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TECHNICAL ASPECTS OF DEEP ICE DRILLING ON LAW DOME

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Abstract: The Dome Summit South (DSS) ice drilling project was designed to obtain a full depth ice core for high resolution studies of the Holocene and the transition from the last glacial maximum.

The project used a new electromechanical drill based on the Danish ISTUK design. The main differences from the original ISTUK were an enclosed roller screw section and the use of a submersible brushless motor operating at ambient pressure in the drilling fluid.

The field work started in 1988 when a 270 mm diameter hole was drilled to 84 m and cased with fiberglass reinforced plastic tube. The hole was continued to 96 m with a smaller thermal drill to make a suitable pilot hole for the mechanical drilling. In 1989 the steel arch drilling shelter was set up over the borehole and the drill winch and tower set up in the shelter.

Most of the EM drilling was done in the 1991/92 and 1992/93 seasons and in February 1993 drilling reached silty ice containing small rock fragments at a depth of 1200 m. This is close to the ice thickness measured by radio echo sounding.

Down to 391 m in-field measurements were made of electrical conductivity, crystal fabrics and peroxide concentrations and samples were cut for later measurement of ^{10}Be and for fine detail determinations of peroxide and oxygen isotope ratios.

The core below 390 m became increasingly more brittle and difficult to handle. Only the last 6.4 m (which was not brittle) was brought back to Australia, the rest being left in the drilling shelter for collection next year after stresses have dissipated.

1. Introduction

The aim of the project 'Deep Ice Drilling on Law Dome' was to obtain a high quality ice core over the full thickness (1200 m) of the ice sheet near the summit of Law Dome, East Antarctica for high resolution studies of the Holocene and the transition from the last glacial maximum. Previous drilling on Law Dome with a CRREL thermal drill had reached depths to 475 m (the length of the thermal drill cable) but this was also about the limit of dry hole drilling. The new work was to be done with an electromechanical drill in a fluid filled hole, and to avoid 're-inventing the wheel' it was decided to make a drill based on the design of the Danish 'ISTUK' drill which had been used successfully in Greenland at Dye 3 and suited the scale of our operation.

The field work started in 1988 when the large diameter thermal drill was used to make a 270 mm diameter hole to 84 m. A sealed hole to the surface was created by casing with glassfibre reinforced plastic tube. Thermal drilling was then continued to 96 m with a 140 mm diameter drill to make a suitable pilot hole for the mechanical drill. Over the following season the drilling shelter was set up over a 3 m deep trench cut around the borehole casing and the drill winch and support equipment were installed. The electromechanical drill was completed and tested over the next two years. EM drilling to a depth of 553 m was done in 1992 and the remainder of the drilling to 1200 m was completed in January and February of 1993.

2. Thermal Drilling

The special large diameter thermal drill has a machined copper head with a brazed on 4000 W heating element. The construction of both the core barrel and the meltwater tank is based on 203 mm ID glassfibre reinforced plastic tube. This tube is the same material as is used for the borehole casing. The top section of the drill incorporates the usual cable termination, suction pump and electronics for cable tension and head temperature sensing. The drill was originally designed to take a 200 mm core for trapped gas analysis and made a 250 mm diameter hole (ETHERIDGE and WOOKEY, 1988). For the Dome Summit South (DSS) drilling a 260 mm diameter hole was required to give clearance for the joins in the borehole casing. An enlarged head was made which worked well but as it only had the same heating power, drilling was rather slow - about 2 hours for a 2 m core. The large diameter hole was drilled to 84 m. To make a hole in which the E-M drill could be started, thermal drilling to 96 m was continued with a modified CRREL drill (BIRD and BALLENTYNE, 1971) which makes a 140 mm hole.

3. Casing

It is desirable to case the part of the borehole that penetrates the porous firn so it can be filled nearly to the surface with loading fluid. This assists in giving sufficient hydrostatic pressure for borehole balancing and the higher pressure at the depth where electro-mechanical drilling is started makes drilling easier by assisting chip suction. At DSS the borehole was cased down to 84 m with ‘permaglass’ glassfibre reinforced plastic artesian well casing. This material proved very suitable as it is easy to use in the field, it produces a smooth inside wall, and the O-ring seals ensure the casing does not leak fluid. Fitting the casing into the borehole took 6 hours.

4. Drilling Shelter

The shelter in which the EM drill is operated is a 5 m high, 18 m by 7 m corrugated steel arch mounted on a sledge/frame. The arch is formed from sixty three 5 mm thick plates which are bolted together. The shelter and sledge were assembled near Casey Station, towed 120 km to the drilling site, and set up over a 3 m deep trench cut around the borehole casing. A square tower, 10 m high and 2.4 m across, at one end of the shelter houses a spiral staircase which gives access to the shelter. A warmed, insulated module inside the shelter houses the drill computer and is also used as a workshop.

5. Electromechanical Drill Rig

The EM drill is operated on a tiltover winch/tower. The winch, tower tilt, drill clamps and cable feed for drilling are all hydraulically operated. There are duplicate sets of hydraulic controls for the winch and tower, one by the drill tower and one in the warm module (Fig. 1). The winch is directly driven by a low speed wheel motor located inside the cable drum. The cable level winder is driven by a stepper motor as the drum design made it difficult to drive a cable guide from the drum rotation. Cable feed for drilling is

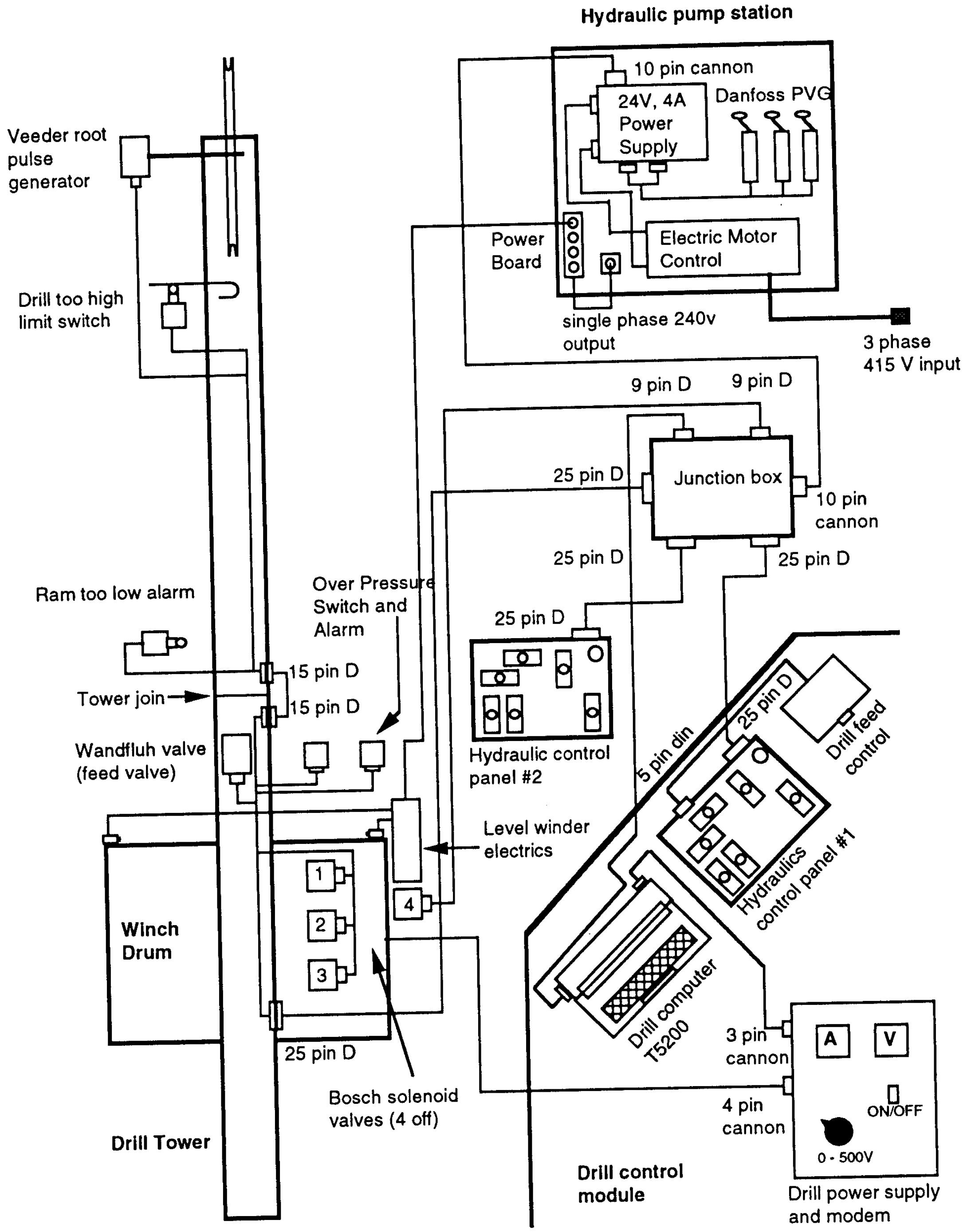

Fig. 1. Electromechanical drill rig-electrical systems. The hydraulic control panel No. 1 is located beside the winch and is used when lowering the drill into the borehole and tilting the tower. The second control panel inside the warmed ventilated room (drill control module) is used when drilling and hauling in the borehole.

produced by lowering the top sheave on the drill tower by an hydraulic ram. Feed speed is controlled by bleeding fluid from the ram through an electric proportional valve. This system, which is also used for the thermal drill, allows very fine control of the feed. A

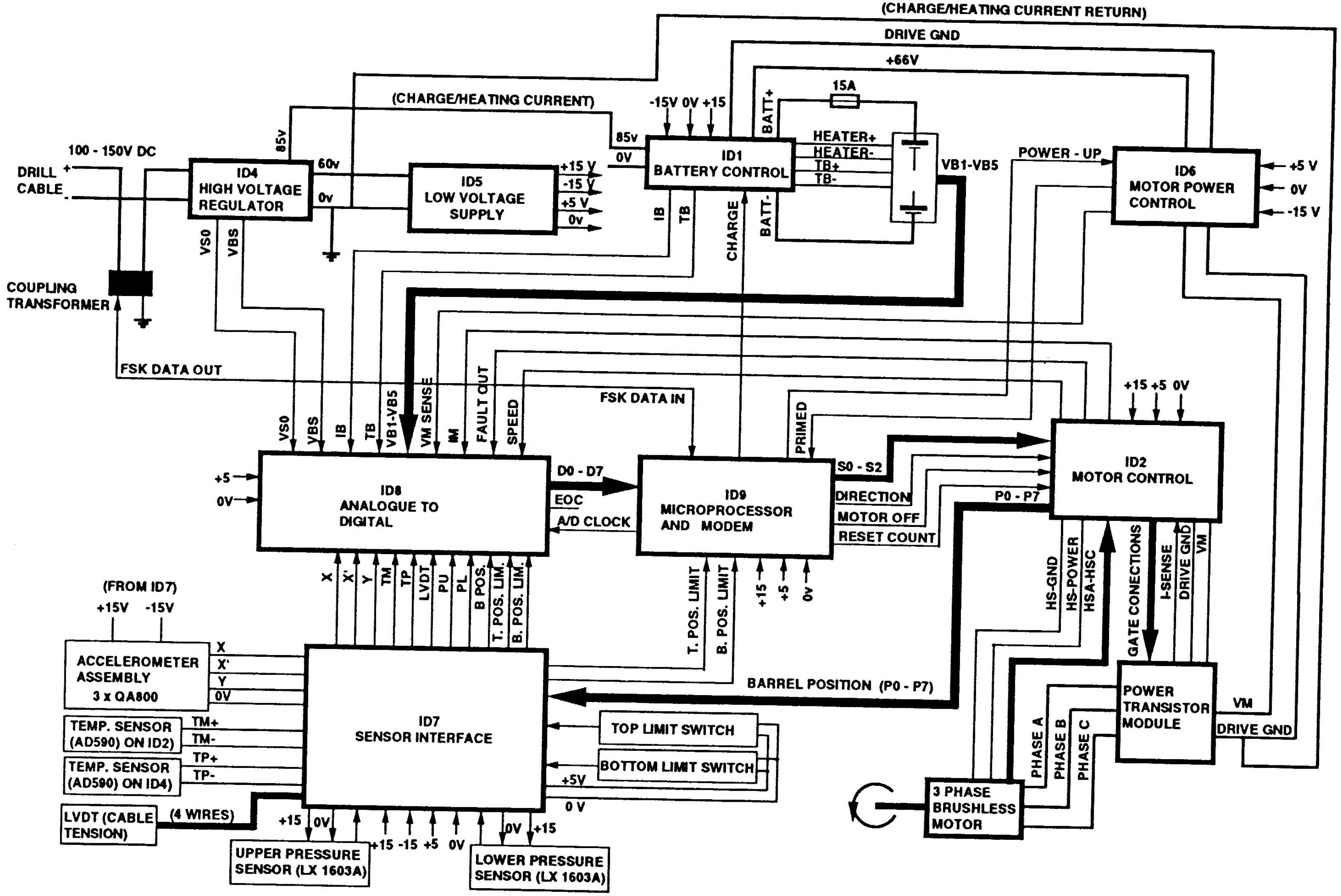

Fig. 2. Ice drill electronics–block diagram.

pressure gauge on the ram indicates cable tension which is useful if the tension is outside the range of the transducer on the drill. Relief valves on the winch and feed ram limit cable tension to about 1/3 of the cable breaking strain.

The drill itself is based on the Danish ISTUK (GUNDESTRUP *et al.*, 1984) but with a number of differences mainly to the motor section, the bearing section and the method of using a roller screw to move the pistons in the chip collection section. The drill comprises:

1) The top section with cable termination, hammer and anti-rotation springs.

2) The electronics section (power regulation, modem, micro controller, sensors interface, motor driver and battery pack) in a fluid proof chamber. A 1200 baud modem provides communication with the surface drill computer (Fig. 2).

3) The motor and gearbox section. The motor is a 3 phase electronically commutated brushless motor which operates immersed in the borehole fluid with a simple mesh screen to keep out ice chips. The planetary reduction gear has a ratio of 45:1. Seven preset speeds are controlled by a feedback system in the motor driver electronics. Drilling is normally done at speed 5 (barrel speed 30 RPM) and rewind at speed 6 (50 RPM).

4) The bearing section. This separates the rotating part of the drill from the top section. The drill rotates on two large roller bearings. Sliprings between the bearings pass electrical signals from limit switches on the roller screw to the electronics section. A form of planetary gearing below the bearings gives an almost stationary inner gear which connects to the rollerscrew nut in the next section. The output and planet gears can easily be changed to alter the output shaft speed. This varies the number of drill turns for the full piston movement and therefore allows tuning the drill for best performance.

5) The rollerscrew and chip chamber section. The roller screw is attached directly to the piston rod and rotates with the outer barrel. The roller nut is held stationary by a shaft from the bearing section. When the drill rotates, the roller screw moves upwards pulling the piston rod and the moving pistons and so expanding the chip chambers. Fluid and chips are therefore sucked away from the cutters via the chip channels and into the chip chambers.

6) The core barrel and cutter head. The core barrel is a plain tube which is bolted to the chip chamber section. This, together with the removable chip channels allow the drill to be dismantled into sections less than 6 m long for transport. The drill head is wire cut from tool steel.

7) The cutters and shoes. The cutters are conventional with a straight horizontal cutting edge, a clearance angle of 15° on the bottom face and a 45° angle on the cutting face. The cutter shoes (which control the depth of cut) are brass and are filed by hand to set the amount of cut.

6. Drilling Fluid

The fluid is a mixture of kerosene (Jet A1) and perchlorethylene. This was known to be satisfactory - it was used in Greenland and similar chemicals had been used previously in Antarctica. Perchlorethylene fits most of the requirements of a drilling fluid additive *i.e.* the density of the mixture can be adjusted to be a little more than ice, it has a freezing point well below –30° and a boiling point above 50°, it has a low viscosity, is electrically non-conducting, it does not react with or dissolve ice and the cost is reasonable. Perchlorethylene is also acceptable environmentally as it is rapidly broken down in the troposphere by photo degradation into (ultimately) carbon dioxide and chloride. It's main disadvantage is it's moderate toxicity. The United States Institute for Occupational Safety and Health recommends that it would be 'prudent to handle it as if it were a human carcinogen'. At DSS a powerful ventilation system was installed in the drilling shelter to ensure fumes were at a safe level. The ventilation also kept the interior of the shelter cool. Separate inlet and exhaust fans blew cool, clean air in at the top of the shelter and removed air from the drill pit below floor level. This produced a continuous downward flow of air so most of the heavy fumes were prevented from rising to head level. Measurements of perchlorethylene vapour typically gave 5–20 ppm except right over the slush tray where levels up to 70 ppm were found. An industrial spin dryer was used effectively to reclaim fluid from the chips and slush from the drill chip chambers.

7. Core Quality

Core quality down to 400 m was generally good. Below 400 m the cores became increasingly brittle so that by about 800 m most cores had some broken sections and a few cores were totally fragmented. The brittleness only disappeared in the last few cores near the bedrock. Air bubbles also seemed to disappear in these cores so it does appear that the incorporation of the gas into the crystal lattice or clathrate formation is associated with the end of the brittle zone. The brittle cores were left in the drilling shelter to allow strain to relieve over the next year. Non-brittle cores were removed from the drill barrel by hand; the brittle cores were pushed out onto a V shaped core tray which provided enough support for cores which merely had many cracks but did not contain cores that broke into fragments. Some of these cores were extracted from the drill in good condition but then broke up within the next 15 minutes. It would probably have been useful to push these cores out of the drill barrel directly into close-fitting rigid plastic tube where they could be stored until the brittleness dissipated. This would serve to keep the pieces in their correct relative position and therefore facilitate later analysis.

8. Core Processing and Analysis

Drilling fluid was removed from the cores by placing them in a drying cabinet which was flushed with clean cold air from the ventilation system. After drying, the cores were examined for stratigraphy and electrical conductivity measurements were made on 2 m long sections. Fine detail samples (12–15 per annual layer) were cut for $\delta^{18}O$ and peroxide and average samples over 50 cm were cut for ^{10}Be and average $\delta^{18}O$ measurement. Some of the peroxide samples were measured in the field as a check on the annual layer interpretation from the conductivity records (the peroxide data gives the clearest indication of seasonal cycles of any of the measurements).

Crystal fabrics were measured at the drilling site on recently drilled core at about 5 m intervals over the full ice thickness.

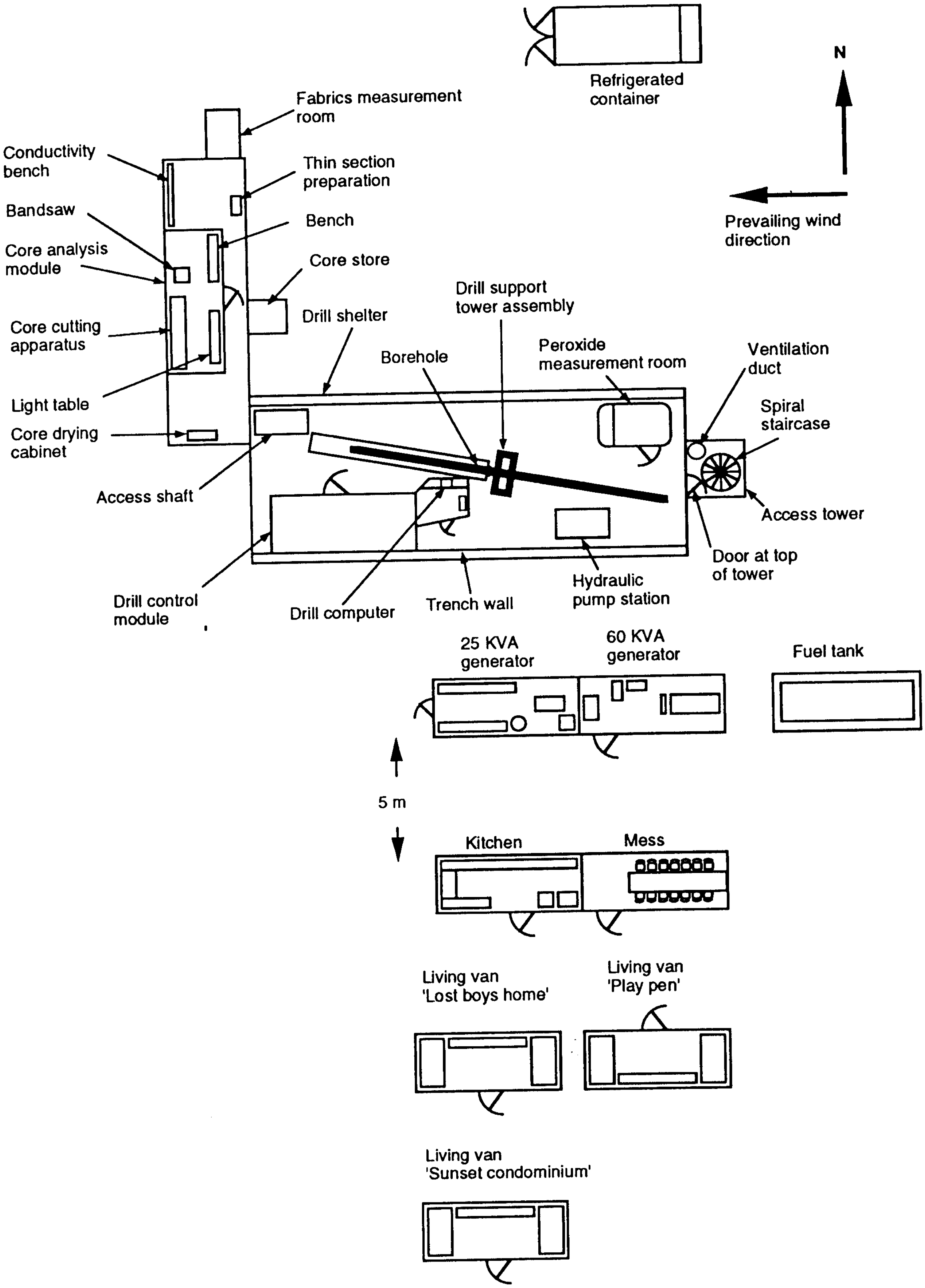

Fig. 3. Dome Summit South (DSS) drilling site–station layout.

9. Field Station

The field camp is comprised of a number of modules based on 6 m long insulated shipping containers (Fig. 3). These are mounted on 'Otaco' or 'Aalener' sledges which are drawn in trains by Caterpillar D5 or D7 tractors. Apart from the drilling shelter all the field camp is dismantled and returned to Casey Station (120 km away) at the end of each Summer season. This is necessary as otherwise the high accumulation would bury the camp. Even over the Summer period large (2 m high) snowdrifts had to be cleared from around the modules. There were nine people at the field station.

10. Operation

Initially there were a number of difficulties with the drill, mostly due to leakage in the pistons and the chip channel joints. In this type of drill where the chips are held in chambers together with the entraining fluid, *i.e.* there is no filtering, it is necessary to have relatively high chip/fluid ratio. This means low fluid flow rates and since the chips and fluid form a thick slush and the chips tend to clump *e.g.* at the channel entrance it is necessary that the suction section is completely leak free. In the development it was also found that small changes to the channel entrance at the drill head (rounding and polishing) had a large effect on the chip collection efficiency. The drill performance improved noticeably with increasing depth and although some of this was probably due to changes to the drill and increased operator skill, there does seem to be an advantage in having a large ambient fluid pressure which can break up clumps of chips. In any future drilling we would continue thermal drilling (in the dry hole) to 300–400 m so that when EM drilling started there would be a few hundred meters of fluid above the drill.

At DSS drilling was generally done by four people in two teams which allowed about 14 hours of drilling per day. Both teams worked on the afternoon shift to allow time for maintenance. A maximum drilling rate of 160 m per week was achieved at a depth of 800 m and the average rate was 120 m per week (Fig. 4). From 500 to 800 m about one hour

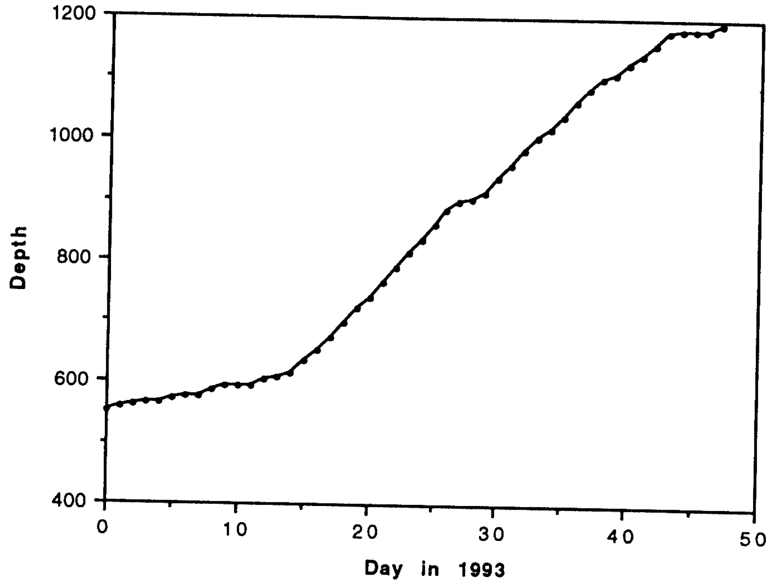

Fig. 4. Drilling progress at DSS in 1993.

was required to complete one full drill cycle - the constancy of the time arising from the usual effect of increased operator skills being compensated by the increased hauling time. For the 1992/93 season the cable tension indicator was modified to have two ranges; a sensitive one for head load when drilling and a larger one which covered 0–600 kg. The large range allowed lowering at ~zero tension and raising at ~500 kg which gave speeds of about 1.5 m/s in the borehole.

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