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Deep ice coring at Vostok Station (East Antarctica) by an electromechanical drill

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Abstract: A deep bore-hole 5 G at Vostok Station (East Antarctica) from the depth of 2755 m was drilled by electromechanical drill KEMS-132. During wintering of the 40th (1995) Russian Antarctic Expedition and summer seasons of the 41st (1995/1996), 42nd (1996/1997) and 43rd (1997/1998) RAE the bore-hole was deepened from 2755 to 3623 m.

At present the bore-hole 5 G has a complicated stepwise structure. The casing with an inner diameter of 165 mm insulates the upper 120 m of the hole from permeable firn. From 120 m to 2200 m the diameter of the hole is 153 mm. In the deeper sections of the hole its diameter decreases to 139 mm (between 2200 and 3095 m), 138.4 mm (3095-3321 m), 137.9 mm (3321-3500 m)-136.2 mm (3500-3570 m), and 135 mm (3570-3623 m).

The drilling fluid, a mixture of kerosene and Forane F-141b as densifier, has an average density of 928 kg/m^3. Its level in the hole is maintained at a depth of 95 m. The difference between the overburden pressure of ice and the hydrostatic pressure of the fluid at the bottom of the hole is estimated to be about 0.1 MPa. Accordingly, the rate of bore-hole closure at the bottom is calculated to be less than 0.1 mm/year.

Data regarding the technology of drilling by electromechanical drill KEMS-132 (description of drilling complex, electromechanical drill, casing, stability of the bore-hole) are given.

1. Introduction

The drilling of deep bore hole 5 G at Vostok Station was started from the surface in 1990, by the 35th Soviet Antarctic Expedition (SAE), using TELGA (Bobin *et al*., 1994) and TBZS (Kudryashov *et al*., 1991) thermal-type drills (the Russian abbreviation TELGA means Thermal Electrical Drill designed in The Leningrad Mining Institute and Arctic and Antarctic Research Institute; TBZS means Thermal Drill for bore-holes filled by liquid). In 1993, 38th Russian Antarctic Expedition (RAE), thermal drilling of the hole was stopped at a depth of 2755 m.

In 1994 (39 RAE), because of financial and logistic problems, Vostok Station was closed and the drilling operations suspended. During the 40th RAE (1995), the drilling of hole 5 G was resumed from a depth of 2755 m with a KEMS electromechanical drill (the Russian abbreviation KEMS means core electromechanical drill) and continued down to 3109 m in the routine mode of operation.

Beginning from the 41st RAE (1997), the drilling operations at Vostok have been reduced to short Antarctic seasons because of a general cut in funding for the Russian Antarctic Expedition. After 1995-96 (41st RAE), 1996-97 (42nd RAE) and 1997-98 (43rd RAE) field seasons the hole 5G reached a depth of 3623 m. Since 1993 ice coring

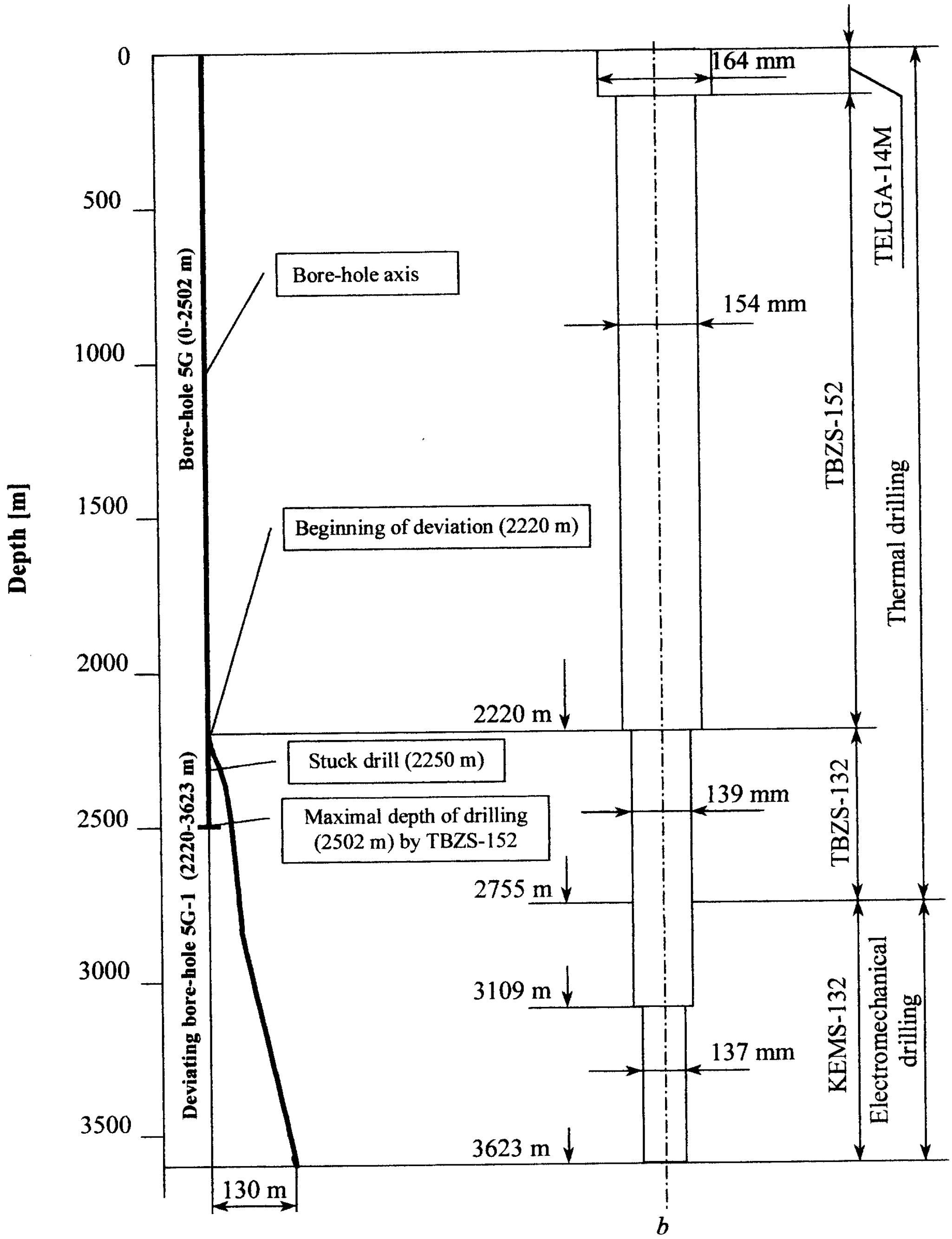

Fig. 1. Bore holes 5G and 5G-1: a-inclination; b-scheme of bore-hole.

and core research at Vostok Station have been continued as a collaborative effort between Russia, France and the USA.

2. Bore-hole

At present the bore-hole 5G has a complicated stepwise structure as shown in Fig. 1. The casing with an inner diameter of 165 mm insulates the upper 120 m of the hole from permeable firn. From 120 m to 2200 m (thermal ice coring with TBZS-152 drill, where 152 denotes the outer diameter of the drill head in mm), the caliper (minimal) diameter of the hole is 153 mm. In the deeper sections of the hole its caliper diameter successively decreases to 139 mm (between 2200 and 3095 m), 138.4 mm (3095–3321 m), 137.9 mm (3321–3500 m)–136.2 mm (3500–3570 m), and 135 mm (3570–3623 m).

At first, the deep bore-hole 5G was drilled to 2500 m with a TBZS-152 thermal drill. After reaching this depth, the drill became stuck at 2250 m depth level during routine pulling-up operation. By applying high tension the cable was broken out of the suspension clip at the top of the drill and pulled out from the hole. This allowed us to start a new hole, 5G-1, by making a deviation from the old trunk 5G at approximately 2200 m depth level, that is, about 50 m above the lost drill. The initial caliper diameter of the hole 5G-1 drilled with a TBZS-132 thermal drill down to 2755 m was 133 mm. Before employing a KEMS-132 electromechanical drill (the outside diameter of the cutters is up to 135 mm), the hole between 2200 and 2755 m was enlarged up to a diameter of 139 mm. Since then, the ice coring has been continued with the mechanical drill and the newly drilled parts of the hole have been enlarged in a systematic way as drilling advanced. As a result, the hole has the stepwise pattern seen in Fig. 1.

The total volume of the fluid in the hole is about 60 m^3. The drilling fluid, the mixture of kerosene and Forane F-141b as densifier, has an average density of 928 kg/m^3 (Pashkevich and Chistyakov, 1989; Talalay and Gundestrup, 1999). Its level in the hole is maintained at a depth of 95 m, near the firn-ice transition. The difference between the overburden pressure of ice and the hydrostatic pressure of the fluid at the bottom of the hole is estimated to be about 0.1 MPa. Accordingly, the rate of the bore-hole closure at the bottom is calculated to be less than 0.1 mm/year.

The hole 5G has a negligible inclination from the surface to the 2200 m depth. In the deeper parts, the deviation of the 5G-1 hole from the vertical ranges from 6 to 8 degrees.

3. Equipment

3.1. Drilling complex

The drilling complex at Vostok station (Fig. 2) includes drilling building 1, tower 2, winch 3 with cable 4, control desk 5, drill 6, drill handling device 7 and DC generator 8. The telemetry control of the drilling process is assured by the system that is able to operate at low temperatures (up to $-60^{\circ}C$), and high pressures (up to 40 MPa) in the bore-hole filled with drilling fluid.

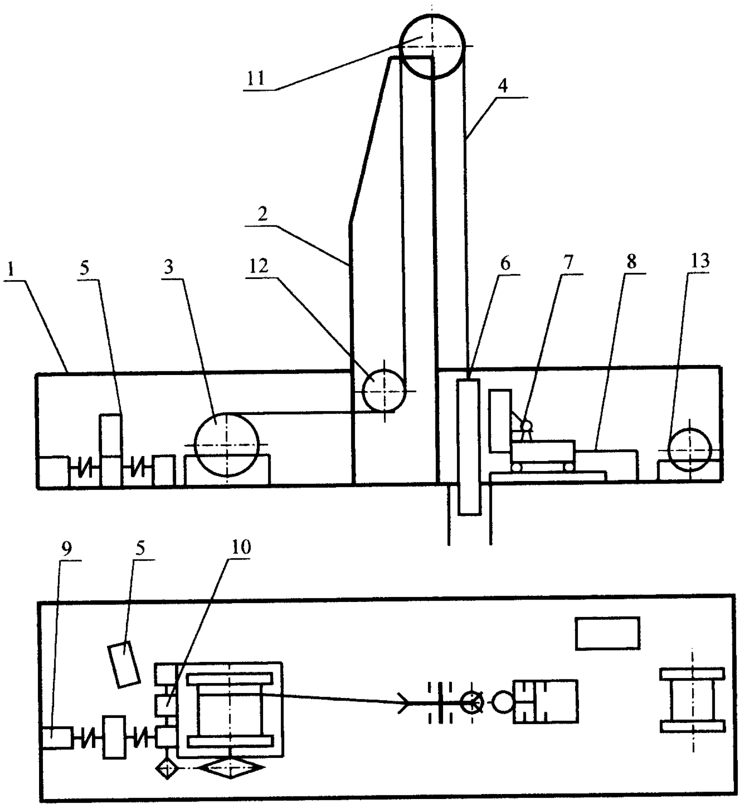

Fig. 2. *Drilling complex at Vostok station: 1-drilling building; 2-tower; 3-hoisting winch; 4-cable; 5-control desk; 6-drill; 7-drill handling device; 8-DC generator; 9-electric motor; 10-worm reducer; 11-pulley; 12-pulley; 13-geophysical winch.*

Technical characteristics of the drilling complex

Length, m	18
Width, m	4
Height, m	3
Height of tower, m	15
Power consumption, kW:	
generator DC	20
electric motor of the winch	20
heating system	12
light	5
Average speed of pulling/lowering operations at maximum depth of the bore-hole (4000 m), m/s	0.7
Cable:	
diameter, mm	16
break force, kN	97
number of conductors	8
specific resistance of one conductor, Ω/km	9

3.2. Casing

Before replacing the thermal drill with an electromechanical one in the upper part of the bore-hole (0–120 m) the casing assembled of fiberglass tubes was mounted in order to insulate the hole from the porous firn strata. All casing equipment (tubes, connections, mechanical reamer, TV camera for observation in hole) was prepared by LGGE (Grenoble, France).

Unlike most of the cases, at Vostok the casing was mounted in the existing deep hole when its depth was already 2755 m. The main difference of this casing from the design utilized in Greenland (Johnsen *et al*., 1994) and at Dome C (see paper in this volume) is the construction of the lower part (Fig. 3).

Before introducing the casing into the hole, the upper part of the bore-hole was enlarged from 180 to 220 mm with a mechanical reamer. Surface holes (6) of the lower casing section were taped and the space between the inner tube (1) and jacket (2) was filled by water. Then water was frozen, tape was removed and an aluminum thermal shoe was attached to the lowest tube.

While tubes were run into the hole, the electric wires were fixed on the surface by clamps. When the shoe (3) of the bottom section reached the ledge at a depth of 120 m the power of thermal element (7) was switched on and the ice began to melt. The casing pulled down smoothly and the heating was stopped when the column had lowered into the ice by 0.5 m. In order to refreeze water near the shoe and to ensure impenetrability of this zone the casing column was left at rest for some time. Then the upper thermal element,

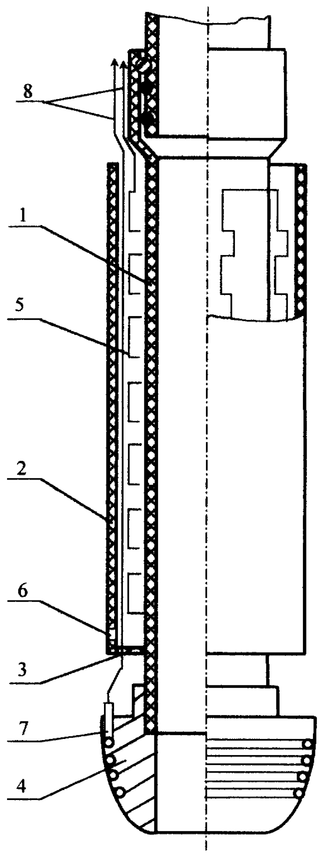

Fig. 3. Bottom section of casing: 1-inner barrel; 2-jacket; 3-bottom of jacket; 4-shoe; 5-nichrome spiral; 6-holes; 7-thermal element; 8-electric wires.

nichrome spiral (5), was switched on, resulting in melting the ice between the inner tube (1) and jacket (2). The total height of the refrozen-water cork that seals the casing to the ice is estimated to be about 2 m.

The behavior of the casing, especially its lowest section, during running was controlled using a TV camera. Observation of the casing bottom revealed the absence of icicles or oozings on the surface of the hole below the shoe.

Then the liquid level was raised but it was impossible to raised it above 42 m from the surface (the level of liquid was measured by a special sensor with accuracy of ± 0.05 m). At first, we decided that the casing was leaking at the depth of 42 m, but then tests with air compressed in the casing showed that casing is water proof. In further drilling the liquid level was at the depth from 66 to 104 m, higher than the depth of the permeable zone at Vostok station. This means that bottom of the casing is water proof too.

3.3. Electromechanical drill

A schematic of the KEMS-132 electromechanical ice-core drill (Kudryashov *et al.*, 1994) is shown in Fig. 4. The electromechanical ice core drill operates in the following mode. The rotation from the rotor of the electric motor (5) is transmitted, through the reducer (4), to the core barrel (2) and the drill head (1). The ice chips carried by the fluid current are collected by the filter (3). The fluid sucked up by the pump (6) flows through the holes that are made in the shafts of the reducer and electric motor. After passing through the filter the clean fluid flows away from the drill. The antitorque system (7) prevents rotation of the upper part of the drill during coring.

Technical characteristics of KEMS-132 ice core drill

Diameter of drill head:	
-outer, mm	135
-inner, mm	106
Length of core barrel, m	3
Driving motor:	
-voltage, V	three-phase AC 220
-rotation speed, r/m	2800
Rotation speed of drill head, r/m	90–220
Average rate of penetration, m/h:	
in ice up to	20
in subglacial rocks up to	1.5
Length, m	8–13
Weight, kg	240

4. Performance

The work of the drill on the bottom includes the following major processes: 1) destruction-cutting of ice; 2) cleaning of the hole bottom from the ice chips; 3) collecting of ice chips in the filter. These three processes are interrelated and affect each other.

The key parameters of an electromechanical drill that controls the efficiency of ice coring are: 1) geometrical characteristics of cutters; 2) speed of drill head rotation (speed of cutting); 3) cutting depth per revolution of the drilling head (shaving thickness); 4)

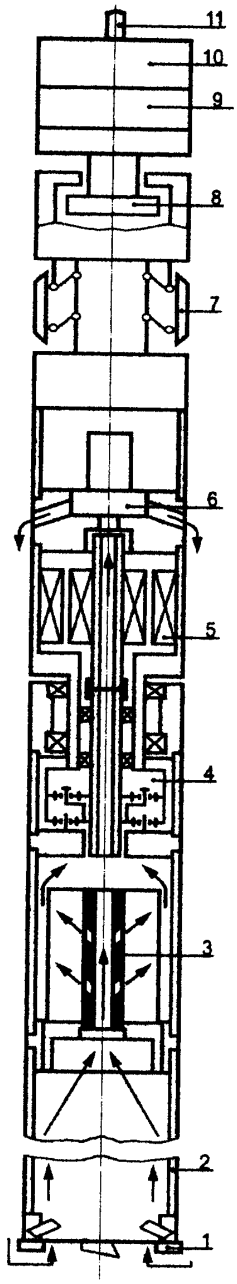

Fig. 4. Electromechanical ice core drill KEMS-132: 1-drill head; 2-core barrel; 3-chip chamber including chip filter; 4-reducer; 5-driving electric motor; 6-pump; 7-antitorque system; 8-hammer block; 9-electric chamber; 10-cable suspension clip; 11-cable.

design of the filters and channels for ice-chip collection; 5) parameters of the pump, creating near-bottom circulation of a fluid.

The beginning of the coring with an electromechanical drill was characterized by gradual increase of the length of a drilling run (Fig. 5), as drillers became more experienced. Then the drilling stabilized at an average run length of about 2.8 m. Deeper than 2930 m, the instability of drilling appeared again, now progressively increasing with depth. Particularly, unexpected jamming of the drilling head often occurred even at low drilling pressures, that is, at penetration speeds of about 1 m/h or less. The increasing of the fluid density by addition of a significant amount of the densifier (Forane F-141b) has made it possible to stabilize the process at the beginning of the 41st RAE season. However, by the

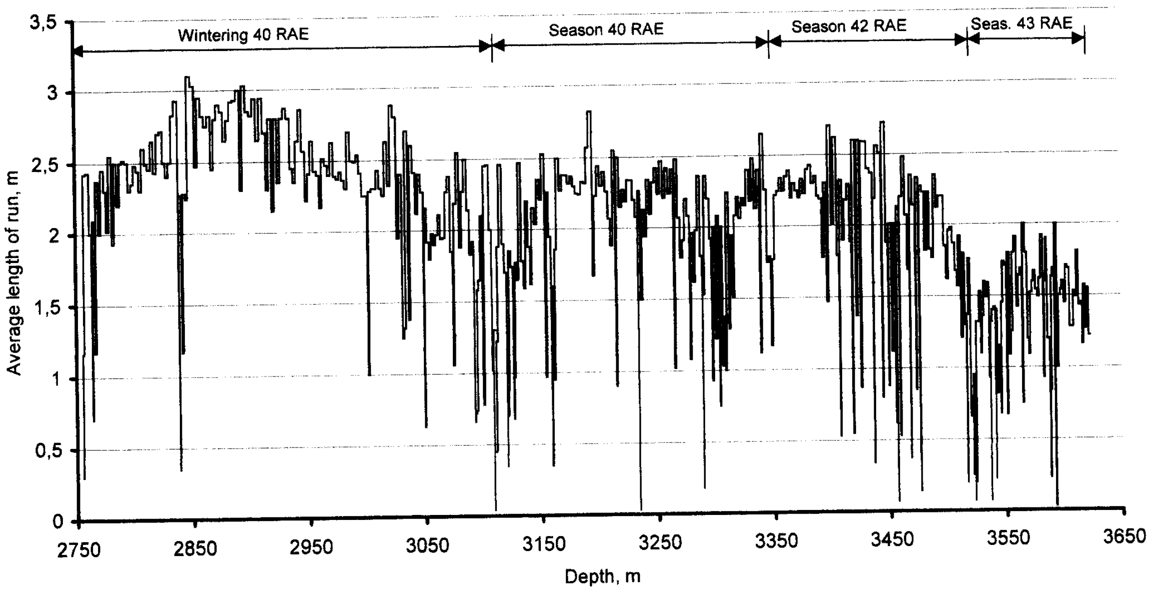

Fig. 5. Average length of run versus drill hole depth.

end of this season, in spite of all possible measures applied, the length of a drilling run was decreasing dramatically, and eventually the drilling operations were practically stopped.

In the next field season, certain changes were brought into design of the drill which allowed resumption of the drilling operations. However, at the end of this season the decrease in the length of a drilling run (up to complete stop of coring) occurred again. It is worth noting that in the two latter cases the stoppage of coring was not associated with jamming of the drill head. Efficiency of drilling was reduced dramatically, and sticking of the drill head due to the presence of ice chips at the hole bottom was occurring immediately after beginning of a drilling run. Interestingly, the problems with penetrating the ice mostly occurred in the ice strata formed under warm (interglacial) climatic conditions as indicated by the isotope content of the recovered ice core. These "interglacial" ice strata are characterized by coarse-grained ice texture in contrast to "glacial" strata that are typically represented by fine-grained ice.

In spite of improvements in the design of some units of the drill, at the beginning of the 43rd RAE season the drilling was unstable again. Only after certain changes in the geometry of the cutter aimed to decrease sticking of the ice chips to the drill head was the drilling continued. The basal section of the ice sheet in the vicinity of Vostok Station is characterized by elevated temperature (-10°C). In cases when the near-bottom fluid circulation slightly differs from its normal mode, the ice chips can stick together and form an icy shoe, which does not allow further ice cutting. All cutters used had a clearance angle of about 5°. Ice chips, sticking on the bottom side of the cutters, form a sort of icy platform, on which the rotating drill head (Fig. 6) can slide in the hole without jamming without penetrating the ice. To prevent sticking, the clearance angle was increased up to 15°; in addition, the cutters and the body of the drill head were covered with a thin Teflon layer. These measures have made it possible to significantly increase the efficiency of ice destruction and chip removal from the hole bottom. As the result, ice coring during the 43rd RAE season was performed in the routine mode of operations.

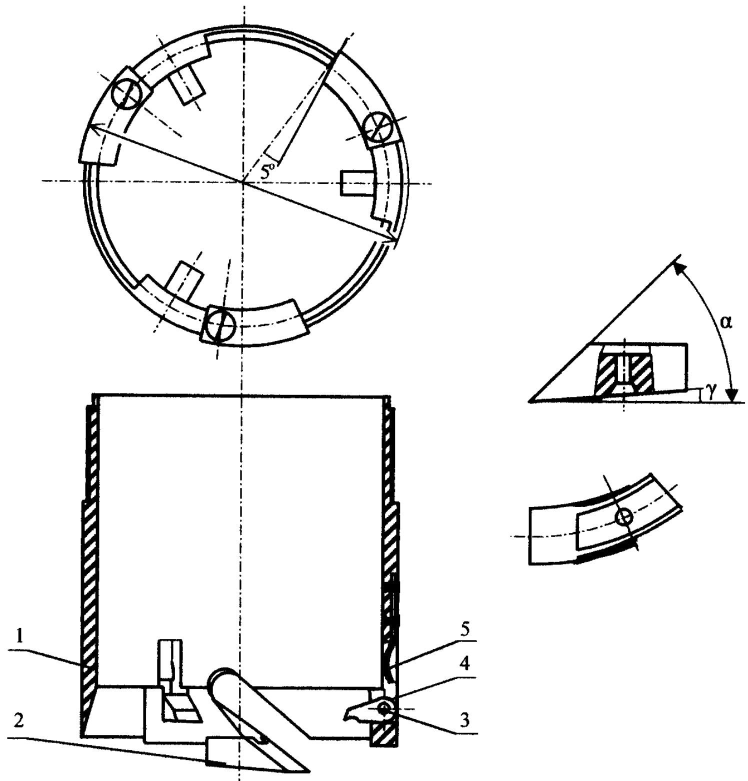

Fig. 6. *Drill head: 1-body; 2-cutter; 3-axis; 4-core catcher; 5-spring (icy platform during drilling in warm ice is marked by black).*

In order to improve collecting of ice chips in the chip chamber (due to increase of the chip density), the diameter of the filter pipe was enlarged by a factor of two. This modification made it possible to slightly increase the density of ice chips. However, this density continued to decrease as the drilling advanced in the basal stratum of the ice sheet formed by accreted ice. It appears that the structure and density of ice chips substantially depend on the textural properties and the temperature of the destroyed glacier ice.

5. Stability of the bore-hole

To prevent hole closure, the bore-hole is filled with a drilling fluid. The hydrostatic pressure of the fluid in the hole can be estimated by using the following two techniques: (1) direct pressure measurements by pressure gauge, and (2) calculation of the fluid pressure based on accurate density measurements performed on the fluid samples that were collected at different depths in the bore-hole.

In the present paper we present only the results obtained by the latter method. The data obtained with the pressure gauge that was employed for the fluid pressure measurements in the hole 5 G after the drilling had been stopped will be discussed elsewhere.

Before the switch from thermal drilling to mechanical drilling, the average density of the hole fluid was about 880 kg/m^3. At that density the difference between the ice pressure and the fluid pressure at the hole bottom exceeded 10 bars provided the fluid level was maintained at 80 m below the surface.

To decrease the pressure difference, a large amount of drilling fluid was removed from the hole so that the fluid level dropped down to 300 m below the surface. Then the bore-hole was filled again from the surface with 6 tons of halogenated solvent and 2 tons of Forane F-141b as densifiers. From a simple estimate, the fluid level after addition of such amount of the densifiers should be found at a depth of 40 m. However, the fluid level was measured to be 120 m below the surface. Measurements of the liquid density in the hole (Figs. 7 and 8) have shown, that the pressure of fluid at the hole bottom did not

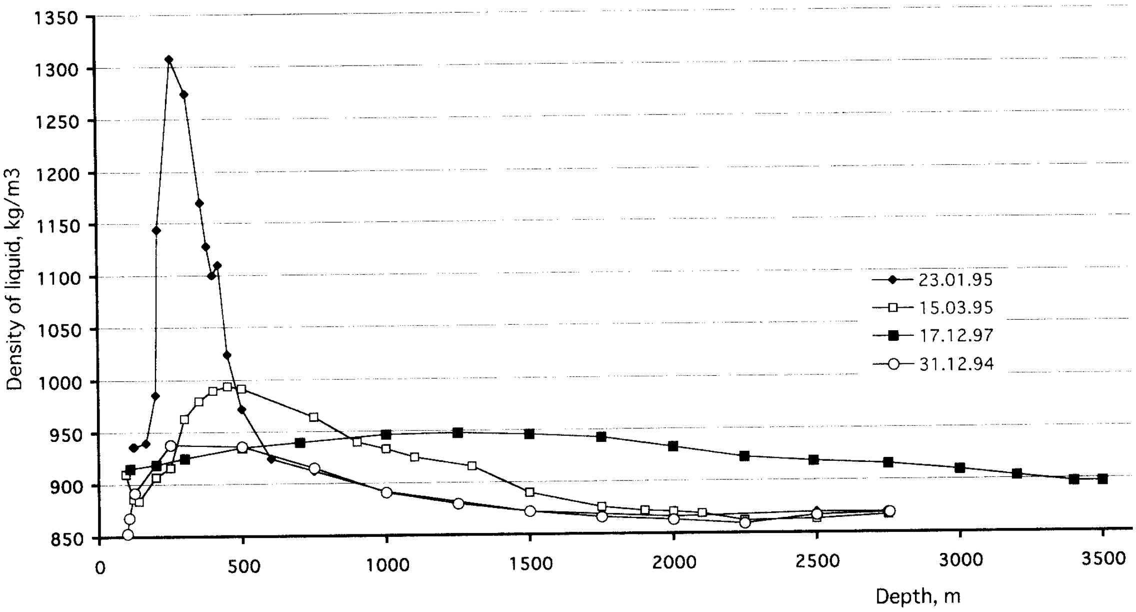

Fig. 7. Density of the hole liquid versus drill hole depth.

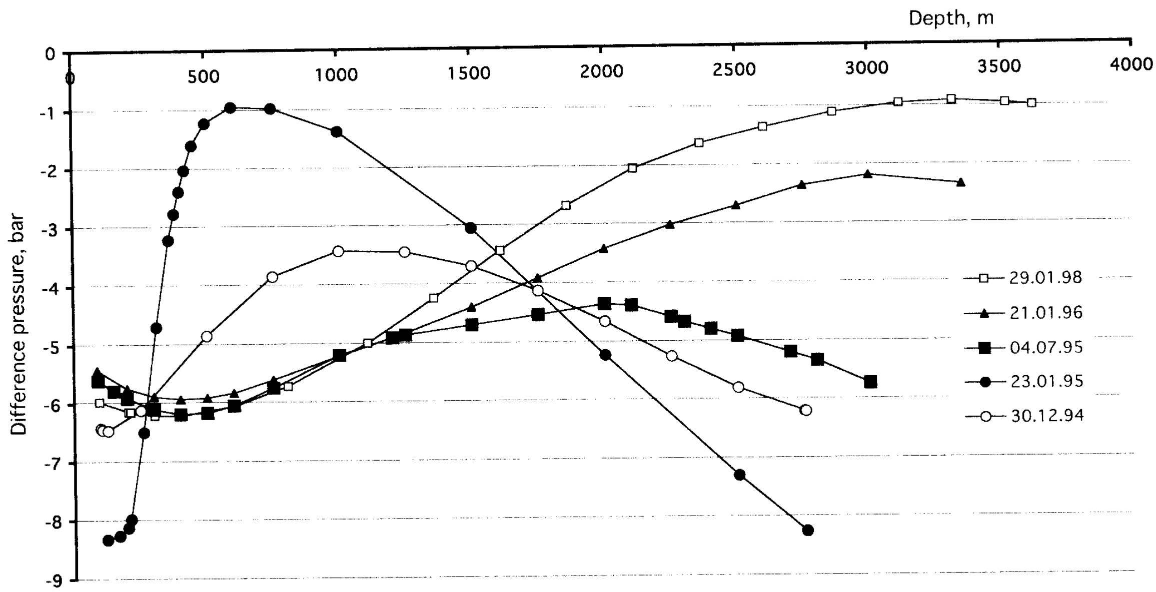

Fig. 8. Difference between the ice pressure and the liquid pressure versus drill hole depth (pressure of liquid is calculated due to measured density of liquid).

change significantly and thus two tons of densifier was been lost in the hole.

It is possible that a significant amount of heavy fluid entered into cracks in the wall of the hole when the fluid level was only 300 m below the surface. As in the case of the fractured ice core that was retrieved from the brittle zone in the ice sheet, these cracks in the hole could occur because of the high pressure in air bubbles in ice.

We have an alternative opinion on this phenomenon. According to preliminary calculations the pressure difference at the depth of 600 m should be equal to 10 bars. However, based of the results of pressure measurements in the bore-hole the fluid pressure at this depth was less than 1 bar than the ice overburden pressure. It is possible that at the depth of 600 m hydraulic fracture had taken place and part of the heavy liquid left the bore-hole 4G. The mouth of the bore-hole 4G was situated 20 m from bore-hole 5G. It was not possible to check this assumption because the hole 4G was plugged by ice chips. The lost densifier did not return to the hole after the drilling was restarted. This fact indirectly supports the latter hypothesis.

The experience with the lost drilling fluid was taken into account to avoid similar accidents during continuation of the operations. For addition of the densifier into the hole, a special device (tanker) was employed which allowed delivering of the densifier to the desired depth in the bore-hole. By doing so, step by step the fluid density profile was "flattened", as can be seen from density-depth curves based on regular density measurements (see Fig. 7). Shown in Fig. 9 are the data on fluid level changes since the time when operations with the electromechanical drill were started.

The analysis of the data presented in Figs. 7 and 9 reveals interesting behavior of the fluid level in the hole. By comparing the data on fluid density and level, one can come to the conclusion that it is impossible to create in the present hole fluid pressure exceeding

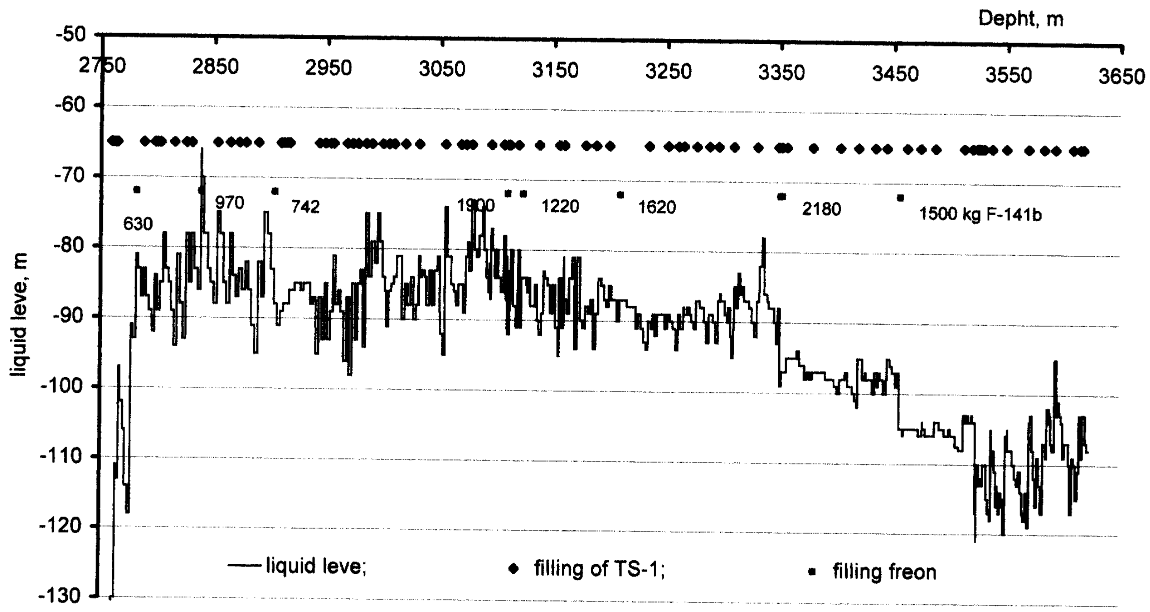

Fig. 9. Diagram of liquid level for drilling by electromechanical drill (the current depths at which the kerosene was poured into the hole are indicated by rhombi; the depths of the densifier pouring are indicated by squares; the figures show the amount of densifier delivered into the hole).

the overburden pressure of ice. This is illustrated by decrease of the fluid level in the last two cases of the densifier addition, and by data of regular measurements of fluid pressure in the bore-hole (Figs. 7 and 9).

6. Conclusions

The experience of deep drilling at Vostok station is unique. The equipment and the technology of drilling at various specific conditions were repeatedly modified to achieve in each case the optimal mode of operation, the maximal productivity of coring and better quality of the ice core retrieved. The data obtained during deep drilling at Vostok Station allow better understanding of the problems that one may face when drilling in the deep and cold ice.

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