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Standard Practice for
Calibration and Use of Thermocouple Reference Junction Probes in Evaluation of Electronic Reference Junction Compensation Circuits[1]

This standard is issued under the fixed designation E2730; 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.

ε[1] NOTE—Note 12 was moved to a new location below Table 2 in November 2015.

1. Scope

1.1 This guide covers methods of calibration and use of thermocouple reference junction probes (cold junction compensation probes) in the evaluation of electronic reference junction compensation circuits. Their use with instruments that measure only voltage is also covered.

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 *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

E230 Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples

E344 Terminology Relating to Thermometry and Hydrometry

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

E1129/E1129M Specification for Thermocouple Connectors

E1684 Specification for Miniature Thermocouple Connectors

E1750 Guide for Use of Water Triple Point Cells

E2623 Practice for Reporting Thermometer Calibrations

2.2 *Other References:*

NIST Monograph 175 Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90

ASTM MNL12 Manual On The Use Of Thermocouples In Temperature Measurement

BIPM JCGM 100:2008 Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement

3. Terminology

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *correction, n*—an offset value added to the result of a measurement to obtain a correct result.

NOTE 1—This definition is from Test Method E220.

3.2.2 *reference junction compensation, n*—the electrical correction of the indication of a thermocouple such that the corrected indication is equivalent to the emf or temperature the instrument would indicate if the reference junctions were physically maintained at 0°C.

3.2.3 *reference junction probe, n*—a probe constructed from thermocouple materials and high purity copper wire for the purpose of serving as the reference junction for a thermocouple assembly. Reference junction probes may be constructed as part of the measuring probe or they can be manufactured separately and later attached to thermocouple sensors via plugs or other connection types.

3.2.4 *UUT, n*—Unit Under Test.

4. Summary of Guide

4.1 Calibration of a Reference Junction Probe (RJP) consists of establishing the emf error in the RJP relative to the applicable thermocouple reference function by placing the measuring junction and the reference junctions at known temperatures while measuring the voltage with a digital voltmeter (DVM) or potentiometer. Three methods are described

[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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[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.

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for establishing the two known temperatures and thus the temperature difference. For the temperature measurement, many devices such as Standard Platinum Resistance Thermometers (SPRTs), Platinum Resistance Thermometers (PRTs), thermistors, or thermocouples, and a variety of readout instruments are suitable, depending on the required accuracy. The measured voltage at the copper leads indicates the emf associated with the temperature difference of the references. Error is determined by comparing the observed emf to the calculated emf for the known temperature difference. The emf error is then applied as a correction. The corrected emf can then be converted to temperature.

NOTE 2—In particular, cold work should be avoided in the sections of copper and thermocouple wire that pass from the top of the ice bath to ambient temperature continuing on to the terminal connection. Careful design of the RJP, with supporting sleeve and strain relief, can minimize cold work in these sections.

4.2 Use of the calibrated RJP consists of applying the corrections obtained during calibration appropriately for the mode of use. Three modes of use with corresponding application equations are described.

NOTE 3—Homogeneity is assumed in both the thermocouple and copper wires. Care should be taken to minimize the stress induced over time and during use on both sets of wire. Cold work in particular should be avoided in the sections of the copper and thermocouple wire from a distance 5 cm (2 in.) below the top of the ice/water mixture to a distance 5 cm (2 in.) above the top of the ice-point bath.

NOTE 4—Proper operation of the measuring instruments is not described in this guide. To ensure correct results, the operator must understand and apply proper technique in the use of all measuring instruments involved.

5. Significance and Use

5.1 Many electronic instruments that are designed to be used with thermocouples use some method of reference junction compensation. In many industrial applications it may be impractical to use a physical ice bath as a temperature reference in a thermocouple circuit. The instrument must therefore be able to measure the temperature at the point of electrical connection of the thermocouple and either add or subtract voltage to give a corrected equivalent of what that thermocouple would indicate had there physically been 0°C reference junctions present in the circuit. There are two types of instruments that generally apply these techniques: electronic thermometer readouts that use a thermocouple as the sensor, and calibrators designed to calibrate these digital thermometer readouts. Additionally, the probe and circuit described in this guide can be used with a voltmeter to emulate a thermometer or a voltage source to calibrate temperature-indicating instrumentation. In all cases the probe must be calibrated if traceability or an uncertainty analysis, or both, is required.

6. Reagents

6.1 Laboratory or commercially produced distilled water is required to create an accurate ice bath. Clean tap water can be used in cases where high accuracy is not a requirement; in this case the temperature of the bath should be measured directly. Chlorine, fluorine, and other chemicals such as dissolved salts in the water or ice will depress the ice point and the amount can be significant in some measurements. See Practice E563 for further guidance.

7. Procedure

7.1 Calibration of RJP (Methods A, B, or C).

7.1.1 *Reference Point Temperature Source:*

7.1.1.1 *Method A: Ice Bath Method*—Prepare the reference point temperature source using an ice-point bath in accordance with Practice E563. Refer to Fig. 1.

NOTE 5—Be careful to closely follow the guidelines in Practice E563 for establishing and maintaining an Ice Point Reference as significant error can occur over time without proper maintenance.

7.1.1.2 *Method B: Triple Point of Water (TPW) Cell Method*—Prepare the reference point temperature source using a triple point of water cell in accordance with Guide E1750. Refer to Fig. 2.

NOTE 6—Be careful to closely follow the guidelines in Guide E1750 for establishing and maintaining a TPW cell as significant error can occur over time without proper maintenance.

7.1.1.3 *Method C: Variable Temperature Source Method*—Prepare the reference point temperature source using a variable temperature source (calibration bath or dryblock calibrator) set to 0.0°C and verify using a reference thermometer. Refer to Fig. 3.

7.1.2 Prepare the room temperature source using a variable temperature source (calibration bath or dry-block calibrator) set to 25°C and verify using a reference thermometer. The temperature of 25ºC is nominal; in actual testing the temperature of the bath should be set as close as possible to the ambient room temperature. Throughout this procedure 25ºC will be used to designate the ambient temperature. There are many cases where the terminal ends may be at a temperature higher than ambient temperature. Connections inside an instrument or control box can reach temperatures of 40°C or higher. The RJP can be calibrated at multiple temperatures and the resulting RJP correction can be modeled as a first- or second-order polynomial correction versus RJP temperature.

7.1.3 Weld, solder, or braze the thermocouple wire ends of the RJP together to create a thermocouple measuring junction and then insert it into a protective sheath. Twisting or crimping the wires is acceptable if a reliable electrical connection can be achieved. The measuring junction should be electrically isolated from the sheath. All fluxes or chemicals that may have been used should be thoroughly removed.

7.1.4 Place the measuring junction and protective sheath in the temperature source that has been stabilized at 25ºC nominal. Place the reference junction probe in the reference point temperature source. Both the sheath and probe should be sufficiently immersed to make stem conduction error negligible. **Warning—**The individual positive and negative connections must be electrically isolated from each other and the sheath regardless of the type connection or temperature stabilizing method used.

7.1.5 Connect the copper leads of the RJP to the voltmeter.

7.1.6 Allow the setup to stabilize as indicated on the voltmeter; the stability required depends upon the level of uncertainty required.

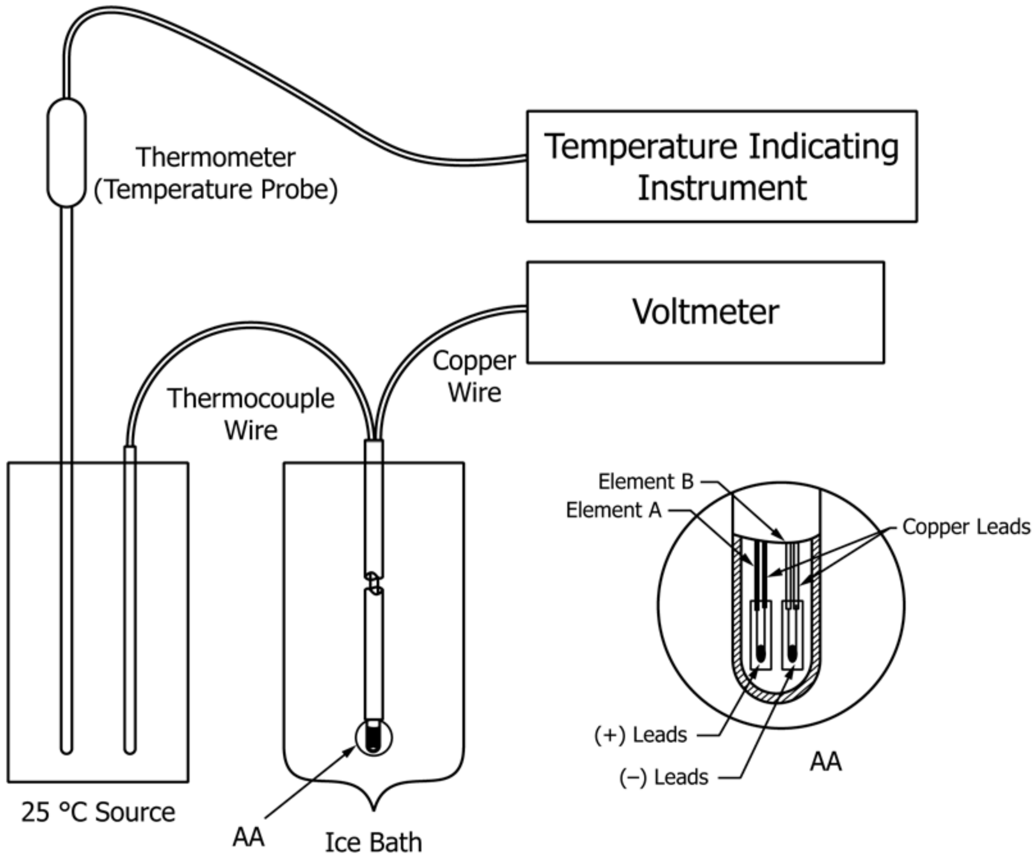

FIG. 1 Schematic Diagram of Calibration Method A

7.1.7 Measure the temperature of the 25°C source (T_{MJ}) and the reference point temperature source (T_{RJ}) if using method C.

7.1.8 The RJP error in microvolts is given by Eq 1.

$$E_{RJP\ error} = E_{observed} - \int_{T_{RJ}}^{T_{MJ}} S_{AB}(T)dT \quad (1)$$

where:

$E_{RJP\ error}$ = RJP error, in µV,
$E_{observed}$ = voltage indication, in µV,
T_{MJ} = ambient source temperature, in °C, as measured by the reference thermometer,
T_{RJ} = reference junction temperature, in °C (assumed to be 0.000°C in Method A, 0.010°C in Method B, and measured by reference thermometer in Method C), and
$S_{AB}(T)$ = Seebeck coefficient at temperature T, in µV/°C.

NOTE 7—Use the correct value for the S_{AB} based on the actual temperature of the reference point temperature source. Values given are based on the ice Melting Point (MP) (0.000°C).

NOTE 8—The values given are taken from NIST Monograph 175.

7.1.9 The RJP error in microvolts is algebraically approximated using Eq 2 for method A.

$$E_{RJP\ error} = E_{observed} - E_{expected} \quad (2)$$

where:

$E_{RJP\ error}$ = RJP error, in µV,
$E_{observed}$ = voltmeter indication, in µV, and
$E_{expected}$ = thermocouple voltage, in µV, at the ambient source temperature, as computed by the reference function or interpolated from the thermocouple table.

7.1.10 The RJP error in microvolts is algebraically approximated using Eq 3 for method B.

$$E_{RJP\ error} = E_{observed} - E_{expected} + 0.010°C \times S_{AB}(0°C) \quad (3)$$

where:

$E_{RJP\ error}$ = RJP error, in µV,
$E_{observed}$ = voltmeter indication, in µV,
$E_{expected}$ = thermocouple voltage, in µV, at the ambient source temperature, as computed by the reference function or interpolated from the thermocouple table, and
$S_{AB}(0°C)$ = Seebeck coefficient at 0°C, in µV/°C (refer to Table 1).

7.1.11 The RJP error in microvolts is algebraically approximated using Eq 4 for method C.

$$E_{RJP\ error} = E_{observed} - E_{expected} + S_{AB}(0°C) \times T_{RJ} \quad (4)$$

where:

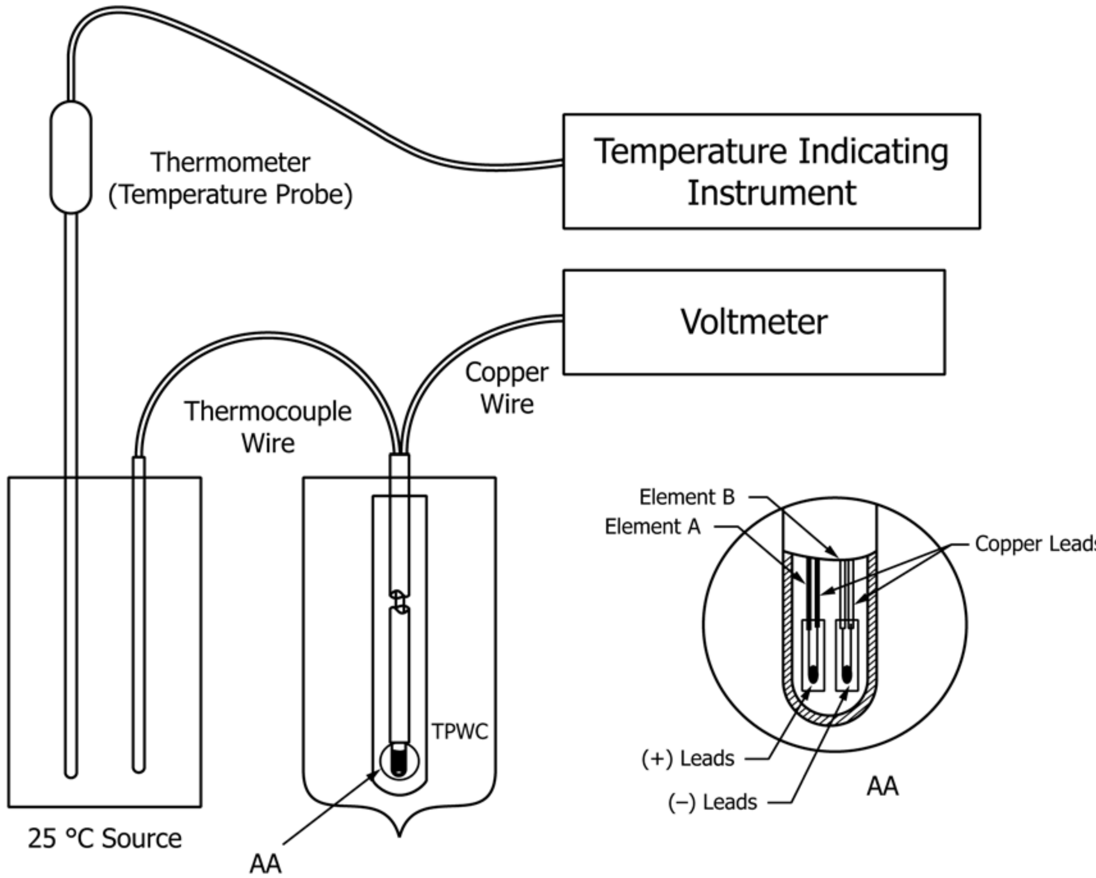

FIG. 2 Schematic Diagram of Calibration Method B

$E_{RJP\ error}$ = RJP error, in µV,
$E_{observed}$ = voltmeter indication, in µV,
$E_{expected}$ = thermocouple voltage, in µV, at the ambient source temperature, as computed by the reference function or interpolated from the thermocouple table,
T_{RJ} = reference junction temperature, in °C, as measured by the reference thermometer, and
$S_{AB}(0°C)$ = Seebeck coefficient at 0°C, in µV/°C (refer to Table 1).

7.1.12 Corrections are identical to errors in magnitude but of opposite sign. Calculate the voltage correction in µV using Eq 5.

$$E_{RJP\ correction} = E_{RJP\ error} \tag{5}$$

where:

$E_{RJP\ correction}$ = RJP correction, in µV, and
$E_{RJP\ error}$ = RJP error, in µV.

7.1.13 Calculate the temperature correction in °C using Eq 6.

$$T_{RJP\ correction} = \frac{-(E_{RJP\ error})}{S_{AB}(0°C)} \tag{6}$$

where:

$T_{RJP\ correction}$ = RJP correction, in °C,
$E_{RJP\ error}$ = RJP error, in µV, and
$S_{AB}\ (0°C)$ = Seebeck coefficient at temperature 0°C, in µV/°C (refer to Table 1).

Warning—Eq 6 may provide incorrect results for thermocouples having significantly different values of S_{AB} at 0°C and 25°C

7.2 Use of the RJP (Modes 1, 2, or 3).

NOTE 9—The following instructions apply to the use of an ice bath, TPW cell, or variable temperature source for the reference point temperature. Thus, the equations are shown in the generalized form. When using the equations, the value for t_1 must be the assumed values for the ice bath or TPW cell, or the actual measured temperature of the variable temperature source, as applicable.

7.2.1 *Mode 1*—Use of the RJP as a reference junction in a thermocouple circuit. Refer to Fig. 4.

7.2.1.1 Prepare the reference point temperature source.

7.2.1.2 Connect the thermocouple end of the RJP to the thermocouple to be measured using an approved thermocouple connector.

7.2.1.3 Connect the copper wire end of the RJP to the measuring instrument, observing polarity.

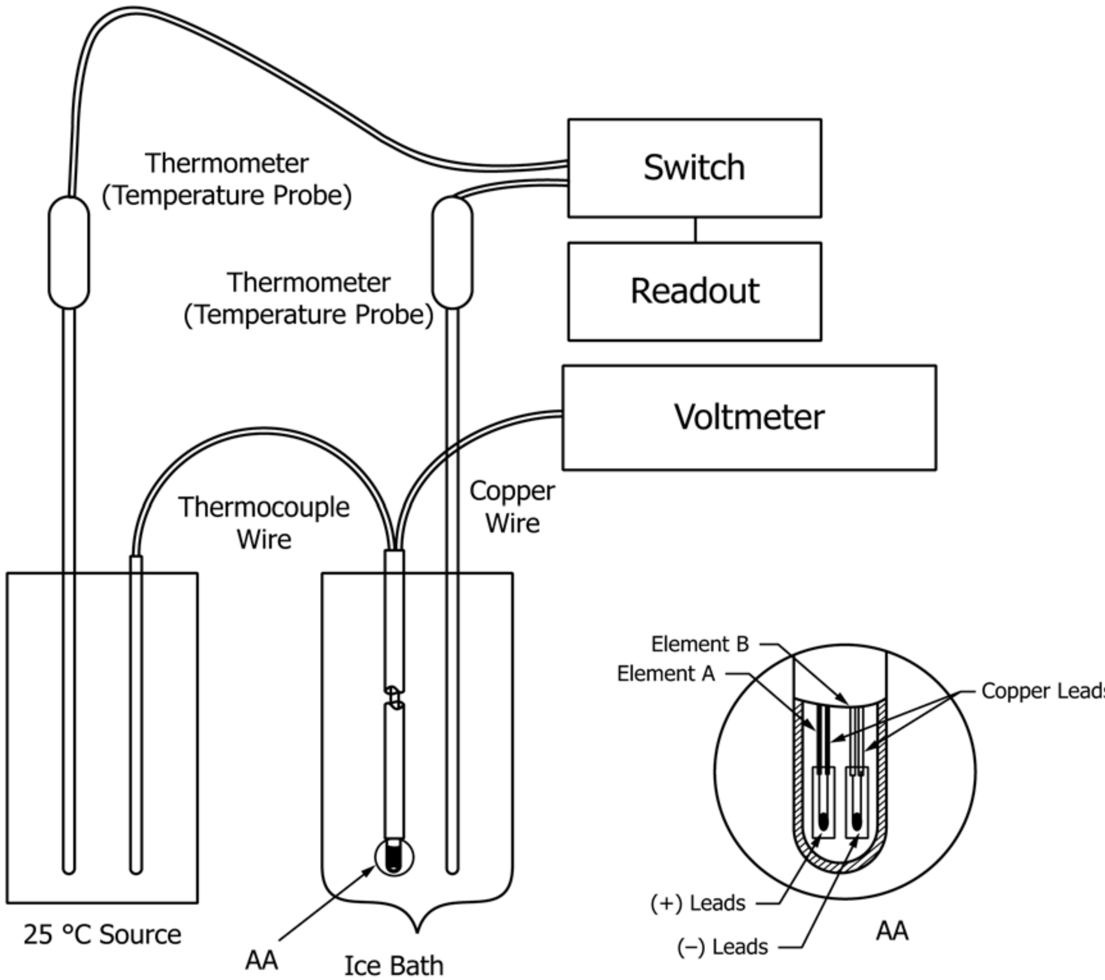

FIG. 3 Schematic Diagram of Calibration Method C

TABLE 1 Seebeck Coefficients at 0°C for Some Common Thermocouple Types[A]

Calibration Type	S_{AB}(0°C) in µV/°C
E	58.666
J	50.382
K	39.456
N	25.929
T	32.854
R	5.290
S	5.403
B	0.102

[A] Source: Specification E230.

7.2.1.4 Place the RJP probe into the reference point temperature source.

7.2.1.5 Place the thermocouple measuring junction in the location to be measured.

7.2.1.6 Allow sufficient time for the indications to stabilize.

7.2.1.7 The thermocouple voltage corresponding to the location being measured is determined by Eq 7. **Warning—** See 8.2.2 regarding the potential for additional error using this method.

$$E_{MJ} = E_{observed} + E_{RJP\ correction} + S_{AB}(0°C) \times T_{RJ} \quad (7)$$

where:

E_{MJ} = corrected thermocouple voltage, in µV,
$E_{observed}$ = voltmeter indication, in µV,
$E_{RJP\ correction}$ = reference junction probe correction, in µV,
$S_{AB}\ (0°C)$ = Seebeck coefficient at 0°C, in µV/°C (refer to Table 1), and
T_{RJ} = reference junction temperature (assumed 0.000°C, 0.010°C, or measured by reference thermometer, as applicable).

7.2.2 *Mode 2*—Use of the RJP in the calibration of the reference junction compensation circuit of a thermocouple-measuring instrument using a voltage calibrator or multifunction calibrator. Refer to Fig. 5.

7.2.2.1 Prepare the reference point temperature source.

7.2.2.2 Connect the thermocouple end of the RJP to the thermocouple input of the thermocouple-measuring instrument, observing polarity; use an approved thermocouple connector if a connector is required.

7.2.2.3 Connect the copper wire end of the RJP to the voltage calibrator or multi-function calibrator.

7.2.2.4 Place the RJP probe into the reference point temperature source.

7.2.2.5 Allow sufficient time for the temperature of the RJP to equilibrate.

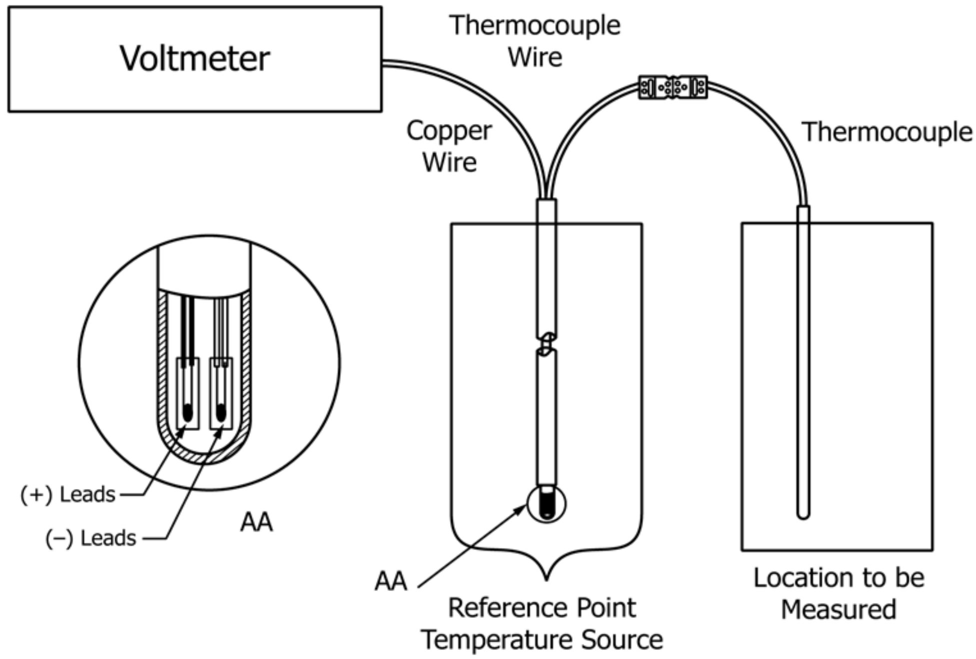

FIG. 4 Schematic Diagram of Usage Mode 1

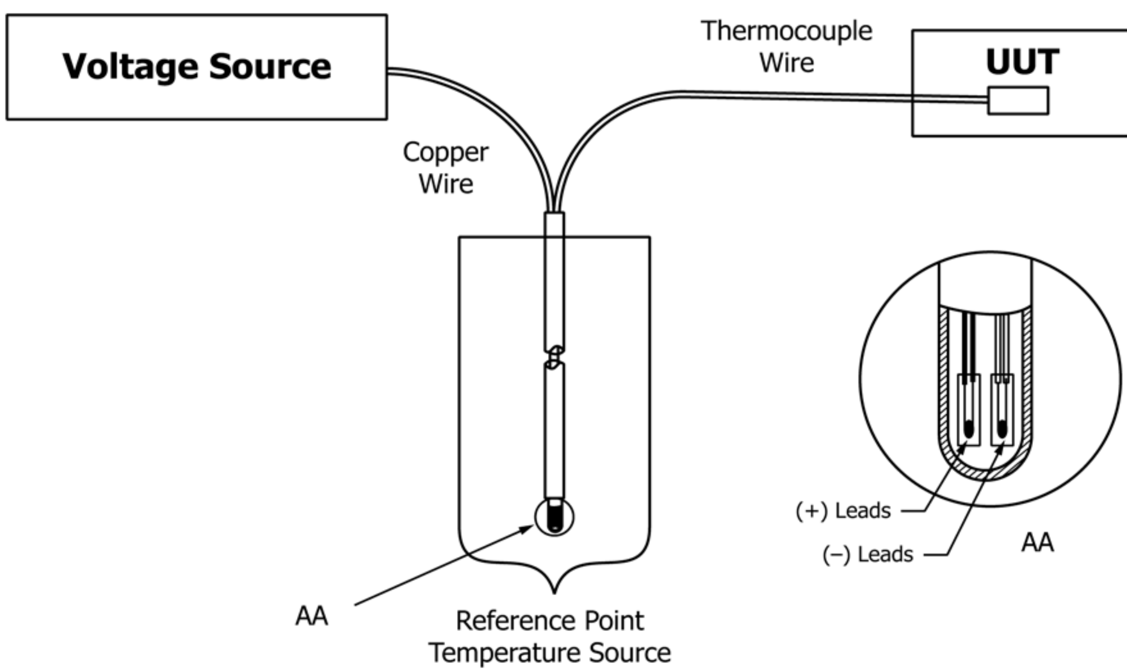

FIG. 5 Schematic Diagram of Usage Mode 2

7.2.2.6 Calculate the voltages required corresponding to the temperature of interest using Eq 8.

$$E_{required} = E_{nominal} - E_{RJP\ correction} - S_{AB}(0°C) \times T_{RJ} \quad (8)$$

where:

$E_{required}$ = corrected voltage, in μV, corresponding to the temperature of interest,

$E_{nominal}$ = thermocouple voltage, in μV, at temperature corresponding to temperature of interest as computed by the reference function or interpolated from the thermocouple table,

$E_{RJP\ correction}$ = reference junction probe correction, in μV. This value may be positive or negative,

$S_{AB}(0°C)$ = Seebeck coefficient at 0 °C, in µV/°C (refer to Table 1), and
T_{RJ} = reference junction temperature (assumed 0.000°C, 0.010°C, or measured by reference thermometer, as applicable).

NOTE 10—S_{AB} *(0°C)* refers to a temperature near 0°C because that is the most common point used. However, in many instances other reference temperatures are appropriate. For these cases the Seebeck coefficient of that temperature should be used.

Use $E_{required}$ values rather than the nominal voltage values for calibration of the thermocouple-measuring instrument. This method is specific to using a source voltage. This section is not intended for multifunction calibrators used in the temperature mode: multifunction calibrators may be used with this method when set to voltage only.

NOTE 11—Proper operation of the measuring instruments is not described in this guide. To ensure correct results, the operator must understand and apply proper technique in the use of all measuring instruments involved.

7.2.2.7 Some types of thermocouple measuring instruments are designed such that the reference junction compensation can be switched off. When this is the case, it is recommended that the compensation accuracy be verified independently with the reference junction switched off and the reference junction compensation calibrated at one simulated temperature, preferably 0°C. The following section guides the user through the process of calibrating instruments compensation accuracy.

7.2.3 *Mode 3*—Use of the RJP in the calibration of the reference junction compensation circuit of a thermocouple calibrator (voltage source with internal reference junction compensation). Normally, this type of instrument is designed such that the voltage accuracy can be verified independently. The following procedure is intended to verify only the reference junction compensation circuit. Refer to Fig. 6.

7.2.3.1 Prepare the reference point temperature source.

7.2.3.2 Connect the thermocouple end of the RJP to the thermocouple output of the thermocouple calibrator; use a thermocouple connector that conforms with Specifications E1129/E1129M or E1684 if a connector is required.

7.2.3.3 Connect the copper wire end of the RJP to the voltmeter.

7.2.3.4 Place the RJP probe into the reference point temperature source.

7.2.3.5 Allow sufficient time for the temperature of the RJP to equilibrate.

7.2.3.6 Program the thermocouple calibrator to 0.000°C and record the voltage indicated by the voltmeter.

7.2.3.7 Calculate the instrument reference junction compensation error using Eq 9.

$$T_{RJC\ error} = \frac{E_{observed} + E_{RJP\ correction}}{S_{AB}(0°C)} + T_{RJ} \quad (9)$$

where:

$T_{RJC\ error}$ = error of instrument RJC circuit, in °C,
$E_{observed}$ = meter indication, in µV,
$E_{RJP\ correction}$ = reference junction probe correction, in µV,
$S_{AB}(0°C)$ = Seebeck coefficient at 0°C, in µV/°C (refer to Table 1), and
T_{RJ} = reference junction temperature (assumed 0.000°C, 0.010°C, or measured by reference thermometer, as applicable).

Warning—Eq 9 may provide incorrect results for thermocouples having significantly different values of S_{AB} at 0°C and 25°C.

8. Precision and Bias

8.1 When using the RJP it should be recognized that it contributes to the total EMF in the circuit and therefore must be calibrated and carefully handled during use. Changes in the thermophysical properties of the wire will affect the overall accuracy. These changes can be due to numerous effects such as oxidation or changes in thermal coupling within the probe, as well as changes in wire homogeneity due to stress induced during use. These potential changes can occur in both the thermocouple and copper wire, although to a lesser degree in the copper wires. Recalibration of the RJP must be performed at regular intervals to maintain accuracy.

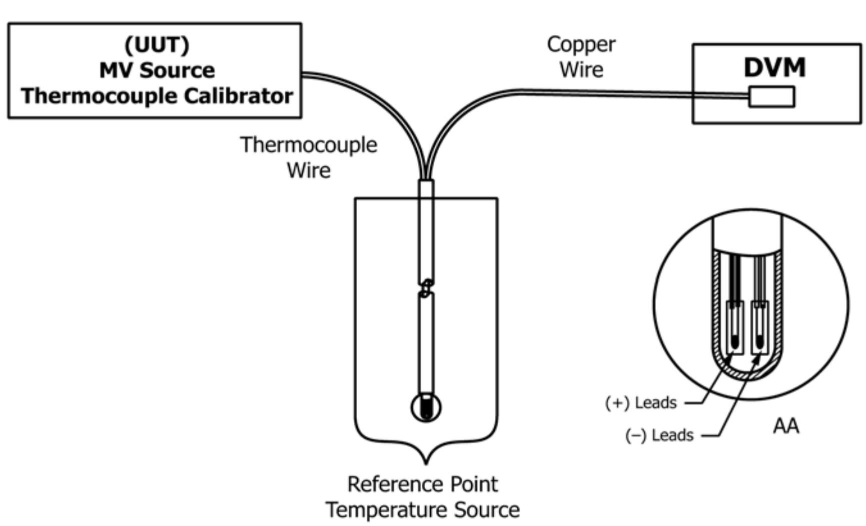

FIG. 6 Schematic Diagram of Usage Mode 3

8.2 *Uncertainty Analysis:*

8.2.1 The uncertainty in the calibration of the reference junction probe is computed by combining the individual components of uncertainty involved in the calibration. An example of an uncertainty budget is shown in Table 2. When using this budget, the actual values determined in the application should be substituted for the sample values shown in the example.

8.2.2 Properly calibrated, the RJP mimics the response of an ideal thermocouple, matching the reference function exactly from 0°C to the temperature of the RJP/thermocouple connection. The response of an actual thermocouple (shown on the left side of Fig. 4) across the same temperature span may not be ideal, since the emf versus temperature relation of an actual thermocouple will differ in general from that of the reference function. This difference may be on the order of several tenths of a degree Celsius for typical thermocouples and in some cases may be even greater. Depending on the application it may be appropriate to treat this difference as an additional source of uncertainty.

8.2.3 See Table 2.

Warning—The uncertainties given represent typical values and each user must independently evaluate actual test conditions. Additionally, the uncertainty and actual measurement values will vary if different wires are used in the setup or if those wires are exposed to different temperature gradients. Further information on this topic can be found in ASTM MNL12.

TABLE 2 Example Uncertainty Budget

Component of Uncertainty	Uncertainty °C
Temperature of reference junction	0.010
Temperature of measuring junction	0.010
Immersion effects in reference junction	0.020
Immersion effects in measuring junction	0.010
Voltage measurement (converted to temperature)	0.021
Voltmeter zero stability (converted to temperature)	0.034
Estimate of the effects of inhomogeneity	0.020
Reproducibility	0.008
Repeatability	0.003
Combined Uncertainty (k = 2)[A]	**0.060**

[A] For more information refer to BIPM JCGM 100:2008 (Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement).

NOTE 12—All contributors were treated as rectangular distributions; the values were combined using the root sum squares method.

9. Report

9.1 In many cases, it is necessary to provide the results of the RJP calibration to a prospective user. When this is the case, care should be taken to ensure that the results are presented in a clear, unambiguous manner. At a minimum, the results should indicate the observed error in µV and the corrections in both µV and temperature. Additional information could include the measurement uncertainties and an outline or short description of the calibration process. It is important to note that the current views on traceability would consider a calibration without an uncertainty not traceable. Refer to Practice E2623 for further information and guidance.

10. Keywords

10.1 calibration; PRT; reference junction compensation; reference junction probe; Seebeck coefficient; SPRT; thermocouple; verification

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