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Temperature Effects on Precision Resistors: A Review of Methods for Determining Temperature and Load Coefficients, Their Advantages, Limitations and Results

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***Abstract*—The electrical resistance of precision resistors is affected by temperature due to two main factors: ambient temperature changes and self-heating from power dissipation. The first factor is quantified by the temperature coefficient of resistance (TCR), which indicates how much the resistance varies with temperature. The second factor, known as the load coefficient or load effect, measures the change in resistance caused by the resistor heating up as it dissipates power due to the current flowing through it. This review examines various methods used to determine temperature and load coefficients, highlighting their advantages, limitations, and the results observed in different studies. Furthermore, the review discusses key findings from past research, comparing the reliability and consistency of different approaches.**

Keywords*—precision resistor, temperature effect, power loading effect, temperature coefficient, thermal resistance, load coefficient.

I. INTRODUCTION

Precision resistors have a key role in high-accuracy electronic circuits, where stability and minimal variation in resistance with temperature and applied load are essential. When determining the resistance value of precision resistors, it is important to know the temperature and load coefficients of all resistors in the measurement circuit. This is especially significant when performing inter-laboratory comparisons, in order to ensure the same conditions in terms of ambient temperature and load power. The load coefficient of a standard resistor is defined as the change in its resistance from its negligible-load value at a constant temperature, under specified loading conditions [1].

This document explores the Temperature Coefficient of Resistance (TCR) and loading effects in precision resistors, providing insight into their significance and methodologies for characterization. A comparative study of different resistor materials, such as Manganin and Evanohm alloys, highlights their advantages and limitations in metrology applications. Based on the findings, recommendations for future research and improved methodologies for high-precision resistance measurements are proposed.

II. TEMPERATURE COEFFICIENT OF RESISTANCE (TCR)

The TCR is a key parameter in determining the accuracy and stability of electrical resistors. This characteristic describes the change in electrical resistance concerning temperature and plays a crucial role in metrology, precision measurements and industrial calibrations. The TCR is typically expressed in parts per million per degree Celsius (ppm/°C) and can be positive or negative, depending on the material properties of the resistor. This paper presents a compilation of findings from several scientific studies on methods for measuring, determining and improving the temperature coefficient of resistors.

The resistance of a resistor as a function of temperature can be expressed by the following equation [2], [3]:

$$R_t = R_0 \cdot (1 + \alpha \cdot (t - t_0) + \beta \cdot (t - t_0)^2), \qquad (1)$$

where:

- R_t (Ω) is the resistance value at temperature t (°C),
- R_0 (Ω) is the reference resistance at a specific reference temperature t_0 (°C),
- α (ppm/°C) is the temperature coefficient of resistance,
- β (ppm/(°C)^2) is the second-order temperature coefficient of resistance.

A. Methods for Determining the Temperature Coefficient of Resistance

Various methods have been used to determine the temperature coefficient of resistance for resistors.

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1) Numerical and analytical methods rely on mathematical modelling techniques such as the Taylor series approximation and least squares fitting to determine the first- and second-order temperature coefficients. These methods provide precise estimations but require highly accurate measurements and controlled conditions [2], [4].

2) Experimental methods involve direct measurements of resistance variations with temperature. These experiments are often conducted in controlled environments, such as oil baths, to maintain temperature stability, as shown in Fig. 1. Direct and indirect voltage measurement techniques help minimize thermoelectric effects, ensuring accuracy. Additionally, reference resistor standards are used for calibration to enhance the precision of the obtained results [5], [6].

3) Hybrid methods combines experimental data with theoretical or numerical models, such as using experimental measurements to adjust a numerical model for TCR prediction or combining finite element simulations with thermal testing to improve resistor designs. The main advantage is that it provides a balance between theoretical estimates and practical confirmation, increasing accuracy and reducing uncertainty. However, it can be complicated and time-consuming to apply, needing a lot of work to properly combine both data and models.

B. Results

The temperature coefficient for the studied resistors in [2] follows a parabolic equation with $\alpha = -0.053$ ppm/°C and $\beta = -0.047$ ppm/(°C)^2, validating their method with low uncertainty. The identification of a stationary thermal point where the temperature coefficient equals zero [5], indicates its usefulness in precision applications. Reference [5] presents the relative change in resistance for seven different reference resistors (R_1 to R_7) compared to their resistance values at 23 °C. The results indicate that all resistors exhibited resistance variations with temperature, remaining within the manufacturer's specifications (below 2 ppm/°C), except for R_4, which exceeded this limit at temperatures above 32 °C. The observed temperature range spans from 18 °C to 38 °C. A reference resistor method was proposed in [6] to reduce uncertainty in TCR measurements, while [7] introduced a foil resistor with an ultra-low TCR of ±0.2 ppm/°C, demonstrating exceptional stability. The analysis in [8] examined resistance behaviour between 20 °C and 26 °C, showing minor resistance variations (±200 nΩ/Ω).

Fig. 1. Temperature stabilization of the standard resistors in an oil bath.

The results indicate a significant variation in the approaches used to determine and minimize TCR. While [7] and [8] emphasize material innovations and long-term stability, [2] and [6] focus on improving measurement methodologies. The identification of a stationary thermal point by [5] introduces another perspective—using intrinsic material properties to reduce temperature variation effects. These findings suggest that a combination of material advancements, improved measurement techniques, and precision calibration is key to achieving optimal performance in resistors with minimal TCR.

C. Advantages and Limitations of Methods

Different methods for determining and controlling the temperature coefficient of resistance offer unique benefits and limitations. Numerical analysis methods, such as those proposed by [2], allow precise estimation of coefficients but require highly accurate measurements. Experimental approaches, like those used by [5], provide excellent temperature stability but need extended measurement times. The indirect reference resistor method introduced by [6] reduces uncertainty and thermoelectric effects but requires additional calibration steps.

The development of zero-TCR foil resistors by [7] offers outstanding temperature stability, yet the complexity and cost of manufacturing remain significant challenges. Reference [8] demonstrated resistors with extremely low temperature coefficients, averaging 0.035 ppm/°C, which minimizes resistance fluctuation due to temperature changes. Such precision reduces the need for additional temperature stabilization, making these resistors highly reliable for industrial and metrological applications.

III. POWER LOADING EFFECT

The power loading effect of a precision resistor refers to the change in resistance value due to self-heating when power is dissipated across the resistor [9]. This effect is crucial in applications requiring high accuracy, such as precision measurement circuits.

To better understand the power loading effect on a resistor, it is necessary to clarify two key concepts: thermal resistance and load coefficient.

A. Thermal Resistance

The thermal resistance of a resistor determines how much its temperature increases under load and depends on two main factors: the amount of heat power dissipated and the resistor's ability to dissipate that heat. Studies on heat transfer show that temperature rise ΔT is directly proportional to the power dissipation, which means that the coefficient of proportionality is a constant [10], and it is defined as thermal resistance R_T. It is expressed as follows [11]:

$$R_T = \Delta T / P, \tag{2}$$

where ΔT represents the temperature rise of the resistor, and P is the load on the resistance when it is working.

A lower thermal resistance results in a smaller temperature increase, helping to maintain the resistor’s stability. By knowing the thermal resistance, it is possible to calculate how much the temperature will rise under a given load and predict resistance changes due to heating. Furthermore, thermal resistance serves as a key indicator of the quality of a resistor's thermal structure and material properties, as it helps evaluate heat dissipation efficiency and long-term performance.

B. *Load Coefficient*

The load coefficient describes the change in the electrical resistance of a resistor due to increased dissipated power. As the resistor heats up, its resistance changes, which can affect the performance of the electrical circuit. This change is expressed in parts per million per watt (ppm/W). The load coefficient is defined as given below [12], [13]:

$$\lambda = (\Delta R / R_0) \cdot (P)^{-1}, \qquad (3)$$

where:

- λ (ppm/W) is a load coefficient,
- ΔR (Ω) is a change in the resistance value,
- R_0 (Ω) is the resistance value at zero-load state,
- P (W) is the dissipated power.

The power loading effect on a resistor depends on these two factors. Higher thermal resistance means the resistor will heat up more for the same power, while a higher load coefficient indicates a greater change in electrical resistance under load. Manufacturers of standard resistors almost never provide data for thermal resistance, which would allow us to easily determine how much the temperature of a resistor will change with a given power load (°C/W). Since the load coefficient is directly proportional to the temperature coefficient [12] and represents a constant expressed in (°C/W), it follows that thermal resistance R_T is precisely the ratio of the load and temperature coefficients:

$$R_T = \lambda / TCR. \qquad (4)$$

In precision electrical circuits, these effects can cause unwanted changes in system performance, which is why resistors with low thermal resistance and a low load coefficient are carefully selected.

C. *Methods and Experimental Approach*

Various techniques have been employed to study load effects in precision resistors, ranked by accuracy from highest to lowest:

- Cryogenic Current Comparator (CCC) Bridges: Used for ultra-high precision resistance measurements. CCC bridges utilize superconducting quantum interference devices (SQUIDs) to achieve extremely low measurement uncertainty, making them suitable for primary metrology applications and quantum resistance standards.
- Direct Current Comparator (DCC) Bridges: Used to assess load-related resistance changes at different current levels. In the DCC bridge, different currents flow through two resistors to generate the same voltage across R_S and R_X. It is insensitive to measurement lead resistance, does not require current stability, and dissipates the most power in the smallest resistance. Fig. 2 shows a simplified diagram of the load effect measurement of the low resistance using a commercial DCC Bridge [14]. The bridge provides an accurate current ratio to evaluate the change in resistance when different currents are applied.

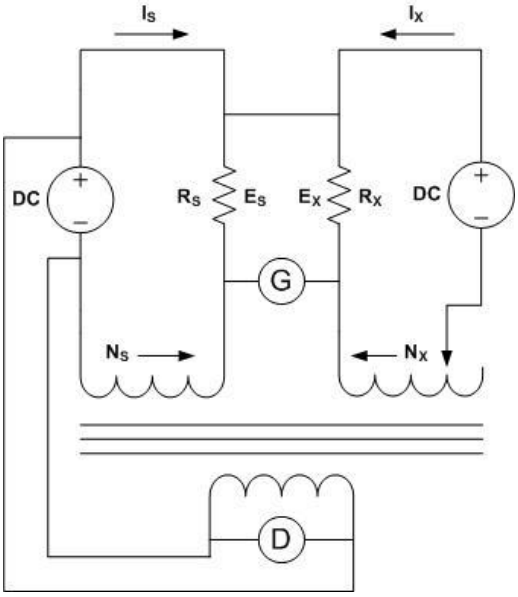

Fig. 2. Diagram of the load effect measurement of the low resistance with DCC [14].

- Resistance Voltage Dividers (RVD): Applied for evaluating high-resistance load effects. These systems allow for precise determination of resistance ratios while minimizing temperature-induced drift.
- Self-Heating Models: Investigating temperature-induced resistance variations and their dynamic behaviour over time. These models help characterize the influence of thermal energy dissipation and its subsequent effect on resistance drift.

D. *Comparative Analysis of Findings*

The effects of power loading, temperature, resistor materials, and measurement optimization are key factors influencing the accuracy of standard resistors. Research has shown that self-heating causes measurable resistance variations, which must be considered during calibration.

It has been found that loading effects in NIS (National Institute of Standards) primary standard resistors lead to significant measurement discrepancies, with a load coefficient of approximately 20 ppm/W [10]. Precise temperature control is crucial for reducing uncertainty, especially in oil-bath environments, where [15] demonstrated that optimized heat dissipation methods can significantly minimize errors due to power dissipation. Regarding materials, manganin and Evanohm alloys exhibit different stability under varying load conditions.

Through a comparative study in [12], it was found that copper resistors are more sensitive to self-heating, making them less suitable for precision applications. Maintaining optimal stability requires careful selection of measurement currents and resistor designs, with [16] developing a high-precision RVD system that reduces loading-induced errors and improves the reliability of resistance standards.

Table 1. presents data from various studies examining the characteristics of resistors under specific load conditions and temperature stabilization settings. Key data points include resistor type and alloy, load power, resistance change, load coefficient and temperature stabilization conditions.

TABLE I. VARIATION OF LOAD COEFFICIENT WITH POWER LOADING

Study	**Resistor**			**Load Power (mW)**	**Resistance Change (ppm)**	**Load Coefficient (ppm/W)**	**Temperature Stabilization**
	Type / Model	***Alloy***	***Value***				
Reference [15]	Thomas	Manganin	1 Ω	10	-0.02	-2	25 °C (Oil bath)
	NML	Evanohm		10	-0.005	-0.5	
Reference [10]	Thomas	Manganin	1 Ω	10	0.2	20	23 °C (Oil bath)
Reference [13]	BZ3	Manganin	1 Ω	10	-3.1	-310	20 °C (Air-room)

The NML (The Australian National Measurement Laboratory, now the NMIA) Evanohm resistor, with a load coefficient of -0.5 ppm/W, is the most stable in terms of load, meaning its resistance is largely unaffected by changes in power dissipation. In contrast, the Thomas Manganin resistor, with a significantly higher load coefficient of 20 ppm/W, is more sensitive to load, making it less stable than the Evanohm. The least stable of the three is the BZ3 Manganin resistor, which has an extremely high load coefficient of -310 ppm/W, indicating that its resistance changes drastically with variations in power dissipation. The least stable resistor was tested at 20 °C in an air-room environment, which may have contributed to its instability due to greater temperature fluctuations. Thus, the stability of these resistors decreases as their load coefficients increase in magnitude.

This analysis emphasizes that the stability of resistors under load is heavily influenced by the selection of resistor material and the specific testing conditions. Factors such as temperature variations, electrical stress, and material properties affect its performance and reliability over time.

IV. DISCUSSION AND SUMMARY

This review examines various methods used to determine temperature and load coefficients, with a focus on improving accuracy and stability in engineering applications, particularly in precision resistors. The methods considered include specific techniques, approaches and solutions.

A. *Experimental Techniques*

Experimental methods for determining temperature and load coefficients typically involve direct measurements in laboratory conditions. These methods can be very accurate, but they are often more expensive and time-consuming. While they provide high precision, they can also be subject to errors caused by external factors, such as changes in environmental temperature or irregularities in the measuring devices.

B. *Numerical Models*

Numerical approaches, such as computer simulations and modelling, allow for predicting thermal behaviour without the need for physical experiments. These approaches can be faster and cheaper compared to experimental methods, but they rely on the accuracy of initial assumptions and input data. In this context, the development of accurate models that take into account various parameters such as material properties, resistor size, and temperature gradients is crucial for improving precision. By integrating these factors into a model, the power loading effect can be simulated more precisely, allowing for better prediction of thermal performance and reliability. This predictive capability reduces the need for costly and time-consuming physical testing, while ensuring that design and safety standards are met.

C. *Data-Driven Approaches (Machine Learning and Statistical Regression)*

Data-driven methods for predicting temperature coefficients and load effects are becoming increasingly popular. Machine learning techniques can analyze large datasets to identify patterns that are not immediately obvious using traditional methods. These techniques can improve prediction accuracy under real conditions, but their success depends on the quality and volume of the data. The application of machine learning algorithms would enable predictive optimization of temperature effects management systems in real time, based on dynamic changes in power load and temperature.

V. CONCLUSION

This paper presents a comprehensive review of methods for determining temperature and load coefficients, emphasizing opportunities for improvement through advanced materials, enhanced computational modeling, and the integration of machine learning algorithms. For metrologists, understanding factors such as power dissipation, self-heating of resistors, and measurement loading effects is essential. These factors can significantly impact measurement accuracy, so designing circuits that minimize these effects is crucial.

The resistance of a standard resistor changes non-linearly with respect to load, which is often the case when the material has specific characteristics or when thermal effects are involved. As the current through the resistor increases, heating occurs, altering its resistance in a way that is not necessarily proportional. The load coefficient likely refers to factors that describe how resistance changes based on current or voltage, taking into account temperature changes, the physical state of the material, or even structural changes in the resistor itself. Using interpolation and linearization methods can help model these nonlinear changes, allowing for more accurate calculations of resistance under different loads. Interpolation would enable the calculation of values between known points, while linearization would simplify complex nonlinear relationships, making them easier to solve in specific ranges.

Future research in characterizing the temperature effects on the resistance of standard resistors could focus on developing advanced materials and construction techniques to reduce the temperature coefficient and improve heat transfer, durability, and flexibility under different temperatures and mechanical stress. Also, future research could involve experimentally gathering data on resistance at different load levels, applying interpolation techniques (such as spline interpolation) to create an accurate model of resistance dependency on load and linearizing nonlinear relationships based on experimental data using approximations like Taylor series, piecewise linearization or other methods.

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