DEVELOPMENT OF A THERMAL MECHANICAL DRILL FOR SAMPLING ICE AND ROCK FROM GREAT DEPTHS

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DEVELOPMENT OF A THERMAL MECHANICAL DRILL FOR SAMPLING ICE AND ROCK FROM GREAT DEPTHS

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ABSTRACT

Obtaining deep ice cores from glaciers and the world's ice caps and rock samples from beneath the ice requires a new approach in coring technology allowing quick access to sampling zones. A combination of mechanical drilling coupled with water as a drilling and hydraulic fluid shows promise in providing quick access to interesting sample areas as well as the ability to obtain quality rock or ice core samples.

The system consists of a deep well pump to circulate drilling water from within the ice, a triplex pump to provide hydraulic power, heaters, specially designed instrumented hoses and a down-hole mud motor to drive the drill. The system is described in detail and thermal models of its effect on cores presented.

1.0 INTRODUCTION

Currently, the Polar Ice Coring Office (PICO) uses two basic drill types for drilling access holes and recovering core: thermal and mechanical. While thermal (hot water) means are primarily used for drilling access holes and mechanical means used for obtaining core, a combination of both is suggested for retrieving ice, debris-laden ice, and subglacial samples from the bottom portions of the glacier. Both types of drills are used extensively in glaciological investigations with excellent results and high reliability.

A mechanical coring system uses cutters with the leading edge slanted at 45° and a 15° relief angle. The cutters are very agressive and penetration must be controlled with penetration shoes limiting the amount of material removed. Typically, penetration rates of 1 m/min are achieved using less than 1 kW of power. Core and chips are retrieved at approximately 1 m intervals. Core catchers which cause stress concentration points reduce core breaks from a potential 3000 kg to approximately 100 kg. Hole coring depth generally is limited by core quality deterioration resulting from increasing bubble pressure from air trapped within the ice. Hole closure due to creep induced by overburden pressure is also a consideration. Adding fluid to the hole prevents hole closure and significantly improves core quality below 200 m to achieve a 100% retrieval.

Drilling fluid weight and environmental considerations suggest considering the use of water as a drilling fluid. While refreezing is a consideration, the additional fuel used to keep the hole open is more than offset by the fact that each liter of fuel generates 60 liter of water (from ice). Further, since the chips are melted downhole, the drill can be shortened and simplified considerably.

Experience with hot water drilling in cold ice began in 1979 at Dome C in Antarctica. Many holes to depths of 60 m were completed successfully with no freezing problems encountered despite ambient temperatures approaching -40°C (-40°F) and ice temperatures down to -54°C (-65.2°F). PICO continued using a small system to drill hundreds of shallow holes successfully. Description of this system and results from its operation in the field are described by Koci (1988).

The need for deeper drilling and recovery of bottom samples requires a high heat input and insulated hose to permit drilling beyond 1000 m. Both are necessary to prevent freeze-up within the hole and preserve heat within the hose for drilling.

An instrumented cable allows drillers to monitor progress of drilling assuring a successful hole at each attempt.

This hot water system is an expansion of drill systems currently in use allowing commonality of parts. Six to ten 80 kW oil fired water tube boilers are used, giving a heat output of 0.5 MW to 0.8 MW depending on water flow rates and inlet temperature.

A modified Rodriguez well is used to supply water to a triplex pump which boosts pressure to over 100 bars at 84 l/min. Development of such water wells is described in Koci (1984). The water is then heated and returned to the drill. A schematic diagram of this hot water system is shown in Figure 1. Pressures and temperatures at all above-hole locations are monitored with standard gauges.

The drill hose is standard Synflex 3000®, 2.4 cm I.D. which has been modified by wrapping with electrical conductors, a Kevlar® strength member and an outer neoprene jacket as displayed in Figure 2. The outer diameter is nearly 5 cm requiring a minimum bending radius of 50 cm. This assembly can be produced in single lengths of up to 700 m which can be attached to achieve the desired length. Since the hose is buoyant (30 kg/100 m), weights must be added to the drill stem.

An electronics package similar to the one used earlier (Hancock and Koci, 1988) is attached to the upper portion of the drill, allowing monitoring of drill progress. Hole diameter, inclination and water outlet temperatures and pressures are available to the driller. This is important when planning drilling progress to prevent freezing of the system.

A standard Spraying Systems Fulljet® 30° nozzle is used to continuously mix water in front of the drill and maximize heat transfer to the ice surface. This type of mixing nozzle works well with the slow drilling speed we use to provide access holes.

2.0 HOT WATER/MECHANICAL DRILL

Figure 3 illustrates various PICO drilling systems from a lightweight hand-auger to the much more complicated electromechanical deep ice coring system for use in fluid-filled holes. The hybrid hot water/mechanical coring drill shown at extreme right on Figure 3 is currently under development at PICO. Our experience with hot water drilling and electromechanical drills can be combined to accomplish a design capability of drilling to over 3000 m. A hose similar to the one used in the Crary Ice Rise Drilling Program, Antarctica (Fig. 2), will be used to provide wire for instrumentation, additional strength, and insulation.

A conceptual drawing of the core barrel and drill head of the hot water/mechanical coring drill appears in Figure 4. The inner barrel will be a composite material to insulate the core from hot water which flows between both barrels to melt chips as they are generated at the cutting head. The core diameter will be at least 20 cm to allow trimming of material that is thermally fractured. A core length of 10 m is limited only by the compressive strength of the ice which is supported by several core catchers. The core catchers produce a stress concentration lowering the force required to break the core loose and serve as retainers while the core is in transit (Fig. 4).

Down-hole instrumentation will consist of the standard electronics package used in the existing electromechanical drill of PICO (Hancock and Koci, 1988) modified to use an ultrasonic distance measuring device for measuring hole diameter. Power to drive the cutting head will be provided by a down-hole mud motor driven by a triplex pump at the surface. Figure 5 shows the details of the new hot water/mechanical coring drill.

Since the downhole mud motor is a standard component used in rock drilling, the system is readily adaptable to standard rock or subsurface techniques available to the mining industry. Standard diamond core barrels have been tested at Longyear in Salt Lake City, Utah. Torque, rpm, weight on bit and pullback requirements are all within the capabilities of the present system. Currently, a standard 94 mm (O.D.) coring system is favored since it allows the use of a casing advancer which permits unconsolidated sample recovery with minimum risk to the drill. Bottom ice samples with less than 5% (by volume) entrained debris can be recovered using the ice coring barrel with cutters modified to accept carbide or diamond faces. Individual pieces of this system are proven technology. However, the pieces have not been tested as a complete system.

3.0 THERMAL MODELING

Before designing a prototype hot water-mechanical drill, we obtained some preliminary findings from analytical heat transfer studies to determine the extent of heat transmission from the drill into the ice core. A very important consideration in this design is to minimize the heat penetration from hot water to the ice core by using an extremely low thermal conductivity material.

During the first phase we have completed the analytical modeling to determine the temperature distribution in a cylindrical ice core subjected to a wide range of temperatures at the boundary due to the circulation of hot water. These temperature distributions can be used by stress analysts to determine if ice cores will crack due to thermal stress under hot water drilling. Three methods, modeling an infinite cylinder, a semi-infinite cylinder and a finite cylinder have been investigated. Here we will briefly outline the case of a finite cylinder model, which is more realistic than the other two models. The approach entails solving the heat conduction equation in cylindrical coordinate system.

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

In equation (1), $T(r,z,t)$ is the variable temperature at a point whose radial and axial coordinates are r and z. Here t represents the time and α the thermal diffusivity of ice. The boundary and initial conditions are:

$$\begin{aligned} &T(b, z, t) = T_s, \text{ the surface temperature;} \\ &T(r,z,o) = T_0, \text{ the initial temperature.} \end{aligned} \tag{2}$$

The solution of this type of problem can be written as the product of two one-dimensional solutions, assuming the problem to be linear and homogeneous (Myers, 1987). The product solution is comprised of heat conduction solution for a slab whose thickness is equal to the height of the finite cylinder, and that of an infinite cylinder. The conventional method of solving this heat transfer problem in a general form is to nondimensionalize the governing equation (1) and boundary and initial conditions (2) using the following dimensionless variables.

$$\Theta_{FC} = \frac{T_s - T}{T_s - T_o}; \quad R = \frac{r}{b}; \tau = \frac{\alpha t}{b^2} \tag{3}$$

Here Θ_{FC} is dimensionless temperature, R the dimensionless radial location, b the ice core radius, and τ the dimensionless time. See Figure 6(a) for the geometry of the cylindrical core.

Detailed derivations of the analytical procedure to obtain the solution are presented in the report by Das *et al.* (1991). The final result in the dimensionless form appears as

$$\Theta_{FC}(R,Z,\tau) = \left[2\sum_{m=1}^{\infty} e^{-\beta_m^2 \tau} \frac{J_0(\beta_m R)}{\beta_m J_1(\beta_m)}\right] \left[\frac{4}{\pi} \sum_{m=1,3,5,\ldots}^{\infty} \frac{1}{m} e^{-(m\pi)^2 \tau (b/L)^2} \sin(m\pi Z)\right] \tag{4}$$

Here L is the length of the finite cylinder and $Z = z/L$ is the dimensionless axial location in the ice core. In equation (4), β_m's are positive roots of the Bessel function

$J_0(\beta_m) = 0$. We have incorporated these roots and the equation in a comprehensive computer program which is listed in the report of Das *et al.* (1991). Another computer program combining the infinite cylinder program and the slab program is also incorporated in Das *et al.* (1991). This report also summarizes results on how fast a core can warm up for different boundary temperatures and what is the risk of melting the core.

Figure 6 (a and b) present the ice core geometry and dimensionless temperature profiles in a finite cylinder based on equation (4) which has been solved by the computer program presented in Das *et al.* (1991). The curves in Figure 6 (b) are computed for a nondimensional Z coordinate of 0.2 which represents a height of 20% above the base of the cylinder, and a length to radius (L/b) aspect ratio of 2. For different axial locations and aspect ratios these parameters in the program can be easily changed and similar plots can be reproduced. Comparison of results in Das *et al.* (1991) clearly shows that for large aspect ratios the finite cylinder approach and the infinite cylinder approach essentially yield the same temperature profiles, as normally would be expected.

Example: Let us look at a sample case of finding the temperature in an ice core. Consider an ice core of 20 cm (8 inches) diameter and of the same length. Find the temperature at r = 8 cm and z = 4 cm after 375 seconds if the initial and surface temperatures are $T_0 = -40°C$ and $T_s = 0°C$ respectively. From given data the radius b = 10 cm, and the thermal diffusivity of ice $\alpha = 1.33 \times 10^{-6}$ m²/s. Therefore, dimensionless time $\tau = \alpha t/b^2$ becomes equal to 0.05. R = r/b = 0.8 and Z = z/L = 0.2 and the aspect ratio L/b = 2. From Figure 6 (b) we read the dimensionless temperature

$$\mathrm{THFC} = \Theta_{FC} = \frac{T_s - T}{T_s - T_0} = 0.325 \qquad (5)$$

which gives $T(r = 8\ cm, z = 4\ cm, t = 375\ sec) = -13°C$.

Using these analytical methods, one can determine the limitation on the core diameter that can be retrieved through thermal coring techniques without jeopardizing the integrity of the core due to excessive penetration of heat. With an objective to expand our modeling capabilities, we are currently developing a finite element program that would be more versatile and be able to handle more realistic field boundary conditions and variation of ice properties. It will further assist us in predicting borehole closure rate in a fluid-filled hole, the outward heat flow from the fluid to the surrounding ice bed, and the inward heat flow into the ice core.

4.0 BOTTOM SAMPLING

In order to access the basal ice and subglacial material (rock, till) shown in Figure 3, we can rapidly drill to that level with the hot water drill, which is an existing technology (Engelhardt *et al.*, 1990). Once basal ice is reached, a downhole mud motor and core barrel (Figs. 4 and 5) replace the drilling nozzle. The mud motor is a modified Moineau type of positive displacement pump. For ice core drilling, warm water will be used to melt chips created during the drilling process. The drill thus requires no chip storage area, unlike the electromechanical drill, which shortens the length considerably. As a result, cores up to 10 m in length are retrievable. Core diameter is expected to be between 20 and 30 cm. Eventually, an insulated core barrel would be considered to allow coring operation in ice to -40°C. Modeling efforts to date demonstrate that it is feasible to retrieve core by this thermal technique.

Methods for sampling ice with entrained debris, saturated till, or bedrock will rely on off the shelf wireline coring technology. Core diameter will be smaller due to increased power requirements and pullback forces required to break the core. Since the mud motor is already adapted for these purposes, modifications are expected to be minimal. Chip storage will be required for rock debris if subice penetration goes beyond a few meters.

5.0 TESTING

Presently two sizes of the prototype hot water-mechanical coring drill: one for a 15.24-cm (6-inch) core and the second for a 20.32-cm (8-inch) core are under development at the University of Alaska Fairbanks. Upon completion, these prototype drills will be tested at the ice drill test well that was completed in the Fall of 1990. A brief description of the capabilities and specifications of this test well follows.

5.1 Well Details

The test well was constructed by the University of Alaska in the test yard of the U.S. Army off Farmers Loop Road in Fairbanks, Alaska. Its casing consisted of a steel pipe 101.5 cm (40-inch) outside diameter, 0.95-cm (3/8-inch) thick wall with a length of 13.63 m (44 feet 9 inches). A bottom plate has been welded to it by water-tight seal weld. Approximately the top 1.5 m (5 feet) of the well is surrounded by the active layer and the rest, 12.1 m (39 feet 9 inches), of it is surrounded by permafrost, guaranteeing fully-frozen condition for any water in the test well.

5.2 Cooling System

The ice test well is provided with its own refrigeration system to freeze the volume of water in the well in a shorter period of time than the natural freezeup period to provide more time for testing the drills. The refrigeration system has five U-shaped coils circulating a 60% solution of ethylene glycol. The circulating fluid is cooled by two air-cooled heat exchangers connected in series with a flow rate of 1.82×10^{-2} m^3 (4 gal) per minute. Both units together can provide a cooling rate of 786 kJ

(745 BTU/min) to freeze the test well when the ambient temperature reaches −28.9°C (−20°F). The cooling system is complete with piping, manifolds, circulating pump, expansion tank, air bleed and separator, arctic grade connecting hoses and series of valves in the loop. For filling ethylene glycol, hose bib and barrel pump are available with the system.

5.3 Other Amenities

Both 3 phase, 230 V, 100 Amp and single phase, 120 V, 20 Amp services are available at the test site from the main power line through a number of receptacles. They can provide the necessary power for instrumentation and measurements and also for running power tools. Thermal measurements can be easily achieved within the ice test well by means of a string of thermistor sensors.

In the winter of 1990/1991 successful freezing of this ice test well was demonstrated. Preliminary ice core drilling was also performed with PICO's existing drills that showed promise for future testing of all types of ice drills at this facility before these drills are shipped out to the field for actual operation.

6.0 CONCLUSIONS

Hot water drilling has been successfully conducted by PICO in both Greenland and Antarctica, and this technology is mature now. Deep drilling by electromechanical coring drills have also been successfully conducted by PICO. The present thrust is centered around combining both systems to develop a hybrid thermal mechanical drill. The drill head and core barrel have been conceptually designed and many common parts and instrumentation package from the earlier coring drills have been retained. The success of these components in older drills and modeling studies show that we can use these techniques to recover good quality ice cores in temperate ice, say about -10°C (14°F). PICO's electrothermal drills have shown good cores in this temperature range. After the testing phase of the prototype, work should continue to make this system work for even colder ice, say up to -40°C (-40°F) at great depths and also in subice bottom sampling.

7.0 ACKNOWLEDGEMENT

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FIGURE CAPTIONS

Figure 1. Components of the water heating system and the well. Adapted from Verrall and Baade (1984).

Figure 2. Schematics of PICO deep hot water hose. Notice the instrumentation wires embedded within the hose wall next to Kevlar® casing.

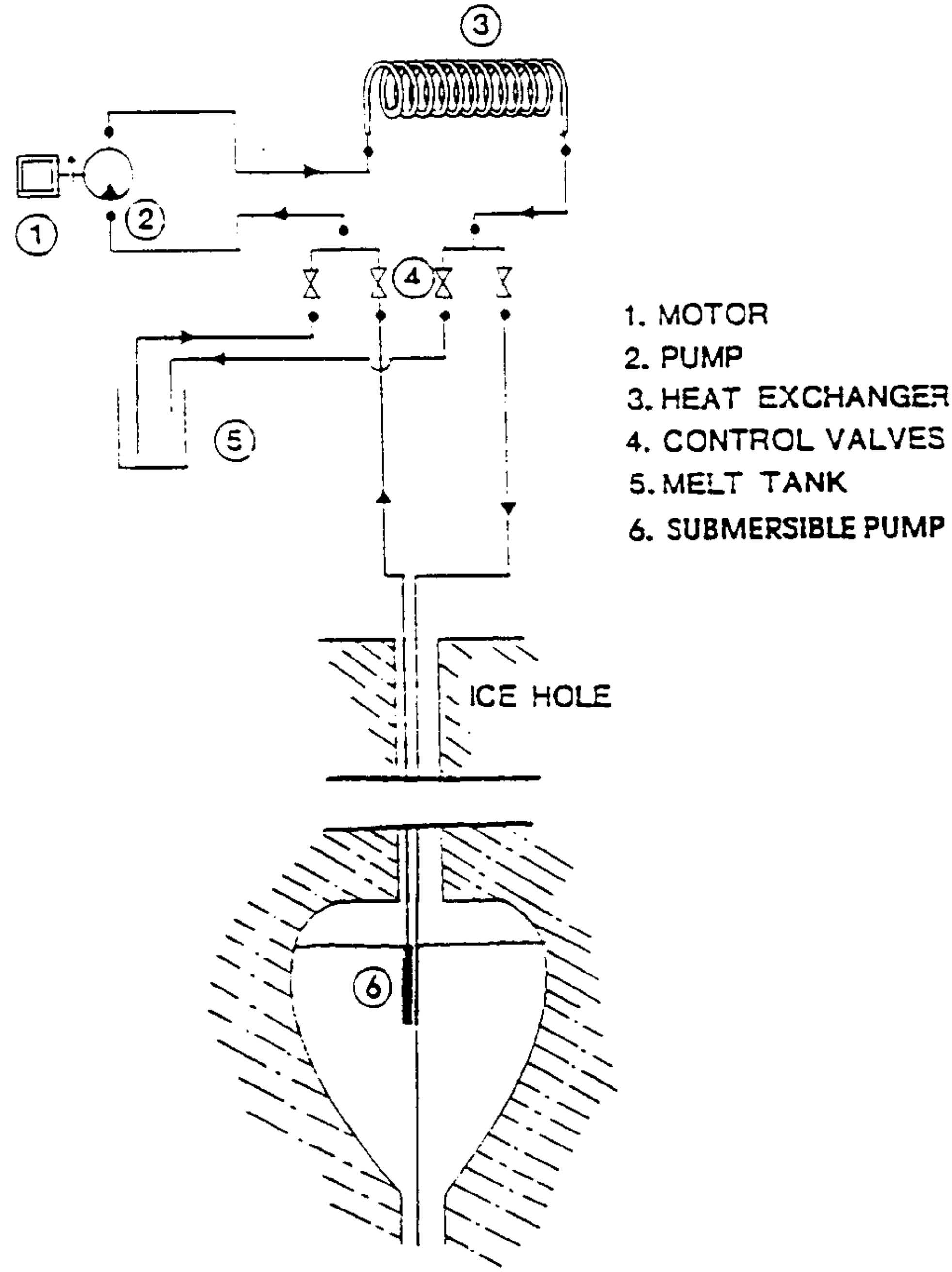
Figure 3. Illustration of various drilling systems and their capabilities.

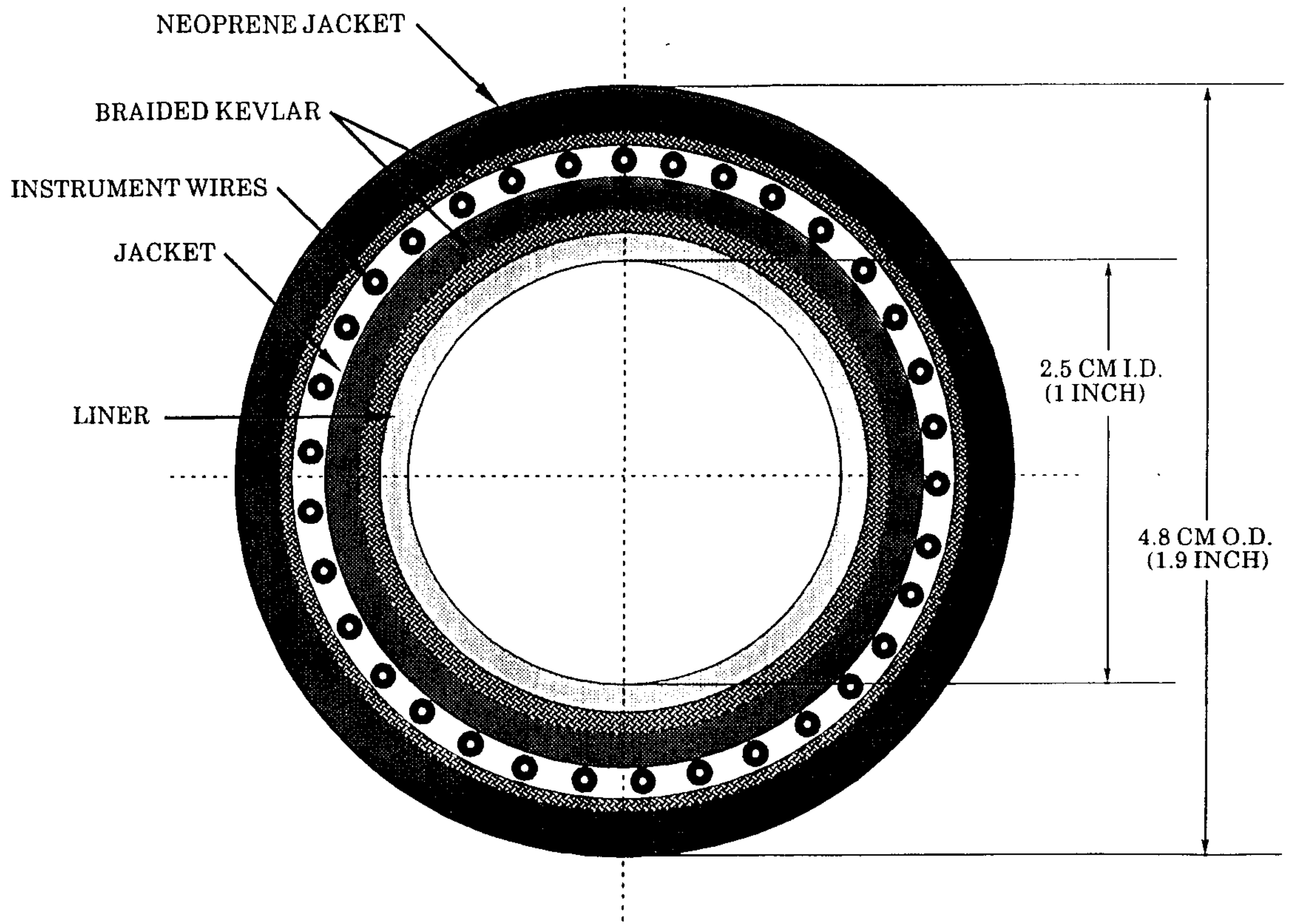
Figure 4. A conceptual drawing of the core barrel and drill head of the new hot water/mechanical drill. Tubes supply fluid to wash/melt ice chips. Core catchers can be seen inside the head.

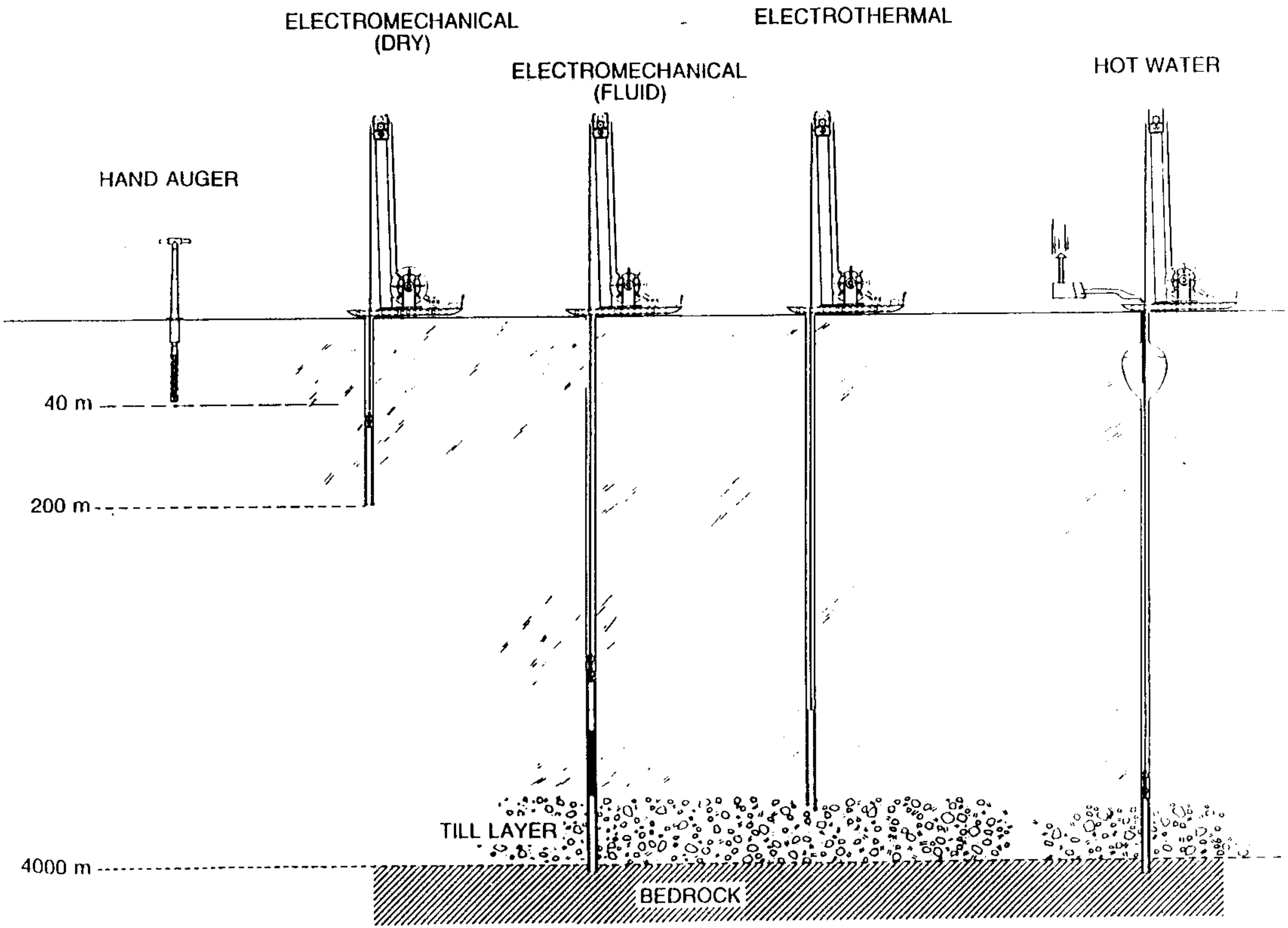
Figure 5. Schematic of the hybrid hot water/mechanical ice coring drill.

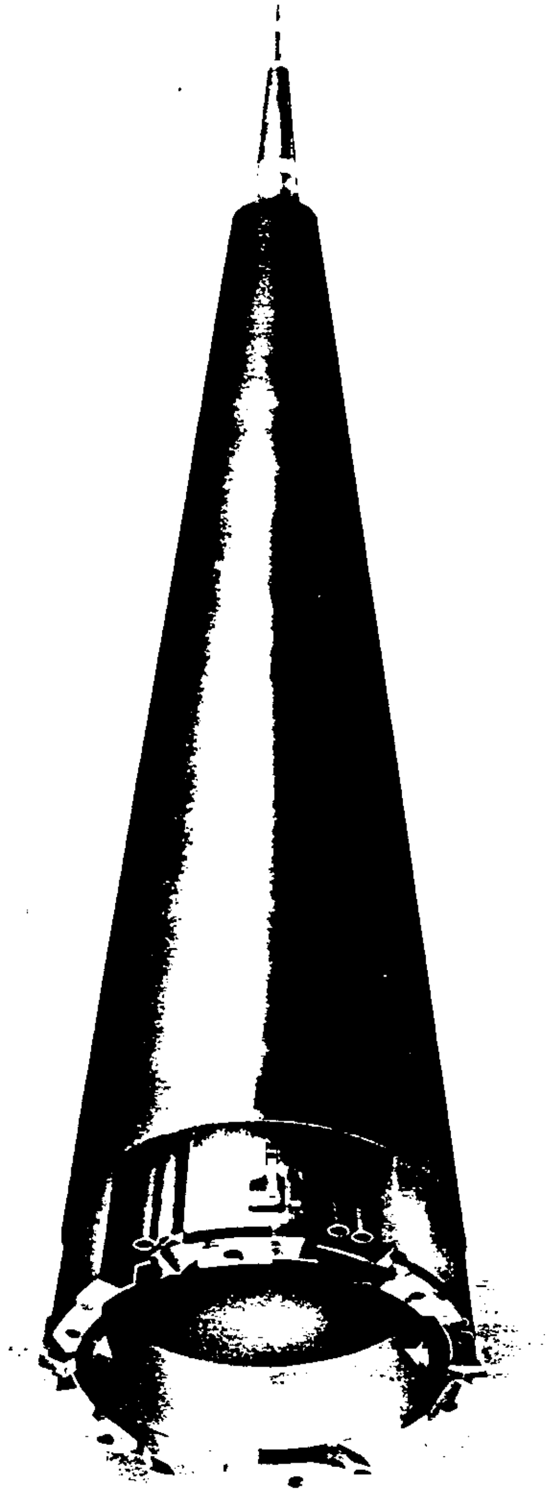
Figure 6. (a) Cylindrical geometry of the ice core. (b) Temperature distribution in a finite cylindrical ice core at various time periods for $Z = 0.2$ and $L/b = 2$. THFC and TAU are dimensionless temperature Θ_{FC} and dimensionless time τ expressed in equation (3).

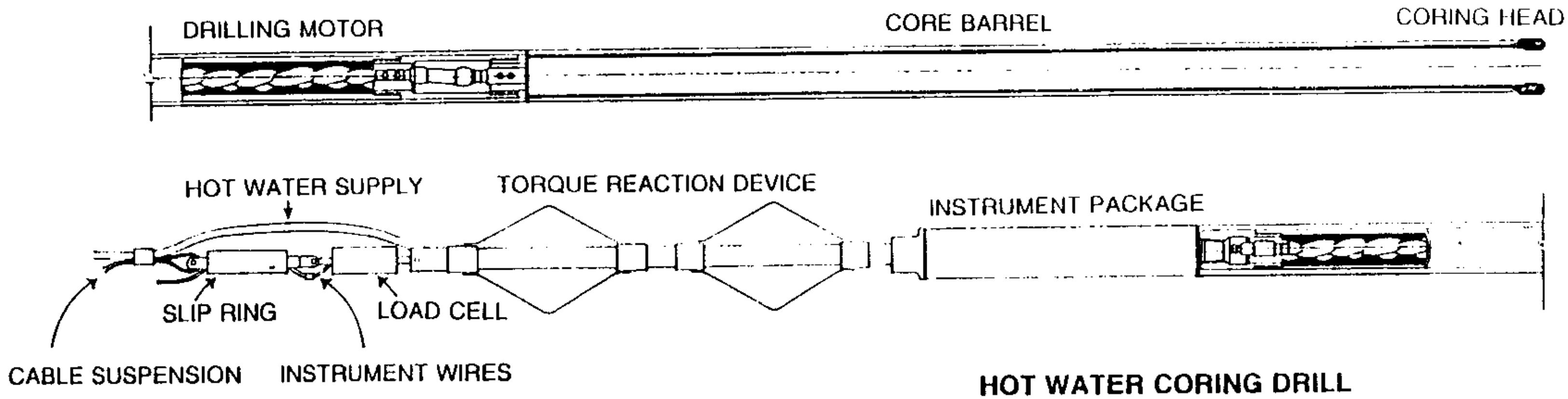
Fig. 1


1. MOTOR
2. PUMP
3. HEAT EXCHANGER
4. CONTROL VALVES
5. MELT TANK
6. SUBMERSIBLE PUMP
ICE HOLE


NEOPRENE JACKET
BRAIDED KEVLAR
INSTRUMENT WIRES
JACKET
LINER
2.5 CM I.D.
(1 INCH)
4.8 CM O.D.
(1.9 INCH)

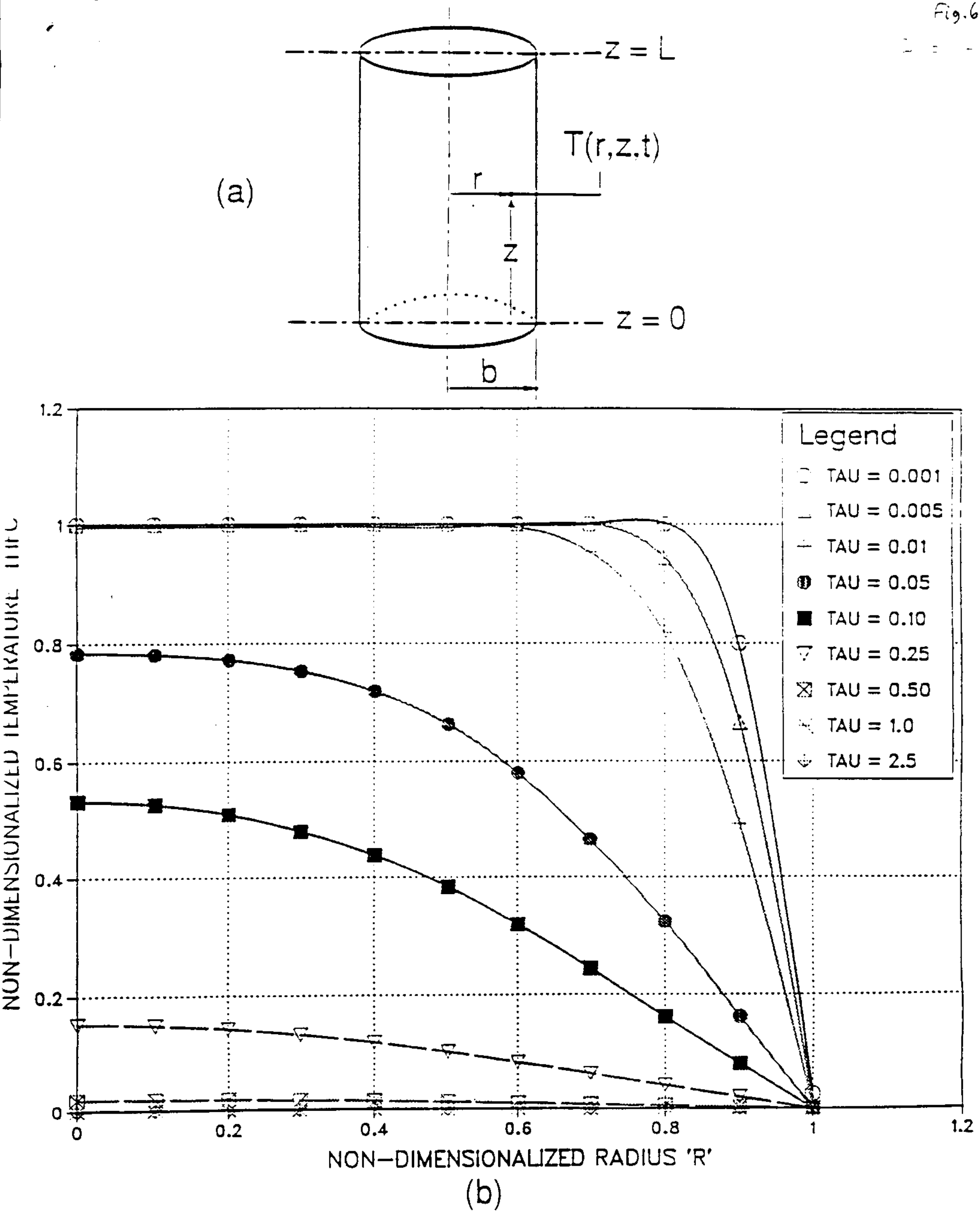

ELECTROMECHANICAL (DRY)
ELECTROTHERMAL
ELECTROMECHANICAL (FLUID)
HOT WATER
HAND AUGER
40 m
200 m
TILL LAYER
4000 m
BEDROCK





HOT WATER CORING DRILL

Fig.6



z = L
T(r,z,t)
(a)
r
z
z = 0
b
Legend
TAU = 0.001
TAU = 0.005
TAU = 0.01
TAU = 0.05
TAU = 0.10
TAU = 0.25
TAU = 0.50
TAU = 1.0
TAU = 2.5
NON-DIMENSIONALIZED RADIUS 'R'
1.2
0.8
0.6
0.4
0.2
0
1
(b)