Tracer testing of the EGS site at Soultz-sous-Forêts (Alsace, France) between 2005 and 2013

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ABSTRACT

Between 2005 and 2013, four chemical tracer operations associated with short (2-3 months) to medium-term (5-6 months) circulation tests were conducted between the geothermal wells GPK-3 and GPK-2 of the EGS site at Soultz-sous-Forêts, in Alsace (France). The used tracers were 150 kg of fluorescein, 1.157 kg of SF_6 gas, 200 kg of 1,3,5-naphthalene tri-sulfonate (1,3,5-nts) and 200 kg of 1,3,6-nts. During the 2005 circulation test, fluorescein injected into GPK-3 was also monitored in the fluid discharged from GPK-4, which was the other productive well. During the 2013 circulation test, a second tracer (200 kg of fluorescein) was also injected into GPK-4 used as another injector well. All these wells have been drilled at a depth of about 5000 m, where temperature is close to 200°C.

This study compares and discusses the results and conclusions drawn from these tracer tests. If most of the data obtained in the tracer tests carried out between 2000 and 2005, and especially in the 2005 tracer test using fluorescein, are presented and commented by numerous authors in the literature, the next tests which were conducted after some stimulation and fluid circulation operations carried out after 2005 are less well known and interpreted. Among the main conclusions, we can notice that all the tracer tests gave evidence of fast and relatively direct hydraulic connections between GPK-3 and GPK-2 (short-scale fluid circulation loop with linear maximum velocities of about 4-8 m/h and predominant N-S fractures) at about 5000 m depth, comparable to those found from GPK-1 to GPK-2, in 1997, between 3500 and 3900 m depths, at a temperature close to 160°C. Except for SF_6 gas, the existence of other larger and slower hydraulic connections between the wells GPK-3 and GPK-2 (large-scale and quasi-infinite fluid circulation loops with predominant NE-SW and NW-SE fractures) was also highlighted. Significant contributions of native geothermal brine (for which a flux was estimated at 1-1.2 m^3/h) as well as relatively low rates of tracer recovery (< 30%) were confirmed in the fluid discharged from GPK-2. A SF_6 gas trapping in the complexity of the porosity of the fracture system when the flow paths lengthen could explain the absence of contribution of the large-scale circulation loop in the shape of the restitution curve of this tracer as well as its very low recovery rate (< 2%) and the absence of dissolved SF_6 in the geothermal fluid discharged from GPK-2. When they exist, the discrepancies found on the shapes of the tracer restitution curves and the associated hydrodynamic characteristics depend mainly on the nature of the tracer (gas or dissolved chemical compound), the fluid reinjection conditions (injection flow-rates and pressure) used for each circulation test and flow-rates of discharged fluid. The increasing values of the tracer mass recovery rates and tracer-swept fracture volumes estimated between the 2005 and 2010 tests (from 15.8 to 25.4% for the total tracer recovery rates and from 10,031 to 26,643 m^3 for the total tracer-swept fracture volumes), using the same modelling methodology and taking into account the differences of discharged fluid volumes, were mainly interpreted as a possible improvement of the fluid circulation loops between GPK-3 and GPK-2, probably due to the stimulation and fluid circulation operations carried out after 2005, which induced an opening of the pre-existing connections. This improvement seems to be confirmed by the results obtained during the 2013 tracer test, but additional modelling tasks must be still performed.

Contrary to the hydraulic connections between the wells GPK-3 and GPK-2, those existing between GPK-3 and GPK-4, or between GPK-4 and GPK-2, appeared to be very poor:

- fluorescein was only detected in GPK-4 after 29 days of its injection into GPK-3 in 2005 and tracer recovery was lower than 2% at the end of the test;
- fluorescein injected into GPK-4 in 2013 could have been detected at very low concentrations in the fluid discharged from GPK-2, after 60-73 days of its injection;
- the linear maximum velocities for both tests were similar and close to 1 m/h.

1. INTRODUCTION

After more than 25 years of scientific and technical investigations, the geothermal site of Soultz-sous-Forêts, in Alsace (France), has presently reached its stage of exploitation, *a priori* over a long-term period, and consequently, represents an unique opportunity to carry out a scientific and technical monitoring program of one the first EGS installations. Among these activities and in the framework of the FP6 European project “Soultz EGS Pilot plant (phase II), 2004-2009” and of a subcontracting for the EEIG Exploitation Minière de la Chaleur “Soutz III - EEIG, 2010-2013”, BRGM has conducted several tracer tests between the different wells of the EGS pilot plant of Soultz-sous-Forêts, in parallel of the geochemical monitoring of the circulating fluid (Sanjuan *et al.*, 2010; Genter *et al.*, 2012, 2013; Mundhenk *et al.*, 2013). Apart from GPK-1, which is more superficial (3590 m), all the other geothermal wells (GPK-2, GPK-3 and GPK-4) have been drilled at a depth of about 5000 m (Fig. 1) and temperature is close to 200°C, at bottom-hole.

All the tracer tests were carried out in order to better characterize the circulation of the fluids in this EGS pilot plant as well as its evolution, during the site exploitation. They had to make it possible to improve the knowledge and understanding of the fluid circulation in this EGS site. These tests also completed the results obtained in the tracer test associated with the four-month forced fluid circulation operation carried out in 1997, between the wells GPK-1 and GPK-2 at depths varying from 3590 to 3890 m, respectively (Vaute, 1998; Aquilina *et al.*, 2004), and in the previous tracer tests conducted from 2000 to 2005 (Sanjuan *et al.*, 2006a). As the EGS configuration was modified by EEIG following the obtained results and the encountered problems between 2005 and 2013, these tracer tests had to be adapted to the modified configuration in agreement with EEIG.

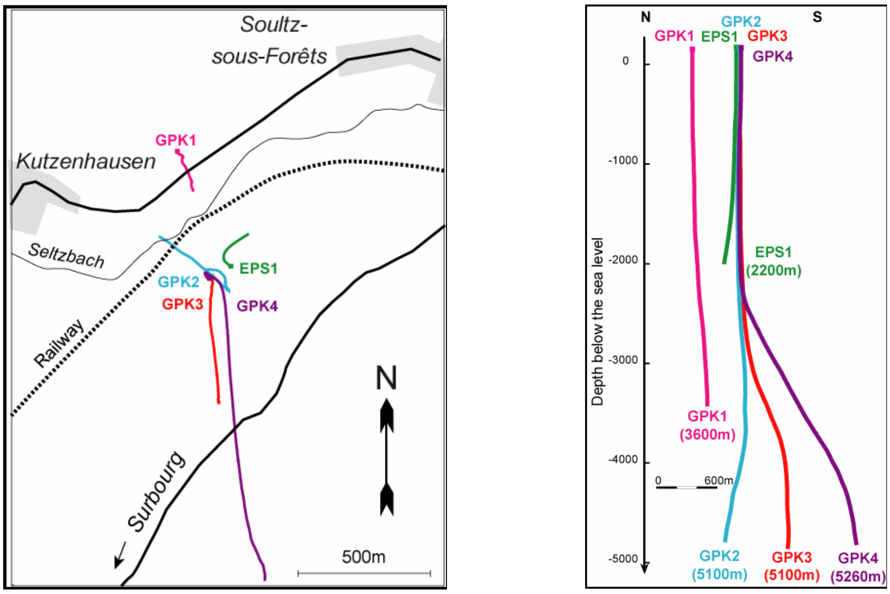

Figure 1: Location map and profiles of the geothermal wells (from Dezayes *et al.*, 2005).

Four tracer tests were conducted between the deep wells GPK-3 and GPK-2 (Fig. 1), associated with short (2-3 months) to medium-term (5-6 months) circulation operations in 2005, 2009, 2010 and 2013. The tracers used for these tests were 150 kg of fluorescein, 1.157 kg of SF_6 gas, 200 kg of 1,3,5-naphthalene tri-sulfonate (1,3,5-nts) and 200 kg of 1,3,6-nts, respectively. Fluorescein and the two last tracers were injected into GPK-3 under aqueous form, after dissolution in water. SF_6 gas was injected in a mixing with nitrogen gas. If the conditions of fluid re-injection into GPK-3 were similar for the tests carried out between 2005 and 2010, they were very different for the tracer test conducted in 2013. On the one hand, because of problems which occurred in the surface heat exchangers, the fluid discharged from GPK-2 could not be directly re-injected into GPK-3 at high pressure (> 20 bars) and had to be deviated in different atmospheric cooling ponds, after phase separation, and before re-injection at low-pressure (< 3 bar). On the other hand, the re-injection flow-rate into GPK-3 (about 7 l/s) was much lower than for the previous tests (≥ 15 l/s), given that a part of the fluid discharged from GPK-2 was also re-injected into GPK-4 at a flow-rate close to 7 l/s. In 2010, the fluid discharged from GPK-2 was not also exclusively re-injected into GPK-3, but only a low amount of fluid was re-injected into GPK-1 (Fig. 1), at a low flow-rate (about 3 l/s).

During the 2005 circulation test, fluorescein injected into GPK-3 was also monitored in the fluid discharged from GPK-4, which was the other productive well. During the 2013 circulation test, 200 kg of fluorescein were injected into GPK-4, which was used as the other injector well, at the same period as the injection of 1,3,6-nts into GPK-3.

The main aim of this study is to compare and discuss the results and the first conclusions drawn from these tracer tests. All the results obtained in the tracer tests carried out between 2000 and 2005, and especially in the 2005 tracer test using 150 kg of fluorescein, were presented and commented in Sanjuan *et al.* (2006a, b). These results were also used in modelling works and interpreted more in details (Blumenthal *et al.*, 2007; Gessner *et al.*, 2009; Gentier *et al.*, 2010; 2011; Radilla *et al.*, 2012; Sanjuan, 2012; Vogt *et al.*, 2012; Genter *et al.*, 2013; Held *et al.*, 2014). The results obtained in 2009, 2010 and 2013 will be used in additional modelling works and interpreted more in detail in the framework of the BRGM-ADEME project “Soultz III - ADEME”.

2. TRACER TEST USING FLUORESCEIN CARRIED OUT IN 2005 BETWEEN GPK-3 AND GPK-2/GPK-4

The tracer test using 150 kg of fluorescein (82.5% pure) and the geochemical fluid monitoring, which accompanied the fluid circulation test between the injection well GPK-3 and the production wells GPK-2 and GPK-4 from July to December 2005, have brought very useful information about the fluid circulation in the Soultz EGS site at a depth of 4500-5000 m. The detailed study and results are reported in Sanjuan *et al.* (2006a, b). In this section, we only will present the main results and conclusions.

During this fluid circulation test, the average injection flow-rate for GPK-3 was estimated to be close to 15 l/s, with 11.9 and 3.1 l/s produced from GPK-2 and GPK-4, respectively. Based on these values, about 209000 m^3 of fluid was injected into GPK-3, and 165,500 m^3 and 40,500 m^3, respectively, were discharged from GPK-2 and GPK-4. Production temperatures increased during the circulation test from 140 to 160°C for GPK-2 and from 100 to 125°C for GPK-4. The pressure at surface was close to 20 bars.

The analytical fluorescein results obtained from the tracer test and their interpretation using the TEMPO code (Pinault, 2001), a code of signal processing based on a model of dispersive transfer (Pinault *et al.*, 2005), confirmed a relatively direct hydraulic connection between GPK-3 and GPK-2 (short-scale loop 1 in Figure 2, extracted from Sanjuan *et al.*, 2006a) but have also shown evidence for another larger and slower hydraulic connection between these two wells (large-scale loop 2 in Figure 2). The calculated parameters for these loops are reported in Table 1. The hydraulic connections between GPK-3 and GPK-4 seem to be very poor because fluorescein was detected very late in the fluid discharged from GPK-4 (about 28 days after its injection into GPK-3) and at very low concentrations (0.6-32 µg/l). Although the fluorescein-recovery curve for GPK-4 could not be fully interpreted since that the fluorescein concentration did not attain a maximum, it was suggested that GPK-4 was essentially hydraulically connected to the large-scale loop between GPK-3 and GPK-2 rather than directly to GPK-3 (loop 3 in Figure 2).

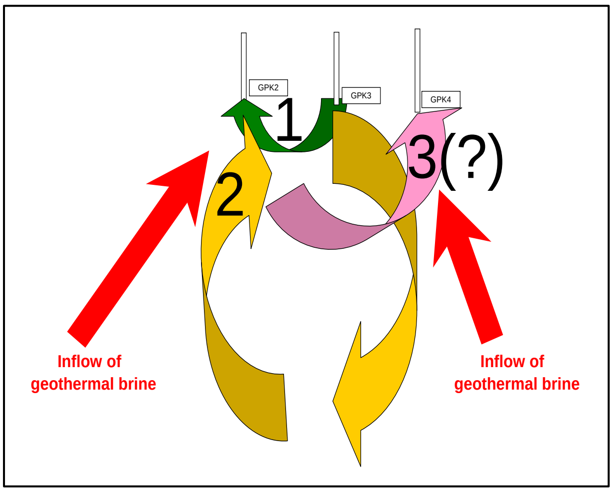

Figure 2: Conceptual model of fluid circulation in the Soultz EGS site: 1. Short scale loop between GPK-3 and GPK-2; 2. Large scale loop between GPK-3 and GPK-2; 3. Connection between the large scale loop and GPK-4 (from Sanjuan *et al.*, 2006a).

Radilla *et al.* (2012) and Sanjuan (2012) confirmed the existence of these loops using different hydrodynamic approaches (equivalent stratified porous medium model for the first one, combination of Shook (2005) and TRAC (Gutierrez *et al.*, 2012) codes for the second one), but obtained different values for the parameters calculated for these loops (Table 1). We can see that these values are very dependent of the used models. The three fluid circulation loops were interpreted as indicating the presence of different networks of fractures close to the deep exchanger, more or less open, and progressively intersected by the injected fluids. Using a DFN model (Discrete Fracture Network) built on the basis of fracture data and integrating structural knowledge, Gentier *et al.* (2011) were able to reproduce the analytical results of this tracer test both between GPK-3 and GPK-2, and between GPK-3 and GPK-4. They showed the role of the various fracture sets in the understanding of the flow between the deep wells and the importance to build a discrete fracture model on the basis of probabilistic analysis of the fracturing data obtained from the well imageries. So, the short-scale fluid circulation loop 1 was mainly associated with a NS fracture contribution whereas the larger-scale loops 2 and 3 were rather associated with NE-SW and NW-SE fracture contributions.

Parameter	Sanjuan *et al.* (2006a; b) Tracer test 2005	Radilla *et al.* (2012) Tracer test 2005	Sanjuan (2012) Tracer test 2005	Sanjuan (2014) Tracer test 2009	Sanjuan (2014) Tracer test 2010	Sanjuan (2012) Tracer test 2010	Sanjuan (2014) Tracer test 2013
Tracer mass (kg)	150	150	150	1.157	200	200	200
Duration of the tracer test (days)	153	153	153	59	163+27=190	163+27=190	102
Mean flow-rate of GPK-3 injection (l/s)	15.0	15.0	15.0	21.0	15.0	15.0	7.0
Mean flow-rate of GPK-2 discharge (l/s)	11.9	11.9	11.9	21.0	18.0	18.0	14.0
Volume of discharged water (m^3)	165500	165500	165500	107000	253086+43070=296156	253086+43070=296156	123400
Time of the first tracer apparition (h)	94			89	89		157
Linear velocity of the first tracer apparition (m/h)	8.1			7.9	7.9		4.3
Maximum signal (µg/l)	630-770			1.320-1.337	1283-1324		626-658
Time of the maximum signal (h)	216-384			175-188	240-360		528-936
Linear velocity of the maximum signal (m/h)	1.9-3.2			3.5-3.8	1.8-2.8		0.7-1.2
Mean transfer time (days) for loop 1 (short-scale loop)	24	14	29			20	
Mean transfer time (days) for loop 2 (large-scale loop)	80	60	54			206	
Mean linear fluid velocity (m/h) for loop 1	1.1						
Mean linear fluid velocity (m/h) for loop 2	0.3						
Tracer recovery (%) for loop 1	15.6	6.3	11.1			18.8	
Tracer recovery (%) for loop 2	7.9	14.1	4.7			6.6	
Total tracer recovery (%)	23.5	20.4	15.8	2.0		25.4	18.0
Fluid volume (m^3) within loop 1	3900	1100	1676			5701	
Fluid volume (m^3) within loop 2	6500	10900	8355			20942	

Table 1: Comparison of the data obtained for the tracer tests carried out by BRGM (in collaboration with GEIE) in 2005, 2009, 2010 and 2013.

The relatively direct hydraulic connection between GPK-3 and GPK-2 had already been highlighted by tracer tests conducted in 2003, using nitrates and 1,6-nds (Sanjuan *et al*., 2006a). If fluorescein was detected in the fluid produced from GPK-2 about 4 days (94 h) after its injection into GPK-3, nitrates were detected 7.25 days after. However, the maximum concentration was observed at similar time as indicated in Table 1. The earlier arrival time for fluorescein can be most likely explained by the higher detection limit of the nitrates. The effective average fluid velocities ranging from 0.3 to 1.1 m/h (Table 1), depending on the traveled paths and relevant for great depth (about 5000 m), are similar or slightly higher to those obtained between GPK-1 and GPK-2, at depths of 3500-3900 m and a temperature close to 160°C, during the circulation test conducted in 1997 with a circulation flow-rate of 21 to 25 l/s (0.25-0.45 m/h; Vaute, 1998; Aquilina *et al.*, 2004). The tracers injected into GPK-1 (benzoic acid, fluorescein, deuterium and SF_6) were detected in the fluid discharged from GPK-2 about 3 to 6 days after their injection. Tracer maxima were observed between 6 and 10 days after the start of their injection.

According to Sanjuan *et al.* (2006a) and Table 1, the total fluorescein recovery through GPK-2 was estimated as 23.5% and the total tracer-swept fracture volume (10,400 m^3) as about 5% of the fluid injected into GPK-3 (209,000 m^3). Using different modelling methodologies, Radilla *et al.* (2012) and Sanjuan (2012) estimated values relatively different for these parameters calculated for each of the loops 1 and 2 (Table 1). However, these values were similar for the total fluorescein recovery and the total tracer-swept fracture volume (20.4 and 15.8%, and 12,000 and 10,031 m^3, respectively). These values are also close to those estimated during the 1997 tracer test (25-30% of total tracer recovery and 16,000 m^3 of total tracer-swept fracture volume, respectively; Vaute, 1998; Aquilina *et al.*, 2004). Fluorescein recovery rate was estimated at 1.8% for the fluid circulation loop 3 (Table 1), but longer tracer tests should be conducted in order to have a better estimation of this rate. The relatively low total fluorescein recovery rate estimated at the end of the circulation test (25.3%; Table 1) could be explained by the existence of a further quasi-infinite loop, which could connect both GPK-2 and GPK-4 to GPK-3, and was suggested by the discrepancies observed between experimental and modelled data at the end of the fluorescein-recovery curves (Sanjuan *et al.*, 2006a). It is also in good agreement with the omnipresence of the native geothermal brine for which the natural flux was estimated to be close to 1-1.2 m^3/h (Sanjuan *et al.*, 2006a). The fluorescein data did not seem to have been much affected by processes of adsorption or chemical degradation because, when compared with those obtained using 1,6-nds between GPK-3 and GPK-2 (41.4/175 kg = 23.7% of 1,6-nds recovery), and between GPK-3 and GPK-4 (3.6/175 kg = 2.1% of 1,6-nds recovery) during the same circulation test, they give similar results (Sanjuan *et al.*, 2006a).

3. TRACER TEST USING SF_6 GAS CARRIED OUT IN 2009 BETWEEN GPK-3 AND GPK-2

This tracer test was carried out with three main objectives. Firstly, it was interesting to experimentally test on site and in real conditions the use of SF_6 gas as tracer in the specific geothermal context of the Soultz-sous-Forêts site. Secondly, this test allowed observing the behaviour of a gas tracer in comparison to aqueous tracers, as previously used, in order to know if the gas tracer took similar or different pathways compared to the aqueous tracers. Thirdly, new estimations of hydrodynamic parameters such as apparent mean fluid velocity, tracer recovery rate between GPK-3 and GPK-2, after the chemical stimulation operation carried out on GPK-3 in 2007, were waited to compare them with the results obtained in 2005.

3.1 Tracer injection

The SF_6 tracer was injected on March 10, 2009, between 16h10 and 16h15. A Messer gas 3 m^3 bottle constituted of 9.78 vol% SF_6 and 90.22 vol% N_2 with a measured pressure of about 138 bars at 3°C (146 bars at 15°C given by Messer) was used in order to directly inject SF_6 into GPK-3 after the EBARA pump. The gas mixing was injected into GPK-3 with the circulating fluid down to a pressure of about 45 bars whereas the pressure measured in the line was 44 bars. If we consider SF_6 as a perfect gas, the corresponding mass of SF_6 injected into GPK-3 was calculated to be m_{SF6} = 1157 g, using the following relationship:

$$m_{SF6} = (P_i - P_f) \times V_{bot} / (R \times T) \times Y_{SF6} \times M_{SF6}$$

where P_i = 138 bars, P_f = 45 bars, V_{bot} = gas bottle volume = 0.02 m^3, T = 276,15 K, R = 8,3143 $J.K^{-1}.mol^{-1}$, Y_{SF6} = 0.0978 and M_{SF6} = molar mass of SF_6 = 146.05 g/mol.

This amount of SF_6 is approximately 7 times higher than that injected in 1997 after dissolution of SF_6 in water (163.5 g; Gardiner and Brock, 1997).

During this tracer test, the flow-rate of the circulating fluid was maintained close to 20-22 l/s with pumping in GPK-2. A volume of about 107,000 m^3 was discharged from GPK-2 during 59 days (Table 1).

3.2 Tracer monitoring and analytical results

Continuous geochemical monitoring of the gases discharged from GPK-2 using the FTIR spectrometer BRUCKER VECTOR22 was carried out by BRGM between March 11 and 20, 2009 (Gentier *et al.*, 2009). The mean gas flow rate coming from GPK-2 and supplying the monitoring system was estimated to about 3 l/mn, even if this last was often irregular. The results were reported in Gentier *et al.* (2009). Gas samples were also collected from GPK-2 in 1 or 2 l Tedlar bags between March 11 and May 8 in order to be analysed by the ANALYTICE laboratory using GC-MS (SHIMADZU 2010 and QP2010+) and by BRGM using FTIR spectroscopy (BRUKER VECTOR22). Relative analytical uncertainty was estimated to be close to 10-15% for both methods. The detection limit was 50 ng/l for the FTIR analyses and 8 ng/l for the GC-MS analyses, respectively. The results were also reported in Gentier *et al.* (2009). All these results are presented in Figure 3.

Water samples were also collected from GPK-2 in polyethylene flasks between March 11 and May 7, 2009, to be analysed by the ANALYTICE laboratory using Head Space equipment (for gas extraction from aqueous solutions) and Gas Chromatography procedure with Electron Capture Detector (HS/GC-ECD). The detection limit was 1 or 2 ng/l. The results were reported in Gentier *et al.* (2009). Except for one only water sample, for which the collection date (19/03/2009 - 16:15) corresponds to one of the highest concentration values determined in the gas samples, no trace of dissolved SF_6 was detected in the water discharged from GPK-2 (Gentier *et al.*, 2009). These results are very different from those found during the 1997 fluid circulation test, which indicated concentration values of dissolved SF_6 ranging from 362 to 698 ng/l (Gardiner and Brock, 1998). They are all the more surprising since a much less amount of SF_6 had been injected in 1997 (163.5 g against 1157 g). The difference of tracer injection (SF_6 dissolved in water before injection into GPK-1 in 1997 and directly introduced into GPK-2 in 2009 under gas form) is probably the cause which can explain these discrepancies.

3.3 Tracer interpretation and discussion

The results obtained by BRGM were systematically about two to three times higher than those determined by ANALYTICE and it was not possible to know the source of this discrepancy in order to select the correct values (Fig. 3). However, all the data indicated the same trends (typical response of a fractured media) and showed that SF_6 was detected in the fluid discharged from GPK-2 approximately 89 h after its injection. The maximum SF_6 concentration (1320-1337 ng/l, according to the BRGM analyses) was observed between 175 h and 188 h after injection. These results showed that the times of tracer apparition and of the major peak arrival were shorter than those determined during the 2005 fluid circulation test using fluorescein (94 h and between 216 and 384 h, respectively). This was interpreted by the fact that SF_6 took similar pathways than the fluorescein injected in 2005, but with higher linear fluid circulation velocities, partially or totally caused by the difference of fluid circulation flow-rate with the 2005 tracer test (injection flow-rate of about 15 l/s in 2005 whereas it is close to 21 l/s in 2009; Table 1). Another explanation could be a better circulation of the SF_6 gas in the fracture porosity than that of the geothermal brine in the shorter flow paths.

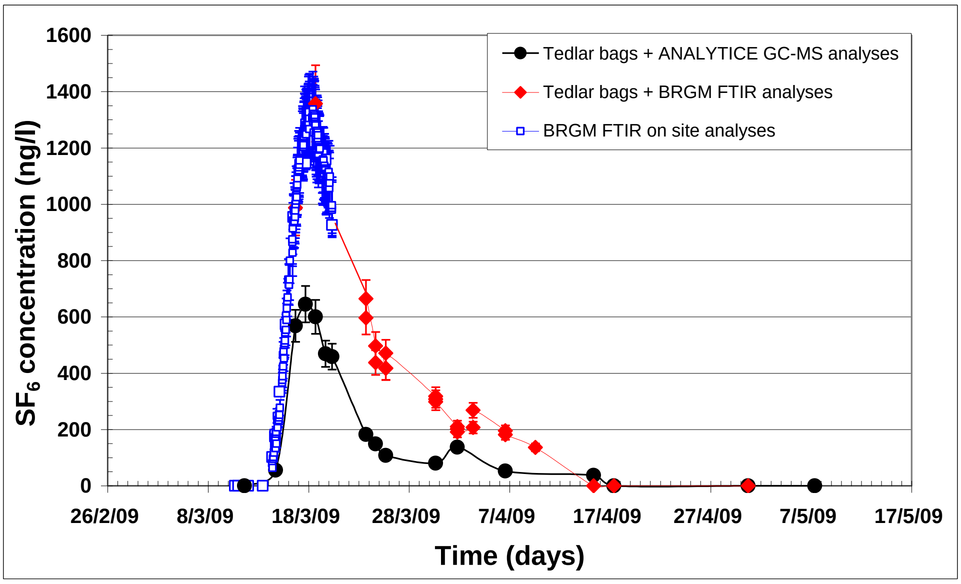

Figure 3: Restitution curve of the SF_6 tracer injected into GPK-3 and monitored from the fluid discharged from GPK-2 (figure extracted from Gentier *et al.*, 2009).

In the absence of representative GLR measurements, the tracer recovery rate could not be estimated in 2009 (Gentier *et al.*, 2009). The first GLR representative values (104 and 107%) determined in 2010, using the micro-cyclonic phase separator constructed by EEIG, allow now to evaluate this tracer recovery rate, if we assume that these values were similar in 2009. Using the data analysed by BRGM (Gentier *et al.*, 2009) and a mean flow-rate of 21 l/s, it could be estimated that only about 23-24 g of SF_6 gas were recovered at the end of the test in relation to the tracer mass of 1157 g injected into GPK-3, which represents a tracer recovery rate close to 2% (Table 1). This value, that would be still inferior using the data determined by ANALYTICE, is strongly lower than that estimated in 2005 for fluorescein (23.5%; Sanjuan *et al.*, 2006a; b). Contrary to the geothermal brine discharged from the well GPK-2 which is re-injected into GPK-3, the associated gases are released in the atmosphere and are not recycled into GPK-3. However, this cannot explain these discrepancies of tracer recovery rate because fluid recycling was taken into account in the estimations made for the Fluorescein recovered in 2005. In contrast with the previously used aqueous tracers, the concentration values significantly decrease after the maximum values and quickly tend toward zero.

As indicated by Gentier *et al.* (2011), only qualitative considerations of this tracer test are possible because the developed model of transport cannot be directly applied to this test, the physics of biphasic flow in fractured medium being not supported by the numerical code 3FLO (Itasca, 2006). However, and as also suggested by Gentier *et al.* (2011), the general shape of the breakthrough curve would correspond to the shorter flow paths (NS sub-vertical fractures), the influence of the longer flow paths being not visible in the restitution curve (mainly, at the end of the curve). The gas trapping in the complexity of the porosity of the fracture system when the flow paths lengthen could explain these results as well as the very low tracer recovery rate and the absence of dissolved SF_6 in the geothermal fluid discharged from GPK-2. This type of tracer would mark the most direct paths with high velocity and low tortuosity.

4. TRACER TEST USING 1,3,5-NTS COMPOUND CARRIED OUT IN 2010 BETWEEN GPK-3 AND GPK-2

4.1 Tracer injection

This tracing operation accompanied the longest fluid circulation test ever carried at Soultz-sous-Forêts, between the two injection wells (GPK-3 and sometimes, GPK-1) and the production well GPK-2 (323 days of fluid circulation without any interruption, from November 2009 to mid-October 2010; Genter *et al.*, 2012). The fluid production flow-rate was about 18 l/s and the fluid injection flow-rates were 15 l/s (for GPK-3) and 3 l/s (for GPK-1), respectively.

As for the previous tracer tests, an organic compound from the naphthalene sulfonate family such as 1,3,5-nts ($C_{10}H_8O_9S_3$) was used because of its properties of quasi-ideal tracer. This compound is inexpensive, environmentally safe, highly soluble in water (200 g/l), non-adsorptive and non-interactive with rocks and minerals of the fractures, thermally stable up to 340°C (Rose *et al.*, 2000), detectable at low concentrations (down to 0.25 µg/l), and absent from natural geothermal fluids.

An amount of 200 kg of 1,3,5-nts was dissolved in a tank of 1 m^3 of freshwater before being injected into GPK-3 on May 4, 2010, using a pump with a flow-rate of about 0.17 l/s. A little more than one hour was necessary to inject the tracer (from 15:39 to 17:20) into GPK-3. After, the tank was rinsed with 1 m^3, then 300 l of freshwater, which were also injected into the well GPK-3.

4.2 Tracer monitoring and analytical results

The tracer was monitored in the fluid discharged from GPK-2 up to October 14, 2010 (163 days after the tracer injection and a volume of 253,086 m^3 of discharged water), date at which the fluid production was stopped. The tracer monitoring restarted with the beginning of GPK-2 production on January 2011 and is presented up to February 22, 2011 (27 days of monitoring and an additional volume of 43,070 m^3 of discharged water).

Up to this date, fluid samples were regularly collected from the well GPK-2 by EEIG and BRGM teams and were stored in polyethylene flasks without conditioning in order to be analysed in the BRGM laboratories, using High Performance Liquid Chromatography (HPLC) with a fluorescence detector. Relative accuracy is about 10%. The obtained analytical results are reported in Sanjuan (2014) and presented in Figure 4.

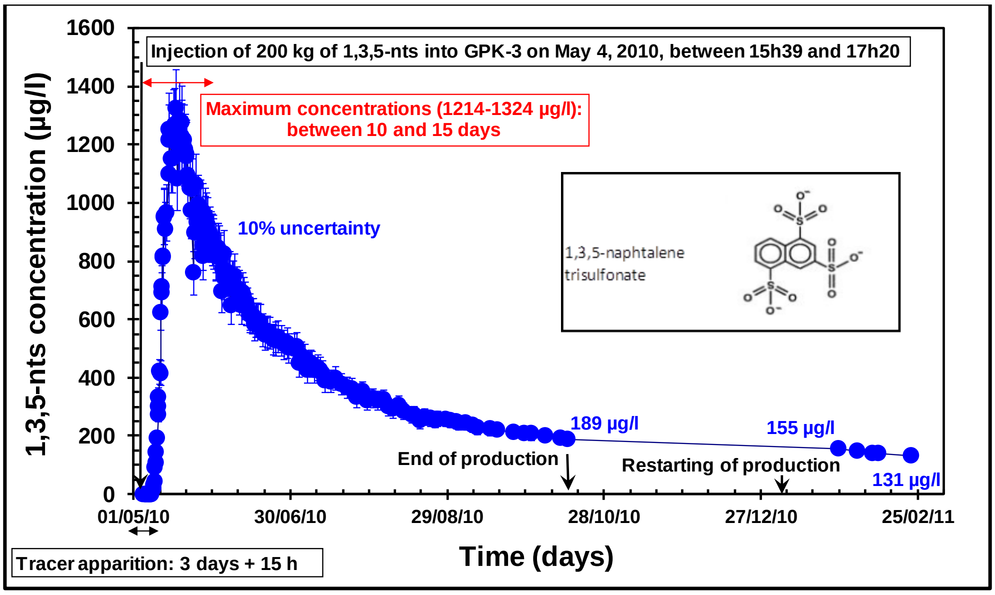

Figure 4: Restitution curve of the 1,3,5-nts tracer injected into GPK-3 in 2010 and monitored from the fluid discharged from GPK-2.

4.3 Tracer interpretation and discussion

As in 2005 and 2009, the tracer data show a typical response of the behaviour of a tracer injected in a fractured medium (Fig. 4). The first apparition of 1,3,5-nts in the GPK-2 fluid occurs 89 hours (3,7 days) after tracer injection. This tracer arrival time is slightly shorter than that observed for the test using fluorescein in 2005 (94 h or about 4 days), and is identical to that of the SF_6 tracer in 2009 (Table 1). A part of this difference (about 3 h) is due to the fact that the time needed by the tracer to descend and ascend in the wellbores (a length of about 5.1 km in each well) is reduced when the flow-rate is higher (mean production and injection flow-rate with pumping in 2010 of 18 l/s against about 12 l/s for production and 15 l/s for injection in 2005).

The other part could be explained by:

- this same discrepancy of flow-rates which would also have an influence on the fluid circulation velocity;
- a slight improvement of the porosity-permeability of the fracture system located near the GPK-3 bottom-hole due to the stimulation operations carried out after 2005;
- a better detection limit for 1,3,5-nts (0.25 µg/l) compared to that for fluorescein (0.6 µg/l).

The maximum 1,3,5-nts concentration is observed between 240 h and 360 h (10 and 15 days), after tracer injection (Table 1). Consequently, the time of the major peak arrival is very close to that observed in 2005 (between 216 and 384 h, or 9 and 16 days), but is longer than for SF_6 (between 175 h and 188 h). These results are well illustrated in Figure 5.

Taking into account the distance between the bottom holes of GPK-3 and GPK-2 of about 650 m and the time needed by the tracer to descend the GPK-3 wellbore and to ascend the GPK-2 wellbore, we can estimate the maximum linear fluid velocity and that of the major peak arrival in 2010 at 7.9 m/h and 1.8-2.8 m/h, respectively (Table 1). These values are close to those determined in 2005 (8.1 m/h and 1.9-3.2 m/h, respectively; Sanjuan *et al.*, 2006a; b) and in 1997 between GPK-2 and GPK-1, at a depth of about 3500 m (6.6 m/h and 1.8-2.2 m/h, respectively; Aquilina *et al.*, 2004). For SF_6, the linear velocity of the major peak arrival is slightly higher (3.5-3.8 m/h).

The maximum tracer concentration observed in 2010 (1283-1324 g/l) is 1.6-1.7 higher than that analysed in 2005 (770 µg/l; Table 1), which is in relatively good agreement with the amount of tracer injected in 2010 (200 kg) in relation to that used in 2010 (150 kg). This difference of tracer amount injected into GPK-3 explains why the tracer concentrations analysed in 2010 are systematically higher than in 2005 (often two to three times). After the maximum concentration, a regular decrease is observed up to October 14 (end of the production) and between January 26 and February 22, 2011 (restarting of the production, Fig. 4). The concentration value analysed on October 14, 2010, a little more than 5 months after tracer injection, is 189 µg/l. The concentration values analysed between January 26 and February, 22, 2011, decrease from 155 to 131 µg/l, respectively (Fig. 4).

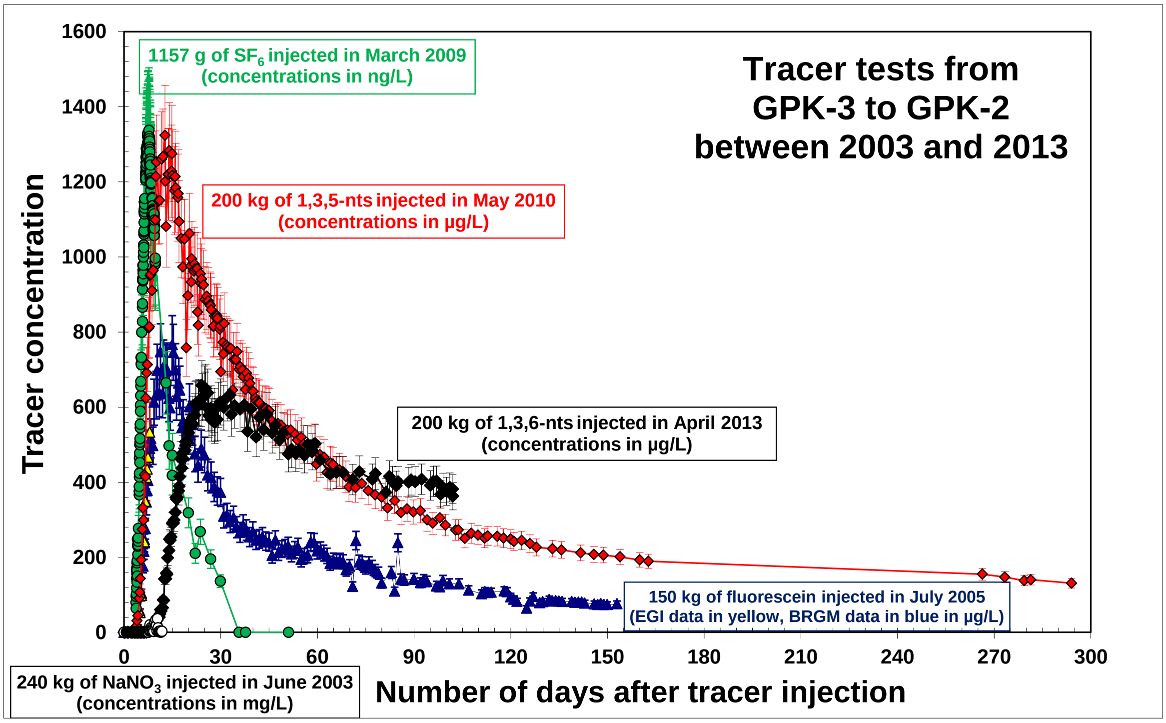

Figure 5: Comparison between tracer concentrations in the fluid discharged from GPK-2 during the tracer tests carried out in 2003, 2005, 2009, 2010 and 2013.

As in the previous curves, the major peak of this curve represents the structures N-S which are at the origin of the shortest and direct flow-paths between the wells GPK-3 and GPK-2. As shown in Figure 5, SF_6 gas seems to better circulate in the shortest and direct flow paths than the aqueous tracers. On the other hand and in contrast with these tracers, the SF_6 concentrations tend relatively quickly toward zero after the major peak, suggesting the trapping of this gas in the longer flow paths.

The tracer mass recovered from GPK-2 up to February 22, 2011 (about 190 days of production and a volume of 296156 m^3 of water discharged from GPK-2, after tracer injection) was estimated at 50.8 kg by eliminating the tracer recycling (Sanjuan, 2012). Consequently, the tracer recovery rate without recycling was evaluated as about 25.4% of the injected tracer mass (Table 1). For the short-scale fluid circulation loop, the tracer recovery rate was estimated at 17.8% and at 7.6% for the large-scale fluid circulation loop. The tracer-swept fracture volumes were 5,701 and 20,942 m^3, respectively (Sanjuan, 2012). These values are higher than those estimated in 2005 using the same modelling methodology (Table 1; Sanjuan, 2012). The total tracer-swept fracture volume estimated for the 2010 tracer test (26643 m^3) is about 3 times higher than all those estimated in 2005 (from 10,031 to 12,000 m^3; Table 1). Even if the fluid volume discharged from GPK-2 was higher in 2010 than in 2005 (165,500 m^3) and can partially explain all these increasing values, the latter were also interpreted as a possible improvement of the fluid circulation loops between GPK-3 and GPK-2, probably due to the stimulation and fluid circulation operations carried out after 2005, which induced an opening of the pre-existing connections (Sanjuan, 2012). The tracer mass recycled *via* the wells GPK-3 and GPK-1 in 2010 was evaluated at about 93.3 kg (Sanjuan, 2012) and then represented about 65% of the total tracer recovery from GPK-2. In comparison, the tracer mass recycled *via* GPK-3 in 2005 was estimated at only 9.4 kg (Sanjuan, 2012) and represented about 28% of the total tracer recovery from GPK-2. In Table 1, we can notice that the estimations of tracer recovery rate and tracer-swept fracture volume for each fluid circulation loop may significantly vary following the used modelling methodology, even if the total estimations for these parameters are relatively close.

Tracer tests are an important tool for estimating reservoir connected porous volume. An estimation of this volume V can be easily obtained using the following relationship (Ito *et al.*, 1977; 1978):

$$V = m/Cf$$

where m is the mass of injected tracer (200 kg) and C_f its final concentration.

However, this relationship can be only used for closed systems, otherwise for systems where the final concentration is approximately constant (no addition of water from external parts of the system). If we apply this relationship at the end of the GPK-2 production in October 2011, a reservoir connected porous volume of approximately 1.1 Mm^3 is found. In February 2011, this value becomes 1.5 Mm^3. As the final concentration values are not still stabilised and have not been corrected taking into account water recycling, these calculated volume values can be considered as minimal. They are very close to those determined during the fluid circulation test carried out in 1997 between GPK-2 and GPK-1 (1.2-1.5 Mm^3; Aquilina *et al.*, 2004) but slightly lower than those deduced in 2005, with fluorescein (about 2.0 Mm^3). All these results are concordant with the estimation given by Sanjuan *et al.* (2006a) concerning the mixing of fresh water injected into the geothermal wells between 2000 and 2005 with a volume of about 750,000 m^3 of reservoir native brine.

For the moment, only simple transport modelling was considered for this tracer test (Sanjuan, 2012) but more complex modelling works must be carried out in order to optimise the data exploitation, and well interpret all the portions of the restitution curve. As for the fluorescein in 2005, the other portions of the 1,3,5-nts restitution curve must be modelled and interpreted using the DFN model built on the basis of fracture data and integrating structural knowledge as well as casing restriction in GPK-2 (3880 m; Jung *et al.*, 2010) and casing leaks in GPK-4 (4140, 4430 m; Held *et al.*, 2014).

5. TRACER TEST USING 1,3,6-NTS COMPOUND CARRIED OUT IN 2013 BETWEEN GPK-3 AND GPK-2

5.1 Tracer injection

Another tracer test using 1,3,6-nts compound has been also carried out by BRGM, with the EEIG collaboration, between April 4 and July 15, 2013 (102 days of monitoring after tracer injection and a volume of about 123,400 m^3 of water discharged from the well GPK-2) in order to study the evolution of the hydraulic connections between the wells GPK-3 and GPK-2, since the tracer test carried out in 2010. On April the 4th 2013, a container with 200 kg of 1,3,6-nts dissolved in approximately 1 m^3 of freshwater was injected into GPK-3 using a low flow-rate pump, between 8:32 and 9:32. Then, from 9:33 to 10:35, 1 m^3 of additional freshwater poured in this container was again injected into GPK-3.

This tracer test accompanied the fluid circulation operation which was carried out between January and July 2013 from the injection wells GPK-3 and GPK-4 to the production well GPK-2. The mean fluid production flow-rate for GPK-2 was about 14 l/s and the fluid injection flow-rates were 7 l/s (for GPK-3) and 7 l/s (for GPK-4), respectively. Because of problems which occurred in the surface heat exchangers and differently to the previous fluid circulation tests, the fluid discharged from GPK-2 could not be directly re-injected into GPK-3 and into GPK-4 at high pressure (> 20 bars) and had to be deviated in different atmospheric cooling ponds, after phase separation, and before re-injection at low-pressure. The phase separation and the evaporation associated to this new surface configuration caused a slight increase (13-14%) of the concentrations of all the dissolved species, including that of the tracer, before fluid re-injection (Sanjuan, 2014).

5.2 Tracer monitoring and analytical results

Fluid samples were regularly collected from the well GPK-2 by EEIG team and were stored in polyethylene flasks without conditioning in order to be analysed in the BRGM laboratories, using High Performance Liquid Chromatography (HPLC) with a fluorescence detector. Relative accuracy is about 10%. The obtained analytical results are reported in Sanjuan (2014) and presented in Figure 5.

5.3 Tracer interpretation and discussion

As the previous tracer restitution curves, the tracer data show a typical response of the behaviour of a tracer injected in a fractured medium. However, the shape of this curve is relatively different from that of 2010.

Firstly, the first apparition of 1,3,6-nts in the GPK-2 fluid occurs much longer than in the previous tests, including the 2005 test: 157 hours (6,5 days) after tracer injection (instead of 89-94 h, or less than 4 days). The high detection limit (2.5 µg/l) for 1,3,6-nts, compared with the previous tracer analyses (0.25 µg/l for 1,3,5-nts and 0.6 µg/l for fluorescein), cannot be responsible of that because the first concentration analysed for 1,3,5-nts was 11 µg/l, which is higher than that determined for 1,3,6-nts (2.7 µg/l). So, the main factor responsible for this longer time is most probably the lower flow-rate value (7 l/s) used for the fluid injection into GPK-3, compared with those in 2005, 2009 and 2010 (≥ 15 l/s), and the lower pressure (< 3 bar).

Secondly, the maximum 1,3,6-nts concentration is observed between 528 h and 936 h (or 22 and 39 days), after tracer injection. Consequently, the time of the major peak arrival is also much longer than those previously observed (Table 1). These results are well illustrated in Figure 5. Taking into account the distance of about 650 m between the bottom holes of GPK-3 and GPK-2 and the time needed by the tracer to descend the GPK-3 wellbore and to ascend the GPK-2 wellbore, we can estimate the maximum linear fluid velocity and that of the major peak arrival in 2013 at 4.3 m/h and 0.7-1.2 m/h, respectively. These values which are practically two times lower than those previously determined (see Table 1) are in good agreement with the lower flow-rate value used for fluid injection into GPK-3 (about 2-3 times lower than in 1997, 2005, 2009 and 2010; Aquilina *et al*., 2004; Sanjuan *et al.*, 2006a, b; Sanjuan, 2014).

Thirdly, the maximum tracer concentration analysed in 2013 (626-658 µg/l; Table 1; Fig. 5) is about 2 times lower than in 2010 (1283-1324 µg/l) and even lower than in 2005 (630-770 µg/l), whereas the same mass of tracer (200 kg) was injected in 2013 and 2010, and this mass was higher than that injected in 2005 (150 kg). By contrast, the regular decrease of the tracer concentrations, after the maximum concentrations, is much slower than those observed in 2005, 2009 and 2010, and the tracer concentrations are higher up to the end of the fluid circulation operation (363 µg/l against 131 µg/l, for example, in 2010; Fig. 5), which was interrupted because unexpected technical problems. This trend is also in good agreement with the use of a flow-rate 2-3 times lower than previously for fluid injection into GPK-3.

The tracer mass recovery rate up to July 15, 2013 (about 102 days of production and a volume of 123,400 m^3 of water discharged from GPK-2, after tracer injection) was estimated at 25.5% with tracer recycling and at about 18% by eliminating this recycling and using the modelling methodology of Sanjuan (2012). If we compare the volumes of fluid discharged from GPK-2 for each of the previous tracer tests (159,000 m^3 in 2005 and 296,000 m^3 in 2010) with that of this test and consider the particular shape of the 1,3,6-nts restitution curve (with maximum concentrations lower than in the other tests and final concentrations which remain still high), this tracer recovery rate is more in agreement with that estimated in 2010, confirming the possible improvement of the fluid circulation loops suggested by the results of the 2010 tracer test. The tracer mass recycled *via* the well GPK-3 was estimated to represent about 25% of the total tracer recovery from GPK-2. This value could be lower if a part of the tracer had not been conserved after the phase separation or especially, in the atmospheric cooling ponds, as suggested by tracer analyses in 19 fluid samples collected just before reinjection into GPK-3 or in samples of mud deposits collected by GEIE from the cooling ponds, which seem to indicate some tracer adsorption (Sanjuan, 2014). In this case, the estimated total tracer mass recovery rate would be comprised between more than 18 and less than 25.5%. The tracer mass recovery rates and the tracer-swept fracture volumes for each loop (short- and large-scale loops) have not still been estimated. This task will be made in the framework of the SOUTZ III -

ADEME project as well as additional complex modelling works integrating fracture data, structural knowledge and leak occurrences (Jung *et al.*, 2010; Held *et al.*, 2014) in order to optimise the data exploitation, and well interpret the portions of the tracer restitution curve (Fig. 5), as for the 2005 tracer test.

6. TRACER TEST USING FLUORESCEIN CARRIED OUT IN 2013 BETWEEN GPK-4 AND GPK-2

In spite of the presence of some fluorescein traces in the GPK-2 fluid, a tracer test using this compound (very cheap and easy to analyse, including on-site) was carried out by BRGM, with the EEIG collaboration, between the wells GPK-4 and GPK-2, from April 3 to July 15, 2013 (103 days of monitoring after tracer injection and a volume of about 124,600 m^3 of water discharged from GPK-2), at the same time than the tracer test using 1,3,6-nts, between GPK-3 and GPK-2. The conditions of fluid circulation are given in section 5.1 and are very different from those used in the previous tracer tests.

6.1 Tracer injection

During this test, 200 kg of fluorescein were injected into the well GPK-4 (used as an injector well since April 2012 by GEIE) and was monitored in the fluid discharged from GPK-2 in order to investigate the hydraulic connections between GPK-4 and GPK-2, which were unknown in this direction, for the moment, even if we knew the very poor hydraulic connections existing between the wells GPK-3 and GPK-4 (Sanjuan *et al.*, 2006a; b).

Two containers with fluorescein solution were prepared for tracer injection by BRGM in advance. During tracer storage, the volumes of the two containers were mixed several times by pumping and re-pumping from one to the other container, as proposed by BRGM. Before injection, the tracer volume was adjusted to approximately 750 litres in each container. On April the 3rd 2013, fluorescein solution of the two containers was injected into GPK-4 using a low flow-rate pump, between 10:06 and 10:36, and 10:37 and 11:00, respectively. Then, from 11:01 to 12:10, 1 m^3 of additional freshwater poured in the two containers were again injected into GPK-4. 1 m^3 of additional freshwater poured in a third container were also injected into GPK-4, from 13:35 to 14:10.

5.2 Tracer monitoring and analytical results

Fluid samples were regularly collected from the well GPK-2 by EEIG team and were stored in polyethylene flasks without conditioning in order to be analysed in the BRGM laboratories, using High Performance Liquid Chromatography (HPLC) with a fluorescence detector. Relative accuracy is about 10%. The obtained analytical results are reported in Sanjuan (2014) and are presented in Figure 6. For the on-site analysis of this tracer using a field spectrophotometer, a specific procedure was preliminarily established by the BRGM laboratories in 2011 and given to the EEIG team.

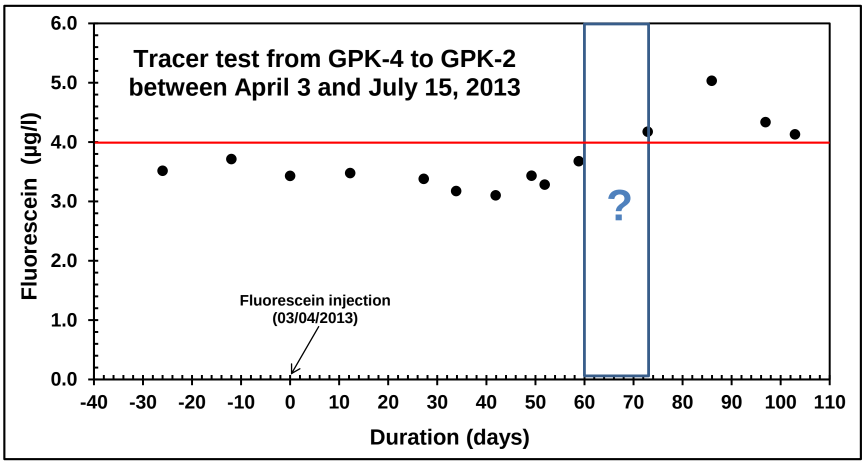

Figure 6: Restitution curve relative to the tracer test using fluorescein carried out between GPK-4 and GPK-2, from April 3 to July 15, 2013.

6.3 Tracer interpretation and discussion

The tracer data obtained from the GPK-2 fluid are presented in Figure 6. As previously discussed, the concentrations of fluorescein before injection of this tracer into GPK-4 ranged from 3 to 4 µg/l. Fifty eight days of monitoring after fluorescein injection into GPK-4, no fluorescein concentration was higher than 4 µg/l in the fluid discharged from GPK-2.

The first values higher than 4 µg/l were determined 73 days after fluorescein injection and after this date, the three following values were also higher than 4 µg/l. Unfortunately, the fluid circulation test was interrupted 103 days after fluorescein injection. If we consider that these very slight increases are due to fluorescein injection into GPK-4 on April 3, 2013, we can conclude that the time of first apparition of this tracer in the GPK-2 fluid is ranging from 60 to 73 days, at least. However, this time could be still longer if these increasing values are not significant. Using this time of first tracer apparition, we can estimate a corresponding value of apparent velocity lower than 0.9 m/h. Of course, the tracer recovery rate can be considered negligible, given the low fluorescein concentrations determined in the fluid discharged from GPK-2.

By comparison and in an opposite pathway (from GPK-3 to GPK-4), the 150 kg of fluorescein were detected in the fluid discharged from GPK-4 about 28-29 days after their injection into GPK-3, in 2005 (Sanjuan *et al.*, 2006a; b). The first detected values of fluorescein concentration, which ranged from 0.6 to 0.8 µg/l, are very close to those observed in 2013, if we consider that the fluorescein concentrations varied from 3 to 4 µg/l, before injection of this tracer into GPK-4. The linear velocity of the first tracer apparition in the fluid discharged from GPK-4 in 2005 was estimated at 1.0 m/h (Sanjuan *et al.*, 2006a; b). This value is not very different from that estimated in 2013. Fluorescein recovery was evaluated at 1.8% in 2005. These values confirmed the poor hydraulic connections between GPK-3 and GPK-4. Consequently, we can also consider that the hydraulic connections between GPK-4 and GPK-2 are poor, even if the production and reinjection conditions are different between the two fluid circulation tests.

7. CONCLUSION

After the tracer test using fluorescein and associated to the 5-month fluid circulation loop carried out in 2005 between the wells GPK-3 (injector) and GPK-2/GPK-4 (producers), four additional inter-well tracer tests (three tests between GPK-3 and GPK-2 and one test between GPK-4 and GPK-2) were conducted between 2009 and 2013, associated with three new fluid circulation operations. If the 2005 tracer test was interpreted and discussed by numerous authors, the next tests which were conducted after some stimulation and fluid circulation operations carried out after 2005 are less well known and interpreted.

The test using SF_6 gas conducted in 2009, between GPK-2 and GPK-3, with a fluid circulation flow-rate of 20-22 l/s, showed that the times of tracer apparition and of the major peak arrival were slightly shorter than those determined during the 2005 fluid circulation. This was interpreted by the fact that SF_6 took similar pathways than the fluorescein injected in 2005, but with higher linear fluid circulation velocities, partially or totally caused by the increase of flow-rate compared to the 2005 tracer test. Another partial explanation could be a better circulation of the SF_6 gas in the fracture porosity than that of the geothermal brine in the shorter flow paths. As indicated by Gentier *et al.* (2011), only qualitative considerations of this tracer test are possible in the absence of available numerical models. The general shape of the breakthrough curve could correspond to the shorter flow paths (NS sub-vertical fractures associated with the 2005 short-scale fluid circulation loop), the influence of the longer flow paths being not visible in the restitution curve (mainly, at the end of the curve). The gas trapping in the complexity of the porosity of the fracture system when the flow paths lengthen could explain these results as well as the very low tracer recovery rate (< 2%) and the absence of dissolved SF_6 in the geothermal fluid discharged from GPK-2. This type of tracer would mark the most direct paths with high velocity and low tortuosity.

The tracer test using the 1,3,5-nts compound, which was carried out between May and October 2010 and accompanied the longest fluid circulation operation ever carried at Soultz-sous-Forêts, between the two injection wells (GPK-3 and sometimes, GPK-1) and the production well GPK-2 (323 days of fluid circulation without any interruption, from November 2009 to mid-October 2010), with a mean discharge flow-rate of about 18 l/s, confirmed numerous results obtained in 2005 and 2009, especially the existence of a short- and a large-scale fluid circulation loop highlighted in 2005, associated with fractures of different directions and properties. If the time of tracer apparition was identical to that of SF_6 in 2009 (similar fluid circulation flow-rates), the time of the major peak arrival was comparable to that of the fluorescein in 2005. Consequently, the mean linear velocities of the maximum signal estimated in 2005 and 2010 for fluorescein and 1,3,5-nts, which range from 1.8 to 3.2 m/h, are slightly lower than that of SF_6 in 2009 (3.5-3.8 m/h). The tracer recovery rates (18.8% for the short loop and 6.6% for the large loop) and the tracer-swept fracture volumes (5,701 m^3 for the short loop and 20,942 m^3) were higher than those estimated in 2005 using the same modelling methodology (Sanjuan, 2012). The difference of fluid volume discharged from GPK-2 between 2010 and 2005 (296,156 m^3 against 165,500 m^3) partially explains these increases, but the latter also suggest a possible improvement of the fluid circulation loops between GPK-3 and GPK-2, probably due to the stimulation and fluid circulation operations carried out after 2005, which induced an opening of the pre-existing connections. The tracer mass recycled *via* the wells GPK-3 and GPK-1 in 2010 represented about 65% of the total tracer recovery from GPK-2. In comparison but based on a smaller volume of fluid discharged from GPK-2, the tracer mass recycled *via* GPK-3 in 2005 represented about 28% of the total tracer recovery from GPK-2. The estimations of a reservoir connected porous volume higher than 1.5-2.0 Mm^3 (2005 and 2010 tests) are very close to those determined during the fluid circulation test carried out in 1997 between GPK-2 and GPK-1, from 3500 to 3900 m depth (1.2-1.5 Mm^3; Aquilina *et al.*, 2004). These results are concordant with the estimation given by Sanjuan *et al.* (2006a) concerning the mixing of fresh water injected into the geothermal wells between 2000 and 2005 with a volume of about 750,000 m^3 of reservoir native brine.

The tests using the 1,3,6-nts and fluorescein compounds were conducted from April to July 2013, between GPK-3 and GPK-2, and between GPK-4 and GPK-2, respectively. Differently to the previous fluid circulation tests and because of problems which occurred in the surface heat exchangers, the fluid discharged from GPK-2 could not be directly re-injected into GPK-3 and into GPK-4 at high pressure (> 20 bars) and had to be deviated in different atmospheric cooling ponds, after phase separation, and before re-injection at relatively low-pressure (< 3 bar). The mean fluid production flow-rate for the well GPK-2 was about 14 l/s and the fluid injection flow-rates were 7 l/s (for GPK-3) and 7 l/s (for GPK-4), respectively. The shape of the 1,3,6-nts restitution curve is relatively different from those obtained for fluorescein in 2005 and for 1,3,5-nts in 2010. The times of tracer apparition and of the major peak arrival are almost two times higher than in 2005 and 2010 and consequently, the linear velocities of the first tracer apparition and maximum signal are about two times lower (4.3 m/h and 0.7-1.2 m/h, respectively). In addition, the maximum signal is two times lower than that observed in 2010 for a same amount of tracer injected into GPK-3, and the regular decrease of the tracer concentrations after maximum is slower than in 2010 (or 2005). These discrepancies were mainly attributed to the different values of fluid injection flow-rate and pressure used during the circulation tests. The fluid injection into GPK-3 was about two times lower in 2013 than in 2005 and 2010 (about 15 l/s). The tracer mass recycled *via* the well GPK-3 was evaluated at about 25% of the total tracer recovery from GPK-2, for a total fluid volume discharged from GPK-2 of about 123,400 m^3. This value could be lower if a part of the tracer had not been conserved after the phase separation or especially, in the atmospheric cooling ponds, as suggested by tracer analyses in 19 fluid samples collected just before reinjection into GPK-3 or in two samples of mud deposits collected by GEIE in the cooling ponds, which seem to indicate some tracer adsorption. In this case, the estimated total tracer mass recovery rate would be comprised between more than 18 and less than 25.5% by eliminating the tracer recycling and using the modelling methodology of Sanjuan (2012). By comparing the fluid volumes discharged from GPK-2 in 2010 and 2013 and taking into account the shape of the tracer restitution curve, it appears this value is more in agreement with that estimated in 2010. This would confirm the possible improvement of the fluid circulation loops suggested by the results of the 2010 tracer test, even if the tracer mass recovery rates and the tracer-swept fracture volumes for each loop (short- and large-scale loops) have not still been estimated. This task would have to be performed in the framework of the SOUTZ III - ADEME project as well as additional complex modelling works integrating fracture data and structural knowledge in order to optimise the data exploitation, and well interpret the portions of the 1,3,5- and 1,3,6-nts restitution curves, as for the 2005 tracer test.

Although different values ranging from 15.8 to 23.5% were estimated for the total tracer recovery rate of the 2005 test between the wells GPK-3 and GPK-2, following the used numerical models, it appears that all these values and those estimated in 2010 and 2013 were lower than 30%. The estimations of the total tracer-swept fracture volumes are rather concordant for the 2005 test, even if they are relatively different for each of the two fluid circulation loops, following the used numerical models. Most of the results estimated during these tracer tests conducted between GPK-3 and GPK-2 at a depth of about 5000 m and a temperature close to 200°C are comparable to those those obtained between GPK-1 and GPK-2, at depths of 3500-3900 m and a temperature close to 160°C, during the circulation test conducted in 1997 with a circulation flow-rate of 21 to 25 l/s, especially for the linear velocities of the first tracer apparition and maximum signal, the effective average fluid velocities or the total tracer recovery rates (6.6 m/h, 1.8-2.2 m/h, 0.25-0.45 m/h and 25-30%, respectively; Vaute, 1998; Aquilina *et al.*, 2004).

Fluorescein injected into GPK-4 in 2013 could have been detected at very low concentrations in the fluid discharged from GPK-2, after 60-73 days of its injection, confirming the poor hydraulic connections between GPK-4 and the other wells GPK-2 and GPK-3, and *vice-versa,* as shown during the 2005 tracer test between GPK-3 and GPK-4. The velocities of the first tracer apparition are similar and close to 1 m/h. Less than 2% of fluorescein injected into GPK-3 was recovered from GPK-2 in 2005.

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