An Integrated System for the Precise Calibration of Four-Terminal Standard Resistors

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Abstract—A description is given of the system currently in use the National Bureau of Standards for measurements of 1-Ω andard resistors of the Thomas type. A tenfold improvement in curacy over the former method has been realized. Resistors of this pe are now reported to eight decimal places with a total uncerinty of 0.08 ppm. The latter figure includes a three-standard-eviation limit for random errors plus an estimate of systematic rrors [1].

The new system is not only more rapid in operation than the old ne (fewer man hours required), but has consistently produced data f superior resolution while operating with a lower test power in esistors. A dc current-linkage balance is used to determine the tandard–unknown differences while both are connected in series nd totally immersed in a specially designed circular oil bath, which emains completely covered during all tests. Bath temperature is aintained constantly at 25 000°C (±0.003°C) in a unique manner.

INTRODUCTION

IN 1963, as reported to the clients of the National Bureau of Standards, the precision of the resistance of double-walled 1-Ω resistors was increased from 1 to 0.1 part/million (ppm). Since this precision was near the limit obtainable on the bridge in use at that time (the Wenner bridge [2]), it seemed prudent to plan a new resistance measurement system capable of meeting expected demands for increased precision. It was planned that this new system would not only be capable of greater precision but, if possible, would be faster and easier to use.

In developing a new system, the following recognized limitations of the old system were kept in mind: 1) the requirement for manually made lead adjustment in the ratio-arm connections; 2) disturbance of the temperature

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equilibrium by handling of the resistors when performing interchange; 3) generation of transient thermal EMFs when changing potential connections to the resistors; 4) uncompensated errors in the ratio set itself caused by unequal power coefficients of certain ratio resistors; 5) temperature-control difficulties partially inherent in the original bath design such as its rectangular shape and placement of heater lamps close to the measured resistors. Lack of a cooling element rendered the bridge inoperative when the ambient room temperature rose above 24.0°C. Temperature control was ±0.01°C at best, but frequently averaged ±0.02°C; and 6) electrostatic disturbance caused by charged objects, e.g., people moving around the room and electromagnetic disturbance caused primarily by the heater lights in the bath turning on and off.

Although most of these limitations of the old Wenner bridge system could have been eliminated by the construction of a modified bridge system, it was decided to use a potentiometric system. This method seemed attractive due to the development of the direct current comparator by Kusters and others at the National Research Council of Canada [3], [4].

INTEGRATED SYSTEM

Constant Temperature Bath

A tank was constructed large enough to accommodate a circular mercury stand holding 15 Thomas-type resistors in a series ring.

Salient features of this bath are the following.

1) It is cylindrical in shape with approximately 550-l capacity. The radial oil flow is produced by a belt-driven propellor located in the bottom center of the tank. The oil flow moves horizontally between two cylindrical screens, a central one (15 cm diameter) of fine mesh capped at the top and an outer very coarse mesh screen (Fig. 1). The oil return path to the propellor is via a false bottom containing coiled tubing designed to form a heat exchanger. The oil circulation is superior to that obtained in the rectangular tank of the Wenner bridge.

2) The resistor ring stand is positioned so as to place all resistors at the same middepth oil level and also equidistant from the central oil distribution screen.

3) No electrical heaters or coolers are installed in the 550-l bath. Temperature control is obtained by regulating the circulation of cooling oil pumped from a smaller (110-l) auxiliary bath through the heat-exchanger tubing located in the bottom of the larger tank. This cooling oil carries away the heat produced by the stirring of the oil in the large bath. It was found that variations of 0.02°–0.03°C in the temperature of the auxiliary bath would be reflected by variations 1/10 or less as large in the larger bath.

The temperature of the bath can be controlled manually by varying the flow of cooling oil by adjusting a needle valve in the oil pipeline. Alternatively, the needle valve can be set high enough to assure cooling of the bath and the flow of oil can then periodically be interrupted by a valve in the cooling oil circulating line that is controlled by an electronic sensor in the large bath.

Current Comparator

The direct current comparator operates on the principle that when two magnetomotive forces imposed on a magnetic core by currents in two windings are equal and opposite, the flux in the core is zero. This balance condition can be detected by a modulation detector. The detector circuit can be used to control the output of a current source, connected into one of the windings so as to automatically maintain the condition of zero flux in the core. How the current comparator can be used to compare resistors can be seen from the equation developed below, with reference to Fig. 2.

The basic equations are as follows when

N_p, N_s	primary and secondary number of turns;
I_p, I_s	primary and secondary currents;
R_D, R_x, R_s	resistances of "dummy," unknown and standard.

At flux balance in the transformer core,

$$N_s I_s = N_p I_p$$

or

$$I_s/I_p = N_p/N_s \tag{1}$$

At voltage balance the IR "drop" across the "dummy" (secondary) resistor R_D and the IR drop across the selected unknown resistor R_X in the primary circuit results in

$$R_x I_p = I_{sx} R_D$$

where I_{sx} is the secondary current at balance or

$$R_x = (I_{sx}/I_p) R_D.$$

Substituting turns for current, from (1) we have

$$R_x = (N_{px}/N_s) R_D \tag{2}$$

where N_{px} is the number of turns in the primary winding at balance.

Similarly when a resistor of known resistance R_s is being measured we have

$$R_s = (N_{ps}/N_s) R_D. \tag{3}$$

Dividing (2) by (3) we then have

$$R_x = (N_{px}/N_{ps}) R_s. \tag{4}$$

Measurement Technique

Briefly, the technique is one in which the voltage drop across each of the client's resistors is compared indirectly (via a stable dummy resistor) with the voltage drop across each resistor in a reference group while all are connected in series and totally immersed in the oil bath

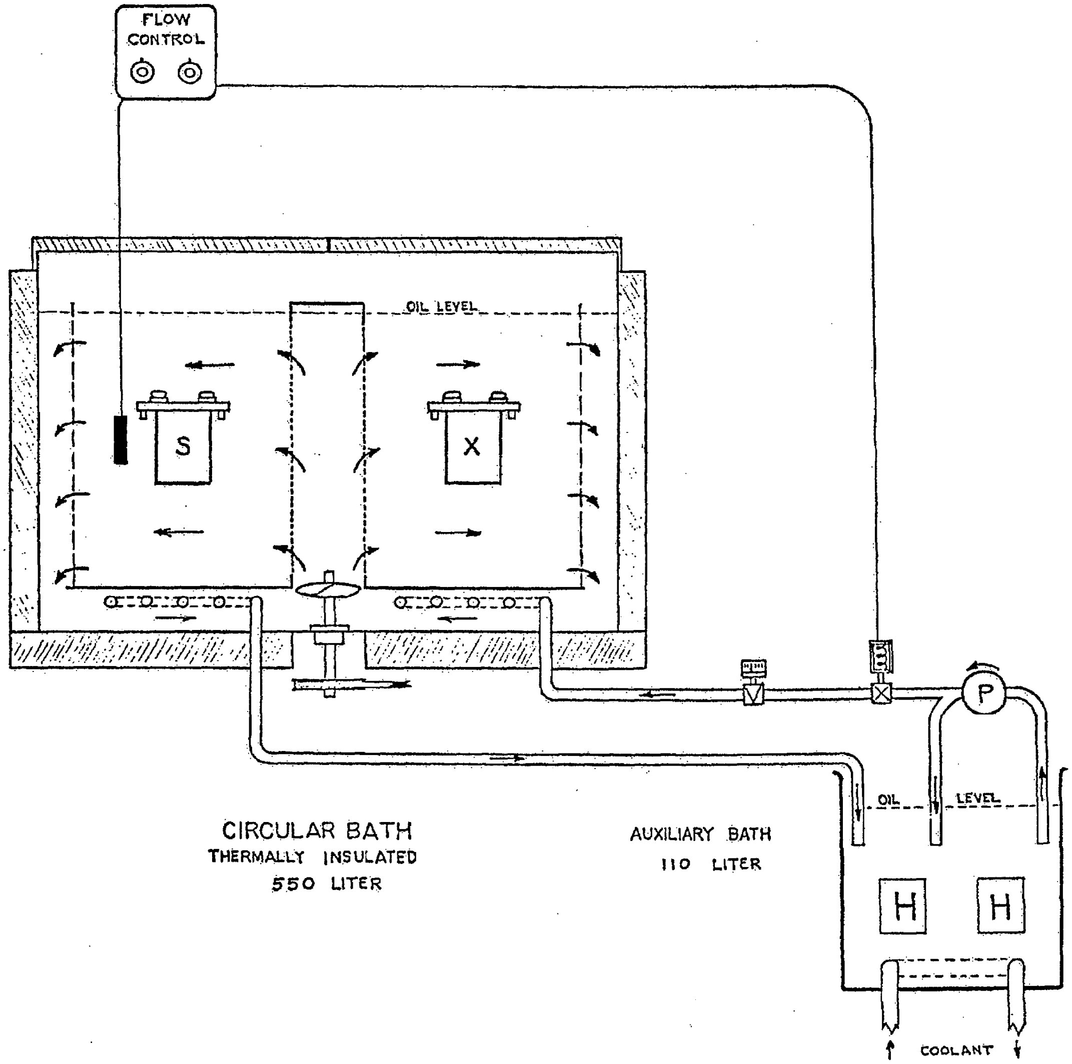

Fig. 1. Two-stage temperature control system.

maintained at 25.000°C ± 0.003°C. The dc-current comparator (ampere-turn balance) is used for making the comparisons while all the standard and unknown resistors are carrying the continuous test current of 0.1 A (0.01 W/Thomas resistor). The comparator is usually used near the maximum setting of the balance dials (2000 turns of the primary winding) and the circuit "trimmed" in such a manner that only the last three or four dials are changed in balancing. Final balance settings of the seven decade controls are recorded and utilized solely to obtain accurate standard–unknown differences.

A series of balances between the 0.5-Ω dummy and each of the standard and unknown resistors in turn is made by adjusting the seven dials controlling the turns of the primary winding. Sensitivity is sufficient to readily discern 0.5 step of the seventh dial. As the first dial has 20 steps and all balances in this instance are made with it at the twentieth step, the 0.5 step is 0.025 ppm.

With the 0.1-A dc primary current automatically controlled and the slave supply tracking it at 0.2-A dc (the zero flux feedback ensures this condition), the series of balances between the 0.5-Ω dummy and of the standard and unknown resistors in turn can be made as rapidly as the technician can operate the potential selector switch and adjust the seven dials controlling the taps to the primary winding using the standard technique of reversing the currents to eliminate the effect of "parasitic" EMF in the detector circuit.

Standard operating procedure at NBS is as follows.

1) The bath is "loaded" with a maximum of eight clients' resistors on the day preceding measurements, oil depth checked, cover replaced, and 0.1-A current

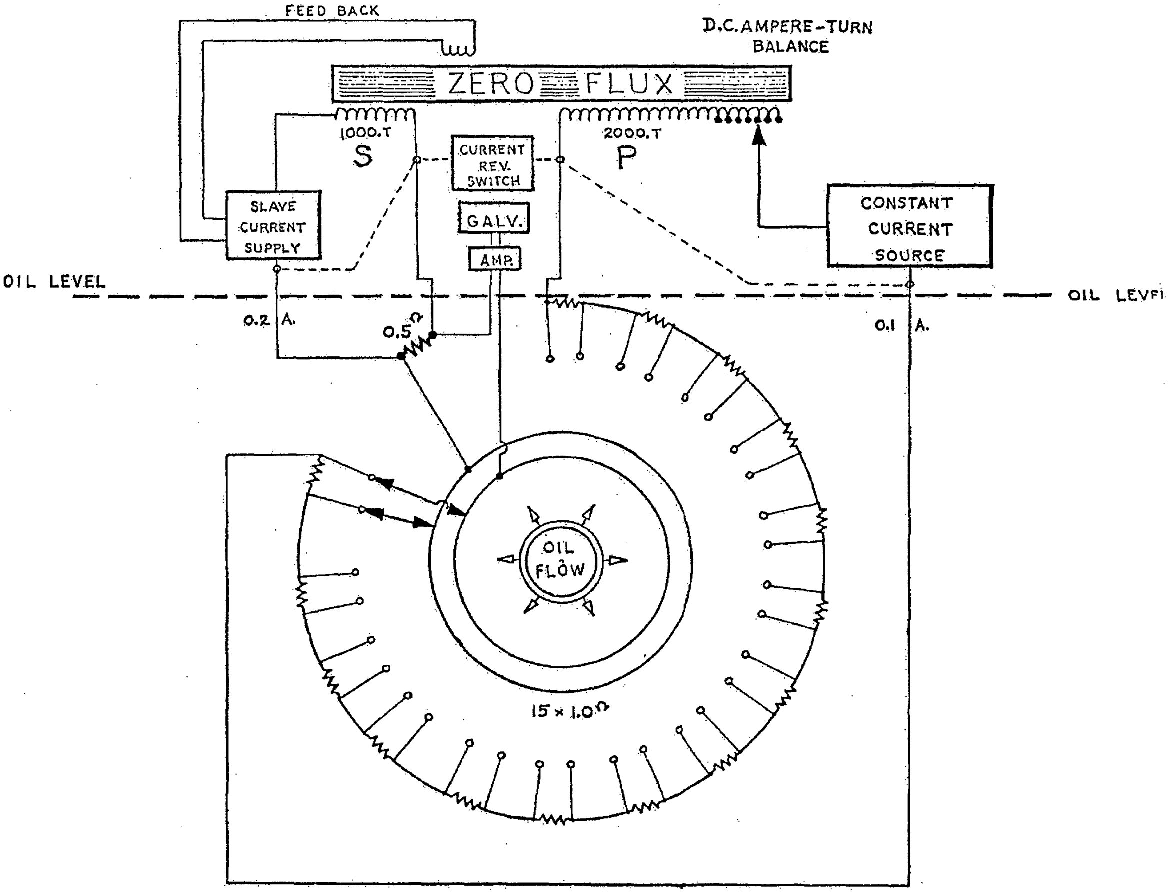

Fig. 2. Circuit for comparison of 1-Ω resistors.

switched on. Note that the bath is in constant temperature control with continuous stirring even when not in use.

2) On the following day, the bath temperature is checked, trimmed slightly if necessary, and the temperature recorder started for the calibration run.

3) Balances are then made as described for each of the 15 selector switch positions, 1–15, and dial readings recorded.

4) Room barometer is read and pressure recorded along with room temperature.

5) Repeat balances are then made in reverse order, 15–1.

6) Approximately five hours later, without opening the bath, steps 2–5 are repeated entirely by another technician.

7) Test current is turned off; bath is opened and unloaded.

We now have four balances for each switch position. Averaging these and knowing the average correction of the five NBS reference resistors, only simple arithmetic is necessary to arrive at the proper corrections for each of the unknown resistors. The value of the dummy 0.5-Ω resistor is unimportant as it does not enter into the calculations. However, its resistance must remain constant during a given run. A low power coefficient is desirable for the 0.5-Ω resistor although in this case the secondary current is essentially constant because only small changes are made in the primary turns setting.

In addition to the five reference standard resistors, there are always present in the series an extra pair of NBS Thomas 1-Ω resistors that are measured and serve as controls in the data analysis.

Resistors of the double-walled type such as these are affected slightly by pressure variations [5], [6]. Therefore, if maximum use is to be made of the reported values, the effect of pressure must be considered. Although the temperature and oil-immersion depth are held constant, the ambient air pressure will naturally vary; therefore, before a mean value for the correction of the five can be utilized, it must be adjusted back to the 101 325 N/m^2 pressure base, from the total pressure as measured in a given calibration run.[1] Pressure coefficient tests were carefully made on each of the reference resistors at NBS. Results have shown the effect to be positive and linear with no appreciable hysteresis.

Clients' resistors whose individual pressure coefficients are not known in most cases are simply reported at the total pressure existing during the testing period. An approximate figure for commercial units is 0.000 015-ppm decrease in resistance per newton per square meter decrease in pressure on resistor (multiply pressure in millimeters of mercury by 133.32 to obtain pressure in newtons per square meter). For a user located at an altitude of one mile the resistance of this type resistor will be about 0.3 ppm less than the value at the altitude of the NBS Gaithersburg Laboratory.

SYSTEM PERFORMANCE

The resistance values of Thomas-type standard resistors submitted to NBS for calibration prior to July 1, 1970, were reported to 0.1 ppm with an uncertainty of ±1.0 ppm. Since that date, using the new system the values have been stated to 0.01 ppm with an uncertainty of only 0.08 ppm. The latter figure includes a three-standard-deviation value for random error due to minute temperature, pressure, resistance fluctuations, and lack of resolution plus estimated amounts for the uncertainty in temperature and pressure measurements, the only known sources of systematic errors.

The test power, formerly 0.05 W/resistor (intermittent) is now 0.01 W (continuous). The performance of the oil bath now permits specification of temperature at which the calibrations are performed as 25.00° rather than 25.0°C, as was previously the case. The new reports state the total pressure on the resistor during calibration.

Additional advantages of the new system include: elimination of the tedious and time consuming lead balances that were necessary with the Kelvin double-ratio circuitry; and elimination of a secondary or working group of NBS standards. Clients' resistors are now compared directly with the National Reference Group of standards.

This measurement system was completed in 1969 and has been in successful operation since that time. The initial circuitry was designed solely for 1-Ω comparisons of Thomas-type standard resistors. Experiments indicate that with proper modifications the same type of system can be extended to perform one to one comparisons of resistors in the range 0.1–100 Ω and such extension is contemplated.

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[1] Total pressure existing at the level of the surfaces of the amalgamated current terminals when the resistor is immersed so as to place the terminal surfaces 60 mm below the oil level.