

A COMPARISON OF HYDRAULIC STIMULATION EXPERIMENTS AT THE SOULTZ, FRANCE AND COSO, CALIFORNIA ENGINEERED GEOTHERMAL SYSTEMS

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ABSTRACT

Hydraulic stimulation experiments were conducted on tight injection wells at the Soultz-sous-Forets, France and the Coso, California geothermal systems. Significant improvements in injectivity were observed at both reservoirs, although lower stimulation pressures and less fluid were required in order to achieve better injectivity for the Coso well. Following the stimulation experiments, circulation tests were conducted and hydraulic communication was confirmed through tracer testing. The tracer data were analyzed in order to compare the tracer-swept pore volume and the relative degree of dispersion within each stimulated reservoir. The tracer data indicate greater dispersion and therefore a possibly more extensive fracture network at Soultz, although the stimulated-fracture-volume appears to be greater at Coso.

INTRODUCTION

Hydraulic stimulation has been conducted by geothermal developers in an effort to increase either the injectivity or productivity of tight wells (Entingh, 1999). However, few (if any) studies have been conducted and published that compare approaches and results from different reservoirs and that include results from both the stimulation experiments and the subsequent circulation experiments.

Hydraulic stimulation experiments were conducted at the Soultz-sous-Forets, France and Coso, California geothermal fields in 1993-1994. Following each stimulation, a circulation test was conducted by injecting continuously for a long duration into the stimulated well and by monitoring production fluids within an adjacent well. In the Soultz experiment, circulation was between the stimulated injector GPK-1 and the producer GPK-2, which were separated by approximately 450 m at depth. For the Coso experiment, flow was primarily between the stimulated injector 34A-9 and the closest production well, 38-9, also separated by approximately 450 m at

depth. Each data set includes stimulation methods and results as well as results from the subsequent circulation tests, including tracer-test data. In the present study, these experiments are described, compared and contrasted.

STIMULATION EXPERIMENTS

Hydraulic stimulation experiments were conducted on Soultz well GPK-1 and Coso well 34A-9 during 1993-1994 in an attempt to increase the injectivity and reservoir permeability. During these experiments, water was injected in large volumes at pressures below the least principle stress. Such injection has been shown to increase permeability in fractures that optimally oriented and critically stressed for shear failure (Weidler et al, 2002; Jung and Weidler, 2000).

Stimulation Experiment at Soultz Well GPK-1

Shown in Figure 1 is a plan view of the geothermal reservoir at Soultz-sous-Forets, France, as it existed in 1997.

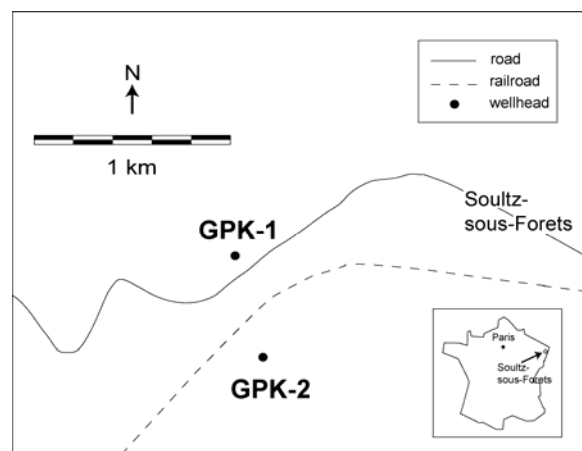


Figure 1. Plan view of the wellhead locations of wells GPK-1 and GPK-2 at the reservoir at Soultz-sous-Forets, France as it existed in 1994.

During 1993, Soultz well GPK-1 was deepened to 3590 m (11,800 ft), at which depth the formation temperature measured 160°C. The casing shoe was set at 2850 m, leaving approximately 740 m of open hole (Baumgaertner et al, 1996).

Using a downhole pump, a production test was conducted in order to determine a pre-stimulation productivity. A flow rate of about 0.5 l/s was achieved at a drawdown of approximately 1 MPa, for a productivity of about 0.5 l/s/MPa (0.055 gpm/psi) (Jung et al., 1995).

A relatively large and conductive naturally fractured zone had been encountered deep in the well during drilling. It was decided, therefore, to first sand off the bottom 190 m of the hole, including this naturally fractured zone, and to conduct a hydraulic stimulation over the shallower and tighter section. The lower, naturally fractured zone would subsequently be stimulated in a separate step.

During the stimulation of the shallow open-hole section, the flow rate was gradually increased from 0.15 l/s to 36 l/s over a period of approximately 16 days. The wellhead pressure attained a fairly constant value of 10 MPa (1450 psi) towards the end of this period. By the end of the first stimulation, 25,300 m³ of fluid had been injected.

The sand was subsequently removed from the bottom 190 m of the hole and a second stimulation experiment was initiated over the entire open hole section between 2850 and 3590 m. The flowrate was maintained at 40 l/s over the first 4 days and subsequently increased to 50 l/s (790 gpm) at 10 MPa (1450 psi) wellhead pressure for a fifth day of injection. By the end of this second period, 19,300 m³ had been injected.

The two stimulation experiments had required a total of approximately 21 days of pumping with a total injection volume of 44,400 m³ (280,000 bbl) with rates as high as 50 l/s (800 gpm) (Jung et al, 1995). The injectivity had increased to 5 l/s/MPa at a flow rate of 18 l/s.

Stimulation Experiment at Coso Well 34A-9

Coso well 34A-9 was drilled to a depth of approximately 2,740 m (9,000 ft) in 1993 with the trajectory shown in Figure 2. The well was drilled into one of the hottest portions of the field with measured temperature exceeding 300°C. However, the well had such low productivity that it could not be made to flow. The well possessed some zones of lost circulation and it was decided to attempt a hydraulic stimulation at low wellhead pressures to determine if the injectivity of the well might be

increased to the extent that it could serve as an injection well.

The pre-stimulation injectivity of Coso well 34A-9 was not well documented, and no downhole pressure data were recorded during the stimulation. Initially, the well would accept about 2.5 l/s (40 gpm) of steam condensate at a WHP of 0.62 MPa (90 psi).

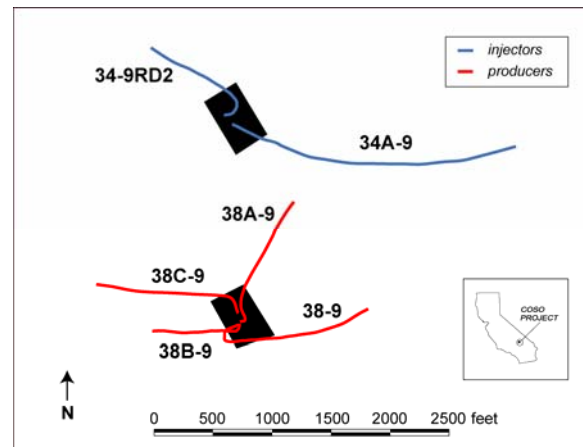


Figure 2. Plan view of the northeast section of the Coso geothermal field, showing the trajectory of the target stimulation well 34A-9.

High pressure pumps were unavailable for the stimulation experiment, and as a result, low-pressure pumps were used and wellhead pressures never exceeded about 0.7 MPa. After less than 240 m³ (1500 bbl) of injection of steam condensate at a rate of 2.5 l/s, the wellhead pressure had dropped to 0 MPa. The injection rate was increased to 28 l/s (450 gpm) and maintained at that rate for one day, while the wellhead pressure remained at 0 psi. Finally, the injection flow rate was raised to 50 l/s (800 gpm) for eight days, with the wellhead pressure at 0 psi. The total volume injected for the entire stimulation was only 12,700 m³ (80,000 bbl). Significant microseismicity was recorded during the stimulation experiment by the Navy Geothermal Program Office's microseismic sensor array.

CIRCULATION EXPERIMENTS

Circulation experiments including tracer testing followed each of the stimulation experiments described above. Such circulation served to determine the degree of hydraulic connection between the stimulated well and a neighboring production well.

Circulation Test at Soultz

GPK-2 was drilled in 1994 to a depth of 3880 m (12,700 ft) as the production well in the Soultz

doublet (see Figure 1). At depth, GPK-1 and GPK-2 were separated by approximately 450 m.

A circulation test was conducted for approximately four months in the summer and fall of 1997, with injection of 23 l/sec into GPK-1 and production at an equal rate at GPK-2 using a downhole pump. Over this duration, the reinjection pressure decreased from an initial value of approximately 4.5 to about 2.0 MPa (290 psi). During this circulation test, a series of tracers was injected for the purpose of characterizing the fluid-flow patterns within the reservoir (Aquilina et al, 1998). 292 kg of the tracer sodium benzoate was injected as a pulse on August 1, 1997 and monitored at GPK-2 for the duration of the circulation test.

The tracer data were analyzed using a systematic approach developed at Idaho National Laboratory (Shook and Forsman, 2005). Using this approach, the tracer data are first converted to an “age distribution function”, $E(t)$:

$$E(t) = \frac{C(t) \cdot q_{inj}}{M_{inj}}$$

where $C(t)$ is the measured tracer concentration in mass per volume, q_{inj} is the injection-fluid flow rate, and M_{inj} is the mass of tracer injected. The units of $E(t)$ are inverse time. Shown in Figure 3 is a plot of $E(t)$ for the sodium benzoate tracer (upper curve) measured in samples taken from GPK-2 during the circulation test.

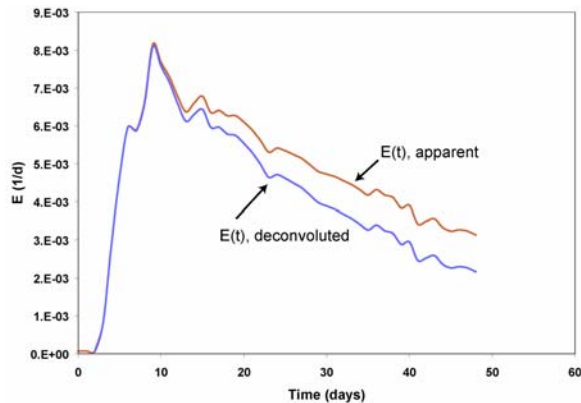


Figure 3. The age distribution function plotted for the sodium benzoate tracer data from the 1997 circulation test at the Soultz reservoir, after 48 days into the test. The figure shows both the apparent $E(t)$ data and the deconvolution of those data.

Since all of the produced fluid was recycled in a closed loop from GPK-2 to GPK-1, the sodium benzoate tracer was likewise constantly reinjected

into GPK-1 throughout the duration of the circulation test. The INL program calculates the effect of the reinjected tracer and subtracts it from the apparent return curve. The lower curve in Figure 3 shows the resultant “deconvoluted” tracer return. The deconvoluted curve represents a single pass of tracer through the Soultz 1997 reservoir, or what would have been measured if no tracer were reinjected.

Next, the program extrapolates the deconvoluted curve to infinite time assuming an exponential decay of the long-tailing portion of the return curve (Shook, 2005). The mean-residence time and the area under the extrapolated curve are then used to calculate the tracer-swept pore volume V_p according to the expression:

$$V_p = \frac{m}{M} \cdot Q \cdot t^*$$

where m is the mass of tracer recovered, M is the mass of tracer injected, Q is the average rate of fluid injected into the injection well and t^* is the mean-residence time. Details on the computational approach have been reported elsewhere (Shook and Forsman, 2005). Using the 1997 Soultz tracer test data, the fraction of tracer recovered was 20% and the tracer-swept pore volume was 16,000 m³.

Circulation Test at Coso

34A-9 was put on line in 1994 and used as an injection well for several years until damage to the shallow casing rendered it inoperable. In 2004, a tie-back repair of the casing resulted in the well being put back on line as an injector (Rose et al, 2005). At the end of the workover in 2004, a second hydraulic stimulation was conducted, again at low wellhead pressures. At the end of the stimulation, 34A-9 would accept 126 l/s of hot, separated brine with a wellhead pressure of 0.41 MPa (60 psi). Significantly microseismicity was measured within the reservoir volume in and around the injection zone for several weeks after 34A-9 was put on injection.

A tracer test was initiated on 1 September, 2004 by injecting 100 kg of the tracer 1,3,6-naphthalene trisulfonate as a pulse into 34A-9. The neighboring liquid-producing east flank wells were subsequently sampled and analyzed for the tracer. Figure 4 shows a plot of the age distribution function $E(t)$ for 1,3,6-naphthalene trisulfonate returns to the neighboring well 38-9. A strong but delayed return of the tracer was likewise observed within well 38A-9, but for the purposes of this analysis only the returns to 38-9 are considered. No tracer was reinjected into 34A-9 and, therefore, no deconvolution was required.

For purposes of comparison with the Soultz 1997 tracer test, the data from the 2004 34A-9 test were truncated at 48 days. The fraction of tracer returned to 38-9 and the tracer-swept pore volume, as calculated by the INL software were 35% and 41,000 m³, respectively.

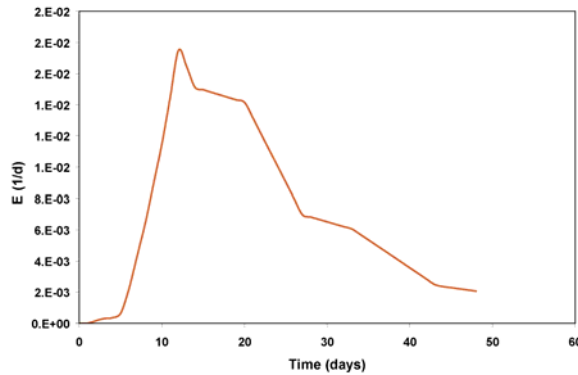


Figure 4. The age distribution function $E(t)$ plotted for the 1,3,6-naphthalene trisulfonate tracer data from the 2004 circulation test at the Coso reservoir, after 48 days into the test.

RESULTS AND DISCUSSION

Due to differences in conventions for calculating injectivity and/or a lack of downhole data, it was not possible to calculate and compare injectivities before and after the stimulation experiments at Soultz and Coso. It is nevertheless possible to make comparisons based upon the data that are available. Shown in Table 1 are the total volumes of fluid used in each stimulation as well as the maximum flow rates and maximum wellhead pressures for each experiment.

Table 1. Summary of Data Obtained from the Stimulation Experiments at Soultz and Coso in 1993-1994.

Well Name	Total Injection Volume (m ³)	Max. Flow Rate (l/s)	Max. Pressure (MPa)
Soultz GPK-1	44,400	50	10
Coso 34A-9	12,700	50	0.62

It is evident from Table 1 that the maximum wellhead pressures and the injection volumes required to achieve comparable injection rates were significantly greater at GPK-1 than at 34A-9.

Further evidence of differences between the injectivities and/or permeabilities surrounding the two wells is available from the data obtained during

the circulation tests following the stimulation experiments. Shown in Table 2 is a summary of those data. Perhaps the most striking difference is that a wellhead pressure of only 0.4 MPa was required to sustain a flow rate of 126 l/s for 34A-9, whereas 2 MPa was required to sustain a much lower injection rate of 23 l/s in GPK-1.

Table 2. Data Recorded During the Circulation Tests at Soultz and Coso.

Well Name	Max. Flow Rate (l/s)	Wellhead Pressure (MPa)	Tracer-Swept Pore Volume (m ³)	Tracer Recovery (%)
Soultz GPK-1	23	2	16,000	20
Coso 34A-9	126	0.4	41,000	35

Although the pre-stimulation injectivity of Coso well 34A-9 may have been greater than that of Soultz well GPK-1, it is evident that after the above-described hydraulic stimulation experiments that the Coso-reservoir formation was rendered significantly more permeable than the Soultz reservoir. Such differences in permeability may be explained in part as follows:

1. More fractures may have been optimally oriented and critically stressed for shear failure at Coso than at Soultz. Likewise, pre-stimulation reservoir stresses may have been greater at Coso, resulting in greater shear and/or dilation displacements.
2. The formation temperatures at Coso well 34A-9 exceeded 300°C, whereas at Soultz they were approximately 160°C at the depths of GPK-1 and GPK-2. The greater difference between injection-fluid temperatures and formation temperatures at Coso may have resulted in greater thermal contraction of rock adjacent to the fractures upon cooling and a concomitantly greater increase in fracture apertures. Larger fracture apertures would have provided a greater increase in fracture permeability.
3. Steam condensate was used as a stimulation fluid at Coso, whereas at Soultz the stimulation fluid was a mixture of produced brine and groundwater. The higher degree of undersaturation of the stimulation fluid at Coso may therefore have provided for a more aggressive mineral dissolution capacity over the Soultz stimulation fluid. Given the retrograde thermal solubility of calcite, this mineral would be less soluble at the high formation temperatures at Coso than at the moderate formation temperatures at Soultz.

SUMMARY AND CONCLUSIONS

Hydraulic stimulation experiments were conducted on tight injection wells at the HDR reservoir at Soultz-sous-Forets, France and at the geothermal reservoir at Coso, California. Significant improvements in injectivity were observed at both reservoirs, although lower stimulation pressures and less fluid were required in order to achieve better injectivity for the Coso well. Following the stimulation experiments, circulation tests were conducted and hydraulic communication was confirmed through tracer testing. The tracer data were analyzed in order to compare the tracer-swept pore volume and the relative degree of dispersion within each stimulated reservoir. A volume of 16,000 m³ was calculated from the 1997 Soultz data as the tracer-swept pore volume, whereas a pore volume of approximately 41,000 m³ was calculated from the Coso data. The tracer data also indicate greater dispersion and therefore a possibly more extensive fracture network at Soultz than at Coso.

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