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From HOT DRY ROCKS to ENHANCED GOETHERMAL SYSTEMS: The SOULTZ-sous-FORETS PROJECT

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In a traditional industrial geothermal plant, the objective is to exploit the heat stored in the ground through the production of existing geothermal fluids. Like all energy production systems, geothermal plants are characterized by their production power, which is simply the product of the produced flow rate, the heat capacity of the geothermal fluid and the difference between the temperature of the fluid at the production wells and that at the re-injection wells.
Traditionally, two different types of geothermal energy systems are considered: High enthalpy systems that produce electricity and low enthalpy systems that produce heat for direct use, like space heating. But heat cannot be transported over long distances (maximum of 15 to 20 km, in the best of cases), and exploitation of low enthalpy geothermal energy (temperature of geothermal fluid below 100°C) has been restricted to domains where high porosity and permeability (located either in zones of volcanic activity or in proper sedimentary layers) is also a site where heat is needed locally commercially.
Further, because of the poor efficiency of the heat to electricity conversion for temperatures lower than 250°C, high enthalpy systems have been restricted to very specific site conditions, mostly encountered in volcanic regions. Its present potential remains fairly limited. This prompted, in the mid seventies of the last century, some research activity in the so called domain of Hot Dry Rocks (HDR), in which the objective was to develop artificial geothermal systems in rock masses with temperature high enough (larger than 300°C) for electricity production but with no pre-existing geothermal fluids in commercially significant quantity. Unfortunately, the experiment undertaken near Los Alamos, at Fenton Hill (New Mexico) failed to reach most of the anticipated figures for an economical plant and the project was stopped in the mid eighties.
But the recent development of binary cycles for electricity production out of geothermal fluids has rendered commercially attractive temperatures in the 150-200°C range, especially when combined with direct use of heat. This range in temperatures is encountered in vast domains of the earth, around depths of 5 km, but in most places there is too little quantity of geothermal fluid to warrant the development of an economical geothermal plant. Hence the original HDR concept has evolved toward that of Enhanced Geothermal System (EGS) in which the objective is to stimulate the local permeability of a deep rock mass, whether it involves or not pre-exiting geothermal fluids, and whether it concerns the production of electricity, the production of heat for direct use, or a combination of both applications.
In this paper, first the main features to be considered for the design of an economical EGS system are presented. Then some results obtained at the existing experimental site of Soultz-sous-Forêts in north eastern France are discussed. Like most EGS systems developed or planned in north-western Europe, the experimental Soultz program aims at producing electricity out of rocks at about 180-200°C encountered at depths between 4 and 5 km.

Reservoir Engineering elements that control the design of an economical EGS system

Through the local thermal gradient at a given site and its variation with depth, the planned production temperature at a geothermal plant imposes the depth at which the reservoir is to be developed. Then the planned power production of the plant imposes the total production flow rate that is needed for reaching the expected goal. This production flow rate in turn defines the number of production wells and injection wells required for the plant, given the hydraulic characteristics of the stimulated reservoir. The efficiency of such deep geothermal loops depends on both the power required to produce and to re-inject the circulating fluid as well as the fluid losses that may occur within the reservoir after re-injection.
Once the system has been developed and fits its design requirements, a most important consideration is the life time of the system. The lifetime has two very different definitions. From the economical perspective, it is the time required for all the investment involved in the plant development to be recovered and an acceptable profit to be made. From the physical perspective, it is the time during which the temperature of the produced fluid remains above a given threshold, which is controlled by the efficiency of the commercial exploitation of the produced heat. Hence, an EGS system is of commercial interest only if the commercial life time is smaller than the physical lifetime.
This physical life time depends on the downhole efficient heat exchange area of the reservoir. Its evaluation has been conducted so far only with models derived from evaluation of the efficient heat exchange area as determined from chemical tracer tests. But many questions have been raised on the long term evolution of this efficient heat exchange area, whether it expands thanks to thermal cracking, or whether it shrinks because of the formation of more and more localized channels.
The goal of the experimental geothermal program that has been conducted at Soultz-sous-forêts, over the last 20 years, has been first to develop a system large enough to be significant for the design of future EGS projects of economical interest (combined use of heat and production of electricity). We outline here after the main actions that have been undertaken to reach the present characteristics of the system which is operating today. It is hoped that the long term operation actually planned will provide the presently missing data characterising the aging of such systems.

Reservoir development from hydraulic stimulations at Soultz

While the thermal gradient was close to 100°/km in the upper sediments of the Soultz area, it dropped nearly to zero once the granite was reached below the sediment, around 1500 m. Then a slow temperature increase was observed at depths greater than 3000 m and finally a 200 °C temperature was reached around 5 000m. So the reservoir has been developed between 5 and 4 km depth.
Three wells have been drilled, a vertical one for injection and two deviated wells for production, aligned on the direction of the maximum horizontal principal stress direction (N 170°E). At ground surface the three well heads are within 50 m from each other while the distance between the bottoms of the production wells at 5 km depth is close to 1 km, about 500 m on both sides of the vertical injection well (see figure)
The natural injectivity or productivity of the wells ranged from 0.02 to 0.2 $ls^{-1}bar^{-1}$ so that a massive hydraulic stimulation program was undertaken. The objective was to induce shear along existing fractures rather than develop real hydraulic fractures. Indeed, real Hydraulic Fractures (i.e. normal to the minimum principal stress) would have required the emplacement of propant the stability of which was more than uncertain at those temperatures.
While significant improvement of the productivity was achieved by large scale hydraulic stimulation, it became clear that the system could be operated only through a loop system. The objective was to pump from the two deviated production wells, inject into the central

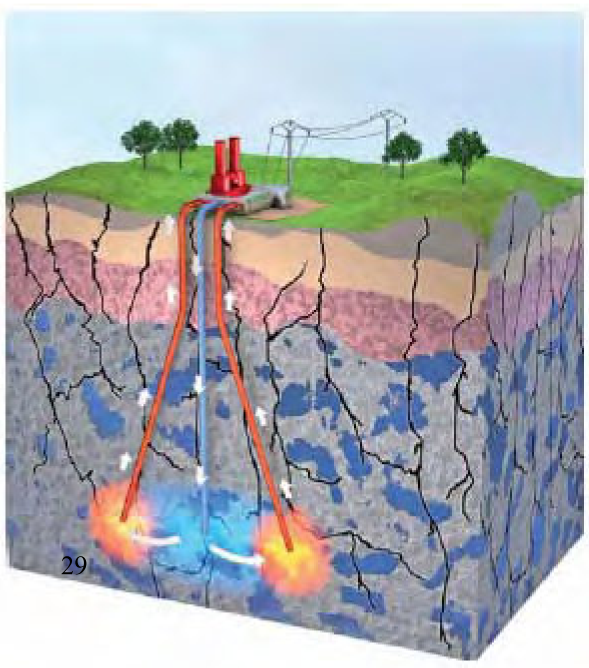
vertical well and investigate the possibility of operating under high pressure in order to decrease the system hydraulic impedance and control scaling problems in pipes.
But induced seismicity has revealed to be the limiting factor for such stimulation operations. Indeed events with magnitude close to 3 have been observed at the end of stimulation experiments and the goal, thereafter, has been to limit the induced seismicity below thresholds felt by the local population.
During the various large hydraulic stimulations close to 200 000 m^3 of water have been injected altogether over the years, but the hydraulic performance of the system remained lower than the values considered to be of economical interest. Indeed the goal was to reach production rates in the order of 30l/s per well while the achieved rates was 12l/s for one well and about 3 l/s for the other well. But results from chemical tracer tests suggested that a large geothermal reservoir had been developed (only 30 % of the injected tracer has been recovered suggesting large mixing of water during circulation).
So, chemical stimulations were undertaken in order to improve the connectivity between the boreholes and this newly developed geothermal system.

Results from chemical leaching

Several acid systems such as hydrochloric acid, Regular Mud Acid (a mixture of hydrochloric and hydrofluoric acids) and Organic Clay Acid were injected to dissolve mineral deposits filling the natural fractures close to the borehole. Whereas acid treatments have resulted in a productivity increase up to 50% in both production wells, nearly no effect was observed in the injection well.
Results from these stimulations experiments were evaluated using short term hydraulic tests, conventional pressure transient analysis, interference pressure data, microseismic monitoring as well as temperature and flow logs.
Although injections occurred along the whole open hole section of the wells, stimulation revealed efficient mostly in pre-existing fractures where the filling material could be dissolved. This suggests that further chemical treatments should be focussed within these specific zones.

The present situation

Results have demonstrated that the significant flow zones in the granite at Soultz involve nearly exclusively large pre-existing fractures. Large hydraulic stimulation programs increase significantly the volume of the geothermal reservoir but they induce seismicity felt by the population on ground, a feature that must be kept in better control if EGS is to be generalized.
Chemical stimulation improves drastically the connectivity between these large fractures and the wellbores. They do not generate large heat exchange area.



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).(after Genter et al., 2009)

In summer 2008 a pump with a 350 m long line shaft, has been installed in one of the production wells (GPK2) and has produced 25 l/s of water at 155°C during about 6 weeks. In the second production well (GPK4), an electro-submersible pump set at about 500 m depth has produced during the same period about 12.5 l/s of brine at 155°C.
Some scaling problems occurred along the long shaft pump that resulted in the failure of the shaft. But the scaling problem has been solved and today the system is producing regularly. The electrical production capacity of the system is 1.5 Mwe. The electrical generator delivers 11kv that will be soon injected into the local electrical power network.
Hopefully, this production experiment will be conducted long enough so as to produce data on the aging characteristics of such an EGS system.

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