CHARACTERISTICS OF STANDARD CARBON RESISTORS AT HELIUM TEMPERATURES AND THEIR DEPENDENCE ON THE MEASURING CURRENT INTENSITY

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Systematic measurements of the effect of the intensity of the measuring current on the characteristics of five standard carbon resistors used as secondary resistivity thermometers in the helium temperature range (1.74-4.24°K) were carried out.

A method is proposed for determining the admissible intensity of the measuring current.

The electric resistivity of standard carbon resistors varies sharply with the temperature, especially in the range of helium temperatures. Subsequent to scaling *e.g.* by helium vapour pressure, such carbon resistors are frequently employed as secondary, resistivity thermometers. It will be remembered that scaling in this case consists in determining the resistivity-temperature characteristics $R = f(T_{He})$, where R is the resistivity in Ohms and T_{He} the absolute temperature of the helium bath. In the process of scaling resistivity carbon thermometers, however, it was found that the intensity of the measuring current should not exceed a specific, admissible value, to be denoted as I_{adm} (Clement and Quinnel 1952, Berman 1954, 1958); otherwise, a rise in the measuring current intensity (at constant temperature of the helium bath T_{He}) is accompanied by an increase in the temperature of the thermometer lowering its electric resistivity. The rise in temperature of the carbon thermometric element with respect to that of the bath is due to Joule's heat being produced in the carbon resistor (Clement and Quinnell 1952). Berman (1954, 1958) was even able to measure the rise in temperature of the carbon sample *versus* the energy produced in it per unit time. His formula allows to obtain the rise in temperature dT of the carbon resistor as a function of the power produced

$$dT = \frac{dP}{20aK\pi}.$$

Herein, dP is the increase in power produced in the resistor and raising its temperature by the amount dT, a — the radius of the resistor's cylinder and K — the coefficient of thermal conductivity of the material of which the resistor is made.

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Thus, the rise in temperature of a thermometer resistor can be determined from the thermal conductivity of the material. This procedure of determining the admissible power, however, fails to take account of the thermal resistivity of the outer shield. As a matter of fact, resistors are commonly used of which hardly anything is known. This is especially true of homemade resistor elements produced in a laboratory. We accordingly undertook to investigate systematically the effect of the intensity of the measuirng current on the characteristics of standard carbon resistors of which we assumed that nothing was known as to their parameters as certified by their makers. By investigating such resistors we hoped to verify to what extent it is possible to determine the admissible intensity of the measuring current by a purely empirical procedure.

In order to collect more experimental data, two cylindrical carbon resistors made by Allen-Bradley, Co., two cylindrical resistors from Speer Resistor Co. of Bradford and one resistor made by a British firm were investigated.

Accordingly, their characteristics were found to be the following:

Specimen A (Allen-Bradley): $R_{300} = 475\ \Omega$, $R_{4.2} = 920\ \Omega$, $l = 9.5$ mm, $2a = 4$ mm

Specimen B (Allen-Bradley): $R_{300} = 475\ \Omega$, $R_{4.2} = 920\ \Omega$, $l = 9.5$ mm, $2a = 4$ mm

Specimen C (Speer-Resistor): $R_{300} = 110\ \Omega$, $R_{4.2} = 510\ \Omega$, $l = 9.8$ mm, $2a = 4$ mm

Specimen D (Speer-Resistor): $R_{300} = 110\ \Omega$, $R_{4.2} = 510\ \Omega$, $l = 9.8$ mm, $2a = 4$ mm

Specimen E (a British firm): $R_{300} = 27\ \Omega$, $R_{4.2} = 175\ \Omega$, $l = 9.0$ mm, $2a = 3.5$ mm

R_{300} stands for the resistivity at 300°K, $R_{4.2}$ for that at 4.2°K, l for the lenght of the resistor and a for its radius.

Specimens A, B, C, D were prepared as resistivity thermometers, *i.e.* they were covered with a layer of *БФ*-2 adhesive and windings of insulated copper wire whose terminals commonly serve as thermometer leads. Specimen E was left in the form of a usual radio-set resistor with no additional coating.

Measurements of the electric resistivity of the carbon specimens *versus* the temperature of the helium bath (in which they were immersed fully) were effected at various intensities of the measuring current. The temperature of the bath, T_{He}, was determined to within no better than 0.05°K from measurements of the helium vapour pressure. To check the reproductibility of the readings from the resistor carbon elements used, 3-4 series of measurements were carried out at intervals of several days. Thus, each series of measurements involved consecutive raising the temperature of the specimen to room temperature and cooling it once more to that of liquid helium. The results of the measurements of the characteristics $R = f(T_{He})$ are given in Figs 1-5.

The resistivity-temperature characteristics were determined at four values of the measuring current intensity. In the case of the specimens A, B, C, D these amounted to 17×10^{-7}, 17×10^{-6}, 17×10^{-5} and 3×10^{-4} A whereas in that of specimen E to 50×10^{-7}, 50×10^{-6}, 25×10^{-5} and 50×10^{-5}A.

From the graphs of $R = f(T_{He})$ in Figs 1-5, the divergences as between the intensities 10^{-7} and 10^{-6} A are but insignificant. At 10^{-5} and 10^{-4} A of the measuring current, the decrease

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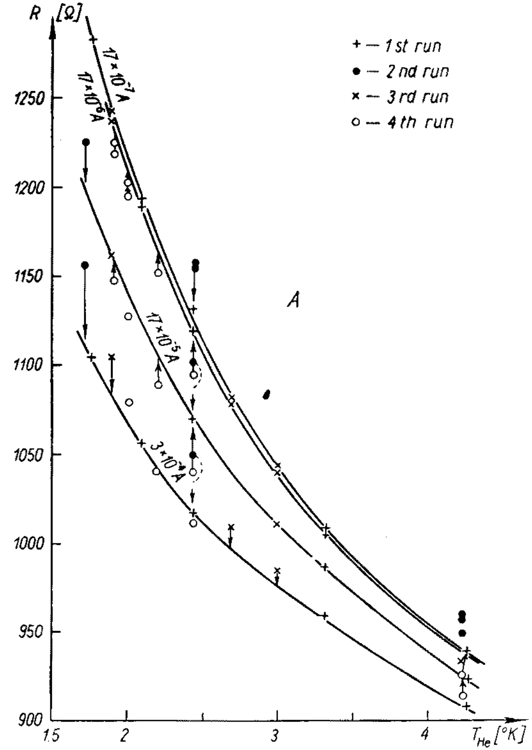

Fig. 1. Characteristics of an Allen-Bradley resistor at various intensities of the measuring current (Specimen *A*): + — first series of measurements, ● — second series, × — third series, ○ — fourth series

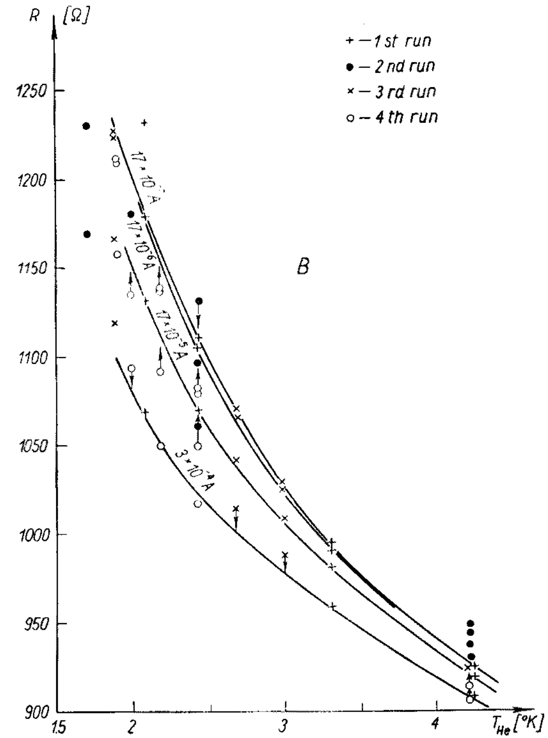

Fig. 2. Characteristics of an Allen-Bradley resistor at various intensities of the measuring current (Specimen *B*)

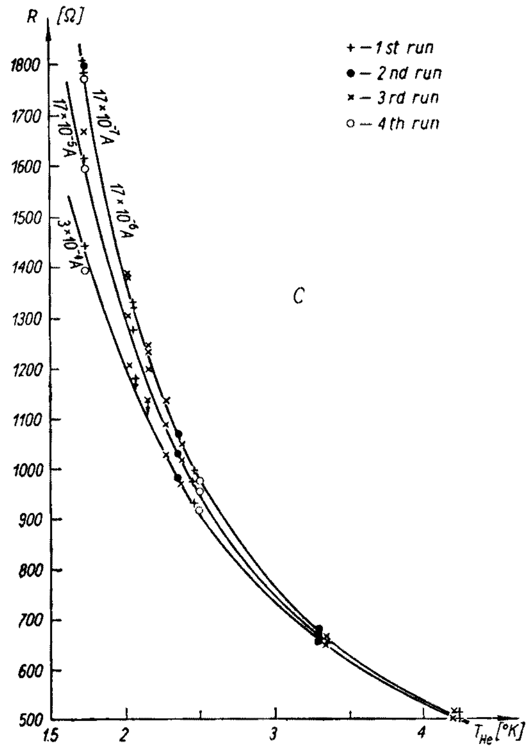

Fig. 3. Characteristics of a Speer-Resistor element at various intensities of the measuring current (Specimen *C*)

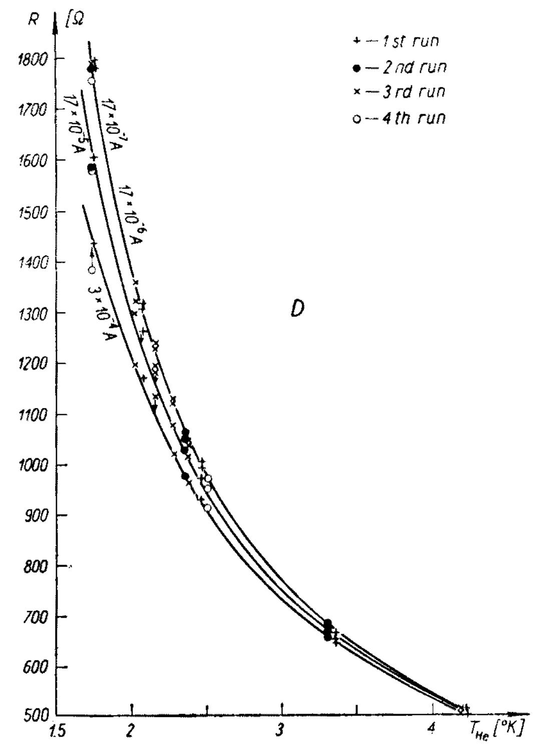

Fig. 4. Characteristics of a Speer-Resistor element at various intensities of the measuring current (Specimen *D*)

in resistivity of the resistor thermometer becomes growingly marked at a given value of T_{He}, owing to the production of Joule's heat. As T_{He} is lowered, the divergences increase. This is reasonable considering that the thermal conductivity of the graphite decreases. Indeed, according to Berman (1958), the thermal conductivity of graphite varies quadratically with the temperature in the liquid helium range: $K \sim T^2$.

Specimens A and B, like C and D, despite their identical parameters R_{300}, $R_{4.2}$, l and $2a$, exhibit differences amounting to several per cent in the shape of their resistivity-temperature characteristics. This happens usually when the specimen is taken out of the cryostat and is kept in atmospheric air. The problem of whether and to what extent these changes may be related to absorption and diffusion of helium or atmospheric gases into the bulk of the resistor (Sujak 1961) must be left open.

To determine how the intensity of the measuring current affects the resistivity of the specimen immersed in the helium bath of constant temperature, graphs of $R = f(\log I)$, the resistivity *versus* the logarithm of the measuring current, were plotted for various temperatures T_{He} of the bath. These are shown in Figs 6-10. Qualitatively, the graphs are seen to resemble one another for all the specimens investigated. A critical intensity of the current is seen to exist on exceeding which the effect of Joule's heat becomes clearly measurable. From Figs 6-10, with lower temperatures of the helium bath T_{He}, the admissible intensity of the measuring current at which Joule's heat is still insufficient for producing a measurable change in the resistivity of the specimen decreases. From these graphs, it is moreover possible to deduce the value of the difference between the mean temperature of the volume of the cylindrical carbon resistor and that of its surface. Thus *e.g.* when a measuring current of 3×10^{-4} A flows through specimen A (Fig. 6) immersed in a helium bath of temperature $T_{He} = 1.76$°K, the mean temperature of the specimen assumes a value that is higher than 2.5°K. Specimens C and D (Figs 8 and 9) exhibit smaller differences in temperature along the radius of the cylinder. Thus, a current of 3×10^{-4} A flowing through specimen C (Fig. 8) immersed in liquid helium at 1.74°K raises the mean temperature of the specimen to about 2°K. This is *i.e.* probably due to the smaller thermal resistivity of the outer coating of the specimen. In specimen E (Fig. 10), a current of 3×10^{-4} A produces a difference in temperature that is still smaller.

The curves of Figs. 6-10 allow to determine graphically the admissible intensity of the measuring current in its dependence on the temperature of the helium bath. The critical values of the measuring current for the various specimens are plotted in Figs 11-13 *versus* T_{He}. From the graphs of $I_{adm} = f(T_{He})$ for specimens A and B (Fig. 11), these differ strongly notwithstanding the fact that they belong to specimens having identical parameters R_{300} and $R_{4.2}$ (except for the coating, which is not subjected to control) and identical geometry. This would point to a considerable difference between the thermal resistivity of their respective surface insulating layers on the reasonable assumption that the two specimens do not differ greatly as to their thermal conductivity. The values of the electric conductivity of resistors A and B are much the same (differing by no more than several per cent). When immersed in the helium bath, the admissible measuring current intensity I_{adm} of specimen A amounts to 26×10^{-6} A at 2°K and 70×10^{-6} A at 4°K, whereas that of specimen B — to 34×10^{-6} A and 100×10^{-6} A, respectively (Fig. 11).

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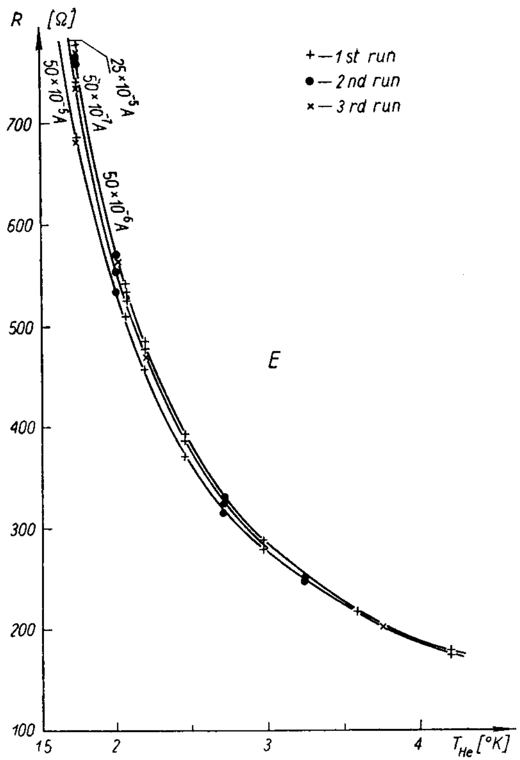

Fig. 5. Characteristics of the resitsor produced by a British firm, at various values of the measuring current (Specimen E)

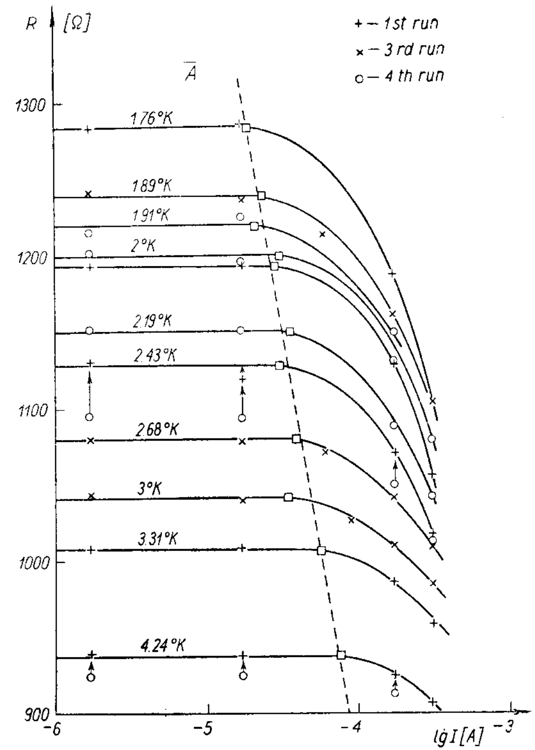

Fig. 6. The electric resistivity of the resistor *versus* the logarithm of the measuring current intensity, at various temperatures of the helium bath T_{He} — Specimen A; □ represent the graphically determined points corresponding to the maximum value of the measuring current intensity at which no measurable change in the specimen's resistivity appeared

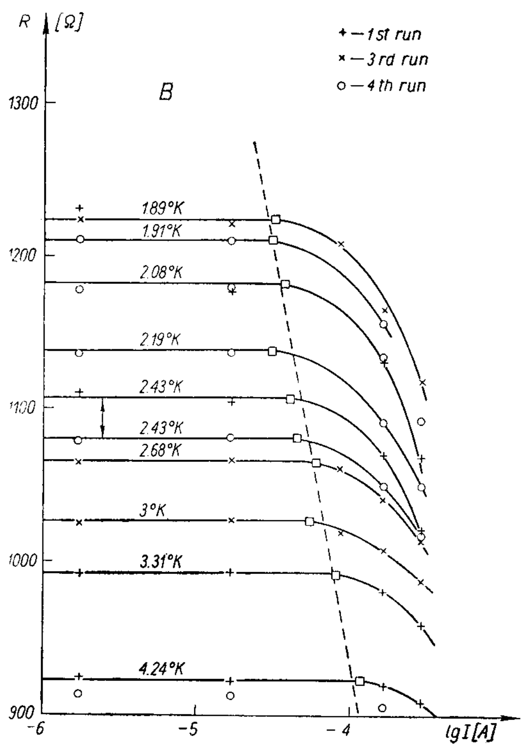

Fig. 7. The electric resistivity of the resistor *versus* the logarithm of the measuring current intensity, at various temperatures of the helium bath T_{He} — Specimen B; □ are the graphically determined points corresponding to the maximal measuring current intensity at which no measurable change in the specimen's resistivity occurs yet

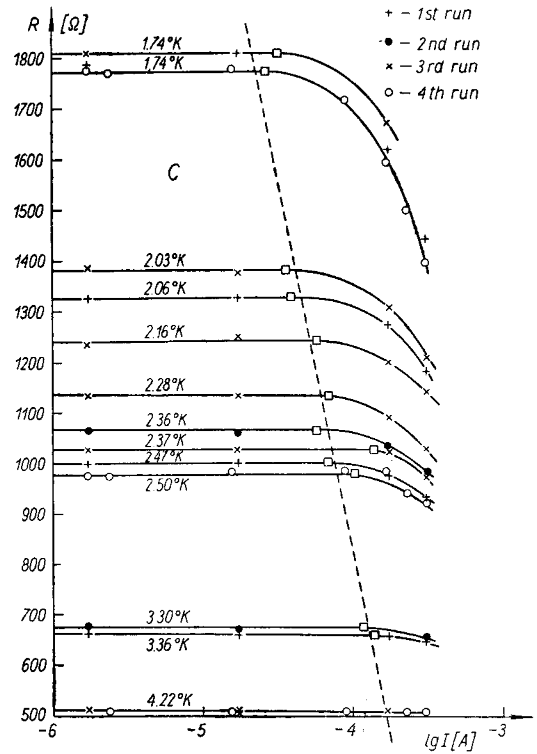

Fig. 8. The electric resistivity of the resistor *versus* the logarithm of the measuring current intensity, at various temperatures of the helium bath T_{He}, for Specimen C; □ denote the graphically determined points of the maximum measuring current intensity producing as yet no measurable changes in the specimen's resistivity

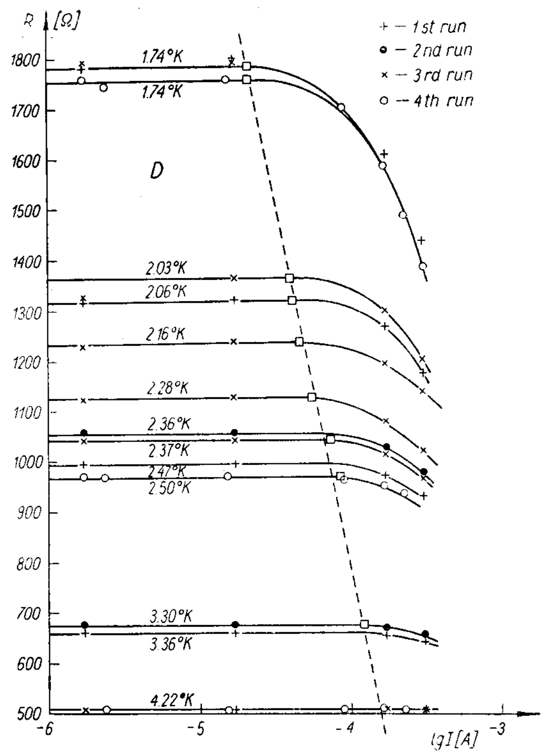

Fig. 9. The electric resistivity of the resistor *versus* the logarithm of the intensity of the measuring current, at various temperatures of the helium bath, T_{He}, for Specimen D; □ are the graphically determined points of the maximum intensity of the measuring current still leaving measurably unchanged the resistivity of the specimen

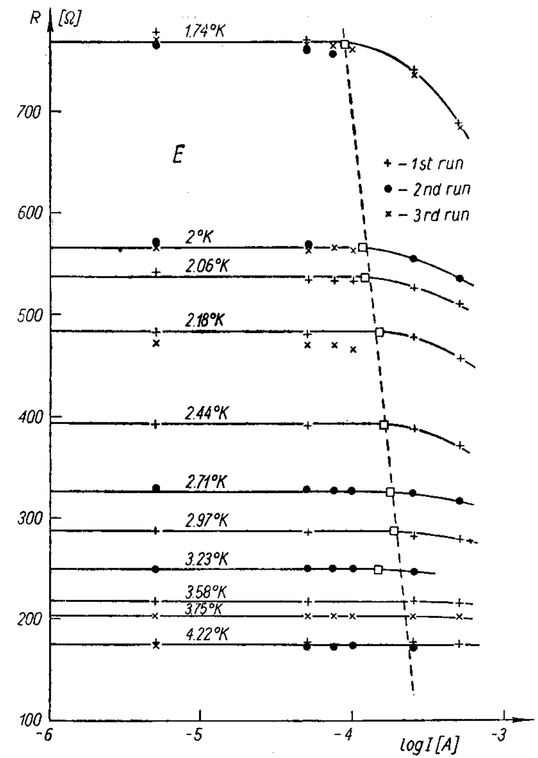

Fig. 10. The electric resistivity of the resistor *versus* the logarithm of the measuring current intensity, at various temperatures T_{He} of the helium bath, for Specimen E; □ stand for the graphically obtained points corresponding to the maximum value of the measuring current at which no measurable change is still discernible in the specimen's resistivity

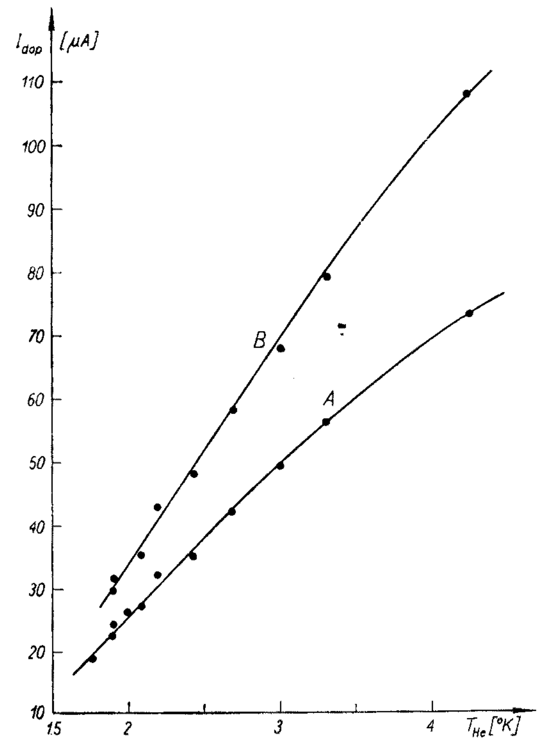

Fig. 11. Admissible maximum intensity of the measuring current, I_{adm}, as *versus* the temperature T_{He} of the helium bath, for Specimens *A* and *B* ($I_{dop} \equiv I_{adm}$)

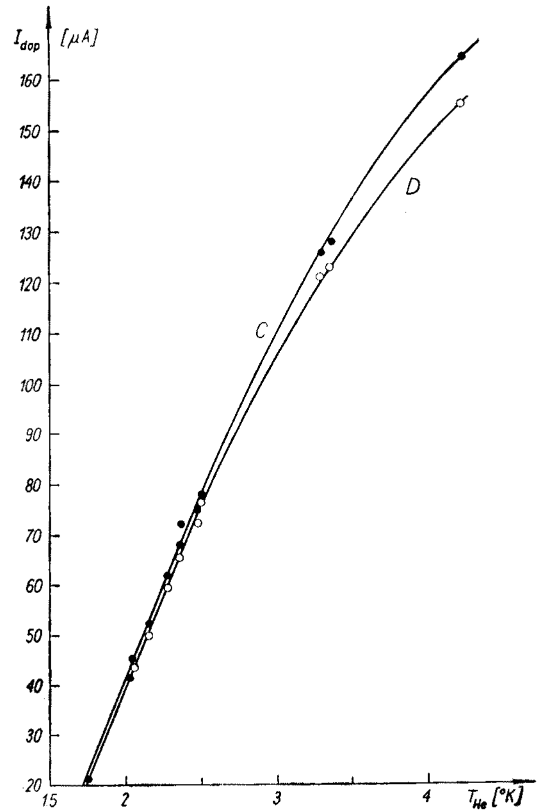

Fig. 12. Admissible maximum intensity of the measuring current, I_{adm}, *versus* the temperature T_{He} of the helium bath, for Specimens *C* and *D* ($I_{dop} \equiv I_{adm}$)

The respective admissible measuring current intensities for specimens C and D and the respective temperatures of the bath are shown in the graphs of Fig. 12. The fact that the latter resemble one another points to the same thermal resistivity of the insulating layer of the carbon resistors marked C and D. The admissible current intensity of either, at 2°K, amounts to about 40×10^{-6} A, whereas at 4°K it amounts to 158×10^{-6} A in specimen C and to 150×10^{-6} A in specimen D.

Fig. 13 gives $I_{\mathrm{adm}} = f(T_{\mathrm{He}})$ for specimen E. In this case, I_{adm} amounts to about 120×10^{-6} A for 2°K and to as much as approximately 230×10^{-6} A for 4°K. Hence, specimen E is seen to present a distinctively high value of the admissible measuring current. This is most probably due in the first place to the low thermal resistivity of the outer layer of the cylindrical resistor. Maybe another reason for this resides in the higher value of the

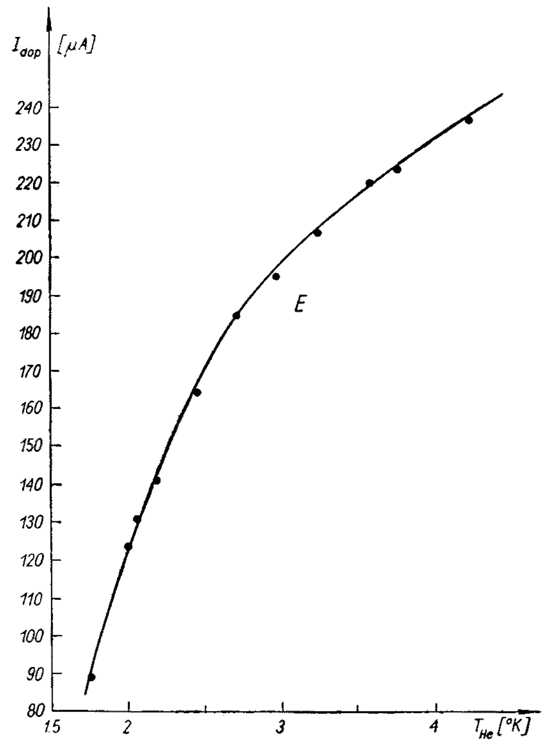

Fig. 13. Admissible maximum intensity of the measuring current, I_{adm}, *versus* the temperature T_{He} of the helium bath, for Specimen E ($I_{\mathrm{dop}} \equiv I_{\mathrm{adm}}$)

thermal conductivity of the material itself. The problem of the extent to which the measurement of the resistivity of a carbon (in general: a semiconductor) specimen at a measuring current exceeding I_{adm} allows to determine its coefficient of thermal conductivity K will be dealt with in a separate paper (Rafałowicz, in preparation).

Finally, it should be stated that the temperature dependences were determined with an accuracy of the order of 0.05°K. However, this is of hardly any importance to the problems under consideration.

On the other hand it is noteworthy that the method of determining I_{adm} and the effect of I_{adm} on the resistivity-temperaturecharacte ristics of carbon resistors destined for temperature determination based on the measurement of the resistivity, as proposed by the present authors, is a more highly direct and competent method than the computational method proposed by Berman (1958), since when applying the latter one has to assume that the thermal conductivity of graphite is known and no account is taken of the thermal properties of the outer layer. This layer usually differs from one resistor (thermometric element) to another, according to the technique used in producing it. Hence, it is hardly possible to predict the thermal properties of that layer.

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