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Improvements to the JARE deep ice core drill

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Abstract: The second phase of the deep ice core drilling at Dome Fuji, Antarctica is planned to be carried out in three successive summer seasons starting from 2003/2004 with an improved JARE deep ice core drill. On the basis of tests, major improvements were made including extension of the core barrel to 4 m, addition of a more powerful chip-collecting pump, addition of a check valve to avoid loss of collected chips while hoisting the drill in borehole liquid, and a more powerful drill motor. This report describes the improvements and results of the tests as of December 2000.

1. Introduction

In 1996, the Japanese Antarctic Research Expedition (JARE) drilled a 2503 m deep ice core at Dome Fuji, Antarctica with an electro-mechanical drilling system (Dome-F Deep Ice Coring Group, 1999; Fujii *et al*., 1999, 2002). The development of the drill (we hereafter call it the Phase 1 drill) was reported in Fujii *et al*. (1990), Tanaka *et al*. (1994), Narita *et al*. (1995), and Takahashi *et al*. (1996). The phase 1 drill had a capability to obtain 2.2 m core in each drilling run. Ice core quality was perfect but we had to spend much time collecting chips that leaked from the chip chamber in the drill to the bore hole liquid during hoisting of the drill, repairing bad electrical contact in the drill and so on (Fujii *et al*., 2002).

The second phase of deep ice core drilling at Dome Fuji will aim to reach bedrock at a depth of 3030 m from the surface in three summer seasons starting from 2003/2004. Preliminary fieldwork commenced in 2001 to install a casing in a pilot hole for the subsequent deep ice core drilling. The limited drilling time resulting from working in only three summer seasons will require a reliable, high-speed drill. The JARE phase 2 drill requires performances which enable whole depth core drilling to be done during three summer seasons. The major areas of modification of the phase 1 drill are summarized as follows.

1) The 2.2 m long barrel used in the Phase 1 drill will be extended to 4 m.
2) A more reliable chip-collecting device will be installed in the drill. In the phase 1 drill an Archimedean pump and one turn screw booster were employed. This system will not be sufficient for transportation and storage of the increased chip amount.
3) A check valve will be installed in order to prevent flushing of collected chips out of the chip chamber during hoisting of the drill.
4) A more powerful drill motor will be required. The drill motor used in phase 1, an AC brushless motor, required a complicated electronic driver and the high motor speed led to troubles with the reduction gear. The phase 2 drill will use a simple DC brush motor.

2. Effect of extending the core barrel

Table 1 shows estimated drilling times and rates at different depths for the phase 2 drilling. The table assumes the following: 1) An average core length of 3.5 m. Although the core barrel will be 4 m long, a full length core will not be obtained in every run. 2) An average hoisting and lowering speed of 0.8 m/s. This speed was obtained in the phase 1 drilling at Dome Fuji. We are planning to increase this speed for the phase 2 drilling but we use the phase 1 statistical values for the estimation. 3) A cutting speed of 15 cm/min. 4) A drilling time of 16 hrs/day. The remaining 8 hours will be used for chip collection and maintenance, or extra drilling if required. 5) To estimate realistic total working days, we add some days to the total days theoretically estimated for unexpected work based on experience during the phase 1 drilling.

With these assumptions we estimate 128 days for the phase 2 drilling provided that there are no major problems such as a drill becoming stuck. This means that three summer seasons should conservatively provide enough time for the phase 2 drilling.

Table 1. Estimation of drilling time.

Depth (m)	Winching time per run (min)	Drilling time per run (min)	Service time (min)	Time loss due to troubles (min)	Total time for 1 run (min)	Daily run number (run)	Progress per day (m)	Total days to the depth (day)	Total realistic days to the depth (day)
500	22.7	23.3	15	15	76	13	45.5	8	31
1000	43.5	23.3	15	10	91	10	35	21	52
1500	64.3	23.3	15	10	112	9	31.5	36	68
2000	85.2	23.3	15	0	123	8	28	52	85
2500	106	23.3	15	0	144	7	24.5	72	105
3000	126.8	23.3	15	0	165	6	21	95	128

3. Chip pump system

3.1. Pumps considered

Because of the larger volume of chips that will be produced by the longer core drilling, we require a more effective pump system than the phase I drill. Four types of pump, including a one turn screw booster similar to that used in the phase I drilling, are being tested.

All pumps tested are made to fit into a 112 mm diameter tube which is the actual diameter. The pumps tested are:

(1) A one-turn screw booster (Fig. 1a; Suzuki and Shinbori, 1985, 1986). This booster is the same as the booster used for phase I drilling. We also tested boosters with pitches of 25 mm, 50 mm, 100 mm and 150 mm for comparison.

(2) A three-vane screw pump (Fig. 1b). This pump was designed on the assumption that the booster pump works mainly as a liquid impeller, but the three-vane screw pump is expected to move a larger volume than the other types of pump. We have tested two different kinds with vanes at 45° and 60° from the horizontal. We have also tested both single and double pumps.

(3) Conveyer pump (Fig. 1c). This pump works as a mechanical conveyor transporting the chips and slush. The conveyer lead is put around the drive shaft over half or more of the length in the chip chamber.

(4) Mohno pump (Fig. 1d). This type of pump, generally known as a "progressive cavity pump", was used successfully by the Polar Ice Coring Office in the GISP 2 deep drilling (Wumkes, 1994). Since this pump can carry even solid material such as mud and sand, it can easily transport ice slush. The pump tested is a Model NTL30PSL of Heishin Engineering & Equipment Co. Ltd. with specifications of transportation ability of 7 *l*/min at 70 rpm and discharge pressure of 0.1 MPa. The power consumption of the motor is 0.75 kW.

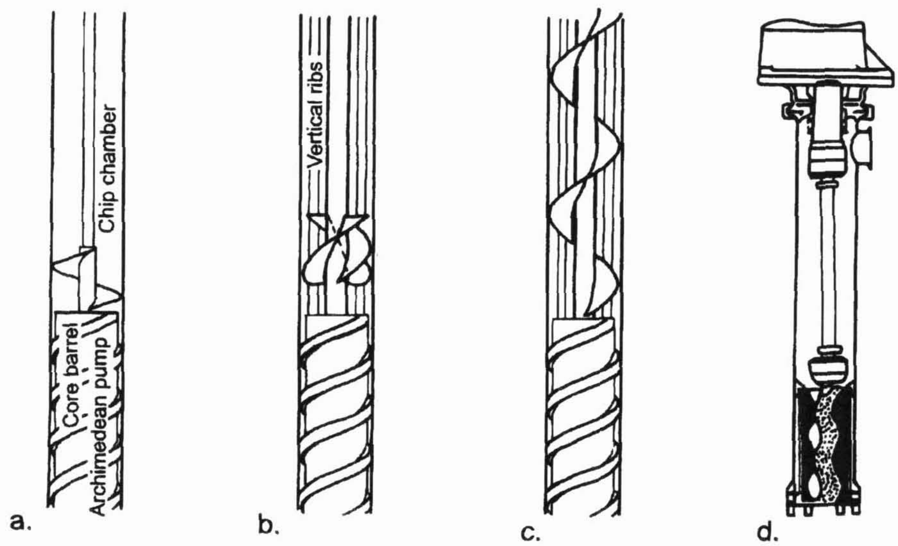

Fig. 1. Four types of pump used for test. a: a one-turn screw booster, b: a three-vane screw pump, c: a conveyer pump and d: a Mohno pump.

(5) The NGRIP drill dual action pump borrowed from the University of Copenhagen.

3.2. Results of the pump comparison test

The test of four pumps evaluated efficiency from the view point of practical use. The first test was conducted in December 2000 using a device as shown in Fig. 2. The results are shown in Table 2 and are summarized as follows.

(1) None of the booster type pumps can create discharge pressure and hence are not said to be liquid pumps. They apparently carry ice chips by mechanical conveyor action. There are two important requirements for the booster type of pump: one is that multiple vertical ribs are required on the inside wall of the jacket in order to restrict circumferential movement of the slush and create progressive flow, the other is that the flow resistance through the chip chamber must be minimized, *e.g.* by expanding the filter area or cutting large chips because these pumps can't create pressure.

(2) A double booster type pump does not create discharge pressure as we expected. We expected that double boosters would suck the same quantity as a single booster but would produce a higher pressure as in a multi-stage pump.

(3) The Mohno pump and NGRIP pump are liquid displacement pumps because the liquid flow is semi-independent of the flow resistance.

(4) The Mohno pump's discharge rate is as small as 7 liters per minute which is insufficient for an ice drilling pump. The bigger model of this kind of pump cannot be installed in the drill.

(5) The Mohno pump also consumed the most power among the pumps tested.

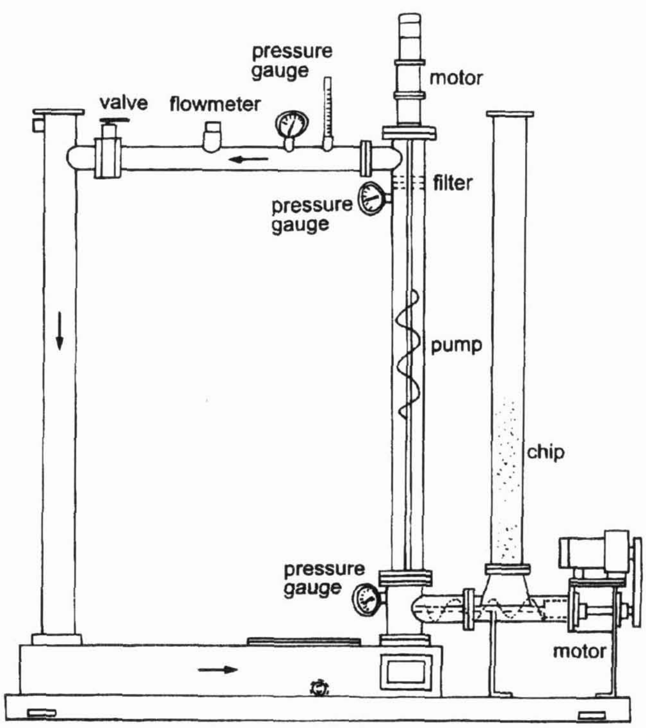

Fig. 2. A device for testing pumps.

Table 2. Results of pump comparison test under the shaft rotation speed of 70 rpm (50 rpm for NGRIP pump) and water temperature of 16–17°C. Q: flow rate (l/min), P: water pressure (mm of water), W: power consumption (W).

	Booster pitch: 25mm			Booster pitch: 50mm			Booster pitch: 100mm			Booster pitch: 150mm		
Choke position	Q	P	W	Q	P	W	Q	P	W	Q	P	W
Open	13.3	0	50	21.5	0	51	28.1	0	54	29.4	0	49
1	13.3	0	50	19.9	0	51	25.2	0	54	25.4	0	49
2	10.7	0	50	15.3	0	51	17.0	0	54	16.8	0	49
3	7.8	0	50	9.1	1	51	8.5	1	54	8.7	0	49
4	2.9	0	50	3.9	1	51	2.2	1	54	3.2	1	49
Closed	0	0	49	0	3	49	0	2	49	-	-	-

	3-vane screw 45°			Double 3-vane screw 45°			3-vanes screw 60°			Double 3-vane screw 60°		
Choke restriction	Q	P	W	Q	P	W	Q	P	W	Q	P	W
Open	31.9	0	51	38.8	0	54	34.7	2	53	35.8	1	49
1	26.4	2	51	33.0	1	54	29.7	3	53	30.6	2	49
2	17.3	2	51	22.5	1	54	18.9	4	53	19.6	2	49
3	9.0	3	51	12.7	2	54	9.9	4	53	10.3	3	49
4	2.6	3	51	2.8	3	54	2.1	4	53	1.9	4	49
Closed	0	1	50	0	3	57	0	4	53	0	4	-

	Conveyer pump			Mohno pump			NGRIP pump		
Choke restriction	Q	P	W	Q	P	W	Q	P	W
Open	39.1	3	60	6.5	0	386	21.8	1	54
1	33.4	3	60	6.7	0	386	21.4	1	54
2	23.3	3	60	6.7	0	386	21.8	11	54
3	13.4	4	60	6.5	1	386	21.0	19	54
4	3.0	4	60	6.4	52	386	18	184	54
Closed	0	1	64	-	-	-	-	-	-

Booster type pumps and the NGRIP pump had low power consumption. The NGRIP pump also showed high efficiency with steady flow and is physically very small.

4. Drill motor and communication devices

In the phase 1 drilling at Dome Fuji, using the DC brushless drill motor caused damage or short life for the reduction gear due to its high rotational speed. The complicated electronic driver forced difficult maintenance. For the phase 2 drilling, we plan to use a simpler brush type DC motor.

The power consumption of the drill motor used in phase 1 is summarized in Table 3, where power consumption, output power and motor torque are calculated by the following equations:

$$\text{Power consumption, } W\text{: } W = V \times A, \qquad (1)$$

$$\text{Output power, } P\text{: } P = W \times k_1 \times k_2, \qquad (2)$$

where k_1 and k_2 are efficiencies of the motor driver and the motor, taking the values of 0.9,

Table 3. Power consumption of a drill motor in the phase I drilling at Dome Fuji.

Situation	Voltage input to motor V (V)	Current A (A)	Speed of motor & core barrel N (rpm)	Power consumption W (Watts)	Output power P (Watts)	Required motor torque T Nm (kgf.cm)
Idling in liquid	185	0.6	11500 68	111	90	0.07 (0.7)
Cutting at 600 m depth	186	2.0	11150 66	372	301	0.26 (2.7)
Cutting at 2300 m depth	196	2.1	11236 67	411.6	333	0.28 (2.9)

respectively.

$$\text{Motor torque, } T\text{: } T\ (\text{Nm}) = P/\omega, \tag{3}$$

where ω is angular velocity given by $\omega = 2\pi f$, where $f = N$ (rpm)/60. Then, eq. (3) can be expressed as follows.

$$T\ (\text{Nm}) = 9.55\ P/N. \quad (1\ \text{kgf·cm} = 0.098\ \text{Nm},\ 1\ \text{Nm} = 10.2\ \text{kgf·cm}) \tag{4}$$

The pump test showed that the motor output power while idling in liquid was as low as 90 W, more power was required to cut at a depth of 2300 m than at 600 m, and the maximum power and torque required were 333 W and 0.28 Nm. The drill motor will be chosen on the basis of this power consumption.

Two motors with diameters less than 80 mm were selected for testing (Table 4). Both motors are of permanent magnetic type, with brushes. These motors have the advantage of not requiring a complicated motor driver, a simple rectifier is sufficient; but they have the disadvantage that the brushes constantly give off small sparks. Durability tests were conducted on both brushless motors, and the drill communications system was checked to see if there was likely to be any problem from sparking at the brushes.

The motors were tested under conditions which simulated actual drilling except for temperature. The motor and drill computer were operated in a pressure chamber and a 1000 m length of armored cable was used for power supply and communications. We

Table 4. Specifications of drill motors tested.

Model No. & maker	Venti-lation	Diameter & length (mm)	Output power (W/15min)	Torque (Nm)	Speed (rpm)	Voltage (V)	Current (A)
PM60 Parvalux Co., U.K	open	78 196	575	1.1	5000	200	3.0
T500 Tsugawa Co., Japan	closed	80 160	500	1.2	4000	200	2.7

Table 5. Results of motor durability and computer communications test.

Time (min)	Voltage (V)	Current (A)	Speed (rpm)	Noise on commu-nication	Temp. of motor (°C)	Temp. of reduction gear (°C)	Temp. of motor chamber (°C)	Temp. of outside water (°C)
Motor: PM 60								
Start	160	2.0	4000	none	14.8	16.8	17.2	14.1
27	160	2.0	4000	none	45.5	28.6	23.6	14.5
Motor: T500								
start	130	2.2	5000	none	12.7	11.9	14.0	10.7
27	130	2.0	5000	none	33.1	28.6	19.3	10.7
33	130	2.0	5000	none	38.3	30.3	20	10.7
41	130	2.0	5000	none	44.0	32.2	20.5	10.7

brake the shaft rotation to create a load for the motor. The results are shown in Table 5. As can be seen in this table, no noise or error occurred on the signal from the drill computer, and neither motor overheated even after running for more than 40 min under a motor load. Both motors and the drill computer seemed to be reliable enough for the new drill. In addition, there was no problem with the Harmonic Drive reduction gear fitted to the motor for the test.

5. Final design of phase 2 JARE deep ice core drill

Most of the major mechanical design for the phase 2 deep ice core drill has been decided (Fig. 3). The most important remaining decision concerns the chip pump. Other minor details, which are not addressed in this paper, are not expected to be significant. Table 6 shows specifications of the improved drill.

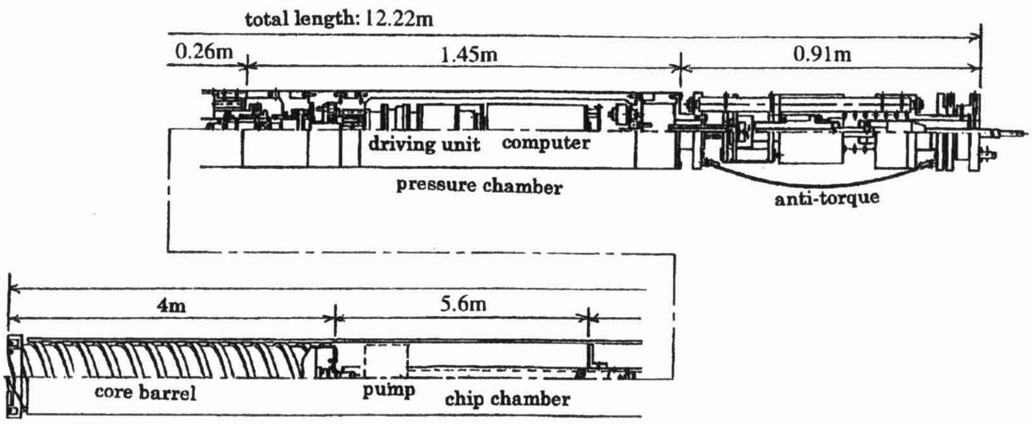

Fig. 3. Final design of the JARE phase 2 deep ice core drill.

Table 6. Specifications of the phase 1 drill and the improved drill.

Item	Phase 1 model	Phase 2 model
Type	Electro-mechanical drill	Same as phase 1
Core ϕ×L	94 mm ×2200 mm	94 mm× 3800-3900 mm
Cutting speed	15-20 cm/min	Same as phase 1
Static pressure	30 MPa	Same as phase 1
Drill size ϕ×L	122 mm×8593 mm	122 mm×11940 mm
Cutter	3×block type	Same as phase 1
Core barrel ϕ×L	101.6 mm×2321 mm	101.6 mm×4000 mm
Chip chamber ϕ×L & density	112 mm×3260 mm ρ=500 kg/m^3	112 mm×5000 mm ρ=550 kg/m^3
Chip pump	Archimedean pump & 1 turn screw booster	Archimedean pump &?
Motor output power	DC brush-less motor 600 W for 15 min	DC permanent magnet motor with brushes. 600 W for 15 min
Reduction gear type & ratio	4 stage planetary gear 1/170	Harmonic drive type: CSF17 or 20 1/50
Electronics	Monitoring computer (10 parameters)	Same as phase 1 (version 2)
Pressure chamber ϕ×L & pressure	122 mm×1700 mm 30 MPa	Same as phase 1
Anti-torque	3×Leaf spring	Same as phase 1
Cable ϕ×L	7H-314K 7.72 mm×3500 m	Same as phase 1

Acknowledgments

Although we still have some insignificant improvements of the phase 1 drill to make and we need experiments and tests to ensure reliability, the framework design of the drill for Dome Fuji phase 2 deep drilling is thought to be ready, after improving major weak points of the phase 1 drill. We would like to express deep appreciation to the NGRIP drilling members, who gave us useful suggestions and information for our drill improvement. Special thanks go to Dr. N. Gundestrup and Dr. S. Johnsen of the Niels Bohr Institute for Astronomy, Physics and Geophysics, University of Copenhagen, for providing an NGRIP pump for the test.

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