A new 122 mm electromechanical drill for deep ice-sheet coring (DISC): 3. Control, electrical and electronics design

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ABSTRACT. The deep ice-sheet coring (DISC) drill developed by Ice Coring and Drilling Services under contract to the US National Science Foundation is an electromechanical drill designed to take 122 mm ice cores to depths of 4000 m. Electronic, electrical and control systems are major aspects of the DISC drill. The drill sonde, the down-hole portion of the drill system, requires approximately 5 kW of d.c. power for the cutter and drill motors and instrumentation. Power is transmitted via a drill cable from a modified, commercially available surface d.c. power supply operating at 1000 V to power modules in the sonde instrumentation section. These modules regulate the power to the motors to 300 V d.c. and to lower voltages for the instrumentation and control electronics. Cutter and pump motors are controlled by electronics that include motor controllers. There are 20 distinct sensors in the drill sonde which measure conditions such as hole fluid temperature, motor fluid temperature, drill orientation, etc. On-board electronics facilitate communication of control commands and data between the surface and the drill sonde. Electronics also play an integral part in the operation of surface equipment such as the winch in raising and lowering the sonde in the borehole. Overall control of the DISC drill system is provided by a PC-based supervisory control system that allows the drill operators to monitor and control all aspects of the drilling operation.

INTRODUCTION

With the increased interest in global climate, the ice-coring community finds itself challenged with new and harder demands for data collection, ice-core quality and drilling speed, all driving an industrial approach to drilling and increased drill system complexity. In consequence, the electrical design of the deep ice-sheet coring (DISC) drill system has been heavily influenced by the need for accurate motor control, self-monitoring, data collection and high cutting and pumping powers. As a result, the system incorporates a large amount of state-of-the-art control and power electronics. In addition, software plays an important role in the drill operation. On the surface, the drill team has access to a graphical user interface allowing easy and manageable control of the system. The down-hole system uses software to handle data communication.

It is advantageous to describe the DISC drill system in two sections: 'Surface system' and 'Down-hole system'. Consequently, this approach has been adopted herein. This paper can be read with advantage together with parts 1, 2, 4 and 5 (Johnson and others, 2007; Mason and others, 2007; Shturmakov and Sendelbach, 2007; Shturmakov and others, 2007).

EARLY CONSIDERATIONS

Prior to the onset of electrical design of the DISC drill, a review of previous drills was performed. While it is not the object of this discussion to provide a detailed in-depth review of drilling technology, it is useful to examine some details of a few select drills, and establish a brief overview of some of the considerations that went before any hardware design.

The European drilling project 'European Project for Ice Coring in Antarctica' (EPICA) at Dome Concordia was particularly interesting because a recently designed successful deep coring drill was used. It involved electronics that provided closed-loop motor control, on-board sensors and data transmission capabilities (Augustin and others, 2007). The EPICA drill had experienced difficulties while drilling warm ice. Ice tended to build on the cutters of the drill, and above them, eventually causing loss of penetration and abortion of the drill run (C.R. Bentley and B. Koci, http://scarsale.tamu.edu/technology/Bentley_2006.doc). Upon review by Ice Coring and Drilling Services (ICDS), it was thought that this problem could be mitigated if a higher pump flow rate could be achieved. This point of view had also been suggested during EPICA operations by the EPICA crew (A. Eustes and others, http://www.ssec.wisc.edu/icds/reports/). Having a high flow rate was therefore always a priority with the DISC drill design. To achieve a higher flow rate, a powerful pump is required. Providing power to such a pump was therefore equally a priority, and a major requirement of the DISC drill power system. Indeed, the consensus within ICDS was that the EPICA drill was under-powered for warm ice operations, with its $\sim$600 W of power (A. Eustes and others, http://www.ssec.wisc.edu/icds/reports/). The data-transfer capabilities were considered to be of high importance, as continuous information about pressure, force, temperature, vibration, etc., gives the operator a better idea of how the drill is performing, the overall goal being to rapidly retrieve core of high quality.

Another point considered to be important was the use of two independently operated motors for pump and cutter, instead of only one as had traditionally been the case. The one-motor approach had been used successfully on several deep coring drills (e.g. EPICA Dome Concordia (A. Eustes and others, http://www.ssec.wisc.edu/icds/reports/); the Vostok KEMS-132 electromechanical core drill (Ueda and

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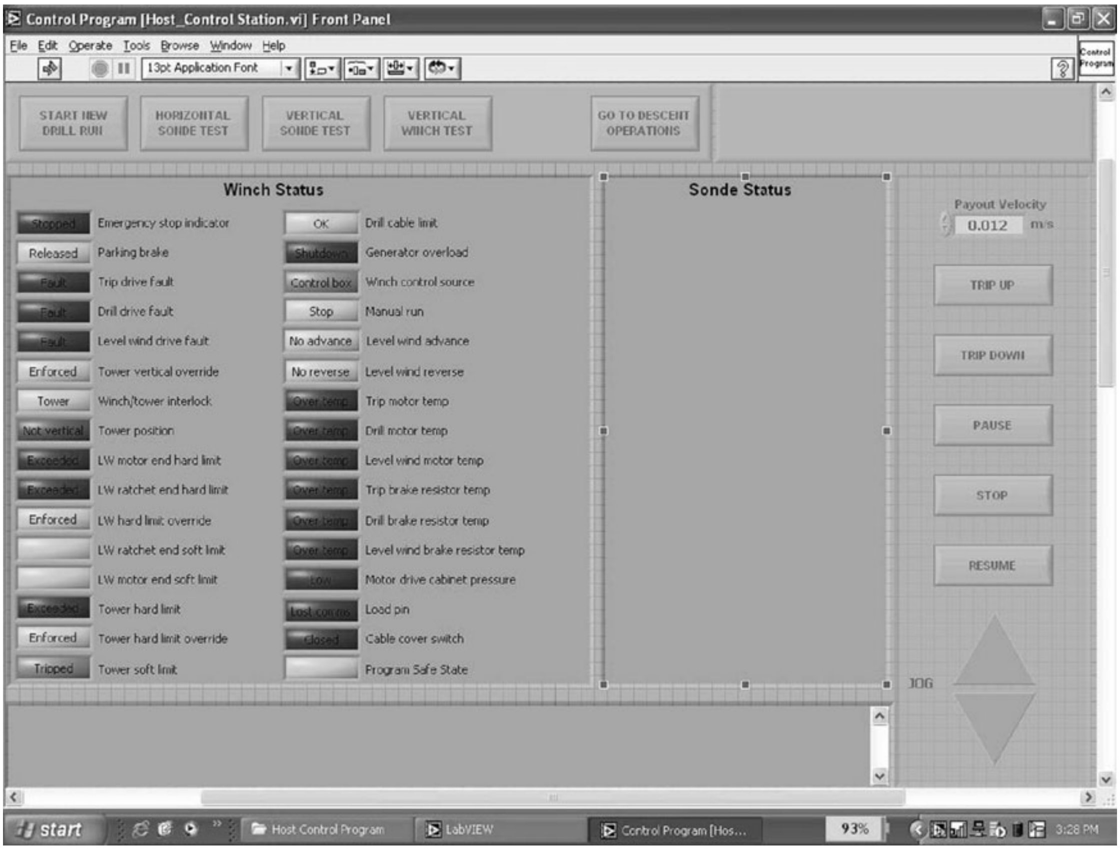

Fig. 1. Winch control screen. A number of control lights inform the operator of problems with the system. Winching speed is adjusted by entering desired speed into a data field. Direction is determined by 'Up' and 'Down' buttons. Depending on the state of the drilling action (ascent, descent, coring, etc.) the winch screen changes appearance accordingly.

Talalay, 2007); Electrodrill (Byrd Station) (Ueda and Garfield, 1970); JARE (Japanese Antarctic Research Expedition) (Dome Fuji) (Motoyama, 2007); ISTUK (Greenland, various sites) (Johnsen and others, 1994)). Meanwhile, a two-motor approach should perform at least as well as a single-motor approach while allowing an extra degree of freedom, which is desirable.

Estimation of the power needed to run the DISC drill was based on experience from a number of drills and resulted in an initial value of 3 kW delivered from a three-phase 480 V a.c. power feed (A. Eustes and others, http://www.ssec.wisc.edu/icds/reports/). This was later changed to 5 kW, delivered from a 1000 V d.c. feed. The higher voltage allows a smaller-diameter cable to be used, with only two conductors instead of three.

Regarding the surface system, the winch was of particular interest. Again the EPICA project provided inspiration, and it was decided to use off-the-shelf controllers with closed-loop speed control, the velocity feedback coming from an encoder on the winch. The target tripping speed was 3 $m\,s^{-1}$ (A. Eustes and others, http://www.ssec.wisc.edu/icds/reports/). Data logging was also made a priority: both data from the in-hole and surface systems were to be logged to a local computer hard drive (A. Eustes and others, http://www.ssec.wisc.edu/icds/reports/).

To summarize:

Two motors in the drill – for added flexibility.

High down-hole power – to achieve high flow rate as a safeguard against warm ice.

'Visibility' – sensors in the drill to provide data to assist the operator in making good decisions, and to 'see' how the drill is performing.

Closed-loop motor control for pump and cutter motor – to make it easy for the operator to run the drill at constant speed.

Closed-loop motor control for winch motors – 3 $m\,s^{-1}$ speed targeted.

Data logging for both surface and in-hole systems.

These observations served as a first, coarse, framework for the DISC electronics design and architecture which are discussed in the following sections.

SURFACE SYSTEM

The surface system has many functions to enable the sonde to operate in the hole. Three computers control the operations. A dedicated computer controls the two motors that make up the DISC drill winch system. The two motors are a big (112 kW) tripping motor and a smaller (2.24 kW) drilling motor which is used to slowly lower the sonde down the hole during the actual drilling operation. Each of the motors is driven by a Yaskawa drive providing closed-loop motor control. There is a clutch between the two motors to choose between fast and slow operation. The computer controls the hand-off between the two motors to allow slack to be taken up in the drive trains without the cable jerking the sonde. The winch control system maintains the state of the drilling

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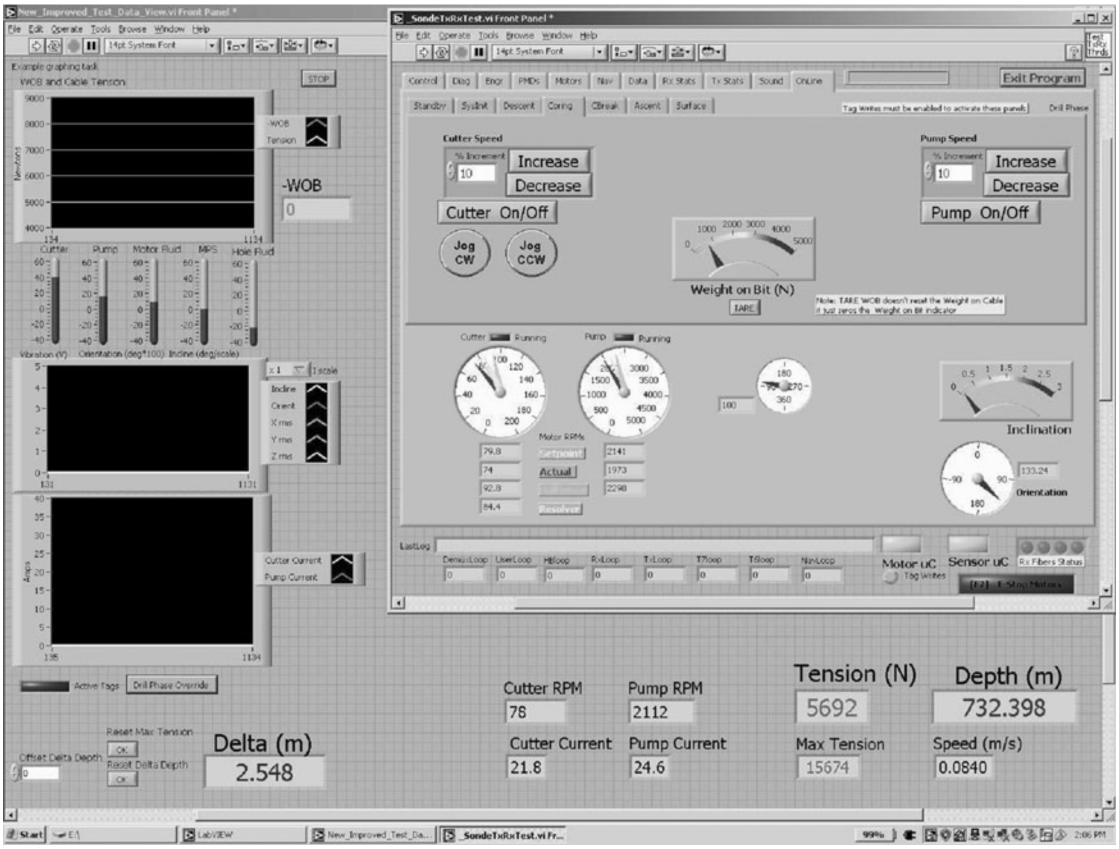

Fig. 2. Sonde control screen. A multitude of indicators present cutter speed, pump speed, temperatures, etc., to the operator. Motor speeds can be set by entering desired rpm into data fields. Real-time graphs are used to display critical data (motor torques, WOB, etc.).

operations, i.e. descent, drilling, core break or ascent. During any operation, only the appropriate data are displayed on the monitor to keep the operator from getting distracted. The winch computer constantly monitors the status of the winch motors, along with any other external winch controls, and displays the status on the screen. If the status is good, the buttons are green and a red button shows where any problem is. Manual winch operations are available if the operator needs to do something out of the ordinary. If the winch computer senses a condition out of the ordinary, it proceeds to 'safe mode' which places all the equipment and motors in their safest state. A watchdog timer in the computer must be updated on a regular basis. Otherwise the system will enter the safe mode upon the computer hanging up. The winch control screen is shown in Figure 1.

The second control computer runs the sonde operations. This computer shows the status of all sensors inside the sonde, and enables motor controls. All data from the system are shown on this computer screen, including total drilling depth, depth increment, cable tension, weight-on-bit (WOB), accelerometer data, navigation data, motor velocities and currents and other parameters. Some of the data are displayed in continuous graphical format to give the driller an idea of how conditions are changing while drilling. While drilling, the orientation of the navigation sensor is used to monitor slippage of the anti-torque section, and automatically shuts the motors down if the top end of the drill starts rotating. The accelerometer data display the vibration of the drill head and allow for motor adjustments to be made to obtain better core quality. Temperatures of the important areas of the sonde are monitored and sections can be shut down if overheating is detected. At the point of core break, the sonde computer prepares to record maximum cable tension and also records the orientation of the core barrel. When the drill returns to the surface, the driller can rotate the sonde to the correct orientation using an automated algorithm. The algorithm remembers the azimuth of the core at the point where the core break was performed. This information, together with core-barrel resolver information, allows the orientation of the core to be determined. Additionally, the core aligns with the previous core. The sonde control screen is shown in Figure 2.

The last computer is the data storage computer, which takes data from the other two computers and stores them in a database. This database allows engineers to examine prior drill runs to see what happened. These data can be shown on its monitor while other operations are still going on.

A Glassman power supply gives 750–1000 V at the surface end of the drill cable to deliver adequate power to the sonde. The sonde power travels down the inner conductor of the drill cable and returns on the adjacent copper conductor. This scheme keeps current flow off the outside of the cable, which is very advantageous for personnel safety in case of a conductor fault. A ground-fault interrupter circuit after the power supply ensures that if any voltage is detected on the outside of the cable, the system automatically shuts down. The winch system has a slip ring at the winch drum to allow the wires to rotate. There is a corresponding slip ring inside the sonde to get the power to the electronics without twisting.

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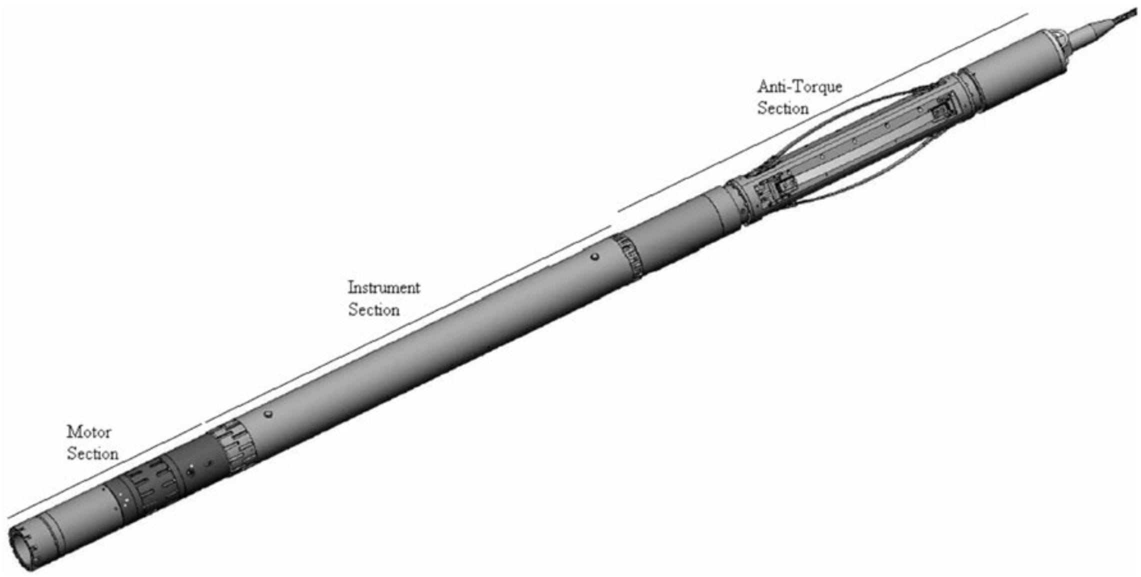

Fig. 3. Upper sonde. Though shown in isometric view, the sonde normally hangs vertically in the borehole on its cable. The cable attachment can be seen in the upper right corner. Most of the upper sonde does not rotate. The bottom half of the motor section rotates, providing the rotation needed for the cutting action.

DOWN-HOLE SYSTEM

The drill (or sonde) contains a large amount of electronics, located in three drill sections: the anti-torque, instrument and motor sections. Figure 3 shows the upper sonde. By far the bulk of the electronics is housed in the instrument section.

The sonde can be thought of as solving four basic tasks: motor control, data acquisition, power conditioning and communications.

Motor control

The drill sonde makes use of two three-phase brushless d.c. (BLDC) motors for cutting and pumping purposes. Motor specifications are outlined in Table 1. Each of the two motors is driven from a motor driver. Thus the motors operate independently of each other. The motor drivers are designed such that low-power control electronics are isolated from the power stage. This results in better noise performance and reduces the risk of fault propagation in the event of a failure in any of the electronics. Closed-loop control is achieved by using a dedicated motor-control integrated circuit, type MC73110 from Performance Motion Devices, Inc.

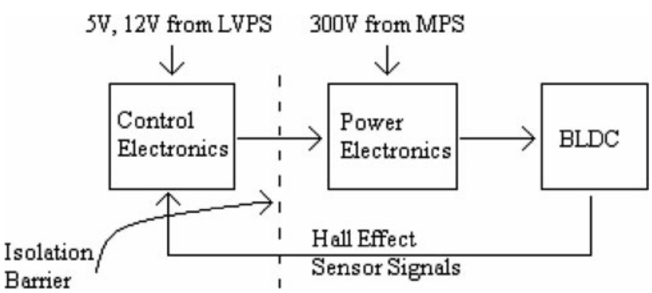

Fig. 4. Block diagram of motor-driver architecture. Control electronics govern a power stage which, in turn, drives the BLDC motor. Velocity feedback is achieved using Hall-effect sensor signals. The Hall-effect sensors also provide commutation information. An isolation barrier protects the control electronics and other associated electronics from over-voltage in the event of a motor failure.

The velocity feedback is derived from the Hall-effect sensor signals generated within the BLDC motor. Figure 4 shows a block diagram of the motor driver architecture. Arrows indicate teh idrection of information flow. The power electronics include current-measuring technology that senses the phase currents and reports these back to the control logic (not shown in Fig. 4). This allows closed-loop current control. As motor torque is proportional to current, torque control can be achieved using this approach. Auxiliary functions include over-temperature protection, current (or torque) limiting, digital communications of control functions and parameters, and emergency stop.

Data acquisition – sensors

There are many sensors within the sonde to allow many data to be gathered during the drilling operation. Five sensors measure the temperature of the electronics plate, drilling fluid, cutter motor, pump motor and motor fluid. Four pressure sensors are used to determine the status of the sonde. The instrument section is pressure-sealed and is designed as a tube capped off at each end by two end caps. The instrument section must be pressure-sealed to protect the instrumentation from damaging pressure and drill fluid. Each end cap therefore incorporates pressure seals. The seals

Table 1. Motor parameters

Cutter motor	
Power	2.4 HP (1.8 kW)
Voltage	300 V
Torque	2.28 Nm
Speed	7500 rpm
Pump motor	
Power	3.4 HP (2.5 kW)
Voltage	300 V
Torque	6.99 Nm
Speed	3500 rpm

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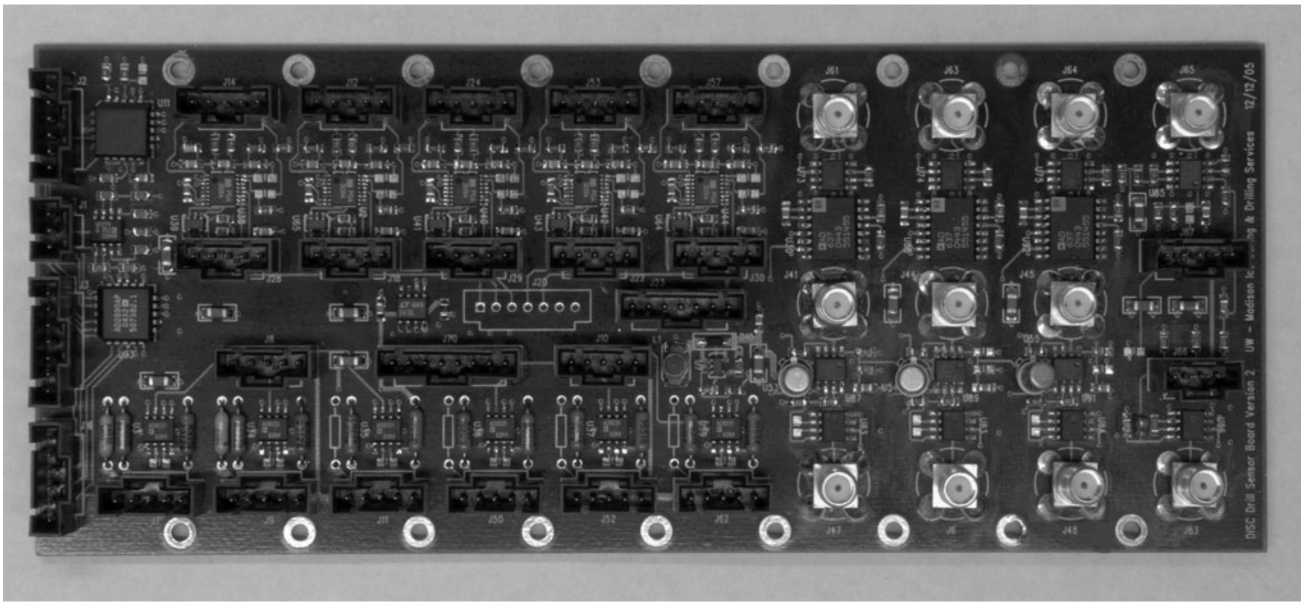

Fig. 5. Sensor board. A large number of connectors are used to connect the sensor board's conditioning electronics to the individual sensors. Additional connectors transfer the conditioned analog signals to the on-board computers.

are double seals for redundancy. Two pressure sensors measure the pressure between the seals, one sensor per end cap. If one of these sensors indicates a pressure significantly above atmospheric pressure, this indicates that an outer seal has failed and that repairs are needed. Since the end caps are double-sealed, a high pressure reading does not necessarily mean that fluid is leaking into the instrument section; it is possible that the inner seal is sealing correctly. This sensor arrangement is intended to provide the operator with an early warning. A third sensor measures the pressure inside the instrument section. A slight increase in pressure suggests that a leak has occurred and that corrective measures are needed. Hole pressure is also measured. Hole pressure is useful as a benchmark by which the end-cap pressures are compared. If an end-cap pressure sensor reads pressure similar to the hole pressure sensor, it is almost certainly due to a failed outer seal (except at low depths where all pressure sensors read near-atmospheric pressure). Additionally it is desired to use the hole pressure as a means of estimating fluid density.

An accelerometer is mounted inside the electronics section. The data from the three axes are amplified and available in graphical format. These data also go through a root-mean-square (rms) module for an estimation of the energy involved in each axis. This information is useful for the operator in regard to the drilling action (e.g. if an increased amount of vibration is recorded by the accelerometer, the operator uses that information to adjust drilling parameters, such as payout speed). A resolver circuit computes the absolute position of the barrel with respect to the non-rotating part of the drill, i.e. anti-torque and instrument sections. A navigation module supplies data about the

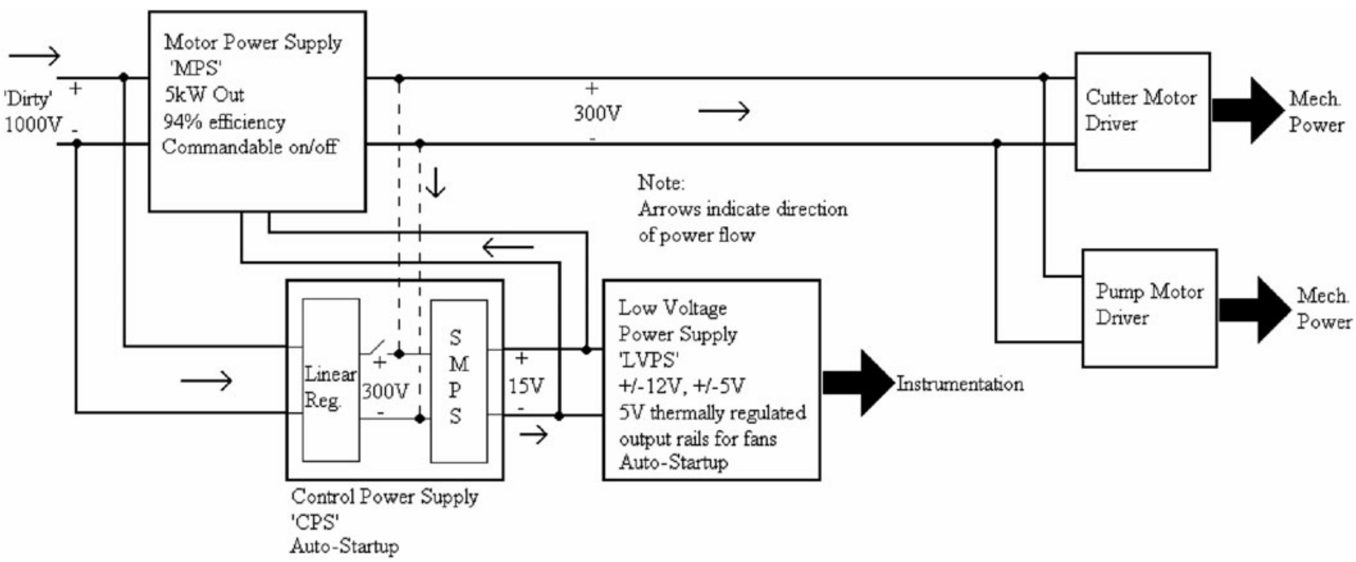

Fig. 6. Power system architecture. Automated start-up capability allows for the system to power up automatically as soon as 1000 V power is applied. As a safety feature, the MPS requires a separate control signal from the surface computer to start.

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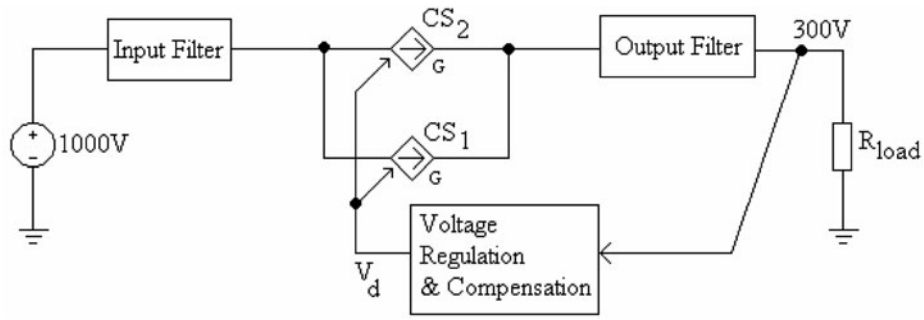

Fig. 7. Simplified MPS operating principle. Two voltage-controlled current sources are operated in parallel. A voltage loop ensures constant output voltage over the load range of 0–5 kW. Input and output filters provide low-noise power buses.

inclination and absolute position of the sonde. Both the resolver data and the navigation data allow the operator to align the core barrel after drilling, such that the new core will always be in alignment with the preceding core, and the north direction is recorded. As shown in Figure 5, there are many connectors on the sensor board to allow attachment to all the various places in the sonde.

Power conditioning

The sonde contains various devices that require electrical energy to operate. The range of power needed is large: for example, the motors operate in the kilowatt range while some sensors use only a fraction of a watt. With this type of variance it is necessary to design a power system that will allow high power levels to be supplied to the motors and their drivers, while also providing low-voltage and low-noise supplies to the low-power on-board electronics (such as the sensors).

The power system was designed using several custom-designed modules as illustrated in Figure 6. While the individual components of the power system are described in subsequent sections, a basic understanding can be obtained by considering the start-up sequence outlined below:

A 1000 V bus voltage is applied (from the cable), causing the control power supply (CPS) to turn on automatically.

Once the CPS provides 15 V to the low-voltage power supply (LVPS), the LVPS turns on automatically.

The LVPS now powers all the on-board control electronics including the microcontrollers, and the sonde is operational.

The motor power supply (MPS) can be turned on, powering the motor drivers so the drill cycle can be initiated.

Shown with dashed lines in Figure 6, a 300 V feed from the MPS to the CPS allows the CPS to be run from 300 V when the MPS has been powered. This increases system efficiency since the (highly inefficient) linear regulator internal to the CPS is bypassed.

Motor power supply

The purpose of the MPS is to deliver up to 5 kW of power to the motor drivers at 300 V d.c. The MPS is custom-designed specifically for the DISC drill. It can be viewed as two converters operating in parallel. Each converter is designed as a buck converter with peak current control (Andreycak, 1999; Erickson and Maksimovic, 2001), thus acting as a current source. This results in the concept shown in Figure 7. The current sources CS_1 and CS_2 represent the two buck converters operating in peak current mode, each with a gain G. A voltage regulator ensures that a demand voltage V_d is adjusted (on the fly) such that the output voltage is 300 V regardless of load variation. Auxiliary functions of the MPS include under-voltage protection, over-voltage protection, over-current protection, over-temperature protection and

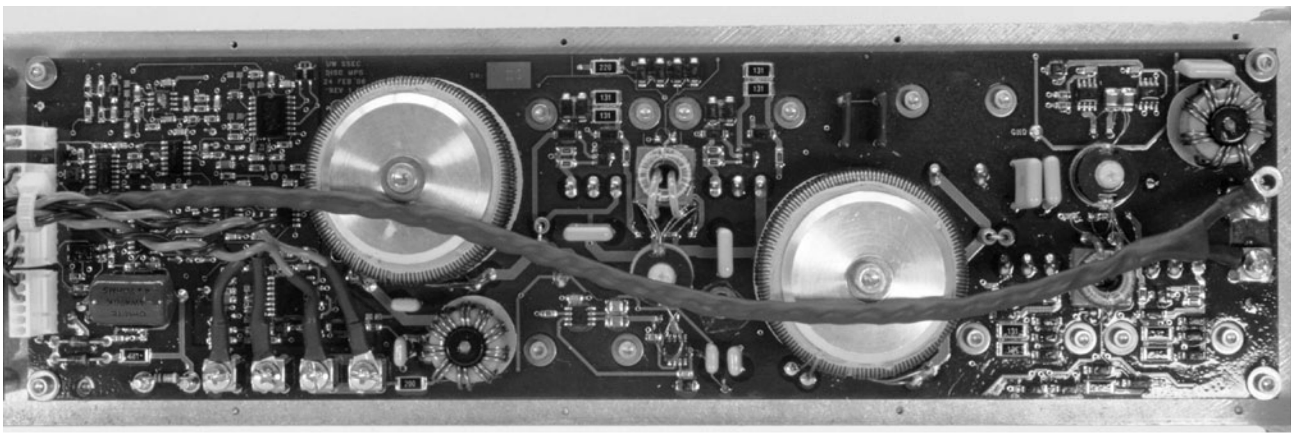

Fig. 8. Assembled motor power supply. The MPS makes use of a number of custom-designed magnetic components to maximize power density. The switching devices, MOSFETs, are located beneath the circuit board.

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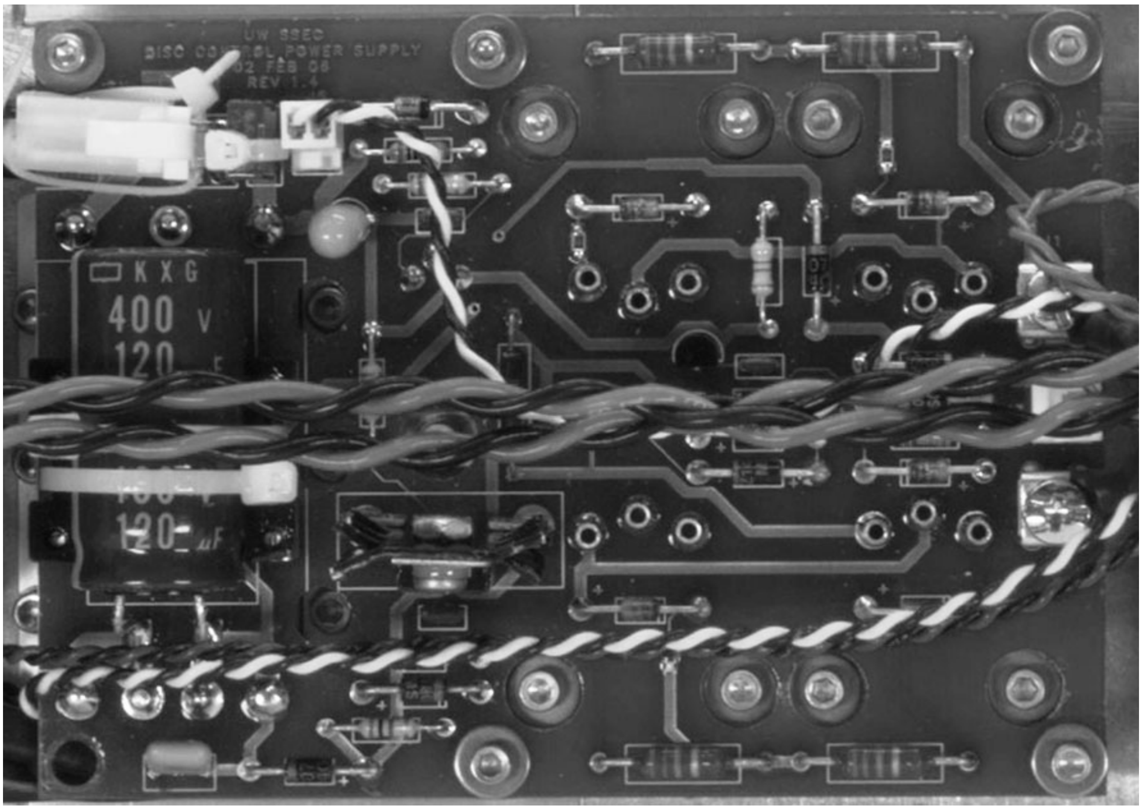

Fig. 9. Control power supply. The CPS is implemented using a simple linear regulator (note the low amount of components on the circuit board). The pass element of the linear regulator is implemented using MOSFETs located between the circuit board and the base plate. The size of these large components determines the overall size of the CPS.

TTL (transistor-to-transistor logic)-level on/off command. An assembled MPS is shown in Figure 8.

Control power supply

As discussed previously, the CPS serves to provide power for the low-power system. As shown in Figure 4, the CPS is designed using two power-regulation schemes: linear regulation and switch-mode power regulation. During start-up, the MPS is off and the CPS therefore derives its input power directly from the 1000 V bus. Once the MPS is powered, the CPS will automatically select the 300 V rail, thus achieving a higher efficiency. The linear regulator is designed based on metal-oxide field-effect transistor (MOSFET) technology where power MOSFET transistors act as pass elements dropping voltage down to an intermediate level, 300 V, suitable for the switch-mode power converter within the CPS. The maximum CPS output power is 100 W, and the switch-mode power supply (SMPS) used in the design is an off-the-shelf device from Vicor. Figure 9 shows an assembled CPS.

Low-voltage power supply

The LVPS serves to provide the majority of the on-board low-power electronics with their supply rails. For reasons of noise performance, an added requirement is that the output rails be galvanically isolated from the 15 V input power rail. The design uses power modules from Densei-Lambda. To

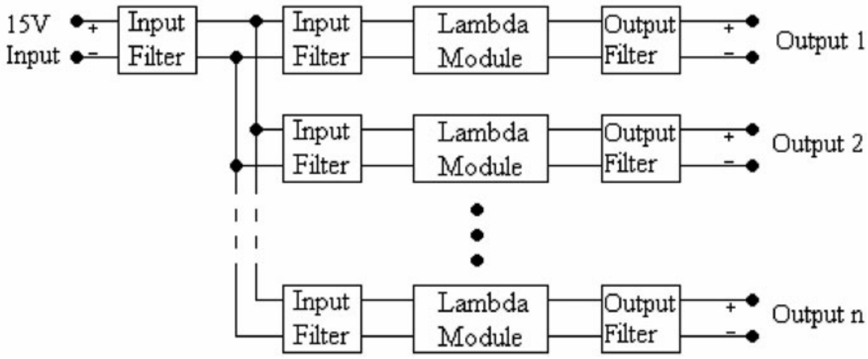

Fig. 10. Block diagram of LVPS design. The use of off-the-shelf power modules enables a simple design strategy. The same basic design is simply repeated for each required output. Not shown is the isolation barrier between the input 15 V rail and each output rail. The output rails are also generally isolated from each other.

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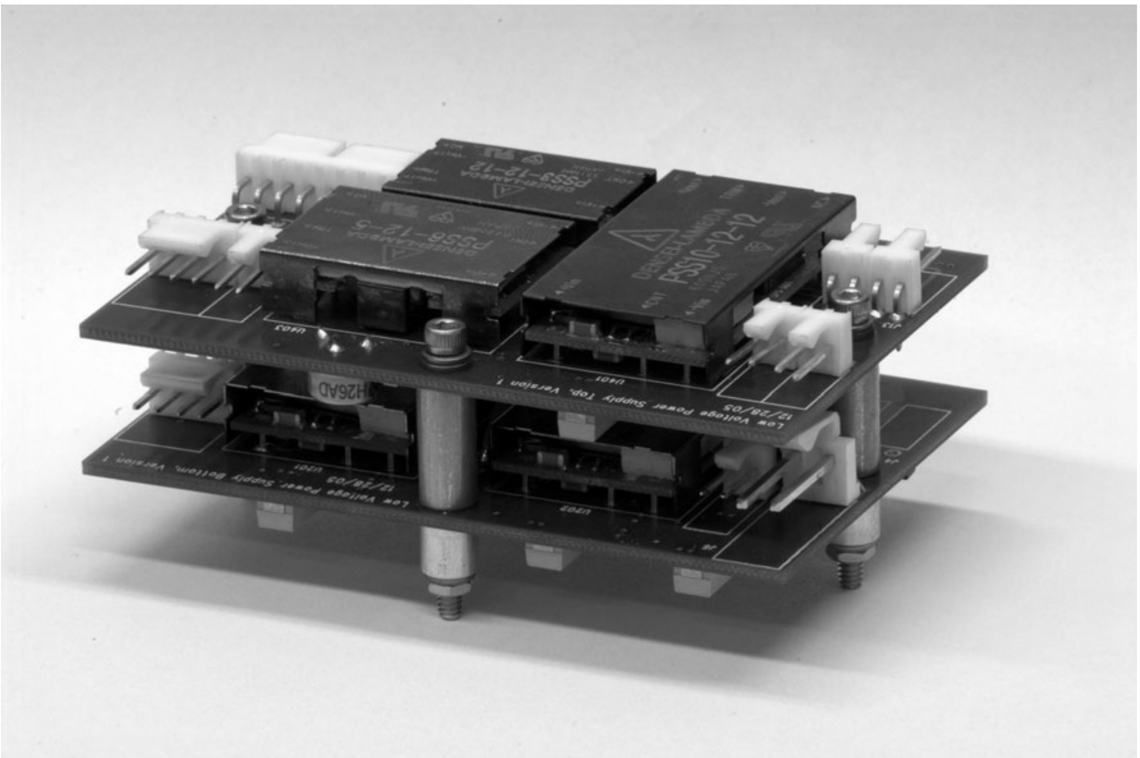

Fig. 11. Assembled LVPS. A stacked assembly is used to achieve more efficient use of space.

ensure stability and power quality, each lambda power module is fitted with input and output filters as described in Figure 10. A modular design allows easy implementation of the desired number of output rails. Figure 11 shows an assembled LVPS.

Single-point grounding

Most of the power conversion, including the motor controllers, is undertaken by means of switch-mode technology. As a result, parasitic noise currents from the switching networks must be expected. In order to avoid noise currents flowing through sensitive signal-conditioning electronics (e.g. the sensor board) which would cause signal corruption, a single-point grounding arrangement was used. The low-power circuitry depicted in Figure 12 (microcontrollers, sensors, etc.) is only connected to power ground through one connection. Therefore, theoretically no noise current can flow (a current needs both an entry and an exit point to form a loop), and signal integrity has been preserved.

Communications

Communications with the sonde are enabled with a multi-mode fiber-optic link. There are six optical fibers inside the drill cable that allow communications over the 3800 m cable. Data transmission over a cable this long with electrical wires would have been difficult due to losses and electrical noise present. The ends of the fibers are connected to optical transceivers operating at 38 400 Bd. There are two full duplex links and two upward fibers to allow the sonde more data transfer going up because of all the sensor data. A laptop computer connects to the four transceivers over four RS232 links. If one of the fibers fails during drilling, the software automatically sends the data traffic over another working fiber.

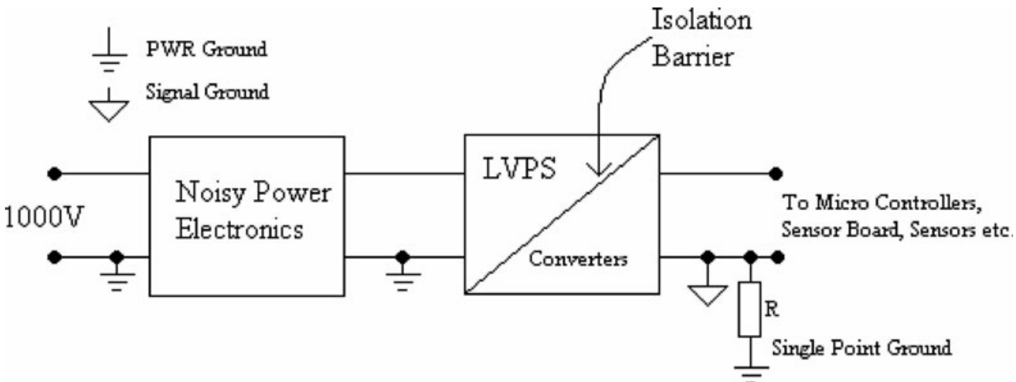

Fig. 12. Single-point grounding. Signal ground connects to power ground at one point only, through resistor R. This allows the noise currents from noisy members of the system to be steered away from the sensitive low-noise electronics.

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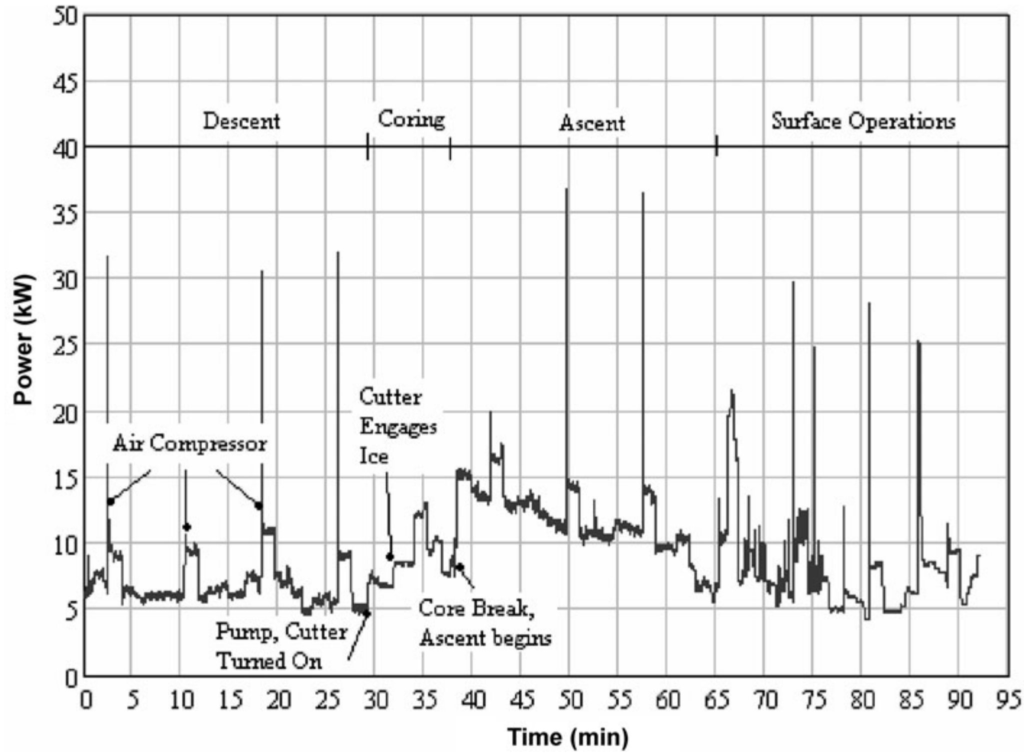

Fig. 13. Power consumption during a drill run. Power consumption is low during descent, climbs during ascent and becomes erratic during surface operations where various machines are used. Tripping speeds were 0.5 m s^{-1} during this drill run.

OVERALL SYSTEM POWER USAGE

Power use of the entire drilling operation, including both down-hole and surface systems, is of high importance as it determines the amount of generator capacity and fuel consumption that will be used in the field. To address this issue, power was monitored during select drill cycles. Figure 13 shows the apparent power used by the DISC drill system during drill run 279, Greenland test season 2006, from start to finish. Note that an air compressor runs at regular intervals. Only the first three air-compressor runs are indicated in Figure 13. Figure 13 can be used as a guide for determining power requirements of the field power plant. The DISC drill system generally uses 5–10 kW when the winch is not running. The ascent phase of run 279 was performed at a speed of 0.5 m s^{-1}. At higher speeds, higher power consumption must be expected in the order of 120 kW assuming that the winch is run to its full capacity. It is desirable to operate at the highest possible winching speeds, to minimize the amount of time spent tripping in and out of the hole. This applies mostly to the ascent phase, where speed is limited only by how hard the winch can pull on the cable. During descent, it is the terminal velocity of the drill in fluid that sets the upper speed limit. During ascent, the winch can theoretically deliver 120 kW of power. At low depths, this is adequate for winching speeds up to 3 m s^{-1}, which is the maximum design speed and must not be exceeded even if available power levels are sufficient to do so. At higher depths the system is power-limited, meaning that the winching motor is operated at constant full power. The resulting cable speed will be less than the desirable maximum speed of 3 m s^{-1}, but will slowly climb as cable is spooled in. At some point, the amount of weight from the cable (and sonde) in the borehole will have dropped enough that the winch has adequate power to operate at its maximum speed. After this point, the system is speed-limited. While operating in the speed-limited regime, the power required to maintain a constant speed will gradually decrease as cable is spooled in, lowering the load on the winch. This effect is visible in Figure 13 in which a decline in power usage during the ascent phase can be observed. It may be concluded that the drill system demands very high levels of power for short periods of time, namely the time used for ascent. Figure 13 shows a maximum power of ~15 kW, starting approximately 38 min into the drill run. This is where the ascent phase has been initiated, and the power usage must therefore be expected to increase. This power usage is well below the available 120 kW, and the difference is due to the low winching speed, 0.5 m s^{-1}, used during the Greenland test season. During later deployment to Antarctica (or elsewhere) power usage is expected to increase to levels in excess of 120 kW, taking into account system inefficiencies which cause losses and therefore a corresponding increase in input power.

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