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The Soultz-sous-Forêts' Enhanced Geothermal System: A Granitic Basement Used as a Heat Exchanger to Produce Electricity

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1. Introduction

The increasing need for energy, and electricity in particular, together with specific threats linked with the use of fossil fuels and nuclear power and the need to reduce CO_2 emissions leads us to look for new energy resources. Among them, geothermics proves to be efficient and clean in that it converts the energy of the earth into heating (domestic, industrial or agricultural purposes) or electricity (Lund, 2007). Numerous geothermal programs are producing energy at present and some of them have been performing for several decades in the USA (Sanyal and Enedy, 2011), Iceland and Italy for example (Minissale, 1991; Romagnoli et al., 2010). From statistics presented in World Geothermal Congress 2010, the installed capacity of geothermal power generation reaches 10,715 MW in the world. It increased by nearly 20% in 5 years. Its average annual growth rate is around 4%. USA, Indonesia and Iceland increased by 530MW, 400MW and 373MW respectively. Many countries all around the world develop geothermal exploitation programs. As a consequence, scientists from the whole world meet each year at the Annual Stanford Workshop on Geothermal Reservoir Engineering to discuss new advances in geothermics.

Conventional geothermal programs use naturally heated groundwater reservoirs. In many sedimentary provinces, depths of a few hundreds of meters are enough to provide waters with a temperature around 90°C. Such resources give rise to low and very low enthalpy geothermics. Very low enthalpy geothermal resources are used through geothermal heat pumps for various purposes including hot water supply, swimming pools, space heating and cooling either in private houses or in public buildings, companies, hotels and for snow-melting on roads in Japan (Yasukawa and Takasugi, 2003). In 1999 the energy extracted from the ground with heat pumps in Switzerland reached 434 GWh. The same level of utilization in Japan would bring the Japanese figure to 8 TWh per year (Fridleifsson, 2000). Technically, heat pumps can be applied everywhere. It is the difference between surface (atmospheric) and underground temperatures at 20 m or deeper that provides the advantage of geothermal heat pumps over air-source heat pumps.

In volcanic zones (like in Iceland), geothermics depends on specific geological contexts that are rather rare on the earth even though quite numerous in specific zones e.g. in the vicinity of subduction zones like around the Pacific Ocean as in Japan (Tamanyu et al., 1998) or in zones where the earth's crust is expanding like in Iceland (Cott et al., 2011). Such geothermics is called high enthalpy. It allows the production of electricity like in the Uenotai geothermal power plant in Japan which started operation in 1994 as a 27.5 MW electric power generation facility (Tamanyu et al., 1998). Electricity production from geothermal resources began in 1904 in Italy, at Larderello (Lund, 2004; Massachusetts Institute of Technology [MIT], 2006). Since that time, other hydrothermal developments led to an installed world electrical generating capacity of nearly 10,000 MWe and a direct-use, nonelectric capacity of more than 100,000 MWt (thermal megawatts of power) at the beginning of the 21st century from the steam field at The Geysers (California, USA), the hot-water systems at Wairakei (New Zealand), Cerro Prieto (Mexico), Reykjavik (Iceland), Indonesia and the Philippines (MIT, 2006).

Complementary to conventional geothermics, Enhanced Geothermal Systems (EGS; also called Engineered Geothermal Systems) aim to develop reservoirs in rocks where little (or no) water is available (Redden et al., 2010). This concept was invented, patented and developed in the early 1970s at Los Alamos National Laboratory and was first called Hot Dry Rock (HDR) geothermal energy. As defined by these early researchers, the practical HDR resource is the heat contained in those vast regions of the earth's crust that contain no fluids in place—the situation characterizing by far the largest part of the earth's drilling-accessible geothermal resource (Brown, 2009).

This concept was developed for electricity production in any kind of area at the surface of the earth even though the geodynamical context is not in favour of geothermics (Redden et al., 2010 and references therein).

However, because of the general low thermal gradient in the earth (30°C/km in sedimentary basins), reaching a temperature around 150-200°C needed for the production of electricity make things more difficult than first considered. Technical and economical problems linked to such deep drillings (Culver, 1998; Rafferty, 1998) have restricted EGS to zones where the thermal gradient is high enough to reduce the depth of the exchanger. Now, EGS include all geothermal resources that are currently not in commercial production and require stimulation or enhancement (MIT, 2006).

Table 1 gives an overview of HDR/EGS programs in the world.

In such difficult technical conditions, one can wonder whether the geothermal energy resource and electricity production process are sustainable. According to Clarke (2009) and authors cited therein, the management and use of the geothermal resource (Rybach and Mongillo, 2006) and the environmental impacts during geothermal energy production (Bloomfield et al., 2003; Reed and Renner, 1995) were the first concern about sustainability of geothermal energy. These studies have shown that there is less impact on land use, air emissions including greenhouse gases, and water consumption from geothermal electricity generation than from fossil-fuel–based electricity generators. However, the environmental impacts from the construction of geothermal energy production facilities being less well understood, especially for enhanced geothermal systems (EGS) subsequent studies were conducted. The life-cycle analysis of the EGS technology (including pre-production process such as drilling, construction, production and transportation) had to be discussed, especially when the potential for large-scale development exists. Because of increased depth and decreased water availability, environmental impacts may be different from those of

Country	Site	Depth (m)	Dates	Production of electricity
France	Le Mayet		1975-1989	
	Soultz-sous-Forêts	5000 (3 boreholes)	1985-	1.5 MWe Since June 2008
Germany	Bad Urach	4500 and 2600	1976-	
	Falkenberg	300	1975-1985	
UK	Rosemanowes	2700	1975-1991	
Australia	Cooper Basin	4300	2001-	
USA	Fenton Hill	5000	1973-2000	
	Coso		2001-	
	Desert Peak	5420	2001-	
Japan	Hijori	2300	1987-	

MWe: MWelectricity (raw production minus consumption of electricty required for the production).
Data after MIT (2006), Davatzes and Hickmann (2009) and Genter et al. (2009)

Table 1. Overview of some HDR or EGS programs in the world.

conventional geothermal power generation. It is expected that EGS will produce less dissolved gas (mostly carbon dioxide CO_2 and hydrogen sulfide H_2S) than conventional energy by recovering the heat through a heat exchanger and reinjecting the fluid without releasing any gas during operation. As concerns subsurface water contamination it is unlikely because all the produced fluid is reinjected. EGS is also characterized by a modest use of land since with directional-drilling techniques, multiple wells can be drilled from a single pad to minimize the total wellhead area (MIT, 2006). EGS requires no storage and the plant is built near the geothermal reservoir because long transmission lines degrade the pressure and temperature of the geofluid as well as the environment. As a consequence EGS power plants require about 200 m^2/GWh while a nuclear plant needs 1200 m^2/GWh and a solar photovoltaic plant 7500 m^2/GWh (MIT, 2006). Most of EGS developments are likely to occur in granitic-type crystalline rocks, at great depth. Careful management of the water resource is unlikely to induce subsidence (lowering of the ground's level as in shallow mining activity; MIT, 2006). Seismic activity linked to engineering of EGS reservoirs during hydraulic stimulation (injection of water under pressure to create or open pre-existing joints) has conducted managers of these sites to prefer chemical stimulations (use of chemicals to dissolve minerals responsible for the sealing of joints) in or close to urban areas (Hébert et al., 2011; Ledésert et al., 2009) in order to avoid earthquakes. Another force of the EGS technology is the possible use of CO_2 instead of water because of its favourable thermodynamic properties over water in EGS applications (Brown, 2000; Magliocco et al., 2011) thus leading to a possible sequestration of carbon dioxide produced by the use of fossil fuel. However EGS might have increased visual impact and noise levels compared to conventional geothermal power plants but no more than fossil fuel driven power plants (MIT, 2006). The highest noise levels are usually produced during the well drilling, stimulation, and testing phases (about 80 to 115 decibels). For comparison, congested urban areas typically have noise levels of about 70 to 85 decibels, and noise levels next to a major freeway are around 90 decibels. A jet plane just after takeoff produces noise levels of about 120 to 130 decibels (MIT, 2006). Finally, considering all these factors, EGS has a low overall environmental impact when the production of electricity is considered compared to fossil or nuclear generation (MIT, 2006). As concerns the demand, supply and economic point of view, MIT (2006) provides a rather detailed analysis.

Geothermal energy and EGS in particular is studied world-wide and the annual Workshop on Geothermal Reservoir Engineering (Stanford, California, USA) allows scientists and industrials to compare data and improve renewable energy production. Proceedings of the workshop can be downloaded very easily and for free on the Internet. As a consequence, the latest advances in geothermal technology are available to the scientific community.

2. EGS technology

Flow rates on the order of 50 $L.s^{-1}$ and temperatures of 150° C to 200° C are required to allow an economical generation of electrical energy from geothermal resources (Clauser, 2006). Heat source risk can be quantified via a detailed assessment of surface heat flow together with measurements of temperature in boreholes (for example, for the Desert Peak Geothermal area, at 0.9 to 1.1 km depth, the ambient temperatures is of ~180 to 195° C in rhyolite tuff and argillite; Hickman and Davatzes, 2010). Thermal insulation (measured on core or cuttings samples) together with precision surface heat flow measurements allows the prediction of temperature distribution at depth in one, two or three dimensions (Beardsmore and Cooper, 2009). For regions outside natural steam systems and high surface heat flow (for example Iceland, Indonesia, Turkey, etc.) conditions necessary for electricity production are met at depths below 3 km provided the underground rock heat exchanger is engineered in order to increase the paths available for the fluid flow. Such systems are called Engineered (or Enhanced) Geothermal Systems (EGS) or Hot Dry Rock (HDR). In these techniques, the host rock is submitted to stimulations (Economides and Nolte, 2000) in order to increase the heat exchange surface between the rock and the injected fluid. Stimulations are derived from petroleum technology where they have been used for decades. The first method consists in the injection of water under high pressure to create irreversible shearing and opening of fractures and is called hydraulic stimulation (Portier et al., 2009). The second method, called chemical stimulation (e.g. Nami et al., 2008; Portier et al., 2009) uses various kinds of chemical reactants to dissolve minerals and to increase permeability. Both methods have proven successful for enhancing permeability at depth but it is still a challenge to plan and control the stimulation process. Details about stimulations can be found in the abundant litterature (e.g. Kosack et al., 2011; Nami et al., 2008; Portier et al., 2009 and references therein). During or after stimulations, tracers are used to assess the connectivity between the wells and the speed of fluid transfer. Many examples of use of tracers are found in the literature (e.g. Radilla et al., 2010; Redden et al., 2010; Sanjuan, 2006). In addition, prior to any stimulation or circulation test between the wells, in-situ stress and fracture characterization have to be considered with great attention in order to better constrain the geometry and relative permeability of natural or artificially created fractures (e.g. Hickman and Davatzes, 2010 for the Desert Peak geothermal field). A subsequent modelling of the 3D fracture network (Genter et al., 2009; Sausse et al., 2010, Dezayes et al., 2011) and of flow and transport along the fractures can be profitably performed (e.g. Karvounis and Jenny, 2011) to predict the behaviour of the thermal exchanger and ensure its financial viability. Such modelling is based on the accurate knowledge of the fracture network obtained through seismic records performed during stimulation or production tests (Concha et al., 2010) and thanks to thorough characterization of the fracture network (Hébert et al., 2010, 2011; Ledésert et al., 2009). When the rock heat exchanger is finally operated, careful reservoir engineering and monitoring has to be performed to ensure the viability of the EGS (Satman, 2011). The produced hot fluid is continuously replaced by cooled injected water. After the thermal breakthrough time the temperature of the produced fluid decreases. However if after a time the field is shut-in the natural energy flow will slowly replenish the geothermal system and it will again be available for production. Therefore when operated on a periodic basis, with production followed by recovery, doublets are renewable and sustainable (Satman, 2011). Triplets (one injection and two production boreholes) are now considered as being the best configuration (MIT, 2006; Genter et al., 2009). However, it must be taken into consideration that when an EGS reservoir is developed through hydraulic fracturing, the size of the reservoir might extend too much and attendant high water losses might occur compromising the sustainability of the project as at Fenton Hill (MIT, 2006; Brown, 2009). When shearing occurs through reopening of pre-existing sealed fractures during hydraulic stimulation (e.g. at Fenton Hill; Brown, 2009) or when the mineral deposits are dissolved through chemical stimulation (e.g. at Soultz; Nami et al., 2008; Portier et al., 2009; Genter et al., 2009) the size of the exchanger is better constrained and fluid losses are limited.

Other risks such as technology (reliable supply of produced geofluids with adequate flow rates and heat content), finances (cost of construction, drilling, delays), scheduling, politics, etc…have to be estimated in order to make an EGS project viable. They are presented in MIT (2006) for the different stages of a project. In addition, seismic risk has to be fully taken into account where EGS programs are to be developed in urban areas in order to produce both electricity and central heating (Giardini, 2009): the Basel (Switzerland) experience (see section 4.4) had to be stopped because of a 3.4 magnitude earthquake generated by stimulation in a naturally seismic area. As a consequence to these numerous constraints, no financially viable EGS program is operating at present but the production of electricity that began at Soultz-sous-Forêts (France) in June 2008 is highly promising.

As a conclusion, Table 2 shows some forces and difficulties of EGS programs inferred from the literature.

Forces	Difficulties
Production of electricity	Deep drilling (technical and financial difficulties)
Sustainability of the resource provided its correct management	Risk of water loss in case of pure hydraulic fracturing
Low to no GHG emissions	Engineering of the reservoir to increase permeability
Low global environmental impact compared to fossil-fuel and nuclear electricity	Adequate flow rate and temperature
Available on continents worldwide	No financially viable program operating at present

Table 2. Forces and difficulties of EGS programs inferred form the abundant literature on the subject (see reference list). GHG: greenhouse gases.

3. The Soultz-sous-Forêts EGS

The Soultz-sous-Forêts′ (called Soultz in the following) project began in the late eighties thanks to a particular geological context. Several zones in France are submitted to high heat flows, among which the Soultz area, because of the development of a rift system in northern Europe (Figure 1). Initiated by a French-German team (Gérard et Kappelmeyer, 1987), the Soultz program 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 present (Genter et al., 2009). The Soultz projetc represents a multinational approach to develop an EGS in Europe.

3.1 Geological context

The Soultz EGS site is located in the upper Rhine graben (Figure 2) where a high heat flow was measured at shallow depth in old oil wells (110 °C/km). Natural water being found in great amount at depth in the granitic heat exchanger, the project was not HDR anymore and was then called EGS since numerous stimulations (first hydraulic and then chemical with several steps and chemical reactants) were necessary to improve the connection between the 3 deep wells (around 5 000 m deep). First investigations of the fracture network showed that they are grouped in clusters separated by little or no-fractured zone, following a fractal organisation (Ledésert et al., 1993).

Figure 2 shows the more detailed location of the Soultz site and extension of the thermal anomaly related to the upper Rhine graben(URG) also showed on a geological cross section on which the Soultz horst can be distinguished.

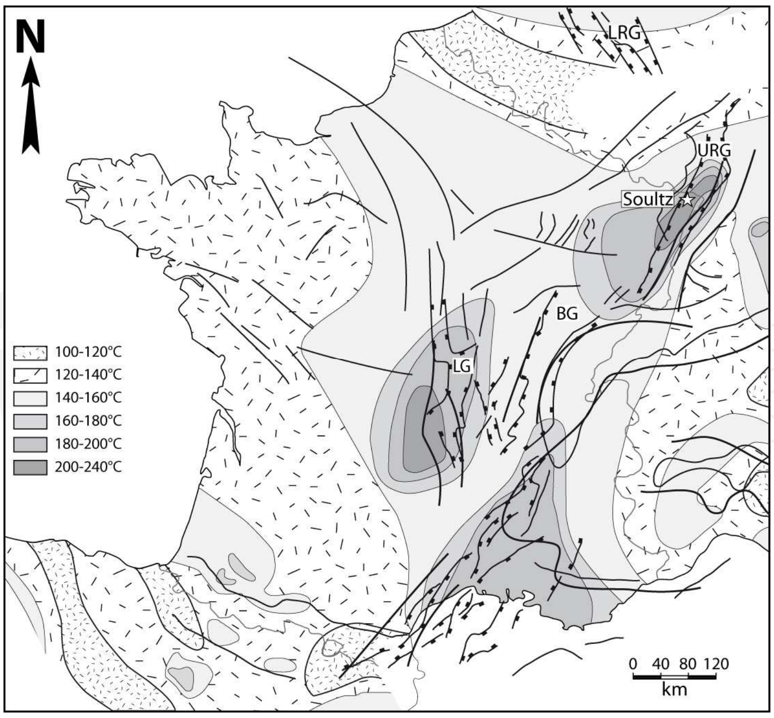

Fig. 1. Map of extrapolated temperatures at 5 km depth and location of some major structural structures (modified after Hurtig et al., 1992 and Dèzes et al., 2004). LRG : Lower Rhine Graben; URG : Upper Rhine Graben; BG : Bresse Graben; LG : Limagne Graben.

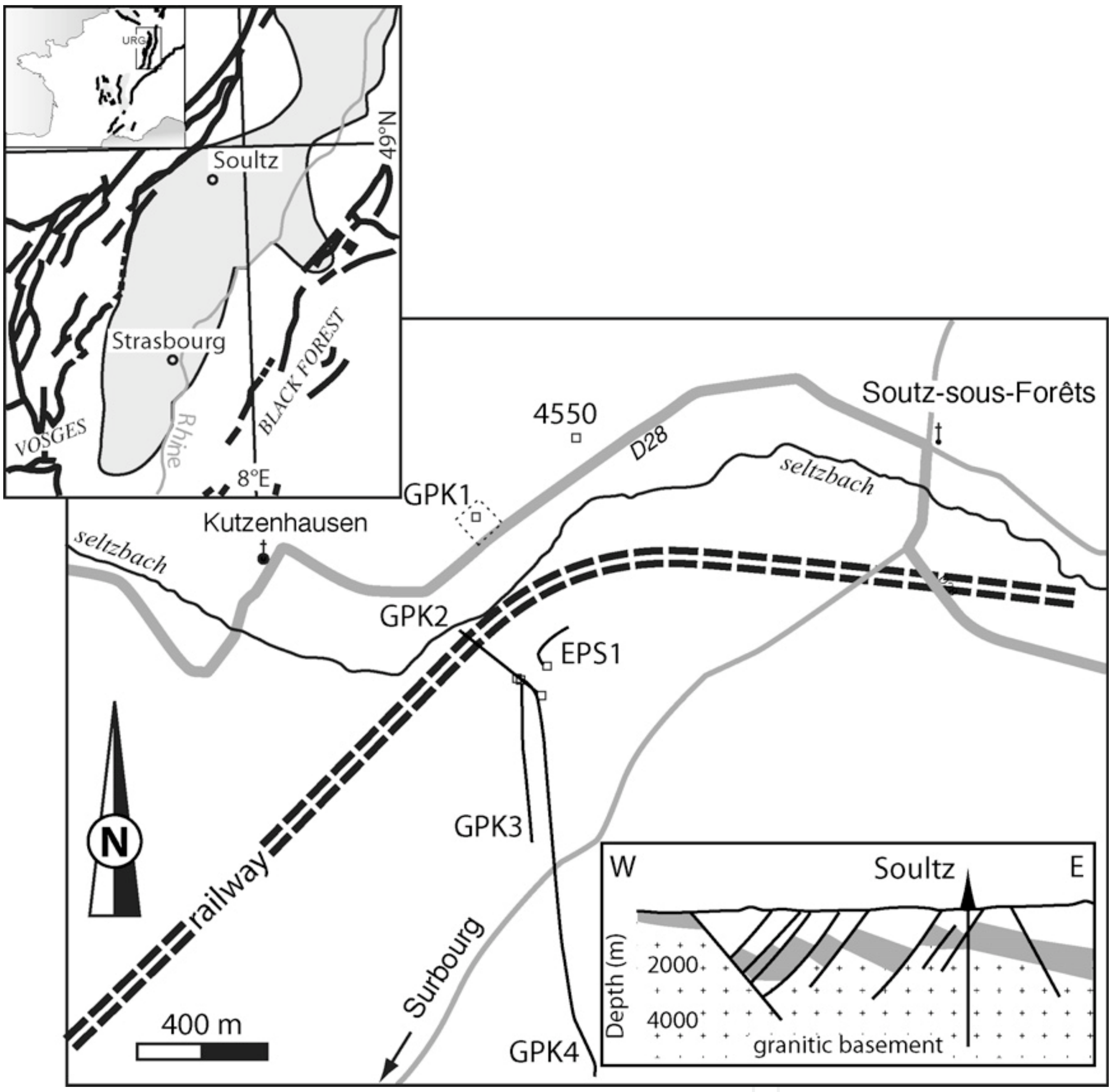

Fig. 2. Location map of the upper Rhine graben (URG) in eastern France and of the Soultz-sous-Forêts' site, 50 km North of Strasbourg, in a zone of high thermal anomaly (grey on the map). Six boreholes are present : 4550 (previous oil well), GPK1 (first HDR borehole), EPS1 (entirely cored scientific HDR borehole), GP2-GPK3-GPK4 (5 000m deep boreholes forming the triplet of the EGS). Their horizontal trajectories are shown on the main map. The E-W geological cross section shows the geometry of the upper Rhine graben and of the Soultz horst. Dots represent the granite while inclined grey and white layers correspond to the sedimentary cover. After Ledésert et al. (2010).

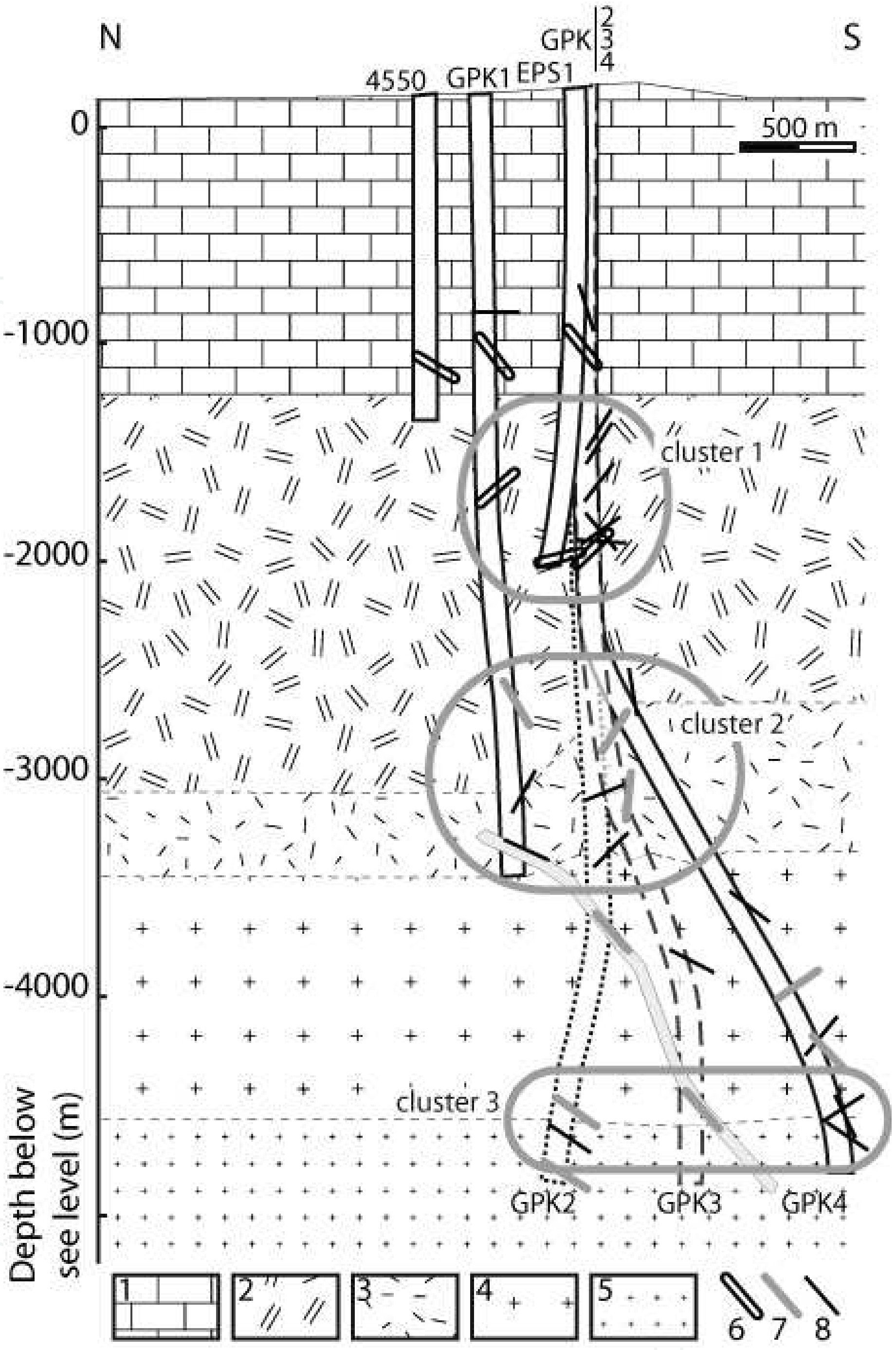

Fig. 3. Cross-section of the Soultz geothermal system. Note 3 zones intensely fractured and altered by natural fluids, noted cluster. A major drain is encountered in GPK1 near 3200m and is found in GPK2 around 3500m and GPK3 close to 4500m (represented with a light-grey curvated wide line). 4550 (oil drill hole); EPS1 (cored scientific hole); GPK1 (scientific hole, destructive conditions, few core pieces). 1: sedimentary cover, 2: standard porphyritic Bt-Hbl granite, 3: standard granite with fractures and vein alteration, 4: Bt+Hbl - rich granite becoming standard granite at depth, 5: two-mica and Bt-rich granite, 6: Level 1 fracture, 7: Level 2 fracture, 8: Level 3 fracture. Figure modified after Dezayes and Genter (2008) and Hébert et al. (2011). Mineral abbreviations according to Kretz (1985), Bt : biotite, Hbl : hornblende.

3.2 Development of the Soultz EGS

The granite body is used as a heat exchanger in which the fracture planes are surfaces of heat exchange between the injected water and the hot rock mass. As a consequence, the knowledge about the fractures is necessary to better understand and predict the behaviour of the heat exchanger. This is why numerous studies have been performed on the natural fracture network (Ledésert et al., 1993; Genter et al., 1995; Sausse et al., 2007, 2008, 2009; Dezayes et al., 2008; Dezayes et al., 2011). Dezayes et al. (2010) have classified the fracture zones into three different categories (or levels) on the basis of their relative scale and importance as fluid flow paths (see complete review in Dezayes et al., 2010). Level 1 corresponds to major fracture zones, which were permeable prior to any stimulation operation (Figure 3) and were subject to important mud loss during the drilling operation. Fracture zones of level 2 are characterized by at least one thick fracture with a significant hydrothermal alteration halo. They showed a flow indication higher than 20% of fluid loss during stimulation. Fracture zones of level 3 show a poorly developed alteration halo and a fluid loss below 20% during stimulation. Figure 3 shows the location of the boreholes and that of fracture clusters that were reactivated during stimulations allowing connection between the wells.

According to the abundant literature on the subject, developing an EGS is a difficult and costly task that deserves thorough studies. The knowledge of the geometry of the fracture network being crucial as explained before, many methods are used to improve it. Concha et al. (2010) indicate that microseismic data can be used profitably in that they provide information about reservoir structure within the reservoir rock mass at locations away from boreholes, where few methods can provide information. They used microseismic events induced from production and hydrofracturing tests performed in 1993 as sources for imaging the Soultz EGS. These tests injected 45,000 m^3 of water at depths between 2850 and 3490 m and resulted in over 12,000 microseismic events that were well recorded by a four station downhole seismic network. Concha et al. (2010) began by determining a three dimensional velocity model for the reservoir using Double Difference Tomography for both P and S waves. Then they analyzed waveform characteristics to provide more information about the location of fractures within the reservoir. Using such methods, it appears that the volume of the exchanger stimulated during operation of the Soultz EGS is approximately $1km^3$.

The Soultz EGS is characterized by three deep boreholes (CPK2, GPK3 and GPK4; ca 5000 m; Figure 3). They were drilled after GPK1 and EPS1 boreholes that could not be used for the EGS development because of technical problems, and oil wells such as 4550 (Figures 2 and 3).

Genter et al. (2009) provide an overview of the Soultz project. The first exploration of the geothermal Soultz site consisted in exploration by drilling at shallow depth (GPK1, 2 km). Then convincing results were obtained between 1991 and 1997 through a 4 month circulation test successfully achieved between 2 wells in the upper fractured granite reservoir at 3.5 km. Based on these encouraging results, 3 deviated wells (GPK2, GPK3, GPK4) were drilled down to 5 km depth between 1999 and 2004 for reaching down-hole temperatures of 200°C (Genter et al., 2009). They form the geothermal triplet. Geothermal water is pumped from the production wells (GPK2, GPK4) and re-injected together with fresh surface water at lower temperature into the injection well GPK3. On a horizontal view, the 3 deep deviated wells are roughly aligned along a N170°E orientation (Figure 2) corresponding to the orientation of both the main fracture network and present-day principal maximal horizontal stress, allowing the best recovery of the injected water. The three deep boreholes were drilled from the same platform, about 6 m apart at the surface whereas at their bottom, the distance between each production well and the re-injection well is about 700 m. The 3 wells are cased between the surface and about 4.5 km depth offering an open-hole section of about 500 m length (Genter et al., 2009).

	GPK3 (injection well)	GPK2	GPK4
Pumping rates (L/s)	15	11.9	3.1
Arrival time for fluorescein (days)	injection	4	24
Volume of fluid	209 000	165 000	40 000
Permeability relative to GPK3 (m^2)		10^{-13}	10^{-15}
Quality of connection with GPK3		High	Low

Table 3. Results of circulation tests between the three deep wells showing the strong discrepancy between the two production wells, GPK2 and GPK4. Data in Sanjuan et al. (2006); Genter et al. (2009) and Kosack et al. (2011).

The geothermal wells were stimulated (hydraulically and chemically) between 2000 and 2007 in order to enhance the permeability of the reservoir that was initially low (Table 3) in spite of a large amount of fractures (up to 30 fractures/m; Ledésert et al., 1993; Genter et al., 1995). Figure 4 provides a synthetic view of the increase in the productivity/injectivity rates for each of the Soultz deep boreholes after hydraulic and chemical stimulations. A 5-month circulation test, carried out in 2005 in the triplet, showed similar results as in 1997 in terms of hydraulics (Nami et al., 2008): in both cases, a recovery of about 30% of the fluid mass was obtained at the production wells showing the open nature of the reservoir (Gérard et al., 2006). This result is opposed to the HDR concept where the reservoir is closed (Brown, 2009) and no water naturally exists in the reservoir prior to its injection. The limited recovered mass of injected fluid was continuously compensated by native brine indicating direct connections with a deep geothermal reservoir (Sanjuan et al., 2006). To give an example of stimulation test, from July to December 2005, about 209 000 m^3 of fluid were injected into GPK3 and 165 000 m^3 and 40 000 m^3 were produced from GPK2 and GPK4 respectively (Sanjuan et al., 2006), yielding a nearly even mass balance. In addition, a mass of 150 kg of 85 % pure fluorescein was dissolved in 0.95 m^3 of fresh water and was used as a tracer injected into GPK3 over 24 hours, while geochemical fluid monitoring started at GPK2 and GPK4. Fluorescein was first detected in GPK2, 4 days after the injection into GPK3. In GPK4, fluorescein was detected only 24 days after the injection. The average pumping rates were 11.9 $L.s^{-1}$ in GPK2, 15 $L.s^{-1}$ in GPK3, and 3.1 $L.s^{-1}$ in GPK4, already indicating a reduced water supply to GPK4 (Sanjuan et al., 2006; Genter et al., 2009). These results show that the hydraulic connection is very heterogeneous: it is rather easy between GPK3 and GPK2 while it is much more difficult between GPK3 and GPK4 (Table 3). The permeability in most of the reservoir is on the order of 10^{-17} m^2. A good connection is naturally established between GPK2 and GPK3 with a mean permeability on the order of 10^{-13} m^2, while a barrier exists to GPK4 (Kosack et al., 2011).

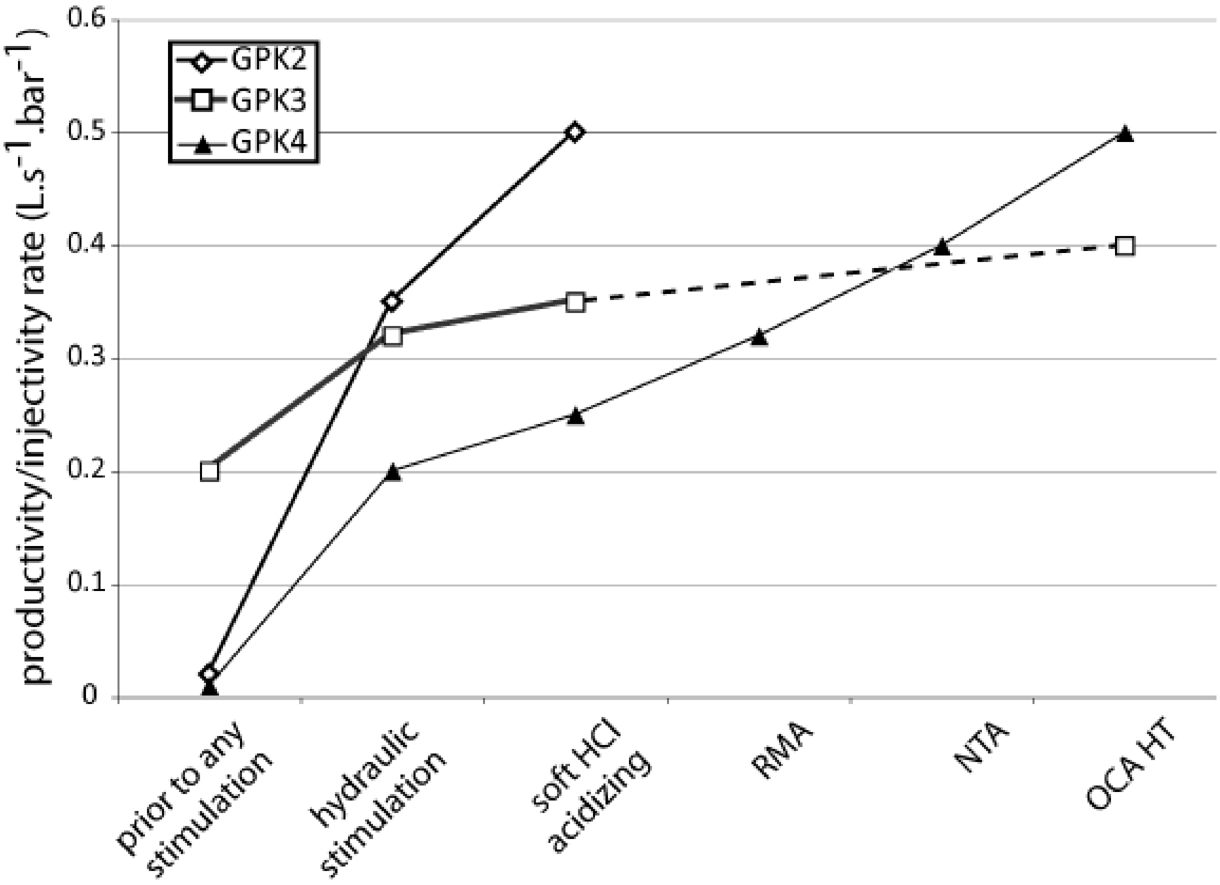

Fig. 4. Increase in the productivity/injectivity rates for each of the Soultz deep boreholes after hydraulic and various chemical stimulations (after Hébert et al., 2011). GPK3 had an initial rate higher than GPK2 and GPK4 (prior to any stimulation data). Because of its very low initial rate and different behaviour, GPK4 had to face multiple chemical stimulations and finally reached the same level as GPK2 even though its rate was only half that of GPK2 after the soft HCL acidizing. RMA : regular mud acid; NTA : nitrilo-triacetic acid (chelating agent); OCA HT : organic clay acid for high temperature.

Following processes run in oil-production wells to improve the permeability of a rock reservoir, two basic types of chemical stimulations can be conducted: matrix acidizing and fracture acidizing. Matrix stimulation is accomplished, for example in sandstones, by injecting a fluid (e.g. acid or solvent) to get rid of materials that reduce well productivity or injectivity. Fracture acidizing is used to develop conductive paths deeper into the formation. This treatment consists of injecting an acid fluid into the formation at a rate higher than the reservoir matrix will accept. This rapid injection produces a wellbore pressure build-up leading to a fracturing of the rock. Continued fluid injection increases the fracture's length and width (Portier et al., 2009).

At Soultz, thorough petrographic studies of the fracture network (Dubois et al., 2000; Genter et al., 1995; Hébert et al., 2010, 2011; Ledésert et al., 1999, 2009, 2010) have shown that more than 90% of the fractures are sealed by minerals that precipitated because of natural fluid flow. K-Ar dating of illite (K-bearing clay mineral) found in a fractured and altered zone located at 2200 m in the Soultz granite (Bartier et al., 2008) indicate at least two episodic illitization at 63 Ma or slightly more for the coarsest particles and at 18 Ma or slightly less for the smallest. Other minerals precipitated at the same time (Bartier et al., 2008; Dubois et al., 2000; Ledésert et al., 1999), such as tosudite (Li-bearing mixed-layer clay mineral) and calcite (calcium carbonate). Calcite precipitated from the Ca-ions liberated by the dissolution of primary plagioclases present in rather great abundance in the granite (nearly 40% of 10%-Ca oligoclase; Ledésert et al., 1999; Table 4) during hydrothermal flow and from sedimentary brines enriched in Ca-ions during its flow within the calcareous Muschelkalk layers that penetrated into the granite (Ledésert et al., 1999).

Recently we have focused on calcite since this mineral is thought to impair the permeability between the 3 deep wells and especially between GPK3 and GPK4 (Hébert et al., 2010, 2011; Ledésert et al., 2009, 2010). To this aim, we performed a compared study of calcite-content, other petrographic data (alteration degree of the rock and illite content) and fluid flow from well-tests. Petrographic data were obtained on cuttings by mano-calcimetry (for the calcite content) and X-Ray diffraction (for the illite content). In the Soultz granite, like in many other granites (Ledésert et al., 2009), the base level of calcite amount is around 1.8 wt % (Hébert et al., 2010; Ledésert et al., 2009). As a consequence, calcite contents over 2% are considered as calcite anomalies by these authors.

The three deep wells show distinct behaviours in the deep part of the exchanger (open holes, below 4500m depth; Table 5).

In GPK2, two main groups of fracture zones are distinguished. The less conductive ones are characterized by low alteration facies, moderate illite content and low calcite content (below 2 wt.%) likely resulting from the early pervasive fluid alteration. It suggests that these fracture zones are poorly hydraulically connected to the fracture network of the geothermal reservoir. On the opposite, the fracture zones with the best conductivities match with high to moderate calcite anomalies (respectively 11, 8, ~5 wt.%), high to moderate alteration grade and high illite content. This suggests massive precipitation of calcite from later fluid circulations within the fractured zone. Thus, the calcite content seems possibly proportional to conductivity.

In GPK3, the less conductive fracture zones are concentrated in a zone that extends from ~ 4875 to ~ 5000 m measured depth (MD), where they correlate with a large and high calcite anomaly zone. The main fracture zone, which accommodates 63–78% of the fluid flow, has the lowest calcite anomaly (2.9 c wt.%) of all the fracture zones of this well. Nearly all the moderate calcite anomalies occur in the vicinity of fracture zones. In this well, regarding the fracture zones data and the calcite anomalies, it seems that the more calcite the less fluid flow and therefore calcite plays a major role in the reduction of the conductivity of the fracture zones of this well. Thus, in GPK3, the maximum fluid flow and significant calcite deposit are not correlated as it is observed in the open-hole section of GPK2.

The highest calcite anomaly of all three deep wells is found in GPK4 (18%). In GPK4, the fluid flow is mainly accommodated via a single zone. All the other fracture zones are considered to have a similarly low fluid flow and are characterized by moderate or high

Site	Habanero (Cooper Basin, Australia)	Hijori (Hijori caldera, Japan)	Soultz (Rhine graben, France)
Rock type	Granite	Tonalite/granodiorite	Granite
Quartz	39.3	35.3	28.4
Plasioclase	29.7	38.2	39.9 (oligoclase)
K-feldspar	18.1	2.1	18.8
Muscovite/Biotite	8.4	0.4	8.4 (biotite)
Carbonate	1.1	1.3	*≤1.8-18*
Chlorite/Clay M	0	6.5	*<1*
Sericite	0	9.5	*up to several % (illite)*
Pyroxene	2.2	0	4.5 (amphibole)
Epidote	0	1.8	*< 1*
Calcopyrite	1.1	0	0
Anhydrite	0	4.9	0
Total	100	100	100, depending on the zones

Table 4. Mineral composition of EGS rock bodies (mostly expressed in volume %). Data from Ledésert et al. (1999) and Yanagisawa et al. (2011). At Soultz, some zones are strongly fractured and altered by natural hydrothermal fluids. In such zones, the composition of the granite is strongly modified: primary quartz has been totally dissolved, oligoclase is replaced by illite or tosudite (clay minerals), biotite and amphibole by chlorite and epidote. Newly-formed minerals are indicated in italics.

	GPK2	GPK3	GPK4
Highly conductive fractures	High alteration High illite High calcite	Low calcite	Low calcite
relationship	Calcite proportional to conductivity : calcite is found in highly conductive fractures	The less calcite, the more fluid flow : calcite reduces conductivity	The less calcite, the more fluid flow : calcite reduces conductivity
Permeability	high	high	low
Connectivity	high	high	low

Table 5. Relationships between the amount of calcite and the intensity of fluid flows in the three deep Soultz wells. Comparison with permeability data (from table 3). The connectivity between the wells is deduced. No petrographic data (alteration degree and illite content) are available for GPK3 and GPK4 because of poor quality cuttings.

calcite anomalies. Therefore it seems that in GPK4, the highest the fluid flow, the lowest the calcite anomaly, as in GPK3.

However, GPK3 shows a high permeability while that of GPK4 is low (Table 5). Combining data of calcite content and permeability, one can infer that calcite may represent a serious threat to the EGS reservoir when the connectivity of the fractures is low while it does not impair the permeability when the connectivity is high. A solution can be brought by hydraulic fracturing that allows developing the extension of fractures. However, such process was employed in Basel (Switzerland) resulting in an earthquake of a 3.4 magnitude that scared the population in 2006. The EGS Basel project had to be stopped. At Soultz, an earthquake of 2.9 magnitude had been felt by local population during the stimulation of GPK3 in 2000 thus no further hydraulic stimulations were driven to prevent this problem. As a consequence, chemical stimulations had to be performed in order to improve the permeability and connectivity of the three deep wells. Particular efforts were put on GPK4. Figure 4 shows the results of chemical stimulations. The behaviour of the 3 deep wells has been largely improved. Given the good results of the circulation test conducted in 2005, and the improvement of the hydraulic performances of the three existing deep wells by stimulation, it was decided to build a geothermal power plant of Organic Rankine Cycle (ORC) type (using an organic working fluid). Thus, a first 1.5 MWe (electricity; equals 12 MW thermal) ORC unit was built and power production was achieved in June 2008 thanks to down-hole production pumps. The power plant was ordered to a European consortium made of Cryostar (France) and Turboden, Italy. A three year scientific and technical monitoring of the power plant has started on January 2009 focused on the reservoir evolution and on the technologies used (pumps, exchanger; Genter et al., 2009).

3.3 Technical data about the heat exchanger and the EGS (after Genter et al., 2009 and Genter et al., 2010)

The geothermal fluid is produced from GPK2 and GPK4 thanks to two different kinds of pumps and, after electricity production (or only cooling if electricity is not produced), it is reinjected in the rock reservoir through GPK3 and GPK1.

3.3.1 Pumps

It was necessary to install down-hole production pumps because the artesian production was not sufficient. Thus, two types of production pumps were deployed in the production wells: a Line Shaft Pump (LSP; in GPK2) and a Electro-Submersible Pump (ESP; in GPK4).

The LSP itself is in the well while the motor is at surface. The connection is obtained through a line shaft. The main advantage is to avoid installing the motor in hot brine, but the possible installation depth is limited and the line shaft has to be perfectly aligned. The LSP was supplied by Icelandic Geothermal Engineering Ltd. 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 8″ casing. The pump itself is from Floway (USA) and made of 17 different stages of 20 cm (3.4 m total 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. 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 that 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, (07th July to 17th August), after six weeks of geothermal production (25 l/s, 155°C), scaling problems were observed 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 was set up. The LSP pump was re-installed at 250 m depth in GPK2 and worked properly afterwards.

Both the ESP 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 was delivered by Reda/Schlumberger. Due to the expected maximum temperature (185°C) and the salty composition of the brine, specific design and noble metallurgy had to be used. The electrical motor is beneath the pump and connected to it through a seal section that 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 ESP and allows monitoring the motor temperature and gives downhole information about the geothermal draw-down in the well. 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. GPK2 flow rate was stabilized at 17.5 l/s for a temperature around 158°C. Both flows coming from GPK2 and GPK4 were 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 was maintained around 70-80 bars for reinjection.

3.3.2 Heat exchanger

A schematic view of the Soultz' binary power plant is given in Figure 5. As the purpose of the project was first to demonstrate the feasibility of power production, a binary system utilizing an organic working fluid called an Organic Rankine Cycle (ORC) technology was chosen. Due to the high salinity of the geothermal brine, the geothermal fluid cannot be vaporized directly into the turbine as occurs in classical "simple flash" power plants.

Then, a secondary circuit is used that 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-fan system. The turbine is radial and operates around 13000 rpm. The generator is asynchronous and is running around 1500 rpm. The generator is able to deliver 11 kV and the produced power is to 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. On surface, the pressure in the geothermal loop is maintained at 20 bars in order to

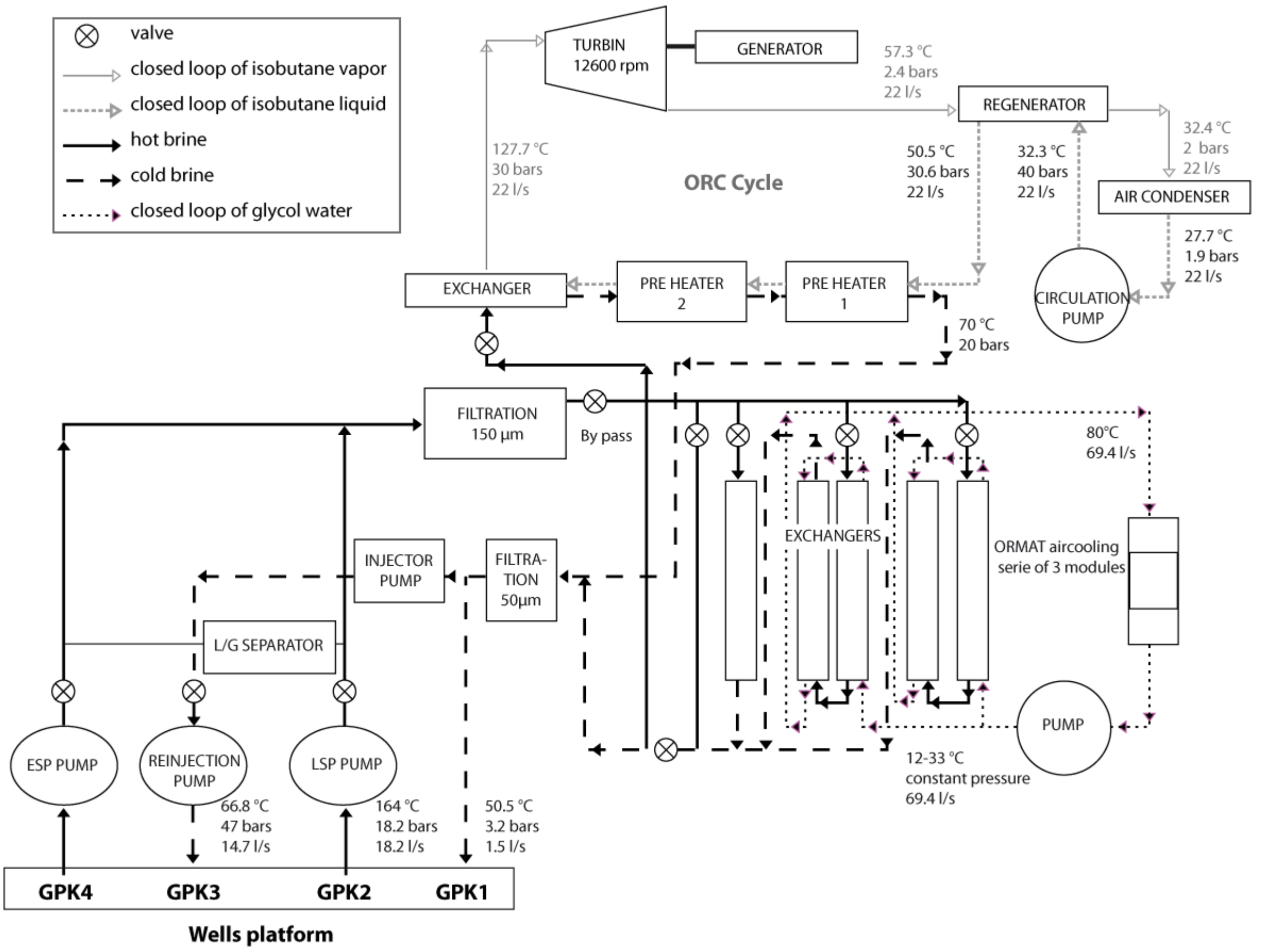

Fig. 5. Schematic view of the Soultz' binary power plant after Genter et al. (2010). Each production well can be run separately thanks to the valves. The hot geothermal fluid (around 165°C) is filtered (150 µm) before entering the surface network. After the complete cycle, the fluid is reinjected in the natural rock exchanger thanks to one or two wells : with a reinjection pump in GPK3 and in addition if necessary by gravity in GPK1. The temperature, pressure and flow figures indicated are those obtained during the 8 months circulation test performed in 2008. If the Organic Rankine Cycle dedicated to electricity production is not activated (the last valve being closed), the geothermal fluid goes through 5 exchangers in the cooling cycle (lower part of the figure with the ORMAT aircooling system) in order to be reinjected after filtration (50 µm) at low temperature (around 50 to 67°C). The last of these five exchangers is used only when necessary.

avoid mineral precipitations. Locally, in the filtering system, some scaling was observed with barite, celestine, iron oxides, galena and calcite mainly. In order to investigate corrosion and scaling, an innovative corrosion pilot was set up on the surface geothermal loop and tested for the first time between September 2008 and February 2009. Different kinds of steel were investigated for corrosion in the geothermal conditions of re-injection (20bars, < 80°C).

The liquid hot brine is pumped from the rock reservoir and first filtered in the surface geothermal loop in a self-cleaning 150µm filter. Whether the ORC cycle is or not in function, either the geothermal fluid feeds the ORC exchanger to produce electricity or it feeds the

Barriquand's exchangers to cool the brine to be reinjected. In that last case, the brine is injected in the 5 exchangers (Fig. 5). The fifth exchanger is used only when needed. The exchangers allow heat transfer between the brine and a fluid composed of water and mono propylene glycol.

3.4 Review of 20 years of research at Soultz

About 40 PhD theses have been written on the Soultz project in the last 20 years together with about 200 publications in international journals between 2001 and 2008. With this scientific background and the current production of electricity (1.5 MWe), the Soultz site is now a world reference for EGS. It appears that cooling 1 km^3 of rock by only 20°C (initial temperature around 160-200°C) liberates as much energy as the combustion of 1 275 000 tons of oil and thus saves as much non-renewable fossil fuel (SoultzNet, 2011).

3.5 Future of the Soultz EGS

The total cost of the Soultz pilot operating now is 54 M€ (Soultznet, 2011). A prototype of 20-30 MWe will follow the first pilot presently in production (1.5 MWe). On a longer term, industrial units will be constructed (Soultznet, 2011). Large-scale production units inspired from the Soultz EGS might transform the world of energy since it is clean and sustainable. It preserves fossil fuels and limits the emissions of GHG and allows a continuous production of electricity 8000 hours/year, at night as well as at day, whatever the climate conditions (SoultzNet, 2011).

4. Other EGS programs in the world

The Soultz EGS is the only operating site at present. It benefited from the experience developed on other sites all around the world. The objective here is not to provide a complete review of these projects but to show the impact they had on the Soultz project. More details on these projects can be found in MIT (2006) and in the abundant literature easily available (e.g. Brown, 2000, 2009; Yanagisawa et al., 2011; Yasukawa and Takasugi, 2003). An overview of HDR/EGS programs in the world is given in table 6.

4.1 Fenton Hill (U.S.A.; after Brown, 2000, 2009; MIT, 2006)

The first attempt to extract the Earth's heat from rocks with no pre-existing high permeability was the Fenton Hill HDR experiment. It was initially totally funded by the U.S. government, but later involved active collaborations under an International Energy Agency agreement with Great Britain, France, Germany, and Japan. The Fenton Hill site is characterized by a high-temperature-gradient, a large volume of uniform, low-permeability, crystalline basement rock. It is located on the margin of a hydrothermal system in the Valles Caldera region of New Mexico, not far from the Los Alamos National Laboratory where the project was conceived.

The Fenton Hill experience demonstrated the technical feasibility of the HDR concept by 1980, but none of the testing carried out yielded all the performance characteristics required for a commercial-sized system (sufficient reservoir productivity, maintenance of flow rates with sufficiently low pumping pressures, high cost of drilling deep (> 3 km) wells in hard rock becoming the dominant economic component in low-gradient EGS resources).

Country	Site	Depth (m)	Temperature (°C)	Dates	Production of electricity
France	Le Mayet		22 (production)	1975-1989	
	Soultz-sous-Forêts	5000 (3 boreholes)	155 (production)	1985-	1.5 MWe Since June 2008
Germany	Bad Urach	4500 and 2600	180 (reservoir)	1976-	
	Falkenberg	300	13 (reservoir)	1975-1985	
Switzerland	Basel	4500	180 (reservoir)		
UK	Rosemanowes	2700	70 (production)	1975-1991	
Australia	Cooper Basin	4250	212 (production)	2003-	
USA	Fenton Hill	5000	191 (production)	1973-2000	
	Desert Peak	5420		2001-	
Japan	Hijori	2300	180 (production)	1981-1987	

MWe : MWelectricity (raw production minus consumption of electricty required for the production).
Data after MIT (2006), Davatzes and Hickmann (2009), Genter et al. (2009) and Wyborn (2011).
Temperatures are given for the production phase for successful EGS sites or for the reservoir when no production occurred.

Table 6. Overview of some HDR or EGS programs in the world.

The program was divided into two major phases. Phase I (1974 – 1980), focused on a 3 km deep reservoir with a temperature of about 200°C. Phase II (1979-1995) penetrated into a deeper (4.4 km), hotter (300°C) reservoir. The two separate, confined HDR reservoirs were created by hydraulic fracturing and were flow-tested for almost a year each. A major lesson learned from the Fenton Hill HDR experience is that the characteristics of the joint system are highly variable : the joint-extension pressure in the Phase I reservoir was only half that obtained for the Phase II reservoir (MIT, 2006). This pressure is controlled by the interconnected joint structure that cannot be discerned either from borehole observations or from the surface. Only microseismic observations might show the portion of the induced seismicity that is really related to the opening of the joints allowing the main flow paths. However, by the early 1980s, HDR projects (Table 6) showed that in most of the cases, hydraulic stimulation did not only create new fractures but also re-opened by shearing natural joints favourably aligned with the principal directions of the local stress field and generally sealed by mineral deposits.

Several lessons were learnt at Fenton Hill. First, deep (5 km) high-temperature (up to 300 °C) wells can be completed in hard, abrasive rock. Second, it was possible to create or reactivate large-scale fracture networks and thanks to seismic monitoring and directed boreholes to intercept them. It was also possible to circulate the fractures with fluids thanks to the boreholes. The first models of flow and heat transfer were developed and used to predict the behaviour of the EGS reservoir. However, if injection pressures were lowered to reduce water loss and reservoir growth, the flow rates were lower than expected. An expert panel of the Massachusetts Institute of Technology estimated in 2006 that EGS could provide up to 100 000 megawatts of electricity in the United States by 2050, or about 10% of the current national capacity (high proportion for an alternative energy source). Up to US$132.9 million from the recovery act are to be directed at EGS demonstration projects.

4.2 Rosemanowes (UK; after MIT, 2006)

As a result of experience during Phase I at Fenton Hill, the Camborne School of Mines undertook an experimental HDR project at Rosemanowes (Cornwall, U.K.) in a granite. The project was funded by the U.K. Department of Energy and by the Commission of the European Communities. The temperature was restricted deliberately to below 100°C, to minimize instrumentation problems. This project was never intended as an energy producer but was conceived as a large-scale rock mechanics experiment about the stimulation of fracture networks. The site was chosen because of its clearly defined vertical jointing, high-temperature gradients between 30-40°C/km and its strike-slip tectonic regime.

Phase 1 of the project started in 1977, with the drilling of several 300 m wells dedicated to test fracture-initiation techniques. Phase 2 was characterized by the drilling of 2 wells that reached 2000 m and a temperature of nearly 80°C. Both were deviated in the same plane to an angle of 30 degrees from the vertical in the lower sections, and separated by 300 m vertically. Stimulation of the injection well was performed, initially with explosives, and then hydraulically at rates up to 100 kg/s and wellhead pressures of 14 MPa. A short circuit unfortunately developed between the two wells, which allowed cool injected water to return too rapidly to the production well: the temperature dropped from 80°C to 70°C. In phase 3A, with no further drilling, lowering the pressure in the production well seemed to close the joint apertures close to the borehole and increase the impedance. An experiment to place a proppant material (sand) in the joints near the production borehole was performed with a high viscosity gel and significantly reduced the water losses and impedance but also worsened the short circuiting and lowered the flow temperature in the production borehole even further. It was concluded that the proppant technique would need to be used with caution in any attempt to manipulate HDR systems. At Rosemanowes, it became clear that everything one does to pressurize a reservoir is irreversible and not necessarily useful for heat mining. For example, pumping too long at too high a pressure might cause irreversible rock movements that could drive short circuits as well as pathways for water losses to the far field (MIT, 2006). A packer assembly was placed close to the bottom of the borehole to seal off the short-cut and was successful but resulted in a subsequent low flow rate. This was interpreted as a new stimulated zone poorly connected to the previous one and demonstrated that individual fractures can have independent connections to the far-field fracture system leading to a globally poor connection of the reservoir.

4.3 Hijori (Japan; after MIT, 2006 and Yanagisawa et al, 2011)

This HDR project is located on Honshu island, on the edge of the Hijori caldera, where the high thermal gradient is related to a recent volcanic event (10 000 years old). The stress regime is very complex. The site was first drilled in 1989 after the results obtained at Fenton Hill to which Japan contributed. One injector and three producer wells were drilled from 1989 to 1991 between 1550 and 2151m. The temperature reached more than 225°C at 1500 m and 250°C at 1800 m. The spacing between the bottom of wells was about 40-55 m. The deep reservoir (about 2200 m), drilled from 1991 to 1995, was characterized by natural fractures. The distance between the wells, at that depth was 80 to 130 m. Hydraulic fracturing experiments began with injection of 2000 m^3 of water. The stimulation was carried out in four stages at rates of 1, 2, 4 and 6 m^3/min. A 30-day circulation test was conducted following stimulation. A combination of produced water and surface water was injected at

1-2 m^3/min (17-34 kg/s), and steam and hot water were produced from 2 production wells. During the test, a total of 44500 m^3 of water was injected while 13000 m^3 of water were produced. The test showed a good hydraulic connection between the injector and the two producers, but more than 70% of the injected water was lost. The test was short and the reservoir continued to grow during the entire circulation period. After additional circulation tests in 1996, a one-year test began in 2000 for the shallow and the deep reservoirs with injection of 36°C water at 15-20 kg/s. Production of steam and water occurred at 4-5 kg/s at about 163-172°C. Total thermal power production was about 8 MWt. Test analysis showed that production was from both the deep and shallow reservoir. While the injection flow rate remained constant at about 16 kg/s, the pressure required to inject that flow decreased during the test from 84 to 70 bar. Total production from the two wells was 8.7 kg/s with a loss rate of 45%. Because of a dramatic cooling from 163°C to about 100°C, that long-term flow test was stopped. The measured change in temperature was larger than that predicted from numerical modelling. One lesson learnt from Hijori joined to Fenton Hill and Rosemanowes experiences was that it is better to drill a single well, stimulate it and map the acoustic emissions during stimulation, then drill additional wells into the acoustic emissions cloud rather than to try to drill two or more wells and attempt to connect them with stimulated fractures. In addition, injecting at low pressures for long time periods had an even more beneficial effect than injecting at high pressures for short periods. The Hijiori project also showed how important it is to understand not only the stress field but also the natural fracture system. Both Fenton Hill and Hijiori were on the edges of a volcanic caldera with very high temperature gradients (need for rather shallow wells, less expensive than deep ones) but also extremely complex parameters (geology, fractures, stress conditions) making these projects very challenging. The mineralogical composition of the Hijori EGS is close to that of Soultz and Habanero rock bodies and one can account for a rather similar chemical reaction with injected water, but the geological contexts are highly different resulting in different circulation schemes within the fracture networks.

4.4 Basel (Switzerland; after MIT, 2006 and Giardini, 2009)

Switzerland developed a Deep Heat Mining project to generate power and heat in Basel and Geneva. At Basel, in the southeastern end of the Rhine graben, close to the border with Germany and France, a 2.7 km exploration well was drilled, studied, and equipped with seismic instrumentation. A unique aspect of the Basel project is that drilling took place within city limits, and the heat produced by the system had the potential for cogeneration (direct use for local district heating as well as electricity generation). The project was initiated in 1996 and partly financed by the Federal Office of Energy together with private and public institutions. The plant was to be constructed in an industrial area of Basel, where the waste incineration of the municipal water purification plant provides an additional heat source. The core of the project, called Deep Heat Mining Basel, was a well triplet into hot granitic basement at a depth of 5 000 m. Two additional monitoring wells into the top of the basement rock were equipped with multiple seismic receiver arrays in order to record the fracture-induced seismic signals to map the seismic active domain of the stimulated reservoir volume. Reservoir temperature was expected to be 200°C. Water circulation of 100kg/s through one injection well and two production wells was designed to result in 30 MW of thermal power at wellheads. In combination with this heat source and an additional gas turbine, a combined cogeneration plant would have produced annually up to 108 GWh of electric power and 39 GWh of thermal power to the district heating grid. North-northwest trending compression and west-northwest extension creates a seismically active area into which the power plant was to be located. Therefore, it was important to record and understand the natural seismic activity as accurately as possible, prior to stimulation of a deep reservoir volume characteristically accompanied by induced seismicity. The first exploration well was drilled in 2001 into granitic basement at 2,650 m. The next well was planned to the targeted reservoir depth of 5000 m. On December 8th, 2006, an earthquake of magnitude 3.4 occurred, responsible for 7 million CHF of property damage. It has been attributed to stimulation operations. In such a seismically active area, one has also to consider the likely impact of the geothermal reservoir on the occurrence of a large earthquake like the event that caused large damage to the city in 1356. As a consequence of this 2006 earthquake, the Basel project was totally stopped in 2009. Many newspaper articles can be found about this story.

4.5 Habanero (Australia; after MIT, 2006 and Wyborn, 2011)

Australia has the hottest granites in the world thanks to radioactive decay characterized by temperatures approaching 250°C at a depth of 4 km in the Innamincka granite (Cooper Basin, south Australia) where the Habanero EGS is developed. Like at Soultz, the Habanero EGS is based on 3 drillings reaching a 4250 m depth. In this white two-mica granite containing 75%SiO_2, biotite is widely chloritized, feldspar is also altered and calcite precipitated as secondary mineral as already described for the Soultz granite (see section 3). Some fractures intersected in the first well were overpressured with water at 35 MPa above hydrostatic pressure. The fractures encountered were more permeable than expected likely because of slipping improving their permeability and resulting in drilling fluids being lost into them. The well intersected granite at 3668 m and was completed with a 6-inch open hole. It was stimulated in November and December 2003. A volume of 20000 cubic meters of water was injected into the fractures at flow rates from 13.5 kg/s to 26 kg/s, at pressures up to about 70 MPa. As a result, a volume estimated from acoustic emission data at 0.7 km^3 was developed into the granite body. A second well was drilled 500 m from the first one and intersected the fractured reservoir at 4325 m. During drilling pressure changes were recorded in the first well. The second well was tested in 2005 with flows up to 25kg/s and a surface temperature of 210°C was achieved. Testing between the two wells was delayed because of lost equipment in the second well. The first well was stimulated again with 20000 m^3 of water and it appeared, thanks to acoustic emission, that the old reservoir was extended by another 50% and finally covered an area of 4 km^2. A third well was drilled 568 m from the first one and was stimulated in 2008. The well productivity was doubled. As a result of these stimulations, two parallel fracture planes with a 15°W dip developed separated by about 100 m around 4200-4400 m and 4300-4600 m depths. The open-loop test performed in 2008 injected 18.5 kg/s in the first well. The third well produced 20 kg/s of water at a temperature around 212°C thanks to flow in the main fracture plane cited before. The productivity obtained during this test was nearly similar to that obtained in the Soultz GPK2 well allowing electricity production from June 2008. The main challenges to future progress are the reduction of drilling costs, an increased rate of penetration for drillings in hard formations, increasing flow rate by improving well connection to reservoir and through development of multiple reservoirs

(Wyborn, 2011). The concept of a 25MWe commercial plant is now designed with 3 injection wells and 6 production wells. The ultimate potential is to supply up to 6500 MWe of long-term base-loadpower, equivalent to electrical supply from ~750 MT thermal coal (Wyborn, 2011).

5. Forthcoming developments and challenges of EGS projects

Many research teams are currently working on improvement of existing techniques of innovation developments to ensure better production rates and minimized constraints. Among these innovations, the following are particularly promising but of course non exhaustive.

5.1 CO_2 EGS

The use of supercritical CO_2 as a heat transfer fluid has been first proposed as an alternative to water for both reservoir creation and heat extraction in EGS (Brown, 2000). Numerical simulations have shown that under expected EGS operating conditions, CO_2 could achieve more efficient heat extraction performance than water (Magliocco et al., 2011). CO_2 has numerous advantages for EGS: greater power output, minimized parasitic losses from pumping and cooling, carbon sequestration and minimized water use. Magliocco et al. (2011) have performed laboratory tests of CO_2 injection while Plaskina et al. (2011) made a numerical simulation study of effects of CO_2 injection to provide a new method to improve heat recovery from the geopressured aquifers by combining the effects of natural and forced convection.

5.2 *In situ* formation of calcium carbonate as a diversion agent

During stimulation of EGS wells, water is injected in order to open sealed fractures through shear failure. When the fractures are open, the stimulation fluid flows into them and becomes unavailable for stimulation elsewhere. Fluid diversion agents can serve to temporarily plug newly stimulated fractures in order to make the injected water available to stimulate new fractures (e.g. Petty et al., 2011). The diversion agent is subsequently removed to allow flow from those previously sealed fractures. As demonstrated by Ledésert et al. (2009) and Hébert et al., (2010), calcite is found naturally in fractures of EGS reservoirs and prevents the fluid from flowing into fractures. The in situ precipitation of calcium carbonate was studied by Rose et al. (2010) for use as a diversion agent in EGS.

5.3 Use of oil and gas reservoirs for EGS purposes

A lot of oil and gas reservoirs have been or will be abandoned in petroleum industry. According to Li and Zhang (2008) these oil and gas reservoirs might be transferred into exceptional enhanced geothermal reservoirs with very high temperatures. Air may be injected in these abandoned hydrocarbon reservoirs and in-situ combustion will occur through oxidization. The efficiency of power generation using the fluids from in-situ combustion reservoirs might be much higher than that obtained by using hot fluids coproduced from oil and gas reservoirs because of the high temperature.

6. Conclusion

Enhanced Geothermal Systems experiences at Fenton Hill (USA), Rosemanowes (UK), Hijori (Japan) and Basel (Switzerland) allowed scientists to develop a European thermal pilot-plant producing electricity in Soultz-sous-Forêts (France) since June 2008. This project is the result of 20 years of active research based on geology (petrography, mineralogy, fracture analysis), geochemistry, geophysics (seismic monitoring, well-logging), hydraulics and modelling. Technical improvements were also necessary to allow deep drilling (down to 5000 m) in a hard (granite), highly fractured rock and circulation of water at great depth (between 4500 and 5000 m). The rock behaves as a heat exchanger in which cold water is injected. The water circulates in the re-activated fracture planes where it warms up. It is pumped to the surface and activates a 1.5 MWe geothermal Organic Rankine Cycle power plant that converts the thermal energy into electricity. In such a project challenges are numerous and difficult since the injected water must circulate at great depths between the 3 wells of the triplet with no or little loss and the flow rate and fluid temperature must be and remain high enough to allow production of electricity. Provided careful monitoring of the reservoir during operation, EGS are a sustainable, renewable and clean way to produce electricity. It has been proven that environmental impacts of EGS are lower than those of nuclear or fossil fuel power plants dedicated to the production of electricity. The Soultz EGS pilot plant is the first one in the world to produce electricity and it should be followed in the forthcoming years by industrial units that will produce electricity at a commercial scale. Many other EGS projects have begun all around the world and a lot of scientific and technical targets are in development to improve the production of energy (electricity and central heating through district networks).

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Selecting and bringing together matter provided by specialists, this project offers comprehensive information on particular cases of heat exchangers. The selection was guided by actual and future demands of applied research and industry, mainly focusing on the efficient use and conversion energy in changing environment. Beside the questions of thermodynamic basics, the book addresses several important issues, such as conceptions, design, operations, fouling and cleaning of heat exchangers. It includes also storage of thermal energy and geothermal energy use, directly or by application of heat pumps. The contributions are thematically grouped in sections and the content of each section is introduced by summarising the main objectives of the encompassed chapters. The book is not necessarily intended to be an elementary source of the knowledge in the area it covers, but rather a mentor while pursuing detailed solutions of specific technical problems which face engineers and technicians engaged in research and development in the fields of heat transfer and heat exchangers.

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