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Review

Hydraulic performance history at the Soultz EGS reservoirs from stimulation and long-term circulation tests

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ABSTRACT

The technical feasibility of Enhanced Geothermal Systems (EGS) has been demonstrated for the first time in fractured crystalline basement rocks at the Soultz-sous Forêts project (France), thus creating a unique and vast data base. At this EGS reference site, different hydraulic and chemical stimulation procedures and experiments were performed in four wells at three different reservoir levels located between 2 and 5 km depth. These measures enhanced significantly the hydraulic yield of the three reservoirs, in some instances by about two orders of magnitude.

In this compilation of hydraulic data, we summarize the achievements at Soultz during the development of three reservoirs by more than 15 major stimulations over a 20-year period between 1988 and 2007. We evaluate the efficiency of the different injection schemes used and provide details on the performance history and testing conditions. In addition to the 52 experiments described for the testing phase, this compilation includes nine tests under operational conditions conducted over the 2008–2013 period.

The evolution of hydraulic yield resulting from various injection, production, and circulation experiments is a major achievement of the Soultz reservoir development. This experience points to two important results: 1) the amount of total volume circulated between wells has a very significant effect on reservoir performance and 2) given the large flow rate variation a common linear trend of pressure increase at higher fluid flow rates develops that manifests over all three reservoirs. A strong focus is on the well tests in the intermediate reservoir allowing for a characterization of productivity and injectivity indices. Our analysis showed that initial hydraulic conditions from single-well injection tests are comparable to each other in the three reservoirs, but individual fault zones may determine the stimulation behaviour. We identify progressive cyclic injection in combination with circulation between wells reaching high hydraulic yields at comparatively low pressure. The Soultz data suggest how to maximize injection and minimize induced seismicity. This unique data base illustrates the learning curve achieved in Soultz and provides a strong basis for further conceptual model developments.

1. Introduction

The International Energy Agency aims at a world-wide increase in renewable electricity production using geothermal energy from presently about 10 GW_e to 140–160 GW_e installed capacity by 2050 (IEA, 2011). Part of this growth is expected to be covered by Enhanced Geothermal Systems (EGS), whose current capacity of about 10 MW_e would grow by more than four orders of magnitude, reaching 70–90 GW_e by 2050. Against this background, what was learned at the EGS test site at Soultz-sous-Forêts (France) in the Upper Rhine Graben (e.g., Gérard et al., 2006), has contributed significantly to the reservoir engineering and operational aspects of these systems. Along the Soultz learning curve, a number of milestones in reservoir stimulation have been reached. The objective of the present review is to highlight and reappraise these major achievements.

At Soultz, EGS development comprises crystalline basement rock and extends over three reservoir levels; i.e., at 2000 m depth (R2, at the top of the granitic basement), at 3500 m (R3), and at 5000 m (R5). About 15 major hydraulic and chemical stimulations were carried out to improve reservoir condition at those different levels. The shallowest reservoir lying at 1200 m (R1) in the Triassic sediments has shown some occurrences of partial or total mud losses related to fractures

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zones during drilling operation (Vidal et al., 2015). R1 was never hydraulically tested or stimulated. During nine periods in 1997, 2005 and between 2008 and 2013, long-term productivity was demonstrated in R3 and R5. The deepest reservoir (R5) was developed to ensure electricity production.

EGS technology has been advanced further in follow-up projects such as at Landau (Germany), Insheim (Germany), and Rittershoffen (France, e.g., Baujard et al., 2017). At these sites, the concept of enhancing the naturally most productive reservoir level at the top of the granitic basement was applied, as well as specific hydraulic stimulation techniques (e.g., Schindler et al., 2010).

Monitoring hydraulic performance development in a reservoir is typically based on different types of hydraulic tests. At Soultz, in the initial phase of engineering of the different wells, mostly injectivity index (JI) was determined, while at more advanced stages depending on the performance of the well, productivity index (PI) is tested. Typically at Soultz, PI and JI were measured at single wells, i.e. without pressure measurement in a second well. It is important to note that the present evaluation of Soultz tests is strongly related to an engineering approach based on simplified hydrogeological concepts consisting of representative elementary volumes of a single fracture and the surrounding matrix (Bear, 1972). During the development phase, JI and PI were determined using

$$JI \text{ or } PI = \frac{Q}{\Delta P}$$

where Q is the flow rate and ΔP is pressure difference obtained at quasi-stationary conditions downhole. IJ and PI are summarized under the term hydraulic yield (HY) or reversely, the hydraulic impedance. For specific test condition, we refer to the original reports and publications listed in Annex A. Furthermore, it would exceed the scope of this paper to compile the complex conceptual models developed (e.g., Baujard and Bruel, 2006; Kolditz, 2002) that are relevant to understanding the details of effects of massive injections in a heterogeneous fractured medium by accounting for the importance of the coupling between the thermo-hydraulic-mechanical-chemical (THMC) processes.

At Soultz, the naturally fractured and engineered R5 fulfils most of the EGS criteria established by Garnish (2002 Table 1). R5 has been enhanced between 2000 and 2005 using different chemical and hydraulic stimulations and further improved by circulation during operation. Until 2013, when a major restructuring started at Soultz, this site was run as a multi-well and multi-reservoir experiment. The contribution of natural hydrothermal fluids to total production is of about 75 % (Sanjuan et al., 2006).

In the framework of developing new environmentally friendly stimulation and circulation concepts, this study comprises a total of 61 tests and circulation experiments and aims at providing general conclusions for EGS reservoir engineering. It summarizes and compares the

Table 1
Definition of Enhanced Geothermal System (EGS) by reservoir parameters (Garnish, 2002) in comparison with the R5 parameter of Soultz-sous-Forêts from 2011 (Cuenot et al., 2011). .

	EGS definition	2011 R5 parameters
Flow rate	50–100 kg s^{-1}	23 L s^{-1}
Mean wellhead fluid temperature	150–200 °C	157.5 °C
Effective heat exchange area	> $2{\cdot}10^6$ m^2	n/a
Rock volume	> $2{\cdot}10^8$ m^3	about $2.7{\cdot}10^9$ m^3
Hydraulic impedance	< 0.1 MPa kg^{-1} s^{-1}	0.1 MPa L^{-1} s^{-1} (GPK1, inj.) 0.05 MPa L^{-1} s^{-1} (GPK2, prod.) 0.25 MPa L^{-1} s^{-1} (GPK3, inj.; GPK4, prod.)
Water loss at the surface	< 10 %	0% (total reinjection)

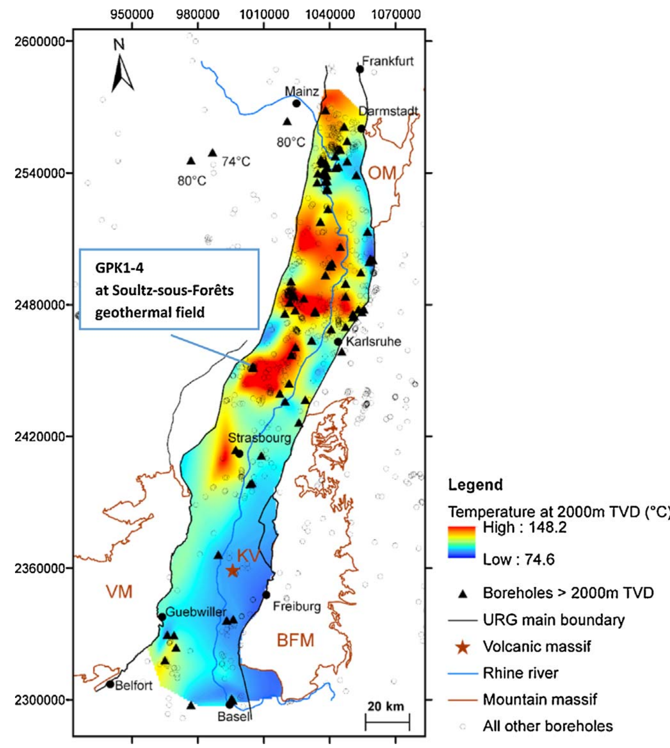

Fig. 1. Temperature distribution at 2000 m TVD in the Upper Rhine Graben, URG, (modified after Baillieux et al., 2013) based on (Agemar et al., 2012). Boreholes with depths > 2000 m TVD are indicated by triangles. VM: Vosges mountains; BFM: Black Forest mountains; OM: Odenwald mountains; KV: Kaiserstuhl Volcanic massif. Lambert II coordinates.

conditions and effectiveness of the major stimulations performed at Soultz between 1988 and 2007 that to date are mainly published in internal reports and found in the project's archives. Additionally, we provide a summary and present new data on circulation experiments up to 2013. The study adds to an earlier assessment of Nami et al. (2008) that discussed the reservoir enhancement resulting from chemical stimulation operations in the deep reservoir suggesting that chemical stimulation of different types may contribute more than 50% of the post-stimulation PI.

This first comprehensive compilation of the performance across all reservoirs includes the key information for all hydraulic operations during development and operation phase at Soultz. It is part of a 4D object-oriented database launched by GEIE Exploitation Minière de la Chaleur and the University of Strasbourg (Jahn et al., 2017).

2. Natural geothermal and hydraulic settings

The Soultz EGS site is located in the central Upper Rhine Graben (Fig. 1), where local subsurface temperature maxima with thermal gradients up to > 100 K km^{-1} in the sedimentary cover of the Variscan crystalline basement, provide favourable condition for geothermal utilization (Genter et al., 2003). The origin of these temperature anomalies has been attributed to free convection along the major faults (Bächler et al., 2003 ; Kohl et al., 2000) that supported hydrothermal circulation in the crystalline basement at the graben scale (Baillieux et al., 2014; Guillou-Frottier et al., 2013; Pribnow and Schellschmidt, 2000; Schellschmidt and Clauser, 1996). At depths > 3700 m the temperature gradient recovers from < 10 K km^{-1} to a normal geothermal gradient of 30 K km^{-1} (Pribnow and Schellschmidt, 2000). Maximum temperature of 201 °C is reached at 5097 m bottomhole depth in GPK2.

The spatial relationship between temperature anomalies and neotectonic patterns indicates a compressional shear and uplift regime for the major thermal anomalies of the central segment of the graben (Illies