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Soultz-sous-Forêts: Main technical aspects of deepening the well GPK2

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ABSTRACT

Between mid February to end of May 1999 (in 104 days) the well GPK2 at the Soultz HDR site was successfully re-entered and deepened from 3876 m to a final depth **of** 5084 m and fully completed. Re-entry included the pulling of the existing 3211 m long internal 9 5/8" by 7" casing string, fishing of a submersible pump and some 150 m of 2 3/8" tubing, sealing of a major loss zone and opening of a 6 1/4" well section in granite (3211 - 3876 m) to 8 1/2" hole size. The well was extended to 5048 m in 8 1/2" hole size and again completed with a floating 9 5/8" by 7" casing string. The casing shoe is at 4431 m. A bottom hole core was taken in the depth range 5048 - 5051 m. The core recovery was app. 40%. A pilot hole in 6 1/4" was drilled from 5051 - 5084 m for in situ stress measurements.

The re-entry and deepening of the well GPK2 was accompanied by several technical developments. New casing packer elements based on inflatable metal shells were developed in a close cooperation between SOCOMINE and MeSy GmbH (patent pending). These packer elements were successfully integrated into the completion of the well. The full weight of the casing string is supported by these elements which are filled with and imbedded in cement. High temperature cementing strategies (up to 170 – 190 °C) for the complex saline fluids encountered in Soultz (High Magnesium Resistant Cements) were developed in a cooperation between Schlumberger Dowell (Vechta), SOCOMINE, SII of Houston, Ruhr-University Bochum, BGR Hannover and IFP Paris.

KEYWORDS

Deep drilling, crystalline rocks, well completion.

The background

The future industrial deployment of the HDR technology developed at Soultz requires that the past experiments be replicated at higher temperatures and larger flow rates in order to further improve the efficiency and economy of the technology. Consequently, following the success of the 1997 circulation experiment at Soultz, it was decided to re-enter and deepen the GPK2 well from 3,876 m to 5,000 m. At this depth temperatures of around 200°C were anticipated.

The well GPK2 had been completed in early 1995 to a depth of 3876 m (figure 1). The temperature exceeded 168° C at 3800 m (deepest observation point). During the drilling of GPK2, a large'permeable fault was encountered at around 2110 m depth. From there onwards this fault caused total fluid losses during drilling. **A** small injection test performed immediately after drilling showed that the injectivity of this fault was in the order of 50 Darcy m **!**

In spring 1995 a submersible pump, 150 m of 2 3/8" tubing, some power cable and a tubing clamp had been lost in GPK2 during a scientific hydraulic experiment and were still lying at the bottom of the well. Wireline measurements showed the top of the fish at about 3623 m (probably crumbled power cable). Any deepening of the well would require the removal of this obstacle.

The open hole section of GPK2 had been stimulated twice in 1995 and 1996 in order to create an underground heat exchanger (figure 1, GBrard et al., 1997). **A** total of 58,000 m^3 **of** water were injected below the casing shoe at a maximum flow rate of about 78 l/s. In 1997, during a 4 months "closed loop" circulation experiment, 244.000 tons of hot brine at rates of up to 90 tons per hour had been produced fkom the stimulated section in GPK2 (Baumgartner et al., 1998, Jung et al. 1998).

Based on past experience in drilling the granites at Soultz, an extension of the well in 6 1/4" hole size (through the existing casing) appeared to be not safe to operate at a depth **of** more than 4000 m because the tools (bits, drill collars, 3 1/2" drill string) can be considered as too weak. Consequently, the existing 9 5/8" by 7" casing string had to be removed in order to allow an extension of the well in 8.5" hole size.

Up to now the internal casing in GPK2 was designed as a floating string, compensating the temperature changes in the well (figure 1). If the well was deepened in 8.5" hole size up to TD, no diameter change would be available in the bottom part of the well to support the weight of an extended floating casing string, it would have to be carried by the anchoring assembly (casing packers & casing shoe cementation).

The new completion would also have to take into consideration the previous experiences from GPKl and GPK2 which had shown,

- that considerable difficulties exist for cementing operations in the hot brines found in Soultz and,
- that rubber packers are not suitable for the temperatures encountered in Soultz.

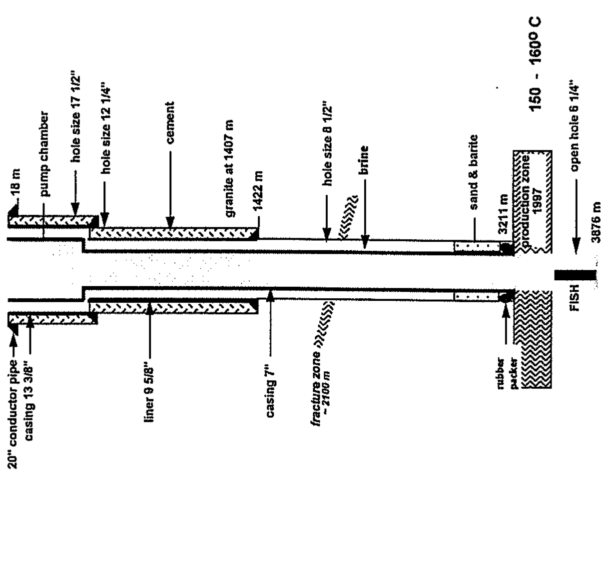

Figure 1: GPK2 well before extension

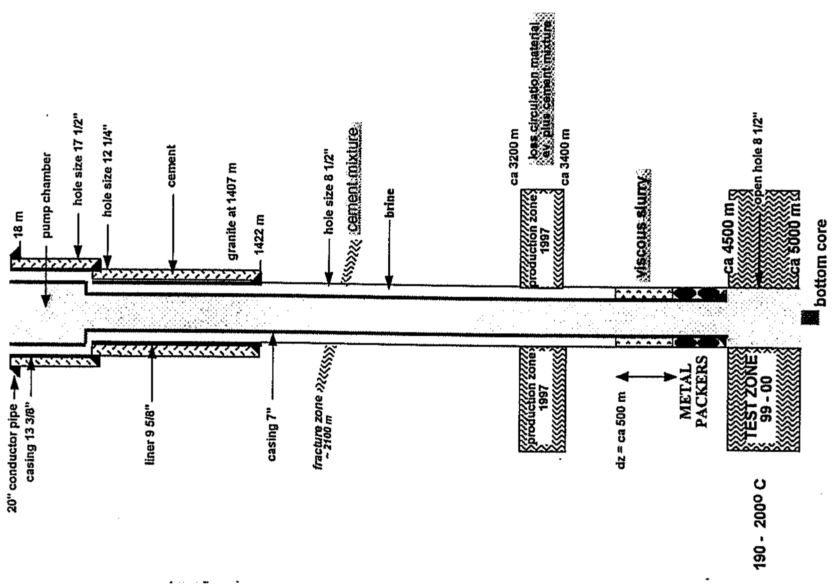

Figure 2: Planned completion for GPK2 well after extension

Cementing strategies

Cementing at higher temperatures is a primary cause of wellbore problems, major time losses and casing problems throughout the geothermal industry as whole. Working in mixed brines at varying salt concentrations adds considerably to the problem. Having this in mind, the Soultz project has been making strong efforts to overcome these problems, new cementing strategies were developed. In the case of GPK2, cementing operations were anticipated

- to seal the loss zone at 2110 m
- to isolate the bottom section of the new internal casing string and to inflate the casing packers.

Work on the development of new cementing strategies started as early as mid 1998. The following organizations participated to these research activities: Schlumberger Dowell, Vechta; Socomine, Soultz; Bundesanstalt für Geowissenschaften & Rohstoffe, Hannover; Ruhr-Universitat, Bochum; Southern International Inc., Houston; Institut Français de Pétrole (IFP), Paris.. **As** a result of the joint investigations, a three-step program was proposed:

The first step was to replace cement wherever possible with a filler which should form a hydraulic seal but which should not bind with the casing string. Such materials should be used to seal longer sections of the annulus of the floating internal casing string. Numerous laboratory experiments with fly ash as base material were performed in 1998. These tests and analyses showed that some fly ashes have excellent settling and thus sealing capacities as long as they are kept in the slag below a critical concentration (this critical concentration depends on the type / origin of the fly ash). During the course of these investigations, clear differences in the settling capacity were observed between fly ashes of different origin !

The second step was to eliminate Portland cement, as far as possible, from the cement mixtures in order to reduce the time constraints. Portland cement (especially under high temperatures) has the characteristic to harden very rapidly ("flash") - once the retardation period has passed. Furthermore, especially Magnesium Chlorides as they are found in the brines at Soultz destabilize the cement reaction.

In co-operation with Schlumberger Dowell of Vechta and BGR of Hannover, numerous laboratory experiments, adapted to the conditions encountered in the Soultz granites, were performed with cement mixtures based on blast furnace based cements (BFC) and fly ash. These developments were triggered through experiences fiom oil wells in North Germany which had shown that cement mixtures based on BFC are less sensitive to mixed brines in the well than conventional API class G cements. Independent test series for the various mixtures were run also at IFP, Paris, to confirm the results. The resulting cements are called HMR cements (High Magnesium Resistant cement). Beside their insensitivity to various chlorides they are characterized by a high stability towards chloridic acids. The compressive strengths achieved with these cements in laboratory are comparable to those observed for API type class G cements. Furthermore, HMR cement mixtures set only gradually with time, no flashing is observed ! This behavior clearly improves the safety of the operations at high temperatures. However, hardening of the cement occurs also somewhat slower than for class G-cements.

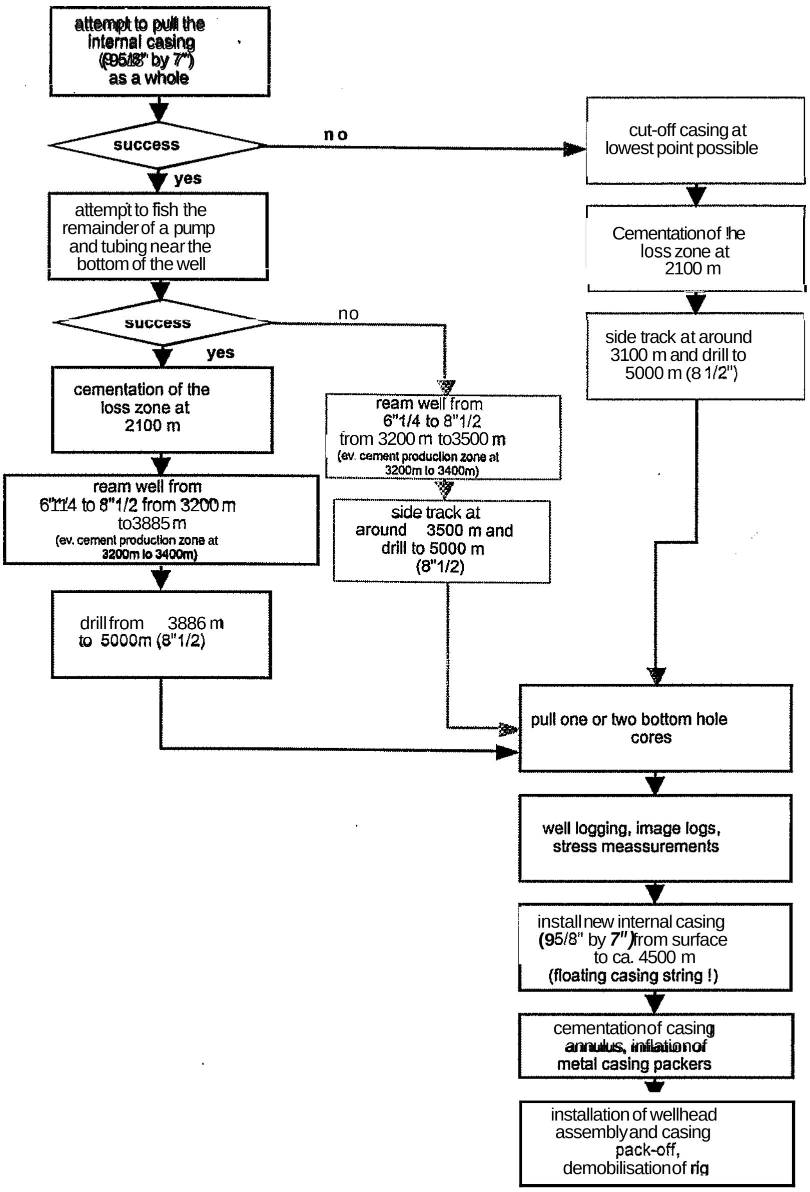

Figure 3 : Planned sequence of operations during the re-entry and deepening of GPK2

Before being used in situ, every premixed charge was tested once more in the laboratory of Schlumberger Dowell. It was observed that considerable differences in thickening time (for the same amount of retarder) may occur for different delivery charges of HMR cement ! Testing of the pre-mixed cement charges to be actually used in the field again proved to be an absolute requirement !

The third step taken was to overcome the salinity problems by calibrating, testing and making up all cements slurries using a brine with an NaCl concentration of 200 g/l, which is nearly twice the total natural salt concentration found in the Soultz area. This way a contamination of the cement with the much more complex natural brine could be eliminated.

Casing-packer technology

Past experience at Soultz had shown that - at least for the hostile conditions found in Soultz (hot brines, gases) - for temperatures exceeding 120 to 140° C conventional rubber based packer elements cannot be used. This experience was gained using conventional rubber based inflatable packer elements as well as compression type mechanical packers, both of various brands. Packer failures observed include brittle fractures of rubber sleeves as well packer leaks due to gas intrusion and expansion when changing packer depths. Further temperature related problems were observed with several kinds of valves and packer ports. On the other hand, the planned completion for the extension of GPK2 required casing-packers (ID 6.25"), which

- would set properly in the hostile environment at Soultz (brine, gas) at temperatures between 170 - 190° C, and
- would be able to support the full weight of the internal 9 5/8" by 7" casing string (> 4400 m, estimated weight in water: 160 tons).

Consequently, fully new casing-packers had to be developed. This development started early in 1998 and was performed in close cooperation between MeSy GmbH of Bochum and SOCOMINE. Decision was made to eliminate all rubber products from these packer elements (with the exception of static O-rings for sealing purpose). The packers were designed to be as simple and sturdy as possible, trying to avoid problems with complex mechanics at high temperatures. **A** solution was found by using inflatable soft metal packer shells. Selecting the right alloy, the behavior of such metals can be adapted to the prevailing chemical and temperature boundary conditions. For the extension of GPK2, for the **8.5"** open hole section in granite, a packer design with a mandrill of 7" 26 lb./ft C 95 casing and a sleeve made of a salt water resistant Cu alloy was chosen. The packer sleeve is inflated through cement injection ("packer setting"). Numerous laboratory tests with such metal packer elements were run. Deformation of the sleeve (at room temperature) started at around 10 MPa. Setting pressures could be as high as 25 MPa. The packer elements designed for an 8.5" open hole could inflate up to 10" hole size.

A special test set up was designed in order to measure the anchoring strength of a single packer element. The anchoring tests were performed inside test pipes with varying IDs from 8.5" to 10". The anchoring force of a single element increased from a minimum of 30 tons inside a totally smooth steel pipe to over 100 tons as soon as some minor irregularities (simulating a rough borehole wall) were machined into the test pipe. For the application in the GPK2 well, in order to facilitate the handling, the casing-packer elements were designed in such a way that 7 packer elements together with an upper and lower casing pop-joint (necessary to be able to set the slips on the rig floor and to run centralizers) could be pre-assembled to one long single packer unit at the length of a Range 3 casing joint (app. 12 m). The elements were connected via 7" BTC casing couplings. Each packer element had an overall length of app. 1.5 m (incl. one coupling). The sealing section for each element had a length of app. 0.8 m. Patents for the metal casing-packer technology are pending.

The rig selected

In order to safely re-enter and deepen the well GPK2 from 3976 m to 5000 m, a land rig of the 1500 hp class (1300 - 1700 hp) was necessary. After an extensive review, it was decided to select a rig of ENEL (Italy) based on the cost and the quality of the rig, the associated equipment (tubing, mud logging, coring, casing handling), the support to the rig, the size and the power of the rig. The main parameters of the rig selected are listed below:

Rig type	MASSARENTI 6000 EE, DIESEL-ELECTRIC' 1700 hp
Max. drilling depth (5" DP)	5.200 in
Hook load	453.000 kg
Setback load	272.000 kg
Rotary load	453.000 kg
Comb. substructure load	725.000 kg
Motors	4 x ISOTTA FRASCHINI / 16 cyl / 900 hp ea..
Generators	4 x ANSALDO M2V 500 CH / 670 KW / 600 Volts
SCR unit	1 x G.E. µDrill 3000 / 6 bays

Main operational steps

During the re-entry and deepening of the well GPK2 several crucial technical operations had to be performed. These are described below in the sequence of operations (see figures 1, 2 and 3).

Pulling of the existing 9 5/8" by 7" internal casing string

The 9 5/8" by 7" casing string in GPK2 which had been installed in 1995 was isolated by a rubber casing packer and some 150 m of a sand and barite packing in the annulus (figure 1). As the weight of the casing string in brine was in the order of 110 tons (128 tons in air) the maximum pulling force had to be restricted to 204 tons (i.e. 450.000 lb.), in order to not risk to tear apart the string. The plan was to engage the casing string with an ITCO casing spear and to work the casing loose by pulling and slacking off.

The pulling of the casing was performed between February 16th -18th. In order to be able to install the spear properly, two separate scraper runs were necessary inside the 9 5/8" (removing scaling, 8.5" and 8 5/8" blades). The casing was engaged and worked in the load range between 100 to 190 tons for about 5.5 hours before it came free. When the casing was laid down it appeared that one 7" centralizer, part of a 9 5/8" centralizer and some bands of the packer re-enforcement were missing. As the casing appeared to be still in good condition, it was decided to inspect and repair the best joints and to re-run them after the extension of the well in order to reduce the overall cost of the well.

Recovery of a submersible pump and some 150 m of 2 3/8" tubing

The second critical operation was the recovery of a submersible pump and some 150 m of 2 3/8" tubing which had been lost in the well in spring 1995 (on top of this some 200 m of power cable and a tubing clamp had dropped in the well at that time). Again this operation was critical due to the fact that if the recovery was not successful the well would have had to be side-tracked (figure3).

The fishing operation was engaged immediately after the 9 5/8" by 7" casing was pulled (dates of fishing / milling operations: 19. - 25.2. and again 15. - 16.3.99). First the well was cleaned to the top of the fish with a 6 1/4" bit. The fish had been tagged by wireline wireline at 3623 m. During the next step of the operation more than 1 m of the 2 3/8" tubing (first collar) was milled using a 5 7/8" flat bottom mill. Once the top collar was milled it was possible to grab the tubing with an overshot and retrieve the 150 m tubing in one run. At this point, the submersible pump, the tubing clamp, the power cable plus some centralizer pieces fiom the casing removal still remained at the bottom of the well. During a second mill run with a 5 1/2" flat bottom mill it was possible to destroy the vast majority of these pieces. As it turned out, after the cementation of the loss zone and the opening of the well to 8 1/2", another mill run (5 7/8" flat bottom mill) was required to fully clean the well (15. - 16.3.99). During this last mill run high torque and drag values were observed, It became obvious, that this operation was performed in a difficult section of the well (remark already in 1995, at the end of the drilling operations, very high values of torque and drag had been observed in this depth range, i.e. below 3870 m).

Sealing-off of a major loss circulation zone at a depth of around 2110 m

During drilling of GPK2 in 1994 / 95 a major loss zone was encountered at 2110 - 2111 m. From this point on, GPK2 had to be drilled without returns (total losses). In order to improve the control of the drilling operations, it was decided that this zone has to be cemented. Past experience had shown that treatments with pills of slag slurry and LCM did not promise a large probability of success. Before the cementation, a 3 m^3 high viscosity was spotted below the loss zone at 2110 m. The loss zone was then successfully isolated during 3 subsequent cementing operations using HMR cements (March 6th - 9th, 1999). For this application BFC and fly ash were mixed in equal proportions. The cement was designed for a bottom hole curing temperature of 120° **C.** The retarder used was D13. All three cement jobs were pumped through open ended drill pipe.

Drilling hot and fractured granite at greater depth

At the beginning of the drilling operations 665 m of hole inside granite had to be opened from 6.25" to 8.5" (figure 2). Hole opening was performed with a standard 3 cone roller bit (SECURITY H100 FL, (IADC code 837Y). A standard bottom hole assembly consisted of:

8.5" bit,
8.5" 6pt roller reamer
6.5" short drill collar
8.5" **3** pt roller reamer
6.5" drill collar
8.5" 3 pt roller reamer
6.5" drill collar
8.5" 3 pt roller reamer
10 - 6.5" drill collars (ca. 91.5 m)

Total length of BHA: app. 122 m

The 665 m (3211 - 3876 m) were reamed in 102.5 hours, consequently the average penetration rate was close from 6.5 m/h at an average weight on bit of 7 tons. **4** bits were used, the average length of hole opened per bit was 166 m.

Drilling in 8.5" was mainly performed with **drill bits** of the type H100 FL of SECURITY. With increasing depth the temperature impact on the roller bearings became apparent, more sealing failures could be observed. The penetration rates continuously dropped from about 2.8 to less than 2 m/h at weights on bit between 8 - 12 tons. The meters per bit dropped in parallel from 127 m (3900 - 4000 m depth range) to 50 to 70 m at depths below 4500 m. Some difficulties were encountered with **drilling breaks** i.e. zones of increased alteration or fracturing within the granite. The most important zone of this kind was intersected right at the bottom of the old well. In 1995, using a smaller rig, drilling of GPK2 had been stopped at 3876 m because a rapid increase of torque and drag was observed at this depth. The experience from the deepening of GPK2 proved that this had been the correct decision. The following major drilling breaks were observed during the extension of GPK2:

Depth	**Caliper**	**Remark**
3876 - 3900 m	partly wide open (> 30")	rapid increase of torque and drag, hole inclination increases, loose material in zone, falls out when circulating while passing this zone
4350 - 4370 m	up to 30"	increase of drag & torque
4560 - 4580 m	minor enlargement	drills at 4 m/h with zero weight on bit !

Some of the technical difficulties described here - and which had to be solved one *after* the other - are clearly also directly related to the well trajectory (figure 4). Down to 3876 m, i.e. within the existing well, GPK2 can be described as "near vertical" (< *6*" inclination). Near the bottom of the well before extension, at 3850 m, less than 1" was measured by Schlumberger. During the extension of the well borehole inclination was recorded at intermittent intervals using a TOTCO and a high temperature PEE WEE single shot tool (inclinometer) fiom Scientific Drilling. On 7.5.99 a wireline gyro survey was run by Scientific Drilling inside the drill string from 2764 m (last gyro survey before deepening) to 5014 m. During this log it was confirmed that a dog leg exists in GPK2 in the depth range between 3870 - 3910 m. In this depth range a considerable hole enlargement was observed during caliper logging. Within this zone, the bottom hole assembly obviously had no wall contact and lost its capacity to steer.

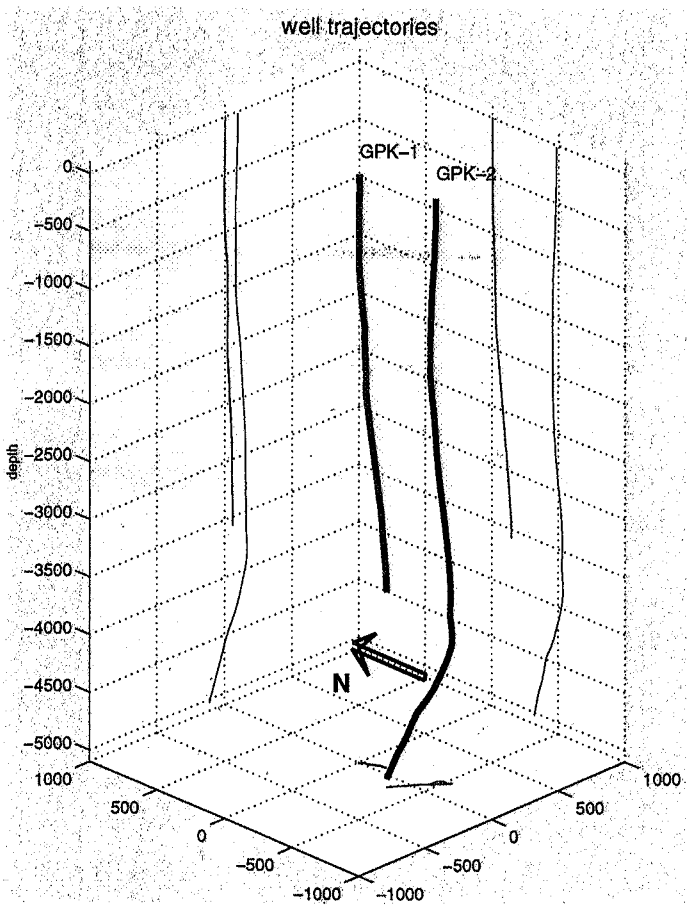

Figure 4: 3D projection of the well trajectories of GPKI & GPK2 (courtesy of R. Weidler, BGR, depth, distances in meter)

It is interesting to observe also that this dog leg had probably already been initiated in 1995 using a 3.5" drill string and a slimmer, more flexible bottom hole assembly ! Between **3870** - 3910 m hole inclination jumped from 1" to **8**" and continued to build from there on until it approached 26" at 4450 m. At this depth the inclination was dropped again slowly to about 16" near the bottom of the well. Considering the above described difficulties with hole drag and torque, drilling engineering concentrated in maintaining the well trajectory, reducing the build tendency and finally dropping the well.

It has to be noted that as far as the gyro log was recorded (5014 m), the extension of GPK2 walks along a continues North-West trend. This North-West trend probably represents a formation tendency of the rock at this depth which will have to be taken into consideration for all future well planning.

Coring near bottom

The deepest core at the Soultz site before the deepening of GPK2 had been collected near the bottom of the GPKl well (3523 - 3526 m). At that time, in early 1993, coring had been performed using a positive displacement motor and a diamond coring assembly. Two main problems had been observed during the coring operation in 1993:

- a motor failure,
- a partial unscrewing of the core barrel (occurred twice !!).

Both problems could be identified as temperature related technical difficulties.

As the conditions for coring after deepening of GPK2 had to be expected as even more hostile, after a careful analysis of all available techniques, it was decided to run a conventional roller cone coring bit without any motor in the well. Both, the core bit (SMITH X3TC7 7 7/8") and the core barrel (Christensen *6* 1/4" x 3") were furnished by the drilling contractor, ENEL.

Coring in GPK2 was performed on May 9th 1999 in the depth range fiom 5048 m - 5051 m. The 7 7/8" coring bit was operated at 55 rpm and **5** tons on bit. The penetration rate averaged 1.7 meters per hour. After 3 meters of coring, the penetration rate dropped significantly, indicating that the bit was worn. A total of app. 1.2 m of core **(40** %) could be recovered. The remainder of core had been lost on bottom (and had to be broken up later) because it was not caught by the core catcher. The core retrieved was broken up to pieces of 5 - 10 cm length, probably caused by vibrations within the bottom hole assembly. Nevertheless, this short core appeared to be a very good example of the varying types of granite encountered at this depth !

Installation and isolation of a floating casing string at a depth of 4431 m

GPK2 was completed in the period between 13.5. to 28.5 1999. Again, a floating 9 518" by 7" mixed casing string was installed as the production / injection string (figure *5).* To a large degree it was possible to re-run those casing joints which had been pulled at the beginning of the operations. Before being re-used each of these joints was carefully inspected and repaired if necessary. The casing to be installed was a mixed string assembled of:

- 0-501 m 9 5/8" 47 lb./ft N80 BTC (pump chamber)
- cross-over 9 5/8" 47 lb./ft - 7" 23lbs/ft (L80)
- 501 m - 2167 m 7" 23 lb./ft L80 BTC
- 2167 m - 4419 m 7" 26 lb./ft C95 BTC
- 4419 m - 4431 m packer assembly (7 metal packers), float shoe & float collar.

The whole casing string was designed and inspected for a special drift of 6.25" ! In order to isolate and anchor the casing string near the shoe and to support the weight of the casing string it was planned

- to first pump some 1000 m of a filler (fly ash),
- followed by app. 250 m of cement in the annulus of the casing,
- and to install 7 metal casing-packers which are inflated with cement.

Critical points for the design of the completion were:

- the weight of the string hanging on the top joints of the 7" 23 lb./ft casing during installation of the casing,
- the burst pressure of the 7" 23 lb./ft casing during the inflation of the packer elements,
- to avoid a break-down respectively fluid losses in the open hole section due to the increased weight of the fluid column in the well,
- identification of a suitable zone (caliper < 10") for the setting of the inflatable packer elements.

The weight of the casing string during installation was controlled running a float shoe and float collar in combination (double safety). In order to reduce the differential pressure across the 7" 23lbs/ft casing it was decided to tail the cement in the casing string with a heavy brine of 1.20 density. To avoid fluid respectively cement losses in the open hole section it was decided to sand-up the well fiom the bottom to some 10 m below the casing shoe. Although this was a somewhat lengthy operation it offered the maximum guarantee to circulate the filler and cement behind the casing string. The open hole section for the setting of the packer elements was carefully selected on the basis of the results of wireline logging (caliper, UBI). Difficulties occurred trying to achieve a depth match between drilling and wireline depths because of the very different thermal stretch observed in the wireline and the 5" drill string.

The installation of the casing could be performed without any difficulties. A total of 34 m^3 of fly ash, 8 m^3 of HMR high temperature cement and - after a plug - 2 m^3 of HMR cement for packer inflation and 97.3 m^3 of displacement were pumped. For this application the HMR cement contained BFC and fly ash at a ratio of 78 : 22. The salt content in the cement was again 200 g/l. The cement density was 1.90 g/cm^3. The retarder used was D28.

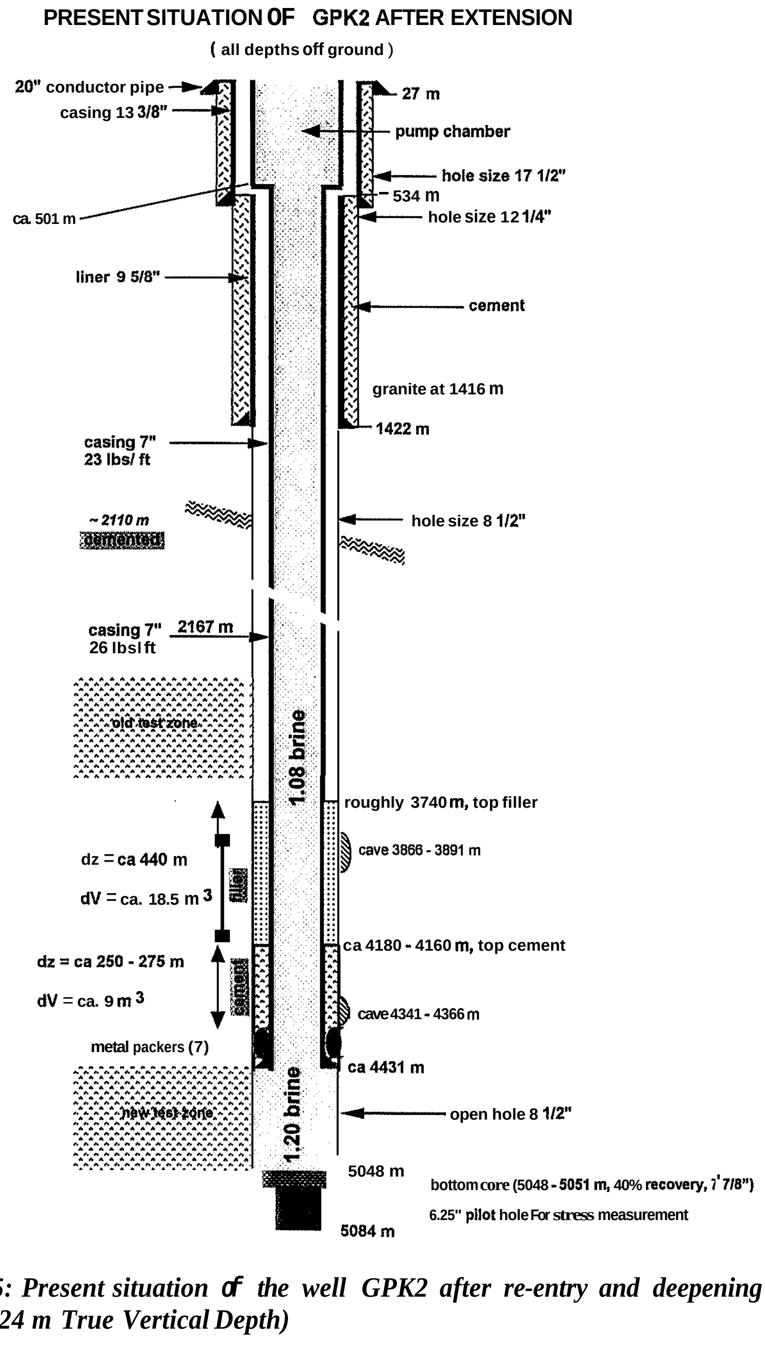

Figure 5: Present situation of the well GPK2 after re-entry and deepening to 5084 m (app. 5024 m True Vertical Depth)

This way a pumping time (thickening time) in the order of 10 hours at 170° C could be achieved. The fly ash filler was mixed at a density of 1.37 g/cm³. During various laboratory tests it had shown good settling capacities, solid settled sediment was observed after 24 hours. During the cementing and filler injection minor difficulties occurred due to:

- A short period failure of the data acquisition system.
- The fact that the 1.20 g/cm³ tail brine got mixed and diluted in the mud tanks with return fluid. The leak in the tanks could not be identified. Consequently, the tail fluid density dropped to 1.16.
- A leak which occurred during packer inflation. Rapidly increasing the injection rate it was possible to raise the packer setting pressure to about 17 MPa for a short period of time. About 1 m³ of additional cement volume was pumped through this leak into the annulus.

After cementation, the well was shut-in for 2 days with the casing still being held in the elevators. After these 2 days, first the casing pressure was checked (casing integrity test). The casing was holding 7.5 MPa. At this point decision was made to fully slack-off the casing weight. The packers and the cement were fully supporting the string weight. The casing and the sand from the open hole section were cleaned using a 6.25" tooth bit. Once the plug and float shoe were drilled only 4 meters of cement was found below the casing shoe indicating that the cement and filler had fully risen into the annulus.

Summarizing, it has to be stated that out of the 104 days of operations only 54 days were consumed for actual drilling operations, i.e. 52% of the total rig time (9 days for opening hole from 6.25" to 8.5", 42.5 days drilling 8.5", 1 day coring, 1.5 days drilling 6.25" pilot hole).

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