DRILLING OF HOT AND FRACTURED GRANITE AT SOULTZ-SOUS-FORETS (FRANCE)

Baumgärtner Jorg (1), Moore Perry Lyman (2) and Gerard André (1)

(1) SOCOMINE, Route de Kutzenhausen, BP39, F-67250 Soultz-sous-Forêts, France
(2) Southern International Incorporated, Oklahoma City, Oklahoma 73 107, USA

KEY WORDS: drilling techniques, mud composition, well completion, milling aluminium packers

ABSTRACT

The results of a drilling operation at Soultz **sous** Forits, France, are reported here which involved reaming and drilling of hot and fractured granites using a low cost clear brine water mud. Highly permeable zones were temporarily sealed (to be available later for scientific investigations) by spotting pills of **loss** circulation material (LCM). Experience in Soultz indicated that the effectiveness of LCM pills under geothermal conditions (160°C at 3600 m) can be increased considerably by giving the heat sufficient time to act on the mixture before resuming drilling. The well was completed with an uncemented 7" internal casing (0 - 2850 m) which is only supported at the bottom by an open hole casing packer and a short cementation. Thermal expansion and contraction, of the otherwise self-supporting pipes, (during injection and production experiments) are compensated in the well head assembly. Drilling operations (well cleaning, casing removal, reaming, drilling 8-1/2" and 6-1/4", completion) were finished after 60 days, some 20 days ahead of schedule.

1. INTRODUCTION

The mining of heat from relatively impermeable crystalline rocks has been a research subject in various countries for over 20 years. This technology to extract heat from impermeable rock mass is generally called "Hot Dry Rock". In 1986 some of the French and German research groups active in HDR research joined to concentrate their activities on the most important heat anomaly in central Europe: The Upper Rhine Graben. The project was sited about 50 km north of Strasbourg at Soultz-sous-Forits, Alsace (fig. 1). In 1990 British scientists joined the project. Recently, a close co-operation with the Italian geothermal industry is being established.

The project at Soultz was designed to validate a modified HDR concept. In the geological setting of a Graben structure with a well-known geothermal anomaly (Baria et al., 1992) of probably hydrothermal origin, a dense fracture network intersected by major geological features can he expected at depth. Some degree of interconnectivity between these fractures (fig. 2) has to be assumed in order to allow for long distance fluid movements. The basic idea was to turn the fracture and fault network (once accessed through boreholes) through proper stimulation into some form of natural heat exchanger. It should then be possible to operate the exchanger by maintaining sufficient pressure differential between the injection and production boreholes. This implied that some downhole pumping would be required in the production boreholes. The produced fluids would be a mixture of formation and re-injected fluids. The exchanger will have to be continuously replenished in order to be not rapidly depleted.

Having such an intermediate concept between the initial idea of an HDR system and the exploitation of a conventional natural geothermal resource in mind, exploratory drilling at Soultz-sous-Forits started in 1986. With some difficulties the well GPK-1 was drilled in 1987 to 2002 m. The top of the granite was found at 1377 m. A high temperature gradient of 10.5°C per 100 m was observed in the upper 1000 m which then dropped to a "normal" gradient of 2.8°C per 100 m in the Buntsandstein. The bottom hole temperature was 141°C at 2002 m. Formation fluids found were brines with a density of 1.07 g/cm^3. Between 1987 and 1992

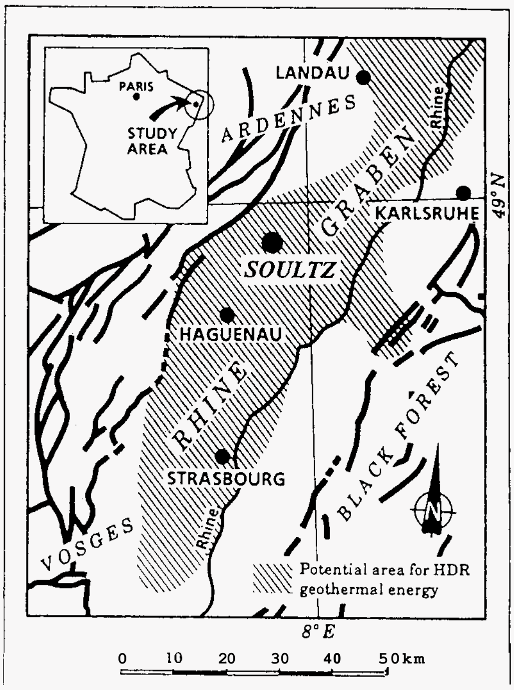

Fig. 1: Location of the European Geothermal Energy Project at Soultz-sous-Forêts, France

numerous scientific investigations were performed in this well (Baria et al., 1992, Garnish et al., 1994). In early 1992 it was decided to deepen GPK-1 to about 3500 - 3600 m in order to investigate the underground in the Rhine Graben at higher temperatures. This drilling operation was designed to demonstrate that the granites in Soultz can be drilled safely and at a reasonable cost. This paper summarizes the results of the deepening of GPK-1 which was performed in the period of October 1992 until January 1993.

2. THE SITUATION IN SUMMER 1992

The status of GPK-1 in Summer 1992, just before the beginning of the deepening operation, is shown in fig. 3. The well had been drilled in 1987 to a depth of 2002 m. The completion included two casing strings to a depth of 1420 m. The outer 9-5/8" string protects the sedimentary cover. The inner tubing was uncemented and only supported at the bottom end by a casing packer. This completion was selected in order to allow the well to be used as an injection well (cooling) and as a production well (heating). The internal casing was free to shrink or expand according to the temperature changes. The thermal expansion or shrinkage are compensated in the wellhead.

A series of hydraulic stimulation tests which had been previously camed out in the granite between 1700 - 2002 m depth had left several hydraulically active zones which were potential problems for the mud system. Also, as a result of various scientific

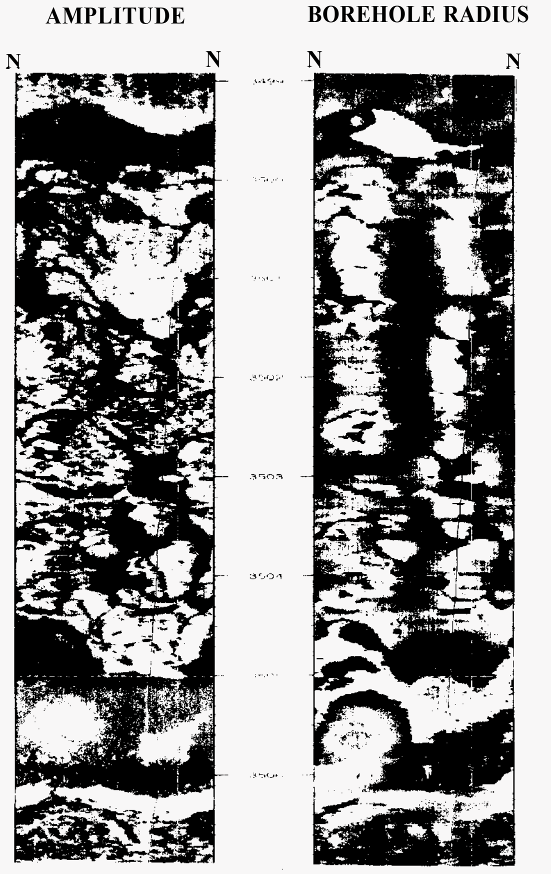

Fig.2: Accoustic televiewer image of the fracture network at Soultz-sous-Forêts

operations, an assortment of junk and debris had been left at the bottom of the well.

Filled with formation brines (density 1.07 g/cm^3) the well was artesian, generally at a wellhead pressure of about 2 bar.

3. THE DRILLING PLAN

The deepening of GPK-1 involved the following steps :

- Preparatory operations
1. -removal of the existing uncemented internal 7" casing
2. cleaning of the bottom of the well

- Drilling, completion and scientific operations
1. enlargement of the open hole section from 6-1/4" to 8-1/2" (1420 - 2002 m)
2. drilling 8-1/2" hole (2002 m to about 2800 m)
3. decision *to* run 7" casing or continue drilling
4. drilling 6-1/4" hole (2800 m to about 3500 m)
5. scientific programme (coring, logging)
6. run new 7" casing to about 2800 m
7. set packer and cement bottom section of 7" casing
8. clean out well to bottom
9. logging and stress measurement including the removal of aluminum packers (scientific programme)

Within this programme the hole enlargement and the mastering of the fluid losses were considered to be critical. Generally, the drilling plan was based on the experiences from 1987 (drilling to 2002 m). At that time an average penetration rate of 1.71 m/h (drilling in 6-1/4") had been achieved in granite using a polymer based mud.

4. THE DRILLING RIG

The drilling rig selected was a 1000 hp Massarenti **MAS** 3000 type rig from COFOR (France). This rig has a lo-lift "open face" PYRAMID- type cantilever mast (43 m height) with a static hook capacity of 227,000 kg (500,000 lbs). The "swing-up" type substructure has a capacity of 500,000 lbs casing load and 181,600 kg (400,000 lbs) set back load. The draworks are equipped with two 550 hp Caterpillar 3412TA engines and National N/C 195-64 torque converters. Two Gardner Denver PZ8 7" x 8" 750 hp triplex mud pumps were utilized on the rig.

The draworks, engines and compound, mud pump engines, generator shelter and rig floor were fully sound proofed.

5. PREPARATORY OPERATIONS

The well was killed with salt water (density 1.08 g/cm^3) on October 7th. 1992. A 7" casing spear and pack-off were used to engage the 1420 m of 7" casing. The casing packer was worked loose within one hour using a maximum overpull of 40 tons. The 7" casing was then laid down in 12 hours. When the casing packer was removed it was noted that no rubber was left on the packer and one slip was missing. These items were added to the collection of junk on the bottom of the well !

Various kinds of debris which had been gathered on the bottom of the well during the preceding scientific operations (packer sleeves, centralizer parts, steel buttons from seismic calibration shots and now the slip of the casing packer) were removed by both fishing and milling during the following week. For fishing operations a reverse circulation basket, magnets and an ADT tool were used. Due to the various types of junk in the wellbore, 14 runs had to be performed.

Before resuming operations a 6 m^3 pill of loss circulation material (LCM) was spotted on the bottom of the well (Bentonite and Nut Plug).

During the fishing operations which had been performed using a 1.08 g/cm^3 density brine fluid losses of 4 to 8 m^3/hour had been observed (stimulated zone near the bottom of the well). The result of this high viscosity pill was that losses were almost stopped completely after the pill had set for 4 to 6 hours.

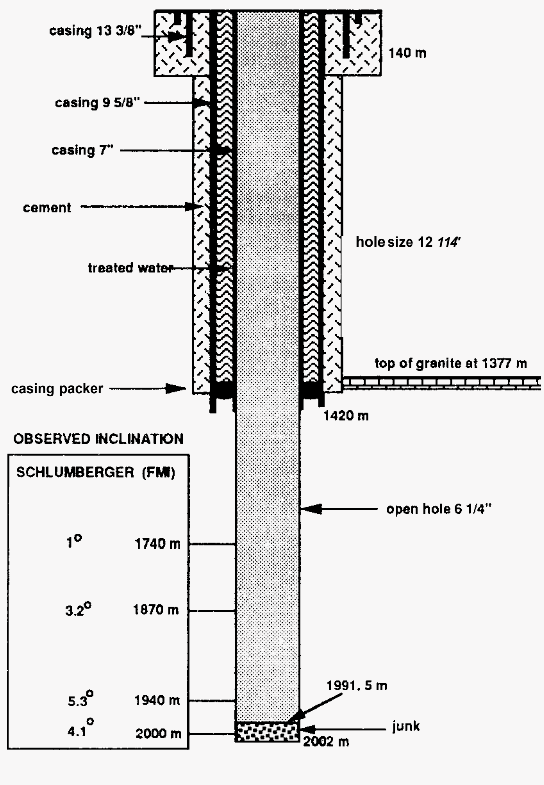

Fig. 3: Wellbore schematic of GPK-1 before extension

6. DRILLING OPERATIONS
6.1 Enlargement of the open hole section (6-1/4" to 8-1/2") - (1420 to 2002 m)

Initially an 8-1/2" **SECURITY** H-100F bit was run with (15) 6-1/2" drill collars and no stabilization. Stabilization was not used until sufficient penetration allowed stabilization to be introduced into the wellbore below the 9-5/8" casing. The reaming parameters throughout the operation involved turning the bit at 65 rpm and bit weights being varied between 5 to 10 tons.

The first bit was pulled after 46 hours (tab. 1) and a total progress of 216 m. Overall (3) H-100F bits were used during reaming operations at an average rate of 5.63 m/h. Bit runs # 2 and 3 utilized the following stabilized bottom hole assembly (fig. 4): bit, 6-point roller reamer, short drill collar, 3-point roller reamer, 6-3/4" drill collar, 3-point roller reamer, 6-3/4" drill collar, 3-point roller reamer and 6-1/2" drill collars. Although it is recognized that integral blade stabilizers provide slightly better stabilization, roller reamers were used because they provide an assembly that is much easier to turn in crystalline rock.

Deviation surveys were taken every 30 meters and the enlarged hole followed the trajectory of the existing 6-1/4" hole. The high viscosity pill spotted before the reaming operation still proved to be very effective as losses peaked only at about 1.5 m^3/h. The depth of 2002 m was reached after 6-1/2 days on October 23rd, 1992.

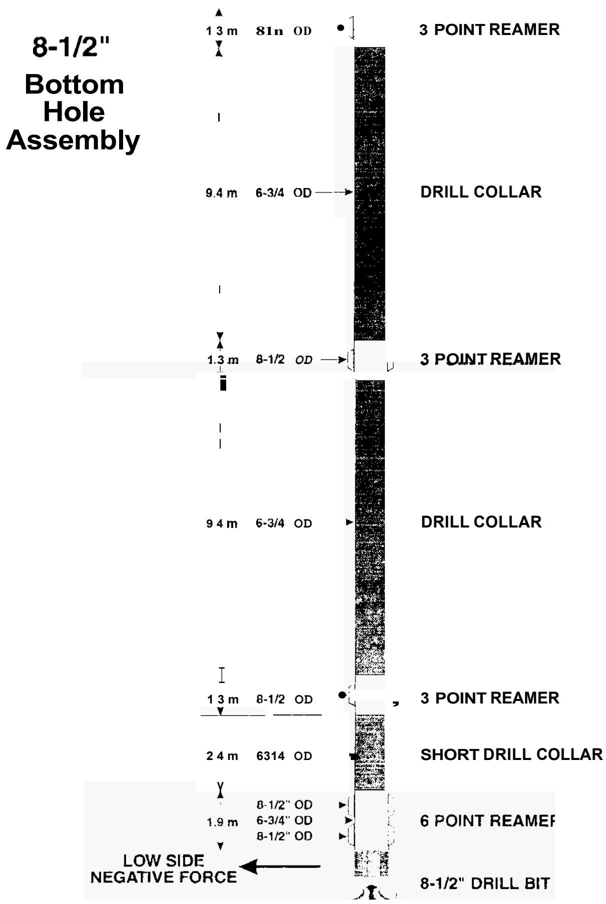

Fig. 4: Stabilized bottom hole assembly used during the extension of GPK-1

6.2 Drilling in 8-1/2" (2002 m to 2850 m)

Advancing the 8-1/2" section of the wellbore continued using the same stabilized bottom hole assembly and the same type of bits used during the reaming operations. Utilizing drilling parameters of 60 rpm and 15 tons of bit weight, drilling safely at a rate of 4.7 m/h was possible. The mud weight was kept constant at a 1.08 g/cm^3 density and a circulation rate of 1250 l/min was continued. Bits # 4, 5 and 6 were all Security H100F type bits and

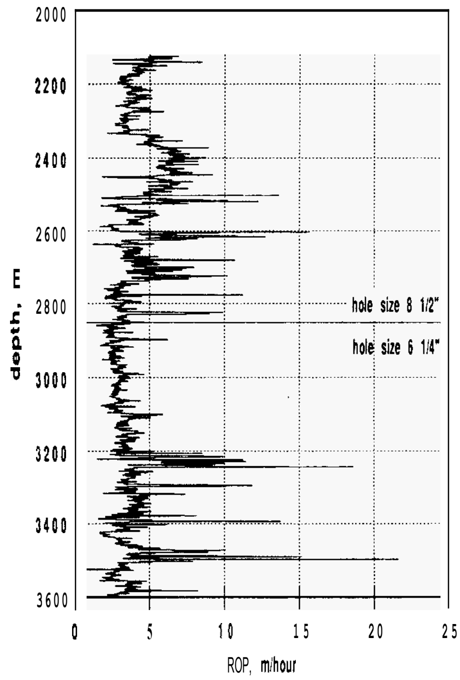

Fig. 5: Penetration rate as a function of depth

averaged 3.9 m/h to a total depth of 2332 m (tab. 1). A small amount of loss circulation continued (1 to 2 m^3/h) and the mud weight was lowered to a 1.07 g/cm^3 density. It was then decided to run a Security M89TFL bit to evaluate a bit with a somewhat softer cutting structure. This bit averaged 4.7 m/h (fig. 5). The remainder of the bits run in the 8-1/2" section were of the M89F series.

Drilling remained fairly constant with little indication of fractures down to 2494 m. Multiple drilling breaks (penetration rate increases) were recorded due to alternating sections of fresh and altered granite with penetration rates sometimes exceeding 10 m/h. This determination is corroborated by the lithology section of the mud loggers report (GEOSERVICES, 1993). Through the intermittent use of the high viscosity gel pills, the loss circulation rate could be maintained at 1 to 1.5 m^3/h while drilling.

The temperature of the returning drilling fluid would slowly build during each bit run and would then cool and fall back during the trip for a new bit. A maximum of around 60°C was reached at the bottom of the 8-1/2" hole section. No difficulties handling the drilling fluid at these temperatures with the normal rig equipment were experienced.

Deviation held steady at around 4° to 2436 m. Below 2436 m depth, wellbore deviation built up slowly to a maximum of 6-3/4° at 2643 m and then gradually dropped back to 5-1/2° at 2850 m.

The 8-1/2" hole section was completed after 17 days on November 19th, 1992.

6.3 Drilling in 6-1/4" (2800 m to about 3500 m)

The hole size was reduced to 6-1/4" at 2850 m without running casing due to the good hole condition and the success in controlling the loss circulation with high viscosity pills.

The 6-3/4" bottom hole assembly that had been used in the 8-1/2" section was replaced by the same stabilized roller reamer assembly utilizing 4-3/4" drill collars, 6-1/4" stabilizers and a 6-1/4" Security M89TF rock bit.

A mixed drill sting of 1300 - 1350 m of 5" X-95 drill pipe and the remainder of 3-1/2" G-105 drill pipe was kept in use. After each 6-1/4" bit run, an appropriate amount of 5" drill pipe was laid down when starting **out** of hole and an equal amount of 3-1/2" was added above the bottom hole assembly after the bit change.

The first 6-1/4" bit (# 12) was run from 2857 to 2913 m using the

Bit no.	Bit make	Bit type	IADC code	Jets	Depth out (in m)	Total meters (in m)	Hours run	Meters per hour (m/h)	Weight (in tons)	Mud weight (g/cm3)
1	Security	H 100FL	837Y	10-10-11	1645	216	46	4.7	5-10	1.08
2	Security	H 100FL	837Y	10-10-11	1817	172	25.5	6.8	10	1.08
3	Security	H 100FL	837Y	10-10-10	2010	193	31.5	6.1	10	1.08
4	Security	H 100F	837Y	10-10-10	2125	115	24	4.8	15	1.07
5	Security	H 100F	837Y	10-10-10	2228	103	29	3.6	15-18	1.07
6	Security	H 100F	837Y	10-10-11	2332	104	31.25	3.3	15	1.07
7	Security	M89TFL	627X	10-10-11	2451	119	25.5	4.7	15	1.07
8	Security	M89F	637Y	10-10-11	2551	100	27.25	3.7	15	1.07
9	Security	M89F	637Y	10-10-11	2645	94	27.75	3.4	15	1.08
10	Security	M89F	637Y	10-10-11	2157	112	29.5	3.8	12	1.07
11	Security	M89F	637Y	10-10-11	2857	100	34.5	2.9	12	1.07
12	Security	M89TF	627X	9-10-10	2913	56	23.2	2.4	5-7	1.08
13	Security	M89TF	627X	9-9-10	2986	73	26.25	2.8	7	1.08
14	Security	M89TF	627X	9-9-10	3059	73	24.7	3	7	1.07
15	Security	M89TF	627X	9-9-10	3136	77	24.75	3.1	7-9	1.07
16	Security	M89TF	627X	9-9-10	3219	83	23.5	3.5	7-10	1.07
17	Security	M89TF	627X	9-9-10	3314	95	23	4.1	9	1.07
18	Security	M89TF	627X	9-9-10	3396	82	21.9	3.7	9	1.07
19	Security	M89TF	627X	9-9-10	3457	61	22	2.8	10	1.08
20	Security	M89TF	627X	9-9-10	3523	66	15.5	4.3	4-8	1.07
21	Security	M89TF	627X	9-9-10	3547	21	8.6	2.4	7	1.07
22	Security	M89TF	627X	10-10-10	3597	50	15.2	3.3	9	1.07

Note: coring was done for three meters between 3523 and 3547 meters

Tab. 1: Bit record for the deepening of GPK-1

parameters of 60 rpm and 5 to 7 tons of bit weight. The well was circulated at a rate of 880 l/min. The bit averaged 2.4 m/h (tab. 1) and after extensive evaluation set the parameters for drilling the remainder of this section.

It was noted that the drilling fluid temperature returning at the reduced flow rates had dropped considerably from the 8-1/2" bit runs. Where the return drilling fluid temperature had been running 55° to 60°C in the 8-1/2" section, it now varied from 40" to 45°C.

The mud losses continued to average 1 to 1.5 m^3/h while drilling with a 1.07 g/cm^3 density but problems with the well trying to flow during trips began to be experienced. The system used to overcome this problem simply involved raising the mud weight to 1.08 g/cm^3 immediately prior to tripping and then reducing to 1.07 g/cm^3 when drilling resumed.

A strong drilling break was experienced from 3478 m to 3488 m where the mud losses increased to 20 m^3/h. Three (3) loss circulation pills were mixed and spotted on bottom using the high viscosity gel mixture with nut plug additive. After successfully reducing the losses to 3 to 5 m^3/h, drilling was resumed to complete bit run # 20. Upon completion of bit run # 20 at 3523 m, a 10 m^3 high viscosity pill was spotted on bottom immediately before pulling out of the wellbore. After completion of the trip, operations were resumed with losses back in the 1-2 m^3/h range.

Between 3516 - 3519 m drilling in 6-1/4" was interrupted in order to take core samples (see also below "Scientific Programme").

The borehole deviation continued to decline gradually from 5-1/2° at 2850 m to 2" at 3590 m. A total of 11 Security M89TF bits were used in drilling the 6-1/4" hole section. They made 737 m of hole in 228.75 drilling hours at an average penetration rate of 3.22 m/h (which is nearly twice the penetration rate experienced in 1987 !). **A total depth *of* 3590 m** was reached on December 5th, 1992. Drilling from 2850 - 3590 m in 6-1/4" had lasted 26 days.

THE DRILLING **OPERATIONS** WERE COMPLETED SOME 20 DAYS AHEAD OF TARGET (see fig. 6, fig. 7) !

6.4 Experiences with the mud system

The original plan for drilling fluids had several objectives in the planning stages. The first was to provide an adequate mean to transport cuttings to the surface. Second to control the flow from the active zones in the wellbore and thus provide a stable wellbore. Third, provide a cost effective mechanism for controlling fluid losses. Fourth, minimize damage to the drill string via chemical corrosion (oxidation) and mechanical abrasion on the wellbore walls. Finally, reduce or eliminate environmentally sensitive materials from use.

Originally, it was planned to use an expensive HEC polymer (which had been used during the drilling of the first section of GPK-1 down to 2002 m) as a viscosifying agent to assure cuttings transport, if necessary. It was proven here that a low cost salt water fluid (sodium chloride) is absolutely sufficient to assure successful drilling in the Soultz granites. Beside a strong reduction of costs for mud materials, such a mud system has the inherent advantage of producing environmentally "friendly" cuttings which could be discharged (after a careful laboratory analysis) mixed with cement without further treatment at a local disposal site.

During the whole operation of deepening **GPK-1** the drilling fluid consisted of salt water (densities were modified between 1.07 - 1.08 g/cm^3) with additions of caustic soda to aid in corrosion

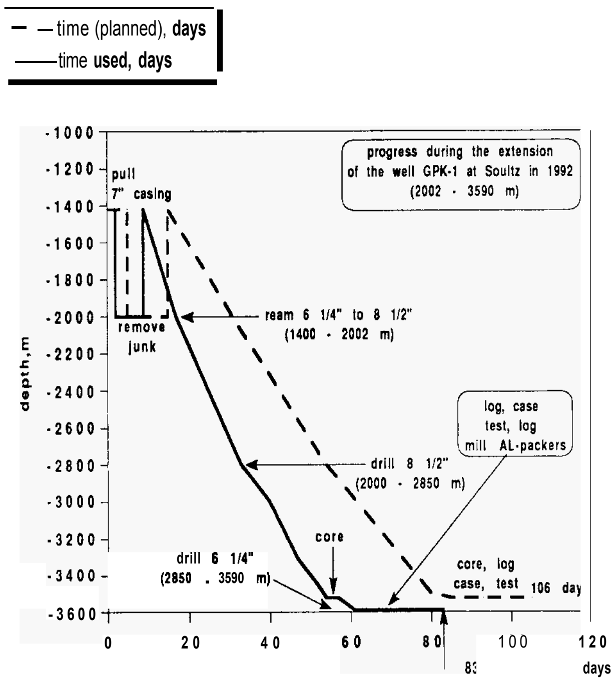

Fig. 6: Progress chart of the cleaning, reaming and deepening of GPK-1

protection for the drill pipe (maintaining a pH of 10 - 11) and (at irregular intervals) defoamer (MI DEFOAMEX). At irregular intervals viscous sweeps (Bentonite) were performed to clean the bottom of the well. Pumping rates varied from around 1250 l/min in the 8 1/2" well section to some 850 l/min in the 6 1/4" well section.
As no viscosifier was added to the mud system, some wear had to be accepted on the bottom hole assembly. The chert and knobby cutters of the roller reamers had to be changed after each bit run.

Loss circulation problems were encountered throughout all drilling intervals with the most severe being at 3478 - 3488 m. The losses in this interval were as great as 20 m^3/h.
Principally, mud losses could be controlled through adjustment of the mud density in the narrow range between 1.07 and 1.08 g/cm^3. Where extensive mud losses occurred they were stopped or considerably reduced spotting pills of high viscosity loss circulation material (LCM). Cementing was not considered as the flowing fractures are the exploration target of the project. Nut Plug and wood fibber pills are of limited life and can later be removed hydraulically if necessary.
The LCM pills consisted of pre-hydrated Bentonite with the addition of Nut Plug. No synthetic materials were used. These pills proved to be very successful especially when allowed to set and be exposed to the heat. **It is assumed that this waiting time is important for the effectiveness of the pill and that the heat acts on the mixture causing the viscosity to increase even more and create additional sealing.**

Generally, the simplicity of the fluid system greatly simplified operations on the GPK-1 well. As salt, caustic soda and the occasional Bentonite pills were the only materials added to the system during operations, maintaining the system was simple and the routine checks utilized for operations were ran by the supervisors and the drilling crews while mixing. Cuttings transport did not require any additional materials to be added to the fluid system as evidenced by the lack of fill on bottom while drilling. As more expensive materials were not required for cuttings transport, corrosion, or control of loss of circulation, the final cost of the drilling fluid was only around 50% of the budgeted amount.

6.5 Mud logging

Drilling operations as well as the maintenance of the mud system were supported through a detailed mud logging service. A mud logging unit (GEOSERVICES) was rigged up and made operational when the well had reached 2125 m. An engineering log was started that recorded lithology, rate of penetration, weight on bit, rpm, torque, temperature in and out for the drilling fluid, gases (CO_2 and H_2S) being represented in % and C1 to C4 in ppm. Additional Helium logging was performed by BRGM.

7. WELL COMPLETION

7.1 Running of 7" casing (0 to 2850 m)

2850 m (212 joints) of 7", 23 lbs/ft S95 steel casing (BTC R-3, seamless) were run on December 11th, 1992. This casing had been manufactured according to especially tight tolerances (ovality, standoff, pitch diameter). No problems occurred during running the casing. A total of 49 centralizers (Davis-Lynch spring bow centralizers) was run in the open hole section (1420 - 2850 m). 23 rigid blade centralizers (Weatherford PO1) were run inside the 9-5/8" casing (0 - 1420 m).
A Davis-Lynch (type 778-100 series) 7" packer stage cementing collar (23 ppf, S95 buttress, 8-14" O.D., 6-1/4" drift) dressed with high temperature rubber was run at one joint above the casing shoe. The length of the pack-off of this assembly is 3 ft (about 0.9 m).

7.2 Cementation of the casing shoe

Cementing services were supplied by Halliburton on December 11th and 12th, 1992. A pre-pad of 1 m^3 of high temperature retarded cement (retarder HR12) was pumped around the casing shoe in a fist stage. The purpose of this stage was to guarantee a proper cementation of the casing shoe - even in case of a malfunctioning of the packer assembly under these high temperature conditions.
This first stage of cementation was followed by an opening plug and a cement slug to set the packer. The packer was successfully set but the by-pass ports did not open. Consequently, only the length from the casing shoe to approximately 30 meters above the packer was cemented successfully through the first batch which had been pumped before setting the packer (comment: originally it had been planned to cement a length of about 100 m during a second stage). A post-cementation temperature survey confirmed cement curing on a length of some 30 m above the packer.

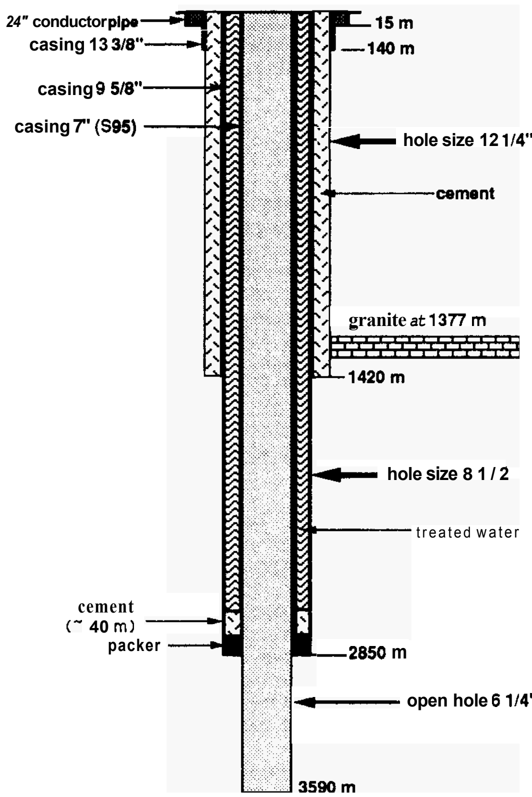

Fig. 7: Wellbore schematic of GPK-1 after extension

7.3 Wellhead design

As the new 7" casing (0 - 2850 m) is only cemented on a short section near the bottom end, the wellhead has to compensate for the thermal expansion and contraction of the casing during "cold" injection respectively "hot" production tests. Geochemical thermometers indicated the potential for produced water in excess of 200°C (as compared to the bottom hole temperature of 160° C, possibility upward water migration to the well through the natural fracture network, Baria et al., 1995). Injection fluid temperatures observed in the past were as low as 5°C. For safety reasons, the wellhead design was based on the assumption of full heating respectively full cooling (5 - 200°C) of the casing string. Under these assumptions and considering also the pressure buckling of the casing string during injection tests the present wellhead design allows for 3.30 m of contraction and 3.0 m of elongation of the 7" casing string. The hydraulic sealing of the annulus of the 7" and the 9-5/8" casing strings in the wellhead is achieved through pre-stressed rubber sealing packages (see fig. 8).

8. SCIENTIFIC PROGRAMME

8.1 Coring (3516 m to 3519 m)

Two (unoriented) coring runs were made in the interval from 3516 to 3519 m. It was decided to use the same coring system that had previously been used successfully on the EPS-1 well in Soultz as well as with the continental deep drilling programme in Germany.

The first run utilized a Christensen positive displacement motor to drive a 6" Christensen B-9 diamond coring assembly in order to core with 150 rpm and 2 tons bit weight. The coring run (3516 to 3517 m) was prematurely aborted because of a motor failure. The 1 meter of core was not recovered in the core barrel and the inner barrel of the core barrel was found partially unscrewed.
The second run utilized the same bit and assembly without the motor. When the assembly arrived at bottom, the 1 meter piece of core was still intact on the bottom. After carefully working over

the piece of core, coring operations were resumed and the interval from 3517 to 3519 m was cored with 70 rpm and 2 tons bit weight. The run was terminated because of a jammed core barrel.
When the core barrel was returned to the surface, 3 meters of core of excellent quality were recovered, the inner barrel was unscrewed again and severely damaged and the bit was 80% worn. It is believed that heating effects on different metal compositions in the threads of the inner barrel were causing the unscrewing problems. As there was not a practical alternative immediately available for this coring system, the decision was made to resume other operations.

8.2 Logging

A full sweep of geophysical wireline logs (Schlumberger) was performed in GPK-1 before running the 7" casing. This set of logs included (among others) nuclear logs, digital sonic logs and derived logs for fracture zone detection and rock property analyses, Stoneley wave analyses for open joint characterization and electrical and acoustic imaging logs for joint network characterization (fig. 2). Totally 4 days of rig time were used up for logging operations at this point. The maximum temperature observed during logging was 159° C.

8.3 Milling of aluminum full metal high temperature packers

After the 7" internal casing had been set, full metal aluminum packers were run in GPK-1 for the purpose of hydraulic fracturing stress measurements. These packers had been developed by MeSy GmbH in Germany for operation in hostile environments. The packers are operated on a 7-conductor wireline in a straddle configuration (about 3 m length). An hydraulic line (8 mm I.D. high pressure coil tubing) is run in parallel to the cable and clamped to the cable at intervals of about 50 m (Klee and Rummel, 1993). With this technology the inflated aluminum shells are left in the well after the hydraulic test has been completed.

The ability to drill these aluminum packers and successfully remove the shells from the wellbore walls had not been seriously questioned prior to starting this project. The general assumption among drilling engineers was that they could be drilled up in a short time period with very little effort. However, the previous experiences with the MeSy packers gave only a very limited data base to ascertain what might be expected. A decision was made by the project management to initially only run two tests and then drill out the packers before continuing. This was only done at this time as a precautionary measure in view of the limited experience with these packers.

The first milling attempt was made with a 6-1/4" tungsten carbide insert bit. No visible progress was made in 4-1/2 hours and it was decided to change to a junk mill for the next run. A 6-1/8" junk mill was started milling on the packer at 3321.5 m and one meter had been cut in one hour when the mill became stuck in the packer. After 20 hours, the mill was freed and pulled out of the hole. This mill had been worn to a point slightly over 6 centimeters in diameter at the tip and a tapered wear out to full size some 30 cm from the tip. The stabilization lugs on the mill were still full size. Signs of an extremely abrasive material being in contact with the mill were evident.

A mill tooth bit was run next and 0.5 m was made before progress again stopped. The next mill run became stuck in the packer and when jarred loose brought the packer shell from the wellbore attached to the mill. The shell showed signs of the material having been hot enough for the material in the shell to become unstable and start running. The remains of the packer at 3321.5 m were loose in the wellbore and were pushed down to 3509 m where milling resumed. This mill was successful in drilling up the remainder of the upper packer and the first half of the lowest packer.

Another 6-1/8" flat bottom mill was used to drill up the remaining part of the lower packer and push it to bottom. A caustic soda pill was spotted on bottom over the packer debris, 1.1 g/cm^3 fluid was left in the wellbore and the drill pipe was laid down. An FMI log run at total depth confirmed that no aluminum shells were left on the wellbore walls and the wellbore was clear.

After the experience in Soultz, it appears that the soft aluminum packer shells can be drilled using very little weight and slow rpm. Aluminum seems to wad up when being drilled and must be drilled

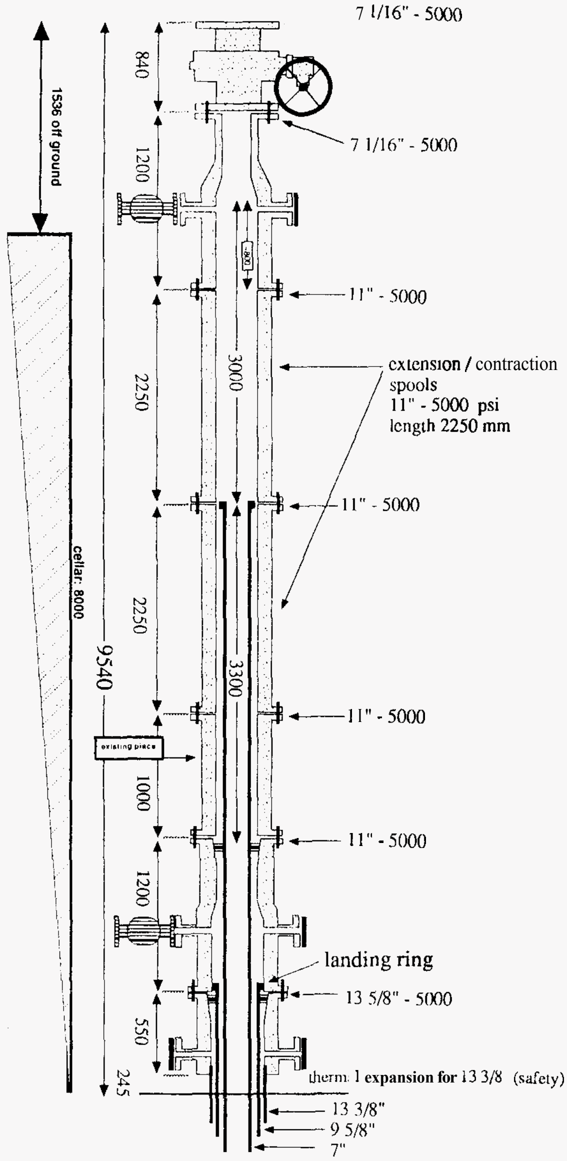

Fig. 8: Schematic of the GPK-1 wellhead

in short intervals, repeatedly cleaning the bits. It was easy to jam tools in the partly drilled packer shells, but the use of drilling jars made this significantly less dangerous. It was always straight forward to knock the string loose by utilizing the jars. In the future, the use of sharper edged cutting tools, shorter drilled intervals and repeated working in and out of the packer should help to simplify the process. It is also evident that caustic soda can be used to clean up packer debris.

It is recommended to test the milling of such packers for future operations in a drilling-simulator - especially in view of the fact that these packers which had been set and operated without any problems under rather hostile conditions could support large loads even after being fully deflated (in GPK-1 the packer supported loads of 10 - 13 tons without moving) ... which opens the door for a full range of new applications (side-tracking, bridge plugs, casing packers, ...under hostile conditions).

9. CONCLUSIONS

9.1 Technical summary

Penetration rates in crystalline rocks could be considerably improved since drilling started in Soultz 1987. When GPK-1 was drilled to 2002 m an average penetration rate of 1.71 m/h in 6-1/4" was achieved in granite. During the here described operations the average penetration rate in the same diameter (6-1/4") and in the

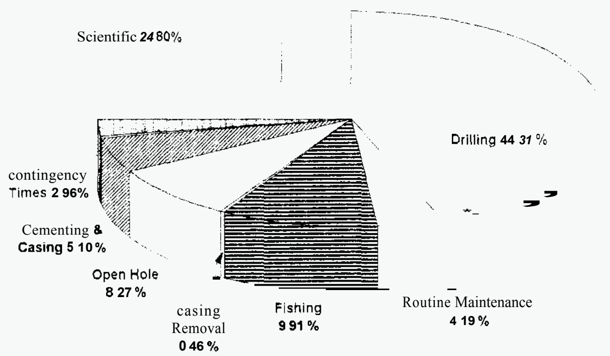

Fig. 9: Operational hours allocated by task during the extension of GPK-1

same formations could be outperformed by a factor of nearly *2* as penetration rates averaged *3.22* m/h. This is mainly due to improved bits and well adapted drilling parameters.

It could be proven during the extension of GPK-1 that a low cost salt water based mud (brine) is absolutely sufficient to assure successful drilling in the Soultz granites. Viscous sweeps (Bentonite) performed at irregular intervals ensured a clean bottom of the well. Beside a strong reduction in cost for mud materials, such a mud system had the significant advantage that the cuttings produced did not require cleaning before disposal.

Principally, mud losses could be controlled through adjustment of the mud density in the narrow range between 1.07 - 1.08 g/cm^3 (which per se requires a permanent accurate control of mud density). High viscosity loss circulation pills were spotted where losses exceed *2* - 3 m^3/h. For cost reasons as well as for technical reasons no cement was used. The **loss** circulation material (LCM) pills consisted of pre-hydrated Bentonite with the addition of some nut plug. No artificial materials were used. After completion of the well these LCM pills can be removed hydraulically giving access to the fracture network for scientific investigations. The LCM pills proved to be very successful when allowed to set and be exposed to heat.

Experiences in Soultz showed that difficulties involved in the drilling of soft aluminum (here aluminum high temperature packers) were generally underestimated by the drilling engineers. The conclusion of the operations in Soultz was that sharp cutting tools, patiently operated at low rpm and with little weight on bit could be the most successful means for drilling soft aluminum. It is recommended to study this approach during a series of tests in a drilling simulator.

9.2 Cost analysis

Fig. 9 shows a pie diagram which splits the operational hours during the deepening of GPK-I by **tasks.** It can be seen that a large portion of the operational time (and therefore the operational costs) was allocated to scientific tasks. Many of these will not be required for a commercial geothermal operations resulting in further reduced costs.

The accumulative costs of the various cost items monitored during the deepening of GPK-1 are shown in fig. 10. **The total cost of the operation (including site preparation, etc...) amounts to 1.8 Million ECU.** By far the largest cost item is the drilling rig, followed by supervision and engineering (day rate contract), site preparation, environmental, mud and mud treatment, casing and stabilization. Overall the deepening of GPK-1 remained some 20% under budget. The main savings were made in rig time, drill bits and environmental, mud and mud treatment.

10. REFERENCES

Baria R, Baumgärtner J, Gérard A and Kappelmeyer O, 1992; *HDR project at Soultz-sous-Forêts*, Geothermal Resources Council Transactions, 16, 387-394.

Baria R, Garnish J, Baumgartner J and GCrard A 1995; *Recent developments in the European HDR research programme at Soultz-sous-Forêts (France)* - submitted to **IGA,** World Geothermal Congress in Florence, Italy (May 1995).

Garnish J, Baria R, Baumgartner J and Gerard A, 1994. *The European Hot Dry Rock Programme 1994-1995,* GRC Trans., 1994, In press.

GEOSERVICES (company), 1993; *Final mud logging report on the deepening of the well GPK-I at Soultz* - Socomine internal report.

Klee G, and Rummel **F,** 1993; *Hydrofrac stress data for the European HDR research project test site Soultz-sous-Forêts.* International Journal of Rock Mechanics, Mining Science and Geomechanics Abstracts, vol. 30, no. 7, pp. 973-976.

Moore P.L, 1993; *GPK-1final report* - Socomine internal report.

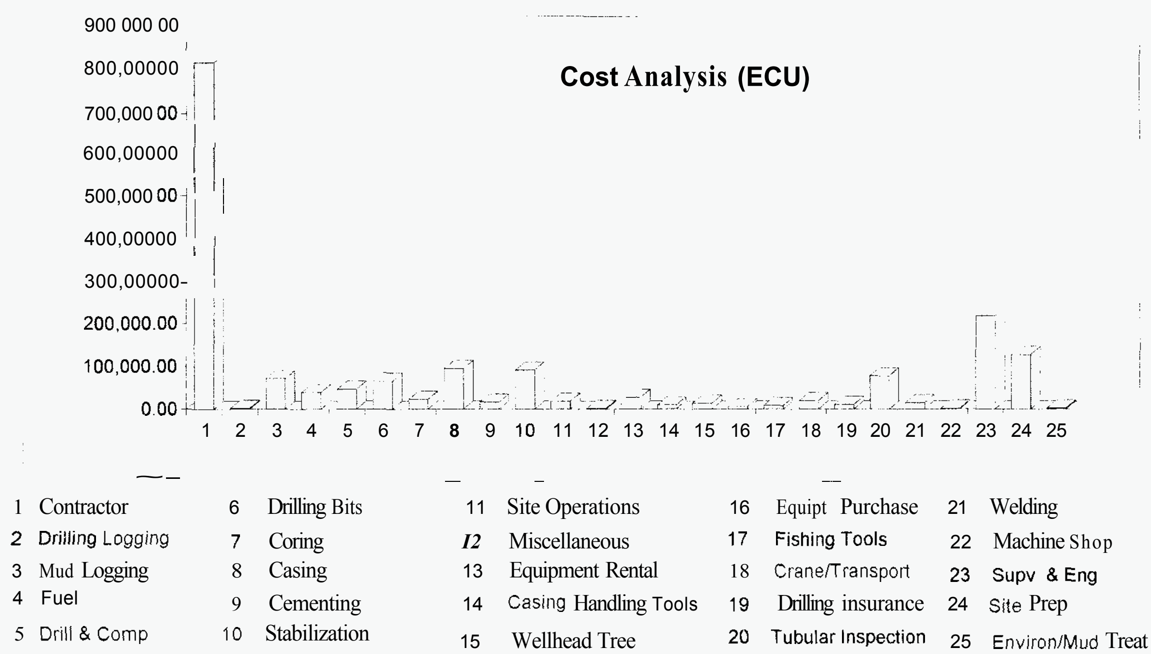

Fig. 10: Cost analysis of the extension of GPK-1 **(all values in ECU)**