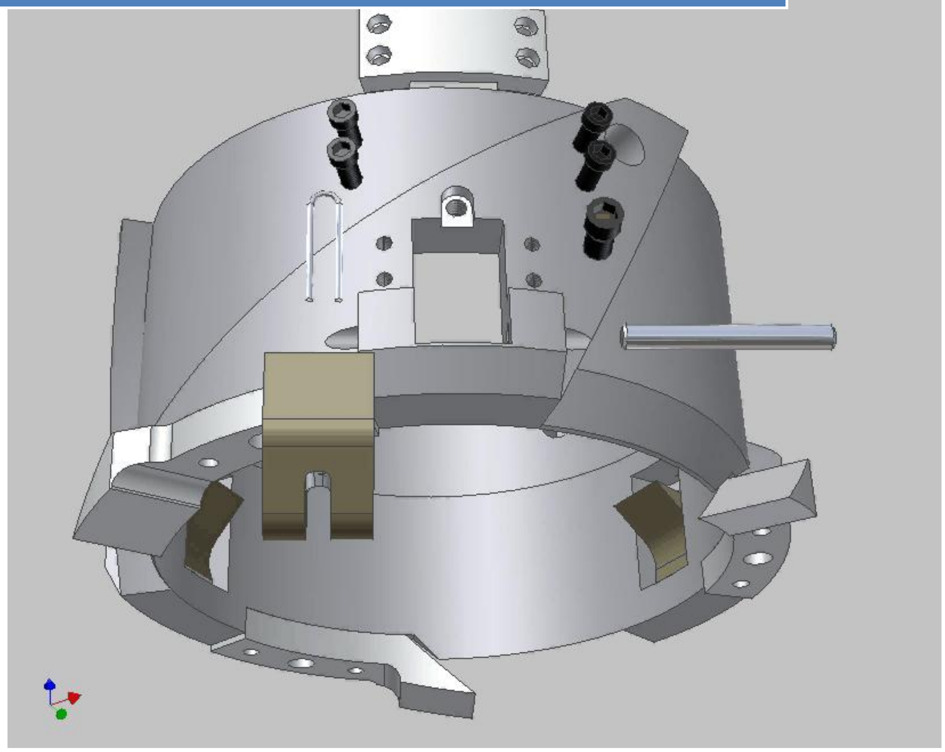
Technical Report
PRC 12-03

DRILL HEADS OF THE DEEP ICE ELECTROMECHANICAL DRILLS



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Abstract: Electromechanical drilling is widely used for recovering deep ice cores in Antarctica and Greenland. Choosing an optimal drill head design is one of the most important challenges for the development of ice drilling technology because it affects not only the efficiency of the ice cutting action, but other important drilling parameters: rate of penetration, core quality, length of the run, borehole trajectory, etc. Different schemes of ice-core drill heads are reviewed, and recommendations for designing are given.

Cover: Drill head from Hans Tausen electromechanical drill, shoes are not shown (*S.Hansen. IPY International deep ice core drilling project NEEM 2007-2011.* Second Symposium "Polar Earth Sciences and Exploration", 15th September, 2011, Jilin University, Changchun, China)

Contents

1. INTRODUCTION

Drilling operations in the Polar Regions are complicated by extremely low temperatures at the surface and within glaciers, glacier flow, the absence of roads and other infrastructure, storm winds, snowfalls, etc. In principle, it would be possible to use conventional rotary drilling technology for coring in ice, but the weight and power requirements of conventional rotary drilling rigs make them unsuitable for glacial exploration. For deep ice coring special cable-suspended electromechanical drills were developed and designed which are quite different from conventional drilling rigs.

The main feature of electromechanical ice-drilling technology is the method of lowering and lifting the drill in the hole. Instead of pipes, which are used in the conventional rotary drilling rigs to provide power for rock destruction at the borehole bottom and to retrieve the down-hole unit, an armored cable and a winch are utilized. The use of a cable not only decreases the mass and power consumption of the drilling equipment, but it also shortens the time of travel in and out of the hole and simplifies the cleaning cuttings out of the hole.

Ice electromechanical drilling with fluid near-bottom circulation was carried out first by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL, Hanover, New Hampshire) at Camp Century in 1966 and then at Byrd Station in 1967-1968 (*Ueda and Garfield*, 1968, 1969). During these drilling projects the lower part of the boreholes were filled with an aqueous ethylene glycol solution and the upper part was filled with diesel fuel of arctic blend (DF-A) mixed with a densifier (trichlorethylene).

Over the following fifty years, nearly twenty deep fluid filled bore-holes have been drilled in the Antarctic and Greenland ice sheets using electromechanical drills on armored cables. At least 7 different electromechanical drills with near-bottom fluid circulation have been designed in USA, Denmark, Russia, France, Germany and Japan for ice deep drilling:

- CRREL (*Ueda and Garfield*, 1968, 1969);
- ISTUK (*Gundestrup et al*., 1984);
- KEMS (*Kudryashov et al*., 1994),
- PICO-5.2″ (*Stanford*, 1992; *Wumkes*, 1994);

- JARE (*Fujii et al*., 1999; *Takahashi et al*., 2002);
- Hans Tausen (*Johnsen et al*., 2007);
- DISC (*Shturmakov et al*., 2007).

The 5-m long Hans Tausen drill was a prototype for the EPICA and NorthGRIP drills which were mechanically identical to the Hans Tausen drill, but extended with a much longer core barrel and chips chamber. The Hans Tausen drill versions were also used for the Berkner Island (2002-2006) and Talos Dome (2004-2008) drilling projects in Antarctica. In all modifications, the drill head design was almost the same.

There have been a few other designs of deep electromechanical drills, for example, the French electromechanical drill and Italian IDRA. The French drill used a centrifugal basket for chips collecting and packing (*Donnou et al*., 1984). During tests it was not possible to retrieve cores due to defects in the core catchers. Moreover, the power consumption was extremely high due to the speed of the centrifuge assembly in the fluid.

The IDRA drill system combined the KEMS pumping system and the more classical lower part of the Hans Tausen drill (*Ramorino*, 2008). The IDRA drill was tested at Talos Dome during the 2007-08 season, but only over a few runs. The chip compaction in the chip chamber did not work properly, and this did not allow the drill to produce a long enough core. The development and improvement of the French electromechanical drill and IDRA drill were terminated, that is why we do not discuss them further here.

Generally, electromechanical cable-suspended drills use the following working procedure. The rotor of the down-hole electric motor produces a rotation that is transmitted through a reducer to the core barrel to which the *drill head* (referred in conventional drilling as '*drill bit'*) is attached. Rotary drill heads cut ice to create the core and the borehole. Ice chips generated by the cutting action of the head are removed by the near-bottom fluid circulation to a special chamber. In the borehole drilling fluid serves not only for removal of cuttings but also to compensate for the hydrostatic pressures acting to close it.

The upper part of the electromechanical drill includes: (1) the antitorque system to prevent spinning of the non-rotating section of the drill; (2) a hammer to make core breaking easier and to retrieve a stuck drill; (3) a pressure chamber containing the sensors and controls; (4) a slip ring unit to prevent cable twisting if antitorque system fails; (5) a cable termination to connect drill with armored cable. The details of the various internal components give each drill its own unique operating capacities and weaknesses.

2. GENERAL DESIGN OF THE DRILL HEADS

Choosing of the optimal drill head design is one of the most important challenges for the development of ice drilling technology, because it affects not only the efficiency of ice cutting, but other important drilling parameters: rate of penetration (*ROP*), core quality, length of the run, borehole trajectory, etc.

Typically a drill head consists of the body, cutters mounted to the bottom side, shoes to control *ROP*, and core catchers. Drill heads sizes and performances differ from drill to drill (Table 1).

Table 1

Drill heads specification*

Drill type	CRREL	ISTUK	KEMS	PICO-5.2″	JARE	Hans Tausen	DISC
Number of cutters	8	3	3	3	3	3	4
Cutting angle δ, deg	90	45	60	45	50; 60; 75	42.5	50
Relief angle α, deg	9	8.6	5	unknown	15	10	15
Cutters OD, mm	155.6	129.5	132; 135	177.5	135	129.6; 132; 134	170
Cutters ID, mm	114.3	102.35	107	137	94	98	122
Outer barrel OD, mm	146	Single barrel	Single barrel	171.3	122	118	Single barrel
Outer barrel ID, mm	unknown			157.1	115	113	
Inner barrel OD, mm	unknown	110	127	143.34	101.6	104	157
Inner barrel ID, mm	117.6	104	117	137	97.4	100	137
Rotation speed, rpm	225	37.5	230	100	66	50-60	80
Pitch, mm	~0.5	9.8	1-1.5	10	2; 3; 4; 5; 6	4.2	5.9
***ROP*, m/hr**	~7	22	12-20	60	6-20	15	28
Swept area of the cutter, cm^2	87.5	49.4	46.9; 53.2	100.0	73.7	56.5; 61,4; 65.6	110.0
Outer barrel/inner barrel clearance, mm	unknown	no	no	13.76	6.7	4.5	no
Borehole walls/ outer barrel clearance, mm	4.8	9.75	2.5; 4	3.1	6	5.8; 7; 8	6.5
Core/inner barrel clearance, mm	1.65	0.75	5	0	1.7	1.0	7.5
References	*Ueda and Garfield*, 1969	*Gundestrup et al*., 1984	*Kudryashov et al.*, 1994	*Stanford*, 1992	*Fujii et al*., 1999	*Johnsen et al*., 2007	*Shturmakov et al*., 2007; *Johnson et al*., 2007

*Some data are taken from *Augustin et al*., 2007b

In the PICO 5.2″, Hans Tausen, and JARE drills, the heads are attached to a rotating inner core barrel that has spiral flights. This inside barrel receives the ice core, and the annulus between the two barrels constrains the borehole fluid to flow with the chips into a screen section above the barrel. The outer surface of the head has an auger style with associated flights to carry the chips up to the fluid flow channel (Fig. 1).

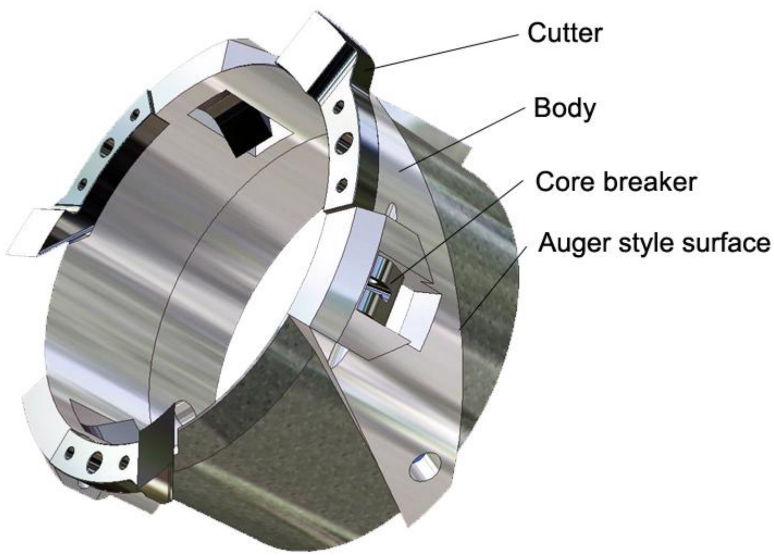

Fig. 1. Hans Tausen drill head
(shoes located right behind cutters for controlling pitch are not shown) (*Johnsen et al*., 2007)

An attempt to improve the auger concept on the head surface, however, did not work as expected for the Hans Tausen design (*Johnsen et al*., 2007). As an experiment, the flights on the drill head were extended out to the hole wall (Fig. 2) in order to better guide the cuttings away from the cutters towards the spiral transport system. This ‘improvement’ made the chips pack immediately on the drill head, and confirmed earlier, similar experiences with the ISTUK drill. New ‘improved’ drill heads, manufactured later in the EPICA drilling project, with more confined conduits for guiding the chips also had the same problem. The drill head design shown on Fig. 1 gave the best results to achieve free mixing of fresh cuttings and liquid, which is imperative for proper lubrication and transport of the chips.

Fig. 2. Extra flights on the Hans Tausen drill head extending to the hole wall produced immediate packing (*Johnsen et al*., 2007)

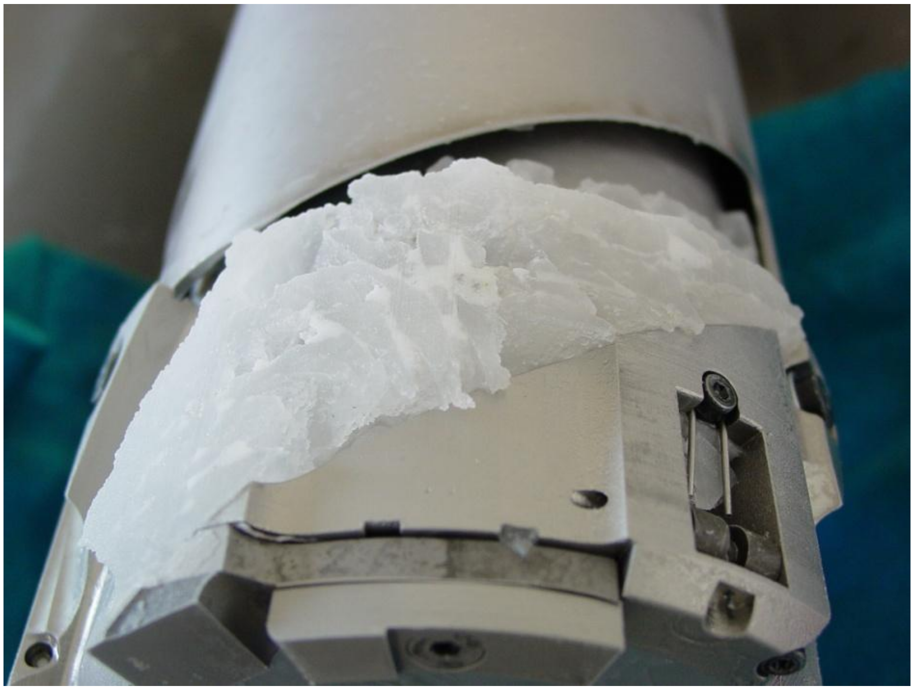

Fig. 3. Hans Tausen drill head with the buildup of ice that occurs in the warm ice, Dome C, Antarctica (Credit: *Laurent Augustin, EPICA*)

The Hans Tausen drill head does not perform well in the near-bed 'warm' ice[1] that melts from the heat generated by the cutting process and then refreezes, causing the chips to get stuck (Fig. 3). This ice buildup prevents further penetration, reduces core quality, and greatly increases the likelihood of the drill becoming stuck (*Gundestrup et al*., 2002).

The problem seems to be caused by the peculiarity of the near-bottom circulation path: the drilling-fluid flow turns through 180 degrees relatively far from the bottom (Fig. 4). This means that the space between the borehole walls and the drill head is filled with slush from the bottom to height *f*. *Azuma et al*. (2007) assumed that the frictional heat due to the rotation of the slush column could raise the ambient temperature of the drill head by several degrees.

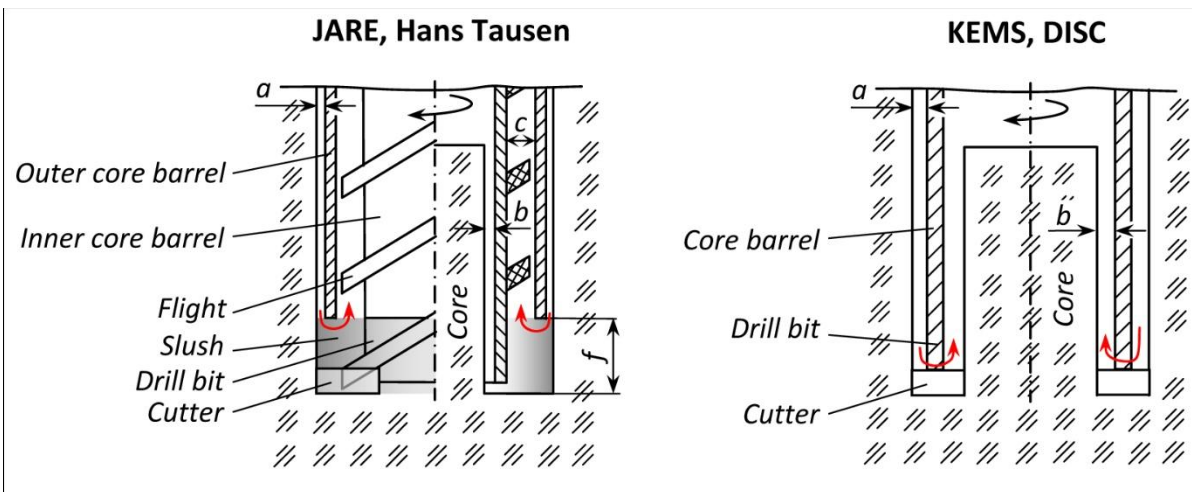

Fig. 4. Schematic of the near-bottom circulation

Modified drill heads with improved fluid circulation at the cutter edges were tested in the EPICA Dome C 2 borehole at the beginning of 2002/2003 field season (*Augustin et al*., 2007a). It was thought that this would prevent the warm ice build-up in the channels of the drill-head. Unfortunately, none of the designs was successful, despite good results in the LGGE laboratory in Grenoble, France.

[1] Ice close to its pressure melting point where drilling becomes complicated by icing of the cutters and drill head, packing of drill clearances, and a decrease in penetration rate. The exact temperature range of the warm ice cannot be defined exactly because temperatures associated with the 'first difficulties' are differed from drill to drill and from site to site [*Augustin et al*., 2007b]. Typically, the problems start at temperatures above -2.8…-7.9 °C.

KEMS and DISC drills use a single core barrel which features a simpler construction of the drill head with flat inner and outer surfaces (Fig. 5). The fluid flows near the cutters, clearing chips effectively and keeping the cutters cool. There are special windows in the front of the cutters to pass fluid flow. Drilling in the rather warm ice with temperatures up to –6 °C with the DISC drill surprisingly presented no obstacle at all[2].

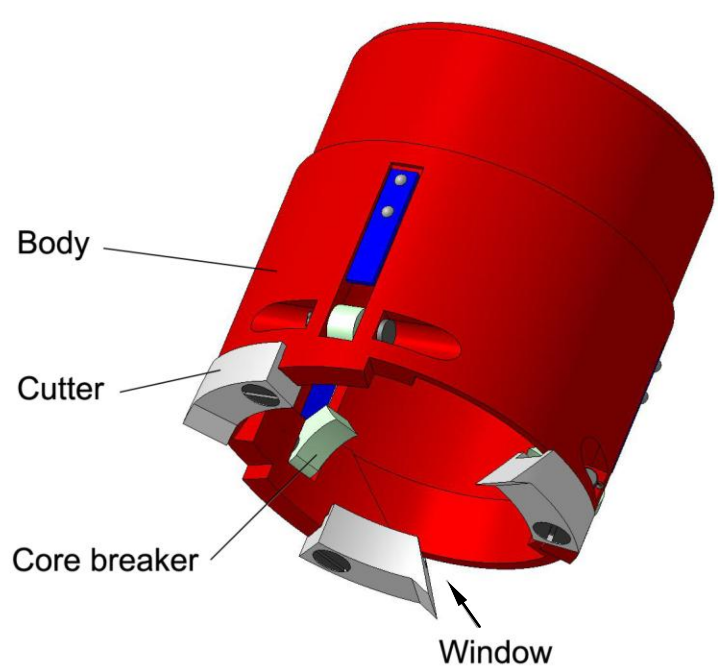

Fig. 5. KEMS drill head

3. CUTTERS

3.1. Moving mode of cutters

During drilling, any point of the cutter is moving through a helix (usually right-handed) making the following angle with horizontal line (Fig. 6):

$$\theta = \mathrm{arctg}\frac{p}{\pi D_y}; \qquad (1)$$

$$\theta_i \le \theta \le \theta_o;$$

$$D_i \le D_y \le D_o,$$

[2] K. Dahnert. 1st Jan. 2012. PROJECT SITUATION REPORT No. 7. DISC Drill 2011-12 Season.

where p is the pitch, mm; D is the helix diameter at arbitrary point of the cutter, м; θ_i and θ_o are the helix angles estimated at the inner diameter D_i and the outer diameter D_o of the cutter, respectively.

The *pitch* (*penetration per revolution*) is the width of one complete helix turn, measured parallel to the drilling axis. It affects the time of drilling:

$$p = \frac{ROP}{60n}, \tag{2}$$

where ROP is the rate of penetration, m/hr; n is the drill head rotation speed, rpm.

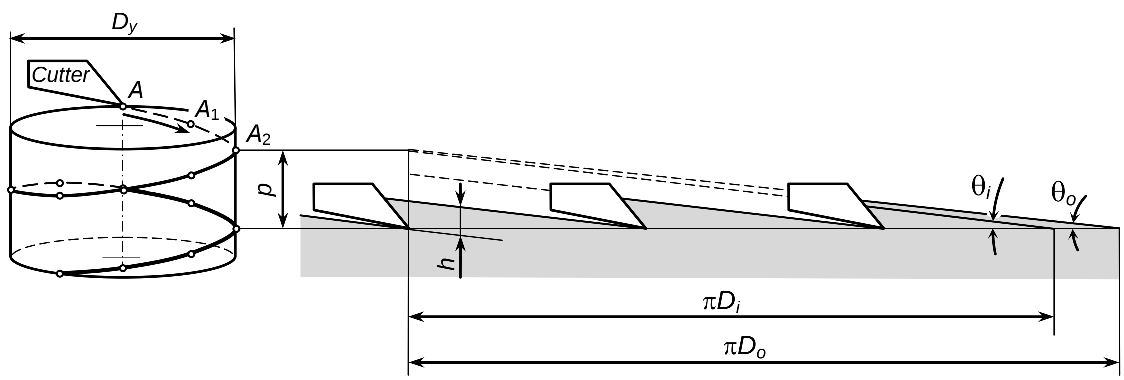

Fig. 6. Schematic of a three-cutter drill head moving mode

Typically the pitch is in the range 3-5 mm which produces coarse cuttings that are easy to handle. The pitch is summed from cutting depths of all cutters. On the assumption that cutting depths h of all cutters are equal to each other:

$$h = \frac{p}{m}, \tag{3}$$

where m is quantity of cutters.

In the drilling process every cutter marks out a visible helix line on the surface of the core (Fig. 7). To estimate the pitch and the average cutting depth, the distance L between grooves is measured, and then pitch and cutting depth can be estimated:

$$p = m\frac{L}{N}; \tag{4}$$

$$h = \frac{L}{N}, \tag{5}$$

where N is the number of grooves.

Fig. 7. Estimation of the pitch and cutting depth
(Credit: *Laurent Augustin, EPICA*)

3.2. Cutter shape

Rounded, chevron, flat and scoop cutting edges have been tested (Fig. 8). In at least one study, shallow drilling with rounded cutters gave probably better ice core quality than drilling with the flat cutters (*Gillet et al*., 1984). During drill tests, *Schwander and Rufli* (1994) tried chevron cutters, but they observed no difference in performance compared to flat ones. PICO drillers found that the flat type compared with the chevron type provides a coarser ice chip which is more easily handled for retrieval and also seems to provide a better ice cutting action with lighter weight (*Stanford*, 1992). This enhances drill stability and minimizes vertical deviation of the borehole.

Scoop cutters were tested in the course of Greenland field testing of the DISC drill (*Johnson et al*., 2007). According to the initial idea, the scoop shape of the cutters should freely permit sideways cutting. However, during the test the scoop cutters produced poor-quality core and the surface of the core had a ribbed helical pattern and very coarse surface.

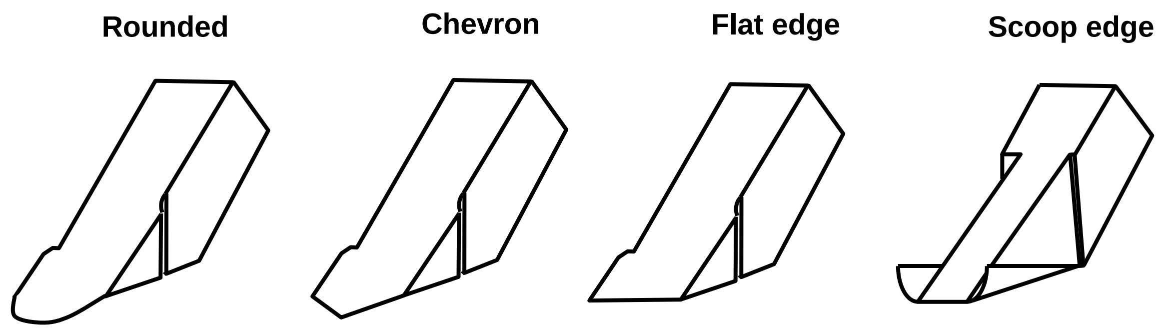

Fig. 8. Tested shapes of the cutter's edge

The radius of the cutting edge of a typical cutter is 20-30 microns. Due to progressive blunting of this edge during drilling, torque and axial load increase significantly as drilling progresses (*Bobin et al*., 1988). Consequently, these cutting edges require frequent sharpening (usually cutters need to be sharpened after each 10-20 meters of penetration).

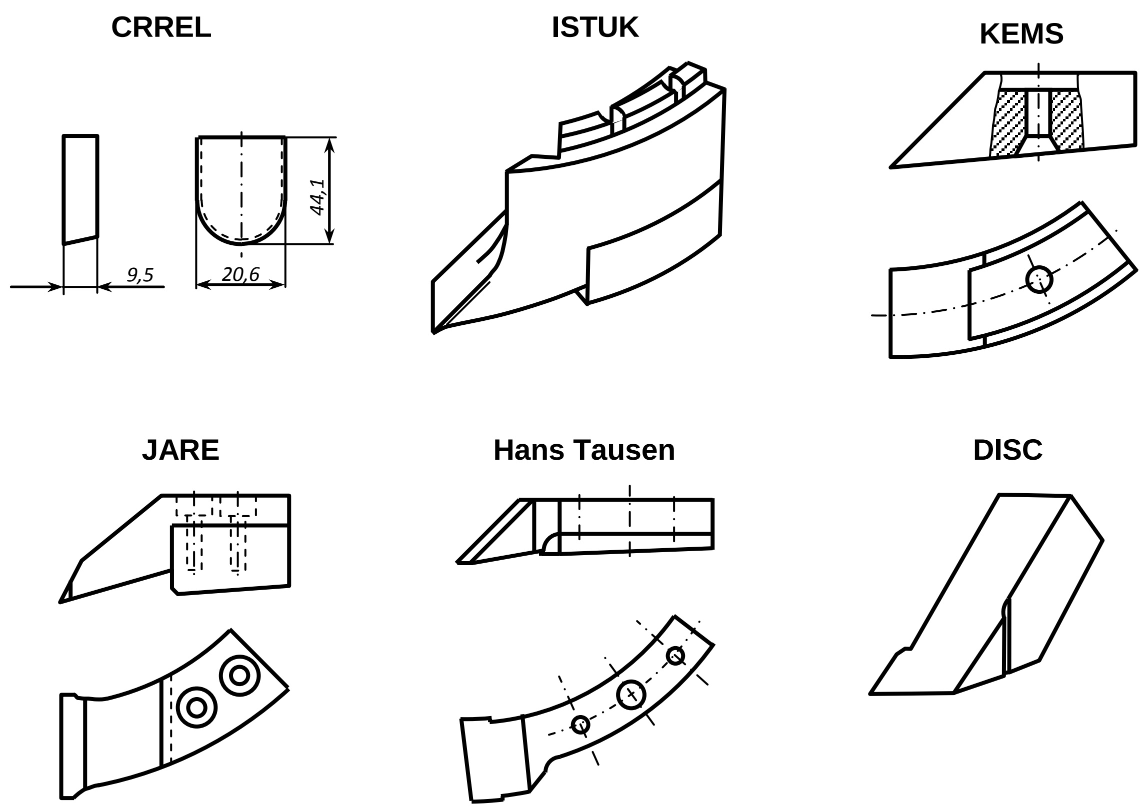

Fig. 9. Shapes and designs of cutters

In deep ice electromechanical drills, cutters with flat edges are usually used because they give the good-quality core, ensure the minimal energy consumption, and can be easily manufactured and sharpened (Fig. 9). The cutters are mounted on the drill head using a keyway or pins with one or two screws. This mounting method is very rigid and ensures a core with constant diameter. The front of the cutter can be shaped to guide chips into the flow pass (e.g. ISTUK cutters).

3.3. Slotted and staggered cutters

Slotted and staggered cutters have been used to address problems with drill penetration in warm ice. Slotted cutters were first tested at Vostok station (Fig. 10), and they seemed to solve the problems with poor penetration and resulted in increased run length (*Vasiliev et al*., 2007). Later the slotted cutters were tested in the Dome C 2 borehole but, in this instance, they did not improve drill performance in the warm ice.

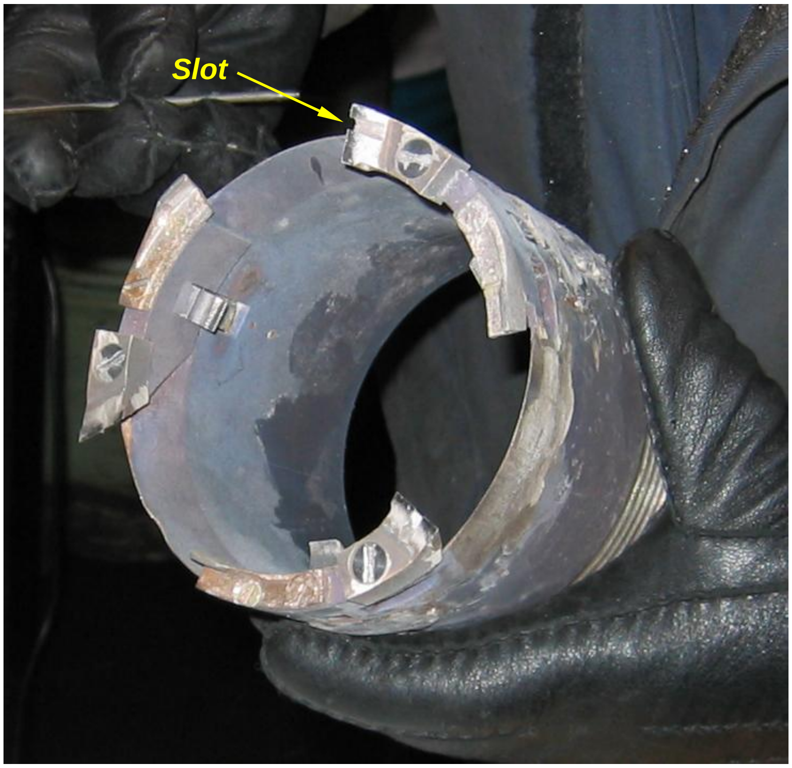

Fig. 10. KEMS drill head with special slotted cutters for drilling in the warm ice, Vostok Station, January 2006 (Credit: *Alexey Ekaykin*)

In order to reduce the torque and generate coarser cuttings, *Zagorodnov et al*. (2005) suggested using the staggered cutters shown in Fig. 11. In this instance, there are two options to mount cutters on the drill-head body: cutting edges can be at the same height from the bottom (Fig. 12, a) or at different heights (Fig. 12, b). In the latter case, the resulting borehole bottom has a stepped profile. Each of the three staggered cutters cuts only one-third of the width of the bottom and penetrates three times deeper per revolution than a conventional cutter and therefore generates coarser chips. Required torque are 30-50 % lower than with conventional cutters. Coarse cuttings are less sticky and are easy to transport from the bottom. Coarse cuttings also occupy less volume (*Talalay*, 2005). This made a 20% reduction of length of the chip compartment possible.

Fig. 11. Staggered cutters (*Zagorodnov et al*., 2009)

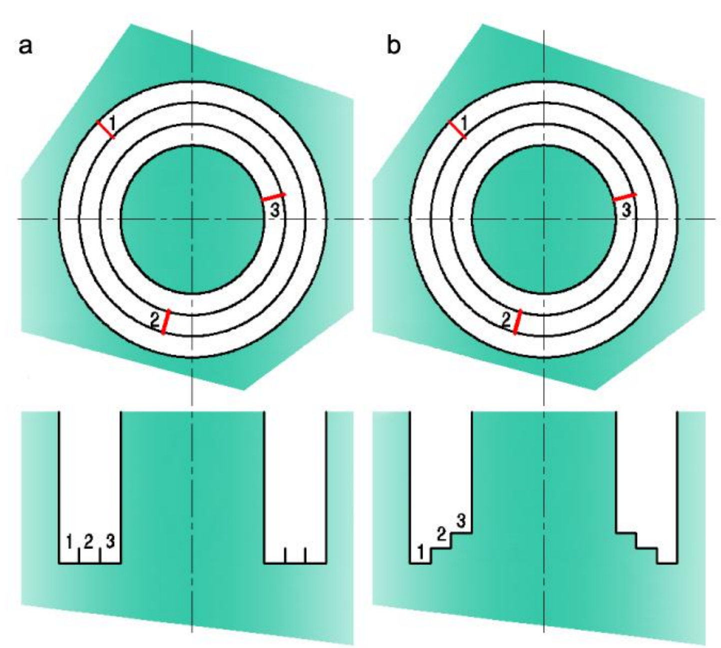

Fig. 12. Borehole bottom shaping with staggered cutters (a) and step-staggered cutters (b) (*Zagorodnov et al*., 2009)

Staggered cutters were tested for the first time in the boreholes drilled in high-altitude glaciers on the saddle of Mount Bona and Mount Churchill in Alaska in 2002. There was almost no difference in drilling performance with conventional and staggered cutters at the depths of near 180 m (*V. Zagorodnov*, pers. comm.). But in the next test in 2003, the step-staggered cutters performed significantly better than conventional cutters in the Quelccaya ice cap, Peru borehole in the depth range 76–126 m, where temperatures were close to the melting point (*Zagorodnov et al*., 2005).

In the Greenland NEEM borehole some penetration problems caused by the warm ice were encountered 100 m above bedrock (*S. Hansen*, pers. comm.). The standard cutters were modified to a staggered configuration (Fig. 13). The staggered cutters did not improve penetration in the warm ice, but they gave a nice stable current which was slightly lower than before, and they produced nicer and coarser chips which were ideal for transportation and also for the cleaning of the drill at the surface.

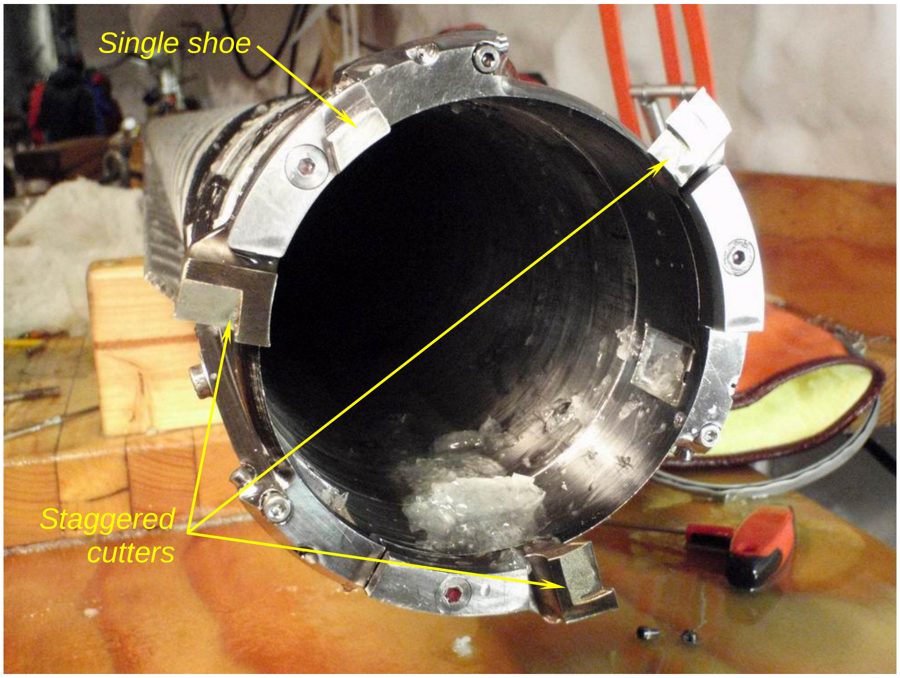

Fig. 13. Staggered cutters mounted on the Hans Tausen drill-head, NEEM, July 2010 (Credit: *Steffen Hansen*)

3.4. Cutter quantity

Drill heads are usually fitted with three cutters. Using three cutters rather than two provides smoother cutting without vibration of the drill and produces better ice-core quality (*Johnsen et al*., 1980; *Gillet et al*., 1984). There is no motivation to use four or more cutters because it is difficult to ensure steady running for each cutter.

Schwander and Rufli (1994) tested a unique drill head made of three segments with four cutters integrated in the lowest segment (Fig. 14). In order to achieve optimum roundness and stability, the cutters and ring were machined in one piece. The borehole walls were cut by side-wall disc-shaped cutters mounted at the upper part of the drill head. The drill head was centered by helical contact areas that touched the wall of the borehole over the entire circumference of the head. Their width was about 1 mm. Each of the four cutters had a pre-cutter on the inner side, the purpose of which was to reduce the cutting depth for each of the main cutters. Field tests in the dry borehole in Greenland resulted in unstable drilling at depths below 130 m. The rate of penetration was substantially reduced due to difficulties with cutters engaging the ice. The drilling moment was unusually high, the antitorque section often started to rotate, and the core was fractured into multiple pieces.

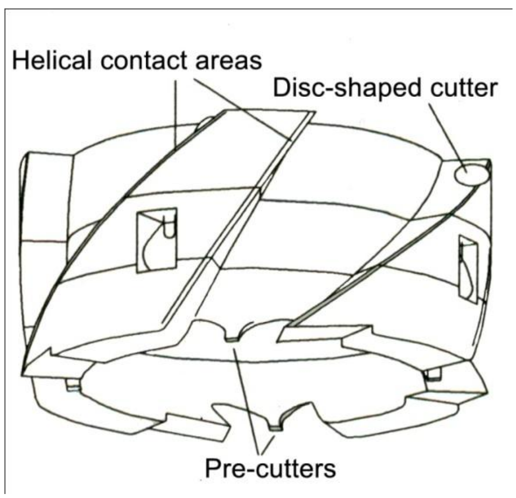

Fig. 14. Swiss drill head with pre-cutters and side-wall cutters
(*Schwander and Rufli*, 1994)

Using side-wall cutters for drilling in ice has no practical sense, since the face edges of more conventional cutters can successfully cut the borehole walls and the surface of the core simultaneously.

3.5. Cutter geometry

The main cutter geometrical parameters are (Fig. 15): α – relief angle; β – wedge angle; γ – rake angle; δ – cutting angle. Cutters used in the ice core electromechanical drills have cutting angles δ in the range from 45 to 90° and relief angle α in the range from 5 to 15° (see Table 1). The most common angles used in cold ice are δ= 45° and α=8-10° (*N.S. Gundestrup et al.*, 1984). *N.S. Gundestrup et al.* (1984) also suggested using cutting edges with a relief angle on the side of the cutter which reduces the power requirements to turn the drill head and produces stable drilling characteristics.

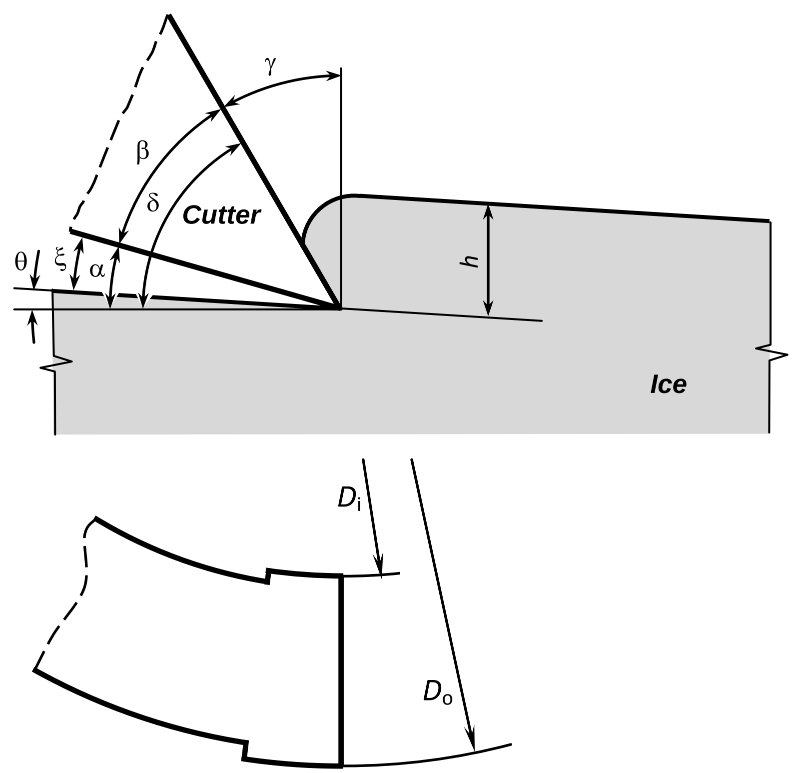

Fig. 15. Schematic of cutter's geometry

Cutter geometry has tended to favor minimum power consumption but the relationship between the cutting angle and required cutting force is not clear.

A considerable number of cutting experiments in natural lake ice were carried out by USA CRREL (*Ueda and Kalafut*, 1989). Parameters that were varied included the cutting angle of cutter (from 30 to 95°), cutting velocity (from 0.1 to 0.265 m/s) and cutting depth (from 0 to 5 mm). The strain rates for these tests were estimated to be 10^1–10^2 s^{-1}, which should have assured brittle behavior. The maximum horizontal force was 298 N with a 95° cutting angle. The 30°, 40° and 60° cutters produced the lowest horizontal forces (the 60° cutting angle cutter had the lowest specific energy).

A special stand simulating the borehole conditions of the KEMS-112 electromechanical drill was constructed at the St. Petersburg Mining Institute (*Vasiliev and Talalay*, 1994). Cutters with cutting angles of 30°, 45°, 60°, 75° and 90° and clearance angles of 2°, 3°, 5°, 7° and 10° were used. The velocity at the middle of the cutters was constant (1.2 m/s), and the temperature of the artificial ice was -20 to -25 °C. Minimum torque was obtained for a cutting angle of 75° and maximum torque for cutting angles of 45° and 90°.

The tests carried out on a special stand at a temperature of -40±3 °C and a cutter velocity the middle of the cutting edge of 1.2 m/s gave results opposite to described above (*Talalay*, 2003). The horizontal force increased almost linearly with increasing cutting angle in the range from 30 to 90°. The horizontal force at cutting angle of 90° was on 30-40 % higher than force at cutting angle of 30°.

The cutters with small cutting angles are too aggressive and can cause problems with mechanical resistance. That is why, from the minimal power consumption and resistibility points of view, cutting angles of near 60° are preferable.

In order to allow embedding of the cutter into the borehole bottom, the relief angle should be not less than the helix angle of cutter trajectory and can be bounded to:

$$\delta = \theta + \xi. \tag{6}$$

where ξ is the safety angle between the lower surface of the cutter and the borehole bottom.

Mellor (1976) suggested utilizing a safety angle $\xi \geq 5°$. In order to minimize cutter load *Vasiliev and Talalay* (1994) recommended using a safety angle $\xi \geq 3°$. On the other hand, tests with PICO-5.2″ cutters having a small clearance angle of 0.8°, 1.0° or 1.2° equal to the helix pitch angle showed that this configuration can also produce excellent core (*Wumkes*, 1994).

3.6. Cutters outer/inner diameters

Electromechanical drills are lowered to the bottom of the bore-hole by gravity, and the running speed depends mainly on two parameters: (1) clearance between borehole walls and drill surface, and (2) drilling fluid viscosity.

The rational values of the running speed were found by *Talalay and Gundestrup*, 1999 (Table 2). Over-speed is senseless because it has a very small influence on the total time of drilling. The rational range of the average drill's running speed depends on the final depth of bore-hole.

Table 2

The rational range of the average drill's running speed (*Talalay and Gundestrup*, 1999)

Final depth of bore-hole, m	Average running speed, m/s
1000	0.3 – 0.4
1500	0.4 – 0.5
2000	0.5 – 0.6
2500	0.6 – 0.8
3000	0.8 – 1.0

Estimations were made for the following pre-conditions: length of run 3.4 m; time of drill servicing at the surface 0.35 h; *ROP* 10 m/h.

There are two alternative ways to achieve the rational drill running speed. Either a low-viscosity fluid must be used, or bore-holes with the larger clearance between the drill and the bore-hole walls must be drilled (Table 3). Drilling with the larger clearance between the drill and the borehole walls leads to an undesirable significant increase of cuttings, and that is why the outer diameter of the cutters should be as small as possible.

Table 3

Free drill's running speed versus kinematic viscosity of the drilling fluid and clearance between drill and borehole walls

Kinematic viscosity, cSt	Running speed, m/s		
	Clearance 6 mm	Clearance 7 mm	Clearance 8 mm
1	0.93	1.85	3.38
2	0.46	0.92	1.69
3	0.31	0.62	1.13
4	0.23	0.46	0.84
5	0.19	0.37	0.67
6	0.15	0.31	0.56
7	0.13	0.26	0.48
8	0.11	0.23	0.42
9	0.10	0.21	0.38
10	0.09	0.18	0.34

Estimations were made for the following pre-conditions: bore-hole diameter 130 mm; length of the drill 11 m; mass of the drill m 130 kg; density of the drilling fluid 930 kg/m^3.

In electromechanical drill design the clearances between the core barrel and the borehole walls are typically in the range of 2.5 – 9.75 mm (see Table 1). If the kinematic viscosity of the drilling fluid is not more than 3-5 cSt, we recommend drilling with a clearance in the range of 4 – 6 mm for intermediate depths up to 1000-1500 m, and 6 – 8 mm for deep drilling up to depths of 3000 m or more.

The inner diameter of the cutters should be as large as possible in order to create a clearance between the core and the inner surface of the core barrel in the range of 0.5 – 1.0 mm for double-core barrel scheme and 5 – 6 mm for single-barrel scheme.

The width of cutters should be as small as possible in order to minimize the amount of generated ice chips. The quantity of generate chips influences the required length of the ice chips chamber and total length of the drill. Among others the DISC drill head produces the largest amount of ice chips (see Table 1, Fig. 16).

3.7. Cutter material

Proper materials selection for cutters is essential. The presence of carbon in most tool steels causes brittleness as the temperature drops below -20 °C. *Koci*, 1984 suggested using maraging steels, 440 stainless steel, or high cobalt tungsten carbide to provide the required hardness and toughness. Evaluation of these materials in -52 °C ice was carried out in a shallow borehole at South Pole during the 1981/1982 season. In this evaluation, A-2 tool steel was found to be the best of the available tool steels since it did not chip as readily as the high speed steels. The 440C stainless and margining grades of steels were slightly better than A-2 in resistance to chipping and could generally be kept sharper.

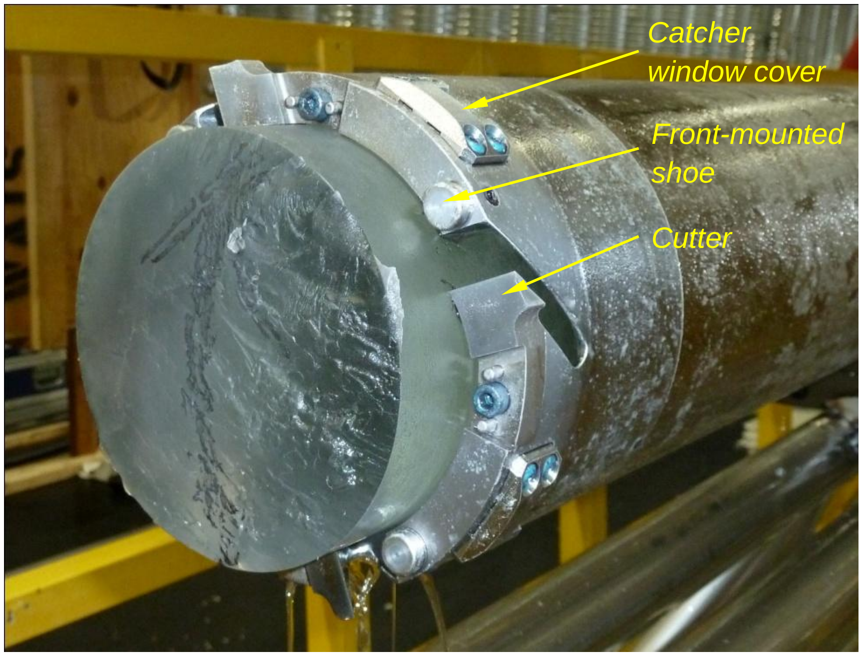

Fig. 16. DISC drill head, WAIS Divide, January 2011 (Credit: *Jay Johnson*)

KEMS cutters are made of ‘У8’ Russian tool steel type (U.S. analogue of W1-0.8C Extra) with hardness 62...65 HRC. Hans Tausen cutters are manufactured from high speed steel of S390 type with hardness 64 HRC for the blade part and 56…58 HRC for the remainder (*L. Augustin*, pers. comm.).

B. Koci (1988) suggested making cutters of sintered tungsten-carbide which should drill many holes without sharpening. Tungsten carbide has been well known for its exceptional hardness up to 89…92 HRC for conventional grades. A comparison of carbide and steel cutters showed that steel provides a good cutting edge, is easier to handle and is more cost effective (*Wumkes*, 1994). Usually carbide inserts are fixed to the body of cutting tool by cold pressing or brass soldering, and so it is almost impossible to dismount and to sharpen such inserts in the field. Therefore this material has not found widespread use in ice drilling.

To prevent ice building-up in the warm ice, the cutters and the body of the drill head can be covered with a thin Teflon® layer (*Vasiliev et al*., 2007). This measure increased the efficiency of chip removal from the borehole bottom at Vostok, but at Dome F although the normal drill was replaced with a special short teflon-coated drill in the warm ice, it did not help to improve drilling mode (*Motoyama*, 2007).

4. SHOES

Shoes are installed at the open side of the drill head in order to limit and to control the cutting depth and the pitch. Three styles of the shoes can be considered (Fig. 17): (1) rear-mounted, (2) front-mounted, and (3) skate-type.

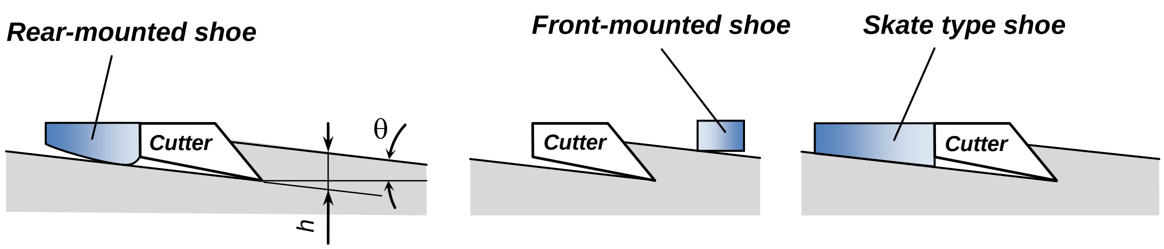

Fig. 17. Shoes types

Most electromechanical drills use rear-mounted shoes (e.g. EPICA drill shown in Fig.3). On the DISC drill head, shoes are mounted just behind cutters (see Fig. 16). *Mason et al*. (2008) considered that such mounting of the shoes is too sensitive to control pitch: shoes were designed to cut with a 5 mm pitch, but moving the cutting edge 0.1 mm closer to the shoe along the axis of the head will produce an actual pitch of 3 mm. The skate-type shoe has a fixed helix angle determined by the pitch it was designed to produce.

For any shoe designed for a specific pitch, installation and use of that shoe should produce the desired pitch within reasonable expectations. The clearance between of the rear-mounted shoe and the bottom of the borehole is equal to (Fig. 18):

$$g = \frac{h\varpi}{360}\ , \tag{7}$$

or accounting for equations (2) and (3):

$$g = \frac{ROP\varpi}{2.16\times10^{4} mn} \quad , \tag{8}$$

where *h* is the cutting depth, m; ϖ is the central angle between the cutting edge and the point of the shoe that touches the borehole bottom, deg; *ROP* is the rate of penetration, m/h; *m* is the quantity of cutters; and *n* is the rotation speed, rpm.

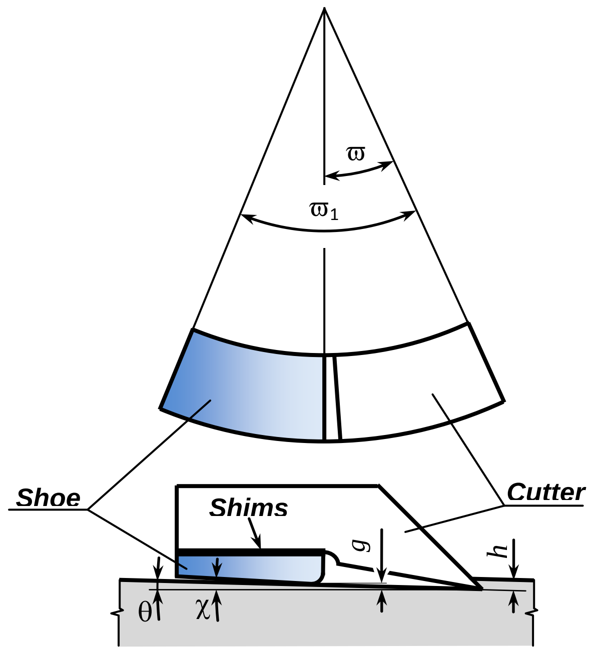

Fig. 18. Working scheme of the rear-mounted shoe

The shoe clearance ***g*** estimated for Hans Tausen drill head is given in the Table 4, and it can be measured by clearance gages with the help of special device centered by the inner side of the cutters (Fig. 19). Usually the shoe clearance is regulated by the shims installed between the shoe and the drill head body.

Table 4

Estimated shoe clearance for Hans Tausen drill head
(*n* = 50 rpm; *m* = 3; ϖ =18°)

g, μm	*h*, mm	*p*, mm	*ROP*, m/h
55.5	1.11	3.33	10
83.3	1.66	4.99	15
111.1	2.22	6.67	20
138.8	2.77	8.31	25
166.6	3.33	9.99	30

Fig. 19. Measurement of the shoe clearance, Hans Tausen drill head
(Credit: *NGRIP ice core drilling project*, www.gfy.ku.dk)

The following considerations might be taken into account for the design of rear-mounted shoes:

- The contact arris of the shoe should be rounded with the radius of ~0.5-1.0 mm;
- The central angle ϖ should be as large as possible in order to facilitate convenient adjustment of the cutting depth;
- The canting angle of the shoes χ should be greater than the helix pitch angle θ, otherwise the back-end of the shoe will contact the borehole bottom and the overall geometry will change (the central angle rises from ϖ to ϖ_1), affecting performance.
- Shoe clearance cannot be adjusted during penetration. This means that the cutting depth, pitch and *ROP* are considered to be constant while drilling. However, the cutting depth, pitch and *ROP* are changed with rotation speed of the drill head.
- It is difficult to obtain exactly the same cutting depths for all cutters because of the dimensional precision of shims and low measurement accuracy.

The main problem with rear-mounted shoes is related to icing of the space between the cutter and the shoe when drilling in the warm ice (Fig. 20). As a consequence, several special shoes have been designed for drilling in warm ice.

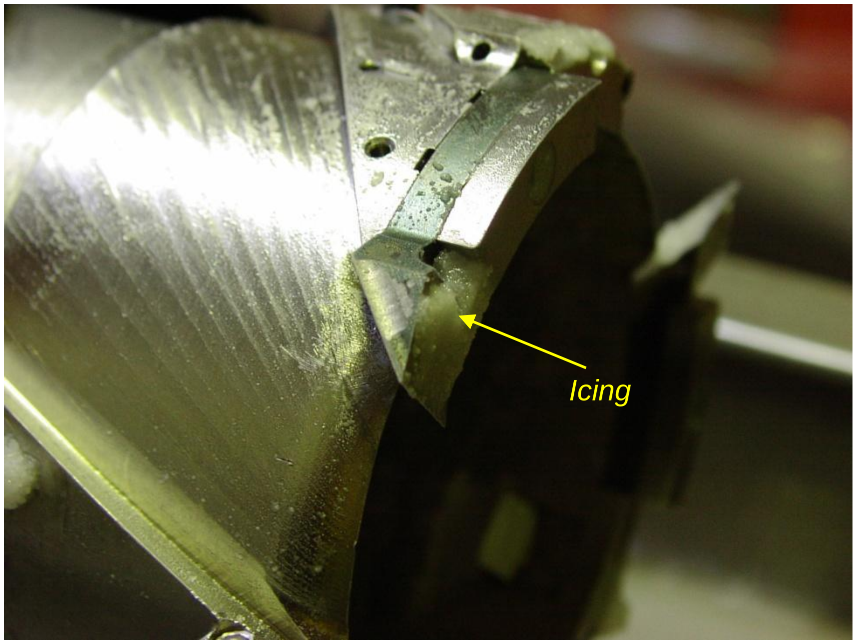

Fig. 20. Icing in the warm ice, NGRIP borehole, 4th of July 2001
(Credit: *NGRIP ice core drilling project*, www.gfy.ku.dk)

One of the warm ice shoes designs (‘dolphin’ type) featuring a small contact area was proposed by JARE specialists (Fig. 21). Unfortunately, these shoes did not produce the hoped-for improvement of drilling in the warm ice. In the fourth drilling season 2006/2007 at Dome F, Antarctica borehole, using these cutters the total drilling progress was only 6.70 m, and the average core length was approximately 10 cm (*Motoyama*, 2007). The final drilling depth reached was 3035.22 m during the working period of 39 days.

It seems that shoe re-design alone cannot solve the problem of lack of penetration in the warm ice. Nevertheless, when problems with icing of the drill head were first encountered at ~100 m above bedrock at the NEEM borehole in Greenland, the shoe design was changed (*S. Hansen*, pers. comm., see Fig. 13). Only one shoe was mounted with a very small contact area, and full penetration was recovered. Perhaps the reason for the drilling improvement in this instance was related not only design of the drill head, but also to the properties of the new oleiferous viscous drilling fluid that prevented agglutination of the ice chips in this case.

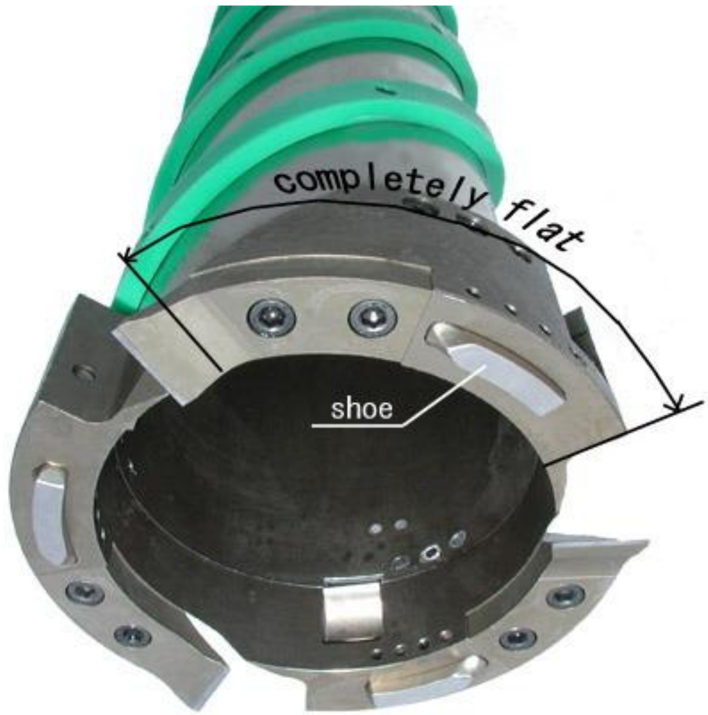

Fig. 21. JARE cutters and shoes for drilling in the warm ice
(Credit: *H. Motoyama*)

5. CORE CATCHERS

5.1. Ice core catchers

In conventional drilling special split-ring core lifters are usually used to break the core and to hold it during the trip out the borehole (Fig. 22). This type of core lifter consists of a hardened steel ring having an open slit, an outside taper, and an inside or outside serrated surface. In its expanded state it allows the core to pass through it freely, but when the drill string is lifted, the outside taper surface slides downward into the bevel of the bit or reaming shell, causing the ring to contract and tightly grip the core which it surrounds.

Fig. 22. Split-ring core lifters for conventional prospecting drilling
(Source: http://www.metaldrillingsac.com/metal05.htm)

Ice core drilling produces much coarser chips than conventional rock drilling and the fluid passages of conventional split-ring core lifters are too small to permit the larger ice chips to pass. Therefore this type of catcher is not used in electromechanical drilling in ice. In ice drilling, 'dog leg' type core catchers are usually used (Fig. 23).

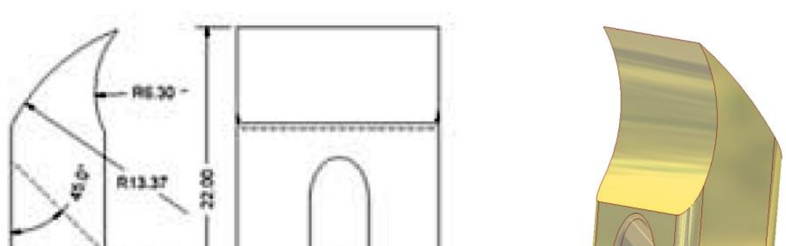

Fig. 23. 'Dog leg' type core catchers
(*Zagorodnov et al*., 2005)

Typically three core catchers are integrated with the drill head and are brought to bear against the core surface aided by a plate or wire spring (Fig. 24). Breaking the core perpendicular to its axis is easier than breaking it along its axis because the tangential shearing strength of ice is 1.2-1.3 times less than its tensile strength This is why some specialists recommend using two core catchers instead of three – in order to produce an additional shearing force at the core catchers and thus decrease the lifting force required to break the core off the bottom of the hole.

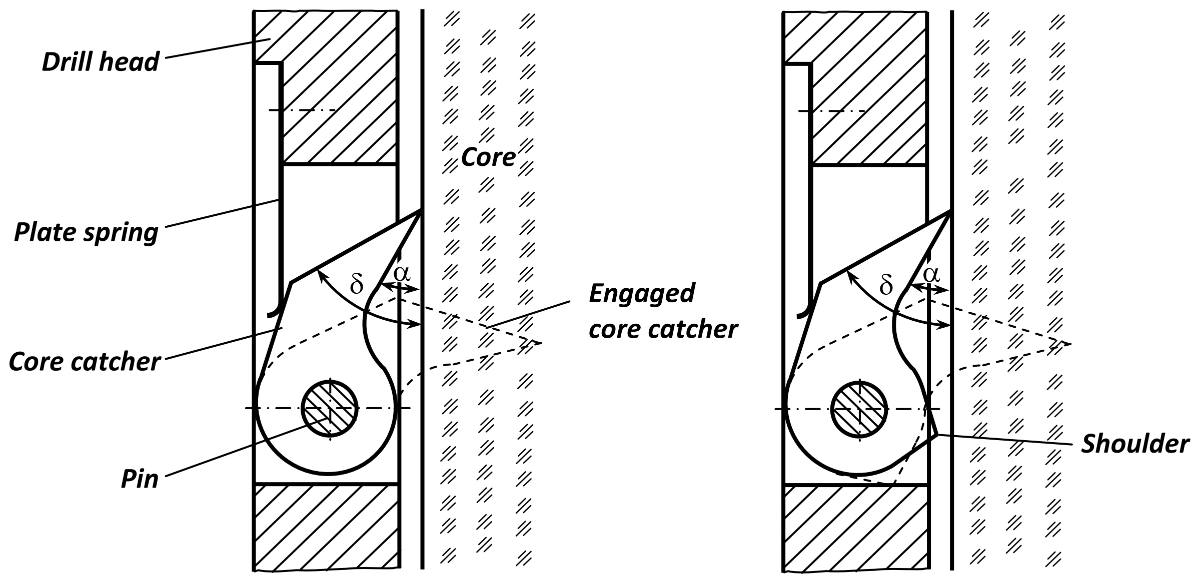

Fig. 24. Core catcher of ‘dog leg’ type: on the left – without shoulder; on the right – with shoulder

When the penetration is finished and the string is pulled up, the cutting edges of the core catchers engage into the core. Further lifting leads to the core breaking off. Core catchers can also have a special shoulder in order to limit their rotation during engaging.

The efficiency of the core catcher engagement depends mainly on the two parameters: (1) geometry of the catcher edge, and (2) the force clamping the catcher into the core surface. *Gundestrup et al*. (1988) suggested using core catchers with $\delta = 55^\circ$ and $\alpha = 30^\circ$. *Koci* (1984) noticed that generally the bisector of the point angle should enter the core at angle of 30° (Fig. 25), which is a more aggressive position than recommended by *Gundestrup et al*. (1988). *Koci* (1984) mentioned that when the core catchers are working properly, the bottom of the core should have a slightly concave shape since the initial fracture will start with an upward component. Selection of a rounded cross-sectional shape of the edge makes the core catchers penetrate the ice more easily than a flat cross section.

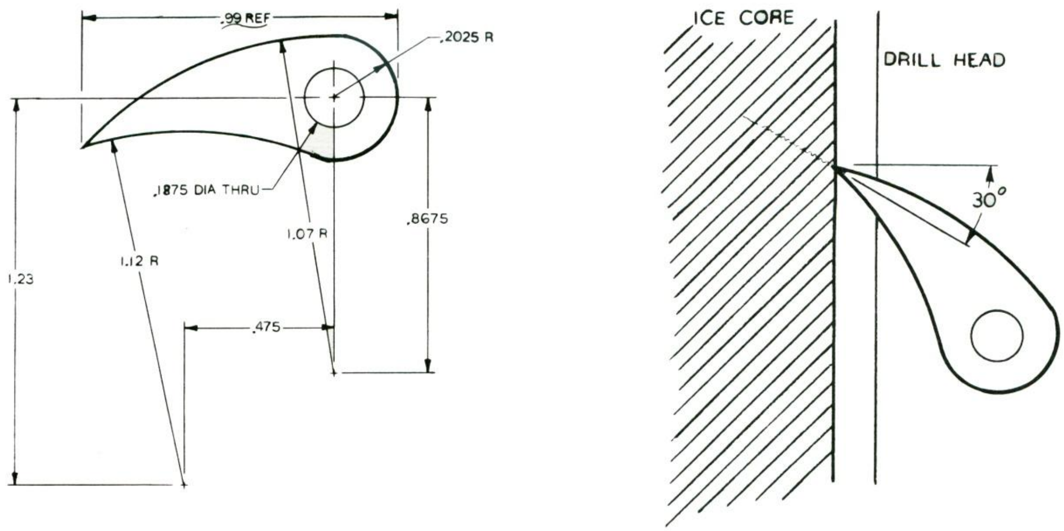

Fig. 25. Recommended by *Koci* (1984) shape of the core catcher (on the left) and core catcher position relative to ice core (on the right)

Zagorodnov et al. (2005) suggested using closed-framed 6.25 mm thick core catchers which can be incorporated in the 8 mm radial space (Fig. 26). This design of the core catcher prevents cross-flow of the drilling fluid through open windows with core catchers. These core catchers were tested during ice coring at the summit of Quelccaya, Peru, in the summer of 2003 and performed well. Another approach to preventing this fluid cross-flow is to cover core-catcher windows with a plate as was done with the DISC drill head (see Fig. 16).

Fig. 26. Closed framed core-catchers (*Zagorodnov*, 2004)

The edges of core catchers should be as sharp as possible. To increase their mechanical strength they should be made from tool steel hardened up to 62...65 HRC.

The force of clamping catcher down to the core surface is estimated according to:

$$P = bP_s, \tag{8}$$

where b is the catcher width, m; P_s is the specific force on the catcher edge, N/m.

The specific force for engaging the catcher can be defined similarly to the vertical cutting force in the rotary drilling process as 0.7-2 kN/m (*Talalay*, 1993; *Narita et al*., 1994). This means that the force of catcher clamping is equal to 8-24 N at a catcher width of 12 mm.

The core breaking strength F_{br} [N] can be rated according to:

$$F_{br} = \frac{\pi D^2[\sigma]}{4}, \tag{9}$$

where D is the core diameter, m; [σ] is the fracture stress of ice (also referred as *ultimate tensile stress*), Pa.

The dependence of the fracture stress (right axis) versus temperature (bottom axis) is shown on Fig. 27 for raw (grey dots) and average (error bars) data (*Wilhelms et al*., 2007). The left axis of the figure is the breaking strength (core diameter is 98 mm) and the top axis presents the coincident depth in the EPICA DML borehole and pressure for the perspective ordinate temperature. A more succinct description is given by an empirical curve to the averaged data. Fitting an exponentional function, yields a best fit for [kPa]:

$$[\sigma] = 505 + 1.4 \times 10^{-20} e^{\frac{T}{5.17}}, \tag{9}$$

where T is the absolute temperature, K.

The core breaking force increases with depth because the breaking behavior changes from brittle failure in ‘cold’ ice to plastic strain in the warm ice. At ice temperatures ∼-5 °C (at atmospheric pressure) the transition from plastic to brittle strain takes place at a strain rate in the range of 10^{-4} to 10^{-2} s^{-1} (*Epifanov*, 1984). Moreover, the ice becomes very coarse-grained under warm ice conditions. So, on average the core breaking strength is 3.8-4.0 kN with the core diameter of 98 mm at temperatures below -20 °C, and it rises to ∼10 kN at temperatures close to the melting point. Under these conditions, core catchers of the ‘dog leg’ type can cut long grooves in the warm ice and the barrel will slip up the core when attempting to break off the bottom, until the core finally breaks (Fig. 28).

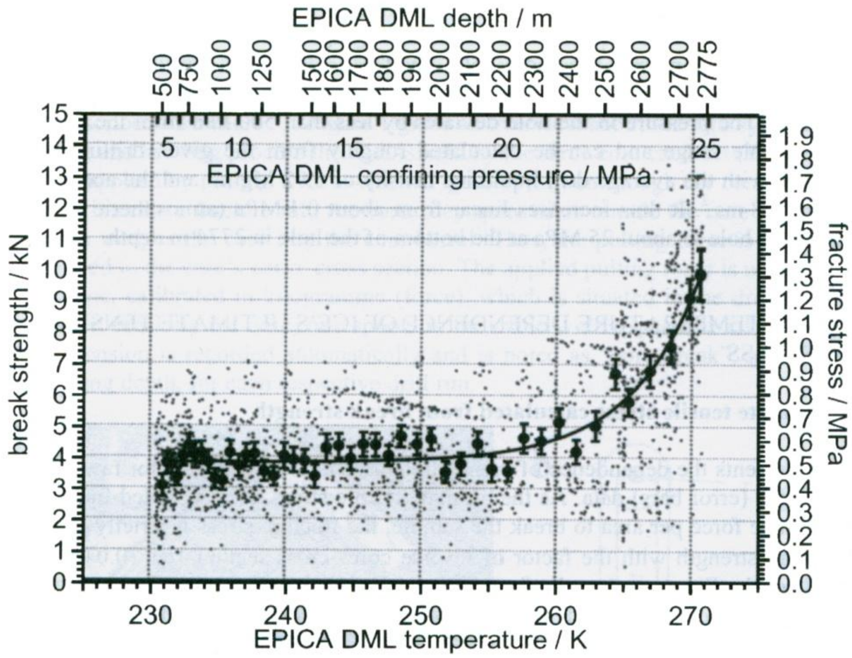

Fig. 27. Fracture stress of the core versus temperature estimated in EPICA DML borehole (*Wilhelms et al*., 2007)

Fig. 28. In the warm ice core catchers formed deep long grooves on the surface of the core, Vostok station, Antarctica, January 2007 (Credit: *Alexey Ekaykin*)

Mellor and Sellman (1976) suggested estimating the force to cut ice F_c [N] using the specific energy, which is the energy consumed per unit volume of cutting:

$$F_c = mbhE_S \,, \tag{10}$$

where m is the number of catchers; b is the width of the catcher, m; h is the depth of cut, m; and E_s is specific energy, N/m^2.

According to *J.J. Bailey*, who made wedge indention experiments in ice, the specific energy values ranged from 0.48 to 3.4 MN/m^2 depending on the ice temperatures (from –3 to –30 °C) and other factors (data published by *Mellor and Sellman*, 1976). *Ueda and Kalafut* (1989) determined that the specific energy also depends on the cutting velocity (Table 5). The specific energy of the -5° rake angle cutters tends to decrease with increasing cutting velocity to a minimum value, and then tends to increase at higher velocity.

Table 5

Experimental data on the cutting process in ice (*Ueda and Kalafut*, 1989)

Cutting velocity, m/s	0.092-0.095	0.104-0.106	0.138-0.158	0.246-0.248
Specific energy, MN/m^2	4.70-4.86	1.70-2.59	1.77-2.66	3.76-3.99

Pre-conditions: cutters with the rake angle -5°; ice temperature -12.6 °C; depth of cut 5.1 mm

Taking into account b=12 mm, h=5 mm and E_s=4.8 MN/m^2 three catchers cut the ice with a force of only 0.86 kN. This value is an order of magnitude lower than the ice core breaking strength. In order to prevent cutting of vertical grooves by core catchers and to decrease breaking force the following measures can be taken in the warm coarse-grained ice:

- The width, depth of engaging and/or quantity of core catchers can be increased.
- While breaking, the core barrel can be rotated. The core break may be easier, but the core surface is likely to be damaged.
- The core catchers can be modified as shown on Fig. 29. During reverse rotation of the core barrel, these core catchers engage into the core and cut a shallow sub-horizontal groove. Such a groove decreases surface area and produces stress concentration encouraging core break off.

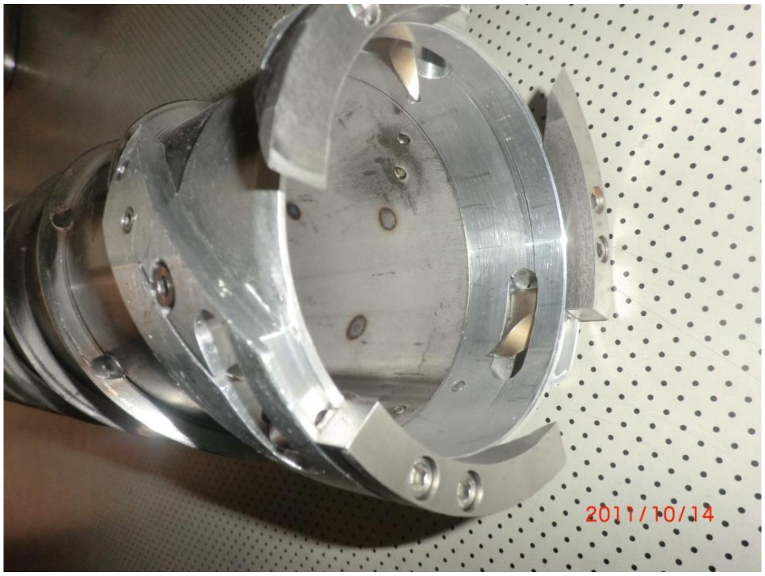

Fig. 29. Core catchers for reverse cutting neck on the core surface
(hand auger designed by *H.Rufli*, picture was taken by author in AWI)

- *Thomas M. Myrick*[3] suggested using two eccentric core barrels for core break-off in the Honeybee Robotics planetary core-sampler. Borrowing this idea we suggest breaking the core with an eccentric core catcher working in reverse rotation of the core barrel (Fig. 30).

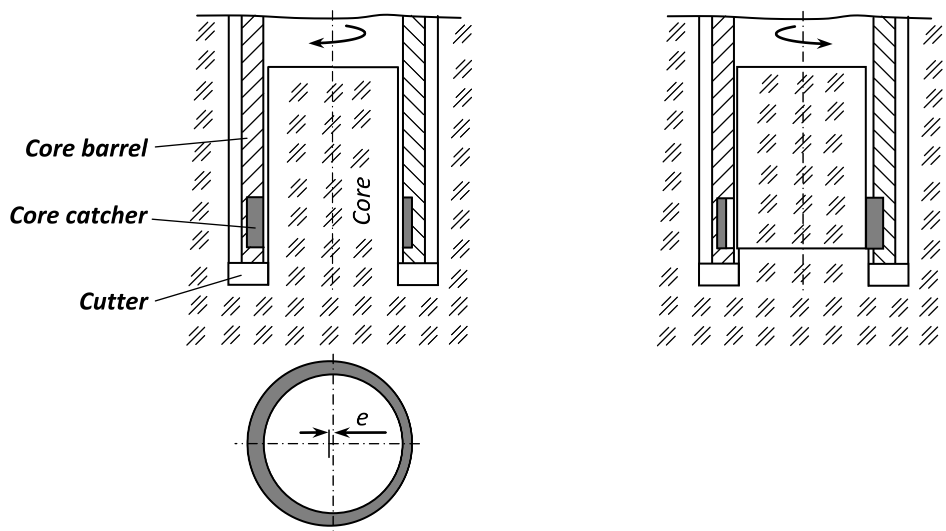

Fig. 30. Eccentric core catcher working at reverse rotation of the core barrel

[3] US Patent 6 550 549. "Core Break-off Mechanism", 2001-04-22.

5.2. Snow/firn core catchers

The upper part of the Antarctic and Greenland ice sheets are built up from the snow/firn layer which is permeable and non-coherent. The thickness of the snow/firn zone depends on the accumulation rate and temperature conditions of the glacier, and the depth of the firn-ice transition at which permeability drops to near zero varies from 64 to 115 m at different Polar drilling sites (*Cuffey and Paterson*, 2010).

When drilling in snow or firn a basket style-core catcher gives the best recovery, especially in cases where unconsolidated material might fall out of the core barrel during ascent. The basket catcher is made from: (1) thin spring wire (∅ 1-2 mm), or (2) thin sheet metal (1.0-1.5 mm) (Fig. 31).

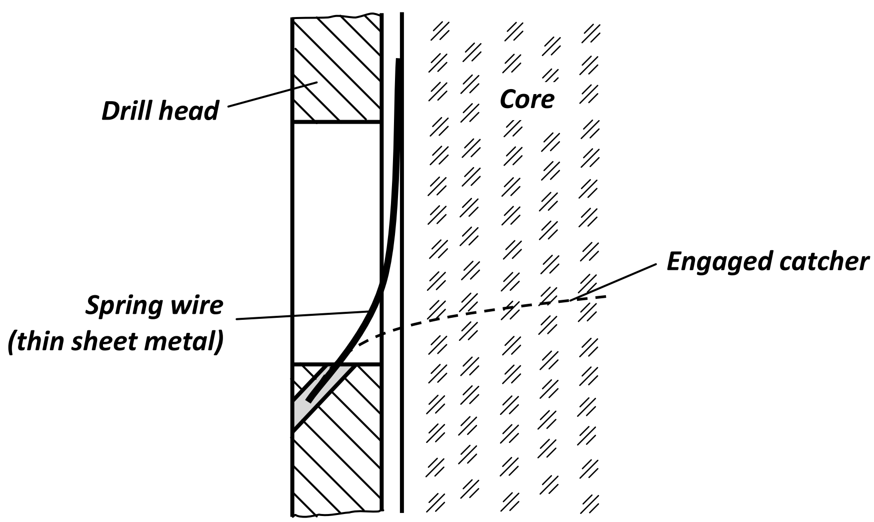

Fig. 31. Basket style-core catcher

The number of the circumferentially spaced flexible elements (wires or plates) should be enough to cut the core and to prevent the loss of poorly-consolidated core samples during the ascent of the drill. During drilling, the catchers squeeze the core and do not hinder its free passage into the core barrel. When lifting, the ends of the core catchers are embedded in a porous snow/firn material and break it from the bottom of the borehole. The sheet metal core catcher for very soft and loose strata used in conventional drilling is illustrated in Fig. 32.

Fig. 32. Sheet metal basket style-core catcher produced
by Forsun Ultra-Hard Material Industry Co., Ltd. (China)
[http://www.twfta.com/cn00159598/showroom_80704.htm]

6. CONCLUSIONS

Electromechanical cable-suspended drills are equipped with special drill heads in order to (1) cut ice, (2) break-off and hold core in the barrel, and (3) control pitch and rate of penetration. Several design concepts for drill heads have been designed and tested. At this time, current drill head design and drilling modes are successful for coring in ‘cold’ ice . The primary remaining problem is improving performance of drill heads in warm ice. Drilling in warm ice is complicated by icing of the drill head body resulting in loss of penetration, as well as difficult core breaks.

There have been several attempts to solve the icing problem by changing the head design but the ultimate solution has not yet been found. In the opinion of the author, changing the drill head design can bring minute improvements in drilling performance, but it cannot provide a fundamental solution to problems with penetration in the warm ice. The key to improving drill performance in warm ice lies in increasing the drilling fluid flow rate and the output pressure of the mounted pumps. Use of a drilling fluid with the high suspending and anti-stick properties is another potential route to improved performance in warm ice.

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