

11. Carbon Resistance Thermometers

Carbon resistors are widely used as secondary thermometers at low and very low temperatures. They are very sensitive, their readings depend little on magnetic field, and they are compact and easy to handle. They are stable enough for a 10 mK precision or even better with special care. In every case, one must be cautious of any overheating because the thermal conductance of the sensor is very low.

11.1 Fabrication and Use

Commercial carbon-composition resistors manufactured by Allen-Bradley were introduced as temperature sensors by Clement and Quinnell (1952). Since that time carbon resistance thermometers (CRTs) have been widely used for low temperature applications from about 100 K to below 1 K. Although they are less reproducible than the resistance thermometers described in Part 1, they are exceedingly inexpensive and their small size is advantageous. Since they are selected from mass-produced components for use in electronic circuits, it is not surprising that differences from batch to batch can occur. The carbon composition resistor is a small cylinder consisting of graphite with a binder encased in an outer phenolic shell. Embedded in the phenolic are two opposing copper leads which make ohmic contact with the graphite. The types used as thermometers are generally characterized by their room temperature resistance and their wattage [Rubin (1980)], and have come largely from the following manufacturers: Allen-Bradley, Airco Speer (usually referred to simply as Speer), Ohmite (prior to 1970, Ohmite supplied Allen-Bradley resistors under their own label. Both had the same characteristics. Thereafter the company distributed Speer resistors.), Matsushita, CryoCal, Physicotechnical and Radiotechnical Measurement Institute (PRMI).

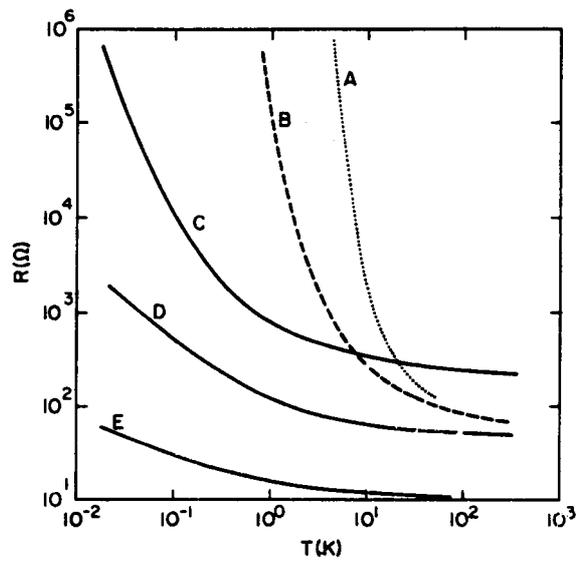
CRTs can be mounted directly as received, but generally the outer epoxy coating is removed and lead contacts are resoldered. The resistor is then inserted inside a tube (a copper tube for example) with grease as a convenient bonding agent. Great care must be taken with these operations because they can have a great influence on the stability of the sensor (see below). Some general recommendations for the use of a CRT are: do not modify the electrical contacts once they are soldered; do not heat the resistor excessively during the connection of the leads; protect the resistor from high humidity and solvents; cool it slowly; if the resistor is to be used in vacuum, it should be calibrated in vacuum.

11.2 Resistance-Temperature Characteristics and Sensitivity

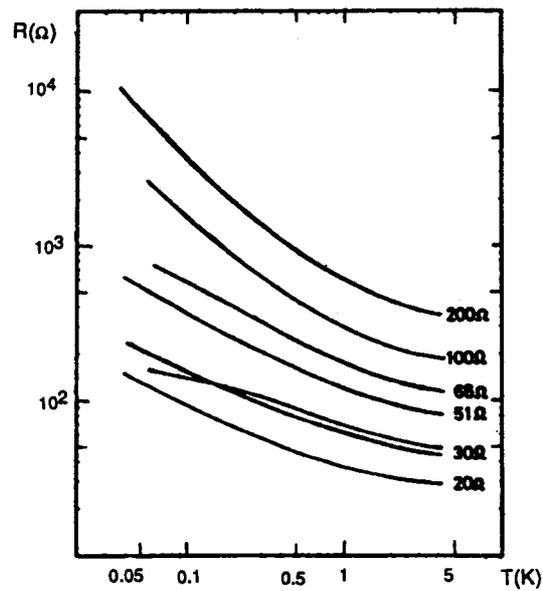
The resistance of a CRT increases roughly exponentially (Fig. 11.1) and the sensitivity increases smoothly (Fig. 11.2) with decreasing temperature. The resistance of a typical unit will be roughly 1 k Ω at 1 K. The nominal resistance value $R(300\text{ K})$ determines the temperature range of use; the region where the slope of the R-T curve becomes very steep shifts towards higher temperatures for higher values of $R(300\text{ K})$, and at any given temperature, the smaller the value of $R(300\text{ K})$, the smaller the sensitivity $(dR/R)/(dT/T)$. This characteristic is independent of the size (wattage) of the unit provided that $R(300\text{ K})$ is the same, although significant differences are often found between units that are nominally the same but come from different batches, even from the same manufacturer. Thus interchangeability of units is not possible, or otherwise, because the cost is small, it is recommended to purchase all resistors that will be needed for a given application at the same time [Anderson (1972), Ricketson (1975), Kopp and Ashworth (1972), Kobayasi et al. (1976)].

Baking a resistor for a short time ($\sim 1\text{ h}$) at a relatively high temperature ($\sim 400\text{ }^\circ\text{C}$) modifies its R- T characteristic. For example, baking a 100 Ω Matsushita unit at 375 $^\circ\text{C}$ in argon for one hour reduces R by a factor of three [Steinback et al. (1978)]. The sensitivity and (mainly) $R(300\text{ K})$ are reduced while the general behaviour remains unchanged. Thus, one can adjust the sensitivity of a thermometer by annealing. This can be advantageous since a lower slope at low temperatures means a wider useful range of temperature for a given sensor, without the resistance becoming prohibitively high [Anderson (1972), Johnson and Anderson (1971)]. On the other hand, any local heating of the thermometer, even for short periods, such as when soldering new electric contacts, will irreversibly alter its characteristic and necessitate recalibration.

Heating of the resistor can arise from [Oda et al. (1974), Hudson et al. (1975)] the measuring current (Joule effect), vibrations, spurious emfs, thermal conduction along the leads, residual gas in the cryostat, thermal radiation, and radio frequency pickup. In the latter case, heating of 10^{-10} W is easily introduced below 1 K by switching circuits, digital equipment, noise from power supplies enhanced by ground loops, etc. The problem becomes much more serious as the temperature is reduced. Shields and filters are effective in reducing the heat leak to 10^{-15} W but caution is needed to avoid interference with the resistance measurement if an ac technique is used.



a)



b)

Fig. 11.1: Resistance-temperature characteristic for several commercial resistors: (a) A, thermistor; B, 68 Ω Allen-Bradley; C, 220 Ω Speer (grade 1002); D, 51 Ω Speer (grade 1002); E, 10 Ω Speer (grade 1002) [Anderson (1972)]; (b) various nominal Matsushita carbon resistors of grade ERC-18SGJ [Saito and Sato (1975)].

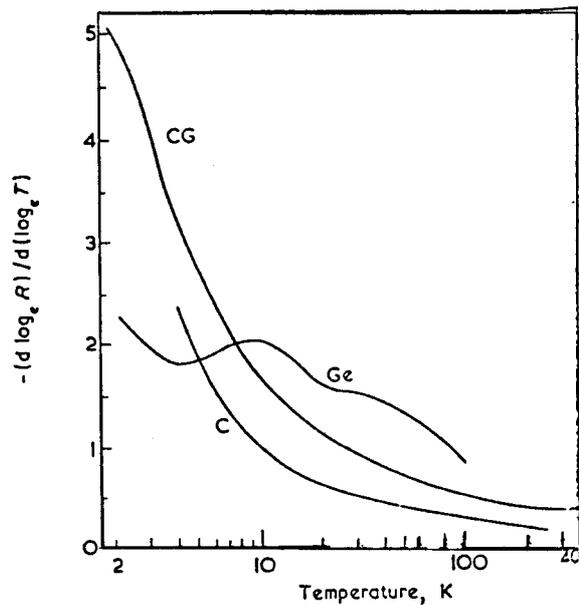


Fig. 11.2: Relative sensitivity versus temperature for carbon (C), carbon-glass (CG), and germanium (Ge) thermometers [Swartz and Swartz (1974)].

11.3 Thermal Contact

Providing good thermal contact is one of the main problems that limits the usefulness of carbon resistors. The heat dissipated in the sensor must flow to the surroundings without causing a relative temperature rise greater than $\Delta T/T \approx 10^{-3}$. At 1 K, for a 220Ω Speer resistor for example, the maximum power dissipated in the CRT must remain smaller than 10^{-7} W for a 1% accuracy in the measurement.

The thermal boundary resistance between the unit and the environment depends upon the mounting, but is roughly 10^{-2} K/W for an area of 10^{-4} m².

Different thermal grounding techniques have been proposed [Polturak et al. (1978), Johnson and Anderson (1971)]. Thermally grounding the resistor via its leads only is not recommended. It is important to bind the unit with a copper housing that is thermally anchored to the device to be studied, with grease, stycast, varnish or other equally good agent. The paint used for color coding the resistor should be removed because it may loosen after several thermal cycles.

11.4 Response Time

The thermal response time of a CRT is short; some typical values are given in Table 11.1. Longer time constants (up to tens of minutes) can be observed if the copper

Table 11.1: Typical Time Constants, τ , for a Carbon Resistance Thermometer [Linenberger et al. (1982)].

Temperature	4.2 K		77 K	
	$\tau(\text{ms})$		$\tau(\text{ms})$	
Environment	Liquid	Vapour	Liquid	Vapour
Type of Sensor				
AB 1/8 W 220 Ω	6	7	113	7276
AB 1/2 W 220 Ω	30	31	426	3290

leads are not thermally grounded. Grinding the resistor clearly shortens the thermal time constant. Also, to improve time response, attempts have been made to use carbon thin films deposited on different substrates. Time constants approaching 0.42 ms at 4.2 K have been achieved [Bloem (1984)]. :

11.5 Influence of External Factors

a. Pressure

CRTs are only slightly dependent upon pressure [Dean and Richards (1968) and Dean et al. (1969)]; a typical value for the pressure dependence is $\Delta R/R \sim -2 \times 10^{-9} \text{ Pa}^{-1}$.

b. Radiation

CRTs are relatively insensitive to nuclear irradiations. After long exposure to gamma rays and fast neutrons, changes observed in resistance were less than 1 % at 20 K [NASA (1965)].

c. Humidity

CRTs are very sensitive to humidity. The nominal resistance value $R(300 \text{ K})$ increases by 5 to 10% after the resistor has been soaked for 240 h at 95% humidity [Ricketson (1975)]. Since $\Delta R/R$ is about the same at 77 K and at 300 K, the indication is that the absorbed water introduces, a temperature dependent resistance, i.e. changes in calibration come from changes in the exponential coefficient. The process is not reversible, but the resistance can be reduced by heating the unit.

d. Magnetic Field

The effects of magnetic fields on CRTs is discussed in Chapter 19.

11.6 Stability and Reproducibility

It is difficult to determine the extent of the repeatability of CRTs. Reports on repeatability vary widely, from ± 1 mK up to 2% change in resistance at 4.2 K. By cycling resistors between room temperature and the temperature of use, it is possible to select units that are stable to within 10 mK. Nevertheless, one must be alert for changes in the R-T characteristic. Provided that they are not mistreated between runs, both Allen-Bradley and Speer units will retain their calibration within about 1 % over a two year span and 30 or 40 thermal cyclings.

When the resistance is monitored at a fixed temperature, a drift with time is observed which is mostly towards higher resistance, giving an apparent reduced temperature. It occurs in all units tested [Ricketson (1975), Johnson and Anderson (1971), Forgan and Nedjat (1981)]. For example, at 77 K, drift rates have been as high as 50 mK/h just after immersion, decreasing to 25 mK/day after a two-day soak. The higher the temperature sensitivity of the unit, the greater the drift in terms of $\Delta T/T$. This means that the problem becomes more serious for a given thermometer as the temperature is reduced. Resistors of the same nominal value and brand exhibited the same drift rates to within about 15%. Therefore, the drift is intrinsic to the resistance material itself and is probably associated with a decrease in carrier concentration.

An increase in the resistance at liquid helium temperature is always observed after the first few thermal cycles (2% for a 1000 Ω Allen-Bradley unit). The phenomenon is associated with carbon granule rearrangement due to thermal shocks. Typically, maximum changes observed for an Allen-Bradley unit of 220 Ω are 13 mK at 4.2 K, 337 mK at 20 K and 2 K at 60 K [Ricketson (1975)]. After nearly twenty thermal cyclings between low temperature and 300 K during two years, the change in resistance of Matsushita units have remained within 1.5% [Kobayasi et al. (1976)]. The observed instabilities can be roughly explained by the thermal history of the unit, remembering the extreme sensitiveness to annealing and thermal heating of a CRT.

Broadly speaking, CRTs are less stable by more than an order of magnitude than germanium thermometers. Considerable improvement might be achieved if the low-cost CRTs were treated with as much care as encapsulated germanium sensors. Nevertheless, it is always wise to check that the resistance has not drifted nor undergone a step change during measurements. Whether a carbon resistance thermometer requires a new

calibration after each cool-down depends upon the accuracy desired. In practice the calibration may be no better than several parts in 10^3 , in terms of $\Delta T/T$, so to obtain a thermometer capable of better reproducibility and stability than this after an arbitrary history, one should choose a unit having lower temperature sensitivity and sacrifice resolution. When recalibration is needed, it may be sufficient to check only a few points and to derive the new calibration curve from the original one.

11.7 Calibration and Interpolation Formulae

The lack of a simple R-T characteristic has limited large scale use of CRTs. Their initial low price is partially offset by the need for individual calibration. One of the advantages of the CRT is its smooth R-T dependence, close to exponential, without any higher-derivative irregularities. Nevertheless, none of the existing interpolation equations are sufficiently exact to allow precise measurement to better than 10^{-3} T over a wide range that includes temperatures above 20 K. Many of the various equations that have been used (summarized by Anderson (1972)) relate $\ln R$ to $1/T$ in some non-linear fashion, with the number of coefficients to be determined by calibration ranging from two to five depending upon the temperature range, the accuracy required, and the type of CRT. For their original empirical equation, which is still widely used

$$\ln R + \frac{C}{\ln R} = A + B/T \quad (11.1)$$

Clement and Quinnell (1952) found an accuracy of $\pm 0.5\%$ in the range 2 K to 20 K when applied to a group of Allen-Bradley resistors. Schulte (1966) found Eq. (11.1) accurate to within several percent for 270 Ω Allen-Bradley resistors over the much wider range from 4 K to about 200 K when the three coefficients were obtained from least-squares fits to four calibrations at the boiling points of helium, hydrogen, and nitrogen, and at room temperature. On the other hand, when applied to some specially constructed resistors, Eq. (11.1) failed by up to 0.25 T, although replacement of the term in $(\ln R)^{-1}$ by one in $(\ln R)^2$ provided an interpolation accuracy of 0.3% from 4 K to 20 K.

Oda et al. (1974) found that Eq. (11.1) also fitted Speer Grade 1002, 1/2 W, 220 and 100 Ω CRTs from 1 K to 0.1 K but below 0.1 K the deviations became large. The equation

$$\ln R = a(\ln T)^2 + b \ln T + c \quad (11.2)$$

fitted the experimental data from 1 K to 30 mK. Similarly, Kobayasi et al. (1976) found that Eq. (11.1) fitted Matsushita ERC 18 SG 1/8 W CRTs from 0.4 K to 4 K, but that Eq. (11.2) provided a better fit over the range 15 mK to 1 K.

It may be more economical in time to proceed to a least-square analysis with a polynomial relationship of the type

$$1/T = \sum_{i=0}^n a_i (\ln R)^i \quad (11.3)$$

It is sufficient for most practical applications to limit the regression to third degree. With 15 to 30 experimental points, Kopylov and Mezhev-Deglin (1974) were able to describe the R-T characteristic of an Allen-Bradley 1/8 W, 40 Ω CRT in the range 1.2 K to 8 K with an error less than the random error of the measurement. For calibrations to higher temperatures, Groger and Strangler (1974) used Eq. (11.3) with index i running from -1 to 3 and calibration at five temperatures and found a maximum error in computed temperatures of ± 1.5 mK at 4.2 K, ± 20 mK at 20 K, ± 80 mK at 77 K, and ± 400 mK at 190 K.