

## AN EXPERIMENT ON ICE CUTTING UNDER HIGH LIQUID PRESSURE AND LOW TEMPERATURE

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**Abstract:** In order to examine dependencies of hydro-pressure and ice temperature in ice cutting performance of a drill for deep ice coring, experiments on ice cutting were carried out under liquid pressure from 0.1 MPa to 30 MPa at temperatures of 12.3,  $-40.3^{\circ}\text{C}$  and  $-62.0^{\circ}\text{C}$  changing the rake angle of the ice cutter. The results showed the penetration speed of the drill for a given rake angle decreased for at lower temperature and higher pressure; for a constant penetration speed, larger torque was required at higher pressure and lower temperature. Also, the larger the rake angle, the smaller the penetration speed. When the rake angle of the ice cutter was  $17^{\circ}$ , the drill performed at the designed penetration speed.

### 1. Introduction

Deep ice core drilling will be carried out by the Japanese Antarctic Research Expedition (JARE) from 1995 at Dome F, Queen Maud Land, East Antarctica. Dome F is located at  $77^{\circ}18'S$ ,  $39^{\circ}41'E$ , about 1000 km south west of Syowa Station. The annual average temperature and elevation at Dome F are estimated to be  $-58.6^{\circ}\text{C}$  and 3810 m above sea level. The inhospitable environment under these conditions is quite severe for drilling and logistics. The first priority of the core drilling is to obtain a good quality of core and proper drill penetration speed. The aim of our experiment is to know the best design of the drill (cutter) which satisfies the above priorities under low temperature and at high liquid pressure. The experiments were done in the liquid pressure range of 0 (atmospheric pressure) to 30 Mpa at ice temperatures of  $-12.3^{\circ}\text{C}$ ,  $-40.3^{\circ}\text{C}$  and  $-62^{\circ}\text{C}$  in order to learn the ice cutting performance at different rake angles.

### 2. Experimental Apparatus and Method

The first experiment was carried out in order to examine the performance of the drill cutter in coring under various liquid pressures at temperatures of  $-12.3^{\circ}\text{C}$  and  $-40.3^{\circ}\text{C}$ . For the experiment under high liquid pressure, an apparatus having a pressure chamber was prepared as shown in Fig. 1. A test drill and ice sample are set in the pressure chamber. The design of the drill head is given in detail in Fig. 2. The rake and relief angle of the cutter were set to  $40^{\circ}$  and  $20^{\circ}$ , respectively. The pitch was 2.5 mm. The drill was fixed on rod A (in Fig. 1) which can turn and move vertically almost without friction (the turning is stopped by the torque measuring load cell), and is supported by the movable outside frame B. The rod C fixed on frame B is equipped to keep the pressure of the chamber constant during the drilling. That is, as the diameters of rod A and C are equal, the volume

change in the chamber due to penetration of rod A into the chamber can be canceled by the withdrawal of rod C from the chamber. The ice samples were cut out from an ice block, and put into a cylindrical vessel. The gap between the sample and the vessel was filled with water which is allowed to freeze. The vessel was attached to a rod D (Fig. 1), which was rotated by a motor with reduction gears at 134 rpm. A silicon liquid was used to

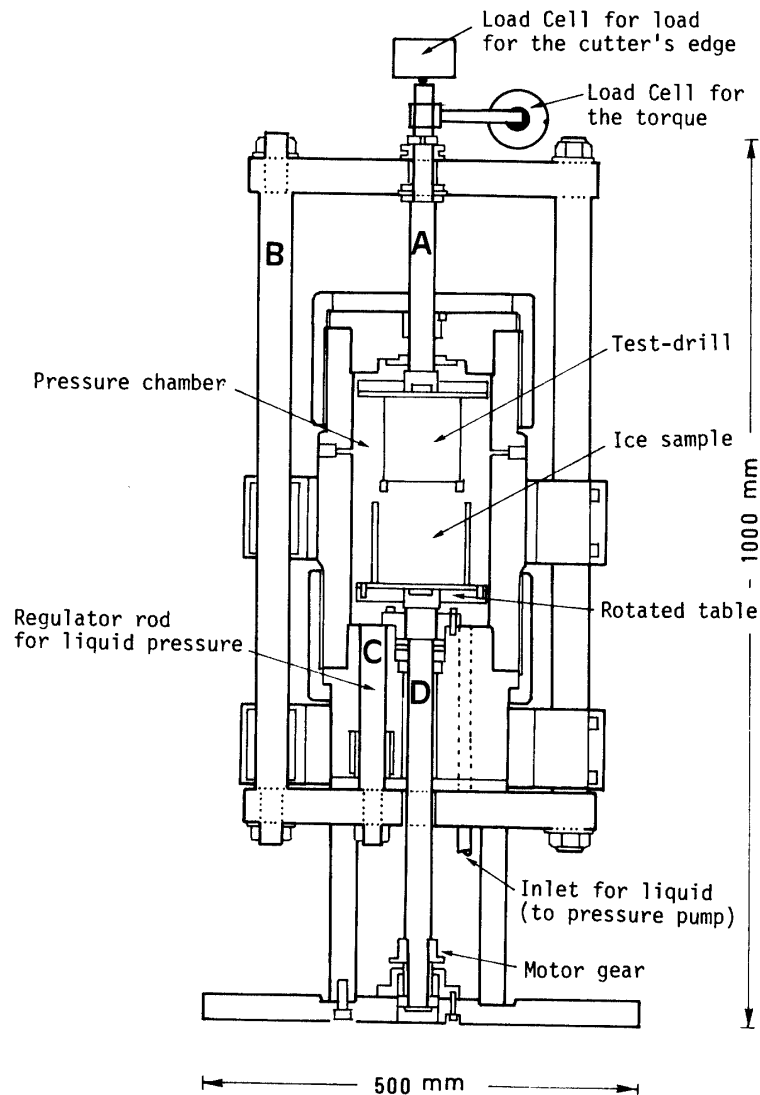


Fig. 1. Experimental apparatus for ice cutting in a liquid under high pressure.

apply the hydrostatic pressure to the ice sample in the chamber.

The experimental procedure was as follows: After the ice sample was set in the chamber filled with the Silicon liquid, the pressure was applied by use of an oil hydraulic pump. The sample was kept under the setting pressure for 1 to 2 hours in order to settle the sample at the high pressure. Then, the drill was caused to penetrate into the rotating ice sample by pushing the outer frame B through a load cell by hand, keeping the penetration speed as constant as possible. The load and torque applied at the cutter edge and the liquid

pressure in the chamber were recorded automatically through the load cells. The temperature was measured by using a thermo-couple sensor.

In the second experiment, the performance of the drill cutter with different rake angle (Fig. 2) at  $-62^{\circ}\text{C}$  was tested. A handy electro-mechanical drill 23 kg in weight and 50 cm in length was used. The design of the drill head is similar to that shown in Fig. 2 (b), but three cutters are arranged in this drill instead of two. An ice block 50 cm high was used in the experiments. The penetration speed was measured directly.

All of these experiments were carried out in a cold room which was controlled in the temperature range of  $-5^{\circ}\text{C}$  to  $-65^{\circ}\text{C}$ .

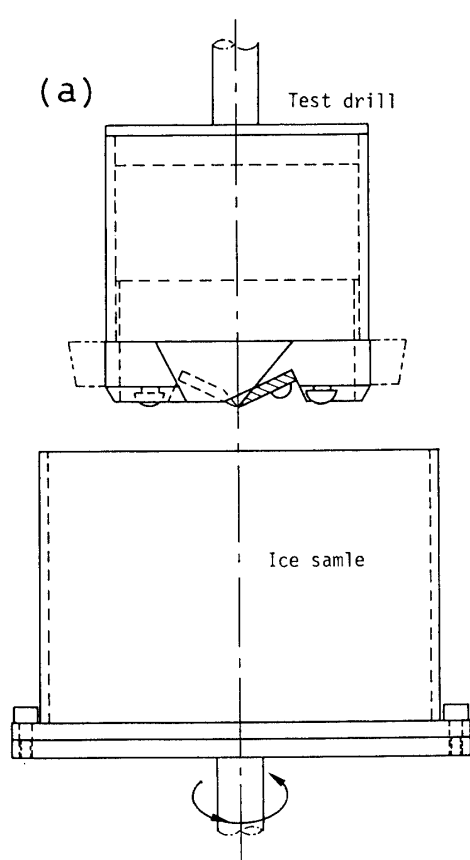


Fig. 2a. The enlarged test drill head and vessel for ice sample (side view).

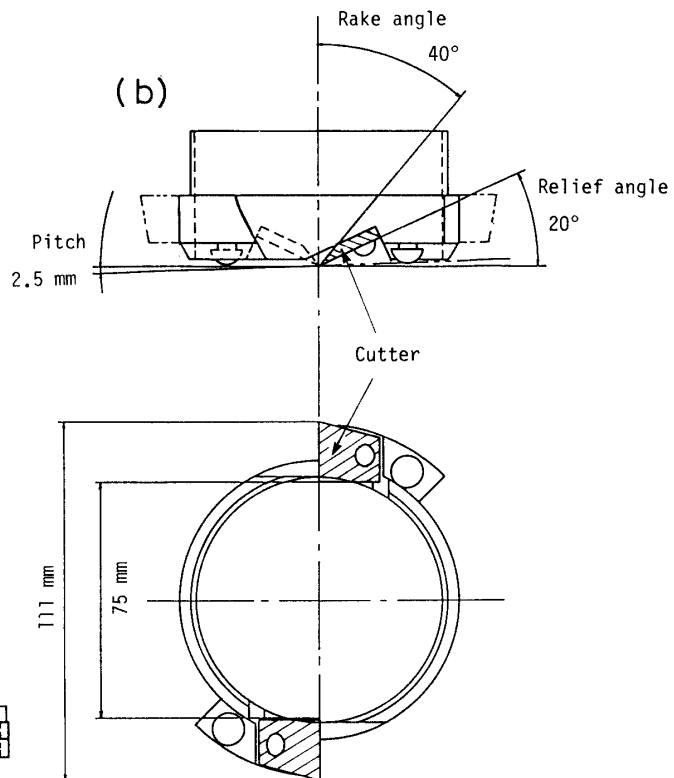


Fig. 2b. Vertical and horizontal sections of the cutter's edge.

### 3. Experimental Results

#### 3.1. Dependence on liquid pressure and temperature

In this experiment, the applied load (*i.e.* contact pressure) at the cutter edge and the rotational torque of the drill were recorded automatically through the load cells. The penetration speed of the drill can be determined from the design pitch and the drill rpm. However, as the drill could not penetrate into the ice sample with the design pitch, the average width between spiral flaws, made by the cutter edges, on the surface of the ice core was used as the pitch.

Figure 3a shows the results of the relationship between pitch and the load at the cutter's edge. Here, the load means the contact pressure which is applied along a cutter edge. The boxes in the figure show the range of the measured values. The values of  $P$  in the figure are the liquid pressures in each measurement. The pitch changes due to the pressure applied to the frame B in Fig. 1. As found from this figure, the pitch increases linearly with increase of the load for constant liquid pressure. It is also shown in Fig. 3a that increase of liquid pressure and the decrease of temperature cause increase of the penetration load when the pitch is constant. That is, drilling under lower temperature and higher pressure requires larger load at the edge of cutter when the drilling is done at a constant pitch. The relationships between load and pressure at  $-40.3^{\circ}\text{C}$  and  $-12.3^{\circ}\text{C}$  and pitch 1 mm are shown in Fig. 3b. The best fit lines in Fig. 3b can be expressed by the following equations.

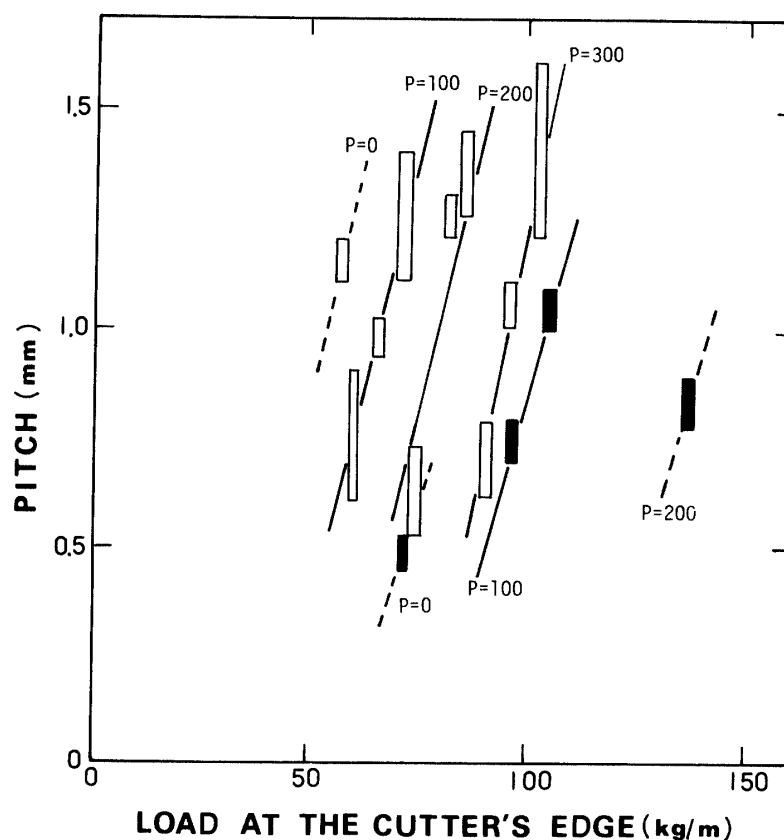


Fig. 3a. The relationship between the pitch and load at the cutter's edge. The hollow boxes indicate data at  $-12.3^{\circ}\text{C}$ ; the solid boxes are at  $-40.3^{\circ}\text{C}$ . The rake angle, relief angle and pitch are constant as shown in Fig. 2b. The size of boxes indicates the range of the data.

At  $-12.3^{\circ}\text{C}$ ,

$$L = \exp ( 0.002 P + 1.66 ), \quad (1)$$

and at  $-43.3^{\circ}\text{C}$ ,

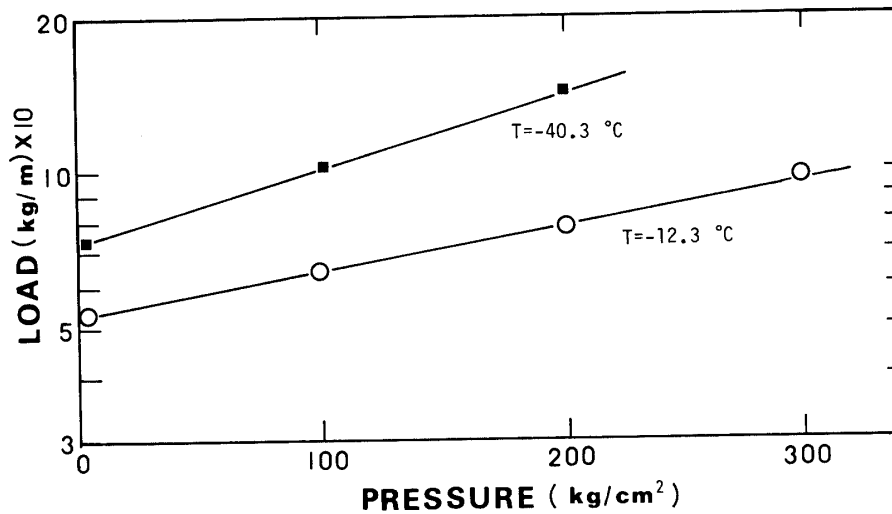


Fig. 3b. The relationship between load and pressure obtained from Fig. 3a for a pitch of 1 mm.

$$L = \exp ( 0.003 P + 2.0 ), \quad (2)$$

where  $L$  is load on the cutter's edge and  $P$  is the liquid pressure. The load increases exponentially with increase of liquid pressure. Also, as shown in Fig. 3a, the relationship between the pitch and load at  $T = -12.3^\circ\text{C}$  and  $P = 30$  MPa was almost the same as that at  $T = -40.3^\circ\text{C}$  and  $P = 10$  MPa.

The values of rotational torque were plotted against the load on the cutter edges in Fig. 4a.  $P$  is the liquid pressure in the chamber. The value of torque was about 0.15 kg-m at  $-12.3^\circ\text{C}$  and  $-40.3^\circ\text{C}$  without liquid pressure (atmospheric pressure) for all load values. However, when the pressure is applied in the chamber, the torque for penetration increases quickly with only small increase of the load. The change of torque against the load at  $P = 30$  MPa and  $T = -12.3^\circ\text{C}$  indicated the same tendency as at  $P = 10$  MPa and  $T = -40.3^\circ\text{C}$ . The relationship between the liquid pressure and cutter load  $L$  at torque of 1.0 kg-m (Fig. 4b) can be expressed by the following equation.

At  $-12.3^\circ\text{C}$ ,

$$L = \exp ( 0.002 P + 1.16 ), \quad (3)$$

and at  $-40.3^\circ\text{C}$ ,

$$L = \exp ( 0.003 P + 1.97 ). \quad (4)$$

Equations (3) and (4) are almost equivalent to eqs. (1) and (2), respectively. This means that the rotational torque is closely related to the pitch for drill penetration, *i.e.* in order to obtain larger pitch, larger torque is required under constant temperature and liquid pressure.

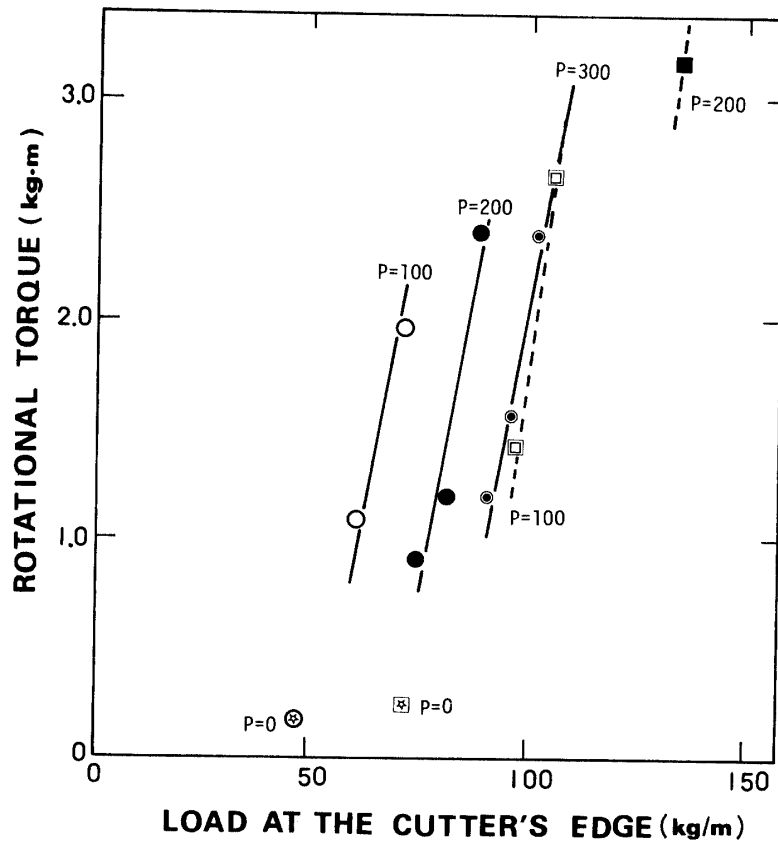


Fig. 4a. The relationship between rotational torque and load at the cutter's edge. The circles and squares indicate data at  $-12.3^{\circ}\text{C}$  and  $-40.3^{\circ}\text{C}$ , respectively. The rake angle, relief angle and pitch are the same as in Fig. 3a.

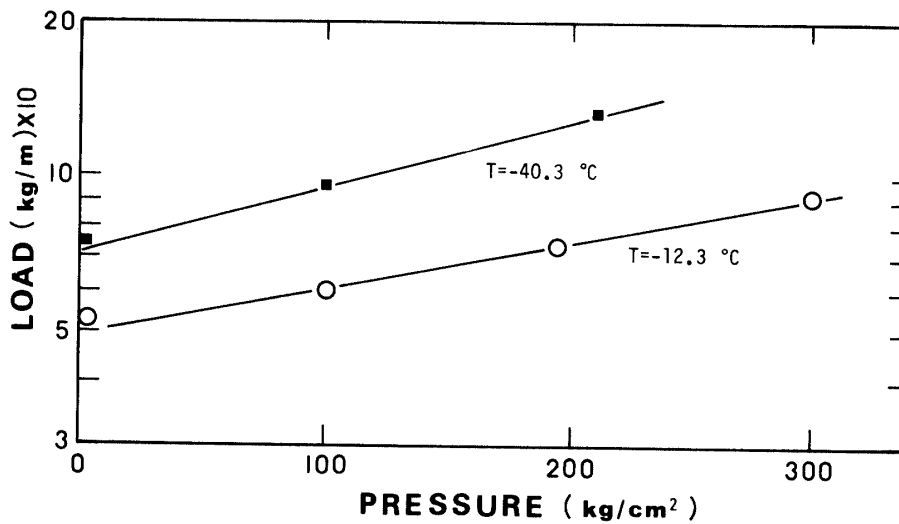


Fig. 4b. The relationship between the load and pressure obtained from Fig. 4a for the torque of  $1\text{ kg}\cdot\text{m}$ .

### 3.2. Rake angle dependence

An experiment was carried out in order to examine the performance of an ice cutter at

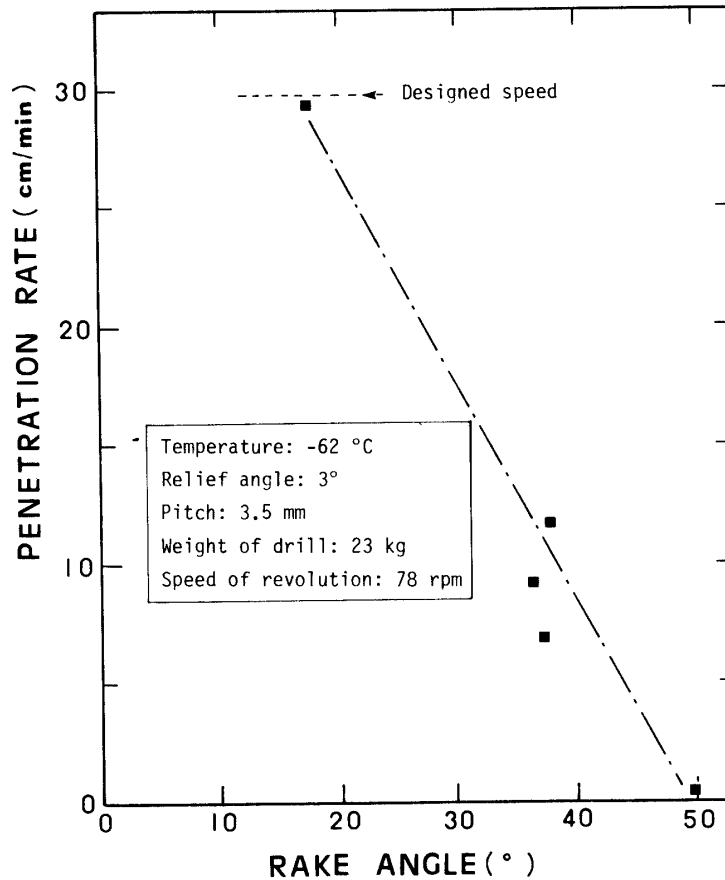


Fig. 5. The penetration speed dependency on the different rake angles at the temperature of  $-62.0^{\circ}\text{C}$ . The dotted line indicates the designed penetration rate of the test drill.

different rake angles. The relationship between the penetration rate and the rake angle is shown in Fig. 5. When the rake angle was  $17^{\circ}$ , the design penetration rate could be obtained. However, at a rake angle of  $50^{\circ}$  the drill could not penetrate.

#### 4. Concluding Remarks

Experiments on ice cutting were carried out in a compressed liquid at  $-12.3^{\circ}\text{C}$  and  $-40.3^{\circ}\text{C}$  and without liquid at  $-62^{\circ}\text{C}$  by using test drills. The following results were obtained:

- (1) When the liquid pressure increases and the temperature is lowered under constant load on the cutter edge, the penetration rate of the drill decreases. Larger load is required to maintain the same penetration rate at higher liquid pressure and lower temperature.
- (2) In order to obtain the penetration rate as designed, the rake angle should be small. When the temperature of ice is  $-62^{\circ}\text{C}$  and the load 23 kg, the rake angle should be  $17^{\circ}$  to obtain the design penetration rate.

The results in (1) are attribute to the increase of ice strength at lower temperature and the loss of ice brittleness at higher liquid pressure (DURHAM *et al.*, 1983). According to the experimental results, the rotational torque for ice cutting at  $-12.3^{\circ}\text{C}$  and liquid pressure 30

Mpa was equivalent to that at  $-40.3^{\circ}\text{C}$  and atmospheric pressure.

In (2), the design penetration rate was obtained by using a drill with rake angle  $17^{\circ}$  in spite of the load at the cutter's edge being very small. It is particularly thought that this result is applicable for ice drilling under the pendulous condition which keeps the bore-hole vertical.

### Acknowledgments

The authors are indebted to the National Institute of Polar Research (NIPR) for providing the apparatus. Also, the experiment at  $-62^{\circ}\text{C}$  was conducted by the members of the committee for the development of deep ice drilling. The authors would like to express their thanks to the members.

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