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INSTRUMENTED PROBES FOR DEEP GLACIAL INVESTIGATIONS

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Haldor W.C. Aamot

MAY 1968

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
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PREFACE

The development of thermal probes is a USA CRREL In-House Laboratory Initiated R&D project of the Measurement Systems Research Branch, Mr. William H. Parrott, Chief. Dr. Karl Philberth, Expert to the Laboratory, participated in the heat transfer calculations and advised on numerous problems. Mr. John Kalafut, Electrical Engineer, performed extensive assembly and testing throughout the program. Mr. Ronald T. Atkins, Electronics Engineer, developed and tested the differential temperature control circuit. Mr. B. Lyle Hansen, Chief, Technical Services Division, supervised the work and promoted continual improvement and new approaches. He and Mr. Malcolm Mellor reviewed the manuscript. Mr. Haldor W.C. Aamot, Research Mechanical Engineer, was project engineer.

USA CRREL is an Army Materiel Command laboratory.

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SUMMARY

Thermal probes have been developed that can carry instrumentation packages into polar ice sheets for geophysical investigations and long-term observations by remote measurement. They are self-contained, surface-controlled devices. During development work at USA CRREL problems with materials, fabrication, and heat transfer analysis were solved. The Philberth probe, named after its inventor, demonstrated its performance capability in Greenland. The pendulum probe was a further development with increased performance and versatility.

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Introduction

Instrumented probes are used to obtain information by remote measurement. The thermal probes described here are non-recoverable vehicles designed to carry instrumentation payloads to any depth in polar ice sheets by melt penetration. They are controlled and powered from the surface through internally stored conductors which pay out of the advancing probes and become anchored in the refrozen melt water above.

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

Philberth (1962, 1966a) proposed such a probe and conducted penetration and stabilization tests using electrically heated hot points in Switzerland (Philberth, 1964). USA CRREL obtained his plans as part of a mutual agreement to exchange information on and experience gained with probes (Hansen, 1966) and in 1964 the technological development of the Philberth probe began in cooperation with the inventor.

The pendulum probe is a further USA CRREL development to increase capabilities in polar ice sheet exploration and related applications. High speed and automatic self-adjustment to widely varying operating conditions make this probe simple to use and attractive for many purposes.

General description

Thermal probes consist of a hot point for melt penetration, internally stored conductors as a surface link, a reservoir extension to keep the dielectric fluid filling at a level above the internal components, and an instrument package. The components are housed in a long, slender casing.

The probes require a means of stabilization to keep them in a plumb attitude and on a vertical course. The probe stands on its tip, the hot point. This unstable situation leads to a progressive leaning and a gradual toppling over. K. Philberth recognized the problem and proposed a mercury steering principle which has proven 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. K. Philberth (1966b) discusses 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 efficient performance.

The heat produced by 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

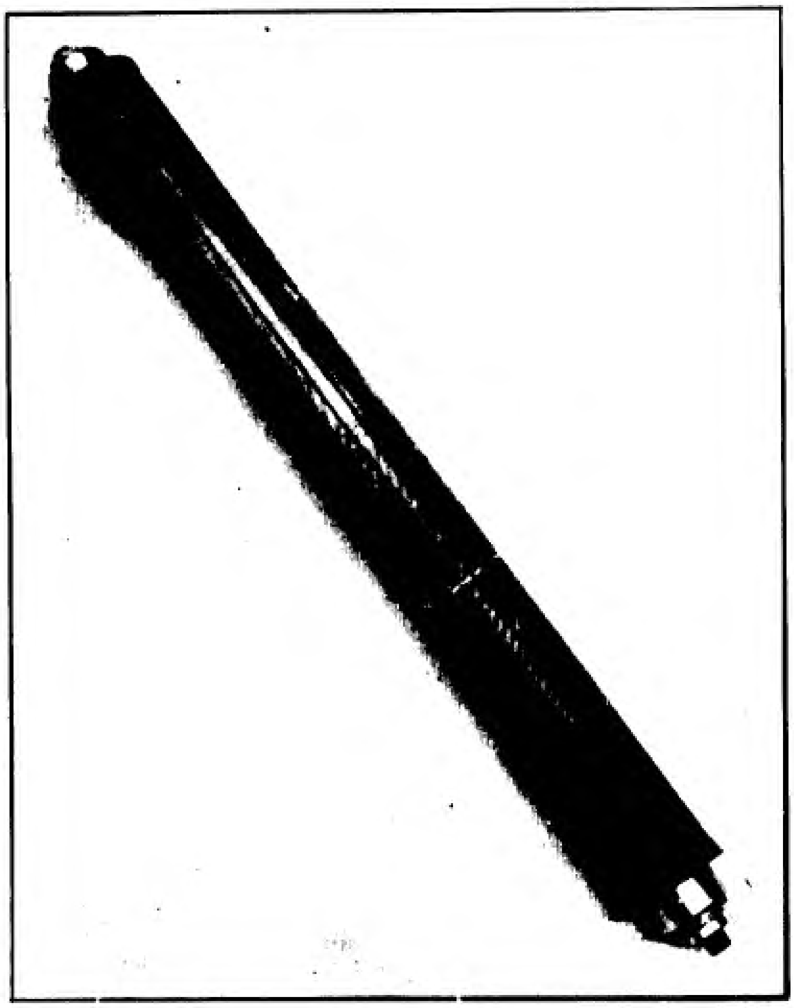

Figure 1. Coil wound orthocyclically on a collapsible mandrel. After permanent installation in the probe housing, the mandrel is removed. The cable pays out freely and reliably from inside the assembled probe.

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 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 and 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 for charting the optimum probe speeds for various operating conditions are given by Aamot (1967a).

The insulation of the cable in the probe is designed and produced to be suitable for the transmission of power at high voltage and to allow winding of the cable into an orthocyclic coil. The selected construction uses two cross-wrapped servings of Kapton tape (a polyimide film with FEP Teflon backing for thermoplastic bonding and sealing). The complete cable is tested before winding by water immersion for 4 hours under a potential of 3000 v dc. The uniformity of the finished cable diameter, required for successful winding of the coils, is achieved through careful production control.

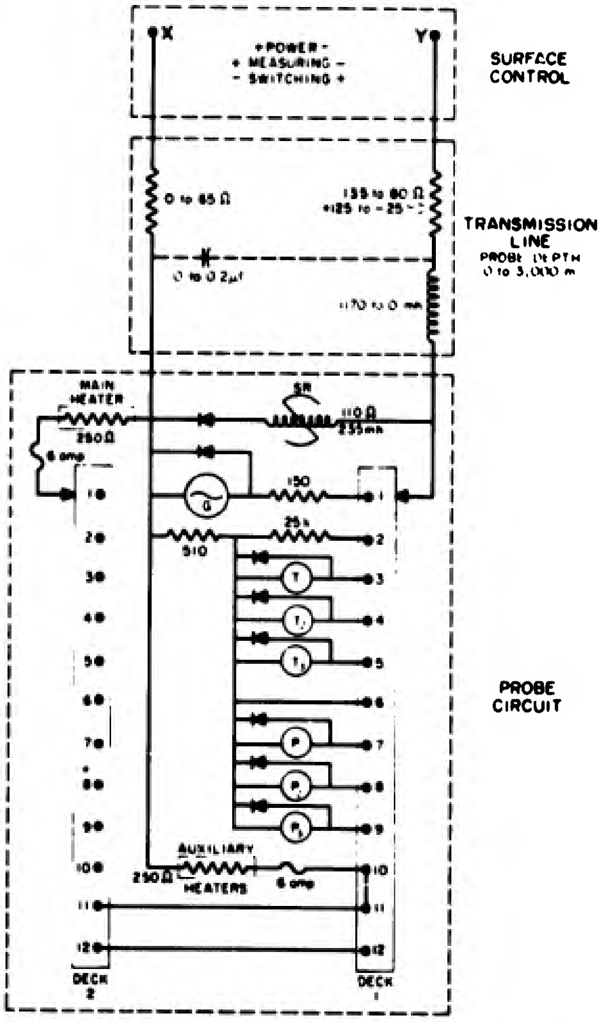

Figure 2. The circuit diagram contains a switching network for operating and measuring functions. The diodes control the current and protect sensitive components. The electrical characteristics of the transmission line change as the probe advances and the conductors pay out.

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 to 65 cm long with cable lengths over 1800 m have been wound at USA 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. The various circuits for measurement and probe operation are switched through a multi-position stepping relay.

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 USA CRREL with tests in Greenland resulted in a design (Fig. 3) that is being used by the International Glaciological Greenland Expedition (EGIG) for the construction of two probes for use at the Jarl Joset Station in 1968. This design incorporates evolutionary changes from Dr. Philberth's first plans and some features that are achievements in materials and fabrication capability.

Early in the probe development the antifreeze 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 protects it from freezing damage. At the same time a reservoir was added in which the oil level can drop as the conductors pay out. The reservoir is an open cylinder with smooth inner walls to permit reliable release of the probe during restarting after it has been stopped and frozen 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 advantage 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 restarting. 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 loss of contact with the probe. In 1966, the second probe, Century 2, was tested at the same site. 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, are presented by Aamot (1967b).

The latest model of the probe (Fig. 3) is 10.92 cm (4.30 in.) in diameter and nominally 250 cm (about 100 in.) long. The conductors are nominally 3000 m (about 10,000 ft) long. The power required by the probe for a speed of 2.5 m/hr (8.25 ft/hr) in ice at -28C 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, 1967c; pat. pend.), so called because it places the center of support above the center of gravity. A probe using pendulum steering 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 upper hot point is slightly underpowered and therefore supports most of the probe weight.

Early tests with a model demonstrated the effectiveness of the self-plumbing action but also revealed 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 portion of the probe, particularly the coil section. Thus the probe compensates automatically for changing 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 point 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 #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 3000-m cable is about 0.85 μf, the series inductance is about 0.35 mh, the characteristic impedance is about 20 ohms.

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.

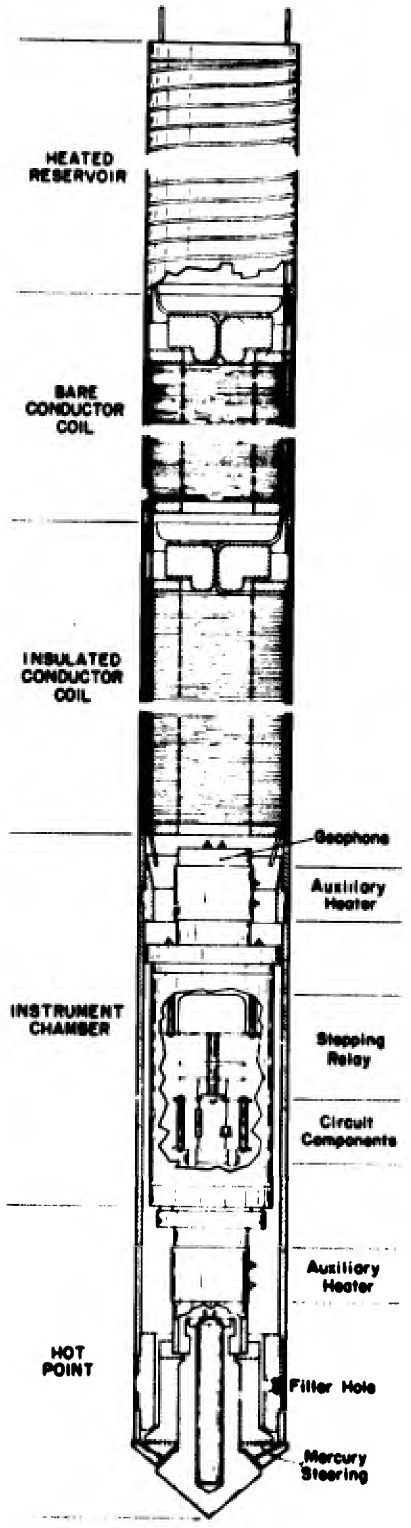

Figure 3. The Philberth probe is capable of penetrating polar ice sheets to depths of 3000 m or more for remote measurement. The internally stored conductors pay out of the advancing probe. They are the only surface link for power and control. The refreezing melt water seals the probe permanently into the ice.

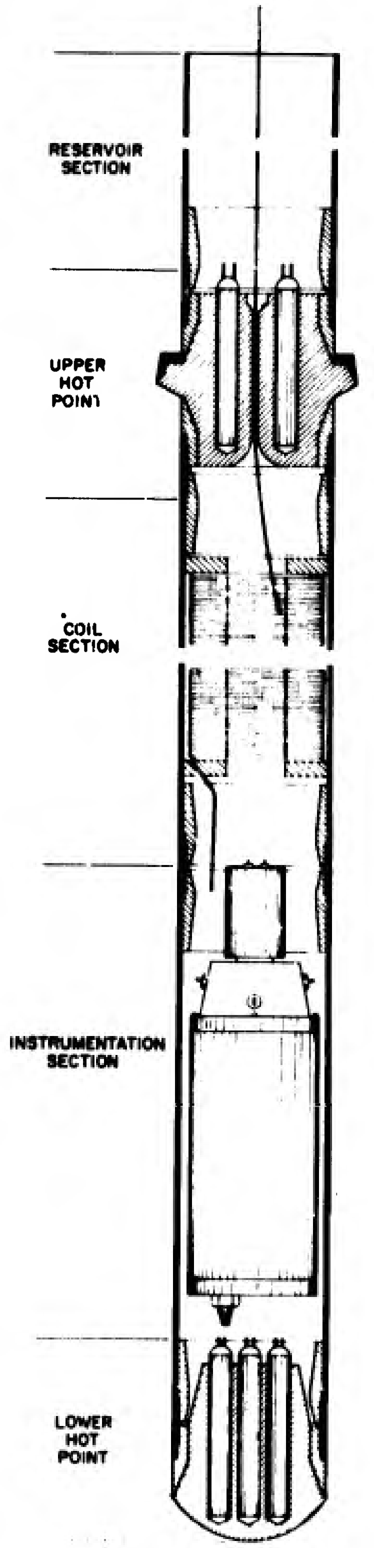

Figure 4. The pendulum probe is stabilized to maintain a vertical path by suspending it from its upper hot point. It features high performance and flexibility in self adjustment to a wide range of operating conditions.

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/hr (19.7 ft/hr) in ice at -28C is about 15 kw.

The penetration rate depends on the available power and the ice temperature. The probe adjusts to 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 portion 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. 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 help in developing 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 antennas can observe natural magnetic fields or storms; they may also offer new opportunities in communications.

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13. ABSTRACT

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