Power Loading Effects in Precision 1 Ω Resistors

Speaker: George R. Jones, Quantum Electrical Metrology Division, National Institute of Standards and Technology[*], 100 Bureau Drive, Stop 817-01, Gaithersburg MD 20899, 301-975-4225, Fax: 301-975-2115, george.jones@nist.gov

Authors: George R. Jones, Randolph E. Elmquist
Quantum Electrical Metrology Division,
National Institute of Standards and Technology

Abstract

Five Manganin[†] alloy Thomas-type 1 Ω resistors serve as primary working standards at the National Institute of Standards and Technology in the precision potentiometer direct current comparator system used for special 1 Ω customer calibrations. To maintain and predict the values of these resistors, the value of this bank is compared to the quantized Hall resistance (QHR) standard at NIST approximately twice a year. This is accomplished through the use of several precision 1 Ω resistors manufactured from 1975 through 1992 by the Australian National Measurement Laboratory (NML), using the resistance alloy Evanohm. Over many years of careful monitoring, the relative values of these transfer resistors were seen to have discrepancies that were not related to the drift in the value of the primary working standards and exceeded the Type A evaluation of standard uncertainty in the measurement systems. Some of these variations were believed to be due to power loading in the transfer resistors.

Recent experiments on different types of precision 1 Ω resistors have demonstrated that conditions of power dissipation within the resistors and the duty cycle of the power applied to the resistors can have significant effects on the uncertainty of the measurements. This paper describes the experimental results and measurement uncertainty due to these power loading effects. Additional measurements have examined loading effects in Thomas-type and certain other precision 1 Ω resistors. The relationship between the loading effect and the temperature coefficient will be described, as well as possible temperature gradient contributions to the changes of resistance observed in these measurements.

I. Introduction

The Quantum Electrical Metrology Division at National Institute of Standards and Technology (NIST) maintains two duplicate precision 1 Ω measurements systems [1] based on very similar

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direct current comparator (DCC) systems. Customer calibration of precision 1 Ω resistors is accomplished using the system designated as Thomas I, which incorporates five Manganin alloy Thomas-type 1 Ω resistors as the working standards. This system is also used to determine the temperature coefficients of resistance (TCRs) of precision 1 Ω resistors [1] through the use of an auxiliary oil bath. The second system, Thomas II was initially constructed to maintain the NIST precision 1 Ω calibration services during our move to the Advanced Measurement Laboratory (AML) in the spring of 2004, and was subsequently used in the determination of pressure coefficients of precision 1 Ω resistors. The Thomas II system uses as the working standards two Manganin alloy Thomas-type 1 Ω resistors and one Evanohm resistor constructed by Measurements International, Ltd. (MIL).

To maintain the reference values of the two precision 1 Ω DCC systems, the standard resistor banks are compared to the quantized Hall resistance (QHR) standard at NIST approximately twice a year. This procedure begins with comparing a bank of five precision 100 Ω resistors against the QHR using a cryogenic current comparator (CCC) system. Next, the three precision NML 1 Ω transfer resistors are measured against the 100 Ω resistors through a second CCC system. These resistors have very low TCR [1] and are extremely stable mechanically due to the annealing and mounting process used in their construction [2]. Thomas-type resistors made from Manganin are much more sensitive to temperature and pressure, and these effects are thought to increase the uncertainty of resistance scaling based on those standards. It has been shown however that the temperature coefficient of an Evanohm coil varies along the length of the winding [2], and in the presence of a temperature gradient this can produce changes in the measured value of the resistance.

The transfer resistors are finally measured in both of the DCC systems. Any differences between the values obtained by the CCC and DCC systems were attributed to drifts in the group average of the reference banks. Over time, the relative values of the NML transfer resistors have been seen to have discrepancies that did not seem likely to be related to the drift in the value of the resistors and exceeded the relative Type A standard uncertainty of no more than 5×10^{-9} in the measurement systems. Several experiments were conceived to examine the possible basis for these discrepancies including humidity variations and power loading.

2. Humidity Tests

The resistance elements of the NML resistors are open to the environment, and some NIST data indicated that their value might be sensitive to the relative humidity (RH) levels within the laboratory. To test this supposition two NML resistors were first measured in the Thomas I system at 35 % ± 5 % RH and then subjected to a change in humidity, using an environmental chamber which was maintained at 25 °C and 55 % RH. After approximately two weeks the resistors were then placed back in the Thomas I system and immediately measured to determine if there had been any shifts in the value of the resistors due to humidity. No differences in the values were seen, and the environmental chamber was again used with a setting of 25 °C and 17 % RH. With both resistors no discernable shift could be detected outside of the Type A standard uncertainty of the measurements as shown in Figure 1.

These precision resistance measurements could not test for changes in the resistor's values while the resistors were in the environmental chamber. A second test was suggested by Brian Pritchard of the National Measurement Institute Australia (formerly NML), who was visiting NIST as a Guest Researcher in the laboratory. The three NML resistors were placed in the auxiliary oil bath attached to the Thomas I system and the air space above this small oil bath was then sealed and dry nitrogen was bubbled into the oil while the resistors were again measured for a period of one week. As in the first tests, no measurable shift in the value of the resistors was detected (see Figure 2). From these experiments it was determined that the NML resistors did not react to the humidity level within the laboratory.

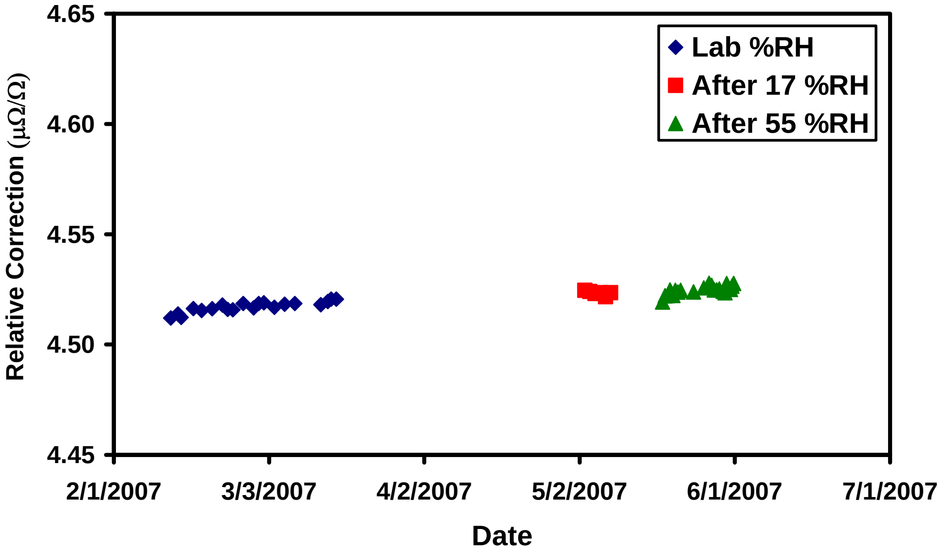

Figure 1. Response of a NML resistor after exposure to different humidity levels.

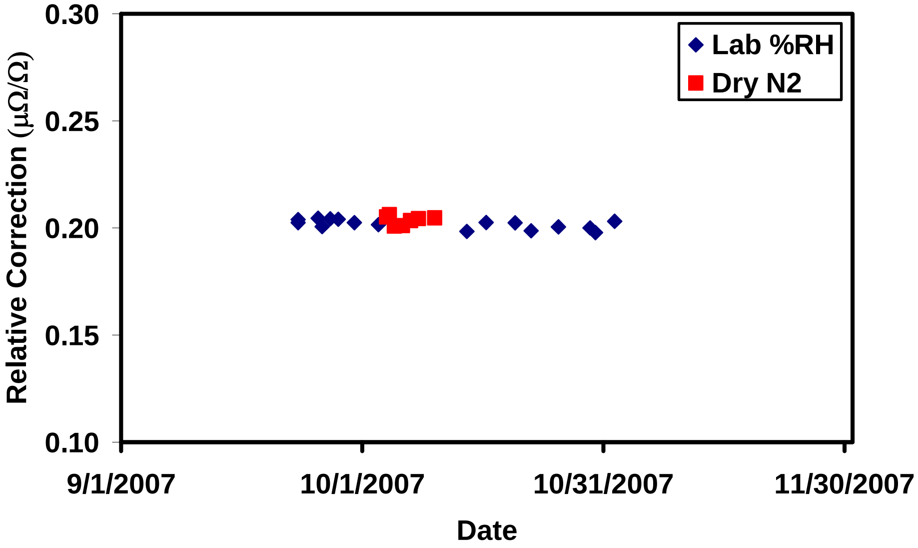

Figure 2. Response of a NML resistor after exposure to dry nitrogen.

3. Power Loading Measurements

Power loading is generally associated with the effect of heat generated in a resistor by the applied current. In all of the tests only the measurement current itself was used as the source of self-heating to determine load coefficients of resistance (LCRs). Other methods in which self-heating of the resistance element is supplied by dc as well as ac current are possible only when specially designed resistors are used [3], and these methods limit the range of possible measurements. Instead, the CCC and DCC methods that are used at NIST on a daily basis were employed together with well-characterized precision resistance standards.

Several experiments were designed to see how power loading affected the value of the Thomas-type, NML and MIL precision 1 Ω resistors.

- In some tests using the CCC system, ratios were measured with the 1 Ω resistors at 100 mA and 50 mA against 100 Ω resistors measured at 1.0 mA and 0.5 mA. Because of the large resistance ratio, negligible power was dissipated in the 100 Ω resistors. This technique is also based on the low ratio uncertainty of the CCC bridge and low TCR of the Evanohm-type 100 Ω resistors used for QHR scaling.

There are several differences between measurements made with the CCC bridge and those made with the DCC systems which are difficult to eliminate. The measurement current in the CCC is applied only during the measurement, but the NIST DCC measurement current flows through all resistors continuously. This helps to stabilize the DCC bridge current source and the temperature of oil near the resistors in the oil bath, which is maintained to 25.000 °C ± 0.003 °C. Also, current supplied in the CCC system is ramped from one polarity to the other over a period of several seconds, whereas in the DCC systems the measurement current polarity is switched within milliseconds. Over the measurement run, the duty cycle of the CCC system is approximately 90 % of that of the DCC systems. This difference between duty cycles between the two systems could allow some additional cooling in the CCC system, and the measurement results could differ between the two methods. Finally, the transfer resistors are measured in different oil baths with somewhat different oil stirring speeds. In both baths the oil flow is laminar and relatively slow. To test these effects another set of tests were conducted.

- The Thomas II system was reconfigured using relays and shunt resistors so that the measurement current could be applied to several resistors only just before and during the period that they were being measured. This change in the system reduces the effect of self-heating prior to the measurement period and makes comparison with CCC measurements more meaningful. The Thomas II system was also reconfigured to run at 50 mA. Various 1 Ω resistors were compared against 1 Ω NIST standards in the Thomas II system at 100 mA and at 50 mA with the measurement current bypassing the test resistors except during the time of measurement.

- The Thomas I system can be used with an auxiliary oil bath that has a relatively high stirring speed and non-laminar oil flow. Resistance values measured in the main oil bath were compared to values measured at 25.000 °C ± 0.003 °C in the auxiliary oil bath.

These measurements are described in the following sections.

3.1 CCC Power Tests

Various resistors were compared to the bank of precision 100 Ω resistors using the CCC system. The measurements were repeated for each resistor in the sequence of 50 mA followed by 100 mA in order to reduce carryover loading. The predicted value of the test resistors, as determined by ongoing measurements using the Thomas II system, are subtracted from the values obtained using the CCC system to obtain the results shown in Figure 3.

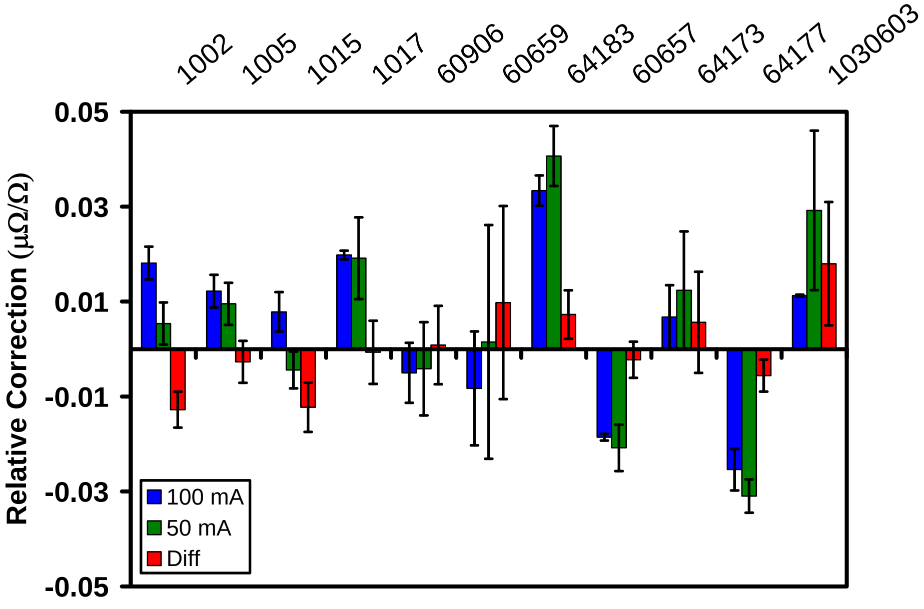

Figure 3. Differences between data from CCC system and Thomas II DCC system at 100 mA and 50 mA. The error bars are the Type A standard uncertainty of the measurements used to calculate the differences.

Resistors 1002, 1005, 1015, and 1017 are Thomas-type and in general the values measured with the CCC system are larger than the values measured with the Thomas II system. No definite trend is seen for the NML resistors 60906 to 64177. The CCC system measurements are consistent between the two current levels to within the combined standard uncertainty of 0.006 µΩ/Ω for 50 mA data and 0.004 µΩ/Ω for 100 mA data. Resistor 1030603 is a MIL type precision 1 Ω resistor, and a difference in resistance between the two CCC current levels is observed. A second MIL resistor, 1030607, exhibited a difference between the CCC system and the Thomas II system that was twice as large as the greatest discrepancy shown in Figure 3. This particular resistor consistently had the largest difference in any power loading test performed and appeared to have a more serious power loading effect, which could be observed as a drift in the first ten minutes of measurements using the CCC bridge at 100 mA.

Figure 4 shows the difference between the CCC and Thomas II data, plotted against the first order temperature coefficient α of the resistors. No obvious dependence on the temperature coefficient can be seen for the NML and MIL resistors. However, as can be seen, there is a small positive correlation between the difference and the temperature coefficient α for Thomas-type resistors.

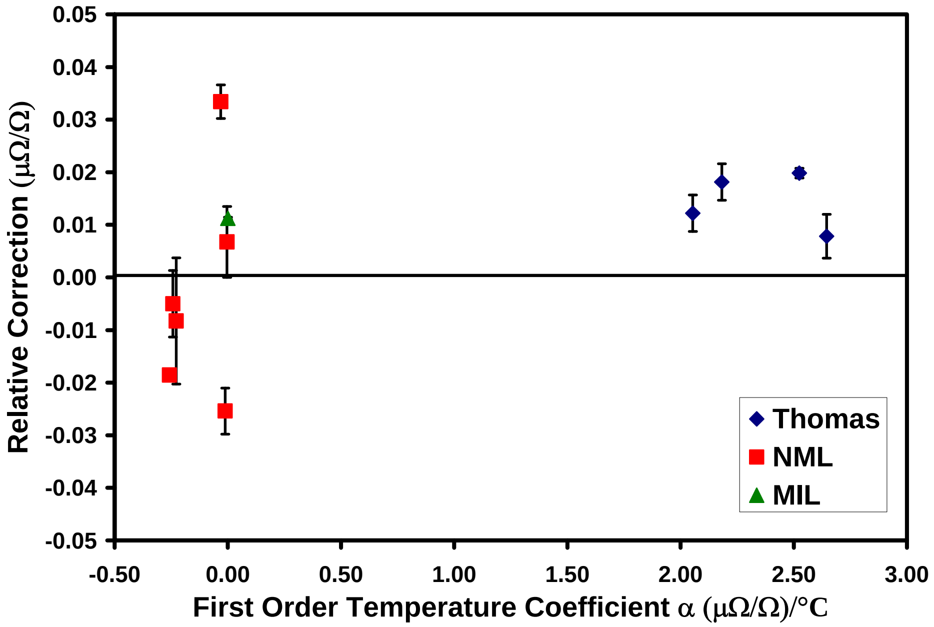

Figure 4. Difference between data from CCC system and Thomas II system at 100 mA versus first order temperature coefficient.

3.2 Duty Cycle Tests

In either of the two Thomas systems the measurement current (normally 100 mA) is applied to all of the reference resistors, controls, and test units continuously. This current is never turned off except when resistors are being changed or moved. This allows the measurement system, oil temperature, and resistors to come to thermal equilibrium before any measurements are made. Since it was probable that there was some power loading effects in the resistors as determined from the CCC results an experiment was devised to turn off the measurement current to any one of three positions in the Thomas II system and apply the current to the resistor under test just before the measurements were performed. After each measurement the current was again turned off. This therefore would give a value of the resistor from a “cold start” without the usual time to reach thermal equilibrium.

As in the tests in section 3.1, various types of resistors were tested in the Thomas II system using the new modifications. The predicted value of the resistors as determined from previous measurements at 100 mA was subtracted from the results, and the differences are given in Figure 5. In general, all but one of the NML resistors exhibited lower resistor values when the current was applied just before the measurements, compared to the measurements with continuous power. In one resistor, 1030607, the difference was larger than in any other resistor. This particular resistor had the largest difference in the CCC tests and is obviously affected by the duty cycle of the applied current.

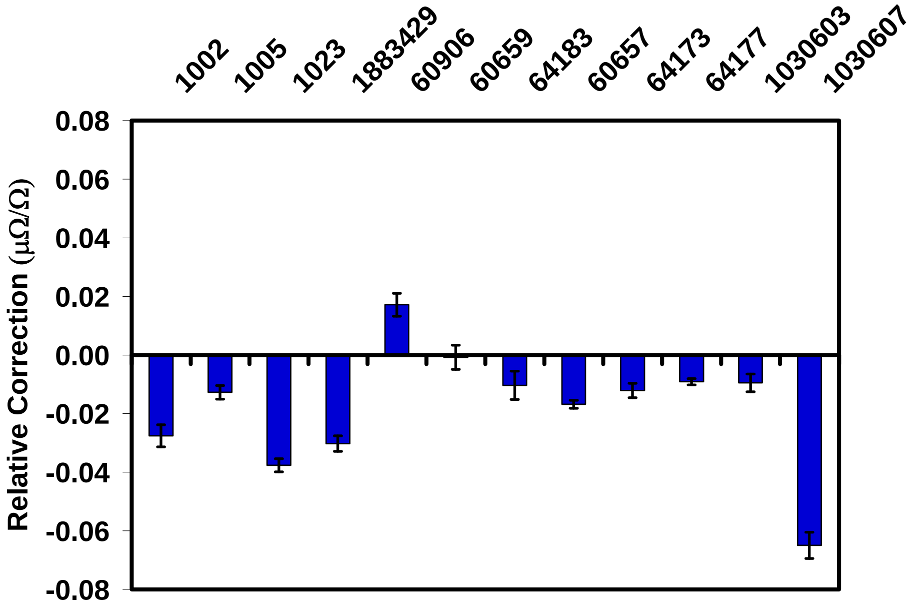

Figure 5. Difference between data from power-off tests and continuous power at 100 mA.

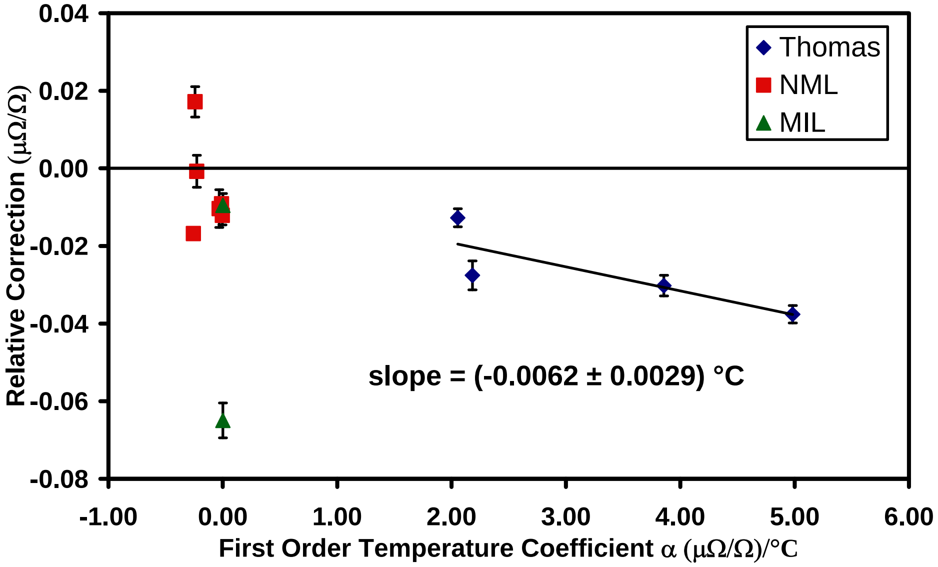

Figure 6. This shows the effect of the temperature coefficient, which tends to correlate with an increase in the power-loading difference for continuous power in Thomas-type resistors.

In Figure 6 the differences shown in Figure 5 are plotted versus the first order temperature coefficient, α. The data from the NML and MIL resistors exhibited no obvious correlation with α, however the data from the Thomas-type resistors did appear to have a linear fit to the data giving a slope of (-0.0062 ± 0.0029) °C. For Thomas-type precision 1 Ω resistors the value of resistance increases with temperature around 25 °C.

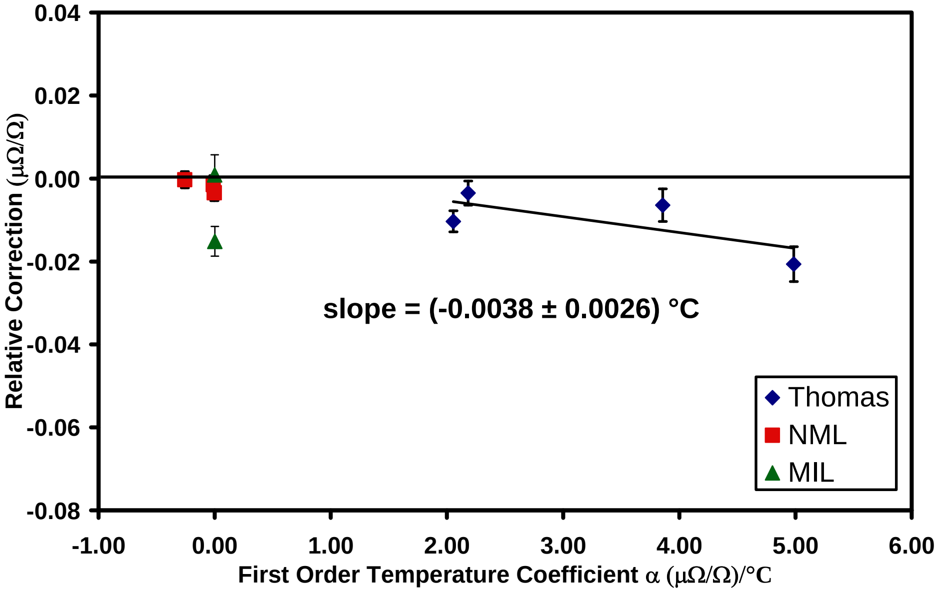

Figure 7. Difference between data from "cold start" and continuous power at 50 mA versus the first order temperature correction , α.

The Thomas II system was reconfigured to operate at 50 mA. Measurements were taken for several weeks to establish baseline values at 50 mA. Then the power tests were performed exactly as in the case of 100 mA current. Figure 7 is a plot of the results at 50 mA. Again, only with the Thomas-type resistors is there a relationship between the difference and the first order temperature coefficient. As expected, since the current level is half that at 100 mA, the amount of self heating and hence the difference at any given α is less than what it was at 100 mA. In this case the slope is (−0.0038 ± 0.0026) °C at 50 mA, with power dissipation in the resistor element that is 25 % of that at 100 mA.

As discussed above, the Thomas II system was operated at 50 mA and at 100 mA. After the tests with a modified duty cycle were completed at 50 mA, this system was returned to operation at 100 mA. The resistance values at 50 mA showed some significant differences from the before and after data at 100 mA. The plot of the data, shown in Figure 8, is similar to the data depicted in Figure 7. As in the previous tests, there does not appear to be any obvious pattern or relationship for the NML and MIL resistors. The Thomas-type resistors show a marginal effect, but there does appear to be a significant correlation between this difference and the TCR alpha.

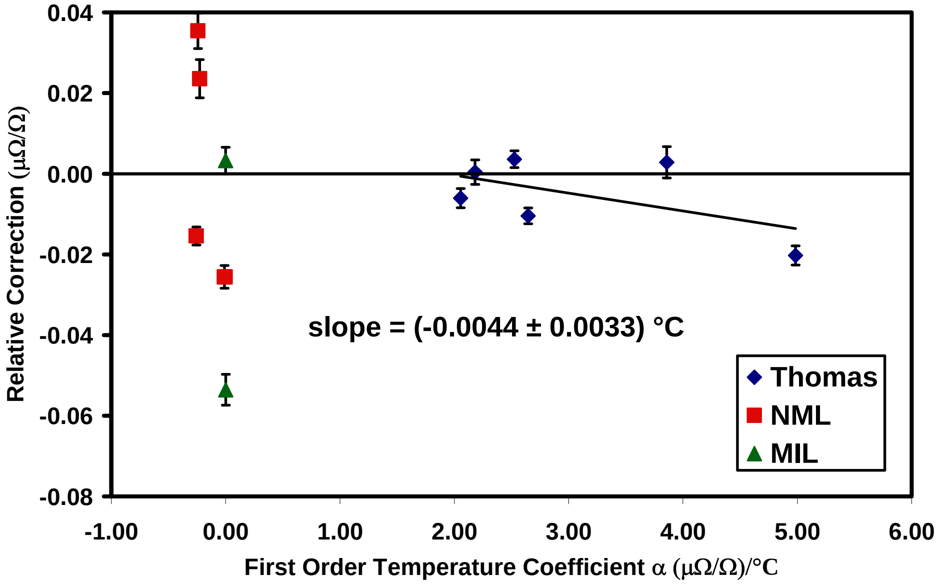

Figure 8. Difference between data at 50 mA and 100 mA versus the first order temperature correction, α.

3.3. Auxiliary Bath Tests

This auxiliary bath has been used to determine the temperature coefficients of a variety of resistors [1], however in those measurements only the relative differences between values at different temperatures were considered to be significant. In the present case the absolute value of the measurements between the main and auxiliary baths was examined. As in the other experiments several types of resistors were tested. First a base line was established by measuring the resistors in the main bath of the Thomas I system. Then the resistors were placed within the auxiliary bath and measured for several weeks using Thomas I. Finally the resistors were returned to the main bath and measured again. The data (see Figure 9) again shows some correlation with the first-order temperature coefficient α for the Thomas-type resistors.

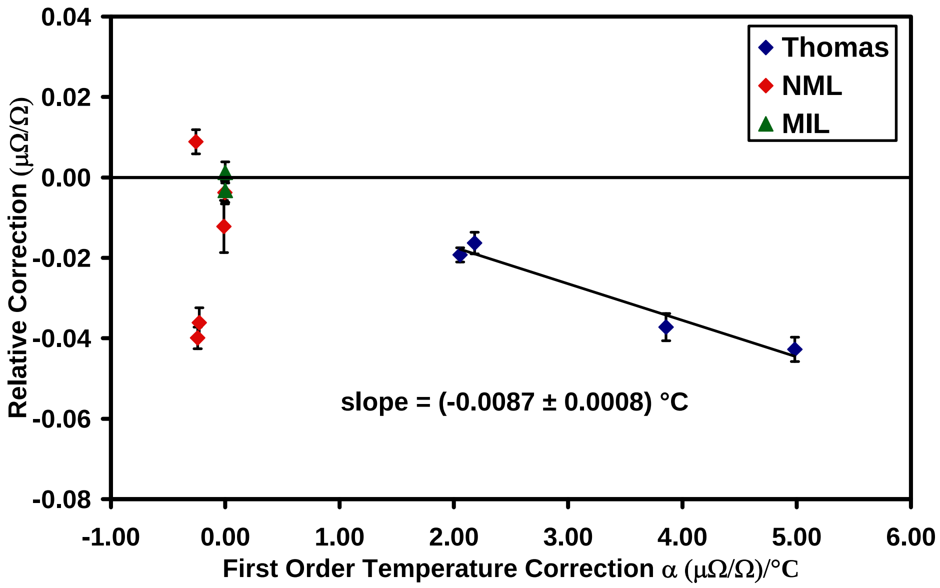

Figure 9. Differences between data from auxiliary bath and main bath of the Thomas I system versus the first order temperature correction , α.

5. Discussion and Summary

We have conducted a number of experiments to determine the relationship between measured resistor values and power loading for various types of resistors. Figure 10 is a summary plot of the various power loading tests that were performed on the different types of resistors. In general, lower power levels lower duty cycle, or measurement from a cold start gives values of the resistance that are lower than those obtained by measuring the resistors under the full 100 mA current. Also, in general, placing the resistors in an auxiliary oil bath with increased oil flow tends to lower the measured value of the resistors. However, this is not a universal condition. The NML resistors 60906 and 60659 actually showed a significant increase in the value of the resistance at lower power levels. These resistors do have a negative first order temperature coefficient, −0.2421 (μΩ/Ω)/°C and −0.2274 (μΩ/Ω)/°C respectively, so this is the direction one would expect. However, these coefficients are approximately an order of magnitude less than those of the Thomas-type resistors and do not fully explain the large discrepancies in the measurements of 60906 and 60659 or why the resistance values decreased by such a large amount when placed in the auxiliary oil bath. Further, resistor 60657 has a first order temperature correction of −0.2572 (μΩ/Ω)/°C, yet does not exhibit the same behavior.

Two other NML resistors, 64173 and 64177, have first order temperature coefficients of −0.0034 (μΩ/Ω)/°C and −0.0113 (μΩ/Ω)/°C. The MIL resistors 1030603 and 1030607 have coefficients alpha of 0.0003 (μΩ/Ω)/°C and 0.0006 (μΩ/Ω)/°C, orders of magnitude less than those of the Thomas-type resistors. However, these resistors exhibit differences in our measurements that in some cases exceeded the variations seen in the Thomas-type resistors. One explanation for these observations is tied to the fact that temperature gradients are set up in the resistance elements by the increase in power dissipation. The Evanohm resistance elements may be less homogeneous than the Manganin resistance elements, producing greater variation of the TCR in different sections of the wire. The product of TCR and the change in temperature, taken for different sections of the resistance element, may be larger in the Evanohm type resistors in some cases.

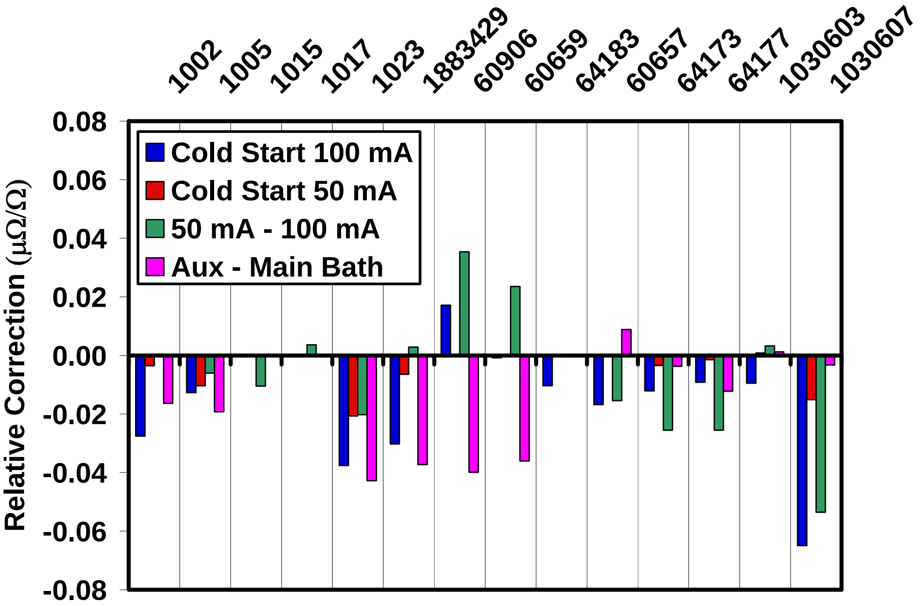

Figure 10. Summary of various power experiments on precision resistors, with the baseline being the DCC measurement condition with power on continuously. For the data labeled “Cold Start 50 mA, the baseline is measured value with power on continuously at 50 mA.

The value of precision 1 Ω resistors is affected both by how the power is applied to the resistors and how it dissipates. This can lead to detectable variations of several parts in 10^8, and there does not appear to be a clear method by which one can predict the behavior of a particular resistor for the sample tested. One exception is the Thomas-type resistor, where the larger the first order temperature correction, the larger the difference due to power effects. Thus the differences in the Thomas-type resistors appear to be dependent on the first order temperature coefficient of the resistors. A recommendation would be to maintain the measurement current continuously in Thomas-type resistors for at least 15 min before they are measured, to obtain the best agreement with the NIST calibration value.

The discrepancies in the CCC data are a more pressing concern at NIST since for fundamental reasons, the ramping method for the application of current cannot be changed. The CCC is based on a superconducting quantum interference device (SQUID) sensor that cannot track fast changes in the measurement current. This study indicates that by using several NML type resistors, an average result can be obtained that shows good agreement between the DCC and CCC systems. For approximately 20 years, NIST has been using NML resistors 60906 and

60659 as transfer standards from the QHR to the 1 Ω reference bank. In early 2007, we added NML standard 64183 to the process, transferring the QHR reference value through all three of these NML resistors. Recent international comparisons indicate that both of these processes give good agreement with other National Measurment Institutes (NMIs) [4,5].

6. References

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