Inter-well chemical tracer testing at the Rittershoffen geothermal site (Alsace, France)

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ABSTRACT

The ECOGI Company develops a project of deep geothermal energy located in the Rittershoffen site, in Alsace, in the Upper Rhine Graben area, 50 km north of Strasbourg and 10 km east from the Soultz EGS site, in order to produce steam for the industrial drying of starch from a well doublet (injection and production wells). The first geothermal well, GRT-1, with a vertical depth of about 2,550 m (drilled length of about 2,580 m) was drilled in 2012, and tested and successfully stimulated in 2013. The second well, GRT-2, with a vertical depth of about 2,750 m (drilled length of about 3,196 m) and distant from GRT-1 from approximately 1.2 km at the bottom-hole, was recently completed in July 2014. The open-hole section is made of Triassic clastic sandstones and fractured crystalline basement. On the request of the ESG Company and under ECOGI funding, a chemical tracer test using fluorescein and 2,7-naphthalene disulfonate (2,7-nds), associated with a short-term circulation loop between the wells GRT-1 and GRT-2, was conducted over a period of 25 days in 2014. During this test, about 60,000 m^3 of fluid were discharged from GRT-2 with a mean temperature close to 162°C and 54,000 m^3 of fluid were injected into GRT-1 with a mean temperature close to 40°C. Only fluorescein was analyzed both on site and in laboratory. As expected, the 2,7-nds results obtained in laboratory were the most reliable and relevant ones for data quantitative interpretation of this tracer test. The tracer detection in the GRT-2 fluid (corresponding to a volume of about 27,000 m^3 of fluid discharged) occurred at about 12 days after tracer injection. The maximum signal of 2,7-nds was not reached during the production time of 25 days, after about 60,000 m^3 of fluid discharged from GRT-2. The concentration values of both tracers analyzed in the fluid discharged from GRT-2 remained relatively low (< 15 µg/l for fluorescein and < 40 µg/l for 2,7-nds). Consequently, after 25 days of production, the recovery rates for fluorescein and 2,7-nds were very low, close to 0.06 and 0.2% in mass, respectively. If we compare these tracing results with those obtained in the Soultz EGS site, we can conclude that the hydraulic connections between GRT-1 and GRT-2 are much poorer than all those observed between the Soultz wells.

1. INTRODUCTION

The ECOGI Company is developing a project of deep geothermal energy located in the Hatten-Rittershoffen site, in Alsace, in the Upper Rhine Graben area, 50 km north of Strasbourg and 10 km east from the Soultz EGS site. The main objective of this project is to produce steam for the industrial drying of starch from a well doublet (injection and production wells).

The first geothermal well, GRT-1, with a vertical depth of about 2,550 m (drilled length of about 2,580 m) was drilled in 2012, and tested and successfully stimulated in 2013. The second well, GRT-2, with a vertical depth of about 2,750 m (drilled length of about 3,196 m) and distant from GRT-1 from approximately 1.2 km at the bottom-hole, was recently completed in July 2014.

In order to investigate the hydraulic connections between GRT-1 and GRT-2, a program of production tests was conducted between September and October 2014 by the ES-Géothermie (ESG) Company in charge of the supervision of the monitoring works for the ECOGI Company. In addition to these production tests, a chemical tracer test using fluorescein and 2,7-nds, associated with a short-term circulation loop between the wells GRT-1 and GRT-2 was carried out between September 17 and October 12, 2014, over a period of about 25 days, by BRGM with the close collaboration of the GEIE "Exploitation Minière de la Chaleur (EMC)" team (Scheiber and Moeckes, 2014). During this test, about 60,000 m^3 of fluid were discharged from GRT-2 (with a mean flow-rate of 103 m^3/h, temperature and pressure close to 162°C and 9 bar, respectively) and 54,000 m^3 of fluid were injected into GRT-1 (with a mean flow-rate of 89 m^3/h and temperature close to 40°C).

The main aim of the tracer test was to investigate the hydraulic connections between these wells, especially the breakthrough time and that of the maximum tracer concentration, as well as the recovered tracer rate through these connections, if these connections existed. This paper written from the reports of Scheiber and Moeckes (2014) and Sanjuan *et al.* (2014) presents the main results obtained during this tracer test.

2. TRACING TEST RESULTS

2.1 Tracer preparation and injection

200 kg of fluorescein were dissolved in two cubicles (100 kg in each cubicle; Fig. 1a) with 700 litres of freshwater in order to easily dissolve this tracer. The final concentration of the fluorescein solution in each cubicle was 143 g/l. However, during the installation of one of the small scale pumps for fluorescein mixing, 10 litres of traced solution were lost, which is an equivalent of 1.4 kg of fluorescein. Consequently, instead of 1,400 l of traced solution (200 kg of fluorescein), only 1,390 l (198.6 kg of fluorescein) could be injected into the well GRT-1 (Fig. 1b).



Figure 1a: Placement of tracer cubicles close to GRT-1 at the ECOGI site.



Figure 1b: GRT-1 well-head in which the tracers were injected.

For the 2,7-nds tracer, 200 kg were dissolved in only one cubicle with 1,000 litres of freshwater (Fig. 1a). The final concentration of 2,7-nds solution injected into GRT-1 was 200 g/l.

The tracer preparation, storage, transportation and injection were carried out by GEIE "EMC" (Scheiber and Moeckes, 2014). The solutions of the two organic tracers were injected into the well GRT-1 on 17/09/2014 under the BRGM supervision. The injection of the 2,7-nds solution started at 7:27 and finished at 9:20. One additional cubicle of freshwater was injected afterwards, between 9:42 and 10:17, in order to clean the cubicle and inject the tracer in its totality. The 1,390 liters of fluorescein solution were injected between 10:18 and 11:07 followed by two cubicles of freshwater between 11:07 and 12:07, in order to clean the cubicles and inject the tracer in its totality.

The detailed conditions of injection of both tracers are summarized in Scheiber and Moeckes (2014). During tracer injection, the injection flow-rate of the well GRT-1 was reduced to 80 m^3/h and re-adjusted to 100 m^3/h, after finishing tracer injection; the production conditions from the well GRT-2 were nearly constant between 94 and 108 m^3/h.

Over all the period of tracer test from September 17 to October 12 (about 25 days), the mean injection and production flow-rates were monitored by GEIE "EMC" (Scheiber and Moeckes, 2014; Sanjuan *et al.*, 2014). The values for the injection flow-rates range from 59 to 105 m^3/h (with a mean value of about 89 m^3/h) and for the production flow-rates from 80 to 153 m^3/h (with a mean value of 103 m^3/h). At the end of the tracer test, approximately 54,000 m^3 of fluid were injected into the well GRT-1 and 60,000 m^3 were discharged from GRT-2.

2.2 Tracer monitoring in the fluid discharged from the well GRT-2

a) Chemical monitoring of the fluid discharged from the well GRT-2

One time per day, physical parameters such as temperature, conductivity, pH and Redox potential (Eh) were measured by the GEIE "EMC" team during fluid sampling in a plexi-glass flow cell which was directly connected to the cooling unit, in order to avoid the contact of the fluid with atmosphere (Fig. 2a). All the data obtained during the tracer test are reported in Scheiber and Moeckes (2014).

Conductivity, pH, chloride and silica concentrations were nearly constant over all the period of the tracer test (about 25 days), which indicate that there was no significant change of fluid chemistry during this period (Scheiber and Moeckes, 2014).

The conductivity and pH values close to 130 mS/cm and 5.0, respectively, as well as the values of chloride concentrations around 57 g/kg, suggest that the fluid discharged from GRT-2 is a geothermal brine with a

chemical composition similar to that observed for the fluids discharged from GRT-1 (Dezayes *et al.*, 2013; Sanjuan *et al.*, 2016) and from the Soultz geothermal wells (Sanjuan *et al.*, 2010; 2016; Sanjuan, 2014).

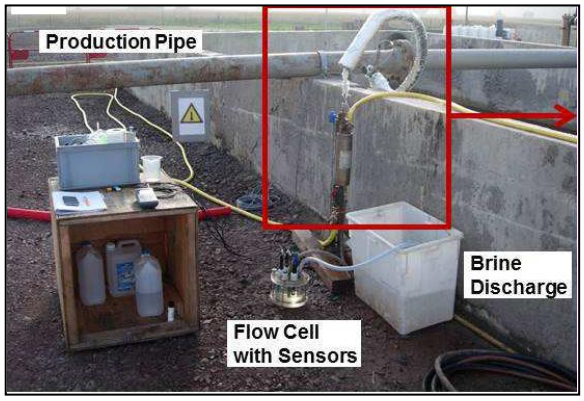

Figure 2a: Brine sampling station at the ECOGI site: coiled tubing connected to the production line, cooling unit for brine cooling and flow cell for measurement of physical brine parameters and brine sampling.

b) Fluid sampling

For this operation, four samples of fluid from GRT-2 were collected per day by the GEIE "EMC" team, during all the period of tracer test, using a fluid cooling unit connected to the GRT-2 production pipe at the surface installations by coiled tubing (Fig. 2b).

During each fluid sampling, 2 x 60 ml were collected in dark brown high density PE Nalgene bottles for tracer determination. One of these bottles was used by the GEIE "EMC" team for the fluorescein determination in its field laboratory, using the fluorescence spectrometer and the corresponding analytical procedure provided by BRGM (Sanjuan *et al.*, 2014; Scheiber and Moeckes, 2014). The other one was sent to the BRGM laboratories for fluorescein and 2,7-nds analyses, using HPLC method with fluorescence detection. Additionally, a volume of about 100 ml of fluid was filtered (0.45 µm pore-width membrane filter) and collected in a PE bottle for alkalinity, chloride and silica determination at the GEIE "EMC" field laboratory.

c) Tracer analytical data

Fluorescein was analyzed in the fluid discharged from GRT-2 both in the GEIE "EMC" field laboratory, using a fluorescence spectrometer (VARIAN Cary Eclipse), and in the BRGM laboratories, using HPLC method with fluorescence detection (WATERS system). For both methods, the detection limit is 0.1 µg/l and the relative analytical uncertainty is close to 15%.

Even if it is well known that fluorescein is less stable and less relevant that 2,7-nds, this first tracer was additionally used in order to quickly have on-site analytical results. As a matter of fact, thanks to the field fluorescein monitoring, the tracer test duration was elongated up to October 12 because fluorescein was detected at values higher than 0.1 µg/l from October 2 (Scheiber and Moekes, 2014).

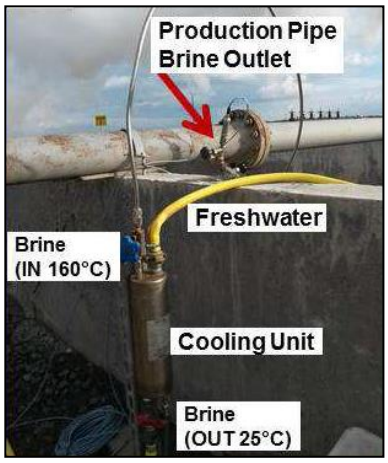

Figure 2b: Controlled cooling of production brine by freshwater from 160°C to 25°C in the cooling unit (figures extracted from Scheiber and Moeckes, 2014).

In contrast, it is obvious that the 2,7-nds data will have to be privileged relative to those of fluorescein for quantitative tracer data interpretation.

The 2,7-nds tracer was only analyzed in the BRGM laboratories, using HPLC method with fluorescence detection (WATERS system). The fluid samples were preliminary treated using MAXI-CLEAN IC-Ag PLUS ($AgNO_3$) cartridges to eliminate their chloride matrix in order to decrease the possible interferences, saturation problems, and the fluid dilution necessary for tracer analyses. Due to the impurity of the used organic product, the detection limit for the analysis of this tracer is relatively high (2.5 µg/l); the relative analytical precision is close to 15%.

The analytical data obtained for both tracers are reported in Scheiber and Moekes (2014), Sanjuan *et al.* (2014) and presented in Fig. 3 to 5.

3. TRACER DATA INTERPRETATION AND DISCUSSION

3.1 Fluorescein and 2,7-nds data

The field fluorescein data obtained by GEIE "EMC", using the BRGM fluorescence spectrometer (Fig. 3a to 5a), have been presented and discussed in detail by Scheiber and Moekes (2014). These data were important to have quick on-site results, adapt the tracer test duration and draw up the first interpretations, which suggested the existence of very poor and no dominant hydraulic connections between GRT-1 and GRT-2, and indicated an evolution of the tracer restitution curve close to that determined using HPLC method (Fig. 3a to 5a). However, knowing that HPLC method is the recommended technique to analyse fluorescein in saline matrices, it is obvious that the data determined using this method must be considered as the most relevant ones.

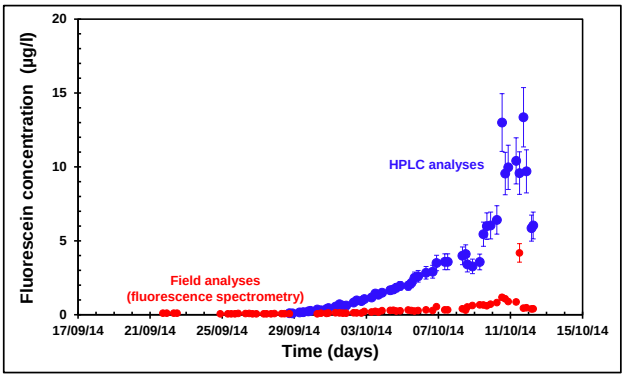

Figure 3a: Fluorescein concentrations determined using fluorescence spectrometry (field analyses) and HPLC as a function of time.

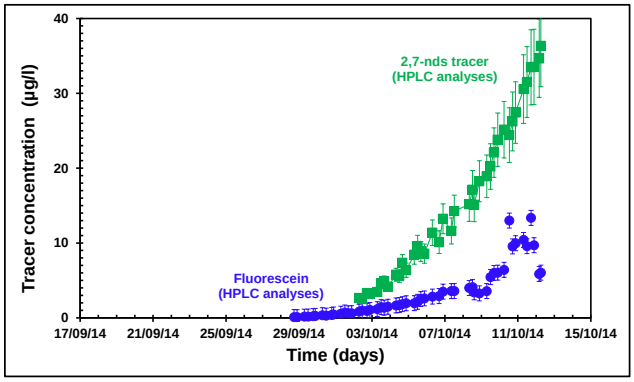

Figure 3b: Fluorescein (HPLC) and 2,7-nds concentrations as a function of time.

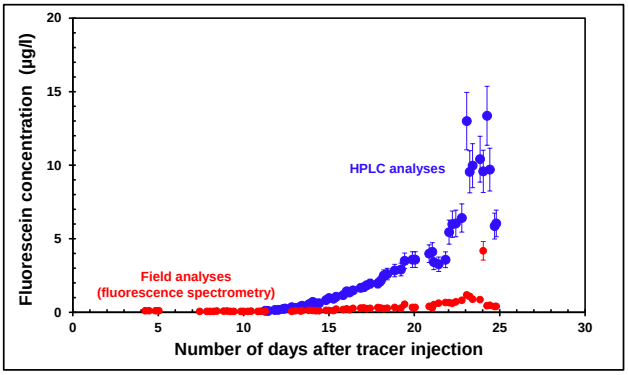

Figure 4a: Fluorescein concentrations determined using fluorescence spectrometry (field analyses) and HPLC as a function of time duration after tracer injection.

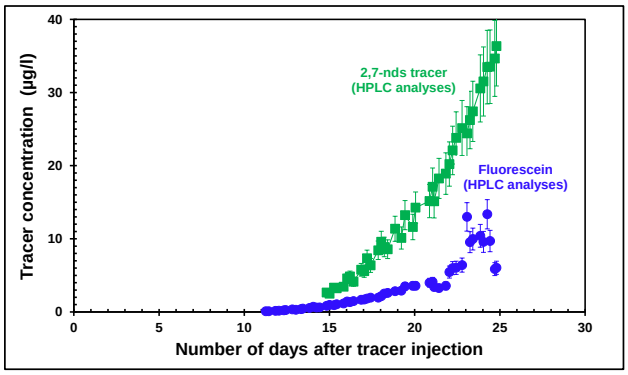

Figure 4b: Fluorescein (HPLC) and 2,7-nds concentrations as a function of time duration after tracer injection.

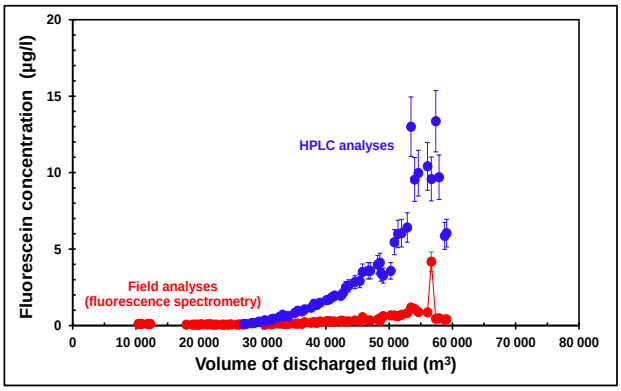

Figure 5a: Fluorescein concentrations determined using fluorescence spectrometry (field analyses) and HPLC as a function of discharged fluid volume from the well GRT-2.

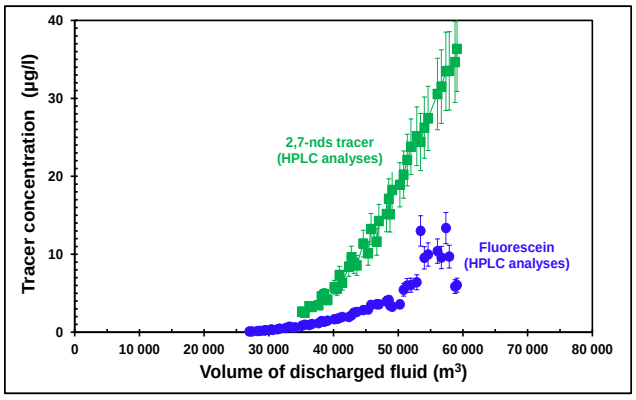

Figure 5b: Fluorescein (HPLC) and 2,7-nds concentrations as a function of discharged fluid volume from the well GRT-2.

If the shape of the tracer restitution curves is similar for the data of both analytical methods (Fig. 3a, 4a and 5a), the fluorescein concentration values are much higher for those determined using HPLC method. These discrepancies could be mainly due to interference problems caused by the saline matrix of the fluid samples, relative to the fluorescence spectrometry method.

Nevertheless, the HPLC fluorescein concentration values remain relatively low (< 15 µg/l) and confirm the existence of very poor and no dominant fast hydraulic connections between the wells GRT-1 and GRT-2. Fluorescein is detected about 11-12 days after the injection of this tracer into GRT-1, and after a volume of about 27,000 m^3 of fluid discharged from GRT-2 (Fig. 4a and 5a). The fluorescein recovery rate is very low and estimated to be close to 0.06% in mass, at the end of the tracer test.

As expected, it appears that the 2,7-nds results obtained in the BRGM laboratories are the most reliable and relevant ones for data quantitative interpretation of this tracer test. However, as the detection limit of this compound is higher than that of fluorescein (2.5 against 0.1 µg/l), we can consider that the first apparition of fluorescein analysed using HPLC in the fluid discharged from the well GRT-2, estimated at 11-12 days after tracer injection and after a produced volume of about 27,000 m^3, is representative of both tracers, even if 2,7-nds has only been detected about 14 days after its injection, at a concentration value of 2.7 µg/l.

Although the maximum concentration of 2,7-nds in the tracer restitution curve has not been reached during the production time of 25 days, after about 60,000 m^3 of fluid discharged from GRT-2, and that the 2,7-nds concentration values remain relatively low (< 40 µg/l), the latter are higher than those of fluorescein (Fig. 3b, 4b and 5b).

A significant part of these discrepancies can be explained by the fact that the concentration of the 2,7-nds solution (200 g/l) injected into GRT-1 was almost two times higher than that of fluorescein (143 g/l). On the other hand, the 2,7-nds tracer is usually considered as more conservative than fluorescein at temperatures higher than 150°C and in natural environments. It is also possible that fluorescein has a behaviour different from that of 2,7-nds relative to its dispersivity and diffusion properties. Contrary to the fluorescein results, it is not observed decreasing concentrations for 2,7-nds at the end of the tracer test (Fig. 1b, 2b and 3b). However, only the three last fluorescein concentrations determined using HPLC method show decreasing values and it is not possible to indicate if this trend is confirmed.

As the 2,7-nds concentration values remain relatively low after 25 days of production, the recovery rate for this tracer is also low, close to 0.2% in mass. These data confirm the existence of very poor and no dominant hydraulic connections between the wells GRT-1 and GRT-2, already highlighted by fluorescein data.

3.2 Comparison with Soultz tracer test data

Several inter-well tracer tests associated with fluid circulation operations have been carried out in the Soultz geothermal site.

In 1997, a four-month forced circulation operation accompanied by tracer testing (Vaute, 1998; Aquilina *et al.*, 2004) showed that it was possible to circulate about 90 m^3/h of water between the wells GPK-1 (3,590 m) and GPK-2 (3,890 m), drilled into the granitic basement. Although the 1997 circulation test yielded relatively good results, the temperature (140-150°C) was not high enough to generate electricity economically.

In 1999, the decision was therefore taken to deepen GPK-2 to 5,084 m, where a temperature close to 200°C was measured. From 2002, two new roughly 5,000 m deep wells (GPK-3 and GPK-4) were also drilled into the granitic basement. These three wells constituted the basic building blocks for the deep heat exchanger.

In 2005, a tracer test using 150 kg of 82.5% pure fluorescein accompanied the 5-month circulation experiment carried out injection well GPK-3 and production wells GPK-2 and GPK-4 in July-December 2005 (Sanjuan *et al.*, 2006; 2015). On average, the injection rate was estimated to be close to 54 m^3/h, with about 43 m^3 coming from GPK-2 and 11 m^3/h coming from GPK-4. Based on these values, about 209,000 m^3 of fluid were injected into GPK-3, and 165,500 m^3 and 40,500 m^3, respectively, were discharged from GPK-2 and GPK-4. The temperature of the produced fluids increased during the circulation test from 140 to 160°C in GPK-2 and from 100 to 125°C in GPK-4.

Three other tracer tests were also carried out between the wells GPK-3 and GPK-2 in 2009, 2010 and 2013, and another one between the wells GPK-4 and GPK-2 in 2013 (Sanjuan *et al.*, 2015).

If we compare the ECOGI tracing results with those obtained in the Soultz EGS site (Vaute, 1998; Aquilina *et al.*, 2004; Sanjuan *et al.*, 2006; 2015), we can conclude that the hydraulic connections between the wells GRT-1 and GRT-2 are not only much poorer than those observed between the deep wells GPK-1 and GPK-2 or between GPK-3 and GPK-2, but they are also poorer than those existing between GPK-3 and GPK-4 (Fig. 6), for which the mean production flow-rate was approximately nine times lower (about 11 m^3/h) than for GRT-2 (about 103 m^3/h).

This low production flow-rate value for GPK-4 is one of the main factors that explains why fluorescein was only detected in the fluid discharged from this well, 28 days after its injection into GPK-3 in 2005 (Sanjuan *et al.*, 2006).

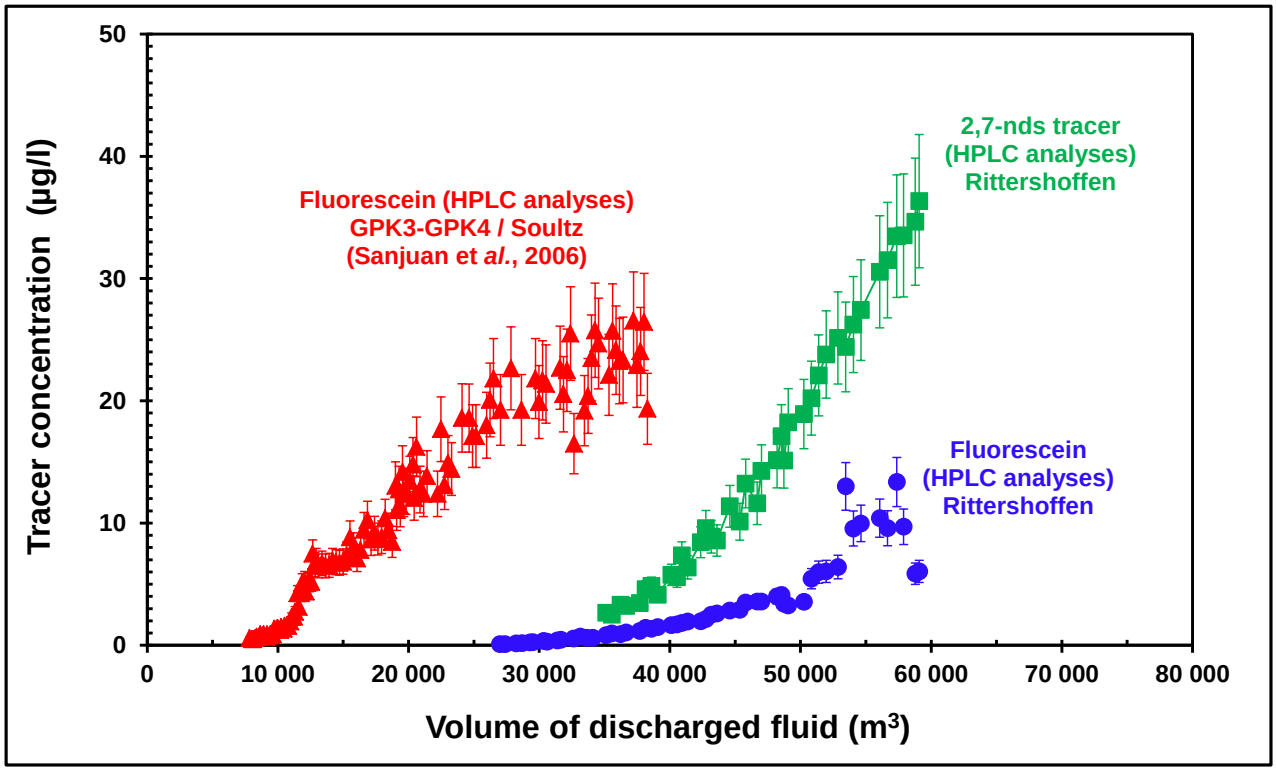

Figure 6 - Results of the ECOGI tracer test between the wells GRT-1 and GRT-2 compared with those obtained between the wells GPK-3 and GPK-4, in 2005, at Soultz-sous-Forêts.

Despite the differences of production low-rate between GRT-2, GPK-2 and GPK-4 and of distances from GRT-1 to GRT-2 (close to 1.2 km) and from GPK-3 to GPK-2 (close to 0.7 km), the linear velocity of the first tracer apparition between GRT-1 and GRT-2 (3.6-4.5 m/h) is ranging from those determined between GPK-3 and GPK-2 (4.3- 8.1 m/h) to that calculated between GPK-3 and GPK-4 (1 m/h), or even between GPK-4 and GPK-2 (0.9 m/h; Sanjuan *et al.*, 2015).

Between the wells GPK-1 and GPK-2 or between GPK-3 and GPK-2, the tracer recovery rates ranged from 15 to 26% in mass (Vaute, 1998; Sanjuan *et al.*, 2006; 2015). Between the wells GPK-3 and GPK-4, this parameter was estimated at about 2% in mass. For the moment, it is calculated to be close to 0.2%, after a fluid discharge of about 60,000 m^3 from the well GRT-2, in the ECOGI tracer test. Moreover, for comparable volumes of fluid discharged from the wells GRT-2 and GPK-4, the lower tracer concentrations observed for GRT-2 (Fig. 6) indicate that the tracers injected into the Rittershoffen site have been mixed with a larger volume of native geothermal brine than in the Soultz geothermal site.

4. CONCLUSIONS

The main conclusions of the ECOGI tracer test, using fluorescein and 2,7-nds, and associated with a short-term circulation loop between the wells GRT-1 and GRT-2, have allowed better knowing the hydraulic connections between these two wells. This test has been carried out by BRGM and GEIE "EMC", between September 17 and October 12, 2014, over a period of about 25 days. During this test, about 60,000 m^3 of fluid were discharged from GRT-2 (with a mean flow-rate of 103 m^3/h, temperature and pressure close to 162°C and 9 bar, respectively) and 54,000 m^3 of fluid were injected into GRT-1 (with a mean flow-rate of 89 m^3/h and temperature close to 40°C).

As expected, it appears that the 2,7-nds results obtained in the BRGM laboratories are the most reliable and relevant ones for data quantitative interpretation of this tracer test. However, as the detection limit of this compound is higher than that of fluorescein (2.5 against 0.1 µg/l), we can consider that the breakthrough time of fluorescein analysed using HPLC in the fluid discharged from the well GRT-2, estimated at about 11-12 days after the tracer injection into GRT-1, is representative of that of the two tracers, even if 2,7-nds was only detected at a concentration of 2,7 µg/l, about 14 days after its injection. This breakthrough time corresponds to a volume of about 27,000 m^3 of fluid discharged from GRT-2.

Additionally, the maximum concentration of 2,7-nds was not reached during the production time of 25 days, after about 60,000 m^3 of fluid discharged from GRT-2. The concentration values of the two tracers analyzed in this fluid remain relatively low (< 15 µg/l for fluorescein and < 40 µg/l for 2,7-nds). Consequently, after 25 days of production, the recovery rates for fluorescein and 2,7-nds are very low, close to 0.06 and 0.2% in mass, respectively.

A significant part of the discrepancies observed between the concentrations of fluorescein and 2,7-nds in the fluid discharged from GRT-2 is due the difference of the injection conditions but this explanation is not sufficient. The 2,7-nds tracer is usually considered as more conservative than fluorescein at temperatures higher than 150°C and in natural environments. It is also possible that fluorescein has a behaviour different from that of 2,7-nds relative to its dispersivity and diffusion properties.

If we compare these tracing results with those obtained in the Soultz EGS site, we can conclude that the hydraulic connections between the wells GRT-1 and GRT-2 are not only much poorer than those observed between the wells GPK-1 and GPK-2 or between GPK-3 and GPK-2, but they are also poorer than those existing between the wells GPK-3 and GPK-4.

Between the wells GPK-1 and GPK-2 or between GPK-3 and GPK-2, the tracer recovery rates ranged from 15 to 26% in mass. Between the wells GPK-3 and GPK-4, this parameter was estimated at about 2%. Moreover, for comparable volumes of fluid discharged from the wells GRT-2 and GPK-4, the lower tracer concentrations observed for GRT-2 indicate that the tracers injected into the Rittershoffen site have been mixed with a larger volume of native geothermal brine than in the Soultz geothermal site.

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