

ANSI/ASHRAE Standard 41.6-1994 (RA 2006)
Reaffirmation of ANSI/ASHRAE Standard 41.6-1994



ASHRAE STANDARD

Standard Method for Measurement of Moist Air Properties

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NOTE

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FOREWORD

This is a reaffirmation of ASHRAE Standard 41.6-1994. This standard falls under the Standards Committee classification of Standard Method of Measurement. This standard was prepared under the auspices of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). It may be used, in whole or in part, by an association or government agency with due credit to ASHRAE. Adherence is strictly on a voluntary basis and is merely in the interest of obtaining uniform standards throughout the industry.

The changes made for the 1989 revision were:

- moving "Definitions" in old Section 8 into Section 3
- moving old Subsection 3.2, "Instruments and Sensors," to new Section 5
- adding Subsection 7.5, "International Temperature Scale of 1990"
- adding Appendix D, "Calculation of Moist Air Properties"

There were no changes made for the 2006 reaffirmation.

1. PURPOSE

1.1 This standard sets forth recommended practices and procedures for the measurement and calculation of moist air properties in order to promote accurate measurement methods for specific use in the preparation of other ASHRAE standards.

1.2 This standard recommends procedures for measurement of moist air properties in connection with

- a. the establishment of the desired moist air environment for tests of heating, refrigerating, humidifying, dehumidifying, and other air-conditioning equipment and
- b. the determination of the quantity of moisture in air-streams moving through or within such equipment or spaces.

2. SCOPE

The scope of this standard is to describe various instruments and techniques for the measurement of moist air properties. Attention is given to methods appropriate for use in ASHRAE standard methods of test for rating or for determining compliance with ASHRAE environmental standards. These descriptions include the range of conditions over which their use is practicable, the associated attainable accuracy, and proper techniques of use to achieve desired accuracy. Specific attention is given to the wet-bulb and dry-bulb psychrometer and the dew-point hygrometer, while other methods also are discussed. A discussion also is presented concerning calibration, reference standards, and traceability to standards of the National Institute of Standards and Technology (NIST) to help ensure accurate measurements.

3. DEFINITIONS OF PSYCHROMETRIC TERMS, INSTRUMENTS, AND INDICATION ELEMENTS

The relationship between various units in humidity measurement is shown in Figure 3-1.

3.1 **Definitions and Calculations of Psychrometric Terms.** Moist air is defined as a mixture of dry air and water vapor. The thermodynamic state of any two-component mixture is fixed if three independent properties are known. For moist air, two of the properties are usually temperature (*t*) and

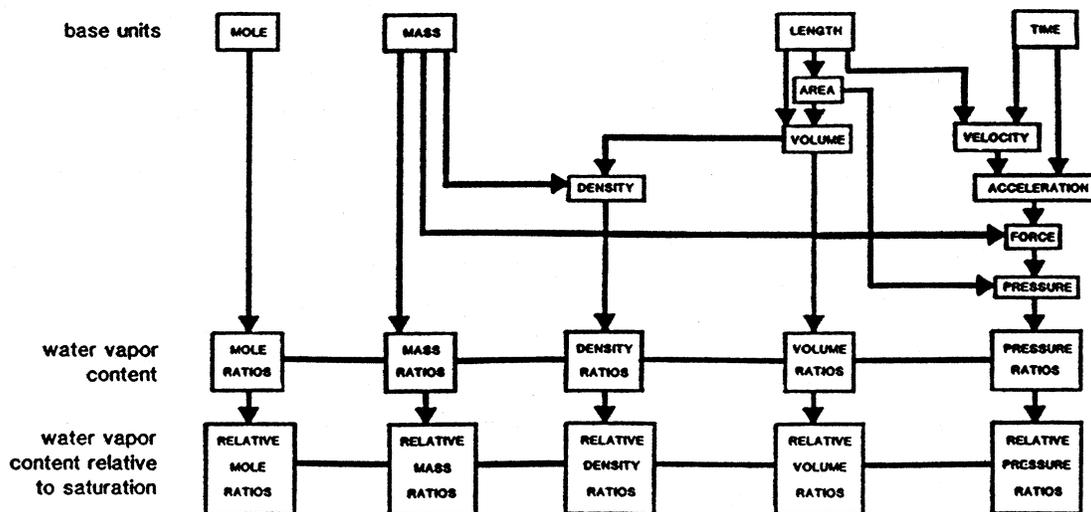


Figure 3-1

pressure (p), and the third is some property that indicates the moisture content of the mixture. The various types of moisture-measuring devices described in this standard do not express the moisture content in the same way. It is the purpose of this section to show how the various properties of moist air other than those measured can be calculated. In general, these other properties can be determined from Hyland and Wexler, ASHRAE RP-216,⁹ ideal gas equations, and psychrometric charts.

The Hyland and Wexler methods are the most accurate available; but, except for standard atmospheric pressure (101.3 kPa), they require computerized calculations. For information about Hyland and Wexler methods, see *ASHRAE Transactions*, volume 89, part 2, 1983, pp. 500-548.

The ideal gas relations can be used for the majority of air-conditioning problems to substantially increase the ease, rapidity, and economy of the calculations with only a slight loss of accuracy. The errors decrease with decreasing pressure. At one atmosphere, when ideal gas relations are used in the calculation of the mixing (humidity) ratio, enthalpy, and specific volume, the errors will be less than 0.7% in the temperature range from -50°C to $+50^{\circ}\text{C}$. The ASHRAE psychrometric chart is the simplest and quickest method to estimate other properties, except for partial water vapor pressures and entropy. With careful use, a large chart that is appropriate for the pressure of the environment can give good accuracy for engineering design and field work.

3.1.1 Fundamental Humidity Parameters

Mixing (humidity) ratio (W): For a given moist air sample, the ratio of the mass of water vapor (m_w) to the mass of dry air (m_a) contained in the sample:

$$W = m_w/m_a \quad (1)$$

Mole fraction (X_i): For a given component in a mixture, the number of moles (n_i) of that component divided by the total number of moles (n) of all components in the mixture. The mole fraction for dry air is X_a ; for water vapor, X_w ; for water vapor at saturation, X_{ws} . By definition, $X_a + X_w = 1$. Also, W is equal to the mole fraction ratio (X_w/X_a) multiplied by the ratio of molecular weights, namely, $18.01528/28.9645 = 0.62198$, i.e.,

$$W = 0.62198X_w/X_a \quad (2)$$

Specific humidity (q): The ratio of the mass of water vapor to the total mass of the moist air sample:

$$q = (m_w/(m_w + m_a)) \quad (3)$$

In terms of the mixing (humidity) ratio,

$$q = (W/(W + 1)) \quad (4)$$

Absolute humidity (alternatively, water vapor density) (d_v): The ratio of the mass of water vapor to the total volume (V) of the sample:

$$d_v = m_w/V \quad (5)$$

Density (ρ): For a moist air mixture, the ratio of the total mass to the total volume:

$$\rho = (m_a + m_w)/V = (1/v)(1 + w) \quad (6)$$

where

v = specific volume of the moist air mixture (m^3/kg dry air), as defined by Equation 22.

3.1.2 Humidity Parameters Involving Saturation

Saturation mixing (humidity) ratio, $W_s(t, p)$: The mixing (humidity) ratio of moist air saturated with respect to water (or ice) at the same temperature, t , and pressure, p .

Degree of saturation, μ : The ratio of the air mixing (humidity) ratio, W , to the mixing (humidity) ratio, W_s , that the air would have if it were saturated with respect to water at the same temperature and pressure:

$$\mu = (W/W_s)_{t,p} \quad (7)$$

Relative humidity, ϕ : The ratio in percent of mole fraction of the water vapor, X_w , in a given moist air sample to the mole fraction, X_{ws} , in a saturated air sample at the same temperature, t , and pressure, p :

$$\phi = 100(X_w/X_{ws})_{t,p} \quad (8)$$

Thermodynamic dew-point temperature, t_d : For moist air at pressure p and with mixing (humidity) ratio W , the temperature at which the moist air, saturated with respect to water (or ice) at the given pressure, has a saturation mixing (humidity) ratio, W_s , equal to the given mixing (humidity) ratio, W . It is defined as the solution, $t_d(p, W)$, of the equation

$$((W/W_s)(t_d))_p = 1 \quad (9)$$

Thermodynamic wet-bulb temperature, t^* : For moist air at pressure p , temperature t , and mixing (humidity) ratio W , the temperature t^* attained by the moist air when brought adiabatically to saturation at pressure p by the evaporation into the moist air of liquid water at pressure p and temperature t^* . In this process, the mixing (humidity) ratio is increased from a given initial value W to the value W_s^* corresponding to saturation at temperature t^* ; the enthalpy is increased from a given initial value h to the value h_s^* , corresponding to saturation at temperature t^* ; the mass of water added per kilogram of dry air is $(W_s^* - W)$, which adds energy to the moist air of amount $(W_s^* - W)h_w$, where h_w denotes the specific enthalpy of the water added at temperature t^* . Therefore, in adiabatic isobaric processes, the conservation of enthalpy requires that

$$h + (W_s^* - W)h_w^* = h_s^* \quad (10)$$

The properties W_s^* , h_w^* , and h_s^* are functions only of temperature t^* for a fixed value of pressure. The value of t^* , which satisfies Equation 10 for given values of h , W , and p , is called the thermodynamic wet-bulb temperature.

3.1.3 Ideal Gas Relationships for Dry and Moist Air: When moist air is considered to be a mixture of independent

ideal gases, dry air, and water vapor, each is assumed to obey the ideal gas equation of state:

$$\text{Dry Air: } p_a V = N_a R T \quad (11)$$

$$\text{Water Vapor: } P_w V = N_w R T \quad (12)$$

where

p_a = partial pressure of dry air,

p_w = partial pressure of water vapor,

V = total mixture volume,

N_a = number of moles of dry air,

N_w = number of moles of water vapor,

R = universal gas constant (8.31441 (Pa·m³)/(mole·K)), and

T = absolute temperature (K).

The mixture also obeys the ideal gas equation:

$$pV = NRT \quad (13)$$

or

$$(p_a + p_w)V = (N_a + N_w)RT \quad (14)$$

where

p = $p_a + p_w$ =total mixture pressure and

N = $N_a + N_w$ =total number of moles in the mixture.

From Equations 11 and 12, the mole fractions of dry air and water vapor are, respectively,

$$X_a = p_a / (p_a + p_w) = p_a / p \quad (15)$$

and

$$X_w = p_w / (p_a + p_w) = (p_w / p) . \quad (16)$$

Mixing (humidity) ratio (W): From Equations 2, 15, and 16, the mixing (humidity) ratio is given by

$$W = 0.62198 p_w / (p - p_w) . \quad (17)$$

Degree of saturation: The degree of saturation, μ , is (by definition, Equation 7)

$$\mu = (W / W_s)_{t,p}$$

where one may write

$$W_s(p, t) = (0.62198(p_{ws}(t)) / (p - p_{ws}(t))) . \quad (18)$$

The term $p_{ws}(t)$ represents the saturation pressure of water vapor at the given temperature, t . This pressure, $p_{ws}(t)$, is a function only of temperature and differs slightly from the vapor pressure of water in saturated moist air, designated by p_s . The latter, a function of both the pressure and the temperature of the mixture, is defined by the relation $p_s = p X_{ws}$.

Relative humidity: The relative humidity, ϕ , in percent is (by definition, Equation 8):

$$\phi = 100(X_w / X_{ws})$$

Substituting Equation 16 for X_w and X_{ws} ,

$$\phi = 100 p_w / p_{ws}(t) . \quad (19)$$

Combining Equations 2, 7, 8, and 16 yields

$$\phi = 100 \mu / [1 - (1 - \mu)(p_{ws}(t) / p)] . \quad (20)$$

Both ϕ and μ are zero for dry air and unity for saturated moist air. Their values will differ at intermediate states and substantially so at higher temperatures.

Specific volume: The specific volume, v , of a moist air mixture is expressed in terms of a unit mass of dry air, i.e.,

$$v = V / m_a = V / (28.9645 N_a) \quad (21)$$

where

V = total volume of the mixture,

m_a = total mass of dry air, and

N_a = number of moles of dry air.

By Equations 11 and 21, with the relation $p = p_a + p_w$,

$$v = R_a T / (p - p_w) \quad (22)$$

where

$$R_a = R / 28.9645 = 0.287055 \text{ (Pa·m}^3\text{)/(mole·K)}.$$

By utilizing Equations 17 and 22, one can develop the following equation for convenience in calculations:

$$v = (R_a T / p) (1 + 1.6078 W) \text{ for } p_w / p \ll 1 \quad (23)$$

In Equations 22 and 23, v is specific volume (m³/kg dry air), T is absolute temperature (K), p is total pressure (kPa), p_w is the partial pressure of water vapor (kPa), and W is the mixing (humidity) ratio (kg water/kg dry air).

Enthalpy: The enthalpy of a mixture of ideal gases equals the sum of the individual partial enthalpy of the components. Therefore, the enthalpy of moist air can be written as

$$h = h_a + W h_g \quad (24)$$

where

h_a = specific enthalpy for dry air (assigned a value of 0 for 0°C) and

h_g = specific enthalpy for saturated water vapor at the temperature of the mixture.

Therefore,

$$h_a \approx 1.005 t \text{ kJ/kg} \quad (25)$$

and

$$h_g \approx 2500.9 + 1.805 t \text{ kJ/kg} \quad (26)$$

where

t is the dry-bulb temperature (°C). The moist air enthalpy then becomes

$$h \approx 1.005 t + W(2500.9 + 1.805 t) \text{ kJ/kg dry air.} \quad (27)$$

Note: Consult the information given in 3.1 regarding the range of applicability of Equations 25, 26, and 27.

Thermodynamic wet-bulb temperature: This property of a given moist air sample is independent of the measurement techniques utilized. Clear understanding of its concept is important in correctly applying psychrometric data. Equation 10 is exact since it defines the thermodynamic wet-bulb temperature, t_w^* . Substituting the approximate ideal gas relation (Equation 27) for h , the corresponding expression for $h_s[p, t^*, W_s^*]$, and the approximate relation

$$h_w^* \approx 4.186t^* \text{ kJ/kg} \quad (28)$$

into Equation 10 and solving for the mixing (humidity) ratio, then

$$W \approx [(2501 - 2.381t^*)W_s^* - (t - t^*)] / (2501 + 1.805t - 4.186t^*) \quad (29)$$

where t and t^* are in degrees Celsius.

Dew-point temperature: The thermodynamic dew-point temperature (t_d) of moist air with mixing (humidity) ratio W and pressure p was defined earlier as the solution $t_d(p, W)$ of $W_s(p, t_d) = W$. For the case of ideal gases, this reduces to

$$p_{ws}(t_d) = p_w = pW / (0.62198 + W), \text{ kPa} \quad (30)$$

where

P_w = water vapor partial pressure for the moist air sample and

$P_{ws}(t_d)$ = saturation pressure of water vapor at temperature t_d . The saturation vapor pressure may be found from the *ASHRAE Handbook—Fundamentals*¹² psychrometric tables.

Alternatively, the dew-point temperature may be calculated directly by one of the following equations.

For the temperature range of 0°C to 93°C,

$$t_d = 6.54 + 14.526[\ln(p_w)] + 0.7389[\ln(p_w)]^2 + 0.09486[\ln(p_w)]^3 + 0.4569(p_w)^{0.1984} (\text{°C}) \quad (31)$$

where p_w is in kPa.

The errors in the dew-point determination using Equation 31 are shown in the following table.

Dew-Point Temperature (°C)	Error (°C)
65	-0.0181
55	+0.0084
45	+0.2301
35	+0.0245
25	+0.0015
15	-0.0278
5	-0.0170
0	-0.0294

For temperatures from 0°C to 45°C,

$$t_d = 6.09 + 12.608[\ln(p_w)] + 0.4959[\ln(p_w)]^2 (\text{°C}) \quad (32)$$

where p_w is in kPa and t_d' is the frost-point temperature. The errors in frost point resulting from the use of Equation 32 are shown in the following table.

Frost-Point Temperature (°C)	Error (°C)
0	-0.0023
-5	-0.0057
-15	-0.0024
-25	-0.0692
-35	-0.3322
-45	-0.9677
-55	-2.1732

3.1.4 Aspirated Psychrometer

Thermometer: For purposes of this standard, except where a specific type is indicated, the term *thermometer* means any temperature-measuring device.

Psychrometer: An instrument for measuring relative humidity that essentially consists of two thermometers, the sensors of which are, respectively, wet and dry. The wet and dry sensors are termed *wet* and *dry bulbs*.

Wet-Bulb Covering and Wick: The wet bulb is provided with a water-retaining covering made of a woven cotton material. A cotton wick that connects the covering to a water reservoir may be provided so that water is fed continuously to the covering by capillary action.

Ventilation and Aspiration: The wet and dry bulbs (and the psychrometer) are described as ventilated because there is provision for a flow of air over the bulbs. Aspiration is the provision of forced ventilation by drawing air over the bulbs by suction. The flow may be either transverse or parallel to the axes of the bulbs.

Temperature Depression: The difference between the readings of the wet-bulb and dry-bulb thermometers is termed the *wet-bulb temperature depression* or, simply, the temperature depression.

4. CLASSIFICATION OF INSTRUMENTS

The majority of the more common humidity-measuring instruments are defined in Section 5. Some of these instruments are more suitable for laboratory work than others, and several can be used as calibration standards. The relationship between the types of instruments is shown in Figure 4-1.

The national humidity standard is the National Institute of Standards and Technology gravimetric hygrometer, which is described in 4.1. Precision humidity generators are described in 4.2. Secondary standards are presented in 4.3, working standards in 4.4, and working hygrometers in 4.5.

4.1 National Institute of Standards and Technology Gravimetric Hygrometer

The current state of the art in a precision humidity instrument is the gravimetric hygrometer developed and maintained by the National Institute of Standards and Technology, Gaithersburg, Maryland. The gravimetric hygrometer yields a determination of absolute water vapor content, since the

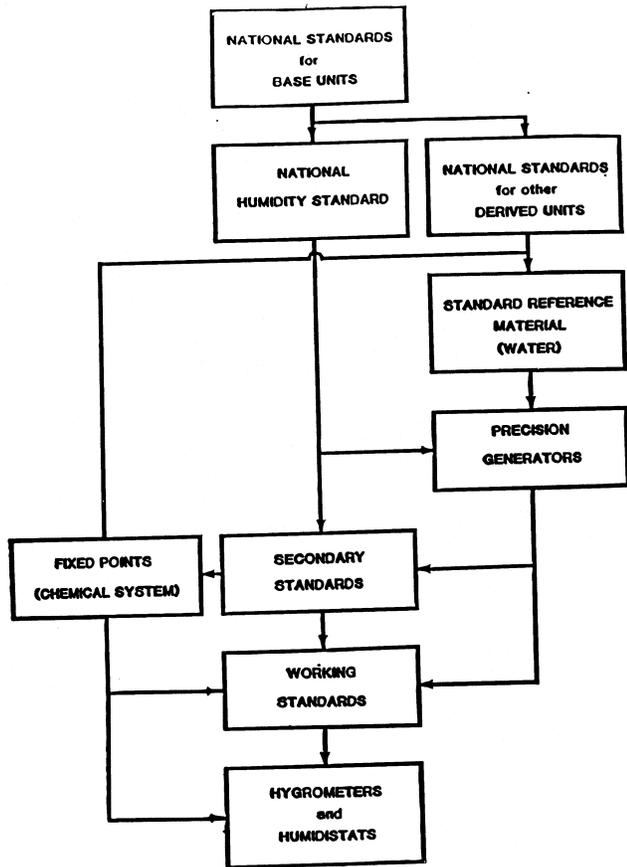


Figure 4-1 Hierarchy of humidity standards.

weight of the water absorbed and the precise measurement of the gas volume associated with the water vapor determine the absolute humidity of the incoming air.

In this system, the test gas flows from a humidity generator through a drying train and into a precision gas-volume-measuring system contained within a temperature-controlled bath. The precise measurements of the mass of water vapor absorbed from the test gas and the associated volume of dry gas as measured at closely controlled temperatures and pressures (which allows computation of the mass of dry gas associated with the collected mass of water) accurately define the mixing (humidity) ratio of the test gas or any other expression of humidity. When employed as a calibration instrument, the humidity generator provides the test gas to the gravimetric hygrometer as well as to the instrument undergoing calibration.

This system has been chosen as the primary standard because the required measurements of mass, temperature, pressure, and volume can be made with extreme precision. However, the NIST gravimetric hygrometer is a rather unwieldy instrument to use and, in the low humidity ranges, may require up to 30 hours per calibration point. For this reason, the gravimetric hygrometer is not used for normal calibration purposes and would not be useful for process measurement and control. NIST has developed and calibrated a two-pressure humidity generator, which is commonly used as the NIST calibration standard.

4.2 Precision Humidity Generators. Moist air generators are humidity sources that can be used to calibrate other instruments (secondary standards and working standards) and for other uses. They work on basic physical principles and are of the following types:

- two-pressure humidity generator (4.2.1),
- two-temperature humidity generator (4.2.2),
- divided-flow system (4.2.3), and
- saturated salt solutions (4.2.4).

4.2.1 Two-Pressure Humidity Generator. The two-pressure system is a humidity generator that operates on the principle of saturating a gas 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 gas behavior is assumed, the percent relative humidity at the new pressure (P_t) may be expressed as a ratio of the two absolute pressures:

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

where

P_t = test chamber pressure,

P_s = saturator pressure, and

t = temperature of test chamber and saturator.

The amount of deviation from ideal gas laws was determined by Hyland of the National Institute of Standards and Technology 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.

4.2.2 Two-Temperature Humidity Generator. In the two-temperature system, air is saturated at one temperature, then is heated to a higher one. This results in a new relative humidity, which is a function of the two temperatures. In this method, the air normally is recirculated around a closed loop that includes the two chambers. A pressure difference exists

because of piping loss, which must be taken into account when calculating relative humidity.

4.2.3 Divided-Flow System. In the divided-flow system, a stream of dry air is divided into two parts. One part is saturated, and the two then are recombined. The final humidity depends on the ratio of the initial division.

4.2.4 Saturated Salt Solutions. Saturated salt solutions are suitable 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 many 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 approximately 5% to 100%, depending on the temperature and the salt used. Table 4-1 contains results based on a number of studies.

Saturated salt solutions are useful in controlling humidity in enclosed spaces, but leakage of moisture into or out of the enclosure may affect the humidity level significantly. The use of a slushy mixture permits relatively 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, care must be exercised to ensure that some liquid is present.

Most 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 such a quadruple point, there may be some doubt as to the vapor pressure. It is advisable, therefore, to exercise care or to avoid using a salt solution within 3°C to 5°C of such a temperature.

Care should be taken in the selection of salts because some appear to affect the Dunmore-type sensors adversely and possibly other sensors as well.

Sulfuric acid and glycerine water solutions can be used to produce known humidities through selection of the correct concentration. Care should be employed by ensuring that the particular sensor to be calibrated will not be damaged by the vapor.

4.3 Secondary Standards

Secondary standards are those devices or instruments that can be used for calibration of working standards (4.4) or can be used to directly determine the humidity level of a sample of moist air. They may require an initial calibration (4.6). The accepted secondary standards are

- aspirated psychrometer (5.1),
- chilled-mirror dew-point devices (5.2), and
- pneumatic bridge device (5.3).

4.4 Working Standards. Working standards or devices are those instruments that are easy to use in laboratory or field applications but require periodic calibration (4.6), such as

- expansion chambers (5.10) and
- electric hygrometers (5.4, 5.6, 5.7, 5.8, and 5.9).

4.5 Working Hygrometers. Several mechanical devices are available for indicating the moisture content of air. These devices are discussed in 5.10. They are not acceptable for precise humidity measurements because of unstable calibration, hysteresis effects, and poor response times.

4.6 Calibration. In order to relate the output from a humidity sensor to the actual humidity, it is necessary to employ calibration. For example, the relationship between the ambient humidity and the indication given by a hair hygrometer or the electrical resistance of a Dunmore-type sensor could not be

**TABLE 4-1
Equilibrium Relative Humidities over Saturated Salt Solution**

Salt	Temperature, °C										
	0	10	20	30	40	50	60	70	80	90	100
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

predicted accurately except through the use of experimental observations involving known humidity. Also, the response of certain instruments can be expected to drift with time; therefore, periodic calibration is required. The need for recalibration depends on the required accuracy, the stability of the sensor, and the conditions to which the sensor is being subjected. Other hygrometers, such as the psychrometer and the dewpoint hygrometer, yield an output that can be related to the ambient humidity in a more readily predictable way. For these, an initial calibration may be required to account for small, indeterminate errors arising from their principle of operation and the peculiarities of individual instrument design. Once this has been done, however, the calibration may be adequate for the hygrometer for a period of one to two years. When periodic recalibration of a hygrometer is necessary, the user may find it practical to set up a calibration system or may find it advantageous to make use of an agency that provides calibration services, such as the National Institute of Standards and Technology in the United States or the National Research Council, Division of Building Research, in Canada.

Calibration Systems. Calibration requires a reliable technique for developing humidity of an accurate, known level. Accepted techniques are the

- two-pressure system (4.2.1),
- two-temperature system (4.2.2),
- divided-flow system (4.2.3),
- pneumatic bridge device (4.2.4).

5. INSTRUMENTS AND SENSORS

There are a variety of instruments available for measuring the moisture content of air. The indication sensors that are used on these instruments respond to different levels of moisture content. These responses are related to parameters such as wet-bulb temperature, relative humidity, mixing (humidity) ratio, dew/frost point, and others. These parameters can be measured by a number of different types of instruments, each capable of accurate measurement under certain conditions and within specific limitations. The most common types of instruments are described in the following paragraphs.

5.1 Psychrometers (Wet-Bulb and Dry-Bulb Measurements). Psychrometers have been used for a long time, primarily because of their simplicity and low cost. A typical industrial psychrometer consists of a pair of matched electrical or mechanical temperature sensors, one of which is maintained in a wetted condition with a moistened wick. A blower aspirates the sensor at a specific flow rate. This causes a depression of the moistened temperature sensor and one observes the lowest depression. The lowest depression occurs when the evaporation rate required to saturate the moist air adjacent to the wick is constant. This is a steady-state, open-loop, nonequilibrium process and is dependent upon the purity of the water, cleanliness of the wick, ventilation rate, radiation effects, size and accuracy of the temperature sensors, and the transport properties of the gas.

A properly designed and utilized psychrometer, such as the Assman laboratory type, is capable of providing accurate data. However, very few industrial psychrometers meet these

criteria and therefore are limited to applications where low cost and moderate accuracy are the underlying requirements. The accuracy for psychrometric measurements is not limited to the accuracy of temperature measurements. Some of the other factors involved are the accuracy of the psychrometric coefficient, pressure error, radiation and conduction errors, etc.

The psychrometer does have certain inherent advantages:

- a. Psychrometers will not suffer irreversible damage to the sensors at 100% RH, as will occur with most electric hygrometers.
- b. Although large errors can occur if the wet bulb becomes contaminated or is improperly fitted, the simplicity of the device affords easy repair at low cost.
- c. The psychrometer can be used at ambient temperatures up to 100°C and the wet-bulb measurement is usable up to 100°C.

Major shortcomings of the psychrometer are as follows:

- a. As relative humidity drops to values below approximately 20%, the problem of cooling the wet bulb to its full depression becomes difficult. The result is seriously impaired accuracy below 20% RH, and only a few psychrometers will function below 10% RH.
- b. Wet-bulb measurements at temperatures below 0°C are difficult to obtain with a high degree of confidence. Automatic water feeds are not feasible because of freezing.

5.2 Condensation-Type Dew-Point Instrument (Chilled Mirror). The condensation-type (chilled mirror) dew-point hygrometer is an accurate and reliable instrument with a wide humidity range. However, these features are obtained through an increase in complexity and cost. In the condensation-type hygrometer, a surface is cooled (either thermoelectrically, mechanically, or chemically) until dew or frost begins to condense out. The condensate surface is maintained electronically in vapor pressure equilibrium with the surrounding gas, while surface condensation is detected by optical, electrical, or nuclear techniques. The measured surface temperature is the dew-point temperature. The largest source of error in a condensation hygrometer stems from the difficulty in accurately measuring condensate surface temperature. Typical industrial versions of the instrument are accurate to $\pm 0.5^\circ\text{C}$ over wide temperature spans. With proper attention to the condensate surface-temperature-measuring system, errors can be reduced to about $\pm 0.2^\circ\text{C}$. Condensation-type hygrometers can be made surprisingly compact using solid-state optics and thermoelectric cooling.

Wide span and minimal errors are two of this instrument's primary features. A properly designed condensation hygrometer can measure dew points from 95°C down to frost points of 73°C. Typical condensation hygrometers can cool to 65°C below the ambient temperature, establishing lower limits of the instrument to dew points corresponding to approximately 0.5% RH. Accuracies for measurements above -40°C can be $\pm 1^\circ\text{C}$ or better, deteriorating to $\pm 2^\circ\text{C}$ at the lower temperatures.

The response time of a condensation dew-point hygrometer usually is specified in terms of its cooling/heating rate, typically 2°C/s for thermoelectrically cooled mirrors. This makes it somewhat faster than a heated salt hygrometer. Perhaps the most significant feature of the condensation hygrometer is its fundamental measuring technique, which essentially renders the instrument self-calibrating. For calibration, it is only necessary to manually override the surface cooling control loop, causing the surface to heat, and to witness that the instrument recools to the same dew point when the loop is closed. Assuming that the surface-temperature-measuring system is correct, this is a reasonable check of the instrument's performance. Although condensation hygrometers can become contaminated, they can be cleaned easily and returned to service with no impairment of performance.

5.3 Pneumatic Bridge Hygrometer. The pneumatic bridge is shown in Figure 5-1. It uses two sets of flow nozzles of proper shape and size over a fixed range of downstream to upstream pressure ratios. For ideal gases over certain ranges of pressures, the mass flow is proportional to the absolute upstream (inlet) pressure and independent of the exact downstream pressures. A desiccant is placed between the two nozzles in one arm of the bridge. Since the mass flow rate through

the downstream nozzle is proportional to its upstream pressure (i.e., the intermediate pressure), the change in mass flow introduced by the desiccator between the nozzles affects the intermediate pressure in the test branch. The intermediate pressure in the test branch is then compared with that in the reference branch by means of a differential manometer. From this measurement, together with the absolute value of pressure in the reference branch, the change in moisture concentration produced by the desiccator in the test branch can be determined.

5.4 Saturated, Heated Lithium Chloride. The sensor measures the dew point or partial pressure of water vapor, but not relative humidity. Moisture determination is based on the fact that, for every water vapor pressure in contact with a saturated salt solution, there is an equilibrium temperature, always higher than ambient, at which this solution neither absorbs nor gives up moisture. This equilibrium temperature is known as the characteristic line. Below the equilibrium temperature, the salt solution absorbs moisture. Above this temperature, the saturated salt solution dries out until only dry crystals are left. The sensor consists of a thin wall tube, generally metal, with a conventional temperature-measuring element inside it. This tube is covered with a woven glass or inert fabric sleeve. The entire bobbin then is wound with a bifilar

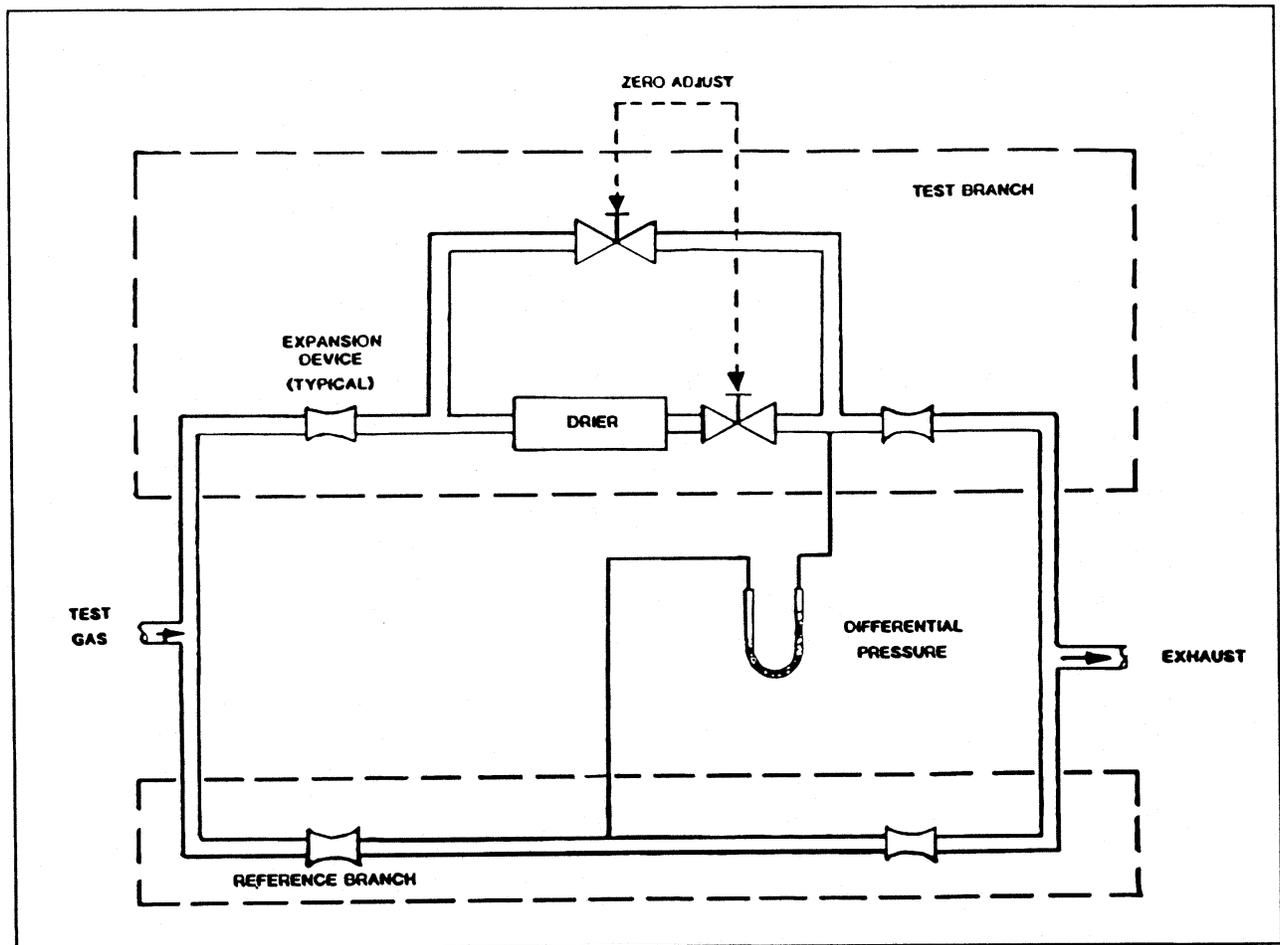


Figure 5-1 Pneumatic bridge hygrometer.

winding that is used for heating the entire sensor assembly. The inert fabric sleeve is impregnated with a salt solution. The sensor is heated to its equilibrium temperature as measured by the resistance of the salt solution.

Lithium chloride is the only salt widely used in self-heating hygrometers because it reaches its natural equilibrium humidity at approximately 11% RH. The temperature of the bobbin is measured and related to the corresponding water vapor dew point. Other solutions have higher transition humidities and therefore are limited in range.

Lithium chloride sensors are widely used; however, they suffer from some problems. Lithium chloride has hydrates with one, two, three, and five molecules of water per molecule of salt. In certain dew-point regions, two temperature values are possible, depending on the direction of approach to the hydrate transition point. The regions of highest precision are between 12°C and +34°C and above 41°C dew point. Another problem is that the lithium chloride solution gets washed off if exposed to water. This type of sensor also is subject to contamination problems that can affect its accuracy. Lastly, the response time is very slow, being approximately two minutes for a 67% step change.

5.5 Spectroscopic (Infrared/Ultraviolet). These devices operate on the principle that selective absorption of radiation is a function of frequency for different media. Water vapor absorbs infrared radiation at 2- to 3- μm wavelengths and ultraviolet radiation centered about the Lyman-Alpha line at 0.122 μm . The amount of absorbed radiation is related directly to the absolute humidity or water vapor content in the gas mixture according to Beer's law. The basic unit consists of an energy source and optical system for isolating wavelengths in the spectral region of interest and a measurement system for determining the attenuation of radiant energy caused by the water vapor present in the optical path. The measurement of the absorbed radiation is extremely fast and independent of the degree of saturation of the gas mixture. Response times of 0.1 second to 1 second for a 90% change in moisture content are common. The spectroscopic hygrometers are used primarily where a noncontact application is required. This may include atmospheric studies, industrial drying ovens, and harsh environments. The primary disadvantages of this device are its high cost and relatively large size.

5.6 Electrolytic Hygrometer. The electrolytic humidity sensor utilizes a bifilar winding on a thin film of phosphorous pentoxide. As the incoming water vapor is absorbed by the desiccant and electrolyzed into hydrogen and oxygen, the current of electrolysis determines the mass of water vapor entering the sensor. Precise control of the flow rate of the entering gas is necessary to maintain a standard sample mass flow rate.

Several phenomena affect the operation of the electrolytic hygrometer. The most troublesome is recombination, a term applied to the reverting to water of electrolysis products in either hydrogen-rich or oxygen-rich sample streams. At low moisture levels, this effect can produce relatively large errors in the instrument readout when the recombined water is reelectrolyzed.

5.7 Piezoelectric Sorption. This hygrometer compares the changes of frequency of two hygroscopically coated quartz crystal oscillators. As the mass of the crystal changes because of water vapor absorption, the frequency changes. The amount of water adsorbed on the sensor is a function of relative humidity, i.e., partial pressure of water as well as the ambient temperature.

A commercial instrument uses a hygroscopic polymer coating on the crystal. The humidity is measured by monitoring the vibration frequency change of the quartz crystal when the crystal is alternately exposed to wet and dry gas.

5.8 Electric and Electronic Hygrometers

5.8.1 Dunmore Type. Dunmore, at the National Institute of Standards and Technology, 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 small 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, whereas resistance curves for specific humidity changes can be developed. This results in several resistance elements required to cover a standard range, called Dunmore elements. Systematic calibration is essential since the resistance grid varies with time and contamination as well as with exposure to temperature and humidity extremes.

5.8.2 Polymer Film Electronic Hygrometers. These devices are manufactured using a hygroscopic organic polymer deposited with thin or thick film-processing technology on a water-permeable substrate. There are two basic types of polymer-based sensors classified according to their electrical measurement characteristics, namely, capacitance and impedance. The impedance-type devices are either ionic or electronic conduction types.

The capacitive-type sensors use either polyamide or cellulose acetate polymer thin films deposited between conductive electrodes. The film, acting as a capacitor dielectric with interjected surface metal as electrodes, changes its dielectric constant as moisture is adsorbed or desorbed by the thin film. An alternative construction method uses a porous top metal layer that allows moisture transmittance. These devices typically are manufactured using integrated circuit (IC) processing techniques. When IC techniques are used, hybrid circuits may be manufactured. Relative humidity and temperature measurement, as well as signal conditioning, may be accommodated on one hybrid device, or multifunction single-chip devices may be produced in which all the desired functions are incorporated into one integrated circuit package.

The primary advantages of this sensor technology are small size, low cost, and fast response times on the order of 1 to 120 seconds for 63% changes in RH. Until recently, the primary disadvantages of this technology were the degree of water resistivity, protection from contamination, and severe hysteresis. The sensitivity to liquid water or dew drops required that these devices be limited to measuring relative humidities lower than 95%. However, through the use of

cross-linking and/or copolymerizing hydrophilic monomers with hydrophobic monomers, water resistance has been improved to the extent that many of these sensors may operate immersed in water without catastrophic damage to the device. The addition of a porous polymer film to cover the humidity-sensitive film enables the device to withstand exposure to contaminants such as dust, oil, etc.

5.8.3 Ion Exchange Resin Electric Hygrometers.

Another common hygroscopic element of electric hygrometers is the ion exchange resin. A conventional ion exchange resin consists of a high-molecular-weight polymer having polar groups of positive or negative charge in a cross-linked structure. Associated with these polar groups are ions of opposite charge, which are held to the fixed polar groups by electrostatic forces. In the presence of water or water vapor, the electrostatically held ions become mobile, and, when a voltage is impressed across the resin, the ions are capable of electrolytic conduction. The Pope cell is an example of an ion exchange element. The Pope cell is a wide-range sensor, typically covering 15% to 95% RH. Therefore, one sensor can be used where several Dunmore elements would be required. The Pope cell, however, has a nonlinear response characteristic from approximately 1,000 ohms at 100% RH to several megohms at 10% RH.

5.8.4 Impedance-Based Porous Ceramic Electronic Hygrometers. Utilizing the adsorption characteristics of oxides, humidity-sensitive ceramic oxide devices have been developed. These devices employ either ionic or electronic 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, which connect the device to an impedance-measuring circuit for linearizing and signal conditioning. These sensors have excellent sensitivity, are resistant to contamination and high temperature (up to 200°C), and may become fully wet without sensor degradation. These sensors are accurate to approximately $\pm 1.5\%$ RH or to $\pm 1\%$ RH when they are temperature compensated. These sensors have a modest cost factor.

5.8.5 Silicon Sensor Hygrometers. The sensing element is a semiconductor that acts as a moisture detector. Moisture in the gas sample is detected as an impedance change, which is a function of the vapor pressure of water in the sample gas.

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 gas sample temperatures.

5.8.6 Aluminum Oxide Hygrometer. The sensor consists of an aluminum strip that is anodized by a special process 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 what essentially is an aluminum oxide capacitor.

Water vapor is transported rapidly through the gold layer and equilibrates on the pore walls in a manner functionally related to the vapor pressure of water in the atmosphere surrounding the sensor. The number of water molecules adsorbed on the oxide structure determines the capacitance between the two electrodes. Although the sensor output varies with the vapor pressure of water, it usually is calibrated in terms of dew-point temperature.

5.9 Adiabatic Expansion. The adiabatic expansion hygrometer is a variation of the two-pressure systems discussed in 4.2.1. A sample of gas is drawn manually into the instrument and is then pumped to a higher pressure, indicated by a pressure ratio meter. If the pressurized sample then is expanded suddenly to atmospheric pressure and if it has been cooled below its dew point during this adiabatic expansion, a fog will form in the chamber. The operator must obtain, through trial and error, the proper pressure ratio and visually monitor the fog. The water vapor pressure or dew point is determined directly from the expansion pressure ratio.

5.10 Mechanical Hygrometers. Many organic materials indicate changes in humidity by changes in weight or dimensions. These materials include human hair, plastic polymers, cotton and wool fibers, wood, animal bones, and goldbeater's skin. They are coupled to pneumatic leakports, mechanical linkages, or electrical transducers to form hygrometers. Their inherent nonlinearity and hysteresis must be compensated for within the hygrometer. These devices generally are unreliable below 0°C. Their response generally is inadequate for monitoring changing processes.

6. SPECIFICATION, PERFORMANCE CRITERIA, AND RECOMMENDED PRACTICE

6.1 Sensor and Instrument Properties. The characteristics of various sensors or instruments are presented in Table 6-1.

6.2 Airstream Temperature Measurements. For applications where a stream of moist air is readily available, the procedure for air temperature measurement shall be defined by *ASHRAE Standard 41.1-1986, Standard Method for Temperature Measurement*,² except where the procedure, equipment, or instrumentation is amended by this standard.

6.3 Moist Air Samples Between 1°C Wet-Bulb and 80°C Dry-Bulb Temperatures. When moist air samples are between 1°C wet bulb and 80°C dry bulb and greater than 10% RH, the aspirated psychrometer (wet-bulb and dry-bulb measurements) may be used. A description of this instrument and its recommended practice are found in Section 9. These recommendations and practices shall be followed when using the aspirated psychrometer.

6.4 Dew/Frost Points of Moist Air Samples Between –70°C and 90°C. When the dew/frost points of the moist air samples are between –70°C and 90°C, the chilled-mirror dew-point instrument may be used. A description of this instrument and its recommended practice is in Section 8. These recommendations and practices shall be followed when using the chilled-mirror dew-point instrument.

TABLE 6-1
Sensor Properties

<u>Sensor</u>	<u>Sensor Category</u>	<u>Method of Operation</u>	<u>Approximate Range</u>	<u>Some Uses</u>
Acoustic Wave	Electrical	Impedance	7 to 98%RH @ 5-60°C	Measurement, control
Change Resin	Electrical	SAW Attenuation	85 to 98%RH	Measurement, control
Thin Film	Electrical	Impedance or Capacitance	10 to 100%RH @ -40 to 90°C	Measurement, control
Oxide	Electrical	Capacitance	5 to 100%RH	Measurement, control
			-80 to 60°C DP	Trace Moisture Measurement, control
Ceramic	Electrical	Impedance or Capacitance		Trace Moisture Measurement, control
n Oxide	Electrical	Capacitance	-80 to 80°C DP	Measurement
olytic Hygrometer	Electrical	Capacitance		Trace Moisture Measurement
ed Laser Diode	Electrical	Optical Diodes	0.1 to 100 ppm	Measurement, control
ose Materials	Mechanical	Dimensional Change	5 to 100%RH	Measurement, control
	Mechanical	Dimensional Change	5 to 100%RH	Measurement
Thread	Mechanical	Dimensional Change	5 to 100%RH	Measurement
sters Skin	Mechanical	Dimensional Change	5 to 100%RH	Measurement
Sensor	Mechanical	Dimensional Change	5 to 100%RH	Measurement
lectric	Mass Sensitive	Mass changes due to absorbed moisture	-80 to -20°C DP	Trace Moisture Measurement, control
Change	Physical	Color changes		+5°C DP
d Mirror	Dev Point	Optical determination of moisture formation	10 to 80%RH	Warning device
Saturated Salt	Water Vapor	Vapor pressure depression	-80 to 95°C DP	Measurement, control, meteorology
on	Pressure	in salt solution	-30 to 70°C DP	Measurement, control, meteorology
etric	Direct Measurement of Mixing Ratio	Comparison of sample gas with dry air stream	0.12 to 20 g/Kg mixing ratio	Primary Standard, Research and Laboratory Measurement
etric	Electrolytic Cell	Electrolysis due to absorbed moisture	1 to 1000 ppm	Measurement
ometer	Evaporative Cooling	Temperature measurement	0 to 80°C	Measurement, standard
lb	Evaporative Cooling	Temperature measurement of thermodynamic wet bulb	5 to 30°C	Measurement, standard
ometer	Moisture Absorption	Moisture absorption by UV or IR radiation	-20 to 80°C DP	Measurement, control, meteorology

This table does not encompass all of the available technology for the measurement of moisture. The approximate range for the device types listed is based upon surveys of device manufacturers. The approximate accuracy is based upon manufacturers' data. Essentially the National Institute of Standards and Technology will only certify instruments whose operating range is within -75 to 100°C dew point.

7. CALCULATION OF MOIST AIR PROPERTIES

The following sections specify how moist air properties are to be calculated using the measured properties obtained by instruments specified in Section 6.

7.1 Using Measured Wet-Bulb and Dry-Bulb Temperatures and Pressure. Using the approximation of the measured wet-bulb temperature as being equal to the thermodynamic wet-bulb temperature (t^* , in °C), dry-bulb temperature (t , in °C), and atmospheric pressure (p , in kPa), the other commonly used moist air properties are found as follows.

7.1.1 Mixing (Humidity) Ratio

$$W = [(2501 - 2.381t^*)W_s^* - (t - t^*)] / (2501 + 1.805t - 4.186t^*) \quad (33)$$

where

$W_s^* = 0.62198p_{ws}^* / (p - p_{ws}^*)$, and p_{ws}^* —the saturation pressure (kPa) of water at t^* —can be found in psychrometric tables.

7.1.2 Vapor Pressure

$$p_w = pW / (0.62198 + W), \text{ kPa}$$

7.1.3 Dew Point. Find the temperature that produces vapor pressure (p_w) in the *ASHRAE Handbook—Fundamentals*¹² psychrometric tables or use Equation 31 or 32.

7.1.4 Degree of Saturation

$$\mu = W / W_s, \text{ a decimal fraction}$$

where

$W_s(p, t) = 0.62198p_{ws}(t) / (p - p_{ws}(t))$, and $p_{ws}(t)$ —the saturation pressure of water at t —can be found in the *ASHRAE Handbook—Fundamentals*¹² psychrometric tables.

7.1.5 Relative Humidity

$$\phi = (p_w / (p_{ws}(t))) \times 100$$

7.1.6 Specific Volume

$$v = R_a(t + 273.15) / (p - p_w), \text{ m}^3/\text{kg of dry air}$$

where

$$R_a = 0.287055 \text{ (Pa}\cdot\text{m}^3)/(\text{kg}\cdot\text{K}).$$

7.1.7 Enthalpy.

Where h_a is assigned a value of 0 for 0°C,

$$h \approx 1.005t + W(2500.9 + 1.805t), \text{ kJ/kg of dry air.}$$

7.2 Using Measured Dew-Point and Dry-Bulb Temperatures and Pressure. From the measured dew-point temperature (t_d , in °C), dry-bulb temperature (t , in °C), and atmospheric pressure (p , in kPa), the other commonly used moist air properties are found as follows.

7.2.1 Vapor Pressure. The value of $p_w = p_{ws}(t_d)$ can be found in the *ASHRAE Handbook—Fundamentals*¹² psychrometric tables at temperature t_d or by Equation 3 or 4 of chapter 6 in the *1993 ASHRAE Handbook—Fundamentals*.¹²

7.2.2 Mixing (Humidity) Ratio

$$W = (0.62198 p_w / (p - p_w))$$

7.2.3 Degree of Saturation

$$\mu = W / W_s$$

where

$W_s(p, t) = 0.62198 p_{ws}(t) / (p - p_{ws}(t))$, and $p_{ws}(t)$ —the saturation pressure of water at t^* —can be found in the *ASHRAE Handbook—Fundamentals*¹² psychrometric tables.

7.2.4 Relative Humidity

$$\phi = (p_w / p_{ws}(t)) \times 100$$

7.2.5 Specific Volume

$$v = R_a(t + 273.15) / (p - p_w), \text{ m}^3/\text{kg of dry air}$$

where

$$R_a = 0.287055 \text{ (Pa}\cdot\text{m}^3)/(\text{kg}\cdot\text{K}).$$

7.2.6 Enthalpy

Where h_a is assigned a value of 0° for 0°C,

$$h \approx 1.005t + W(2500.9 + 1.805t), \text{ kJ/kg of dry air.}$$

7.2.7 Thermodynamic Wet-Bulb Temperature. t^* can be found only by trial-and-error calculations using the following equations:

$$W_s^* = 0.62198p_{ws}^* / (p - p_{ws}^*)$$

and

$$W = [(2501 - 2.381t^*)W_s^* - (t - t^*)] / (2501 + 1.805t - 4.186t^*)$$

Guess at a value for t^* between t and t_d , then calculate W_s^* . Using W_s^* , t , and t^* , calculate W and compare it to the true W . If the calculated W is larger than the true W , choose a smaller t and repeat the procedure. Continue this until the true W and the calculated W are as close to each other as accuracy warrants.

7.3 Using Relative Humidity, Dry-Bulb Temperature, and Pressure. From relative humidity, dry-bulb temperature (t , in °C), and atmospheric pressure (p , in kPa), find the other moist air properties.

7.3.1 Vapor Pressure

$$p_w = \phi p_{ws}(t) / 100, \text{ kPa}$$

where

$p_{ws}(t)$ = saturation pressure of water at temperature t .

$p_{ws}(t)$ can be found in the *ASHRAE Handbook—Fundamentals*¹² psychrometric tables at t or can be calculated from Equation 3 or 4 in chapter 6 of the *1993 ASHRAE Handbook—Fundamentals*.¹²

7.3.2 Mixing (Humidity) Ratio

$$W = 0.62198p_w / (p - p_w)$$

7.3.3 Degree of Saturation

$$\mu = W / W_s$$

where

$$W_s(p, t) = 0.62198p_{ws}(t) / (p - p_{ws}(t)).$$

7.3.4 Dew Point

$$p_{ws}(t_d) = p_w$$

In the *ASHRAE Handbook—Fundamentals*¹² psychrometric tables, find a temperature at which the saturation pressure equals p_w . The temperature is the dew-point temperature. The temperature t_d can also be found through Equation 31 or 32.

7.3.5 Specific Volume

$$v = R_a(t + 273.15) / (p - p_w), \text{ m}^3/\text{kg of dry air}$$

where

$$R_a = 0.287055 \text{ (Pa}\cdot\text{m}^3)/(\text{kg K}).$$

7.3.6 Enthalpy.

Where h_a is assigned a value of 0 for 0°C,

$$h \approx 1.005t + W(2500.9 + 1.805t).$$

7.3.7 Thermodynamic Wet-Bulb Temperature. t^* can be found only by trial-and-error calculations using the following equations:

$$W_s^* = 0.62198p_{ws}^*/(p - p_{ws}^*)$$

and

$$W = [(2501 - 2.381t^*)W_s^* - (t - t^*)] / (2501 + 1.805 - 4.186t^*).$$

Guess at a value for t^* , then calculate W_s^* . Using W_s^* , t , and t^* , calculate W and compare it to the true W . If the calculated W is larger than the true W , choose a smaller t^* and repeat the procedure. Continue this until the true W and the calculated W are as close to each other as accuracy warrants.

7.4 Determination of Moist Air Properties with a Psychrometric Chart. A psychrometric chart maps the properties of moist air for a single pressure. An ASHRAE psychrometric chart is available for a pressure corresponding to sea-level altitude (101.326 kPa).

Figure 7-1 is an example of an ASHRAE psychrometric chart. The thermodynamic state point of the moist air can be located if two other properties are known in addition to the pressure (i.e., t and t^*).

7.5 International Temperature Scale of 1990. On January 1, 1990, the International Committee of Weights and Measures adopted the International Temperature Scale of 1990 (ITS-90). The ITS-90 supersedes the International Practical Temperature Scale of 1968 (IPTS-68) as the authority for defining the values of fixed-point temperatures, the value of the degree Celsius, and the interpolation formulas for the instruments recommended for measuring temperature. Because the formulae for the calculation of moist air properties are based on temperatures in units of Kelvin and degrees Celsius on the thermodynamic temperature scale, the calculated values of water vapor pressure do not change with the adoption of the ITS-90. Most thermometers and other temperature-measuring instruments are calibrated today according to IPTS-68. Values of water vapor pressure and other moist air properties from such measurements will be slightly in error.

At 100°C, the difference between vapor pressure calculated according to IPTS-68 and ITS-90 is 95 Pa, or about 0.1 %. Where improved accuracy is required, it is recommended that measurements according to ITS-90 be used when calculating moist air properties.

8. STANDARD METHOD USING THE COOLED-SURFACE CONDENSATION HYGROMETER

8.1 Scope. This section considers hygrometers that determine the dew point or frost point of air by detecting visible condensation of moisture on a cooled surface. Many different types of instruments operating in different ranges are used to measure humidity by this method. Guidance is given on their general design principles and the major precautions regarding their use without introducing detailed descriptions of any particular pattern of instrument.

8.2 Field of Application. The field of application of this type of instrument is particularly wide. It is one of the few instruments that may be used to determine, without changing calibration, the water vapor pressure in systems operating at total pressures above, at, or below normal atmospheric pressure containing any inert gas or gases. The relationships between the water vapor pressure and the observed dew point or frost point are firmly established, giving this method the character of an absolute measurement. In this standard, the principal application is the determination of absolute or relative humidity in enclosures or chambers used for conditioning or testing at about normal atmospheric pressure or at reduced pressures. Meteorological applications are excluded from consideration, being covered by documents of the World Meteorological Organization.

Strictly, the relationship between observed dew point or frost point and water vapor pressure is always a function of other gas or gases in the tested atmosphere that dissolve in the condensed water in the instrument. For the great majority of common gases, this effect is negligible, but certain gases have a very important effect, as discussed in 8.5.2.3.

8.3 Principles of Operation and Calculation

Principle of Instrument. In the type of instrument considered in this standard, which measures the humidity of air or any other gas by measuring its dew point or frost point, a surface (usually a metal mirror), the temperature of which can be lowered artificially and measured accurately, is exposed to a sample of the air or gas in question. This surface is then brought to a temperature such that visible condensation in the form of dew or frost occurs on it in stable form, that is, neither growing nor diminishing with time. Below this temperature, condensation will increase with time, while above it, the condensate either will diminish or will not be formed. This surface temperature is, for all practical purposes, the dew point or frost point of the air passing through the instrument. For brevity, this point is referred to in this standard as its "condensation temperature."

8.4 General Forms of Instrument

8.4.1 General. A condensation instrument may take many physical forms. The essential differences lie mostly in the nature of the surface on which the condensate is formed,

the methods used to cool this surface and control its temperature, and the arrangements for the detection of condensation.

The mirror and associated components normally are arranged in a small cell through which the sample gas is passed. However, at low pressures, this procedure may require modification (see 8.5.1.5), and, at high pressures, it is necessary to ensure that the strength of the cell is adequate. Selection of the most suitable arrangement depends almost entirely upon the range of condensation temperature the instrument will need to cover, the applications for which the instrument is required, and the way in which it will be used.

8.4.2 Ranges of Condensation Temperature. Condensation instruments can be used to measure humidities in test enclosures for condensation temperatures from as high as $+100^{\circ}\text{C}$ to as low as 70°C , but the nature and construction of the instrument, the problems of its use, and the accuracy it is reasonable to expect all vary widely according to the condensation temperature to be measured. The fewest problems arise for condensation temperatures between ambient (normally about $+20^{\circ}\text{C}$) and 0°C . In this range, observation is easy and instruments of the simplest types often are adequate, as outlined in 8.6.1. When condensation temperatures above normal ambient temperature are to be measured, observation remains easy, but the instrument usually requires modification. For condensation temperatures from 0°C down to approximately 20°C , a simple instrument often is adequate but there are difficulties in correctly interpreting the observations. These two ranges are considered in 8.6.2 and 8.6.3, respectively. Finally, as condensation temperatures fall below approximately 20°C , other types of instruments and other techniques of use become increasingly important. These are considered in 8.6.4.

8.4.3 Manual vs. Automatic Forms. An instrument for measuring condensation temperatures may be required to make isolated measurements at various times or to make an essentially continuous record of humidity. For isolated measurements, methods of cooling the mirror may be chosen that require continuous action by the operator in responding to changes of the condensed deposit, which are observed and assessed by sight alone. As the humidity of the sample air decreases, for lower condensation temperatures the quantity of water vapor brought into the instrument per unit time is smaller, so that the rate of change of the condensate is reduced and it becomes more difficult to judge by sight alone whether the condensate is growing, diminishing, or has reached the required stable state. Valuable assistance may be given by observing the deposit using a photocell or other light-sensitive device to operate a simple indicating instrument yet still retaining manual control of the cooling arrangements. As a further step, the instrument can be made completely automatic by using the output of the photocell to control the temperature of the mirror so as to maintain a constant quality of condensate, i.e., to maintain the mirror at the required condensation temperature. Automatic operation is essential to provide a continuous reading or recording.

8.4.4 Illumination of Mirror. Simple instruments in which condensates are observed by sight normally rely on the ambient lighting, but where photocell observation is used, the mirror is illuminated by a filament or neon lamp incorporated

in the test cell. Many arrangements of lamp and photocell are possible. For most purposes, it is satisfactory to illuminate the mirror at approximately 45 degrees from the mirror normal (suitably absorbing the reflected rays) and placing a single photocell on the mirror normal to where it receives scattered light from any condensate on the mirror. It is necessary to minimize light affecting the photocell in the absence of any condensate. Scattering from the mirror itself is minimized by final polishing in the direction of the illumination. The effect of light scattered from interior cell surfaces is minimized by blackening these surfaces, and this precaution is aided by arranging condenser lenses and diaphragms so that only the mirror is illuminated and the photocell views only the mirror. At very low frost points (below about -60°C), observation becomes very difficult, and it is claimed that illumination tangential to the mirror is preferable.

8.4.5 Observation of Mirror. Automatic instruments always should embody means for observing the condensate on the entire mirror by sight, preferably at a magnification of at least three or four times. This visual observation may be conveniently along an axis at 45 degrees to the mirror normal but at 90 degrees (in plane) to the direction of lighting. This assists in detection of abnormal operation because of contamination (see 8.5.2) or "pooling" or "flooding" (8.6.1.1) and also enables the form of the condensate to be checked just below 0°C (8.6.3).

8.4.6 Methods of Cooling Mirror and Controlling Mirror Temperature. The following methods have been used to lower and control the mirror temperature.

8.4.6.1 Evaporation of Solvent. A volatile liquid in contact with the back of the mirror may be evaporated and cooled by passing air through it, thus cooling the mirror. It is usual to use a hand-operated bellows for this purpose, controlling the mirror temperature by the rate of operation of the bellows, but a controllable source of low-pressure compressed air is more convenient. The liquid used is generally diethyl ether, which is the most effective liquid for this purpose, giving approximately 30°C cooling of the mirror with little difficulty when using hand bellows. If the flammability and toxic hazards of ether are objectionable, acetone may be used to give nearly 20°C mirror cooling using hand bellows or greater cooling using compressed air.

8.4.6.2 Gas Cooled by Adiabatic Expansion. The mirror may be cooled by passing a gas over the back of it, which has been expanded by passing through a nozzle. Compressed carbon dioxide, being available in small cylinders, often is used for this purpose, although compressed air or compressed nitrogen may also be used. Mirror temperatures at least 40°C below the temperature of the gas sample are practicable.

8.4.6.3 Use of Gas Cooled by Passing Through Refrigerant. In place of the adiabatic expansion described in 8.4.6.2, the gas passing over the back of the mirror may be cooled by having been passed through a refrigerant such as ice and salt, solid carbon dioxide in acetone, or liquid nitrogen. The temperatures of these refrigerants are, respectively, approximately -15°C to -20°C , -78.5°C , and -196°C . The mirror will not be cooled to these temperatures but, depending on the design of the instrument, the rate of flow of sample air,

and the rate of flow of refrigerated gas, mirror temperatures of approximately 0°C, -30°C to 40°C, and -80°C and lower are practicable. The mirror temperature is controlled by varying the rate of cold gas flow, although control normally is not very precise.

8.4.6.4 Direct Contact with Refrigerant. The mirror may be cooled by its back being in direct contact with a refrigerant mixture. One usual and convenient arrangement is to have the mirror in the form of a polished cup or thimble with the refrigerant contained within it. The only practicable refrigerant that allows control of the temperature is one in which pieces of solid carbon dioxide are dropped into acetone or into another low-freezing-point liquid. The carbon dioxide sublimates completely so that the process can be continued indefinitely. Control of temperature is achieved by careful control of the rate of addition of solid carbon dioxide. Alternatively, the cold liquid may be sprayed over the back of the mirror by means of a hand pump. The mirror temperature is controlled by the pumping rate.

8.4.6.5 Indirect Contact with Refrigerant. All of these methods require constant attention by an operator and, therefore, are unsuitable for automatic instruments. Two cooling methods are used for automatic instruments, namely, indirect contact with a refrigerant or Peltier (thermoelectric) cooling.

When cooled by indirect contact with a refrigerant, the mirror is linked to the coolant via a thermal resistance. Normally, a relatively massive copper rod is immersed in a coolant. It is joined to the mirror by a small block of insulating material that creates a thermal resistance. The mirror is heated by a resistance element wound around or on it. By controlling the current through this element, the mirror temperature can be easily and accurately controlled. Using liquid nitrogen as the coolant, mirror temperatures down to -70°C to -80°C offer no difficulties. For temperatures down to about -20°C (depending on the design of the instrument), solid carbon dioxide and acetone can be used. In designing such an instrument, for a mirror of given mass and heat capacity a balance must be struck between a low thermal resistance (which enables the mirror temperature to be brought down quickly to a low value but requires a higher heat input and refrigerant consumption) and a high thermal resistance, which economizes refrigerant use but makes rapid control of mirror temperature more difficult. These problems are reduced as the mass of the mirror is reduced.

Care must also be taken that the overall thermal resistance will remain approximately constant with use. Continuous heating and cooling tends to fracture adhesive bonds or loosen contact afforded by fasteners, making control difficult.

8.4.6.6 Peltier Cooling. The mirror may be attached to one face of a Peltier element. Unless the mirror is very small, to avoid differences of temperature over its area, it is preferable to ensure that the mirror has a high thermal conductivity. A 20/80 copper/silver alloy has been used, which is rhodium plated to result in a surface resistant to tarnish and handling; or a 22-carat gold alloy also may be used. If corrosion is likely, stainless steel may have to be used.

The other face of the Peltier element is attached to a heat sink, which may be a finned metal structure or casting, constituting a naturally cooled or fan-cooled air radiator, to maintain this face of the element close to ambient temperature. Alternatively, the heat sink may be arranged for cooling by ice or by another refrigerant.

A single-stage Peltier element normally achieves a maximum cooling level of approximately 30°C. Peltier elements may be cascaded to achieve greater cooling, but the electrical losses of the colder elements must be dissipated by the cooling action of the warmer ones; little benefit is gained from using more than two stages. Two stages can give cooling of approximately 50°C. The mirror temperature can be controlled by controlling the direct current passing through the Peltier elements, but the thermal mass tends to be high, and more rapid control is possible by maintaining a constant cooling current, connecting the mirror via a thermal resistance, and heating the mirror with a controlled electrical heater.

8.4.6.7 Measurement of Mirror Temperature. It is important to measure as accurately as possible the temperature of the mirror where the deposit is formed. For instruments in which coolant is in direct contact with the back of the mirror, a liquid-in-glass thermometer placed in the coolant generally is used, although a thermocouple may be employed if more convenient. This simple arrangement is not very satisfactory because of the temperature difference between the coolant and the mirror surface, although vigorous stirring of the coolant will minimize this error. All other types of instruments use an electrical temperature sensor (i.e., a resistance thermometer, a thermistor, or a thermocouple) that must be embedded in or otherwise placed in intimate contact with the mirror in order to measure surface temperature. The size of such temperature sensors, the size of the hole into which the sensors are inserted, and the diameter of the sensor leads should be as small as practicable to minimize errors resulting from local disturbances of mirror temperatures. It probably is easiest to achieve these conditions by using a thermocouple.

8.5 Sources of Error—General Operating Precautions (Applicable to All Instruments)

8.5.1 Correctly Representative Sampling

8.5.1.1 Operation of Instrument Inside Enclosure. It always is necessary to carefully consider the conditions under which a measurement should be made and the location from which the air sample should be drawn. Thus, for example, an enclosure designed to accommodate hygroscopic materials should be tested with appropriate materials present. Similarly, if personnel are to work in the enclosure, a suitable number of people should be working during the test. In the latter case, it is permissible and normally most convenient for the hygrometer and its operator to be inside the enclosure. It should be remembered that, apart from gross errors caused by breathing near the inlet to the hygrometer, the operator and other personnel will give off water vapor at low humidities and tend to increase the enclosure humidity, especially close to them. Also, at high humidities, the clothing of the people in the enclosure will absorb water vapor and tend to decrease the general air humidity for perhaps a half-hour after entering an enclosure. The hygrometer should be fitted with an extension

tube at the inlet so that the operator's body is not near the sampling point. If the enclosure is intended to produce particular working conditions at particular points, the air samples should be drawn from those points. When an average humidity assessment is required, samples should be drawn from points remote from the operator and upstream of him in any air movement. The sampling point should be located away from cold pipes, doors that may leak, or objects that may be absorbing or emitting water.

8.5.1.2 Sampling Through Tubes. For an enclosure not designed to accommodate personnel, it always is desirable to measure humidities by means of a sample extracted through a tube to an instrument outside the enclosure. This may be essential if humidities are particularly low or high or where the enclosure is relatively small. An average humidity usually is required, and the downstream (higher pressure) side of a circulating fan, if one is used, often is a satisfactory sampling point. The precautions stated in 8.5.1.1 against sampling from near cold pipes, doors, etc., should be observed. It is essential to take the precautions described in 8.6.2 if there is any chance of the condensation temperature inside the chamber rising above the ambient temperature outside the chamber. The need to heat the connecting piping and any part of the instrument that comes into contact with the test air sample should not be overlooked.

8.5.1.3 Sorption and Desorption of Water by Tubing. Most flexible tubing materials absorb water vapor and may take away from or add to the water in the test stream. This may lead to considerable error when air passes through the tubing into the hygrometer, especially at low humidities. Rubber (natural or synthetic), in particular, is to be avoided. PTFE or polyethylene tubing should be used. Joints may be made by butting lengths of tubing together inside a tightfitting sleeve of good-quality rubber or by the use of compression fittings. Alternatively, clean metal tubing may be used having all-metal (soldered or compression-type) joints, or the rubber-sleeved butt joint technique may be used. The oxide layers that are unavoidable in many tubes also may absorb water vapor, and stainless steel tubing is essential where humidities are very low (for example, below -50°C condensation temperature).

It is essential that materials used for the construction of the hygrometer test cell do not absorb water vapor. Plastic materials that incorporate hygroscopic fillers are to be avoided. Stainless steel is preferred for metal construction parts.

8.5.1.4 Air Leakage. When withdrawing samples from a test enclosure to an external instrument via tubing, even minute leakage from the external atmosphere can produce serious errors, especially at low enclosure humidities. Leakage often can occur where a sampling tube enters the enclosure, air duct, etc. This error can be best avoided by carrying the sample tube through the wall of the enclosure or duct without a break, terminating it several inches inside the wall. If this is impractical, a completely airtight joint is essential. Joints in the sampling tube also must be completely airtight, as well as in the hygrometer cell itself. At low enclosure humidities, vacuum techniques (using O-rings, etc.) are necessary to ensure adequate seals between parts of the hygrometer cell.

8.5.1.5 Flow of Sample Gas Through Instrument. It is necessary for the sample of the tested atmosphere that passes through the hygrometer to always be of adequate quantity. At normal atmospheric pressure, an adequate airflow may be ensured by using a simple vacuum or diaphragm suction pump connected to the outlet of the hygrometer. Too high a flow rate is undesirable, as it may prevent sufficiently low mirror temperatures from being achieved or, in some cases, may lead to overheating of the mirror, making it difficult to measure the mirror temperature or leading to cold-spot errors (see 8.5.3). To obtain a representative air sample without excessive airflow through the hygrometer, a bypass to the hygrometer may be used. It is of considerable benefit if the airflows are indicated by simple flowmeters. At low enclosure pressures, it may be difficult or impossible to withdraw an adequate sample through small-bore tubing, and the possibility should be kept in mind of incorporating the hygrometer cell in the external pipework to the enclosure or mounting the open hygrometer cell inside the enclosure.

8.5.2 Contamination. Substances other than air and water vapor may be present that affect the performance of the instrument. These substances may be solid particles, dust, etc., that may be deposited on the mirror. Vapors other than water may be present, which could condense on the mirror. Gases soluble in water, deliberately or accidentally present in the test chamber, also may affect the observed condensation temperature.

8.5.2.1 Solid Contaminants. If solid contaminants are completely insoluble in water, they do not affect the observed condensation temperature but may hinder observation of the condensate. In an automatic instrument without compensation for such contaminants, these contaminants will tend to make the instrument stabilize with decreasing amounts of condensate and, eventually, will cause the instrument to fail. However, while working, the instrument readings will be correct. Failure because of excessive solid contamination of the mirror usually is indicated by the mirror temperature rising unexpectedly over a period of a few minutes. The instrument must be dismantled in order to clean the mirror. (It is essential that the hygrometer cell may be readily dismantled for this purpose. If solid contaminants drawn into the instrument are soluble in water, the observed condensation temperature no longer will correspond to the actual water vapor pressure. Any condensation type of instrument is unusable for assessing water vapor content under these conditions. It may be practical to filter out solid contaminants by using a nonhygroscopic filter to avoid the above difficulties.)

8.5.2.2 Vapor Contaminants. Vapors of oil, etc., may condense on the mirror. At condensation temperatures above 0°C , it is rare for the quantity of oil to be significant and little or no trouble will occur. Again, when only small quantities of oil, etc., are present and the water condensation temperature is below 0°C , it often is possible to obtain an approximate frost point before significant oil is deposited, but long-term automatic operation may not be practical because the oil quantity will grow until the instrument attempts to monitor the oil rather than the water. It may be possible to periodically heat the mirror, either automatically or manually, and evaporate all deposits in such a case. However, manual cleaning usually is essential.

8.5.2.3 Errors Caused by Particular Gases Soluble in Water. The test atmosphere may contain gases other than air, which, while dissolving in the water on the mirror, can in time affect significantly the vapor pressure and lead to error in determining the water content. Examples of gases likely to cause trouble in this respect are sulfur dioxide, carbon dioxide, hydrogen sulphide, chlorine, and hydrogen chloride. In the presence of these gases, a condensation-type hygrometer cannot be used reliably to determine water vapor pressures.

Note: Instances in which the actual condensation temperature is required in its own right, rather than a measure of humidity (e.g., flue gas atmospheres), are not considered in this standard.

8.5.3 Cold-Spot Errors. It is essential that parts of the tubing and parts of the instrument other than the mirror be warmer than the condensation temperature; otherwise water vapor will condense at the coldest point and alter the humidity of the sample gas. For example, this problem may occur where liquid nitrogen is used as a refrigerant and the design of the instrument allows the emitted cold gas to cool parts of the hygrometer cell below mirror temperature. Similar problems arise when dew points are being measured that are above the ambient temperature of the instrument (see 8.6.2).

8.5.4 Fluctuating Humidities. Increases or decreases of test enclosure humidity that are slow in comparison with the response time of the hygrometer offer little difficulty, and the instrument will indicate the condensation temperature correctly. More rapid changes (usually rapid increases) of humidity may lead to considerable difficulty. For example, some systems for test enclosure humidity control give periodic, rapid increases of humidity that neither a manual nor an automatic instrument can follow successfully. In an automatic instrument, "flooding" of the mirror often results (see 8.6.1.1) or severe overshooting of mirror temperature occurs. In either case, stable operation may not be obtained for some time after the change of humidity or not at all. Good accuracy is not possible under these conditions. Rapidly changing mirror temperatures in automatic instruments should be regarded only as very approximate indications of humidity.

8.5.5 Approach to Equilibrium Temperature. It is essential to remember that the condensate cannot build up faster than the amount corresponding to water vapor carried into the instrument along with the gas sample. If the mirror cooling is too rapid, the mirror may be cooled below the true condensation temperature before any deposit is seen. However, for condensation temperatures near 0°C, visible dew requires so little condensate (see note) that difficulty seldom arises.

Note: The minimum quantity of dew that can be detected by sight is on the order of 10^{-5} g/cm². Automatic instruments, if very sensitive, sometimes can detect a water film too small in quantity to be seen. However, the standard relationships between vapor pressure and dew point do not necessarily hold under these conditions, and the sensitivity should be reduced so that an easily visible dew film is present.

When a manual instrument is used, the chance of error from overly rapid cooling increases as the humidity decreases

until, at frost points below -30°C, the formation of frost is so slow even with high sample gas flow rates that overcooling of the mirror is almost unavoidable. If a manual instrument must be used, particularly at lower frost points, the following precautions always should be taken.

- a. The rate of cooling of the mirror should be as slow as possible in the region of the condensation temperature. (It is good practice to make a fairly rapid trial run to establish the approximate condensation temperature before attempting an accurate measurement.)
- b. Either (1) the mirror should be held at constant temperature for several minutes to establish that frost is neither growing nor decreasing and thus to establish directly the true (equilibrium) condensation temperature, or (2) the mean between the temperature at the first appearance of frost, with the mirror temperature falling slowly, and the temperature at which frost disappears, with the mirror temperature rising slowly, may be taken as the approximate condensation temperature.

8.6 Special Notes Applicable to Instruments for General Ranges

8.6.1 Dew Points from Approximately +20°C to 0°C. For measurements in this range, at approximately standard atmospheric pressure, the simplest instruments will suffice. These include the traditional Regnault hygrometer in which a polished, plated metal cup is enclosed in a transparent cell into which sample air is passed (often via a jet to impinge on one spot on the outside of the cup). The cup is cooled, usually by evaporation of solvent. The condensate forms only in one area near the jet and may easily be seen against the remaining surface. For assessing low humidities, this type of instrument may be cooled by solid carbon dioxide in acetone, etc. In another variant, the mirror forms one flat wall of a small circular cell through which the test gas passes. In this case, the coolant is an evaporating solvent that cools only part of the mirror, leaving the remainder clear for comparison. Alternatively, the airstream across the mirror is in jet form, resulting in local condensation.

Instruments in which the mirror is cooled by the Peltier effect are ideally suited to this range of operation. These may be operated manually, but automatic operation can easily be arranged. Instruments employing other cooling methods (intended for application to a wider humidity range) are used frequently in this range as well.

8.6.1.1 "Pooling" and "Flooding." Under automatic operation in this range, there is danger of abnormal operation because of "pooling" and "flooding." Pooling is a phenomenon that may occur after many hours of continuous operation. Minute droplets of dew may coalesce to form larger droplets that scatter much less light onto the photocell than did the original dew. These pools may overflow the mirror and, by settling in warmer parts of the cell, may modify the humidity of the sample air. Because the control loop attempts to operate to give constant light scattered onto the photocell, ever-increasing quantities of water tend to be condensed. The overall effect is to cause serious measurement errors. Where water has overflowed the mirror, it usually is necessary to dismantle the instrument for cleaning.

8.6.1.2 Preventive Measures. Preventive measures include

- a. automatic operation with only moderate quantities of dew on the mirror,
- b. regular mirror heating to evaporate all deposits,
- c. design to prevent water droplets from leaving the mirror surface, and
- d. visual check on form of condensate.

Flooding occurs when there is a sudden large rise of sample air humidity (often caused by disconnection of the instrument inlet so that normal atmospheric air enters it). Within two seconds, liquid water (or, if the instrument has been operating at frost points below the present range, frost that is quickly melted to form water) is condensed in large quantities before the mirror temperature can be raised adequately by the mirror heater. As with pooling, mirror overflow may result and, possibly, partial or complete loss of control of mirror temperature due to lack of light scattered from the large water droplets. If the instrument is designed to prevent water from leaving the mirror surface, manually controlled heating of the mirror will restore normal operation.

8.6.1.3 Accuracy. The condensed temperature in this range usually is indicated to an accuracy within $\pm 0.2^\circ\text{C}$ for both manual and automatic operation.

8.6.2 Dew Points Above Ambient Temperature. In enclosures operating at an elevated temperature, the dew point may be above normal ambient temperature. If a hygrometer is used outside the enclosure, it is necessary to guard against the "cold-spot" error noted in 8.5.3. All parts of the system (including all parts of the hygrometer cell except the mirror, all tubing connecting the instrument to the test room, and approximately one-half meter of tubing at the instrument outlet) are required to be maintained at a temperature above the measured dew point in order to avoid condensation of water vapor in the system. Special arrangements usually will be needed for control of mirror temperature for instruments used in this range. In a Regnault pattern instrument, water or alcohol will afford adequate cooling of the mirror in this range. With other instruments, a simple electric heater with an air-cooled heat sink may be used, or an instrument to cover a wide range may use a Peltier element with normal or reversed-current flow to enable a mirror temperature below or above ambient to be reached. Accuracies in this range are similar to those stated in 8.6.1.3.

8.6.3 Frost Points Between 0°C and 20°C . In this range of frost points, it is possible for the condensate to be in the form of supercooled water droplets rather than ice crystals. Provided that the actual form is known correctly, the humidity still may be obtained with full accuracy and, for this reason, visual observation of the condensate is essential. In practice, supercooled water forms only on a freshly cleaned mirror and spontaneously changes to ice after a short period of use. It is usual to wait for this to occur before using the instrument for observations.

8.6.4 Frost Points from -20°C to Approximately -70°C . The assessment of frost points down to -30°C or, per-

haps, -40°C still may fall within the range of operation of instruments using simple two-stage Peltier cooling or adiabatic expansion of a gas. Where the frost point is likely to be below this range, instruments using other methods of mirror cooling must be employed. Suitable methods include cooling by a refrigerant-cooled gas (8.4.6.3, 8.4.6.4, and 8.4.6.5). Alternatively, it may be convenient to extend the range of a Peltier-cooled instrument by refrigerating the heat sink.

Precautions against leakage and absorption and desorption errors (see 8.5.1.3 and 8.5.1.4) assume ever-increasing importance as humidities decrease. Special techniques for estimating the true equilibrium temperature as outlined in 8.5.5 are essential if manual operation is attempted, but automatic operation is strongly recommended for this range of humidity.

Accuracy of indication decreases with decreasing frost point, from approximately the values stated in 8.6.1.3 at the upper end of this range to no better than $\pm 2^\circ\text{C}$ at the lower end of the range.

9. STANDARD METHOD USING THE ASPIRATED PSYCHROMETER

9.1 General. This method provides for the determination of the relative humidity of air within the temperature range of $+5^\circ\text{C}$ to $+80^\circ\text{C}$ with an uncertainty not exceeding $\pm 3\%$ RH when the temperature depression is measured to $\pm 0.2^\circ\text{C}$ or better and not exceeding $\pm 2\%$ RH when the depression is measured to $\pm 0.1^\circ\text{C}$ or better. It is restricted to wet-bulb temperatures not lower than $+1^\circ\text{C}$, dry-bulb temperatures not higher than $+80^\circ\text{C}$, relative humidities greater than 10%, and pressures not differing from standard atmospheric pressure by more than 30%. This method should not be used where significant contamination from gases, vapors, or dust can occur.

9.2 Principle. The wet-bulb temperature depression, the dry-bulb temperature, and an approximate value for the pressure (within $\pm 1\%$) provide the basis for deriving relative humidity.

9.3 Apparatus and Materials

9.3.1 Thermometers

9.3.1.1 The recording range of the thermometers shall include the range of 0°C to $+80^\circ\text{C}$. This range may be achieved by providing more than a single pair of thermometers.

When the uncertainty in the derived relative humidity is required to be not more than $\pm 3\%$ RH, the thermometers shall be such that their readings give the temperature depression with an uncertainty of not more than $\pm 0.2^\circ\text{C}$. When the uncertainty in the relative humidity is required to be not more than $\pm 2\%$ RH, they shall be such that their readings give the temperature depression with an uncertainty of not more than $\pm 0.1^\circ\text{C}$. The uncertainty in the reading of the dry-bulb temperatures shall not be greater than $\pm 0.2^\circ\text{C}$.

9.3.1.2 Electrical thermometers may be connected so that the readings give both the temperature depression and the dry-bulb temperature directly.

9.3.1.3 Each thermometer shall consist of a temperature sensor of essentially cylindrical shape that is supported on a

single stem. The free end of each sensor shall be smoothly rounded. If the diameter of the stems is small compared with that of the sensors, both ends of each sensor shall be smoothly rounded. The sensor of a mercury-in-glass thermometer shall be that part of the thermometer extending from the bottom of the bulb to the top of the entrance flare of the capillary.

9.3.1.4 With transverse ventilation, the diameters of the sensors (excluding wet covering) shall be not less than 1 mm and not greater than 7 mm.

9.3.1.5 With axial ventilation, the diameters of the sensors (excluding wet covering) shall be not less than 2 mm and not greater than 7 mm and their length shall be not less than 10 mm and not greater than 30 mm.

9.3.1.6 The connecting wires of electrical thermometers shall be contained within the supporting stems and shall be isolated from the moisture of the wet covering.

9.3.1.7 Mercury-in-glass thermometers are preferred for reasons of variety reduction, availability, and low cost, their use not being associated with unduly onerous disadvantages. Such thermometers shall be graduated to 0.5°C or closer and be capable of being read to the nearest 0.1°C or better. (A specification for mercury-in-glass thermometers suitable when the uncertainty in the derived relative humidity is not required to be less than 3% RH is given in Appendix A.)

9.3.1.8 Heat from the fan or its motor shall not affect thermometer readings.

9.3.2 Wet-Bulb Covering, Wick, and Water Reservoir

9.3.2.1 The wet-bulb covering shall be fabricated from hydrophilic undressed white cotton muslin made from thread of linear density between 10 and 15 tex and having 20 to 25 threads per cm warp and weft.

A seamless sleeve is preferred, but a seam is permitted provided that it does not add appreciably to the general roughness that the weave imparts to the surface. (If the diameter of the stem differs substantially from that of the sensor, a seamless covering cannot properly fit both the sensor and the stem as would be required by 9.3.2.3.)

9.3.2.2 After fabrication, the covering and wick shall have been washed in a dilute solution of sodium carbonate and thoroughly rinsed with pure water (9.4.2). They should not be touched subsequently by fingers.

9.3.2.3 The covering shall cover the sensor completely and with a snug fit. It shall extend onto the stem for such a distance that the error in the observed wet-bulb temperature due to heat conduction along the stem does not exceed 0.05°C. (A method for determining the distance for which the covering must extend onto the stem to achieve this accuracy is outlined in Appendix B. For mercury-in-glass thermometers with solid stems, a distance of two times the stem diameter usually is adequate.)

9.3.2.4 The stem of each thermometer shall, for a length measured from the sensor and not less than 1.5 times the length of the extension of the covering required by 9.3.2.3, be clear of obstructions and freely exposed to the airstream.

9.3.2.5 During the test, the covering shall be completely permeated with water as evidenced by a glistening appearance in a beam of light.

9.3.2.6 The covering shall be washed in situ with water (9.4.2) from time to time and be renewed when it shows any evidence of permanent change.

9.3.2.7 When a wick is provided, it shall consist of twisted threads of white cotton and shall have the minimum cross section consistent with an adequate water feed to the wet bulb for the highest rates of evaporation. The free length of a wick shall be at least twice the diameter of the wet bulb and at least three times the wick diameter, ensuring that water arriving at the covering is already nearly at the wet-bulb temperature. The wick shall be limp.

9.3.2.8 Air that passes over a wick other than in close proximity to the wet bulb shall not impinge on the wet bulb. With axial ventilation, the wick, if provided, shall be attached to that part of the covering that extends onto the stem.

9.3.2.9 A water reservoir shall not obstruct the airflow, and its contents shall not affect the humidity of the sample air.

9.3.2.10 The water level in the water reservoir shall be not more than 25 mm below the level of the lowest part of the wet bulb.

9.3.3 Water. The water shall be pure water produced by multiple distillation or by deionization followed by distillation.

9.3.4 Airflow

9.3.4.1 The flow of air over both the wet and dry bulbs shall be a forced flow of 4±1 m/s for transverse ventilation and 2±0.5 m/s for axial ventilation.

9.3.4.2 The sample air shall not pass over any obstruction or through a fan before it passes over the wet and dry bulbs.

9.3.4.3 With axial flow, the flow direction shall be from the free end of each sensor toward the support end.

9.3.4.4 No air that has been cooled by the wet bulb or by the wick shall impinge on the dry bulb. (This may be ensured by having two separate incoming airstreams.) Air that has been discharged from the instrument shall not return locally to the incoming air.

9.3.5 Radiation Shields

9.3.5.1 With transverse ventilation, radiation shields in the form of parallel plates, polished on the outside and blackened on the inside, may be provided to shield the wet and dry bulbs from extraneous radiation. The clearance between the wet and dry bulbs and the shields shall be not less than half the diameter of the wet bulb. The shields should be flared outward at the inlet to prevent the flow separating from the shields on the inside (vena contracta effect). The shields may form part of a duct of rectangular cross section for the airflow. A second, outside shield is unnecessary.

9.3.5.2 With axial ventilation, concentric radiation shields shall be provided for the wet and dry bulbs and shall be polished inside and out. (The shield around the wet bulb plays a vital role in reducing the radiative heat transfer between the bulb and its surroundings by approximately a factor of three.) The diameter of the shield shall be not less than 1.8 d and not greater than 2.5 d , where d is the overall diameter of the wet bulb. Its length and position shall be such that its projection

beyond each end of the wet covering is not less than d and not greater than $3d$. The entrance to the shield should be flared to form a bellmouth to prevent flow separation from the inside of the shield. The shield also may serve as a duct for the airflow. A second, outside shield is unnecessary.

9.3.5.3 Any radiation shields shall be of metal, 0.4 to 0.8 mm thick. Surfaces required to have a polished finish shall be made of a bare, brightness-retaining metal.

9.4 Procedure

9.4.1 Location. Choose a practical location where the air sample is representative and where it is not affected by factors such as machinery and personnel.

9.4.2 Preparation. Ensure that water has permeated the whole of the wet-bulb covering. If the covering was initially dry, allow several minutes for saturation. Avoid touching the covering or the wick, if present, with fingers. Ensure that the dry bulb is dry.

9.4.3 Ventilation and Observation

- Establish the airflow and maintain it until a constant wet-bulb temperature is attained. (With mercury-in-glass thermometers, approximately two minutes ventilation time is required.) If the measurements are being made in an enclosed space and steadily rising wet-bulb and dry-bulb temperatures are observed, consider whether heat and moisture liberated by the instrument are affecting conditions.
- Read the thermometers with the necessary precision, obtaining the dry-bulb temperature with an overall uncertainty of $\pm 0.2^\circ\text{C}$ or better, and the temperature depression with an overall uncertainty of $\pm 0.2^\circ\text{C}$ or better, resulting in an uncertainty in the relative humidity of $\pm 3\%$ RH, or with an overall uncertainty of $+0.1^\circ\text{C}$ or better, resulting in an uncertainty in the relative humidity of $\pm 2\%$ RH.
- For measurements in nominally constant conditions, e.g., where a control cycle is long compared with the measurement time, repeat steps (a) and (b), rewetting the covering if necessary, until in three successive readings the greatest temperature depression differs from the least by not more than 0.2°C for an uncertainty of $\pm 3\%$ RH or not more than 0.1°C for an uncertainty of $\pm 2\%$ RH.
- Where measurements are being made under conditions fluctuating rapidly under control, take a number of readings over at least two cycles.
- Where measurements are being made while conditions are being changed under control, the readings may not be meaningful.

9.5 Reduction of the Observations

9.5.1 By Means of a Psychrometric Table or Chart. Take a psychrometric table or chart, the values in which are consistent with the equations and appropriate value of psychrometer coefficient A as given in 9.5.2 and, from the dry-bulb temperature and the temperature depression, obtain the relative humidity or the humidity in whatever desired measure. (To facilitate the identification of suitable tables or charts, values of relative humidity for various dry-bulb tem-

peratures and temperature depressions are given in Appendix C for standard atmospheric pressure and three relevant values of A , namely, 6.5×10^{-4} , 6.7×10^{-4} , and $6.9 \times 10^{-4}\text{K}^{-1}$.

9.5.2 By Calculation. The following psychrometer equation, or an equation that is equivalent for the prevailing conditions, shall be used:

$$p_w = p_{ws}^* - A(t - t^*)p$$

where

- p_w = partial pressure of water vapor in the atmosphere,
- p_{ws}^* = saturation partial pressure at the wet-bulb temperature t^* ,
- t = dry-bulb temperature ($^\circ\text{C}$),
- t^* = wet-bulb temperature ($^\circ\text{C}$),
- p = total (atmospheric) pressure, and
- A = psychrometer coefficient (K^{-1}), where P_w , P_{ws}^* , and p are expressed in the same units.

The value of A shall be chosen in the range of 6.5×10^{-4} to $6.9 \times 10^{-4}\text{K}^{-1}$. If the value of A has been determined for the particular design of the psychrometer and lies within this range, then it shall be used. If a value has been determined that lies outside this range, then the closer extreme value of the range shall be used. If no value of A has been determined, then the value $6.7 \times 10^{-4}\text{K}^{-1}$ shall be used. (It may be noted that if, for example, at $+20^\circ\text{C}$ and standard atmospheric pressure, use of the value $6.5 \times 10^{-4}\text{K}^{-1}$ led to a derived relative humidity of 50.0%, then use of the value $6.9 \times 10^{-4}\text{K}^{-1}$ would lead to a derived relative humidity of 48.9%.)

- The psychrometer equation gives p_w , the partial pressure of water vapor in this atmosphere.
- The percent relative humidity is given by $100p_w/p_{ws}(t)$, where $p_{ws}(t)$ is the saturation partial pressure of water vapor at the dry-bulb temperature t .
- The dew-point temperature may be calculated if required. It is the temperature at which the saturation partial pressure is equal to p_w .

9.6 Accuracy. The uncertainty in the derived relative humidity is estimated not to exceed $\pm 3\%$ RH if the temperature depression has been measured with an overall uncertainty of $\pm 0.2^\circ\text{C}$ or better and $\pm 2\%$ RH if the depression has been measured with an overall uncertainty of $\pm 0.1^\circ\text{C}$ or better.

9.7 Test Report. The test report shall give

- a reference to this standard,
- the instrument identification and the accuracy of the instrument,
- the date and time of measurement,
- the location (9.4.1),
- the dry-bulb temperature and the percent relative humidity or the dry-bulb temperature and humidity in whatever other desired measure, and
- any influencing factors (9.5.2 and 9.4.3).

10. NOMENCLATURE

A	= psychrometer coefficient
$^{\circ}\text{C}$	= degrees Celsius
d_v	= water vapor density (kg/m^3)
$f(p_s, t)$	= enhancement factor at saturator pressure and temperature t
h	= specific enthalpy of moist air mixture (kJ/kg)
h_a^*	= specific enthalpy of dry air (kJ/kg)
h_{fg}	= latent heat of vaporization of t^* (kJ/kg)
h_g	= specific enthalpy of saturated water vapor (kJ/kg)
$h(p, t, W)$	= specific enthalpy of moist air mixture at p, t^*, W (kJ/kg)
h_s^*	= specific enthalpy of a saturated mixture at p, t^*, W_s^* (kJ/kg)
h_w^*	= specific enthalpy of water at t^* (kJ/kg)
K	= degrees Kelvin ($273.16 + ^{\circ}\text{C}$)
m_a	= mass of dry air in mixture (kg)
m_w	= mass of water vapor in mixture (kg)
N	= total moles in a mixture (mole)
N_a	= moles of dry air in a mixture (mole)
N_i	= moles of component i in a mixture (mole)
N_w	= moles of water vapor in a mixture (mole)
P	= pressure of the moist air mixture (kPa)
P_a	= partial pressure of dry air in a mixture (kPa)
P_s	= vapor pressure of water in saturated moist air or saturator pressure (kPa)
p_t	= test chamber pressure in two pressure humidity generators (kPa)
P_w	= partial pressure of water vapor in a mixture (kPa)
$p_{ws}(t)$	= saturation pressure of water vapor at t (kPa)
$p_{ws}(t^*)$ or p_{ws}^*	= saturation pressure of water vapor at t (kPa)
$p_{ws}(t_d)$	= saturation pressure of water vapor at t_d (kPa)
q	= specific humidity
R	= universal gas constant ($\text{Pa}\cdot\text{m}^3/\text{mole}\cdot\text{K}$)
R_a	= specific gas constant for dry air ($\text{Pa}\cdot\text{m}^3/\text{mole}\cdot\text{K}$)
t	= temperature of the moist air mixture (dry bulb) ($^{\circ}\text{C}$)
t^*	= thermodynamic wet-bulb temperature ($^{\circ}\text{C}$)
t_d	= thermodynamic dew-point temperature ($^{\circ}\text{C}$)
t_d'	= frost-point temperature ($^{\circ}\text{C}$)
$t_d(p, W)$	= thermodynamic dew-point temperature of moist air mixture at p and W ($^{\circ}\text{C}$)
T	= absolute temperature of the moist air mixture ($^{\circ}\text{C}$)
V	= volume of the mixture (m^3)
W	= mixing (humidity) ratio
W_s^*	= saturation mixing (humidity) ratio at t^* and p
$W_s(t, p)$	= saturation mixing (humidity) ratio at t and p

$W_s(t_d)$ or $W_s(p, t_d)$	= saturation mixing (humidity) ratio at t_d and p
x_a	= mole fraction of dry air in a mixture
x_i	= mole fraction of component i in a mixture
x_w	= mole fraction of water vapor in a mixture
x_{ws}	= mole fraction of water vapor in a saturated mixture
ρ	= density of an air-water vapor mixture (kg/m^3)
v	= specific volume of a moist air mixture (m^3/kg)
μ	= degree of saturation
ϕ	= relative humidity (%)

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APPENDIX A
MERCURY-IN-GLASS THERMOMETERS SUITABLE
WHEN THE UNCERTAINTY IN THE MEASURED
RELATIVE HUMIDITY IS NOT REQUIRED TO BE
LESS THAN ±3% RH

Mercury-in-glass thermometers conforming to the following specifications are suitable when the uncertainty of the measured relative humidity is not required to be less than ±3% RH.

A1 Type. The thermometers shall be of the solid-stem type and the stem may have a slight neck near the bulb to allow the wet-bulb covering to be secured more easily by a cotton thread.

A2 Temperature Scale. The thermometers shall be graduated for total immersion and in accordance with the Celsius scale that corresponds to the International Temperature Scale current at the time.

A3 Range. The nominal temperature range of the thermometers shall be 0°C to 80°C.

A4 Materials. The stem shall be of a suitable glass with an enamel back. The bulb shall be of one of the thermometric glasses listed in Table A1 or of a glass that has properties similar to any of those listed.

A5 Annealing and Stabilization. The glass shall be suitably annealed and the thermometers shall be stabilized by a suitable heat treatment before they are filled with mercury.

A6 Expansion Chamber. Each thermometer shall include an expansion chamber above the highest scale line so that a temperature of at least +100°C can be sustained without the likelihood of damage.

TABLE A1
Thermometric Glasses *

Type	Identification	Manufacturer
Corning Normal 7560	CN	Corning Glass Co., Corning, N.Y., USA
Kimble R6	—	Kimble Glass Co., Toledo, Ohio, USA

* Note: Glasses equivalent to items listed may be made by other manufacturers.

A7 Dimensions.

	mm
Length from bottom of bulb to underside of button or ring top (maximum).....	240
Scale length corresponding to the nominal range (minimum).....	130
Bulb length.....	15 to 25
Bulb diameter.....	3 to 4
Stem diameter.....	4 to 5
Distance of neck (if any) from top of bulb *	8 to 12
Distance of lowest scale line from top of bulb * (minimum).....	30
Distance of expansion chamber from highest scale line (minimum).....	10

*Note: The top of the entrance flare of the capillary is taken to be the top of the bulb.

A8 Graduation and Figuring. The thermometers shall be graduated at each 0.5°C, with a longer line at 1°C. The graduations shall be numbered at each 5°C.

A9 Accuracy. Readings of each thermometer made by a knowledgeable and experienced observer with the thermometers totally immersed shall not be in error by more than 0.2°C for any temperature in the nominal range. For any two temperatures in the nominal range, readings of the two thermometers, so made, shall give the difference of the temperatures with an error not exceeding 0.2°C.

A10 Spare Thermometer. If a third thermometer is associated with the psychrometer, then Section 8 shall apply to each of the three possible combinations of two thermometers.

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APPENDIX B
DETERMINATION OF THE DISTANCE FOR WHICH
THE WET-BULB COVERING MUST EXTEND
ONTO THE THERMOMETER STEM TO LIMIT
THE HEAT-CONDUCTION ERROR TO 0.05°C

Temporarily fit the bulbs (sensors) of both thermometers with coverings similar to that to be used on the wet bulb, but allow the coverings to extend onto the stems considerably farther than usual, say, 1.5 times the actual distance.

Operate the instrument in the usual manner but with both coverings wet, choosing a location where the conditions are steady. Observe the difference of the thermometer readings as accurately as possible. (This difference is due mainly to the errors of the thermometers themselves.) Progressively reduce

the extension of one of the coverings onto the stem until the difference of the readings of the thermometers is estimated to have changed by 0.05° C. The extension existing at that stage is the minimum permissible.

A more accurate determination can be made if the difference of the readings is plotted against the extension for a number of extensions both greater than and less than that corresponding to a change of 0.05°C. The minimum extension that corresponds to a change of this amount may then be read easily from the plot.

During the procedure, as in normal operation of the psychrometer, care must be taken to preserve the cleanliness of the coverings and, in particular, to avoid touching them with fingers.

The procedure determines the extension necessary for the conditions prevailing at the time. If it is carried out under conditions that differ substantially from those under which the psychrometer is normally used, allowance should be made for the fact that, for a given extension of the covering, the temperature error due to the heat conduction is roughly proportional to the temperature depression. For example, if the present procedure is carried out under atmospheric conditions such that the temperature depression is twice the value that occurs in normal use of the instrument, then the extension that results in a change of 0.1°C in the temperature difference is the required minimum.

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APPENDIX C SKELETON TABLE OF RELATIVE HUMIDITIES

Relative humidities rounded to the nearest 0.5% RH are tabulated for various temperatures and temperature depressions and for standard atmospheric pressure and three values of the psychrometer coefficient. The table is given so that other more detailed tables may be compared with it. The dry-bulb temperature interval of 10°C and the temperature depression interval of 2°C are too wide to allow the table to be used for routine humidity measurement.

The saturation vapor pressure of water has been taken from A. Wexler, *J. Res. Nat. Bur. Std. (USA) 80A* (1976), p. 775. Standard atmospheric pressure is 1.01325×10^5 Pa.

Upper values: $A = 6.5 \times 10^{-4} \text{ K}^{-1}$

Intermediate values: 6.7×10^{-4}

Lower values: 6.9×10^{-4}

(See Table of Relative Humidities)

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APPENDIX D CALCULATION OF MOIST AIR PROPERTIES

Since most users of this standard have become proficient in the use of "in-house" computers, the following algorithms and logic diagrams are incorporated as an appendix to aid the programmer.

D1 U.S. Standard Atmosphere

- a. From NACA #1235 (1955),

$$P = 101.325[1 - (2.25569 \times 10^{-5})Z]^{5.2561},$$

where P is in kPa and Z is in meters.

- b. From U.S. Std (1976),

$$P = 101.325(T/288.15)^{5.255877},$$

$$T = 288.15 - (6.500 \times 10^{-6})[(6370.949Z)/(6370.949 + Z)],$$

where P is in kPa, T is in degrees K, and Z is in meters.

D2 Partial Water Vapor Pressure

- a. When temperature T is less than or equal to 0°C (from *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 3):

$$p_{ws}^t = e^{A1}$$

where

$$A1 = [(C_1/T) + C_2 + C_3T + C_4T^2 + C_5T^3 + C_6T^4 + C_7(\ln T)]$$

$$p_w = e^{A2};$$

where

$$A2 = [(C_1/T_d) + C_2 + C_3T_d + C_4T_d^2 + C_5T_d^3 + C_6T_d^4 + C_7(\ln T_d)]$$

$$p_{ws}^* = e^{A3};$$

where

$$A3 = [(C_1/T^*) + C_2 + C_3T^* + C_4(T^*)^2 + C_5(T^*)^3 + C_6(T^*)^4 + C_7(\ln T^*)];$$

where

p_{ws}^+ , p_w , and p_{ws}^* are in Pa; T , T_d , and T^* are in K; and constants are:

$$C_1 = 5.6745359 \times 10^3 C_2 = +6.3925247$$

$$C_3 = 9.677843 \times 10^{-3} C_4 = +6.22115701 \times 10^{-7}$$

$$C_5 = +2.0747825 \times 10^{-9} C_6 = 9.484024 \times 10^{-13}$$

$$C_7 = +4.1635019$$

Table of Relative Humidities

Dry-bulb Temperature, t, °C								
Temperature depression t - t _w	10	20	30	40	50	60	70	80
0.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2.0	76.5	82.5	86.0	88.0	89.5	90.5	91.0	92.0
	76.5	82.5	86.0	88.0	89.5	90.5	91.0	92.0
	76.5	82.5	86.0	88.0	89.5	90.5	91.0	92.0
4.0	54.5	66.5	73.0	77.0	79.5	81.5	83.0	84.5
	54.0	66.0	73.0	77.0	79.5	81.5	83.0	84.5
	53.5	66.0	72.5	77.0	79.5	81.5	83.0	84.5
6.0	34.0	51.5	61.0	67.0	70.5	73.5	75.5	77.0
	33.0	51.0	60.5	66.5	70.5	73.5	75.5	77.0
	32.0	50.5	60.5	66.5	70.5	73.0	75.5	77.0
8.0	14.5	37.5	50.0	57.0	62.0	65.5	68.5	70.5
	13.5	36.5	49.5	57.0	62.0	65.5	68.5	70.5
	12.0	36.0	49.0	57.0	62.0	65.5	68.5	70.5
10.0		24.5	39.5	48.5	54.5	58.5	62.0	64.5
		23.5	39.0	48.5	54.5	58.5	62.0	64.5
		22.5	38.5	48.0	54.0	58.5	61.5	64.5
12.0		12.0	30.0	40.5	47.5	52.0	55.5	58.5
		11.0	29.5	40.0	47.0	52.0	55.5	58.5
		10.0	29.0	40.0	47.0	52.0	55.5	58.5
14.0		0.5	21.0	33.0	40.5	46.0	50.0	53.5
			20.5	32.5	40.5	46.0	50.0	53.0
			20.0	32.5	40.0	45.5	50.0	53.0
16.0			13.0	26.0	34.5	40.5	45.0	48.5
			12.0	25.5	34.5	40.0	44.5	48.0
			11.5	25.5	34.0	40.0	44.5	48.0
18.0			5.0	20.0	29.0	35.0	40.0	43.5
			4.5	19.5	28.5	35.0	40.0	43.5
			3.5	19.0	28.5	35.0	39.5	43.5
20.0				14.0	23.5	30.5	35.5	39.5
				13.5	23.5	30.0	35.0	39.0
				12.5	23.0	30.0	35.0	39.0
22.0				8.5	19.0	26.0	31.0	35.5
				7.5	18.5	26.0	31.0	35.0
				7.0	18.0	25.5	31.0	35.0
24.0				3.0	14.5	22.0	27.5	31.5
				2.5	14.0	21.5	27.0	31.5
				2.0	13.5	21.5	27.0	31.5
26.0					10.5	18.0	23.5	28.0
					10.0	18.0	23.5	28.0
					9.5	17.5	23.5	28.0
28.0					6.5	14.5	20.5	25.0
					6.0	14.5	20.0	24.5
					5.5	14.0	20.0	24.5
30.0					3.0	11.5	17.5	22.0
					2.5	11.0	17.0	22.0
					2.0	11.0	17.0	21.5
32.0						8.5	14.5	19.0
						8.0	14.5	19.0
						7.5	14.0	19.0
34.0						5.5	12.0	16.5
						5.5	11.5	16.5
						5.0	11.5	16.5
36.0						3.0	9.5	14.0
						2.5	9.0	14.0
						2.5	9.0	14.0
38.0						0.5	7.0	12.0
						0.5	7.0	12.0
							6.5	11.5
40.0							5.0	10.0
							5.0	10.0
							4.5	9.5

- b. When temperature T is greater than or equal to 0°C (from *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 4):

$$p_{ws}^t = e^{B1}$$

where

$$B1 = [(C_8/T) + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}(\ln T)]$$

$$p_w = e^{B2};$$

where

$$B2 = [(C_8/T_d) + C_9 + C_{10}T_d + C_{11}T_d^2 + C_{12}T_d^3 + C_{13}(\ln T_d)]$$

$$p_{ws}^* = e^{B3};$$

where

$$B3 = [(C_8/T^*) + C_9 + C_{10}T^* + C_{11}(T^*)^2 + C_{12}(T^*)^3 + C_{13}(\ln T^*)];$$

where

p_{ws}^+ , p_w , and p_{ws}^* are in Pa; T , T_d , and T^* are in K; and constants are:

$$C_8 = 5.8002206 \times 10^3 C_9 = +1.3914993$$

$$C_{10} = 4.8640239 \times 10^{-2} C_{11} = +4.1764768 \times 10^{-5}$$

$$C_{12} = 1.4452093 \times 10^{-8} C_{13} = +6.5459673$$

- c. When the humidity ratio, W , is known (from *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 34),

$$(p_{ws})t_d = p_w = [(pW)/(0.62198 + W)],$$

where

p_w and p are in kPa and W is the (kg moist/kg dry air) ratio.

D3 Dew-Point Temperature

- a. When temperature (t_d) is less than or equal to 0°C (from *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 36),

$$t_d = 6.09 + 12.608[\ln(p_w)] + 0.4959[\ln(p_w)]^2,$$

where

p_w is in kPa and t_d is in $^\circ\text{C}$.

- b. When temperature (t_d) is greater than or equal to 0°C (from *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 35),

$$t_d = a + b[\ln(p_w)] + c[\ln(p_w)]^2 + d[\ln(p_w)]^3 + e(p_w)^{0.1984},$$

where

p_w is in kPa, t_d is in $^\circ\text{C}$, and constants are:

$$a = 6.54 \quad b = 14.526$$

$$c = 0.7389 \quad d = 0.09486$$

$$e = 0.4569$$

D4 Humidity Ratio

From *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 20:

$$W = 0.62198(p_w)/(p - p_w).$$

From *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 21:

$$W_s = 0.62198(p_{ws})/(p - p_{ws})$$

and

$$W_s^* = 0.62198(p_{ws}^*)/(p - p_{ws}^*).$$

Use Equation 33a when t^* is greater than or equal to 0°C :

$$W = [(2501 - 2.381t^*)W_s^* - c_{pa}(t - t^*)]/(2501 + 1.805t - 4.186t^*).$$

Use Equation 33b when t^* is less than or equal to 0°C :

$$W = [(2167.57 - 0.2340t^*)W_s^* - c_{pa}(t - t^*)]/(2167.57 + 1.805t - 2.039t^*)$$

where

p , p_w , p_{ws} , and p_{ws}^* are in kPa; W , W_s , and W_s^* are the (kg moisture/kg dry air) ratio; t and t^* are in $^\circ\text{C}$; and c_{pa} is the specific heat of dry air (kJ/kg $^\circ\text{C}$).

D5 Relative Humidity. From *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 22:

$$\phi = p_w/p_{ws}$$

where

p_w and p_{ws} are in kPa or consistent units.

D6 Specific Volume

From *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 25:

$$v = R_a T / (p - p_w) = 0.287055 T / (p - p_w).$$

From *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 26:

$$v = [R_a T / p] \cdot (1 + 1.6078 W)$$

where

v is in m^3/kg , p and p_w are in kPa, T is in K, and W is the (kg moisture/kg dry air) ratio.

D7 Enthalpy

From *ASHRAE Handbook—Fundamentals*, chapter 6, 1993, Equation 30:

$$h = t + W(2501 + 1.805 t)$$

where

h is in kJ/kg, t is in $^\circ\text{C}$, and W is the (kg moisture/kg dry air) ratio.

D8 Wet-Bulb Temperature (Iterative Procedure Required)

Use Equation 33a when t^* is greater than or equal to 0°C :

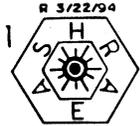
$$t^* = [2501 W_x^* - c_{pa} t - W(2501 + 1.805 t)] / (2.381 W_s^* - c_{pa} - 4.186 W).$$

Use Equation 33b when t^* is less than or equal to 0°C :

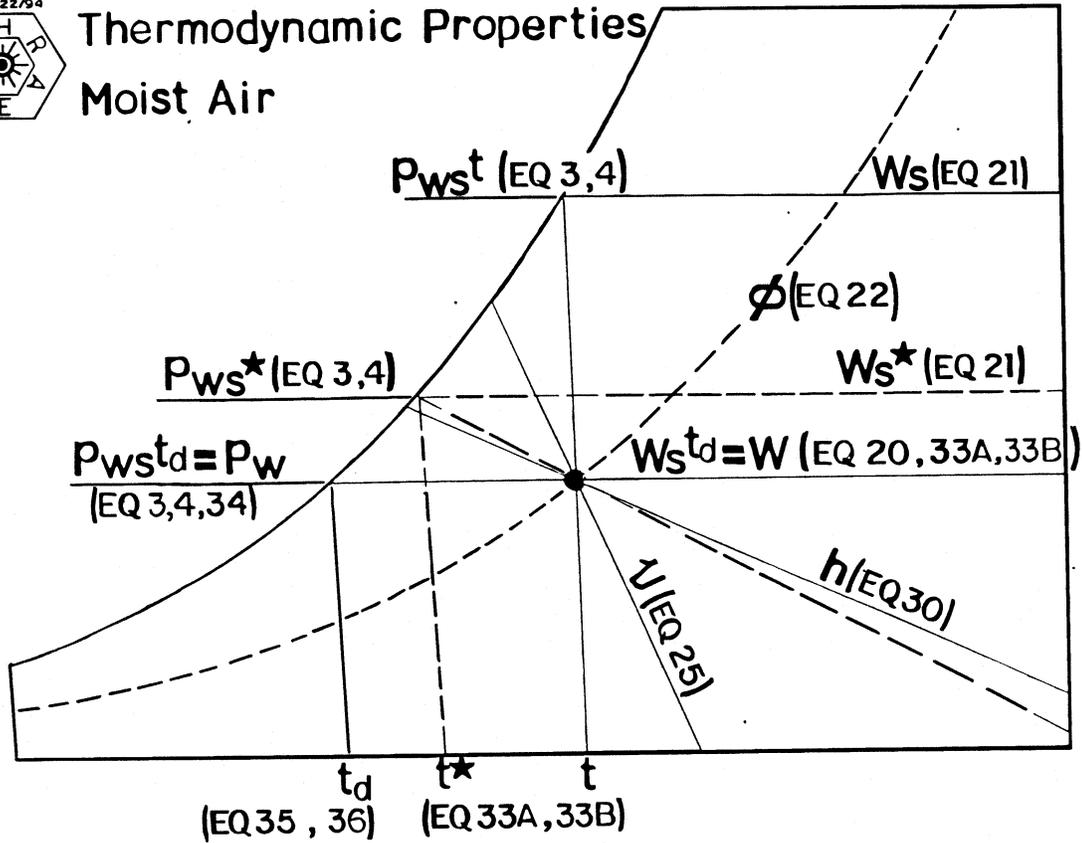
$$t^* = [2167.57 W_x^* - c_{pa} t - W(2167.57 + 1.805 t)] / (0.234 W_s^* - c_{pa} - 2.039 W),$$

where

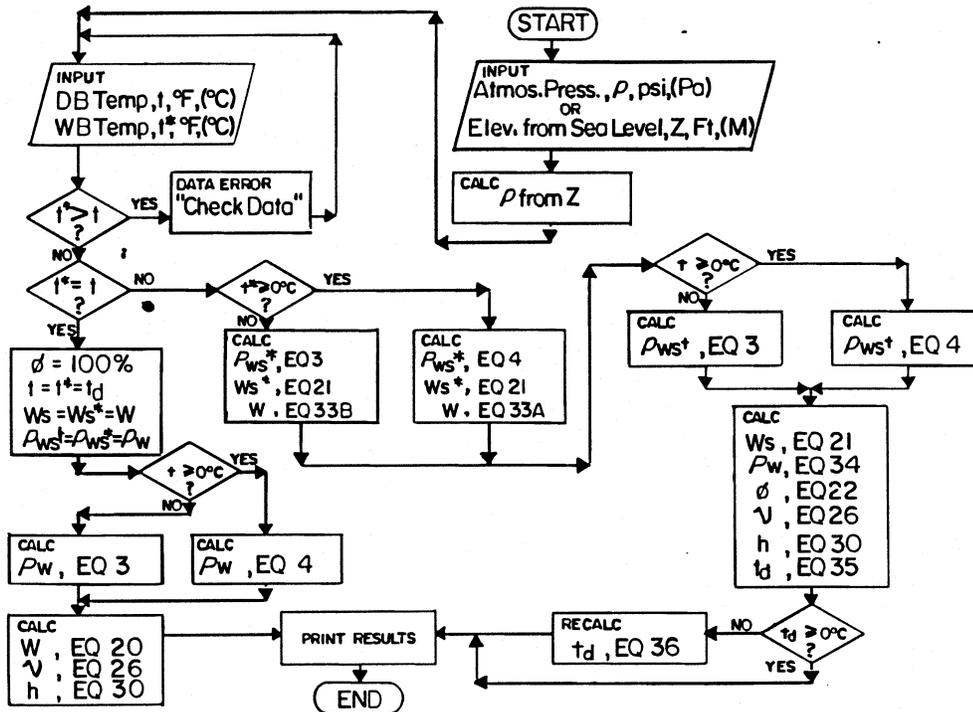
t and t^* are in $^\circ\text{C}$, W and W_s^* are the (kg moisture/kg dry air) ratio, and c_{pa} is the specific heat of dry air (kJ/kg $^\circ\text{C}$).



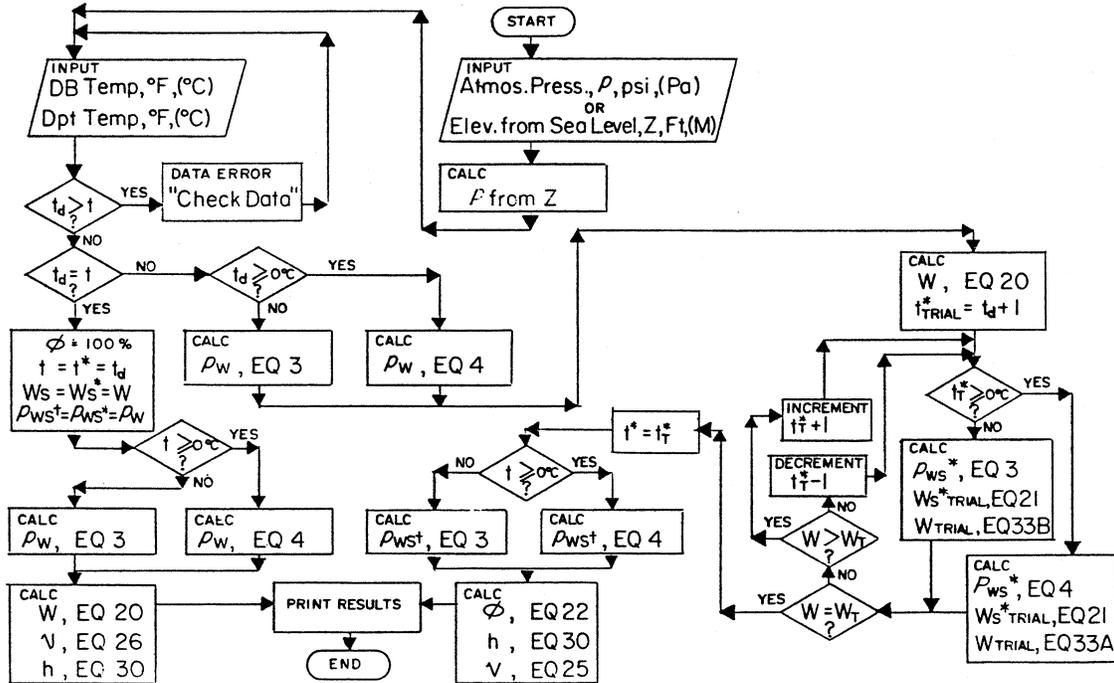
Thermodynamic Properties Moist Air



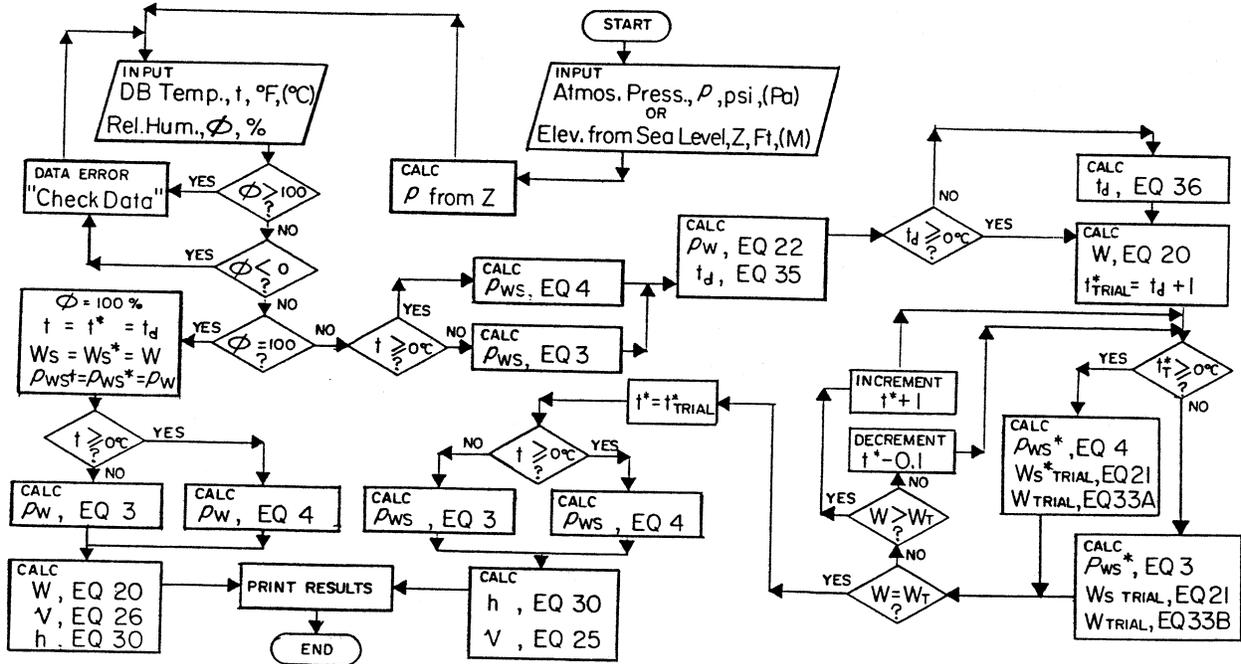
State Point Calculation Sequence for P, t, t^*



3  State Point Calculation Sequence for P, t, t_d



4  State Point Calculation Sequence for P, t, φ



**POLICY STATEMENT DEFINING ASHRAE'S CONCERN
FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES**

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effect on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the standards and guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive technical committee structure, continue to generate up-to-date standards and guidelines where appropriate and adopt, recommend, and promote those new and revised standards developed by other responsible organizations.

Through its *Handbook*, appropriate chapters will contain up-to-date standards and design considerations as the material is systematically revised.

ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating standards and guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.

