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THE EUROPEAN HDR PROJECT AT SOULTZ SOUS FORÊTS: STIMULATION OF THE SECOND DEEP WELL AND FIRST CIRCULATION EXPERIMENTS

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ABSTRACT

By February 1995 the European HDR project at Soultz was operating 6 boreholes: 2 deep hydraulic test wells (GPK-1, 3590 m & GPK-2, 3876 m) and 4 seismic observation wells with depths between 1500 and 2200 m (Fig.1). In 1993 the first section of a deep underground exchanger had been created through massive stimulation (injection of some 45000 m^3 of water). Between November 1994 until January 1995 a second deep well, GPK-2, was drilled at the periphery of this exchanger. A complex test programme involving the stimulation of GPK-2 (connecting it to the existing exchanger) and various circulation experiments with different production techniques (flash throttled and unthrottled, submersible pump) and varying injection rates was performed between June and August 1995.

INTRODUCTION

The Soultz project is located in northern Alsace (France) in the central part of the Upper Rhine Graben, about 50 km north of Strasbourg. Funding for the project comes from the European Commission, France and Germany and between 1992 to 1994 from UK. The project started in 1987 with the drilling of a first exploration well (GPK-1) to 2000 m (crystalline found at 1377 m, saline formation fluids, density 1.07 g/cm^3). During 1990 and 1991 three old oil wells were deepened into the crystalline basement as seismic observation wells and a fourth well (EPS-1) was cored to 2227 m for further geological investigations. The results of the scientific investigations in these wells have been widely published (Bresee (ed.), 1991, Genter and Traineau, 1992, Jung, 1992) Baria et al., 1995, Beauce et al, 1995, Elsass et al., 1995).

The idea behind the initiation of the project was an evolution of the HDR concept away from the model of single crack(s) in an impermeable media towards the use of a Graben structure with some degree of natural permeability.
The reasons for the continuation of the investigations at the Soultz site included the large resource available (a heat anomaly with a surface of some 3000 km^2), the densely populated towns in the vicinity of the resource, the geological characteristics (low stresses (Klee and Rummel, 1993), joint network aligned with the stress regime, for northern European standards high temperature gradient) and the potential for sharing resources between France and Germany.

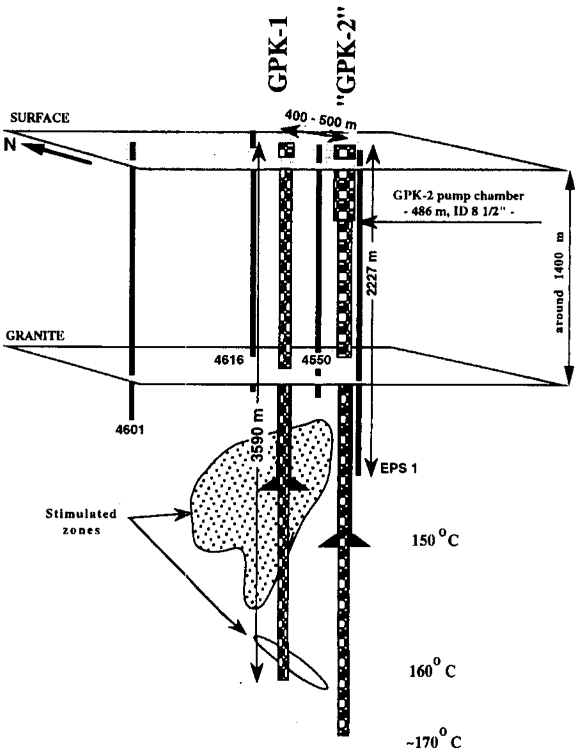

Fig. 1. The situation of the European HDR project at Soultz s. F. before the stimulation of GPK-2 (spring 1995)

THE 1992 - 1994 PROGRAMME

The initial exploration well GPK-1 was extended from 2000 to 3600 m depth during the winter of 1992 / 1993 (Baumgärtner et al., 1995). This operation was followed by a large scale stimulation experiment in the summer of 1993 during which in excess of 45000 m^3 were injected at increasing flow rates up to a maximum of 50 l/s and in various sections of the open hole (Jung et al., 1995). Fracture extension was mapped using the microseismic network at Soultz (Jones et al., 1995). The data indicated that two zones of the rock mass were hydraulically stimulated. The larger one centred around 2900 m, extended horizontally about 700 m on both sides of the borehole and was oriented approximately N-S. The smaller one centred around 3500 m depth, extended horizontally about 600 m on either side of the borehole (with a preference for the southern branch) and was oriented approximately NNW-SSE. The upper zone was associated with the majority of fluid leaving in the uppermost part of the open hole (2850 - 2900 m) while the deeper zone was associated with fluid leaving at a major fault at 3500 m depth (~10% of the flow injected into the open hole left at this depth).

A short production test from the stimulated zones of 1993 was carried out in 1994 (Jung et al., 1995). The test showed a continuously decreasing trend of the production rate. Unthrottled about 11 l/s (down from ~ 15 l/s and still decreasing) were observed after only one day when the production rate had to be reduced for logistic reasons. The majority of the flow produced entered the well in the uppermost part of the open hole. Only about 10% came in at the fault at 3500 m.

THE SECOND DEEP WELL GPK-2

The second deep borehole, GPK-2, was completed in early 1995 to a depth of 3876 m (Fig. 2). The temperature exceeded 168° C at 3800 m (deepest observation point). GPK-2 was positioned to the South of GPK-1 at a distance of around 450 m, targeting the deeper stimulated zone in GPK-1 (at around 3500 m). During the drilling of GPK-2, a large fault was encountered at around 2100 m depth. A small injection test showed that the injectivity of this fault was around 50 Darcy m. After the completion of the well (casing shoe at 3211 m), small scale hydraulic injection tests showed an apparent permeability of the 660 m long open section in the order of 150 μDarcy.

THE STIMULATION OF GPK-2

After the stimulation of 1993 and the subsequent production test in 1994 (both in GPK-1) it became apparent that the density of the injected fluid in a brine-filled formation like in Soultz was very important as it could strongly influence the initiation and growth (upward, horizontal or downward) of the exchanger due to the hydraulic uplift. It was expected that heavy brines could assist in the creation of a more homogenous distribution of flow exits (opened fractures) with depth and not create a main flow exit near the casing shoe as it happened in GPK-1 using fresh water. Furthermore, it was planned to establish an as deep as possible link towards GPK-1. Therefore, it was decided to stimulate GPK-2 in a similar manner to that carried out in GPK-1 but to use as heavy brine as possible as injection fluid. During fracture initiation GPK-1 was kept shut-in in order to monitor the pressure response. A hydrophone was deployed in GPK-1 during this period. Once the brine stored on the surface was nearly used up, GPK-1 was vented in order to produce further brine for fracture extension. The produced brine was cooled in a surface heat exchanger and then injected in GPK-2.

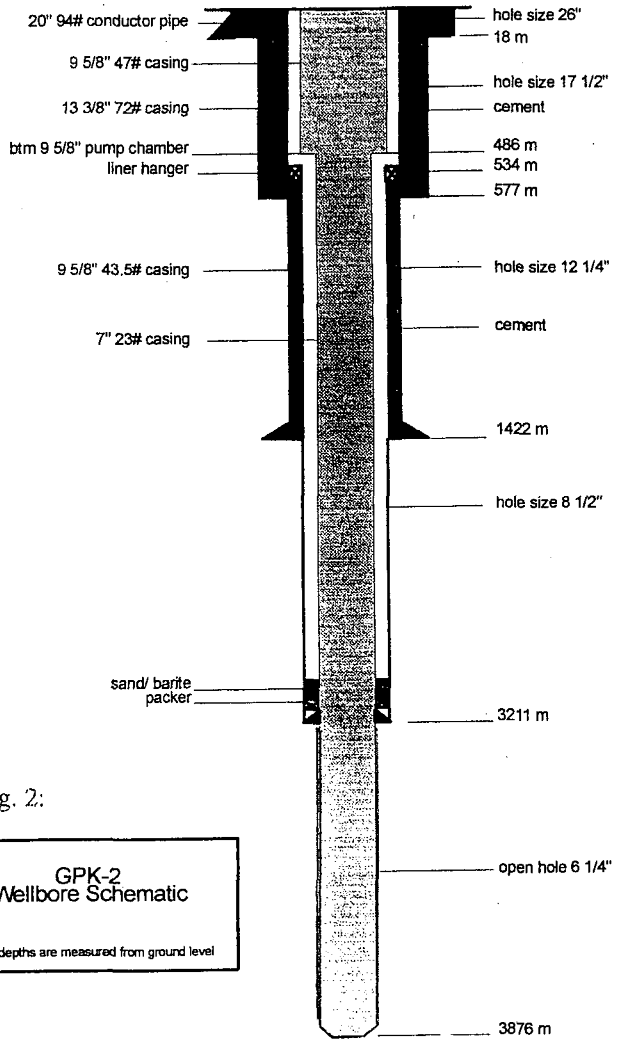

Fig. 2:

GPK-2
Wellbore Schematic

all depths are measured from ground level

For logistic reasons (limited availability of brine and storage capacity on site), a progressively decreasing density of the brines injected in GPK-2 had to be accepted during the test sequence from:

- heavy brine (~ 1.18 g/cm^3 for fracture initiation ~ 300 m^3)

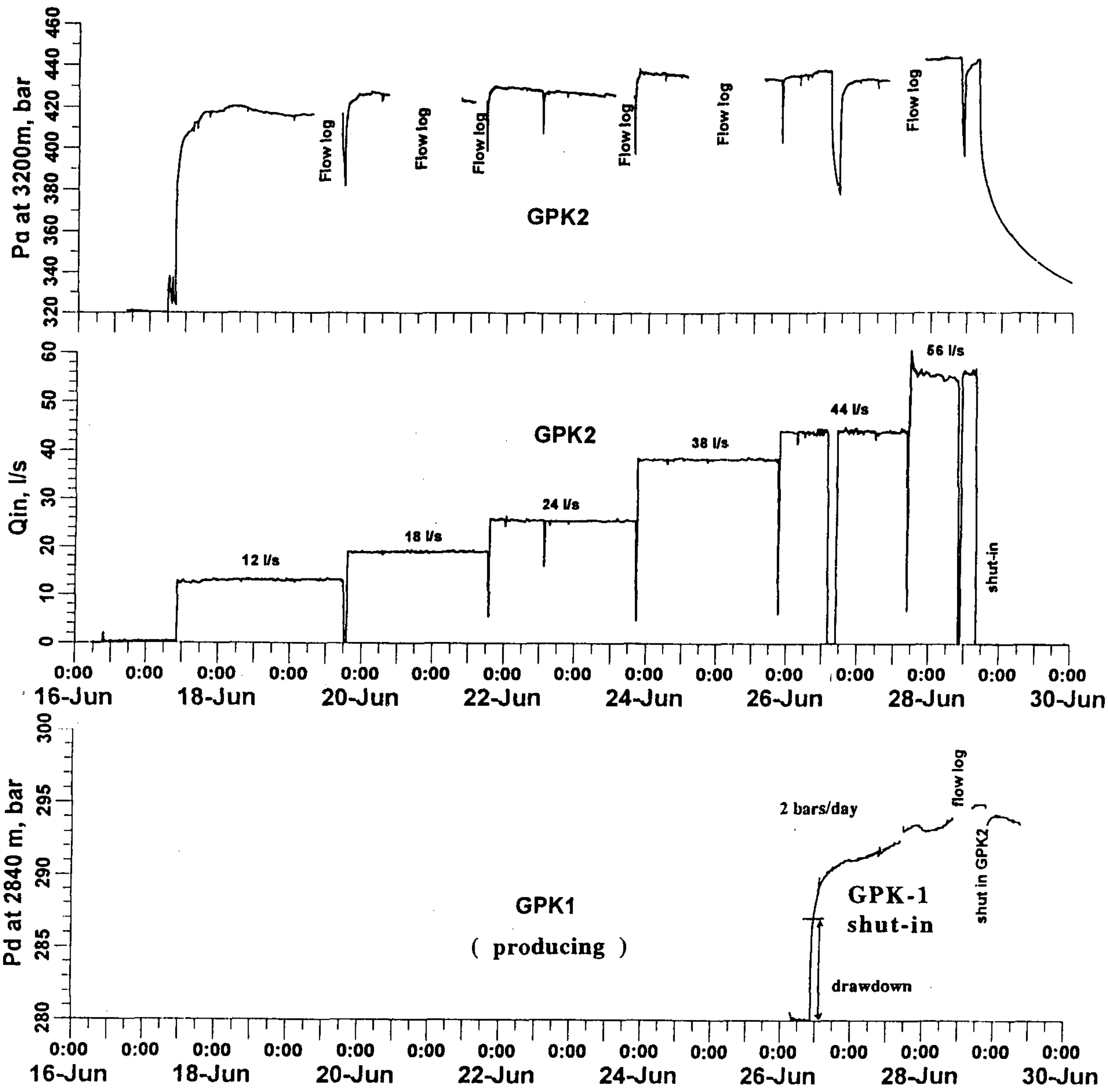

Fig. 3 Injection pressure (downhole at 3200 m), flow rate in GPK-2 during stimulation and pressure response in GPK-1 (downhole at 2840 m) when the well was shut-in during 44 l/s injection in GPK-2

- through formation fluid produced from GPK-1 (~1.06 g/cm^3) for initial fracture extension
- through a mixture of formation fluid with an increasing quantity of fresh water
- to pure fresh water once GPK-1 had been shut-in during the 44 l/s injection step in order to monitor the pressure response of GPK-1.

Due to the injection of about 300 m^3 of heavy brine for fracture initiation in GPK-2 an immediate pressure response in GPK-1 of 0.6 bars was observed.
Microseismic activity in GPK-2 started near the casing shoe (3211 m) and migrated down to 3700 m.

During a subsequent stepped injection test (12 - 56 l/s, Fig. 3) for fracture extension a maximum over pressure of 120 bars was recorded at 3200 m depth in GPK-2 while injecting at 56 l/s. The fact that the injection pressure increased continuously with increasing flow rate and the shape of the pressure record indicated that the jacking pressure had not been reached. Flow logs and microseismicity monitoring showed that several fractures in the open hole had been stimulated with no preference for the uppermost section (as it had been observed before in

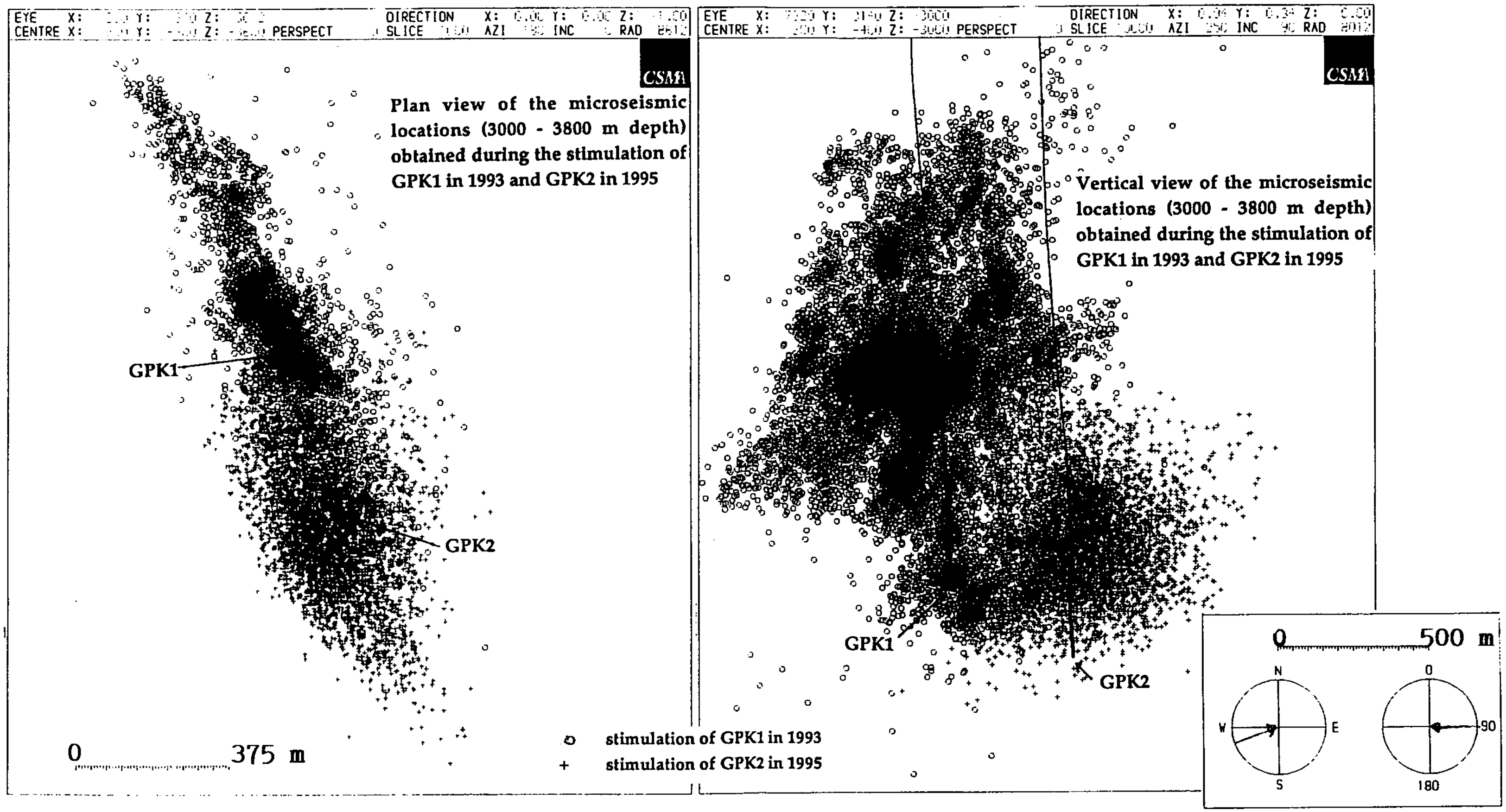

Fig. 4 Locations of microseismic events recorded at the Soultz site during stimulation experiments in the 2 deep boreholes GPK-1 (1993) and GPK-2 (1995)

GPK-1). This demonstrated that in Soultz the effect of the stress gradient can be overcome through adjustment of the density of the injected fluid.

While stimulating GPK-2, GPK-1 showed a gradual increase in the (at 4 bars wellhead pressure throttled) production flow. GPK-1 was producing ~ 13 l/s (and still increasing) while stimulating GPK-2 at 44 l/s. This value has to be compared to a productivity of GPK-1 of 8 - 9 l/s for the same drawdown pressure prior to stimulating GPK-2.

Microseismic monitoring showed that a large volume of rock near GPK-2 was stimulated which merged with that created from GPK-1 in 1993 (Fig.4). The new seismicity was centred on GPK-2 but with relatively more events to the South of GPK-2 and forming a halo near GPK-1 (while venting GPK-1 !). Microseismic data also indicated that the objective of connecting GPK-2 to the bottom stimulated zone of GPK-1 using higher density brine had been successful (Fig.4).

As the seismic events approached GPK-1, this well was shut-in for some 13 hours within the 44 l/s injection period. This was done in order to allow formation pressure to build and thus to improve the conditions for shearing and mapping of the development of the fracture system near GPK-1. Once GPK-1 was shut-in a remarkable pressure increase was observed; the downhole pressure (at 2840 m) rose nearly instantaneously by 10 bars (compensating the 7 bars draw-down pressure) and then increased linearly in the order of 2 bars per day as long as the injection in GPK-2 was continuing.

Flow logging in GPK-1 (with GPK-1 shut-in) after the end of the stimulation revealed an upward flow in the open hole section of GPK-1 in the order of 3 l/s (entry point at the fault at 3500 m and exit in the uppermost section of the open hole around 2850 - 2900 m). This observation supported the microseismic image (Fig. 4) which indicated a preference for a deep connection between GPK-2 and GPK-1. It also puts emphasis on the above mentioned pressure increase in GPK-1 which was monitored with the GPK-1 wellhead shut-in while stimulating GPK-2. It became obvious that this pressure increase occurred despite the fact that the uppermost section of the open hole of GPK-1 which had been stimulated in 1993 acted as a permanent drainage.

The total volume injected in GPK-2 during the stimulation was more than 28000 m^3 of which nearly 10000 m^3 had been produced from GPK-1.

A short post-stimulation step injection test sequence (6, 13, 19, 26 l/s) and the analysis of the hydraulic data showed that GPK-1 and GPK-2 had nearly identical hydraulic characteristics after stimulation. In both wells ~ 20 l/s (= target circulation rate for the here described phase of the scientific programme at Soultz) could be injected after stimulation at an overpressure of around 35 bars (i) - which is significantly lower than the critical pressure for fracture propagation ! The short post-stimulation step injection test also revealed a non linear, almost quadratic relation between the injection pressure and the flow rate which could be a result of turbulence.

CIRCULATION TESTS

Following the stimulation of GPK-2, two circulation tests were carried out by producing from GPK-1 and injecting in GPK-2.

a) USING THE NATURAL BUOYANCY EFFECT TO DRIVE THE PRODUCTION

The first circulation test consisted of flashing near the wellhead and using the natural buoyancy effect to drive the production from GPK-1. A nearly balanced circulation of 15 l/s was maintained for the first 6 days. The increased wellhead pressure and wellhead temperature observed at GPK-1 indicated from the beginning of the experiment a very inefficient flash process inside the slim "exploration well" GPK-1. During this test period a tracer consisting of 20 kg of fluorescene mixed with 40 m^3 of fresh water was injected in GPK-2.

The 15 l/s production rate represented an increase of ~ 40% when compared with 1994 data and this was the contribution of the injection in GPK-2, i.e. ~ 30% of the reinjected flow. The fact that near steady state production conditions could be achieved means (in view of the decreasing "natural" productivity trend of GPK-1) that the impact of the reinjection in GPK-2 was still increasing.
Following the 15 l/s circulation the injection rate in GPK-2 was increased to 22 l/s for 9 days in order to carefully monitor the reaction of GPK-1. There was an immediate increase in the production flow from GPK-1 but this was counteracted by a scaling problem (calcite, the scaling inhibitor mixture used was revised after this experiment) which developed in the wellhead installations of GPK-1 and by a leak which occurred in the wellhead of GPK-2 (internal casing pack-off) reducing the net injected flow rate into the exchanger to probably around 15 l/s.

b) USING A SUBMERSIBLE PUMP IN GPK-1

The second circulation test was performed using a 24 stage high temperature submersible pump in GPK-1

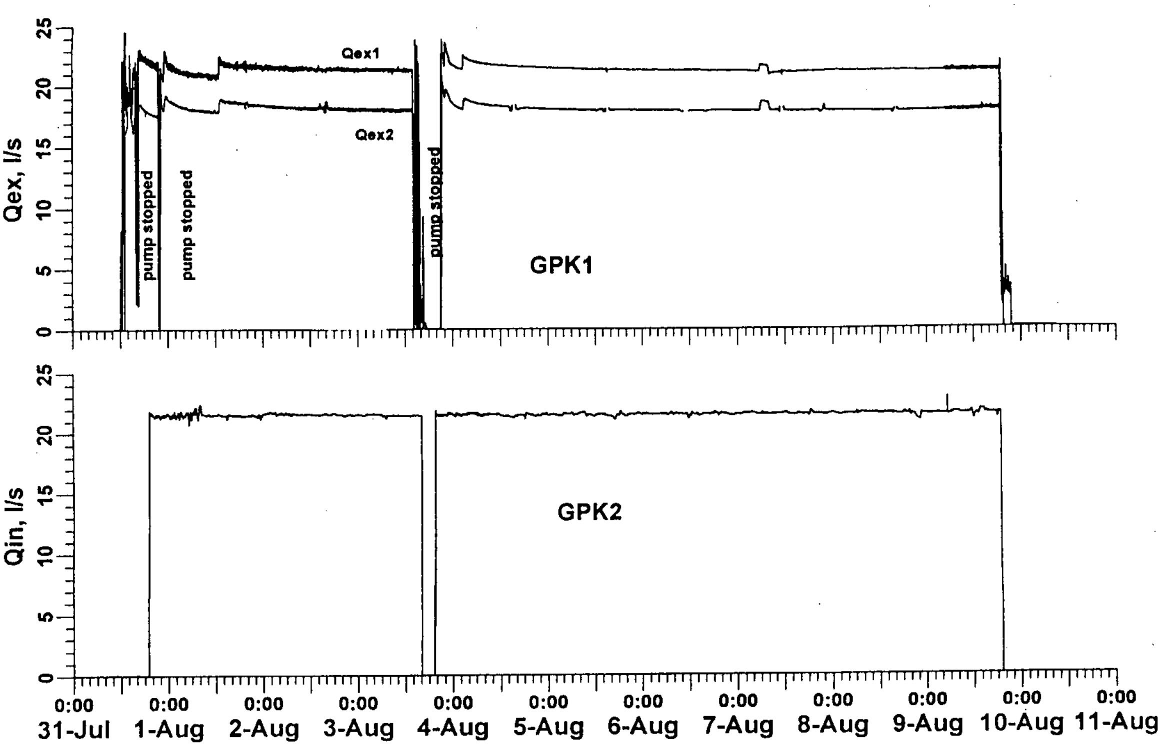

Fig. 5 Production flow rate from GPK-1 (before and after flash) and injection rate in GPK-2 during circulation with a submersible pump in GPK-1

(CENTRILIFT) at 383 m depth (using a 3.5" production tubing) while injecting in GPK-2. A balanced circulation was established for 9 days. During this period about 23000 m^3 were produced from GPK-1 at an average rate of 21.3 l/s (Fig. 5) and the same amount was reinjected in GPK-2. The downhole pump worked satisfactorily and the water level in GPK-1 stabilised after 7 days of production at around 190 m (which included about 40 m as a consequence of the ~4 bars pressure maintained in the annulus of the production tubing at the wellhead). Including the buoyancy effect the estimated total drawdown was less than 24 bars $^{(ii)}$. The surface temperature reached 135° C after 1.5 days and continued to increase slowly (135.8° C recorded after 9 days).

The use of a downhole pump and the corresponding decrease of the fluid pressure in the fracture network did not cause any reduction of the productivity of the well ("pinch-off effect"). On the contrary (comparing $^{(i)}$ and $^{(ii)}$ above), the productivity appeared to be larger than the injectivity. This effect may be attributed to the reinjection in GPK-2 as well as to the pump's ability to act as a collector.

An improved scaling & corrosion inhibitor mixture was injected in the surface lines near the GPK-1 wellhead which worked exceedingly well as no scaling or corrosion was found in the pipes.

A production log performed in GPK-2 towards the end of the circulation period showed that another casing leak, this time at the casing shoe, had developed causing around 40 - 50 % loss in the injected flow. The net injected flow rate into the deep exchanger during circulation can be estimated at 12 - 14 l/s. On top, increasing injection pressures recorded in GPK-2 indicated a gradual clogging of fractures through mud particles. The origin of these particles is not certain up to now as investigations are still ongoing (first analyses point towards a mixture of silica gel and the deposits of an oxidation process which occurred while the brine was stored on surface in an open pit) but there will have to be a full revision of the surface management of the produced formation fluids for the upcoming circulation experiments at Soultz.

No tracer (injected in the previous test) was recovered during this test implying that the exchanger was very large.

The leak at the casing shoe of GPK-2 could be sealed completely through the injection of a mixture of sand, Barite and Bentonite into the annulus of the internal casing string (see Fig. 2).

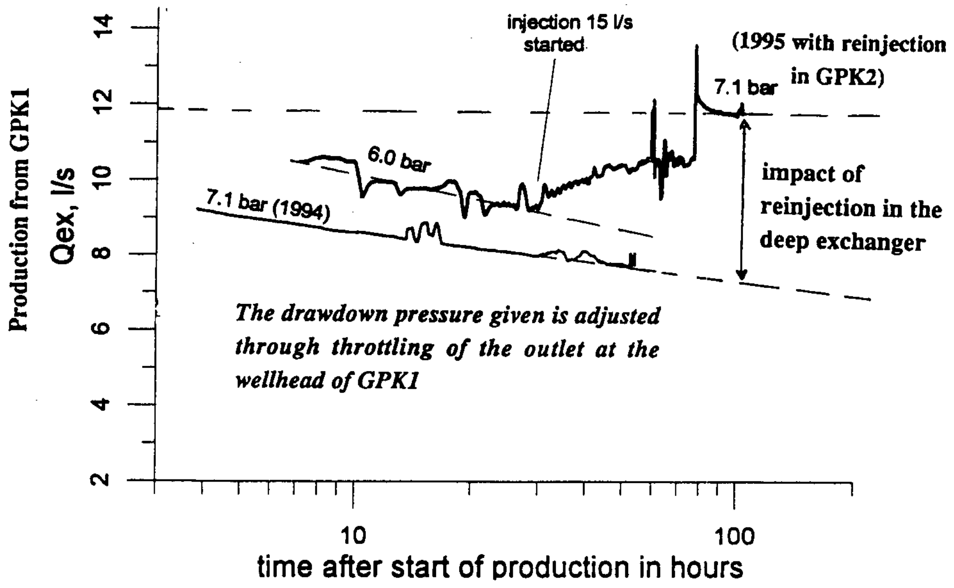

Fig. 6 Impact of reinjection in the deep exchanger in GPK-2 on the production rate of GPK-1
The production flow was recorded behind the flash point and has to be increased by 8% (steam losses) in order to obtain the actual produced flow !

COMPARISON OF PRODUCTION FROM THE EXCHANGER WITH & WITHOUT RE-INJECTION

A final short circulation test was carried out in order to compare the production rate from GPK-1 with and without reinjection in GPK-2. During the period with no reinjection in GPK-2, the production from GPK-1 (buoyancy driven, for technical reasons throttled) dropped in the order of 1.3 l/s per day. As soon as the reinjection in the deep exchanger started the production rate from GPK-1 increased from 9.3 to 10.6 l/s where it stabilised. Comparing the overall production rates from GPK-1 as observed in 1994 and 1995 for similar downhole pressure conditions, it can be seen (Fig. 6) that after about 100 hours the total gain in the production of GPK-1 (due to stimulation and reinjection (15 l/s) in GPK-2) was in the order of 4 l/s - and it was apparently still increasing towards the end of the test, compensating a decreasing trend of the "unsupported" production rate. The compared to the 1994 data apparently increased initial production rate from GPK-1 (without reinjection) is obviously a result of the still deflating exchanger (note the merging trends of the production rates !) as for management reasons the time span between the experiments had to be as short as possible (here 3 days).

It can be concluded that at this stage of the experiment the production of GPK-1 had been enhanced by more than 50 % due to stimulation and reinjection in GPK-2.

Tracer and fluid sampling and microseismic monitoring was continuous during all circulation tests. Seismic events were detected at a rate of 1-2 events per day and these were located near the boundary of the previously stimulated zone indicating that the reservoir was stable.

CONCLUSIONS

Keeping in mind that the Soultz project is presently only approaching the end of an extended feasibility study for the Upper Rhine Graben, it can be stated that a significant progress has been made during 1995. After all, during the circulation with a submersible pump in GPK-1 a thermal energy output in the range of 8 - 9 MW was achieved (which - assuming a power conversion to electricity - would even at this experimental stage give a positive electrical power balance). On the other hand, at various stages of the test programme the limitations of the existing surface installations became apparent (the production well was a slim 6.25" exploration well, the existing surface lines, transfer pipe lines and the surface heat exchanger are under-dimensioned and could not be replaced for financial reasons).

Summarising the experiences at Soultz, it can be concluded that

- a dramatic increase of the injectivity due to stimulation,

- the successful use of a submersible pump to enhance recovery without observing a "pinch-off effect",
- relative low pressures required to circulate (significantly lower than the critical pressure for fracture propagation)
- and virtually no water losses

all these observations indicate that future development of an HDR type technology can successfully be targeted at an area similar to the Rhine Graben structure or on the margins of existing hydrothermal systems.

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REFERENCES

Baria, R., Garnish, J., Baumgärtner, J., Gérard, A. and Jung, R. (1995), "Recent Developments in the European HDR Research Programme at Soultz-sous-Forêts (France)", Proceedings of the World Geothermal Congress, 1995, Florence, Italy, International Geothermal Association, **vol. 4**, 2631-2637, (ISBN 0-473-03123-X)

Baumgärtner, J., Moore, P.L. and Gérard, A. (1995), "Drilling of Hot and Fractured Granite at Soultz-sous-Forêts (France)", Proceedings of the World Geothermal Congress, 1995, Florence, Italy, International Geothermal Association, **vol. 4**, 2657 - 2663, (ISBN 0-473-03123-X)

Beauce, A., Jones, R., Fabriol, H. and Hulot, C. (1995), "Seismic Studies on the Soultz HDR Project (France) During Phase IIa", Geotherm. Sci. & Tech., **vol. 4(4)**, 253 - 272, Gordon Breach Science Publishers

Bresee, J.C. (ed.), 1991, "European HDR Project at Soultz-sous-Forêts", Geotherm. Sci. & Tech., **vol. 3**, nos. 1-4, 308 p, Gordon Breach Science Publishers

Elsass, Ph., Aquilina, L., Beauce, A., Benderitter, Y., Fabriol, H., Genter, A. and Pauwels, H. (1995), "Deep Structures of the Soultz-sous-Forêts HDR Site (Alsace, France)", Proceedings of the World Geothermal Congress, 1995, Florence, Italy, International Geothermal Association, **vol. 4**, 2643 - 2647, (ISBN 0-473-03123-X)

Genter, A. and Traineau, H.(1992), "Borehole EPS-1, Alsace, France. Preliminary Geological Results from Granite Core Analyses for Hot Dry Rock Research", Scientific Drilling, **vol. 3**, 205 - 214

Jones, R.H., Beauce, A., Jupe, A., Fabriol, H. and Dyer, B.C. (1995), "Imaging Induced Microseismicity During the 1993 Injection Tests at Soultz-sous-Forêts, France", Proceedings of the World Geothermal Congress, 1995, Florence, Italy, International Geothermal Association, **vol. 4**, 2665-2669, (ISBN 0-473-03123-X)

Jung R. (1992), "Connecting a Borehole to a Nearby Fault by Means of Hydraulic Fracturing", Transactions Geothermal Resources Council 1992 Annual Meeting, 4 - 7 Oct. 1992, San Diego, Cal., **vol. 16**, p. 433 - 438

Jung, R., Willis-Richard, J., Nicholls, J., Bertozzi, A. and Heinemann, B. (1995), "Evaluation of Hydraulic Tests at Soultz-sous-Forêts, European HDR Site", Proceedings of the World Geothermal Congress, 1995, Florence, Italy, International Geothermal Association, **vol. 4**, 2671-2676, (ISBN 0-473-03123-X)

Klee, G. and Rummel, F. (1993), "Hydrofrac Stress Data for the European HDR Research Test Site Soultz-sous-Forêts", Int. J. Rock Mech. Min. Sci & Geomech. Abstr., **vol. 30, no. 7**, 973 - 976