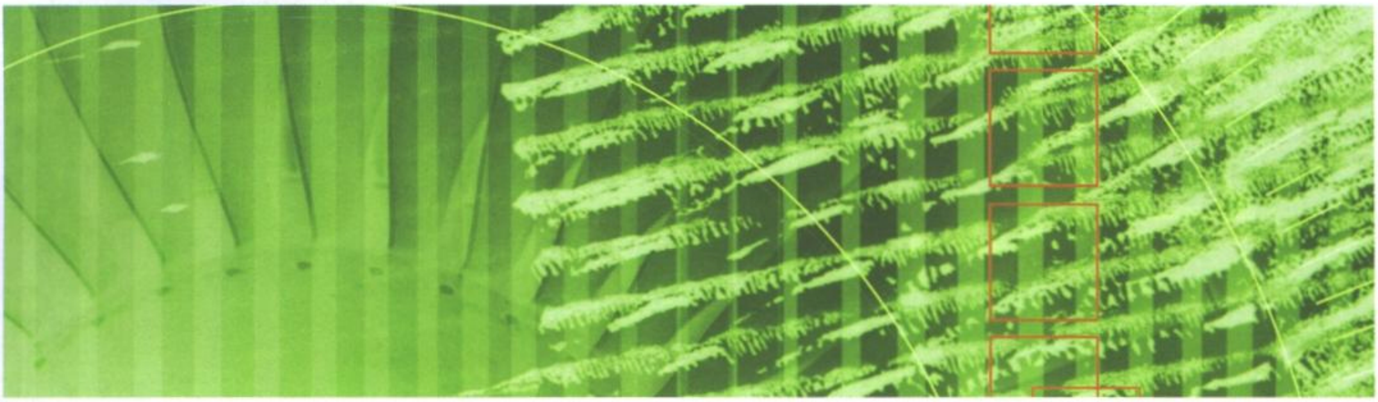

Temperature and Pressure Coefficients of Resistance for Thomas 1 Ω Resistors[1]

George R. Jones and Randolph E. Elmquist

Abstract: While preparing to move the precision 1 Ω resistance measurement service to the new Advanced Measurement Laboratory (AML) in the spring of 2004, staff at the National Institute of Standards and Technology (NIST) first assembled a second precision 1 Ω measurement system in the AML. This allowed the calibration service to continue uninterrupted during the transition. Both systems are fully automated and all calibrations include the measurement of laboratory "influence factors" including bath temperature and atmospheric pressure. Over the past year additional components have been added to these two systems that enable NIST to characterize the behavior of precision 1 Ω resistors over a wide range of temperatures and pressures. These modifications include both an auxiliary thermal oil bath and a pressure chamber, each having capacity for up to three precision 1 Ω resistors. Approximately 20 resistors have gone through a battery of thermal and pressure tests at temperatures from 20 °C to 26 °C and at pressures from 80 kPa to 110 kPa (11.6 psi to 16.0 psi). Tests have shown that some Thomas-type resistors experience non-reversible shifts in their values due to pressure changes.

1. Introduction

In the spring of 2004, the Quantum Electrical Metrology Division at National Institute of Standards and Technology (NIST) was preparing to move the precision 1 Ω measurement system [1] into laboratory space in the new Advanced Measurement Laboratory (AML) building. The system had to be completely dismantled, transported, and reassembled at the new site. Once operational, measurements had to be taken to ensure that no significant shifts in the values of our standard and control resistors had occurred due to changes in the physical configuration of the system, or due to transportation of our working standards. We also decided that various components should be replaced with more modern equipment during this transition. We estimated that it would require at least two to three months to meet all of these requirements and for the customer calibration service to be operational in the AML.

To prevent any loss in calibration services, a second precision 1 Ω measurement system was constructed in the AML and brought to operational condition before the original system was moved. This was accomplished by rebuilding an auxiliary measurement system which had

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been used in the past to calibrate precision 100 Ω resistors. Since the two systems were based on similar direct current comparator bridges and used automatic switching and a substitution method to calibrate resistors, the transformation was reasonably straightforward. The new equipment included nanovolt detectors, relay scanners, and temperature and pressure measurement instruments. In addition, new control and analysis software was developed using Visual BASIC.net.[3]

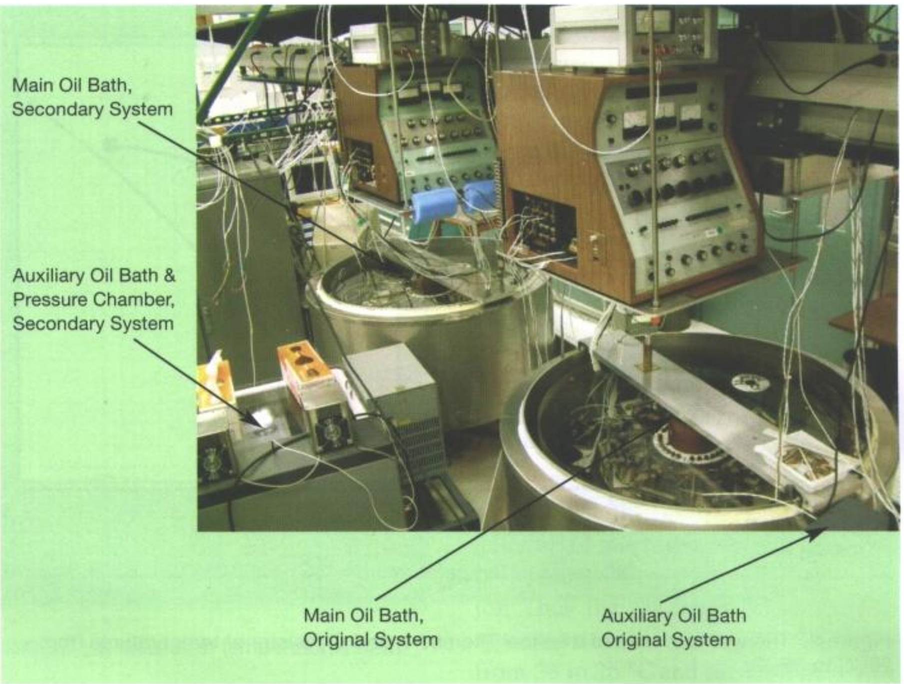

Figure 1. Picture of the physical apparatus for the two Thomas 1 Ω measurement systems.

Once the second system was functioning correctly, a new set of standard 1 Ω reference resistors had to be selected for this system. Three standard resistors were chosen from a group of 1 Ω resistors that had been measured over time using the original measuring system. Using this new set of standard resistors, we determined that differences in the measured value of a significant number of precision 1 Ω resistors interchanged between the two systems were less than a few parts in 10^9. This allowed us to transfer customer calibrations over to the second system, and to disassemble and move the original 1 Ω system into the AML. The original system also was upgraded with new equipment to make both systems as identical as possible. The original system was placed back into calibration service once the measured values of the working standards and control resistors used in this system were determined to be within a few parts in 10^9 of their predicted values as calculated from measurements performed before the system was moved. As a result, NIST now has two precision 1 Ω systems capable of simultaneously calibrating 33 resistors with an expanded uncertainty of 0.04 μΩ/Ω (2σ) or better.

NIST provides calibration services for a variety of 1 Ω resistors. The uncertainty assigned to Thomas-type resistors [2] by NIST is 0.04 μΩ/Ω (2σ) at a measurement current of 100 mA. The precision oil-type Thomas standards include Leeds and Northrop[2] (L&N) 4210 and Measurement International[2] (MI) 9210A. For other 1 Ω resistors (including air-type and Rosa-type [3]), an automatic commercial current comparator calibration system is used and the assigned expanded uncertainty is 0.3 μΩ/Ω (2σ). NIST also has the capability to calibrate certain ac/dc resistors at reduced dc measurement currents from 1 to 20 mA with an assigned expanded uncertainty of 0.3 μΩ/Ω (2σ).

2. Determination of Temperature and Pressure Coefficients of Resistance at NIST

2.1 Past Measurements and Present Requirements at NIST

To achieve the lowest uncertainty in a calibration of L&N Thomas-type standards, corrections due to temperature and pressure variations must be applied to the measured resistance values. Usually, in a customer resistor these coefficients are unknown. Prior to 1986 these coefficients were determined for the working standards and control resistors used in the original measurement system at NIST. This allowed NIST to correct for temperature and pressure influences in the measured value of the standards and thus reduce the measurement uncertainty assigned to customer resistors.

The determination of the thermal (TCR) and pressure (PCR) coefficients of resistance for precision 1 Ω resistors has been offered for many years by NIST as a special test. [4] However, these tests required prior arrangements and the temporary inclusion of various components into the measurement system, thereby increasing both the measurement uncertainty and the time required for the calibration. The new measurement systems allow NIST to offer customers the determination of the pressure or temperature coefficient of a resistor within a reasonable time frame of four to six weeks, including the precision resistor calibration at 25.0 °C.

2.2 New Systems Used to Determine Temperature and Pressure Coefficients of Resistance

To facilitate the determination of the temperature and pressure coefficients of resistance, several auxiliary subsystems were permanently incorporated into the measurement apparatus during the move

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[3] 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.

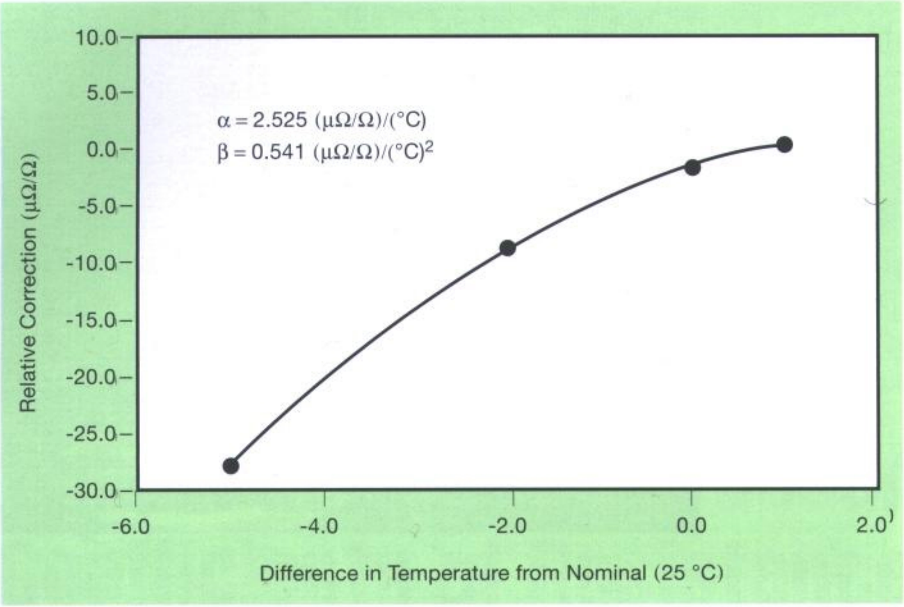

Figure 2. Thermal response of a typical Thomas-type 1 Ω resistor at temperatures from 20 °C to 26 °C.

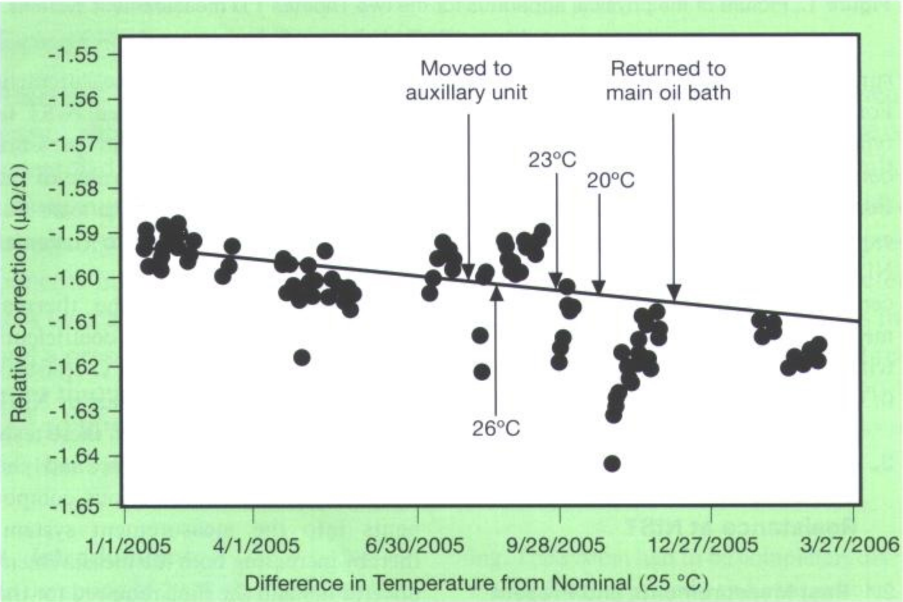

Figure 3. The 25 °C behavior of a typical Thomas-type resistor during thermal tests at various temperatures.

and reconstruction. A small oil bath for TCR characterization was placed next to the main oil bath of the original system (TCR system). A sealed pressure chamber immersed in an additional oil bath was located next to the second system. Both of the auxiliary subsystems have current and potential leads for up to three resistors. The measurement and analysis software was updated to include options specific to the various thermal and pressure tests that could be performed.

Before a resistor was placed within a particular test subsystem, it was first measured at a temperature of 25 °C and atmospheric pressure in the main oil bath of the respective system. This established a base resistance value for the resistor under test within that particular system. Once a resistor was placed within an auxiliary subsystem, it was again measured at 25 °C and at atmospheric pressure to ensure that shifts in the value of the resistor (either actual or due to positional effects due to the measurement system) had not occurred. Since the resistor was being measured by the same physical apparatus each time, differences between the parent and subsystem should be less than several parts in 10^9.

3. Resistor Thermal Tests

In order to perform thermal tests, the resistor under test is moved from the main oil bath into the auxiliary oil bath. The depth of the oil in the auxiliary bath is different from that of the main bath so the pressure correction to the resistance value is changed accordingly. After the initial measurements at 25 °C have been finished, the temperature in the auxiliary bath is adjusted and held at temperatures ranging from 20 °C to 26 °C. Measurements are made at each temperature for at least a week to check for any drift in the resistance value at the new temperature. Usually, between tests at a particular temperature, the auxiliary oil bath is returned to 25 °C or the resistor under test is returned to the main oil bath at 25 °C. This checks for any possible permanent shifts in the resistance values due to the thermal cycling.

The thermal response for a typical Thomas-type 1 Ω resistor is given in Fig. 2. At NIST the first order temperature correction coefficient is designated by α, and the second order by β. The values of 2.525 (μΩ/Ω)/(°C) for α and –0.541 (μΩ/Ω)/(°C)^2 for β are typical for the Thomas-type resistor. The largest values of α in the group of fourteen Thomas resistors tested were 3.05 (μΩ/Ω)/(°C) and 4.98 (μΩ/Ω)/(°C). The average value of α for the group of fourteen Thomas type resistors was 2.735 ± 0.841 (μΩ/Ω)/ (°C) and the average value for β was -0.526 ± 0.018 (μΩ/Ω)/(°C)^2. The estimated uncertainty in the measured TCR of a resistor is approximately 6.4×10^{-9}/°C for α and approximately 1×10^{-9}/(°C)^2 for β.

Figure 3 shows the 25 °C resistance values of the same test resistor as in Fig. 2 when it was brought back to 25 °C during and after the thermal tests. The arrows indicate the temperature and time frame of the test resistor. The straight line is the best fit through the measured resistance data for this resistor before thermal tests began. As with all resistors there is a temporal drift in the 1 Ω resistance value. The resistance value did tem-

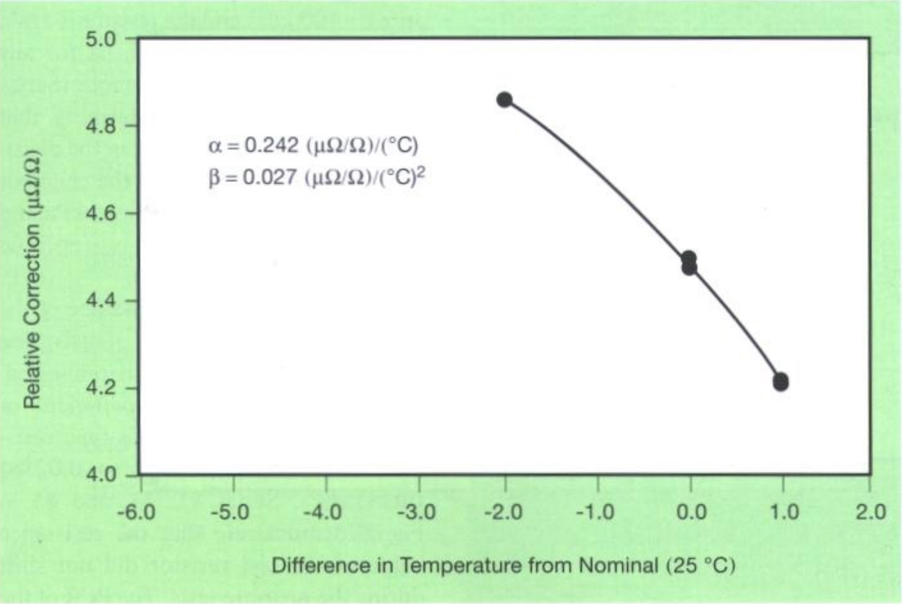

Figure 4. Thermal response of a typical NML Evanohm 1 Ω resistor at temperatures from 23 °C to 26 °C.

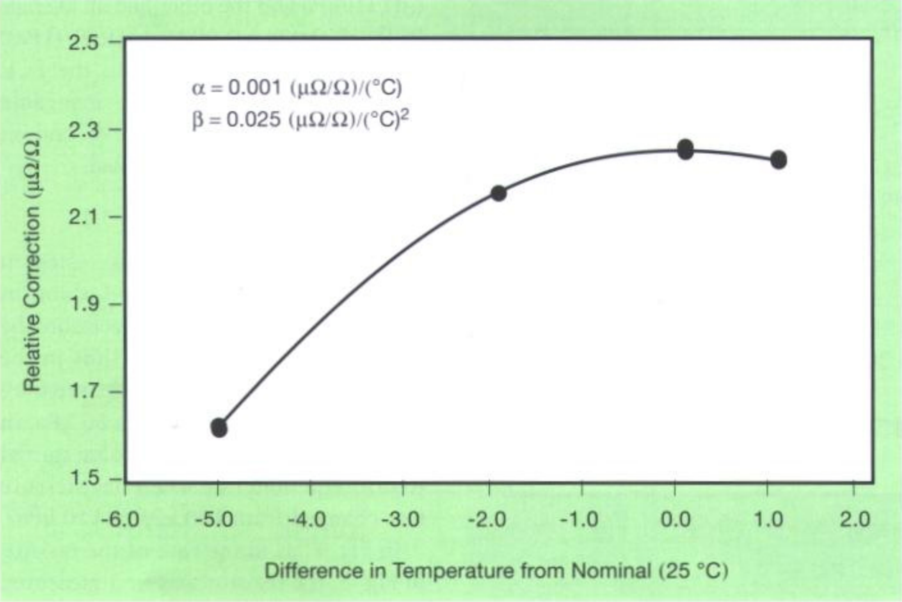

Figure 5. Thermal response of a typical MIL model 9210A Evanohm 1 Ω resistor at temperatures from 20 °C to 26 °C.

porally shift after the resistor had been tested at a temperature other than the nominal temperature maintained at NIST (25 °C). However, in time the resistor returned to the value expected from the base line data collected before the thermal tests were started. The longest time required to return to the expected value was approximately a month after the resistor had been tested at 20 °C for approximately two weeks. Also note that after the 26 °C measurements, the resistance value was higher that the expected value, while after both the 23 °C and 20 °C measurements, the resistance value was below the expected value. In both cases, the resistance slowly returned to a value near the expected value. Before measuring a customer's resistor, NIST usually maintains the resistor in the 25 °C oil bath for a week before starting resistance measurements. This is done to minimize potential thermal drifts due to any temperature shock the resistor received during shipment to NIST.

NIST has also tested several resistors constructed using Evanohm[4] wire. These resistors typically have smaller thermal coefficients of resistance (TCR) than the Manganin wire used in the L&N Thomas-type resistors. These newer resistors were acquired from the Australian National Measurement Laboratory (NML, now part of the National Measurement Institute) and Measurements International Limited (MIL).

Figure 4 demonstrates the typical thermal response of the two NML resistors [5] NIST has tested. As can be seen when comparing these data to Fig. 2, the thermal coefficients are approximately an order of magnitude smaller than that of the Manganin wire Thomas-type resistor. Thus the Manganin wire Thomas-type resistor changes about 28 μΩ/Ω from 20 to 26 °C and the Evanohm wire Thomas-type resistor changes only 0.6 μΩ/Ω from 23 to 26 °C

Early measurements of the MIL model 9210A resistors acquired by NIST indicated that these resistors had negligible thermal coefficients of resistance. These measurements were accomplished using the original measurement system at NIST. It should be noted that the MIL resistors are only a few years old and therefore could have temporal drifts that are less predictable than older standards. The typical thermal response of a NIST-owned MIL 1 Ω Thomas-type resistor is given in Fig. 5. The first order coefficient is insignificant (four orders of magnitude smaller than that of the Manganin wire Thomas-type resistors). Further testing at lower temperatures will be completed by the summer of 2006. These resistors will also undergo pressure tests.

4. Resistor Pressure Tests

4.1 Normal Resistors

The pressure chamber is an air-tight aluminum box that can be sealed and connected to the laboratory pressure and

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[4] Evanohm is a commercial alloy with a resistivity of about 1.34 μΩ–m with a nominal composition of 75% Ni, 20% Cr, 2.5% Al. By suitable annealing and heat treatment, its temperature coefficient of resistance (TCR) can be adjusted to nearly zero from 20 °C to 30 °C.

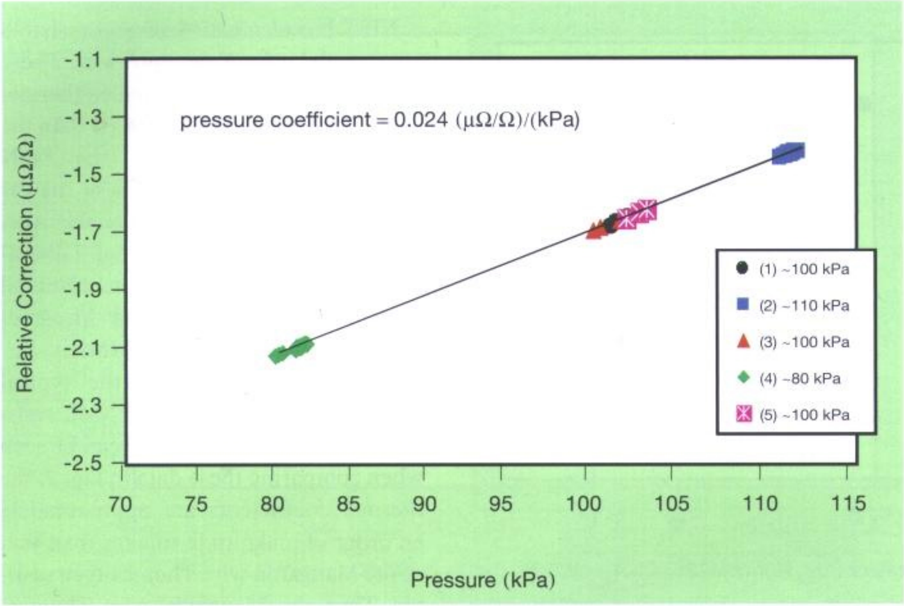

Figure 6. Pressure response of a typical Thomas-type 1 Ω resistor at pressures from 80 kPa to 110 kPa.

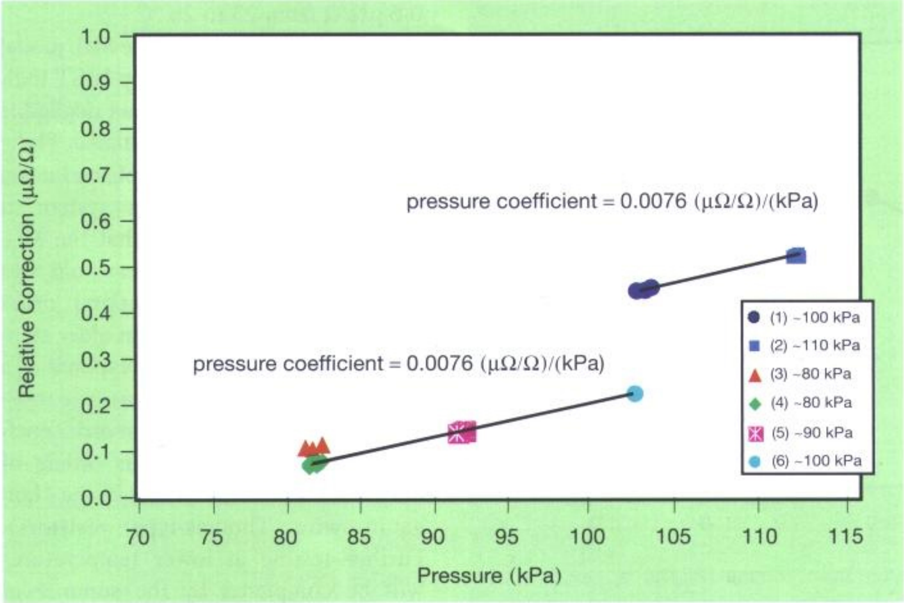

Figure 7. Pressure response of a Thomas-type 1 Ω resistor exhibiting a permanent shift in the resistance value as the pressure was reduced from 110 kPa to 80 kPa.

vacuum lines. Up to three resistors can be placed within the chamber, which is filled with enough mineral oil to completely cover the resistors to a depth of 65 mm above the top of the resistors. Once the resistors are in place, the chamber is completely immersed in an oil bath maintained at 25 °C.

The pressure response for a typical Thomas-type 1 Ω resistor is shown in Fig. 6 where the pressure is varied from 80 kPa to 110 kPa (11.6 psi to 16.0 psi). As with the thermal tests, initial measurements are made to ensure that shifts in the resistor values had not occurred during the move to the pressure chamber and to establish a base-line resistance value for the test resistors in this subsystem. This is accomplished by taking measurements at our laboratory pressure of approximately 100 kPa (Series #1 in Fig. 6). The pressure is then increased to approximately 110 kPa with measurements taken over a period of 10 to 14 days (Series #2 in Fig. 6). The chamber is then brought back to atmospheric pressure (≈ 100 kPa) and the resistor is again measured for a week to check for any permanent shifts in the resistance (Series #3 in Fig. 6). After establishing that there is no appreciable shift in the resistance value, the pressure in the chamber is reduced to approximately 80 kPa and the measurement cycle is repeated (Series #4 and #5 in Fig. 6).

This particular resistor had one of the higher pressure coefficients of resistance of the Thomas-type 1 Ω resistors tested. Values of the pressure coefficient of resistance for other Thomas-type resistors varied from (0.0027 to 0.0238) (μΩ/Ω)/kPa. Series #1, #3, and #5 in Fig. 6 demonstrate that the resistance value of the test resistor did not shift during the pressure tests. The PCR of the tested resistors tended to fall between two distinct values. One set had an average PCR of 0.005 ± 0.001 (μΩ/Ω)/kPa and the other had an average PCR of 0.024 ± 0.0001 (μΩ/Ω)/(kPa). This second value is close to the PCR (0.23 (μΩ/Ω)/(kPa) of bare manganin wire. It is probable that these second set of resistors are no longer sealed.

4.2 Anomalous Resistors

Not every resistor that was tested at NIST behaved in the linear fashion as shown in Fig. 6. On one occasion the resistor exhibited a sudden shift in the value of the resistance when the pressure was reduced from 110 kPa to 80 kPa. In another case, the resistance value started to drift at a high rate when the pressure was changed from 100 kPa to 110 kPa.

In Fig. 7, as in the case of the resistor in Fig. 5, the resistor was first measured at the atmospheric pressure of the laboratory (Series #1 in Fig. 7). When the pressure was increased to approximately 110 kPa, the resistance value increased similarly as to that of Fig. 6 giving a pressure coefficient of resistance equal to 0.0076 (μΩ/Ω)/(kPa). However, when the pressure was reduced to approximately 80 kPa, the resistance value dropped below what would have been expected if the effects due to pressure had been linear (Series #3 in Fig. 7). Furthermore, after several days of measuring this resistor, the resistance value shifted again to that represented by Series #4 of Fig. 7. The pressure was increased to

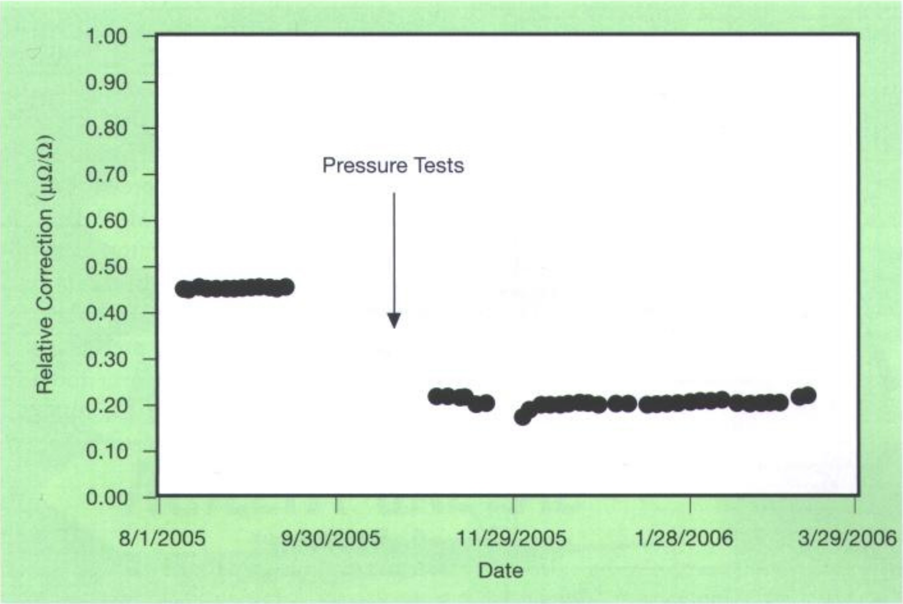

Figure 8. Resistance value before and after pressure tests that resulted in a permanent shift in the value of the resistor.

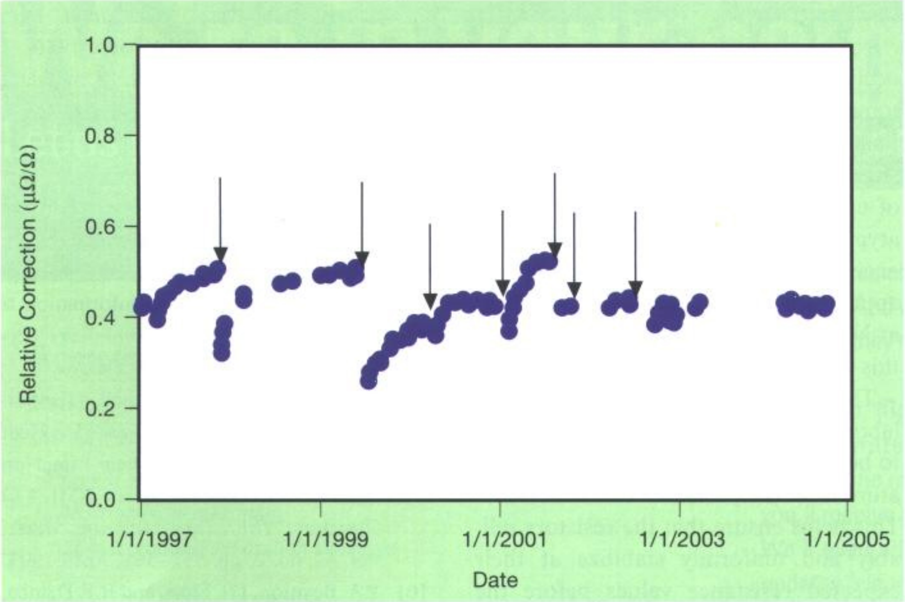

Figure 9. Resistance value over time of the resistor in Figs. 6 and 7. The arrows indicate periods of time where MAP transfers took place.

approximately 90 kPa (Series #5 in Fig. 7, and then brought back to atmospheric pressure (Series #6 in Fig. 7.) Using the data in Series #4 thru #6, the pressure coefficient of resistance was 0.0076 (μΩ/Ω)/(kPa), the same value that was derived from the first sets of data (Series #1 and #2 in Fig. 7).

The resistor was responding to pressure as it had initially, however there had been a permanent shift in the value of the resistor as shown in Fig. 8. After four months at our nominal laboratory pressure of approximately 100 kPa this particular resistor has not returned to the previous value. In a continuation of this experiment additional pressure tests will again be performed on this resistor to learn whether there will be another shift, or if this was a one-time mechanical relaxation. It should be noted that two additional resistors which underwent the exact same measurement procedure as that of the resistor in Fig. 7 did not exhibit any anomalous behavior but reacted in a similar manner as shown in Fig. 6.

The resistor in Figs. 7 and 8 had been used in the past as one of four Thomas type resistors used in the NIST Measurement Assurance Program (MAP). [6] Examining our data back to 1997 for this resistor did indicate that the correction from nominal for this resistor on some occasions shifted its value down by several parts in 10^7 after being transported to another laboratory (Fig. 9). Further, it took up to twenty months before the resistor stabilized. However, the resistor did not exhibit this behavior following its use in two MAPs after the start of 2002.

In a second case, as usual, the base resistance value was first determined by measuring the resistor at approximately 100 kPa. When the pressure was increased to 110 kPa the value of the resistance immediately started to drift at a rate of 0.17 (μΩ/Ω)/month as shown in Fig. 10. The resistance value of the resistor stabilized when the pressure was reduced back to approximately 100 kPa. The resistor was then removed from the pressure chamber and placed within the main oil bath of the original measuring system. It is clear that the value of this resistor has also been permanently shifted as in the previous example. This resistor is also undergoing a second round of pressure testing.

5. Conclusions

NIST has developed measurement systems that can accurately, and relatively rapidly, determine the temperature and pressure coefficients of resistance for precision 1 Ω resistors. Our experiments have demonstrated that 12 of the 14 Thomas-type resistors behaved in a predictable manner. By using well characterized resistors, temperature and pressure effects in interlaboratory comparisons should be reduced to insignificant values. However, it should be noted that depending on the severity and length of a potential temperature shock during transportation, Thomas-type 1 Ω resistors can require several weeks to fully equilibrate with the test temperature in a particular laboratory.

The MIL resistors exhibited much lower temperature coefficients of resistance than those of the Thomas-type resistors. However, the long term stability of

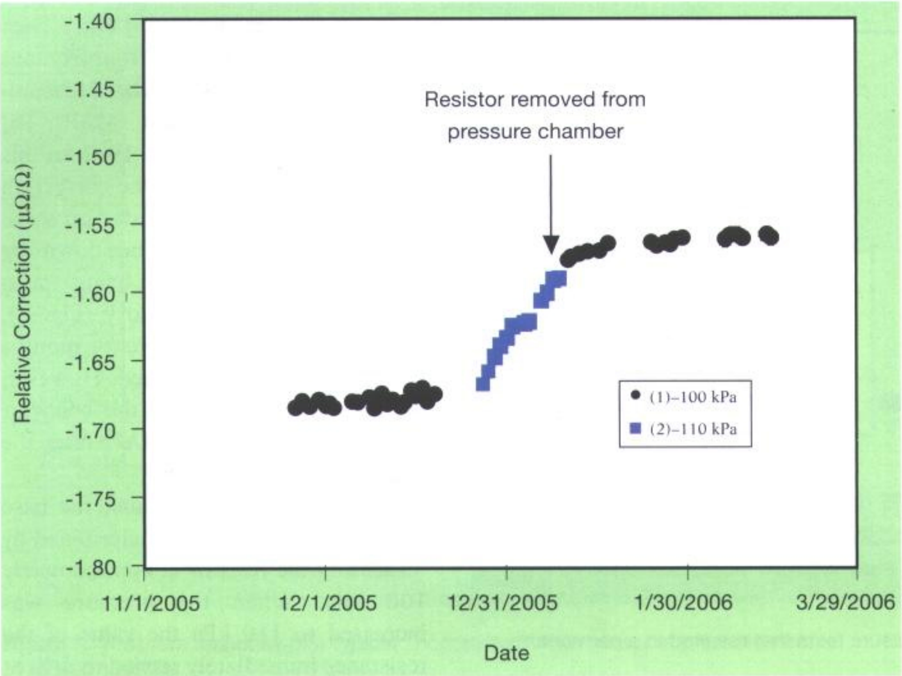

Figure 10. Resistance value before and after pressure tests that resulted in a permanent shift in the value of the resistance.

these resistors is as yet to be determined as both are fairly new. Also, the pressure coefficients of resistance for these resistors have yet to be determined.

Before this study, previous measurements of the two resistors which exhibited unusual pressure characteristics did not indicate that a change in pressure would result in a permanent shift in the value of the resistor. In recent measurements both resistors exhibited stability at 25 °C consistent with similar resistors at NIST. Perhaps the unusual characteristics signify some mechanical defect within the construction of the resistor. Further experiments will be performed to see if the cause of these behaviors can be determined.

The findings do stress the importance of being aware of the effects transportation can have on precision resistors. The pressure and temperature variations that occur during transportation of a customer's resistor to NIST are far greater than the day-to-day changes at the NIST site. We monitor the daily measurements of customer resistors and look for any atypical drift in the value of the resistance. If the value of a customer resistor appears to drift dramatically after arrival at NIST, we will notify the customer of this condition.

The resistors that NIST sends to other laboratories for the MAP program need to be checked for any abnormal temperature and/or pressure characteristics. This helps ensure that the resistors reliably and uniformly stabilize at their expected resistance values before the customer begins the MAP process. During the customer measurements, the customer records the temperature and pressure at their location. Once the resistors have been returned to NIST, we can make the necessary corrections to the resistance value due to the environmental conditions at the customer's location. The resistors now being used for the MAP program have undergone all the recent temperature and pressure tests. The requirements for the MAP program also extend to inter-laboratory comparisons between NIST and other primary standards laboratories. NIST will continue to test many of the precision 1 Ω resistors that we possess over the next year to fully characterize the different types of precision 1 Ω resistors that are available.

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