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Characteristics of precision 1 Ω standard resistors influencing transport behaviour and the uncertainty of key comparisons

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Abstract

National measurement institutes (NMIs) participate in international key comparisons organized by the Bureau International des Poids et Mesures (BIPM), the Regional Metrology Organizations (RMOs) or the Consultative Committees of the Comité International des Poids et Mesures (CIPM) in order to provide evidence of equivalent reference standards and measurement capabilities. The US National Institute of Standards and Technology (NIST) and the National Measurement Institute of Australia (NMIA) have recently examined power loading and several other influences on the value of precision transportable 1 Ω resistors that can increase the uncertainty of key comparisons. We have studied the effects of temperature, barometric pressure, humidity, power loading and heat dissipation in oil on transportable wire-wound 1 Ω resistance standards that are based on different alloys and construction principles. This work focuses on standards manufactured from 1970 through 2000 by the NMIA made of Evanohm alloy and on Thomas-type resistors designed in the 1930s and made of Manganin alloy. We show that the relative standard uncertainty related to transport can be less than 0.01 $\mu\Omega\,\Omega^{-1}$ when using certain resistors of these two types that are characterized and selected for stability. We describe the characterization process, and relate the environmental influences to the physical design, as well as to the mechanical properties and condition of the standards.

1. Introduction

The quantized Hall resistance (QHR) standard, under proper measurement conditions, provides discrete reference values that were defined in 1990 as the representation of the ohm in the International System of Units (SI) [1]. QHR-based measurement capabilities have been compared in an ongoing direct comparison programme carried out between the BIPM and some national measurement institutes (NMIs) through the use of a transportable QHR system [2–5]. The comparison protocol for this BIPM programme limits the participants to NMIs that have achieved a relative combined standard uncertainty (u_c) $< 0.01\,\mu\Omega\,\Omega^{-1}$ in measurements of the 1 Ω, 100 Ω and 10 kΩ resistance values in terms of the conventional value of the von Klitzing constant, R_{K-90}. These direct comparisons have achieved relative standard uncertainties ($k = 1$) below $u_c = 0.002\,\mu\Omega\,\Omega^{-1}$ in the value of $(R_{lab} - R_{BIPM})/R_{mean}$.

Comparisons of similar uncertainty at the 1 Ω level would help many NMIs improve the traceability of dc electrical resistance, which is used to support thermometry and current measurements. The conventional process of participation in key comparisons using decade-value resistance standards can be time-efficient, relatively inexpensive and highly effective if the instability of the transport standards is less than the majority of the participants' measurement uncertainties. To be fully

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successful in this context, conventional comparison methods depend on the development of an improved understanding of the behaviour of transportable resistors. Transport behaviour in precision 100 Ω resistors was the subject of a study designed to improve the selection of resistance standards for the CCEM.K10 key comparison [6, 7].

The first key comparison for dc resistance was the CCEM-K1 international comparison of 1 Ω and 10 kΩ resistance standards [8] carried out in 1990 under the direction of the CIPM Consultative Committee for Electricity and Magnetism (CCEM). In the CCEM-K1 comparison, each of the 18 participants provided its own transport standards which were compared with like-value standards maintained by the BIPM. In this comparison the relative standard uncertainty associated with the stability of the travelling standards was estimated to be about $0.04\,\mu\Omega\,\Omega^{-1}$. The protocols of some more recent key comparisons, including those of the BIPM, specify using particular artefact standards so that all participants use standards of similar quality. In particular, in 1993–1994 eight members of the Asia Pacific Metrology Programme (APMP) participated in the APMP.EM-K1 regional key comparison of 1 Ω and 10 kΩ resistance standards [9]. In 2006–2007 the Inter-American Metrology System (SIM) conducted SIM.EM-K1 at the 1 Ω resistance level [10] with the participation of six members. The APMP is now developing the protocol for a new RMO comparison at the 1 Ω and 10 kΩ resistance levels.

This paper describes the results of a study on the characteristics and transport behaviour in the two types of 1 Ω resistors that were used in the two RMO comparisons cited above. The APMP.EM-K1 comparison employed standards manufactured by the Australian National Measurement Laboratory (NML), now the NMIA, which were made from the resistance alloy Evanohm[4]. These precision resistors were produced first in the 1970s and redesigned in the early 1990s specifically to improve resistance stability when transported. The SIM.EM K1 comparison employed the Thomas-type resistor, an older but equally important class of resistor because of its wide use as a primary standard in many NMIs. The next two sections describe these two types of 1 Ω resistance standards (section 2) and compare their behaviour in transport (section 3). In section 4 the influences of temperature cycling, pressure and power loading which are likely to affect transport behaviour are probed under laboratory measurement conditions. In most comparisons the laboratory conditions of barometric pressure, temperature and measurement current vary among the participants. Characterization for these effects is valuable for the selection of standards and is required for the analysis of the comparison results.

2. Thomas-type and NML standard resistors

In the 'international-reproducible' system of metrology used from 1893 through 1947 the 1 Ω value of resistance was defined by the mercury ohm, based on the resistance at 0 °C of a column of mercury of specified physical characteristics. Artefact standards in the form of wire-wound resistors at the 1 Ω resistance level were developed extensively in this period for comparison with the mercury ohm and as working dc resistance references. The alloy Manganin, with nominal composition 84% Cu, 12% Mn and 4% Ni [11], was used for a wide range of standard resistors of which many were developed at the German Physikalisch-Technische Reichsanstalt.

Around 1930 at the US National Bureau of Standards (now the NIST), James L Thomas constructed bifilar wire-wound 1 Ω resistors based on the Reichsanstalt design but incorporating thoroughly annealed coils of Manganin wire sealed within double-walled brass containers [12–14]. These used a Manganin alloy that features a broad maximum in the temperature–resistance curve in the range of 25 °C to 30 °C. According to Peterson [15], the desirable resistance maximum near room temperature was obtained by adjusting the iron content of the alloy, which was originally introduced unintentionally as an impurity in the manganese available at the time. Thomas-type resistors were then commercially produced by the firm Leeds and Northrup (model 4210) for more than 40 years. The Thomas-type 1 Ω resistor wire element is sealed in dry air and heat dissipation is provided through contact with the silk-insulated inner brass wall of the enclosure. In order to help maintain the resistor at nearly uniform and constant temperature when in use, the sealed resistor is fully immersed in a temperature-controlled oil bath. Many hundreds of these are still in use in metrology laboratories. Some of the most stable of these resistors date from the 1960s and 1970s.

Compared with Manganin, the Evanohm alloy (with nominal composition 74% Ni, 20% Cr, 2% Al and balance of other elements) has about three times higher resistivity and features a broader region of linearity in its temperature–resistance curve [16]. This alloy is a metastable solid-solution in which the aluminium together with copper, manganese, silicon or other atoms are interstitial and harden the structure. High-temperature annealing produces a linear coefficient of resistance as a function of temperature near $+35 \times 10^{-6}\,{}^\circ C^{-1}$ at room temperature and this coefficient can be adjusted very close to zero by further heat treatment. The NML 1 Ω resistor is formed by a partially self-supporting 2.1 mm diameter Evanohm wire wound as a bifilar coil. The coil is protected by a metal case that allows the oil to flow over the wire, thus maintaining constant temperature. Between 1970 and 2000 a total of 76 NML 1 Ω resistors were made at the NMIA. These resistors now are used in 25 laboratories throughout the world. The initial 14 NML resistors were made from the Evanohm-R alloy and were given serial numbers beginning with S-60. The remaining 62 resistors were built in the 1990s and used the Evanohm-S alloy containing about 5% Mn. For improved transportability their coils were supported using three hinged carriers that allow radial movement [17] and help to eliminate strains from differential thermal expansion. These were given serial numbers that begin with the digits 64.

[4] Certain commercial equipment, instruments or materials are identified in this paper to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

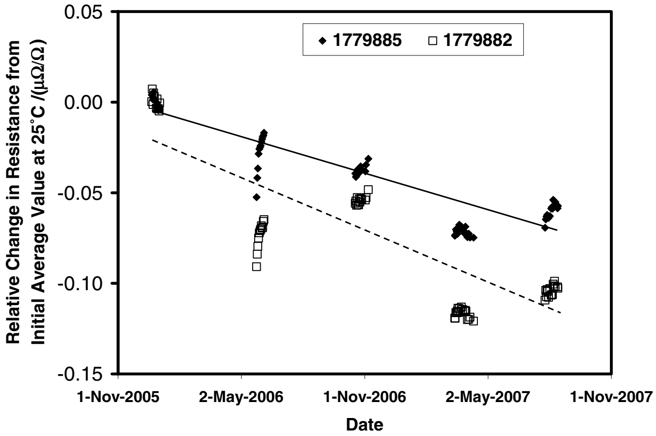

Figure 1. The 2006–2007 SIM.EM-K1 RMO key comparison pilot laboratory data for two Thomas-type 1 Ω transport standards. The resistors were measured in an oil bath at 25.000 °C ± 0.003 °C after equilibrating in the oil for at least 24 h. The standard deviations of the residual differences from the two regressions as described in the text are 0.019 μΩ Ω^{-1} (dashed line, serial number 1779882) and 0.010 μΩ Ω^{-1} (solid line, serial number 1779885).

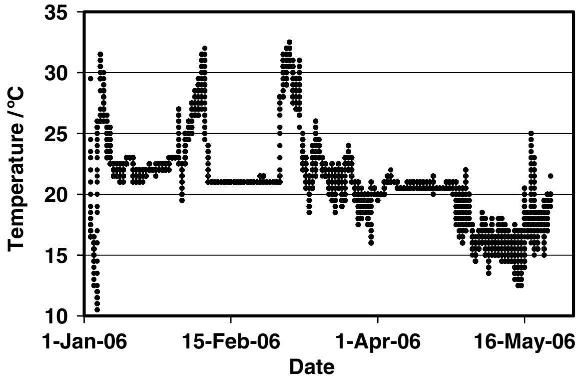

Figure 2. A graph of temperature readings from a battery powered recorder shipped with the SIM-EM.K1 transport standards. The periods of unstable temperature occurred while the resistors were shipped between the USA, Argentina, Brazil, Uruguay and the USA.

3. Transport behaviour

Key comparisons are evaluated based on time-series data from participants. There can be significant intervening periods during which the standards travel between the NMIs and are processed through customs. Repeated observations with low relative uncertainty from at least one pilot laboratory are needed to assess the transport behaviour of the standards; thus the standards travel in rounds to one or more participants and then return to the pilot laboratory for additional measurements to evaluate their stability. The analysis of the results usually consists of applying a linear model for the variation of the resistance with time. Thus the uncertainty of the comparison depends on the behaviour of the transport standards throughout the entire set of transportation cycles. Linear drift does not contribute to the uncertainty u_c but mechanical and thermal shocks that cause irreversible changes in the resistance value can significantly contribute when a standard is transported [6, 9].

A number of commercially manufactured Thomas-type standards have been used in measurement processes at the NIST for many years and some of these have been transported to other US laboratories on a regular basis. Two such 1 Ω standards, constructed in 1971, were selected to be used in the 2006–2007 SIM.EM-K1 regional key comparison. Figure 1 shows the change in value for each resistor as measured by the pilot laboratory (NIST) over the course of the SIM.EM-K1 comparison. The figure also shows linear regressions fit to each resistor's measured values from the comparison analysis [10]. Deviations from the linear model include identifiable settling effects, most clearly evident in the second NIST measurement period (25 May 2006 to 5 June 2006).

Figure 2 shows a record of temperature values obtained from a sensor packaged in the shipping container used for these SIM.EM-K1 resistors. This plot covers the time from 2 January 2006 to 25 May 2006 when the resistors were measured at three NMIs, between the first and second measurement periods at the NIST. The plot shows several periods of rapid temperature change and one extended period, near the end of the plot, during which the temperature dropped below 15 °C while the resistors were being cleared by customs before return to the NIST. In the period after 25 May (see figure 1) both Thomas-type resistors show changes in value that are typical of the relaxation of strain after temperature cycling; the observed time constant of this relaxation process is approximately two days. These strains were probably introduced in the resistors by differential thermal expansion between the resistance elements and the supporting inner walls of their sealed cases. The SIM.EM-K1 analysis and the two resulting linear regressions shown in figure 1 excluded the first three data points in the second period at the NIST (25 May 2006 to 27 May 2006). The relative standard uncertainty ($k = 1$) of the key comparison reference value at 1 Ω for this comparison was 0.0047 μΩ Ω^{-1} [10].

The 1993–1994 APMP.EM-K1 comparison did not give results of low enough uncertainty for a comparable detailed evaluation of the transport behaviour of the standards. The three NML resistors that served as transfer standards in APMP.EM-K1 were characterized in this study and their transport behaviour was re-evaluated in 2007–2008. These three resistors were shipped together in a single container, at different times of the year, for a series of measurements at the NMIA and the NIST [18]. Figure 3(*a*) shows the relative changes in resistance value for one of these resistors as measured at each of the two NMIs. While the results for this resistor (S-60657) show one occurrence of a small irreversible change in the resistance value around July 2007, no evidence of relaxation of strain is seen. Figure 3(*b*) is a plot of the changes in resistance for all of the NIST measurements on the three resistors. The standard deviations of the residuals for the results shown in figure 1 are 1.9×10^{-8} Ω and 1.0×10^{-8} Ω. These are similar in average magnitude to the standard deviation of residuals obtained here for the one NML standard constructed in 1976 (S-60657), which is 1.8×10^{-8} Ω. The results for the two newer NML resistors shown in figure 3(*b*) give standard deviations from linear regressions that are less than one-half as large, at 0.3×10^{-8} Ω and 0.7×10^{-8} Ω.

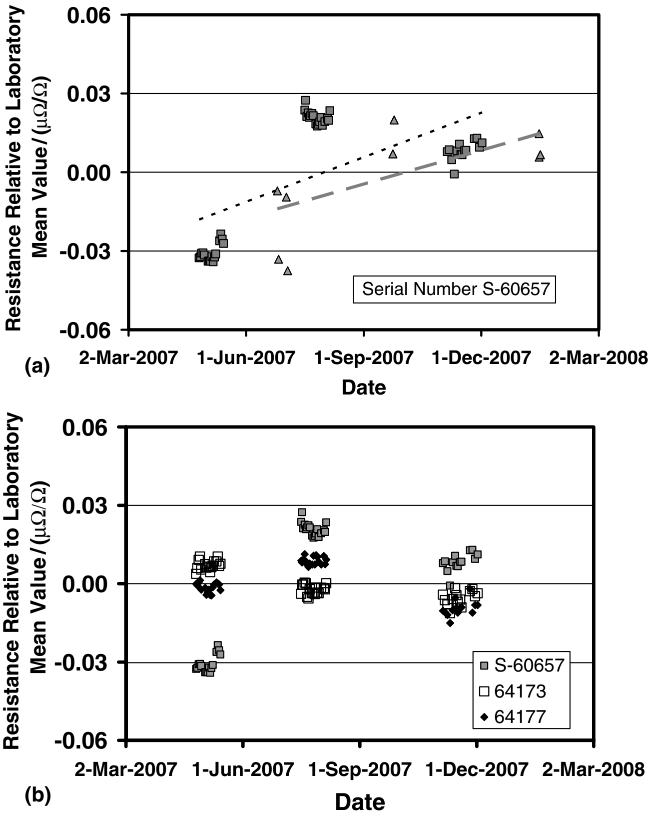

Figure 3. (*a*). All results for one NML standard resistor (S-60657) are plotted relative to the average values from the 2007–2008 transportation experiment. The results of measurements from the NMIA (triangles) have residual differences from their linear regression (long dashes) of standard deviation 0.014 $\mu\Omega\ \Omega^{-1}$ and those from the NIST (squares) have residual differences from their linear regression (short dashes) of standard deviation 0.018 $\mu\Omega\ \Omega^{-1}$. (*b*) Results of NIST measurements on the three NML standards from the 2007–2008 transportation experiment. The standard deviations of the residual differences for the three resistors are 0.018 $\mu\Omega\ \Omega^{-1}$ (S-60657), 0.003 $\mu\Omega\ \Omega^{-1}$ (64173) and 0.007 $\mu\Omega\ \Omega^{-1}$ (64177).

4. Environmental and measurement influences

4.1. Pressure and relative humidity (RH)

Bridgman used Manganin wire manufactured around 1900 in Germany to produce electronic pressure gauges having linear responses to atmospheric pressure up to at least 1.25 MPa [19]. In both Manganin and Evanohm resistance wire the resistance is a linear function of pressure over the range of atmospheric pressures found in a typical laboratory (75 kPa to 105 kPa). The pressure dependence is described by

$$R(P) = R_r[1 + \gamma(P - P_r)], \tag{1}$$

where $R(P)$ is the resistance at pressure P, R_r is the resistance at a reference pressure P_r and γ is the first-order coefficient of barometric pressure. In an unsealed resistor, the response to pressure ideally depends solely on the material properties of the wire. For bare Manganin, the pressure coefficient is positive, and has a value of approximately 2.3×10^{-8} kPa^{-1} [19]. For Evanohm alloys, this pressure coefficient of resistance is smaller, approximately $\gamma = -1.1 \times 10^{-9}$ kPa^{-1} [20]. The NMIA measured the pressure coefficient for an unsealed NML 1 Ω resistor made from Evanohm-S to be -1.9×10^{-9} kPa^{-1} and for an Evanohm-R standard to be -0.4×10^{-9} kPa^{-1} [21], both with a relative standard uncertainty of 0.1×10^{-9} kPa^{-1}.

The effect of barometric pressure is exerted on the bifilar coil of resistance wire in sealed Thomas resistors through close contact with the inner wall of the brass enclosure. An increase in external pressure causes this inner cylinder to expand, and this causes changes in strain in the material of the winding. Among 19 commercial Thomas resistors in use at the NIST, 14 have pressure coefficient values ranging from 2.2×10^{-9} kPa^{-1} to 8.1×10^{-9} kPa^{-1}. These values are considerably lower than that of the bare wire. Four have pressure coefficients in very close agreement with that of bare Manganin. The reason for this is thought to be that in these four resistors the seals of the hermetic cases have broken, allowing the surrounding mineral oil in the bath to equalize the internal pressure. This failure of the seal is relatively common in Thomas-type standards, and does not necessarily degrade the uncertainty of resistance comparisons when accurate corrections for barometric pressure are applied.

Observations on one Thomas-type resistor indicate that the pressure coefficient value is low (7.6×10^{-9} kPa^{-1}) under normal conditions, but when subjected to a large negative change in external pressure this value may change to that of an unsealed resistance element [22]. This behaviour is thought to indicate an intermittent leak in the hermetic case. However, in most Thomas-type resistors, either sealed or unsealed, our results indicate that there is little or no hysteresis or delay in response to changes in barometric pressure; this is in agreement with the results of other studies [23]. Thomas-type resistors can be cycled quickly from 105 kPa to 75 kPa and back, and this should produce no hysteretic change in resistance.

Characterization of 1 Ω resistance standards for the effect of RH is uncommon, although typical values of RH in NMIs range from about 10% to 60%. Possible effects of RH include chemical surface effects in the resistor element or supports of unsealed resistors. We subjected two NML resistors to high and low RH levels for ten days, followed by measurements to detect any drifts or changes in value, but no effect was observed. We also measured these resistors in an oil bath saturated with dry nitrogen gas, and over a period of ten days observed no change from results in normal laboratory conditions with RH = 35% to 40%.

4.2. Temperature cycling

Near the normal maintenance temperature of wire-wound resistors, the resistance is generally described as a function of temperature by a second-order equation,

$$R(T) = R_r(1 + \alpha_r(T - T_r) + \beta(T - T_r)^2). \tag{2}$$

Here $R(T)$ is the resistance at temperature T and R_r is the resistance at a reference temperature T_r, while α_r is the slope of the curve at T_r and β is the second-order coefficient of resistance over some temperature interval as determined from a least-squares fitting procedure. Temperature characterization curves are produced from measurement results with the resistor

Table 1. Temperature cycling and characterization results for Thomas-type resistors measured at 25.000 °C. Relative standard uncertainties ($k = 1$) are 0.005 μΩ Ω^{-1} for the changes in resistance, 0.0064 (μΩ Ω^{-1}) °C^{-1} for first-order coefficient α_{25} and 0.0010 (μΩ Ω^{-1}) °C^{-2} for second-order coefficient β. The reference temperature $T_r = 25.000$ °C was used in fitting using equation (2).

Resistor, date of characterization	Cycled to 23 °C/ (μΩ Ω^{-1})	Cycled to 20 °C/ (μΩ Ω^{-1})	Coefficient α_{25}/ (μΩ Ω^{-1}) °C^{-1}	Coefficient β/ (μΩ Ω^{-1}) °C^{-2}
1779 882 (2005)	−0.0053	−0.0097	2.1820	−0.5429
1779 885 (2005)	0.0020	−0.0067	2.0542	−0.5467
1842 307 (2005)	−0.0032	0.0001	2.8132	−0.5234
1844 269 (2005)	−0.0015	−0.0160	2.4710	−0.5298
1883 403 (2005)	0.0088	−0.0229	2.3968	−0.4961
1883 409 (2005)	−0.0118	−0.0647	3.1296	−0.4967
1883 418 (2005)	−0.0136	−0.0661	2.1374	−0.4962
1779 882 (2008)			2.1874	−0.5431
1779 885 (2008)			2.0750	−0.5461
1842 307 (2008)			2.8136	−0.5252

in equilibrium at several temperature values that span some range, typically between 20 °C and 30 °C. The coefficients for these curves depend on the reference temperature T_r. All of the measurements described in this section were conducted in an auxiliary oil bath at 25.000 °C ± 0.003 °C, with oil flowing quickly around the resistors under test.

The temperature stability of resistors in thermally stabilized oil baths is much better than that of resistors maintained in air bath enclosures because the liquid provides superior thermal conduction and can be maintained with excellent temperature uniformity compared with air. Both white mineral oil and silicone fluid have been used in baths for standard resistors. While silicone fluid is more stable and can maintain a higher electrical resistance for longer periods of time, it is not inert with respect to silicone rubber used in the NML resistor mountings. For this reason, only high-purity mineral oil should be used with these resistors.

In addition to the variations of resistance with temperature described by (2), the resistance of 1 Ω standards may exhibit hysteresis with changes in temperature. Table 1 shows the magnitudes of hysteretic changes in resistance measured at 25 °C as well as the coefficients α_{25} and β derived for six Thomas-type resistors. In 2005, these values were derived from resistance values measured while the auxiliary oil bath temperature was held for one week at each of the temperatures 20 °C and 23 °C. Before and after each new temperature cycle the resistors were measured for at least a week at the normal maintenance temperature of 25 °C. In two of the six Thomas-type resistors significant changes in resistance of about −0.065 μΩ Ω^{-1} occurred at 25 °C after cycling to 20 °C while the others showed much smaller effects. The pressure coefficients γ for these six standards are all between 4.0×10^{-9} kPa^{-1} and 6.0×10^{-9} kPa^{-1} and show no correlation with these residual changes. At the bottom of table 1, the coefficients α_{25} and β obtained from a second temperature characterization performed in July 2008 are given. These values agree within the estimated uncertainty for two resistors and differ in the value of α_{25} by about 2.1×10^{-8} °C^{-1} for the third standard.

To observe the effects of larger temperature excursions, we subjected three of the Thomas-type resistors that exhibited relatively large temperature hysteresis to progressively higher oil bath temperatures between 30 °C and 38 °C. The resistors were held at each test temperature for about 48 h, followed by a longer period of observation at 25 °C. When this sequence was complete the three standards were cycled to progressively lower temperatures of 20 °C and 18 °C. In the sequences in figure 4(*a*), the cumulative effect of temperature cycling to both higher and lower temperatures is shown for two of these resistors. Although the magnitudes of the changes in resistance at 25 °C differ among the three standards, each resistor increased in resistance after being subjected to temperatures above 25 °C and decreased in resistance when the temperature prior to the measurements was below 25 °C. The short-term drift of the resistance values after each period of thermal cycling shows that the change in value induced by elevated or reduced temperature is partially relaxed with a time constant of two to three days. In some cases the process of relaxation then continues for much longer periods, and can result in a change in the drift rate for some months after the temperature event. Similar hysteretic behaviour and subsequent relaxation has been observed in studies of Thomas-type resistors in other laboratories [24, 25].

Hysteretic effects due to temperature have also been observed in precise capacitance standards. This was described in the comparison report of the CCEM-K4 key comparison of 10 pF fused-silica capacitance standards [26]. In preparation for the capacitance comparison a prescription of temperature cycling was developed to remove the effects of temperature hysteresis. The capacitor temperature cycling process consisted of three cycles, each cycle being 25 °C to 50 °C and back to 25 °C. The capacitors were held at each temperature for approximately 48 h, and then allowed to settle at 25 °C for several weeks. With this process the capacitance standards showed improved predictability in their final value.

For Thomas-type resistors we have observed that the change in value depends on the most recent temperature cycle and to a lesser degree on earlier cycles. For example, as described in [25], a symmetric sequence of a higher and a lower temperature did not restore the resistor to its original value, but repeating this process caused the resistance to alternate between the same two values. Structural changes may occur

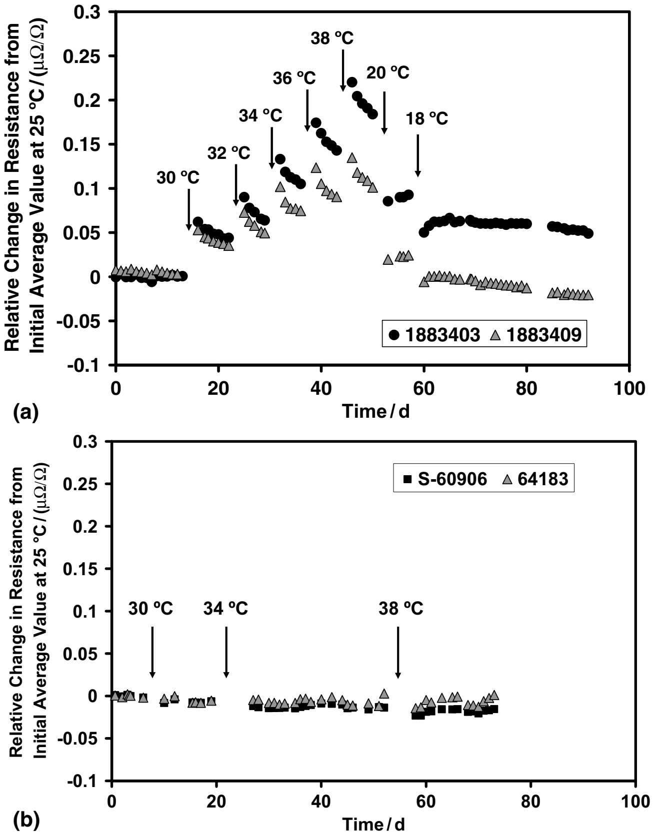

Figure 4. (*a*) Results of measurements for two Thomas-type standards at 25 °C with repeated soaking for 48 h intervals at the various temperatures shown above the arrows, used to simulate temperature changes in transport. The results have a standard relative uncertainty ($k = 1$) of 0.005 μΩ Ω^{-1} and are normalized to an average starting value of zero. (*b*) Similar results for two NML standards at 25 °C with soaking for 48 h intervals at various temperatures. The results have a standard relative uncertainty ($k = 1$) of 0.005 μΩ Ω^{-1} and are normalized to an average starting value of zero.

in Thomas-type resistors that are specific to strains already present in the wire, so a prescription to remove hysteretic changes may not be practical at the level of a few parts in 10^8. The results of [25] indicate, however, that symmetric cycling by +10 °C and −10 °C about the laboratory measurement temperature, with decreasing temperature excursions to +5 °C, −5 °C, +2 °C and −2 °C each lasting about 8 h, should bring the resistor's value closer to its undisturbed long-term trend for Thomas-type resistors of superior construction.

Unlike the Thomas resistors, NML resistors are mounted in strain-reducing fixtures that absorb differential thermal expansion. A resistance hysteresis of less than 0.02 μΩ Ω^{-1} was observed in [25] due to temperature cycling of NML resistors over a range of 25 °C. We confirmed this result by following a sequence of progressively higher oil bath temperatures between 30 °C and 38 °C, as shown in figure 4(*b*). The newer Evanohm-S NML resistor is nearly ideal in its temperature dependence, with both α and β made very close to zero by heat treatment. The earlier Evanohm-R type of NML resistor typically has a value of β near 0.025 (μΩ Ω^{-1}) °C^{-2}, and their temperature dependence curves have maxima near the temperature 20 °C at which oil-type resistors are maintained at the NMIA.

4.3. Power coefficient

Power loading in a resistor refers to the variation of resistance as a function of electrical power generated in the resistor. It is generally considered to be due to Joule heating generated by the measurement current in the resistance element, and is widely observed for high-current shunt resistors. To first order this effect causes a uniform increase in the temperature of the element, so that one may expect the power coefficient of resistance to be proportional to the dominant first-order temperature coefficient. The power loading effect also depends on laboratory measurement conditions and the construction of the resistor in ways that are relatively poorly understood compared with other effects. Non-uniform heating and certain thermoelectric effects can be significant in standard resistors. Measuring low values of resistance requires establishing a potential difference large enough to measure with small uncertainty; this in turn dissipates significant power in the resistor, and power loading can become a major systematic error for very low values below 1 Ω. One ohm is the lowest value of dc resistance where measured resistance values regularly attain a relative standard uncertainty below 0.01 μΩ Ω^{-1}, and for this reason, 1 Ω resistors are widely used as references for comparisons with lower resistance levels.

Increased power dissipation can produce thermoelectric effects that appear as changes in resistance, but these are unlikely to be significant in this study of 1 Ω resistors for the following reasons: (1) any thermal voltage effects that are constant or changing linearly in time are cancelled in precision resistance measurements by current reversal techniques, (2) the thermal electromotive forces against copper of the two precision resistance alloys of interest are relatively small—both are approximately 2 μV °C^{-1}—and they do not vary depending on the annealing and heat treatment, and, (3) by design the current and potential leads of the Thomas-type and NML resistors are sufficiently separated to avoid the Peltier effects observed in some 1 Ω standard resistors.

We measured the resistance change at power levels of 10 mW and 2.5 mW (100 mA and 50 mA measurement currents). We have investigated the small changes in power coefficients observed when standards are under power continuously leading up to the measurement process, rather than energized only during the measurements. We also observed a similar small dependence on the power duty cycle defined as the equivalent percentage of the measurement time that full power is dissipated in the resistor and on the rate of flow of the surrounding oil which removes internal heat [27]. All of the processes were designed so that the laboratory reference standards were not significantly affected by the changes in measurement conditions experienced by the 1 Ω resistors under test. In all measurements, the resistors were maintained at 25.000 °C ± 0.003 °C in stirred mineral oil baths. Data in figures 5(*a*) through 5(*d*) show changes in the measured resistance plotted against the temperature coefficients α. These comparisons were set up with the following conditions.

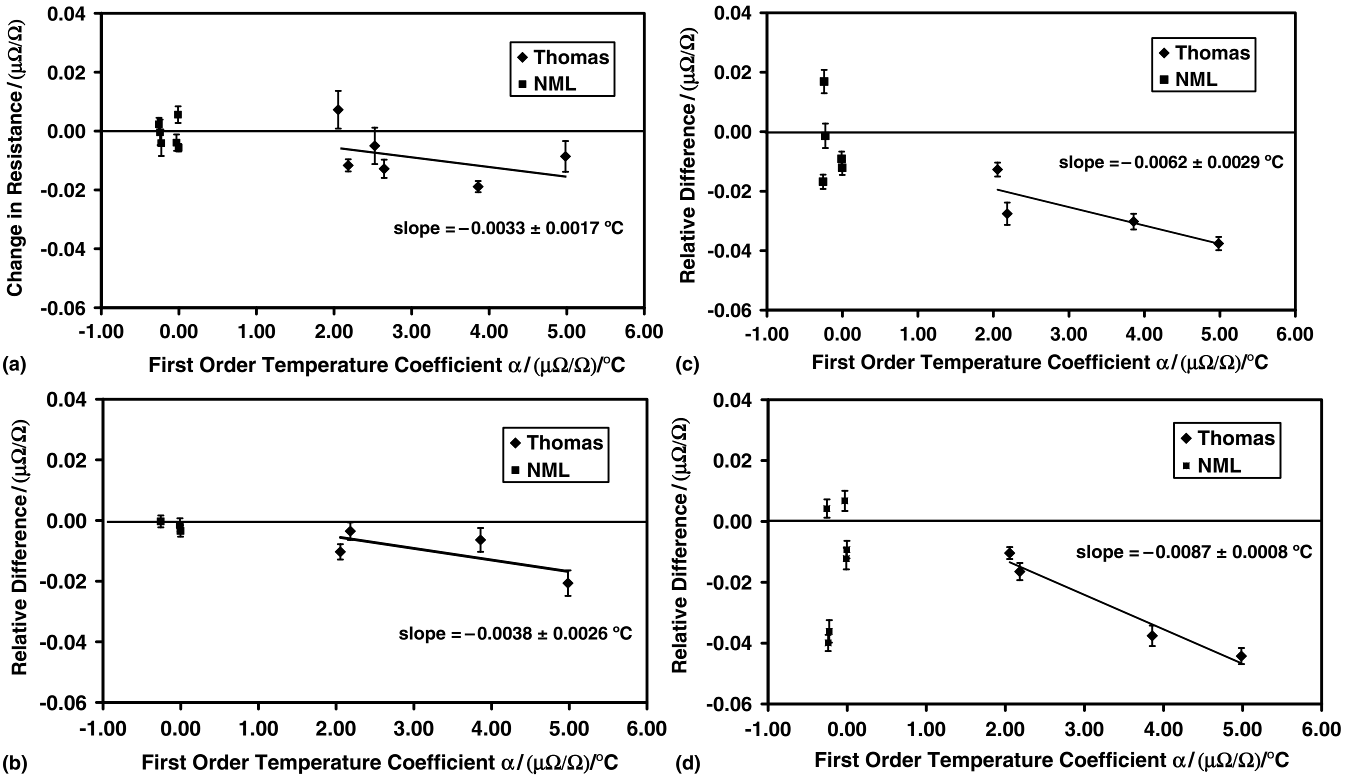

Figure 5. (*a*) Relative differences in the results of CCC comparisons at power levels of 2.5 mW and 10 mW, as explained in the text, plotted versus the first-order temperature coefficients of the resistors (α_{25}). (*b*) Relative differences in the results of DCC measurements at 2.5 mW power level for two different conditions of applied current, as explained in the text, plotted versus the first-order temperature coefficients of the resistors (α_{25}). (*c*) Similar differences as in figure 5(*b*), for DCC measurements at 10 mW power level. (*d*) Relative differences in the results of DCC measurements at 10 mW for resistors measured in a turbulent bath with high heat removal rate minus those measured in a laminar-flow bath with lower heat removal rate. The values are plotted versus the first-order temperature coefficients of the resistors (α_{25}).

Figure 5(a). Resistance scaling measurements were made using a NIST cryogenic current comparator (CCC) [28] with a ratio of 100-to-1, so that low power was applied to the 100 Ω resistors used as reference standards. Each data point in figure 5(*a*) represents CCC results for one 1 Ω resistor, and shows the relative change in resistance $\{R_i(2.5\,\text{mW}) - R_i(10\,\text{mW})\}/(1\,\Omega)$ versus the temperature coefficient α_i. These resistors were at temperature equilibrium with no power dissipation immediately prior to each measurement. Because of limitations on the rate of current reversal in the CCC bridge there is a reduction of about 15% in the average power dissipation in these measurements compared with the 100% duty cycle in the measurement process of the following measurements. The resistors were measured in a laminar-flow oil bath with a relatively slow flow rate.

Figure 5(b). In this test, power loading was measured using a NIST room temperature direct current comparator (DCC) bridge which compares like-value resistors that all carry the same measurement current and all dissipate a power level of 2.5 mW. To overcome this limitation, power was applied to the tested resistors in two different ways. In one process the measurement current of 50 mA was applied to the tested resistor only for the period of about 600 s necessary to measure its value with an uncertainty below $0.005\,\mu\Omega\,\Omega^{-1}$. This resulted in a resistance value R_{j1} (2.5 mW). A second measurement was made at the same level of power but by continuously applying the measurement current to the tested resistor for at least 24 h prior to the measurement, resulting in a resistance value R_{j2} (2.5 mW). Figure 5(*b*) shows a graph of these DCC results $\{R_{j1}(2.5\,\text{mW}) - R_{j2}(2.5\,\text{mW})\}/(1\,\Omega)$. The reference resistors in the DCC bridge were under continuous power and at a nearly 100% duty cycle. All resistors were measured in the same laminar-flow oil bath with relatively slow flow rate.

Figure 5(c). The tests yielding the results plotted in figure 5(*b*) were repeated at a higher power level (10 mW) using the same room temperature DCC bridge as well as the same procedure of brief power application. Here, the results shown represent $\{R_{j1}(10\,\text{mW}) - R_{j2}(10\,\text{mW})\}/(1\Omega)$.

Figure 5(d). A similar DCC bridge was operated at the 10 mW power level to measure resistors which were placed, in groups of three, in one of two types of oil bath. The first is the laminar-flow bath used for the reference resistors as well as in all of the tests above. The second is a smaller, turbulent-flow bath with relatively fast flow rate. Both baths were maintained continuously at 25.000 °C ± 0.003 °C. Plotted in figure 5(*d*) are the values of resistance measured in the turbulent bath minus those measured in the laminar flow bath under otherwise nearly identical conditions, divided by the nominal value of resistance. These results represent the average differences for two one-week periods of measurements in each bath.

Table 2. Relative differences between resistance values measured using CCC and DCC systems, for six listed NML resistors maintained at 25.000 °C ± 0.003 °C. 'Primary' refers to continuous-power DCC measurements made at 10 mW in the primary DCC system oil bath with slow laminar oil flow. 'Auxiliary' refers to similar DCC measurements made in a smaller bath with fast turbulent oil flow. The values have a relative standard uncertainty ($k = 1$) of approximately 0.005 μΩ Ω^{-1}. The last column shows NML resistor data that are displayed graphically in figure 5(*d*).

Transfer standard	ΔR (CCC − primary) (μΩ Ω^{-1})	ΔR (CCC − auxiliary) (μΩ Ω^{-1})	ΔR (auxiliary − primary) (μΩ Ω^{-1})
S-60657	0.006	0.002	0.004
S-60659	−0.008	0.028	−0.036
S-60906	−0.011	0.029	−0.040
64173	0.015	0.024	−0.009
64177	−0.005	0.006	−0.011
64183	0.027	0.020	0.007

In general, the power loading changes versus α for Thomas resistors fall on straight lines that nearly intersect the origin of each plot, indicating that their power loads of the resistors are directly proportional to the temperature coefficients, as expected. The temperature changes in the Thomas resistors thus can be inferred from the slopes in the figures. They agree in sign with the assumed cooling effect of reduced power load (figure 5(*a*)), reduced time at elevated power level (figures 5(*b*) and (*c*)) and greater heat removal in fast-moving oil (figure 5(*d*)). Inspection of the slopes in the first three figures compared with that of figure 5(*d*) indicates that a large fraction of the heat dissipated in the resistors is removed by the fast-flowing oil. The variations among results for the NML resistors shown in figures 5(*c*) and (*d*) indicate that more complex effects related to power loading may exist in these standards for the conditions tested.

The observed differences between Thomas and NML resistors seen in figures 5(*c*) and (*d*) may be caused by differences in their design. For example, due to the higher resistivity of Evanohm, the NML coil has a more coarse winding pitch and a surface area of about one third that of the Thomas coil. These features, along with the open case design, may allow greater variation in the surrounding oil temperature which would support larger gradients along the coils of the NML resistors. Thus it is possible to attribute some changes in the resistance values of the NML resistor to localized heating in thermal equilibrium, which is expected to be greatest in the slowly moving laminar-flow oil bath when 10 mW is continuously applied.

Earlier studies help to explain the noted differences in power loading among individual NML resistors. The differences in figures 5(*c*) and (*d*) among the NML resistors are more significant among the older series of resistors, which have $\alpha \approx -0.25$ (μΩ Ω^{-1}) $°C^{-1}$ for $T_r = 25$ °C. While those older resistors have not been tested in this way, an investigation at the NMIA [29] determined that in at least some NML standards of the newer series the value of α can significantly vary in different sections of the wire. For one of the tested resistors the observed differences between α for the middle section and α for the two end sections were approximately 4 (μΩ Ω^{-1}) $°C^{-1}$. Typically, dissipation of internal heat causes temperature to rise in the middle sections of a resistor more quickly and to a higher final temperature than that of the wire close to the connecting terminations. This is due to the high thermal mass and low power dissipation in the terminating connectors. Compared with uniform heating, the temperature gradients from self-heating may create a more significant change in resistance by accentuating any localized variation in α.

For at least the last 15 years the NIST has maintained traceability at the 1 Ω level through comparison of the values assigned to two or three NML standards by two measurement systems, one using the CCC and the other using the DCC. Traceability to the QHR standard is provided by the CCC measurements. Differences between these scaling results for the three resistors were a motivating factor for conducting this study. Six NML resistors were used in this study, and table 2 shows presumed power loading effects specific to the individual resistors. The standard deviations of the six differences shown in the first and second columns of data are 0.015 μΩ Ω^{-1} and 0.011 μΩ Ω^{-1}, indicating that the differences are significant compared with the relative standard uncertainty of approximately 0.005 μΩ Ω^{-1}. In these six NML resistors, only two give no significant differences when the resistor is measured in circulating oil of slow and fast flow rates and also when the resistor is measured from a 'cold start' compared with continuously applied measurement current.

5. Conclusions

Characterization of transport standards is used to select standards with predictable behaviour and to make accurate corrections for varying conditions of measurement such as barometric pressure. Comparison protocols can specify temperature conditions very closely in order to reduce the need for corrections and thus reduce their contributions to uncertainty. Conversely, the protocol can allow a range of temperature conditions in order to allow more direct comparison under the specific conditions used in each participant laboratory. Depending on the level of uncertainty contributed by temperature corrections, the use of well-characterized and stable resistance standards should allow laboratories to measure comparison standards at their typical oil bath temperatures, rather than at a single specified oil bath temperature for all laboratories. Typical maintenance temperatures for standard resistors in oil baths vary from 20 °C to 25 °C in different NMIs.

The careful selection of transport standards can increase the validity of the results as verification of traceability to the QHR standard and of resistance scaling measurement capabilities for NMI participants. The results of many studies indicate that NML resistors can provide superior transport uncertainty (below $0.01\,\mu\Omega\,\Omega^{-1}$ since their temperature dependence is quite small and laboratory temperature cycling tests have no significant effect on their resistance values. Two Thomas-type resistors that yielded the most repeatable results in temperature cycling tests have performed well in transport, as shown in the results of the SIM.EM-K1 RMO comparison. Thomas-type resistors would typically perform less reliably in this regard than NML resistors because of the significant hysteresis that can result from temperature-induced strain. Power loading in either type of 1 Ω resistor may amount to $0.02\,\mu\Omega\,\Omega^{-1}$ or more when a measurement current of 100 mA is used, so a measurement current of 50 mA can provide the best assurance of low uncertainty in comparisons. This is shown to be important when the resistors are maintained under different oil bath conditions or when the measurement current is applied for different lengths of time.

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References

[1] Hartland A 1992 *Metrologia* **29** 175–90

[2] Delahaye F, Witt T J, Piquemal F and Genevés G 1995 *IEEE Trans. Instrum. Meas.* **44** 258–61

[3] Delahaye F, Witt T J , Jeckelmann B and Jeanneret B 1995/96 *Metrologia* **32** 385–8

[4] Delahaye F, Witt T J, Pesel E, Schumacher B and Warnecke P 1997 *Metrologia* **34** 211–14

[5] Delahaye F, Witt T J, Elmquist R E and Dziuba R F 2000 *Metrologia* **37** 173–6

[6] Schumacher B *et al* 2001 *IEEE Trans. Instrum. Meas.* **50** 242–4

[7] Schumacher B 2007 *Metrologia* **44** (*Tech. Suppl.*) 01004

[8] Delahaye F, Bournaud D and Witt T J 1992 *Metrologia* **29** 273–83

[9] Jones K and Gabriel W P 1995 *IEEE Trans. Instrum. Meas.* **44** 196–8

[10] Elmquist R E, Jarrett D J and Zhang N F 2009 *Metrologia* **46** (*Tech. Suppl.*) 01001

[11] Matsumoto E 2003 *IEEE Instrum. Meas. Mag.* **6** 46–50

[12] Thomas J L 1930 *Bur. Stand. J. Res.* **5** 295–304

[13] Thomas J L 1946 *Natl Bur. Stand. RP1692* **36** 107–10

[14] Witt T J 1998 *Rev. Sci. Instrum.* **69** 2823–43

[15] Peterson C 1955 *Proc. Symp. on Precision Electrical Measurements (National Physical Laboratory, Teddington, UK, 17–20 November 1954)* (London: HMSO) paper no 14

[16] Arnold H M 1956 *Proc. IEE* B **103** 439–47

[17] Pritchard B J and Grime R C 1990 *CPEM'90 Digest (Ottawa, Canada, 11–14 June 1990)* IEEE Cat. 90CH2922-5 pp 290–1

[18] Pritchard B J 2008 *CPEM-2008 Digest (Broomfield, CO, 8–13 June 2008)* IEEE Cat. CFP08PEM-PRT pp 394–5

[19] Bridgman P W 1949 *The Physics of High Pressure* (London: G Bell) pp 72–4

[20] Andersson P and Bäckström G 1975 *Rev. Sci. Instrum.* **46** 1292–3

[21] Pritchard B J and Luong K S 2005 *Proc. 6th Biennial Conf. of the Metrology Society of Australia (Australian National University, Canberra, ACT, 19–21 October 2005)* pp 35–8

[22] Jones G R and Elmquist R E 2007 *NCSLI Meas.* **2** 42–8

[23] Karlsson H and Sørsdal T 1995/96 *Metrologia* **32** 389–91

[24] Leontiew H and Warnecke P 1992 *PTB Mitt.* **102** 289–90

[25] Pritchard B J 1995 *Proc. 1995 Annual Conf. of the Metrology Society of Australia (National Measurement Laboratory, Lindfield, NSW, 29 November–1 December 1995)* pp 155–8

[26] Jeffery A M 2002 *Metrologia* **39** (*Tech. Suppl.*) 01003

[27] Jones G R and Elmquist R E 2008 *NCSLI Meas.* **3** 50–6

[28] Elmquist R E and Dziuba R F 1991 *Rev. Sci. Instrum.* **62** 2457–60

[29] Pritchard B J and Small G W 1993 *IEEE Trans. Instrum. Meas.* **42** 557–61