BSR/ASHRAE Standard 41.1-2020R

Public Review Draft

Standard Methods for Temperature Measurement

First Public Review (August 2023)
(Complete Draft for Full Review)

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FOREWORD

Compared to the 2020 version, this version includes (a) updated methods for determining when steady-state operation has been achieved for data recording, (b) changes to make it easier for higher-tier standards to adopt this standard by reference, and (c) a new uncertainty example prepared in accordance with the latest uncertainty methods. This revision of ASHRAE 41.1-2020 meets ASHRAE’s mandatory language requirements.

Selecting an appropriate temperature measurement system can be a daunting task given the wide variety of operating principles, measurement precision, and costs of commercial products. Whether temperature measurements are under laboratory or field conditions, selecting the temperature measurement system should be based on the required measurement accuracy and dynamic response. Once a temperature measurement system has been selected, the user may need to consult with the source regarding installation specifics, operating range limits, and calibration limits to obtain the expected measurement accuracy.

1. PURPOSE

This standard prescribes methods for measuring temperature under laboratory and field conditions.

2. SCOPE

2.1 This standard applies to temperature measurements under laboratory and field conditions for use in performance testing heating, ventilating, air-conditioning, and refrigeration systems and components.

2.2 This standard does not apply to wet-bulb and dew-point temperature measurement methods within the scope of ANSI/ASHRAE Standard 41.6.

3. DEFINITIONS

accuracy: the degree of conformity of an indicated value to the corresponding true value.

(Informative Note: Accuracy is a term sometimes used by instrument manufacturers to represent instrument uncertainty.)

the difference between the observed value of the measurand and its corresponding true value.

measurement system: the instruments, signal conditioning systems, if any, and data acquisition system, if any.

operating tolerance limit: the upper or lower value of an operating tolerance that is associated with a test point or a targeted set point.
post-test uncertainty: an analysis to establish the uncertainty of a test result after conducting the test.

pretest uncertainty: an analysis to establish the expected uncertainty interval for a test result before conducting the test.

random error: the portion of the total error that varies randomly in repeated measurements of the true value throughout a test process.

steady-state criteria: the criteria that establish negligible change of temperature or temperature difference with time.

systematic error: the portion of the total error that remains constant in repeated measurements of the true value throughout a test process.

targeted set point: a specific set of test conditions where the required temperature or temperature difference is known and has an associated operating tolerance.

test point: a specific set of test operating conditions for recording data where the measured required temperature or temperature difference unknown and has an associated operating tolerance.

true value: the unknown, error-free value of a test result.

uncertainty: the limits of error within which the true value lies for specified confidence level.

unit under test: equipment that is subjected to temperature or temperature difference measurement.

4. CLASSIFICATIONS

4.1 Temperature and Temperature Difference Measurement Conditions. Temperature and temperature difference measurement test conditions that are within the scope of this standard shall be classified as one of the following types:

4.1.1 Laboratory Conditions. Laboratory temperature and temperature difference measurements under laboratory conditions are engineering development tests or tests to determine product performance.

(Informative Note: Laboratory temperature and temperature difference measurements tend to use more accurate instruments than field measurements.)

4.1.2 Field Conditions. Temperature and temperature difference measurements under field conditions are tests to determine installed system temperatures and temperature differences.

(Informative Note: Field temperature and temperature difference measurements tend to use less accurate instruments than laboratory measurements.)
4.2 Temperature Measurement Methods. Temperature measurement methods that are within the scope of this standard are the methods listed in Table 4-1.

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5. REQUIREMENTS

5.1 Test Plan. The test plan shall be one of the following options:
   a. A document provided by the person or the organization that authorized the tests.
   c. A rating standard.
   d. A regulation or code.
   e. Any combination of items a. through d.

The test plan shall specify:
   a. The maximum allowable value for either the accuracy or the measurement uncertainty of the temperature or temperature difference measurement system.
   b. The values to be determined and recorded are selected from this list: temperature measurements, temperature measurements pretest uncertainty, temperature measurements post-test measurements uncertainty, temperature difference measurements, difference measurements pretest uncertainty, and temperature difference measurements post-test uncertainty.
   c. Any combination of test points and targeted set points to be performed together with operating tolerances.

5.2 Values to be Determined and Reported

The values that are specified in the test plan in Section 5.1 shall be determined and recorded. Unless otherwise specified in the test plan, temperature measurements, temperature difference measurements, temperature measurement uncertainties, and temperature difference measurement uncertainties, shall be reported as °C (°F).

5.3 Test Requirements

5.3.1 Accuracy or Measurement Uncertainty. A selected temperature or temperature difference measurement system accuracy or measurement uncertainty shall meet or exceed the required temperature measurement system accuracy or measurement uncertainty specified in the test plan in Section 5.1 over the full range of operating conditions.
5.3.2 Pretest Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected uncertainty for each temperature or temperature difference test point prior to the conduct of that test in accordance with the pretest uncertainty analysis procedures in ASME PTC 19.1.

5.3.3 Post-test Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected liquid flow measurement uncertainty for each temperature or temperature difference test point in accordance with the post-test uncertainty analysis procedures in ASME PTC 19.1. Alternatively, if specified in the test plan, the worst-case uncertainty for all test points shall be estimated and reported for each test point.

5.3.4 Steady-State Test Criteria. Temperature and temperature difference test data shall be recorded at steady-state conditions unless otherwise specified in the test plan in Section 5.1.

5.3.4.1 Steady-State Test Criteria for Temperature Measurements Under Laboratory Test Conditions. If the test plan requires temperature or temperature difference test data points to be recorded at steady-state test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, then determine that steady-state test conditions have been achieved using one of the following methods:

a. Apply the steady-state criteria in Section 5.3.4.3 if the test plan provides test points for temperature measurement.

b. Apply the steady-state criteria in Section 5.3.4.4 if the test plan provides test points for temperature difference measurement.

c. Apply the steady-state criteria in Section 5.3.4.5 if the test plan provides targeted set points for temperature measurement.

d. Apply the steady-state criteria in Section 5.3.4.6 if the test plan provides targeted set points for temperature difference measurement.

5.3.4.2 Steady-State Test Criteria for Temperature or Temperature Difference Under Field Test Conditions. If the test plan requires test data points to be recorded at steady-state test conditions and provides the operating condition tolerance but does not specify the steady-state criteria, the methods in Section 5.3.4.1 are optional.

(Informative Note: The steady-state methods in Section 5.3.4.1 are likely to be impractical under field test conditions. Section 5.3.5 provides instructions for making measurements that are not at steady state conditions.

5.3.4.3 Steady-State Temperature Criteria for Test Points

Starting with the time set to zero, sample not less than 30 temperature measurements \( N \) at equal time intervals \( \delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-1 states the relationship of the test duration to the number of temperature samples and the equal time intervals.

\[
\Delta t = (N - 1)\delta t \quad (5-1)
\]

(Informative Note: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed temperature difference fluctuations during operation near the steady-state conditions.)

Record each sampled temperature measurement \( T_i \) and the corresponding time \( t_i \). Apply the least-squares line method to determine the slope \( b \) of the temperature data trend line using Equation 5-2.
5.3.4.4 Steady-State Temperature Difference Criteria for Test Points

Starting with the time set to zero, sample not less than 30 temperature difference measurements \( N \) at equal time intervals \( \delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-6 states the relationship of the test duration to the number of samples and the equal time intervals.

\[
\Delta t = (N - 1) \delta t
\]  

(Informative Notes: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed temperature difference fluctuations during operation near the steady-state conditions.)

Record each sampled temperature difference measurement \( \Delta T_i \) and the corresponding time, \( t_i \). Apply the least-squares line method to determine the slope \( b \) of the temperature difference data trend line using Equation 5-7.

\[
b = \left\{ \frac{[N(\Sigma_{i=1}^{N} t_i \Delta T_i) - (\Sigma_{i=1}^{N} t_i)(\Sigma_{i=1}^{N} \Delta T_i)]}{[N(\Sigma_{i=1}^{N} t_i^2) - (\Sigma_{i=1}^{N} t_i)^2]} \right\}
\]  

(Informative Note: It should be noted that the units for the slope in Equation 5-7 are temperature difference, °C (°F), divided by the units that the user has selected for time.)

The mean of the sampled temperature differences, \( \overline{\Delta T} \), is defined by Equation 5-8.
The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-9 where $\Delta T_L$ is the operating tolerance limit.

$$\Delta T_{max} - \Delta T_{min} \leq \Delta T_L \quad ^\circ \text{C} (^\circ \text{F})$$  \hspace{1cm} (5-9)

The restriction on the slope of the trend line $b$ is defined in Equation 5-10 where $\Delta t$ is the sample time interval.

$$|b \times \Delta t| \leq 0.5 \times \Delta T_L \quad ^\circ \text{C} (^\circ \text{F})$$  \hspace{1cm} (5-10)

$\overline{\Delta T}_L$ as determined by Equation 5-8, represents the steady-state mean temperature difference where Equations 5-9 and 5-10 are both satisfied.

*(Informative Note: For further reading about this method of determining steady-state conditions, refer to Informative Appendix A, References A1 and A2.)*

### 5.3.4.5 Steady-State Temperature Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 temperature difference measurements $N$ at equal time intervals $\delta t$ over a test duration $\Delta t$ where $\Delta t$ is in time units. Equation 5-11 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t$$  \hspace{1cm} (5-11)

*(Informative Notes: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed temperature fluctuations during operation near the steady-state conditions.)*

Record each sampled temperature difference measurement $T_i$ and the corresponding time, $t_i$. Apply the least-squares line method to determine the slope $b$ of the temperature data trend line using Equation 5-12.

$$b = \frac{\left[ N \left( \sum_{i=1}^{N} t_i \bar{T} - \left( \sum_{i=1}^{N} t_i \right) \left( \sum_{i=1}^{N} T_i \right) \right) \right]}{\left[ N \left( \sum_{i=1}^{N} t_i^2 \right) - \left( \sum_{i=1}^{N} t_i \right)^2 \right]}$$  \hspace{1cm} (5-12)

*(Informative Note: It should be noted that the units for the slope in Equation 5-12 are temperature, $^\circ \text{C} (^\circ \text{F})$, divided by the units that the user has selected for time.)*

The mean of the sampled temperatures, $\bar{T}$, is defined by Equation 5-13.

$$\bar{T} = \frac{1}{N} \left[ \sum_{i=1}^{N} T_i \right] \quad ^\circ \text{C} (^\circ \text{F})$$  \hspace{1cm} (5-13)

The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-14 where $T_L$ is the operating tolerance limit.

$$T_{max} - T_{min} \leq T_L \quad ^\circ \text{C} (^\circ \text{F})$$  \hspace{1cm} (5-14)

The restriction on the slope of the trend line $b$ is defined in Equation 5-15 where $\Delta t$ is the sample time interval.
\[ |b \times \Delta t| \leq 0.5 \times T_L \quad ^\circ C (^\circ F) \quad (5-15) \]

The difference between the test condition and mean of the sampled values shall be less than or equal to half of the specified operating tolerance limit as defined in Equation 5-16 where \( T_{SP} \) is the set point temperature difference and \( T_L \) is the operating tolerance limit.

\[ |T_{SP} - \bar{T}| \leq 0.5 \times T_L \quad ^\circ C (^\circ F) \quad (5-16) \]

\( \bar{T} \), as determined by Equation 5-13, represents the steady-state mean temperature difference where Equations 5-14, 5-15, and 5-16 are all satisfied.

*(Informative Note: For further reading about this method of determining steady-state conditions, refer to Informative Appendix A, References A1 and A2.)*

### 5.3.4.6 Steady-State Temperature Difference Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 temperature difference measurements \( N \) at equal time intervals \( \delta t \) over a test duration \( \Delta t \) where \( \Delta t \) is in time units. Equation 5-16 states the relationship of the test duration to the number of samples and the equal time intervals.

\[ \Delta t = (N - 1)\delta t \quad (5-16) \]

*(Informative Notes: Circumstances for measurement vary, so the user should select a duration of test and the equal time intervals based upon the longest period of the observed temperature difference fluctuations during operation near the steady-state conditions.)*

Record each sampled temperature difference measurement \( \Delta T_i \) and the corresponding time, \( t_i \). Apply the least-squares line method to determine the slope \( b \) of the temperature difference data trend line using Equation 5-17.

\[
    b = \left\{ \frac{N(\sum_{i=1}^{N} t_i \Delta T_i) - (\sum_{i=1}^{N} t_i)(\sum_{i=1}^{N} \Delta T_i)}{N(\sum_{i=1}^{N} t_i^2) - (\sum_{i=1}^{N} t_i)^2} \right\} \quad (5-17)
\]

*(Informative Note: It should be noted that the units for the slope in Equation 5-17 are temperature difference, \( ^\circ C (^\circ F) \), divided by the units that the user has selected for time.)*

The mean of the sampled temperature differences \( \overline{\Delta T} \) is defined by Equation 5-18.

\[ \overline{\Delta T} = \frac{1}{N} \left( \sum_{i=1}^{N} (T_i) \right) \quad ^\circ C (^\circ F) \quad (5-18) \]

The difference between the maximum and minimum sampled values shall be less than or equal to the specified operating tolerance limit as defined in Equation 5-18 where \( \Delta T_L \) is the operating tolerance limit.

\[ \Delta T_{\text{max}} - \Delta T_{\text{min}} \leq \Delta T_L \quad ^\circ C (^\circ F) \quad (5-19) \]

The restriction on the slope of the trend line \( b \) is defined in Equation 5-20 where \( \Delta t \) is the sample time interval.

\[ |b \times \Delta t| \leq 0.5 \times \Delta T_L \quad ^\circ C (^\circ F) \quad (5-20) \]
The difference between the test condition and mean of the sampled values shall be less than or equal to half of the specified operating tolerance limit as defined in Equation 5-21 where \( \Delta T_{SP} \) is the set point temperature difference and \( T_L \) is the operating tolerance limit.

\[
|\Delta T_{SP} - \overline{\Delta T}| \leq 0.5 \times \Delta T_L \quad \text{°C (°F)}
\]

\( \overline{\Delta T} \), as determined by Equation 5-18, represents the steady-state mean temperature difference where Equations 5-18, 5-20, and 5-21 are all satisfied.

**Informative Note:** For further reading about this method of determining steady-state conditions, refer to Informative Appendix A, References A1 and A2.)

### 5.3.5 Unsteady Temperature Measurements

If required by the test plan in Section 5.1, temperature and temperature difference test data shall be recorded:

a. at operating conditions that are not steady state,
b. at the time intervals specified in the test plan,
c. within the test condition limits specified in the test plan, and
d. using instrument response times specified in the test plan.

### 5.3.6 Thermowells

A thermowell consists of a tube closed at one end that is chemically compatible with the selected sensor materials. ASME PTC 19.3 TW2 provides descriptions and application specifics for thermowells. Thermowells shall be used in fluid temperature measurement applications where the selected temperature sensors are not mechanically or chemically compatible with the fluid.

### 6. INSTRUMENTS

#### 6.1 Instrumentation Requirements for All Measurements

6.1.1 Instruments and data acquisition systems shall be selected to meet the measurement system accuracy specified in the test plan in Section 5.1.

6.1.2 Measurements from the instruments shall be traceable to primary or secondary standards calibrated by the National Institute of Standards and Technology (NIST) or to the Bureau International des Poids et Mesures (BIPM) if a National Metrology Institute (NMI) other than NIST is used. In either case, the indicated corrections shall be applied to meet the uncertainty stated in subsequent sections. Instruments shall be recalibrated on regular intervals that do not exceed the intervals prescribed by the instrument manufacturer, and calibration records shall be maintained. Instruments shall be installed in accordance with the instrument manufacturer’s requirements, or the manufacturer’s accuracy does not apply.

### 7. TEMPERATURE MEASUREMENT METHODS

#### 7.1 Liquid-In-Glass Thermometers

A liquid-in-glass thermometer is a direct-reading thermometer that consists of a sealed glass enclosure that is partially filled with a liquid with a reservoir, called a sensing bulb, on one end. Immersing the sensing bulb into a fluid that is at a temperature different from the sensing bulb temperature causes the trapped liquid to change to occupy a greater or lesser portion of the interior volume of the glass. The glass tube is either marked in temperature units or is mounted onto a plate that is marked in temperature units. Follow
the specific installation and operating instructions provided by the source of the selected liquid-in-glass thermometer.

(*Informative Note:* See Informative Appendix C Section C1 for supplemental information.)

### 7.2 Thermocouples

A thermocouple consists of two wires made of different metals that are joined at one end, and that end is positioned where temperature is to be measured. The other end is electrically connected to an object, called a reference junction, that is maintained at a specific temperature. The relationship of the electrical voltage measured at the reference junction to the sensed temperature for alternative metal wire pairs are provided in references³,⁴.

(*Informative Note:* See Informative Appendix C Section C2 for supplemental information.)

### 7.3 Resistance Temperature Detectors

Resistance temperature detectors (RTDs) are temperature sensors that contain a resistor that changes resistance value as a function of temperature changes. The metals that are used as the resistor element in RTDs include platinum, nickel copper, and nickel-iron. RTDs with platinum resistors are applied at temperatures ranging up to 850°C (1560°F). Temperature measurement using RTDs involves measuring resistance and correlating the measured resistance to the corresponding temperature.

Equation 7-1 shows the resistance of the RTD as a function of the reference resistance, the temperature coefficient, and the sensed temperature.

\[
R_\text{t} = R_0 \times (1 + \alpha \times T)
\]  

(7-1)

where

- \( R_\text{t} \) = measured RTD resistance at the sensed temperature, \( \Omega \) (\( \Omega \)) at °C (°F)
- \( R_0 \) = reference resistance at a reference temperature, \( \Omega \) (\( \Omega \)) at °C (°F)
- \( \alpha \) = temperature coefficient, \( \Omega/\Omega \) °C (\( \Omega/\Omega \) °F)
- \( T \) = sensed temperature, °C (°F).

(*Informative Note:* See Informative Appendix C Section C3 for supplemental information. Follow the specific installation and use instructions provided by the source of the selected RTD thermometer.)

### 7.4 Thermistors

Thermistors are temperature sensors that have a resistance that is a function of temperature. The mathematic model for thermistor temperature-resistance curves is the Steinhart-Hart equation⁶ that is provided in Equation 7-2:

\[
\frac{1}{T} = a \times b \times (\ln R) + c + (\ln R)^3
\]  

(7-2)

where

- \( T \) = measured temperature, K
- \( a \) = first coefficient, dimensionless
- \( b \) = second coefficient, dimensionless
Follow the specific installation and operating instructions provided by the source of the selected thermistor.

*(Informative Note: See Informative Appendix C Section C4 for supplemental information.)*

### 7.5 Radiation Pyrometers

Radiation pyrometers are used to measure surface temperature without contacting the surface by detecting electromagnetic radiation emitted from a flat surface in the visible and infrared portions of the electromagnetic spectrum. Radiation pyrometers include optical pyrometers, thermal sensing pyrometers, and photon sensing pyrometers.

A disappearing-filament optical pyrometer consists of a lens system that includes a heated filament wire. In operation, the direct-current voltage to the heated filament is adjusted until the optical brightness of the heated filament matches the brightness of the surface causing the filament wire to become indistinguishable from the surface. Through calibration, the measured direct-current voltage is correlated to the surface temperature of the surface.

One variation of a thermal sensing pyrometer uses a lens system to focus the electromagnetic radiation emitted from the measured surface onto a thermopile. Through calibration, the measured direct-current voltage from the thermopile is correlated to the temperature of the surface.

Photon sensing pyrometers use a lens system to focus the electromagnetic radiation emitted from the measured surface onto a photodetector. Through calibration, the measured electrical signal from the photodetector is correlated to the temperature of the surface.

*(Informative Note: See Informative Appendix C Section C2.6 for a description of thermopiles, and see Informative Appendix C Section C5 for supplemental information regarding radiation pyrometers.)*

### 7.6 Solid-State Temperature Measurement Sensors

Solid-state temperature sensors use a diode or voltage reference that has an established voltage versus temperature characteristic together with signal-processing electronics to generate a voltage or current output that is proportional to temperature. Follow the specific installation and operating instructions provided by the source of the selected solid-state thermometer sensor.

*(Informative Note: Solid state sensors are commonly packaged within electronic equipment that includes signal conditioning and other measuring circuits.)*

### 7.7 Bimetal Thermometers

If two strips of metal A and B with different thermal expansion coefficients $\alpha_A$ and $\alpha_B$ but at the same temperature are bonded together, a temperature change causes different expansion and the strip, if unrestrained, will deflect into a uniform circular arc. Bimetallic sensors that use this principle by using bimetallic that, before being subjected to a temperature change are in various geometries including spiral, helix, and U-shape. Figure 7-1 shows a schematic of a bimetallic thermometer that uses a spiral shape.
7.8 Pressure Thermometers

Pressure thermometers consist of a sensitive bulb, an interconnecting capillary tube, and a pressure-measuring device that include Bourdon tubes, bellows gauges, and diaphragm gauges as shown schematically in Figure 7-2.4

7.9 Method for Measuring the Temperature Rise in Motor Windings

This section describes a method for measuring the average temperature of the windings in a copper AC or DC motor by measuring electric resistance.

Before operating the motor, measure the resistance across the motor terminals after the motor temperature has stabilized at room temperature. Then operate the motor under load until the measured resistance reaches a steady-state condition in accordance with the criteria in Section 5.5. To calculate the average motor
windings temperature and the temperature rise during motor operation under load, use Equation 7-3 and Equation 7-4 for SI units or use Equations 7-5 and 7-6 for I-P units.

In SI units:

\[ T_{UL} = \frac{R_{UL}}{R_{RT}} (234.5 + T_{RT}) - 234.5 \]  
(7-3)

\[ \Delta T = T_{UL} - T_{RT} \]  
(7-4)

where

- \( T_{UL} \) = Average windings temperature under load, °C
- \( R_{UL} \) = Measured resistance under load, ohms
- \( R_{RT} \) = Measured resistance at room temperature, ohms
- \( T_{RT} \) = Windings temperature at room temperature, °C
- \( \Delta T \) = Temperature rise in the motor windings under load, K

In I-P units:

\[ T_{UL} = \frac{R_{UL}}{R_{RT}} (390.1 + T_{RT}) - 390.1 \]  
(7-5)

\[ \Delta T = T_{UL} - T_{RT} \]  
(7-6)

where

- \( T_{UL} \) = Average windings temperature under load, °F
- \( R_{UL} \) = Measured resistance under load, ohms
- \( R_{RT} \) = Measured resistance at room temperature, ohms
- \( T_{RT} \) = Windings temperature at room temperature, °F
- \( \Delta T \) = Temperature rise in the motor windings under load, °R

*(Informative Note: This same method can be applied to measuring the average windings temperature and the temperature rise in transformers operating under load.)*

8. UNCERTAINTY REQUIREMENTS

8.1 Post-Test Uncertainty Analysis. A post-test analysis of the measurement system uncertainty, performed in accordance with ASME PTC 19.1\(^1\), shall accompany each temperature and temperature difference measurement if specified in the test plan in Section 5.1. Installation effects on the accuracy of the instrument shall be included in the uncertainty analysis for each installation that does not conform to the instrument manufacturer’s installation requirements.

*(Informative Note: An example of temperature measurement uncertainty calculations is provided in Informative Appendix B.)*

8.2 Method to Express Uncertainty
All assumptions, parameters, and calculations used in estimating uncertainty shall be clearly documented prior to expressing any uncertainty values. Uncertainty shall be expressed as shown in Equation 8-1:

\[ v = \bar{X}_m \pm U_{\bar{X}} (P\%) \]  

where:
- \( v \) = the variable that is a measurement or a calculated result
- \( \bar{X}_m \) = the best estimate of the true value
- \( U_{\bar{X}} \) = the uncertainty estimate for the variable
- \( P \) = the confidence level, %

*Informative Note:* For example, temperature measurement = 23.4°C ± 0.974°C (74.1°F ± 1.78°F); 95% states that the measured temperature is believed to be 23.4°C (74.1°F) with a 95% probability that the true value lies within ± 0.97 °C (±1.78°F) of this value.

9. TEST REPORT

If the test plan in Section 5.1 defines the test report requirements, the test report requirements in the test plan supersede the test requirements in Section 9. Otherwise, Section 9 specifies the test report requirements.

9.1 Test Identification
- a. Date, place, and time.

9.2 Unit Under Test Description
- a. Model number and serial number.

9.3 Instrument Description
- a. Temperature or temperature difference sensor description, model number, serial number, and location within the UUT.
- b. Operating range.
- c. Instrument accuracy based on specifications or calibration.
- d. Documentational evidence of instrument calibrations.

9.4 Measurement System Description
- a. Description of instrument installation specifics.
- b. Measurement system accuracy based on specifications or calibration.
- c. Documentational evidence of measurement system calibrations.

9.5 Test Conditions
- a. Test conditions in accordance with the test plan in Section 5.1
- b. Ambient temperature, °C (°F).
- c. Barometric pressure Pa, (psia) if pressure instruments are measuring gauge pressure.

9.6 Test Results if Required by the Test Plan in Section 5.1
- a. Temperature, °C (°F).
- b. Pretest uncertainty of temperature measurement, °C (°F).
- c. Post-test uncertainty of temperature measurement, °C (°F).
- d. Temperature difference, °C (°F).
f. Pretest uncertainty in temperature difference, °C (°F).
g. Post-test uncertainty in temperature difference, °C (°F).

10. REFERENCES


(Informative Notes:
  a. Reference 2 is only required if thermowells are included in the thermocouple temperature measurement.
  b. Reference 3 is only required if thermocouples are used for the temperature measurement.
  c. Reference 4 is only required if solid state devices, bimetallic thermometers, or pressure thermometers are used for the temperature measurement.)
(This appendix is not part of this standard. It is merely informative and does not contain requirements necessary for conformance to the standard. It has not been processed according to the ANSI requirements for a standard and contains material that has not been subject to public review or a consensus process. Unresolved objectors on informative material are not offered the right to appeal at ASHRAE or ANSI.)

INFORMATIVE APPENDIX A: BIBLIOGRAPHY


INFORMATIVE APPENDIX B: EXAMPLE OF AN UNCERTAINTY ESTIMATE FOR A TEMPERATURE MEASUREMENT WITH AN RTD

This example uses ASME PTC 19.11 to establish a framework for estimating the systematic standard uncertainty ($b_r$) of the temperature measured by an RTD. Where the result ($R$) is a function of independent parameters. For this example, $b_r = \Delta T$ and, $R = T$. Note that, in general, using a commercial equation solver software significantly reduces the time and effort required to complete an uncertainty analysis. Note that, in general, using a commercial equation solver software, such as MATLAB or EES, significantly reduces the time and effort required to complete an uncertainty analysis.

TABLE B-1 Parameter Descriptions for this Example

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_t$</td>
<td>Resistance of the RTD</td>
<td>$\Omega$ ($\Omega$ at °C (°F))</td>
</tr>
<tr>
<td>$R_0$</td>
<td>Reference Resistance</td>
<td>$\Omega$ ($\Omega$ at °C (°F))</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Temperature Coefficient</td>
<td>$\Omega/\Omega$ °C ($\Omega/\Omega$ °F)</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>°C (°F)</td>
</tr>
</tbody>
</table>

B1. DERIVE THE UNCERTAINTY EQUATION

Equation B-1 relates the electrical resistance of a Resistance Temperature Detector (RTD) to the temperature that the RTD is sensing.

$$R_t = R_0 \times (1 + \alpha \times T) \quad (B-1)$$

Rearranging Equation B-1 to solve for $T$ yields Equation B-2

$$T = (R_t - R_0)/(\alpha \times R_0) \quad (B-2)$$

Equation B-2 can be expressed generally as shown in Equation B-3.

$$T = f(R_t, R_0, \alpha) \quad (B-3)$$

In ASME PTC 19.11, the contribution of each parameter is defined as the systematic standard uncertainty of the parameter [$\Delta( )$] multiplied by the sensitivity coefficient $\frac{\partial T}{\partial ( )}$ and then squared. Applying the uncertainty equation to Equation B-3 yields Equation B-4:
\[ \Delta T = \left[ \left( \Delta R_t \times \frac{\partial T}{\partial R_t} \right)^2 + \left( \Delta R_o \times \frac{\partial T}{\partial R_o} \right)^2 + \left( \Delta \alpha \times \frac{\partial T}{\partial \alpha} \right)^2 \right]^{1/2} \]  

(B-4)

Calculating the partial differentials of T with respect to each of the variables gives:

\[ \frac{\partial T}{\partial R_t} = -\frac{1}{(\alpha \times R_o)} \]  

(B-5)

\[ \frac{\partial T}{\partial R_o} = -\frac{R_t}{(\alpha \times R_o^2)} \]  

(B-6)

\[ \frac{\partial T}{\partial \alpha} = \frac{(R_o - R_t)}{(\alpha \times R_o^2)} \]  

(B-7)

Substituting Equations B-5, B-6, and B-7 into Equation B-4 yields Equation B-8.

\[ \Delta T = \left[ \left( \frac{\Delta R_t}{\alpha \times R_o} \right)^2 + \left( \frac{-R_t \Delta R_o}{\alpha \times R_o^2} \right)^2 + \left( \frac{\Delta \alpha (R_o - R_t)}{(\alpha \times R_o^2)} \right)^2 \right]^{1/2} \]  

(B-8)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Description</th>
<th>Value</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{t1} )</td>
<td>Resistance of the RTD</td>
<td>100 ( \Omega ) (( \Omega )) at 0(^\circ)C (32(^\circ)F)</td>
<td>± 0.004 ( \Omega )</td>
</tr>
<tr>
<td>( R_{t2} )</td>
<td>Resistance of the RTD</td>
<td>113.7375 ( \Omega ) (( \Omega )) at 35(^\circ)C (95(^\circ)F)</td>
<td>± 0.004 ( \Omega )</td>
</tr>
<tr>
<td>( R_{01} )</td>
<td>Reference Resistance</td>
<td>100 ( \Omega ) (( \Omega )) at 0(^\circ)C (32(^\circ)F)</td>
<td>± 0.0001925 ( \Omega )</td>
</tr>
<tr>
<td>( R_{02} )</td>
<td>Reference Resistance</td>
<td>100 ( \Omega ) (( \Omega )) at 0(^\circ)C (32(^\circ)F)</td>
<td>± 0.375 ( \Omega )</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Temperature Coefficient</td>
<td>0.00385 ( \Omega/\Omega^\circ)C (0.001925 ( \Omega/\Omega^\circ)F)</td>
<td>± 0.000001 ( \Omega/\Omega^\circ)C (± 0.000005 ( \Omega/\Omega^\circ)F)</td>
</tr>
</tbody>
</table>

### B2. COMPUTE THE UNCERTAINTY FOR APPLICATION 1

Application 1: High accuracy instrument where \( \Delta R_{01} = \pm 0.0001925 \Omega \)

**B2.1 Evaluation at \( R_{t1} = 100 \text{ ohm at } 0^\circ\text{C in SI Units} \)**

\[ \Delta T_{R_{t1}} = \left[ \left( \frac{0.004}{0.00385 \times 100} \right)^2 + \left( \frac{-100 \times 0.0001925}{0.00385 \times 100^2} \right)^2 + \left( \frac{0.000001 \times (100-100)}{0.00385^2 \times 100} \right)^2 \right]^{1/2} \]  

(B-9)

\[ \Delta T_{R_{t1}} = \pm 0.010^\circ\text{C} \]  

(B-10)

Uncertainty contribution by term:

\[ R_{t1 \text{ term}} = 99.77\% \]  

(B-11)
\[ R_{0_1 \text{ term}} = 0.23\% \]  
\[ \alpha \text{ term} = 0\% \]  

**B2.2 Evaluation at \( R_{t_1} = 100 \text{ ohm at } 32^\circ\text{F in I-P units} \)**

\[
\Delta T_{R_{t_1}} = \left[ \left( \frac{0.004}{0.00192 \times 100} \right)^2 \right. 
+ \left. \left( -\frac{100 \times 0.0001925}{0.00192 \times 100^2} \right)^2 \right. 
+ \left. \left( \frac{0.000005 \times (100 - 100)}{0.00192^2 \times 100} \right)^2 \right]^{1/2} 
\]  
\[ \Delta T_{R_{t_1}} = \pm 0.002^\circ\text{F} \]  

Uncertainty contribution by term:

\[ R_{t_1 \text{ term}} = 99.77\% \]  
\[ R_{0_1 \text{ term}} = 0.23\% \]  
\[ \alpha \text{ term} = 0\% \]  

**B2.3 Evaluation at \( R_{t_2} = 113.7375 \text{ ohm at } 35^\circ\text{C in SI units} \)**

\[
\Delta T_{R_{t_2}} = \left[ \left( \frac{0.004}{0.00385 \times 100} \right)^2 \right. 
+ \left. \left( -\frac{113.7375 \times 0.0001925}{0.00385 \times 100^2} \right)^2 \right. 
+ \left. \left( \frac{0.000001 \times (100 - 113.7375)}{0.00385^2 \times 100} \right)^2 \right]^{1/2} 
\]  
\[ \Delta T_{R_{t_2}} = \pm 0.014^\circ\text{C} \]  

Uncertainty contribution by term:

\[ R_{t_2 \text{ term}} = 55.59\% \]  
\[ R_{0_1 \text{ term}} = 0.17\% \]  
\[ \alpha \text{ term} = 44.24\% \]  

**B2.4 Evaluation at \( R_{t_2} = 113.7375 \text{ ohm at } (95^\circ\text{F}) \text{ in I-P units} \)**

\[
\Delta T_{R_{t_1}} = \left[ \left( \frac{0.004}{0.00192 \times 100} \right)^2 \right. 
+ \left. \left( -\frac{113.7375 \times 0.0001925}{0.00192 \times 100^2} \right)^2 \right. 
+ \left. \left( \frac{0.000005 \times (100 - 113.8575)}{0.00192^2 \times 100} \right)^2 \right]^{1/2} 
\]  
\[ \Delta T_{R_{t_2}} = \pm 0.028^\circ\text{F} \]  

Uncertainty contribution by term:

\[ R_{t_2 \text{ term}} = 55.03\% \]  
\[ R_{0_1 \text{ term}} = 0.17\% \]  
\[ \alpha \text{ term} = 44.80\% \]
The uncertainty is heavily weighted towards the RTD the closer to the reference temperature the measurement is.

**B3. COMPUTE THE UNCERTAINTY FOR APPLICATION 2**

Application 2: Low accuracy reference instrument \( \Delta R_{02} = \pm 0.375 \, \Omega (\pm 0.0003465 \, \Omega) \)

**B3.1 Evaluation at \( R_{t1}=100 \, \Omega \) at 0℃ in SI units**

\[
\Delta T_{R_{t1}} = \left[ \left( \frac{0.004}{0.00385 \times 100} \right)^2 + \left( \frac{-100 \times 0.375}{0.00385 \times 100^2} \right)^2 + \left( \frac{0.000001 \times (100-100)}{0.00385^2 \times 100} \right)^2 \right]^{1/2} \quad (B-29)
\]

\[
\Delta T_{R_{t1}} = \pm 0.974^\circ C \quad (B-30)
\]

Uncertainty contribution by term:

- \( R_{t1} \) term = 0.011% \quad (B-31)
- \( R_{02} \) term = 99.99% \quad (B-32)
- \( \alpha \) term = 0% \quad (B-33)

**B3.2 Evaluation at \( R_{t1}=100 \, \Omega \) at 32℃ in I-P units**

\[
\Delta T_{R_{t1}} = \left[ \left( \frac{0.004}{0.00385 \times 100} \right)^2 + \left( \frac{-100 \times 0.375}{0.00385 \times 100^2} \right)^2 + \left( \frac{0.000005 \times (100-100)}{0.00192^2 \times 100} \right)^2 \right]^{1/2} \quad (B-34)
\]

\[
\Delta T_{R_{t1}} = \pm 1.953^\circ F \quad (B-35)
\]

Uncertainty contribution by term:

- \( R_{t1} \) term = 0.01% \quad (B-36)
- \( R_{02} \) term = 99.99% \quad (B-37)
- \( \alpha \) term = 0% \quad (B-38)

**B3.3 Evaluation at \( R_{t2}=113.7375 \, \Omega \) at 35℃ in SI Units**

\[
\Delta T_{R_{t2}} = \left[ \left( \frac{0.004}{0.00385 \times 100} \right)^2 + \left( \frac{-113.7375 \times 0.375}{0.00385 \times 100^2} \right)^2 + \left( \frac{0.000001 \times (100-113.7375)}{0.00385^2 \times 100} \right)^2 \right]^{1/2} \quad (B-39)
\]

\[
\Delta T_{R_{t2}} = \pm 1.108^\circ C \quad (B-40)
\]

Uncertainty contribution by term:

- \( R_{t2} \) term = 0.01% \quad (B-41)
\[ R_{0z \text{ term}} = 99.98\% \]  
\[ \alpha \text{ term} = 0.01\% \]

**B3.4 Evaluation at \( R_{t2} = 113.7375 \text{ ohm at 95°F in I-P Units} \)**

\[
\Delta T_{R_{t2}} = \left[ \left( \frac{0.004}{0.00192 \times 100} \right)^2 + \left( \frac{-100 \times 0.375}{0.00192 \times 100^2} \right)^2 + \left( \frac{0.000005 \times (100 - 113.737)}{0.00192^2 \times 100} \right)^2 \right]^{1/2} \]  
\[ B-44 \]

\[ \Delta T_{R_{t2}} = \pm 2.222 \text{ °F} \]  
\[ B-45 \]

Uncertainty contribution by term:

\[ R_{t2 \text{ term}} = 0.01\% \]  
\[ R_{0z \text{ term}} = 99.98\% \]  
\[ \alpha \text{ term} = 0.01\% \]

Here, the uncertainty is dominated by the low accuracy of the RTD sensor.

The accuracy of the reader is just as important as the accuracy of the RTD sensor.
INFORMATIVE APPENDIX C:
SUPPLEMENTAL INFORMATION REGARDING
TEMPERATURE MEASUREMENT METHODS

C1. LIQUID-IN-GLASS THERMOMETERS

C1.1 The liquid-in-glass thermometer is a direct reading temperature instrument. It should be so placed that its indication measures the temperature at the location intended, while at the same time it should be accessible for reading. Typical accuracy for liquid-in-glass thermometers is equal to one half of the smallest scale division.

C1.2 Precautions are necessary to ensure that heat from the body of the reader, an electric lamp, or from other extraneous sources does not affect the reading.

C1.3 Glass thermometers should not be inserted directly into a conduit conveying fluid unless calibration corrections are applied to compensate for pressure effects. For such measurements, the thermometer should be inserted into a thermometer well inserted into the conduit.

C1.4 Glass thermometers require correction for depth of immersion and for the temperature of the ambient around the stem. This is the emergent stem correction.

C1.5 Glass thermometers require correction for orientation. For example, a glass thermometer inserted upside down in an air duct reads high by as much as 0.05°C (0.10°F).

C1.6 Glass thermometers are comparatively simple to interchange between two positions for alternate readings in order to obtain an average temperature difference reading that is unaffected by the calibration of the thermometers.

C1.6 Liquid-in-glass thermometers should not be used for transient temperature measurements.

C2. THERMOCOUPLES

C2.1 Thermocouple Operating Principle. In 1821, a German physicist named J.T. Seebeck took two dissimilar metals, with one at a higher temperature than the other, and constructed a series-type electrical circuit by joining the two dissimilar metals together to form a junction, and then measured an electromotive force (emf). Emfs are voltages. Seebeck found that the greater the temperature differences between the two dissimilar metals, the greater the generated voltage regardless of their shapes. His discovery, called the Seebeck effect, is the basis of thermocouple thermometry.

C2.2 Thermocouple Laws. There are five empirical fundamental laws for thermocouple circuits:

Law 1. The emf of a thermocouple depends only on the temperatures of the junctions and is independent of the temperatures of the wires connecting the junctions. This means that exposing the leads to temperature fluctuations will not change the measurement. See Figure C-1.
FIGURE C-1. Thermocouple Law 1

Law 2. The emf is not changed where a new conductor is introduced into one of the dissimilar metals provided that both new junctions are at the same temperature. This means that a voltmeter added to the circuit will not change the emf. See Figure C-2.

FIGURE C-2. Thermocouple Law 2

Law 3. If a third metal, C, is inserted at one of the junctions, the emf is unchanged provided that both new junctions are at the same temperature. This law allows us to put the voltmeter at the reference junction. See Figure C-3.

FIGURE C-3. Thermocouple Law 3
**Law 4.** The law of intermediate metals states that the emf of metals AC can be predicted if the emfs of metals AB and BC are known. See Figure C-4.

![FIGURE C-4. Thermocouple Law 4](image)

\[
E_{T_1 \rightarrow T_2}^{A/B} = E_{T_1 \rightarrow T_2}^{A/C} + E_{T_1 \rightarrow T_2}^{C/B}
\]

**Law 5.** The law of intermediate temperatures states that if two junctions at temperatures \(T_1\) and \(T_2\) produce voltage \(V_2\), and temperatures \(T_2\) and \(T_3\) produce voltage \(V_1\), then temperatures \(T_1\) and \(T_3\) will produce a voltage \(V_3 = V_1 + V_2\). See Figure C-5.

![FIGURE C-5. Thermocouple Law 5](image)

\[
E_{T_1 \rightarrow T_2}^{A/B} = E_{T_1 \rightarrow T_2}^{A/B} + E_{T_2 \rightarrow T_3}^{A/B}
\]

**C2.3 Basic Thermocouple Circuit.** Thermocouples are connected to measuring instruments directly or using thermocouple extension wires. Figure C-6 shows a basic thermocouple circuit that includes extension wires. This circuit includes a reference junction that is maintained at a known temperature and a voltage-measuring device to measure the voltage generated by the thermocouple. Each of the components identified in Figure C-6 is a potential source of errors.
C2.4 Wire Splices. Best practice is to not splice thermocouple wires between the measuring junction and the reference junctions.

C2.5 Switches. If switches are used to alternately connect thermocouples to the reference junction, there should be no dissimilar metals in switching circuits unless isothermal conversion junctions are used to eliminate spurious thermocouple junctions in switch wiring.

C2.6 Series Thermocouple Circuits – Thermopiles. Multiple thermocouples are connected in series to increase the measurement sensitivity because the measured emf is the sum of the individual thermocouple emfs. Figure C-7 shows multiple thermocouples connected in series – this arrangement is called a thermopile. Sometimes a pair of thermopiles are used to make temperature difference measurements where thermocouples are the selected temperature measurement method.
C2.7 Parallel Thermocouple Circuits. Figure C-8 shows multiple thermocouples connected in parallel and connected to a common reference junction. This arrangement is often used to measure the average temperature at a single sensing location.
C2.8 Thermocouples Used for Temperature Measurements. Thermocouples used for temperature measurements in heating, ventilating, air-conditioning, and refrigeration include, but are not limited to, the types that are described in Table C-1.4

<table>
<thead>
<tr>
<th>Type</th>
<th>Alloy Combination</th>
<th>Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+ Lead</td>
<td>– Lead</td>
</tr>
</tbody>
</table>
| T    | Cu                | Cu-Ni                      | -200°C to +350°C  
-328°F to +662°F |
| K    | Ni-Cr             | Ni-Al-Si                   | -200°C to +1300°C  
-328°F to +2372°F |
| J    | Fe                | Cu-Ni                      | -150°C to +1000°C  
-328°F to +1832°F |
| E    | Ni-Cr             | Cu-Ni                      | -270°C to +1000°C  
-454°F to +1832°F |
| N    | Ni-Si             | Ni-Cr-Si                   | -200°C to +1300°C  
-328°F to +2372°F |
| R    | Pt-13%Rh          | Pt                         | 0°C to +1500°C  
32°F to +2732°F |
| S    | Pt-10%Pt          | Pt                         | 0°C to +1500°C  
32°F to +2732°F |

C2.9 Thermocouple Measuring Junction Configurations. The types of thermocouple measuring junction configurations shown in Figure C-9 are:

C2.9.1 Bare wire butt-welded and bare wire beaded configurations. Bare wire thermocouples inserted in a gas or liquid stream respond to temperature transients more rapidly than insulated junctions. Exposed thermocouple wires are more prone to corrosion and degradation than ungrounded or grounded junctions. Bare wire junctions are constructed by welding or silver brazing. Soft solder is an alternative to silver braze on copper-constantan thermocouples that are subjected to temperatures that are not high enough to compromise the mechanical joint strength.

C2.9.2 Insulated (ungrounded) configuration. Ungrounded thermocouple wires are welded together but insulated from the sheath. The wires are often separated by mineral insulation.

C2.9.3 Grounded configuration. In grounded thermocouples, the measuring junction and the sheath are welded together to form one junction at the tip. Grounded thermocouples respond to temperature transients more rapidly than ungrounded thermocouples. However, grounded thermocouples are more susceptible to electrical interference than ungrounded thermocouples.
C2.10 Best Practice Thermocouple Installation Guidelines.

C2.10.1 For each UUT application, construct all thermocouples to have the same length of lead wires and extension wires so that the electric resistance is the same in each thermocouple circuit.

C2.10.2 Test each thermocouple by moving a heat source not greater than 93°C (200°F) along each wire before the thermocouple is installed into the test setup. Replace any thermocouple that has a measurable emf during this test because a measurable emf during this test indicates that the thermocouple is inhomogeneous.

C2.10.3 Before installing any thermocouple into the test setup, immerse each thermocouple into a known temperature liquid bath to calibrate the measurement system. If this *in situ* test is not practical, include the uncertainties for each of the measurement system elements uncertainties in the uncertainty estimates.

C2.10.4 Each thermocouple used to detect surface temperatures shall have the measuring junction attached directly to the surface with the lead wires and extension wires electrically insulated.

C2.10.5 Methods for attaching thermocouples to a surface include embedding, taping, spot-welding, soldering, and magnetic clamps.

C2.11 Potential Thermocouple Errors

C2.11.1 To minimize such errors, the thermocouple wire should be taped to the metal surface for a minimum of 25 mm (1 in.) so that the portion of the wire in the vicinity of the junction is kept at surface temperature.
C2.11.2 There should be no thermal insulation between the wires and surface, but the two wires must not contact each other at any other point except at the cold junction.

C2.11.3 If thermocouples are electrically grounded at the point of measurement, precautions should be taken to eliminate voltage differences between the point of measurement and the measuring instrument.

C2.11.4 Vapor-sealed thermal insulation is then placed over the junction and adjacent wires, if necessary, where temperature differences are great and/or ambient velocities are high.

C3. RESISTANCE TEMPERATURE DEVICES (RTDs)

C3.1 The Platinum RTD is used by NIST to define the International Temperature Standard (ITS-90). Platinum is often used in RTDs because of its high melting point, which allows manufacturing of high purity, better than 99.999%. Platinum has excellent malleability, linearity, corrosion resistance, and sensitivity which allows production of accurate and stable temperature elements. Platinum RTD elements are fabricated as wire-wound and thin film.

C3.2 Platinum RTDs have a positive temperature coefficient and are standard in two resistance temperature coefficients; 0.00385 and 0.003925 ohm/ohm-C. The “385” coefficient is more commonly used by manufacturers. Connections to RTD elements include: 2-wire, 3-wire, and 4-wire. Three- or four-wire leads should be used for all temperature measurements where an accuracy greater than or equal to ±0.2°C (±0.4°F) is required.

C3.3 Platinum RTD elements are typically manufactured for 100 ohms at 0°C (32°F). Other standards resistances include 200, 500, and 1000 ohms. Thin film Platinum elements are commonly manufactured for 1000 ohm at 0°C (32°F) and are used for small diameter and fast response time applications. The higher resistance elements are often less accurate and subject to higher self-heating losses, depending on the instrumentation used to derive the temperature measurement.

C3.4 RTD probes include sheath materials of 316 stainless steel and Inconel. Diameters range from 0.5 mm (0.020 in.) to 9.5 mm (3/8 in.) and lengths from 25.4 to 500 mm (1 in. to 20 in.). Response times or time constants define the time required for a 63% change in resistance due to a sudden temperature change, such as 0 to 100°C (32°F to 100°F) or 25°C (77°F) to 80°C (176°F), with the probe immersed in flowing liquid.

C3.5 RTDs require an electronic instrument, recorder, indicator, meter, or data logger to derive temperature. The instrument should be calibrated for the RTD type, configuration, and coefficient, and the error should be used to determine the uncertainty of the measurement.

C3.6 Platinum RTD temperature measurement range is -200°C to 3000°C (-328°F to 1112°F). Accuracy of wire-wound Platinum RTDs range from 0.005°C to 0.30°C (0.01°F to 0.55°F) depending on manufacturing technique. Best accuracies are stated at 0°C (32°F) but vary at lower and higher temperatures. Accuracy of thin-film Platinum RTDs range from 0.05°C to 0.55°C (0.1°F to 1.0°F).

C3.7 Resistance temperature device bridge circuits include the three that are shown in Figure C-10.
C4. THERMISTORS

C4.1 Thermistors, or thermally sensitive resistors, are manufactured from ceramic oxide semiconductors. Different from RTDs, thermistors have a negative thermal coefficient. Metals for precision thermometry include: metal oxides of manganese, nickel, and cobalt. Thermistors have significantly higher resistance sensitivities than RTDs, which make them less sensitive to long copper conductor lead lengths.

C4.2 Thermistors are fabricated in the form of beads, rods, and disks in sizes as small as 0.13 mm (0.005 in.) and are not stable until aged for multiple months. The elements are sintered integral with lead wires then encapsulated with various materials such as glass, polytetrafluoroethylene (PTFE), and epoxy. This configuration provides better durability, smaller size, and faster response than RTDs.

C4.3 The high sensitivity of thermistors limits their temperature span to small ranges of about 55°C (100°F) over the temperature range of -73°C to 290°C (-100°F to 550°F). Low temperature range resistances are 2000 to 10,000 ohm, with high temperature resistances from 10,000 to 50,000 ohm. The nonlinearity and absence of internationally recognized standard ranges requires unique temperature-resistance curves for each batch of manufactured thermistors. Equation C-1, known as the Steinhart – Hart equation, is used to construct these curves and requires the coefficients to be used by the corresponding temperature indicating device.

\[
\frac{1}{R} = a + b \times (\ln R) + c \times (\ln R)^3
\]  

(C-1)

C4.4 Manufacturers of narrow range thermistors with matched and calibrated electronic indicating or monitoring devices provide measurement accuracies greater than or equal to ± 0.002°C (± 0.004°F). For interchangeability of identical span and type, accuracies are more commonly ± 0.2°C (± 0.4°F).

C4.5 An example of a thermistor circuit is shown in Figure C-11.
C5. RADIATION PYROMETERS

C5.1 The radiation pyrometer uses a disappearing filament or a lens system to focus the radiation onto a detector to derive temperature. The detector may be either a photocell for specific radiation bands or a thermopile for total radiation (also called wideband).

Materials at temperatures above absolute zero emit electromagnetic radiation over a broad spectrum and exhibit a characteristic maximum radiation. The wavelength of the maximum radiation intensity is inversely proportional to its temperature. Wilhelm Wien discovered the relationship between temperature and the maximum radiation wavelength. This relationship, defined by Equation C-2, is known as the “Wien displacement law.”

\[
\lambda_{\text{max}} = \frac{b}{T}
\]

where

- \( \lambda_{\text{max}} \) = maximum wavelength, m (ft).
- \( T \) = absolute temperature K (°R).
- \( b \) = Wien’s displacement constant, \( 2.898 \times 10^{-3} \) m-K (0.016 ft-°R).

C5.2 The temperature range for radiation pyrometers is -40°C to 3300°C (-40°F to 6000°F). Devices are manufactured and calibrated for smaller ranges to provide better accuracy. Handheld units have accuracies of ± 1°C (2°F). Mounted units typically have accuracies of ± 1% of reading or 1°C (2°F).

C6. SOURCES OF TEMPERATURE MEASUREMENT ERRORS

C6.1 Sources of temperature measurement error should be addressed with regard to the sensor type, usage, location, and mounting requirements based on the test plan requirements for test plan accuracy and uncertainty.

C6.2 Sources of measurement error include:

- Sensor probe stem effect
- Not used in the optimum sensor operating temperature accuracy range
- Poor thermal conductivity of mounting method
- Lead wire thermal conductivity
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- External radiation effects
- Self-heating of the sensor element
- Sensor reaction time constants
- Sensor calibration procedure
- Thermal gradient

C6.3 Thermal gradient effects from the temperature differential of the measured value and the surrounding ambient temperature should be addressed by insulating the temperature probe with an insulating material supplying not less than R4.5.