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Standard Guide for Accuracy Verification of Industrial Platinum Resistance Thermometers¹

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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 ~~is does not intended intend~~ to describe the procedures necessary for the calibration of platinum resistance thermometers ~~intended to be 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/NC SL Z540-2-1997 “U.S. Guide to the Expression of Uncertainty in Measurement².”

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/NC SL Z540-2-1997 U.S. Guide to the Expression of Uncertainty in Measurement³

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 of similar in design but superior stability than the UUTs to the unit under test, but of superior stability, which is included in the calibration process for the purpose of quantifying the process variability.

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.

3.2.3 *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.

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*).

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

3.2.10.2 *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

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

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

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

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

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

3.2.10.8 *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 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 by laboratories interested in for verifying the calibration resistance-temperature characteristics 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 choice of apparatus and instrumentation. It is understood that the limits of uncertainty obtained depend in a 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.

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

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 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.

$$Accuracy_t = \frac{Accuracy_{\Omega}}{Sensitivity} \quad (2)$$

where:

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

7.1.1 *Bridge*—Precision bridges are available with linearity specifications ranging from 10 ppm of range to 0.01 ppm of range and with 6½ to 9½ digit resolution. 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 manufactured resistors designed 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 calibration (yearly or semi yearly) 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 (care) 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 *Freeze-Point Cell and Furnace*—Metal freeze 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 must 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 over the temperature range 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 over the temperature range over which the calibration will be performed. The assembled UUT should be affixed into 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. When annealing is undertaken, it is advised to consult the manufacturer of the UUT or other technical expert knowledgeable in the design and limitations of the UUT before attempting any annealing procedure. (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 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 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 must 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 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 must be observed until stability is achieved. Once thermal equilibrium 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 measurement 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 is dependant upon the stability of the calibration medium and the speed of the measurement system. Refer to Appendix X1 for guidance on non 4-wire PRTs.

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

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

| Case | Range of Interest | Calibration Sequence |
|------|---|---|
| 1 | Single point, T | T |
| 2 | $T_{min} < T < T_{max}$, $T_{min} = 0^{\circ}\text{C}$ | 0°C , T_{mid} , T_{max} , T_{mid} |
| 3 | $T_{min} < T < T_{max}$, $T_{max} = 0^{\circ}\text{C}$ | 0°C , T_{mid} , T_{min} , T_{mid} |
| 4 | $T_{min} < T < T_{max}$, $T_{min} > 0^{\circ}\text{C}$ | T_{min} , T_{max} , T_{min} |
| 5 | $T_{min} < T < T_{max}$, $T_{max} < 0^{\circ}\text{C}$ | T_{max} , T_{min} , T_{max} |
| 6 | $T_{min} < T < T_{max}$, $T_{min} < 0^{\circ}\text{C} < T_{max}$ | T_{min} , 0°C , T_{max} , 0°C |

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 |
| 12.2.2 | Propagated Rtpw Uncertainty | B |
| | 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 |
| 12.2.4 | Hysteresis | B |
| | Comparison Apparatus | |
| | Temporal Stability | A |
| 12.2.5 | Spatial Uniformity | A |
| | Immersion Effects | B |
| | Process Repeatability | A |

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 | $1/\sqrt{3}$ | 0.006 |
| b | Reference Thermometer Stability | A | 0.002 | None | 0.002 |
| c | Resistance or Voltage Uncertainty | B | 0.010 | $1/\sqrt{3}$ | 0.006 |
| d | Precision of Temperature Measurement | A | 0.002 | None | 0.002 |
| e | Propagated Rtpw Uncertainty | B | 0.007 | $1/\sqrt{3}$ | 0.004 |
| 12.2.3 | Measurement of UUT Resistance | | | | |
| a | Resistance Measurement Uncertainty | B | 0.010 | $1/\sqrt{3}$ | 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 | $1/\sqrt{3}$ | 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 | $1/\sqrt{3}$ | 0.001 |
| 12.2.5 | Process Repeatability | A | 0.015 | None | 0.015 |
| | Combined | | | | 0.023 |
| | Expanded ($k = 2$) | | | | 0.046 |

proceed to the next temperature where the procedure is repeated. If the change is too large, based on uncertainty requirements, the process must 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 must 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 must 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 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 $-200^{\circ}\text{C} \leq t \leq 0^{\circ}\text{C}$, Eq 3 is used and for the range $0^{\circ}\text{C} \leq t \leq 650^{\circ}\text{C}$, Eq 4 is used.

$$R_t = R_0 [1 + At + Bt^2 + C(t - 100)t^3] \Omega \quad (3)$$

$$R_t = R_0 [1 + At + Bt^2] \Omega \quad (4)$$

where:

t = temperature (ITS-90), °C,