THE DRILL SYSTEM USED BY THE 21ST JAPANESE ANTARCTIC RESEARCH EXPEDITION AND ITS LATER IMPROVEMENT

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***Abstract*:** A drill system designed by the first author and made by Koken Shisui Kogyo K.K. was successfully used by the other author to drill several holes down to 143 m in 1980 in Antarctica. The system and its performance are presented together with brief reference to its predecessors and successors.

1. Introduction

Having planned to carry out several seismic surveys of bed-rock, each requiring an explosion of up to 500 kg of dynamite in dense firn or ice, in 1979 by JARE-20 (the 20th Japanese Antarctic Research Expedition) and in 1980 by JARE-21, late in 1977 JARE asked the first author to design a system capable of charging dynamite at a depth deeper than 50 m in the Antarctic ice sheet.

His first idea was to bore a hole down to 60 m and expand its bottom thermally. But as it seemed difficult to charge a cavity with dynamic through a thin hole, he proceeded to the alternative idea of boring a hole deep enough for its lower part below 50 m to make the required volume, which had been estimated to be 1.5 m^3. The necessary depths for a hole of diameter 14, 20 and 28 cm are 150, 100 and 75 m, respectively.

Since JARE had drilled a 147-m hole of diameter 17 cm in 1975 with a thermal drill (SUZUKI and TAKIZAWA, 1978), a natural choice for the system might be a thermal drill system. But with future use of the system by glaciologists in mind, he decided to develop a light-weight electromechanical drill system, which would be faster and much lighter than a thermal drill system.

From a logistical viewpoint, a larger hole is preferable because it requires a shallower depth and hence a shorter operation time. But as glaciological interest is more in the depth than in the diameter of a hole, he decided to attempt a 150-m drilling, which could be done within the 100 hours JARE had allocated for one operation.

2. Basic Specifications of the System

The first thing to do in making a drill system is to determine its basic specifications, which is rather a complicated procedure where many factors must be considered. A detailed discussion of the procedure will be given elsewhere. Below the final suggested specifications will be given with brief explanation if necessary.

2.1. *Operation time*

The total time T required to core-drill to a depth D is given by a well known formula

$$T = D^2/L/V + D/v + s \cdot D/L = N(D/V + L/v + s)\ , \tag{1}$$

where L, V, v and s are the core length for a run, the winching speed, the drilling speed and the constant time necessary for each run, respectively, while N $(=D/L)$ is the number of runs. These should be as follows: $L = 0.5$ m, $V = 1000$ m/h (*ca.* 0.3 m/s), $v = 25$ m/h (*ca.* 7×10^{-3} m/s) and $s = 0.1$ h. With these values it takes less than 81 hours to drill to 150 m.

2.2. *The drill*

(1) General: The drill should be a conventional double tube type with an inner tube (the barrel) rotating and chips being transported between the outer tube (the jacket) and the barrel by helical fins and contained in the upper part of the barrel (see, *e.g.*, RUFLI *et al.*, 1976).

(2) Basic diameters: The core diameter d_0, the inner diameter (ID) and the outer diameter (OD) of the barrel d_1 and d_2, ID and OD of the jacket d_3 and d_4, and the hole diameter d_5 were suggested to be 107, 110.1, 114.3, 130, 137 and 140 mm, respectively, the barrel and the jacket being expected to be made of a stainless steel and an FRP pipe of commercially available sizes.

(3) Barrel length: The ratio x of the core length against the barrel length is calculated from the following formula

$$\rho \cdot x(d_5^2 - d_0^2) = \rho_0[(1-x)d_1^2 + k(d_3^2 - d_2^2)]\ , \tag{2}$$

where ρ_0 is the density of chips and ρ is that of drilled ice or firn. With k taken to be 0.5, the above values of the diameters gave $x = 0.38$ for $\rho/\rho_0 = 3.0$ ($\rho_0 = 306$ kg/m^3 and $\rho = 917$ kg/m^3). Hence, the barrel length should be longer than 1.3 m to be able to take an 0.5-m ice core.

(4) Bit: Two drag bits of SIPRE auger type should be used (see Fig. 2).

(5) Core-cut and -hold: Two horizontally rotating paws should be used to bite and break the core by the reverse rotation of the barrel. Conventional vertically rotating paws would be added. The inner wall of the bit-holder should be tapered to help hold the core (see Fig. 2).

(6) Driving unit: The required output power of the motor is estimated from

$$P/A = E_s \cdot v\ , \tag{3}$$

where A is the cutting cross-section $(= (d_5^2 - d_0^2) \cdot \pi/4)$ and E_s is a quantity having a dimension of energy per volume or force per area and represents in a sense the reciprocal of the efficiency of the drill. E_s may be as low as 10^6 N/m^2. But some safety factor and transmission loss being considered, E_s should be taken to be 10^7 N/m^2, which gave $P=448$ W for $A=6.4\times10^{-3}$ m^2 and $v=7\times10^{-3}$ m/s. The barrel should rotate at *ca.* 100 rpm.

(7) Anti-torque mechanism: Any of the three types, (a) two side drills, (b) four side cutters and (c) conventional three leaf springs, should be attachable to the driving unit. (For (a) and (b), see SUZUKI, 1978.)

2.3. Winch

This should hoist 150 kg (75 kg of the drill and 75 kg of the 150-m cable) at 0.3 m/s. This requires *ca.* about 450 W. With a transmission efficiency of 60%, the winch motor output should be 750 W. To increase the winching speed is the easiest way to shorten the total operation time. But the speed was chosen as low as reasonable in order to reduce the size of the generator.

3. The System for JARE-20

Two drills, ID-140 and -140A, and a winch, W-12-180 of the above specifications were ordered in May 1978 from Koken Shisui Kogyo K.K. (The names mean "Ice Drill with a nominal hole diameter of 140 mm" and "Winch with an armoured cable 12 mm in diameter and 180 m long". The cable was lengthened to 180 m at the request of JARE-20.) The two drills differed from each other only in the rotational direction of their side cutters, that of ID-140 being such as to increase while that of ID-140A to decrease the thrust on the bits (see SUZUKI, 1978). Each drill could use either a 2-m long barrel or a 1.4-m long one with the corresponding jacket.

The system was completed in mid-October and immediately tested in a cold laboratory. The result was quite disappointing. The FRP jacket had so large a deviation in its diameter that in spite of the nominal clearance of 1.5 mm between the jacket and the hole the drill could not proceed without a large thrust being applied. A stainless steel jacket of OD 135 mm and ID 130 mm was hurriedly machined from a thick pipe. The test with this jacket was again disappointing. Chips were hardly transported upward and only a 20 to 30-cm drilling was possible.

In retrospect, the reason was that the machined inner wall of the jacket was so smooth that chips rotated with the barrel without any upward motion. Something to hinder the rotation of chips, such as ribs or grooves, should be supplied to the inner wall of the jacket. Though unaware of this simple solution, the designer (Y. S.) ordered the third jacket rolled out from thin steel sheet. If tested, its juncture would have served as the rib and chips would have been transported upward, revealing the mechanism of the transportation of chips. But with no time left for the test with the third jacket, the system was sent to Antarctica without any instructions on how to improve the second jacket.

The performance of the system was described elsewhere (IKAMI *et al.*, 1980). Unfortunately, the third jacket was so weak that on the first run it was crushed, and JARE-20 had to use the inefficient second jacket. Nevertheless, they drilled 62 m in 66 hours (see Table 1 in Subsection 6.3).

Several recommendations or suggestions by JARE-20 were:

(1) Suitable surface treatment of the jacket and the barrel might improve the transportation of chips.

(2) Helical fins of teflon bars should be replaced by stronger ones.

(3) The barrel should be 1.5 m long for easy handling.

(4) Core-cut and -hold mechanism had failed in 59 runs out of the total of 247 runs. They should be improved.

(5) Side cutters were effective. But if they and the guided fins behind them were totally in a weak firn layer, the drill might turn, making its hoisting very difficult. Additional side cutters behind (above) the guide fins should be considered.

(6) The joint between the barrel and the driving unit should be more reliable.

4. A Test Drill ILTS-140

Early in 1979, the second author was appointed chief of the JARE-21 drilling operation. The authors preferred to build a new system to remodel the old one. Still unaware of the reason for poor transportation of chips in the old drill, they decided to test if changes in such factors as the pitch of fins, the bottom shape of the jacket, the barrel rpm, etc. would improve the transportation of chips. A short test drill, ILTS-140, was made at the machine shop of the Institute of Low Temperature Science. Its jacket was made of a seemed steel pipe of OD 139.8 mm and ID 135.8 mm. (For other specifications, see Table 2.) To the authors' surprise, chips were smoothly transported on the first try where the pitch of fins and the rpm of the barrel were similar to those of the ID-140 and the jacket was simply cut straight. The seam, only 0.2 to 0.3 mm high, served as the rib.

The importance of the rib was more explicitly verified by the following tests: Chips were hardly transported when the jacket was replaced by an acryl pipe of OD 140 mm and ID 134 mm. Then a wire 0.8 mm in diameter was attached to the inner wall of the pipe with an adhesive tape. Now, chips were seen to be transported upward along the wire.

The test drill was later remodeled to ILTS-140A and used by Dr. F. NISHIO of the National Institute of Polar Research (NIPR) in December 1979 at Allan Hills (McMurdo Sound) to drill blue ice down to 7 m in 5 hours, where a hand-driven winch was used to suspend the drill and electric power was supplied through an independent rubber-jacketed cable from a variable transformer which in turn was connected to a 1.2-kW generator. The transformer was to control the barrel rpm. The drill was again remodeled to ILTS-140B and successfully used by Mr. H. NISHIMURA of JARE-22 to drill several holes down to 30 m in 1981 in East Enderby Land.

5. The System for JARE-21

The results of tests with ILTS-140 and the recommendations by JARE-20 being taken into consideration, a new drill MID-140B was designed together with

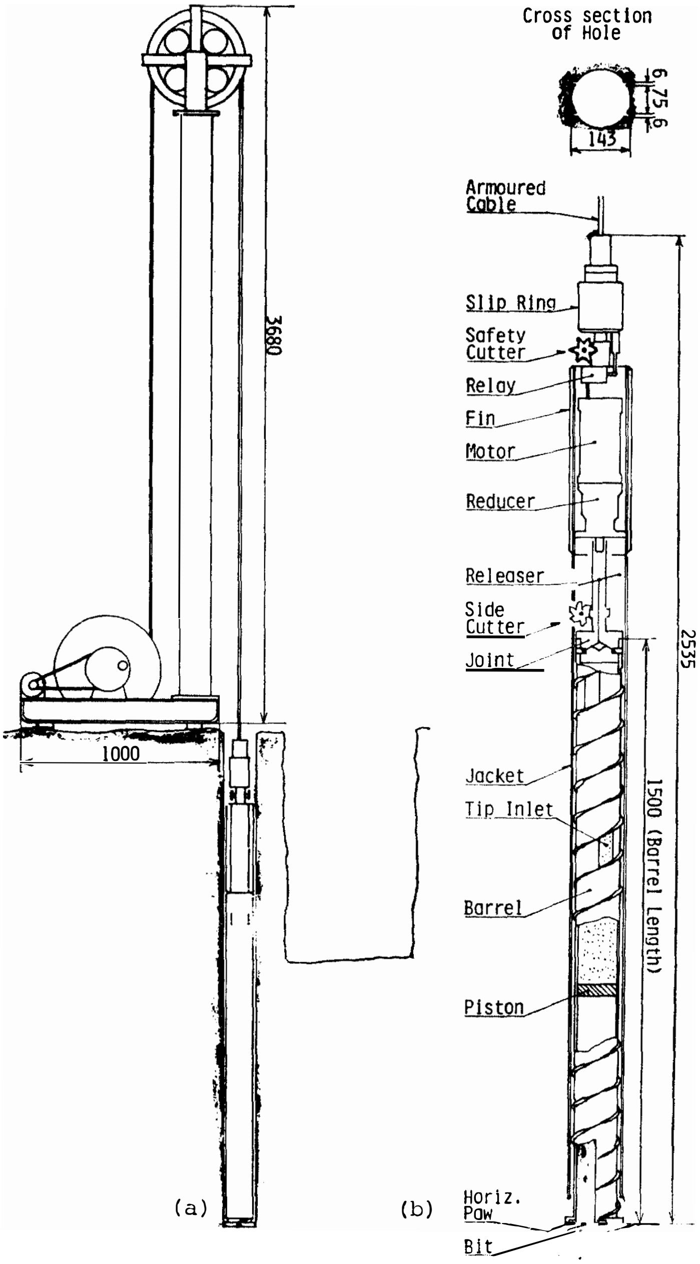


Fig. 1. (a) The drill MID-140B and the winch W-9-150 in operation. The winch was actually mounted on a sledge.
(b) Schematic diagram of the drill MID-140B.

a new winch W-9-150. (As JARE had decided again to develop thermal drills along with mechanical ones, the letter M was added to the naming, where the figure 140 indicated the jacket diameter rather than the hole diameter.) The drill and the winch will be described in some detail below. They are also shown schematically in Fig. 1.

5.1. The drill MID-140

5.1.1. Basic diameters

The diameters d_0, d_1, d_2, d_3, d_4 and d_5 are 105.0, 110.1, 114.3, 136.6, 139.8

and 146 mm. (A proposed model MID-170 with enlarged values of 130.0, 135.6, 139.8, 162.0, 165.2 and 172 mm was judged premature because of an expected difficulty in core-cut, which had been yet to be solved even for a core of the small size.) From the formula (2) with $k=0.5$, the ratio x is calculated 0.35 for $\rho/\rho_0=3$. A barrel 1.5 m long will easily take an ice core 0.5 m long.

5.1.2. Power source and drilling speed

A series commutator motor of rated output of 1 kW (made by Shibaura Seisakusho K.K.) is coupled with the same 100:1 reducer as used in ID-140 (made by Harmonic Drive Systems K.K., Type: CS-25-100-GPSP). The test by the maker shows that the motor delivers 460 W at 12900 rpm with an input of 1 ϕ, 200 V, 50 Hz, 5.3 A and 1080 W at 10000 rpm with 9.6 A.

The tip of the bit protrudes 4 mm beyond the bottom of the bit-holder (see Fig. 2). Assuming that each bit intrudes into ice by 4 mm in the drilling, the drilling speed v is 80 cm/min (13.3 mm/s or 48 m/h) at a barrel rotation of 100 rpm and 102 cm/min (17 mm/s or 61 m/h) at 129 rpm. As the cutting cross-section A is 8.08×10^{-3} m^2, the value of E_s in the formula (3) is 10^7 N/m^2 for the former case and 3.35×10^6 N/m^2 in the latter case. We may expect a drilling speed of about 50 m/h for ice and 60 m/h for firn.

5.1.3. Structure of the drill

The drill can be easily disassembled into three parts: the driving unit, the jacket and the barrel.

The driving unit consists of two parts. The cylindrical case of the upper part contains a relay (for the reverse rotation of the motor) and the power source. At

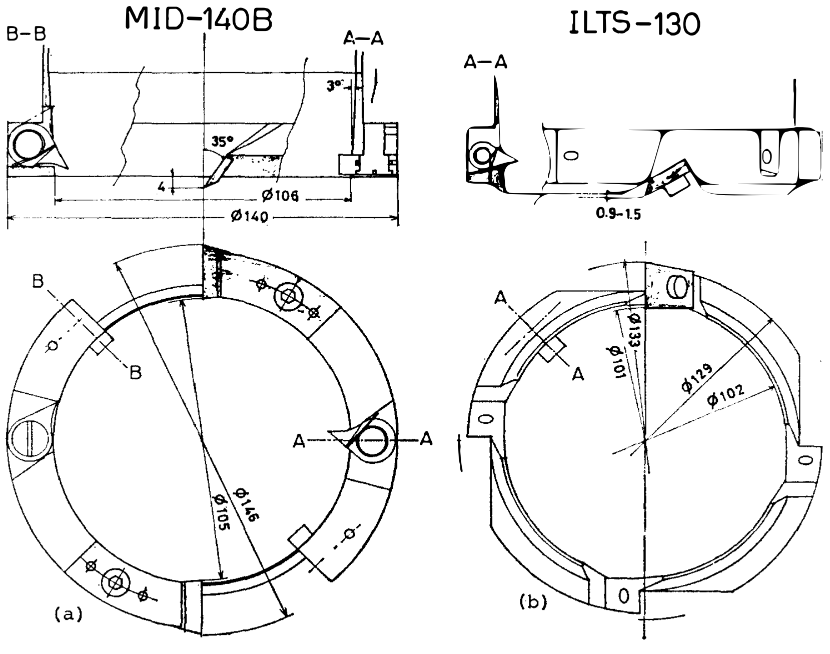


Fig. 2. (a) The bit-holder of the MID-140B. Two bits (shaded), two vertical paws and two horizontal paws are shown in the under view.

(b) That of the ILTS-130 series. Only one bit (shaded) and one vertical paw are shown in the under view.

the top of the case there are four free-wheeling safety cutters and a connector to the slip-ring assembly. Four guide fins are welded on the side of the case over all its length. The lower part houses the main shaft, which has a plug-joint for the barrel at its lower end, a barrel-release mechanism and a mechanism to drive four side cutters. The jacket is to be attached to this lower part. The upper part can slide by 30 mm relative to the lower part, allowing a hammering action on the latter and hence on the barrel. The driving unit is about 80 cm long and weighs about 45 kg. The main differences from the driving unit of the ID-140 are: (1) Disuse of the side drills and the leaf springs, (2) addition of safety cutters and elongation of guide fins, (3) addition of the hammering mechanism, (4) improvement of the barrel-release mechanism and (5) increase in the output power.

The barrel is made by welding a joint-socket at the top, a bit-holder at the bottom and two helical fins on the side of a main pipe of OD 114.3 mm and ID 110.1 mm. All are of stainless steel. The helical pitch is 167 mm. The outer diameter of the fins is finished to 130 mm. The barrel is 1.5 m long and weighs about 13 kg. The jacket is a steel pipe of OD 139.8 mm and ID 136.6 mm with three ribs 8 mm wide and 1.5 mm thick spot-welded on its inner wall. The length of the jacket is such that its end is 10 mm above the upper surface of the bit-holder. The jacket weighs about 9 kg. The barrel and the jacket are teflon-coated. The bit-holder is schematically shown in Fig. 2 with the bits and the paws.

5.2. *The winch W-9-150*

One hundred and fifty meters of a seven-conductor armoured cable (made by Rochester Corporation, Culpeper, Va. 22701, U.S.A. Type: 7-H-374A, weight: 357 kg/km, resistance of each conductor: 34.1 ohms/km) is spooled on an aluminum drum 360 mm in diameter and 320 mm in effective width. Both ends of the cable are connected to slip-ring assemblies, one to be connected to the drill and the other to be fixed on the shaft of the drum. A 100:1 reducer made by Harmonic Drive Systems K.K. (type: CS-65-100) is incorporated in the drum. A handle can be attached to the input axle of the reducer, which is also connected by a 6:1 belt drive to a 1 kW motor the same as that of the drill. The standard rpm of the drum is thus about 17 rpm (a winching speed of about 20 to 24 m/min). The mast is of a single-pole type. A sheave assembly with an aluminum sheave 495 mm in diameter is mounted on a 3-m long FRP pipe of OD 158 mm and ID 150 mm with an aluminum flange at its bottom. The mast can be easily disassembled from the main frame of the winch. Including the mast, the winch weighs about 200 kg.

5.3. *The controller*

In order to protect the reducer, care should have been taken not to change the rotational direction of the drill motor without cutting the power supply to it. In the used wiring shown in Fig. 3a, a special rotary switch S2 takes such care, but with a limited success (see Section 6). One should stop at the stage 3 or 2 for a while before going to the stage 4 or 1. (More positive care should have been taken as shown for example in Fig. 3b.) A variable transformer with rated output of 10 A, 0 to 260 V controls both the winching speed and the barrel rpm. The controller weighs about 20 kg.

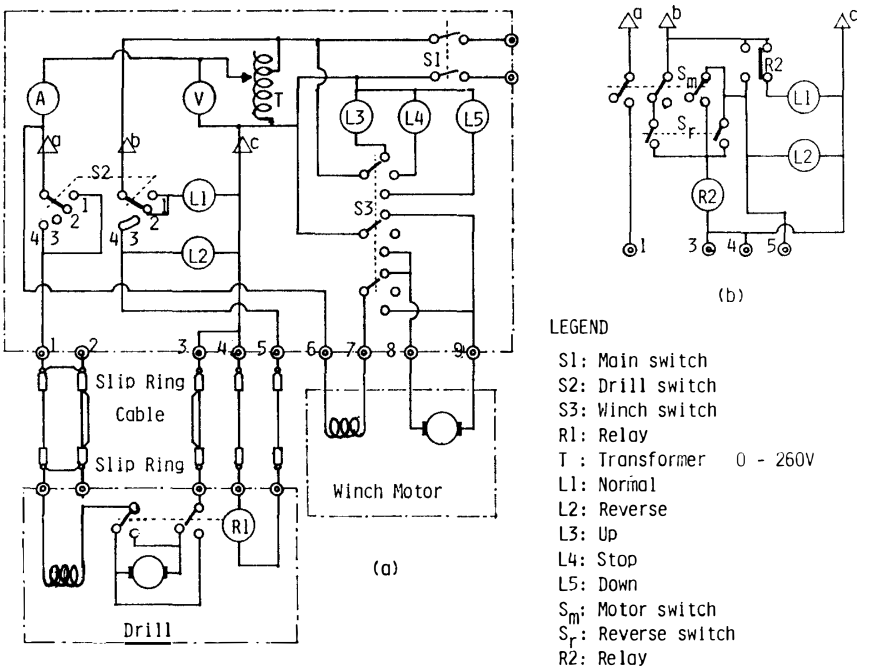


Fig. 3. (a) Circuit diagram of the controller with the drill and the winch.
(b) Suggested improvement.

Note: A sudden change in the rotational direction of the motor while running will damage the reducer. Though the switch S2 in (a) turns the motor off at stages 2 and 3, one is apt to go through those stages too quickly to stop the motor completely (see text). In (b), one cannot change the direction without switching the motor off by using switch S_m.

5.4. *The generator*

As the simultaneous use of the drill and the winch is uncommon, a power supply of 200 V, 10 A is enough for the system. But with the altitude of Mizuho Station taken into consideration, a gasoline generator of rated output of 1 ϕ, 50 Hz, 200 V, 14 A is chosen, which weighs about 63 kg, making the total net weight of the system about 350 kg.

6. The Drilling Operations by JARE-21

6.1. *Preliminary drillings*

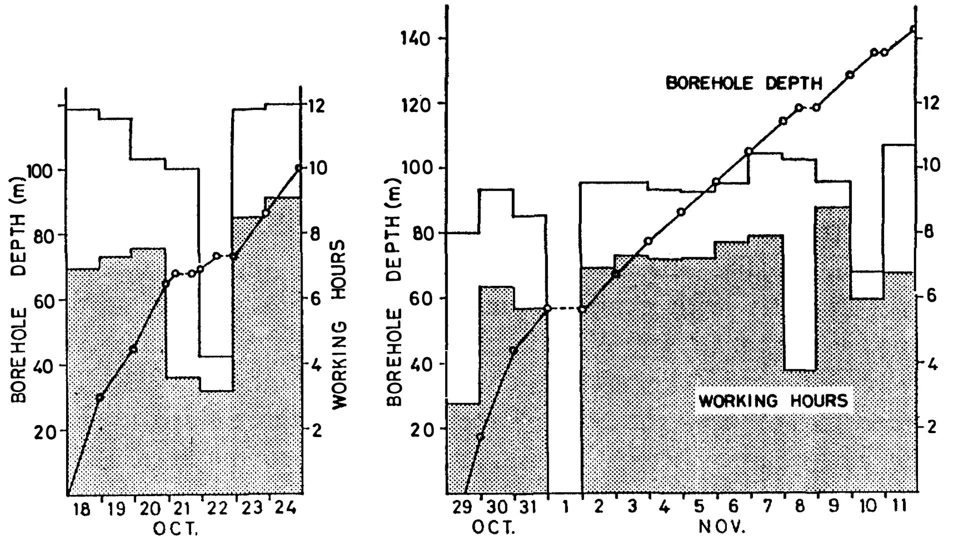
After a field test of the drill at a snow field on Mt. Tateyama in September, participated in by the drill team of JARE-21, some minor modifications of the drill based on the experience of the test, and a final test of the system in late October, the system was shipped to Syowa Station, where for the easier operation on ice sheet the system was mounted on a sledge, which was 4 m long and had a canvas cabin 2.3 m long on it. The winch was set on the open space while the generator was in the cabin.

The preliminary test drillings on Antarctic ice sheet were carried out in July 1980 at S-22 (69°01.6′S, 40°19.5′E) and S-27-3 (69°02.4′S, 40°33.8′E). At the first site, a 30.5-m hole was drilled on July 16 to 18 and another 15.6-m hole on July 19, while at the latter site a 30.5-m hole was drilled on July 28. Though it required two and a half days to drill the first hole, the third hole of the same depth was drilled in less than 7 hours, as the team had mastered the system.

In general, the drill worked smoothly, though slip of the drill and/or failure in core-cut or -hold were occurred in several runs below 10 m. In a typical smooth run, a 0.5-m drilling was done in 25 seconds with power input of 200 V, 4.5 A at the surface. As the cable resistance was 5 ohms, the input voltage to the motor was 177.5 V. Though the exact characteristics of the motor at this voltage were unavailable, it was estimated that the motor delivered about 350 W. Then, the value of E_s in the formula (3) was about 2×10^6 N/m^2 in such a run in firn lighter than 600 kg/m^3.

6.2. *The drillings at H-231 and at Mizuho Station*

The drilling team left Syowa Station on October 16, 1980 and arrived at the drilling site H-231 (69°46.4′S, 42°27.6′E) in the afternoon of the next day. The preparation of the drilling was begun immediately and finished in less than two hours by five men. The procedure of the preparation was as follows: The sledge was placed with its winch side windward. The mast was assembled. A pit 1-m deep was dug in front of the winch. And finally, a wind shield, which was a canvas sheet 1.5 m wide and 8 m long with 9 aluminum poles 2 m high being attached at every meter, was set in a half circle on the windward side of the pit. The shield had been prepared at Syowa Station based on the experience in the preliminary drillings.



(*a*) (*b*)

Fig. 4. Progress diagrams at H-231 (a) and at Mizuho (b). Shaded areas represent the drilling hours.

The team began drilling on October 18 and reached 100 m on October 24. The total drilling time was 46 hours. As shown in Fig. 4a, the work progressed smoothly except on October 21 and 22. On the former day a hasty reversing of the drill rotation at the depth of 68 m broke the reducer (see Subsection 5.3) and it took 6 hours to replace it by the reducer of ID-140A, which had fortunately been kept at hand, while on the latter day extremely bad weather stopped the work for a half day.

After they had finished the hole at H-231, the team moved to Mizuho Station (70°41′53″S, 44°19′54″E), where they began drilling at the site Z-140-1, some 2 km apart from the station. They stayed at Mizuho and tripped to the site every day. The weather was so severe that the mean temperature and wind speed at 0900 LT during the operation were $-28.7\,^{\circ}\mathrm{C}$ and 13.8 m/s, and blizzards occurred on nine days out of the two weeks of the operation, even halting the work completely on November 1. Despite such severe weather, the operation proceeded smoothly to 108 m, where on November 8 the barrel was accidentally dropped to the bottom of the hole. After a laborious six-hour work, the drillers managed to recover the barrel and resumed the operation, which was halted however at 135 m because of breakdown of the reducer on November 10. Though only another 8 m or so was left to the maximum attainable depth by the system, the team did not give up. A mechanic of the team flew to Syowa Station with the broken driving unit to replace its reducer by that of the ID-140. He flew back in the next morning with the repaired unit and the final 8 meters was drilled in that day. The 143-m drilling required 81 hours. The progress diagram is shown in Fig. 4b.

6.3. *Discussions on the two drillings*

Though unapparent in the progress diagrams, the slip of drill and the failure in core-cut/hold, which had been met even in the preliminary drillings, occurred more and more frequently with increase in depth.

Especially, the slip was common below 65 m (or in firn denser than 850 kg/m^3), where the drill usually began to slip after proceeding 10 to 15 cm. Pulled up by 0.5 m or so and lowered slowly with the motor on, the drill could resume progress for another 10 to 15 cm. However, as it required several such procedures for the drill to proceed 0.5 m, the effective drilling speed was considerably reduced.

Meanwhile, in this 10 to 15 cm progress, the drilling speed was about 12.5 mm/s (45 m/h) with power input of 200 V, 6 A at the surface, or with estimated motor output of 500 W. The value of E_s in the formula (3) for firn of the density of 850 to 870 kg/m^3 was considered to be about 5×10^6 N/m^2.

In order to see how the slip of the drill and the failure in core-cut/hold affected the performance of the system, we will analyze the H-231 drilling more closely. We now transform the formula (1) as follows

$$(T_2-T_1)=((D_2-D_1)/L)\cdot((D_2+D_1)/V+L/v+s)\,, \qquad (4)$$

where $t=T_1-T_2$ is the required time and $n=(D_2-D_1)/L$ the required number of runs for the drilling from D_1 to D_2. Using the actual values of t and n, we compute the mean drilling length L and the mean time per run $t_r=(D_2+D_1)/V+L/v+s$ over each of the four depth ranges shown in Table 1. Then, assuming $V=20$ m/min and $s=5.5$ min based on experience, we compute the mean value of v from the computed values of L and t_r.

Now, if there had been no slip of the drill and no failure in core-cut/hold, t, n, L and t_r would have been different values, which will be denoted by the same

Table 1. *Results of the analysis of the H-231 drilling.*

	D_1-D_2 m	t mim	v_s m/h	n	L cm	t_r min	t_c min	v m/h	n'	n^o	L^o cm	v^o m/h	t_r^o min	t^o min	n^o/n %	t_r^o/t_r %	t^o/t %
	1- 30	415	4.19	55	53	7.55	6.00	64	5	50	58	70	7.55	377	91	100	91
	30- 65	890	2.36	81	43	10.99	6.24	35	11	70	50	55	10.80	756	86	98	85
	65- 73	405	1.19	26	31	15.58	8.68	6	10	16	50	45	13.07	209	62	84	52
	73-100	1050	1.54	67	40	15.67	7.02	16	13	54	50	40	14.90	805	81	95	77
	1-100	2760	2.15	229	43	12.05	7.00	17	38	191	52	45	11.24	2147	83	93	78
JARE-20	1- 62	3960	0.99	247	25	16.03			59	188	32		21.06		76		

Note: (1) The time t_c is the mean value of $(L/v+s)$ estimated from t_r with the assumption of $V=20$ m/min. (2) The values of v and v^o for 1–100 m were estimated from $t_r=12.05$ min and $t_r^o=11.24$ min, respectively.

symbols with a superscript o; t^o, n^o, L^o and t_r^o. By definition

$$t^o=n^o\cdot t_r^o \quad \text{and} \quad L^o=(D_2-D_1)/n_0. \tag{5}$$

The effect of the two problems on the performance of the system will be quantitatively shown by the performance factor defined by

$$t^o/t=(n^o/n)\cdot(t_r^o/t_r). \tag{6}$$

We computed the performance factor for each of the four depth ranges of the H-231 drilling from the formulae

$$n^o=n-n' \quad \text{and} \quad t_r^o=(D_2+D_1)/V+L^o/v^o+s, \tag{7}$$

assuming n' being the number of coreless runs in the actual drilling and v^o taking the values shown in Table 1 which would be consistent with the observed drilling speeds of about 72 m/h in shallow depth and about 45 m/h below 65 m mentioned in the previous sections.

The results of the analysis are shown in Table 1, where for the total depth the performance factor was computed not by the above procedure but by assuming the total drilling time t^o to be the sum of each t^o, and t_r^o was computed by the first formula of (5) and v^o by the second formula of (7). In Table 1, some corresponding data of the JARE-20 drilling were cited from IKAMI *et al.* (1980) for the sake of comparison.

The poor performance of the drill in the depth range from 65 m to 73 m was certainly attributed to the third trouble, poor core-quality, which was most frequently met in this range. There, a retrieved core was usually broken into pieces, many of which were thin disk-like ones. Even a few longer pieces had many horizontal cracks and were easily broken into disk-like ones with minimum stress. Frequent failures in retrieving cores was understandable because such a broken core would be hard for the drill to hold. Moreover, in a failed run, the broken pieces would fill the hole, so that the next run would have to drill an extra length through a pile of them. This might explain the severe decrease in the drilling speed there ($v/v^o=13\%$), which could not be explained by the slip of the drill alone.

7. Suggested and Attempted Improvement

7.1. Suggestions to solve the problems

The improvement of a system may be considered to have two meanings: The first is to make the system to be able to develop its ability more fully and the second to change its specifications so as to make it more suitable for another purpose. We may call the first debugging and the second the development. We will first discuss debugging.

As described in the previous section, three major troubles hindered the drill from developing its ability fully: the failures in core-cut/hold, the slip of drill and the poor core-quality. The third trouble was one of the causes of the other two, and the first had a worse effect on the drill-performance than the second. We will study them carefully to find how to solve them.

The drill was equipped with two horizontal and two vertical paws to cut and hold the core (Fig. 2a). It was expected that the core would break easily by hammering bites of either the formers in a sudden reverse rotation of the drill or of the latters in a sudden pull of the drill and that the intruded paws could hold the broken core. In actual operations, however, even repeated hammering bites of the horizontal paws often failed to break the core, only making many tiny cracks in and a groove around it. (The vertical paws were not operative probably because chips clung around them and prevented them from touching the core.) Then, it was necessary to apply tension on the core to break it completely, and, if the pulled drill could not deliver the necessary tension, the core was not cut but only scratched by the intruded paws. Such would be the cause of the failures in core-cut/hold except those caused by the third trouble. Suggestions are (1) to change the form and number of paws so as to allow more effective hammering bites and a firmer grip of the core and (2) to add another mechanism to hold the core, if necessary.

The slip of the drill was certainly due to the decrease in the effective thrust at the tip of the bits. The drilling team suggested that the accumulation of stray chips between the drill and the hole might cause the decrease. But the designer (Y. S.) considered that their accumulation below the bits or the bit-holder was more responsible for the slip. There, the chips would become wet from frictional heat and apt to cling to the bits and the bit-holder. Suggestions are (3) to change the form of the bit and the bit-holder so as to prevent chips from accumulating below them and (4) to strengthen the ability of chip-transportation so as to lessen stray chips.

Core quality depends on so many factors of cutting that we cannot say what kind of a combination of them produces a core of the best quality from firn of such and such characteristics. All we can do now is allow a driller to choose the combination as freely as possible and expect him to proceed on a trial-and-error basis. Among the factors, the form and number of the bit are easily controlled. A rule of thumb is that the more the number and the less the intrusion depth, the better the core quality. The rotational speed and torque of the barrel of MID-140B can be, though very roughly, controlled by input voltage and monitored by input current.

More precise control and monitoring of them are desirable but may not be worth the necessary complication. On the other hand, the control and monitoring of the thrust, which can be estimated from the tension of either the main shaft or the end of cable, may deserve consideration. Suggestions are (5) to allow the bit-holder to hold more than two bits, (6) to supply various bits and (7) to add a tension monitor at the end of the cable.

7.2. *A new design of the bit-holder*

The above analysis revealed that all of the troubles of MID-140 were more or less related to the bit-holder. Hence, the first priority was given to its improvement, and a new design of it was made in accordance with the suggestions 1, 3, 5 and 6. The new design used for the 130-series drills is shown in Fig. 2b. (That for the 140C and the remodeled 140B is similar but with different dimensions. As for the drills, see later.)

Of the design, the relation is evident with some suggestions. Namely, the bit-holder can hold four bits (with the fifth suggestion); The form of a bit is so simple that it is easy to prepare various kinds of bits (with the sixth); a bit in place has no horizontal face and the holder bottom has a smaller horizontal portion than the old one (with the third).

A few remarks on paws will help to see the relation of the new design with the first suggestion. In order to bite a core in the sudden moves of the drill as described before, the paws must be pressed on the core just before the moves. For the sake of simplicity, the paws are usually spring-loaded and pressed on the core even during drilling. Then, if their form or pressure is inadequate, they will thin out the core during drilling so as to make their following hammering bites impossible. It is rather difficult to find an adequate form or pressure of the vertical paws, though not of the horizontal paws. As we had experienced some such difficulties for the vertical paws of the test drill ILTS-140, in using the drill MID-140B we relied mainly on its horizontal paws to cut and hold the core, and in order to prevent the vertical paws from thinning out the core we set their pressure as weak as possible (later found in the actual operation to be too weak to work).

However, as the vertical paws of an improved form of the drills ILTS-140A and B, both without horizontal paws, had worked well in Antarctic blue ice and firn, we determined to abolish the horizontal paws in the new design.

The vertical paws are more effective for core-cutting than the horizontal ones because the activating force for the formers can be as large as the cable strength allows (>10000 N) while that for the latters is limited by the motor (~ 1500 N for the MID-140B). The replacement of two horizontal paws by two vertical ones in the new design thus satisfies the requirements of the first suggestion.

7.3. *Several new drills*

7.3.1. The drills for JARE-23

For use by JARE-23, a new drill MID-140C was made and the barrel of the MID-140B was remodeled in 1981, both with the new bit-holder. The driving unit of the MID-140C was almost the same as that of the MID-140B, except that the former had no hammering mechanism and that the alignment of the guide fins with the side cutters of the former became better than that of the latter. The poor alignment of the latter might have been partly responsible for the slip of drill, because it might have caused large friction of the guide fins against the grooves in dense firn.

7.3.2. The drills, ILTS-130 series

Three drills, ILTS-130A, B and C have so far been made of this series. Unlike the MID-140C, they are different from the MID-140B in many points. Primarily intended as a component of a handy drilling system for shallow drilling, they are designed to make a hole 132 mm in diameter with a drilling speed up to 45 m/h producing an ice core 102 mm in diameter and 35 cm long. With a barrel 1-m long, they are shorter than 1.6 m (1.4 m for C), lighter than 30 kg (21 kg for C)

Table 2. Specifications of the drills.

	ILTS-140B	ID-140A	MID-140B(C)	ILTS-130A	ILTS-130B	ILTS-130C	ILTS-130S
Basic diameters							
Std. core dia.: d_0 (mm)	105.0	107.0	105.0	101.0	101.0	101.0	107.0
Holder ID: d'_0	106.0	108.0	106.0	102.0	102.0	102.0	107.6
Barrel ID: d_1	110.3	110.1	110.1	105.0	105.0	105.0	111.1
OD: d_2	114.3	114.3	114.3	109.0	109.0	109.0	114.3
Jacket ID: d_3	135.8	131.0	136.6	124.6	123.0	124.6	123.8
OD: d_4	139.8	135.0	139.8	127.0	127.0	127.0	127.0
Holder OD: d'_5	142.0	137.0	140.0	129.0	129.0	129.0	130.0
Std. hole dia.: d_5	146.0	140.0	146.0	133.0	133.0	133.0	132.0
Barrel							
Length (std.): L_0 (m)	1.0	2.0	1.5	1.0	1.0	1.0	1.5
Number of vert. paws	2	2	2(4)	4	4	4	4
Number of horiz. paws	0	2	2(0)	0	0	0	0
Number of bits	2	2	2(4)	4	4	4	4
Std. bit protrusion (mm)	2	4	4(2)	2	0.9	0.9	0.9
Std. rpm	100	100	100	100	120	120	120
Calc. speed: v_0 (m/h)	24	48	48	48	26	26	26
Number of fins	2	2	2	2	2	2	2
Slope of fins (°)	30	30	25	30	30	30	30
Driving unit							
Input: (V)×(A)	100×9	200×4	200×9	200×4	100×4	100×6	100×6
Output: (W)/ at (rpm)	500/ 4000	450/ 10000	1000/ 10000	450/ 10000	220/ 15000	350/ 15000	350/ 15000
Reducer: Type Ratio	Cyclo 40:1	Harmonic drive 100:1			3-stage planetary 5×5×5:1		
Reverse rotation?	no	yes	yes	no	no	no	no
Weight (approx.) (kg)	20	50	45	19	10	10	10
Length (approx.) (m)	0.60	0.80	0.80	0.52	0.47	0.42	0.40
Overall dimensions (std.)							
Weight (approx.) (kg)	30	70	65	30	25	21	26
Length (approx.) (m)	1.6	2.8	2.3	1.5	1.5	1.4	1.9

and require less than 1 kW (0.6 kW for C). At present, the drill is suspended by a manual or electric winch with an ordinary steel wire, and power is supplied through an independent electric wire. An electric winch with an armored cable is to be made. The total net weight of a system consisting of the drill, ILTS-130C, a mast, a manual winch with a 40-m, 4-mm-ϕ steel wire, a 40-m rubber electric wire winded on a drum, a controller and a 800-W generator, is only about 70 kg. The replacement of the winch and the wire with an electric winch with an armored cable will increase the weight by 10 kg.

In the field tests so far, the model A drilled Himalayan glacier ice to 31 m (Nagoya University), the model B Antarctic firn to 22 m at Halley Base (Dr. Y. Fujii of NIPR) and the model C Arctic silt-contaminated ground ice to 22 m at Tuktoyakutuk, N.W.T., Canada (ILTS). The results were encouraging. More detailed discussions on the tests and description of the drills, including the new 130S, will be given elsewhere.

7.4. Concluding remarks

Specifications of the drills are given in Table 2. Remarkable decreases in length and weight of the driving unit from 80 cm and 45 kg of the MID-140B to only 42 cm and 10 kg of the ILTS-130C are due to the simpler structure and the smaller motor and reducer of the latter. Because of the improved chip-transport ability and the decrease in cutting area, the drilling speed of the latter is expected to be over 25 m/h despite the small motor, thus little affecting the total drilling time. An elongated version of the 130 model with a barrel length of 1.5 m or more will surely replace the MID-140C in the future.

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