BSR/ASHRAE Standard 41.6-2021R

Public Review Draft

Standard Methods for Humidity Measurement

First Public Review (March 2025)
(Complete Draft for Full Review)

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FOREWORD

Selecting an appropriate psychrometer or hygrometer can be a daunting task given the wide variety of operating principles, measurement precision, and costs. Whether humidity measurements are to be taken in a laboratory or in the field, selecting the appropriate hygrometer should be based on the required measurement accuracy.

Users need to (a) construct a psychrometer or hygrometer in accordance with the specifications defined in this in this standard, (b) select a psychrometer or hygrometer from commercial products, or (c) obtain a psychrometer or hygrometer from other sources. Next, the user may need to consult with the source of the a psychrometer or hygrometer regarding installation specifics, operating range limits, calibration limits, and other similar specifics in order to obtain the expected measurement accuracy or uncertainty.

The 2025 edition of this standard makes it easier for the higher tier ASHRAE standards to adopt this standard by reference and updates of the steady-state criteria requirements. This edition of ASHRAE Standard 41.6 meets ASHRAE's mandatory language requirements.

1. PURPOSE

This standard prescribes methods for measuring the humidity of moist air with instruments.

2. SCOPE

2.1. This standard applies to the measurement of humidity of moist air from sea level to 3048 m (10,000 ft), and within the dry-bulb temperature range of -50°C to 160°C (-58°F to 320°F), and within the dew point temperature range of -50°C to 99°C (-58°F to 210°F).

2.2. This standard applies to methods for the measurement of wet-bulb temperature, dew-point temperature, and relative humidity.

3. DEFINITIONS

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

error: the difference between the test result and its corresponding true value.

frost point: the temperature where visible frost forms on a surface being chilled.

humidity: the moisture content of an air/water mixture

> ***absolute humidity:*** in a mixture of water vapor and dry air, the ratio of the mass of water vapor to the total volume of the sample.
>
> ***relative humidity:***

  a. ratio of the partial pressure of water vapor to the saturation pressure in a given moist air sample at the same dry bulb temperature.
  b. ratio of the density of water vapor to the air density at the same dry-bulb temperature and ambient air barometric pressure.
  c. ratio of the mole fraction of water vapor to the mole fraction of water vapor saturated at the same temperature and barometric pressure.

hygrometer: an instrument used to measure humidity in the atmosphere.

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 for a test result before conducting the test.

psychrometer: an instrument used to determine the humidity of air by simultaneously measuring the wet-bulb and dry-bulb temperatures.

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 humidity 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 humidity or humidity difference is known and has an associated operating tolerance.

temperature measurement:

  a. ***adiabatic saturation temperature***: the saturation temperature where moist air is adiabatically cooled by evaporation of water at the same temperature into the moist air. Also known as *thermodynamic wet-bulb temperature*.
  b. ***dew-point temperature***: the temperature where water vapor has reached the saturation point (100% relative humidity).
  c. ***temperature depression:*** the difference between the dry-bulb and wet-bulb temperature.
  d. ***dry-bulb temperature:*** the temperature indicated by a temperature sensor after correction for radiation errors.
  e. ***wet-bulb temperature:*** the temperature indicated by a thermometer covered with a water-saturated wick where the convective heat gain directly balances out the evaporative heat loss.

test point: a specific set of test operating conditions for recording data where the measured humidity or humidity difference is 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.

unit under test (UUT): equipment that is subjected to humidity measurements.

4 CLASSIFICATIONS

4.1 Humidity Measurement Methods. Humidity measurement methods that are within the scope of this standard are the methods that are listed below and are described in Section 7.

a. Aspirated Wet-Bulb Psychrometer.
b. Chilled Mirror Dew-Point Sensor.
c. Porous Ceramic Electronic Hygrometer.
d. Polymer Film Electronic Hygrometer.
e. Aluminum Oxide Hygrometer.
f. Silicon Sensor Hygrometer.
g. Dunmore Hygrometer
h. Electrolytic Hygrometer.
i. Ion Exchange Resin Electric Hygrometer.

Informative Note: Typical accuracies and the typical operating ranges for these humidity measurement methods are provided in Informative Appendix D, Table D-1.

4.2 Humidity Measurement Applications. Humidity measurement applications that are within the scope of this standard shall be classified as one of the types in Section 4.2.1 and 4.2.2.

4.2.1 Laboratory Applications. Humidity measurements under laboratory conditions are engineering development-tests or tests to determine product performance.

Informative Note: Laboratory humidity measurements tend to use more accurate instruments than field measurements, and the installation of those instruments normally meets the instrument manufacturer's installation requirements.

4.2.2 Field Applications. Humidity measurements under field conditions are tests to determine installed system humidity value.

(Informative Note: Field humidity measurements tend to use less accurate instruments than laboratory measurements, and the installation of those instruments often do not meet the instrument manufacturer's installation requirements.)

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 and calculations to be performed.
b. A method of test standard.
c. A rating standard.
d. A regulation or code.
e. A combination of items a. through d.

The test plan shall specify:

a. The minimum value for the accuracy or the maximum value of the measurement uncertainty of the humidity measurement system over the full range of operating conditions.
b. The values to be determined and recorded that are to be selected from this list: wet-bulb temperature, pretest wet-bulb temperature uncertainty, post-test wet-bulb temperature uncertainty, dew-point temperature, pretest dew-point temperature uncertainty, post-test dew-point temperature uncertainty, relative humidity, pretest relative humidity uncertainty, post-test relative humidity uncertainty.
c. Any combination of test points and targeted set points to be performed together with operating tolerances.

5.2 Values to Be Measured and Reported if Specified in the Test Plan in Section 5.1

5.2.1 Humidity. Humidity shall be measured using one of the following three measured humidity variables:

a. Wet-bulb Temperature, °C (°F), at a given absolute pressure and at a given dry bulb temperature
b. Dew-point Temperature, °C (°F), at a given absolute pressure
c. Relative Humidity (RH), ~~%~~ ×100%, dimensionless, at a given absolute pressure and a given dry bulb temperature

(Informative Note: Section 5.2.1 items (a), (b), and (c) are measurable humidity variables – more than 60 humidity properties, including humidity ratio, can be calculated from these measurable humidity variables.)

5.2.2 Pretest Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the expected uncertainty for each humidity test point prior to the conduct of that test in accordance with the pretest uncertainty analysis procedures in ASME PTC 19.1[1].

5.2.3 Post-test Uncertainty Analysis. If required by the test plan in Section 5.1, perform an analysis to establish the humidity measurement for each humidity test point in accordance with the post-test uncertainty analysis procedures in ASME PTC 19.1[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 Steady-State Test Criteria. Humidity test data shall be recorded at steady-state conditions if specified in the test plan in Section 5.1.

5.3.1 Steady-State Test Criteria Under Laboratory Test Conditions. If the test plan requires humidity 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 by applying one of the methods that are described in:

a. Section 5.3.3, Steady-State Test Criteria for Wet-Bulb Temperature Measurements,
b. Section 5.3.4, Steady-State Test Criteria for Dew-Point Temperature Measurements, or
c. Section 5.3.5, Steady-State Test Criteria for Relative Humidity Temperature Measurements.

5.3.2 Steady-State Test Criteria Under Field Test Conditions. If the test plan humidity 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 the methods in Section 5.3.1 are optional.

(Informative Note: The steady-state methods in Section 5.3.1 are likely to be impractical under field test conditions. Under these circumstances, the user may want to select another method to determine the conditions for field test data to be recorded.)

5.3.3 Steady-State Test Criteria for Wet-bulb Temperature Measurements

d. Apply the steady-state criteria in Section 5.3.3.1 if the test plan provides test points for wet-bulb temperature measurement.
e. Apply the steady-state criteria in Section 5.3.3.2 if the test plan provides targeted set points for wet-bulb temperature measurement.

5.3.3.1 Steady-State Wet-bulb Temperature Criteria for Test Points

Starting with the time set to zero, sample not less than 30 wet-bulb temperature measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-1 states the relationship of the test duration to the number of wet-bulb temperature samples and the equal time intervals.

$$\Delta t = (N-1)\delta t \tag{5-1}$$

(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 wet-bulb temperature fluctuations during operation near the steady-state conditions.)

Record each sampled wet-bulb temperature measurement WB_i and the corresponding time t_i. Apply the least-squares line method to determine the slope b of the wet-bulb temperature data trend line using Equation 5-2.

$$b = \left\{\frac{\left[N\left(\sum_{i=1}^{N} t_i WB_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} WB_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} {t_i}^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]}\right\} \tag{5-2}$$

(Informative Note: It should be noted that the units for the slope in Equation 5-2 are wet-bulb temperature, °C (°F), divided by the units that the user has selected for time.)

The mean of the sampled wet-bulb temperatures $\overline{WB}$ is defined by Equation 5-3.

$$\overline{WB} = \frac{1}{N}\left[\sum_{i=1}^{N}(WB_i)\right] \text{ °C (°F)} \tag{5-3}$$

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 5-4 where WB_L is the operating tolerance limit.

$$WB_{max} - WB_{min} \leq WB_L \text{, °C (°F)} \tag{5-4}$$

The restriction on the slope of the trend line b is defined in Equation 5-5 where Δt is the sample time interval.

$$|b \times \Delta t| \leq 0.5 \times \text{WB}_L \text{, °C (°F)} \tag{5-5}$$

$\overline{WB}$, as determined by Equation 5-3, represents the steady-state mean wet-bulb temperature where Equations 5-4 and 5-5 are both satisfied.

(Informative Note: For further reading about methods of determining steady-state conditions, refer to Informative Annex A – Bibliography items A1 and A2.)

5.3.3.2 Steady-State Wet-bulb Temperature Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 wet-bulb temperature measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-6 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \tag{5-6}$$

(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 wet-bulb temperature fluctuations during operation near the steady-state conditions.)

Record each sampled wet-bulb temperature measurement, WB_i, and the corresponding time, t_i. Apply the least-squares line method to determine the slope b of the wet-bulb temperature data trend line using Equation 5-7.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i WB_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} WB_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} {t_i}^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]} \right\} \tag{5-7}$$

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

The mean of the sampled wet-bulb temperatures $\overline{WB}$ is defined by Equation 5-8.

$$\overline{WB} = \frac{1}{N}\left[\sum_{i=1}^{N}(WB_i)\right] \text{ °C (°F)} \tag{5-8}$$

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 WB_L is the operating tolerance limit.

$$WB_{max} - WB_{min} \leq WB_L \text{, °C (°F)} \tag{5-9}$$

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

$$|b \times \Delta t| \leq 0.5 \times \ WB_L \text{ , °C (°F)} \tag{5-10}$$

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 5-11 where WB_{SP} is the set point wet-bulb temperature and $WB_L$is the operating tolerance limit.

$$|WB_{SP} - \overline{WB}| \leq 0.5 \ \times \ WB_L \ \ \text{°C (°F)} \tag{5-11}$$

$\overline{WB}$, as determined by Equation 5-8, represents the steady-state mean wet-bulb temperature where Equations 5-9, 5-10, and 5-11 are all satisfied.

(Informative Note: For further reading about methods of determining steady-state conditions, refer to Informative Annex A – Bibliography items A1 and A2.)

5.3.4 Steady-State Test Criteria for Dew-Point Temperature Measurements

a. Apply the steady-state criteria in Section 5.3.4.1 if the test plan provides test points for dew-point temperature measurement.
b. Apply the steady-state criteria in Section 5.3.4.2 if the test plan provides targeted set points for dew-point temperature measurement.

5.3.4.1 Steady-State Dew-point Temperature Criteria for Test Points

Starting with the time set to zero, sample not less than 30 dew-point temperature measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-12 states the relationship of the test duration to the number of dew-point temperature samples and the equal time intervals.

$$\Delta t = \ (N - 1)\delta t \tag{5-12}$$

(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 dew point temperature fluctuations during operation near the steady-state conditions.)

Record each sampled dew-point temperature measurement DP_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the dew-point temperature data trend line using Equation 5-13.

$$b = \left\{ \frac{\left[N(\sum_{i=1}^{N} t_i DP_i) - (\sum_{i=1}^{N} t_i)(\sum_{i=1}^{N} DP_i)\right]}{\left[N(\sum_{i=1}^{N} {t_i}^2) - (\sum_{i=1}^{N} t_i)^2\right]} \right\} \tag{5-13}$$

(Informative Note: It should be noted that the units for the slope in Equation 5-13_are temperature, °C (°F), divided by the units that the user has selected for time.)

The mean of the sampled dew-point temperatures $\overline{DP}$ is defined by Equation 5-14.

$$\overline{DP} = \ \frac{1}{N}\left[\sum_{i=1}^{N}(DP_i)\right] \ \ \text{°C (°F)} \tag{5-14}$$

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 5-15 where DP_L is the operating tolerance limit.

$$DP_{max} - DP_{min} \leq DP_L \text{ , °C (°F)} \tag{5-15}$$

The restriction on the slope of the trend line *b* is defined in Equation 5-16 where Δt is the sample time interval.

$$|b \times \Delta t\,| \leq 0.5 \times DP_L \text{ °C (°F)} \tag{5-16}$$

$\overline{DP}$, as determined by Equation 5-14, represents the steady-state mean dew-point temperature where Equations 5-15 and 5-16 are both satisfied.

(Informative Note: For further reading about methods of determining steady-state conditions, refer to Informative Annex A – Bibliography items A1 and A2.)

5.3.4.2 Steady-State Dew-point Temperature Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 dew-point temperature measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-17 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N-1)\delta t \tag{5-17}$$

(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 dew point temperature fluctuations during operation near the steady-state conditions.)

Record each sampled dew-point temperature measurement DP_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the dew-point temperature data trend line using Equation 5-18.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i DP_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} DP_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} {t_i}^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]} \right\} \tag{5-18}$$

(Informative Note: It should be noted that the units for the slope in Equation 5-18 are dew point temperature, °C (°F), divided by the units that the user has selected for time.)

The mean of the sampled dew-point temperatures $\overline{DP}$ is defined by Equation 5-19.

$$\overline{DP} = \frac{1}{N}\left[\sum_{i=1}^{N}(DP_i)\right] \text{ °C (°F)} \tag{5-19}$$

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 5-20 where DP_L is the operating tolerance limit.

$$DP_{max} - DP_{min} \leq DP_L \text{ °C (°F)} \tag{5-20}$$

The restriction on the slope of the trend line *b* is defined in Equation 5-21 where Δt is the sample time interval.

$$|b \times \Delta t| \leq 0.5 \times DP_L \text{ °C (°F)} \tag{5-21}$$

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 5-22 where DP_{SP} is the set point dew- point temperature and DP_L is the operating tolerance limit.

$$|DP_{SP} - \overline{DP}| \leq 0.5 \times DP_L \text{ °C (°F)} \quad (5\text{-}22)$$

$\overline{DP}$, as determined by Equation 5-19, represents the steady-state mean dew-point temperature where Equations 5-20, 5-21, and 5-22 are all satisfied.

(Informative Note: For further reading about methods of determining steady-state conditions, refer to Informative Annex A – Bibliography items A1 and A2.)

5.3.5 Steady-State Test Criteria for Relative Humidity Measurements

a. Apply the steady-state criteria in Section 5.3.5.1 if the test plan provides test points for relative humidity measurement.
b. Apply the steady-state criteria in Section 5.3.5.2 if the test plan provides targeted set points for relative humidity measurement.

5.3.5.1 Steady-State Relative Humidity Criteria for Test Points

Starting with the time set to zero, sample not less than 30 relative humidity measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-23 states the relationship of the test duration to the number of relative humidity samples and the equal time intervals.

$$\Delta t = (N - 1)\delta t \quad (5\text{-}23)$$

(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 dew point temperature fluctuations during operation near the steady-state conditions.)

Record each sampled relative humidity measurement RH_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the relative humidity data trend line using Equation 5-24.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i RH_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} RH_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} {t_i}^2\right) - \left(\sum_{i=1}^{N} t_i\right)^2\right]} \right\} \quad (5\text{-}24)$$

(Informative Note: It should be noted that the units for the slope in Equation 5-24 are relative humidity ×100%, dimensionless, divided by the units that the user has selected for time.)

The mean of the sampled relative humidities $\overline{RH}$ is defined by Equation 5-25.

$$\overline{RH} = \frac{1}{N}\left[\sum_{i=1}^{N}(RH_i)\right] \times 100\%, \text{ dimensionless} \quad (5\text{-}25)$$

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 5-26 where RH_L is the operating tolerance limit.

$$RH_{max} - RH_{min} \leq RH_L \times 100\%, \text{ dimensionless} \quad (5\text{-}26)$$

The restriction on the slope of the trend line *b* is defined in Equation 5-27 where Δt is the sample time interval.

$$|b \times \Delta t\,| \leq 0.5 \times RH_L \times 100\%, \text{ dimensionless} \tag{5-27}$$

$\overline{RH}$, as determined by Equation 5-25, represents the steady-state mean relative humidity where Equations 5-26 and 5-27 are both satisfied.

(Informative Note: For further reading about methods of determining steady-state conditions, refer to Informative Annex A – Bibliography items A1 and A2.)

5.4.5.2 Steady-State Relative Humidity Criteria for Targeted Set Points

Starting with the time set to zero, sample not less than 30 relative humidity measurements N at equal time intervals δt over a test duration Δt where Δt is in time units. Equation 5-28 states the relationship of the test duration to the number of samples and the equal time intervals.

$$\Delta t = (N-1)\delta t \tag{5-28}$$

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 relative humidity fluctuations during operation near the steady-state conditions.

Record each sampled relative humidity measurement RH_i and the corresponding time t_i. Apply the least-squares line method to determine the slope *b* of the relative humidity data trend line using Equation 5-29.

$$b = \left\{ \frac{\left[N\left(\sum_{i=1}^{N} t_i RH_i\right) - \left(\sum_{i=1}^{N} t_i\right)\left(\sum_{i=1}^{N} RH_i\right)\right]}{\left[N\left(\sum_{i=1}^{N} t_i^{2}\right) - \left(\sum_{i=1}^{N} t_i\right)^{2}\right]} \right\} \tag{5-29}$$

(Informative Note: It should be noted that the units for the slope in Equation 5-29 are relative humidity, × 100%, dimensionless divided by the units that the user has selected for time.)

The mean of the sampled relative humidities $\overline{RH}$ is defined by Equation 5-30.

$$\overline{RH} = \frac{1}{N}\left[\sum_{i=1}^{N}(RH_i)\right] \quad \times 100\%, \text{ dimensionless} \tag{5-30}$$

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 5-31 where RH_L is the operating tolerance limit.

$$RH_{max} - RH_{min} \leq RH \ \times 100\%, \text{ dimensionless} \tag{5-31}$$

The restriction on the slope of the trend line *b* is defined in Equation 5-32 where Δt is the sample time interval.

$$|b \times \Delta t| \leq 0.5 \times RH_L \ \times 100\%, \text{ dimensionless} \tag{5-32}$$

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 5-33 where RH_{SP} is the set point relative humidity and RH_L is the operating tolerance limit.

$$|RH_{SP} - \overline{RH}| \leq 0.5 \times RH \times 100\%, \text{ dimensionless} \qquad (5\text{-}33)$$

$\overline{RH}$, as determined by Equation 5-30, represents the steady-state mean relative humidity where Equations 5-31, 5-32, and 5-33 are all satisfied.

(Informative Note: For further reading about methods of determining steady-state conditions, refer to Informative Annex A – Bibliography items A1 and A2.)

5.4 Unsteady Humidity Measurements. If required by the test plan in Section 5.1, humidity 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.

6. INSTRUMENTS AND CALIBRATION

6.1. Instrumentation Requirements for All Measurements

6.1.1 Instruments and data acquisition systems shall be selected to meet the measurement system accuracy or the uncertainty 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.

(Informative Note: For further reading, ISO/IEC 17025, *General Requirements for the Competence of Testing and Calibration Laboratories*[A3], defines good test laboratory practices.)

6.1.3 Instruments shall be applied and used in accordance with the following standard:

a. Temperature: ANSI/ASHRAE 41.1[2]
b. Pressure: ANSI/ASHRAE 41.3[3]

6.6 Time Measurements

Time measurement system accuracy shall be within ±0.5% of the elapsed time measured, including any uncertainty associated with starting and stopping the time measurement unless (a) otherwise specified in the test plan in Section 5.1, or (b) a different value for time measurement system accuracy is required to be consistent with the humidity measurement system accuracy specified in the test plan.

7. HUMIDITY MEASUREMENT METHODS

7.1 Aspirated Wet-Bulb Psychrometer. ASHRAE Research Report RP-1460[4] provides design specifications for a wet-bulb aspirator apparatus that measures wet-bulb temperatures in a device that is operating at a constant velocity of 3.5±0.25 m/s (690±50 ft/min) with a minimum adiabatic saturation temperature uncertainty of ±0.05°C (±0.09°F).

(Informative Notes: Prior to testing, check to be sure that the measured wet-bulb temperatures (when dry) and dry-bulb temperatures agree within the operating tolerance that is provided in the test plan.)

7.2 Chilled Mirror Dew-Point Hygrometer. Chilled mirror dew-point hygrometers directly measure the dew point and frost point for a moist air sample. The methods for chilling the mirror include (a) evaporation of solvent, (b) adiabatic expansion of gases, (c) direct and indirect contact with refrigerants, and (d) by Peltier cooling. A platinum resistance temperature detector (RTD), a thermistor, or a thermocouple is placed in direct contact with the chilled mirror to measure surface temperature.

7.3 Polymer Film Hygrometer. The sensing element in a polymer film hygrometer consists of a hygroscopic organic polymer deposited with thin or thick film-processing technology onto a water-permeable substrate. There are two types of polymer film hygrometers: capacitance and impedance. The impedance-type devices are either ionic or electrical conduction types.

7.4 Aluminum Oxide Hygrometer. The sensor in an aluminum oxide hygrometer consists of an aluminum strip that is anodized to provide a porous oxide layer. A very thin coating of gold is evaporated over this structure. The aluminum base and the gold layer form the two electrodes of an aluminum oxide capacitor that is sensitive to the vapor pressure of water. Ionic conduction is produced by dissociation of water molecules forming surface hydroxides. This dissociation causes migration of protons such that device impedance decreases with increasing water content.

7.5 Porous Ceramic Hygrometer. Porous ceramic hygrometers use either ionic or electrical measurement techniques to relate adsorbed water to relative humidity. Ionic conduction is produced by dissociation of water molecules forming surface hydroxides. This dissociation causes migration of protons such that device impedance decreases with increasing water content. The ceramic oxide is sandwiched between porous metal electrodes that connect the device to an impedance-measuring circuit for linearizing and signal conditioning.

7.6 Silicon Sensor Hygrometer. The sensing element is a semiconductor that acts as a moisture detector. Moisture in the air sample is detected as an impedance change that is a function of the vapor pressure of water in the sample air.

The silicon sensor is equipped with a heating element that is used to remove water and contaminants from the sensor and for diagnostic purposes. An optional temperature sensor is used to provide feedback for temperature control and to eliminate errors caused by variations in ambient and air sample temperatures.

7.7 Dunmore Hygrometer. Dunmore, at NIST, developed the first lithium chloride resistance hygrometer in 1938. The instrument operates on the principle that a lithium chloride solution immersed in a porous binder changes its ionic conductivity depending on changes in relative humidity. With a fixed concentration of lithium chloride, a linear change of resistance is observed for a narrow range of relative humidities. Because of the steep resistance to relative humidity change, it is necessary to vary the bifilar element spacing or the concentration of lithium chloride, or both, to develop resistance curves for specific humidity change. This results in a number of resistance elements, called Dunmore elements, required to cover a standard range. Calibration is essential because the resistance grid varies with time and contamination, as well as with exposure to temperature and humidity extremes.

7.8 Electrolytic Hygrometer. The electrolytic humidity sensor utilizes a bifilar winding coated with a thin film of phosphorus that is wrapped around a non-conductive tube. A constant incoming flow rate of moist air is absorbed by the phosphorous desiccant and electrolyzed into hydrogen and oxygen by means of electrolysis. The current of electrolysis process is measured and used to determine the mass of water vapor entering the sensor.

(Informative Note: Electrolytic hygrometers are affected by recombination that occurs in hydrogen-rich or oxygen-rich airstreams. Low moisture levels in the airstream will result in measurement errors when the recombined water is re-electrolyzed.)

7.9 Ion Exchange Resin Electric Hygrometer. A conventional ion exchange resin hygrometer consists of a high-molecular-weight polymer that contains polar groups of positive or negative charge configured in a cross-linked structure. The polar groups consist of ions of opposite charge that are held to the fixed polar groups by electrostatic forces. In the presence of water or water vapor, the electrostatically held ions become mobile. Where a voltage is applied across the resin, the ions are capable of electrolytic conduction.

8. UNCERTAINTY ANALYSIS

8.1 Post-Test Uncertainty Analysis. A post-test analysis of the measurement system uncertainty, performed in accordance with ANSI/ASME PTC 19.1[1], shall accompany each refrigerant mass flow rate 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: Informative Appendix F contains an example of humidity measurement uncertainty calculations.)

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:

$$v = \bar{X}_m \pm U_{\bar{X}}\ (P\%) \tag{8-1}$$

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: humidity = 15.7% RH ± 0.74% RH; (95%) states that the measured humidity is believed to be 15.7% RH with a 95% probability that the true value lies within ±0.74% RH of this value at a given absolute pressure and at a given dry-bulb temperature.)

9. TEST REPORT

If the test plan in Section 5.1 defines the test report requirements, the test report requirements in the test plan supersedes all of the requirements in Section 9. Otherwise, Section 9 specifies the test report requirements.

9.1 Test Identification

a. Date, place, and time.
b. Operator identification.

9.2 Unit Under Test Description

a. Model number and serial number.

9.3 Instrument Description

a. Psychrometer or hygrometer 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 calibration in accordance with Section 6.

9.4 Measurement System Description

a. Description of instrument installation specifics.
b. Measurement system accuracy based on specifications or calibration.
c. Documentational evidence of calibration in accordance with Section 6.

9.5 Test Conditions

a. Test conditions in accordance with the test plan in Section 5.1
b. Ambient temperature, ºC (ºF).
c. Barometric pressure Pa, (psia) if pressures instruments are measuring gauge pressure.

9.6 Test Results if Specified in the Test Plan in Section 5.1.

a. Wet-bulb temperature, °C (°F).
b. Pretest wet-bulb temperature uncertainty, °C (°F).
c. Post-test wet-bulb temperature uncertainty, °C (°F).
d. Dew-point temperature, °C (°F).
e. Pretest dew-point temperature uncertainty, °C (°F).
f. Post-test dew-point temperature uncertainty, °C (°F).
g. Relative humidity × 100%, dimensionless
h. Pretest relative humidity uncertainty × 100%, dimensionless
i. Post-test relative humidity uncertainty × 100%, dimensionless

10 REFERENCES

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INFORMATIVE APPENDIX B
PRIMARY HUMIDITY CALIBRATORS

B1. NIST Gravimetric Hygrometer

NIST's gravimetric hygrometer is a primary standard calibrator for humidity measurements. The gravimetric hygrometer determines absolute water vapor content, because the weight of the water absorbed and the precise measurement of the air volume associated with the water vapor determine the absolute humidity of the incoming air.

In this system, the airflows from a humidity generator through a drying train and into a precision air-volume-measuring system contained within a temperature-controlled bath. The precise measurements of the mass of water vapor absorbed from the air and the associated volume of dry air as measured at controlled temperatures and pressures accurately define the humidity ratio of the test air or any other expression of humidity. Where used to calibrate an instrument, the humidity generator provides the test air to the gravimetric hygrometer as well as to the instrument undergoing calibration.

However, the NIST gravimetric hygrometer in the low humidity ranges requires up to 30 hours per calibration point. For this reason, NIST has developed and calibrated a two-pressure humidity generator that is used as the NIST humidity calibration standard.

B2. Primary Standard Humidity Generators

Primary standard humidity generators consist of the following types:

a. two-pressure humidity generator as described in Section B3
b. two-temperature humidity generator as described in Section B4,
c. divided-flow system as described in Section B5, and
d. saturated salt solutions as described in Section B6.

B3. Two-Pressure Humidity Generator.

The two-pressure humidity generator operates on the principle of saturating a air sample at a constant temperature and elevated pressure and then expanding the sample isothermally to a lower pressure. The principle of operation is based on Dalton's law in that the ratio of partial pressures varies directly with the total pressure. The saturator water-vapor partial pressure is determined from steam or psychrometric tables by assuming complete saturation at the saturator temperature.

For a generator of this type, air is saturated with water vapor at a given pressure (P_s) and temperature (t). The air flows through an expansion valve, where it is expanded isothermally to a new pressure (P_t). If ideal air behavior is assumed, the percent relative humidity at the new pressure (P_t) is expressed as a ratio of the two absolute pressures:

% RH at $P_t = (P_t / P_s)_t \times 100$

where

P_t = test chamber pressure,

P_s = saturator pressure, and

t = temperature of test chamber and saturator.

The amount of deviation from ideal air laws was determined by Hyland of NIST and varies with temperature and pressure:

$\% \text{ RH} = (P_t/P_s)_t \times f(P_s, t)/f(P_t, t) \times 100$

where

$f(P_s, t)$ = enhancement factor at saturator pressure and temperature t,

$f(P_t, t)$ = enhancement factor at-test chamber pressure and temperature t.

Relative humidity produced in the test chamber of this type of device does not depend on measuring the amount of water vapor in the test chamber, but it is dependent upon the measurement of pressures and temperatures only and upon the maintenance of isothermal system conditions. The precision of the system is determined by the accuracy of the pressure measurement and the uniformity of temperature throughout the system.

B4. Two-Temperature Humidity Generator.

In the two-temperature humidity generator, air is saturated at one temperature, and then heated to a higher temperature. This results in a new relative humidity that is a function of the two temperatures. In this method, the air is recirculated around a closed loop that includes the two chambers. A pressure difference exists because of piping loss that shall be used to calculate relative humidity.

B5. Divided-Flow System.

In the divided-flow system, a dry air stream is divided into two parts. One part is saturated, and then the two streams are recombined. The combined humidity is a function of the volumetric ratio of the divided streams.

B6. Saturated Salt Solutions.

Saturated salt solutions are used for humidity generation. A given saturated water/salt solution determines the equilibrium water vapor pressure by its ambient temperature. Water vapor pressure versus temperature curves have been defined and verified experimentally for salt solutions. Because of the complexity of the theory of concentrated solutions, vapor pressure curves of saturated solutions are determined experimentally.

Solutes reduce the solvent vapor pressure roughly in proportion to the amount of dissolved material. For salt in water, the maximum vapor depression is reached when the solution is saturated. The equilibrium relative humidities obtained over saturated solutions range from 5% to 100%, depending on the temperature and the salt used. Table B-1 contains results based on a number of studies.

TABLE B-1 Equilibrium Relative Humidities over Saturated Salt Solution

Salt Temperature	**0ºC**	**10ºC**	**20ºC**	**30ºC**	**40ºC**	**50ºC**	**60ºC**	**70ºC**	**80ºC**	**90ºC**	**100ºC**
	32ºF	**50ºF**	**68ºF**	**86ºF**	**104ºF**	**122ºF**	**140ºF**	**158ºF**	**176ºF**	**194ºF**	**212ºF**
Lithium Bromide	7.8	7.1	6.6	6.2	5.8	5.5	5.3	5.2	5.2	5.3	5.4
Lithium Chloride	11.2	11.3	11.3	11.3	11.2	11.1	11.0	10.8	9.4	10.3	12.1
Magnesium Chloride	33.7	33.5	33.1	32.4	31.6	30.5	29.3	27.8	26.1	24.1	22.0
Potassium Carbonate	43.1	43.1	43.2	43.2		40.9	39.2	37.4	35.4	33.4	31.3
Magnesium Nitrate	60.4	57.4	54.4	51.4	48.4	45.4					
Sodium Nitrite									48.5	44.9	41.0
Sodium Bromide		62.2	59.1	56.0	53.2	50.9	49.7	49.7			
Sodium Nitrate									63.0	60.7	58.3
Sodium Chloride	75.5	75.7	75.5	75.1	74.7	74.7	74.5	75.1	73.9	73.8	73.9
Potassium Chloride	88.6	86.8	85.1	83.6	82.3	81.2	80.2	79.5			
Barium Chloride									85.1	83.9	82.6
Potassium Sulfate	98.8	98.2	97.6	97.0	96.4	95.8	96.6	96.3	95.8	95.2	94.5

Saturated salt solutions are useful in controlling humidity in enclosed spaces, but leakage of moisture into or out of the enclosure affects the humidity level. The use of a slushy mixture provides quick exchange of moisture with the solution, hence better control than if a thick layer of liquid lies over the salt (unless the latter is stirred). At the same time, liquid must be present.

These salts exhibit changes from one hydrate level to another at characteristic temperatures. This causes a discontinuity in the vapor pressure and, in the vicinity of a quadruple point, the vapor pressure is suspect. Do not use a salt solution within 3°C to 5°C (5.4°F to 9.0°F) of such a temperature.

Sulfuric acid and glycerin water solutions are used to produce known humidities through selection of the correct concentration.

Verify that the sensor manufacturer approves each specific salt solution as a calibration method.

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INFORMATIVE APPENDIX C
USER GUIDANCE REGARDING HUMIDITY MEASURMENTS

C1. Guidance for Below Freezing Measurements with Wet-Bulb Sensor

C2. When it is necessary to measure wet-bulb temperature at or below freezing in a moving airstream, the problem of ice forming on the wet-bulb sensor is eliminated by continuously withdrawing a sample of air and adding heat. The dry-bulb temperature of this air is first determined. Then this air sample is heated to a temperature above freezing. The dry-bulb and wet-bulb temperatures of the heated sample are then measured. From these data, the humidity ratio is established. This humidity ratio, together with the lower dry-bulb temperature and the psychrometric properties of moist air, is then used to determine the wet-bulb temperature prevailing at the lower dry-bulb temperature.

C3. Where it is necessary to directly measure wet-bulb at temperatures below freezing, a wet-bulb temperature sensor with an ice-coated bulb (0.5 mm (0.02 in) thickness), without a wet-bulb sock, is used. The wet-bulb sock at below freezing temperatures, no longer serves the usual purpose, for ice, unlike water, does not respond to capillary forces. Wet-bulb temperature measurements are obtained only when the surface of the wet-bulb sensor is completely covered with a layer of ice.

C4. As a result of the reduced vapor pressure at low temperatures, a longer time is necessary to reach equilibrium than at higher temperatures. This condition is offset, however, by the ice remaining on the bulb for a much longer time.

C5. The ice film is best formed by dipping the chilled temperature sensor into distilled water at 0°C (32°F). The temperature sensor is then removed from the water and the film is allowed to freeze. The process is repeated to build up a film thickness (defined above).

C6. Air velocity, radiation shields, and other geometry described in Appendix E must be maintained.

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INFORMATIVE APPENDIX D
HUMIDITY MEASUREMENT METHODS ACCURACIES AND OPERATING RANGES

Table D-1 provides typical accuracies, and typical operating ranges for each of the test methods described in Section 7.

TABLE D-1 Typical accuracies and typical operating ranges

Humidity Test Method	**Typical Relative Humidity Accuracy**	**Typical Operating Range**
Aspirated Wet Bulb Psychrometer	±2% to 5% RH	Dew point: 2°C to 30°C (36ºF to 86ºF)
Chilled Mirror Dew Point Hygrometer	±0.4 to 4 ºF	-120°C to +150°C (-184ºF to +302ºF)
Polymer Film Hygrometer	±2 to 3% RH	10 to 100% RH
Porous Ceramic Hygrometer	±1 to 1.5 % RH	Up to 204°C (400ºF)
Aluminum Oxide Hygrometer	±3% RH	5 to 100% RH
Silicon Sensor Hygrometer	Not available	Not available
Dunmore Hygrometer	±1.5% RH	7 to 98% RH at 4°C to 60°C (40ºF to 140ºF)
Ion Exchange Hygrometer	±1.5% RH	10 to 100% RH at -40°C to 88°C (-40ºF to 190ºF)

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INFORMATIVE APPENDIX E:
TIPS TO SPECIFYING THE ACCURACY REQUIREMENT IN SECTION 5.1

The source of the Test Plan in Section 5.1 needs to specify the required accuracy for the measurements, but the required accuracy is dependent upon the dry bulb temperature for each test point and the humidity units selected – wet bulb temperature, dew point temperature, and relative humidity. Table E-1 shows the examples of the accuracy that should be specified at sample test points. The wet bulb temperature in each example is assumed to be ±0.11°C (±0.20°F) with the tolerance on dew point temperature and relative humidity at the enthalpy that matches the enthalpy for the assumed wet bulb temperature. For simplification, the minus tolerances shown in Table E-1 were assumed to be the same values as the plus tolerances even though it is clear that the minus tolerances will not be quite the same as the plus tolerances.

TABLE E-1: Example accuracy tolerances for different-test conditions that have the same enthalpy

Test Condition	Dry Bulb Temperature	Wet Bulb Temperature	Dew Point Temperature	Relative Humidity
A/B Test ID	-15°C (5°F)	±0.11°C (±0.20°F)	±0.20°C (±0.36°F)	±0.65%
A Test OD	-8.3°C (17°F)	±0.11°C (±0.20°F)	±0.19°C (±0.35°F)	±0.48%
H Test ID	1.7°C (35°F)	±0.11°C (±0.20°F)	±0.25°C (±0.45°F)	±0.75%
H0 Test OD	8.3°C (47°F)	±0.11°C (±0.20°F)	±0.18°C (±0.33°F)	±1.04%
H1 Test OD	17°C (62°F)	±0.11°C (±0.20°F)	±0.26°C (±0.46°F)	±1.32%
H2 Test OD	21°C (70°F)	±0.11°C (±0.20°F)	±0.27°C (±0.48°F)	±1.79%
H3 Test OD	27°C (80°F)	±0.11°C (±0.20°F)	±0.48°C (±0.87°F)	±3.02%
H4 Test OD	35°C (95°F)	±0.11°C (±0.20°F)	±0.79°C (±1.43°F)	±4.84%

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INFORMATIVE APPENDIX F: EXAMPLE OF AN UNCERTAINTY ESTIMATE FOR A WET-BULB MEASUREMENT

F1. Problem Statement and Assumptions

Determine the expected measurement uncertainty at ~19°C (~66°F) WB.

An aspirated wet bulb psychrometer is installed downstream of an air sampler and upstream of an air mover, both as prescribed by ASHRAE Standard 37[A8]. The psychrometer complies with design guidelines of ASHRAE Research Report RP-1460[3].

Assumptions regarding the set up and test:

- The air sampler / psychrometer / air mover apparatus is be used to measure the WB temperature of the inlet air stream during an ASHRAE Standard 37 cooling capacity test.
- As prescribed, the test room reconditioning apparatus and the equipment under test shall be operated until steady-state performance with an operating tolerance of 0.3K (0.54°R) and variation of average from set-test condition of 0.1K (0.18°R).
- Data shall be recorded for 30 minutes.
- The temperature sensor, a 100Ω Platinum RTD, is connected to a computer-based data acquisition system. Sample rate is 2 per minute for a total of 61 samples.

F2. Method

Follow the step-by-step procedures outlined in Section 5, Uncertainty of a Measurement, of ASME PTC 19.1-~~2018~~[4] 2018[1] to estimate the uncertainty in SI units in Section F3.1 and in I-P units in Section F3.2. Note that, in general, using a commercial equation solver software significantly reduces the time and effort required to complete an uncertainty analysis.

Note about the measured value:

The terms *adiabatic saturation temperature*, *true wet-bulb temperature*, and *wet-bulb temperature* are defined in Section 3 of this standard.

To measure wet-bulb temperature, a moist air stream is forced across a temperature sensor kept wetted by a moist cotton sock. Cooling of the sensor below the ambient dry-bulb temperature leads to convective heat gain from the air stream to the temperature sensor in a nearly adiabatic fashion.

Both the *ASHRAE Fundamentals Handbook* – 2017, Chapter 1: Psychrometrics[A9] and ASHRAE RP-1485 Thermodynamic Properties of Real Moist Air, Dry Air, Steam, Water, and Ice[A10] utilize Thermodynamic Wet-Bulb temperature in their analyses. Thus, the wet-bulb temperature of this uncertainty estimate is used to represent the thermodynamic wet-bulb temperature.

F3. Uncertainty ~~Procedures~~[4] Procedures[1] in SI and IP units

F3.1 Uncertainty ~~Procedures~~[4] Procedures[1] in SI units

F3.1.1 Random Standard ~~Uncertainty~~ Deviation of the Sample Mean

F3.1.1.1 General Case

The mean $\bar{X}$ is calculated by

$$\bar{X} = \frac{\sum_{j=1}^{N} X_j}{N} \tag{F-1}$$

where

$N =$ the number of measurements made in the sample

X_j =the value of each individual measurement in the sample.

The sample standard deviation is only an estimate of the population standard deviation and is given by

$$s_X = \sqrt{\sum_{j=1}^{N} \frac{\left(X_j - \bar{X}\right)^2}{N-1}} \tag{F-2}$$

An appropriate random standard ~~uncertainty~~ deviation of the sample mean is

$$s_{\bar{X}} = \frac{s_X}{\sqrt{N}} \tag{F-3}$$

Degrees of freedom

$$\nu = N - 1 \tag{F-4}$$

F3.1.1.2 Using Previous Values of $s_{\bar{X}}$

Previous values of $s_{\bar{X}}$ are not applicable for this evaluation because a relatively large number of measurements, 61, will be made over a significant time frame, 30 minutes and steady state is determined prior to making measurements.

F3.1.1.3 Using Elemental Random Error Sources

Another method of estimating the random standard ~~uncertainty~~ deviation of the sample mean for a measurement is from information about the elemental random error sources in the entire measurement process. If all the random standard uncertainties are expressed in terms of their contributions to the measurement, then the random standard ~~uncertainty~~ deviation for the sample mean is the root-sum square of the elemental random standard uncertainties of the mean from all sources divided by the square root of the number of current readings, averaged. The expected random error of wet-bulb temperature is given by RP-1460 and random error of the RTD calibration will be calculated from calibration data.

$$s_{\bar{X}} = \frac{1}{\sqrt{N}} \left[\sum_{k=1}^{K} \left(s_{\bar{X}_k} \right)^2 \right]^{1/2} \tag{F-5}$$

where

$K =$ the total number of random error (or uncertainty) sources.

The degrees of freedom for the estimated random standard deviation_of the_sample mean is dependent on the information used to determine each of the elemental random standard deviation of the_sample mean and is calculated as

$$\nu = \frac{\left(\sum_{k=1}^{K}\left(s_{\bar{X}_k}\right)^2\right)^2}{\left(\sum_{k=1}^{K}\frac{\left(s_{\bar{X}_k}\right)^4}{\nu_k}\right)} \tag{F-6}$$

where

$\nu_k =$ the degrees of freedom corresponding to each $s_{\bar{X}_k}$.

When all error sources have large sample sizes, the calculation of ν is unnecessary.

F3.1.2 Systematic Standard Uncertainty of a Measurement

The systematic standard uncertainty $b_{\bar{X}}$ of a measurement is a value that quantifies the dispersion of the systematic error associated with the mean. The true systematic error β is the unknown, but $b_{\bar{X}}$ is evaluated so that it represents an estimate of the standard deviation of the distribution for the possible β values. It should be noted that while $b_{\bar{X}}$ is an estimate of the dispersion of the systematic errors in a measurement, the systematic error that is present in specific measurement is a fixed single value of β.

The systematic standard uncertainty of the measurement is the root-sum-square of the elemental systematic standard uncertainties $b_{\bar{X}_k}$ for all sources following the Taylor Series Method (TSM).

$$b_{\bar{X}} = \left[\sum_{k=1}^{K}\left(b_{\bar{X}_k}\right)^2\right]^{1/2} \tag{F-7}$$

where

$b_{\bar{X}_k} =$ each estimate of the standard deviation of the k^{th} elemental error source

$K =$ the total number of systematic error sources

The elemental systematic standard uncertainties are expressed in terms of their contributions to the measurement. For each systematic error source in the measurement, the elemental systematic standard uncertainty must be estimated from the best available information. Usually, these estimates are made using engineering judgment. Sometimes previous data are available to make estimates of uncertainties that remain fixed during a test.

There can be many sources of systematic error in measurement, such as the calibration process, instrument systematic errors, transducer errors, and fixed errors of method. Also, environmental effects, such as radiation effects in a temperature measurement, can cause systematic errors of method. There usually will be some elemental systematic standard uncertainties that will be dominant. Because of the resulting effect of combining the elemental uncertainties in a root-sum square manner, the larger or dominant ones will control the systematic uncertainty in the measurement; however, one should be very careful to identify all significant sources of fixed error in the measurement.

F3.1.3 Classification of Uncertainty Sources

Type A uncertainties are the calculated standard deviations obtained from data sets. Type B uncertainties are those that are estimated or approximated rather than calculated from data. Type B uncertainties are also given as estimated standard deviations. Uncertainties are classified by their effect on the measurement, either random or systematic, rather than by their source. When it is convenient to classify elemental uncertainties by both effect and source, the following nomenclature for dual classifications is recommended:

$b_{\bar{X}_{k,A}}$ = elemental systematic standard uncertainty calculated from data, as in a calibration process
$b_{\bar{X}_{k,B}}$ = elemental systematic standard uncertainty estimated from the best available information
$s_{\bar{X}_{k,A}}$ = elemental random standard uncertainty calculated from data
$s_{\bar{X}_{k,B}}$ = elemental random standard uncertainty estimated from best available information

F3.1.4 Combined Standard and Expanded Uncertainty of a Measurement

For simplicity of presentation, a single value is often preferred to express the estimate of the error between the mean value $\bar{X}$ and the true value $U_{\bar{X}}$ with a defined level of confidence $P\%$. The interval

$$\bar{X} \pm U_{\bar{X}}\ (P\%) \tag{F-8}$$

represents a band about $\bar{X}$ within which the true value is expected to lie with a given level of confidence. The uncertainty interval is composed of both the systematic and random uncertainty components.

The general form of the expression for determining the uncertainty of a measurement is the root-sum-square of the systematic and random standard uncertainties for the measurement, with this quantity defined as the combined standard uncertainty, $u_{\bar{X}}$, TSM:

$$u_{\bar{X}} = \sqrt{(b_{\bar{X}})^2 + (s_{\bar{X}})^2} \tag{F-9}$$

where

$b_{\bar{X}}$ = the systematic standard uncertainty

$s_{\bar{X}}$ = the random standard deviation of the sample mean

In order to express the uncertainty at a specified confidence level using the TSM, the combined standard uncertainty must be multiplied by an expansion factor taken as the appropriate Student's t value for the required confidence level. Depending on the application, various confidence levels may be appropriate. The Student's t is chosen on the basis of the level of confidence desired and the degrees of freedom. The degrees of freedom used is a combined degrees-of-freedom based on the separate degrees of freedom for the random standard uncertainty and the elemental systematic standard uncertainty. A t value of 1.96 (usually taken as 2) corresponds to large degrees of freedom and defines an interval with a level of confidence of approximately 95%. This expansion factor of 2 is used for most engineering applications.

The expanded uncertainty for a 95% level of confidence and large degrees-of-freedom (t = 2) is calculated per the TSM:

$$U_{\bar{X}} = 2u_{\bar{X}} \tag{F-10}$$

The expression for the expanded uncertainty given in Equation F-10 applies when the measurement $\bar{X}$ is the desired result of the experiment.

TABLE F-1: Measured wet bulb temperature

Elapsed Time, min	Measured Wet-Bulb Tempera-ture, °C	Elapsed Time, min	Measured Wet-Bulb Tempera-ture, °C	Elapsed Time, min	Measured Wet-Bulb Tempera-ture, °C
0	18.87	10.5	18.91	20.5	18.89
0.5	18.87	11	18.90	21	18.90
1	18.87	11.5	18.89	21.5	18.89
1.5	18.88	12	18.89	22	18.90
2	18.88	12.5	18.88	22.5	18.89
2.5	18.88	13	18.88	23	18.89
3	18.88	13.5	18.87	23.5	18.89
3.5	18.89	14	18.87	24	18.88
4	18.90	14.5	18.87	24.5	18.88
4.5	18.89	15	18.87	25	18.87
5	18.89	15.5	18.87	25.5	18.87
5.5	18.89	16	18.87	26	18.87
6	18.90	16.5	18.87	26.5	18.87
6.5	18.90	17	18.87	27	18.86
7	18.90	17.5	18.87	27.5	18.86
7.5	18.91	18	18.88	28	18.87
8	18.91	18.5	18.88	28.5	18.87
8.5	18.91	19	18.88	29	18.87
9	18.92	19.5	18.89	29.5	18.87
9.5	18.92	20	18.89	30	18.87
10	18.91				

The sample mean, or average value, of the wet-bulb temperature measurements is determined using

$$\bar{X} = \frac{\sum_{j=1}^{N} X_j}{N} = 18.88°\text{C} \qquad \text{(F-11)}$$

The sample standard deviation is determined using

$$s_X = \sqrt{\sum_{j=1}^{N} \frac{\left(X_j - \bar{X}\right)^2}{N-1}} = 0.015°\text{C} \qquad \text{(F-12)}$$

The random standard ~~uncertainty~~ deviation of the sample mean is determined using

$$s_{\bar{X}} = \frac{s_X}{\sqrt{N}} = 0.0019°\text{C} \qquad \text{(F-13)}$$

The lab in question utilizes a water bath to calibrate resistance temperature detectors (RTDs) against a reference Platinum Resistance Thermometer (PRT), a higher degree of accuracy than standard RTD, over an array of setpoints. The stability of water bath is held to produce <0.05°C variation during the calibration run. A linear interpolation table is generated for use by the data acquisition system correction of RTD to

Reference PRT. Once the calibration is successful, a one-minute check is performed which is shown in the following table.

TABLE F-2: RTD Calibration check

Elapsed Time, s	RTD, °C	Reference PRT, °C	Elapsed Time, s	RTD, °C	Reference PRT, °C
0	22.193	22.246	31	22.193	22.246
1	22.249	22.246	32	22.249	22.245
2	22.193	22.246	33	22.193	22.245
3	22.193	22.247	34	22.193	22.244
4	22.249	22.247	35	22.193	22.244
5	22.193	22.247	36	22.193	22.244
6	22.193	22.246	37	22.193	22.245
7	22.193	22.246	38	22.249	22.245
8	22.193	22.246	39	22.193	22.246
9	22.193	22.246	40	22.193	22.246
10	22.193	22.245	41	22.249	22.246
11	22.193	22.246	42	22.193	22.245
12	22.193	22.246	43	22.193	22.244
13	22.193	22.246	44	22.249	22.245
14	22.249	22.246	45	22.193	22.244
15	22.193	22.246	46	22.193	22.245
16	22.249	22.246	47	22.193	22.245
17	22.193	22.246	48	22.193	22.244
18	22.193	22.246	49	22.193	22.245
19	22.193	22.245	50	22.193	22.243
20	22.193	22.245	51	22.193	22.244
21	22.193	22.246	52	22.193	22.244
22	22.193	22.246	53	22.193	22.244
23	22.193	22.246	54	22.249	22.244
24	22.193	22.246	55	22.193	22.244
25	22.193	22.246	56	22.193	22.244
26	22.193	22.245	57	22.193	22.245
27	22.193	22.246	58	22.193	22.244
28	22.193	22.245	59	22.193	22.245
29	22.193	22.245	60	22.193	22.244
30	22.193	22.245			

The sample mean, or average value, of the RTD measurements is determined using

$$\bar{X}_{RTD} = \frac{\sum_{j=1}^{N} x_j}{N} = 22.20°\mathrm{C} \tag{F-14}$$

The sample standard deviation of the RTD readings is determined using

$$s_{X_{RTD}} = \sqrt{\sum_{j=1}^{N} \frac{\left(X_j - \bar{X}\right)^2}{N-1}} = 0.020°\mathrm{C} \qquad \text{(F-15)}$$

The random standard ~~uncertainty~~ deviation of the sample mean for the RTD is determined using

$$s_{\bar{X}_{RTD}} = \frac{s_{X_{RTD}}}{\sqrt{N}} = 0.0025°\mathrm{C} \qquad \text{(F-16)}$$

The sample mean, or average value, of the PRT measurements is determined using

$$\bar{X}_{PRT} = \frac{\sum_{j=1}^{N} X_j}{N} = 22.25°\mathrm{C} \qquad \text{(F-17)}$$

The sample standard deviation of the PRT readings is determined using

$$s_{X_{PRT}} = \sqrt{\sum_{j=1}^{N} \frac{\left(X_j - \bar{X}\right)^2}{(N-1)}} = 0.00075°\mathrm{C} \qquad \text{(F-18)}$$

The random standard ~~uncertainty~~ deviation of the sample mean for the PRT is determined using

$$s_{\bar{X}_{PRT}} = \frac{s_{X_{PRT}}}{\sqrt{N}} = 0.00010°\mathrm{C} \qquad \text{(F-19)}$$

The systematic uncertainty of the RTD calibration is equal to the difference in sample mean between RTD and PRT.

$$b_{\bar{X}_{1,A}} = 0.05°\mathrm{C} \qquad \text{(F-20)}$$

The single value systematic uncertainty of the measured wet bulb $b_{\bar{X}_{2,B}}$ using the aspirated psychrometer as prescribed in RP-1460 accounts for RTD orientation with respect to sample flow, radiation parasitic, conduction parasitic, wetting length, RTD diameter, and sample velocity.

The systematic standard uncertainty of the Wet-Bulb temperature is calculated using the values in Table F-3

$$b_{\bar{X}} = \left[\sum_{k=1}^{K} \left(b_{\bar{X}_k}\right)^2\right]^{1/2} = 0.071°\mathrm{C} \qquad \text{(F-21)}$$

The random standard uncertainty of the Wet-Bulb temperature is calculated using

$$s_{\bar{X}} = \frac{1}{\sqrt{N}} \left[\sum_{k=1}^{K} \left(s_{\bar{X}_k}\right)^2\right]^{1/2} = 0.00056°\mathrm{C} \qquad \text{(F-22)}$$

The expanded uncertainty (TSM) for a 95% level of confidence and large degrees of freedom of the average Wet-Bulb temperature is evaluated using

$$U_{\bar{X}} = 2\sqrt{(b_{\bar{X}})^2 + (s_{\bar{X}})^2} = 0.14°\mathrm{C} \qquad \text{(F-23)}$$

TABLE F-3: Elemental standard uncertainties

Elemental Standard Uncertainty Classification	Description of Uncertainty Source	Elemental Uncertainty Value, °C
$b_{\bar{X}_{1,A}}$	RTD Calibration	0.05
$b_{\bar{X}_{1,B}}$	Calibration Reference	0.01
$b_{\bar{X}_{2,B}}$	Aspirated Psychrometer Method	0.05
$s_{\bar{X}_{1,A}}$	RTD Calibration	0.0025
$s_{\bar{X}_{2,A}}$	Random Standard U~~ncertainty~~ Deviation of Sample Mean	0.0019

Finally, the true average wet-bulb temperature (WBT) uncertainty during experiment is expected to lie within the following interval with 95% level of confidence. The annotation method of Equation 8-1 is shown in Equation F-24:

$$WBT = \bar{X} \pm U_{\bar{X}}\ (confidence\ level\ \%) = 18.88°\mathrm{C}\ \pm 0.14°\mathrm{C}\ (95\%) \qquad \text{(F-24)}$$

F3.2 Uncertainty Procedures[4] in IP units

F3.2.1 Random Standard ~~Uncertainty~~ Deviation of the Sample Mean

F3.2.1.1 General Case

The mean $\bar{X}$ is calculated by

$$\bar{X} = \frac{\sum_{j=1}^{N} X_j}{N} \ldots \qquad \text{(F-25)}$$

where

$N =$ the number of measurements made in the sample

X_j =the value of each individual measurement in the sample. The sample standard deviation is only an estimate of the population standard deviation and is given by

$$s_X = \sqrt{\sum_{j=1}^{N} \frac{\left(X_j - \bar{X}\right)^2}{(N-1)}} \qquad \text{(F-26)}$$

An appropriate random standard ~~uncertainty~~ deviation of the sample mean is

$$s_{\bar{X}} = \frac{s_X}{\sqrt{N}} \qquad \text{(F-27)}$$

Degrees of freedom

$$\nu = N - 1 \qquad \text{(F-28)}$$

F3.2.1.2 Using Previous Values of $s_{\bar{X}}$

Previous values of $s_{\bar{X}}$ are not applicable for this evaluation because a relatively large number of measurements, 61, will be made over a significant time frame, 30 minutes and steady state is determined prior to making measurements.

F3.2.1.3 Using Elemental Random Error Sources

Another method of estimating the random standard deviation of the sample mean for a measurement is from information about the elemental random error sources in the entire measurement process. If all the random standard uncertainties are expressed in terms of their contributions to the measurement, then the random standard uncertainty for the measurement mean is the root-sum square of the elemental random standard uncertainties of the mean from all sources divided by the square root of the number of current readings, averaged. The expected random error of measured Wet-Bulb temperature is given by RP-1460 and random error of the RTD calibration will be calculated from calibration data.

$$s_{\bar{X}} = \frac{1}{\sqrt{N}}\left[\sum_{k=1}^{K}\left(s_{\bar{X}_k}\right)^2\right]^{1/2} \quad \text{(F-29)}$$

where

$K =$ the total number of random error (or uncertainty) sources.

The degrees of freedom for the estimated random standard deviation of the sample mean is dependent on the information used to determine each of the elemental random standard uncertainties of the mean and is calculated as

$$\nu = \frac{\left(\sum_{k=1}^{K}\left(s_{\bar{X}_k}\right)^2\right)^2}{\left(\sum_{k=1}^{K}\frac{\left(s_{\bar{X}_k}\right)^4}{\nu_k}\right)} \quad \text{(F-30)}$$

where

$\nu_k =$ the degrees of freedom corresponding to each $s_{\bar{X}_k}$.

When all error sources have large sample sizes, the calculation of ν is unnecessary.

F3.2.1.2 Systematic Standard Uncertainty of a Measurement

The systematic standard uncertainty $b_{\bar{X}}$ of a measurement is a value that quantifies the dispersion of the systematic error associated with the mean. The true systematic error β is the unknown, but $b_{\bar{X}}$ is evaluated so that it represents an estimate of the standard deviation of the distribution for the possible β values. It should be noted that while $b_{\bar{X}}$ is an estimate of the dispersion of the systematic errors in a measurement, the systematic error that is present in specific measurement is a fixed single value of β.

The systematic standard uncertainty of the measurement is the root-sum-square of the elemental systematic standard uncertainties $b_{\bar{X}_k}$ for all sources following the Taylor Series Method (TSM).

$$b_{\bar{X}} = \left[\sum_{k=1}^{K}\left(b_{\bar{X}_k}\right)^2\right]^{1/2} \quad \text{(F-31)}$$

where

$b_{\bar{X}_k}$ = each estimate of the standard deviation of the k^{th} elemental error source

K = the total number of systematic error sources

The elemental systematic standard uncertainties are expressed in terms of their contributions to the measurement. For each systematic error source in the measurement, the elemental systematic standard uncertainty must be estimated from the best available information. Usually, these estimates are made using engineering judgment. Sometimes previous data are available to make estimates of uncertainties that remain fixed during a test.

There can be many sources of systematic error in measurement, such as the calibration process, instrument systematic errors, transducer errors, and fixed errors of method. Also, environmental effects, such as radiation effects in a temperature measurement, can cause systematic errors of method. There usually will be some elemental systematic standard uncertainties that will be dominant. Because of the resulting effect of combining the elemental uncertainties in a root-sum square manner, the larger or dominant ones will control the systematic uncertainty in the measurement; however, one should be very careful to identify all significant sources of fixed error in the measurement.

F3.2.1.3 Classification of Uncertainty Sources

Type A uncertainties are the calculated standard deviations obtained from data sets. Type B uncertainties are those that are estimated or approximated rather than calculated from data. Type B uncertainties are also given as estimated standard deviations. Uncertainties are classified by their effect on the measurement, either random or systematic, rather than by their source. When it is convenient to classify elemental uncertainties by both effect and source, the following nomenclature for dual classifications is recommended:

$b_{\bar{X}_{k,A}}$ = elemental systematic standard uncertainty calculated from data, as in a calibration process
$b_{\bar{X}_{k,B}}$ = elemental systematic standard uncertainty estimated from the best available information
$s_{\bar{X}_{k,A}}$ = elemental random standard uncertainty calculated from data
$s_{\bar{X}_{k,B}}$ = elemental random standard uncertainty estimated from best available information

F3.2.4 Combined Standard and Expanded Uncertainty of a Measurement

For simplicity of presentation, a single value is often preferred to express the estimate of the error between the mean value $\bar{X}$ and the true value $U_{\bar{X}}$ with a defined level of confidence $P\%$. The interval

$$\bar{X} \pm U_{\bar{X}}\ (P\%) \tag{F-32}$$

represents a band about $\bar{X}$ within which the true value is expected to lie within a given level of confidence. The uncertainty interval is composed of both the systematic and random uncertainty components.

The general form of the expression for determining the uncertainty of a measurement is the root-sum-square of the systematic and random standard uncertainties for the measurement, with this quantity defined as the combined standard uncertainty $u_{\bar{X}}$ TSM:

$$u_{\bar{X}} = \sqrt{(b_{\bar{X}})^2 + (s_{\bar{X}})^2} \tag{F-33}$$

where

$b_{\bar{X}} =$ the systematic standard uncertainty

$s_{\bar{X}} =$ the random standard deviation of the sample mean

In order to express the uncertainty at a specified confidence level using the TSM, the combined standard uncertainty must be multiplied by an expansion factor taken as the appropriate Student's t value for the required confidence level. Depending on the application, various confidence levels may be appropriate. The Student's t is chosen on the basis of the level of confidence desired and the degrees of freedom. The degrees of freedom used is a combined degrees-of-freedom based on the separate degrees of freedom for the random standard uncertainty and the elemental systematic standard uncertainty. A t value of 1.96 (usually taken as 2) corresponds to large degrees of freedom and defines an interval with a level of confidence of approximately 95%. This expansion factor of 2 is used for most engineering applications.

The expanded uncertainty for a 95% level of confidence and large degrees-of-freedom (t = 2) is calculated per the TSM:

$$U_{\bar{X}} = 2u_{\bar{X}} \tag{F-34}$$

The expression for the expanded uncertainty given in Equation F-34 applies when the measurement $\bar{X}$ is the desired result of the experiment.

TABLE F-4: Measured wet bulb temperature

Elapsed Time, min	Measured WET-BULB TEMPERATURE, °F	Elapsed Time, min	Measured WET-BULB TEMPERATURE, °F	Elapsed Time, min	Measured WET-BULB TEMPERATURE, °F
0	65.97	10.5	66.04	20.5	66.00
0.5	65.97	11	66.02	21	66.02
1	65.97	11.5	66.00	21.5	66.00
1.5	65.98	12	66.00	22	66.02
2	65.98	12.5	65.98	22.5	66.00
2.5	65.98	13	65.98	23	66.00
3	65.98	13.5	65.97	23.5	66.00
3.5	66.00	14	65.97	24	65.98
4	66.02	14.5	65.97	24.5	65.98
4.5	66.00	15	65.97	25	65.97
5	66.00	15.5	65.97	25.5	65.97
5.5	66.00	16	65.97	26	65.97
6	66.02	16.5	65.97	26.5	65.97
6.5	66.02	17	65.97	27	65.95
7	66.02	17.5	65.97	27.5	65.95
7.5	66.04	18	65.98	28	65.97
8	66.04	18.5	65.98	28.5	65.97
8.5	66.04	19	65.98	29	65.97
9	66.06	19.5	66.00	29.5	65.97
9.5	66.06	20	66.00	30	65.97
10	66.04				

The sample mean, or average value, of the Wet-Bulb temperature measurements is determined using

$$\bar{X} = \frac{\sum_{j=1}^{N} X_j}{N} = 65.99°\text{F} \qquad \text{(F-35)}$$

The sample standard deviation is determined using

$$s_X = \sqrt{\sum_{j=1}^{N} \frac{\left(X_j - \bar{X}\right)^2}{(N-1)}} = 0.027°\text{F} \qquad \text{(F-36)}$$

The random standard ~~uncertainty~~ deviation of the sample mean is determined using

$$s_{\bar{X}} = \frac{s_X}{\sqrt{N}} = 0.0034°\text{F} \qquad \text{(F-37)}$$

The lab in question utilizes a water bath to calibrate RTDs against a Reference Platinum Resistance Thermometer PRT over an array of setpoints. The stability of water bath is held to produce <0.09°F variation during the calibration run. A linear interpolation table is generated for use by the data acquisition system correction of RTD to Reference PRT. Once the calibration is successful, a one-minute check is performed which is shown in the following table.

TABLE F-5: RTD calibration check

Elapsed Time, s	RTD, °F	Reference PRT, °F	Elapsed Time, s	RTD, °F	Reference PRT, °F
0	71.948	72.042	31	71.948	72.042
1	72.048	72.043	32	72.048	72.041
2	71.948	72.043	33	71.948	72.041
3	71.948	72.044	34	71.948	72.04
4	72.048	72.044	35	71.948	72.039
5	71.948	72.044	36	71.948	72.039
6	71.948	72.042	37	71.948	72.041
7	71.948	72.043	38	72.048	72.041
8	71.948	72.042	39	71.948	72.042
9	71.948	72.043	40	71.948	72.042
10	71.948	72.041	41	72.048	72.042
11	71.948	72.042	42	71.948	72.041
12	71.948	72.042	43	71.948	72.04
13	71.948	72.042	44	72.048	72.041
14	72.048	72.042	45	71.948	72.04
15	71.948	72.043	46	71.948	72.041
16	72.048	72.043	47	71.948	72.041
17	71.948	72.043	48	71.948	72.04
18	71.948	72.042	49	71.948	72.041
19	71.948	72.041	50	71.948	72.038
20	71.948	72.041	51	71.948	72.04
21	71.948	72.042	52	71.948	72.039
22	71.948	72.042	53	71.948	72.039
23	71.948	72.042	54	72.048	72.039
24	71.948	72.043	55	71.948	72.04
25	71.948	72.043	56	71.948	72.04
26	71.948	72.041	57	71.948	72.041
27	71.948	72.042	58	71.948	72.04
28	71.948	72.041	59	71.948	72.041
29	71.948	72.041	60	71.948	72.04
30	71.948	72.041			

The sample mean, or average value, of the RTD measurements is determined using

$$\bar{X}_{RTD} = \frac{\sum_{j=1}^{N} X_j}{N} = 71.96°\text{F} \tag{F-38}$$

The sample standard deviation of the RTD readings is determined using

$$s_{X_{RTD}} = \sqrt{\sum_{j=1}^{N} \frac{\left(X_j - \bar{X}\right)^2}{N-1}} = 0.034°\text{F} \tag{F-39}$$

The random standard deviation of the sample mean for the RTD is determined using

$$s_{\bar{X}_{RTD}} = \frac{s_{X_{RTD}}}{\sqrt{N}} = 0.0046°\text{F} \tag{F-40}$$

The sample mean, or average value, of the PRT measurements is determined using

$$\bar{X}_{PRT} = \frac{\sum_{j=1}^{N} X_j}{N} = 72.04°\text{F} \tag{F-41}$$

The sample standard deviation of the PRT readings is determined using

$$s_{X_{PRT}} = \sqrt{\sum_{j=1}^{N} \frac{\left(X_j - \bar{X}\right)^2}{(N-1)}} = 0.0014°\text{F} \tag{F-42}$$

The random standard deviation of the sample mean for the PRT is determined using

$$s_{\bar{X}_{PRT}} = \frac{s_{X_{PRT}}}{\sqrt{N}} = 0.00017°\text{F} \tag{F-43}$$

The systematic uncertainty of the RTD calibration is equal to the difference in sample mean between RTD and PRT.

$$b_{\bar{X}_{1,A}} = 0.08°\text{F} \tag{F-44}$$

The single value systematic uncertainty of the measured wet bulb $b_{\bar{X}_{2,B}}$ using the aspirated psychrometer as prescribed in RP-1460 accounts for RTD orientation with respect to sample flow, radiation parasitic, conduction parasitic, wetting length, RTD diameter, and sample velocity.

The systematic standard uncertainty of the wet-bulb temperature is calculated using the values in Table F-6

$$b_{\bar{X}} = \left[\sum_{k=1}^{K} \left(b_{\bar{X}_k}\right)^2\right]^{1/2} = 0.12°\text{F} \tag{F-45}$$

The random standard uncertainty of the Wet-Bulb temperature is calculated using

$$s_{\bar{X}} = \frac{1}{\sqrt{N}} \left[\sum_{k=1}^{K} \left(s_{\bar{X}_k}\right)^2\right]^{1/2} = 0.001°\text{F} \tag{F-46}$$

The expanded uncertainty (TSM) for a 95% level of confidence and large degrees of freedom of the average Wet-Bulb temperature is evaluated using

$$U_{\bar{X}} = 2\sqrt{(b_{\bar{X}})^2 + (s_{\bar{X}})^2} = 0.24°\text{F} \tag{F-47}$$

TABLE F-6: Elemental standard uncertainties

Elemental Standard Uncertainty Classification	Description of Uncertainty Source	Elemental Uncertainty Value, °F
$b_{\bar{X}_{1,A}}$	RTD Calibration	0.08
$b_{\bar{X}_{1,B}}$	Calibration Reference	0.018
$b_{\bar{X}_{2,B}}$	Aspirated Psychrometer Method	0.09
$s_{\bar{X}_{1,A}}$	RTD Calibration	0.0045
$s_{\bar{X}_{2,A}}$	Random Standard Deviation of Sample Mean	0.0034

Finally, the true average measured wet-bulb temperature (WBT) during experiment is expected to lie within the following interval with 95% level of confidence, The annotation method of Equation 8-1 is shown in Equation F-48:

$$WBT = \bar{X} \pm U_{\bar{X}}(confidence\ level\ \%) = 65.99°\text{F} \ \pm 0.26°\text{F}\ (95\%) \tag{F-48}$$