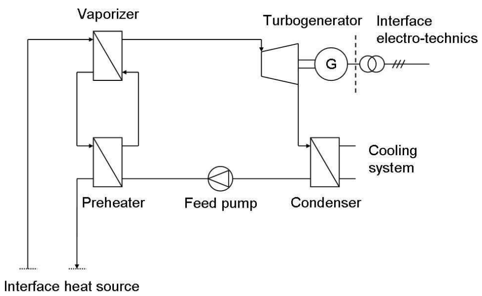

Fig. 9. General scheme of an ORC power plant

Once it expanded in the turbine, the working fluid enters a second heat exchanger (Condenser) to get condensate. A feed pump then pressurizes it before entering a pre-heater, which increases the global efficiency of the system, by the use of the heat, which is still available at the output of the turbine. Figure 10 presents the ORC power plant adapted to the Soultz project, which is supplied by a joint consortium between Cryostar and Turboden. Temperature and pressure are indicated at each step of the cycle.

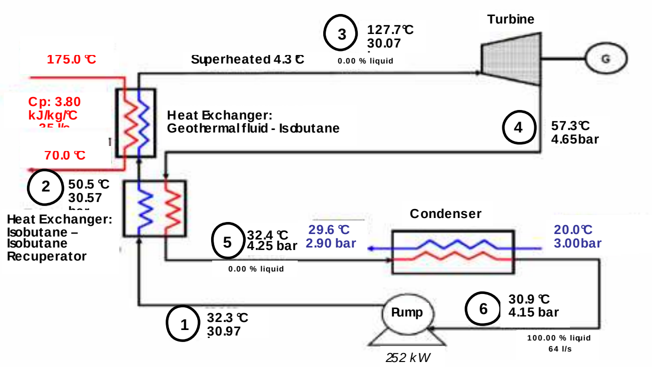

Fig. 10. ORC cycle for the Soultz power plant [12]

2) Working Fluid:

In ORC binary plants, the working fluids are mostly organic fluids. Here isobutane was proposed by the supplier of the ORC system. This high molar mass fluid shows a lower heat of vaporization (12℃ at atmospheric pressure), which allows high running pressures and high flow rates, with a limited volume of fluid and a rather low heating source.

3) Cooling System:

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. Figure 11 shows the air cooling system being installed.

Fig. 11. Installation of the air cooling system

4) Turbine and Generator:

The turbine (Figure 12) is radial and should operate at around 13000 rpm.

Fig. 12. The turbine being installed.

The generator (Figure 13) is asynchronous and is running at around 1500 rpm. A gearbox is installed between the two.

The generator shall deliver 11 kV and the produced power will be increased and injected into the 20 kV local network.

D. Upcoming Operations

2 kinds of operations are planned for the beginning of 2008. The first is the long-term test of the 1.5 MWe power plant and the second is a production test involving GPK4. The ORC unit is planned to run with the geothermal water produced from GPK2 only, once all the components of the plant will be installed and connected. This will allow getting many data about the long-term behaviour of the system. The important issues are:

Fig. 13. Generator (foreground) aligned with the turbine.

- The sustainability of geothermal water production, and consequently, of power generation,
- The behaviour of the production pumps, especially their ability to withstand wearing, corrosion and temperature,
- The seismic response of the reservoir under long-term circulation conditions.

As the borehole GPK4, since the improvement of its hydraulic parameters, has never been fully tested under production conditions, a further test is necessary before connecting the well to the power plant. So a test circulation loop will be installed in parallel to the main circulation loop. It is also useful to have this secondary system in case of maintenance or stop of the power plant: as stopping the downhole production pumps should be avoided, the production can be transferred to this loop. It involves other heat exchangers and a second air-cooling system to simulate the transfer of heat from the geothermal water. The overall scheme of the installation is presented on figure 14.

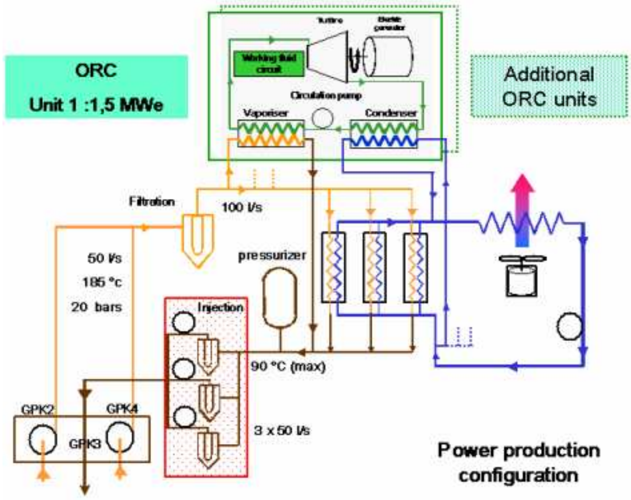

Fig. 14. Scheme of the circulation loops. In yellow: production line; in brown, re-injection line; in green, power production loop; in blue, circulation loop for testing.

The system is built so that the production coming from each well or both can easily be used to feed either the power production loop or the testing loop. If the sustainability of the production is established, then one or two other ORC units could be added to increase the power production of the plant.

V. Conclusion

After 20 years of extensive research, the Soultz project is about to deliver its first power production. The success of the demonstration power plant could open the way for a new kind of geothermal power plants using the heat stored in deep, fractured crystalline rocks. The Soultz project has indeed yield to a lot of scientific concepts and technical developments, as well as a better knowledge of the deep, hot, geothermal reservoir. The project has also been a test site for a lot of industrial equipments, which needed to be adapted to the specific temperature and water conditions. The last unknown is the long-term sustainability of power production, which will be tested in 2008. Therefore the methodology to develop and run such a project is now quite clearly established and can be used to develop other future EGS project, involving similar conditions of geology, temperature and water resource. For example a geothermal project has just started with power production in Landau, Germany, whose development took benefits from the experience gained in Soultz-sous-Forêts [18].

VI. References

Periodicals:

[1] A. Cocherie, C. Guerrot , M. Fanning, and A. Genter (2004), “Datation U-Pb des deux faciès du granite de Soultz (Fossé Rhénan, France)”, *C.R. Geoscience* 336, pp. 775-787.

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VII. Biography

Nicolas Cuenot received in 2000 a Master's Degree in Engineering Geophysics at the Ecole et Observatoire des Sciences de la Terre (EOST), University Louis Pasteur in Strasbourg (France). His main research interest was seismology and he began a PhD work at the EOST. His studies dealt with the analysis of the microseismicity induced by hydraulic stimulation at the EGS site of Soultz-sous-Forêts, in order to characterize the physical properties of the geothermal reservoir. Then in 2005 he joined the EEIG "Heat Mining", which manages the Soultz project. He is in charge of the monitoring of the microseismic activity. This involves analysis of the recorded data, but also installation and maintenance of the downhole seismological sensors. His duty was then extended to the general environmental impacts of the project, that is, evaluation and prevention of all possible problems, which could be caused on the surroundings by the development of the project. He is also involved in different kinds of geophysical measurements, which are performed in collaboration with various institutes or companies.