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Continuous Coring of the KTB Pilot Hole: A Case History

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ABSTRACT

The German Continental Deep Drilling Program (KTB) was initiated in 1987 to investigate the physical and chemical conditions and processes of the deep continental crust. Involving participation of several hundred scientists and technicians, the program comprises drilling a pilot hole of 3000 to 5000m depth, and a superdeep borehole to a planned target depth of 10,000 to 14,000m in the Oberpfalz region of northeastern Bavaria during 1987-97.

The drill site for both holes is located in a complex geology at the junction of the Moldanubian and Saxothuringian zones. Downhole temperatures in excess of 300 degrees C. are expected. To meet the geoscientific requirements under financial and time constraints, a pilot hole with a planned depth of 3000 to 5000m was be cored prior to beginning the superdeep hole.

The pilot hole provides means of gathering geoscientific data, analyses of the temperature profile, minimization of core runs and borehole measurements in the ultradeep hole over the section of the pilot hole, obtaining data about problem sections such as water inflow or lost circulation zones and their corresponding pressure gradients, and testing of drilling and logging tools for the ultradeep borehole.

Sufficient depth capacity, borehole diameter, and continuous coring capability were established as major requirements for the pilot hole. Also in view of optimum scientific data gathering, it was determined that a combination of rotary drilling and wireline coring techniques would provide the best method for realizing program standards. To apply the wireline coring technique to a maximum depth of 5000m in the 6" diameter pilot hole, it was necessary to develop and manufacture an entirely new drillstring and coring system, which provides the focus of this paper.

In September 1987, the pilot hole was spudded approximately 200m from the planned location of the superdeep hole. The operation was successfully completed on April 4, 1989, employing the newly developed coring system to a total depth of 4001.1m with a 98% core recovery rate.

INTRODUCTION

In addition to the primary goal of drilling the superdeep hole, core recovery from subsurface formations was determined to be of major importance to the KTB drilling operation. The core samples will be analyzed in an effort to gain the most information about the downhole rock environment.

Although many other methods for investigating the deep borehole sections have been established, such as downhole logging or mud analysis, coring still offers the most comprehensive way of investigating the earth.

The KTB Continental Deep Drilling Project (Kontinetale Tiefbohrung der Bundesrepublik Deutschland) very much focuses on the discovery of the deep continental crust through coring. During the very early planning stages for the project, careful planning of coring and other drilling operations was determined to be a basic requirement for meeting the geoscientific goals.

As a consequence, prior to such an operation, the availability of the required methods had to be examined. KTB operation and geoscientific management both realized that special means and methods had to be developed in order to reach project goals.

GEOSCIENTIFIC GOAL OF THE KTB PROJECT

The KTB is a project of basic geoscientific research, with program goals set by a board of the Senate Commission on Geosciences of the German Research Foundation (Deutsche Forschungsgemeinschaft DFG). A budget of 450 Mill. DEM has been approved by the Federal Ministry of Research and Development (BMFT).

Through this key experiment in a series of research projects dealing with the physical structure, chemical composition, and geological-structural evolution of the Central European crust, the scientific project management expects to gain a better understanding of the dynamics of intracontinental structural evolution. Scientific targets include a deeper insight into origin and cause of geophysical anomalies, physical and chemical in-situ conditions, fluid systems and their influence on the upper crust, geophysical structures and crust evolution, as well as the installation of the deep earth laboratory for long term testing.

During a very comprehensive and long-term investigation, two locations were determined as possible sites for the KTB superdeep project: the Oberpfalz and the Schwarzwald areas. There are substantial differences between these two basement complexes, both of which hold major interest for the international geoscientific community. A final decision was made in favor of the Oberpfalz drill site due to the more interesting geological situation:

The site of the KTB is located on the western margin of the Bohemian Massif, a few kilometers south of the structurally significant Saxothuringian Moldanubian boundary of the Central European Hercynian orogene, and several kilometers east of one of the most important permian mesozoic strike slip zones of Central Europe, the Franconian line. The borehole will be drilled in the Moldanubian segment.

With respect to today's political landscape, the drill site is located in the Oberpfalz region of Northern Bavaria, near the town of Windischeschenbach, about 40 kilometers southeast of Bayreuth. (Figure 1)

A very detailed mapping and geological analysis of surface geology and sedimentary cover in Central Europe has been established, and now will be enhanced by cutting a "window" through the earth's crust at the selected site. Although the borehole will only offer a limited view through the present upper crust, accompanying projects will extend the 10,000 to 14,000m drill profile to about 35,000m depth through indirect investigation.

The planned deep borehole of 10,000 to 14,000m depth will penetrate high grade metamorphic crystalline rocks with intruded granites, and will certainly encounter large ductile and vertically deformed zones. A very comprehensive logging program will be established to the bottom of the hole. Also, a long open hole section at the bottom will serve as the long-term measuring observatory.

The center of interest, however is maximum recovery of cores from the downhole formations. Overall, the geoscientific targets of KTB present an outstanding challenge with respect to the drilling and coring technology.

PILOT HOLE DRILLING CONCEPT

KTB PPROJECT MANAGEMENT FUNDAMENTALS

The KTB drilling operational concept is based on several different resources, among which are the geoscientific project goals: results of geophysical, geological, and geochemical drill site exploration; and national as well as international experience in comparable projects.

The KTB is subsidized to a large degree by the German Ministry of Research and Technology (BMFT), while the German Research Foundation (DFG) holds responsibility for the geoscientific aspects of the project. The KTB Technical Management, which was established in 1985 at the Lower Saxony Geological Survey in Hannover, holds responsibility for planning and performing drilling and coring operations, and serves as functional coordinator at the rig site.

The KTB management in Hannover recognized from the beginning its responsibility for providing geoscientists with rock samples from the site as soon as possible. However, preliminary feasibility studies showed that major technical development work would be necessary to meet the goal of drilling and coring a superdeep borehole in crystalline rock. Therefore, in 1986, a decision was made to drill two wells in proximity to one another at the location. The first, the "pilot hole," would be continuously cored from the surface to total depth using a drill diameter of about 6". Drilling the pilot hole would provide sufficient time for planning the superdeep well, as well as for developing the required drilling and measuring tools.

The total depth of 3000m to 5000m was held to be reasonable for the pilot hole. In addition to recovery of cores from every meter drilled, the pilot hole operation would provide comprehensive information on special formation problems which may have bearing on the planning of the superdeep borehole. Other technical and scientific gains of the pilot hole operation are listed in Table 1.

KTB Operation Management at the Lower Saxony Geological Survey in 1987, contracted Eastman Christensen GmbH of Celle, Germany, to investigate several drilling and coring alternatives for the KTB pilot hole. Coring techniques were evaluated with respect to technical and economic optimization in view of the KTB requirements. Also, the available performance data of drilling in crystalline rock had to be collected.

This study was conducted in close cooperation with three drilling companies: ITAG of Celle for rotary drilling experience; Gewerkschaft Walter of Essen with respect to mining wireline coring; and Microdrill of Grabo, Sweden, for slimhole coring operations. In view of a required hole diameter of about 6", and total core depth of 3000-5000m, a major decision had to be made whether to apply conventional rotary drilling and coring techniques, or a somewhat modified mining coring methods. (Figure 2)

Remarkably reduced operating costs, much improved core recovery and clearly greater flexibility with respect to core blocking problems were identified as major advantages of wireline coring techniques. On the basis of these conclusions, KTB management decided to use a combination of rotary and mining coring techniques for the pilot hole operation. The upper section of about 400m would be drilled with rotary techniques in a hole diameter of 10-5/8". After casing was set to this depth, an open hole would be drilled to TD with a wireline mining coring system. (Figure 3)

To save time and money, the smallest borehole diameter possible was selected to reach the specified TD of 3000-5000m. On the other hand, in view of available logging tools, a certain minimum hole diameter was necessary. Discussions between drilling management and geoscientists within KTB led to the decision to drill a 6" (152.4mm) diameter hole.

Next, comprehensive market research was conducted by KTB to find a wireline coring drill string and core barrel which met requirements regarding borehole diameter and depth capability, and mechanical strength. As an additional requirement, an externally flush rod design had been set up. The equipment to be used for the pilot hole operation had to comply with requirements listed in Table 2.

As no appropriate tools existed, major drilling service companies were invited to submit proposals for development of such equipment, qualified with respect to technical performance and delivery cost. Due to the technical advantages of the proposed system, Eastman Christensen GmbH received the order to lay out and manufacture the drill string for a planned pilot hole spud date in September, 1987.

PILOT HOLE OPERATION EQUIPMENT

There are major differences between conventional rotary drilling and mining drilling rods. (Figure 4) The drill pipe used in rotary drilling typically employs a tool joint with internal and external upsets which provide high strength for extended depths. Usually, a full hole diameter is cut; and only seldom are cores taken. In these circumstances, a wide kerfed core bit is required to cut the spaces necessary for the tool joint. Within a given hole diameter, only a small size core can be cut, while a relatively large area of rock is destroyed.

As the functional basis of the wireline drill string, enough space must be provided within the tool joints to recover the inner tube with core sample. Thus, only a relatively small internal upset can be allowed.

Also, wireline drill strings are typically operated at relatively high speeds. Performance is improved if the annular space between drill string and borehole wall is reduced, as in an externally flush design. The measures result in a much smaller kerf of the core bit than is possible with rotary drilling drill pipes. In our example, the area to be destroyed with the wireline system can be reduced to about 1/5 the equivalent area in the rotary technique. This will typically lead to higher penetration rates and longer bit life when drilling in hard crystalline rock.

In addition to drilling string and core barrel, items of major importance to the coring operation are drill rig and drilling mud, both of which are briefly described later.

KTB-EC WIRELINE DRILL PIPE AND CORING SYSTEM

The drill string and coring system clearly comprise the equipment most essential to the success of the entire coring operation. Based on the technical requirements outlined by KTB management, Eastman Christensen proposed several drill string design alternatives -- the major differences being in details of the shape of the tool joints between the rods.

As mentioned, the decision was made to have an externally flush design with slight internal upsets. Given the 6" hole diameter, a pipe outer diameter (OD) of 5-1/2" was selected which produces an annular space of 1/4" on both sides of the pipe. Drillpipe optimization was achieved with respect to maximum load, or depth capacity, and minimum kerf/maximum core diameter. Through careful selection of materials, and layout of a special thread design to improve operating conditions under the extended depth environment, drill collars, which are essentially heavy weight drill rods, were manufactured.

KTB/EC wireline drill collars have one uniform inner diameter (ID) from top to bottom which corresponds to the ID of the tool joints. While common to oilfield rotary drilling, this is an unusual measure for the mining drilling industry. Also, the length of one drill pipe or drill collar corresponds to that of oilfield tubulars, which is 9m or 30 feet.

There are two advantages in using the 9m length rather than 6m or 3m. One is that fewer connections mean fewer potential failures, especially in view of the fact that pipe stands of about 27m can be stored on the rig floor without problems. The decision to have 9m lengths also was supported by the results of a vibration analysis; at the expected 250 to 320 rpm, the occurrence of eigenfrequencies could be best avoided using the 9m length. (Figure 5)

The mechanical load capacity of the wireline drill pipe was calculated with the assumption that a maximum of 20 pieces of drill collar are connected to the drill pipe on bottom. Buoyancy effect has not been considered. Drill pipe with a wall thickness of 7.1 mm has a weight of 25 kg/m. Drill collars have a weight of about 44 kg/m with a wall thickness of 14 mm. Major dimensions and design parameters are listed in Table 3.

Wireline drill collars were manufactured integrally, while the wireline drill pipe tool joints, pin and box were completed separately, then friction-welded to the pipe body. For increased wear protection, drill pipes and collars were provided with a hardfacing. The drill collar has one band each on the pin and the box, while the wireline drill pipe has one band on the box.

For durability under dynamic loading, the distribution of specific forces within a single thread connection was thoroughly investigated by using the inhouse finite element analysis tool. Optimization ultimately was achieved by providing the pin of each thread connection with a non-uniform pitch. (Figure 6)

The calculated values of mechanical strength were checked through various laboratory tests prior to sending the rods to the drill site.

The design of the wireline core barrel was directly influenced by the smallest ID, or drift diameter, previously calculated for tool joints of wireline drill pipes. Taking into account the ID of 110mm, and the required wall thickness of the retrievable core barrel inner tube, as well as annular space for the landing ring etc., an effective core diameter of 94mm was determined optimal.

The design is based primarily on Christensen's well-proven wireline mining core barrels, with some additional features added. (Figure 7)

The outer barrel has two outside stabilizers with tungsten carbide hardfacing. An alternative near-bit stabilizer was made with diamonds. The maximum retrievable core length is 6m. A special all-metal core blocking indicator is provided. On jamming of the rock samples in the inner barrel, a flow channel within the core barrel is restricted to a certain extent, thus leading to a pressure increase of about 15 bar at the surface. The inner barrel can then be tripped without delay.

An electronic sensing and recording unit is installed in the small compartment directly above the core storage room within the inner barrel assembly. This system is initialized on the surface by a personal computer and afterwards, is sent downhole inside the inner barrel. At predetermined intervals measurements are taken for inclination, tool face orientation, and temperature. Readout of data is arranged after recovery of the inner barrel by reconnecting the system to the PC. Information on the core measuring system is given in Table 4.

Included with the system is a user-friendly PC software program which correlates the measurements with the actual depth of borehole, and allows manipulation of data as required. The system proved to be especially useful when operating in the core-orientation mode.

For this purpose, the inner tube shoe is equipped with three knives which are especially suited to the hard rock. The "high side" orientation is accomplished with the running electronic tool before tripping the inner barrel system downhole. Three grooves are then cut into the core as it enters the inner barrel. (Figure 8)

Recorded measurements of relative bearing orientation and scribe marks are later correlated to regular tool orientation measurements taken in the open hole.

The lower end of the core barrel is connected to a diamond core bit which was, in most cases, an impregnated type.

DRILL RIG INSTALLATION AND MUD SYSTEM

To provide optimum operating conditions, an oilfield rotary rig was adapted to the requirements of wireline drilling. The rig GH 1400 E was contracted by KTB from DST (Deutsche Schachtbauand Tiefbohrgesellschaft). This rig has a nominal hook load capacity of 2040 kN. All major components are electrically driven by energy from the public power network. A racking capacity of 5000m of 5-1/2" drill pipe is available.

This rig has been furnished with an hydraulic top drive system giving a rotational speed of 300 rpm with simultaneous torque capacity of 11,000 Nm. By upgrading the top drive, a torque capacity of 13,000 Nm ultimately was provided. The brake may be automatically operated, either for constant weight on bit, or constant rate of penetration. (Table 5)

In addition, the rig is equipped with sensors which automatically monitor drilling parameters such as depth, rpm, weight on bit, pump pressure, and so on. This data is sent simultaneously to a main frame computer and an on-line rig site "local area terminal network." This way, the actual drilling parameters can be monitored simultaneously by the driller on the rig floor, the supervisor of the contracting company, the KTB operating management, and other personnel.

Altogether, the computer system registers and operates nearly 100 different measures, about 1/3 of which are the so-called "mud logging parameters," including the technical drilling data mentioned above. Approximately 20 measures are taken of the chemical composition of the drilling mud. The remaining 30 measurements refer to the determination of solids content in the mud, with the system for non-air contaminated mud gas analysis currently still in testing.

DRILLING MUD

A totally new fluid system was used which has a silicotic structure, and is composed primarily of silicium, magnesium, natrium, lithium and oxygen. One major requirement of the geoscientific project management was use of a drilling fluid which would not hinder the geochemical analysis of the mud with respect to its loading with subsurface chemicals. The basic product was developed by Henkel Co., and was made available for its first commercial application through the cooperation of Henkel, NL Baroid, and KTB.

Due to its completely inorganic composition, this particular component system provides excellent conditions for geochemical investigation. (Table 6)

During most operating time, a concentration of 1 wt % of Dehydril additive was added to the drilling water. To increase the specific weight, the concentration was increased to 2% in early 1989.

One of the most remarkable features of this drilling mud is its unusual thixotropic rheological behavior: Motionless, the mud exhibits a clear gel structure which offers good carrying capacity for cuttings. With any movement, such as drill string rotation, the effective viscosity is reduced extensively. Typical mud properties of an actual KTB drilling fluid system are given in Table 7.

Effective lubrication proved to be another advantage of this unconventional mud system. And because no environmental impairment is possible, the simple inorganic composition affords very easy handling and disposal.

CORING AND DRILLING OPERATION

The KTB pilot hole operation started on September 22, 1987, and was successfully completed on 4 April 1989, at a total depth of 4,000.1m.

The primary initial task was to core the hole completely from the surface to total depth. The upper section to 480m was cored with roller cone core bits, while diamond core bits were used for subsequent sections to total depth. To compensate for unwanted hole inclination build up, three directional control operations were required. Twice, borehole problems occurred which required partial cementation of the hole and drilling a new hole along a whipstock.

ROLLER CONE CORING OF SURFACE SECTION

With the 17-1/2" diameter surface hole drilled to 27.4m, 13-3/8" conductor pipe was run to this depth and cemented. On 25 September 1987, coring began using roller cone core bits of 10-5/8" OD, and a standard 8-1/4" x 4" NL double-tube core barrel. A total of nine bits were used for this section, five of which were 6-cone core bits manufactured by Security, and four of which were 4-cone core bits by RBI. (Figure 9)

This section was completed after 450.4m at a total depth of 478.5m, with a total core recovery of 193.5m. Major complications with respect to core recovery were observed, particularly from the surface to about 300m, where fragmented and brittle formations occurred. Drilling parameters are given in Table 8.

Between 330 and 478.5m, a relatively stable formation was encountered which increased average core recovery to nearly 80%. Operating time of core bits was limited primarily by worn cutters rather than by destroyed bearings. No distinct differences were observed between performances of the two core bit designs, although the RBI bits achieved slightly increased footages. Due to the limited number of total runs and consistently changing formation conditions, however, no clear conclusions can be drawn.

On 12 November 1987, at 478.5m TVD, an 8-5/8" K-55/32 lbs. anchor casing was run to depth and cemented. In addition, a 7" retrievable guide casing was hung into the anchor casing to a depth of 479.5m. This protective casing, which shields the anchor casing against wear during tripping, can be exchanged if worn; or, in case of severe hole problems below the casing shoe, can be withdrawn to allow a larger borehole diameter to be drilled.

On November 14, 1987, wireline coring with diamond core bits began. The coring operation commenced out of 7" casing, providing the same hydraulic conditions to the wireline drill string as the 6" open hole diameter. From here, the KTB-EC wireline drill pipe and drill collar, together with special core barrels, were used as described earlier. Typical operating parameters for this phase are given in Table 9.

A total of 69 6" x 94mm diamond core bits were used. Nine of these were surface set, and were used mainly in the upper section to about 980m. Diamond impregnated core bits were supplied by Eastman Christensen and Longyear.

During the course of the study on pilot hole coring methods, a footage of 20m was found to be a common measure, whereas 40 to 50m was held to be achievable with further development. An acceptable rate of penetration was 1.1 m/h.

At Eastman Christensen's comprehensive laboratory, testing and improvement work commenced far in advance of the KTB pilot hole operation, thus raising the standard of performance accordingly. Continuous improvement and development work also took place during the pilot hole operation, resulting in sophisticated core bit designs such as the one shown in Figure 10.

In this advanced core bit, 12 impregnated segments are bonded to the bit body. The height of these segments was increased to 18mm during the improvement phase. Synthetic diamonds mixed into the matrix have a grain size of about 32 to 50 mesh. Triangular synthetic diamond cutters also are set so as to protect the inner and outer gage against premature wear. The active cutting area of one of these core bits amounts to 49 cm^2, which is equivalent to about 50% of the area to be destroyed.

The KTB-EC wireline operation was terminated on February 6, 1989, at a depth of 3893m when the drill pipe became stuck and the tool joint pin broke. A total section of 3142.6m had been cored with a total core length of 3074.74m, resulting in an average recovery rate of 97.84%. (Table 10)

No cores could be taken during directional control or milling work using full-hole tools. When coring with the KTB-EC wireline coring system and diamond core bits, core recovery was close to 100%. During the course of the pilot hole operation, considerable time was also spent performing borehole logging and other measuring activities. Table 11 gives the general progression of the 560-day operation.

HANDLING OF PROBLEMS REGARDING THE DRILLING PROCESS

Maintaining directional control proved to be the major problem during drilling of the KTB pilot hole, due mainly to the very complex geology at the drilling site. In most cases, the different layers of gneisses, amphibolites, and other base rocks were found to be inclined at an angle of 60 to 90 degrees, which often caused a tendency for unwanted hole build up. Because the coring measuring system could be run with any inner barrel, early detection of inclination build was possible; the maximum inclination that occurred was 9-10 degrees.

To overcome these difficulties, stabilization of the bottomhole assembly was analyzed and optimized through comprehensive computer modeling and field testing. However, only moderate improvement was been achieved.

Minimizing doglegs and directional changes was a major requirement in order to keep drill string, torque, and drag at a minimum, and required directional drilling activities to be performed twice. Correction work took place at depths of 993.0m, 1816.4m, and at 2635.0 m. In this situation, 6" diameter tungsten carbide insert bits and diamond bits were used, while 4-3/4" positive displacement motors with bent subs, or bent housings and orienting subs, were run on a 3-1/2" API rotary drill string. Beyond a depth of 2700m, no further hole build up occurred; a relatively constant inclination of 4.5 degrees was maintained.

Serious borehole problems occurred twice. First, during a course correction, the drill string became stuck at 1998m. Ultimately, a back-off operation and subsequent back cementing was required. Borehole VB1a was spudded at a depth of 1709m.

A more serious problem occurred on 5 February 1989, at a depth of 3893m. Due to a wash out and a corrosion impaired drill string, a tool joint pin was destroyed. The remaining string fell to the bottom of the hole and stuck. After extensive attempts to recover the fish, a packer whipstock combination finally was set in the hole so a new section could be started from a depth of 3,766m, A rotary string and flat bottom diamond bit were used.

It was then decided not to continue wireline coring, but rather to apply a 4-3/4" Navi-Drill Mach 1 PDM and roller cone bit for further straight-hole drilling. The coring and drilling operation of the KTB pilot hole was finished on 4 April 1989, when this bottomhole assembly reached a depth of 4,000.1m.

CORING RESULTS AND SCIENTIFIC FINDINGS

After 560 days of drilling, approximately 3600m of core had been recovered; 20,000 rock and liquid samples collected; and comprehensive geophysical logging conducted. Now follows a one year period of long-term logging and testing, which will be performed primarily by university groups and service companies. The drill rig remains on location with reduced personnel.

WIRELINE CORING BIT PERFORMANCE

Coring with 152.4mm x 94mm diamond bits has been the center of interest during the whole operation. A total of nine surface set diamond core bits were used. (Table 12)
A chronological overview of diamond core bit footage attained during KTB pilot hole operation is shown in Figure 11.

Surface set diamond bits were applicable only in the upper sections of the hole where more broken and brittle formations were encountered. Table 13 lists corresponding data regarding the performance of diamond impregnated bits which were supplied nearly exclusively by Eastman Christensen and Longyear Companies. Performance of those impregnated diamond core bits supplied Eastman Christensen in particular, is shown in Table 14.

A total of 31 Eastman Christensen impregnated diamond bits each attained footage in excess of 30m, while five bits each were able to withstand more than 100m of coring.

A complete overview of diamond core bit penetration rates in the pilot hole operation is shown in Figure 12. Most came very close to the average value of 1.7 m/h, due in part to the fact that the drill rig's automatic brake was run mostly in a constant ROP mode.

Material properties as well as design considerations of diamond impregnated core bits were major factors in enhancing performance over comparative field experience. (Table 15) Performance improved steadily during the process of coring the KTB hole, especially with respect to total footage, which increased from about 40m in the first phase, to about 80m in the later coring phases.

The results described here are considerably better than could be expected before. Moreover, through laboratory and field research, new ways of enhancing the diamond impregnated core bit performance have since been determined.

CORING SYSTEM PERFORMANCE EVALUATION

Based on experience in developing tools of this kind, a completely new wireline drill string and coring system was developed for the KTB project by Eastman Christensen. Major components include the diamond core bit, the core barrel with integrated core jamming indicator and electronic core measuring system, a wireline retrievable inner barrel, high-strength wireline drill collars and drill pipe.

Even without benefit of any prior field testing, the system functioned properly in the KTB borehole from the start. Moreover, continuous support was given by Eastman Christensen to KTB management during the entire drilling operation.

In addition to minor improvement to the system, comprehensive advice was given with respect to proper handling of the equipment. Of particular interest was proper selection and application of a thread grease. At the request of geoscientific personnel, KTB first tried an unconventional thread compound consisting of inorganic composition. However, this grease did not properly lubricate the threads, and therefore, after a short trial phase, was replaced by standard KOPR COTE lubricant.

To avoid some problems in the superdeep hole operation, and as a result of experience gained during the coring operation, the following modifications and improvements have been made:

- Manufacture of inner core barrels with increased material strength to avoid plastic deformation during core jamming. Deformation of the inner barrel in some cases prevented pulling the inner barrel from the core barrel.
- Design modifications to the landing nut/landing shoulder system. Elastomer parts which were exposed to wear during the operation have been eliminated.
- Mechanical stability of the quint latch system for connecting the inner barrel to the overshot has been improved.

- Some minor modifications have been made to the layout of the bearing assembly with respect to the spring-controlled inner barrel displacement during breaking out the core.
- A special overshot has been manufactured which catches the inner core barrel if it becomes stuck in the drill string.
- A special wireline controlled spear has been made which allows removal of rock debris from the inside of the drill string.

All modifications were done in close cooperation between KTB and Eastman Christensen, and at no time delayed the coring operation.

CORE RECOVERY AND EVALUATION

A total core length of 3600m was recovered, the core having a diameter of 94 mm. Most, about 3140m, was cored with the wireline method. The remaining 450m, with a diameter of 4", was recovered from the roller cone coring section.

Once broken out from the inner barrel, the rock is put into a special container and transported to the rig site laboratory a few meters from the rig. Every sample is then registered, and an evaluation made of core length, quality, and determination of hole depth. The bulk material is then stored in a separate building. (Figure 13)

Later, samples of the rock are further analyzed in the Windischeschenbach laboratory. In addition, certain rock samples are distributed to national and international universities for more specific evaluation.

Determination of inclination and azimuth orientation of formation samples is of major interest. As an upgrade of the core measuring system, the core orienting system being developed by Eastman Christensen offers the capability to take oriented cores at minimum expense. Operational steps are described in Table 16.

This method was been successfully applied several times, producing results in agreement with control measurements. The system requires no special care with respect to drilling parameters such as RPM or WOB, and does not affect penetration rates, footage or other drilling performance criteria.

CURRENT SCIENTIFIC RESULTS

All anticipated scientific and technical goals of the KTB pilot hole operation have been met. Spudding of the superdeep borehole is planned for mid-1990. In the meantime, more hole logging and other measurements within the KTB pilot hole will continue.

In terms of preliminary scientific results, the following summary of the operation includes some remarkable findings, some of which were unexpected.

A series of rock layers consisting of gneisses, amphibolites, basic and ultra-basic compositions was found to be more folded and broken than had been expected.

In certain sections, the occurrence of large quantities of graphite led to serious drilling problems.

Small amounts of helium, methane, and hydrogen were found to escape from open cracks. An extraordinarily large open crack, found at a depth of 3447m, produced a methane content of 15% in the entrapped gas.

Core disking was monitored and occurred much earlier than had been expected, thereby giving an indication of unusual earth crust stresses.

The first seismic reflectors were drilled in, giving an indication of earth crust discontinuities.

A much higher temperature gradient was found than had been forecast. The actual gradient of 30 degrees C per 1000m exceeded the expected average of 25 degrees C. A temperature of approximately 125 degrees C has been measured at 4,000m depth.

Results achieved to date are currently used for updating planning of the KTB superdeep drilling operation. With successful completion of the pilot hole coring operation, an important milestone has been achieved. Although primarily the subject of basic geoscientific research, the project has resulted in remarkable innovative progress with respect to drilling and coring technology. Further enhancements will be realized with the preparation and execution of ultra-deep drilling.

TECHNICAL CONCEPT OF KTB SUPERDEEP WELL

The decision to drill two separate holes for the KTB project was made primarily to save time and money. Planning the KTB superdeep hole started more than two years earlier. Several enhancements to the existing plan were the result of experience in the pilot hole operation. The well plan, updated from time to time, is shown in its current version in Figure 14.

In addition to the very shallow depths, a section to 1500m of the superdeep borehole is planned to be drilled with pilot bit and reaming tool, providing a borehole diameter of 22". The borehole is then planned to be deepened to 3000m with a 17-1/2" drill bit.

Out of 16" cemented casing, the next section -- to 7000m -- is drilled with a 14-3/4" tool, then deepened with a 12-1/4" diameter as long as drilling conditions allow. Eventually, the hole size is reduced to 10-5/8". The section below 10,000m will be drilled with a maximum 8-1/2" diameter.

The concept for the superdeep hole was established so as to minimize the risk of trouble. Major precautions will be taken to maintain a stable hole and a vertical course to minimize friction and wear during movement of the drill string; one available option will be setting an additional casing and drilling out of this casing with the next smaller diameter tool.

The maximum total depth will depend on borehole temperatures; major geoscientific goals will be fulfilled upon reaching a temperature of 300 degrees C.

If the current average temperature gradient remains, this milestone might well occur at a depth of about 10,000m. If the temperature gradient decreases, which cannot be forecast at this time, further deepening of the hole to 12,000 or 14,000m might be reasonable. The technical design of the drill rig, all other installations and equipment, as well as the drilling diameter and casing planning, are presently accommodated to a depth exceeding 10,000m.

As originally planned, no coring operations will be performed in the superdeep hole at any depth above that of the pilot hole, which is now 4,000m. Control measurements will be performed by geoscientific methods.

Down to the anticipated 14-3/4" depth of 7000m, it has been proposed that some "spot cores" be taken in certain zones of specific interest. Below a depth of 7000m, approximately 20 to 30% of the hole will be cored, with the application of a continuous coring system presumably offering the most economic way of core sampling.

Major features of the existing concept are identified in Table 17. The goal in the upper section to 7000m is characterized by drilling a hole as vertical and straight as possible. This is held to be a basic requirement for reaching extended depths, according to experience gained during the pilot hole operation.

Those scientific requirements regarding coring were attained in the pilot hole, as will be shown. Drilling tools and systems have to be provided which are able to drill a vertical hole. Below 7000m, more extensive coring is planned as it remains the only available method of directly gathering information on the composition of rock at these depths.

PROPOSED DEVELOPMENT OF DRILLING AND CORING SYSTEMS FOR KTB

Planning for the superdeep borehole operation is based on information gathered about comparable international drilling projects. With respect to special problems regarding borehole stability, and stresses in deep holes in a hard rock environment, valuable experience has been gained from both the Russian Kola SG-3 well and the Swedish Gravberg-1. In addition, the now-completed KTB pilot hole operation currently contributes considerably to setting up detailed planning, especially with regard to formation and temperature environment at the Windischeschenbach site.

Also, economic aspects must be considered when identifying the proper allocation of money for deepening of the hole, and for scientific work. It is, however, a basic understanding that reaching the scientific goals of the overall project is a priority.

It has been evident from the start that, beyond the scientific approach to be taken, quite a comprehensive development program would be required with respect to the drilling and coring technology. Major development emphasis includes drilling the hole as vertically as possible; coring the required sections as economically as possible; recovering cores, especially from extended depths; and, in general, making available certain drilling systems, such as hydraulic downhole motors or hammering devices, which are especially adapted to hard rock, extended depths, and elevated temperatures.

Of major interest in upper sections of the superdeep hole is vertical drilling, for which comprehensive development activities are currently underway at the Eastman Christensen Drilling Research Center located in Celle, West Germany. The basic idea behind the vertical drilling system -- a steerable stabilizer tool -- is a downhole electronically controlled loop system which automatically compensates for any directional changes being generated by formation disturbances.

In terms of coring and downhole motor systems for the KTB superdeep hole, detailed studies have been conducted to identify the existing state-of-the-art, as well as to propose reasonable development directions. Currently, detailed planning of hardware development is underway, with consideration to be given the findings from the studies mentioned. And of course, drilling technology and geoscientific results from the pilot hole operation will influence the proposed work to a certain extent.

Continuous coring systems offer an important advantage over discontinuous tools in that the drill string does not have to be tripped completely when recovering the core. A systematic overview of some continuous coring system options is shown in Figure 15. Most of the systems use downhole motors in some way. A more or less continuous core might also be taken by recovering rock samples from the borehole wall, for which four characteristic types of mechanisms have been evaluated for further consideration. (Figure 16) Characteristic data of such sidewall coring systems is shown in Table 18.

An additional option for gaining rock samples might be to employ special bit designs which feature a means of ejecting or crushing cores. This would provide to the surface, continuous rock particles with dimensions larger than those of the ordinary cuttings.

SUMMARY

A major milestone of the continental deep drilling program of the Federal Republic of Germany has been reached with successful completion of the coring and drilling operations in the KTB pilot hole. This well, which is located near the small town of Windischeschenbach in northern Bavaria was completed after 560 days of drilling on April 4, 1989, at a depth of 4,000.1m. With respect to scientific and technical goals, all important tasks have been performed.

A new drilling concept was developed and realized which employs the advantages of both rotary and mining wireline drilling. A new high-strength wireline drill string was developed and manufactured and was run successfully in the first application.

Although the complete evaluation of core material will require still more time, preliminary findings about formation composition and temperature distribution are regarded as new and valuable.

Major development emphasizes drilling and coring tools planned or in part, already underway in preparation for the KTB superdeep operation to be spudded in mid-1990. Technical development programs will be examined with regard to vertical drilling tools, downhole motors, hammering tools, and coring systems. Identification of the scope of work to be performed also takes into account experience gained during the pilot hole operation.

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Table 1 Major Purposes of KTB Pilot Hole

- Recovery of high-quality continuous core samples over total depth
- Gathering of geoscientific data
- Analysis of the temperature profile for improved estimation of superdeep temperature distribution
- Minimization of core and logging runs over corresponding sections of the superdeep hole
- Obtaining information on problem sections
- Testing of drilling and logging tools for the ultradeep operation

Table 2 Pilot Hole Operation Requirements

- Depth capacity of 3000 m, with capability of 5000 m coring at maximum
- 6" hole diameter for logging and testing purposes
- Continuous coring capability

Table 3 Major Design Parameters of KTB-EC Tubulars

	KTB-EC-WLDP	KTB-EC-WLDC
Weight (in air)	25.0 kg/m	43.9 kg/m
OD	139.7 mm	139.7 mm
ID	125.5 mm	111.3 mm
OD Tool Joint	142.0 mm	139.7 mm
ID Tool Joint	110.0 mm	111.3 mm
Max. Torque	24 kNm	15 kNm
Max. Tension	2400 kN	1400 kN
Pipe Capacity	12.1 l/m	9.7 l/m
Annulus Capacity	2.9 l/m	2.9 l/m

Table 4 Core Measuring System

Memory storage capacity	
- with inclination and temperature	10,000 records
- with inclinination, temperature, and core orientation	6,000 records
Temperature measuring range	0..125°C
Temperature resolution	±0.05°C
Inclination measuring range	0..12.8°C
Inclination resolution	±0.04°
Tool face measuring range	0..360°
Tool face resolution	±2.5°
Data rate (Interal between two records)	4,8,16,32s 1, 2,4 or 8 min
Length	1,000 mm
Diameter	80 mm
Weight (incl. batteries)	22 kg
Battery types:	Rechargable Ni-Cd Alkaline-Manganese Lithium

Table 5 Drilling Rig Specifications

Type	GH 1400 E
Height	49 m
Nominal hook load	2,040 kN
Installed power	3,700 kW
Power supply	Public electric power line
Length of Stands	27 m
Racking capacity 5 1/2"	5,000 m

Table 6 Features of Drilling Mud Additive

- Purely inorganic one component system
- Aqueous colloidal solution
- Has silicate structure composed of Si, Mg, Na, Li, O
- Concentration of 0.8 to 2.5 wt-% is recommend for control of rheological properties
- ph of 9 to 11 for corrosion control with NaO

Table 7 Typical Mud Properties for KTB Drilling Fluid

- Specific gravity: 1.03 kg/dm
- Bingham plastic viscosity: 13 cp; yield point: 12 lb/100 sqft
- Powerlaw n: 0.54; K: 0.41
- Gelstrength: 10 sec, 2 lb/100 sqft; 10 min, 3 lb/100 sqft
- API-Filtrate: 26.5 ml/30 min
- CST-(capillary suction time): 2,258 sec
- Sand content: 0.1% (by Vol.)
- Ph: 10.5
- Chloride: 62 ppm
- Conductivity: 3 ms/cm

Table 8 Roller Cone Bit Coring Performance

• Weight on bit:	30 to 60 kN
• RPM:	30 to 60 l/min
• Flow rate:	2,000 l/min
• Average ROP:	1.17 m/h
• Average footage per bit:	57.5 m
• Maximum footage per bit:	112.5 m
• Number of core runs:	74
• Average core length:	2.6 m
• Average core recovery:	42.9 %

Table 9 Wireline Coring Operating Parameters

Type of drill pipe:	5 1/2" 16.8 lb/ft EF KTB-EC-WLDC
No. of drill collars:	20 pcs. 5 1/2" 29.5 lb/ft EF KTB-EC-WLDC
WOB:	30 to 40 kN
RPM:	280 min^{-1}
Flow rate:	220 l/min
Bit size:	152.4 mm • 94 mm

Table 10 Wireline Cored Sections & Recovery

Section of hole	Cored length	Recovery
480 m - 1,998.3 m (VB1)	1,105.6 m	98.4 %
1,677 m - 3,009.7 m (VB1a)	1,164.7 m	96.9 %
3,010.7 m - 3,893.0 m (VB1b)	882.3 m	97.1 %
480.0 m - 3,893.0 m	3,142.6 m	97.84 %

Table 11 Time Distribution of Pilot Hole Operation

ACTIVITY	PERC
Coring / Drilling	19.8
Inner Barrel Operation	16.5
RT / Reaming / Cleaning	22.8
Direction Control / Fishing	17.2
Logging / Testing	13.5
Maintenance / Other	10.2

Table 12 Surface-Set Diamond Core Bit Performance

Total no. of core bits	9
Average footage:	35.8 m
Average ROP:	1.8 m
Maximum footage:	89.5

Table 13 Diamond Impregnated Core Bit Performance

Total no. of core bits:	62
Average footage:	47.9 m
Average ROP:	1.7 m
Maximum footage (5 runs)	135.5 m
Maximum footage w/o tripping:	109.2 m

Table 14 Eastman Christensen Diamond Impregnated Bit Performance

Total no. of core bits:	45
Average footage:	53.8 m
Average ROP:	1.7 m
Maximum footage (5 runs)	135.5 m
Maximum footage w/o tripping:	109.2 m

Table 15 Major Items for Core Bit Improvement

- Opimize liquid flow through kerf area
- Adapt ratio of matrix hardness and diamond concentration to formation
- Select appropriate diamond quality
- Increase height of cutting segments and improve bonding techniques
- Provide gage protection through thermally stable PCD cutters

Table 16 Orientation Procedure w/Core Measuring System

- Adopt orienting inner tube shoe with knives
- Initialize core Orientation Mode with PC and CMS
- Install CMS to inner tube
- Determine high side of tool in an inclined position
- Run the inner barrel downhole
- Take core as usual
- Back on surface copy data to PC
- Run azimuth tool in the open hole at any time
- Correlate relative bearing (toolface) data to azimuth and scribe mark

Table 17 Superdeep Hole Drilling & Coring Strategy

- Drill a straight vertical hole to 4,000 m with geophysical control measurements
- Drill further full hole to 7,000 m and take spot cores at specific sections
- Further deepen the hole and core about 20 to 30 %, most probably with continuous coring tools

Table 18 Characteristics of Four Sidewall Coring Systems

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)

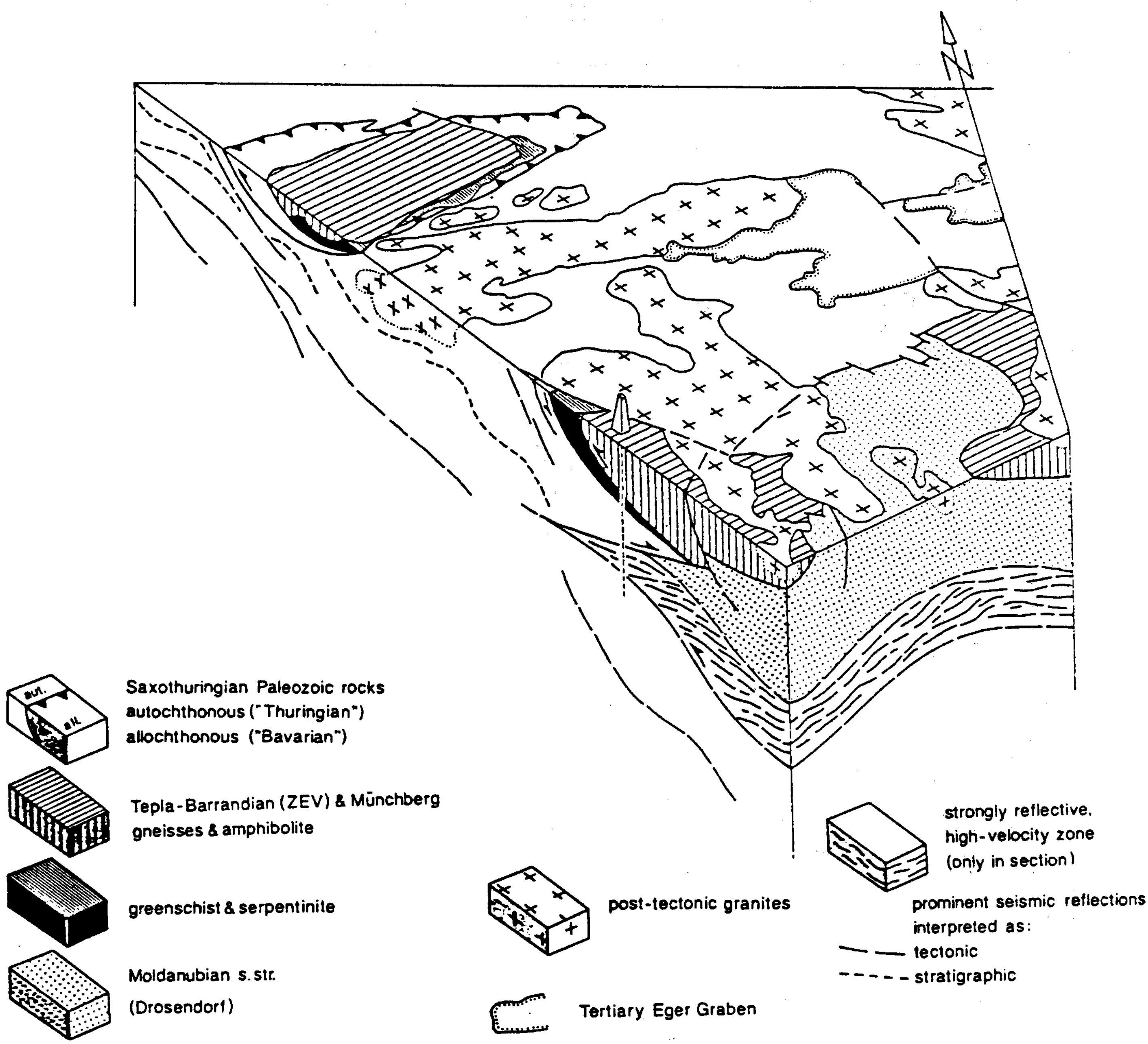


Fig. 1 Geological Map of the KTB Drill Site

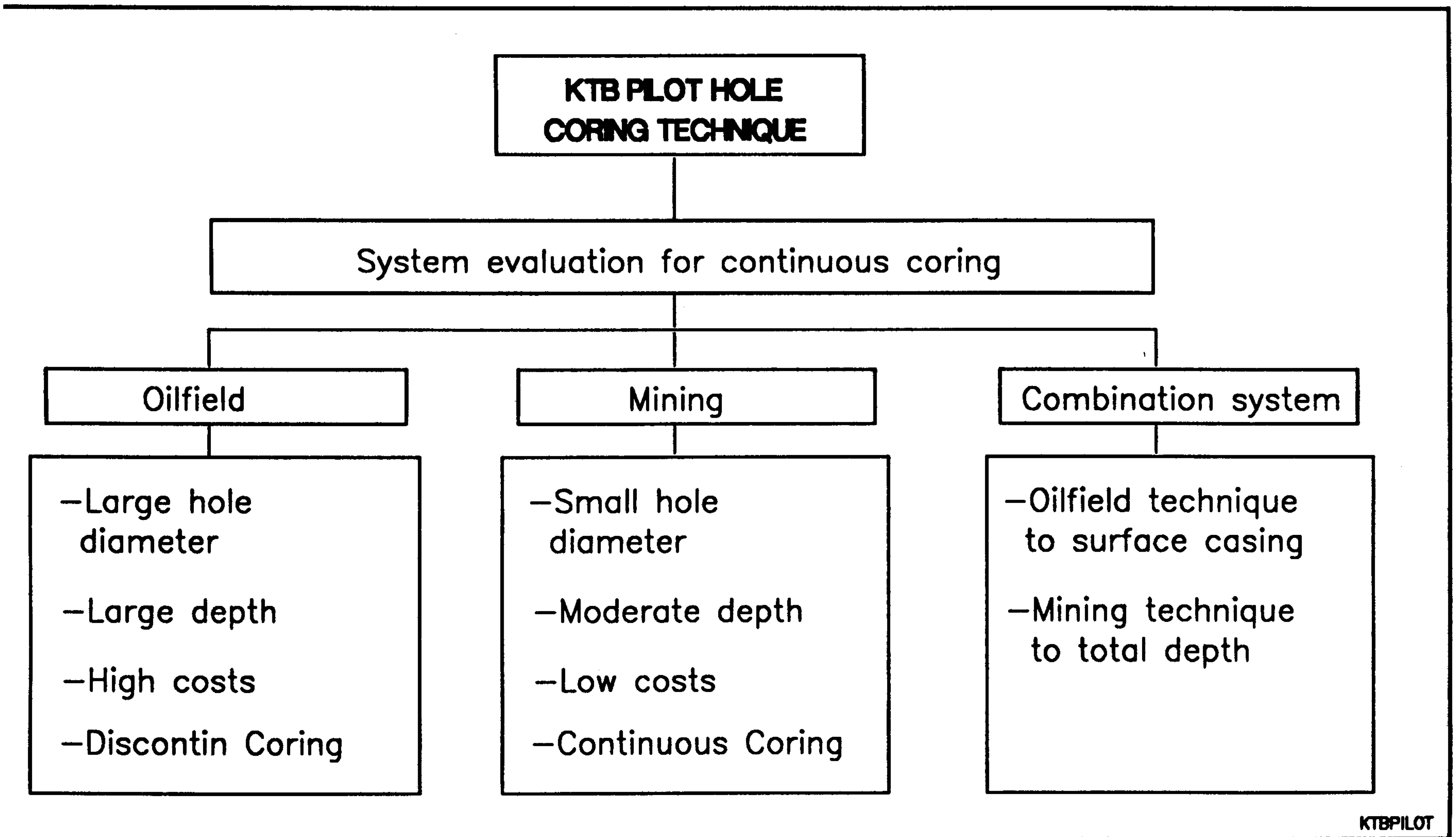
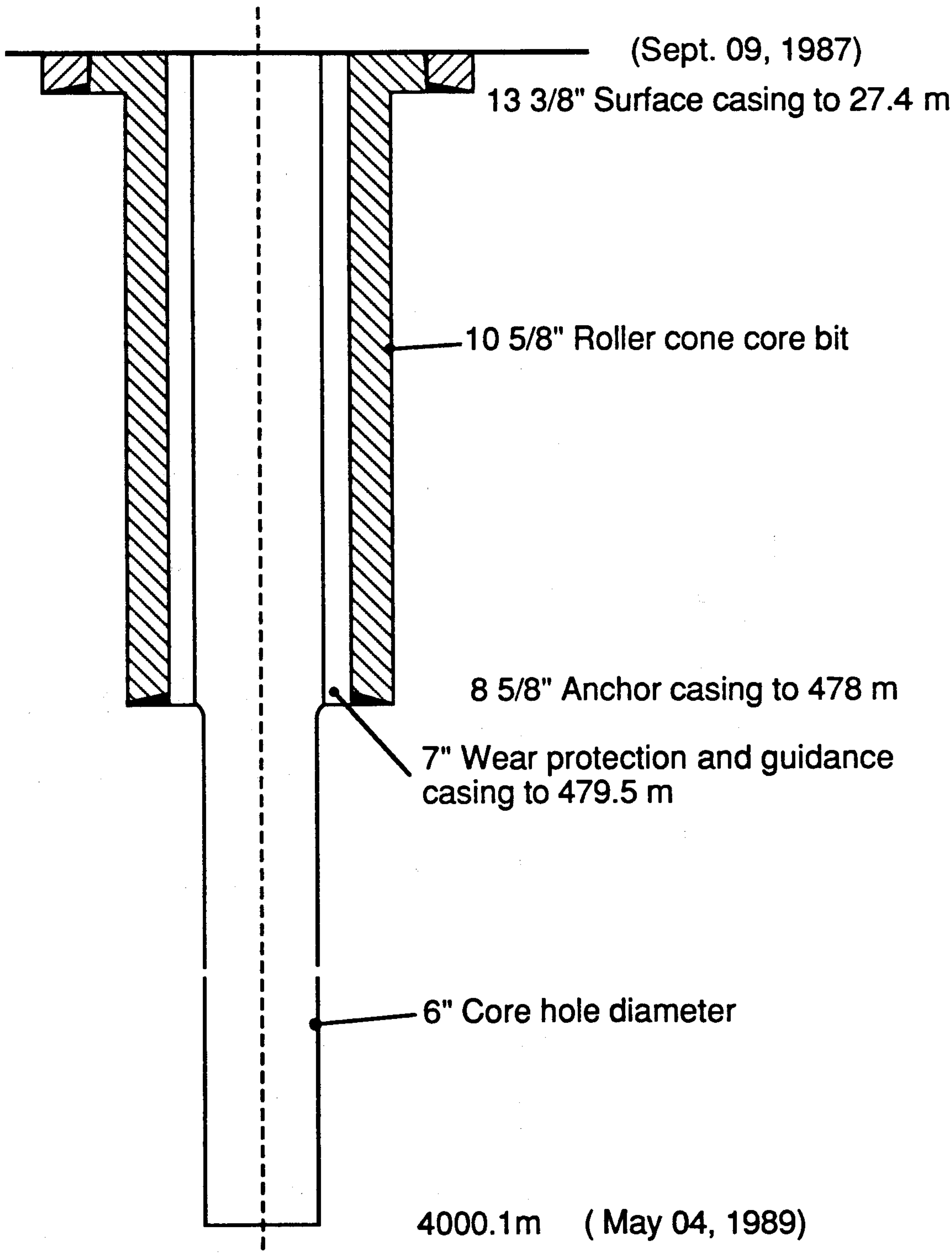


Fig. 2 Evaluation of Coring Methods

KTB - Pilot Hole



Casing and Drilling Plan

KTB

Fig. 3 Pilot Well Planning

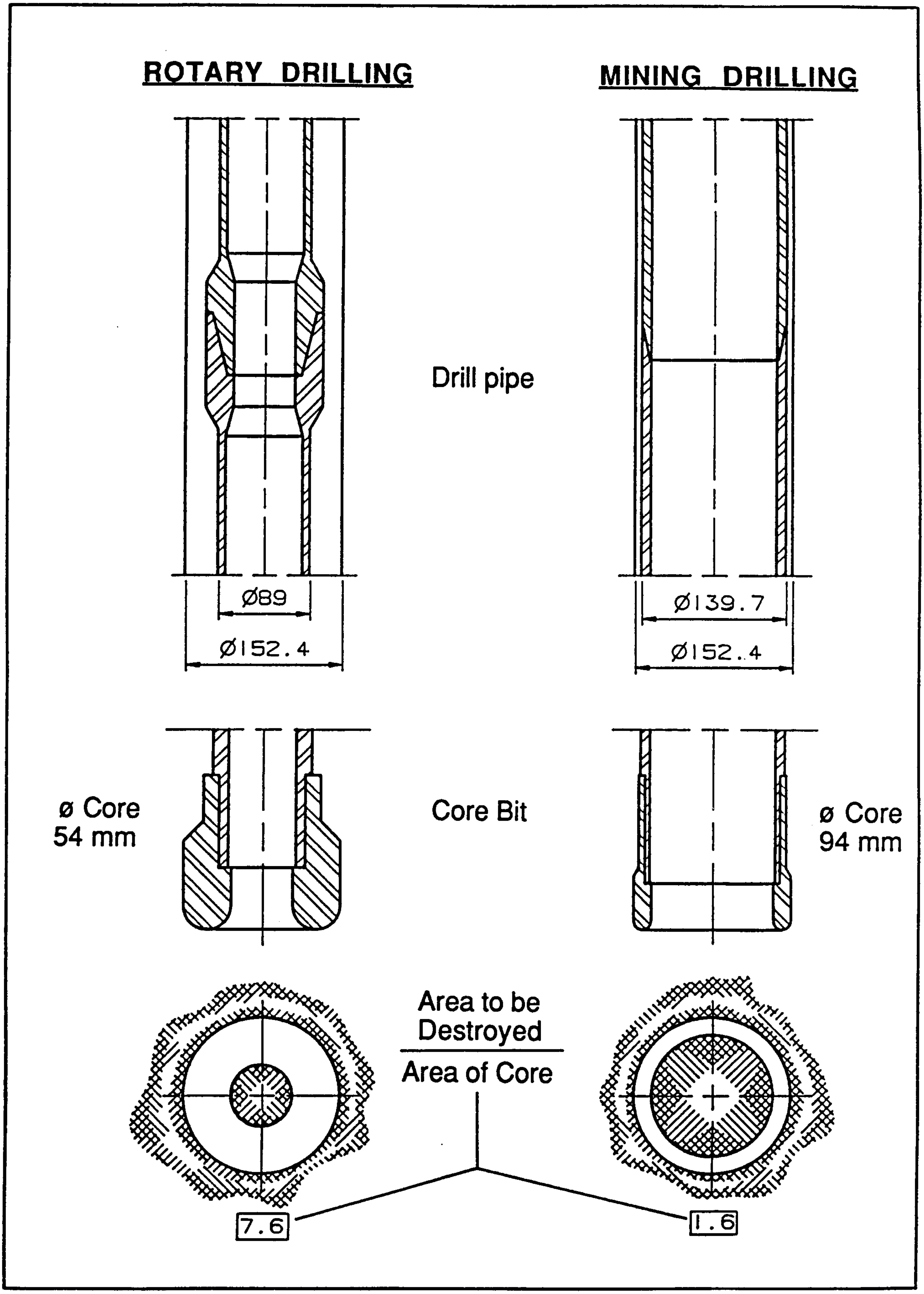


Fig. 4 Comparison of Rotary/Wireline Mining Drill Rod Design

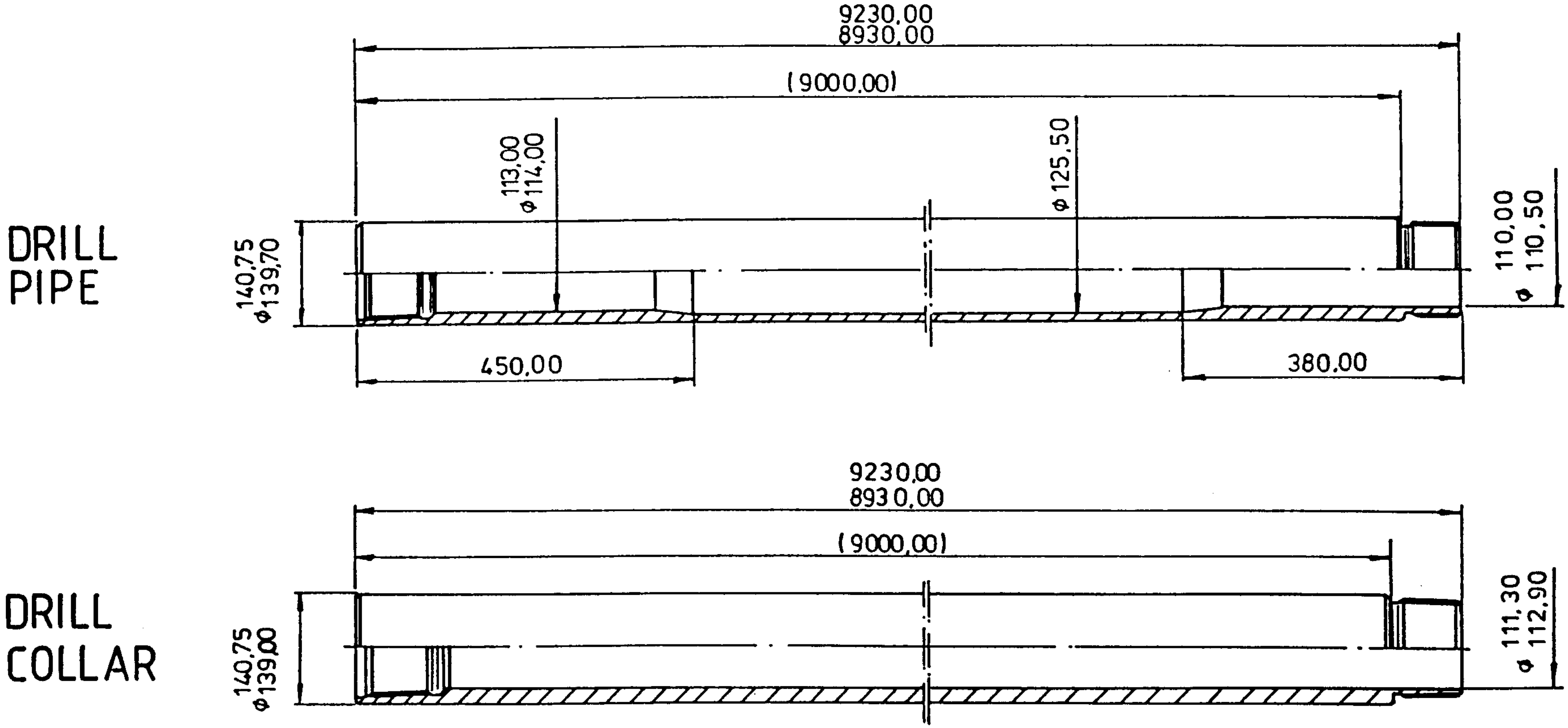


Fig. 5 Drawings of KTB-EC Wireline Drill Pipe & Drill Collar

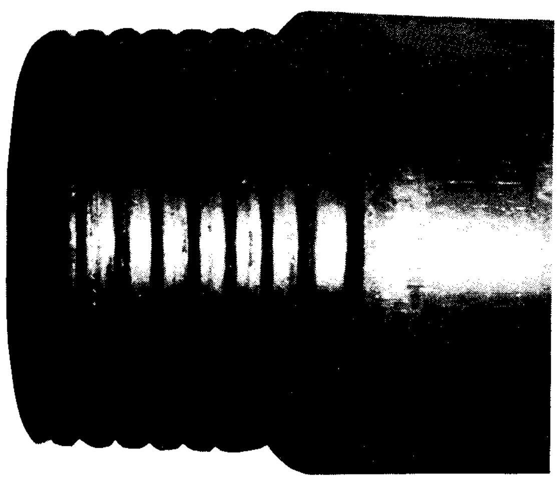


Fig. 6 Photographic View
of Drill Collar Pin Thread

KTB-EC 5 1/2" Core Barrel

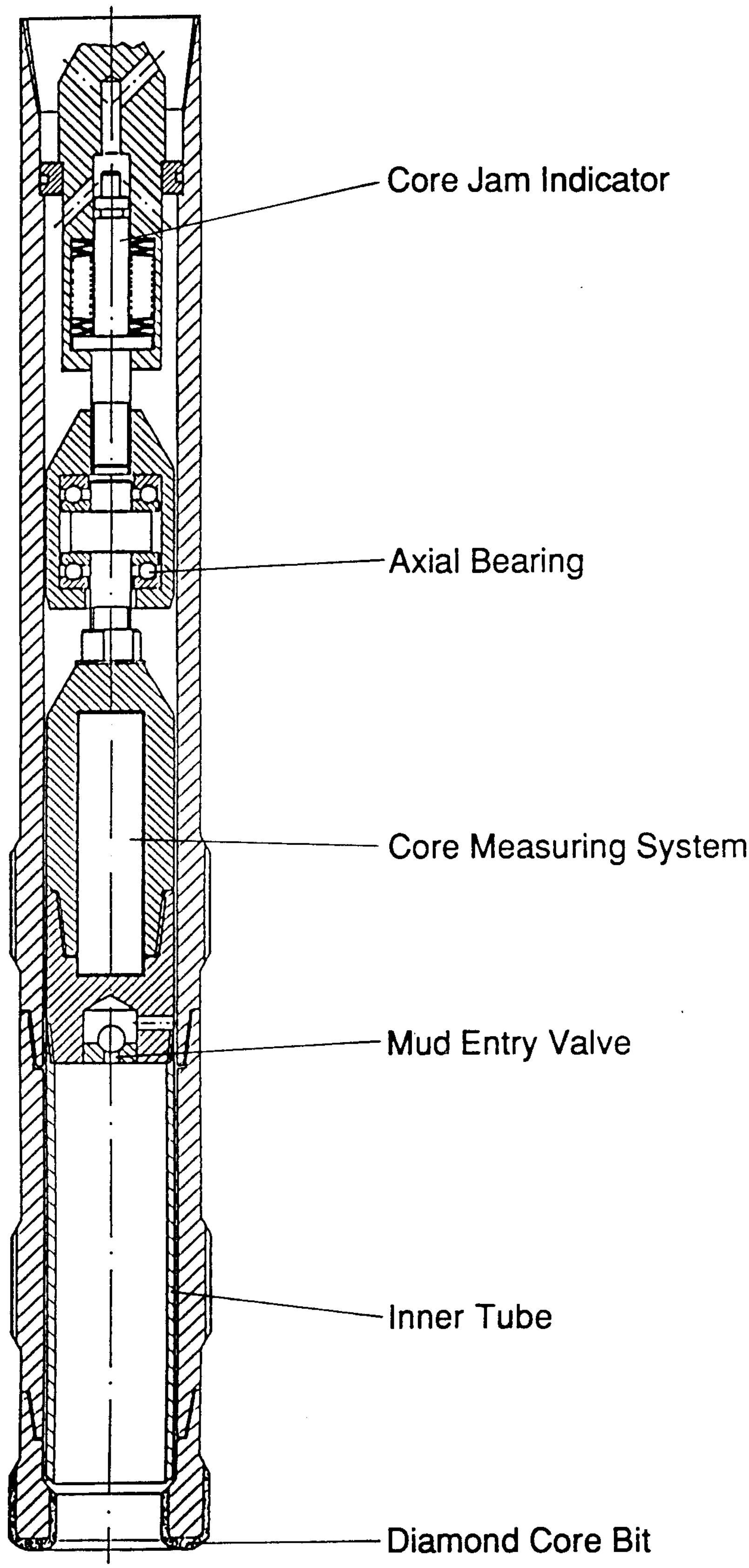


Fig. 7 KTB-EC Wireline Core Barrel

Orientation Equipment & Sample

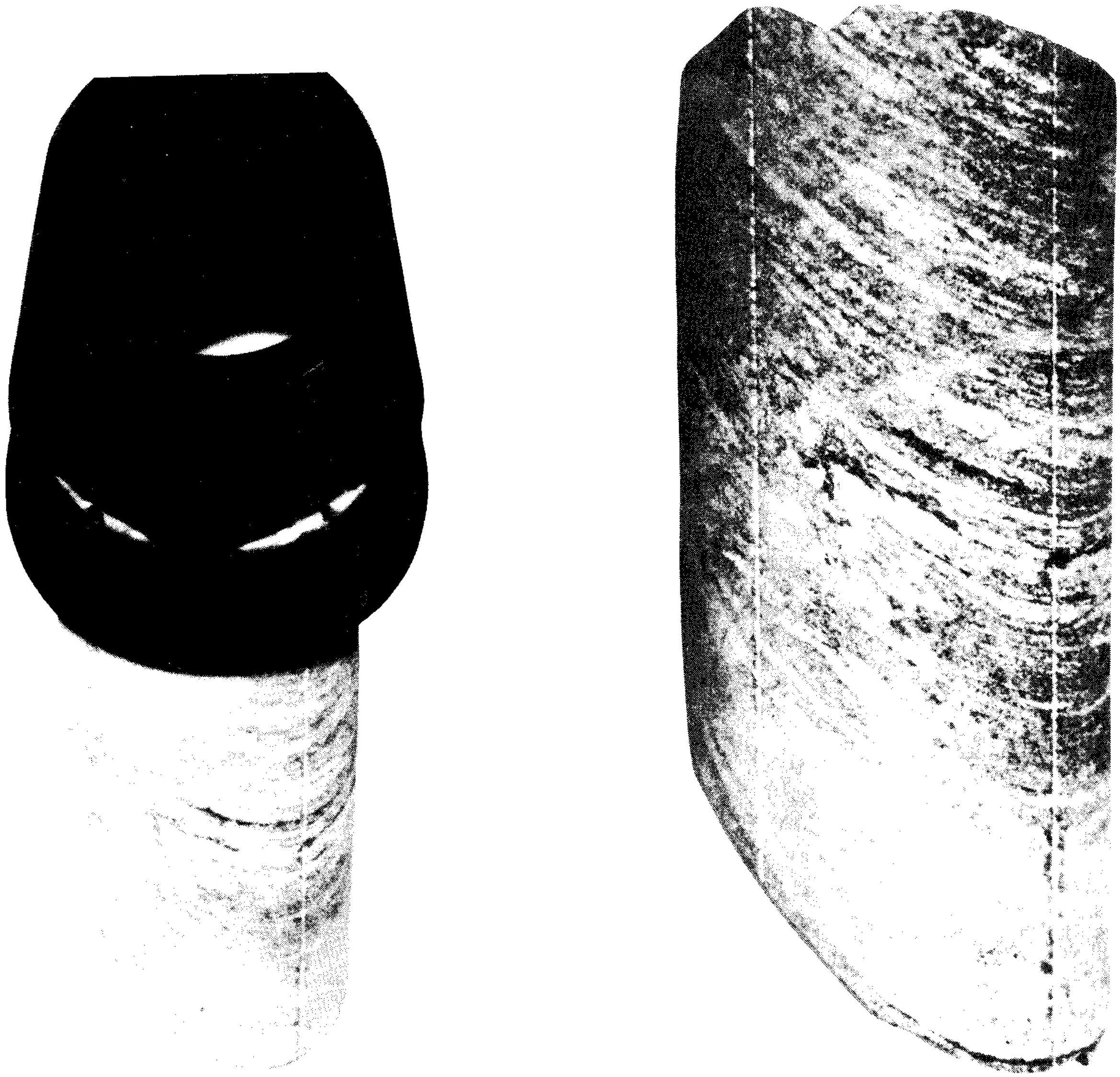


Fig. 8 Inner Tube Shoe

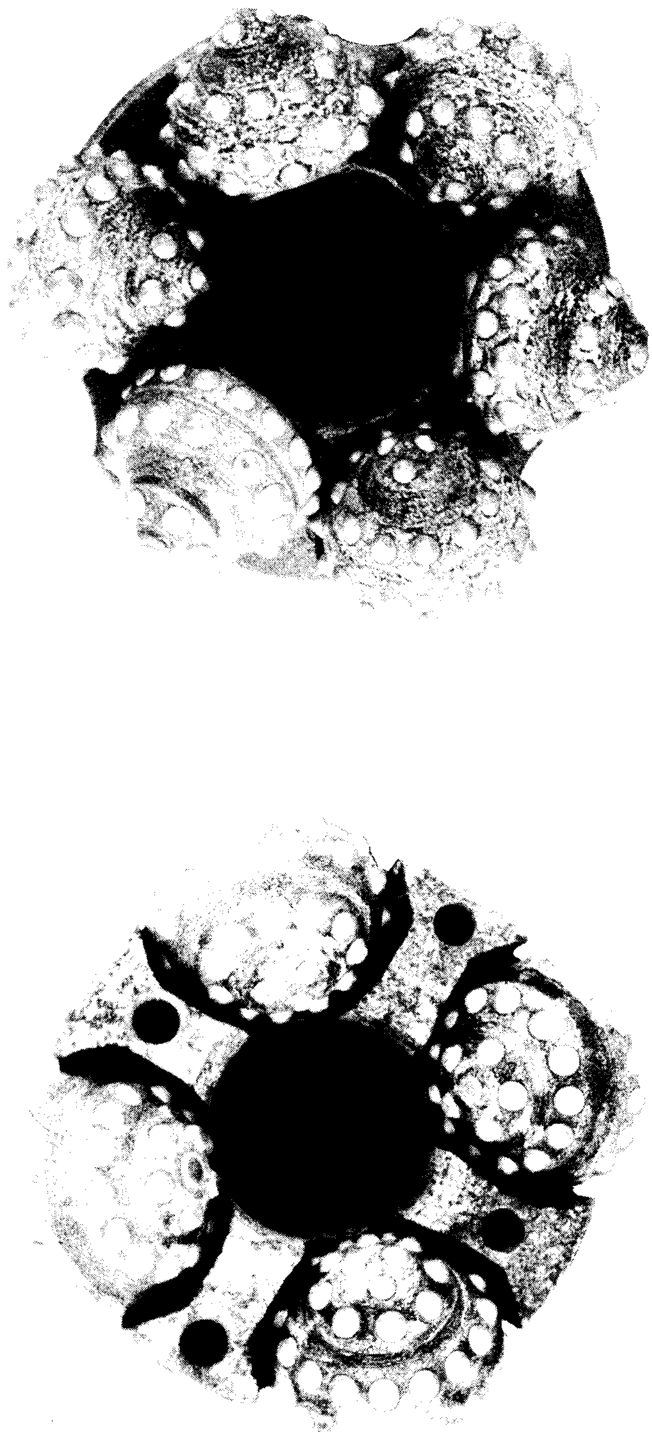


Fig. 9 Roller Cone Core Bits (10-5/8" x 4")

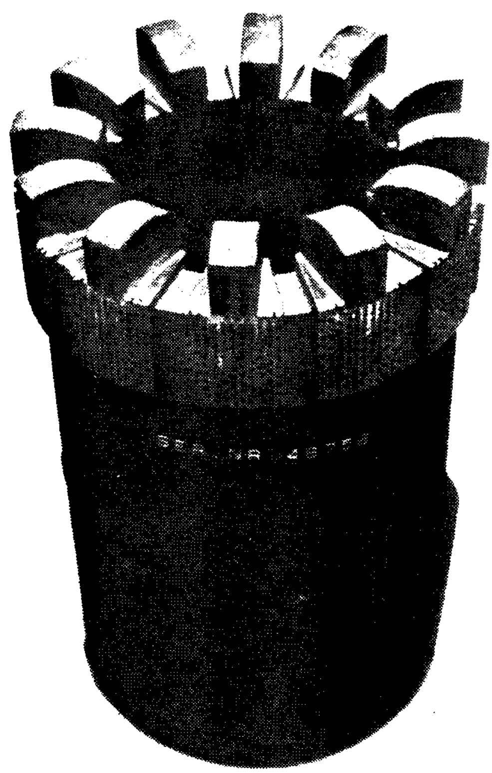


Fig. 10 Diamond Impregnated Core Bit

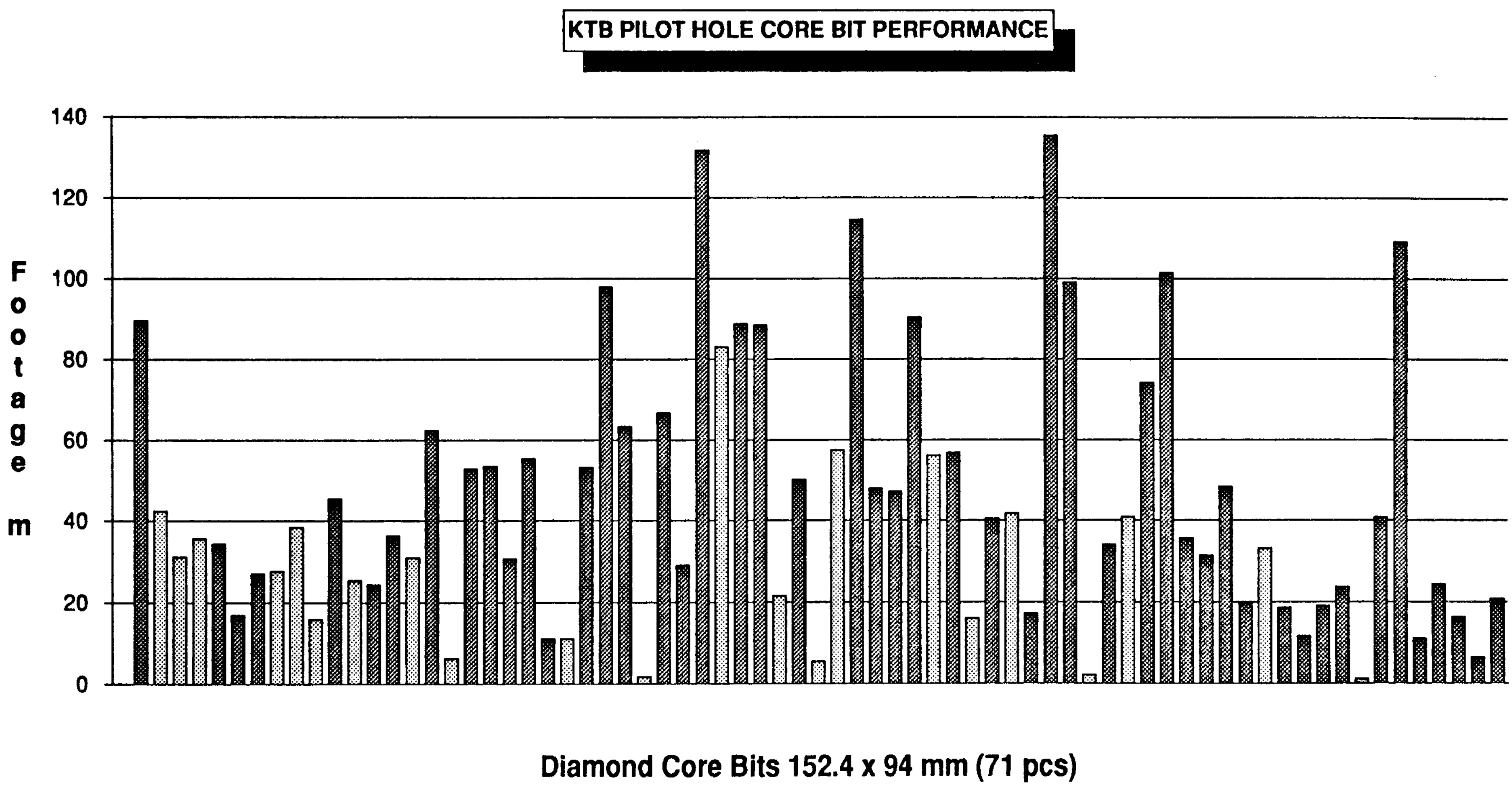
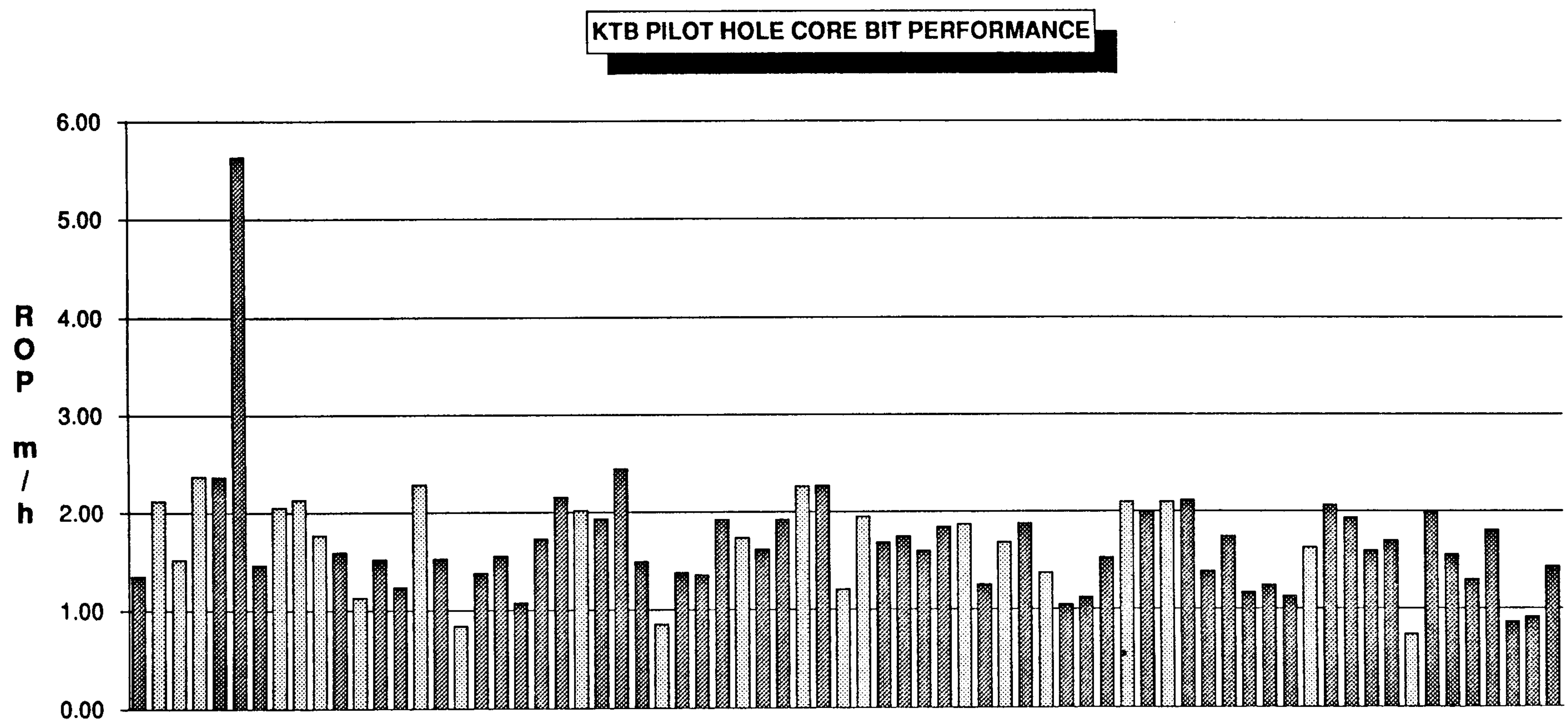


Fig. 11 Diamond Core Bit Footage - Overview



Diamond Core Bits 152.4 x 94 mm (71 pcs)

Fig. 12 Diamond Core Bit ROP - Overview

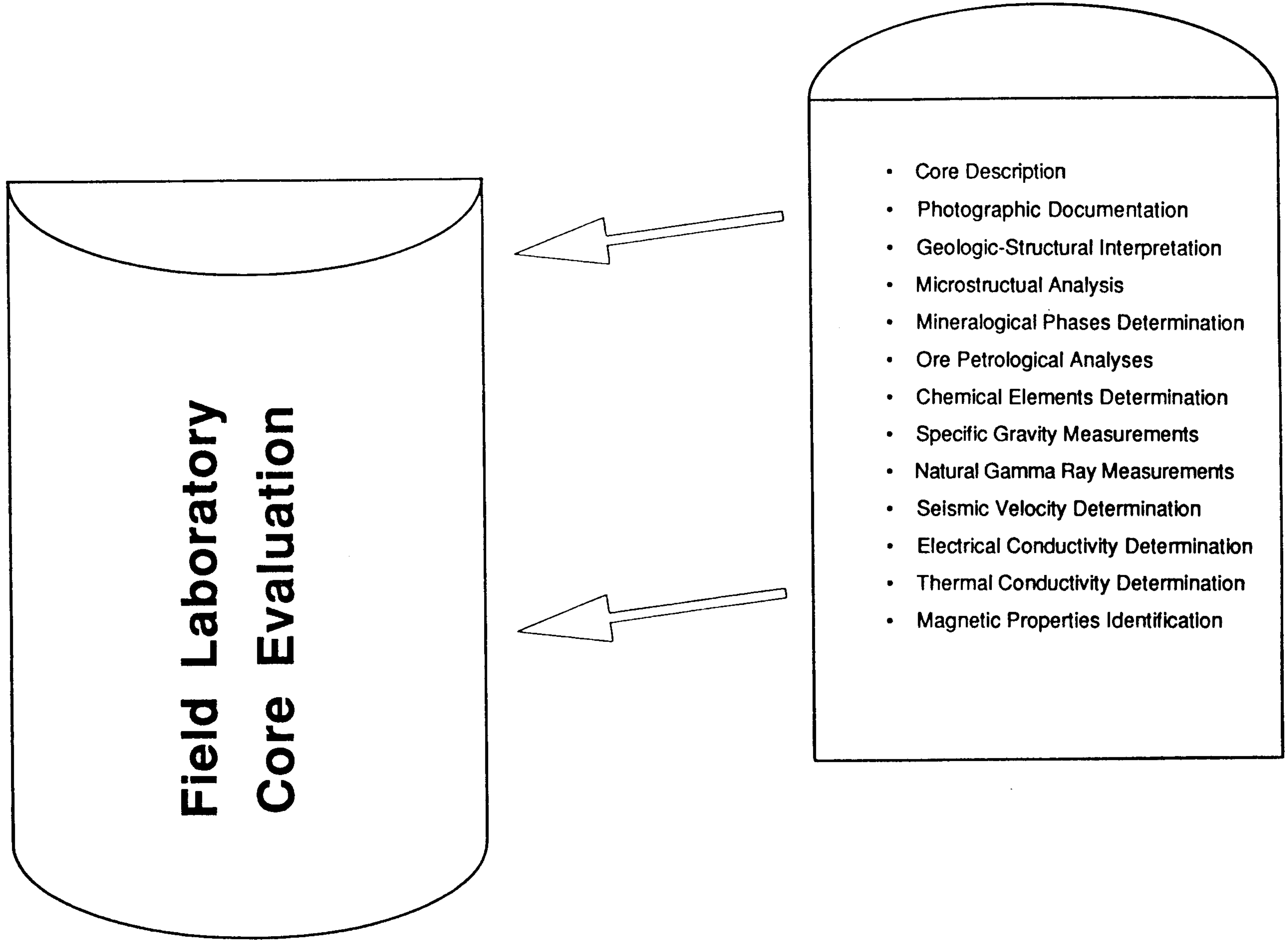


Fig. 13 Rig-Site Core Evaluation

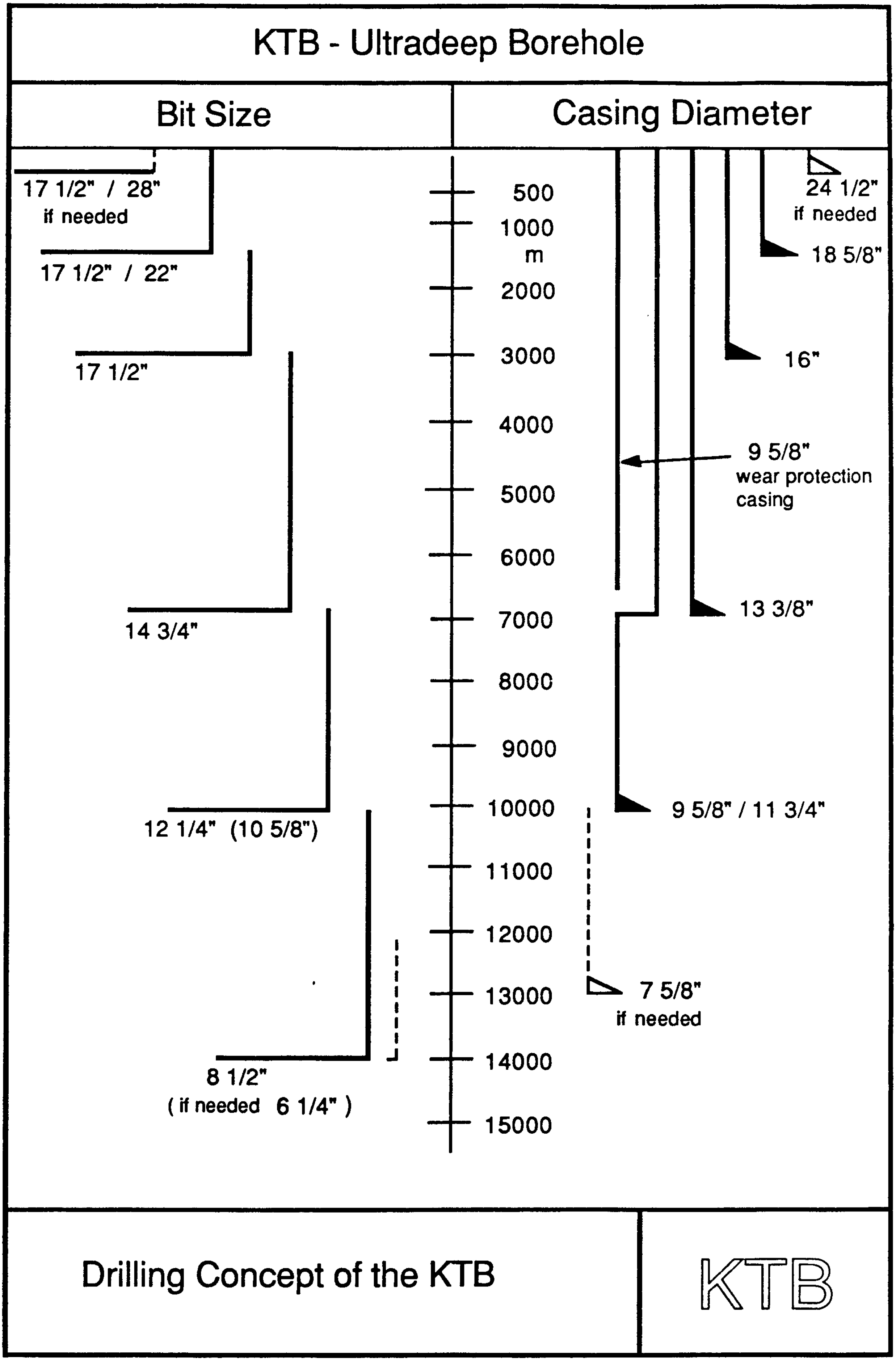


Fig. 14 Well Planning for KTB Superdeep Hole

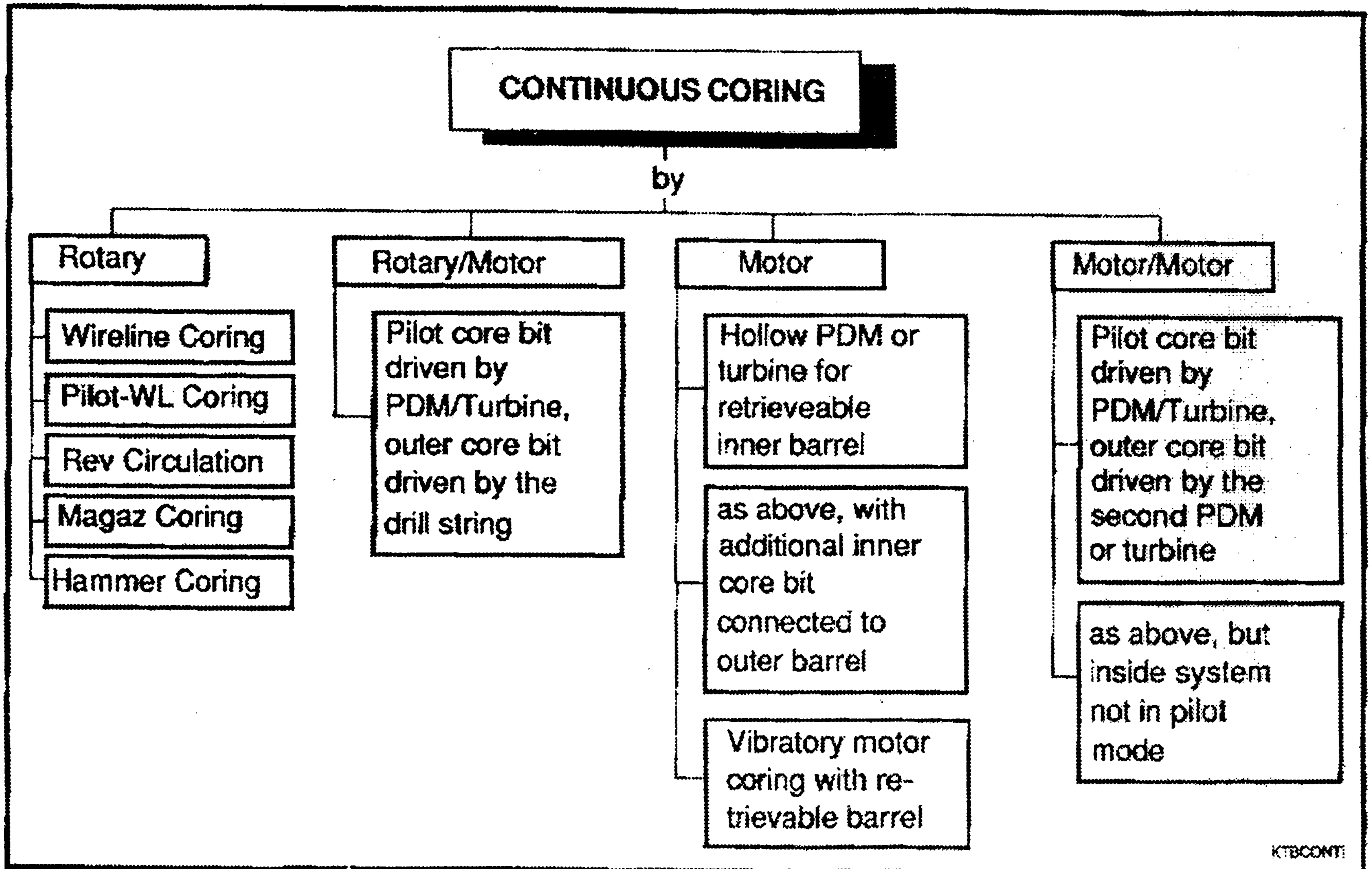
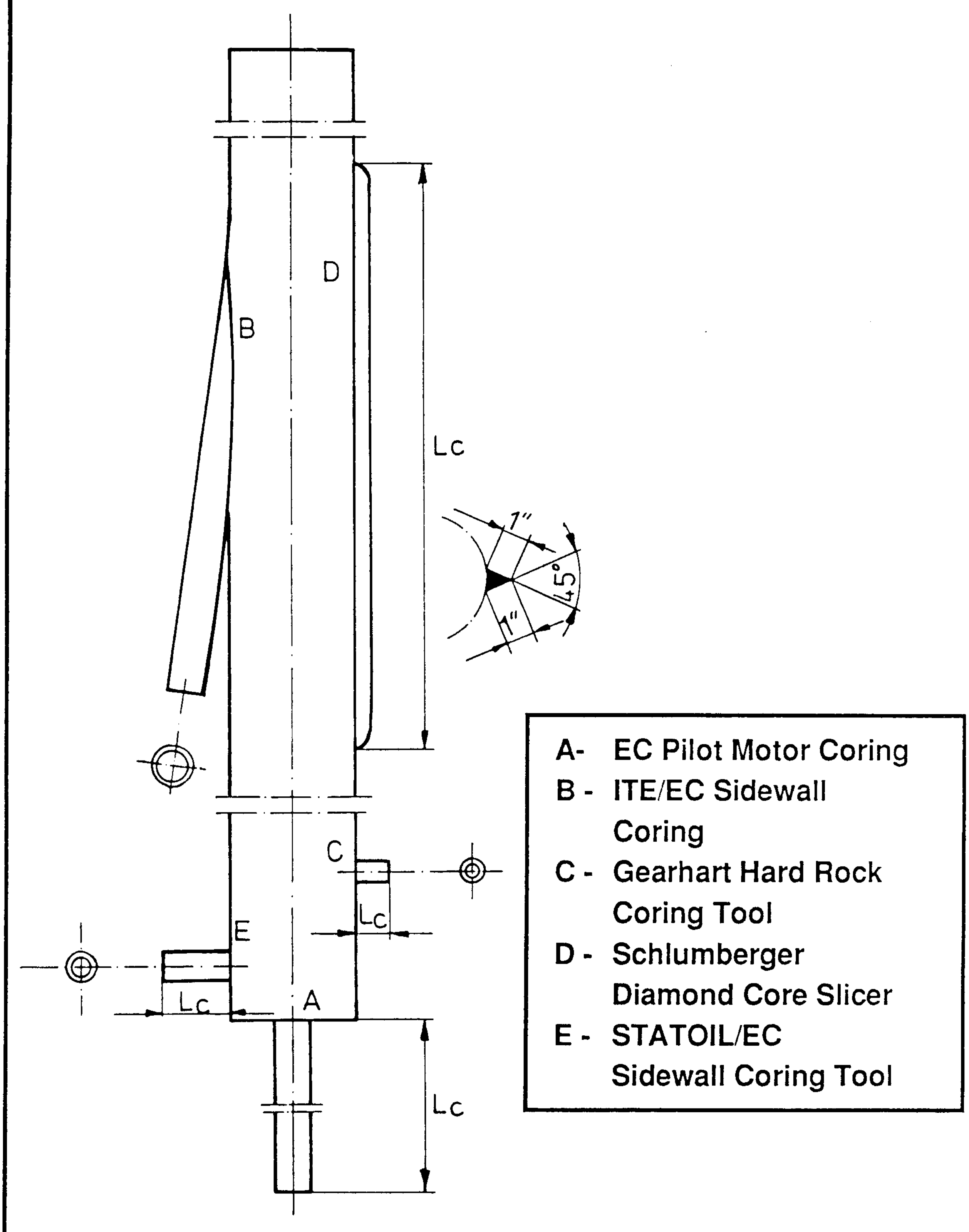


Fig. 15 Systems Options for Continuous Downward Coring



ITE/EC,1988

Fig. 16 Dimensions of Sidewall Cores