TRANSPORT BEHAVIOR AND CHARACTERIZATION OF PRECISION 1 Ω RESISTORS FOR INTERNATIONAL COMPARISONS

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Abstract: The U. S. National Institute of Standards and Technology (NIST) and the National Measurement Institute of Australia (NMIA) have recently examined two types of precision transportable 1 Ω resistors that are based on different alloys and construction principles to determine characteristics that can reduce the uncertainty of international comparisons. This work focuses on standards manufactured from 1970 through 2000 by the NMIA, and Thomas-type resistors designed in the 1930s by James L. Thomas and manufactured commercially through about 1980. The effects of temperature, barometric pressure, humidity, power loading, and heat dissipation in oil are described in these two types of transportable wire-wound 1 Ω resistance standards, and the process of characterization of these resistors for use as transport standards is described.

Key words: electrical resistance standard, key comparison, temperature coefficient, power loading.

1. INTRODUCTION

International comparisons of dc resistance measurement capabilities are generally based on a small number of transportable resistance standards, measured by a sequence of National Measurement Institutes (NMIs), with intervening periods in which the standards travel between laboratories. The results are analyzed using a (usually linear) model of the drift in the resistance values. To determine the rate of drift, and to assess the transport behavior of the standards, several sets of measurements of low relative uncertainty made at the lead or "pilot" laboratory are needed. Typically, the standards travel to two or three participants and then return to the pilot laboratory for a set of closure measurements. The linear model used in the analysis of the results does not account for changes in the values of the resistance standards that can occur due to mechanical and thermal shocks. These changes may introduce systematic errors in the data and increase the uncertainty of the comparison. They are sometimes a major component of the comparison uncertainty, especially for laboratories that maintain a quantum Hall effect resistance standard.

Precision 1 Ω resistors are normally maintained and measured at constant temperature, and so are protected from thermal cycling except when they are transported, or when they are intentionally measured at different temperatures to determine the characteristic behavior of the resistance value. This behavior due to external temperature is described by a second-order curve,

$$R\,(T) = R_{\mathrm{r}}\,[1 + \alpha\,(T - T_{\mathrm{r}}) + \beta(T - T_{\mathrm{r}})^2]\,. \qquad (1)$$

Here $R(T)$ is the resistance at temperature T, and R_{r} is the resistance at a reference temperature T_{r}, while α 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 measured with the resistor temperature held constant at several values that span the useable range, typically between 20 °C and 30 °C. For some resistors temperature cycling in this range may reveal a small and reversible change (hysteresis) in the value at T_{r}.

Because laboratories are located at various elevations above sea level, another significant influence on the resistors used in international comparisons is barometric pressure. The dependence on pressure is described by

$$R\,(P) = R_{\mathrm{r}}\,[1 + \gamma\,(P - P_{\mathrm{r}})]\quad, \qquad (2)$$

where $R(P)$ is the resistance at pressure P, R_{r} is the resistance at a reference pressure P_{r}, and γ is the coefficient of resistance versus barometric pressure. An important part of any comparison is to understand and eliminate all such external influence factors in order to compare the maintained standards and measurement methods in use at each laboratory.

Ideal transport standards of resistance should be stable under external influences so that they provide reproducible values under similar conditions in different laboratories, after accounting for linear drift with time. This paper describes how the process of characterization and selection of 1 Ω resistors provides an understanding of the behavior of the standards, reduces the uncertainty of the results, and ensures that the critical comparison results, i.e., the participating laboratories' difference values, can be accurately corrected for the characteristics of the standards.

2. TYPES OF RESISTOR

The Asia-Pacific Metrology Program (APMP) performed the 1993−1994 APMP.EM-K1 comparison [1] which employed three 1 Ω resistance standards manufactured by the Australian National Measurement Laboratory (NML), now the NMIA. These standards were made from the resistance alloy Evanohm* and were produced first in the 1970s and redesigned in the early 1990s specifically to improve transportability. In the Inter-American Metrology System (SIM), the SIM.EM-K1 comparison of 2006−2007 [2] employed three Thomas-type resistors − an older but equally important class of resistor because of its wide use as a primary standard in many NMIs in all parts of the world. The paper will describe these 1 Ω resistance standards and compare their measurement properties, including the characteristics and influences likely to effect transport behavior. These results help to build and clarify selection and measurement criteria for these types of resistors.

The NML 1 Ω resistor is formed by a partially self-supporting 2.1 mm diameter Evanohm wire wound as a bifilar coil. The metal case allows mineral oil in which the resistor is immersed to flow over the wire so as to maintain the wire at a constant temperature. The resistors constructed at the NML have very low temperature coefficients of resistance (TCRs) and are extremely stable mechanically and thermally due to the annealing and mounting process used in their construction. It has been shown however that the temperature coefficient of the Evanohm wire used in the NML resistors can vary along the length of the winding [3], and in the presence of a temperature gradient this can produce a change in the measured value of the resistance. The Thomas-type resistors made from Manganin are much more sensitive to temperature and pressure than standards made from

Evanohm, and these effects are thought to increase the uncertainty of resistance measurements based on the Thomas standards. The bifilar coil of Manganin wire is sealed within a double-walled cylindrical brass container and is wound tightly on the silk-insulated wall of the inner cylinder.

3. CHARACTERIZATION

Over the past five years NIST has used two automated direct current comparator (DCC) bridges to measure precision 1 Ω resistors. Temperature and pressure characterization requires two auxiliary thermal oil baths. Thus, the temperature of resistors can be altered independently from that of the reference resistors, which are measured at NIST at 25 °C. In order to measure the pressure coefficient, a pressure chamber is used in which three precision resistors can be placed. The chamber is partially filled with oil and submerged in another oil bath where the temperature is again maintained at 25 °C. The chamber's internal pressure is stable and can be increased or decreased in the range of 70 kPa to 110 kPa.

So far, twelve Thomas-type Manganin resistors and eight NML Evanohm resistors have been characterized. Figure 1 shows the results of tests on two Thomas-type resistors when the storage temperature of the resistor is caused to vary by +5 °C to +13 °C and −5 °C to −7 °C from the normal maintenance temperature. For these two Thomas-type resistors, the measured resistance values at 25 °C are not stable after the periods at higher and lower temperature and do not return to their pre-test level.
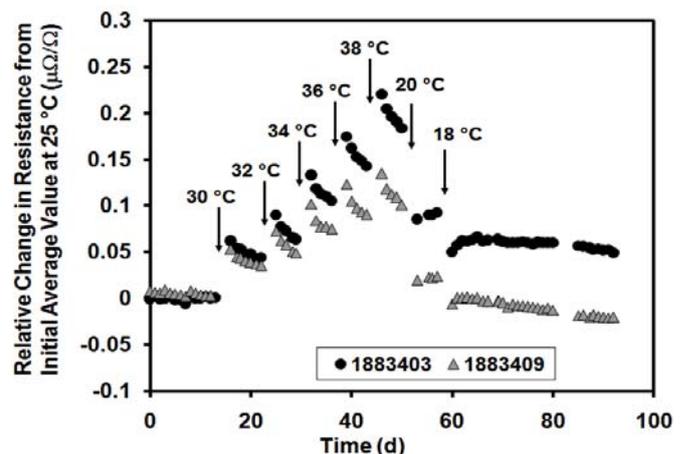
Fig. 1. Values of two Thomas-type resistors at 25 °C with repeated soaking for 48 h intervals at the temperatures shown. The soaking may simulate temperature changes in transport. The values have a standard uncertainty ($k = 1$) of 0.005 μΩ/Ω and are normalized to an average starting value of zero.

The unstable behavior observed in Fig. 1 is thought to be caused by strain induced in the resistance element by unequal thermal expansion coefficients of the resistor wire element and its support. The long-

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* 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.

term effect of this strain is a semi-permanent or hysteretic change in the resistance value. These two resistors are affected strongly by hysteresis and have greater long-term instability than most. Although the magnitudes of the changes in resistance at 25 °C differ, Thomas-type resistors in general tend to increase in resistance after being subjected to temperatures above 25 °C and decrease in resistance after being subjected to temperatures below 25 °C. The data show that the change in resistance value tends to relax partially with a time constant of two to three days. The complete process of relaxation can continue for much longer periods, and can result in changes in drift rates that last many months for some Thomas-type resistors.

Table 1 shows the magnitudes of hysteretic change in resistance for smaller temperature changes up to ±5 °C, a range that is more normal for characterization of Thomas-type resistors. The values were measured as the temperature was changed to 23 °C and 20 °C for one-week periods. Before and after each temperature cycle, the resistance was measured for at least a week at the normal maintenance temperature of 25 °C. Among these seven Thomas-type resistors are two resistors that were subjected to the larger temperature changes shown in Fig. 1. One of the two Thomas-type resistors in Fig. 1 (#1883409) shows very significant changes in Table 1 after cycling to 20 °C, while the other resistor shows much smaller effects.

Table 1. Resistance changes measured at 25.000 °C after temperature cycling, with temperature characterization results for Thomas-type resistors. Relative standard uncertainties ($k = 1$) are 0.005 $\mu\Omega/\Omega$ for the changes in resistance, 0.0064 ($\mu\Omega/\Omega$)/°C for first-order coefficient α, and 0.0010 ($\mu\Omega/\Omega$)/(°C)^2 for second-order coefficient β. Data was analyzed using Eq. (1) with T_r = 25.000 °C.

Resistor, date of measurements	Cycled to 23 °C ($\mu\Omega/\Omega$)	Cycled to 20 °C ($\mu\Omega/\Omega$)	Coefficient α ($\mu\Omega/\Omega$)/°C	Coefficient β ($\mu\Omega/\Omega$)/°C^2
1779882 (2005)	-0.0053	-0.0097	2.1820	-0.5429
1779885 (2005)	0.0020	-0.0067	2.0542	-0.5467
1842307 (2005)	-0.0032	0.0001	2.8132	-0.5234
1844269 (2005)	-0.0015	-0.0160	2.4710	-0.5298
1883403 (2005)	0.0088	-0.0229	2.3968	-0.4961
1883409 (2005)	-0.0118	-0.0647	3.1296	-0.4967
1883418 (2005)	-0.0136	-0.0661	2.1374	-0.4962
1779882 (2008)			2.1874	-0.5431
1779885 (2008)			2.0750	-0.5461
1842307 (2008)			2.8136	-0.5252

The temperature coefficients given in Table 1 were derived from this temperature cycling process using Eq. (1). The TCRs of three of the standards were remeasured in 2008, and for two of these standards the coefficients α and β had not changed by more than

their measurement uncertainties. For most Thomas-type resistors and for all NML resistors that have been tested the temperature coefficients remain unchanged over many years. Evanohm NML 1 Ω resistors in general do not show any significant hysteretic change in resistance in similar temperature cycling tests. This may be because the wire is held by flexible fixtures which eliminate strain from thermal cycling.

Power loading is a change in resistance caused by Joule heating from the measurement current. Power-loading changes are usually small, but can be significant contributions to the Type B uncertainty for state of the art resistance measurements. Figure 2 illustrates the behavior of each type of standard due to power loading. Only the Thomas-type resistors follow the direct relationship between power loading and the temperature coefficient. The random power-loading effects observed in the NML standards are thought to be related to thermal gradients as described earlier. For the data shown in Fig. 2, the resistors were maintained in an oil bath with relatively slow laminar circulation. Both types of precision 1 Ω resistors can exhibit a measurable power loading with 100 mA applied current (10 mW applied power) in this oil bath, but the effect can be reduced by measuring the resistors at 50 mA (2.5 mW). Many commercial bath designs utilize turbulent flow, and tests at NIST have shown that such baths also reduce power- loading effects in both types of resistor.
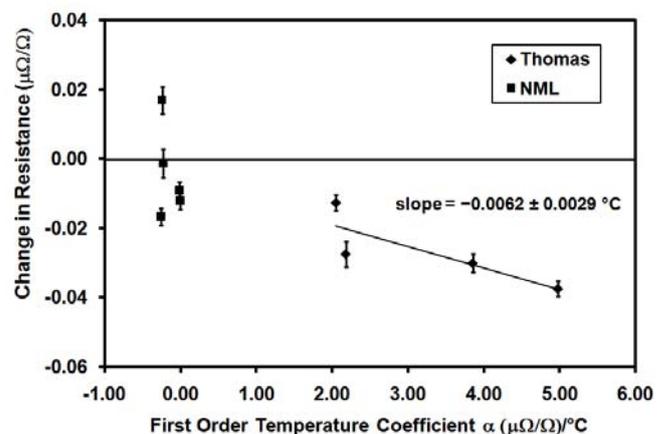
Fig. 2. DCC results $\{R_{j1}(10\text{ mW}) - R_{j2}(210\text{ mW})\}/(1\ \Omega)$. For $R_{j1}(10\text{ mW})$, the measurement current of 100 mA was applied to each tested resistor only for the period of about 600 s necessary to measure its value with a standard deviation below 0.005 $\mu\Omega/\Omega$. For $R_{j2}(10\text{ mW})$, the 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. The DCC bridge reference resistors were measured under continuous power.

Barometric pressure and humidity can affect the value of some resistance materials. Higher-valued resistance standards made from Manganin are packaged in sealed metal enclosures for this reason. In unsealed wire-wound resistors the response to pressure

is give by Eq. 2 and the coefficient γ depends 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 [4]. For Evanohm alloys, this pressure coefficient of resistance is smaller and negative, approximately $\gamma = -1.1 \times 10^{-9}$ /kPa. The pressure coefficient for unsealed NML 1 Ω resistors is known to be approximately of this magnitude [5, 6]. Tests on two NML resistors have shown no effect on the resistance values for different relative humidity levels below 60 %.

The properties of the material used for supporting the resistor element also can change with pressure and with chemical action, and these changes can be transmitted to the resistor element. In particular, NML resistors are constructed with silicon rubber rings to provide soft flexible constraints where the element is attached to its support. This material swells when it is placed in silicone oil with the result that the resistor changes significantly in value due to strain and/or pressure. Only mineral oil should be used in oil baths that are used to maintain NML type resistors. Thomas-type resistors are constructed with soft-solder seals between the inner and outer walls of their enclosures, and with the resistor elements sealed in dry nitrogen gas. The thin brass inner wall does expand and contract somewhat due to external pressure changes, resulting in typical pressure coefficient values in the range of 2×10^{-9} /kPa to 8×10^{-9} /kPa. Characterization tests have shown that some Thomas-type resistors have apparently lost the integrity of the metal-to-metal seal, a condition that increases their pressure coefficients to 2.2×10^{-8} /kPa to 2.4×10^{-8} /kPa [6].

Pressure coefficients are especially important in 1 Ω Thomas-type resistor comparisons because of the effect of altitude on barometric pressure. Equation 3 gives an approximate relation that describes the pressure (kPa):

$$P = 5.30 \times 10^{-7} A^2 - 1.198 \times 10^{-2} A + 101.325 \ . \quad (3)$$

Here the altitude A is in meters, and P is adjusted to standard atmospheric pressure at sea level. For an unsealed Thomas-type resistor this effect results in a resistance change of -0.5 μΩ/Ω at an altitude of 2000 m. In precise measurements, it is necessary also to correct for the pressure of oil above a resistor as well as normal variations in atmospheric pressure.

4. SIM COMPARISONS

Two 1 Ω transport standards listed in Table 1 were selected to use in the SIM.EM-K1 comparison based on their low pressure coefficients and stable temperature characteristics. The resistance values from this comparison shown in Fig. 4a and 4b illustrate a

successful application of the temperature characterization process. The NIST measurements were made with the resistors at 25 °C. INTI (Instituto Nacional de Technolgia Industrial, Argentina) uses 20 °C for the normal measurement process, and so made all measurements at 20 °C and corrected the results to equivalent 25 °C values using the 2005 data from Table 1. This difference in the measurement process required that temperature corrections of order +24.3μΩ/Ω (Fig. 4a) and +23.8 μΩ/Ω (Fig. 4b) be applied to the INTI data. Better agreement would be evident in Fig. 4b if the correction for temperature had been made using the average of 2005 and 2008 temperature coefficients for standard 1779885.
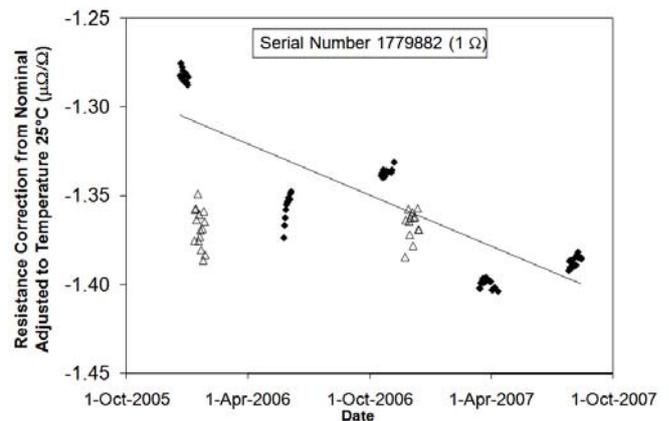
Fig. 4a. Key comparison results from the pilot laboratory (NIST) and one participant (INTI) in the SIM.EM-K1 comparison for Thomas-type resistor 1779992, corrected to 25 °C.
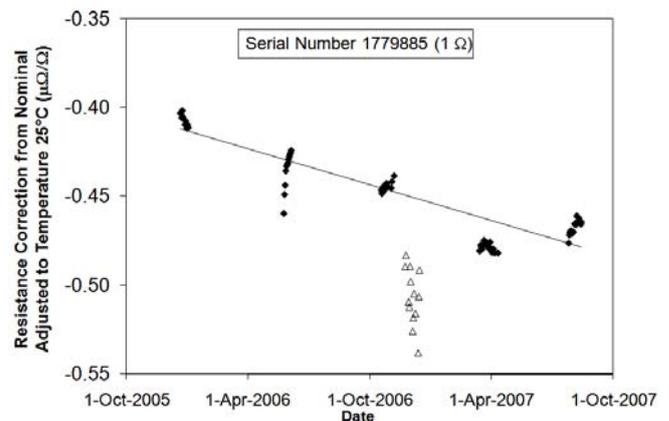
Fig. 4b. Key comparison results from the pilot laboratory (NIST) and participant (INTI) in the SIM.EM-K1 comparison for Thomas-type resistor 1779995, corrected to 25 °C. The first set of INTI results for this resistor, in the first time period as shown in Fig. 4a, had significant drift and is not shown on the scale of this graph.

The results shown in Fig 4 illustrate several of the uses of the characterization process. First is that each laboratory that participated in the comparison used measurement conditions normal to their own laboratory process. The temperature characterization data made it unnecessary for all laboratories to measure the transport standards at 25 °C; instead they could use 20 °C or 23 °C as the laboratory oil bath

temperature. The additional uncertainty ($k = 1$) related to the temperature correction process was 0.032 µΩ/Ω when measurements were made at 20 °C, and 0.018 µΩ/Ω when measurements were made at 23 °C.

The most important reason for characterization is to select resistors that will perform in a superior manner in transport for comparison measurements at different laboratories. Fig 5 shows a graph of the temperatures experienced by the SIM.EM-K1 transport standards between the first and second sets of measurements at NIST. The range of temperatures is typical of that experienced in international air freight transport and the extremes in temperature are similar in magnitude to those in the tests shown in Fig. 1. The transport standards showed reasonably good behavior even under these adverse conditions. Based on the pilot laboratory data, the values of the SIM.EM-K1 transport standards were relatively predictable and the residual differences from linear drift were of order 0.02 µΩ/Ω throughout the comparison. The extreme temperatures near 10 °C at the beginning of the data in Fig. 5 may also help to explain the drift in one Thomas-type standard at the INTI laboratory in January 2006.
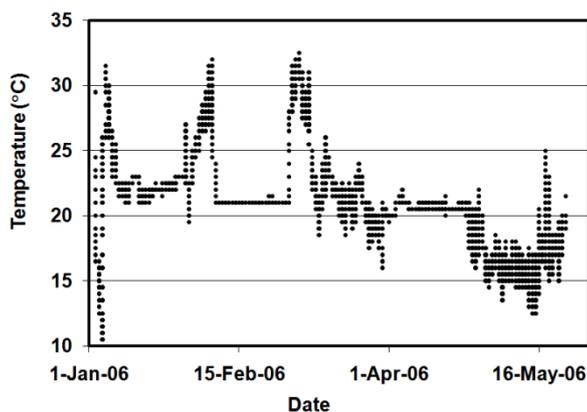
Fig. 5. Temperature data measured in the transport container during part of the SIM.EM-K1 comparison. This record covers only the first part of the comparison when the standards were shipped between the USA, Argentina, Brazil, Uruguay, and the USA. Periods of temperature extremes were recorded in transport and while the package was held in customs.

The SIM.EM-K1 standards have relatively low pressure coefficients for Thomas-type resistors. This helped to reduce the uncertainty of the pressure corrections that were applied in the comparison. The laboratory in Mexico, CENAM (Centro Nacional de Metrologia) is situated at an elevation of about 1800 m above sea level. Some Thomas-type resistors would change in value by as much as 0.45 µΩ/Ω when measured at this altitude compared to their values at sea level, or the altitudes at which most other SIM NMIs reside. The changes in the two resistors used in the comparison were less than 0.12 µΩ/Ω, and the

uncertainty in the barometric pressure correction was less than 0.003 µΩ/Ω.

5. CONCLUSIONS

When selecting and characterizing standard resistors for international comparisons, one must be aware of the effects transportation can have on precision resistors. There are often pressure and temperature variations during international comparisons that are far greater than the day-to-day changes at any one laboratory site, and careful selection of the transport resistors is necessary to minimize the effects of the laboratory measurement environment. When a Thomas-type 1 Ω resistor experiences significant temperature changes in transport, its value as measured at constant temperature may show hysteresis, and may drift to a new, stable value with a time constant of a few days. This settling is sometimes followed by long-term drift if the temperature variations were extreme. The magnitudes of these effects depend on the individual characteristics of each resistor.

REFERENCES

[1] Jones, K., Gabriel, W. P., "Second APMP Resistance Intercomparison," *IEEE Trans. Instrum. Meas.*, 1995, **44**, 196-198.
[2] Elmquist, R. E., Jarrett, D. J., Zhang, "SIM.EM-K1-K2-S6 RMO Comparison Final Report," *Metrologia*, 2009, **46**, *Tech. Suppl.*, 01001.
[3] Pritchard, B.J, and Small, G.W., "Temperature Coefficient Variations in Evanohm and Their Effect on the Transient Behavior of the NML 1 Ω Resistors," *IEEE Trans. Instrum. Meas.*, **42**, 1993.
[4] Bridgman, P.W., *The Physics of High Pressure*, G. Bell and Sons, Ltd., London, 1949.
[5] Pritchard, B.J., and Luong, K.S., "Pressure Coefficient of a sealed NML 1 Ω resistor," *Proceedings of the Sixth Biennial Conference of the Metrology Society of Australia held at the Australian National University*, October 2005.
[6] Jones, G.R., and Elmquist, R.E., "Temperature and Pressure Coefficients of Resistance for Thomas 1 Ω Resistors," NCSLI Measure, **2**, 2, 2007.