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INSTRUMENTS AND METHODS

INSTRUMENTED PROBES FOR DEEP GLACIAL INVESTIGATIONS

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ABSTRACT. Thermal probes can carry instrumentation packages into polar ice sheets for geophysical investigations and long-term observations by remote measurement methods. They are self-contained surface-controlled devices. The development work at U.S. Army CRREL solved problems of materials, fabrication and heat-transfer analysis. The Philberth probe, named after its inventor, has demonstrated its performance capability in Greenland. The pendulum probe is a further development with increased performance and versatility. The probes are a tool to widen Man's knowledge in glaciology and geophysics, and to increase his capability in seismics and possibly communications.

RÉSUMÉ. *Sondes pour études profondes dans la glace.* Des sondes thermiques pour études glaciologiques peuvent porter des blocs d'instruments à l'intérieur des indlandsis polaires pour des études géophysiques et des observations à long terme par des méthodes de mesure à distance. Ce sont des équipements compacts controlés en surface. Le travail de développement à U.S. Army CRREL résolut les problèmes de matériaux, de fabrication et d'analyse de transfert de chaleur. La sonde Philberth, nommée d'après son inventeur, a démontré ses possibilités au Groenland. La sonde à pendule est un autre développement avec une performance et une possibilité accruées. Les sondes sont un outil pour élargir la connaissance de l'homme en glaciologie et en géophysique, et pour accroître ses possibilités en sondages sismiques et d'autres communications.

ZUSAMMENFASSUNG. *Instrumentierte Sonden für Tiefeisforschungen.* Thermische Sonden können Instrumentenpakete in polares Inlandeis für geophysikalische Untersuchungen und langfristige Beobachtungen durch Fernmessung einführen. Es sind selbständige, von der Oberfläche aus kontrollierte Geräte. Die Entwicklungsarbeit am U.S. Army CRREL löste Probleme des Materials, der Herstellung und der Wärmeübertragungsanalyse. Die Philbert-Sonde, benannt nach ihrem Erfinder, hat ihre Leistungsfähigkeit in Grönland bewiesen. Die Pendelsonde ist eine weitere Entwicklung mit erhöhter Leistung und Vielseitigkeit. Die Sonden sind ein Mittel zur Erweiterung der glaziologischen und geophysikalischen Kenntnisse des Menschen und zur Steigerung seiner seismischen und nachrichtentechnischen Fähigkeiten.

INTRODUCTION

Instrumented probes are used to obtain information by remote measurement methods. The described thermal probes are non-recoverable vehicles designed to carry instrumentation payloads into polar ice sheets to all depths. They sink into the ice by melt penetration with electrically heated hot points. They are surface controlled and powered through internally stored conductors which pay out of the advancing probes and become anchored in the re-frozen melt water above.

With suitable instrumentation they serve to measure properties and conditions deep in the ice. They also supplement deep core-drilling work by providing pertinent advance information. Finally, they can place instruments or active devices into position for long-term observations and other functions.

Philberth (1962, 1966[a]) proposed such a probe and conducted hot-point penetration and stabilization tests in Switzerland (Philberth, [1965]). U.S. Army CRREL obtained his plans as part of a mutual agreement to exchange information and experience gained with such probes (Hansen, unpublished), and in 1964 the technological development of the Philberth probe began in co-operation with the inventor.

The pendulum probe is a further development of this Laboratory to increase the capabilities in polar ice-sheet exploration and related applications. Features of high performance and automatic self-adjustment to widely varying operating conditions make this probe simple to use and attractive for many purposes.

General Description

Thermal probes are of a tall slender shape. They consist of a hot point for melt penetration, a supply of internally stored conductors as a surface link, a reservoir extension to keep the dielectric fluid filling always at a level above the internal components and an instrument package for the intended mission.

The probes require a means of stabilization to maintain a plumb attitude and a vertical course. The problem is best understood by recognizing that the probe stands on its tip, the hot point. This unstable situation leads to a progressive leaning and a gradual toppling over. Philberth recognized the problem and proposed a mercury steering principle which has proved to be effective. As a heat transfer medium within the hot point, the mercury directs the penetration of the probe towards the plumb line when a deviation develops. There is a continuous correcting action to counter the leaning tendency of the probe. Philberth (1966[b]) has discussed the probe stabilization problem and various methods in a separate paper.

The term hot point denotes that nearly isothermal part of the probe which is heated and which produces penetration by melting ice with its contact surface. The hot point is heated with a cartridge heating element. Additional heat is required for lateral transfer from the probe to match the heat diffused radially in the ice. If insufficient heat is available for lateral transfer, the hole constricts due to refreezing melt water and eventually the probe stalls. If too much heat is transferred through the probe walls, the hole enlarges and the probe leans more. It is desirable to match the lateral heat transfer from the probe with the heat diffused in the ice to obtain good and efficient performance.

The heat produced due to self-heating in the coil of insulated cable (line resistance) is transferred through the probe walls. In addition, a small amount of heat comes from losses from the hot point through internal transfer. For a given length of stored conductor in the probe, the ratio of heat transferred laterally to heat used for melt penetration is therefore nearly constant for all operating power levels, i.e. probe speeds.

The ratio of heat required for lateral transfer to heat required for melt penetration increases with decreasing ice temperature; it decreases with increasing probe speed. It becomes evident that there is one optimum probe speed for any given ice temperature and stored conductor length at which the lateral heat transfer of the probe matches the heat diffused in the ice. Details of the heat transfer calculations and a practical method to chart the optimum probe speeds for various operating conditions have been given by Aamot (1967[a]).

The insulation of the cable in the probe is designed and produced to be suitable for the transmission of power at high voltage and winding the cable into an orthocyclic coil. The selected construction used two cross-wrapped servings of Kapton tape (a polyamide film with FEP Teflon backing for thermoplastic bonding and sealing). The complete cable is tested before winding by water immersion for 4 h under a potential of 3 000 V d.c. The uniformity of the finished cable diameter, required for successful winding of the coils, is achieved through careful production control.

The orthocyclic method (Lenders, 1961–62) was selected for winding the coils because it offers the highest possible coil density (packing factor) for minimum coil size and best heat transfer. The regular winding pattern also assures reliable unwinding from inside the coil as the probe advances. The completely wound coil (Fig. 1) is potted into the probe housing and the collapsible mandrel is removed. Coils 30–65 cm long with cable lengths over 1 800 m have been wound at CRREL with improvised facilities.

The instrumentation package consists basically of thermistors for temperature measurement, a transducer to measure hydrostatic pressure (overburden stress), calibration resistors for line-resistance measurement (probe depth) and insulation-resistance measurement (insulation-fault detection), and a geophone for seismic soundings. A multi-position stepping relay serves for switching the various circuits for measurement and probe operation.

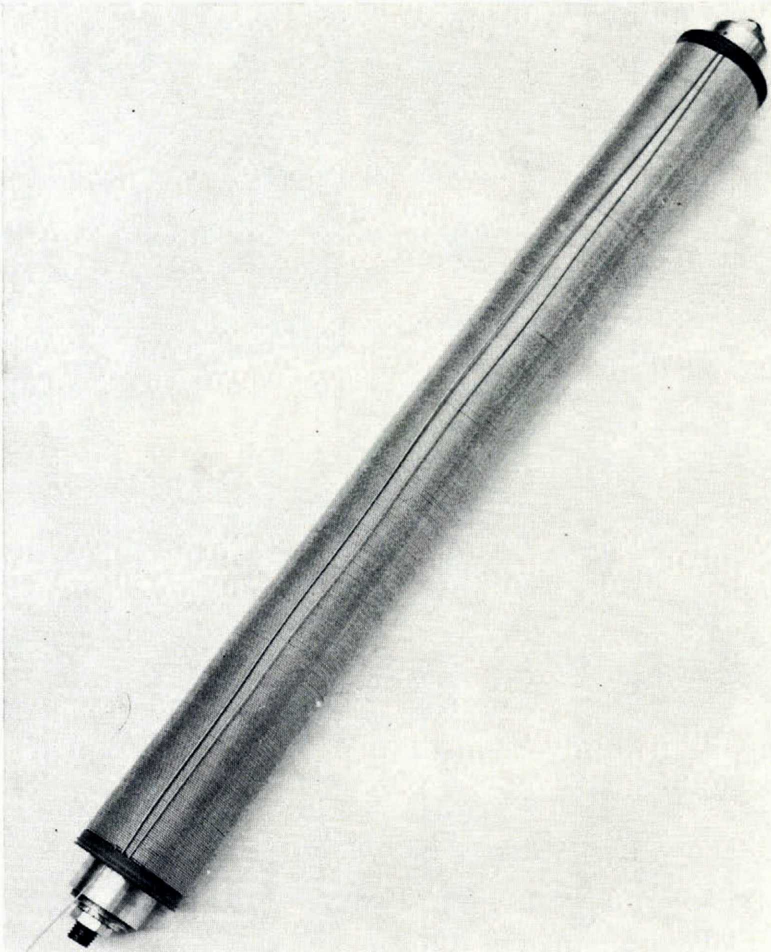

Fig. 1. This orthocyclically wound coil is shown wound on a collapsible mandrel. After permanent installation in the probe housing, the mandrel is removed. The cable pays out freely and reliably from inside the assembled probe

Figure 2 shows the circuit diagram of the Philberth probe. Diodes protect the sensors from switching voltage pulses and control the direction of the operating and measurement currents. The transmission-line characteristics change with probe depth as the conductors pay out.

The Philberth Probe

Two and a half years of effort at CRREL with tests in Greenland resulted in a design, illustrated in Figure 3, that is now being used by Expédition Glaciologique Internationale au Groenland (EGIG) for the construction of two probes for use at "Jarl Joset" station in 1968. This design incorporates features, some of which are outwardly apparent changes from Philberth's first plans and others, less obvious, which represent achievements in materials and fabrication capability.

Early in the probe development the anti-freeze solution filling was changed to a dielectric fluid filling (silicone oil) with density greater than water. The fluid keeps water out of the inside of the probe and serves to protect it from freezing damage. At the same time, a reservoir

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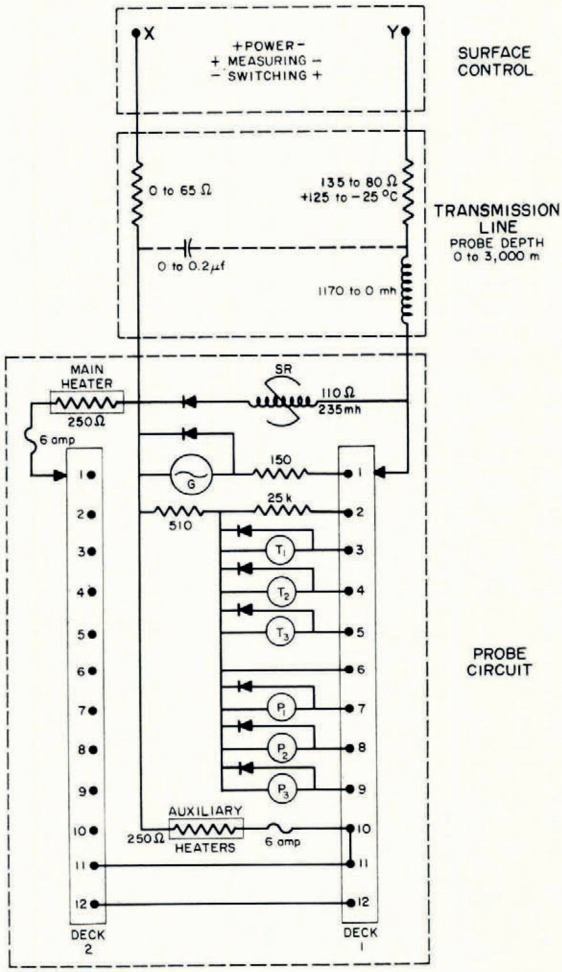

Fig. 2. The circuit diagram contains a switching network for operating and measurement functions. The diodes control the current and protect sensitive components. The electrical characteristics of the transmission line change as the probe advances and the conductors pay out

was added in which the oil level can drop as the conductors pay out. The reservoir is cylindrical and open to permit reliable release during re-starting of the probe after stopping and freezing in.

The change from two insulated conductors to one insulated and one bare wire conductor became practical with the development of a reliable electrical insulation. The benefit of this arrangement is the reduced heat generated in the storage coils and the reduced coil size of the bare wire. At the same time the increasing line resistance due to the paying out of bare wire becomes an indicator of the probe depth.

Surface heating elements are needed over the full length of the probe for melting out during re-starting after it has been stopped and frozen in the ice. A space-saving construction was devised in which the resistance heating-ribbon is built integrally into the cylindrical probe housing walls. The winding is bifilar to prevent inductive coupling with the coil.

The first Philberth probe, designated Century 1, was sent into the Greenland ice sheet at "Camp Century" in 1965. At a depth of about 90 m an insulation failure caused the loss of

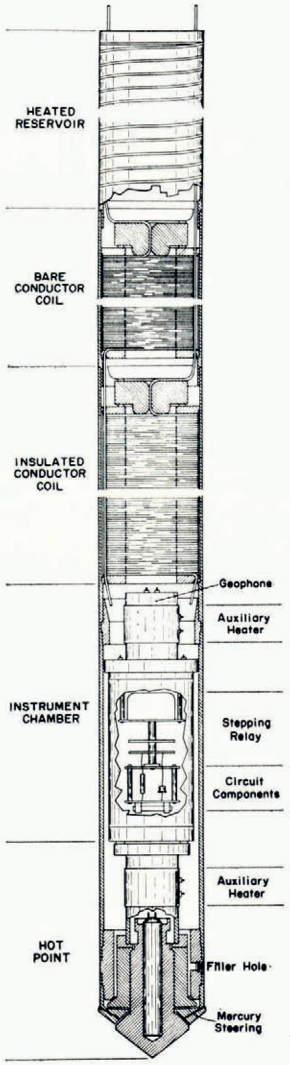

Fig. 3. The Philberth probe, as shown, is capable of penetrating polar ice sheets to depths of 3 000 m or greater for remote measurement applications. The internally stored conductors pay out of the advancing probe. They are the only surface link for power and control. The refreezing melt water seals the probe permanently into the ice

contact with the probe. In 1966, the second probe, Century 2, was tested at the same camp. It was stopped at a depth of about 260 m. A cooling curve and an ice-crystallization pressure and relaxation curve were obtained along with operating and performance experience. Details of this probe and instrumentation design, and results of the field test, have been presented by Aamot (1967[c]).

The probe illustrated in Figure 3 is 10.92 cm (4.30 in) in diameter and nominally 250 cm (about 100 in) long. The conductors are nominally 3 000 m (about 10 000 ft) long. The power required by the probe for a speed of 2.5 m/h (8.25 ft/h) in ice at −28°C is about 5 kW.

The Pendulum Probe

The analysis of the probe stabilization problem led the author to propose in 1964 a pendulum-steering method (Aamot, 1967[b]), so called because it places the center of support above the center of gravity; a probe using pendulum steering, referred to as a pendulum probe, is inherently stable because it hangs plumb at all times. The power levels of the lower, circular hot point and the upper, annular hot point are regulated so that the slightly under-powered upper hot point supports most of the probe weight.

Early tests with a model demonstrated the effectiveness of the self-plumbing action but also emphasized the need for automatic power control. Given such control a pendulum probe can operate efficiently in different ice temperatures and over a wide range of speeds (applied power levels). The automatic control regulates the power to the upper hot point whose relative requirements vary with the hole size, which in turn is influenced by the heat transfer from the lower part of the probe, particularly the coil section. Thus the probe compensates automatically for different operating conditions. This performance flexibility lends itself to the development of one standardized design with obvious advantages of cost, availability and simplicity in use.

The required power control became possible with the development of a differential temperature-control circuit. A thermostatic "off–on" control action was chosen because the selected (and adjustable) temperature differential between upper and lower hot points can be maintained independently of the required power. The relative "on" time of the duty cycle varies with the load.

The differential temperature-control circuit is included in the basic instrumentation package.

A single coaxial cable is used to provide uniform transmission-line characteristics and electrostatic shielding. This permits the reliable telemetry of a.c. signals. The single coil also provides a simple probe design and is economical to wind.

The Kapton insulation is the same as described earlier. It permits high-voltage d.c. power transmission with the smallest practical overall cable diameter and the lowest possible conductor resistance. The coil size is minimized to reduce the size and power requirements of the probe.

The center conductor is No. 20 AWG solid copper; the outer conductor has about the same resistance. Without an outer insulation on the cable the outer conductor resistance is a function of the paid-out length. The shunt capacitance of a 3 000 m cable is about 0.85 μF, the series inductance is about 0.35 mH, and the characteristic impedance is about 20 Ω.

The general configuration of the pendulum probe is illustrated in Figure 4. The two hot points of copper are heated by cartridge heating elements. The housing consists of filament-wound tube structures (glass/epoxy) with built-in heating elements over the whole length.

The diameter of the probe currently in prototype construction is 12.7 cm (5 in); the nominal length is 250 cm (about 100 in). The power requirement for a speed of 6 m/h (19.7 ft/h) in ice at -28°C is about 15 kW.

The penetration rate depends on the available power and the ice temperature. The probe adjusts to the given conditions through the automatic power control of the upper hot point. The voltage at the surface can, therefore, be set at any level within a wide range. As stated earlier, the lateral power requirements become a smaller part of the total power with increasing probe speed. In terms of the energy required to penetrate a given ice sheet, the probe efficiency increases with the speed, i.e. with the power level.

Applications

The capabilities and applications of thermal probes are limited only by the instrumentation that can be installed. The functions may be the initial exploration and measurement of conditions in polar ice sheets and floating ice shelves where little information is available.

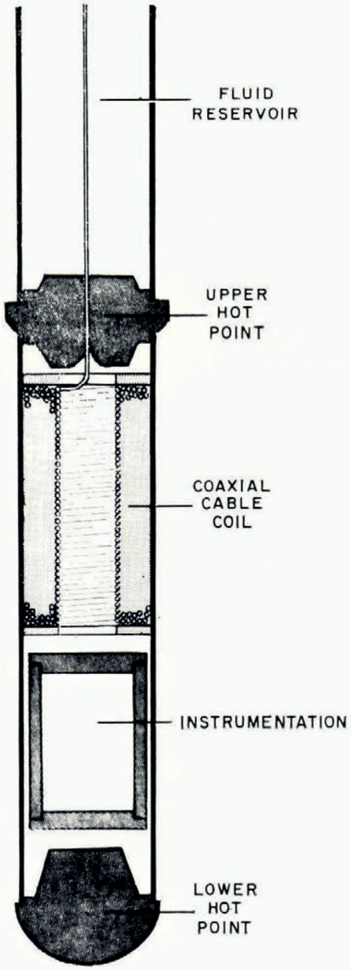

Fig. 4. The pendulum probe is stabilized to maintain a vertical path by hanging from its upper hot point. It features high performance and flexibility in self-adjustment to a wide range of operating conditions

Temperature and temperature-profile measurements provide information about possible bottom melting and net build-up of ice sheets, Earth climatic history and geothermal conditions. Ice-movement measurements give clues to the behavior of ice sheets. Acoustic and seismic studies serve to develop methods for depth measurement, interface profiling, sub-interface exploration of geological features and bottom melt-rate measurements of ice shelves. The dielectric properties of glacier ice can be measured *in situ* with probes as electrodes located as required.

Polar ice sheets offer a very stable and quiet environment for long-term observation and monitoring of events and conditions on Earth, using probes to carry suitable instrumentation for permanent installation. There is a most desirable freedom from noise or interference due to weather or Man's activity; the temperature of the environment is perfectly stable. Sensitive seismometers can listen for earth tremors or large explosions; they can be arranged in large three-dimensional arrays. Suitable magnetometers and antennae can observe natural magnetic fields or storms; they may also offer new opportunities in communications.

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