Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Successful Hydraulic Stimulation Techniques for Electric Power Production in the Upper Rhine Graben, Central Europe

Marion Schindler[1], Jörg Baumgärtner[1], Terry Gandy[2], Peter Hauffe[4], Thomas Hettkamp[1], Heiner Menzel[4], Peter Penzkofer[1], Dimitra Teza[1], Torsten Tischner[3], and Gitta Wahl[1]

[1]BESTEC GmbH, Oskar-von-Miller-Str. 2, D- 76829 Landau, Germany

[2]BESTEC Drilling GmbH, Oskar-von-Miller-Str. 2, D- 76829 Landau, Germany

[3]Federal Institute for Geosciences and Natural Resources, Stilleweg 2, D- 30655 Hannover, Germany

[4]geo x GmbH, Industriestraße 18, D- 76829 Landau, Germany

schindler@bestec-for-nature.com

Keywords: EGS, hydraulic stimulation, crystalline rocks, electric power production

ABSTRACT

The Upper Rhine Graben is the focus of geothermal interest in Western Europe due to high temperatures, hydraulically conductive fault zones and an extensional stress regime with comparably low horizontal stresses. As of the beginning of 2009, two geothermal power plants are in operation in the Upper Rhine Graben, one EGS research pilot plant in Soultz-sous-Forêts (France) and a commercial plant in Landau (Germany). Both projects aim at the heat extraction from crystalline basement and are re-injecting the produced fluid. In both cases, massive hydraulic stimulations in the crystalline rocks were required in order to achieve hydraulic conductivities sufficient for power production. Different stimulation technologies had to be applied according to the pre-existing structures found in the rock mass at depth. All stimulation operations were water based. Flow rates used ranged from 50 l/s up to 190 l/s. Injected volumes were as high as some 30,000 m³. Observed productivity increases were as high as a factor of 20. The characteristics of the hydraulic stimulations in the different settings of Landau and Soultz are compared in this paper, underlining the fact that the stimulation technologies developed for EGS/HDR appear to be a very useful tool also for the improvement of hydrothermal resources.

1. INTRODUCTION

In March 2007, the members of the European Union agreed to a binding target of 20 % of energy consumption coming from renewable sources by 2020 (EREC). Regarding the actual (2005) contribution of the renewable of about 8.5 %, great efforts have to be undertaken to reach this ambitious goal. Exploiting the huge geothermal potential and developing its use as a base load renewable energy source will therefore play an important role in this process.

One focus of geothermal electricity production in Western Europe is the Upper Rhine Graben (URG, Figure 1). The URG is part of the European Cenozoic Rift System and extends about 300 km from Basel (Switzerland) to Frankfurt (Germany) in a NNE-SSW direction. It is about 40 km wide and bounded by large-scale normal faults. The formation of the graben began in the Eocene, and the graben fillings are tertiary sediments. The basement is composed of carboniferous granite and gneiss. Tertiary volcanism, thermal springs and deep earthquakes are correlated with the graben structure (Hettkamp et al., 2004).

The extensional stress regime of the graben structure and the existence of hydraulically conductive faults make the URG favorable for EGS systems based on the artificial increase in conductivity by the means of stimulation. Moreover, elevated temperature gradients of up to 100 K/km in the sediments, caused by convection of geothermal fluid on natural faults, cause positive temperature anomalies at depth, as shown in Figure 2. Temperatures as high as 200°C are reached at 5 km depths in the Soultz-sous-Forêts test site in Alsace, France.

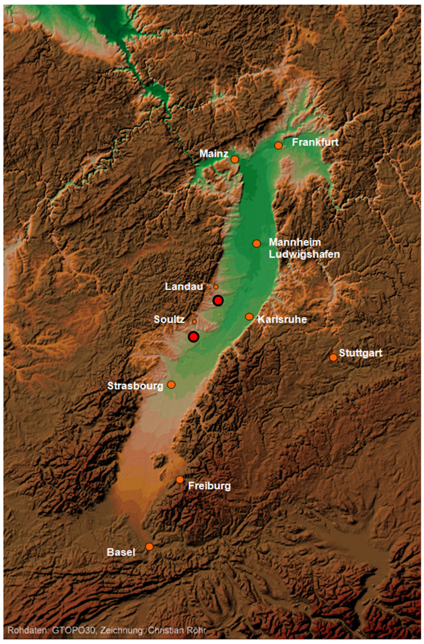

Figure 1: The URG in Western Europe.

The technical potential of the German part of the Upper Rhine Graben for geothermal electricity production is as high as 2 EJ from hot water aquifers, which are mainly the Muschelkalk and Buntsandstein formations, and another 62 EJ from the crystalline basement (Paschen et al., 2003). The contributions of fault zones are considerable, but cannot be estimated at the present time. The theoretical potential of the URG crystalline and aquifers alone covers, for example, 30 times the yearly German electricity consumption.

Nevertheless, the natural permeability of the drilled formations is rarely high enough to allow for economically viable production rates. Hydraulic stimulations, performed by massive water injections, and chemical stimulations are required in most cases to improve well productivity.

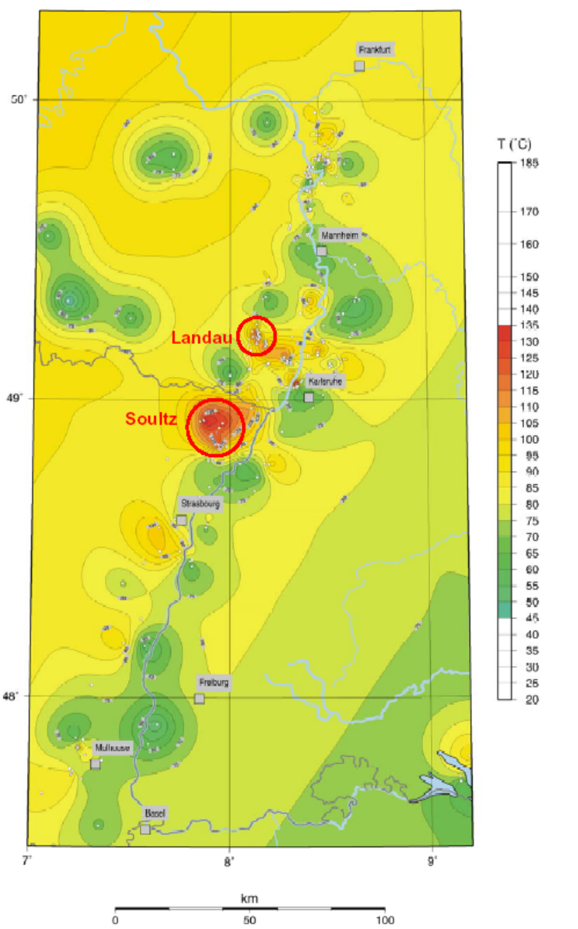

Figure 2: Temperatures in the Upper Rhine Graben at 1500 m depth, indicating the thermal anomalies around Landau and Soultz. (Schellschmidt, 2007)

This paper summarizes different stimulation techniques and their application in the two geothermal projects in Soultz-sous-Forêts (France) and Landau (Germany). The reported improvements by hydraulic stimulation range up to a factor of 20 by hydraulic stimulation and a factor 1.5 for acid injection. Finally, the possibility of improving a reservoir by a circulation is mentioned.

2. DESCRIPTION OF THE TWO GEOTHERMAL SITES

2.1. Soultz

The research power plant in Soultz-sous-Forêts, Alsace (France), is situated some 50 km north of Strasbourg on a horst structure in the former oil exploitation area of Pechelbronn. The fractured granite is covered by 1400 m of sediments (Figure 3). The temperature gradient, as shown in Figure 6, is anomalously high in the first 1000 m with 100 K/km but then decreases to 10 K/km until 3500 m depth, indicating convection of thermal fluid from the granite up to the triassic Muschelkalk and Buntsandstein layers. Below 4000 m, the gradient corresponds to an average of 30 K/km, indicating a conductive regime. The temperature at 5000 m depth is 200 °C.

The geothermal project is based on the EGS concept and extracts heat from the crystalline basement by circulating fluid in an artificially created and extended fracture network. The system consists of three 5 km deep wells having a bottom hole distance of 600 m. The wells are aligned N-S, parallel to the maximum principal stress, as illustrated in Figure 4. Access to the formation is in the last 500 m of the hole from 4500 to 5000 m depth.

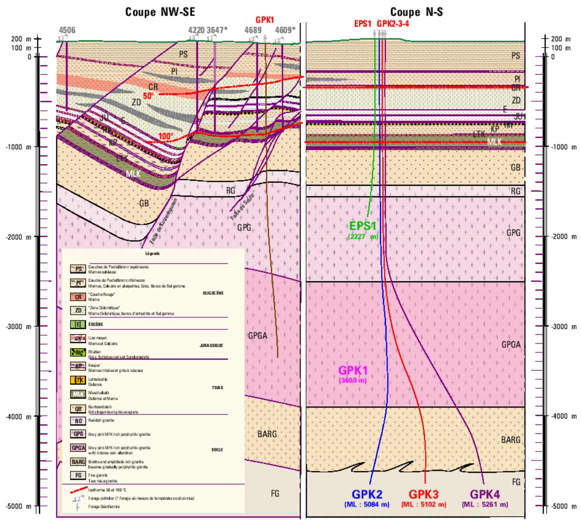

Figure 3: Soultz geology

In the 20 year course of the project, much experience was gained with different stimulation techniques. While initial stimulation experiments in the oldest well GPK1 were performed to investigate the feasibility of inducing fractures under the given stress conditions, later operations in GPK2, GPK3, and GPK4 aimed to improve the hydraulic connection to the natural fracture network and to create a subsurface heat exchanger.

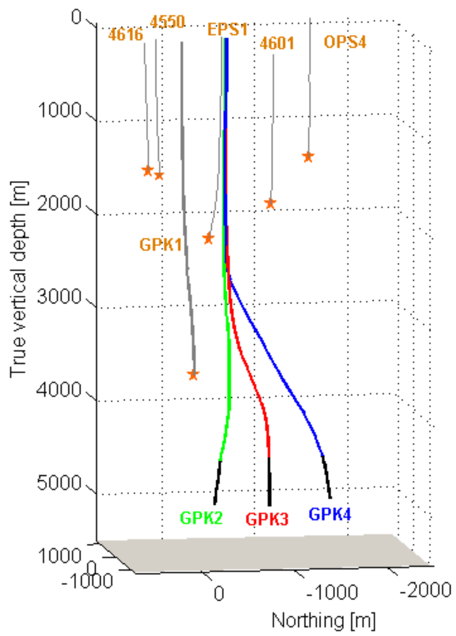

Figure 4: Layout of three wells of the Soultz research project together with observation wells for microseismic location

2.2. Landau

Landau is a project developed by geo x GmbH and located in the German part of the URG, 50 km north of Soultz-sous-Forêts. The commercial power plant is based on a multi-horizon-concept. In contrast to the Soultz model, it aims to produce hot water from a fault system in the Buntsandstein, Perm and the granitic basement.

Two wells were drilled, targeting fault zones in the production zone (Figure 5). The open hole sections are completed by slotted liners (below about 2100 and 2200 m) which allow for the production from these layers. The distance between the wells is about 1200 m.

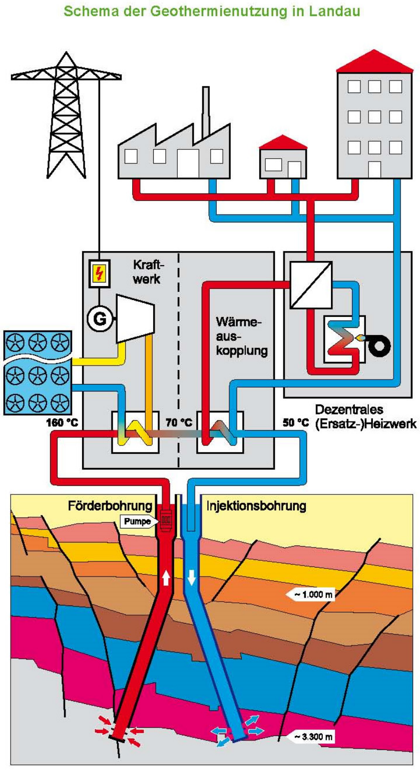

Figure 5: Landau geology and well layout (geo x GmbH).

The granite in Landau was encountered at about 2400 m depth, approximately 1000 m deeper than in Soultz. The temperature logs shown in Figure 6 are influenced by the convection of thermal water also occurring on fault zones and reaching into the Buntsandstein and Perm formations.

The well GtLa1 showed a sufficient productivity right after initial cleaning and testing, while the well GtLa2 needed massive stimulation to improve the permeability of the pay zones. This well was hydraulically stimulated at high rates and additionally treated with acid.

3. COMPARISON OF STIMULATION TECHNIQUES

In general, the stimulation techniques deployed in geothermal research and industry are adopted from the oil industry. Different stimulation concepts exist for crystalline rock: chemical treatments and thermal fracturing improve the near well bore region up to a few tens of meters while hydraulic fracturing has the potential to improve the far field up to several hundreds of meters around the well (ENGINE). Nevertheless, hydraulic fracturing as applied in the oil industry consists of much lower volumes and flow rates than necessary in the geothermal industry. Moreover, stimulation operations in the sediments mostly comprise the use of proppants to keep the fractures open whereas the so-called self-propping effect in granite supports the fractures without any additives.

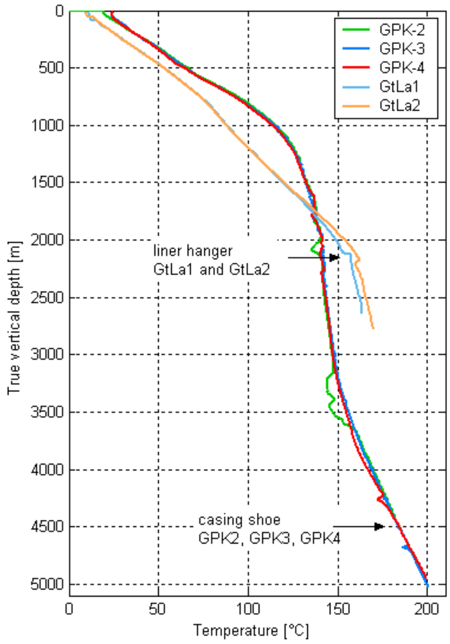

Figure 6: Landau and Soultz equilibrium temperature logs. Both profiles indicate convection of hydrothermal fluid in fault zones: in the Soultz wells, convection reaches up to about 1000 m into the Buntsandstein in the Soultz wells and up to 2000 m into a triassic layer in the Landau wells. In the Landau temperature profile, the liner hanger is clearly visible, and in the Soultz profiles, a cooled zone in GPK2 is the residual of stimulation activities in the upper reservoir at 3.5 km depth.

The hydraulic stimulations performed in Landau and Soultz can be subdivided into several techniques which have in common the injection of some 10,000 m³ of fresh water at varying flow rates for several days. The different measures will be discussed in the next paragraphs.

The following paragraphs demonstrate the stimulations performed in the Soultz and Landau geothermal projects.

3.1 Stimulations in Soultz

3.1.1 Initial State of the Wells

As an example of initial state and to illustrate the necessity to stimulate the Soultz granite, well GPK2 is discussed here. Figure 7 illustrates the recorded downhole pressure curve during an injection of 0.7 l/s – the injectivity deduced from this test is about 0.02 l/(s*bar). A similar test in GPK4 revealed an injectivity of 0.01 l/(s*bar).

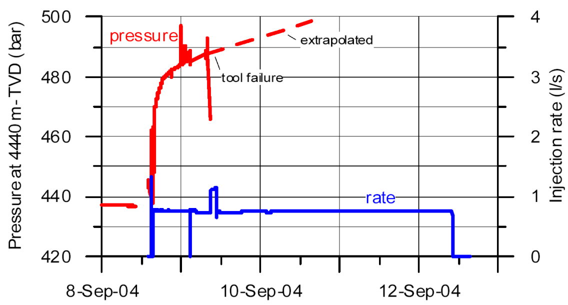

Figure 7: Initial pressure increase of GPK4 at injection of 0.7 l/s. (Tischner et al., 2006).

3.1.2 Brine Injection

The hydraulic stimulations of all wells were performed starting with a brine injection to initiate the stimulation of fractures deep in the borehole. Each time, about 800 m³ of brine at a density of about 1.2 kg/l were injected, followed by several tens of thousands of liters of fresh water.

3.1.3 Massive Stimulation

This is a volume-driven stimulation which consists of injecting water over a longer time to reach high volumes. The long duration and the volume of several 10,000 m³ of fluid are typical. Regarding the duration and the injected volumes, all stimulations in the 5 km deep reservoir in Soultz can be regarded as massive stimulations.

The well GPK2 was stimulated for a duration of six days with a flowrate of about 50 l/s. The wellhead and downhole pressure as illustrated in Figure 8 are almost independent of flow rate but show a slight but continuous pressure increase, which represents the perception of shear fracturing (Tischner at al., 2007). No constant pressure boundaries or infinitely conductive structure was connected to the well by this operation (Schindler et al., 2008). The maximum overpressure of 150 bars is lower than expected and shows that the reservoir is close to its critical state. This well could improve its productivity from 0.02 to 0.4 l/(s*bar).

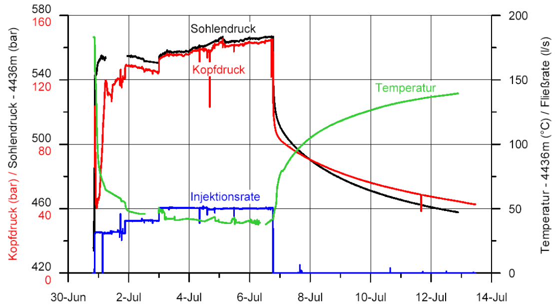

Figure 8: Stimulation of GPK2 (Tischner et al., 2006). Flow rate (blue), wellhead pressure (red), downhole pressure at 4430 m TVD (black) as well as temperature (green) are indicated.

3.1.4 Dual Injection

This concept was applied to pressurize and therefore stimulate especially the area between GPK3 and GPK2 by a simultaneous injection into both wells.

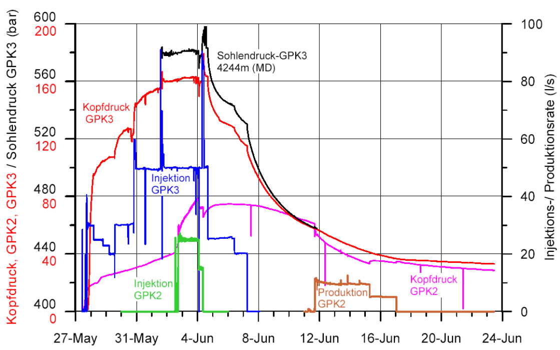

Figure 9: Example of dual injection: Stimulation of GPK3 (Tischner et al., 2006). Blue and green lines indicate flow rates, red and black lines wellhead represent downhole pressure, and the magenta line represents wellhead pressure at GPK2.

The well GPK3 was already productive prior to any stimulation and is characterized by a natural fault at 4760 m depth which takes 70% of the flow. This well was stimulated for a duration of 11 days with a flowrate of about 50 l/s and peaks of up to 90 l/s. For two days, a simultaneous injection into GPK3 and GPK2, the so-called ‘focused stimulation’ (Hettkamp et al., 2004, Baria et al., 2006), aimed to concentrate the fracturing process between the two wells. The wellhead and downhole pressure are illustrated in Figure 9. They show a flow rate-dependent trend and a low overall pressure level (160 bar wellhead pressure), which indicates more the filling of a reservoir than a successful stimulation. The productivity of GPK3 could be improved from 0.2 to 0.3 l/(s*bar), but the hydraulic connection between GPK3 and GPK2 improved strongly and now supports the production from GPK2 in a circulation.

3.1.5 Low Rate Injection

The well GPK4 was only marginally productive before the stimulations, as shown in Figure 7. After the dual stimulation in GPK3, which led to many microseismic events, an injection with lower flow rate was performed. It lasted almost four days at rates of 30 l/s. The high pressure level of 170 bar overpressure at the beginning as well as the slow decrease might indicate the creation of an artificial fracture (Tischner et al., 2006). The productivity could be improved by a factor of 20 to 0.2 l/(s*bar), but the hydraulic connection between GPK3 and GPK4 is still poor. A second stimulation in GPK4 only marginally improved the performance and is therefore not discussed here.

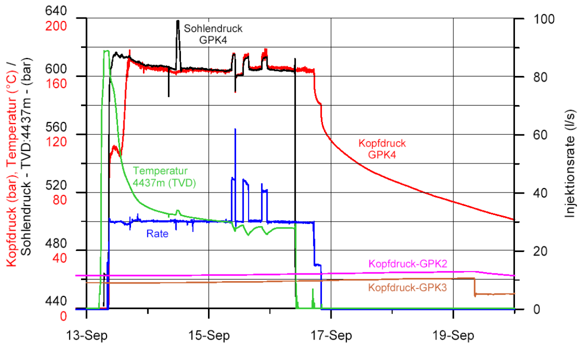

Figure 10: Stimulation of GPK4: dual stimulation (Tischner et al., 2006). Blue line indicates injection rate, black and red indicate downhole and wellhead pressure, and green line indicates temperature. The highest differential pressure was reached compared to the other wells, with the lowest flow rate applied.

3.1.6 Acid Injections

The injection of acid below the fracturing pressure is meant to dissolve secondary minerals in granite fractures. It improves mainly the near well bore injectivity. An acid fracture operation is a hydraulic fracturing with acids, which is performed above the fracture pressure.

Several acid injections and chemical treatments were performed in the Soultz boreholes. They range from simple HCl injections to the application of Regular Mud Acid (RMA), NTA (chelating agents) and OCA (Organic Clay Acid) and were carefully adapted to the mineralogy of the fracture fillings. Detailed descriptions of these operations can be found in work by Nami et al. (2007, 2008) and

Portier et al., (2006). These treatments will not be shown in detail here, but are accounted for in the discussion.

3.2 Stimulations in Landau

With the concept to produce from several potential aquifers and to comprise hydraulically conductive faults and the crystalline basement, another concept of stimulation had to be applied in Landau. Compared to Soultz, higher flow rates were applied. Only the well GtLa2 was subject to stimulation, since the well GtLa1 was productive enough in its initial state.

3.2.1 High Rate Injection

For initially high productivity wells, a high rate injection has to be applied in order to reach stimulation pressure and to yield improvement of the well.

In Landau, the test was performed stepwise: first a hydraulic pre-testing, then a hydraulic stimulation with lower flow rate (but limited volume and time – in contrast to massive injection in Soultz), and finally the high rate stimulation. The different steps are illustrated in Figures 11a and 11b.

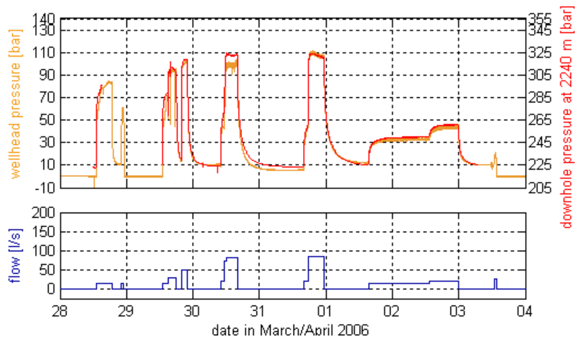

Figure 11 a: Hydraulic stimulation of GtLa2.

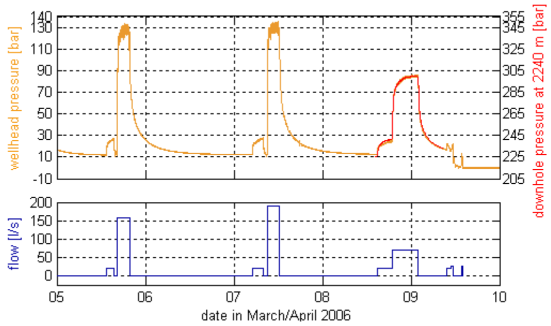

Figure 11 b: Hydraulic stimulation of GtLa2: high rate stimulation.

3.2.2 Acid Injection

In GtLa2, 95 m³ of 33 % inhibited HCl were injected at 10 l/s through coiled tubing, while 30 l/s of fresh water were injected through the annulus. The impact of the acid injection was investigated by the injection of 20 and 70 l/s before and after the treatment. This test is illustrated in Figure 12. The pressure decrease of 10 bars as a result can be observed, which is only a slight improvement.

In contrast to Soultz, the impact of the acid in the well can be clearly identified by temperature logs. Figure 13 compares temperature logs before and after the acidizing and shows that the outlet has shifted from the Buntsandstein to the granite.

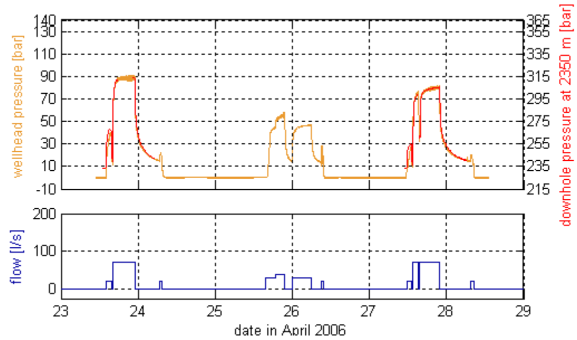

Figure 12: Wellhead and downhole pressure records (orange and red) and flow rates applied during the acid injection in Landau.

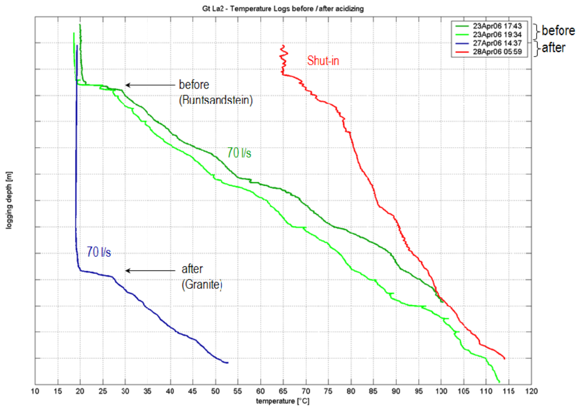

Figure 13: Temperature logs in GtLa2 before and after the acid injection. The productive zone has shifted from the Buntsandstein to the granite in the open hole.

4. RESULTS OF STIMULATIONS IN SOULTZ AND LANDAU

The following table directly compares the different stimulation strategies in Soultz and in Landau. The difference in volume and duration is obvious. The applied flow rates were higher in Landau, whereas the differential pressure was much lower indicating a more efficient stimulation.

During the pre-testing, the overpressure rose to 80 bars at a flow rate of 15 l/s. The hydraulic stimulation with pulses of up to 86 l/s caused a maximal overpressure of 100 bars, already indicating a successful stimulation. The following pretest with 15 and 21 l/s showed a pressure reduction to 25 bars for the 15 l/s injection – an improvement of injectivity by a factor of three (Fig. 11a). The following high rate stimulation consists of pulses of up to 190 l/s with a pressure increase of 125 bars. The successful test with 20 l/s yielded a pressure response of only13 bars (Fig, 11b).

The graphical overview of the Soultz stimulations in Figure 14 emphasizes the potential of hydraulic stimulations to improve a poor initial productivity: the greatest contribution with a factor of 20 in productivity increase comes from the different hydraulic stimulations. Although GPK3 showed an increase only to the 1.5 fold injectivity, its hydraulic connection to GPK2 was improved significantly by the dual injection. Unfortunately, GPK4 could not be well connected to GPK3, so production rates stay low although the stimulation was efficient. The acid injections further decreased the hydraulic impedance, but were of minor radius of influence and had a minor contribution to the overall result.

Table 1: Summary of all hydraulic stimulation measures in Soultz and in Landau.

Well	Dura-tion [d]	Volume [m³]	Flow rate [l/s]	Max Δp [bar]	Initial Prod.	Prod. after stim.
GPK2 massive stimulation	6	23400	50	150	0.02	0.4
GPK3 dual injection	11	34000	50 +30	160	0.2	0.3
GPK4 Low rate injection	3.5 4	9300 12300	30 45	170	0.01	0.2
GtLa2 hydraulic stimulation	Few hours each step	4600	10 steps up to 86	100	0.2	0.6
GtLa2 High rate stimulation	Few hours each step	6600	4 steps up to 190	110		1
GtLa2 Acid stimulatio		95	10 +30			1

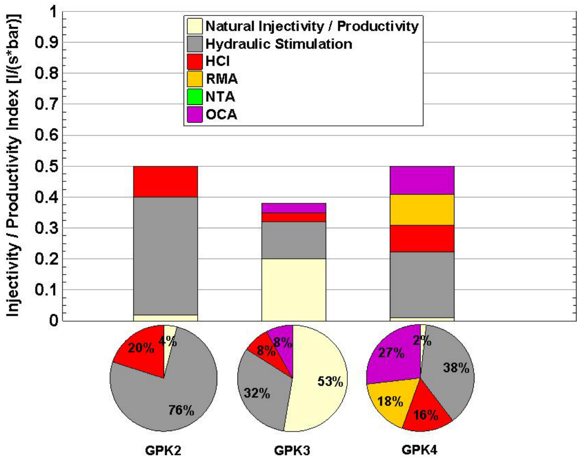

Figure 14: Improvement of injectivity by different stimulation methods in the Soultz wells GPK2, GPK3, GPK4. The hydraulic stimulations account for the largest part of the improvement.

For the stimulations of the Landau well, the figure looks similar: the highest impact comes from the hydraulic stimulations which have been adapted to the different geology by using high flow rates. An overall improvement factor of 5 was realized, and like in Soultz, the acid helped to decrease the impedance, but only for a smaller part.

A final method to decrease the flow resistance was proven in Soultz as well as in Landau: a circulation over several months might be able to reduce the impedance of the injection well by a significant amount. This was first observed in Soultz at a 3.5 km depth in 1997 and also in Landau in 2007, as shown in Figure 16.

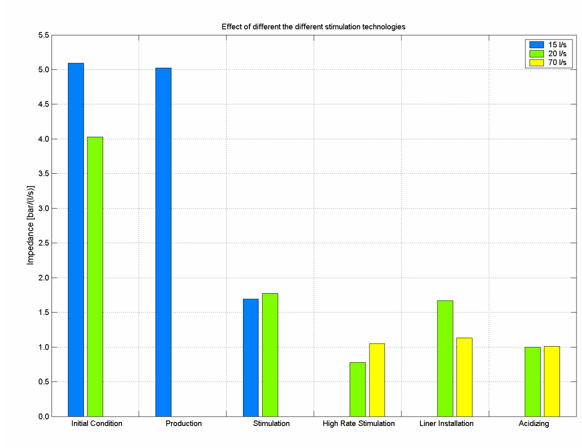

Figure 15: Improvement of injectivity by different stimulation techniques in GtLa2

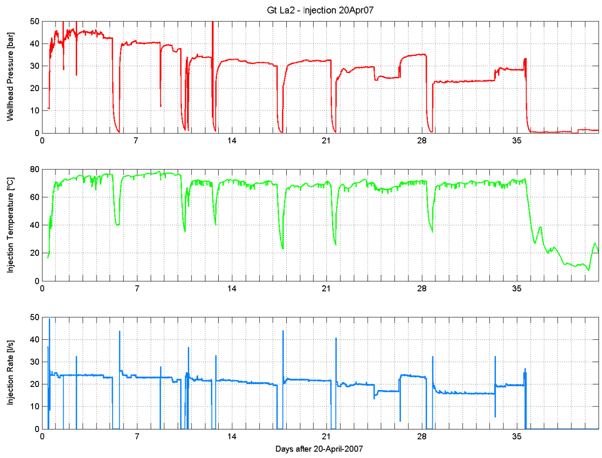

Figure 16: Circulation test in Landau in April and May 2007 demonstrates the improvement of injectivity with time. The wellhead pressure decreased over time by at least 10 bars. The same effect was observed 1997 in Soultz.

5. CONCLUSIONS AND OUTLOOK

This paper has shown the importance of hydraulic stimulations in the development of EGS reservoirs by discussing the examples in Soultz and Landau. While the Soultz reservoir was created in fractured granite by high volumetric stimulations, the Landau reservoir consists of multiple aquifers, faults and a crystalline basement and was stimulated by applying much higher flow rates. Both cases are examples for successful stimulations adapted to the host environment and the stress field and show the importance of such treatments.

The Soultz power plant opened in June 2008 and is in an intensive test phase at the moment. At a flow rate of 35 l/s and a production temperature of 175°C, 1.5 MW of electricity output are available. Power production is hampered by the feed-in tariff in France which is very low compared to Germany and which is being negotiated at the moment.

The Landau power plant was inaugurated in November 2007 and since then has been running continuously, except for some maintenance work. It is able to deliver about 3 MW_{el} and about 4 MW_{th} of heat.

In the future, reservoirs consisting of one fault zone are thinkable and the concept is under testing in the geothermal project in Insheim, close to Landau. Stimulation techniques will again be adapted to this reservoir.

ACKNOWLEDGEMENTS

The authors would like to thank the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) for funding the multi-horizon concept and circulation in Landau (project number 0327522) and Pfalzwerke AG and EnergieSüdwest AG for their technical and financial support. The authors are grateful to geo x, the project company from Landau, for their support and for providing their data. The work regarding Soultz was done in the framework of the European EGS Pilot Plant project, which is supported by the European Commission, BMU and Forschungszentrum Jülich (Germany), ADEME (France), and by a consortium of French and German industrial members (EDF, EnBW, ES, Pfalzwerke, Evonik).

REFERENCES

Baria, R., Jung, R., Tischner, T., Nicholls, J., Michelet, S., Sanjuan, B., Soma, N., Asanuma, H., Dyer, B. and Garnish, J.: Creation of an HDR reservoir at 5000 m depth at the European HDR project, Proceedings thirty-first Workshop on Geothermal Reservoir Engineering, Standford University, Standford, California, (2006), January 30- February 1, 2006.

ENGINE BEST PRACTICE HANDBOOK for the development of Unconventional Geothermal Resources with a focus on ENHANCED GEOTHERMAL SYSTEM, available online from http://engine.brgm.fr/Documents/ENGINE_BestPracticeHandbook.pdf

EREC European Renewable Energy Council Renewable Energy House, 2008.

geo x GmbH: http://www.geox-gmbh.de/

Hettkamp, T., Baumgärtner, J., Baria, R., Gérard, A., Gandy, T., Michelet, S., and Teza, D.: Electricity production from hot rocks, *Proceedings, Twenty-Ninth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, January 26-28, 2004 (2004).

Nami, P., Schindler, M., Tischner T., and Teza, D.: Hydraulic and chemical stimulation experiments in deep crystalline formation for geothermal power production, *First European Geothermal Review – Geothermal Energy for Power Production*, October 29 – 31, 2007 (2007).

Nami, P., Schindler, M., Tischner, T., and Teza, D.: Chemical stimulation results at Soultz and overview of the flow performance of the wells, *Proceedings, EHDRA Scientific Conference*, Soultz-sous-Forêts, France, September 24 - 25, 2008 (2008).

Paschen, H., Oertel, D., and Grünwald, R.: Möglichkeiten geothermischer Stromerzeugung in Deutschland, Sachstandsbericht, 2003.

Portier, S., André, L., Vuataz, F-D.: Review of chemical stimulation techniques and results of acid experiments at Soultz-sous-Forêts, *Proceedings, EHDRA Scientific Conference*, Soultz-sous-Forêts, France, June 15-16, 2006 (2006).

Schellschmidt, R.: Bewertung der Temperaturdaten aus der Erstbohrung des Geothermieprojekts Landau und Prognose der Gebirgstemperaturen für die Zweitbohrung am Standort Landau, Bericht (2006).

Tischner, T., Pfender, M., Teza, D.: Hot Dry Rock Projekt Soultz: Erste Phase der Erstellung einer wissenschaftlichen Pilotanlage, Abschlussbericht zum Vorhaben 0327097, Tgb. Nr. (BGR): B1.15-10125/06, (2006).

Tischner, T., Schindler, M., Jung, R., Nami, P.: HDR project in Soultz: hydraulic and seismic observations during stimulation of the 3 deep wells by massive water injections, *Proceedings, Thirty-second Workshop on Geothermal Engineering*, Stanford University, Stanford, California, January 22-24, 2007 (2007).

Schindler, M., Nami, P., Schellschmidt, R., Teza, D., and Tischner, T, : Summry of hydraulic stimulation operations in the 5 km deep crystalline HDR/EGS reservoir at Soultz-sous-Forêts, *PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, January 28-30, 2008.