Experimental Verification of the Five-Terminal Ten-Kilohm Resistor as a Device for Dissemination of the Ohm

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Abstract—**An experimental evaluation of five-terminal 10-kilohm hermetically sealed standard resistors as interlaboratory (transport) standards indicates that the typical drift is +0.4 ppm per year; the effects of mechanical shock to 100 G and of vibration up to 10 G at 80 Hz, less than 0.1 ppm; the effect of hot shock to 65°C, less than 0.1 ppm after five days recovery; the effect of cold shock to −20°C, less than 0.1 ppm; the effect of temperature, applying corrections, 0.06 ppm over the range 18 to 28°C, and ignoring corrections, 0.92 ppm over the range 20 to 26°C.**

Greater precision of comparison can be achieved at the 10-kilohm than at the 1-ohm level.

Incidental to the test, agreement among the values of the ohm as derived from the computable capacitor at NSL, Australia, and from the national standards at NBS (USA) and NRC (Canada) were found to be within 0.3 ppm of the expected values from data published by the International Bureau of Weights and Measures.

Background

A RESISTANCE measurement system consists of a physical standard (or standards) representing the unit (ohm) and apparatus to determine the ratio between the unknown and the standard. Any number of substandards and pieces of apparatus may intervene, and they may be in various locations and operated at different times. However, in the end, all that the substandards in the measurement system represent are memory devices to carry ratios through the operation. For if we let S = the standard, S_1, S_2, etc., the substandards, r_1, r_2, etc., the respective ratios down the chain, and X the unknown, then

$$S_1 = Sr_1, \quad S_2 = S_1 r_2, \text{ etc., and } \quad X = S_n r_{n+1}.$$

Then

$$X = Sr_1 r_2 \cdots r_{n+1}.$$

It is, therefore, possible to create a resistance measurement system that relies upon an optimized standard to represent the legal unit and accurate ratio devices to permit comparison of the standard and the unknown.

For thirty years, the Thomas-type 1-ohm resistor has been foremost among the resistance standards. Accurate ratio methods founded upon series to parallel networks have very high ratio accuracy, almost independent of the long-term stability of the resistors in the networks. The Drysdale device, used to establish ten-to-one ratio corrections in the Wenner bridge technique [1], and the Hamon device [2]–[4] are two examples. Furthermore, as these ratio accuracies may be verified without reference to the national units, there is no need to establish traceability through NBS testing.

In using a system based upon a group of Thomas-type 1-ohm resistors, we have found a limitation of the system accuracy associated with the characteristics of the standard when in use, namely,

1) at the low impedance of 1 ohm, significant power must be dissipated to raise the error signal output above the noise level of the measuring system;
2) as the temperature coefficient of resistance is significantly high, the resistance of the standard is dependent upon the measurement power.

The interaction of these characteristics can be simply stated: the Thomas-type 1-ohm resistor has a significant power coefficient in normal use. The outstanding merit of the device is its proven long-term stability [5], [6], which is not compatible with a flat temperature-resistance curve in the room-temperature range. The manganin alloys with a zero temperature coefficient of resistance as low as 25°C are, unfortunately, not stable [7].

The problem at the 1-ohm level can be reduced by increasing detector sensitivity and lowering the interferences. However, construction of a new interlaboratory reference standard seems desirable.

The advantages of the 10-kilohm value for a transportable standard have already been discussed [8]. In summary, they are

1) 10-kilohm resistors can be easily and accurately compared by conventional bridge techniques
2) they are not seriously affected by reasonable values of either lead-and-contact resistance or leakage resistance
3) normally encountered thermal EMFs have negligible effects on measurement accuracies
4) the value is near the geometric center of the range of accurate resistor values
5) it is convenient for calibration in computable capacitor derived absolute values [6].

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To serve as an interlaboratory or dissemination standard, the device used should have a highly reproducible value at both ends of an intercomparison, despite the intervention of the passage of time and the vicissitudes of transportation, and the use of different measuring systems in different laboratories.

The Experimental Program

A. Purpose

The purpose was to evaluate a new 10-kilohm standard resistor as a device to disseminate an otherwise defined ohm by observing

1) reproducibility of measured value with respect to
   a) ambient temperature
   b) shock and vibration
   c) humidity and pressure
2) stability with respect to
   a) time
   b) position
   c) temperature history.

B. Method

1) Reproducibility of measurements factors:
   a) determine α and β in the formula

$$R_t = R_{23} \cdot [1 + \alpha(t - 23) + \beta(t - 23)^2]$$

   over the range 18°–28°C
   b) determine effect of shock and vibration
      drop tests
      vibration tests
   c) determine leakage resistance, relate to humidity; determine pressure coefficient
   d) determine power coefficient.
2) Stability factors:
   a) repeated tests against known stability standards
      calculable capacitors
      buildup from 1-ohm standards
   b) determine resistance changes after thermal shocks.

C. Equipment

1) A five-terminal double ratio bridge [9] was used, employing substitution techniques. By five-terminal, as used throughout this paper, is meant the usual four-terminal device, which defines the points of measurement, with the addition of an electrically accessible point for control of the leakage currents. In the usual terminology, it is both a three-terminal and a four-terminal device. It is necessary to continue the control of direct leakage between the terminals of a resistor into the bridge; otherwise, the advantage gained in the resistor construction may be thrown away in the bridge. By using an amplified, feed-back galvanometer [10], we were able to achieve enough sensitivity to make comparisons to parts in 10^8 at 10 kilohms with 2.5 milliwatts dissipation in 10 kilohms and to parts in 10^7 at 1 ohm with 10 milliwatts dissipation in 1 ohm.

The series-to-parallel ratio technique [2]–[4] permitted comparisons of 1-ohm and 10-kilohm resistors using only one-to-one substitution comparisons on the bridge. Two steps accomplished the transfer. A 1-kilohm-per-step Hamon-type transfer standard, set in series configuration, compares directly to the 10-kilohm standard and, in parallel, to a set of 10-ohms-per-step in series. The 10-ohms-per-step transfer standard, in parallel, compares directly with a 1-ohm standard. The power dissipation per section of the transfer sets was not varied by more than $\frac{1}{2}$ milliwatt throughout the measurement series. This power variation would not cause more than 0.01-ppm change in the transfer standards used in the experiment [11].

2) Temperature measurements adequate for the purposes were made as follows:

   a) ambient air—mercury-in-glass thermometers, calibrated against platinum resistance thermometers
   b) 10-kilohm resistors—built-in resistive temperature sensors
   c) oil bath (for Thomas-type 1-ohm resistors)—platinum resistance thermometer.

3) Three Thomas-type 1-ohm resistors were used as standards for some portions of the study. Table I demonstrates that the drift of these resistors is indeterminate, but probably less than 0.02 ppm per year.

4) Shock and vibration were tested on drop-test apparatus, using 11-millisecond duration, and a vibrating table at double amplitudes to 0.06 inch, frequencies 10 to 80 vibrations per second, with 10G as the maximum vibratory acceleration.

Results

A. Temperature–Resistance Relationships

The slope of the parabola at 23°C (α_{23}) is entirely controllable by the selection of the ten 1-kilohm resistors, which, in series, constitute the standard. This slope is maintained within the limits ± 0.2 ppm/°C.

The rate of change of the slope of the curve, however, is always -0.06 ± 0.01 ppm/(°C)^2. This is 2β, the second derivative of the temperature formula. Within these limits, the worst-case deviation of the standard over the range 18° to 28°C, which is associated with maxima of α_{23} and β, is 1.9 ppm. The slope at the worst extreme (18° or 28°, but not both) is 0.55 ppm/°C; therefore, ± 0.1°C temperature determination is adequate for ± 0.06-ppm resistance correction. This requires only ± 100 ppm in the determination of the value of the temperature sensor.

The time constant of the structure is quite long (1 hour minimum); the sensor resistor is closely coupled, thermally, to the standard. This combination of long

TABLE I
1-OHM THOMAS-TYPE STANDARDS
VALUES AT 25°C (NBS TESTS*)

	SN 1586456	SN 1586455	SN 1513449
April, 1968*	1.0000033	1.0000017	0.9999972
September, 1967	1.0000032		
June, 1966 NBS		1.0000018	
April, 1965		1.0000020	
May, 1964	1.0000035		
January, 1964			0.9999971
February, 1963		1.0000016	
July, 1962	1.0000032		
November, 1961			0.9999970
June, 1961			0.999998–
August, 1960	1.000004–		0.999997–
June, 1959			0.999997–

* April, 1968, value is from ESI intercomparison based upon mean of group. The slopes of the temperature-resistance curve for the three resistors indicated in Table I are +2.8, +4.9, and +5.5 ppm per degree C at 25°C, and even more at 23°C. It is, therefore, necessary to know the temperature to ±0.02°C to apply corrections to the nearest 0.1 ppm of resistance. Until 1967, we attempted to use these 1-ohm resistors in a stirred but unheated bath at 23°C in a ±0.1°C regulated room. The uncertainty of about ±0.3 ppm that resulted from this procedure corresponds to ±0.06°C uncertainty in temperature measurement, which is quite in line. In more recent comparisons using these resistors, they were immersed in a large stirred temperature-controlled bath at 25±0.02°C, known to ±0.005°C using a platinum resistance thermometer.

time constant in heat exchanges with the ambient, and short time constant in heat exchanges between the standard resistor and the temperature sensor leads to easy achievement of ±0.1°C definition of temperature as indicated by the sensor. If the sensor is consistently used to define apparent temperature in determining temperature coefficients and calibration conditions, there is no need for concern about true temperatures.

It is, therefore, concluded that the repeatability of the measurement of the resistance value over the range 18° to 28°C is not more than ±1.9 ppm if no corrections for temperature are applied nor more than ±0.06 ppm if corrected to the nearest 0.1°C.

Over the range 20° to 26°, the worst-case results would be 0.92-ppm maximum error with no temperature corrections, or ±0.03 ppm if corrected to the nearest 0.1°C.

The constants α_{23} and β are determined from series of measurements in a regulated air bath at approximately 18°, 23°, and 28°C. The resistances of the built-in temperature sensor are measured and recorded along with measurements of the resistance of the standard. The resistance changes associated with the indicated temperature changes are implicit in these comparisons, which are fitted by a least-squares method to the temperature formula given above. The observed points are then compared with the computed points, which discloses any discrepant observations and generates the data to plot a temperature-resistance curve. All the computations are performed by a computer. Any drift of the resistor during the test is determined by the computer, which reports and also corrects for the drift. Of course, a test that is completed in two weeks cannot provide a reliable long-term drift evaluation.

B. Shock and Vibration

The first and most severe shock test performed on these resistors was to drop them three feet onto a concrete slab. The shock was probably in excess of 100G, although it was not measured. The resistors were repeatedly dropped onto all faces, edges, and corners. The formica case was chipped, but the values of the resistors did not change by as much as 0.1 ppm after the test.

Another resistor was unchanged after five drops on a drop testing machine. The duration of the shocks was 11 milliseconds, intensities were 21, 28, 35, 42, and 44 G. Again, there was no change in the resistor.

Vibration tests were performed at 0.06-inch double amplitude from 10 to 55 vibrations per second, traversing the frequency range up and down in about one minute and continuing for 15 minutes in each of three mutually perpendicular planes for a total of 45 minutes. No changes greater than ±0.1 ppm were observed, either during the test or afterwards. The double amplitude was then reduced to 0.027 inch and another six minutes of continuous cycling performed over the range 55 to 80 vibrations per second. Again, no change in resistance was observed, either during or after the test.

These tests indicate that the value of the resistors is not likely to be disturbed by rough handling or shipment. With the additional protection of packing and packaging, which were absent in the tests, they should be able to travel anywhere, by any common carrier.

C. Pressure Response

The pressure response was determined by measuring the resistance of three resistors over reduced and augmented pressures from 0.1 to 2.7 atmospheres. The coefficient below one atmosphere was -0.2 ± 0.15 ppm per atmosphere; above one atmosphere it was -0.35 ± 0.2 ppm per atmosphere. This indicates that for ±0.1-ppm work, the pressure may vary between 0.7 and 1.2 atmospheres without requiring correction.

In making comparisons to 0.1 ppm with the Thomas-type 1-ohm resistor and possibly with other types, the pressure resistance correction must not be overlooked. Thomas reports that the double-walled 1-ohm resistor has a coefficient of 2 to 4 ppm per half-atmosphere, which would mean that a change as small as 10 mmHg in barometric pressure could produce a 0.1-ppm change.

D. Leakage Resistance (Humidity Effect)

The leakage resistance, or resistance between the elements of the resistor and the case that entirely shields it, was measured by observing the current produced by a 500-volt battery. All measurements were between 1.4 and 14×10^{11} ohms. Variation from 10- to 100-percent relative humidity produced no measurable effects.

In our measurement system, these leakages would appear across 1000-ohm bridge arms, where the error produced would be less than one part in 10^8. With a square bridge, the error could be one part in 10^7.

E. Stability

Long-term stability, measurable as drift, is very difficult to evaluate unless the test time is long enough for the drift to emerge as a significant factor against the uncertainty of the measurement system and of the standard of comparison.

The resistance comparison system outlined above is capable of one part in 10^8 precision and, in one-to-one comparisons, accuracy within five parts in 10^8. For the comparisons of 1 ohm with 10 kilohms, where two series-to-parallel buildups are required, the accuracy is about two parts in 10^7. The reproducibility of repeated measurements is within one part in 10^7.

For a long-term standard against which to evaluate stability, we turned first to the indirect comparison with the standard of length through the quad bridge and the calculable capacitor. Through the kindness of A. M. Thompson of the National Standards Laboratory of the CSIRO in Chippendale, Australia, we have been able to arrange for three sets of determinations of the values of several 10-kilohm standards in absolute electrostatic ohms. These values have been converted to BIPM ohms, assuming 2.997925×10^8 m/s as the velocity of light, and to U. S. legal ohms from the BIPM international intercomparison reports. Normal air shipments for the three round trips to Australia have not produced observable effects. The uncertainty in the NSL absolute values is unlikely to be as great as two parts in 10^7.

For conversions, we are currently using relationships based upon the 1967 BIPM report [12] and the values reported by A. M. Thompson [6],

$$\Omega_{NBS} = \Omega_{BIPM} - 0.19\mu\Omega$$

and

$$\Omega_{BIPM} = 1\Omega - 0.17\mu\Omega$$

whence

$$\Omega_{NBS} = 1\Omega - 0.36\mu\Omega.$$

Prior to 1967, we used the value reported in 1964,

$$\Omega_{NBS} = \Omega_{BIPM} - 0.25\mu\Omega$$

and Thompson's value for 1964,

$$\Omega_{BIPM} = 1\Omega - 0.03\mu\Omega.$$

For our earlier work, we rounded to the nearest 0.1 microhm, using

$$\Omega_{NBS} = 1\Omega - 0.3\mu\Omega.$$

One should not believe that these conversion factors, stated to a part in 10^8, are known to a corresponding accuracy. If we assign the uncertainties claimed by the various laboratories responsible for the statements and for the national units involved, we ought to be quite content with 1- or 2-ppm agreement among measurements based upon various national standards.

TABLE II
VALUE OF 10-KILOHM STANDARD RESISTOR 517003 AT 23°C
(ALL VALUES ADJUSTED TO U. S. NBS OHMS)

Date Month, Year	Reference* Standard	Deviation from Nominal, ppm Measured	Calculated
April, 1968	ESI-5	+0.4	+0.4
April, 1968	ESI-4	+0.2	+0.4
March, 1968	ESI-3	+0.2	+0.4
January, 1968	ESI-2	+0.4	+0.3
June, 1967	ESI-1	−0.1	+0.1
December, 1966	ESI-1	−0.4	−0.1
November, 1966	NSL	−0.15	−0.15
October, 1966	ESI-1	−0.6	−0.2
June, 1966	ESI-1	−0.7	−0.3
May, 1966	NSL	−0.35	−0.35

* Reference standards:
NSL—comparison with computable capacitor by NSL in Australia
ESI—comparison at Electro Scientific Industries, Inc., Portland, Ore.
ESI-1 based on Thomas-type 1-ohm standards in oil at room temperature (23°C), corrected for observed temperature from NBS values at 25°C.
ESI-2 based on 10-kilohm standard 734003 using value assigned from NRC test in Canada, November, 1967.
ESI-3 based on 734003 using value assigned by NBS test in February, 1968.
ESI-4 based on 1-ohm standards in oil, regulated at 25°C, using NBS values (see Table I).
ESI-5 based on 734003 using value assigned by NSL test in Australia, April, 1968.

To determine drift rates, the periodic measurements against the computable capacitor have been quite satisfactory. Table II lists values for Resistor 517003 based upon two determinations at NSL in May and November, 1966. These established a drift rate of +0.4 ppm per year. Seventeen months later, six other similar resistors were calibrated in absolute ohms at NSL. By comparison with those resistors, upon their return, another absolute ohm value was established for 517003, from which the drift rate during the 17-month period was found to be +0.367 ppm per year. The value established in April, 1968, was only 0.05 ppm less than the value predicted by an extrapolation of the original drift rate.

The resistors often have a faster drift rate when new, but the rate changes in the direction of +0.4 ppm per year and in 1 ± 0.5 year is stabilized at that rate. At this time, we are unable to say what the drift rate will be in ten years; the indication is that it will be a little slower, as would be expected.

Since the drift rates tend to become the same for all resistors of this particular type and manufacture, we find remarkable constancy of relative values on intercomparisons over long periods of time. If the computable capacitor-based calibrations were not available, we probably would have thought that the intercomparison agreement indicated that there was no drift at all.

Resistor 517004 is typical of the fast initial drift resistors. It is one of the early test models, identical to 517003 except that it contains no silicone oil. We have observed that one of the effects of oil immersion is shortening of the time to reach the stable drift rate.

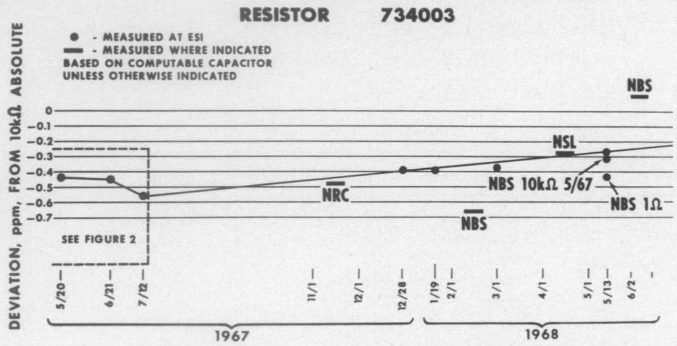

Fig. 1. Interrelation of various national laboratory tests on a typical resistor.

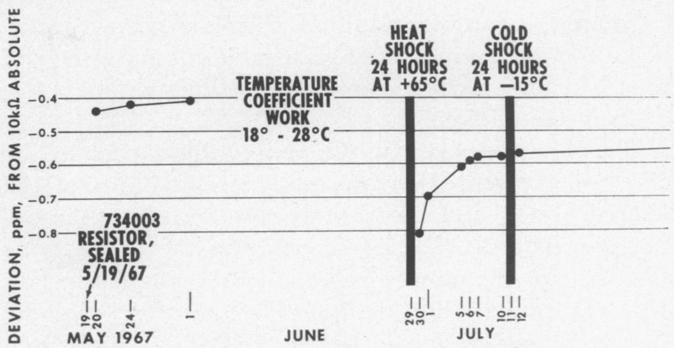

Fig. 2. Illustrating hysteresis effect after heat shock.

During the May to November, 1966, period, 517004 changed at the rate of +1.22 ppm per year. Over the next 17 months, to April, 1968, the average rate was +0.71 and currently (May, 1968) is about +0.5 ppm per year.

With small known drift rates, it is possible to establish a standard value at any particular time with accuracy well within 1 ppm. As an example, see Table II.

In this table, the value and drift rate of 517003 have been established by the two tests at NSL in May and November, 1966, as 9999.9955 absolute ohms in November and +0.4 ppm per year. Converted to NBS ohms and expressed as deviation from 10 kilohms, the value becomes −0.15 ppm. From this value and drift rate are computed the values in the column headed "Calculated." In the column headed "Measured" are listed values for the resistor, measured at Electro Scientific Industries, Inc., Portland, Ore., and based upon various standards, as indicated. The measurements against the 1-ohm standards at 23°C (designated ESI-1) reflect the difficulties of converting the manganin standards from the 25°C test report value and have, therefore, larger uncertainty than the other comparisons.

Fig. 1 represents the entire history of Resistor 734003 from May, 1967, when the resistor was hermetically sealed, up to the present. All the values have been converted to absolute ohms. To report in any other unit would not change the relative values. The values represented by short bars on the chart are reported values from measurements at the indicated national laboratories. During the week of May 13, 1968, the value of 734003 was measured in terms of three different standards values:

1) the absolute ohm as represented by Resistor 517003 in one-to-one comparison,
2) the ohm as represented by the May, 1968, calibration of 746024 at NBS, also a one-to-one comparison, and
3) the ohm as represented by the NBS calibrations of the 1-ohm standards, a 10 000-to-one buildup.

The entire spread of assigned values for 734003 lies within a span of ±0.3 ppm, which is inside the stated uncertainties of the various national laboratories, and speaks well for the international comparisons through which these measurements were correlated.

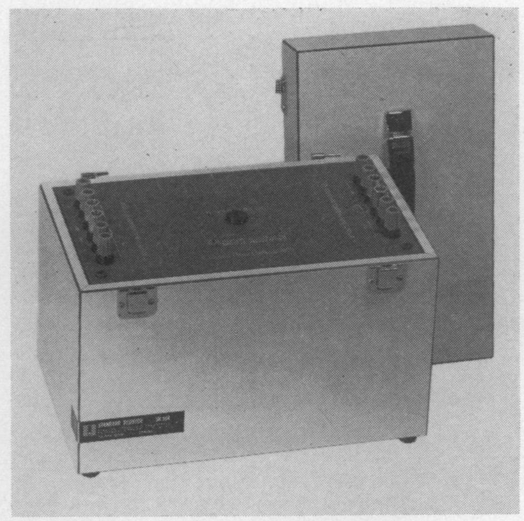

Fig. 3. The 5-terminal 10-kilohm resistor showing standard terminals and sensor terminals.

F. Response to Thermal Shock

The first two months after sealing in the history of 734003 are shown in more detail in Fig. 2, primarily to illustrate response to thermal shock. After the 24-hour exposure to +65°C on June 29th, a period of three to five days was required before the resistor was within 0.1 ppm of its stable value. This was not cooling-off time; the internal temperature sensor was indicating 23°C±0.5° for all observations. There is no analogous effect on cold shock.

Conclusions

A 10-kilohm hermetically sealed five-terminal resistor, made of ten 1-kilohm card-wound resistors, of commercial precision resistor grade with special heat-treat cycles, can serve as a transportable standard to disseminate an otherwise defined unit of resistance (Fig. 3).

So used, it can withstand the shocks of normal transportation and be measured with sufficient accuracy and precision to reproduce the reference unit within a few parts in ten million.

The ohm as derived by the computable capacitor, the ohm as represented by the national standards of the United States, and the ohm as represented by the national standards of Canada, using in the calculations the value of the ohm as represented by the Australian national standard and the interrelations of the national standards as determined by the BIPM, have all been compared in Portland, Ore., using five-terminal 10-kilohm resistors. The maximum disagreements lie within a band ±0.3 ppm wide around the local standard.

It appears that a standard of resistance can be better disseminated at a level of 10 kilohms than at a level of 1 ohm; it is also indicated that a 10-kilohm resistor of sufficient stability to serve as such a standard has been constructed.

Appendix

Typical Equipment List and Experimental Data

1-Ohm to 10-Kilohm Comparisons

With respect to the reproducibility of 1-ohm to 10-kilohm buildups, the following data are typical. Equipment is as follows:

tare: 10 kΩ SR104 517002
transfers: 10 Ω/step SR1010 406043
1 kΩ/step SR1010 R
bridge: ESI Model 120 with Model 876 lead compensator
generator: ESI Model 830
detector: ESI Model 900.

Power levels and sensitivities:

unknown R, Ω	dissipation in unknown, mW	unbalance of bridge required to put 1 nV on null detector, ppm
1	10	0.04
100	5	0.006
10 000	2.5	0.003

1-Ω L&N Model 4210—
$\alpha_{25} = +4$ ppm/°C
temperature, 25±0.01°C (oil)
NBS value (February, 1968) +3.2 ppm
10-kΩ ESI Model SR 104—
$\alpha_{23} = -0.05$ ppm/°C
temperature 23±0.1°C (air)
ESI value (December, 1967) +0.34 ppm (Ω NBS)
expected difference: 2.9 ppm
measured differences:

date	ppm
November 14, 1967	+2.6
November 27, 1967	+2.7
November 28, 1967	+2.7
November 29, 1967	+2.6
December 1, 1967	+2.7
December 13, 1967	+2.7
December 21, 1967	+2.7
December 28, 1967	+2.7

estimated uncertainties:
from temperature of 1 Ω: ±0.04 ppm (temperature of 1 Ω)
from temperature of 10 kΩ: ±0.005 ppm (temperature of 10 kΩ).

The estimate of sigma for the eight comparisons is ±0.05 ppm. Considering the contributions of the temperatures, above, it seems reasonable to estimate the standard deviation of the buildup process itself at ±0.03 ppm:

$$[(0.05)^2 - (0.04)^2 - (0.005)^2]^{1/2}.$$

Acknowledgment

We wish to express our appreciation for the cooperation of the National Standards Laboratory of the CSIRO in Australia and particularly to A. M. Thompson. Without access to testing on their computable capacitor and their capacitance-to-resistance comparisons, this study would not have been possible.

References

[1] "Handbook 77," U. S. Nat'l Bureau of Standards, vol. 1, pp. 169–171, and 177–180.
[2] B. V. Hamon, "A 1–100 ohm build-up resistor for the calibration of standard resistors," *J. Sci. Instr.*, vol. 31, no. 12, 1954.
[3] C. H. Page, "Errors in the series-parallel buildup of four-terminal resistors," *NBS J. Research*, vol. 69C, no. 3, 1965.
[4] J. C. Riley, "The accuracy of series and parallel connections of four-terminal resistors," *IEEE Internat'l Conv. Rec.*, pt. 11, 1965.
[5] J. L. Thomas, "Stability of double-walled manganin resistors," NBS Research Paper RP1692, 1964.
[6] A. M. Thompson, "An absolute determination of resistance based on a calculable standard of capacitance," *Metrolog.*, vol. 4, no. 1, 1968.
[7] US Patent 3 091 527, May 1963. D. D. Pollock to Leeds and Northrup Co., col. 1, lines 50–56.
[8] R. M. Pailthorp, "Advantages of a ten-kilohm transportable resistance standard," *IEEE Conv. Rec.*, pt. 8, 1967.
[9] M. Roberts, "Design of a contemporary direct reading double ratio set and auxiliary lead compensator," *IEEE Internat'l Conv. Rec.*, pt. 11, 1965.
[10] "Specifications, model 900 nanovolt galvanometer," Electro Scientific Industries, Inc., Portland, Ore.
[11] "Specifications, model SR1010/LTC, resistance transfer standard," Electro Scientific Industries, Inc., Portland, Ore.
[12] "International intercomparison of units of resistance," Bureau International des Poids et des Mesures, February 1967.