NEW STRATEGIES FOR ULTRADEEP CORING IN CRYSTALLINE BEDROCK

H. Rischmüller
R. Jürgens
C. Marx
J. Oppelt
A. Sperber
U. Deutsch

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

1 INTRODUCTION

The concept of the German Continental Deep Drilling Program ("Kontinentale Tiefbohrung der Bundesrepublik Deutschland" or "KTB") emphasizes the scientific investigation of the continental crust in order to improve the understanding of the dynamics of intracotinental structural evolution. A drilling location was chosen on the western flanks of the Bohemian Massif in the northeast of Bavaria near the Oberpfalz town of Windischeschenbach.

A total depth of about 12000 to 14000 m for this superdeep borehole to be drilled into the crystalline rock formations has to be reached to meet the scientific goal. This extreme depth poses a very unusual challenge with respect to drilling technology in general. Up to now, only one borehole in the world has approached a comparable depth which is the KOLA SG-3 well. From the publications on this drilling project which is also under way for purely scientific purposes, many technical problems have become apparent to drilling specialists all over the world. Although the geological structures differ from those found in Germany, similar problems will have to be expected for the KTB superdeep hole.

Apart from preparing the planning of the geoscientific experiments and investigations, major emphasis therefore has to be placed on providing the most adequate drilling methods and systems which are capable of meeting the anticipated environment and resulting requirements. It is generally agreed that oilfield drilling technology will only partly be able to meet this task. Tools and drilling systems have to be modified from other already existing technologies such as the mining drilling business or have to be designed totally new.

In order to provide a long enough period of time for conducting such developmental work, and, nevertheless, at the same time to be able to start the scientific investigation of the crystalline rock at the Windischeschenbach location, a new well planning approach was used. This concept consists of drilling a small diameter pilot hole to start with and afterwards spud a second borehole on the same site which has the large diameter required to reach a maximum depth of 14000 m.

The pilot hole has meanwhile been spudded in September 1987. After drilling and coring, mainly by using roller cone bits of 10 5/8" diameter down to 480 m, a 6" anchor casing has been cemented down to this depth. Below 480 m, a specially designed wireline drill string is used which allows to obtain continuous cores of 94 mm diameter from the 6" (152.4 mm) borehole. A total depth of 3000 m has been determined as the minimum target. Any extension below this depth would be appreciated, because the drilling/coring process works quite effectively. Moreover, as the geological scientists have been provided with the core material down to that particular depth, no coring over extended sections is required in this section of the main borehole. The superdeep well which is to be drilled at a distance of no more than 200 m from the pilot hole, can concentrate on other criteria, e.g. verticality of upper sections or optimized penetration rates, because the formation samples have already been obtained earlier.

A major requirement for taking cores from the superdeep KTB well (KTB-HB) will first appear when the hole has arrived at a depth below the TD of the pilot hole. This is the section of the borehole ranging from about 3000 or 4000 m to 12000 or

14000 m, where new coring tools and coring systems have to be provided which are capable of meeting the requirements of effectively taking core samples from the very hostile environment created by the ultradeep target in crystalline bedrock. Existing experience from other drilling activities in crystalline rock has show that, apart from all other technical difficulties, coring under these conditions presents an extremely demanding challenge to both tools and equipment. As the available technology does not provide a comprehensive system for coring in ultradeep crystalline rock, a major development effort has to be made in order to achieve the key scientific objective of the German Continental Deep Drilling Program, the KTB.

2 CORING REQUIREMENTS FOR KTB SUPERDEEP HOLE

Drilling a superdeep hole down to a maximum depth of 14000 m is in the center of interest during the course of the geoscientific KTB project. Below the casing depth of approx. 3000 to 5000 m, depending on the TD reached by the nearby pilot hole, an average of 1/3 of the remaining proposed hole section will be drilling by coring tools in order to provide rock samples for scientific evaluation.

Requirements of adequate coring systems on the one hand are determined by the influence of physical and geological parameters. This is especially true for more extended depths of the well. On the other hand, additional aspects will become apparent with respect to handling capabilities of coring systems.

In general, all coring tools have to show a sufficiently high mechanical stability and reliability in order to be able to withstand the expected downhole conditions. A summary of the most important borehole parameters influencing the coring process is given in Table 1.

- Temperature
- Rock Stresses
- Rock Strength
- Rock Abrasiveness
- Rock Inhomogeneity
- Borehole Depth

Table 1: Effective borehole parameters in deep crystalline rock environment

Selection and design of coring systems have to take into consideration critical parameters as listed in Table 2.

- Core Bit Wear
- Inclination Build-up
- Poor Control of Coring Process
- Low Rate of Penetration
- Low Footage of Core Bits
- Hole Fill by Abrasive Rock
- Core Jamming within Barrel
- Vibrations on Drill String
- Wear on Drill String
- Exceeding the Temperature Limitation of Tools
- Exceeding the Load Capability through extended Length of String
- Mud Losses
- Poor Core Recovery

Table 2: Critical effects during coring of deep crystalline rock

Well Planning

The basic drilling concept of the German Continental Deep Drilling Program includes the drilling of a pilot hole (KTB-VB) at a distance of 200 m from the site of the main well before spudding this main well (KTB-HB). Coring in the superdeep borehole will be performed only in sections below the TD of the pilot hole, e.g. from 3000 m to 5000 m (Fig. 1).

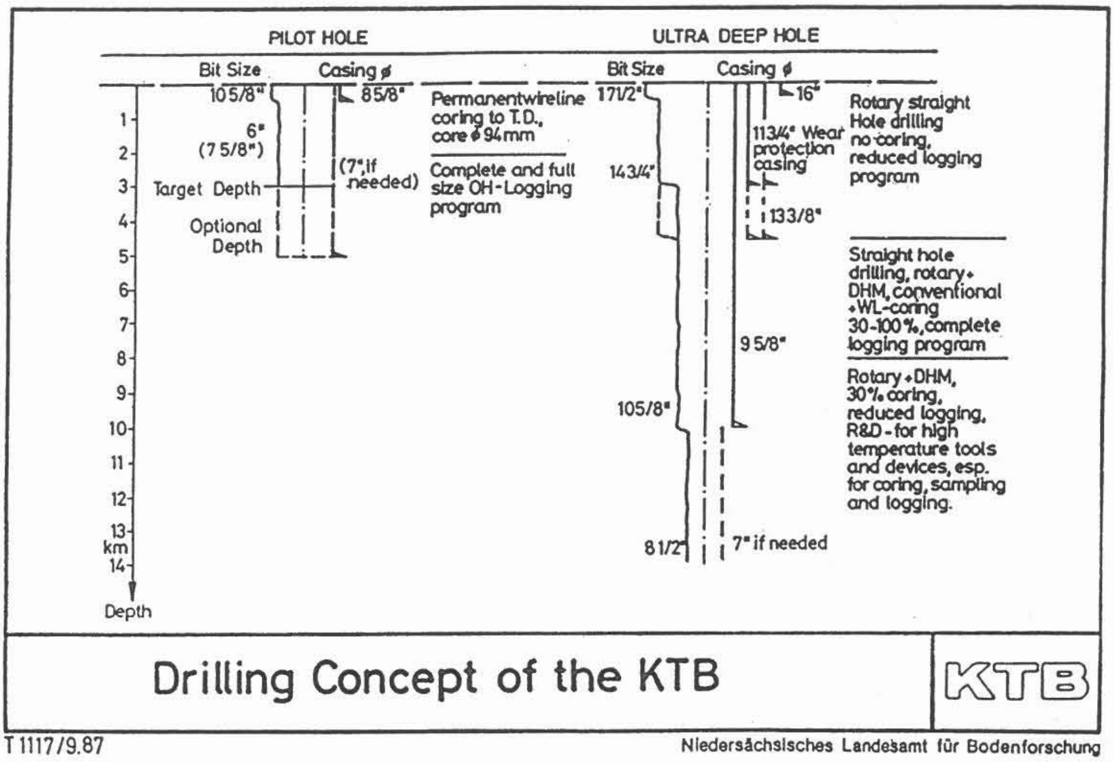


Fig. 1: Well planning for KTB well (Ref. 5)

In addition to the expected overall reduction of drilling time this concept offers a good chance for improving the verticality of the upper hole section.

Geological environment

The well target is located in the Oberpfalz area at the edge of the Bohemian Massif. A preliminary geological prognosis has been published for this location (Ref. 5) by the KTB Technical Project Group. However, the given data are rather vague, except for those layers which have already been drilled in the pilot well.

In any case, uninterrupted crystalline rock will be encountered with the possible exception of a shallow layer of cap rock. Due to the expected abrasiveness, critical tool parts have to be protected against severe wear through special measures such as coatings with hard metal or stabilizers. Due to the extreme formation hardness, the systems under development have to be designed for enhanced sturdiness. There is a risk that diamond cutters may already be damaged during tripping of the string.

Temperature, pressure, and stresses in the borehole

The downhole formation temperature is a critical parameter for the reliable operation of roller cone core bits, downhole motors, coring systems, other moving downhole tools, and even the drill string itself. Development expenditures for the required tools will considerably increase with increasing temperature. A simplified view of the temperature environment for the Windischeschenbach/Oberpfalz location is shown in Fig. 2.

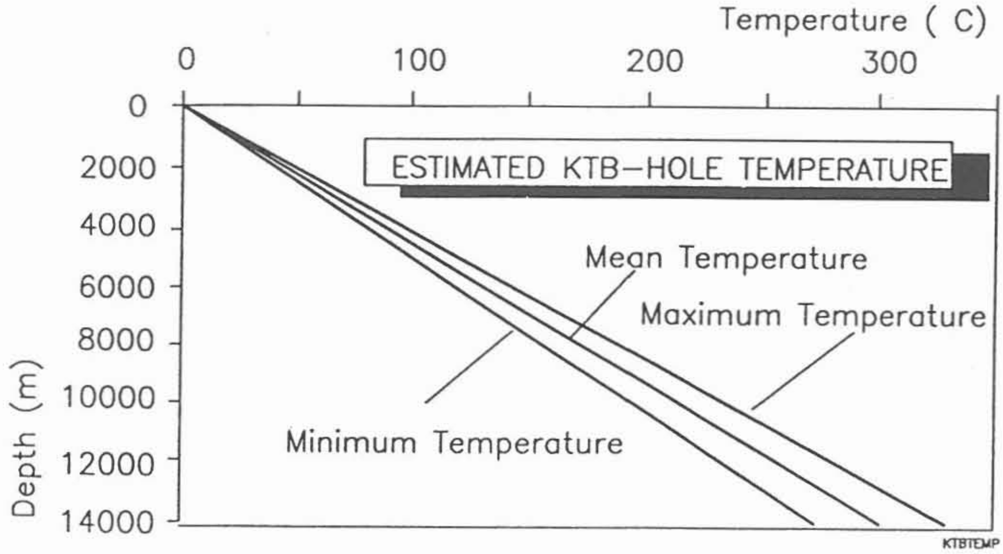


Fig. 2: Estimated depth/temperature diagram for the drilling site

If compared with a temperature gradient of 3 grd/100 m, which is a common order of magnitude, a medium value of 2 grd/100 m leads to moderate temperatures of about 300 °C at 14000 m. Naturally, the mud circulation temperature will always stay below the undisturbed formation temperature. The interim report on the KOLA SG-3 well confirms this very clearly (Ref. 6). In this case, a maximum difference of 30 degrees occurred between circulating mud and undisturbed rock temperature. For safety reasons, the latter has to be considered for design purpo ses.

Borehole stresses are primarily determined by the geostatic pressure, i.e. the weight of the rock formation. The drill site formation will exhibit an average density of 2.9 kg/dm^3. According to the geological prognosis, a downhole pressure of 4000 bars may be estimated at a depth of 14000 m. Taking a specific mud weight of 1.05 kg/dm^3, a mud pressure of only 1000 bars would be opposed by a rock pressure four times that amount.

A general distribution of stresses at the borehole wall is shown in Fig. 3 (Ref. 7).

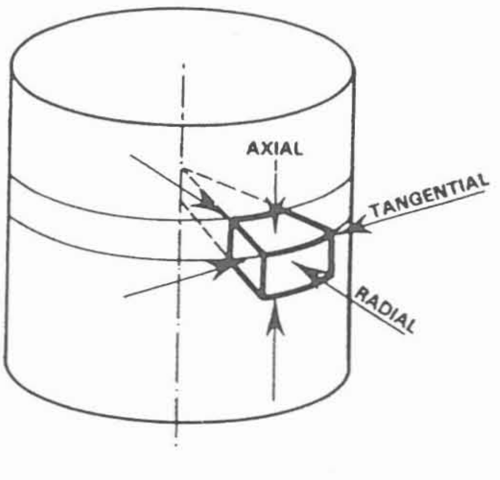


Fig. 3: Stress distribution at the borehole wall (Ref. 7)

Elevated temperatures are critical to many of the presently used coring tools or corresponding components. Some of the materials under use completely lose their function. In other cases, the performance will change considerably.

The stress environment as roughly outlined above will cause drilling problems with respect to the borehole shape and the quality as well as quantity of cores recovered. Both have become known from the KOLA SG-3 well and, with limited experience, from the Gravberg 1 (Siljan Ring, Sweden).

If boreholes are out of gauge over distinct lengths due to rock spalling, the stabilization of the core barrel is affected. Existing vibration might then be intensified which will result in severe problems with respect to maintaining the required trajectory. Breakout and collapse of the borehole wall as well as other instabilities will lead to a fill up with abrasive particles. Especially when tripping the string into the hole, there is a danger of relatively large sized particles entering the inside of the drill string, thus causing major functional troubles when resuming the coring process.

During coring, stress relief will result in volume changes of formation. This may give rise to core jamming and to the tendency that the rock sample will split along pre-existing planes of weakness. In order to overcome or, at least, to minimize these difficulties, the inner surface of the core barrel should be as smooth as possible with a slightly increased inner diameter. Special problems might occur if cores break into thin slices (core disking), as happened during the course of drilling the KOLA well.

Fundamental scope of development of coring tools

Every KTB coring development has to use the existing tools and systems from deep hole drilling as well as mining drilling as a basis. With respect to section of moderate depth, major resources have to be allocated for improving the economy of the coring process. When getting into deeper sections, the reliability of coring systems has to be raised by technological improvement in such a way that coring with a good recovery rate will not disturb deepening the hole. When reaching the superdeep sections of the hole, coring systems have to be designed primarily towards a direction which allows to recover some core at all.

With respect to development planning, characteristic sections of depth are determined as shown in Table 3.

Depth Limitation (m)	Section	Coring Intervals (m)	Major Goals
3000 (5000)	TD KTB-VB	50	Full size coring, sidewall coring, spot coring
6000	Moderate depth	350 - 1000	Core recovery, economy, core quality
10000 (12000)	TD 10 5/8" hole	1300 - 2000	Core recovery, core quality
14000	TD KTB-HB	700 - 1300	Core recovery

Table 3: Coring systems for different sections of the KTB main well

Down to the TD of the pilot well (KTB-VB), no continuous coring is required to be performed in the main well. For the purpose of confirming results from the pilot hole, a limited number of samples might be taken by discontinuous spot coring or by sidewall coring out of the already deepened open hole. In addition, this section of the hole might also be used for the testing of tools which will be under development at this time for more extended depths.

Major research efforts will have to be made to develop coring means and methods which do not require tripping the complete drill string out of the hole after one core barrel has been filled. These systems are to be identified as continuous coring systems. One advantage of such systems is that much time will be saved if the string can remain in a superdeep hole while recovering the core. Another advantage which may be even more beneficial to the whole drilling operation, is the possibility to recover a jammed core sample by wireline or other means.

Reflections on coring and verticality of hole

Verticality of hole is of superior importance for meeting the ambitious goal of a 14000 m TD. Down to TD of the pilot well, no extensive coring is required in the main well. The most adequate systems for vertical full size drilling will be employed here where a truly vertical hole course is really essential. However, the deeper sections which will be cored rather extensively, also require to maintain a straight and vertical course of the hole. Otherwise, there is the danger that the deepest parts of the hole will have to be plugged back if torque and drag exceed the strength of the drill string due to unfavorable direction changes.

There are different principal methods for recovering cores and maintaining verticality as listed in Table 4.

- Take cores and make correctional runs some time afterwards in deeper section if deviation gets untolerable
- Use "hybrid" pilot coring system, trying to pilot core as vertical as possible and later on ream the hole following the course of the pilot
- Use pilot coring system with internal whipstock for borehole corrections
- Pilot core for optimum recovery over a certain length without considering hole verticality, then change BHA completely and employ special full size vertical drilling system to drill optimized vertical hole without considerations on coring

Table 4: Proposed methods for coring and vertical drilling

The decision which method to apply will depend on the drilling parameter environment, lengths to be cored, etc.

3 EXPERIENCE AVAILABLE WITH CORING CRYSTALLINE ROCK

An effective and systematic approach to coring systems development has to make use of the internationally gained experience with drilling of crystalline rock. In addition, the overall state of the art of progressive coring systems from other applications has to be taken into consideration.

Crystalline rock coring performance

Drilling or coring for oil and gas is usually conducted in sedimentary rock formations. However, no continuously operating systems are used here, because they are not needed. As regards drilling and coring in crystalline rock, only limited experience is available in this case. These types of wells are usually either drilled for purely scientific reasons or for the exploration of waste storage facilities. In addition, the few data available are difficult to compare due to unknown drilling and borehole parameters.

From the existing experience with diamond core bits the following conclusions may nonetheless be reached:

- Rate of penetration and footage will both be improved by a reduction of the ratio of borehole to core area (CR = characteristic ratio). Some recent results with respect to footage are shown in Fig. 4 for comparison.
- For equivalent characteristic ratios, a better overall performance is achieved with smaller borehole diameters.

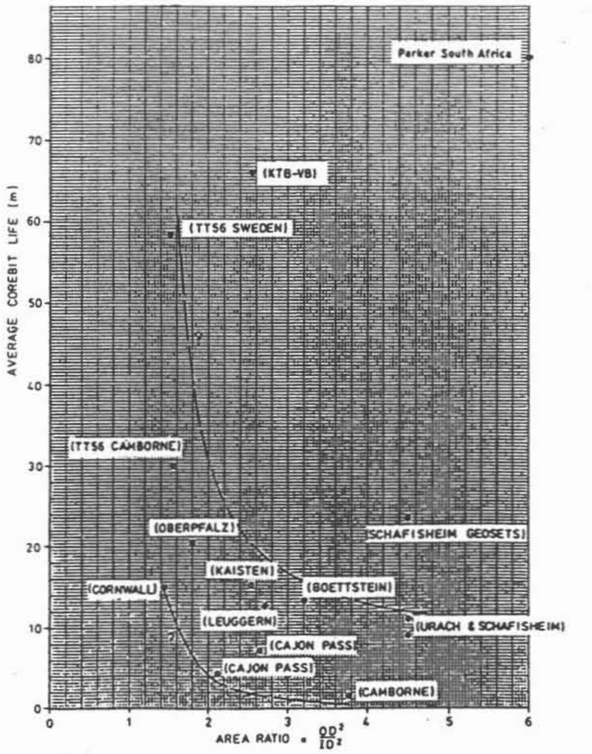


Fig. 4: Average footage of diamond core bits in crystalline rock

- The rate of penetration may be increased through elevated rotary speed corresponding to 2 to 3 m/sec cutting speed at the diamonds, e.g. by employing high-speed top drives or downhole motors. However, this requires effective cooling of the cutting elements at the bottom of the hole.

- Diamond coring performance in deep holes is generally inferior to that in shallow holes. This is due to the fact that with increasing depth the more problem of cutting is overlaid by several additional difficulties.

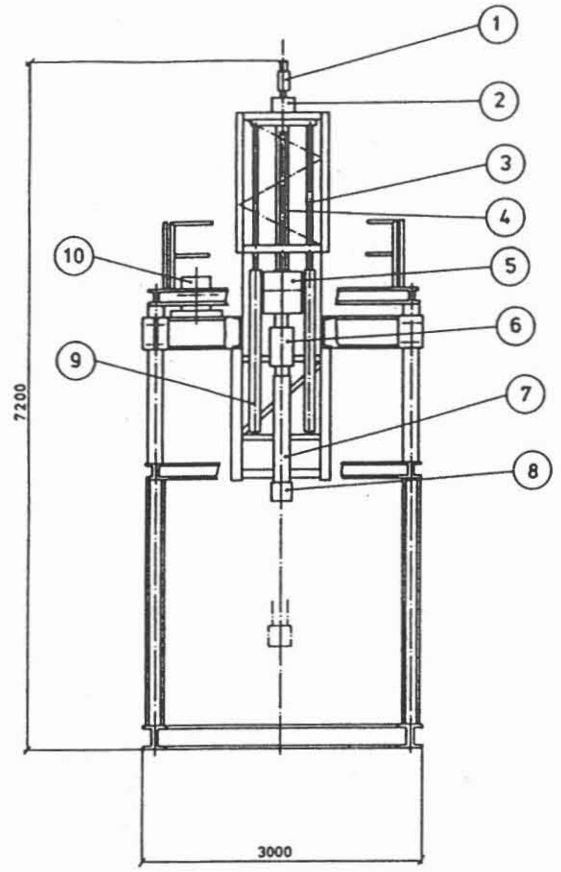
However, these indications may only be trusted to a limited extent. Even for identical geological environments, significant differences in performance may occur which are mostly due to drilling operation parameters being adjusted only more or less for optimum results.

Another major point of interest is to deal with the existing development potential for diamond core bits. Through adequate design modifications, especially diamond impregnated tools may be improved considerably with respect to performance. In order to evaluate different design and material options in the laboratory, this first stage of evaluation is preferably done on a drill test rig. Some recent test results on different core bit design alternatives are shown in Table 5 in terms of related WOB, ROP, and footage. Obviously, considerably different results were obtained, especially with respect to the footage s^*. A sketch of the Eastman Christensen Celle drill test rig is shown in Fig. 5.

This test rig offers a maximum WOB of 2000 kN and maximum RPM of 1300 1/min. Core bits up to the 6 3/4" size may be tested. The measuring data automatically are retrieved and stored. A computer control system allows to drill with constant ROP or with constant WOB.

Test No.	Design-Type	WOB/AD (N/mm^2)	ROP•AK/AD (m/h)	s* (m/mm)
1	A	14.2	16.3	6.3
2	B	15.7	31.0	16.6
3	C	13.2	28.5	28.4
4	C	11.6	15.4	18.6
5	C	12.4	15.6	49.4
6	D	8.2	40.0	51.7
7	D	8.2	32.5	9.9
8	D	8.2	15.0	39.5
9	E	11.7	27.1	6.8
10	F	9.2	19.3	18.6

Table 5: Performance of diamond impregnated core bits size 96 x 63 mm (Formation: Amphibolit; Mud: water)



1 SWIVEL
2 FORCE TRANSDUCER
3 PULL ROD
4 SPLINED SHAFT
5 BEVEL GEAR
6 TORQUE INDICATOR
7 CORE BARREL
8 CORE BIT
9 HYDRAULIC CYLINDER
10 ELECTRIC MOTOR

Fig. 5: Drill test rig of Eastman Christensen GmbH, Celle

The test results have shown that the performance of the core bit may be improved considerably by optimizing the fluid flow around the cutting surfaces, especially with impregnated cutting elements. However, the transformation of a laboratory development to real borehole application needs careful planning, because this drilling environment differs from the laboratory operating conditions in some aspects.

Thick kerfs and large area ratios (R-factor) will influence distinctly negatively the diamond coring performance. With respect to an optimized coring effectiveness, thin kerfs and small area ratios would be the ideal solution, as sometimes realized in mining drilling.

For roller cone core bits, little experience with coring of crystalline rock is available. Leaving aside the KOLA SG-3 well, some information has been published from the Los Alamos Hot Dry Rock Project, the NAGRA radioactive waste storage exploration project, the Camborne School of Mines HDT project, and the Gravberg-1 well in central Sweden. In addition, two different types of roller cone core bits have recently been employed in the upper section of the KTB pilot hole.

Since 1974, experience has been gained with six different roller cone core bit designs. Basic design alternatives are the four-cone core bit, the hybrid four-cone core bit with additional diamond PCD cutting elements for improving the core quality, and the six-cone core bit which has three cones for cutting the hole and the other three for cutting the core.

- Due to the reduced dimensions in comparison with full size roller tools, certain general problems occur with bearing performance. According to information available, however, some progress has been made in this area during the last few years.
- The cutting and wear behavior of hard metal inserts has also undergone some improvement. Further performance increase is believed realistic by coating these cutting elements with superhard materials, e.g. diamond.
- Core recovery with roller core bits seems to be generally inferior to the quality and quantity achievable with diamond core bits.
- Core recovery obviously becomes more critical with increased depth. Therefore, adequate means have to be developed with high priority which support the entering of the cores into the roller cone bit/core barrel system under the stress environment of superdeep boreholes.
- Due to their basic functional principle, roller cone bits will exhibit a penetration rate performance which is comparable to that of well designed diamond coring systems of the same characteristic area ratio.

Today, the general conclusion may be drawn that roller cone core bits will operate in crystalline rock only to depths which do not yet exhibit stress relief phenomena. This is also true for the so-called "Hybrid Core Bits". Roller cone bits offer the general advantage of increased sturdiness. They are thus suitable for performing reaming operations when being tripped into the hole, and the debris at the bottom of the hole may well be crushed into small particles. These cutting and coring tools are capable of withstanding rough treatment without damage. Major improvement is required regarding an effective integration of the roller cone core bit into the core barrel design, in particular with respect to the core catching mechanism.

Existing Coring Systems

In the Western world, at least, systems for continuous coring in crystalline rock have been developed systematically only for the purpose of mining drilling exploration.

However, the diamond coring systems for mining applications, partly operated in connection with wireline core barrel retrieving mechanisms, are not suitable for use in the depths and diameters encountered in the superdeep KTB hole. There is, nevertheless, much sense in adopting some parts or components from the mining technique and modifying them for integration into the proposed new systems. The widely used principle of continuous coring systems is a characteristic feature of the mining technology. The wireline drill string recently developed for the specific purpose of coring the KTB pilot hole seems to prove that reasonable combinations of features from both the mining and the oilfield drilling techniques offer a new performance potential for crystalline rock drilling.

As regards the oilfield rotary drilling, a basic distinction may be made between rotating the complete string by the rotary table or top drive or driving the bore bit by use of a downhole motor. Performance losses through friction in the hole usually increase with depth. In addition, significant wear of the rotating drill string is likely to occur with crystalline rock. Therefore, the general recommendation can be made from the experience available that downhole direct drives should be preferred, at least for intermediate depths of about 6000 to 7000 m. Regarding possible motor types, only mud driven positive displacement motors (Moineau geometry) or turbines are of importance. Using Moineau motors is, however, limited with regard to depth, because standard elastomer fills of stator tubes will operate only up to about 150 °C. As a medium term development goal, a temperature limit of 200 °C seems to be realistic.

Drilling turbines will require relatively few modifications before being applicable for high temperature environments. However, manufacturing costs of turbines are generally quite high. Also, the existing turbines are not suitable for use with roller cone bits due to their high level RPM performance. Considerable development efforts are thus required to reduce the speed (Ref. 8).

The means for taking the core sample itself certainly is the most critical part of the whole coring system. In the upper section of the hole down to about 6000 m, the existing systems will allow to take some cores. In order to improve coring effectivity and quality, however, this range also requires distinct development efforts. With respect to diamond core bits, the major goal is to increase the penetration rate. Roller cone systems strongly need an optimum tuning of the bit/barrel system. Initial steps for improvement have to include design and coating of inner barrel, optimization of core catching mechanism, and measures to stimulate the penetration of rock into the barrel. No continuously operating system exists for this range.

As regards depths below 6000 m, there seems to be no realistic chance at all to recover noteworthy amounts of rock samples with the existing technology. All components, such as actuation drive, core taking facility, and core bit, have to be reworked considerably to allow proper functioning in the hostile environment of extreme temperature, formation stresses, and depth. These parameters become even more critical for depths below the 10000 m mark. As a general conclusion, no system is available that would allow to take continuous cores in crystalline rock with diameters and depths as required in the KTB main well.

As to sidewall coring systems, after thorough investigations, only four basic principles seem to be worthwhile to be pursued further (Table 6). Of these, only the Gearhart and the Schlumberger tool have been used commercially in the field. Both are driven by electric motors which require an electricity supply from the surface through a multi conductor wireline cable. Torque is created hydraulically in the Gearhart tool. The ITE-EC-system as well as the Statoil-EC-system are both run into the hole on the drill pipe. As regards the ITE-EC-tool, a core barrel and a motor are afterwards run into the hole on a wireline while with the Statoil-EC-system a spear with core magazine is run on the wireline. Both tools are driven by the mud flow. The maximum operating depth is limited by the temperature resistance of different critical parts. The principles of operation resp. functions of the various tools is compressed in Fig. 6.

Type	Cutting Tool	Downhole Motor Type	Rotation power via	Control via	Core diameter/ length (mm)	Core magazine	Depth limit parameters
ITE-EC Moineau-System	Impregnated diamond core bit	Moineau motor	Mud/ string	Wireline	41	1	150 °C
Gearhart Hard Rock Coring Tool	Impregnated diamond core bit	Hydraulic motor	Electric conductor	Multi-Conductor	24/44	12	150 °C 1380 bar
Schlumberger Diamond Core Slicer	Diamond saw blades	Electric motor	Electric conductor	Multi-Conductor	25.4 x 914	4	150 °C 1380 bar 6700 m
Statoil-EC SWC	Impregnated diamond core bit	Hydraulic motor	Mud/ string	Multi-Conductor	37/89	15	70 °C (120 ° C) 3000 m (6000 m)

Table 6: Characteristic information on four different sidewall coring systems

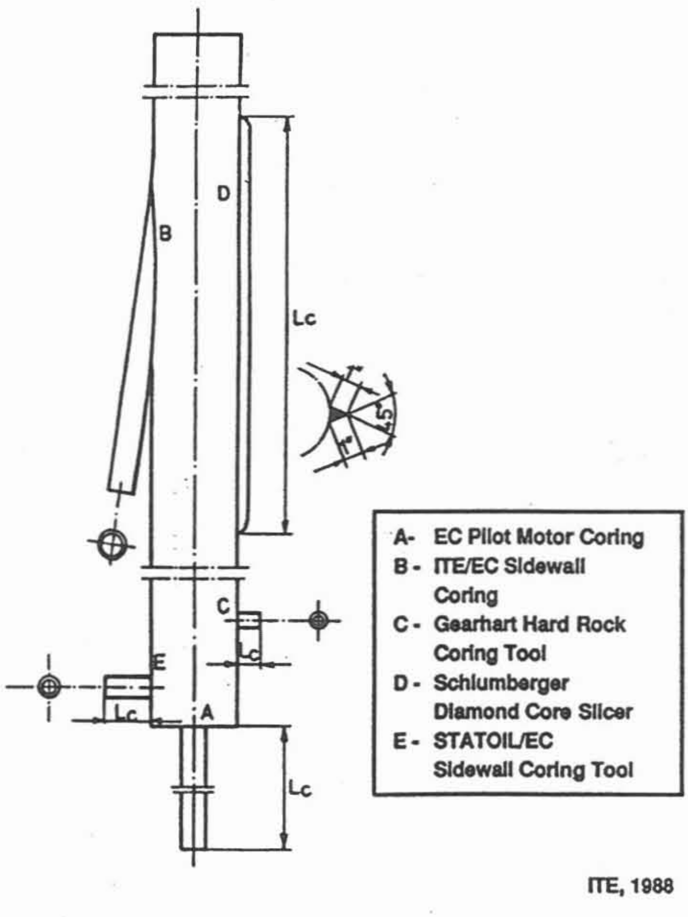


Fig. 6: Dimensions of wireline retrieved cores

4 DEVELOPMENT POTENTIAL FOR KTB CORING SYSTEMS

Many alternative means may be used for the realization of systems for continuous coring downhole and into the sidewall for the KTB-HB. The scope of development goals will be outlined in this chapter. In view of the limited time and total expenditure for development in this matter, some key alternative systems will have to be selected for further development. Finally, a proposal will be made concluding the development of hardware which is deemed essential for the scientific goal of the KTB program.

4.1 Systems for continuous downward coring

As a key feature, continuous coring systems offer saving a considerable amount of trip time by allowing to retrieve the formation samples without tripping out the entire drill string. The life of a core bit should then attain a multiple of the length of one core. In addition, such a system is also highly justified if frequent retrieval of the core barrel is required due to core jamming. The optimum continuous coring system should allow to pull the worn bit in addition to the inner barrel on the wireline. In this case, the drill string could remain in the hole over the complete coring interval.

An overview of alternative continuous coring systems is given in Fig. 7. A basic distinction can be made between systems where the core bit is driven on the rig floor and those which employ downhole motors. As a very promising alternative design proposal, both types of actuation may be employed in combination systems. Hammer drilling has already proven to offer excellent performance in hard rock destruction in shallow holes. Such systems may be used in combination with rotary tables as well as downhole motors.

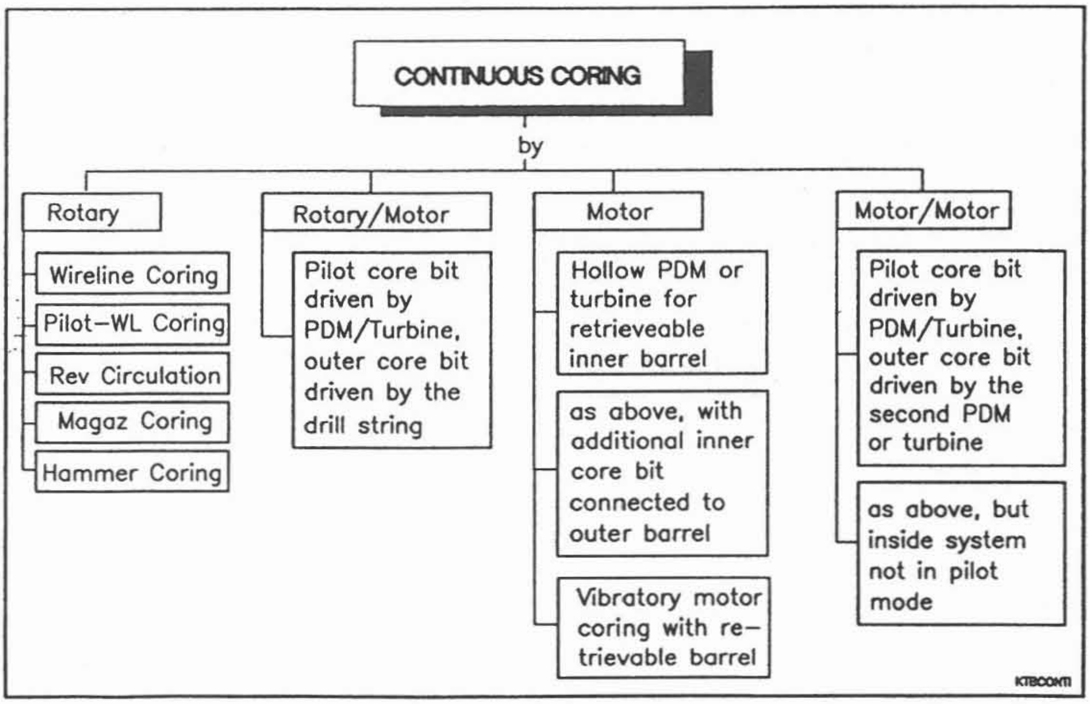


Fig. 7: System options for continuous downward coring

4.1.1 Rotary table driven systems

When using the rotary table or top drive, the wireline coring system as has been used in mining for quite a long time has to be mentioned first. As a basic function principle, the inner barrel together with the core sample is pulled to the surface using a wireline. In mining techniques usually special drill strings are used for this purpose which have only slight restrictions of inner diameter within the tool joint section. If a standard API rotary string were to be applied, the outer diameter of the core barrel has to be accommodated to the reduced tool joint passage. The system as described above is generally operated with one string of constant diameter.

As a modification to this standard design, a principle according to Fig. 8 may be realized. In this case, the hole is drilled with the standard rotary technique to the depth where the coring operation is to be started. After tripping out of the hole, a mining wireline drill string is connected to the API string which should have a length equal to the expected footage of the diamond core bit connected to it. This tapered drill string is now run into the hole. A pilot hole is then drilled with the lower part of the combination string. Continuous core recovery is realized by tripping in and out the inner barrel of the mining system. The inner core barrel has to feature dimensions which will allow to pass through the tool joints of the API string.

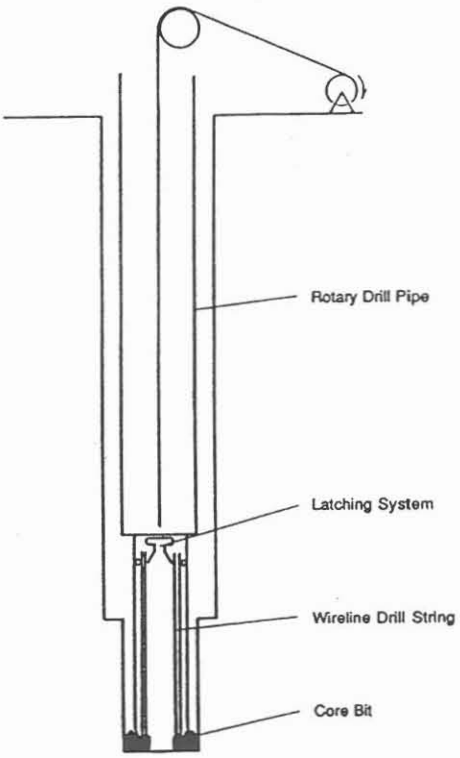


Fig. 8: Mining wireline string on bottom of rotary string

A roundtrip is required only if either the core bit is worn or the length of the mining string has been drilled. The hole diameter will afterwards be enlarged to the size of the upper borehole section by means of a full size bit being connected directly to the API string.

Modified mining diamond coring systems will generally perform better when operated with RPM higher than usually possible with rotary tables. Thus, a primary solution would be to drive the mining string according to Fig. 8 by a downhole motor. This will virtually mean that the "rotary table is shifted to the bottom of the hole", which has several advantages over the standard method. As a first step, the nonrotating part of the motor is connected to the rotary string while the motor drive shaft forms the crossing to the mining string. In order to allow the wireline retrieval of the inner barrel, a sufficiently wide passage diameter has to be provided inside the rotating shaft. In this case, the motor would preferably consist of a large diameter drilling turbine. As a second alternative a mining core barrel and connected downhole motor could be mounted sliding within a bottom drill collar of the rotary string. This latter principle has already been realized as a prototype tool within the course of the international scientific "Ocean Drilling Project". The combination of diamond core bit, core barrel, positive displacement motor, and latching means, is lowered into the drill string. After radial engagement to the drill collar, the mining barrel and core bit are moved by the PDM while the WOB is built up by hydraulic thrust.

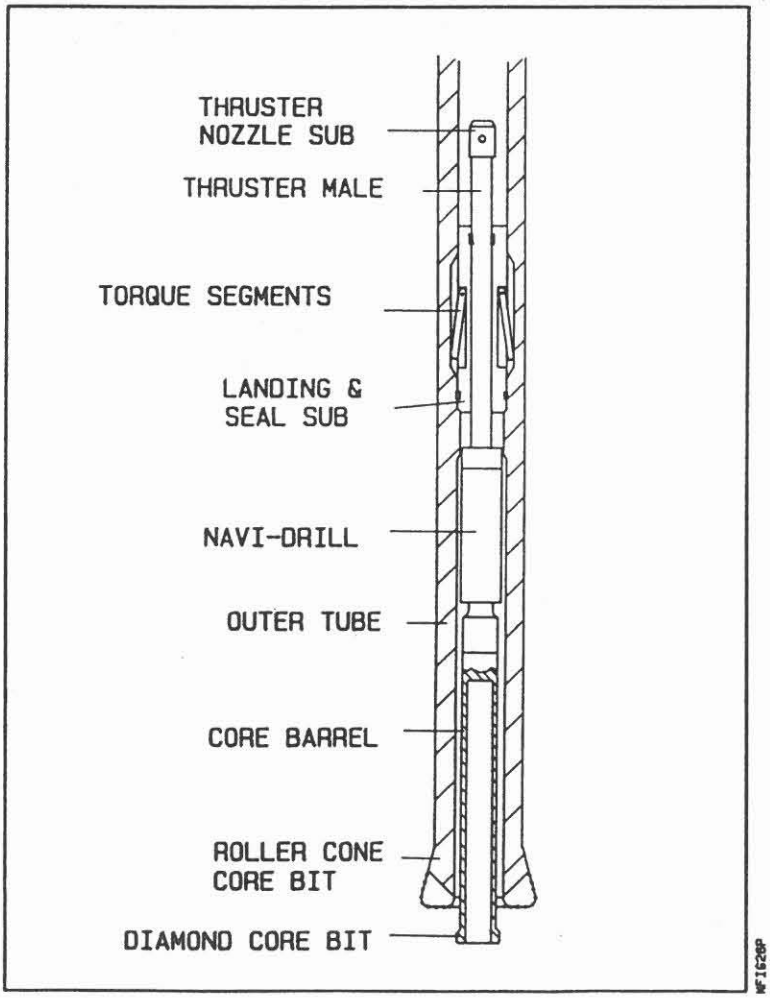


Fig. 9: Pilot motor coring system

For both systems employing the "rotary table on bottom" principle patents have been granted or are pending in favor of Eastman Christensen Company. This is also true for the additional feature which allows to install extension pipes in the inner parts of the embodiment as shown in Fig. 9 in order to increase the depth of the pilot hole.

Up to now, it has generally been assumed that the retrieval of the core sample, eg. inner barrel, is done by connecting an overshot and wireline to the inner barrel for pulling it out of the hole. As an alternative method, however, it needs to be considered whether pumping the core out of the string through a reversal of the mud circulating direction would be possible. The feasibility of such a process which is quite often used for special mining purposes depends on several parameters such as the pressure build up in the annulus between string and formation, the fluid losses to the formation, and the design of the drill string. Another option would be to provide the core barrel with a self-propelling mechanism for transportation to the surface. This principle will need thorough investigation.

Magazine coring offers the opportunity to store downhole a certain number of small core samples.

Due to the effectivity of this special rock destruction process, the feasibility of applying hammer drilling techniques for the coring operation in crystalline rock should be investigated further. Early development of mud driven hammers for oil well application be AMOCO in the '60s had been abandoned due to technical (mud solids content) and economic reasons. In the People's Republic of China, development was restricted to the application in the mining exploration drilling for extremely hard rock. For more than 10 years now, the mud operated downhole hammers have been widely used in the field with excellent results. Lifetime of a hammer tool is reported to reach more than 500 hrs, up to 950 hrs so far. three different hammer designs for coring drilling are documented:

- Double acting nonspring type hammer
- Positive and negative acting spring loaded hammer
- Fluid hammer with no moving parts in the valve.

In accordance with the Chinese mining standard, the hammers are available in the sizes 54, 76, 89, and 150 mm OD. The drilling fluid operated downhole hammers are used in combination with impregnated diamond bits. Because of their availability, the impregnated bits are manufactured with small size grit (50 - 70 US-mesh) and hard matrix for improved bit life. This application led to hammer systems with high frequencies, i.e. 20 - 40 Hz, and low impact energy, i.e. 20 J for hammer type SC-54 and 140 J for hammer type SC-150. The basic design of the fluidic valve hammer is shown in Fig. 10.

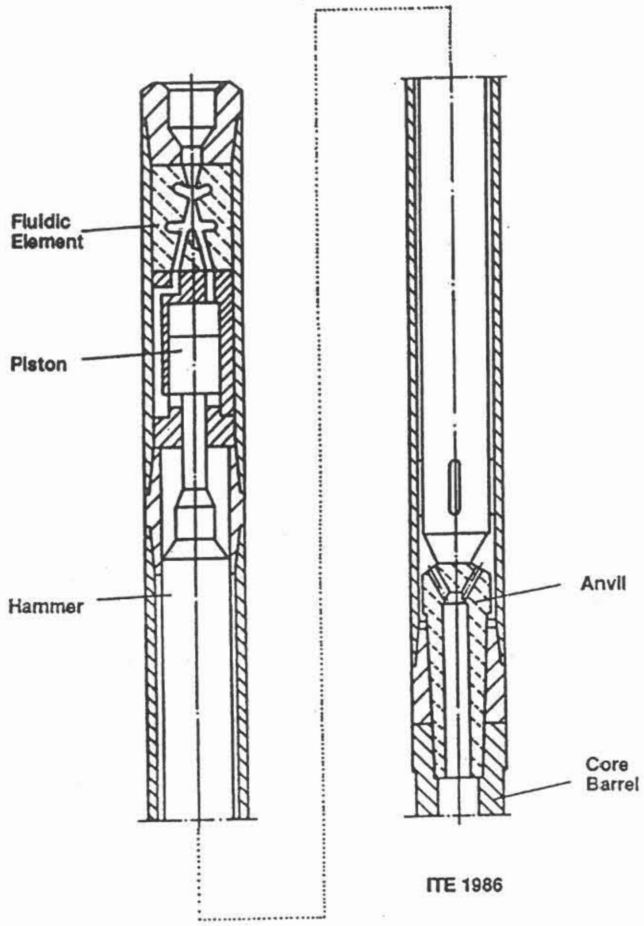


Fig. 10: Basic design of fluidic valve coring hammer

For the KTB drilling program, solid-free drilling fluid was developed. This improves the chance of employing hammer drilling in noncoring operations for the large hole size as well as for the coring operation.

One scenario to apply hammer coring in hard rock and large size boreholes can be envisaged in case the roller core bit leads to poor core recovery because of core breakage. A core bit designed with large sized diamond cutting TC-inserts may be operated successfully by using a hydraulic downhole hammer. In order to apply wireline technique to recover the inner barrel, this would necessitate building a downhole hammer with a hollow shaft. Another approach would be to use the hydraulic hammer in combination with the pilot motor coring system as shown in Fig. 9. In this case, the hammer would be positioned between the downhole motor and the core barrel.

At present, first tests are being performed to optimize the diamond bit for hammer coring in hard crystalline rock. Instead of diamond grit normally used as cutting elements in hard rock coring, new synthetic diamond material known as TSD, such as Geoset or Syndax-3, may serve the purpose.

4.1.2 Application of rotary table and downhole motor

Continuous coring by using a combination of rotary table and downhole motor actuation has already been mentioned in connection with Fig. 9. Within the ODP project, a roller cone core bit of 10 1/2" (267 mm) had been used with this tool. The inner system had been rotated by a Navi-Drill Mach 3 size 3 3/4".

Instead of using the PDM which has the disadvantage of limited temperature capability, a turbine might be employed for the same purpose. As a modification of the described system the outer part of the turbine might be fixed to the rotary drill string while an inner drill string is pushed forward through the hollow rotor of the turbine (Fig. 11). In this case, the downhole motor remains on the bottom of the large diameter hole to actuate the wireline retrievable inner drill string. The turbine also remains on bottom when the thin inner string is pulled out of the hole for core recovery or extension. After having cored a certain distance of about 100 m, the borehole diameter has to be increased to full size by rotating the outer string from the surface. During this phase, a special pilot will guide the outer core bit to follow the section cored.

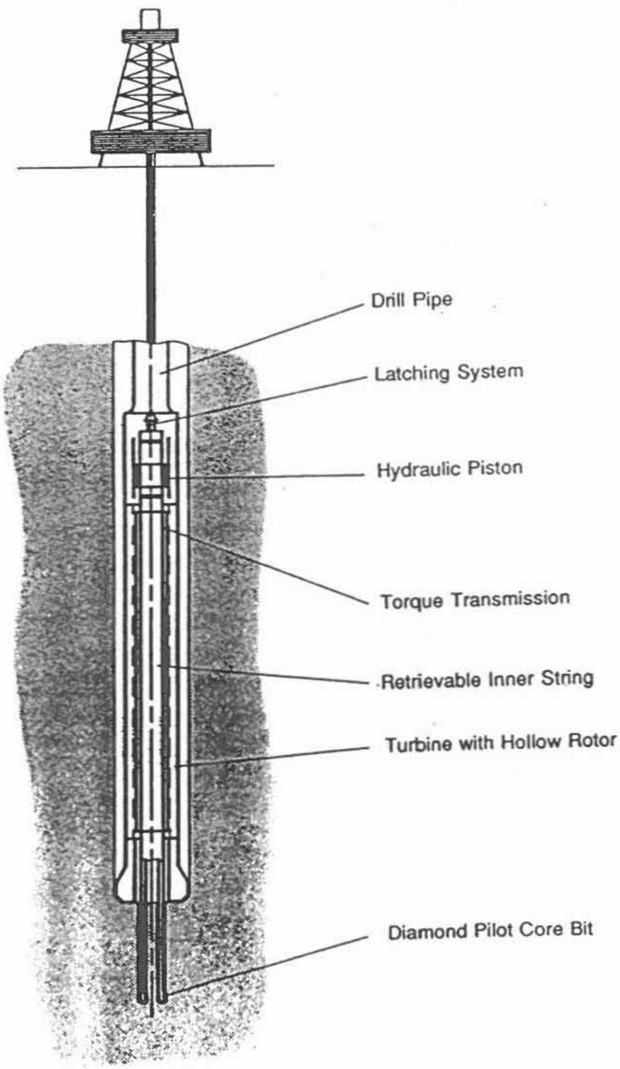


Fig. 11:Pilot coring through hollow turbine

4.1.3 Using a downhole motor

Due to increased borehole friction when rotating the core bit from the surface will cause major problems in extended depths. Then the exclusive employment of direct bit drives is highly recommended. In order to provide the possibility of retrieving the core without tripping the string, the core barrel has to be pulled through the inner part of the motor.

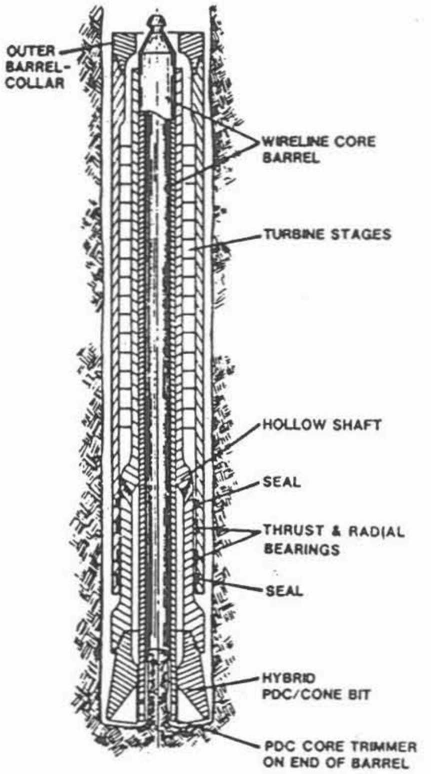


Fig. 12: Drilling turbine with hollow rotor and wireline retrievable inner barrel (Ref. 3)

Such a principle is shown in Fig. 12, where a turbine is used for driving the core bit. In order to support a free penetration of core into the inner barrel inside the rotor part, the inner barrel should be prevented from rotating. Modern double tube core barrels use ball bearings for this purpose. For systems with discontinuous core recovery, Eastman Christensen has already realized an improved embodiment. In that case, the nonrotating drill string is connected to the inner part of the motor which is also fixed to the core barrel. Thus a relative movement between core and barrel is not at all possible.

In order to facilitate core recovery without tripping the string, the inner barrel must be designed retrievable by wireline or reverse circulation. Fig. 13 shows an optimized system featuring at the same time the characteristics of

- direct bit drive
- inner barrel connected to string
- inner barrel retrievable through string for core recovery.

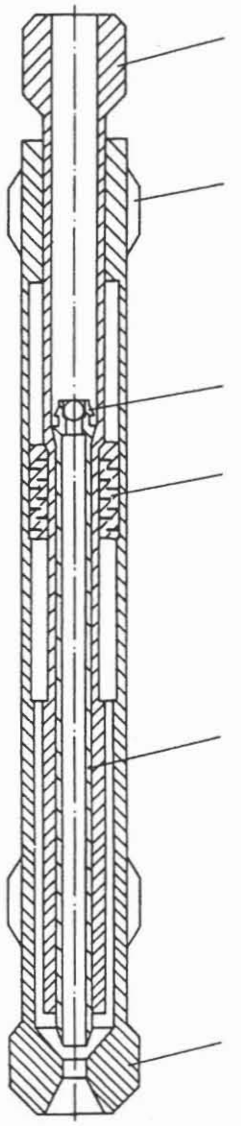


Fig. 13: Turbine corer with stationary inner part, rotating outer barrel, and retrievable inner barrel

Due to the required design dimensions, the core diameter has to be reduced as compared with the nonretrievable version. The kerf of the diamond core bit has to be increased correspondingly which, in turn, leads to a principally inferior performance.

According to the systematic overview in Fig. 7, another modification of the described embodiment might at least be considered in theory, where a second core bit is running inside the outer one. The inner core bit is driven via a planetary drive from the outer barrel at elevated speed, thus optimizing the cutting behavior with respect to both the borehole and the core. A clear disadvantage of such a system would be the required complex mechanical parts.

4.1.4 Using two downhole motors

Major advantages of a pilot coring system with downhole motor can be identified as improved core recovery and core quality. In order to enlarge this pilot hole to the original diameter, the drill string has to be rotated from the surface in a second phase of operation. This is likely to cause problems when reaching deeper or superdeep sections.

In order to overcome such trouble, the use of a downhole motor for this purpose too has to be considered. As long as the protruding inner system is under operation, the outer system would not move. Having pulled out the inner system, the outer one would be activated enlarging the hole diameter. As another modification, both systems could be put into action at the same time. Thus core recovery with the nonprotruding inner system core-drills the large diameter outer hole.

4.2 Sidewall coring systems

As mentioned already earlier when describing the state of the art, the three systems

- EC-ITE with Moineau motor and built-in whipstock
- Gearhart hard rock coring tool
- Schlumberger Diamond Core Slicer

seem to offer some potential for application in the hostile environment of the KTB crystalline rock borehole. The sidewall coring tool which was developed as far as the first prototype stage in cooperation between Eastman Christensen and Statoil of Norway offers some promising advantages over the other systems. However, it seems to be questionable whether the high development expenditure required would be justified under economic aspects with respect to the limited application with the KTB project.

The Gearhart and Schlumberger systems both are electrically driven and connected with the surface by electric cables. Therefore, the resistance in the cable will increase considerably with depth, thus requiring very high voltages to be provided. The cores retrieved with the Gearhart tool are of 24 mm diameter and 44 mm length which corresponds with a rather small rock volume of 20 cm^3. Evaluation of cores gained with the Schlumberger diamond sawing tool is rather inconvenient due to the unusual noncylindrical shape.

Therefore, one recommendation is to try the commercially available Gearhart tool on the one hand. In addition, however, a system should be further developed which fits as far as possible into the complete range of tools that is to be used for the KTB. This means in particular that the actuation of the operation should be done by the drilling mud very close to the place of coring.

From this point of view, the tool shown in Fig. 14 has to be looked at as only one of several possible embodiments featuring a

- whipstock as integral part of the drill string
- retrievable combination of diamond core bit, core barrel, and motor
- packer for settling the string in the hole.

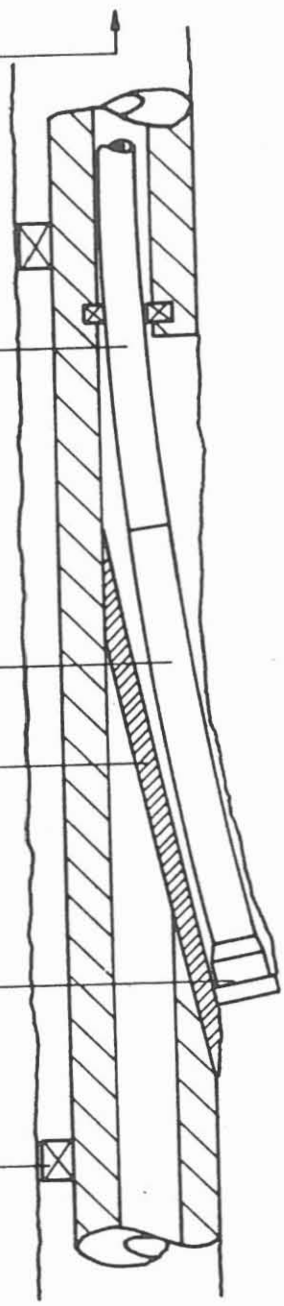


Fig. 14: Laboratory tested sidewall coring prototype tool developed by EC-ITE

The system according to Fig. 14 has been developed jointly by ITE and EC within the course of the German government subsidized development project 03E-3001-A. Weak points of the present development stage include the strength of whipstock, flexible shaft, and the operating temperature of the packer elastomer. The temperature limitation of the motor elastomer becomes critical at more extended depths, because the stator is operated under the influence of the fresh drilling mud. As an alternative, the motor itself may be integrated into the drill string. The motor would then preferably be built as a turbine.

5 REALISTIC CORING SYSTEMS DEVELOPMENT CONCEPT

By analyzing the state of the art in coring systems, the anticipated drilling environment for the KTB superdeep borehole, as well as the requirements regarding core recovery, a variety of approaches may be taken for the development of optimized systems.

A classification of different goals may be proposed with respect to corresponding sections of depth. Some of the technical problems to be expected in the upper section down to 6000 m depth are listed in Table 6.

- Mud Losses in vuggy or permeable formations
- Core jamming
- Abrupt directional changes of borehole trajectory
- Borehole temperatures up to 150°C
- Getting stuck through debris from brittle zones
- Severe rock bit wear and low footage
- Difficulties to break the core in dense and compact formations
- Core losses on bottom of the hole

Table 6: Anticipated coring problems for depths between 3000 and 6000 m

The following additional difficulties have to be taken into consideration for the 6000 to 10000 m range.

- Increased borehole temperature of up to 235°C
- Core disking due to stress relief effects
- Sedimentation of cuttings on the borehole bottom due to low mud weight
- Considerable friction between borehole wall and rotating string, especially at places of increased dogleg severity
- Damage to the borehole wall by tripping operations
- Exceeding the depth capabilities of conventional steel wirelines
- Control of coring operation badly disturbed due to extended distance from surface to bottom

Table 7: Additional coring problems for depths between 6000 and 10000 m

As regards the ultimate section of the proposed superdeep borehole down to 14000 m, additional difficulties will occur. A reduction of borehole size from 10 5/8" to 8 1/2" is likely to be required for this section of hole. Thus the number of system options will be reduced considerably. These critical parameters have to be faced in addition.

• Increased borehole temperature of up to 330 °C • Core jamming, ROP, WOB, and borehole course have to be checked by some kind of telemetry system • Operation with rotary table no longer possible • Problems regarding cuttings removal in upper sections with standard flow rates and small annulus at the core barrel • Due to extremely high stress differences, cores will be destroyed before entering the bore barrel

Table 8: Additional coring problems for depths between 10000 and 14000 m

Coring systems to be employed in these sections have to work with these problems occurring. Drilling experience from other critical environments have shown that more than one alternative coring system should be made available in case that one concept fails due to problems not foreseen.

It is then recommended that both completely new systems as well as others which are based on proven components should be included in this plan. In view of limited time and financial resources, a clear selection of key development areas has to be made.

5.1 Systems for continuous downward coring

Downward coring systems are proposed for the major part of the development work for several reasons.

- The borehole is deepened at the same time while coring
- Options to recover extended cores of 6 to 9 m length or more at a single run
- Relatively large core diameter
- Possibility of adopting comprehensive experience from spot coring of sedimentary rock in oilfield drilling and from continuous coring operations in mining drilling
- Options to gain oriented cores.

Continuous coring systems should be preferred over discontinuous systems for several reasons.

- Improved overall economy through core recovery without roundtrip of string
- Saving of additional roundtrips in case of jammed core

- Integration of wireline or cable measuring system
- Adaptation of special retrievable inner core barrels to optimize core quality

In view of the hostile environment encountered in deep crystalline boreholes, major emphasis must be placed on designing sturdy and reliable coring systems.

5.1.1 Basic assumptions for development

On the basis of the above mentioned know-how, some basic assumptions will be defined which will later on lead to the proposal of a development project.

- Roller cone bits with TC inserts provide a fair penetration rate.
- The footage of roller cone core bits has been improved considerably in the past. Potential for further improvement remains.
- Diamond core bits are a promising tool with respect to core recovery and core quality.
- Roller bits have to be run at low RPM (n <120 min^{-1}) while diamond tools should be operated at elevated cutting speeds (v = 2 - 4 m/s).
- A wireline is employed for transportation of core or core barrel to the surface.
- The importance of downhole motors increases with depth due to several reasons.
- Positive displacement motors based on the Moineau principle have limited depth capabilities due to temperature limitations of the elastomer stator. The critical depth may be raised to higher values if the motor is used only inside the drill string under the influence of fresh mud.
- The drill string run in the 10 5/8" borehole offers a minimum passage diameter of 4" (1016 mm).

In addition, a close contact of all parties involved in the development or planning of other equipment such as drill rig, drill string, mud pumps, etc. is essential for the optimum design of continuous coring systems.

5.1.2 Proposed development subjects

The proposed development project does not include improvement of discontinuous systems which might turn out to be desirable within the course of drilling the hole. Also, the aspired increase of ROP and footage with diamond and roller cone bits will not be considered here.

One basic condition for designing continuous coring systems effectively is an inner diameter as large as possible. The development concept will first have to concentrate on the 10 5/8" diameter section according to the well planning in Fig. 1. This diameter is planned for the depth between 5000 and 10000 m. The hole would be deepened further with this diameter if technically feasible. A minimum inner diameter of 4" (101.6 mm) serves as an important design parameter for many of the proposed systems.

A wireline is planned to be used to retrieve the core to the surface. Systems operating on the reverse circulation principle may be built as an additional design option. Conventional steel wirelines do not offer the strength required for extreme depths. A new concept therefore has to be developed. Possible options include the employment of alternative materials, e.g. high strength plastics, or nonconventional geometries, e.g. tapered steel wirelines with reduced diameter and weight in the lower sections. As regards synthetic materials, such as KEVLAR (Du Pont), certain temperature limitations have to be considered. When designing a new wireline, an electrical conductor line might be included for data transmission purposes.

Coring tools for the 10 5/8" borehole diameter

Due to the effective rock destruction mechanism in crystalline rock, the roller cone core bit has to be included in every development plan. Some experience, although from shallower depths, was gained in the upper section of the KTB pilot hole. Results from the Gravberg-1 well in Sweden confirm that the core recovery has to be considered as very critical, especially with greater depths.

It is therefore recommended to follow up on a development by steps which is based on the employment of a roller cone core bit according to Table 9. This comprehensive system reflects the accepted superior quality of the diamond coring process.

- Core barrel with roller cone core bit 10 5/8" x 3 1/4", inner barrel with outer diameter below 100 mm is wireline retrievable througho, the string
- Core barrel with 10 5/8" roller core bit is wireline retrievable. Pilot coring system consists of diamond core bit size 100 mm x 61 mm, mining core barrel HWD4, and modified 3 3/4" Moineau motor
- System as described above, however, inner core barrel protrudes at a certain angle for directional correction operations
- Core barrel with roller bit 10 5/8" x 3 1/4" is driven by 8 1/2" Moineau motor, inner barrel, and non-rotating inner motor part are wireline retrievable

Table 9: Continuous coring system for roller core bit and 10 5/8"

The basic design will feature a double tube core barrel for roller bits with wireline retrievable inner barrel as known from the mining wireline diamond coring technique. A diamond core bit may be used instead of the roller tool. If the core quality proves to be lower than expected, a hybrid system combining both the advantages of diamond and roller coring should be employed. A modified version of this type of tool would also probably be applicable for directional drilling while coring at the same time.

Having reached certain depths, it might be worthwhile to rotate the string only at reduced speed for the purpose of minimizing friction and wear. It is now proposed to use a downhole motor with low RPM characteristics which drives an outer barrel with retrievable inner core barrel (Fig. 15) connected with the motor shaft.

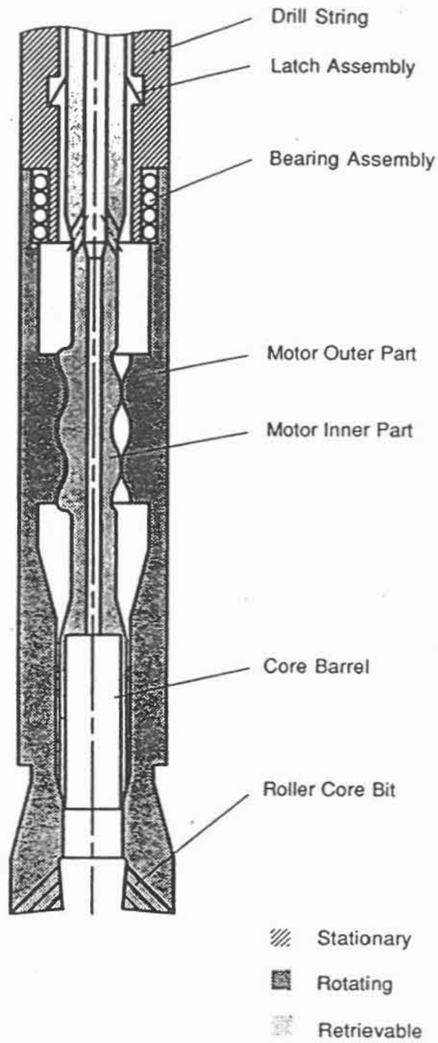


Fig. 15: Motor coring system with retrievable inner barrel and motor shaft

The combination of motor shaft and inner barrel is pulled out of the hole on the wireline for core recovery. Inner barrel and motor shaft are nonrotating.

Diamond coring would be an alternative to operation with roller tools. The core barrel might be rotated by a turbine at elevated speed which will lead to the well known advantages of diamond coring. A summary of the most important key data of such a device is given in Table 10.

Coring principle	Rotating turbine outer tube with diamond core bit and wireline retrievable inner barrel inside a non-rotating turbine shaft
Hole diameter of turbine shaft	101.6 mm (4")
Core bit	Diamond core bit 10 5/8" x 3 3/8" (270 x 86 mm)
Kerf of core bit	92 mm thickness, 515 cm^2 kerf area
Turbine	8 1/2" turbine having RPM of 887 1/min and T = 2964 Nm at a flow rate of 2400 l/min

Table 10: Continuous diamond coring system with turbine for 10 5/8" borehole

The basic design would also allow to run a pilot coring system inside the hollow turbine shaft. This measure might prove to be justified if the core recovery with the full size coring tool becomes critical due to formation problems. If the coring turbine should have to be used with roller core bits, a considerable reduction of RPM would be required.

Coring systems for 8 1/2" borehole sizes

The proposed concept for continuously coring the 8 1/2" section is strongly affected by the reduced dimensions, thus leading to solutions different to those for the 10 5/8" range. Realizing a wireline retrievable pilot coring system, for example, would mean a too high expenditure. The availability of reliable roller core bits of the size is rather doubtful. Also, driving the core bit from the surface has to be looked upon as a critical method. On the other hand, the small diameter is favorable for running diamond tools under technical as well as economic aspects.

Taking into consideration the working conditions as known today, the development of a turbine coring system is proposed. Due to economic reasons as many components as possible from already existing equipment should be utilized for this purpose. A retrievable inner barrel shall be run inside the hollow rotor of a 7 1/4" turbine. The most important system parameters of such a tool are given in Table 11.

Coring principle	Rotating turbine outer tube with diamond core bit and wireline retrievable inner barrel inside a non-rotating turbine shaft
Hole diameter of turbine shaft	101.6 mm (4")
Core bit	Diamond core bit 8 1/2" x 1.875" (215.9 x 47.62 mm)
Kerf of core bit	77 mm thickness, 307 cm^2 kerf area
Turbine	7 1/4" turbine having RPM of 790 1/min and nominal T = 3000 Nm

Table 11: Continuous diamond coring system with turbine for 8 1/2" borehole size

The inner barrel having a maximum outer diameter of 71.4 mm has to pass through the tapered string in th 8 1/2" section of the hole. Therefore, a minimum inner diameter of 3" (76 mm) should be provided here. Diamond core bits have to be optimized with respect to ROP and, more importantly, footage. The combination of these features

- high RPM
- diamond core bit
- integral connection of motor and core barrel

provides the optimum conditions for core recovery at extreme depths.

5.2 Sidewall coring systems

Presently available commercial systems have already been discussed earlier. This overview has shown that virtually only one of these, the Gearhart tool, offers the possibility of sidewall coring with crystalline rock without additional development expenditures. However, clear limitations exist with respect to the dimensions of the core as well as the depth capability. Further improvement of this system does not seem recommendable, because of fundamental disadvantages of the drive system.

With respect to the foreseeable development potential, the mud driven downhole motor with connected core barrel should be given preference. The combination of diamond core bit, core barrel, and motor is forced to penetrate the formation via an inclined plane (whipstock). Apart from the PDM, also a turbine shall be used for actuation which would offer an extended depth capacity. Several embodiments of this basic principle should be taken into consideration. If a decision has been made in favor of following up this kind of sidewall coring system, it has to be decided whether the already existing laboratory prototype by EC-ITE shall be improved or development of a modified concept is preferred.

6 KTB CORING PROJECT PLANNING

One major goal of the evaluation of development options performed above has been to preliminarily determine major guidelines to be followed in the process of developing adequate coring systems in hardware. A final decision on this subject has to be made by the KTB project group after consulting technical and drilling specialists from the industry and scientific organizations.

The overall goal is to provide coring systems which are capable of retrieving cores from the KTB superdeep well over about 1/3 of the section which has not been cored before in the pilot well. One major requirement has been that downward as well as sidewall coring systems should operate on a continuous basis. No tripping of the string is required for retrieving the core samples to the surface.

The hardware development planning for such systems is in the center of interest of this report. However, there are other challenges in connection with the coring and drilling operations that will also have to be considered before and during the development of the continuous systems. These are, amongst others, the need for drilling or coring a trajectory as vertical as possible, the employment of hammer drilling systems including combinations with coring systems, and the development of new downhole measuring and control technologies.

The plan for the development of continuous coring tools reflects the minimum required. The different components have ben planned in such a way that a high degree of compatibility is achieved. Additional items would require also an extension of the proposed budget. If borehole sizes drop below the 8 1/2" diameter, no continuous systems should be developed.

Basic systems as shown in Fig. 16 are now proposed for development.

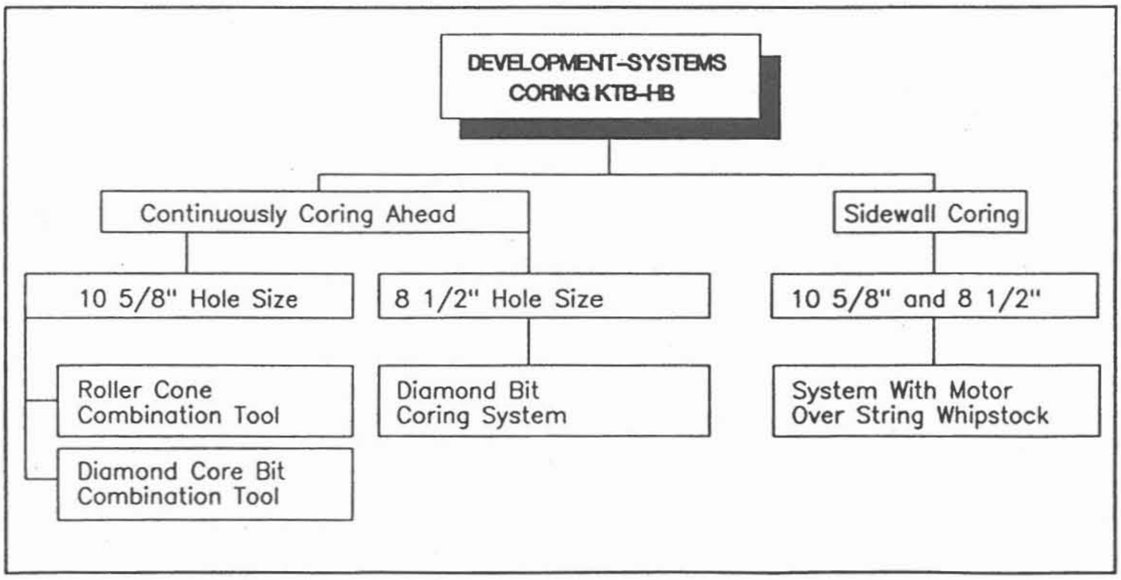


Fig. 16: Continuous coring systems for KTB superdeep well

The separate components considered important for this development are shown in Table 12. Items marked with priority "a" shall form the central development program for downward and sidewall coring systems while options for possible additions are marked by characters "b" or "c".

Item	Component	Priority
1	High strength wireline with 14000 m ultimate depth capacity	a
2	CB with retrievable inner barrel for RC 10 5/8" x 3 1/4"	a
3	same as item 2, but RC 10 5/8" x 4" and pilot coring motor 3 3/4" PDM with DC 100 x 61 mm	a
4	as item 3, but 3 3/4" turbine instead of PDM	c
5	as item 3, but inner system protruding over inclined plane for correction work	b
6	as item 2, but PDM for driving the CB	a
7	8 1/2" TURB with 10 578" x 3 3/8" DC and retrievable inner barrel	b
8	as item 7, but pilot coring system 3 3/8" instead of retrievable inner barrel	b
9	as item 7, but TURB and reduction gear and RC	c
10	7 1/4" TURB with hollow rotor and retrievable inner barrel, DC 8 1/2" x 1.875"	a
11	Sidewall coring tool, protruding on inclined plane, with PDM	a
12	as item 11, but stationary TURB instead of PDM	b

CB	Core Barrel
RC	Roller cone core bit
PDM	Positive displacement motor
DC	Diamond core bit
TURB	Drilling Turbine

Table 12: Development components

A preliminary time schedule for conducting the minimum expenditure development work characterized is shown in Fig. 17.

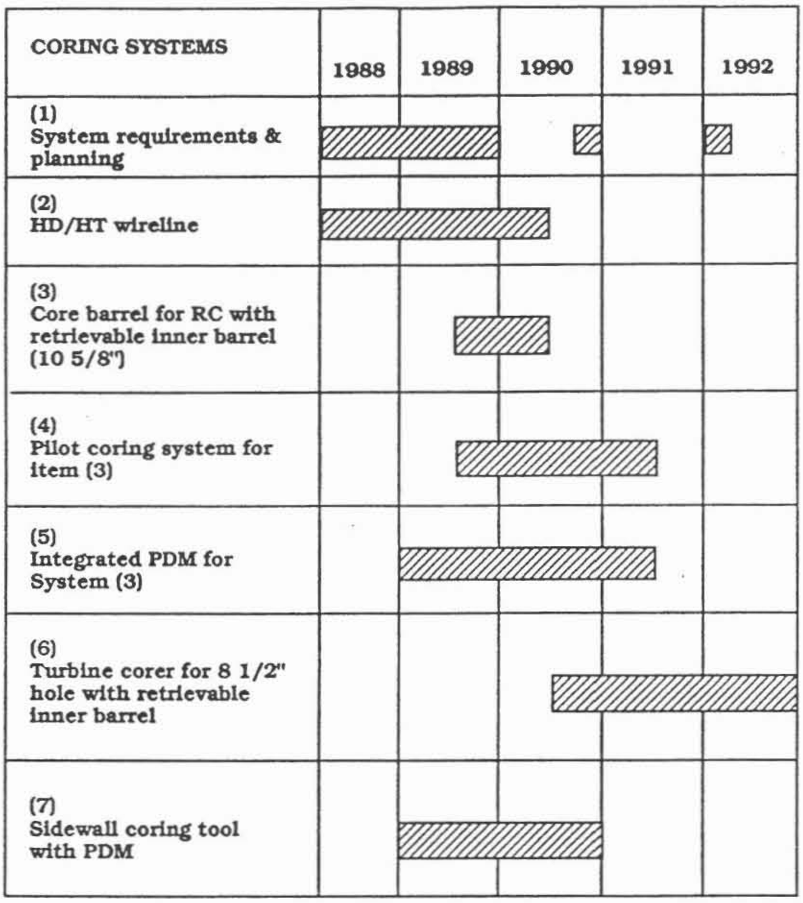


Fig. 17: Schedule for coring systems development

Item (1) mainly calls for the detailed determination of system requirements and consideration of related challenges such as vertical hole drilling and coring. The availability of an adequate wireline is essential for any great depth continuous coring system. In order to be able to start continuous coring after having drilled the upper section of the hole, a core barrel for roller cone core bits with retrievable inner barrel will be developed. Major effort has to be put into the improvement of the penetration process of core into the inner tube. Already during this stage the planned development of retrievable pilot motor coring systems has to be considered. Some preliminary experience with such systems already exists at Eastman Christensen Company. Patent protection is provided for certain embodiments of this principle (Ref. 9).

The systems mentioned up until now are all actuated from the surface. However, the application of downhole motors is often preferred for medium and large depths. Development item (5) therefore features a 8 1/2" Moineau motor with retrievable inner barrel and rotor.

For the 8 1/2" section, a turbine corer with a wireline retrievable inner barrel should be developed due to the high temperature environment.

A major area of application for sidewall coring tools is anticipated to occur in the upper section of the hole where no downward coring runs are planned. A definite decision should be made after further discussion whether to develop a system based on the PDM or the turbine. The latter would also offer the possibility for use in deeper sections of the hole at elevated temperatures. If the turbine stages are mounted within the downhole drill collar, only the inner barrel would have to be retrieved after each operation cycle on wireline. In view of a broad application this tool should be designed for use both in the 10 5/8" (or larger) and the 8 1/2" sections.

7 CONCLUSION

Coring of extensive borehole sections is a major challenge for the drilling of the KTB superdeep hole which is going to be spudded late 1990. However, the coring requirements have to be considered also in view of the absolute necessity for drilling the hole as vertical as possible.

Presently no coring systems exist for the required borehole diameter which provide the opportunity to retrieve the core sample without tripping the whole string. Experience is available only from mining drilling where smaller diameters are applied in shallow holes and, more recently, from the KTB pilot hole. The anticipated total depth of the scientific KTB project and the behavior of the rock formations present additional challenges.

For the recovery of small cores from the wall of the open hole, only one tool is presently commercially available. Relatively small core dimensions, system reliability which is not altogether satisfying, and limited depth capability have to be mentioned as disadvantages with respect to this tool.

After evaluation of the anticipated borehole conditions as well a summarizing the existing experience with coring hard or crystalline rock, possible development directions have been presented.

Major subjects of a realistic development concept for the 10 5/8" hole diameter include roller cone coring systems with or without downhole motor and hybrid systems with a small diameter pilot core barrel and a diamond core bit located in the bottom drill collar.

Regarding the proposed 8 1/2" diameter lower hole section, development emphasis should be concentrated mainly on a turbine coring system (turbo-corer) with diamond core bit and hollow rotor for storing the rock sample.

For taking samples from the borehole wall, the development work should follow the principle of incorporating a motor driven tool which penetrates the formation by drilling along a drill string integrated whipstock. Such a system offers some advantages with respect to simplicity of parts and components over tools which cut into the wall at an angle of 90 degrees.

All systems generally are based upon the application of a steel or plastic wireline to recover the rock sample to the surface. This basic component also needs development. All proposed systems utilize the drilling mud for torque generation, if the string is not rotated from the surface.

This program is strictly limited to the development of continuous systems for coring ahead or into the borehole wall. The presented schedule does not include downhole measuring systems for fluid downhole hammers which are looked upon a supporting the crystalline rock destruction process effectively.

When establishing this development program, existing core barrel and downhole motor equipment have been taken into account in order to enhance compatibility and to reduce additional expenditure.

8 LITERATURE

NOEVIG; T. (1977): Status report on coring procedures in deep-drilling technology. Project report, Energy research and development program - Technische Universität Clausthal

MARX, C. AND YOUNG, F. (1983): Darstellung von Kerngewinnungsverfahren und Bewertung ihrer Einsatzmöglichkeiten in übertiefen Bohrungen, Clausthal

ROWLEY, J.C. (1985): Coring technologies for scientific drilling projects - an overview, Los Alamos National Laboratory, Report No. LA 10485-OBES

OPPELT, J. (1987): Studie Vorbohrung KTB-Bergbautechnik, Eastman Christensen GmbH, at the request of KTB-Projektleitung

WOHLGEMUTH, L. (1987): Personal communication, KTB-Projektleitung

KOZLOVSKY, Y.A. (1987): The superdeep well of the Kola peninsula, Springer Verlag (Original Edition Moscow, 1984)

MAURY, Y.M. and SANZAY, J.-M. (1987): Borehole Instability: Case Histories Rock Mechanics Approach and Results - SPE/IADC Paper No. 16051 - Drilling Conference, New Orleans, Louisiana

KRÜGER, V. AND DAENICKE, H. (1988): Studie Untertageantriebe, Eastman Christensen GmbH, NLfB, Project AZK/15-RG 86040

OSTERTAG, A. and BIEHL, J. (1987): DE 3,701,914 "Direktangetriebenes Kernbohrwerkzeug" - Eastman Christensen patent