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ABSTRACT

The magneto-resistance effect of the metal bismuth has been used in measuring magnetic induction for many years. This report describes significant features of the electrical and mechanical design of an electrically temperature-regulated resistor assembly and associated equipment. Commercial ductile bismuth wire was successfully used in a small probe. Useful resolution of 2 gauss in fields above 5, 000 gauss was readily attained. Limitations and advantages of bismith resistors as devices for measuring magnetic induction are discussed briefly. Some data from the use of the first units are presented.

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INTRODUCTION

Bismuth resistors, in the form of cast spirals, have been used for magnetic-induction measurements for more than half a centruy.[1, 2] Resistors of small size and conveniently high resistance were constructed by H. B. Keller[3] of commercial, ductile bismuth wire,[4] 0.005 inch in diameter. Keller minimized the effect of the temperature coefficient of resistivity and attained large magneto-resistance effects by operating the resistors in the approximately constant temperatures of boiling nitrogen (-196°C) and of boiling Freon-12 (approx. -30°C). The double-walled glass vacuum vessel that contained the boiling liquid and the resistors permitted a probe diameter as small as 9/16 inch.

Even this small a probe, however, was too large for magnetic measurements required in connection with the modification of the 184-inch cyclotron at the University of California Radiation Laboratory in 1956. It was necessary to explore the field in a channel only 1 inch wide, and 5/16 inch was chosen as the maximum diameter for a probe that would permit the necessary measurements.

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[1] G. S. Simpson, Resistance of Bismuth in a Magnetic Field, Phil. Mag. 4, 554, (1902).

[2] Smithsonian Physical Tables, 9th Edition, Temperature Variation of Resistance of Bismuth in Transverse Magnetic Field, Table 487, p. 463.

[3] H. B. Keller, Precision Measurements of Magnetic Induction with Bismuth Wire, UCRL-2249, June 1953.

[4] Fitzpatrick Electric Supply Company, Muskegon, Michigan, "Ductile Bismuth Wire" (pamphlet).

A safety rule observed during the 1956 magnetic measurements of the 184-inch magnet was that no person was permitted in the gap while the magnet was energized. The above rule plus the fact that the channel entrances were relatively inaccessible made measurements with a search coil and fluxmeter inconvenient. A plan to use an electronically temperature-regulated bismuth resistor[5] was formulated on the following assumptions:

(a) An electrically heated probe could be made within the 5/16-inch-diameter limitation.

(b) The reduced magneto-resistance response at (say) +30°C, as compared with the response at -30°C (boiling Freon), could be compensated by increased precision of resistance measurement.

(c) Temperature stability commensurate with the required precision of measurement could be attained.

The plan was completed by developing and using the system described in this report.

The Original Specifications

The following specifications were chosen to guide the development work:

(a) Sensitivity at 23 kilogauss: 0.01 ohm per 15 gauss.
(b) Thermal noise tolerance: 0.02% of 23-kilogauss signal.
(c) Bismuth resistor over-all length: less than 1/4 inch.
(d) Probe diameter: 5/16 inch, maximum.
(e) Amplifier input sensitivity: 20 microvolts.
(f) Operating temperature: 30°C.

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[5] The bismuth resistor assembly was mounted on the mechanical probe-positioner that was designed for the exploration of the mid-gap field, and was positioned inside the 1-inch channel opening by remote control.

THE TEMPERATURE-REGULATOR DESIGN

The design specifications listed in the above section require that the temperature of the probe be held constant to within ± 0.04°C. The probe design includes a platinum resistance thermometer and a heater winding to maintain the probe temperature somewhat above ambient; the temperature of the probe is to be maintained constant by electronically controlling the power to the heater. Figure 1 shows a block diagram of the electronic system used with the probe. Small temperature variations produce variations in the resistance of the platinum wire, which are converted to input signals to an amplifier. The heater is connected to the amplifier output and the amplified input signal counteracts the temperature changes. Conventional proportional control of this type appeared feasible because the heater power requirements are small.

The design requirements led also to the following estimates:

1. If the probe temperature is held 15°C above ambient, and constant to ± 0.04°C, then the required loop gain at zero frequency is $A_0 = (15/0.08) \approx 200$.

2. If (as assumed) the probe has a thermal time constant of about 2 sec and its frequency response rolls off at 6 decibels per octave, the frequency at which the loop gain falls to unity is

$$f_c = \frac{1}{2\pi \times 2 \text{ sec}} \times 200 = 16 \text{ cycles per sec.}$$

3. If a 60-cycle-per-second full-wave chopper amplifier is used, the highest modulation frequency that does not lead to interference from beat notes is about 40 or 50 cycles per second. This is enough greater than f_c that Requirements 1 and 2 above can be met with a margin of nearly three times (about this much is desirable with high-gain feedback systems to allow for variations of vacuum-tube characteristics).

4. Trial calculations indicated that it would probably be practical to wind a platinum resistance element of about 200 ohms resistance. This would have a sensitivity of about 30 μv/0.04°C, with a power dissipation that would not cause more than 0.04°C error in the temperature measured.

The platinum element for sensing temperature is in one leg of a bridge connected so as to feed the unbalance signal to the amplifier. The amplifier readjusts the amount of power in the heater in the direction to reduce the bridge unbalance. In a somewhat similar way the bismuth element is part of a (different) self-balancing bridge— which, however, reads rather than controls the bismuth resistance.[6] In both cases a three-wire system is used to run the long leads from the sensing element to the other parts of the bridge. As is usual with three-wire systems, two wires are used to carry the bridge-element current, and the third wire is arranged to carry a much smaller current. The two current-carrying leads are in opposing arms of the bridge, carry equal currents, and are electrically similar, so that variation in the resistance of these leads does not appreciably affect the bridge balance. The third lead is not part of any arm of the bridge but is in the unbalance-detecting circuit; its resistance does not affect the point at which the bridge balances.

The schematic diagram of the amplifier is shown in Fig. 2. This is a chopper type of dc amplifier, i.e., the dc signal is converted to (60-cycle) ac, amplified, and converted back to dc (with a superimposed ac ripple).

The precision resistors in the box near the input terminals form three legs of the bridge in which the platinum sensing element forms the fourth leg. The input and output converters are the two sections of a double-pole double-throw Stevens-Arnold chopper. The transformer, T-5, is a well-shielded input transformer with a turns ratio of about 40/1. In this application the input transformer sees a 60-cycle square wave; no commercial transformers that have been tried give an entirely adequate low-frequency response. The one shown here (Triad, G-10) is about the best of those which have been tried. The amplifier includes an internal feedback path (R-31, R-8, C-2, C-1, R-7), which can be adjusted to give the amplifier a rising gain characteristic over a chosen frequency band. This was included in case the probe should behave like a device with two time constants. (The probe actually behaved like a single-time-constant device and the internal feedback loop was superfluous).

The output circuit of this amplifier does not include a low-pass filter, and the dc output voltage has a large 120-cycle ripple component. This

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[6] Daniel R. Stull, An Automatic Recorder for Resistance Thermometry, Rev. Sci. Instr. <u>16</u>, No. 11, 318-21 (1945).

ripple does not impair the operation; the thermal time constant of the probe is large enough to prevent thermal oscillations at this frequency, and the probe was so constructed that the signal circuits are well shielded from the heater. It should be noted that if a low-pass filter were built into the amplifier, the filter would introduce additional phase shift in the feedback loop, and stable operation would be harder to attain.

The cathode-follower output uses a 3C 33 type tube. With this large tube an output current of as much as 60 milliamperes is available. This proved more than enough for the application, and resistors R-28 and R-30 have been proportioned to limit the maximum output current to a much lower value.

BISMUTH PROBE ASSEMBLY

Description

The probe described in this section is our latest model (HP-3),[7] and differs somewhat from the probe used in the 184-inch cyclotron measurements program of 1956 (HP-1).

We believe that HP-3 is superior to its predecessors; it is of a more rugged design, and has higher bismuth and platinum resistance, reduced size, and simpler construction.

The probe assembly is illustrated in Fig. 3, in which code letters refer to the parts enumerated in the following description. The principal components are a bismuth resistor (f), a platinum temperature-sensing element (e), and a resistance-wire heater (d). The bismuth resistor consists of 32 ohms of 0.005-inch-diameter analac-insulated wire; the platinum resistor contains 180 ohms of bare 0.001-inch-diameter wire; and the heater is 450 ohms of lacquer-insulated 0.0035-inch-diameter Jelliff "1000" wire. The three circuits are individually electrically shielded, the elements and leads are constructed for minimum inductance, and careful attention has been given to electrical insulation(g).

The above components are mounted coaxially, and, being wound on brass forms, are in close thermal contact with one another. Mounting this group on a flexible Teflon tube (h), and surrounding the assembly with cotton (i), serves the dual purpose of protecting the delicate bismuth from shock and providing thermal insulation between the heater and the external environment. The styrofoam plug (b) and lucite cap (a) at the end of the probe contribute to the latter goal as well as helping restrict heat flow to a direction perpendicular to the probe axis. To prevent heat loss along the wires leading away from the electrical elements, six cotton-covered manganin wires each 3-1/2 mils in diameter and 6 inches long are used as intermediate links between the bismuth and platinum elements and the probe cable wires. These six manganin leads are wound around the Teflon tube and occupy the space (j) under one end of the heater.

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[7] Details of construction are given in UCRL Engineering Note 4310-17, MT-5, June 1957.

A brass mounting post (m) positions the elements via the Teflon tube. In addition, it firmly positions the ends of the eight cable wires (n) so that they may serve as terminals for the manganin isolation leads and heater leads, each of which passes through individual guide holes (k) to get to this terminal section. The probe base (p) serves as a handle for the probe in addition to supporting the probe cover (c) and providing a termination for the probe cable outer braid (q) and plastic sleeving (r).

The photograph in Fig. 4 shows the bismuth and platinum elements before assembly. Figure 5 shows the completed probe.

AN EVALUATION OF THE PERFORMANCE OF THE RESISTOR

Inherent Limitations of Bismuth Resistors

The magneto-resistance response of commercial bismuth wire is a complex nonlinear function of temperature and induction. Operation at constant temperature reduces the important limitations to the following:

(a) The magneto-resistance function, $\frac{R}{R_0}(B)$ (where R is the resistance at the induction B, and R_0 is the resistance at B=0), varies widely from resistor to resistor. Reference 2 gives values of the function similar to those observed with the commerical wire.

(b) At low values of induction the constant-temperature magneto-resistance response of bismuth can be approximated as: $\frac{R - R_0}{R_0} = KB^2$ where K is a constant, and, as shown on Figure 6, the resistor is relatively unresponsive below 2000 gauss. Above 5000 gauss the response is nearly linear.

(c) Solenoidally wound resistors have pronouced anisotropy. The magnitude of the directional effect is a complex function of induction. At constant induction, however, the variation of resistance can be expressed quite accurately by the simple function.

$$R\Big|_{\substack{B=K_1\\T=K_2}} = R_{90^o} + (R_{0^o} - R_{90^o}) \cos^2 A,$$

where A is the angle between the solenoid axis and the induction, R_{90^o} is the resistance for $A=90^o$, etc., and K_1 and K_2 are constants. A typical value for the magnitude of $(R_{0^o} - R_0)/(R_{90^o} - R_0)$ is 1.2.

Valuable Features of Bismuth-Resistor Induction-Measuring Systems

Bismuth resistors are typically used as transfer devices between a magnetic field and some absolute induction-measuring device. When the limitations discussed in the preceding section permit, the following features may be valuable:

(a) Bismuth resistors can be constructed in the form of small probes (permitting their use in very narrow gaps) and with small sensing areas (permitting accurate point measurements in high gradients).

(b) The convenience and precision of standard resistance-measurement techniques simplify measurement problems. Continuous indication, as with a strip-chart recorder, is easily attained.

(c) The response of bismuth to absolute magnitude of induction (rather than to components) is sometimes an advantage, e.g., a transverse probe when suitably calibrated can be used to measure axial fields.

Our Experience With the First Resistors

After several cycles of wire breakage, repairs, design changes, etc., we had a resistor assembly with the hoped-for dc resistance relations between all terminals. The amplifier, which had been running with dummy input and dummy load, was connected to the temperature-sensing platinum winding. When the control was set to the room-temperature threshold, the CRO picture of the dummy heater voltage indicated correct behavior of the circuits. We connected the heater and jubilantly observed that minimum increases of control setting initiated rapid transients of full heater voltage followed by stable low levels of heater voltage. We had made only rough estimates of thermal constants, and the above history describes our release from our number one concern about the design--did we have stability with high loop gain? We did. With the amplifier gain adjusted to give a margin of stability, a rough measurement indicated that the loop gain was more than 300. The loop-gain measurement procedure was as follows:

(a) The temperature control was calibrated (dial divisions per degree centigrade of probe temperature).

(b) The control was set to T degrees above the ambient temperature ($T \approx 15^{o}C$), and the magnitude E of the heater voltage required to maintain the temperature was recorded.

(c) A dummy load was substituted for the probe heater circuit (connected to the output of the amplifier), and the probe was allowed to cool to ambient temperature.

(d) The control-setting increment required to change the amplifier output from zero to E was measured; the corresponding temperature increment defines ΔT.

(e) Loop gain = $T/\Delta T$.

There are unavoidable temperature gradients in the resistor assembly. These gradients are functions of the heater power and are significant because the positions of the bismuth and the platinum elements are not coincident. Although the platinum may remain at constant average temperature as the ambient temperature (and thus the heater power) varies, the average bismuth temperature may vary significantly. The above was one of the design considerations, and the effect was measured as follows:

(a) The bismuth resistor was calibrated as a resistance thermometer between two convenient ambient temperatures.

(b) In zero magnetic induction the probe ambient temperature was changed to give low and high heater power at constant control setting.

(c) The resulting temperature change indicated by the change in resistance of the bismuth element is the combined effect of finite (relative to infinite) loop gain and changes in the average temperature of the bismuth.

(d) The observed bismuth-temperature change corresponding to a 10°C change in ambient temperature was less than 0.1°C.

Previous experience with bismuth resistors had prepared us for the instability of resistance that we actually observed. For example, the first measured resistance of the bismuth element plus the internal leads at constant temperature was 78.311 ohms on a Friday, and the resistance increased 0.152 ohm over the week end. Attempts to correlate observed changes in R_0 with temperature cycling and magnetic-induction cycling were inconclusive.

It is common practice to stabilize precision resistors by baking for 48 hours at 150°C.[8] Because the melting temperature of the low-temperature solder used in the assembly is below 100°C, and because we wished to avoid possible temperature-dependent deleterious changes in structure, we baked our resistor assemblies for a week at the relatively low temperature of 60°C.

Over a period of 4 months beginning 1 month after construction, the first resistor assembly was temperature-regulated to 30°C most of the time. It was disconnected and allowed to cool to room temperature about 10 times during that period. Time spent at room temperature varied from a few minutes to several days. The 30°C bismuth resistance at the beginning of the period was 79.370 ohms; at the end of the period the resistance was 79.441 ohms. (These measurements include 62 ohms of inert

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[8] Forest K. Harris, Electrical Measurements (Wiley, New York, 1952), p. 211.

leads.) The probe was then shelved for 5 months. When it was recommissioned at the end of this time the resistance was 79.458 and increased to 79.470 within 1 week.

When the resistor assembly was slightly deformed, as when it was mounted on a probe carrier, the bismuth resistance changed. The observed rapidity of the changes seems to indicate that they relate mostly to the bismuth circuit; the resistance changes have been on the order of 0.020 ohm.

A second resistor assembly was constructed as a spare as soon as preliminary tests of the first indicated its success. The second resistor was similar to the first except that the outside brass tube was shorter, and screws were substituted for the tape that held the outside tube of the first assembly.

On the basis of our experience with probes Nos. 1 and 2, a number of design changes were made and included in the third probe. These changes are summarized in the section describing the resistor assembly.

One of our principal aims in designing the third resistor was to reduce the temperature gradient between the platinum and bismuth elements. Although preliminary tests showed no reduction in this gradient, the probe is so constructed that the relative positions of the three basic elements and the thickness of the insulating layer at the tip of the probe may all be varied. With this flexibility we feel that the temperature-gradient problem is well under control.

ACKNOWLEDGMENTS

We are indebted to Clarence Vernon and Robert G. Scott for their patient care in constructing the resistor assemblies and correcting troubles; to Robert W. Sorenson for his work in adjusting the amplifier and solving noise problems; and to Joseph H. Dorst for his evaluation of the performance of the resistor.

FIGURE CAPTIONS

Figure 1.	Block Diagram of Bismuth Instrument.
Figure 2.	Schematic of Chopper Amplifier.
Figure 3.	Bismuth Probe Assembly.
Figure 4.	The Sensing Elements. Upper, Platinum; Lower, Bismuth.
Figure 5.	The Assembled Probe.
Figure 6.	Magneto-resistance Response of a Bismuth Resistor.
Table I.	Parts List for Chopper Amplifier.

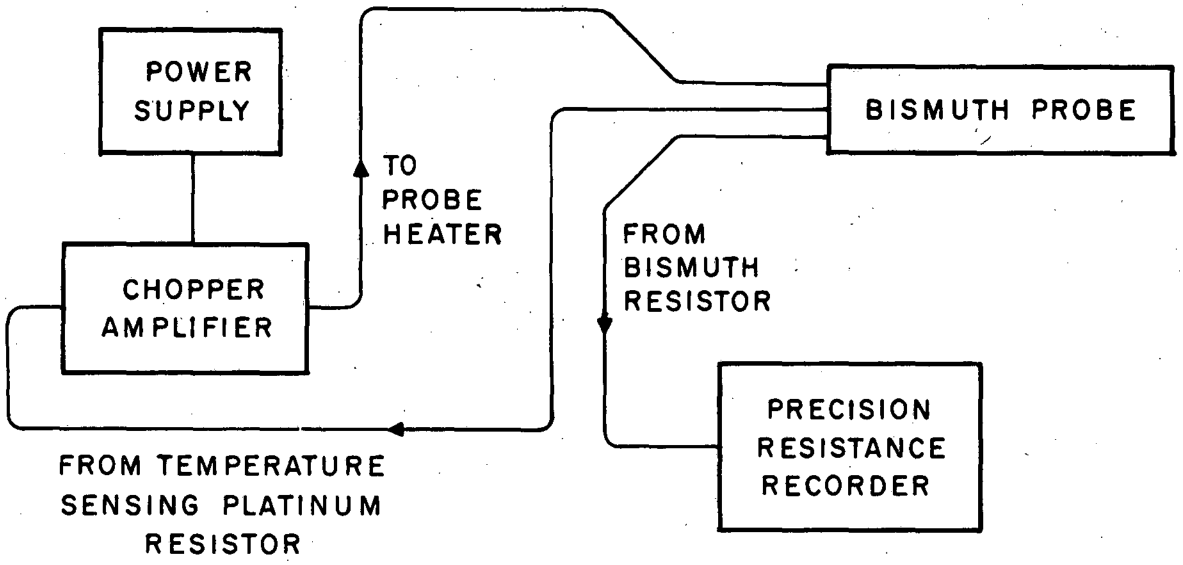

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Fig. 1.

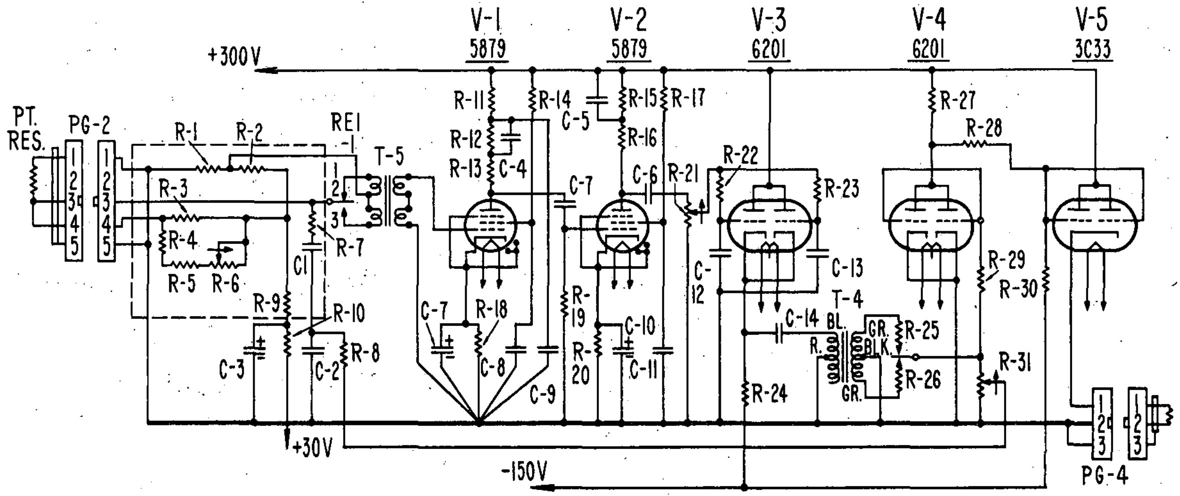

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Fig. 2.

TABLE I

PARTS LIST FOR CHOPPER AMPLIFIER

(See Fig. 2)

C-1	1	0.1 MF	600 V	Polystyrene Capacitor
C-2	1	1 MF	200 V	Paper Capacitor
C-3	1	100 MF	150 V	Electrolytic Capacitor
C-4, 5,	2	0.03 MF	600 V	Paper Capacitor
C-6, 7	2	0.05 MF	600 V	Paper Capacitor
C-7, 10,	2	25 MF	25 V	Electrolytic Capacitor
C-8, 11	2	1 MF	400 V	Paper Capacitor
C-9	1	20 MF	450 V	Electrolytic Capacitor
C-12, 13	2	60 MMF	600 V	Ceramic Capacitor
C-14	1	6 MF	200 V	Paper Capacitor

PG 2	1	5-PIN	Male Receptacle
PG 3	1	3-PIN	Male Receptacle

R-1, 2	2	100 Ω	1/2-Watt Manganin Res.
R-3, 4	2	250 Ω	1/2 - Watt Manganin Res.
R-5	1	1 K	1/2 - Watt Manganin Res.
R-6	1	500 Ω	Helipot
R-7	1	20 M	1/2 - Watt Dep. Car. Res.
R-8	1	2.5 M	1/2 - Watt Dep. Car. Res.
R-11	1	10 K	1 - Watt Carbon Res.
R-12, 13, 15, 16	4	240 K	1 - Watt Carbon Res.
R-14, 17	2	1.3 M	1 - Watt Carbon Res.
R-18, 20	2	5.1 K	1 - Watt Carbon Res.
R-19	1	1.5 M	1 - Watt Carbon Res.
R-21	1	1 M	2 - Watt AB POT
R-22, 23	2	820 K	1 - Watt Carbon Res.
R-24	1	30 K	2 - Watt Carbon Res.
R-25, 26	2	43 K	1 - Watt Carbon Res.

TABLE I (Contd)

R-27	1	47 K	1 - Watt	Carbon Res.
R-28	1	51 K	1 - Watt	Carbon Res.
R-29	1	1 M	1 - Watt	Carbon Res.
R-30	1	68 K	2 - Watt	Carbon Res.
R-31	1	250 K	2 - Watt	AB POT
T-4	1	Stancor A 4774		
T-5	1	Triad G10 Input XFMR		
V-1, 2,	2	5879		
V-3, 4,	2	6201		
V-5	1	3C33		

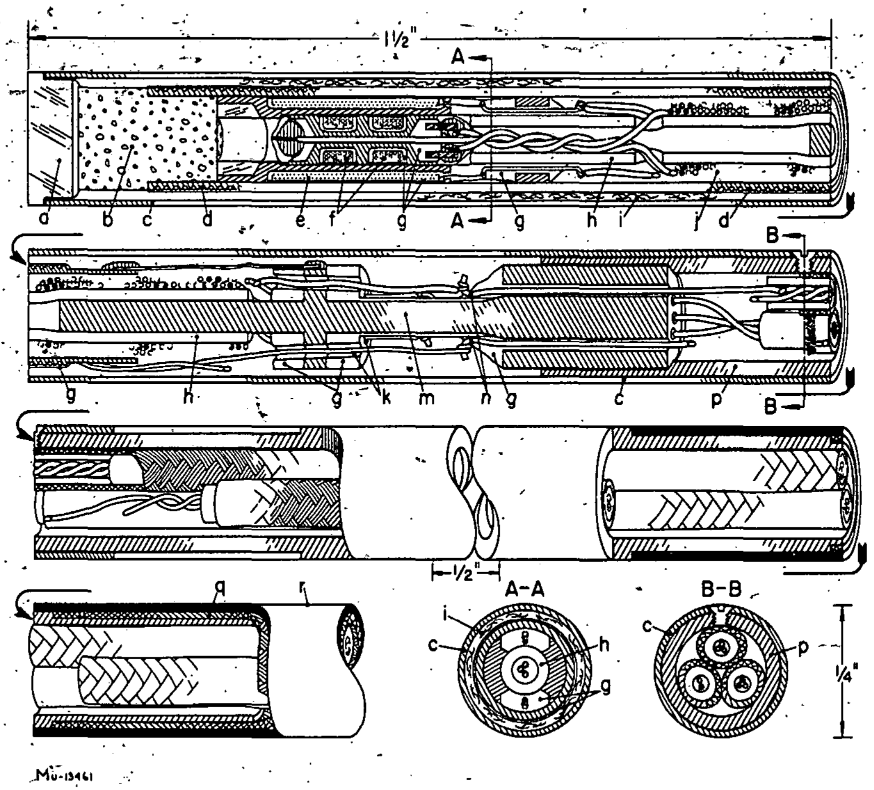

Fig. 3.

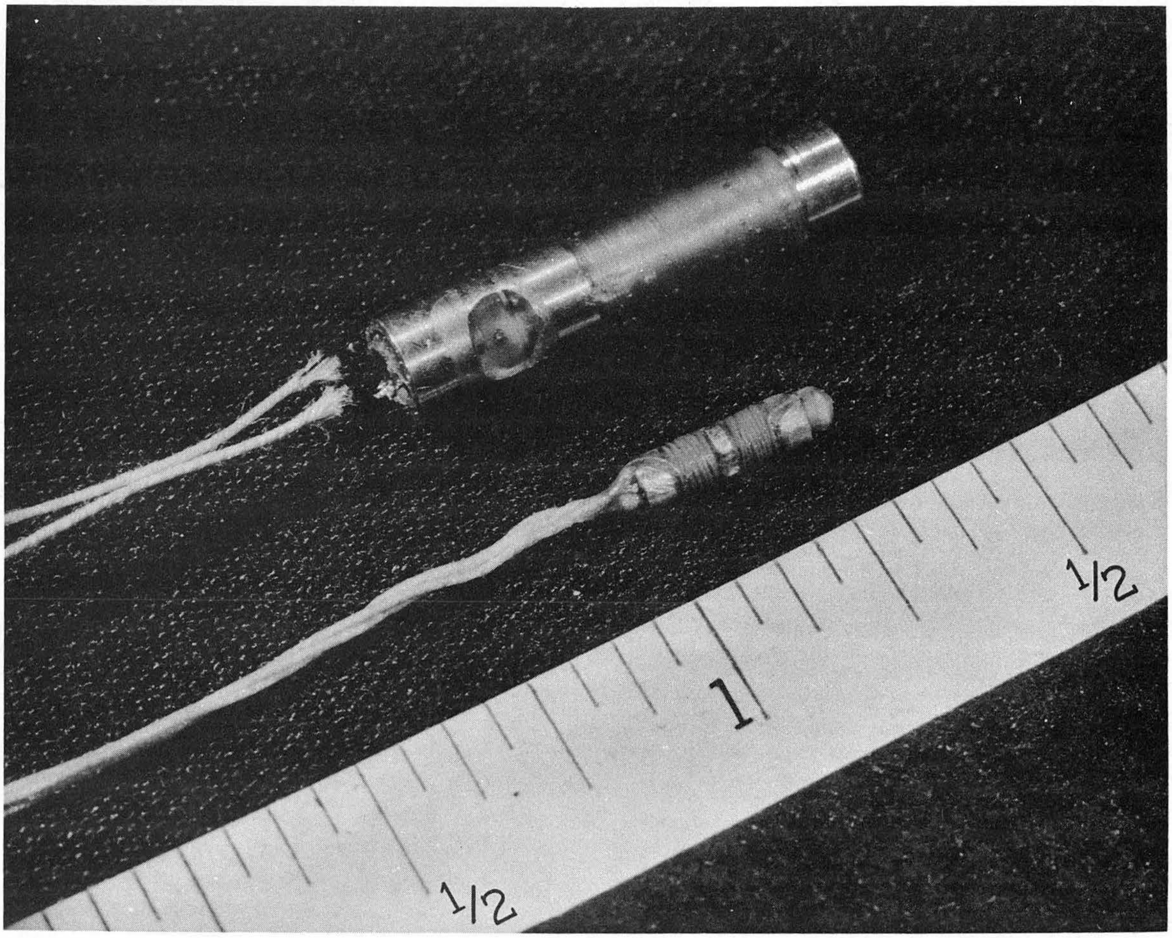

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Fig. 4.

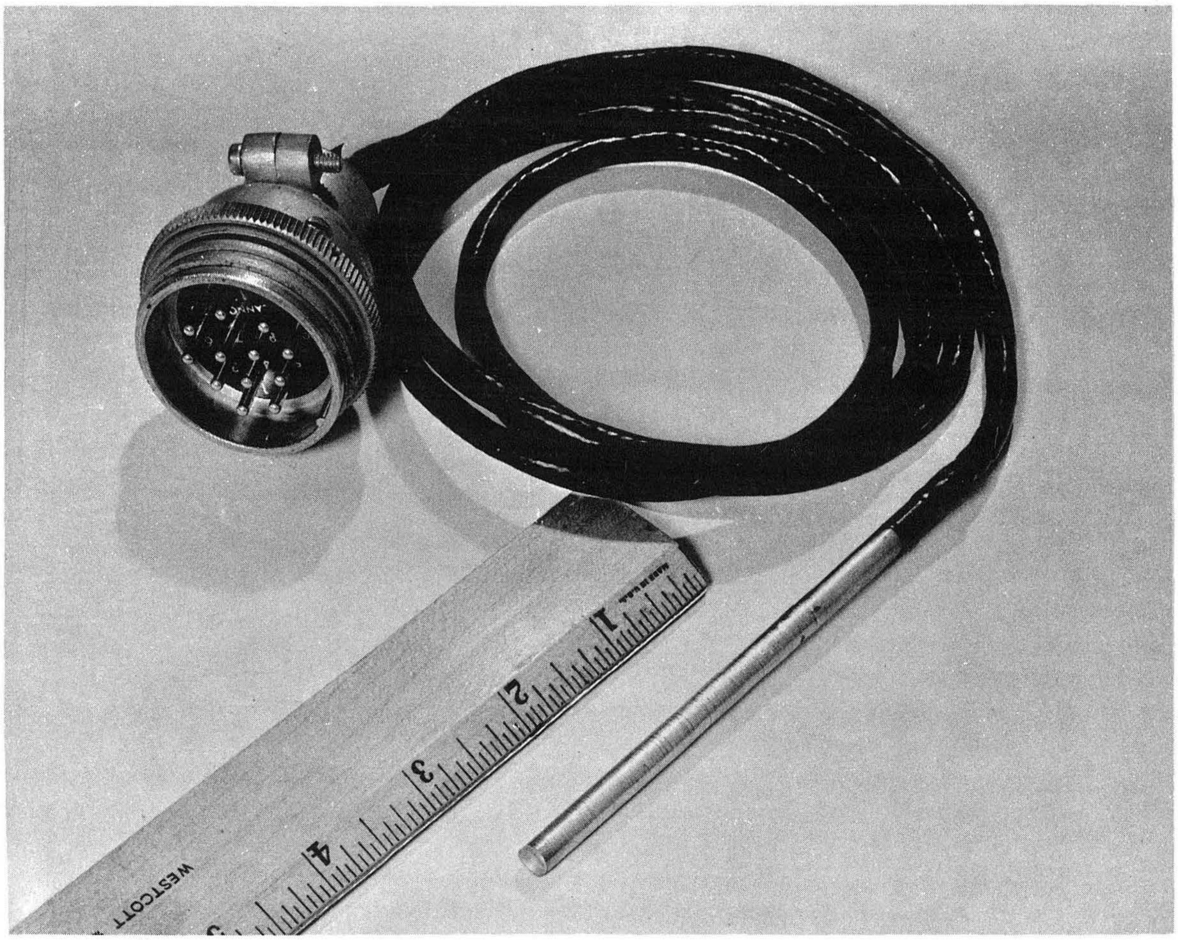

Fig. 5.

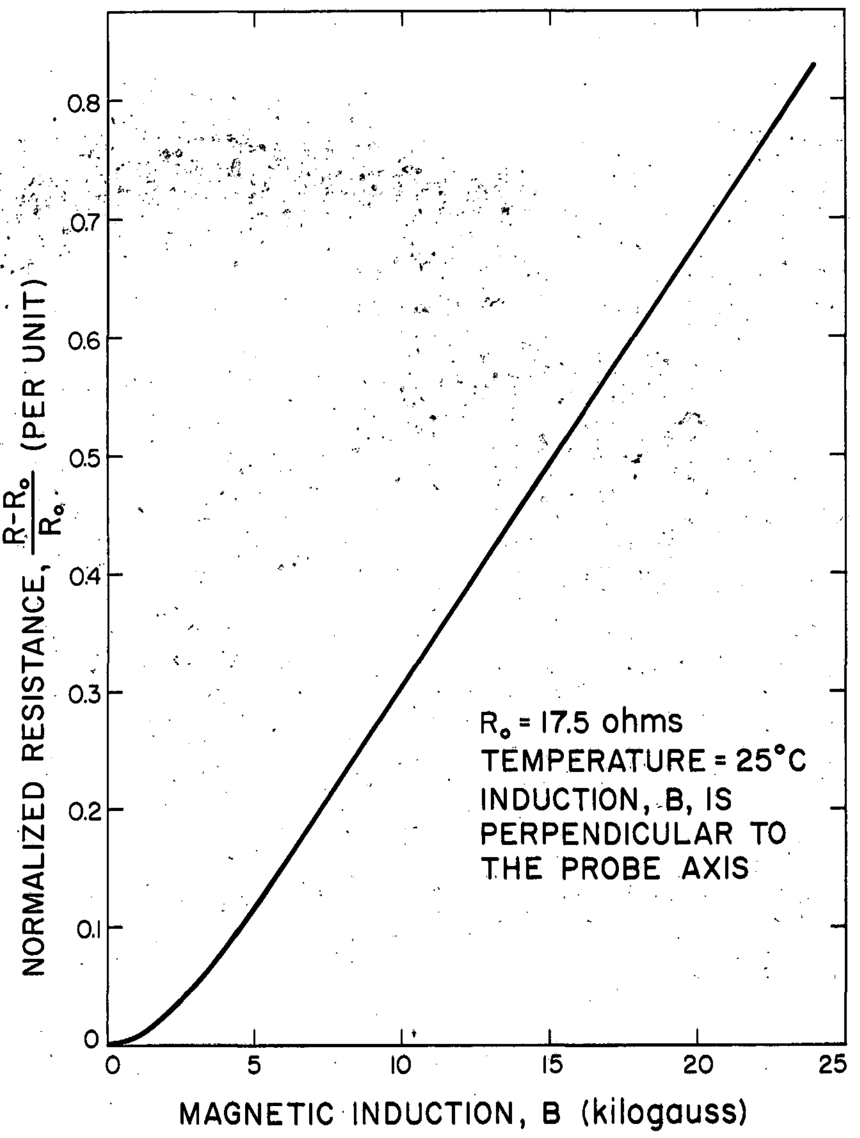

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Fig. 6.