Standard Guide for Accuracy Verification of Industrial Platinum Resistance Thermometers[1]

1. Scope

1.1 This guide describes the techniques and apparatus required for the accuracy verification of industrial platinum resistance thermometers constructed in accordance with Specification E1137/E1137M and the evaluation of calibration uncertainties. The procedures described apply over the range of –200°C to 650°C.

1.2 This guide does not intend to describe procedures necessary for the calibration of platinum resistance thermometers used as calibration standards or Standard Platinum Resistance Thermometers. Consequently, calibration of these types of instruments is outside the scope of this guide.

1.3 Industrial platinum resistance thermometers are available in many styles and configurations. This guide does not purport to determine the suitability of any particular design, style, or configuration for calibration over a desired temperature range.

1.4 The evaluation of uncertainties is based upon current international practices as described in ISO/TAG 4/WG 3 "Guide to the Evaluation of Uncertainty in Measurement" and ANSI/NCSL Z540-2-1997 "U.S. Guide to the Expression of Uncertainty in Measurement."

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E344 Terminology Relating to Thermometry and Hydrometry

E563 Practice for Preparation and Use of an Ice-Point Bath as a Reference Temperature

E644 Test Methods for Testing Industrial Resistance Thermometers

E1137/E1137M Specification for Industrial Platinum Resistance Thermometers

E1502 Guide for Use of Fixed-Point Cells for Reference Temperatures

E1750 Guide for Use of Water Triple Point Cells

2.2 *ANSI Publication:*

ANSI/NCSL Z540-2-1997 U.S. Guide to the Expression of Uncertainty in Measurement[3]

2.3 *Other Publication:*

ISO/TAG 4/WG 3 Guide to the Evaluation of Uncertainty in Measurement

3. Terminology

3.1 *Definitions*—The definitions given in Terminology E344 shall be considered as applying to the terms used in this guide.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *annealing, v*—a heat treating process intended to stabilize resistance thermometers prior to calibration and use.

3.2.2 *check standard, n*—a thermometer similar in design to the unit under test, but of superior stability, which is included in the calibration process for the purpose of quantifying the process variability.

3.2.3 *coverage factor, n*—numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.

3.2.4 *dielectric absorption, n*—an effect in an insulator caused by the polarization of positive and negative charges within the insulator which manifests itself as an in-phase current when the voltage is removed and the charges recombine.

3.2.5 *expanded uncertainty, U, n*—quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

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[1] This guide is under the jurisdiction of ASTM Committee E20 on Temperature Measurement and is the direct responsibility of Subcommittee E20.03 on Resistance Thermometers.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

3.2.5.1 *Discussion*—Normally, *U* is given at a coverage factor of 2, approximating to a 95 % confidence interval.

3.2.6 *hysteresis, n*—property associated with the resistance of a thermometer whereby the value of resistance at a temperature is dependant upon previous exposure to different temperatures.

3.2.7 *normal distribution, n*—a frequency distribution characterized by a bell shaped curve and defined by two parameters: mean and standard deviation.

3.2.8 *platinum resistance thermometer (PRT), n*—a resistance thermometer with the resistance element constructed from platinum or platinum alloy.

3.2.9 *rectangular distribution, n*—a frequency distribution characterized by a rectangular shaped curve and defined by two parameters: mean and magnitude (semi-range).

3.2.10 *standard deviation of the mean, n*—an estimate of the standard deviation of the sampling distribution of means, based on the data from one or more random samples.

3.2.10.1 *Discussion*—Numerically, it is equal to the standard deviation obtained (*s*) when divided by the square root of the size of the sample (*n*).

$$\text{Standard Deviation of the Mean} = \frac{s}{\sqrt{n}} \tag{1}$$

3.2.11 *standard platinum resistance thermometer (SPRT), n*—a specialized platinum resistance thermometer constructed in such a way that it fulfills the requirements of the ITS-90.[4]

3.2.12 *standard uncertainty, n*—uncertainty of the result of a measurement expressed as a standard deviation, designated as *S*.

3.2.13 *Type A evaluation (of uncertainty), n*—method of evaluation of uncertainty by the statistical analysis of a series of observations.

3.2.14 *Type B evaluation (of uncertainty), n*—method of evaluation of uncertainty by means other than statistical analysis of a series of observations.

3.2.15 *test uncertainty ratio (TUR), n*—the ratio of the tolerance of the unit under test to the expanded calibration uncertainty.

3.2.16 *uncertainty budget, n*—an analysis tool used for assembling and combining component uncertainties expected in a measurement process into an overall expected uncertainty.

3.2.17 *unit under test (UUT), n*—the platinum resistance thermometer to be calibrated.

4. Summary of Guide

4.1 The UUT is calibrated by determining the electrical resistance of its sensing element at one or more known temperatures covering the temperature range of interest. The known temperatures may be established by means of fixed-point systems or by using a reference thermometer. Either an SPRT or a PRT is recommended for use as the reference thermometer. However a liquid in glass (LIG) thermometer, thermistor, or thermocouple may be acceptable depending upon the temperature of calibration, required accuracy, or other considerations.

4.2 The success of the calibration depends largely upon the ability of the UUT to come to thermal equilibrium with the calibration temperature of interest (fixed point cell or comparison system) and upon accurate measurement of the sensing element resistance at that time. Instructions are included to guide the user in achieving thermal equilibrium and proper resistance measurement, including descriptions of apparatus and instrumentation.

4.3 Industrial platinum resistance thermometers are available in many styles and configurations. This guide includes limited instructions pertaining to the preparation of the UUT into a configuration that facilitates proper calibration.

4.4 Proper evaluation of calibration uncertainties is critical for the result of a calibration to be useful. Therefore, a considerable portion of this guide is devoted to uncertainty budgets and the evaluation of uncertainties.

5. Significance and Use

5.1 This guide is intended to be used for verifying the resistance-temperature relationship of industrial platinum resistance thermometers that are intended to satisfy the requirements of Specification E1137/E1137M. It is intended to provide a consistent method for calibration and uncertainty evaluation while still allowing the user some flexibility in the choice of apparatus and instrumentation. It is understood that the limits of uncertainty obtained depend in large part upon the apparatus and instrumentation used. Therefore, since this guide is not prescriptive in approach, it provides detailed instruction in uncertainty evaluation to accommodate the variety of apparatus and instrumentation that may be employed.

5.2 This guide is intended primarily to satisfy applications requiring compliance to Specification E1137/E1137M. However, the techniques described may be appropriate for applications where higher accuracy calibrations are needed.

5.3 Many applications require tolerances to be verified using a minimum test uncertainty ratio (TUR). This standard provides guidelines for evaluating uncertainties used to support TUR calculations.

6. Sources of Error

6.1 Uncertainties are present in all calibrations. Errors arise when the effects of uncertainties are underestimated or omitted. The predominant sources of uncertainty are described in Section 12 and listed in Table 2.

7. Apparatus

7.1 *Resistance Measuring Instruments*—The choice of a specific instrument to use for measuring the UUT and reference thermometer resistance will depend upon several factors. Some of these factors are ease of use, compatibility with computerized data acquisition systems, method of balancing, computation ability, etc. All of the instruments listed are commercially

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[4] Mangum, B. W., NIST Technical Note 1265, Guidelines for Realizing the International Temperature Scale of 1990 (ITS-90).

available in high precision designs and are suitable for use. They require periodic linearity checks or periodic calibration. (Refer to Appendix X2 for detailed descriptions and schematics.) The accuracy of the resistance measurements directly impacts the accuracy of the temperature measurement as shown in Eq 2.

$$Accuracy_t = \frac{Accuracy_\Omega}{Sensitivity} \tag{2}$$

where:

$Accuracy_t$ = temperature accuracy at temperature (t), °C,
$Accuracy_\Omega$ = resistance accuracy at temperature (t), Ω, and
$Sensitivity$ = sensitivity at temperature (t), $\Omega\ °C^{-1}$

7.1.1 *Bridge*—Precision bridges with linearity specifications ranging from 10 ppm of range to 0.01 ppm of range and with 6½ to 9½ digit resolution are available. These instruments are available in models using either AC or DC excitation. The linearity is typically based upon resistive or inductive dividers and is generally quite stable over time. Modern bridges are convenient automatic balancing instruments but manual balancing types are also suitable. These instruments typically require external reference resistors and do not perform temperature calculations.

7.1.2 *Digital Thermometer Readout*—Digital instruments designed specifically to measure resistance thermometers are available. Modern versions function essentially as automatic potentiometers and reverse the current to eliminate spurious thermal emf. Precision instruments with linearity specifications ranging from 20 ppm of indication to 1 ppm of indication and with 6½ to 8½ digit resolution are commercially available. Some models have extensive internal computation capability, performing both temperature and statistical calculations. Periodic calibration is required.

7.1.3 *Digital Multimeter (DMM)*—Digital multimeters are convenient direct indication instruments typically able to indicate in resistance or voltage. Some models have extensive internal computation ability, performing both temperature and statistical calculations. The use of DC offset compensation is recommended. Caution must be exercised to ensure that the excitation current is appropriate for the UUT and reference thermometer to avoid excessive self-heating. Periodic calibration is required.

7.1.4 *Reference Resistor*—Reference resistors are specially designed and manufactured to be stable over long periods of time. Typically, they have significant temperature coefficients of resistance and require maintenance in a temperature enclosed air or oil bath. Some have inductive and capacitive characteristics that limit their suitability for use with AC bridges. Periodic (yearly or semi-yearly) calibration is required. Resistors (AC or DC) are required to match the type of measurement (AC or DC) system in use.

7.2 *Reference Thermometers*—The choice of a specific instrument to use as the reference thermometer will depend upon several factors, including the uncertainty desired, temperature range of interest, compatibility with existing instrumentation and apparatus, expertise of staff, cost limitations, etc. All of the instruments listed are commercially available in various levels of precision and stability and may be suitable for use. They all require calibration. The frequency of calibration depends a great deal upon the manner in which they are used and the uncertainty required in use.

7.2.1 *SPRT*—SPRTs are the most accurate reference thermometers available and are used in defining the ITS-90 from approximately –260°C to 962°C. The SPRT sensing element is made from nominally pure platinum and is supported essentially strain-free. These instruments are extremely delicate and are easily damaged by mechanical shock. They are available sheathed in glass or metal and in long stem and capsule configurations. The design and materials of construction limit the temperature range of a specific instrument type. Some sheath materials can be damaged by use at high temperatures in metal blocks or molten salt baths. Calibration on the ITS-90 is required.

7.2.2 *Secondary Reference PRT*—Secondary Reference PRTs are specially manufactured PRTs designed to be suitable calibration standards. These instruments are typically less delicate than SPRTs but have higher measurement uncertainties and narrower usage ranges. They are typically sheathed in metal to allow immersion directly into metal furnaces or molten salt baths. Calibration on the ITS-90 is required.

7.3 *Fixed Point Systems*—Fixed point systems are required in the ITS-90 calibration of SPRTs. Very low uncertainties are attainable with these systems, but their complex procedures and design criteria may limit their application to other types of thermometers. However, certain adaptations are suitable for the calibration of industrial platinum resistance thermometers.

7.3.1 *TPW Cell and Apparatus*—The triple point of water cell is a critical thermometric fixed point for calibration and control of SPRTs. These devices can be useful in the calibration of industrial resistance thermometers but typically are not used because of limited throughput capabilities. For further information refer to Guide E1750.

7.3.2 *Freezing-Point Cell and Furnace*—Metal-freezing point cells are used in the calibration of SPRTs and thermocouples. These devices can be useful in the calibration of industrial platinum resistance thermometers but typically are not used because of limited throughput capabilities. For further information refer to Guide E1502.

7.3.3 *Ice-Point Bath*—The ice point is a relatively simple to realize fixed point that is useful in the calibration of resistance thermometers. The ice point bath can be used as a fixed point with uncertainties attributed to the care of construction and maintenance. For further information refer to Practice E563.

7.4 *Comparison Apparatus*—The choice of a specific comparison apparatus to use will depend primarily upon two factors: the temperature range of interest and the uncertainty required. Secondary factors include ease of use, compatibility with computerized data acquisition systems or automation capability, flexibility, cost etc. All of the apparatus listed is commercially available in various levels of performance and are suitable for use. They may or may not require periodic calibration.

7.4.1 *Liquid Bath*—Liquid baths can be used as the heat source for comparison calibrations. Typically, these instruments are useful over the temperature range of –100°C to 550°C. The actual range of any one bath is limited by the construction of the bath and the bath fluid. Bath fluids typically have narrower temperature ranges than the baths themselves, requiring changes in fluid or multiple baths to cover a typical calibration range. The attainable uncertainty is limited primarily by the temperature uniformity and stability of the bath fluid.

7.4.2 *Liquid Nitrogen Comparison Bath*—A liquid nitrogen comparison bath is essentially a high quality dewar with an equilibration block suspended in liquid nitrogen. Because liquid nitrogen will stratify within the dewar, large temperature gradients will exist without the use of an equilibration block. Consequently, a block is required. Instrument grade liquid nitrogen is widely available and has a normal boiling point of approximately –196.5°C. Since the purity of the liquid nitrogen and the atmospheric pressure are unknown, the temperature of the comparison bath must be established with a reference thermometer. The attainable uncertainty is limited primarily by the temperature uniformity in the block, the conduction losses up the stem of the reference thermometer or UUT, and the stability of the system due to changes in barometric pressure and other factors.

7.4.3 *Equilibration Block*—Although not a comparison apparatus per se, the equilibration block is utilized to enhance the performance of a comparison bath. An equilibration block is a high thermal conductivity block suspended in the comparison bath within which the PRTs and reference instrument are inserted. The block should be cylindrical and contain enough holes to hold the reference thermometer, check standard, and several UUTs. Additionally, the block should be of sufficient depth to completely cover the sensitive portions of all thermometers involved. The block material must be chemically compatible with the bath fluid. Recommended materials include oxygen-free copper, low oxygen copper, and aluminum.

7.4.4 *Dry-Well Bath*—Furnaces with built- in thermometer readouts can be used as the heat source for comparison calibrations. Typically, these instruments are useful over the temperature range of –40°C to 650°C. The attainable uncertainty is limited primarily by the temperature uniformity in the block and conduction losses up the stem of the reference thermometer or UUT. For best results, the thermometer wells should be deep and of the correct diameter to allow a slip fit of the reference thermometer or UUT.

8. Preparation of UUT

8.1 *Physical Configuration*—UUTs that are not already sheathed shall be assembled into protection tubes before calibration. Closed-end glass or thin wall metal tubing of adequate length to allow sufficient immersion is recommended. A diameter that allows a slip fit without being too tight should be chosen. Ensure that the tube is clean and dry before assembly. A thermally conductive filler material may be used within the sheath between the sensor and sheath to enhance thermal conductivity if desired. Ensure that the material will not damage the sensor. The sensor lead wires are welded or soldered to extension wires in 4-wire configuration (unless a 2-wire or 3-wire calibration is specifically required) and the assembly inserted into the tube. If the connections are made using solder, ensure that the solder is compatible with the temperature range over which the UUT will be calibrated. Additionally, if DC measurements are used, the connectors and solder type should be chosen to minimize thermal emf. The insulation of the extension wires and the connection itself must also be suitable for the temperature range over which the calibration will be performed. The assembled UUT should be affixed to the tube at the point where the extension wires exit the tube to ensure that the UUT does not slide up the tube during calibration. If the UUT is to be calibrated below 0°C, the tube should be dried internally and sealed to prevent water vapor from condensing into the sheath.

8.2 *Annealing*—Annealing is not recommended for routine tolerance verification unless requested by the user or instructed otherwise. Before any annealing is undertaken, consult the manufacturer of the UUT or other technical expert knowledgeable in the design and limitations of the UUT. (The stability of the thermometer can be observed by cycling between the ice point and a maximum or minimum temperature.) An annealing procedure that can improve the performance of some UUTs may prove useless or even detrimental to others. If annealing is attempted, a record of the UUT R_{TPW} or R_0 (as applicable) at each step of annealing is required to monitor UUT stability and the results of annealing.

8.3 *Immersion Length Test*—If the immersion length of the UUT is unknown, it must be determined in accordance with Section 7 of Test Methods E644.

8.4 *Insulation Resistance Test*—The insulation resistance should be tested in accordance with Section 5 of Test Methods E644 using the criteria of Section 9 of Specification E1137/E1137M.

9. Procedure

9.1 The number, location, and sequence of temperature points required for UUT calibration depends upon the uncertainty required, the suitability of the mathematical model, and the hysteresis exhibited by the UUT. Thus, the specific calibration points and sequence are best determined through experimentation. Once determined for a specific design of UUT, the measurement strategy can be used in subsequent calibrations provided the results remain satisfactory. It is recommended that the redundant points be included in an effort to reveal hysteresis or stability problems. If hysteresis and instability are small compared to the overall tolerance, the redundant points may be omitted. Refer to Table 1 for recommended points and sequence. Also, it is immaterial if these measurements are performed in fixed-point systems or by comparison. If several UUTs are to be calibrated per run, comparison calibration is usually more efficient. The following procedure assumes concurrent calibration of several UUTs by

TABLE 1 Recommended Minimum Calibration Points and Sequence for PRT Accuracy Verification

Case	Range of Interest	Calibration Sequence
1	Single point, T	T
2	Tmin < T < Tmax, Tmin = 0°C	0°C, Tmid, Tmax, Tmid
3	Tmin < T < Tmax, Tmax = 0°C	0°C, Tmid, Tmin, Tmid
4	Tmin < T < Tmax, Tmin > 0°C	Tmin, Tmax, Tmin
5	Tmin < T < Tmax, Tmax < 0°C	Tmax, Tmin, Tmax
6	Tmin < T < Tmax, Tmin < 0°C < Tmax	Tmin, 0°C, Tmax, 0°C

comparison. If fixed —point systems are being used at one or more temperature points, each UUT must be calibrated at that temperature point individually and the procedure shall be adjusted accordingly.

9.2 *Connection of the UUTs*—If a direct resistance measurement scheme is being used, connect the UUTs to the measurement system. Use a 4-wire configuration (unless a 2-wire or 3-wire calibration is specifically required) and observe polarity. If a potentiometric measurement scheme is being used, connect the UUT current leads in series to the current supply and the voltage leads to the switch system, potentiometer or digital multimeter DMM input, observing polarity. Refer to Appendix X2 for guidance if necessary.

9.3 *Connection of the Check Standard*—Connect the check standard to the measurement system in the same manner as the UUTs.

9.4 *Connection of the Reference Thermometer*—Connect the reference thermometer to the R_X input of the measurement instrument and, if applicable, the reference resistor to the R_S input. A single instrument may be used to measure the UUTs, the reference thermometer, and the check standard if applicable. Refer to Appendix X2 for guidance if necessary.

9.5 *Insertion into Comparison Bath*—Insert the reference thermometer, check standard, and UUTs into the comparison bath in close proximity and with the sensing elements at the same depth if practical. Ensure that sufficient immersion is achieved and maintained during the calibration process. If the calibration is being undertaken from hot to cold, contraction of the bath fluid will cause a decrease in the fluid depth as the temperature is reduced.

9.6 *Temperature Measurement*—The specific steps required to obtain a temperature measurement depend upon the type of reference thermometer and readout instrument employed. The following steps provide a general outline. Allow sufficient time for the system to stabilize and equilibrate. This is easily observed if the readout instrument has graphing capabilities or is connected to a computer system with graphing capabilities. Otherwise, the readout indication shall be observed until stability is achieved. Once a steady state has been achieved, perform several individual temperature measurements using the reference thermometer and calculate the mean, standard deviation, and standard deviation of the mean (sample size ≥ 36 is recommended). The mean represents the measured value. The standard deviation is used to compute the standard deviation of the mean as shown in Eq 1. The standard deviation of the mean represents the measurement noise (or precision of measurement, item 12.2.1d in Table 3). If the values obtained are within the uncertainty limits allowed, proceed with measurements of the UUTs. (Some readout instruments allow simultaneous measurement of the reference and UUTs. If this is the type of instrument being used, steps 9.6 – 9.8 are combined with the statistics calculated in real time.)

9.7 *Measurement of UUTs*—Measure the resistance of the check standard and each UUT. As with the measurement of the reference thermometer, these measurements should consist of several individual measurements. Calculate the mean, standard deviation, and standard deviation of the mean. The mean represents the measured value. The standard deviation is used to compute the standard deviation of the mean as shown in Eq 1. The standard deviation of the mean represents the measurement noise (or precision of measurement, item 12.2.3b in Table 3). If the values obtained are within the uncertainty limits allowed, proceed with a second (closure) measurement of the temperature. The number of UUTs that may be measured between the reference thermometer measurements depends the stability of the calibration medium and the speed of the measurement system. Refer to Appendix X1 for guidance on PRTs not in a 4-wire configuration.

TABLE 2 Uncertainty Summary

Section	Component	Type
12.2.1	Temperature Measurement System	
	Propagated Uncertainty of Calibration	B
	Reference Thermometer Stability	A
	Resistance or Voltage Uncertainty	B
	Precision of Temperature Measurement	A
	Propagated Rtpw Uncertainty	B
12.2.2	Fixed Point System	B
12.2.3	Measurement of UUT Resistance	
	Resistance Measurement Uncertainty	B
	Precision of Resistance Measurement	A
	Lead wire errors (non 4-wire measurements)	B
	Resistance Stability	A
	Hysteresis	B
12.2.4	Comparison Apparatus	
	Temporal Stability	A
	Spatial Uniformity	A
	Immersion Effects	B
12.2.5	Process Repeatability	A

9.8 *Closure Measurement of Temperature*—Repeat step 9.6. At the completion of this measurement, calculate the change in temperature. If the magnitude of the change is acceptable, the measurement can be considered successful and the calibration may proceed to the next temperature where the procedure is repeated. If the change is too large, based on uncertainty requirements, the process shall be repeated until a satisfactory result is obtained. If necessary, the time interval between the opening and closing measurements of the reference thermometer may be reduced by decreasing either the number of samples taken or the number of UUTs measured or both.

9.9 Repeat the above process for all of the temperatures to be covered. To prevent contamination, bath fluid residue shall be removed from the thermometers before immersion into other baths, dry wells, or fixed-point systems.

9.10 The R_{TPW} or R_0 (as applicable) of the reference thermometer should be measured at completion of the comparison measurement to quantify changes that may have occurred during the calibration process. Any instability observed shall be included in the uncertainty analysis.

9.11 Refer to Section 11 for guidance on reporting the data and Section 12 for guidance on estimating the uncertainties.

10. Calculation

10.1 *Specification E1137/E1137M Equation* —Among the many characteristics of industrial PRTs, Specification E1137/E1137M uses two forms of polynomial to describe the

TABLE 3 Uncertainty Example (uncertainty values in example are in °C.)

Section	Component	Type	Start Value	Normalize Value	1 σ Equivalent
12.2.1	Temperature Measurement System				
a	Propagated Uncertainty of Calibration	B	0.010	/√3	0.006
b	Reference Thermometer Stability	A	0.002	None	0.002
c	Resistance or Voltage Uncertainty	B	0.010	/√3	0.006
d	Precision of Temperature Measurement	A	0.002	None	0.002
e	Propagated Rtpw Uncertainty	B	0.007	/√3	0.004
12.2.3	Measurement of UUT Resistance				
a	Resistance Measurement Uncertainty	B	0.010	/√3	0.006
b	Precision of Resistance Measurement	A	0.002	None	0.002
c	Resistance Stability	A	0.010	None	0.010
d	Hysteresis	B	0.010	/√3	0.006
12.2.4	Comparison Apparatus				
a	Temporal Stability	A	0.002	None	0.002
b	Spatial Uniformity	A	0.004	None	0.004
c	Immersion Effects	B	0.002	/√3	0.001
12.2.5	Process Repeatability	A	0.015	None	0.015
	Combined				0.023
	Expanded (*k* = 2)				0.046

resistance-temperature relationship of the PRT. A PRT is said to conform to this aspect of Specification E1137/E1137M if it follows the relationship within the tolerance specified in Specification E1137/E1137M. For the range $-200°C \leq t \leq 0°C$, Eq 3 is used and for the range $0°C \leq t \leq 650°C$, Eq 4 is used.

$$R_t = R_0\left[1 + At + Bt^2 + C(t - 100)t^3\right]\Omega \tag{3}$$

$$R_t = R_0\left[1 + At + Bt^2\right]\Omega \tag{4}$$

where:

t = temperature (ITS-90), °C,
R_t = resistance at temperature (t),
R_0 = resistance at 0°C, Ω (nominal = 100 Ω),
A = 3.9083×10^{-3} °C^{-1},
B = -5.775×10^{-7} °C^{-2}, and
C = -4.183×10^{-12} °C^{-4}.

10.2 *Specification E1137/E1137M Inverse Equation*—For convenience, the inverse equations given in Appendix X1 of Specification E1137/E1137M may be used in lieu of the defined equations given above. Eq 6 is the inverse of Eq 4, and Eq 5 is an approximate inverse of Eq 3. The deviation introduced by this approximation is estimated not to exceed 0.002°C.

$$t = \sum_{i=1}^{4} D_i (R_t/R_0 - 1)^i \tag{5}$$

$$t = \frac{\sqrt{A^2 - 4B(1 - R_t/R_0)} - A}{2B} \tag{6}$$

where:

t = temperature (ITS-90), °C,
R_t = resistance at temperature (t), Ω,
R_0 = resistance at 0°C, Ω (nominal = 100 Ω),
A = 3.9083×10^{-3} °C^{-1},
B = -5.775×10^{-7} °C^{-2},
D_1 = 255.819°C,
D_2 = 9.14550°C,
D_3 = −2.92363°C, and
D_4 = 1.79090°C.

10.3 The resistance–temperature data obtained during calibration are compared to the values calculated using the above equations to verify conformance to the accuracy tolerances given in Specification E1137/E1137M:

$$Grade\ A\ tolerance = \pm\left[0.13 + 0.0017\ |t|\right]°C \tag{7}$$

$$Grade\ B\ tolerance = \pm\left[0.25 + 0.0042\ |t|\right]°C \tag{8}$$

Where:

$|t|$ = value of temperature without regard to sign, °C

10.3.1 The following criterion is used when the specified TUR is satisfied:

$$|T_{uut} - T_{ref}| < Tolerance\ °C \tag{9}$$

Where:

T_{uut} = temperature indicated by unit under test (Eq. 5 or 6)
T_{ref} = temperature indicated by reference thermometer
Tolerance = specified tolerance at T_{ref} (Grade A or B)

10.3.2 Example calculations are included in Table 4.

11. Report

11.1 The results of the calibration may be reported in any convenient form. The report should include at a minimum a title, a unique identification of the item calibrated, a record of the person who performed the calibration, the date of

TABLE 4 Example — Grade B Tolerance Verification for a Thermometer with Nominal Ice-Point Resistance (R_0) of 100 ohms Tested Over the Range -50°C to 200°C

T_{ref}, °C[A]	R_{uut}, ohms[B]	R_{uut}/R_0[C]	T_{uut}, °C[D]	$\lvert T_{uut} - T_{ref}\rvert$, °C	Grade B Tol, °C[E]	Acceptance[F]
-50.105	80.282	0.80282	-50.062	0.043	0.460	Pass
0.000	100.020	1.00020	0.051	0.051	0.250	Pass
199.945	176.011	1.76011	200.422	0.477	1.090	Pass
0.000	100.080	1.00080	0.205	0.205	0.250	Pass

[A] Temperature indicated by reference thermometer.
[B] Measured resistance of the UUT.
[C] Resistance ratio calculated using specified nominal R_0 (100 ohms).
[D] Temperature indicated by the UUT using Eq. 5 ($R_{uut}/R_0 < 1$) or Eq. 6 ($R_{uut}/R_0 \geq 1$).
[E] Grade B tolerance at T_{ref} using Eq 8.
[F] Using criterion $|T_{uut} - T_{ref}|$, Tolerance (Eq 9), assuming minimum TUR is satisfied.

calibration, the temperature-resistance data obtained, the equation used (forward or inverse), and the measurement uncertainties. Supplementary information including a concise description of the calibration method, a list of the reference instruments used, a statement regarding the traceability of the calibration, a reference to or a description of the uncertainty budget, and a citation of this guide may be requested by customers.

12. Uncertainty

12.1 *General Description*—The uncertainty evaluation process consists primarily of five steps. First, determining the variables that contribute to measurement uncertainty. Second, quantifying, assigning values, or modeling the effects of these variables in order to obtain values to represent the effects. Third, normalizing the data into one standard deviation equivalent. Fourth, combining the components in accordance with current practice. Fifth, multiplying the uncertainty by a factor (the coverage factor) to provide adequate statistical coverage. The analysis may include Type A or Type B methods, or a combination of both. The current practice does not suggest a preference for Type A or Type B evaluation. However, the nature of the variables themselves may suggest a method of evaluation. For example, measurement noise is easily evaluated statistically but difficult to evaluate using non-statistical techniques. It is advantageous to select the method of evaluation that fits the variable in a seemingly natural way. Refer to the table at the end of this discussion for a summary of components and possible evaluation category.

12.2 *Evaluation of Uncertainties*—The uncertainties present in the calibration of industrial platinum resistance thermometers fall into several general categories: *(1)* the uncertainty of the temperature measurement at the calibration points including the reference measurement temperature system if applicable, *(2)* the uncertainty of the UUT resistance determination at the calibration points, *(3)* resistance instabilities in the UUT resulting from hysteresis and other effects, *(4)* the spatial and temporal isothermality of the calibration zone that surrounds the reference thermometer and the UUT, and *(5)* the calibration process stability. Additionally, instabilities may exist in the UUT that are difficult to quantify during the calibration experiment may exist in the UUT. Examples of these uncertainties are long-term drift and instability due to thermal cycling.

12.2.1 The uncertainty in temperature measurement using a reference thermometer is a combination of the propagated uncertainty in the calibration of the reference thermometer, the reproducibility (stability) of the reference thermometer, the uncertainty of the resistance or voltage measurement of the reference thermometer, and, if applicable, the propagation of the uncertainty in the measurement of the reference thermometer R_{TPW}. An important but often overlooked component of the reference thermometer measurement is the measurement noise present during the measurement process. This noise may originate with the measurement system, instabilities in the bath or dry block calibrator, or the thermometer itself. For uncertainty analysis the source of the noise is unimportant provided the effect is quantified. Since the source is not clearly known, this component is often referred to as the precision of the measurement and can be quantified by computing the standard deviation of the mean of the individual measurements.

12.2.2 The uncertainty in the temperature value obtained using fixed point systems is a combination of the uncertainty in the fixed point (cell) temperature, the uncertainty in the realization (including the uncertainty in the correction elements), the temporal uncertainty as the fixed point plateau progresses, and the effects of immersion of the UUT into the fixed point.

12.2.3 The uncertainty in the resistance determination of the UUT is a combination of the uncertainty of the resistance measurement of the UUT, the stability of the UUT during the measurement at the temperature point, hysteresis and other effects, and lead-wire errors if the UUT is not measured in a 4-wire configuration. Similarly to the reference thermometer, the precision of the measurement must be quantified. It is not uncommon for this component of uncertainty to vary widely from one UUT to the next, even for UUTs of similar design and construction.

12.2.4 The spatial and temporal isothermality of the zone surrounding the reference thermometer and UUT is a combination of the temporal stability and spatial uniformity of the comparison bath as experienced by the thermometers and the effects of immersion of the thermometers. The thermal mass of the reference thermometer and UUT and the thermal capacity of the calibration bath affect this component or uncertainty. This component can be observed and accounted for in a number of ways. First, the bath stability and uniformity can be measured in separate tests, the results of which can be applied here. Second, the temporal stability can be observed through the reference thermometer and the uniformity can be incorporated into the check standard observations by placing it in a different location within the calibration zone with each run, exploring both horizontal and vertical uniformity. Finally, similar to the second method, the temporal stability can be observed through the reference thermometer and the maximum non-uniformity can be observed by placing the check standard in the UUT position nearest and farthest from the reference thermometer.

12.2.5 The process repeatability is observed through repeated measurement of the check standard and calculated by computing the standard deviation of the repeated observations. This thermometer is included in the calibration run and is measured as if it were a UUT. This instrument should be similar to the UUTs in design and sufficiently stable that it shows instabilities in the process rather than changes in its characteristics. The repeated observations of resistance at temperatures are plotted on a control chart and the standard deviation is calculated. If the readout for the UUTs is capable of temperature calculation, calibration coefficients should be calculated for the check standard. The readout can then be programmed to indicate temperature as observed by the check standard, rather than resistance, and the temperature difference between the reference thermometer and the check standard can be calculated and plotted. However, this is a matter of preference rather than a requirement.

12.3 *Normalization of Uncertainty Values*—Since Type B components are not evaluated statistically, the value of one standard deviation may not be readily available. When such is the case, the standard deviation equivalent of the uncertainty must be approximated using an assumed probability distribution. Current practice recommends the assumption of a rectangular distribution unless information to suggest an alternative distribution (for example Gaussian or U-shaped) exists. The normalization is accomplished for a rectangular distribution using Eq 10. Other distributions require different normalization equations.

$$u = \frac{a}{\sqrt{3}} \tag{10}$$

where:

a = the parameter representing the limits (± a) of the rectangular distribution.

12.4 *Combination and Expansion of Uncertainties*—For uncorrelated uncertainties, the expanded uncertainty, U, is calculated using Eq 11:

$$U = k\sqrt{s^2 + \sum u(i)^2} \tag{11}$$

where:

k = coverage factor, usually 2,
s = Type A standard uncertainty, and
$u(i)$ = estimated Type B standard uncertainty for each component.

12.5 *Example*—An example calculation for a 4-wire PRT at 100°C in a calibration bath, based on the preceding uncertainty summary is shown in Table 3.

12.6 *Uncertainty Budget*—An uncertainty budget is established to identify the sources of uncertainty and to determine their individual contributions to overall uncertainty. This tool is used before the calibration is undertaken to provide a baseline from which to proceed. The result of this exercise is an estimate of the uncertainty believed to be attainable in a system. This process is not a substitute for uncertainty evaluation; it is used to evaluate the anticipated capability of a process. Certain components of uncertainty are not known until the measurement process has been operating for some time. Type B uncertainties (realistic estimates) are included for these components. The method of combination of components is identical to that used in uncertainty evaluation. This exercise can be approached from two directions. The first approach begins with the individual components themselves computed. The second approach begins with a target value established for the uncertainty and the individual components are assigned allocations.

12.6.1 *Error Budget from Individual Components*—The individual components are listed along with their corresponding uncertainties. The components are combined and an overall uncertainty value is calculated. The example shown in Table 3 uses values of uncertainty that represent high accuracy equipment and techniques. This illustrates an uncertainty attainable using the methods and equipment outlined in this guide.

TABLE 5 Example Calibration Uncertainty Budget (Uncertainty Values are Expressed in °C) Illustrating a Calibration Process Intended to Test PRTs to Specification E1137/E1137M Grade A Tolerance

NOTE 1—The required uncertainty was calculated as 25 % of the calculated tolerance at the applicable temperature (4:1 TUR). The component uncertainty values listed in the table are specifications of medium precision instruments available commercially. As shown in the table, the uncertainty figures calculated over the temperature range of –196°C to 550°C are considerably below the required uncertainty values. This would allow some flexibility in the selection of components while still achieving the desired results. The calculated uncertainty over the temperature range of 550°C to 650°C just meets the required uncertainty, indicating that the component values listed must be attained to arrive at the desired result.

Component	LN_2 ≈ –196°C	Alcohol Bath –100°C to 0°C	Water Bath 0.2°C to 95°C	Oil Bath 95°C to 300°C	Salt Bath 300°C to 550°C	Furnace 550°C to 650°C
Digital Readout (8 ppm)[A]	0.001	0.002	0.003	0.004	0.006	0.007
Reference PRT Calibration[A]	0.005	0.005	0.010	0.015	0.020	0.040
Precision of Reference Measurement[A]	0.002	0.002	0.002	0.003	0.005	0.010
UUT readout (8 ppm)[B]	0.001	0.002	0.003	0.004	0.006	0.007
Precision of UUT Measurement[B]	0.002	0.002	0.002	0.003	0.005	0.010
Comparison bath stability[C]	0.005	0.005	0.005	0.010	0.015	0.050
Hysteresis and other effects	0.010	0.015	0.020	0.025	0.025	0.030
Vertical and horizontal gradients[C]	0.005	0.005	0.005	0.010	0.015	0.100
Process repeatability[D]	0.005	0.005	0.005	0.010	0.025	0.050
Combined & Expanded (k = 2)	0.029	0.037	0.049	0.069	0.094	0.267
Required Uncertainty	0.118	0.075 to 0.033	0.033 to 0.075	0.075 to 0.160	0.160 to 0.266	0.266 to 0.309

[A] Corresponds to uncertainty summary section 12.2.1.
[B] Corresponds to uncertainty summary section 12.2.3.
[C] Corresponds to uncertainty summary section 12.2.4.
[D] Corresponds to uncertainty summary section 12.2.5.

12.6.2 *Error Budget from a Required Uncertainty*—The second approach begins with a required value for the uncertainty of the result. The values chosen for the required uncertainty must be consistent with the desired TUR and agreed upon between the user and producer. Once established, the individual components contributing to this figure are allocated portions which, when combined, arrive at the required uncertainty value. This approach is particularly useful when an accuracy requirement is known and the calibration ensemble must be assembled. The example shown in Table 5 illustrates one solution to calibration of PRTs intended to meet Specification E1137/E1137M grade A tolerance.

13. Keywords

13.1 accuracy verification; calibration; industrial platinum resistance thermometer; platinum resistance thermometer; standard platinum resistance thermometer; uncertainty

APPENDIXES

(Nonmandatory Information)

X1. THERMOMETER WIRE CONFIGURATIONS AND MEASUREMENT SCHEMES

X1.1 Typical thermometer wire configurations are shown schematically in Fig. X1.1.

X1.2 Measurements for 2, 3, and 4-wire configurations are shown schematically in Figs. X1.2-X1.7.

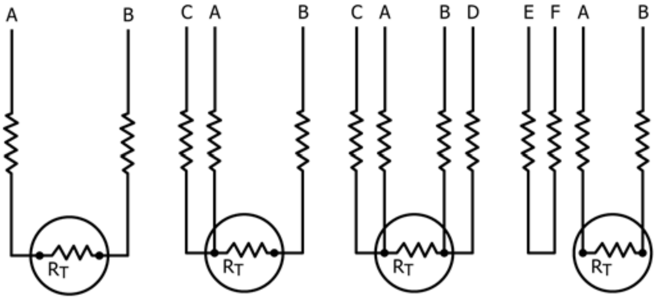


FIG. X1.1 Thermometer Wire Configurations

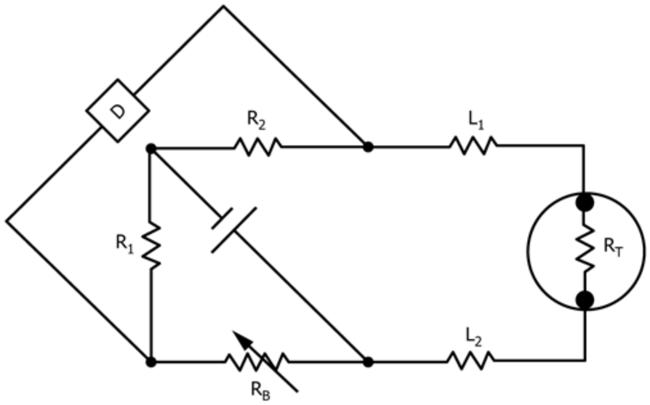


FIG. X1.2 Two-Wire Thermometer Connected to a Simple Bridge

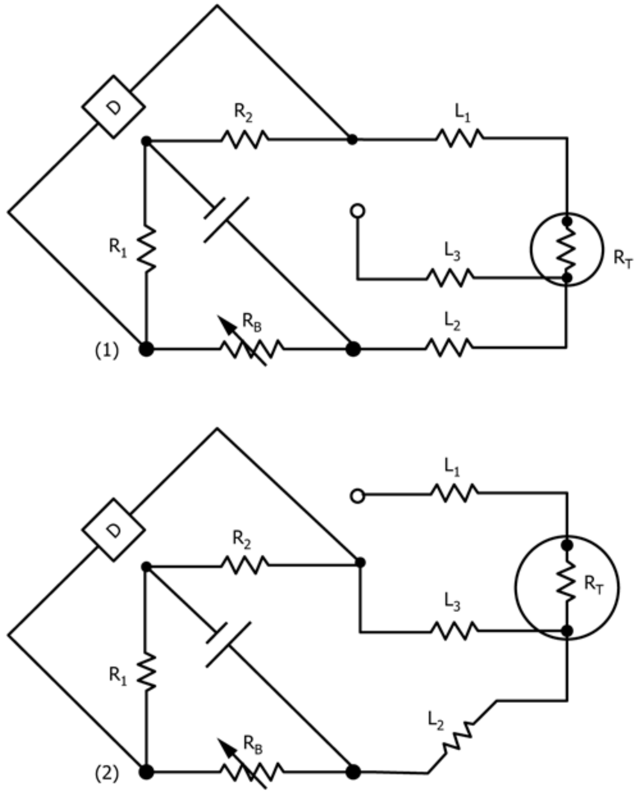


FIG. X1.3 Two Measurement Method for Determining the Resistance of a Three-Wire Thermometer Employing a Simple Bridge

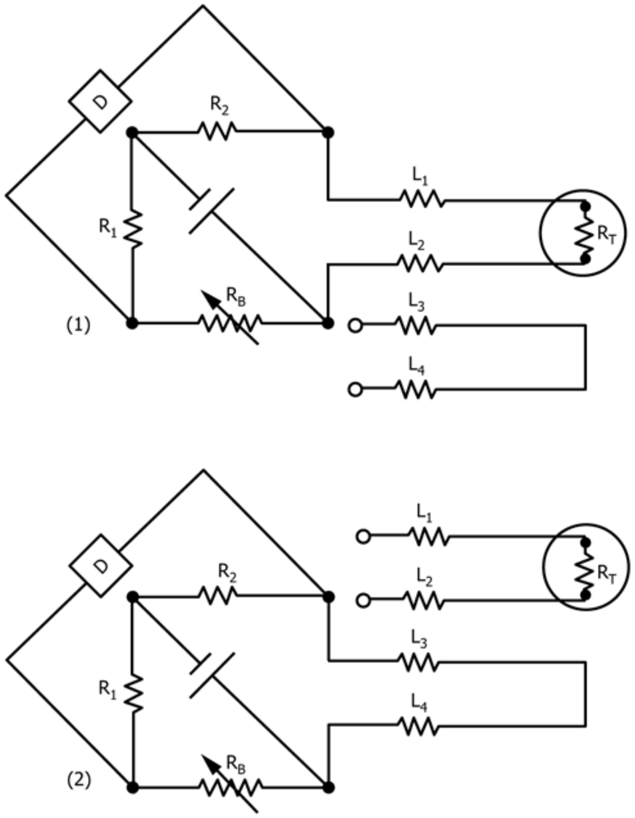


FIG. X1.4 Two-Measurement Method for Determining the Resistance of a Compensating Loop Four-Wire Thermometer Employing a Simple Bridge

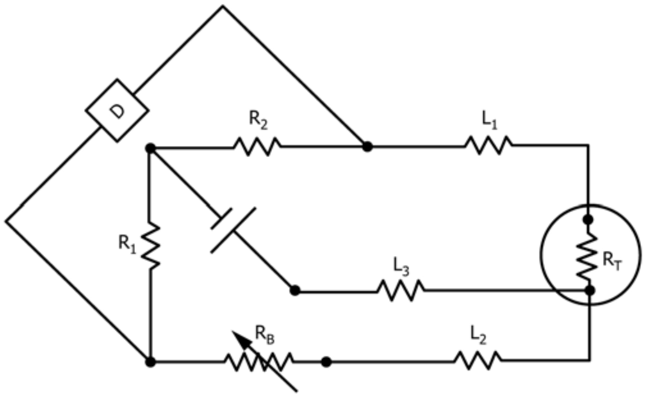


FIG. X1.5 Determination of the Resistance of a Three-Wire Thermometer Employing a Modified Bridge

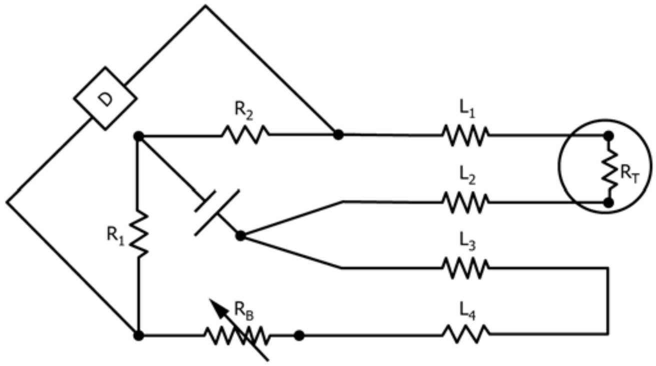
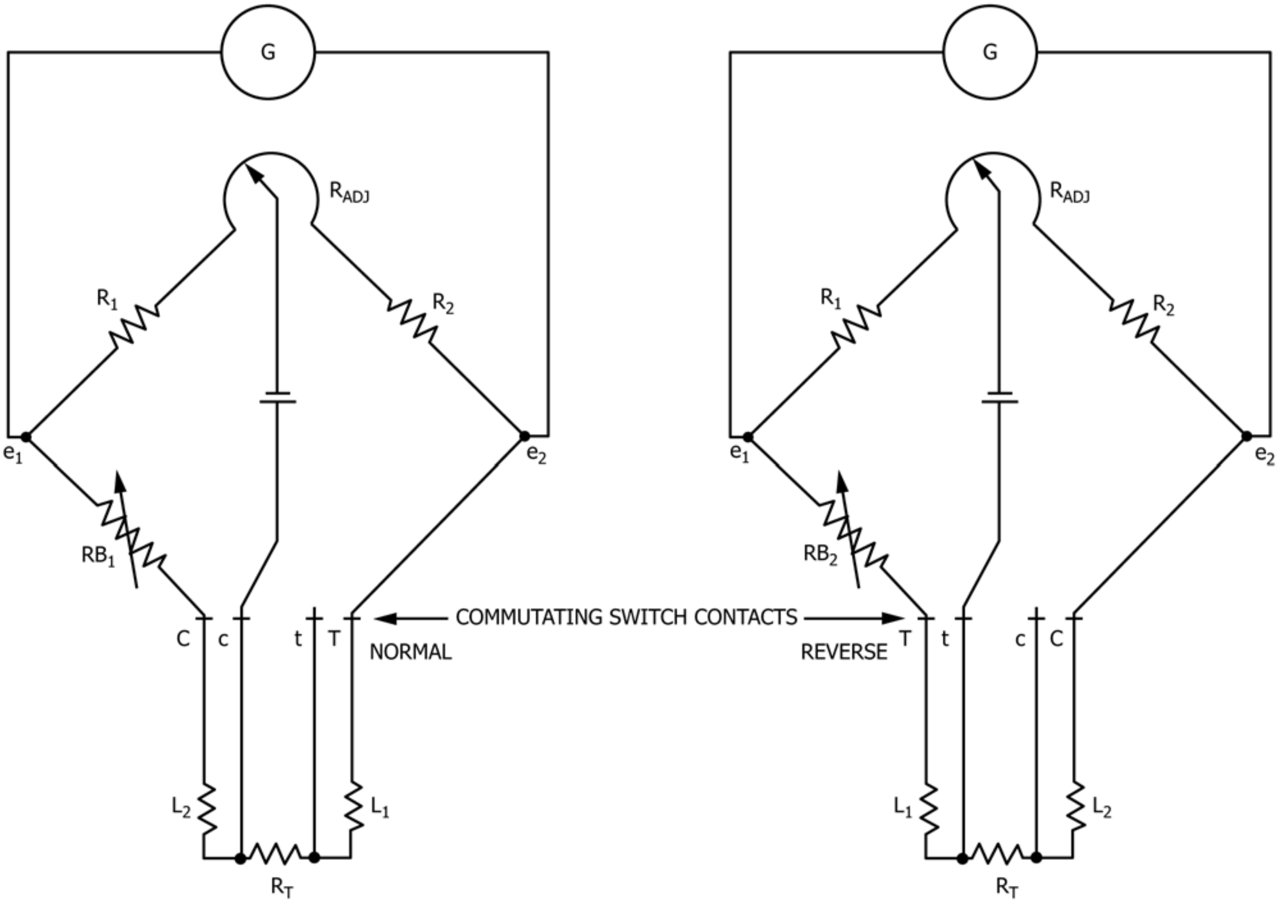


FIG. X1.6 Determination of the Resistance of a Compensated Four-Wire Thermometer Employing a Modified Bridge



NOTE 1—Assumes that $L_1 = L_2$ or that the difference ($L_1 - L_2$) is constant over the period of measurement.

FIG. X1.7 Determination of the Resistance of a Four-Terminal Thermometer Employing a Mueller Bridge

X2. RESISTANCE MEASUREMENT INSTRUMENTS AND SCHEMES

X2.1 *AC Bridge*—AC bridges are resistance bridges that utilize AC excitation. They are commercially available with linearity specifications varying from 10 ppm of range to 0.01 ppm of range and with 6½ to 9½ digit resolution (X.XXX XXX XX5). The linearity is typically based upon inductive dividers. Modern AC bridges are convenient automatic balancing instruments. Typically, the range of measurement is limited to maximum ratios of from 1.3 for the higher accuracy models to 4.0 for the lower accuracy models. These instruments typically require external reference resistors suitable for AC use. AC bridges are immune to thermoelectric effects but are susceptible to effects due to dielectric absorption. By design, these instruments pass the identical magnitude of current through the reference resistor and the UUT. Typically, these instruments do not perform temperature calculations. The indication is in ratio or resistance units only.

X2.2 *DC Bridge*—DC bridges are resistance bridges that utilize switched DC excitation. They are commercially available with linearity specifications ranging from 10 ppm of range to 0.1 ppm of range and with 6½ to 9½ digit resolution. The linearity is typically based upon resistive or inductive dividers. DC bridges are currently available in both manual and automatic balancing types. Typically, the range of measurement is limited to maximum ratios of 11.0 to 13.0. These instruments require external reference resistors. DC bridges are susceptible to thermoelectric effects but are immune to effects due to dielectric absorption. By design, these instruments do not pass the identical magnitude of current through the reference resistor and the UUT. The current through the reference resistor is proportional to the current through the UUT and the ratio measured. Typically, these instruments do not perform temperature calculations. The indication is in ratio or resistance units only.

X2.3 *Digital Thermometer Readout*—Digital thermometer readouts are fundamentally different from conventional bridges and potentiometers. These instruments typically function as automatic potentiometers but rely upon ADC chip technology rather than divider circuits for their linearity. They are commercially available with linearity specifications ranging from 20 ppm of indication to 1.0 ppm of indication and with 6½ to 8½ digit resolution. They typically use switched DC excitation and are automatic indicating. Typically, the range of measurement is limited to ratios of 0.05 to 20.0. These instruments usually contain internal reference resistors but measurement accuracy can be improved through the use of external reference resistors. Sampling voltmeter bridges are minimally affected by thermoelectric emf and effects due to dielectric absorption. By design, these instruments pass the identical magnitude of current through the reference resistor and the UUT, however; the current is calculated by the measurement of the voltage drop across the reference resistor. Typically, these instruments have extensive internal computation ability, performing both temperature and statistical calculations. Because of the complexity of the mathematics and the importance of the accuracy of the calculations, it is prudent to check the mathematical and statistical functions before use.

X2.4 *Digital Multimeter (DMM)*—Digital multimeters are convenient direct indication instruments typically able to indicate in resistance or voltage. They are commercially available with accuracy specifications ranging from 50 ppm of indication to 5 ppm of indication and with 6½ to 8½ digit resolution. Some models have extensive computation ability, performing both temperature and statistical calculations. Because of the complexity of the mathematics and the importance of the accuracy of the calculations, it is prudent to check the mathematical and statistical functions before use. The instrument can be used to directly measure resistance or can be used to measure voltage drops in the same manner as a potentiometer. In either case, the effect of thermal emf should be eliminated by averaging two readings, one taken with normal current and one with the current reversed. Some DMMs are equipped with additional functionality intended to reduce the uncertainty of the measurement. These functions include automatic zero offset compensation (true ohms mode) which reduces the effect of thermal emf, temperature-compensated self calibration which reduces the effect of differences between the temperature during calibration and the room temperature during use, 2-wire or 4-wire settings which configure the input circuitry appropriately for 2 or 4-wire measurements and manual zero offset capability used in conjunction with an input short to reduce the effects of lead wire errors. These functions should be used as needed to obtain the best instrument performance for the given conditions. Additionally, some DMMs use excitation current values that are somewhat higher than optimum. Caution must be exercised to ensure that the excitation current is appropriate for the UUT and reference thermometer to avoid excessive self-heating.

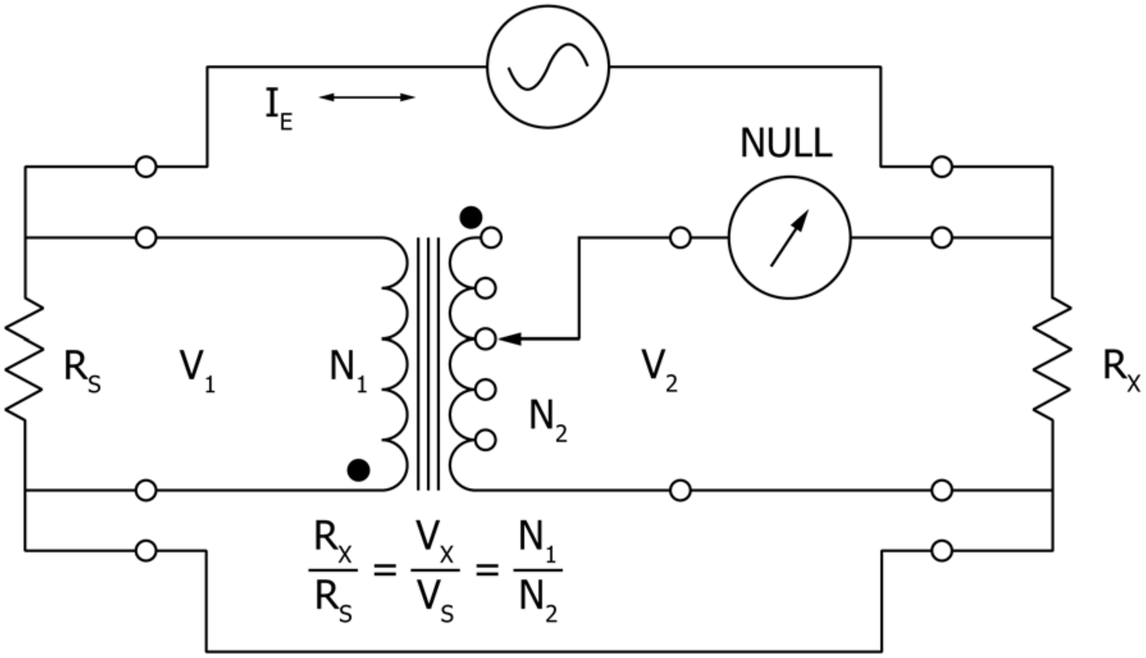


FIG. X2.1 Schematic of AC Bridge Measurement

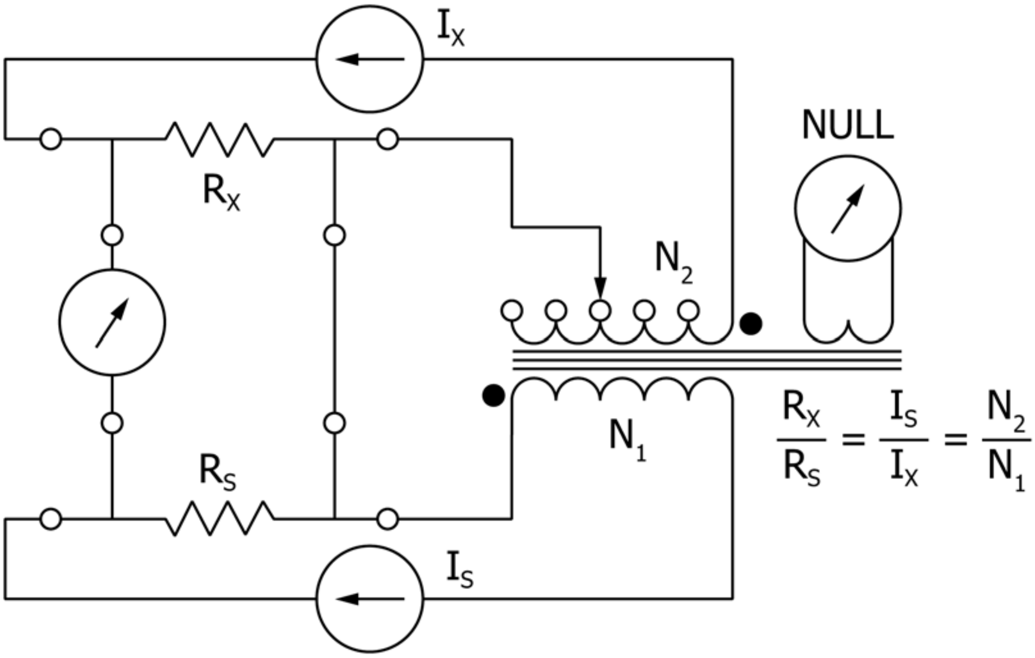


FIG. X2.2 Schematic of DCC Bridge Measurement

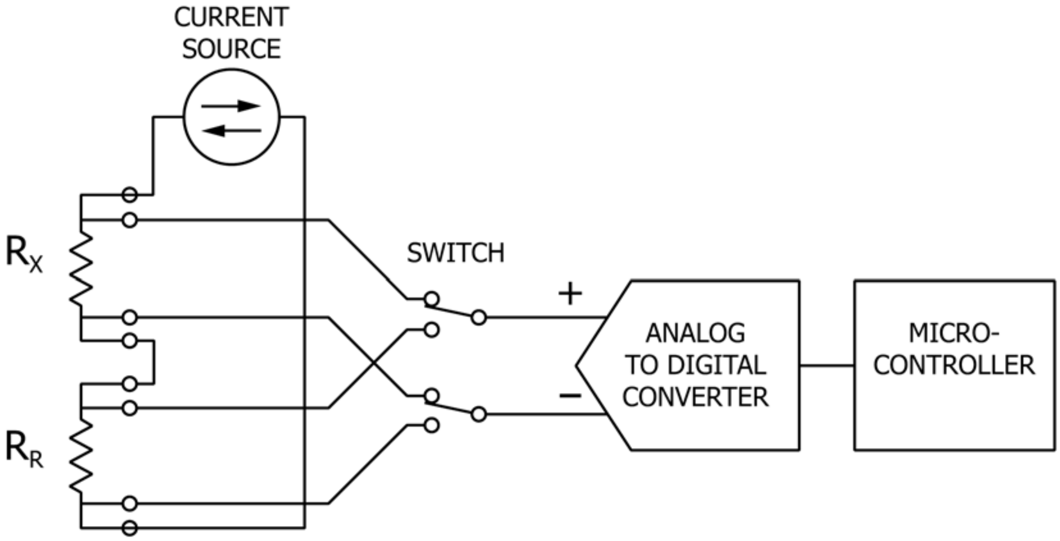


FIG. X2.3 Schematic of Digital Thermometer Readout Measurement

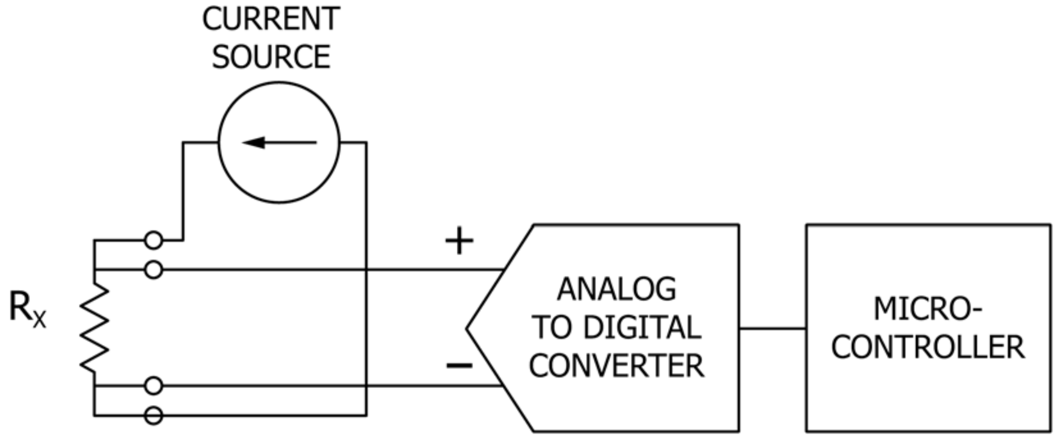


FIG. X2.4 Schematic of Digital Multimeter Resistance Measurement

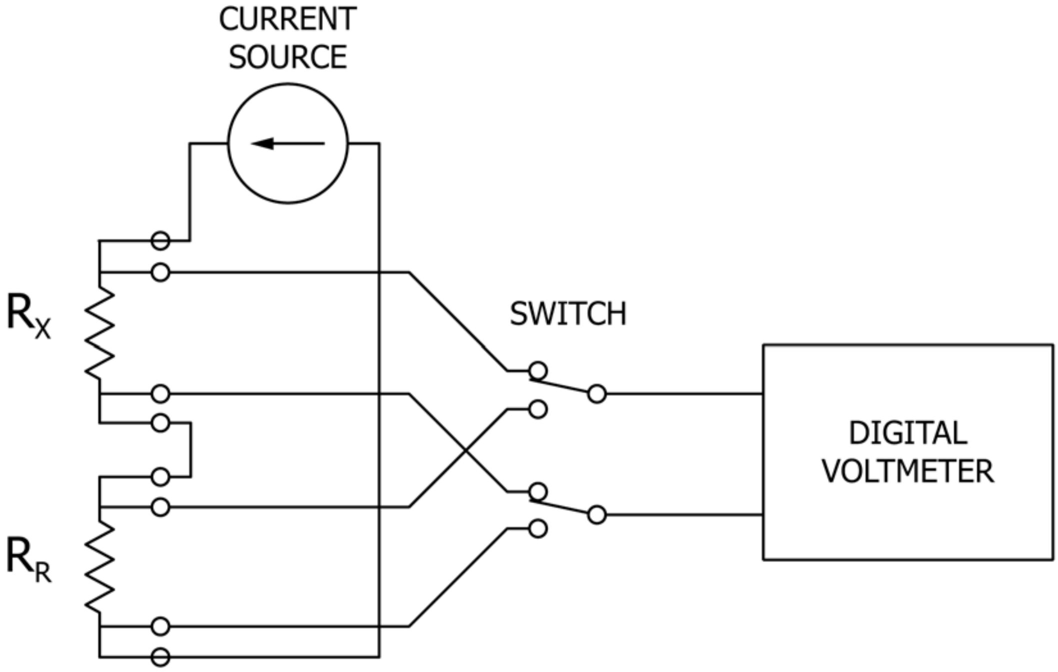


FIG. X2.5 Schematic of Digital Multimeter Potentiometric Measurement

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