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CIRCULATING THE HDR RESERVOIR AT SOULTZ: MAINTAINING PRODUCTION AND INJECTION FLOW IN COMPLETE BALANCE - initial results of the 1997 circulation experiment -

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Abstract

The geothermal research programme for the extraction of energy from hot fractured rocks at Soultz-sous-Forêts started in 1987. The research at this site is based on what is called the "Soultz concept". This consists first of injecting water at great depth under high pressure in order to establish efficient connections between a borehole and the natural fracture system in the basement rocks (which at this site already supports some degree of natural circulation) and to improve the transmissivity of this fracture network. Along the direction of the maximum in situ stress, further boreholes are then drilled at the outskirts of the stimulated fracture system. Again massive hydraulic injections are then used to fully connect these boreholes to the previously stimulated fracture network. In the last step the pressure between the boreholes is adjusted in order to force water to migrate between the wells through the „enhanced" natural fracture system. The same techniques may be applicable to future heat extraction from conventional fractured geothermal systems with reduced permeability, a feature which illustrates that the so-called Hot Dry Rock technology is simply part of a continuous spectrum of geothermal activities.

At the Soultz HDR site a 3. 6 km and a 3.9 km deep well exist for hydraulic experiments which are about 450 m apart at depth. Between 1993 and 1996, in the depth range 2800 - 3500 m a large heat exchanger (estimated at more than 3 km^2) was created through massive stimulations. A series of hydraulic tests, including a 10 day circulation test in 1995 <u>using a submersible pump at the production side</u> showed that the 2 deep wells are hydraulically well connected at depth (Baria et al., 1995; Baumgartner et al., 1996).

In summer and autumn 1997 a 4 months circulation experiment was performed in order to demonstrate that it is possible to circulate in such an environment continuously

- more than 20 kg/s of brine,
- at more than 140°C,
- between two boreholes 450 m apart
- <u>without water losses</u>
- and at a minimum energy consumption

During this experiment 244.000 tons of brine at temperatures of up to 142" C and at flow rates of up to 25 kg/s (90 tons per hour) were circulated. The production temperature continued to increase throughout the whole experiment. The total 'usable' thermal energy produced (assuming reinjection at 40° C in a space heating installation) exceeded 27,600 MWh(th). Of this 20,700 MWh(th) was actually extracted (cooled) on surface. The electric energy consumed during the whole experiment for pumping etc. added to not more than about 600 MWh(el). Several tracer experiments demonstrated the fact that water did circulate between the 2 wells. For benzoic acid, for instance, the break through volume was determined to be about 6,000 - 7,000 m^3, the peak(s) occurred after about 15,000 - 25,000 m^3 (modal volume). First modelling results indicate that the system at Soultz is already sufficiently large to sustain more than 10 years of circulation (at the present rates) with less than 2" C production temperature decrease (Bruel, 1997).

This scientific circulation experiment demonstrated that it is possible at the Soultz site to maintain a circulation at flow rates which are approaching commercially interesting values <u>without water losses</u> over a prolonged period and (at 90 tons per hour) requiring less than 250 kW(el) of pumping power compared with a thermal output of 10 - 11 MW(th). Our experience shows that such a loop can be maintained nearly automatically and without any noticeable environmental impact.

INTRODUCTION

The Soultz HDR test site is located in northern Alsace, France, about 50 km north of Strasbourg, in an area of extensional tectonics (Upper Rhine Graben). In this area the crystalline rocks (granite) are covered by about 1.4 km of sediments. The natural formation fluids are strongly mineralised (brine, salinity 100 g/l). To date, the project is operating 6 boreholes: 2 deep hydraulic test wells (GPK-1, ca. 3600 m & GPK-2, ca 3900 m) which are separated by about 500 m on surface (Baumgartner et al., 1995) and 4 seismic observation wells with depths between 1500 m and 2200 m (Fig.1). The deepest seismic observation well was continuously cored inside the crystalline (1440 - 2200 m). At 3900 m depth temperatures exceeding 165^0 C were encountered.

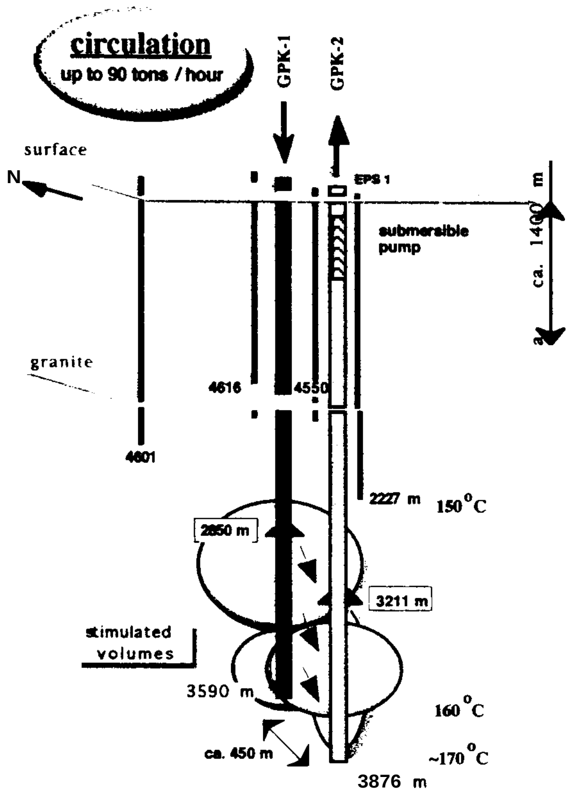

Fig. 1. The situation of the European HDR project at Soultz s. F. in summer 1997

Between 1993 and 1996 a deep underground exchanger had been created through several massive hydraulic stimulation experiments (total injected volume exceeding 100,000 m^3 of water). The fracture surface of this exchanger is estimated from microseismic and hydraulic observations to more than 3 km^2. This exchanger connects the 2 deep boreholes in the depth range from 2850 - 3550 m over a horizontal distance of about 450 m (Baria et al., 1995; Jung et al., 1995; Jung et al., 1997a). Several hydraulic tests (injection & production) showed that the fracture system at Soultz is hydraulically open at its periphery. Therefore, it was obvious that the system as a whole could not be operated at fluid pressures above hydrostatic as this would cause unacceptable fluid losses. Consequently, in 1995, in Soultz for the first time during a 10-day circulation experiment a submersible pump was tested on the production side of an HDR system - with great success. During a 10 day production & reinjection test a continuous production rate of about 20 kg/s could be maintained. As only the produced fluid was reinjected, fluid losses were totally diminished (Baumgärtner et al., 1996). However, this short period test left 2 basic questions unsolved:

Can in such a system a prolonged circulation be maintained without adding fluid ?

Does injected water actually circulate from one well to the other in such a system ?

In order to answer these questions a 4 months circulation experiment was performed at the Soultz site from July to November 1997.

THE SITUATION OF THE 2 DEEP WELLS GPK1 & GPK2 BEFORE THE BEGINNING OF THE 1997 CIRCULATION EXPERIMENT

Fig. 2 shows the technical completion of the two deep wells in Soultz. In summer 1997, both wells still showed the residual effects of the stimulation and production / reinjection tests performed in autumn 1996.

In 1996 the open hole section of the well GPK2 had been restimulated at flow rates of up to 78 l/s (Gérard et al., 1997). This stimulation experiment was followed by a series of step rate hydraulic injection tests in GPK2 (determination of injectivity) and production and interference tests during which the water produced from GPK2 was reinjected in GPK1. The distribution of flow outlets in the open hole sections of both wells can be seen in Fig. 3 a,b which shows 2 spinner flow logs recorded during injection.

In July 1997, 7 months after the last injection experiment in either well, the temperature signature of the cold water hitting the formation can still be clearly seen in both wells. Temperature logs performed just before the beginning of the circulation experiment (Fig. 4 a,b) indicate that the stimulated zone in GPK2 (now the production well) was still cooled by about 20^0 C compared to the equilibrium temperatures. A similar phenomenon, but less pronounced as much less fluid had been injected, was observed in GPK1. Here, the injection zone is still marked by a cooling of about 8^0 C.

It also has to be noted that during the stimulation experiment the underground in Soultz was again contaminated with fresh water (formation fluid:

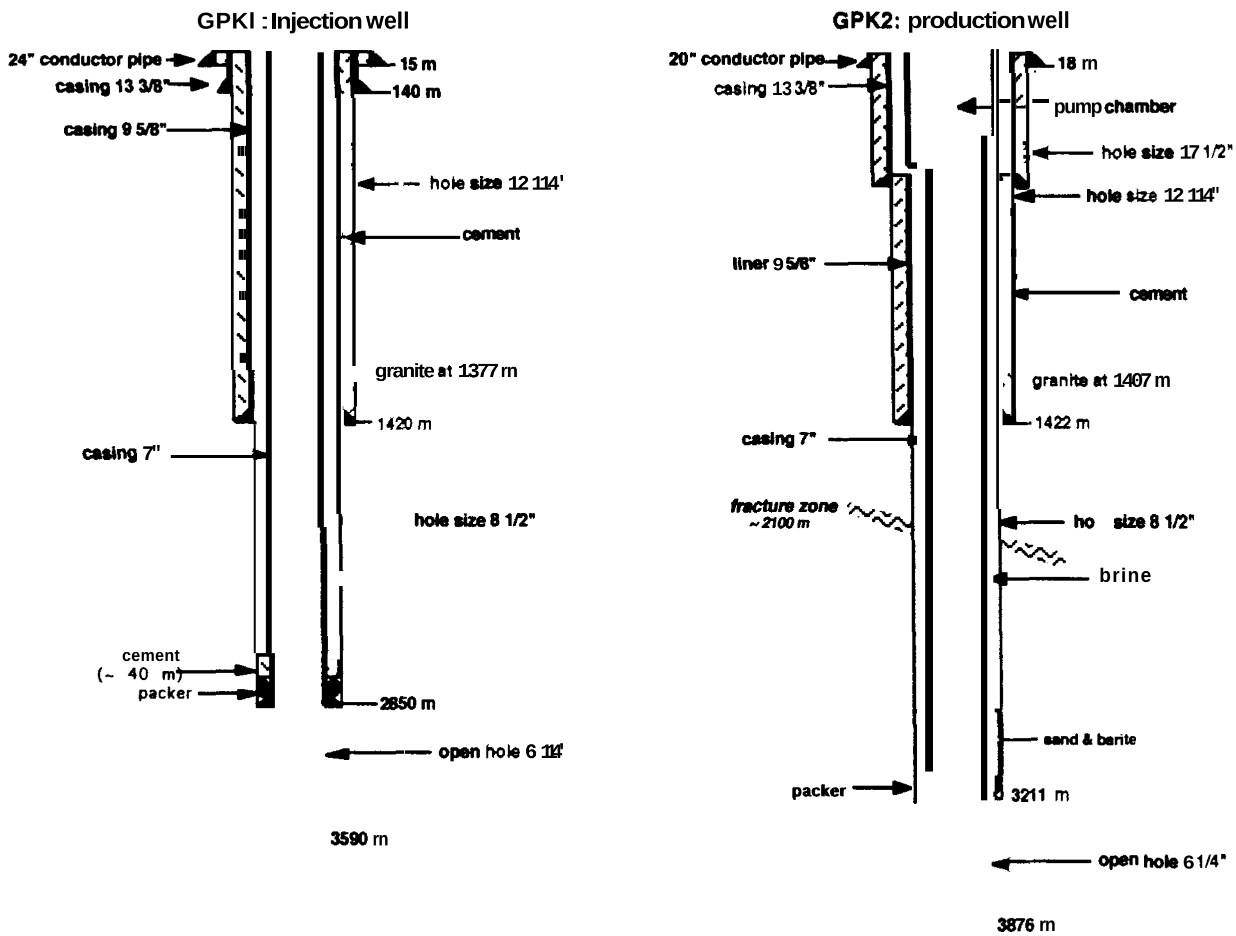

Fig. 2 : Completion of the deep wells GPKl and GPK2 at Soultz s. F.

brine, salinity 100 g/l). During the sequence of stimulation & hydraulic tests in 1995 & 1996 about 80,000 m^3 of fresh water had been injected into the underground around the well GPK2 (later the production well).

SITE INFRASTRUCTURE & TEST SET UP

In the period between January to July 97, completely new surface installations have been put in place at the Soultz site for the circulation experiment. The design of these installations had to take into consideration that the formation fluid at Soultz is strongly mineralised (salinity 100 g/l) and therefore corrosive. A schematic drawing of the test set-up is given in Fig. 6. In this system the produced fluid is kept within a fully closed loop on surface. At the production platform as well as at the reinjection platform the hydraulic lines were built from 6 seamless standard steel pipe. These two platforms were connected through a 600 m long buried 8" pipeline made of composite material. These composite pipes were designed for a maximum operational condition of **4** MPa at 80^0 C to **2.5** MPa at 110^0 C. This pipeline had to cross a railway line, a river and a public road.
On surface, in order to avoid corrosion, any oxygen contact with the produced fluid was avoided by keeping the formation fluid within a gas-tight closed pipe system. The whole system was designed for a maximum fluid pressure of 4 MPa and was buffered **by** Nitrogen filled damping tanks at both platforms in order to minimise hydraulic shocks and short wavelength vibrations. Pressure safety valves installed at both platforms were set at **1.7** MPa. During operations, the fluid pressure on surface was maintained at a level of 1.0 - 1.2 MPa in order to avoid precipitations. The produced brines were pre-filtered at the production side down to 150 µm before entering the heat exchanger. At the reinjection platform the brines were filtered once more, this time down to between 1 and 10 µm.

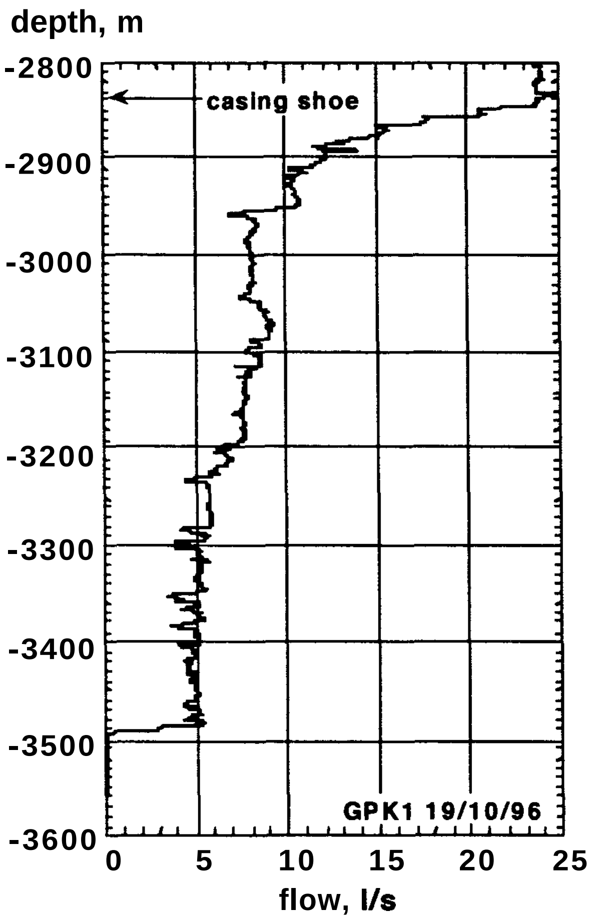

Fig. 3a: Flow log (spinner) in GPK1 during injection at 24 l/s

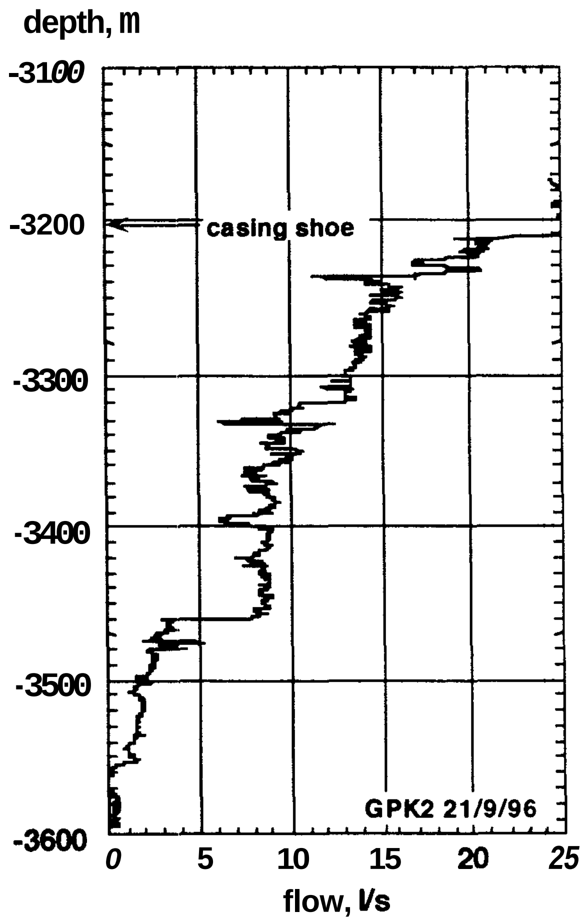

Fig. 3b: Flow log (spinner) in GPK2 during injection at 25 l/s

As the circulation experiment was planned as a scientific experiment, i.e. without any consumer being attached, the whole of the cooling loop (simulating a consumer) was only designed as an auxiliary system with mainly temporary installations. A titanium-palladium plate heat exchanger was used at the production side to extract the majority of the heat produced. The heat was dumped via a cooling loop in an artificial lagoon which contains about 20.000 m^3 of fresh water. This lagoon is located some *300* m from the production platform. The cooling loop was designed for and operated at flow rates of some *300* m^3 / hour.

A 26-stage submersible pump was installed at 430 m depth inside the production well GPK2 using a *5* 1/2" production casing. Re-injection occurred via a centrifugal pump.

The circulation system infrastructure installed was automated and fully instrumented with on-line data available at all the operational, scientific and management points. The automatic circulation system worked by making the downhole pump as the master and the injection pump as the slave. The injection pump followed the production flow. Both pumps were controlled by frequency variators and the system had been designed to fail safely. In case of a power failure air pressure controlled butterfly valves and check valves were used at both platforms to shut the system in.

THE CIRCULATION EXPERIMENT

The circulation test started initially on July 12th 1997 but there was a massive thunderstorm on July 13th which damaged some of the control systems. The circulation was restarted on July 18th **(see Fig 8 for the whole test sequence).** A second storm struck on August 6th but did not cause any serious damage. Otherwise the circulation was almost continuous until November 16th, 1997, except for short regular stoppages (about every 3 - 4 weeks) for maintenance required on the secondary side of the plate exchanger (and only on the secondary side !). The secondary side of the exchanger used to plug with fine biological matter and carbonates from the lagoon which was used as a thermal dump. As the Soultz site is not equipped with an electricity emergency system a few very short stoppages occurred due to voltage fluctuations in the regional electricity network caused by heavy winds (branches touching the power lines).

Beside being a hassle these stoppages which were all caused by external impacts proved the reliability of the underground system and the sturdiness of the surface installations.

Circulation was maintained without adding any make up fluid. Production and re-injection flow were fully balanced. The flow produced was stepwise increased from 21 to 25 kg/s (76 to 90 tons / hour). By the end of the experiment about 244,000 tons of fluid had been produced and reinjected. The temperature at the inlet of the heat exchanger reached 142°C and was still climbing at the end of

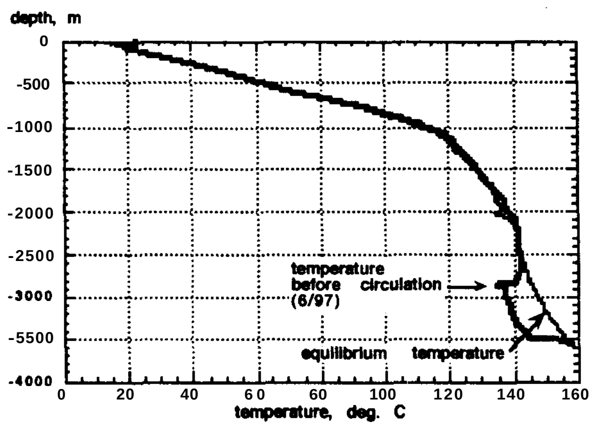

Fig. 4a: Temperature logs in GPK1: equilibrium profile and before circulation

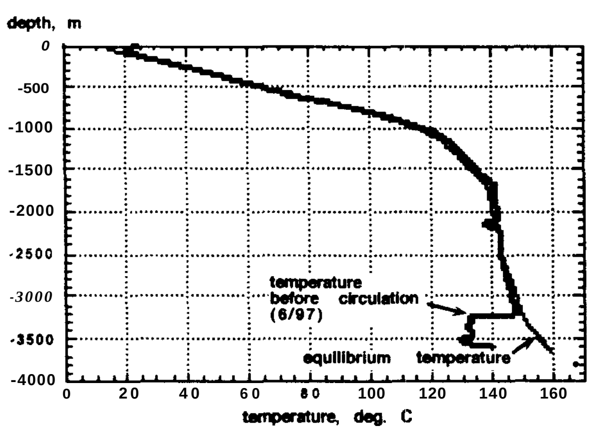

Fig. 4a: Temperature logs in GPK2: equilibrium profile and circulation

the test. The fluid produced at that time still contained some 10% of fresh water from the previous stimulation experiments. This fresh water content was still decreasing.

The reinjection pressure (GPK1) decreased during the course of the experiment from about 4.5 MPa to about 2 MPa. As some Silica deposits had been expected, a biological, non-toxic degradable anti-scaling inhibitor was continuously injected at a very low dosage. However, continuous in line pH measurements showed that the pH level of the produced formation fluid was surprisingly low, in average around 4.8. This did reduce the risk for silica deposits considerably and it was decided to cancel the injection of the scaling inhibitor after some 80 days of circulation. Some 24 hours after the injection of the scaling inhibitor was stopped the reinjection pressure dropped from 3.5 MPa to 2 MPa within 5 days. This pressure drop was associated with a redistribution of major flow outlets in GPK1 (Fig. 9). Here especially the activation of an outlet at 3250 m and the concentration of the flow leaving near the casing shoe into mainly one fracture (~ 2860 m) have to be mentioned. It is suggested that the scaling inhibitor may have caused a skin effect in the vicinity of the wellbore and thus masked the fact that the injectivity near the injection borehole had increased, probably due to the cooling of the rock.

Beside the cooling of the formation the reduction of the injection pressure can also be associated to the fact that during this experiment only brines have been reinjected which contained no free oxygen and which had been filtered down to 1 - 10 μm.

The low reinjection pressure also allowed to continue the circulation without the reinjection pump for 3 days in early November at 77 tons / hour (21.5 kg/s) when the bank of a frequency variator for the reinjection pump failed. This was done by increasing the surface pressure with the submersible pump on the production side. The surface pressure (= reinjection pressure) during this period stabilised at about 1.6MPa.

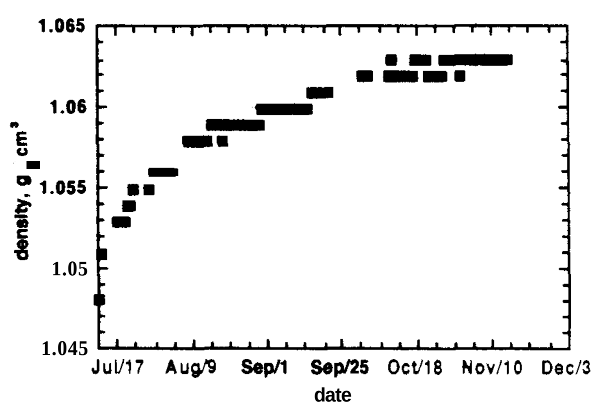

Fig. 5: Fluid density as observed during the 1997 circulation test (from Rummel et al., 1997)

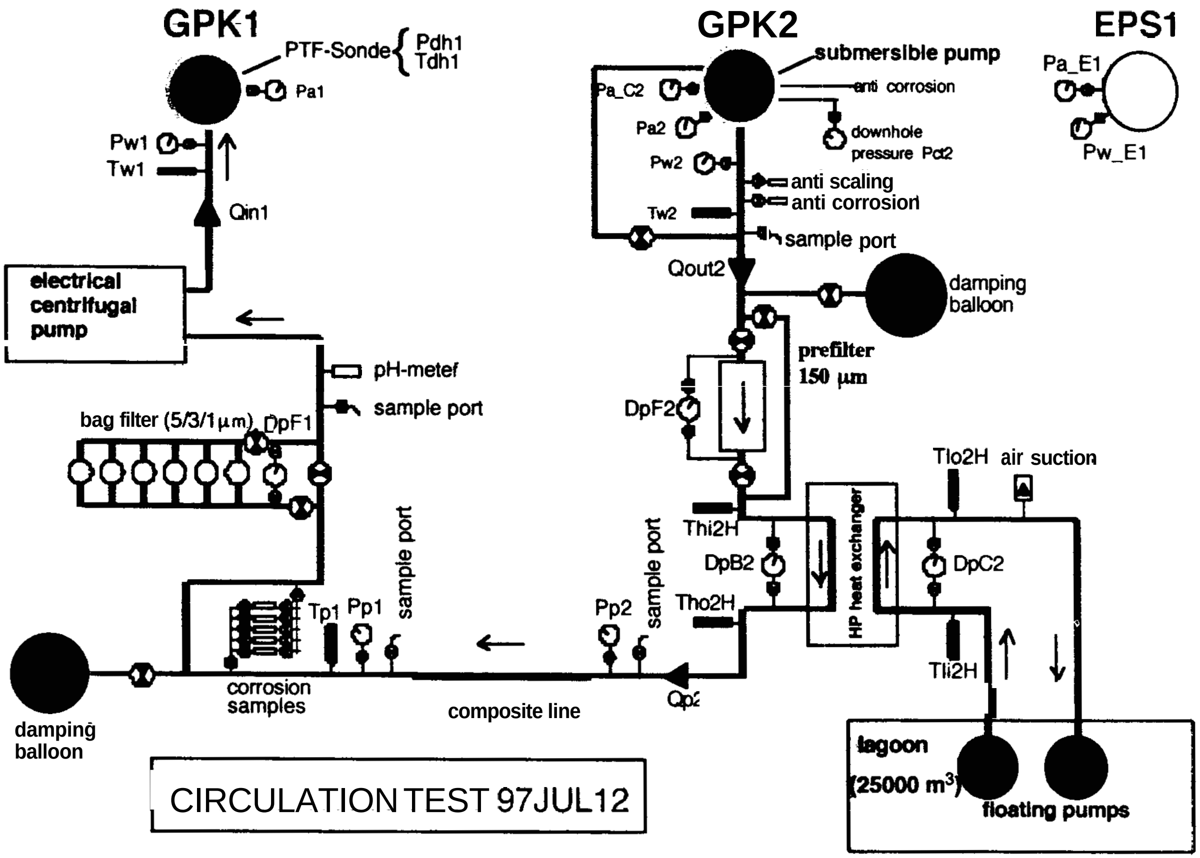

Fig. 6 Surface installations for the circulation experiment

The drawdown in the production well (GPK2) increased slowly during the experiment. To a large degree this can be attributed to the continuous increase of the salinity (fluid density) during the course of experiment (Fig. 5). However, an initial analysis of the hydraulic data (Jung et al., 1997b) indicated that this is probably also due to the gradual warming of the production zone (which was still cooled from stimulation in 1996, see above) causing the near wellbore permeability and thus the productivity to decrease slightly - the inverse effect as observed in the reinjection well. A temperature log performed just after the circulation showed that the equilibrium temperature of the well had still not been reached, after more than 120 days of circulation (still about 5° C below equilibrium temperature) ! While the productivity of GPK2 at the beginning of the experiment was - in absolute terms - higher than the injectivity measured after the stimulation in 1996 (the production zone was still cooler), towards the end of the circulation the productivity had dropped to the

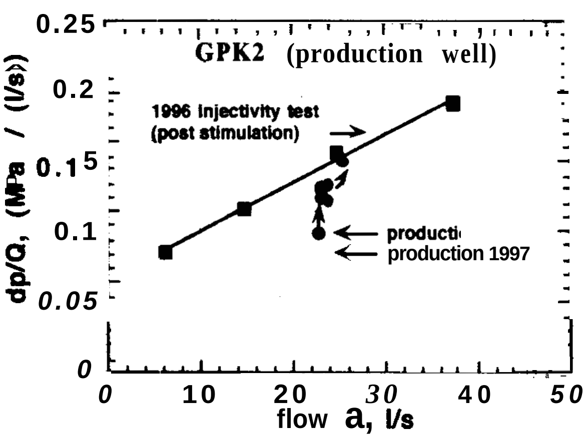

Fig. 7: Impedance of GPK2 during injection and production (from Jung et al., 1997b)

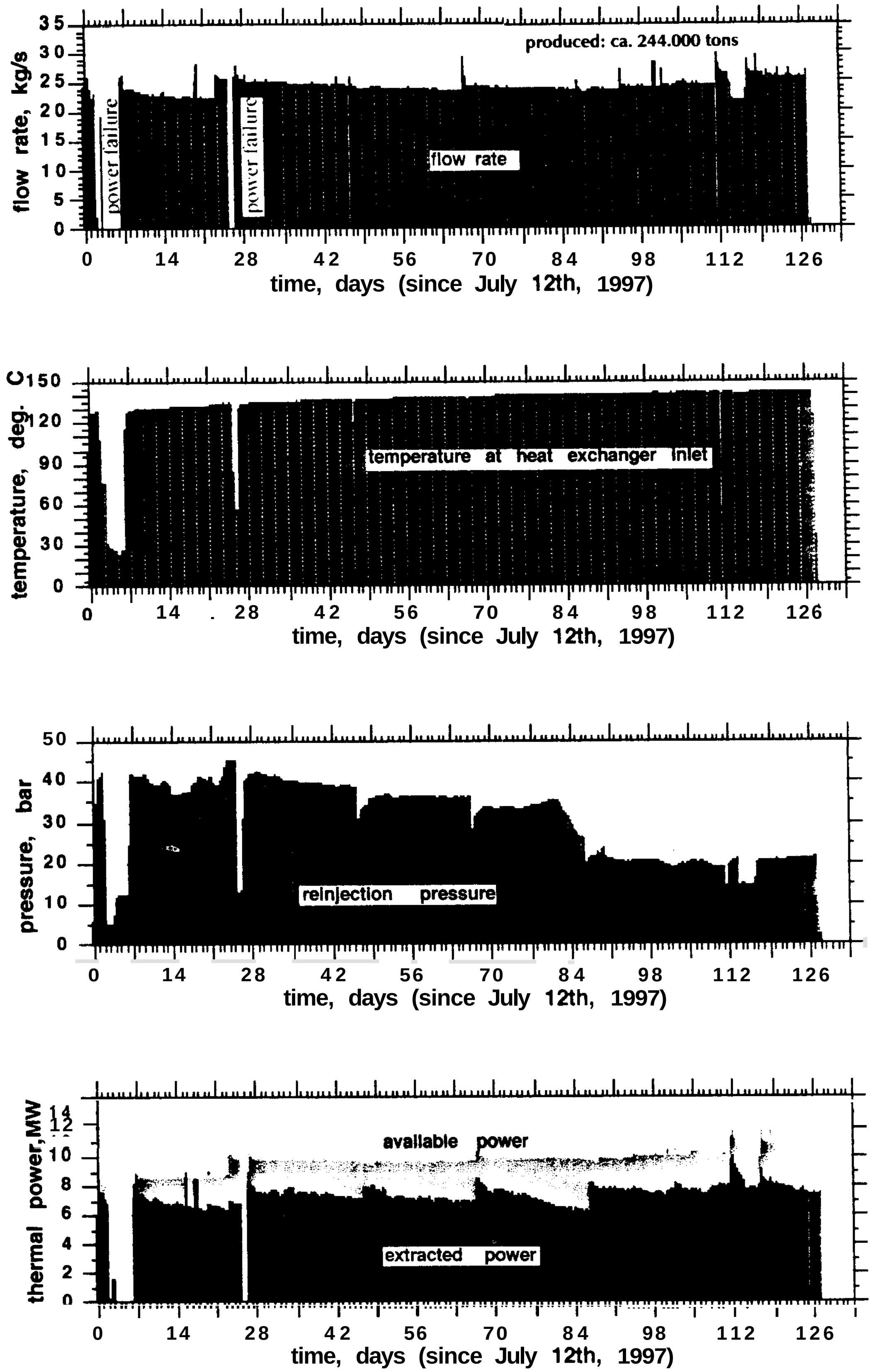

Fig. 8: The 1997 circulation experiment, major parameters

total available energy:	ca. 27,600 MW(th) (assuming reinjection at 40° C)
total extracted energy:	ca. 20,700 MW(th) (reinjection at 60 - 70° C)
consumed energy:	ca. 600 MW(el)

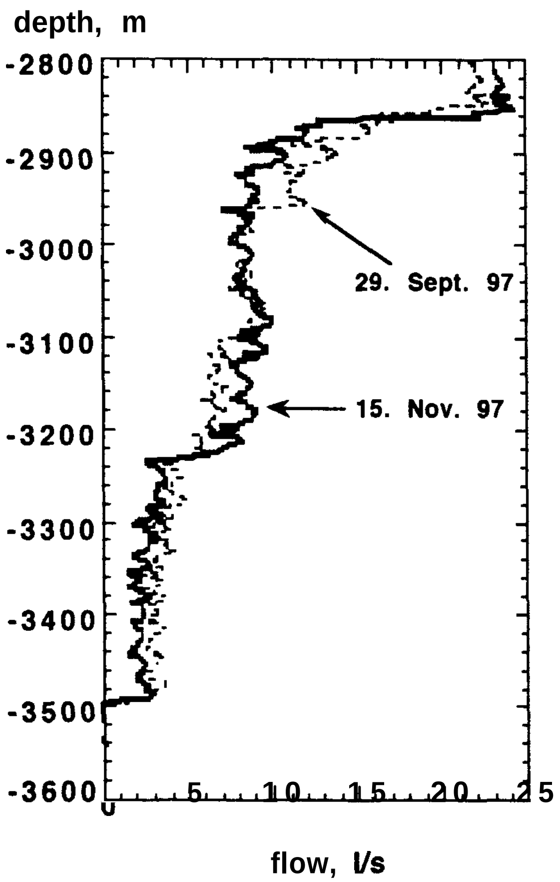

Fig. 9: Flow logs (spinner) in the reinjection well GPKl, before and after the drop of reinjection pressure

level of the injectivity and was stabilising at this level (Fig. 7).

The thermal energy available at the heat exchanger (based on a re-injection temperature of 40 °C for a space heating installation) was in the order of 10 - 11 MW(th) (Fig. 8). Of this some 7 - 8 MW(th) were continuously dumped into the lagoon used for cooling. Due to the continuously dropping reinjection presssure, the electric energy necessary to maintain the circuit dropped during the course of the experiment from 250 to about 220 kW(el) although the circulation rate was increased from about 21.5 to 25 kg/s. A sequence of tracer tests was performed at various stages of the experiment using benzoic acid, fluoresceine, SF6, Deuterium (injected only into the bottom outlet in GPK1), Rhodamine and Amino G. These tracer tests did mark the fact that water is continuously circulating between the 2 wells. For benzoic acid, for instance, the break through volume was determined to be about 6,000 - 7,000 m^3, the peak occurred after around 15,000 - 25,000 m^3 (see Fig. 10). Although the analysis of the tracer data is presently still ongoing, it can be stated already here that these tracers indicate that the exchanger was evolving during the circulation test. This development is marked by a separation of two peaks which appear mainly in the records of the 'later' tracers Rhodamine and Amino G. It can be speculated that this development is related to the redistribution of flow outlets in GPKl which was described above.

More details of the tracer experiments will be reported in the paper of Aquilina et al. (1998) during this workshop.

SOME CONCLUSIONS

The idea behind the initiation of the project in Soultz 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 which offers the possibility to create a "volumetric" exchanger. The reasons for the continuation of the investigations at the Soultz site from 1987 onwards included the large resource available (a heat anomaly with a surface of some 3000 km^2), the densely populated areas in the vicinity of the resource, the geological characteristics (low stresses, joint network aligned with the stress regime, for northern European standards high temperature gradient) and the potential for sharing resources between France and Germany (Klee and Rummel, 1993; Baria et al., 1995; GCrard et al., 1997).

The 1997 circulation experiment represents a milestone in the development of the Soultz project and crowns a decade of successful international collaboration. The main conclusions from this work can be summarised as follows:

- The fracture network in the Upper Rhine Graben has been explored down to 3900 m depth, where temperatures exceed 165°C. Within the volume which has been investigated (up to 1 km around the boreholes), the network appears to be stable and to have the desired properties.

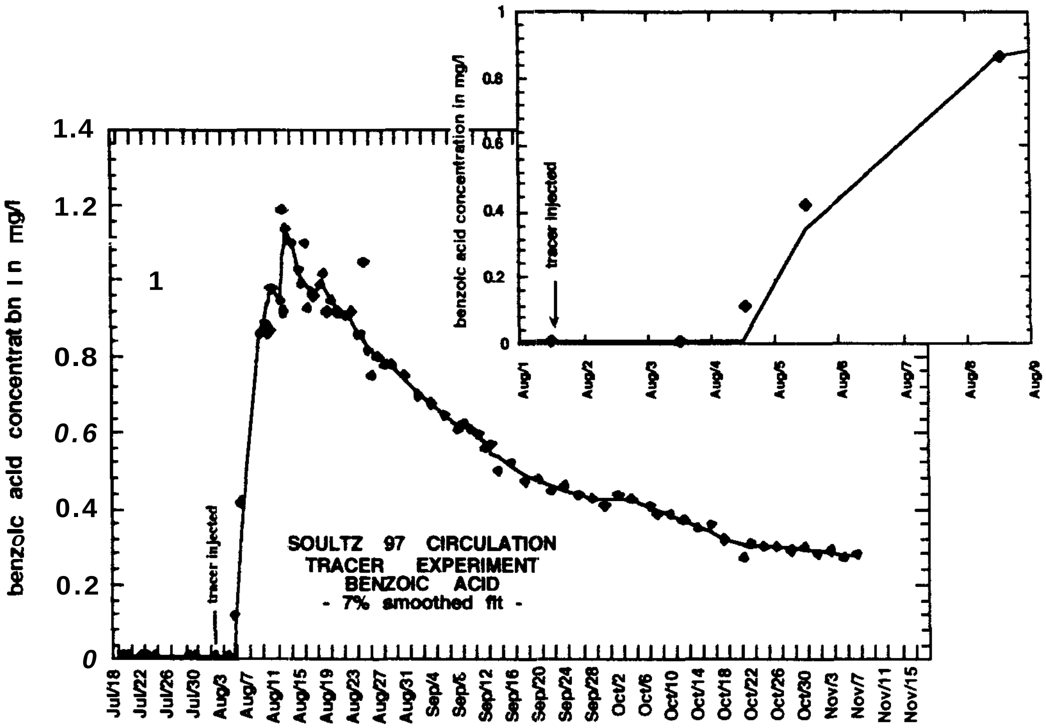

Fig. 10: Tracer concentration (benzoic acid) during the circulation experiment at Soultz. The data are not corrected for the fact that fluid circulated.

- A series of hydraulic tests has been performed, including a forced circulation test of several months duration. This demonstrated that it is possible to circulate continuously at about 90 tons per hour of water, at more than 140°C, between two boreholes 450 m apart without any water losses and requiring less than 250 kW(el) pumping power compared with a thermal output of up to 11 MWth.

- Experience shows that such a loop can be managed nearly automatically, simply and without any noticeable environmental impact.

- Through the on-going learning process, we are beginning to master the required technologies at the scale of the tests performed:
  - economical drilling performance through hard, hot and deep rocks ;
  - stimulation and development of hot and very large "volumetric reservoirs";
  - engineering for development / production adapted to Hot Dry Rock exploitation.

However, it has to be underlined that even though the performance obtained at Soultz is a significant advance on results achieved within the frame of previous experiments at other HDR sites, the project has relied on the continuous transfer of "know-how" from the teams involved in that earlier work, many of whom (from Germany, UK, Japan & US) now form part of the Soultz group.

The future industrial deployment of this technology now requires that the present experiments be extended towards higher flows and temperatures, with continual improvement in the underlying techniques.

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