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Thermal time constants of several Allen Bradley resistors immersed in liquid helium

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The thermal relaxation time constant of several Allen Bradley-type resistors used in low-temperature thermometry are reported. The results indicate that thermal diffusion within the carbon composite controls this characteristic time and that it is independent of surface heat transfer. A simple formulation based on published data shows that the proper functional form and magnitude are predictable. It is most probable that these results can be used to estimate the time constant for resistors of other dimensions. The results confirm that the most effective method for decreasing the thermal time constant of carbon composition resistors is by reducing their thickness.

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The most common method for temperature measurement in the range of liquid helium is that of resistance thermometry because of high sensitivity and adequate reproducibility. Standard carbon radio resistors (trade name Allen Bradley[1]) work effectively as uncalibrated temperature sensors between 1 and 20 K because of low cost and rugged nature. For measurements where temporal response of the resistor is important, one sometimes grinds the resistor into a thin sheet.[2] This approach provides two advantages: it exposes the carbon reducing the thermal resistance due to surface coatings, and it reduces the volume of the resistor and thus, the total heat capacity.

The thermal time constants of four Allen Bradley resistors have been measured. The nominal characteristics of all resistors are listed in Table I. AB_1 was a standard 100-Ω 1/8-W Allen Bradley resistor in "as received" condition. AB_2 and AB_3 were ground flat with an abrasive sandpaper. AB_4 was fabricated by grinding most of the insulation from the original resistor and encapsulating the remainder in a high-purity copper tube of 2.0-mm o.d.

To measure the thermal time constant of the resistors, a pulse self-heating technique was employed. A schematic of the circuit configuration is shown in Fig. 1. The pulse generator is biased with a small dc offset ($V < 100$ mV) which provides the current for the resistance measurement. The voltage across both the standard resistor and the Allen Bradley are input into separate channels of a digital signal recorder (Biomation). The signal recorder is output into a data-acquisition system which computes the resistance on a point-by-point basis. The result of this calculation is a normalized plot of resistance (Allen Bradley) versus time over an interval spanning the time the pulse is applied. The time constant is then determined by a linear fit on a semilog plot.

The summary of the measured time constants is given in

TABLE I. Characteristics of four Allen Bradley resistors.

	AB_1	AB_2	AB_3	AB_4
Dimensions (mm)	1.58 o.d. (as received)	0.580×1.58 (ground)	0.315×1.58 (ground)	1.0 o.d. in 2.0 o.d. Cu tube
Resistance (Ω) 300 K	100	167	328	100
A (ms/K^n)	5.1	1.7	0.57	3.0
n	0.64	0.65	0.64	1.0
$f = \tau D/a^2$	$0.80T^{0.04}$	$0.83T^{0.05}$	$0.95T^{0.04}$	$0.5T^{0.4}$

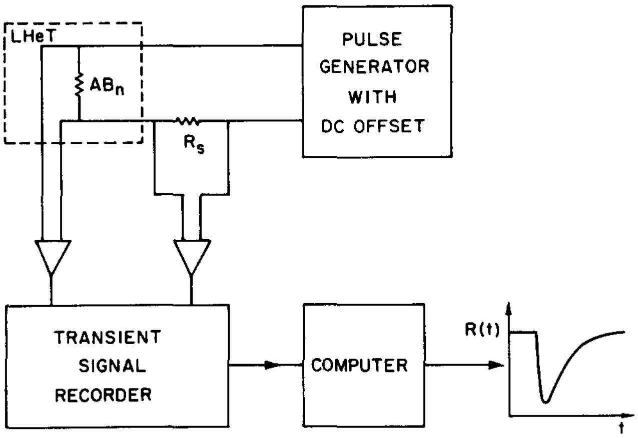

FIG. 1. Schematic of the experimental configuration used to measure the time constant.

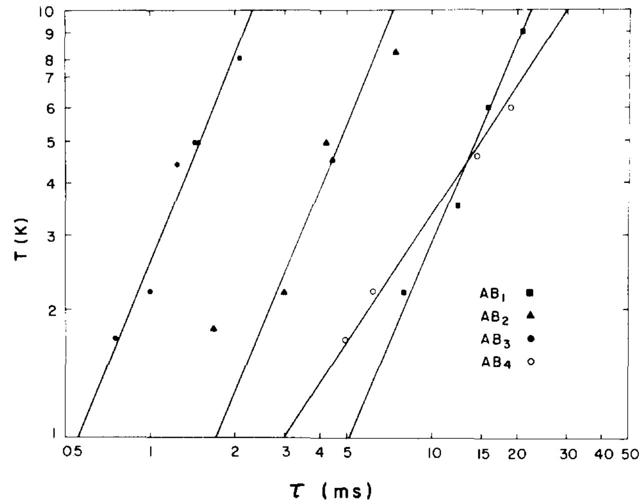

FIG. 2. Temperature dependence of the time constant for the four different resistors.

Fig. 2. For all resistors tested, the linear plot on the log–log scale indicates that within experimental error the time constant may be fit to a general relationship, $\tau = AT^n$, where A and n are empirically determined constants. Listed in Table I are these constants for all four resistors. Two factors should be noted from these results. First, grinding the resistor clearly shortens the thermal time constant. Second, the method utilized for attempting to improve the time constant of AB_4 proved ineffective. For most tests, AB_4 has a time constant within 30% of that for AB_1. It is useful to correlate the form of the thermal time constant in terms of the known properties of Allen Bradley resistors, assuming τ were only dependent on thermal diffusion within the resistor. The heat capacity of a 1/10-W, 116-Ω resistor has been reported to obey a relation similar to that of pure graphite.[3] At temperature above 2 K, where the cubic phonon term dominates,

$$C \cong 4.6T^3 \mu\text{J/cm}^3\,\text{K}, \tag{1}$$

which is normalized to a unit volume of the resistor. The thermal conductivity of Allen Bradley resistors deviates more from that of pure graphite.[4] However, below about 10 K the thermal conductivity can be fit to an equation,

$$K \cong 7.6T^{2.4} \mu\text{W/cm K}, \tag{2}$$

where the magnitude of K varies by at least a factor of 2 between resistors.

Assuming (1) and (2) are reasonably good descriptions of the thermal properties of Allen Bradley resistors and that these properties control the thermal relaxation time, it should be possible to predict τ. The time constant has the form

$$\tau \cong fa^2/D, \tag{3}$$

where $D = K/C$ is the thermal diffusivity and f is a proportionality constant of order unity. The linear dimension a is taken to be the resistor thickness.

The result is to observe that Eq. (3) predicts τ should follow the power law $T^{0.6}$. This is surprisingly close to the experimental dependence observed for AB_1 through AB_3 (see Table I). If we further make an empirical fit to the proportionality factor f for AB_1, AB_2, and AB_3, these quantities are within 20% of each other and almost independent of temperature. Note that it appears that encapsulation of the resistor in the copper tube AB_4 provides no benefit in temporal response for resistors immersed in liquid helium. This fact can be qualitatively understood by the assertion that the time constant is determined by the carbon composite. Although the copper tube serves to distribute any circumferential temperature distribution, it provides little benefit and possibly a detriment in the form of excess heat capacity. AB_4 was found to have a time constant which increases more strongly with temperature than the other resistors, an effect not explained in terms of the above simple diffusion model.

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