Stability of Double-Walled Manganin Resistors

The resistance standard described by James L. Thomas [1] was the result of his extensive effort to develop a new standard by systematically investigating every factor affecting the stability of resistance—time, surface effects, temperature, power, pressure—detectable at the time. The result was a unique standard which was used as part of the National Reference Group of resistors beginning in 1931. Ten of them served solely as the U.S. standard of resistance from 1939 until they were supplanted by the quantized Hall effect (QHE) in 1990. They still serve as working standards at the one ohm level and as a vital check on the QHE standard and the scaling used in the NIST resistance calibration service. The International Bureau of Weights and Measures used this standard to maintain the international unit of resistance, and numerous other national standardizing laboratories around the world used it as their primary standard. This is still largely true for laboratories without QHE standards.

In the period from 1935 to 1980, Thomas's standard provided a basis for evaluating the accuracy of ohm determinations, particularly to compare realizations based on calculable inductors with those based on Thompson-Lampard calculable capacitors. Thomas's standard was commercialized by the Leeds and Northrup Company and Honeywell, and these commercial versions are still used as primary resistance standards by many industrial and commercial standards laboratories, as well as the DOD primary and secondary metrology laboratories. NIST still routinely calibrates about 125 of them annually for domestic users. Thomas's standard remains the most stable resistor of any available, although two more modern designs are nearly a match in predictability.

Much of the research leading to this standard resistor design is described in an earlier paper by Thomas [2]. However, the paper *Stability of Double-walled Manganin Resistors* [1] is the more popularly known and describes the standard in its final form, after some major modifications in size and connections.

In the 1920s, Thomas had taken up the task of improving the long-term stability of wire-wound resistors, which were used to measure the current in absolute determinations. When a resistor is made by winding wire on a spool, parts of the crystalline structure of the wire are stressed past their elastic limit. Thomas developed wire-wound standard resistors that were annealed at high temperature, which released some of the internal strains and reduced the rate of change of resistance with time. Heat-treated manganin wire resistors developed by Thomas incorporated hermetically-sealed, double-walled enclosures, with the resistance element in thermal contact with the inner wall of the container to improve heat dissipation. These 1 Ω Thomas-type standards (see Fig. 1) proved to be quite stable with time [1,2], and quickly came into favor as the primary reference for maintaining the resistance unit at NBS and at many other national metrology institutes.

Work continued on improving the absolute measurements of electrical units and, in 1949, J. L. Thomas, C. L. Peterson, I. L. Cooter, and F. R. Kotter published a new measurement of the absolute ohm [3] using an inductor housed in a non-magnetic environment. Using the Wenner method of measuring a resistance in terms of a mutual inductance and a rate of rotation, their work gave a value of 0.999 994 absolute ohm for the new as-maintained unit of resistance at NBS. The mean value assigned to 10 Thomas-type standard resistors from this experiment was found to have been the same between 1938 and 1948 to within 1 μΩ/Ω. As Thomas *et al.* wrote in the 1949 paper, this was "the first satisfactory method that has been devised for checking the stability of the unit as maintained by a group of wire-wound resistors."

From 1901 to 1990, the U.S. Legal Ohm was maintained at 1 Ω by selected groups of manganin resistance standards. Four different types of resistance standards have been represented in these groups, whose numbers have varied from 5 to 17 resistors. From 1901 to 1909, the group comprised Reichsanstalt-type resistance standards made by the Otto Wolff firm in Berlin. These standards were not hermetically sealed and consequently underwent changes in resistance as a function of atmospheric humidity. In 1907 Rosa at NBS solved the problem by developing a standard whose resistance element is sealed in a can filled with mineral oil [4]. The U.S. representation of the ohm was maintained by 10 Rosa-type 1 Ω resistance standards from 1909 to 1930. Over the years, measurements of differences between the individual Rosa-type resistors indicated that the group mean was probably not constant. In 1930, Thomas reported on the development of his new design for a resistance standard having improved stability [2]. The Thomas resistance standards were more stable immediately following construction than the Rosa-type resistors and two were added to the

Fig. 1. A double-walled 1 Ω standard resistor of the Thomas type.

primary group in 1930. Eventually, in 1932, the Rosa-type resistors in the primary group were replaced by the Thomas resistors. To reduce loading errors, Thomas in 1933 improved the design of his resistor by using manganin wire of larger diameter mounted on a larger diameter cylinder to increase the dissipation surface area, as described in his paper [1]. A select group of the new-design Thomas resistors was used to maintain the U.S. Legal Ohm from 1939 until its re-definition in 1990 based on the quantum Hall effect.

The value of the U.S. representation of the ohm, or "Legal Ohm" maintained at NIST has been adjusted only twice. This occurred first in 1948 when the ohm was reassigned using a conversion factor relating the international reproducible system of units [3] to the precursor of the International System of Units (SI) derived from the fundamental units of length, mass, and time. The second occasion was in 1990 when the ohm became based on the quantum Hall effect. After 1960, ohm determinations were made using calculable capacitors based on the Thompson-Lampard theorem and a sequence of ac and dc bridges. Then came the discovery of the QHE in 1980, which has provided an invariable standard of resistance based on fundamental constants. Consequently, on January 1, 1990 the U.S. Legal Ohm was re-defined in terms of the QHE, with the internationally-accepted value of the quantum Hall resistance (or von Klitzing constant, after the effect's discoverer) based on calculable capacitor experiments and other fundamental constant determinations. At that time, the value of the U.S. Legal Ohm was increased by the fractional amount 1.69×10^{-6} to be consistent with the conventional value of the von Klitzing constant [5].

Shortly after the discovery of the QHE, NBS developed a system based on the QHE to monitor the U.S. Legal Ohm, then maintained by five Thomas-type resistance standards, with a relative uncertainty of a few times 10^{-8} [6]. This system consisted of a constant current source, a potentiometer, and an electronic detector. The current source energized the QHE device and a series-connected reference resistor of nominal value equal to the Quantum Hall Resistance (QHR). With the potentiometer balancing out the nominal voltage across either resistance, the detector measured the small voltage difference between the QHE device and reference resistor. Scaling down to the 1 Ω level was accomplished using specially-constructed Hamon transfer standards.

Since January 1, 1990, the maintenance of the U.S. Legal Ohm has been based officially on the QHE. However, the complexity of the experiment and "odd-value" resistance of the QHR does not make it practical for the routine support of resistance measurements where comparisons are normally made on standard resistors of nominal decade values. Therefore, banks of 1 Ω, 100 Ω, and 10 kΩ standard resistors maintain the ohm between QHR measurements.

Today NIST provides a calibration service for standard resistors of nominal decade values from 10^{-4} Ω to 10^{14} Ω. To achieve low uncertainties, eight measurement systems have been developed that are optimized for the various resistance levels [7]. Over the years from 1982 to 1997, six of the systems, covering the full 19 decades of resistance, have been automated. The main methods of comparing standard resistors for NIST calibrations utilize direct current comparator (DCC) bridges and resistance-ratio bridges.

An unknown standard resistor is indirectly compared to a reference bank of the same nominal value using the substitution technique, where the unknown and reference resistors are sequentially substituted in the same position of a bridge circuit. A robotic switching device is shown in Fig. 2. This technique tends to cancel errors caused by ratio non-linearity, leakage currents, and lead and contact resistances. To verify that the values of the reference banks are consistent with the QHR, scaling measurements are completed periodically proceeding from the 1 Ω, 100 Ω or 10 kΩ banks, whose values are based on recent QHR determinations, to the other reference banks. The up or down scaling is done in steps of 10 or 100 using either a CCC bridge, Hamon transfer standards, or DCC bridge.

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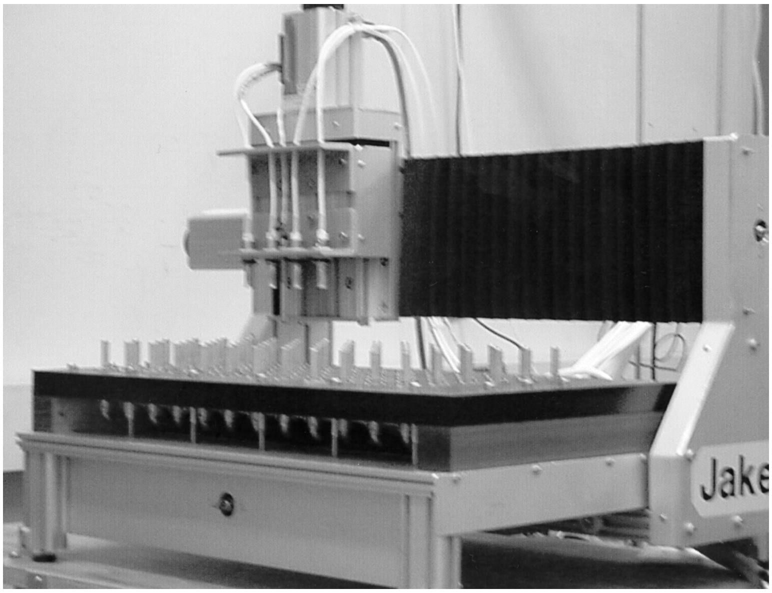

Fig. 2. Photograph of a programmable guarded switching system used in calibrating customers' resistors. The robotic translation stage moves in three axes to accomplish its switching function and has whimsically been named "jake."

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