

5. Rhodium-Iron Resistance Thermometers

Rhodium-iron resistance thermometers were developed by Rusby (1972) for use below the normal range of the platinum resistance thermometer. It was found that, of various small concentrations of iron in rhodium, the one that would give the most sensitive and yet moderately linear thermometer was 0.5 atomic percent iron [Rusby (1975)]. Rusby (1982), who uses a group of them at the National Physical Laboratory to carry the primary temperature scale below 30 K, has given a review of ten years of performance. Present suppliers of rhodium-iron thermometers are listed in Appendix C.

5.1 Range of Use and Sensitivity

The range of use is normally from about 0.5 K to 30 K, although the sensitivity is good up to room temperature and at lower temperatures. For a capsule-type thermometer containing helium gas, the lower limit of about 0.5 K is set by the rapidly-increasing self-heating. The normal upper limit (~ 30 K) is in the region where the superior platinum resistance thermometer has adequate sensitivity.

In contrast to pure metals, for which the sensitivity dR/dT decreases steadily with decreasing T at small values of T , the sensitivity of rhodium with about 0.5% iron impurity is relatively constant at about $0.4 \Omega/K$ down to 100 K, decreases to $\leq 0.2 \Omega/K$ near 25 K, then increases rapidly by about a factor of 10 as T decreases to 0.5 K as illustrated in Fig. 5.1 for a thermometer with an ice-point resistance of 100 ohm. The industrial type has a sensitivity about 6% lower than the standard type. It is in this low temperature region of increasing sensitivity that rhodium-iron has its chief application. The rapid change in sensitivity in the low temperature region means that, to obtain a precision of 1 mK at 30 K, the rhodium-iron resistance must be measured to 1 part in 10^5 , compared to 10 in 10^5 for platinum. Because the rhodium-iron resistance is much higher, however, the voltage sensitivity at 30 K is higher than for platinum. The sensitivity of rhodium-iron is much lower than that of germanium.

5.2 Fabrication

The standard-type thermometer of H. Tinsley and Co., Ltd. (U.K.) is constructed as follows: the 0.05 mm diameter wire is wound in the form of coils inside four glass tubes which in turn are encapsulated in a 5 mm diameter platinum sheath as shown in Fig. 5.2. The sheath contains helium at about 1/3 atmosphere pressure. The leads are 0.3 mm

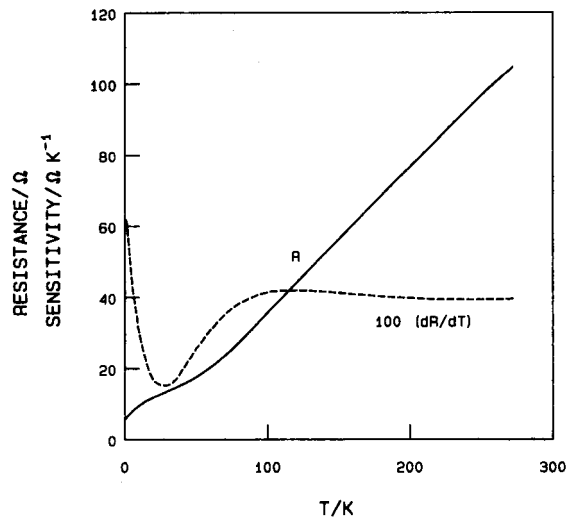


Fig. 5.1: Resistance (Ω) and sensitivity, $dR/dT(\Omega/K)$, of a type 5187W rhodium-iron resistance thermometer [after Rusby (1982)].

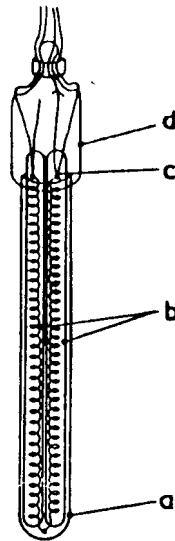


Fig. 5.2: Construction of a rhodium-iron thermometer of the high precision type. The coil of wire is mounted inside four glass tubes, two of which are shown, b; the assembly is inserted into a platinum sheath, a; 4 platinum leads are flame-welded to the rhodium-iron wire, c; the sheath and the leads are sealed in an atmosphere of helium by a glass bulb, d; [after Rusby (1975)].

platinum wire and the element is so mounted as to be strain free. Two versions are available: one (type U) has about 50Ω resistance at 273 K, is 27 mm long, with overall length including a glass seal around the leads of 45 mm; the second (type W) has about twice the resistance and is about 15 mm longer. The 50Ω thermometer has a resistance of about 3.5Ω at 4.2 K.

Oxford Instruments Ltd. supplies two industrial types: Type R3 ($R(0^\circ\text{C}) = 20 \text{ ohm}$) is mounted in a vented stainless steel body, 25 mm long and 3.2 mm in diameter. In type R4 ($R(0^\circ\text{C}) = 27 \text{ ohm}$) the coil is mounted in four cylindrical chambers of an alumina body 22 mm long and 3.2 mm in diameter. Inside each of these chambers is a layer of a very high temperature glass that bonds a part of each loop of the alloy coil to the alumina body. The latter model is intended for use from cryogenic temperatures up to 700°C .

More recently Cryogenic Consultants Ltd. have achieved success in producing thin-film rhodium-iron thermometers [Barber et al. (1987)]. The thermometric material is sputtered on to a sapphire substrate. For films between $0.5 \mu\text{m}$ and $1.0 \mu\text{m}$ thick the sensitivity is similar to or slightly higher than that of wire-wound thermometers, and variation of resistance with temperature is very similar to that for wire-wound thermometers. Thinner films have lower sensitivities. Ice-point resistances are in the same range as those of wire-wound units. Thin-film thermometers are now available commercially.

5.3 Reproducibility and Stability

More than ten years of study have shown that rhodium-iron thermometers have excellent long term stability. For the standard-type, Rusby (1982) reports that for five thermometers, after at least 50 cycles between 273 K and 20 K, the average shift was 0.2 mK and the largest 0.35 mK (in 8.5 years). The latter corresponds to a resistance change of $60 \mu\Omega$ or 5 parts in 10^6 of the resistance. At 4.2 K no shifts larger than $\pm 0.05 \text{ mK}$ were observed. This is at the level of uncertainty of the measurements themselves. Also for the standard-type, Besley (1982) describes similar excellent performance: 9 thermometers were cycled 30 times from 293 K to 6 K and 8 were completely stable; the ninth showed only a small change $< 0.1 \text{ mK}$ at 6 K and 1 mK at 90 K).

Only a limited amount of information is available on the stability of the industrial type. Besley (1984) examined three of the ceramic-type units. After 20 cycles between 20 K and room temperature, stability was almost within the precision of the measurements, i.e. $1 \pm 0.3 \text{ mK}$. However, handling (such as by repeated soldering of the

thermometer wires) caused a more remarkable change of resistance, equivalent to as much as 3 mK at 2.1 K and 16 mK at 30 K. This apparently was due to relief of strain in the wire and seems to limit the stability of this model.

A limited number of thermal cycling tests on thin-film thermometers indicate that stability to within ± 2 mK is achieved after about 15 cycles between room temperature and 4.2 K, about twice the number of cycles as required for the wire-wound industrial type [Barber et al. (1987)].

5.4 Self-heating

Self-heating has been found to be closely the same for both U and W standard-type thermometers; its magnitude is shown in Fig. 5.3 for currents of 0.1 and 0.3 mA. Near 1.5 K the self-heating falls dramatically as the ^4He filling of the capsule condenses to superfluid liquid and thermal contact is vastly improved. As the temperature further decreases, self-heating rises rapidly again. Self-heating in thin-film thermometers is generally smaller than in wire-wound ones.

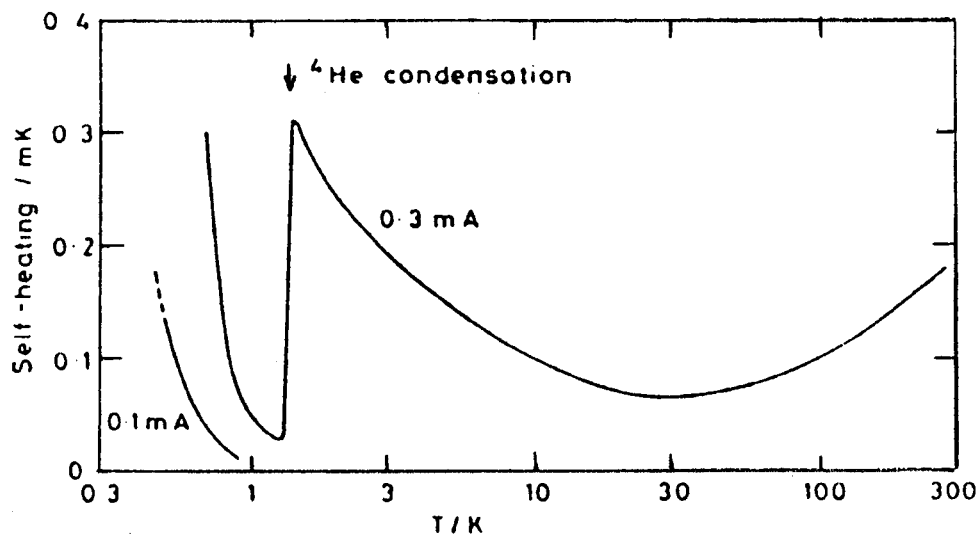


Fig. 5.3: Typical self-heating effect for a ^4He -filled rhodium-iron thermometer with measuring currents of 0.1 mA and 0.3 mA [Rusby (1982)].

5.5 Calibration and Interpolation

A rhodium-iron thermometer is normally calibrated at many points in the range of interest and the data fitted by least squares as described for germanium. The equation chosen is usually of the form

$$T = \sum_{i=0}^n a_i x^i \quad (5.1)$$

where $x = AR + B$, and B and A are origin-shifting and scaling constants respectively that change the range of the independent variable to $-1 \leq x \leq 1$. For a wide range such as 0.5 K to 27 K, $n \sim 10$ is necessary if fitting errors are to be ~ 0.2 mK. For lesser precision or narrower ranges, lower degree can be used - typically $n = 4, 8, 9$ for ranges 0.5 K to 4.2 K, 20 K, 24 K respectively. For temperatures above 27 K, R is usually replaced by $\ln R$ or $\ln Z$ (where Z is defined by Eq. (8.5)) in Eq. (5.1). If a change in calibration occurs, it is possible to account for it by expressing the calibration data in terms of Z with the two calibration points (for Z) near the extremities of the range.

Another equation, requiring fewer calibration points, has been found to fit calibrations of 25 thermometers satisfactorily [Rusby (1982)]:

$$R = \sum_{i=0}^n b_i [\ln(T + \tau)]^i \quad (5.2)$$

For τ of the order of 8 to 10 K, the standard deviation of the residuals is less than 0.3 mK for $n = 6$ and where the points are weighted by dT/dR . Equation (5.2) is of special interest because it allows interpolation in the range from 0.5 K to 25 K using calibrations at a restricted set of easily realizable temperatures - helium vapour pressures, superconductive transitions, and triple and boiling points.

The characteristics of rhodium-iron are such that the constants of the interpolation equation do not vary greatly from thermometer to thermometer from the same batch of wire, in contrast to germanium for which they vary widely from one to another.

From the limited information available on the industrial-type thermometer [Besley (1985)], it appears that the ceramic type may approximate the ITS-90 in the range 77 K to 273 K to within about 10 or 25 mK using a reference function together with a deviation function that requires 2 or 3 calibration points respectively.