Precision Resistors: A Review of Material Characteristics, Resistor Design, and Construction Practices

David W. Braudaway, *Life Fellow, IEEE*

***Abstract*—An understanding of the properties of resistance materials and of the effects on resistor characteristics of construction practice is necessary to assure optimum application. Reviewed are some of the characteristics of moderate-precision film resistors, the nature of the principal high performance resistance alloys and the design and construction of high-precision resistors. The effects of resistor termination and terminals are also reviewed with emphasis on the requirements necessary to produce four-terminal and series–parallel connections.**

***Index Terms*— Manganese alloys, material processing, nickel alloys, resistance, resistance characterization, resistance–temperature characteristic.**

I. INTRODUCTION

A large variety of resistor types confront engineers nowadays. Many resistors have properties that are attractive in moderate- to high-precision applications, especially where computer measurement is used to establish ratio and value at time of measurement. Included are thin and thick films of carbon and of various metals, chemical compounds and metallic alloys, composition materials of resin mixed with conductive constituents, and resistors formed of solid wire or sheet. The performance limits and construction details for many of these may be found in handbooks (or standards) [1], [2]. Older handbooks give the characteristic limits for resistance alloys, usually as wire, while the newer handbooks describe limits for classes of resistors. When the highest level of performance is sought, however, properties of the specific materials, construction techniques, thermal aging, and environment must all be considered. This information is beyond that available in most handbooks. While older references give some excellent information on resistor construction, the information is often given in a form and in units requiring conversion to the current SI derived form.

II. HIGH-PERFORMANCE RESISTANCE ALLOYS

In 1889, a patent was issued to Edward Weston on low-temperature-coefficient alloys and covers such materials as Constantan and Manganin, although the correct alloy proportions were worked out later [3], [4]. Constantan (principally copper and nickel) has a resistivity of about 0.49 $\mu\Omega \cdot$ m, an extremely low temperature coefficient and a large thermoelectric voltage with copper. It is widely used for ac resistors and thermocouples. Manganin (copper, nickel, and manganese), on the other hand, has a resistivity of about 0.48 $\mu\Omega \cdot$ m, a small temperature coefficient and a small thermoelectric voltage with copper. These properties made Manganin an excellent choice for precision dc resistors. The concepts covered in the Weston patent give one way to produce a compensated material or device; the compensation characteristic is given in Fig. 1.

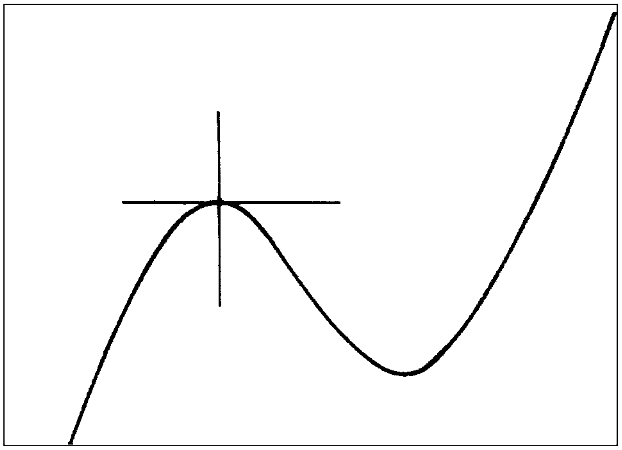

Fig. 1. Compensation characteristic.

For Manganin, the maximum in the resistance-temperature characteristic lies in the range of 20–30 °C and the minimum is at about 350 °C [5]. For more than 10 °C either side of the maximum, the resistance may be accurately represented by

$$R_t = R_{25}[1 + \alpha(t - 25) + \beta(t - 25)^2] \tag{1}$$

where

R_{25} resistance;
α slope;
β curvature, referenced to 25 °C.

Once established, α and β are good for the life of the particular resistor but R_{25} is reestablished periodically as the resistor ages. For good quality Manganin over the range of 15–35 °C, the nominal variation of resistance with temperature lies in the range from 3 (minimum) $(\mu\Omega/\Omega)$°C to 6 (maximum) $(\mu\Omega/\Omega)/$°C. If desired, the equation may be converted to a different reference temperature by a simple change of

---

Manuscript received July 16, 1999.

The author, retired, was with Sandia National Laboratories, Sandia Park, NM 87047 USA. He is now at 103 Ranch Rd., P.O. Box 9, Sandia Park, NM 87047-0009 USA (e-mail: d.braudaway@ieee.org).

Publisher Item Identifier S 0018-9456(99)08387-4.

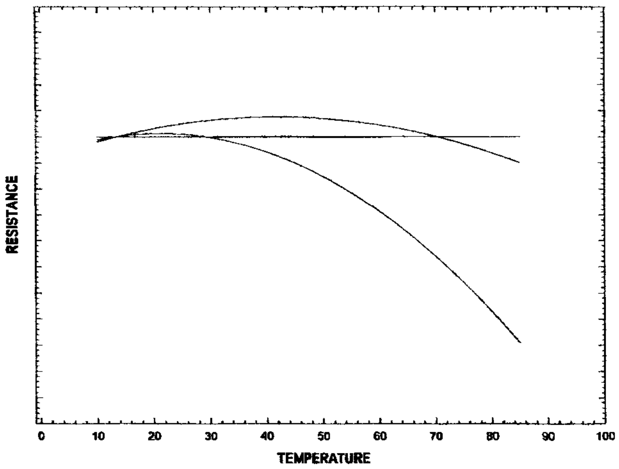

Fig. 2. Manganin characteristics.

variable. R_{25} and α will change to values at the new reference temperature, but the curvature, β, will remain constant.

Thomas [5] observed that it is probable that all resistance alloys having a small temperature coefficient around room temperature will have a characteristic similar to Fig. 1. Indeed, it is probable that all compensated materials and devices have such a characteristic. The Weston Normal Cell (Saturated Standard Cell) exhibits the compensated characteristic with a voltage maximum at about 4 °C. Band-gap voltage sources also show the characteristic and it is observed with Zener diodes, but, because it is a function also of diode structure and current, it is not always evident.

Resistors 1 Ω and above are usually made from wire while lower value resistors and shunts are most often made from sheet material. By changing the formulation of the alloy, the maximum can be changed from around room temperature to 50 °C, which is of advantage in minimizing the resistance change with temperature rise in high-current shunts. A comparison of the two resistance-temperature curves is shown in Fig. 2.

To obtain the indicated results, Manganin must be processed after drawing, forming and brazing and must be thermally aged to relieve stress from forming. This is a crucial and most important part of manufacturing if optimum results are to be obtained. Resistors made of wire are about 2% above the value before aging. Because most wire and sheet is electrically insulated to prevent short circuits and reaction with the environment, temperatures above 150 °C cannot be used in aging. Artificial aging for 48 h or more followed by storage for up to a year is necessary to reach a resistance close to the final value from which accurate trimming may be accomplished. Annealing at red heat, required at several steps in producing the wire or sheet and in brazing the material to terminals, necessitates acid pickling to remove the surface coating left by selective oxidation. To achieve best results, careful control of the alloy melt proportions is necessary to insure the intended end product.

Although Manganin has a resistivity 28 times that of copper, a great length of very small diameter wire is required for high value resistors. For 25 μm wire, the resistance is about 950 Ω/m. Higher resistivity alloys have been available but until 1948 did not have the desirable characteristics for highest quality resistors. In 1948 a new alloy was called Evanohm was announced [4], [5]. This material was the result of attempts to lower the temperature coefficient of Nickel Chromium alloy used for heaters. The result, which added small amounts of other metals, principally copper and aluminum, produced a resistance material with a very small temperature coefficient of about 1 $(\mu\Omega/\Omega)/°\mathrm{C}$ around room temperature and also a very small thermoelectric voltage against copper. The resistivity of these alloys is about 1.34 $\mu\Omega \cdot$ m.

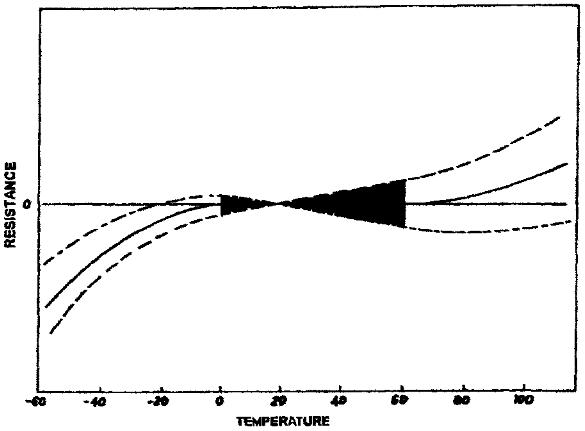

Fig. 3. Zeranin characteristics.

The strain induced by winding Evanohn can be relieved by low temperature aging, but Evanohm resistors often show a change of resistance of about 5 $(\mu\Omega/\Omega)$/year. Experience has shown that care is required in winding and mounting the resistance coil to be sure that it is not stressed unintentionally by the structure, or by handling after construction, if expected behavior is to be met. This material has been most useful in making resistors of high value but has also been successfully used below 0.1 Ω. Evanohm R form has a slightly higher temperature coefficient and follows the compensation curve with a maximum around room temperature. Evanohm S, however, shows a -1 $(\mu\Omega/\Omega)/°\mathrm{C}$ below 25 °C and a value of essentially 0 above.

More recently, another alloy, marketed as Zeranin has been developed but with a somewhat different behavior. Rather than a having a distinct maximum and minimum, a nearly flat resistance-temperature characteristic is produced around room temperature. The behavior is shown in Fig. 3. The material has a temperature coefficient of 0 to ± 3 $(\mu\Omega/\Omega)/°\mathrm{C}$ in the normal temperature range. The temperature coefficient is dependent on the wire diameter and a different melt is required for each diameter produced. For this reason only a few wire diameters are available. In specifying the characteristics of Zeranin, the resistance per meter is the reference factor rather than the wire diameter. For comparison, the resistivity of Zeranin is approximately 0.43 $\mu\Omega \cdot$ m.

At present, many resistors made from Evanohm and Zeranin are used without the benefit of a resistance-temperature correction. Especially for Evanohm S and Zeranin, a simplified resistance-temperature equation is usually appropriate

$$R_t = R_{25}[1 + \alpha(t - 25)]. \tag{2}$$

In describing the special resistance alloys, Zeranin has been listed as a trademark name rather than a generic term. For a very long time, Constantan, Manganin, and Evanohm have been loosely used as generic terms but it should be remembered that these also were trademark names describing specific alloys offered by metallurgical firms when they were introduced.

III. Resistor Applications

A review of history shows that, although there is some initial application of new resistance alloys soon after development, widespread use occurs slowly with several decades required before the performance is established and accepted. A major reason for this delay is that the behavior of existing resistors is well established and their performance is understood. New materials and new designs must stand for proof against the historic; the history of performance is of considerable value in assuring low and repeatable uncertainty of the resistance value represented. For these reasons, most of the highest precision standards in laboratories are still of Manganin, while lower level standards are of the newer alloys. In this process, there is strong competition between the urge to be among the first to employ the "latest and greatest" and the significant risk that either the new material or the new design will fail to meet expectation.

Resistors of moderate-precision, of course, achieve acceptance much more quickly than do high-precision designs. Moderate-precision resistor design benefits from the experience gained with the high-precision alloys and especially with the various construction features developed for high-precision resistors. In addition, while trimming of high-precision resistors is by a shunting or a laborious abrading process, film resistors benefit from techniques, such as laser trimming, that can be quite rapid. In addition, these resistors may also benefit from computer enhancement where their relative value is established by comparison one to another or to an arbitrary reference. Thus established, correction of value from memory produces results that approach the best attainable with fixed standard resistors and high stability apparatus that uses such resistors. It must be noted, however, that the computer-aided instruments tend to have a relatively short lifetime because tolerance limits are reached or electronic components become unreliable (maintenance expenses increase) and because new, ever more enhanced instrument designs become available.

The temperature of resistors in instruments can be controlled at a value above normal environment as a part of the instrument function. Resistors for use in the laboratory are limited by the need to be operated at laboratory temperature or preferably, by operation in an oil bath under temperature control. For optimum stability and repeatability, temperature variation of the resistor environment should be less than ±0.01 °C.

It is often presumed that there has been a continuous development of resistor construction features that enhance their performance; equally often, it is presumed that all knowledge has been applied from the time that the nature of resistance was first realized. Neither version is flawless; there has been an iterative improvement of concept, design, materials and measurement capability. As noted in [6], the stability over time of Manganin resistors was within 2 $(\mu\Omega/\Omega)$/year and that this was about 10% of the uncertainty of knowledge of the unit in 1948. It should also be noted that in that year, the system of maintaining the units changed from the International System to the Absolute System with 1 international ohm $= 1.000\,495$ absolute ohm [6].

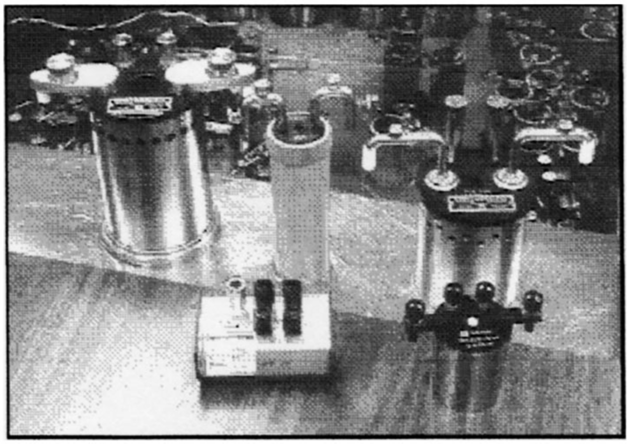

Fig. 4. Resistor patterns.

Design of resistors improved in steps from the turn of the 20th century to 1948 and subsequently but many of the 1948 style resistors are still in use. Measurement capability currently is equal or better than 10 $(\mathrm{n}\Omega/\Omega)$ at 1 Ω and the best resistors at 1 Ω are stable to better than ± 20 $(\mathrm{n}\Omega/\Omega)$. The uncertainty of value of the maintained unit has improved to about ± 60 $(\mathrm{n}\Omega/\Omega)$, with all uncertainty sources considered. Attainable uncertainties for normal laboratory resistors in the range from 1 Ω to 10 kΩ are from 0.15–1 $(\mu\Omega/\Omega)$. Uncertainties increase significantly for resistors outside this range of values, especially for resistors and shunts that are operated in air environment.

IV. Design and Construction Features

General details of design and construction of resistors intended for high-precision dc application are presented in [4] and [5]. Five different patterns of laboratory resistors are shown in Fig. 4.

Back Row Left: A Thomas pattern resistor, 1 Ω, which is the best so far available and forms the basic resistance standard in many laboratories. The resistance element is annealed at red heat and housed in a sealed chamber. The sealed chamber results in a small pressure or altitude coefficient of resistance by transmitting stress to the resistance element.

Back Row Center: A Rosa pattern resistor, which is available in values from 0.1 Ω through 100 MΩ. The resistor is sealed in its own chamber, oil filled in most cases, and equipped with a thermometer well. Reaction of the resistance wire insulation with the oil produces an interesting dielectric absorption effect. The resistor style is widely used as standard. Current and potential connections are made at different points on the single conduction arm that limits uncertainty for lower resistance values.

Back Row Right: A Reichsanstalt pattern resistor, developed originally in Germany. The element is not sealed, but merely protected. The design is widely used for 1–100 mΩ and also for ×2 and ×5 multiples. These resistors can dissipate a reasonable power in an oil bath but are limited in air.

Front Row Left: A small resistor with balanced four terminal construction permitting interchange of potential and current terminals. This form is generally available with the newer resistance alloys.

Front Row Right: A resistor in a relatively new, small format with the element sealed in oil. Although smaller, the general construction is similar to the Rosa pattern in many features. The newer resistance alloys are employed in this design and resistors are fitted with different terminals for current and potential connection.

Not all of the precision resistor styles available today are included in the picture. Resistors similar to the Thomas pattern in size are available in selected values through 10 kΩ and have excellent performance. Shunts are not included either but are normally made of ribbon material or of parallel bars brazed between current spreaders. Like the Reichsanstalt resistors, shunts have clearly identified terminals for current and potential connections. Shunts are intended for use in air but are sometimes used as low resistance standards in oil for better temperature control. Manganin is widely used in shunts, especially those rated 1000 A and higher. Some shunts for lower currents use the newer resistance alloys.

All of the resistors shown are designed to permit four-terminal connection but two-terminal connection is generally sufficient for values 1 kΩ and above. All but the small resistor in the left front of the figure are equipped with current arms intended for quick change using mercury wetted connection bars and also with terminals for potential and current connection.

V. RESISTOR PERFORMANCE FACTORS

A number of factors affecting resistance performance have been indicated in describing high-performance alloys and features of resistor construction. These include the effects of temperature, thermoelectric voltages, induced stress and terminal configuration. These factors affect the performance of all resistors and the effects need to be considered for all applications. Stress in moderate-precision film resistors can be quite high depending on the relative expansion coefficients of the film material and the substrate on which it is deposited. For these resistors, the effect is that of a composite that is highly dependent on construction details.

A. Thermoelectric Effects

Thermoelectric voltages (Seebeck effect) are evident in all resistors. These voltages are the result of temperature differences across junctions of dissimilar materials and, in a dc measurement, have the effect of a small battery in series with the voltage drop across the resistor. Reversal of the current reverses the voltage drop across the resistor but not the thermoelectric voltage. The average of the two values cancels the thermoelectric voltage; ac, of course does not show the effect.

A different thermoelectric effect gives rise to a different, smaller source of voltage in some resistors. Current flowing through the dissimilar materials at the resistor junctions heats one and cools the other (Peltier effect). In turn, this gives rise to a thermoelectric voltage that reverses polarity when the current is reversed. There is, of course, a thermal time constant to the temperature rise. For very low frequency ac, the effect also is observed but, as frequency is increased, the time constant precludes the temperature differential from developing. Above 20 Hz, the effect is not seen in laboratory resistors.

B. Alternating Current Effects

By their very nature, film resistors have excellent ac characteristics. Resistors formed of wire, whether the intended application is for dc or ac, exhibit reactive effects and skin effect, both of which increase as frequency increases. Careful design has been used to produce resistors useful up to about 50 kHz by minimization of the reactive effect. Reference [1] shows nine different methods of winding to reduce inductance effect and [4] gives specific details on a number of these. All methods presume that the smallest practical wire diameter is used and that the area enclosed by the wire is reduced to a practical minimum, which also minimizes the inductance. In addition to the resistance value, a time constant is a convenient way of specifying the ac characteristics of a resistor. The most common methods of reducing the area enclosed by the resistance wire are as follows:

1) bifilar loop;
2) winding resistor on a thin card (usually mica);
3) winding two parallel coils in opposite direction;
4) weaving the wire into a tape or mat;
5) winding an even number of series coils, each successive coil in the opposite direction.

C. Humidity Effects

The coating or encapsulation materials used with film resistors need to be carefully selected so that they do not add further stress to the resistor, either from temperature or humidity. High quality resistors are usually hermetically sealed, which precludes humidity effects. In addition to enamel, resistance wire is often insulated further by a covering of cotton or silk. These two natural fibers have opposite effects from humidity and an insulation of enamel, silk and cotton called ESCO was developed to cancel humidity stress on resistance wire [4].

D. Lead Effects

All resistors include some resistance from lead material in addition to that of the resistance element. For film resistors, the terminations can make up a significant part of the resistance, especially in low value resistors. For laboratory resistors, the leads also affect both the two-terminal and the four-terminal resistance values. The effects are much larger on shunts, where assuring a uniform current through the resistance element or elements must be carefully done. Different methods of connecting the current leads to the shunt may result in differences in the apparent resistance value. There are indications of work done to optimize current and potential terminals before this century [3]. A short analysis of four-terminal resistor and shunt connections is given in [4].

Searle published an in-depth study of the effects of lead resistance in 1911 [7]. In this study, the theoretical analyses by Helmholtz, Heaviside, and Bromwich are used to firmly establish correctness of three and four terminal interconnection nodes for resistor terminations. The three terminal node is basic to connection of a resistor element to a current and a potential terminal; two such terminal nodes are used to make a four-terminal resistor. The four terminal node, which is also called a tetrahedral junction, is basic to interconnection of two resistor elements to one current-potential pair which is used in series-parallel combinations to establish resistance ratios. At the time of this analysis most resistors used only a pair of “stout copper terminals.” However, a significant effort had been expended in setting the basis for more practical connection to low value resistors.

An analysis is also made [7] of the uniformity of current flow in a rod where the contact may be at any point on the end of the rod. It is shown that, at a distance from the end equal to the rod diameter, nonuniformity of the current is about 5% of the mean current density. At a distance down the rod equal to four times the rod diameter, the nonuniformity has dropped to less than 10^{-5} times the mean current density. At this distance from the end of the rod, the current flow is essentially uniform. Such results give significant insight in determination of connection proportions necessary to accurately establish four-terminal resistance.

The ribbon form of the shunt utilizes U-shaped cuts, called “potential tongues,” in the ribbon material to form the potential connections. The “potential tongue” facilitates trimming the shunt to correct value and isolates the potential connections from the current feeds. Shunts of this type are described in [7] and [4]. Two high-precision shunts are shown in Fig. 5. The front shunt is in the ribbon form with potential tongue connections. The second shunt is for higher currents and, to keep the dimensions in reasonable limits, employs a “current spreading” slot in the terminals and recessed potential connections to insure an equipotential sampling of the resistance. Features of this type shunt are discussed in [4]. Both of these shunts have thermocouples attached so that a resistance-temperature characteristic may be used to enhance accuracy.

The possibility of connecting resistor strings in series and parallel without a significant difference in the ratio has received considerable attention. Searle [7] set the basis for the interconnecting tetrahedral junctions. Hamon [8] developed a 100 : 1 ratio standard, which made low uncertainty resistance buildup attractive. Riley [9] published a general analysis of series-parallel resistor configurations and, developed a simplified and useful equation for approximating the maximum uncertainty expected in the transfer. Use of series-parallel transfer devices at both 100 : 1 and 10 : 1 permit very high-precision transfer of the base 1 Ω reference value to 10 kΩ and, with increased uncertainty through 100 MΩ.

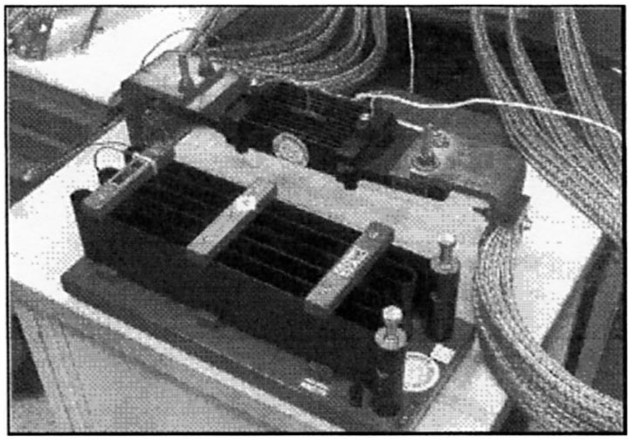

Fig. 5. Shunt patterns.

E. Load Coefficient

Current flowing through all resistance elements dissipates power and raises the temperature of the resistor. The actual temperature rise is limited by heat flow through the thermal conductance from the element to the outside resistor environment. The thermal conductance is through the resistor leads, especially important with film resistors, and through the electrical insulation around the resistance element. The load coefficient in laboratory resistors is small and is the change in resistance produced per watt of heating. The effect is such that 100 or 10 mW dissipation limits are placed on most high quality laboratory resistors for optimum repeatability in an oil bath. Obviously, use in air produces a higher temperature rise and increased resistor uncertainty. Shunts dissipate a considerable power and design is critical for acceptable performance.

VI. CONCLUSIONS

The materials, design and most significant factors affecting performance of moderate and high-precision resistors have been reviewed. The presentation has included a bit of the history of their development from before the beginning of this century to the present time. Computer aided enhancement of moderate-precision resistors has also been introduced and some of the factors affecting this application have been considered. Also covered are many of the application characteristics of moderate-precision resistors and high-precision laboratory resistors.

ACKNOWLEDGMENT

The author would like to thank Sandia National Laboratories for the photographs used in this paper.

REFERENCES

[1] F. E. Terman, *Radio Engineers Handbook.* New York: McGraw-Hill, 1943, pp. 26–29 and pp. 40–46.

[2] *Reference Data For Radio Engineers.* Indianapolis, IN: Sams, 1975, pp. 5-8–5-15.

[3] J. F. Keithley, *The Story of Electrical and Magnetic Measurements: From 500 BC to the 1940's.* New York: IEEE Press, 1999, pp. 193–202.

[4] F. K. Harris, *Electrical Measurements.* New York: Wiley, 1952, pp. 204–228.
[5] J. L. Thomas, “Precision resistors and their measurement,” Nat. Bur. Stand. Circular 470, 1948, pp. 1–10.
[6] F. B. Silsbee, “Establishment and maintenance of the electrical units,” Nat. Bur. Stand. Circular 475, 1949, pp. 19–22.
[7] G. F. C. Searle, “On resistances with current and potential terminals,” *Electrician*, vol. 66, p. 999, Mar. 1911.
[8] B. V. Hamon, “A 1–100 Ω buildup resistor for the calibration of standard resistors,” *J. Sci. Instrum.*, vol. 31, pp. 450–453, Dec. 1954.
[9] J. C. Riley, “The accuracy of series and parallel connections of four-terminal resistors,” *IEEE Trans. Instrum. Meas.*, vol. IM-16, pp. 258–268, Sept. 1967.

David W. Braudaway (S’51–A’55–SM’75–F’90–LF’96) received the B.S.E.E. degree from the University of Colorado, Boulder, in 1954 and the M.S.E.E. and Ph.D. degrees from the University of New Mexico, Albuquerque, in 1962 and 1968, respectively.

From 1956 to 1997, he was with the Primary Standards Laboratory (PSL), Sandia National Laboratories, Sandia Park, NM, where he was Distinguished Member of Technical Staff. He is currently engaged as a Consultant in metrology and in the requirements for standards laboratory environments.

Dr. Braudaway is a Past President of the IEEE Instrumentation and Measurement Society and is Chair of the Conferences and Meetings Committee. He has served on the AdCom since 1981. He is Past Chair of the IEEE Awards Board and has served on a number of IEEE Institute and TAB committees. He has received the NCSL Wildhack Medal, the I&M Society Distinguished Service Award, and the I&M Society Award, and is a registered engineer in New Mexico.