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Standard Guide for Thermocouple Verification[1]

This standard is issued under the fixed designation E2846; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

NOTE- Balloted and approved Figures X2.1, X2.2, X2.3, and Tables X3.1 and X3.2 have been included in the standard and the year date was changed on October 7, 2014.

INTRODUCTION

A thermocouple should be periodically verified (tested for compliance with specifications) to ensure that it has not incurred physical, metallurgical, or chemical changes that inhibit or prevent temperature measurements with acceptable accuracy. Unlike many other sensors, the signal generated by a thermocouple depends on the physical and chemical state of the region of the thermocouple wires or thermoelements where temperature gradients exist rather than the state of the measuring junction. Physical or chemical degradation of the thermocouple along only part of its length results in thermocouple inhomogeneity. Such inhomogeneity causes the measured temperature to depend on the intermediate thermal environment between the measuring and reference junctions of the thermocouple. If a thermocouple becomes more inhomogeneous with time, the temperature measured by that thermocouple may appear to drift from its original value, even though the actual temperature it is measuring is constant. If the intermediate thermal environment during use is different from that during calibration, the temperature measurement of an inhomogeneous thermocouple will be inaccurate. Thermocouples used in a harsh environment often become progressively more inhomogeneous; for such thermocouples it is particularly important to make periodic tests of their performance. In addition, a thermocouple becomes unreliable if it undergoes certain other physical changes. It will not measure properly if its wires or the measuring junction are broken or if its thermoelements are in electrical contact in a location other than the measuring junction. Metal-sheathed thermocouples will perform unreliably if there is excessive electrical leakage between the sheath and the thermocouple wire; this can occur if holes have developed in the sheath or the seal of the end closure develops a leak. Periodic tests can check for these undesirable changes, allowing the user to know whether the performance of the thermocouple can be trusted. These tests are particularly important before the calibration of a thermocouple, because they determine whether the thermocouple's performance is worthy of the effort and expense of calibration.

1. Scope

1.1 This guide describes tests that may be applied to new or previously used thermocouples for the purpose of verification. Some of the tests perform a suitable verification by themselves, but many tests merely alert the user to serious problems if the thermocouple fails the test. Some of the tests examine inhomogeneity and others detect wire or measuring-junction breakage. For Style U mineral-insulated metal-sheathed (MIMS) thermocouples with ungrounded measuring junctions, this guide includes tests that examine the electrical isolation of the sheath as well as sheath deterioration.

1.2 The first set of tests involves measurement verifications designed to be performed while the thermocouple is in its usage environment. The second set is composed of electrical tests and visual inspections designed to evaluate the functionality of the thermocouple; these tests may be performed either in house or in a calibration laboratory. The third set is made up of homogeneity tests designed to be performed in a calibration laboratory. Some of the tests provide simple methods to identify some, but not all, defective thermocouples, and alone do not suffice to verify a used thermocouple. They may need to be complemented by other tests for a complete verification.

1.3 The reader of this guide should decide which of the described tests need to be performed. This decision is dependent on whether the reader uses thermocouples for temperature measurement or performs thermocouple calibrations in a laboratory. For users of thermocouples, it is recommended that appropriate tests from the first and second sets be performed initially, as they provide immediate on-site verification of the thermocouples. The appropriateness of a test is dependent upon the user's temperature measurement uncertainty requirements. Some tests may have lower uncertainties in their verification

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[1] This practice is under the jurisdiction of ASTM Committee E20 on Temperature Measurement and is the direct responsibility of Subcommittee E20.04 on Thermocouples.

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measurements than others. If these tests do not clearly determine the suitability of the thermocouples, they should be sent to a calibration laboratory for performing appropriate tests from the third set, which give the most complete information on the thermocouple homogeneity. For those who perform thermocouple calibrations in a laboratory, it is recommended that appropriate tests from the second and third sets be performed prior to calibration. The appropriateness of a test is dependent on the calibration laboratory's capability and convenience for performing the test, as well as the characteristics of the unit under test (UUT).

1.4 This guide may be used for base metal and noble metal thermocouples. Some of the methods covered may apply to refractory metal thermocouples but caution is advised as suitable reference devices at high temperatures may not be readily available.

1.5 *This guide may involve hazardous materials, operations and equipment. 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]

E220 Test Method for Calibration of Thermocouples By Comparison Techniques

E344 Terminology Relating to Thermometry and Hydrometry

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

E585/E585M Specification for Compacted Mineral-Insulated, Metal-Sheathed, Base Metal Thermocouple Cable

E608/E608M Specification for Mineral-Insulated, Metal-Sheathed Base Metal Thermocouples

E780 Test Method for Measuring the Insulation Resistance of Mineral-Insulated, Metal-Sheathed Thermocouples and Thermocouple Cable at Room Temperature

E839 Test Methods for Sheathed Thermocouples and Sheathed Thermocouple Cable

E1350 Guide for Testing Sheathed Thermocouples, Thermocouples Assemblies, and Connecting Wires Prior to, and After Installation or Service

E2181/E2181M Specification for Compacted Mineral-Insulated, Metal-Sheathed, Noble Metal Thermocouples and Thermocouple Cable

3. Terminology

3.1 *Definitions*—The definitions given in Terminology E344 apply to terms used in this guide.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *expanded measurement uncertainty, n*—product of a combined standard measurement uncertainty and a factor larger than the number one.

3.2.1.1 *Discussion*—The term "factor" in this definition refers to a coverage factor k. For k=2 (the most common coverage factor), a measurement instrument measures correctly to within its expanded measurement uncertainty with a 95.4 % probability.

3.2.2 *gradient zone, n*—the section of a thermocouple that is exposed during a measurement to temperatures in the range from $t_{amb} + 0.1(t_m - t_{amb})$ to $t_{amb} + 0.9(t_m - t_{amb})$, where t_{amb} is ambient temperature and t_m is the temperature of the measuring junction.

3.2.2.1 *Discussion*—This term is used as part of the description of the thermal profile along the length of the thermocouple. The gradient zone definition is intended to describe, in an approximate way, the section of thermocouple in which most of the emf was created.

3.2.3 *half-maximum heated length, n*—the distance between the measuring junction and the position along the length of the thermocouple wires or sheath where the temperature equals the average of the calibration-point and ambient temperatures.

3.2.3.1 *Discussion*—This term is used as part of the description of the thermal profile along the length of the thermocouple.

3.2.4 *homogeneous, adj*—having uniform thermoelectric properties along the length of the thermocouple or thermoelement.

3.2.5 *homogeneous Seebeck coefficient, n*—the temperature-dependent Seebeck coefficient of a thermocouple or thermoelement when it is in a homogeneous state.

3.2.5.1 *Discussion*—The homogeneous Seebeck coefficient is usually determined from measurements of the Seebeck coefficient of the thermocouple or thermoelement when it is new, because then it is usually homogeneous. If segments of the new thermocouple or thermoelement are inhomogeneous, the homogenous Seebeck coefficient is determined from measurements made on the segments demonstrated to be homogeneous.

3.2.6 *inhomogeneity, n*—the deviation of the Seebeck coefficient of a segment of a thermocouple or thermoelement at a given temperature from its homogeneous Seebeck coefficient at that temperature.

3.2.6.1 *Discussion*—In practice, only variations in the Seebeck coefficient along the length of a thermocouple that is exposed to temperature gradients affect the voltage output of a thermocouple. Inhomogeneity of a thermocouple is often reported as a fractional variation in the Seebeck coefficient.

3.2.7 *minimum immersion length, n*—the depth that a thermometer should be immersed, in a uniform temperature environment, such that further immersion does not produce a change in the indicated temperature greater than the specified tolerance.

3.2.8 *referee thermocouple, n*—a thermocouple made from the same lot of wire or MIMS cable as the UUT group, using

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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.

identical construction design and methods and identical annealing methods but not having been placed into permanent service.

3.2.8.1 *Discussion*—Because of the high value of referee thermocouples for performing verification tests by the user, it is strongly recommended that after users receive new lots of thermocouple wire, they construct referee thermocouples along with the thermocouples intended for regular use.

3.2.9 *sensing point, n*—the location on a thermometer where the temperature is (or is assumed to be) measured.

3.2.9.1 *Discussion*—A thermocouple's sensing point is its measuring junction. A resistance temperature detector (RTD) contains a sensing element that may be large enough to experience spatial temperature variations; in this case the sensing point is the central point in the element where the temperature is assumed to be that measured by the RTD.

3.2.10 *standard measurement uncertainty, n*—measurement uncertainty expressed as a standard deviation.

3.2.10.1 *Discussion*—A measurement instrument measures correctly to within its standard uncertainty with a 68.2 % probability.

3.2.11 *tolerance, n*—in a measurement instrument, the permitted variation of a measured value from the correct value.

3.2.11.1 *Discussion*—If a measurement instrument is stated to measure correctly to within a tolerance, the instrument is classified as "in tolerance" and it is assumed that measurements made with it will measure correctly to within this tolerance. An instrument that is not classified as "in tolerance" is classified as "out of tolerance."

3.2.12 *UUT, n*—abbreviation for "unit under test."

3.2.13 *validation, n*—the process of testing a thermometer for acceptable accuracy in its intended use.

3.2.14 *verification, n*—the process of testing a thermometer for compliance with specifications.

3.2.14.1 *Discussion*—Here, "specifications" normally refers to specification tolerances for uncalibrated thermometers and to calibration uncertainties for calibrated thermometers. The same tests may be used for a less stringent verification called validation, defined as "the process of testing a thermometer for acceptable accuracy in its intended use."

4. Summary of Verification Tests

4.1 *In Situ Measurement Verification:*

4.1.1 *Verification with the Reference Thermometer in the Same Access Point*—A UUT is verified *in situ* at an appropriate constant temperature by comparison to a known reference thermometer in the same access point. For the comparison, the thermocouple is temporarily replaced by the reference thermometer in the access point, making sure that the measuring point of the sensor is at the same immersion depth as the measuring junction of the thermocouple. For open access points, the reference thermometer may be a referee thermocouple, a non-referee thermocouple that is new or determined to be homogeneous, or another temperature sensor unaffected by inhomogeneity such as a resistance temperature detector (RTD) or thermistor. If the reference thermometer is not a referee thermocouple, its minimum immersion length shall be less than the immersion depth of the UUT. For access points that are thermowells or protection tubes, the reference thermometer shall be a referee thermocouple.

4.1.2 *Verification with the Reference Thermometer in an Adjacent Access Point*—A thermocouple is verified *in situ* at an appropriate constant temperature by comparison to a known reference thermometer located in an adjacent access point. In this case the comparison can be made without removing the UUT. The reference thermometer may be a referee thermocouple, a non-referee thermocouple that is new or determined to be homogeneous, or another temperature sensor unaffected by inhomogeneity such as an RTD or thermistor. If the reference thermometer is not a referee thermocouple, its minimum immersion length shall be less than the immersion depth of the UUT.

4.2 *Thermocouple Functionality Tests:*

4.2.1 *Measurement of the Loop Resistance*—The loop resistance of the thermocouple circuit is measured to verify that the thermoelements and welded measuring junction are continuous. This test may also be used to identify conditions where the thermoelements are in contact with each other at a point other than at the measuring junction. It may be difficult to identify multiple contact points when they occur near the measuring junction.

4.2.2 *Measurement of the Insulation Resistance of Thermocouples with Style U Measuring Junctions*—The resistance of the insulation between the UUT sheath and the thermoelements is measured to determine if the electrical isolation between them has deteriorated.

4.2.3 *Measurement of Sheath Diameter (Metal-Sheathed Thermocouples)*—Measurements of the UUT sheath diameter are made and compared to measurements made prior to installation to monitor metal erosion in the sensor sheath that may cause the UUT to perform unreliably.

4.2.4 *Visual Inspection of Metal-sheathed Thermocouples*—An inspection is made to look for holes, severe pits, and creases in the sheath and for separation of the end closure from the sheath. All of these items may cause the UUT to perform unreliably.

4.3 *Laboratory Verification of Thermocouples:*

4.3.1 *Ice Point Test*—The measuring junction and reference junction of the UUT are both immersed in ice baths. No thermocouple extension wires are used. If the measured emf is beyond a certain tolerance, the UUT is inhomogeneous. The immersion depth of the measuring junction may be varied to examine for inhomogeneity in different segements of the thermocouple.

4.3.2 *Single Point Verification*—Inhomogeneity is checked by comparing the temperature measured by the UUT with that of a reference thermometer at a single temperature. The difference is compared to that from the original calibration at that temperature. This test is not truly a measurement of inhomogeneity, but rather a test for consistent temperature measurement of the UUT under one particular set of conditions. While an inconsistent measurement will demonstrate that the UUT is inhomogeneous, a consistent measurement does not necessarily indicate that the UUT is free from inhomogeneities.

4.3.3 *Multiple Fixed Immersions in a Furnace or Bath*—Temperatures measured using the UUT are compared with those measured using a homogeneous reference thermocouple or other reference thermometer while the two are in the same thermal environment at a given immersion depth in the liquid bath. The consistency of the temperature measured by the UUT relative to that measured by the reference thermometer at different immersion depths provides information on the measurement errors of the UUT due to inhomogeneity.

4.3.4 *Single-Gradient Scanning*—The measuring junction of the UUT is immersed into a temperature-controlled liquid bath at a constant rate or in a series of steps. The UUT passes through a large temperature gradient near the top surface of the liquid. The UUT emf is recorded as a function of immersion depth into the liquid bath. The data provide information on the location and magnitude of the inhomogeneity.

4.3.5 *Double-Gradient Scanning*—Measurements of Seebeck coefficient variations are made along the length of the UUT using a short movable high-temperature zone. The two gradient zones to which the UUT is exposed are at the edges of the high-temperature zone. The measured emf is used to determine the Seebeck coefficient variation along the segment of the UUT between the two gradient zones. By scanning the UUT along the high temperature zone, this Seebeck coefficient variation is determined as a function of position on the UUT; the result is used to estimate the total inhomogeneity as a function of position on the UUT.

5. Significance and Use

5.1 These verification tests may be performed by users or calibrators of thermocouples. The methods are useful for both new and used thermocouples. They provide a means to assess the accuracy with which a thermocouple is capable of measuring temperature.

5.2 Results from these tests may be used to determine whether to use or discard a thermocouple. If the thermocouple is subsequently used, the test results may be included in the measurement uncertainty budget. In many circumstances, the results of *in situ* verifications may be used to recalibrate a used thermocouple. Laboratory measurements, on the other hand, may be used only to verify the original thermocouple calibration or to determine the uncertainty of temperature measurements with the tested thermocouple. Laboratory measurements generally do not suffice to determine the emf-versus-temperature response of a thermocouple found to be inhomogeneous.

6. In Situ Measurement Verification

6.1 These verification tests are used to verify a UUT in its normal measurement environment by comparison with a reference thermometer. The tests in 6.3 and 6.4 are designed to detect drift in the temperature measured by the UUT at a constant temperature. Both short-term and long-term drifts of this sort are the direct result of changes in the Seebeck coefficient, or inhomogeneity, so measuring this drift is an indirect measure of inhomogeneity. These tests subject the thermocouple to minimal disturbance and do not involve sending it away to a calibration laboratory.

6.2 Any *in-situ* test should only be performed by trained personnel having the necessary qualifications to work on instrumentation and electrical equipment in the usage environment. Precautions and measurements to ensure that thermocouple sensors are not in contact with electrical circuits other than those intended for use with the thermocouple should be made.

6.3 *Uncertainty and Tolerance*—The verification tests described below involve the concepts of measurement uncertainty and measurement tolerance. The terms "standard measurement uncertainty," "expanded measurement uncertainty," and "tolerance" are defined in Section 3. Descriptions of uncertainties and their determination are based on the ISO Guide to Uncertainty in Measurement (**1**). Standard uncertainties are represented by the variable u, expanded uncertainties are represented by the variable U, and tolerances are represented by the variable τ. These variables generally are written with a descriptive subscript. A UUT that passes a tolerance test that meets ANSI/NCSL Z540.3-2006 standards (**2**) will measure correctly to within the stated tolerance with a probability of 98 % (Section 5.3, Clause b). A tolerance may be related to an expanded uncertainty with a coverage factor of $k = 2.33$, as both correspond to a 98 % confidence interval. The relationship between a UUT's tolerance τ and its expanded uncertainty with $k = 2$ is then $U_{\text{UUT}}(k = 2) = 0.858\ \tau$.

6.4 *UUT Criterion*—The criterion for verification is that the UUT measures correctly to within the specified value of either $U_{\text{UUT}}(k = 2)$ or τ. If the UUT meets this criterion, it is deemed acceptable. If it does not meet this criterion, it should be rejected. The first step in performing an *in situ* verification is to specify these values. The three most common values are described below.

6.4.1 *Specification Tolerance Criterion*—The UUT measures correctly to within its stated specification tolerance τ_{spec}, that is, $\tau = \tau_{\text{spec}}$. The expanded measurement uncertainty of the UUT corresponding to this tolerance is then $U_{\text{UUT}}(k = 2) = 0.858\ \tau_{\text{spec}}$.

6.4.2 *Calibration Uncertainty Criterion*—The UUT measures correctly to within its expanded calibration uncertainty

TABLE 1 Summary of In Situ Measurement Verification Tests

Test	Provides	Comments
Verification with the Reference Thermometer in Same Access Point	Verification of thermocouple temperature measurement	Compares thermocouple with a reference thermometer. The thermocouple's access port is used by the reference thermometer. May not be used with active control thermocouples.
Verification with the Reference Thermometer in an Adjacent Access Point	Verification of thermocouple temperature measurement	Compares thermocouple with a reference thermometer. A nearby access port is used by the reference thermometer. May be used with active control thermocouples.

$U_{\mathrm{UUT\_cal}}$, that is, $U_{\mathrm{UUT}}(k = 2) = U_{\mathrm{UUT\_cal}}$. The tolerance related to this uncertainty is $\tau = 1.165\ U_{\mathrm{UUT\_cal}}$.

6.4.3 *Measurement Needs Criterion*—The UUT measures correctly to within an uncertainty $U_{\mathrm{UUT\_accept}}$ based on the measurement needs of the user, that is, $U_{\mathrm{UUT}}(k = 2) = U_{\mathrm{UUT\_accept}}$. The tolerance related to this uncertainty is $\tau = 1.165\ U_{\mathrm{UUT\_accept}}$.

6.5 *Methods of In Situ Verification*—The second step in performing an *in situ* verification is deciding which of the two methods of verification is needed. These methods are described below.

6.5.1 *Measurement Agreement*—This method compares the UUT measurement with a reference measurement, and determines if the two measurements agree to within the combined uncertainty of the measurements. If the two measurements agree, the UUT is deemed acceptable; otherwise, it should be rejected. As the uncertainty of the measurements increases, the probability that a UUT that should be rejected is actually accepted increases. However, the probability that an acceptable UUT is rejected is always constant (4.6 % for $k = 2$).

6.5.2 *Tolerance Verification*—This method determines whether the UUT measures temperature to within the stated tolerance τ, based on a comparison with a reference measurement. The verification test provides a result of either "pass" or "fail." If the UUT passes the test, the UUT is deemed acceptable; otherwise, it should be rejected. The test also provides a calculated value, based on the total measurement uncertainty in the comparison, quantifying the probability that the result is wrong. This probability increases as the total measurement uncertainty increases. An advantage of tolerance verification is that the test criterion may be adjusted to ensure that a minimal number of UUTs that should be rejected are accepted; however, such an adjustment greatly raises the number of acceptable UUTs that are rejected.

6.6 *Reference Measurement*—A reference measurement used for *in situ* verification requires the use of a reference thermometer. The type of reference thermometer to be used depends on the type of access point being used.

6.6.1 *Open Access Point*—The reference thermometer may be a referee thermocouple, a non-referee thermocouple that is new or determined to be homogeneous, or another temperature sensor unaffected by inhomogeneity, such as an RTD or thermistor. The thermal cross section of the reference thermometer shall be similar to that of the UUT. If the reference thermometer is not a referee thermocouple, its minimum immersion length shall be less than the immersion depth of the UUT.

6.6.2 *Thermowell or Protection Tube Access Point*—The reference thermometer shall be a referee thermocouple. It shall be placed in the thermowell or protection tube in the same manner as for the UUT.

6.7 *Verification Test with Reference Thermometer in the Same Access Point*—In this test, a UUT is verified in situ at an appropriate temperature by comparison to a known reference thermometer. The UUT and reference thermometer alternately use the same access point, which is that normally used by the UUT, as shown in Fig. 1.

NOTE 1—This method cannot be used to evaluate a control sensor as removing it would cause the system to go out of control.

6.7.1 *Measurement Protocol*—The temperature of the environment shall be constant with small fluctuations about an average value. For the comparison, the UUT performs a first set of measurements of the temperature at its measuring junction over a period long enough to average out the temperature fluctuations. A minimum of 20 equally spaced measurements are made over this period, and these measurements are used to calculate an average $T_{\mathrm{UUT}}(\mathrm{a})$ and standard deviation σ_{UUT} for the temperature, where the "a" in parenthesis labels the measurement set. Here, the standard deviation characterizes the fluctuations of the temperature measurements over the measurement period. Afterwards, the UUT is temporarily

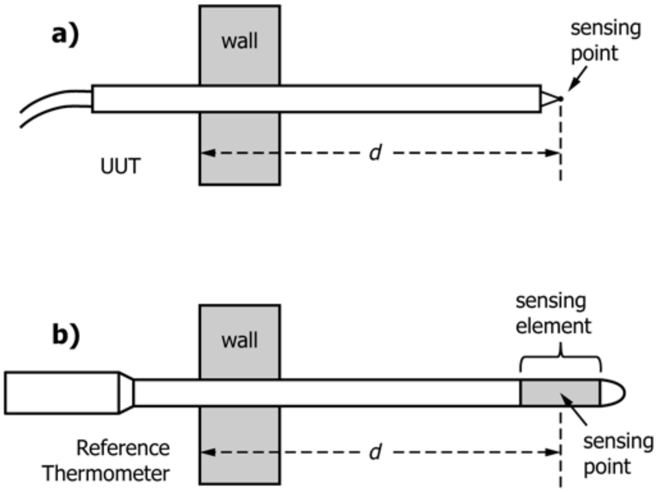


FIG. 1 Verification of a UUT by a reference thermometer in a single access point. In this figure, the reference thermometer is an RTD. In (*a*) temperature measurements are made while the UUT is placed in the access point with immersion depth *D*. In (*b*) the UUT is replaced by the RTD with the same immersion depth and temperature measurements are repeated. The sensing point of the RTD is located at the center of the sensing element. As a result, the end of the RTD probe is immersed further than that of the thermocouple.

replaced by the reference thermometer in the access point. When inserting the reference thermometer, the sensing point of the thermometer should be at the same immersion depth as the measuring junction of the UUT; this may sometimes require that the end of reference thermometer be inserted to a greater immersion depth than the UUT, as shown in Fig. 1. The reference thermometer makes a similar set of temperature measurements, yielding an average T_{ref} and standard deviation σref for the temperature. Finally, the UUT is placed back in the access point, ensuring that the measuring junction is at the same immersion depth as before, and a second set of temperature measurements are made to calculate an average $T_{UUT}(b)$. The temperature measured by the UUT is then represented by

$$T_{UUT} = [T_{UUT}(a) + T_{UUT}(b)]/2 \tag{1}$$

6.7.2 *Data Analysis*—The data described in Table 2 are used for determining whether the UUT meets the verification criterion. It includes the temperature measurements of the UUT and reference thermometers as well as the standard uncertainty values described in the table and in 6.7.3. The verification data may be used for one of the following tests: (*1*) comparison of measurements by the UUT and the reference thermometer, and (*2*) comparison of earlier and present measurements by the UUT and the reference thermometer. The first test provides the best result if the reference thermometer is a referee thermocouple or is calibrated; otherwise, the second test may provide the best results (assuming earlier measurement results are available).

6.7.2.1 *Measurement Agreement Method*—The calculation for the first test determines whether the UUT and reference thermometer measurements agree to within the expanded total measurement uncertainty, considering the verification criterion for the UUT. The calculation for the second test determines whether the earlier and present UUT measurements agree to within the expanded total measurement uncertainty, considering the verification criterion for the UUT.

TABLE 2 Data Used for Verification Calculation for Test With Reference Thermometer in the Same Access Point

Temperature Data	Description
$T_{UUT}(a)$	First temperature measurement made by the UUT
T_{ref}	Temperature measurement made by the reference thermometer
$T_{UUT}(b)$	Second temperature measurement made by the UUT
Uncertainties	
σ_{UUT}	Repeatability of measurements made by the UUT
σ_{ref}	Repeatability of measurements made by the reference thermometer
u_{UUT_inst}	Measuring instrument for the UUT
u_{ref_inst}	Measuring instrument for the reference thermometer
u_{UUT_RJC}	Reference-junction compensator of the UUT (if relevant)
u_{ref_RJC}	Reference-junction compensator of the reference thermometer (if relevant)
u_{ref_cal}	Calibration of the reference thermometer (if relevant)
u_{drift}	Drift between $T_{UUT}(a)$ and $T_{UUT}(b)$
u_{imm}	Immersion depth of the reference thermometer (RTD only)

6.7.2.2 *Tolerance Verification Method*—The calculation for the first test determines whether the UUT and reference thermometer measurements agree to within the UUT specified tolerance. The calculation for the second test determines whether the earlier and present UUT measurements agree to within the UUT specified tolerance. Both calculations provide a result of either "accept" or "reject" for the UUT. The measurement uncertainty is used to quantify the chance that this result is wrong.

6.7.2.3 *Calculations*—The equation needed for determining the expanded total measurement uncertainty from the uncertainty elements is presented in X1.1. The equation used to determine measurement agreement is presented in X2.1, and include example calculations. The equations used to determine tolerance verification are presented in X3.2.1 and X3.3.2. As these calculations are not trivial, it is recommended that qualified software engineers design software tools to facilitate these calculations for those who must regularly perform verification tests.

6.7.3 *Description of Uncertainties*—In the table, σ_{UUT} and σ_{ref} are the standard deviations of the measurements made with the UUT and reference thermometer, respectively, and represent the stability of the measurements. Also, u_{UUT_inst} and u_{ref_inst} are the standard instrument measurement uncertainties, and u_{UUT_RJC} and u_{ref_RJC} are the standard uncertainties of the reference junction compensation (if relevant), and u_{ref_cal} is the standard reference-thermometer calibration uncertainty (if relevant). The instrument measurement uncertainties and reference junction compensator uncertainties are described in the respective manufacturer specifications and may depend on the environment in which the measurements are made. The reference thermometer calibration uncertainty is obtained from its calibration report. If the comparison is made using a referee thermocouple and the user wishes to verify that the UUT measurements are identical to those of the referee thermocouple, then $u_{ref\_cal} = 0$. If an ice bath is used for the reference junction by the UUT or the reference thermometer, or both, instead of an electronic reference junction compensator, then $u_{UUT\_RJC} = 0$ or $u_{ref\_RJC} = 0$, or both, respectively.

The uncertainty u_{drift} is the uncertainty due to drift in the temperature of the environment between the measurements $T_{UUT}(a)$ and $T_{UUT}(b)$. Based on the ISO Guide to Uncertainty in Measurement (**1**), udrift may be estimated as

$$u_{drift} = \frac{1}{2\sqrt{3}} \left| T_{UUT}(a) - T_{UUT}(b) \right| \tag{2}$$

The uncertainty u_{imm}, relevant only when an RTD is used as the reference thermometer, is the uncertainty due to temperature non-uniformities along the length of the RTD's sensing element; these non-uniformities make the measured temperature dependent on the RTD immersion depth. The value of u_{imm} is estimated by first placing the RTD's sensing point at the same immersion depth D as the measuring junction of the UUT. The RTD is then immersed further a distance $\Delta/2$, where Δ is the manufacturer-estimated length of the RTD sensing element, to measure $T(D + \Delta/2)$. Afterwards the RTD is moved back a distance Δ to measure $T(D - \Delta/2)$. These immersion depths are illustrated in Fig. 2. The value of u_{imm} is then (**1**)

$$u_{imm} = \frac{1}{2\sqrt{3}} \left| T_{ref}(D + / 2) - T_{ref}(D - 2) \right| \tag{3}$$

NOTE 2—For thermocouple reference thermometers, u_{imm} is omitted.

6.8 *Verification with the Reference Thermometer in an Adjacent Access Point:*

6.8.1 *Measurement Protocol*—The UUT is verified *in situ* at an appropriate temperature by comparison to a known reference thermometer that is inserted in an adjacent access point, as shown in Fig. 3. The reference thermometer may be a referee thermocouple, a thermocouple that is new or determined to be homogeneous, or another temperature sensor unaffected by inhomogeneity, such as an RTD or thermistor. The thermal cross section of the reference thermometer shall be similar to that of the UUT. If the reference thermometer is not a referee thermocouple, its minimum immersion length shall be less than the immersion depth of the UUT. The reference thermometer is inserted so that the sensing point of the thermometer is located at the same immersion depth as the measuring junction of the thermocouple; this may sometimes require that the end of the reference thermometer be inserted to a greater immersion depth than the thermocouple, as shown in Fig. 1. The temperature is maintained with minimal drifts and fluctuations.

For the comparison, a first series of simultaneous temperature measurements are performed by the UUT and the reference thermometer over a period long enough to average out the temperature fluctuations. A minimum of 20 equally spaced measurements are made over this period, and these measurements are used to calculate averages $T_{\text{UUT}}(\text{a})$ and $T_{\text{ref}}(\text{a})$ for the UUT and reference thermometer, respectively, and standard deviations $\sigma_{\text{UUT}}(\text{a})$ and $\sigma_{\text{ref}}(\text{a})$ for the UUT and reference thermometer, respectively. Here, the "a" in parenthesis refers to the first series of measurements. If possible, the access points for the UUT and reference thermometer are switched, and the set of measurements described above is repeated to obtain $T_{\text{UUT}}(\text{b})$ and $T_{\text{ref}}(\text{b})$, $\sigma_{\text{UUT}}(\text{b})$ and $\sigma_{\text{ref}}(\text{b})$. The final values of T_{UUT}, T_{ref}, σ_{UUT} and σ_{ref} are obtained by averaging the two sets "a" and "b." If it is not possible to switch the access points (for example, the UUT is a control thermocouple), the values for T_{UUT}, T_{ref}, σ_{UUT} and σ_{ref} are represented by their values in set "a."

6.8.2 *Data Analysis*—The data described in Table 3 are used for determining if the UUT meets the verification criterion. It includes the temperature measurements of the UUT and reference thermometer as well as the standard uncertainty values described in the table and in 6.8.3. The verification data may be used for one of the following tests: (*1*) comparison of measurements by the UUT and the reference thermometer, and (*2*) comparison of earlier and present measurements by the UUT and the reference thermometer. The first test provides the best result if the reference thermometer is a referee thermocouple or is calibrated; otherwise, the second test may provide the best results (assuming earlier measurement results are available).

6.8.2.1 *Measurement Agreement Method*—The calculation for the first test determines whether the UUT and reference thermometer measurements agree to within the expanded total measurement uncertainty, considering the verification criterion for the UUT. The calculation for the second test determines whether the earlier and present UUT measurements agree to within the expanded total measurement uncertainty, considering the verification criterion for the UUT.

6.8.2.2 *Tolerance Verification Method*—The calculation for the first test determines whether the UUT and reference thermometer measurements agree to within the UUT specified tolerance. The calculation for the second test determines whether the earlier and present UUT measurements agree to within the UUT specified tolerance. Both calculations provide a result of either "accept" or "reject" for the UUT. The measurement uncertainty is used to quantify the chance that this result is wrong.

6.8.2.3 *Calculations*—The equation needed for determining the expanded total measurement uncertainty from the uncertainty elements is presented in X1.2. The equation used to determine measurement agreement is presented in X2.2, which includes example calculations. The equations used to perform tolerance verification are presented in X3.2.2 and X3.3. As these calculations are not trivial, it is recommended that

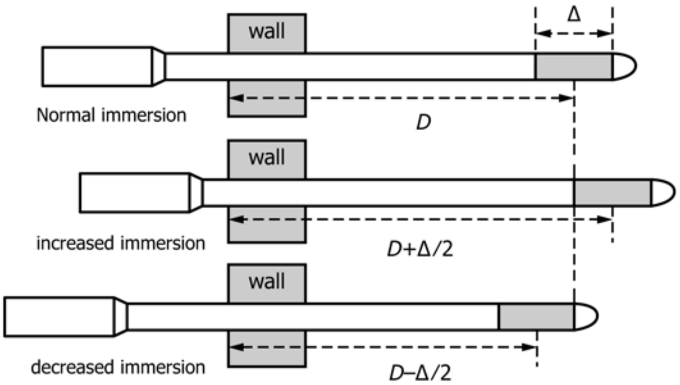


FIG. 2 Placement of Reference RTD at increased and decreased immersion depths for determination of the immersion uncertainty component in the verification test. Here, Δ is the length of the RTD sensing element.

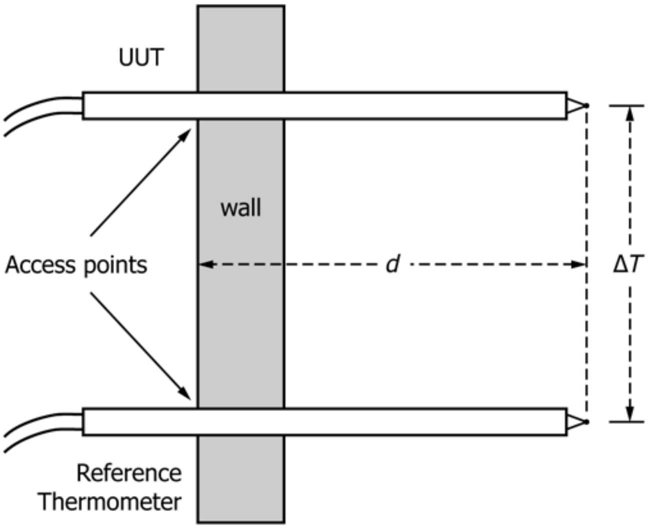


FIG. 3 Verification of a UUT by a reference thermometer using two adjacent access points. Here, the reference thermometer is a thermocouple. Temperature measurements are simultaneously made while the UUT and reference thermometer are placed in the access points with immersion depth *D*. Because of the spatial separation between the sensing points, a temperature difference Δ*T* between them may exist and must be estimated.

TABLE 3 Data Used for Verification Calculation for Test With Reference Thermometer in an Adjacent Access Point

Temperature Data	Description
T_{UUT}	Temperature Measurement made by the UUT
T_{ref}	Temperature Measurement made by the reference thermometer
Uncertainties	
σ_{UUT}	Repeatability of the measurements made by the UUT
σ_{ref}	Repeatability of the measurements made by the reference thermometer
u_{UUT_inst}	Measuring instrument for the UUT
u_{ref_inst}	Measuring instrument for the reference thermometer
u_{UUT_RJC}	Reference-junction compensator of the UUT (if relevant)
u_{ref_RJC}	Reference-junction compensator of the reference thermometer (if relevant)
u_{ref_cal}	Calibration of the reference thermometer (if relevant)
$u_{\Delta T}$	Temperature difference between the sensing points of the UUT and the reference thermometer
u_{imm}	Immersion depth of the reference thermometer (RTD only)

qualified software engineers design software tools to facilitate these calculations for those who must regularly perform verification tests.

6.8.3 *Description of Uncertainties*—Most of the uncertainties shown in Table 3 are described in section 6.7.3. The one uncertainty that is not described there, $u_{\Delta T}$, is the uncertainty due to the temperature difference ΔT between the measuring junction of the UUT and the sensing point of the reference thermometer; this difference is due to temperature non-uniformities in the environment. If the access points are switched as described in 6.8.1, $u_{\Delta T} = 0$ because it is cancelled out by averaging sets "a" and "b". If the access points are not switched, efforts shall be made to estimate ΔT, for example by placing the reference thermometer in a third nearby access point and determining the difference between the temperatures measured in it and the second access point.

7. Thermocouple Functionality Tests

7.1 The following tests examine the functionality of a thermocouple using electrical and dimensional measurements, as well as visual inspections. They can be performed by the user as well as in a calibration laboratory. While these tests are fast and simple, they do not by themselves verify a UUT; they are primarily useful for quickly detecting specific problems that would render the UUT unsuitable for use. The tests, which are based on those described in Test Methods E839 and Guide E1350, are listed in Table 4.

7.2 Electrical tests on a thermocouple performed in an industrial environment should only be conducted by trained personnel having the necessary qualifications to work on instrumentation and electrical equipment in such environments. Before performing any electrical tests on a thermocouple, it should be disconnected from its temperature measurement/control electrical circuit. Precautions should be

TABLE 4 Summary of Thermocouple Functionality Tests

Test	Provides	Comments
Loop Resistance Measurement	Detection of fatal damage to thermocouple	Fast, simple test. Requires multimeter.
Insulation Resistance Measurement	Information to help detect damage or deterioration	Fast, simple test. Requires megohmmeter.
Sheath Diameter Measurement	Information to help detect deterioration	Fast, simple test. Requires micrometer.
Sheath Inspections	Information to help detect damage or deterioration	Fast, simple test. Microscope needed. Helium mass spectrometer needed for leak detection.

taken and measurements should be made to ensure that the thermocouple is not in contact with live circuits other than those used in the test.

7.3 *Measurement of Thermocouple Loop Resistance*—For proper performance of the thermocouple, its wires should not be broken, its separate thermoelements should not be in electrical contact except at the measuring junction, and the weld at its measuring junction shall not be broken. These problems may be tested for by measuring *ex situ* the loop resistance of the thermocouple while it is disconnected from temperature-measurement instruments. The methods for this measurement are described in Test Methods E839. The results of the loop resistance tests are then compared with those from similar tests performed before the UUT was used or on an unused thermocouple from the same manufacturing lot. If the loop resistance has changed significantly (for example, 20 %) since the earlier measurements, the UUT should not be used until other tests, particularly those of Section 6, have verified it.

NOTE 3—Before performing loop resistance measurements, the thermocouple should be disconnected from its temperature measurement/control electrical circuit.

7.4 *Measurement of Insulation Resistance of Style U Mineral-Insulated Metal-sheathed (MIMS) Thermocouples*—The sheath of a Style U MIMS thermocouple should be electrically isolated from the thermocouple circuit. This isolation can be verified by measuring *ex situ* the room-temperature insulation resistance between the sheath and the wires while it is disconnected from temperature-measurement instruments. The methods for this measurement are described in Test Method E780. The tests described in this guide assume knowledge of the insulation resistance of the thermocouple immediately before installation. If this information is not available, Table 4 of Specification E608/E608M or Table 4 of Specification E2181/E2181M may be used to approximate this initial insulation resistance. If the insulation resistance has changed significantly (for example, 20 %) since the earlier measurements, it is recommended that the UUT be verified using full verification tests, such as those described in Section 6. Examples of causes of insulation-resistance changes are sheath rupture, a damaged cold seal, and external contamination of wires or pins.

7.5 *Measurement of the Diameter of Mineral-Insulated Metal-sheathed (MIMS) Thermocouples*—Changes in the diameter of a sheathed thermocouple can be used to assess wear and sheath degradation. In hostile environments the sheath may have a high rate of material loss, leading eventually to sensor failure. Common sheath walls are not sufficiently thick to protect the thermoelements in cases where material loss is significant. Many factors such as velocity, chemical compatibility and abrasion will affect sensor wear. A baseline measurement of the diameter at installation is required. Subsequent measurements can track the wear and make reasonable predictions of failure. Dimensional requirements for the metal-sheathed thermocouple cable used in the manufacture of mineral-insulated metal-sheathed base metal thermocouples can be found in Specification E585/E585M.

7.6 *Visual Inspection of Mineral-Insulated Metal-Sheathed (MIMS) Thermocouples*—Periodic sheath inspections are useful for determining if the thermocouple has experienced damage that could prevent it from making proper measurements. Such damage may be the result of corrosive chemicals, exposure to excessively high temperatures, or physical abuse. Sheath inspection may be performed visually. Sheath inspections are relatively fast and easy to perform, but they cannot quantify inhomogeneity. The thermocouple should be examined for the following signs of damage:

7.6.1 *Holes*—Holes in the thermocouple sheath usually result in degraded performance, as the sheath no longer protects the thermocouple wire from oxidation and corrosion. In addition, moisture can penetrate the sheath, leading to lowered insulation resistance. It is recommended that thermocouples with sheaths containing holes be discarded.

7.6.2 *Severe Pits*—While small pits are often harmless to the thermocouple, severe pits may be the result of serious corrosion and may contain small holes unnoticeable to the naked eye. Such pits should be examined further under a microscope. If the pits are sufficiently deep, they may degrade the insulation resistance between the sheath and the thermocouple wires. Such damage may be tested for by measuring the insulation resistance between the thermocouple wires and the sheath, as described in 7.4.

7.6.3 *Damaged End Closure*—A damaged welded end closure of the thermocouple sheath usually results in degraded performance, due to oxygen and moisture leaking inside. The presence of oxygen can result in oxidation of the thermocouple at high temperatures and the moisture can reduce the insulation resistance between the thermocouple and sheath. Cracks in the closure material and separation of the closure material from the sheath are signs of damage. It is recommended that thermocouples with damaged end closures be discarded.

7.6.4 *Creases*—A crease in the sheath indicates that it was bent excessively. Because the sheath has suffered metal fatigue at the crease, it may crack at the crease if it has not already done so. Such a crack may let oxygen, moisture, or corrosive gases inside the sheath, degrading performance.

8. Evaluation of Thermocouple Performance in a Calibration Laboratory

8.1 The following verification tests perform evaluations of the performance of thermocouples that are appropriate for a calibration laboratory. They include measurement verification tests and inhomogeneity tests. These methods, including descriptions of their yields and respective attributes, are listed in Table 5.

8.2 *Inhomogeneity Testing*—Inhomogeneity tests show whether the UUT is capable of making accurate temperature measurement in all appropriate thermal environments. While the UUT may have already been verified *in situ* at its normal immersion depth, this verification was performed with a particular temperature distribution along the length of the thermocouple. Unless the thermocouple has been demonstrated to be homogeneous, the accuracy of the UUT will be suspect if the temperature distribution changes. This will be the case even

TABLE 5 Summary of Laboratory Verification Tests

Test	Provides	Comments
Ice Point Verification	Measurement Verification	Fast, simple, and inexpensive. Not very sensitive or accurate. Thermocouple extension wires may not be used. Ice bath required.
Single Point Verification	Measurement Verification	Fast and simple. Furnace or bath and reference thermometer required.
Multiple Fixed Immersions	Moderate resolution inhomogeneity data	Convenient and fast when performed before a calibration. Furnace or bath and reference thermometer required.
Single-gradient (SG) Scanning: Basic Method	Moderate resolution inhomogeneity data	Provides good inhomogeneity data at a reasonable cost. Stepper motor and oil bath or furnace required. Reference thermometer may be needed.
SG Scanning: High Resolution	High resolution inhomogeneity data	Provides best inhomogeneity data. Costly. Stepper motor, oil bath, and liquid gallium indium tin eutectic (GITE) required. Reference thermometer may be needed. GITE is toxic and may be a safety hazard.
SG Scanning: Simple Data Analysis	Measurement uncertainty estimates	Provides good results when data are taken in an environment similar to usage environment.
SG Scanning: Seebeck Coeff. Variations	Measurement uncertainty estimates	Provides good results even when data are taken in environment different from usage environment.
Double-gradient Scanning	Low resolution inhomogeneity data	Not as accurate as single-gradient scanning. Practical for long thermocouples. Insensitive to long-distance variations in the Seebeck coefficient.

if the UUT is kept at its normal immersion depth and the temperature to be measured remains the same.

It is always important and appropriate for a calibration laboratory to first test a UUT for inhomogeneity to determine whether it merits the effort and expense of calibration. A number of methods for determining the inhomogeneity of a UUT exist. These methods vary considerably in complexity and cost. They range from simple tests for the presence of large-scale inhomogeneities to quantitative tests that determine the Seebeck coefficient as a function of position on the thermocouple, providing the best possible estimate for the temperature-measurement uncertainty due to inhomogeneity of the thermocouple. The most appropriate method depends on the needs and the resources of the user.

8.2.1 *Ice Point Test*—This test involves immersing the measuring junction and reference junction of the thermocouple in an ice bath, which is a dewar filled with crushed ice and water that is prepared using Practice E563. A portion of the thermocouple between the two junctions is kept at ambient temperature. The junctions are electrically isolated from the ice bath (for example, using glass tubes that are closed at one end). If the thermocouple is sheathed, it is unnecessary to provide additional isolation from the ice bath. The immersion must be sufficiently deep that the measuring and reference junctions are in thermal equilibrium with the ice bath. The immersion depth may be varied, provided that thermal equilibrium is maintained, and one depth should correspond to the normal immersion depth during usage. The emf is measured using copper wires, ideally from the same lot, that are attached to the ends of the reference junction at one end and to the measurement instrument at the other end. If the magnitude of the measured emf is greater than the measurement uncertainty, the thermocouple is inhomogeneous. The temperature measurement error in the ice bath $\Delta\ t$ is given by $\Delta t(t_{\mathrm{amb}}) = \Delta E/S_{\mathrm{amb}}$, where t_{amb} is the ambient temperature, ΔE is the measured emf and S_{amb} is the Seebeck coefficient of the thermocouple near t_{amb}. For noble-metal thermocouples, a rough estimate of the temperature measurement error at temperature t is $\Delta t\ (t) = \Delta t(t_{\mathrm{amb}})\cdot t/t_{\mathrm{amb}}$.

This method is easy, fast, and inexpensive to perform. There are several disadvantages, however. First, this test is not as sensitive as those where the temperature difference along the length of the thermocouple is larger. Secondly, the estimate of temperature measurement errors is not as accurate as that for tests where the measuring junction temperature is close to the temperature being measured during normal usage. Finally, the thermocouple must have a reference junction suitable for immersion into an ice bath, because this method does not yield meaningful results if the thermocouple is tested while using thermocouple extension wires.

8.2.2 *Single Point Verification*—Inhomogeneity may be checked by comparing the temperature measured by the UUT with that of a reference thermometer at a single temperature and immersion depth in a furnace or stirred bath. The reference thermometer may be a referee thermocouple, a non-referee thermocouple that is new or determined to be homogeneous, or another temperature sensor unaffected by inhomogeneity, such as an RTD or thermistor. If the reference thermometer is not a referee thermocouple, its minimum immersion length shall be less than the immersion depth of the UUT. Here, the "immersion depth" of the UUT is quantitatively defined as its half-maximum heated length. The measuring ends of the UUT and the reference must be at the same temperature; this is most easily accomplished by mechanically attaching them together. The comparison is made using the method described in Standard Test Method E220. The immersion depth should not be greater than that encountered in use, as the measurement would then give erroneous results and false confidence in the condition of the tested thermocouple. A significant difference between the temperature measured with the UUT using its original calibration and that with the reference thermometer indicates significant drift in the temperature measurement of the UUT from its original calibration, suggesting significant inhomogeneity in the UUT and that it will not measure temperature accurately.

This test is relatively fast and easy to perform, and can often detect an inhomogeneous thermocouple. However, a thermocouple that passes the single point verification test may still be inhomogeneous and measure temperature incorrectly at different immersion depths.

8.2.3 *Multiple Fixed Immersions in a Furnace or Bath*—This test, described in detail in Test Method E220, Appendix X4, compares the temperature measured using the UUT with that measured using a reference thermometer while the two are in the same thermal environment with their measuring ends at the same temperature (usually accomplished by mechanical attachment). The reference thermometer may be a referee thermocouple, a non-referee thermocouple that is new or determined to be homogeneous, or another temperature sensor unaffected by inhomogeneity, such as an RTD or thermistor. If the reference thermometer is not a referee thermocouple, its minimum immersion length shall be less than the immersion depth of the UUT and its time response shall be comparable to the UUT. The environment will typically be provided by a furnace or temperature-controlled bath. The temperature measurements are made with the UUT and the reference thermometer placed in the environment at several immersion depths. The consistency of the temperature measured by the UUT relative to that measured by the reference thermometer at these different immersion depths provides information on the inhomogeneity and its resulting measurement errors. The resolution of the inhomogeneity measurements is limited by the width of the gradient zone along the thermocouple; for furnaces and baths, this width is typically ~7 cm and ~4 cm, respectively.

This method uses the same experimental system as that used for performing a comparison calibration against a reference thermocouple or reference thermometer, which is described in Test Method E220. This method can be applied before performing such a calibration and is simple and fast.

8.2.4 *Single-gradient (SG) Scanning*—The single-gradient scanning method (**3**) involves vertically immersing the measuring junction of the UUT into a temperature-controlled medium (usually an oil bath or furnace) at a constant rate or in a series of steps. The immersion exposes one location of the UUT to a single sharp gradient. For the most meaningful results, the temperature of the medium should be that experienced during normal use of the UUT. If the temperature of the medium is not very uniform, a reference thermometer is simultaneously immersed such that the immersion depth of the UUT and reference thermometer are equivalent; the temperature measured by the UUT is then compared to that measured by the reference thermometer as a function of immersion depth. The reference thermometer may be a referee thermocouple, a non-referee thermocouple that is new or determined to be homogeneous, or another temperature sensor unaffected by inhomogeneity, such as an RTD or thermistor. If the reference thermometer is not a referee thermocouple, its minimum immersion length shall be less than the initial immersion depth of the UUT. If the temperature of the medium is very uniform, a reference thermometer or thermocouple is not necessary, and the absolute emf variations of the UUT during the immersion may instead be used to determine the inhomogeneity; nevertheless, the presence of the reference thermometer is still useful for verification of the scan results.

8.2.4.1 *Basic SG Scanning with an Oil Bath*—Oil baths may be used as the medium for scan temperatures of 100°C to 250°C. A description and schematic diagram of this arrangement is provided in (**4**). For bath temperatures that are constant and uniform to within 4 mK, use of the reference thermometer is optional. The immersed portion is in thermal contact with the bath but it is physically isolated using a sealed, stainless-steel tube with an inner diameter that is slightly larger than the diameter of the insulator (non-sheathed thermocouples) or sheath (metal-sheathed thermocouples). If the thermocouple is metal-sheathed, it can go into the oil directly if oil residue is not a problem. The temperature gradient to which the thermocouple is exposed exists around the surface of the oil bath. The region of the temperature gradient is minimized by blowing a jet of air onto the thermocouple in the region immediately above the bath. This arrangement typically yields a gradient region that is 4 cm wide, limiting the spatial resolution of the homogeneity test to this length scale.

The scan is performed as follows. First, the reference junction of the UUT is immersed in an ice bath and the measuring junction of the UUT is immersed far enough into the oil bath to ensure that it is at the bath temperature. This immersion depth is typically a minimum of ten times the tube diameter, but it may be determined by immersing the measurement junction of a homogeneous thermocouple until the measured emf is constant to within the measurement noise. The measuring junction of the UUT is then immersed further into the bath at a constant rate, typically 15 cm/hr, and the UUT emf is recorded as a function of immersion depth into the oil bath. Typically, the UUT is moved into the bath with an automated slide, powered by a stepping or synchronous motor. Test Method E220 provides guidance on thermocouple wiring, reference junction configurations, and emf measurement methods. The UUT is immersed as deeply as the system or thermocouple length will allow, typically a maximum of approximately 70 cm.

8.2.4.2 *Basic SG Scanning with a Furnace*—Furnaces are usually used as the medium for temperatures above 250°C. The temperature inside a furnace is not very uniform, so comparison against a reference thermometer is essential. If the UUT is unsheathed, it is mounted in an alumina insulator. The inside of the furnace is lined with an alumina tube for protecting the thermocouples from furnace contamination. The region of the temperature gradient is minimized by blowing a jet of air or nitrogen onto the UUT and reference thermometer in the region immediately outside the furnace. This arrangement typically yields a gradient region that is 7 cm wide, limiting the spatial resolution of the homogeneity test to this length scale. The typical minimum immersion necessary before the scan may begin is 9 cm. The UUT and reference thermometer are then immersed further into the furnace at a constant rate, typically 10 cm/hr, and the emf of the UUT and temperature of the reference thermometer as a function of immersion depth into the furnace are recorded. The UUT and reference thermometer are immersed as deeply as possible, typically between 80 cm and 90 cm. The UUT and reference thermometer shall be at the same temperature for each depth of immersion. Refer to Test Method E220 for guidance on techniques to ensure thermal equilibrium, including the use of isothermal blocks or welding of the test and reference thermocouples.

8.2.4.3 *SG Scanning with Higher Resolution*—With two improvements, SG scanning may be performed with higher resolution if metal-sheathed thermocouples are used. For the first improvement, the measuring junction of the UUT is immersed in a liquid composed of a gallium indium tin eutectic (GITE) (**5**). Schematic diagrams of this arrangement are provided in (**5**). The GITE is held in an inner well immersed in the oil bath, which is controlled at about 100°C. Although the GITE is not stirred, its thermal conductivity (28 W/m K) is considerably higher than that of oil (0.1 W/m K), providing temperature uniformity that is at least as good as that of an oil bath; therefore a reference thermometer or thermocouple is unnecessary. Air at ambient temperature is directed onto the thermocouple in the region immediately above the GITE surface to minimize pre-heating. The high thermal conductivity of the GITE causes the width of the temperature gradient at the surface of the GITE to be considerably smaller than that for the oil bath.

For the second improvement, the immersion is performed incrementally rather than at a constant rate. For incremental immersion, the measuring junction is rapidly immersed a short distance, typically 0.2 cm to 0.4 cm, and subsequently held at this position briefly, typically 5 to 10 s, while the newly immersed portion of the thermocouple approaches the temperature of the GITE; the emf is then recorded and the process is repeated until the thermocouple reaches the bottom of the well. The incremental immersion technique further minimizes pre-heating of the thermocouple in the region immediately above the GITE bath, reducing the width of temperature gradient on the thermocouple. When the GITE bath is used along with the incremental immersion technique, the width of the temperature gradient is typically 2 cm, improving the resolution of the inhomogeneity test by a factor of two. This improvement is not useful for alumina-sheathed thermocouples, as the air gaps between the thermocouple wires and alumina sheath broaden the temperature gradient along the wires.

NOTE 4—GITE is a hazardous material. This guide 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 guide to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.

8.2.4.4 *SG Scanning: Simple Data Analysis*—The simplest data analysis aims only to determine the emf variations during the scan. When the temperature of the medium is very uniform and no reference thermometer/thermocouple is used, the recorded emf values are used for this determination. If the temperature of the medium is not uniform, the UUT emf values shall first be normalized to a reference temperature before the analysis can be made. At a given immersion depth, the normalized emf values are determined by

$$E_{norm} = E_{rec} + S_t(t_{norm} - t_{rec}) \tag{4}$$

where E_{norm} and E_{rec} are the normalized and recorded emf values of the UUT, respectively. Also, S_t is the most recently determined Seebeck coefficient of the UUT, t_{norm} is the reference temperature at which the emf values are normalized, and t_{rec} is the temperature recorded by the reference thermometer/thermocouple.

The scan will yield an average emf value E_{ave} and an emf variation ΔE defined as $\Delta E = E_{\max} - E_{\min}$, where $E_{\max}$ and $E_{\min}$ are the maximum and minimum values of the emf over the course of the scan, respectively. These results may be used to calculate a reasonable estimate of the standard uncertainty due to inhomogeneity of the temperature t measured using the UUT, $u_{\mathrm{i}}(t)$; this uncertainty applies to the value of t where the scan was conducted. Based on the ISO Guide to Uncertainty in Measurement (**1**), the value of $u_{\mathrm{i}}(t)$ is

$$u_i(t/°C) = \frac{\Delta E}{2\sqrt{3}(E_{ave} - E_{amb})} \cdot \frac{(t - t_{amb})}{°C} \tag{5}$$

where E_{amb} is the UUT emf at the ambient temperature t_{amb}. For Pt-Rh type R and S thermocouples, the ratio $\Delta E/(E_{\mathrm{ave}} - E_{\mathrm{amb}})$ is fairly independent of the bath/furnace temperature (**6**), and so Eq 5 is also useful for determining $u_{\mathrm{i}}(t)$ at temperatures that are significantly different from the scan temperature. For other types of thermocouples, however, this has not been shown, so temperature uncertainties for a given temperature shall be determined using scans performed at that temperature.

Example—A type S UUT is scanned in an oil bath at 200°C. Let the maximum and minimum measured values of E be $E_{\max} = 1441$ µV and $E_{\min} = 1355$ µV, respectively. Then $\Delta E = 86$ µV. Also, let $E_{\mathrm{amb}} = 131$ µV and $t_{\mathrm{amb}} = 23$°C. Then, the ratio has a value =0.02, and since the thermocouple is type S, it may be assumed to be temperature-independent. Using Eq 5, the values of $u_{\mathrm{i}}(t)$ for t = 100°C, 200°C, 300°C, and 400°C are then 1.51°C, 3.47°C, 5.43°C, and 7.39°C, respectively.

8.2.4.5 *Determining Seebeck Coefficient Variations*—For some noble-metal thermocouples, the inhomogeneity I of the Seebeck coefficient S may be calculated using a more sophisticated data analysis of the scanning method. Using a method similar to that of (**7**), this analysis calculates I as a function of position x relative to the measuring junction of the thermocouple. Here, I is assumed to be temperature-independent, an assumption that has been validated for type S and type R thermocouples (**6**). Then I may be defined by

$$S(x,t) = S^h(t) + I(x) \tag{6}$$

where $S(x,t)$ and $S^{\mathrm{h}}(t)$ are the Seebeck coefficient and homogeneous Seebeck coefficient (see Section 3) of the UUT, respectively. The value of $S^{\mathrm{h}}(t)$ is obtained from the UUT's original calibration. While this method is considerably more complex than the analysis of 7.1, it is especially useful for determining the measurement uncertainty of the thermocouple when it is used in a thermal environment where the width of the gradient zone (see Section 3) is significantly different from that where the scanning procedure was performed.

The values of $I(x)$ can be determined using the data from a scan of the thermocouple emf during progressive immersion into the bath. This requires knowledge of the temperature profile in the bath $t(D)$, where D is the immersion depth of the measuring junction relative to the point of maximum temperature gradient. The quantity $t(D)$ is measured by a reference thermometer or homogeneous reference thermocouple either before or during the scan. A typical temperature profile is shown in Fig. 4, where the width of the gradient zone is Δ and the temperature change across it is Δt_{g}. The data from the immersion scan provides values of $E(D)$. At the position $x = D$ the value of $I(x)$ may be determined from the value of $E(D)$, the profile $t(D)$, and values of $I(x)$ previously determined at smaller immersion depths.

Measurements of $E(D)$ and $t(D)$ are made at discrete points i, where $i = 1, 2, 3\ldots$ and where $D_{\mathrm{i+1}} - D_{\mathrm{i}} = x_{i+1} - x_i = \delta$. At each i, a calculation is made of $\Delta E_i = E(D_i) - E^{\mathrm{h}}(D_i)$, where E^{h}

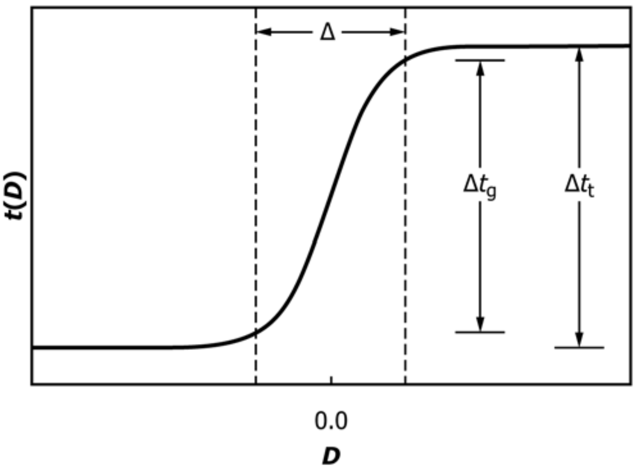


FIG. 4 Temperature$_t$ as a function of the immersion depth into the bath is used for the scanning method to determine the Seebeck coefficient. The depth D = 0 is defined as the point of the largest temperature gradient. The width of the gradient zone (see Section 3) is Δ and the temperature difference across Δ is Δt_g. The total temperature difference between the maximum bath temperature and ambient temperature is Δt_t.

is the emf that the calibrated thermocouple would measure at temperature $t(D_i)$ if it were still homogeneous. The complete equation for calculating $I(x_i)$ is given in Appendix X4 as Eq X4.8. If the bath temperature is very uniform compared to Δt_g, Eq X4.8 may be approximated to

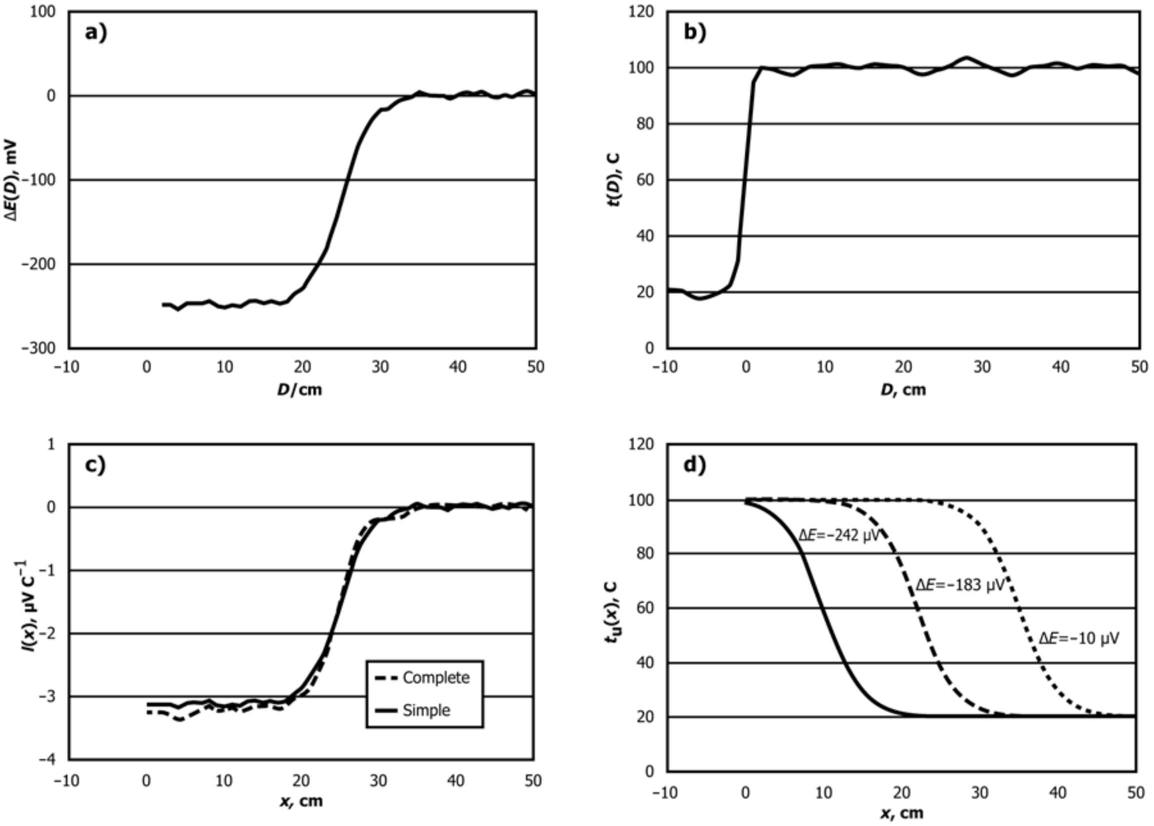


FIG. 5 Example of the determination of the Seebeck Coefficient from a scan. In (*a*), the emf deviation Δ*E* due to inhomogeneity of a thermocouple is shown as a function of immersion depth *D* in a scanning bath for which the temperature profile *t*(*D*) is shown in (*b*). The inhomogeneity *I*(*x*), where *x* is the position along the thermocouple relative to the measuring junction, is plotted in (*c*). Here, the curve obtained using Eq X4.9 (in Appendix X4) is labeled "Complete" and that obtained using Eq 7 is labeled "Simple." In (*d*), the *I*(*x*) values determined by Eq 7 are used to determine the value of Δ*E* for three different temperature profiles $t_u(x)$ that could be encountered in subsequent usage of the thermocouple.

$$I(x_i) = \Delta E_i / \Delta t_t \qquad (7)$$

where Δt_t is the total difference between the maximum bath temperature and ambient temperature, as shown in Fig. 4.

An illustration of this method is provided in Fig. 5. In Fig. 5a, computer-generated example values of ΔE are plotted as a function of D for a fictional immersion of a type R thermocouple in a GITE bath with a temperature of ≈100°C; these values are similar to those experimentally measured in **(4)** for such a thermocouple. Here, the largest deviation of the emf is ΔE = -250 μV. Similarly, example values of t are plotted as a function of D in the bath in Fig. 5b. From the data of these two figures, the inhomogeneity $I(x)$ for the thermocouple, as calculated by Eq X4.8 (labeled "complete") and Eq 7 (labeled "simple"), is shown in Fig. 5c. It can be seen from the figure that the results from Eq 7 closely approximate those from Eq X4.8.

Once $I(x)$ is determined, the uncertainty of the temperature measured by the thermocouple can be estimated as follows. Let x be described in discrete steps $x = x_i = i\Delta$, where i is an index number and Δ is the increment size. The change in E due to the inhomogeneity of the thermocouple, ΔE, is

$$\Delta E = \sum_{i=1}^{N} I(x_i)[t_u(x_i) - t_u(x_{i-1})] = \sum_{i=1}^{N} \delta_i \qquad (8)$$

where $t_u(x_i)$ is the temperature profile along the length of the thermocouple in its usage environment, and N is defined such that $x_N = L$, where L is the length of the thermocouple.

The values of ΔE for the thermocouple of Fig. 5c have been calculated for three usage temperature profiles $t_u(x_i)$, which are shown in Fig. 5d. For simplicity, the highest temperature is 100°C, the same as that of the GITE bath. The ΔE values as calculated by Eq 8 are listed next to each profile curve. For the first temperature profile, where the gradient zone exists over the range of maximum inhomogeneity, ΔE = −242 μV, which is close to the largest emf deviation observed in the scan of Fig. 5a. For the second temperature profile, where the gradient zone exists over the range where $I(x)$ decreases to 0, ΔE = −183 μV. Finally, for the third temperature profile, where the gradient exists over the range where $I(x)$ = 0, ΔE = -10 μV. These examples show that the value of ΔE is strongly dependent on the location of the gradient zone relative to the region of highest inhomogeneity on the thermocouple.

Because of the uncertainties in determining $I(x)$ and $t_u(x)$, as well as the possibility of $I(x)$ being temperature-dependent, the value of ΔE calculated by Eq 8 should be used only to obtain the uncertainty for the temperature t measured by the thermocouple. A reasonable estimate for the standard uncertainty is

$$u(t) = \Delta E / S^h(t) \qquad (9)$$

Example—Table 6 displays values corresponding to the example shown in Fig. 5d, where the temperature profile is represented by the solid curve. Here, the length of the thermocouple is 50 cm. The chosen increment is Δ = 2 cm, so N = 25. However, since the temperature t_u is approximately uniform (and therefore the contribution to ΔE is negligible) for x_i > 24 cm, the values for this range are not shown in the table.

For each row i, the value of δi in each row is calculated using Eq 8. For example,

$$\delta_1 = I(x_1)\cdot[t(x_1) - t(x_0)] = (-3.1\ \mu V/°C)(96.9°C - 98.6°C) = -5\ \mu V$$

$$\delta_2 = I(x_2)\cdot[t(x_2) - t(x_1)] = (-3.2\ \mu V/°C)(93.3°C - 96.9°C) = -11\ \mu V$$

$$\ldots$$

$$\delta_{25} = I(x_{25})\cdot[t(x_{24}) - t(x_{24})] = (-0.0\ \mu V/°C)(20.0°C - 20.0°C) = 0\ \mu V$$

In the table, $t_u(x_i)$ has decreased to ambient temperature by row 12 and so the magnitude of δ_i has decreased to a negligible value and does not increase significantly with higher values of x_i, even when the inhomogeneity $I(x)$ is significant.

The value of ΔE is then

$$\Delta E = \delta_1 + \delta_2 + \ldots \delta_{25} = -5\ \mu V - 11\ \mu V + \ldots + 0\ \mu V = -242\ \mu V$$

8.2.5 *Double-Gradient Scanning*—For thermocouples that require inhomogeneity testing over lengths longer than 70 cm, single-gradient scanning in an oil bath or furnace is generally impractical. For this case, double-gradient scanning **(8)** may be performed. A schematic diagram of this arrangement is provided in Fig. 6. Here, a small length, typically 4 cm, of the testing segment of the thermocouple is exposed to a high temperature, typically 700°C, while the rest of the testing

TABLE 6 Numerical Calculations of δ_i Using Eq. 17 for the Example Shown in Fig. 4d, Using the Temperature Profile Represented by the Solid Curve. The Sum of all the Values of δ_i is −242 μV.

i	x_i cm	$I(x_i)$ μV/°C	$t_u(x_i)$ °C	δ_i μV
0	0	-3.1	98.6	
1	2	-3.1	96.9	-5
2	4	-3.2	93.3	-11
3	6	-3.1	86.6	-21
4	8	-3.1	75.2	-35
5	10	-3.1	60.0	-48
6	12	-3.1	44.8	-48
7	14	-3.0	33.4	-35
8	16	-3.1	26.7	-21
9	18	-3.1	23.1	-11
10	20	-2.9	21.4	-5
11	22	-2.5	20.7	-2
12	24	-1.9	20.3	-1

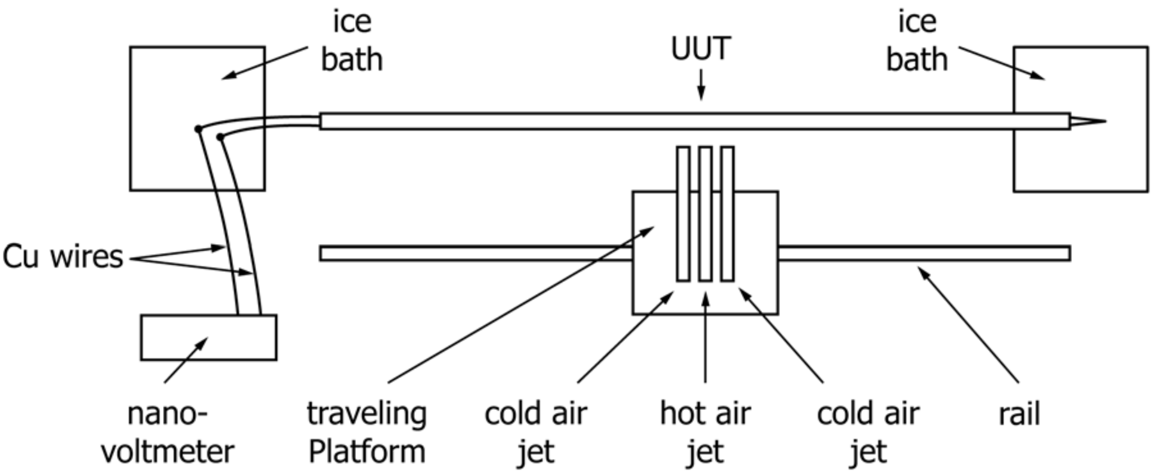


FIG. 6 Schematic diagram of a double-gradient scanning system, showing hot air jets directed onto the UUT from a travelling platform. Although not shown, the measuring junction and reference junctions of the UUT are electrically isolated from the ice baths using glass tubes.

segment is held at ambient temperature. The measuring junction and reference junctions are immersed in an ice bath. The edges of the high temperature zone provide two gradient zones on the thermocouple over which emfs are generated. Assuming the Seebeck coefficient does not vary over either gradient zone, the emf E_i generated over the two gradient zones is

$$E_i = [S(x_{i+1}) - S(x_i)]\Delta T \tag{10}$$

where ΔT is the temperature difference across the gradient zone and x_i and x_{i+1} are the locations on the thermocouple where the gradient zones exist. By scanning the test area of the thermocouple along the high temperature zone, information on the thermocouple inhomogeneity may be obtained. If S varies linearly between x_i and x_{i+1}, and if the scan begins at a location x_1 where the thermocouple is homogeneous, the inhomogeneity I at position x_j is

$$I(x_j) = \sum_{i=1}^{j} \frac{E_i}{\Delta T} \tag{11}$$

Once $I(x_j)$ has been determined, Eq 8 and 9 may be used to determine the temperature measurement uncertainty due to inhomogeneity. Because of the low resolution of these measurements, this method does not determine I nearly as accurately as single-gradient scanning. However, for long thermocouples, where single-gradient scanning may not be possible, double-gradient scanning can provide useful information on the inhomogeneity of the thermocouple.

9. Keywords

9.1 inhomogeneity; thermocouple; verification test

APPENDIXES

X1. CALCULATIONS OF COMPARISON UNCERTAINTIES FOR *IN SITU* VERIFICATION TESTS

The formulas in this Appendix are used to determine the expanded total comparison uncertainties of the *in situ* verification tests described in Section 6. The formulas include the combined uncertainties $u_\mathrm{UUT\_acc}$ (the combined uncertainties of the UUT accessories) and u_ref, (the combined type B uncertainties of the reference thermometer. These uncertainties are defined as

$$u_{UUT\_acc} = \sqrt{u^2_{UUT\_inst} + u^2_{UUT\_RJC}}, \tag{X1.1}$$

$$u_{ref} = \sqrt{u^2_{ref\_inst} + u^2_{ref\_RJC} + u^2_{ref\_cal}}$$

The elements on the right hand side of these equations are listed in Table 1 and described in 6.7.3.

X1.1 Verification Test with the Reference Thermometer in the Same Access Point

X1.1.1 *Comparison of Measurements by the Thermocouple and the Reference Thermometer*—For this test, the expanded comparison uncertainty is

$$U_{comp} = 2\cdot\sqrt{\sigma^2_{UUT} + \sigma^2_{ref} + u^2_{UUT\_acc} + u^2_{ref} + u^2_{drift} + u^2_{imm}} \tag{X1.2}$$

where the elements on the right hand side of Eq X1.2 are either defined in Eq X1.1 or listed in Table 1 and described in section 6.7.3.

X1.1.2 *Comparison of Earlier and Present Measurements by the UUT and Reference Thermometer*—For this test, the expanded comparison uncertainty is

$$U_{comp} = 2\cdot\sqrt{\sum_{i=1}^{2} \sigma^2_{UUT}(i) + \sigma^2_{ref}(i) + u^2_{UUT\_acc}(i) + u^2_{ref}(i) + u^2_{drift}(i) + u^2_{imm}(i)} \tag{X1.3}$$

where the numbers $i = 1$ and $i = 2$ in parenthesis refer to the earlier and present comparison measurements, respectively. Again, the elements on the right hand side of Eq X1.3 are either defined in Eq X1.1 or listed in Table 2 and described in 6.7.3. For this case, the uncertainty $u_\mathrm{ref\_cal}$ is omitted in Eq X1.1, since the correlation of $u_\mathrm{ref\_cal}(1)$ and $u_\mathrm{ref\_cal}(2)$ causes their contributions to U_{comp} to cancel in Eq X1.3. Also, if it is known that the reference thermometer was placed in the access point with exactly the same immersion depth for both earlier and present comparisons, then $u_{imm}(1)$ and $u_{imm}(2)$ are omitted from Eq X1.3, since the correlation of these uncertainties causes their contributions to U_{comp} to cancel.

X1.2 Verification Test with the Reference Thermometer in an Adjacent Access Point

X1.2.1 *Comparison of Measurements by the Thermocouple and Reference Thermometer*—For this test, the expanded comparison uncertainty is

$$U_{comp} = 2 \cdot \sqrt{\sigma_{UUT}^2 + \sigma_{ref}^2 + u_{UUT\_acc}^2 + u_{ref}^2 + u_{imm}^2 + u_{\Delta T}^2} \quad (X1.4)$$

where the elements on the right hand side of Eq X1.4 are either defined in Eq X1.1 or listed in Table 3 and described in 6.7.3 and 6.8.3.

X1.2.2 *Comparison of Earlier and Present Measurements by the UUT and Reference Thermometer*—For this test, the expanded comparison uncertainty is

$$U_{comp} = 2 \cdot \sqrt{\sum_{i=1}^{2} \sigma_{UUT}^2(i) + \sigma_{ref}^2(i) + u_{UUT\_acc}^2(i) + u_{ref}^2(i) + u_{imm}^2(i) + u_{\Delta T}^2(i)} \quad (X1.5)$$

where the numbers $i = 1$ and $i = 2$ in parenthesis refer to the earlier and present comparison measurements, respectively. Again, the elements on the right hand side of Eq X1.5 are either defined in Eq X1.1 or listed in Table 2 and described in 6.7.3 and 6.8.3. For this case, the uncertainty u_{ref_cal} does not appear in Eq X1.1, since the correlation of $u_{ref\_cal}(1)$ and $u_{ref\_cal}(2)$ causes their contributions to U_{comp} to cancel in Eq X1.5. If it is known that temperature gradients in the environment have not changed between the earlier and present comparisons, then $u_{\Delta T}(1)$ and $u_{\Delta T}(2)$ are omitted from Eq X1.5, since the correlation of these uncertainties causes their contributions to U_{comp} to cancel. Similarly, if it is known that the reference thermometer was placed in the access point with exactly the same immersion depth for both earlier and present comparisons, then $u_{imm}(1)$ and $u_{imm}(2)$ are omitted from Eq X1.5, since the correlation of these uncertainties causes their contributions to U_{comp} to cancel.

X2. VERIFICATION USING THE METHOD OF MEASUREMENT AGREEMENT

The following verification calculations apply to the UUT verification test with the reference thermometer in the same access point and the UUT verification test with the reference thermometer in an adjacent access point.

X2.1 Comparison of Measurements by the UUT and Reference Thermometer

X2.1.1 For the UUT verification test with the reference thermometer in the same access point, the comparison data listed in Table 2 and the comparison uncertainty calculated in X1.1.1 are used. For the UUT verification test with the reference thermometer in an adjacent access point, the comparison data listed in Table 3 and the comparison uncertainty calculated in X1.2.1 are used. Then, the two thermometers may be considered to be in agreement and the UUT is verified if

$$|T_{UUT} - T_{ref}| < \sqrt{U_{UUT}^2 + U_{comp}^2} \quad (X2.1)$$

The value of U_{UUT} depends on the verification criterion, as described in 6.4. If the comparison is made using a referee thermocouple and the user wishes to verify that UUT measurements are identical to those of the referee thermocouple, then $U_{UUT} = 0$.

X2.2 Comparison of Earlier and Present Measurements by the UUT

X2.2.1 For the UUT verification test with the reference thermometer in the same access point, the comparison data listed in Table 2 and the comparison uncertainty calculated in X1.1.2 are used. For the UUT verification test with the reference thermometer in an adjacent access point, the comparison data listed in Table 3 and the comparison uncertainty calculated in X1.2.2 are used. Then, the earlier and present measurements by the UUT may be considered to be in agreement and the UUT is verified if

$$|T_{UUT}(1) - T_{ref}(1) - T_{UUT}(2) - T_{ref}(2)| < \sqrt{U_{UUT}^2 + U_{comp}^2} \quad (X2.2)$$

The value of U_{UUT} depends on the verification criterion, as described in section 6.4. If the comparison is made using a referee thermocouple and the user wishes to verify that the UUT measurements are identical to those of the referee thermocouple, then $U_{UUT} = 0$.

X2.3 Examples of Verification Calculations

X2.3.1 *Example of Comparison of Measurements by the UUT and Reference Thermometer, with the Reference Thermometer in the Same Access Point*—The measurement protocol and uncertainty elements for this verification test are described in section 6.7.

NOTE X2.1—The values used in this example are not intended for use in a real calculation.

Here, the UUT has a standard calibration uncertainty of 0.15°C at the temperature of interest, and the user wishes to verify that the UUT measures accurately to within this uncertainty. Let the reference thermometer be a referee thermocouple, and let both the UUT and referee thermocouple use reference-junction compensation. The temperature data and values of the uncertainty elements are shown below. For the temperature data, the temperature was first measured by the UUT, yielding T_{UUT}(a); afterwards the UUT was replaced in the access port by the referee thermocouple, which measured the temperature to be T_{ref}; finally the referee thermocouple was replaced by the UUT and a second temperature measurement was made by the UUT, yielding T_{UUT}(b). Note that the difference between T_{UUT}(a) and T_{UUT}(b) is much greater than σ_{UUT}, reflecting a significant temperature drift between the two measurements, which will be included in the uncertainty analysis. Note also that the uncertainties u_{UUT} and u_{ref_cal} are irrelevant here because the reference thermometer is a referee thermocouple. The values of u_{UUT_inst} and u_{ref_inst} are obtained from the manuals for the instruments used for measuring the emf of the UUT and referee thermocouple, respectively. Similarly, the values of u_{UUT_RJC} and u_{ref_RJC} are obtained from the manual for the reference junction compensator for the UUT and referee thermocouple, respectively. If the value of u_{UUT_inst}, u_{ref_inst}, u_{UUT_RJC} or u_{ref_RJC} provided in the manual is in units of volts, the uncertainty is divided by the Seebeck coefficient of the UUT or referee thermocouple, in units of volts/°C, at that temperature to obtain the value in units of °C.

The UUT is verified if the criterion of Eq X2.1 is satisfied. To determine this, $|T_{UUT} - T_{ref}|$, U_{comp} and U_{UUT} must be calculated. Using the temperature data with Eq 1, $T_{UUT} = 672°C$. Then,

$$|T_{UUT} - T_{ref}| = |672.0°C - 673.5°C| = 1.5°C$$

U_{comp} is calculated as follows. Using Eq X1.1 with u_{ref_cal} excluded,

$$u_{UUT\_acc} = \sqrt{(0.04°C)^2 + (0.50°C)^2} = 0.50°C$$

$$u_{ref} = \sqrt{(0.04°C)^2 + (0.50°C)^2} = 0.50°C$$

Using the temperature data with Eq 2,

$$u_{drift} = \frac{1}{2\sqrt{3}}|673°C - 671°C| = 0.58°C$$

Because the reference thermometer is not an RTD, $u_{imm} = 0°C$.

Using Eq X2.1,

$$U_{comp} = 2\sqrt{(0.04°C)^2 + (0.04°C)^2 + (0.50°C)^2 + (0.50°C)^2 + (0.58°C)^2 + (0°C)^2} = 1.84°C$$

Because the UUT is being compared with a referee thermocouple,

$$U_{UUT} = 0°C$$

Then

$$\sqrt{U_{UUT}^2 + U_{comp}^2} = \sqrt{(0°C)^2 + (1.84°C)^2} = 1.84°C$$

Since 1.5°C < 1.84°C, the criterion of Eq X2.1 is satisfied and the UUT is verified.

X2.3.2 *Example of Comparison of Earlier and Present Measurements by the UUT, with the Reference Junction in the Same Access Point*—Note that the values used here are for the example only and are not intended for use in a real calculation. Here, the standard uncertainty for the UUT calibration is $u_{accept} = 0.25°C$. Let the reference thermometer be a thermocouple of a different type from the UUT, and let both the UUT and reference thermocouple use reference-junction compensation. The temperature data and values of the uncertainty elements are shown below. Note that the calibration uncertainty u_{ref_cal} is irrelevant here because of the nature of this comparison. The values of u_{UUT_inst} and u_{ref_inst} are obtained from the manual for the instrument used for measuring the emf of the UUT and reference thermocouple, respectively. Similarly, the values of u_{UUT_RJC} and u_{ref_RJC} are obtained from the manual for the reference junction compensator for the UUT and reference thermocouple, respectively. If the value of u_{UUT_inst}, u_{ref_inst}, u_{UUT_RJC} or u_{ref_RJC} provided in the manual is in units of volts, the uncertainty should be divided by the Seebeck coefficient of the UUT or reference thermocouple at that temperature to obtain the value in units of °C.

The UUT is verified if the criterion of Eq X2.2 is satisfied. To determine this, $|T_{UUT}(1) - T_{ref}(1) - T_{UUT}(2) + T_{ref}(2)|$, U_{UUT}, and U_{comp} must be calculated. Using the temperature data with Eq 1, $T_{UUT}(1) = 357.79°C$ and $T_{UUT}(2) = 360.35°C$. Then,

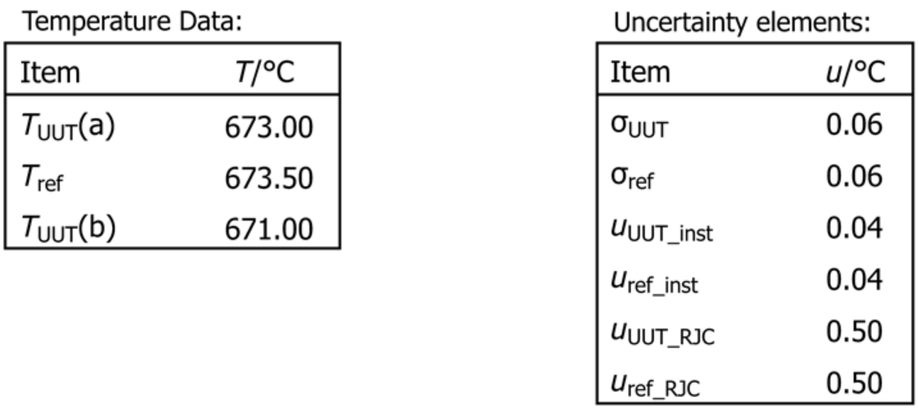
$$|T_{UUT}(1) - T_{ref}(1) - T_{UUT}(2) + T_{ref}(2)| = |357.79°C - 356.44°C - 360.35°C + 359.94°C| = 0.94°C$$

The UUT expanded uncertainty is

$$U_{UUT} = 2u_{UUT\_cal} = 0.5°C$$

U_{comp} is calculated as follows. Using Eq X1.1 with u_{ref_cal} excluded,

$$u_{UUT\_acc}(1) = \sqrt{(0.04°C)^2 + (0.30°C)^2} = 0.30°C$$



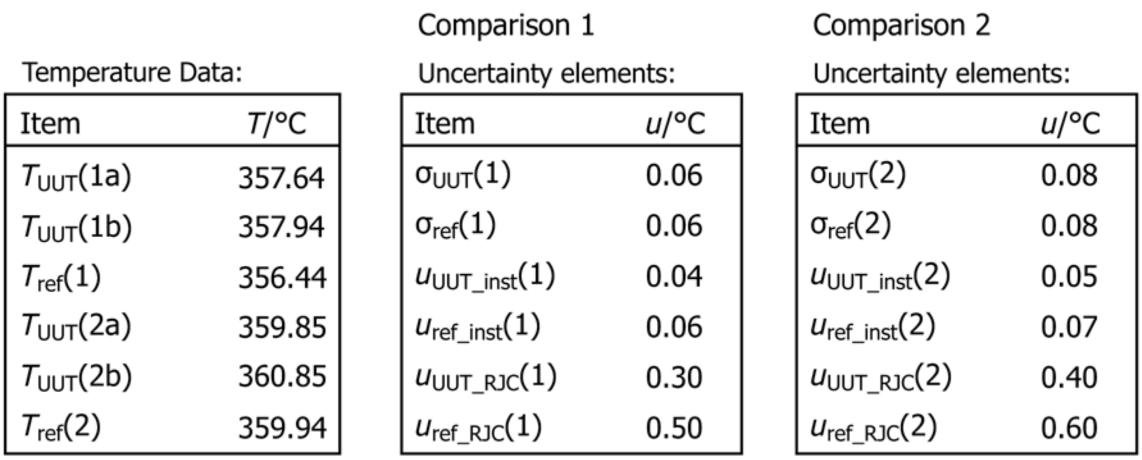
Temperature Data:

Item	T/°C
$T_{UUT}(a)$	673.00
T_{ref}	673.50
$T_{UUT}(b)$	671.00

Uncertainty elements:

Item	u/°C
σ_{UUT}	0.06
σ_{ref}	0.06
u_{UUT_inst}	0.04
u_{ref_inst}	0.04
u_{UUT_RJC}	0.50
u_{ref_RJC}	0.50

FIG. X2.1



Temperature Data:

Item	T/°C
T_{UUT}(1a)	357.64
T_{UUT}(1b)	357.94
T_{ref}(1)	356.44
T_{UUT}(2a)	359.85
T_{UUT}(2b)	360.85
T_{ref}(2)	359.94

Comparison 1

Uncertainty elements:

Item	u/°C
$\sigma_{UUT}(1)$	0.06
$\sigma_{ref}(1)$	0.06
$u_{UUT\_inst}(1)$	0.04
$u_{ref\_inst}(1)$	0.06
$u_{UUT\_RJC}(1)$	0.30
$u_{ref\_RJC}(1)$	0.50

Comparison 2

Uncertainty elements:

Item	u/°C
$\sigma_{UUT}(2)$	0.08
$\sigma_{ref}(2)$	0.08
$u_{UUT\_inst}(2)$	0.05
$u_{ref\_inst}(2)$	0.07
$u_{UUT\_RJC}(2)$	0.40
$u_{ref\_RJC}(2)$	0.60

FIG. X2.2

$$u_{ref}(1) = \sqrt{(0.06°C)^2+(0.50°C)^2} = 0.50°C$$

$$u_{UUT\_acc}(2) = \sqrt{(0.05°C)^2+(0.40°C)^2} = 0.40°C$$

$$u_{ref}(2) = \sqrt{(0.07°C)^2+(0.60°C)^2} = 0.60°C$$

Using the temperature data with Eq 2,

$$u_{drift}(1) = \frac{1}{2\sqrt{3}}|357.64°C - 357.94°C| = 0.09°C$$

$$u_{drift}(2) = \frac{1}{2\sqrt{3}}|359.85°C - 360.85°C| = 0.29°C$$

The immersion uncertainty is irrelevant because the reference thermometer is a thermocouple. Using Eq X1.3, the total uncertainty is then

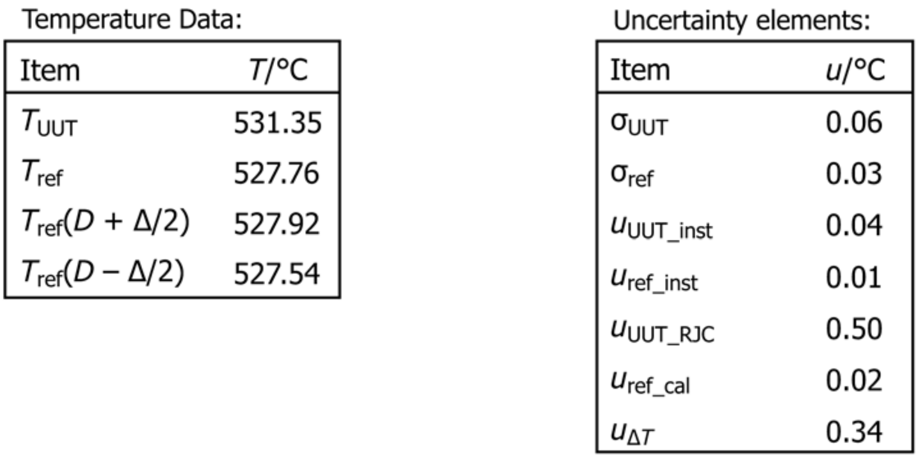
$$\begin{aligned} U_{comp} &= 2\cdot[(0.06°C)^2+(0.06°C)^2+(0.30°C)^2+(0.50°C)^2+(0.09°C)^2 \\ &\quad +(0.08°C)^2+(0.08°C)^2+(0.40°C)^2+(0.60°C)^2+(0.29°C)^2]^{1/2} \\ &= 1.98°C \end{aligned}$$

Then,

$$\sqrt{U_{UUT}^2+U_{comp}^2} = \sqrt{(0.5°C)^2+(1.98°C)^2} = 2.04°C$$

Since 0.94°C < 2.04°C, the criterion of Eq X2.2 is satisfied and the UUT is verified.

X2.3.3 *Example of Comparison of Measurements by the UUT and Reference Thermometer, with the Reference Thermometer in an Adjacent Access Point*—Note that the values used here are for the example only and are not intended for use in a real calculation. Here, the user wishes to perform a validation and verify that the UUT measures accurately to within an acceptable standard uncertainty of u_{accept} = 1.0°C. Let the reference thermometer be an RTD, and let the UUT use reference-junction compensation. The temperature data and values of the uncertainty elements are shown below. Note that the calibration uncertainty u_{ref_RJC} is irrelevant here because the reference thermometer is an RTD. The values of u_{UUT_inst} and u_{ref_inst} are obtained from the manual for the instrument used for measuring the emf of the UUT and the temperature of the reference thermometer, respectively. Similarly, the value of u_{UUT_RJC} is obtained from the manual for the reference junction compensator for the UUT. The values of u_{UUT_cal} and u_{ref_cal} are obtained from the original calibration report of the UUT and the reference thermometer, respectively. If the value



Temperature Data:

Item	T/°C
T_{UUT}	531.35
T_{ref}	527.76
$T_{ref}(D + \Delta/2)$	527.92
$T_{ref}(D - \Delta/2)$	527.54

Uncertainty elements:

Item	u/°C
σ_{UUT}	0.06
σ_{ref}	0.03
u_{UUT_inst}	0.04
u_{ref_inst}	0.01
u_{UUT_RJC}	0.50
u_{ref_cal}	0.02
$u_{\Delta T}$	0.34

FIG. X2.3

of $u_{\mathrm{UUT\_inst}}$, $u_{\mathrm{UUT\_RJC}}$ or $u_{\mathrm{UUT\_cal}}$ provided in the manual is in units of volts, the uncertainty should be divided by the Seebeck coefficient of the UUT at that temperature to obtain the value in units of °C. The method of estimating the value of $u_{\Delta T}$ is discussed in 6.8.3.

The UUT is verified if the criterion of Eq X2.1 is satisfied. To determine this, $|T_{\mathrm{UUT}} - T_{\mathrm{ref}}|$, U_{UUT} and U_{comp} must be calculated. Using the temperature data,

$$|T_{UUT} - T_{ref}| = 3.59°C$$

The acceptable expanded uncertainty for the UUT is

$$U_{UUT} = 2u_{accept} = 2.0°C$$

U_{comp} is calculated as follows. Using Eq X1.1 with $u_{\mathrm{ref\_RJC}}$ excluded,

$$u_{UUT\_acc} = \sqrt{(0.04°C)^2 + (0.50°C)^2} = 0.50°C$$

$$u_{ref} = \sqrt{(0.01°C)^2 + (0.02°C)^2} = 0.02°C$$

Using Eq 3 with the temperature data,

$$u_{imm} = \frac{1}{2\sqrt{3}}|527.54°C - 527.92°C| = 0.11°C$$

Using Eq X1.4 and the above values to calculate the total comparison uncertainty

$$U_{comp} = 2 \times \sqrt{(0.06°C)^2 + (0.03°C)^2 + (0.52°C)^2 + (0.02°C)^2 + (0.11°C)^2 + (0.34°C)^2} = 1.27°C$$

Then,

$$\sqrt{U_{UUT}^2 + U_{comp}^2} = \sqrt{(2.00°C)^2 + (1.27°C)^2} = 2.37°C$$

Since 3.59°C > 2.37°C, the criterion of Eq X2.1 is not satisfied and the UUT is not verified. Troubleshooting tests should be performed to ensure that the verification test was performed properly (for example, by performing the test with an unused thermocouple as the UUT). Also, the tests of Section 7 may be used to further investigate the unverified UUT. If the reason for failure of the UUT to pass the verification test cannot be determined and the problem fixed, it is recommended that the UUT be discarded or sent to a calibration lab for further testing.

X3. VERIFICATION OF THERMOCOUPLE TOLERANCES

X3.1 Verification of thermocouple tolerances involves advanced concepts and may result in the rejection of a significant number of in-tolerance thermocouples. Therefore it is strongly recommended that the methods described below be implemented only by advanced users with a thorough understanding of the risks of this process. The methods for determining tolerance compliance are discussed in depth in ANSI/NCSLI Z540.3-2006 (**2**). A brief discussion of this subject as pertaining to thermocouple verification is below, but readers wishing a more thorough understanding of these methods are referred to this document.

The tolerance verification tests are performed using the methods described in Section 6. The complications in thermocouple verification involve the acceptance criteria, and are a result of the measurement uncertainties of the tests. Because of these uncertainties, no test can verify that a UUT is within tolerance with complete certainty. Therefore, some in-tolerance UUTs will be rejected as out of tolerance and some out-of-tolerance UUTs will be accepted as in tolerance. The person performing the tests must be familiar with the following definitions (**2**):

(1) Test Uncertainty Ratio (TUR)—the ratio of the span of the tolerance of a measurement quantity subject to calibration, to twice the 95 % expanded uncertainty of the measurement process used for calibration. For a symmetric tolerance and a measurement uncertainty with a normal distribution, $TUR = 2\tau/2U = \tau/U$, where τ is the tolerance and U is the total expanded uncertainty ($k = 2$) of the test.

(2) Probability of False Acceptance (PFA)—the probability that an out-of-tolerance UUT will be accepted as in tolerance. Its value is dependent on the *TUR*, the acceptance criterion, and the uncertainty of the UUT bias.

(3) Probability of False Rejection (PFR)—the probability that an in-tolerance UUT will be rejected as out of tolerance. Its value is dependent on the *TUR*, the acceptance criterion, and the uncertainty of the UUT bias.

Methods of calculating *PFA* and *PFR* for this criterion are discussed in (**2**). It should be no surprise that the higher the value of *TUR*, the lower the values of *PFA* and *PFR*. If the value of *TUR* is too low, the resulting *PFA* or *PFR*, or both values may be unacceptable high, making tolerance verification impractical.

A number of tolerance-verification criteria exist, two of which have been frequently used. They are described below.

X3.2 Simple Criterion

X3.2.1 *Comparison of Measurements by the UUT and Reference Thermometer*—The UUT is declared in tolerance if

$$|T_{UUT} - T_{ref}| < \tau \tag{X3.1}$$

where T_{UUT} and T_{ref} are the temperatures measured by the UUT and reference thermometer, respectively, as described in 6.7.

X3.2.2 *Comparison of Earlier and Present Measurements by the UUT and Reference Thermometer*—The UUT is declared in tolerance if

$$|T_{UUT}(1) - T_{ref}(1) - T_{UUT}(2) + T_{ref}(2)| < \tau \tag{X3.2}$$

where $T_{\mathrm{UUT}}(1)$ and $T_{\mathrm{ref}}(1)$ are the temperatures measured earlier by the UUT and reference thermometer, respectively, and $T_{\mathrm{UUT}}(2)$ and $T_{\mathrm{ref}}(2)$ are the temperatures measured presently by the UUT and reference thermometer, respectively, as described in 6.8.

X3.2.3 *Table of PFA and PFR Values*—Table X3.1 shows calculated values of *PFA* and *PFR* for various values of *TUR*. Note that the values of *PFA* and *PFR* are similar for a given value of *TUR*. Note also that when $TUR \geq 5,_{PFA} \leq 2$ %, and $PFR \leq 2$ %, complying with ANSI/NCSLI Z540.3-2006 acceptance specifications.

X3.3 Simple Guardband Criterion

X3.3.1 This criterion is sometimes used for low values of *TUR* (for example, *TUR* < 4) and the user wishes to verify tolerances with *PFA* values that are virtually 0 %.

X3.3.2 *Comparison of Measurements by the UUT and Reference Thermometer*—For the Simple Guardband Criterion, the UUT is declared in tolerance if

$$|T_{UUT} - T_{ref}| < \tau - U_{comp} \qquad (X3.3)$$

where once again U_{comp} is the total expanded uncertainty (k = 2) of the comparison.

X3.3.3 *Comparison of Earlier and Present Measurements by the UUT and Reference Thermometer*—The UUT is declared in tolerance if

$$|T_{UUT}(1) - T_{ref}(1) - T_{UUT}(2) + T_{ref}(2)| < \tau - U_{comp} \qquad (X3.4)$$

X3.3.4 *Table of PFA and PFR Values*—There is a high cost for using the Simple Guardband Criterion: the values of *PFR* increase considerably, resulting in the rejection of a high proportion of in-tolerance UUTs. As an extreme example, when $U_{\mathrm{comp}} \geq \tau$, the criterion can never be satisfied and so all UUTs are rejected, even if they are in tolerance. Table X3.2 gives examples of *PFA* and *PFR* values for various values of *TUR* when the Simple Guardband Criterion is used.

X3.4 Alternative Criteria

X3.4.1 Other criteria have been formulated with the goal of satisfying ANSI/NCSLI Z540.3-2006 acceptance specifications (2 % *PFA*) while maintaining acceptable values of *PFR*, even for low values of *TUR*. While they generally succeed in accomplishing this, they do so at the cost of additional mathematical complexity. More information on these alternative criteria may be found in (**2**).

TABLE X3.1 Calculated Maximum Values of *PFA* and *PFR* for Various Values of *TUR* When the Simple Criterion (Eq X3.1) is Used.

TUR	PFA %	PFR %
1	7.37	13.73
2	4.18	5.71
3	2.91	3.39
4	2.24	2.62
5	1.82	2.06
6	1.53	1.70
7	1.32	1.44
8	1.16	1.26

TABLE X3.2 Calculated Maximum Values of *PFA* and *PFR* for Various Values of *TUR* When the Simple Guardband Criterion is Used.

TUR	PFA %	PFR %
1	0.00	100.00
2	0.09	34.95
3	0.06	20.39
4	0.05	14.37
5	0.04	11.09
6	0.03	9.03
7	0.03	7.62
8	0.03	6.58

X4. DETERMINATION OF THE SEEBECK COEFFICIENT INHOMOGENEITY

This appendix derives the Seebeck Coefficient $I(x)$ as given in Eq 7 using a method similar to that of (**7**). Here, x is the position along the length of the thermocouple relative to the measurement junction. The temperature profile $t(D)$ at the surface of the oil bath is shown in Fig. 3. When the measuring junction is immersed a depth D relative to the maximum temperature gradient, the measured emf will then be the sum of the emf values across three segments on the thermocouple:

$$E(D) = E_1 + E_2\,(D) + E_3\,(D) \tag{X4.1}$$

Here, E_1 is the emf across the first segment, which is that between the reference junction and the bath surface; its value is assumed constant and is the value measured by the thermocouple when its measuring junction is immediately above the bath. Also, E_2 is the emf across the second segment, which is exposed to the gradient zone. This segment is centered at $D = 0$ and has width Δ as shown in Fig. 3; the temperature change across it is Δt_g. Finally, E_3 is the emf across the third segment, which is between the second segment and the measuring junction. If the thermocouple were in its original homogeneous state, its emf value across these three segments would be

$$E^h(D) = E_1^h + E_2^h(D) + E_3^h(D) \tag{X4.2}$$

The difference between the emf measured by the UUT in its current state and that which would be measured by it in its original homogeneous state is then

$$\Delta E(D) = \left[E_1 - E_1^h\right] + \left[E_2(D) - E_2^h(D)\right] + \left[E_3(D) - E_3^h(D)\right] = \Delta E_1 + \Delta E_2(D) + \Delta E_3(D) \tag{X4.3}$$

The principal contribution to E_1 is from the temperature difference between 0°C and ambient temperature. The value of E_1 is easily measured by placing the measuring junction of the thermocouple immediately above the bath; its value may be assumed constant as the thermocouple is immersed in the bath, provided that the temperature of the air above the bath is uniform relative to Δt_g. If the portion of the thermocouple containing the gradient zone between 0°C and ambient temperature is still homogeneous, the value of ΔE_1 will be negligible.

The second segment contains the position x where $I(x)$ is determined. At the center of the second segment, $x = D$, so the value of E_2 is given by

$$\Delta E_2(D) = \int_{D-\Delta/2}^{D+\Delta/2} I(x)\,\frac{dt}{dx}dx \tag{X4.4}$$

Assuming I does not vary much with x over the range Δ for constant t, Eq X4.4 may be approximated as

$$\Delta E_2(D) = I(x = D)\Delta t_g \tag{X4.5}$$

where $\Delta t_g = t(D = \Delta/2) - t(D = \Delta/2)$. Finally, the value of ΔE_3 is determined by the combination of the known temperature profile in the bath and the values of $I(x)$ determined earlier at a smaller immersion depth during the scan. The value of ΔE_3 is given by

$$\Delta E_3(D) = \int_0^{D-\Delta/2} I(x)\frac{dt(D-x)}{dx}dx \tag{X4.6}$$

Combining Eq X4.3-X4.6, $I(x)$ is expressed as

$$I(x = D) = \frac{1}{\Delta t}\left(\Delta E(D) - \Delta E1 - \int_0^{D-\Delta/2} I(x')\frac{dt(d-x')}{dx'}dx'\right) \tag{X4.7}$$

Here, the variable position x from Eq X4.6 is primed to differentiate it from the fixed position $x = D$.

In practice, measurements of $E(D)$ and $t(D - x')$ are made at discrete points i, where $i = 1,2,3\ldots$ and where $D_{i+1} - D_i = x_{i+1} - x_i = \delta\ldots$ If δ is set so that $\delta = \Delta/2$, then Eq X4.7 may be expressed as

$$I(x_i) = \frac{1}{\Delta t}\Delta E(D_i) - \Delta E_1 - \sum_{j=1}^{i-1} I(x_j)\,(t_{i-j} - t_{i-j+1}) \tag{X4.8}$$

If the bath temperature is very uniform compared to Δt_g, Eq X4.8 may be approximated to

$$I(x_i) = \Delta E_i / \Delta t_t \tag{X4.9}$$

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