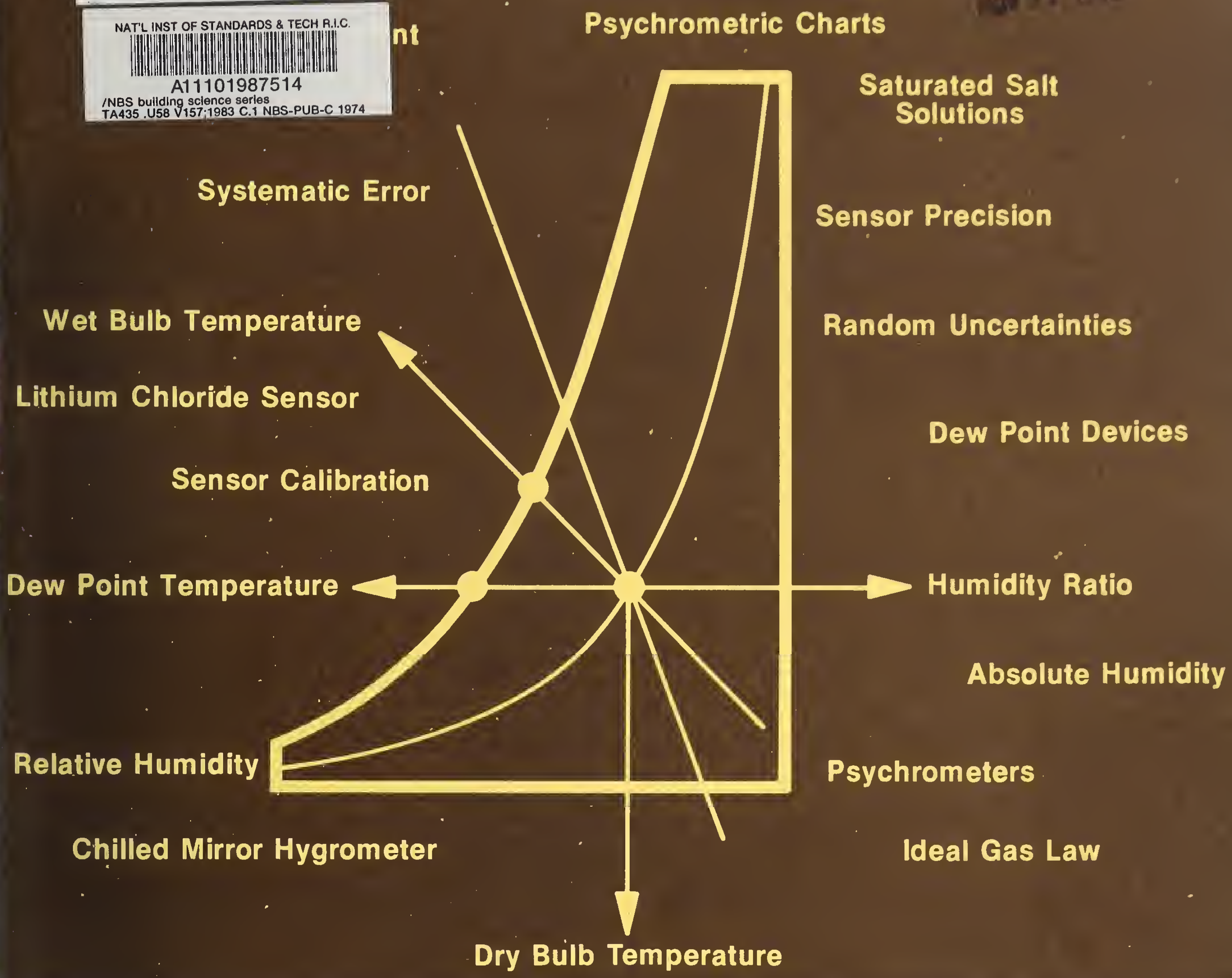

## NBS BUILDING SCIENCE SERIES 157

# General Guidelines for the On-Site Calibration of Humidity and Moisture Control Systems in Buildings

RTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

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NBS BUILDING SCIENCE SERIES 157

# General Guidelines for the On-Site Calibration of Humidity and Moisture Control Systems in Buildings

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# ABSTRACT

The control of the moisture content of the air in buildings directly affects the comfort of the building occupants and is one of the more important tasks of an energy management and control system (EMCS). Unfortunately, a lack of understanding of the principles of operation and calibration of the various instrumentation used in monitoring the moisture content of air often makes this one of the most difficult and most neglected tasks for those assigned the responsibility of maintaining and operating building heating, ventilating and air-conditioning (HVAC) control systems.

This report was written for the purpose of assisting the managers and operators of EMCS in buildings in the understanding and use of various techniques for on-site measurement of the moisture content in the air. In addition, various methods of on-site calibration of typical types of moisture monitoring instruments are also discussed.

The ideal gas law is reviewed because of its direct application in converting the various humidity units. Relative humidity and dew point temperature are defined and their relationship described. Typical types of moisture monitoring instruments are described together with their method of operation. Several calibration techniques are discussed together with their typical advantages and disadvantages. The last section of this report is devoted to assessing and reporting the errors or uncertainties associated with the calibration and functioning of various moisture monitoring instruments. This very important area is often neglected and can result in excessive operating and maintenance costs.

Key words: chilled mirror hygrometer; dew point temperature; humidity generator; humidity sensors; lithium chloride humidity sensors; moisture content of building air; relative humidity; saturated salt solutions; sensor calibration; sensor precision; specific humidity; wet-bulb temperature

Cover: The cover shows an outline of a psychrometric chart and the key words covering the contents of this report on the on-site calibration of humidity and moisture control systems in buildings.

# SI CONVERSIONS

The contents of this report are directed toward assisting field personnel in the calibration of instrumentation monitoring the moisture content of air supplied by mechanical equipment in buildings. In view of the presently accepted practice of the building industry in the United States and the reference material readily accessible to field personnel managing and operating the mechanical equipment in buildings, common U.S. units of measurement have been used in this report. In recognition of the fact that the United States is a signatory to the General Conference of Weights and Measures, which gave official status to the SI system of units in 1960, appropriate conversion factors have been provided in the table below. The reader interested in making further use of the coherent system of SI units is referred to NBS SP 330, 1972 Edition, "The International System of Units,"; E380-72, ASTM Metric Practice Guide (American National Standard Z210.1); or ASHRAE "SI Metric Guide for Heating, Refrigerating, Ventilating, and Air-Conditioning," 1976.

## Metric Conversion Factors

| To convert from | To | Multiply by* |
|---|---|---|
| Area | | |
| ft$^2$ | metre$^2$ (m$^2$) | 9.290304E-02 |
| in.$^2$ | metre$^2$ (m$^2$) | 6.451600E-04 |
| Energy | | |
| Btu (Int'l Steam Table) | joule (J) | 1.055056E+03 |
| calorie (Int'l Steam Table) | joule (J) | 4.186800E+00 |
| erg | joule (J) | 1.000000E-07 |
| Force | | |
| pound-force (lb$_f$) | newton (N) | 4.448222E+00 |
| kilogram-force | newton (N) | 9.806650E+00 |
| Length | | |
| ft | metre (m) | 3.048000E-01 |
| in. | metre (m) | 2.540000E-02 |
| Mass | | |
| gram | kilogram (kg) | 1.000000E-03 |
| lb | kilogram (kg) | 4.5359237E-01 |

---

*The notation "xE±y," where x and y are numbers, is a standard form for indicating multiplication of the number x by the number 10 raised to the power ± y.

### Mass per unit vol.

| | | |
|---|---|---|
| g/cm$^3$ | kg per m$^3$ | 1.000000E+03 |
| lb/ft$^3$ | kg per m$^3$ | 1.601846E+01 |
| lb/in.$^3$ | kg per m$^3$ | 2.767991E+04 |

### Pressure (force per unit area)

| | | |
|---|---|---|
| atmosphere | pascal (Pa) | 1.013250E+05 |
| in. of mercury (60°F) | pascal (Pa) | 3.376850E+03 |
| mm of mercury (32°F) | pascal (Pa) | 1.333224E+02 |
| in. of water (60°F) | pascal (Pa) | 2.488400E+02 |
| in. of water (39.2°F) | pascal (Pa) | 2.490820E+02 |
| dyne/cm$^2$ | pascal (Pa) | 1.000000E-01 |

### Temperature

| | | |
|---|---|---|
| degree Fahrenheit | degree Celsius | subtract 32 and divide by 1.8 |
| degree Celsius | degree Fahrenheit | multiply by 1.8 and add 32 |
| degree Fahrenheit | kelvin | add 459.67 and divide by 1.8 |
| degree Celsius | kelvin | add 273.15 |
| degree Rankine | kelvin | divide by 1.8 |

### Velocity

| | | |
|---|---|---|
| ft/min | metre per second (m/s) | 5.080000E-03 |
| ft/s | metre per second (m/s) | 3.048000E-01 |
| in./s | metre per second (m/s) | 2.540000E-02 |

### Volume

| | | |
|---|---|---|
| ft$^3$ | metre$^3$ (m$^3$) | 2.831685E-02 |
| in.$^3$ | metre$^3$ (m$^3$) | 1.638706E-05 |

### Volume per unit time

| | | |
|---|---|---|
| ft$^3$/min | metre$^3$ per second (m$^3$/s) | 4.719474E-04 |
| ft$^3$/s | metre$^3$ per second (m$^3$/s) | 2.831685E-02 |

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# NOMENCLATURE*

Symbols

°C = temperature in degrees Celsius

$d$ = the absolute humidity: the ratio of the mass of water over the total volume of a given sample

$e(t)$ = the saturation water vapor pressure at temperature t(°F)

$e_i(t)$ = the saturation vapor pressure of water over ice at temperature t(°F)

°F = temperature in degrees Fahrenheit

$m_a$ = mass of dry air in a given sample, pounds

$m_w$ = mass of water vapor in a given sample, pounds

$n$ = sum of the number of moles of dry air and the number of moles of water vapor in a given volume of the mixture

$n_a$ = the number of moles of dry air in a given volume of the mixture

$n_w$ = the number of moles of water vapor in a given volume of the mixture

$N$ = a reading from an instrument

$\bar{N}$ = the average value of a series of readings from an instrument, N1, N2, N3, --------Nn

$P$ = total pressure of mixture, psia

$P_a$ = partial pressure of dry air, psia

$P_w$ = partial pressure of water vapor, psia

psia = pounds per square inch, absolute

$P_c$ = the pressure in the mirror chamber, psia

$q$ = the specific humidity: the ratio of the mass of water vapor over the total mass of the mixture

$R$ = universal gas constant (see table 1)

RH = the relative humidity: 100 times the ratio of the mole fraction of water vapor in a sample of air to the saturation mole fraction of water vapor in the air at the same temperature and pressure.

$\hat{s}$ = the estimate of the standard deviation about the mean of a series of measurements (see section 7)

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*The values noted in this nomenclature are given in U.S. units of measurement (see page iv for conversion to SI units).

## NOMENCLATURE (continued)*

$T$ = absolute temperature, degrees Rankine, °R

$t$ = temperature of air in degrees Fahrenheit

$t_d$ = measured dew point temperature of sample in degrees Fahrenheit

$V$ = volume of mixture, $ft^3$

$W$ = the humidity (mixing) ratio: the mass of water vapor divided by the mass of dry air in a given sample

$X_a$ = the mole fraction of dry air: the number of moles of dry air in a given sample divided by the sum of the number of moles of dry air and the number of moles of water vapor in the sample

$X_w$ = the mole fraction of water vapor: the number of moles of water vapor in a given sample divided by the sum of the number of moles of dry air and the number of moles of water vapor in the sample

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*The values noted in this nomenclature are given in U.S. units of measurement (see page iv for conversion to SI units).

## 1. INTRODUCTION

The measurement and control of the moisture content of air are crucial parameters for the design and operation of building energy management and control systems (EMCS). The efficiency of the personnel working in a building is determined by their comfort, which in turn depends on combinations of temperature, relative humidity, and air motion, among other things. Some laboratories and commercial and industrial facilities must be maintained within certain ranges of temperature and relative humidity to permit operations to be carried out, or prevent product or equipment damage. An engineer or architect selects the climate control not only to provide the desired conditions, but to do it in the most energy efficient manner. Under normally encountered air-conditioning situations, the latent energy associated with humidification or dehumidification can represent as much as 20 percent of the total energy being used. An error of 10 percent in the measurement and control of the moisture content in the air could have a significant impact in the total energy use. Therefore, it is necessary that the devices being used to monitor and control the moisture content in the air be maintained within an acceptable level of accuracy to avoid dollar loss from malfunction, over design, or under design of air-conditioning equipment and its controlling systems. The term "acceptable" must be defined for the individual building or areas of a building being controlled.

This report provides an overview of methods which must be used when performing on-site calibrations of sensors used to determine the moisture content of air for control purposes. It is not to be construed either as a set of universal recommended practices or as a documentary standard. In the context of this report, an on-site or field calibration will mean one not performed under strict laboratory conditions, although it is obvious that the more attention is paid to details, the more reliable the results are likely to be.

The moisture content of gas, air in particular, may be expressed in terms of relative humidity, dew point, parts per million of water vapor per unit volume of the mixture, or various other units. The most common of these units used in EMCS and the factors to convert from one to another are presented in this report followed by a brief discussion of various types of humidity sensors and their accuracy limitations. Next, some convenient methods and devices which may be used as field calibration standards are presented, along with examples of the sensors which may be calibrated by each. Finally, the actual calibration techniques and presentation of the results are discussed, including the assigning of errors to the calibration devices.

There are two underlying assumptions throughout this report. The first is that the accuracies required in the discussed calibrations will not require consideration of sophisticated interactions among the various gases; that is, air-water vapor mixtures will be assumed to be uniform gases which may be described by ideal gas relationships. It is further assumed that precision, high-capacity humidity generators, such as those described in reference [1], are not readily available to EMCS personnel. The reader should be aware that such devices are maintained at the National Bureau of Standards and are generally used to calibrate high quality humidity measuring devices. In general, the high-precision devices are not required for typical EMCS monitoring. Further, the cost of such devices is out of the EMCS range. Therefore, such devices are not included in this report.

## 2. DEFINITIONS OF CALIBRATION AND STANDARD

It is appropriate to define the terms "calibration" and "standard" as used in this report. Calibration is the comparison of the moisture content indication of sensors with the moisture content generated by or measured by a standard method or device. Calibrations may be made over all or part of the range of the sensors in an EMCS. The calibration must also account for all parameters, particularly temperature, which affect the final indication.

A standard is understood to be a moisture indicating instrument whose indication and overall uncertainty at particular values have been determined. It might be any such device; for example, a hair hygometer, an aspirated (motor driven) psychrometer, or a sophisticated dew point device. It may also be an apparatus or technique which produces particular moisture contents, within known error bounds, when certain operating conditions are met. Examples are saturated salt solutions or a variety of humidity generators.

## 3. MOISTURE MEASUREMENT UNITS AND CONVERSION FACTORS

The definitions of several humidity measurement units are given in this section. These definitions are structured to contain measurable variables such as pressure, volume, and temperature. Use has been made of ideal gas relationsips, the details of which are discussed in reference [2].

### 3.1 THE IDEAL GAS LAW

A brief review of the ideal gas law is given because its application permits conversion among the various humidity units. Fortunately, only negligible errors result for EMCS applications by using the ideal gas law for treating moist air as a mixture of independent, perfect gases; namely, dry air and water vapor. The general equation is written,

$$PV = nRT \tag{1}$$

where $P$ = pressure (psia)
$V$ = total volume of mixture ($ft^3$)
$n$ = total number of moles in the mixture
$R$ = universal gas constant [$10.73151 (lb_f/in.^2) ft^3/lb\text{-}mole\ {}^\circ R$]
$T$ = absolute temperature (°R)

(See table 1 for values of R when other units are used.)

The pressure, P, equals the sum of the partial pressure of dry air and the partial pressure of water vapor in the mixture,

$$P = P_a + P_w \tag{2}$$

where $P_a$ = partial pressure of dry air (psia), and
$P_w$ = partial pressure of water vapor (psia).

The total number of moles, n, equals the sum of the number of moles of dry air and the number of moles of water vapor in the volume, V, of the mixture,

$$n = n_a + n_w \tag{3}$$

where $n_a$ = the number of moles of dry air, and
$n_w$ = the number of moles of water vapor.

Combining these equations, we have

$$(P_a + P_w)\ V = (n_a + n_w)\ RT \tag{4}$$

Considering the ideal gas equations for dry air and for water vapor, we have

$$P_aV = n_a\ RT, \text{ and} \tag{5}$$

$$P_wV = n_w\ RT \tag{6}$$

Table 1. Values of the universal gas constant, R, for various units

| | | | | |
|---|---|---|---|---|
| Inch of mercury (32°F) | $ft^3$ | °F abs (degrees Rankine) | pound-mole | 21.84966 (in. Hg)$ft^3$/lb-mole °R** |
| Pound force per sq in. | $ft^3$ | °F abs (degrees Rankine) | pound-mole | 10.73151 (lb force/$in.^2$)$ft^3$/lb-mole °R** |
| Dynes per sq cm | $cm^3$ | Kelvin (K) | gram-mole | 8.31441 x $10^7$ ergs/mole K |
| Millimeter of mercury(°C) | $m^3$ | Kelvin | gram-mole | 6.23634 x $10^{-2}$ (mm Hg)$m^3$/mole K |
| Atmosphere | $m^3$ | Kelvin | gram-mole | 8.20685 x $10^{-5}$ (atm)$m^3$/mole K |
| Pascal | $m^3$ | Kelvin | kilogram-mole | 8.31441 x $10^3$ (N/$m^2$)$m^3$/kg-mole K |

---

The ideal (or perfect) gas law applicable to one mole of ideal gas is $PV = RT$, where $P$ = the pressure, $T$ = the absolute thermodynamic temperature, and $V$ = the volume per mole of the gas. For the case of a mass, m, of an ideal gas whose molecular weight is m, the expression becomes $Pv = m(R/M)T$ where $v$ = the volume of mass, m, of the gas.

**(Here °R = symbol for degree Rankine).

Dividing eq (5) by eq (4), the mole fraction of dry air, $X_a$, is obtained,

$$X_a = \frac{n_a}{n_a + n_w} = \frac{P_a}{P_a + P_w} = \frac{P_a}{P} \tag{7}$$

Similarly, the mole fraction of water vapor, $X_w$, is found by dividing eq (6) by eq (4),

$$X_w = \frac{n_w}{n_a + n_w} = \frac{P_w}{P_a + P_w} = \frac{P_w}{P} \tag{8}$$

The humidity ratio, W, is defined as the mass of water vapor to the mass of dry air contained in the given sample,

$$W = \frac{m_w}{m_a}, \ \frac{\text{lbs water vapor}}{\text{lbs dry air}} . \tag{9}$$

Considering the molecular weights of water and air and their relative mole fractions, we have,

$$W = \frac{18.015}{28.964} * \frac{X_w}{X_a} = 0.62198 \frac{P_w}{P_a} , \text{ or,}$$

$$W = \frac{0.62198 \ P_w}{P - P_w}, \ \frac{\text{lbs moisture}}{\text{lbs dry air}} . \tag{10}$$

Other values which may be obtained from the above equations and may be found useful in field calibration are listed below.

1. The absolute humidity, d, is the ratio of the mass of water vapor to the total volume of mixture:

$$d = \frac{18.015 \ P_w}{RT}, \ \frac{\text{lbs of water vapor}}{\text{ft}^3 \text{ of mixture}} . \tag{11}$$

2. The specific humidity, q, is the ratio of the mass of water vapor to the total mass of the moist air sample,

$$q = \frac{18.015 \ P_w}{18.015 \ P_w + 28.964 \ P_a} , \ \frac{\text{lbs water vapor}}{\text{lbs of mixture}} . \tag{12}$$

It will be noted from the above equations that the one common variable which must be determined is $P_w$, if the total pressure, P, is known since $P_a = P - P_w$.

The amount of water vapor which can be mixed with air before the air becomes saturated is strongly dependent on the air temperature. (There is also a small pressure effect, which can be considered insignificant for normal EMCS applications). The relationship of the air temperature to the saturated partial vapor pressure is well known in the pressure-temperature regions of interest in EMCS. (See tables A-1 and A-2 in appendix A, and references [4,5,11, and 14]).

The saturation may occur over water or ice, and the saturation vapor pressures are designated respectively as $e(t)$ and $e_i(t)$, the (t) emphasizing that the values are different at each temperature, t. We will simply use $e(t)$ unless it is necessary to differentiate between ice and water. If the air mixture is saturated, then $e(t)$ replaces $P_w$ in eq (10), (11), and (12), and those equations then yield the saturation mixing ratio, the saturation absolute humidity, and the saturation specific humidity, respectively.

### 3.2 RELATIVE HUMIDITY

Normally, the air is not saturated, and it is convenient to express the water vapor content as a percentage of the saturation at the same temperature. This is defined as the relative humidity, RH, and may be written as follows:

$$RH = \frac{P_w}{e(t)} \times 100 \text{ percent} \tag{13}$$

Thus, if the relative humidity is measured at a known temperature, eq 13 can be used to find $P_w$ for use in the other humidity expressions.

### 3.3 DEW POINT TEMPERATURE

The final quantity which must be identified is the dew point temperature. Since the maximum amount of moisture which the air can hold is a function of temperature, we could start with non-saturated air at temperature t, and begin to cool it. As it is cooled, the maximum possible saturation vapor pressure, $e(t)$, becomes less and less, while the actual vapor pressure, $P_w$, will remain unchanged. The relative humidity in the air, defined by eq 13, becomes closer and closer to 100 percent until a temperature, $t_d$, is reached at which $e(t)$ is the same as $P_w$, and at which temperature the gas is saturated. That temperature is called the dew point temperature (or frost point temperature, if the saturation occurs over ice). At this temperature, the moisture in the air will just begin to condense.

In some types of dew point measurement devices, a surface whose temperature is being measured is cooled until the water vapor in the ambient air begins to condense. At the condensation temperature, $t_d$, the saturation vapor pressure, $e(t)$, may be read from tables. Since no water was added to or taken from the air being monitored before condensation on the cooled surface, this partial (saturated) pressure, $e(t_d)$, must be the same partial vapor pressure, $P_w$, (not saturated) which was in the air before it was cooled. Thus, from the dew point temperature one obtains the partial pressure of moisture, and $P_w$ may be used to obtain the other humidity units described above. The relationship among dew point and relative humidity are quickly seen on the psychrometric charts (figures 3 and 4) which are described in section 6 of this report.

## 4. GENERAL TYPES AND PROPERTIES OF HUMIDITY SENSORS

Table 2 lists a variety of sensor types, their general principles of operation, the moisture ranges covered, and their inherent accuracies. The table is not all-inclusive; see reference [11] for additional types. Also, the range and accuracy statements are general in nature, and particular devices may behave better or worse than indicated here. The manufacturer's literature should be used as a guide for specific devices. For further discussions of their properties and operational principles, consult the manufacturer's literature, and see references [6,7,8, and 11].

Table 2. Sensor Properties

| Type | Method of Operation | Approximate Range | Approximate (a) Uncertainty | Response Time | Primary Output Parameter |
|---|---|---|---|---|---|
| Psychrometer, sling or aspirated | Measurement of water temperature due to evaporation | 10-100% RH | 3% RH | Medium | Temperature |
| Dew and frost point (chilled mirror) | Measure temperature at which dew or frost forms | -100°F to +200°F (dew or frost point temp) | 4°F to 0.4°F (dew or frost point temp) | Medium - fast | Temperature |
| Dewcell (LiCl sensor) | Measurement of equilibrium temperature of saturated salt solution | -20°F to +160°F (dew or frost point temp) (depends on ambient temperature) | 3°F (dew or frost point temp) | Medium | Temperature |
| Dunmore | Measurement of resistance of aqueous LiCl in binder | 7 - 98% RH | 1.5% RH | Fast | Resistance |
| Jason | Measurement of reactance of $Al_2O_3$ | 25 - 85% RH | 5% RH (increasing slowly to 10% RH from 32°F to -40°F) | Fast | Resistance |
| Ion Exchange | Measurement of resistance of ion exchange resin | 10 - 100% RH | Same as Jason | Fast | Resistance |

Table 2 (continued)

| Type | Method of Operation | Approximate Range | Approximate (a) Uncertainty | Response Time | Primary Output Parameter |
|---|---|---|---|---|---|
| Carbon | Measurement of resistance of a dimensionally-variable carbon impregnated film | 10 - 100% RH | same as Jason | Fast | Resistance |
| Dielectric crystal | Measurement of frequency change of quartz crystal covered with moisture film | -108°F to 77°F (dew or frost point temp.) | 5% of range (for frost points from -67°F to -4°F) | Medium | Frequency |
| Color change | Color change of salts amount of dissolved moisture | 10 - 80% RH | 10 - 20% RH | Slow - medium | Color |
| Mechanical | Dimensional changes of natural and synthetic fibers | 10- 90% RH | ±5% at best | Slow - medium | Dial reading |
| Thin film polymer | Measurement of frequency change of multivibrator as polymer absorbs and releases water vapor (change in dielectric constant or C) | 0 - 80% RH<br>80 - 100% RH | 2% RH<br>3% RH | Medium - fast | Frequency |

---

a) Assumes instruments have been calibrated to remove most systematic errors. Values listed are for state-of-art measurement.

## 5. CALIBRATION METHODS

As described above, even though the mass of water vapor in a given volume of air remains constant, the relative humidity will vary as the temperature of the air changes. Therefore, both the relative humidity at which an instrument is being read or calibrated and the temperature must be specified. In fact, many devices will have to be calibrated at enough different temperatures to permit interpolation between calibrated temperatures to obtain the resulting relative humidity vs. instrument indication curves. Check the manufacturer's literature for guidance.

Calibration methods can be divided into two broad categories: 1) calibrations in which the reference (standard) relative humidity is known because of the manner used to obtain it, and 2) calibrations in which the moisture level is initially unknown and must be determined through use of a standard; that is, through use of a previously calibrated (by whatever means) device. Note that by this definition, the standard may be the same type of device as that being calibrated. In this latter category, the readings of the devices will be compared to the readings of the standard.

### 5.1 CALIBRATION USING SATURATED SALT SOLUTIONS AS STANDARDS

Salt solutions are widely used to generate known relative humidities. If certain salts are mixed with enough water to form a slush, the relative humidity in an undisturbed gas volume at uniform temperature above the surface of the solution will be maintained at a constant level. This means that if the salt solution is placed within a chamber which is kept at a uniform temperature, the entire volume within that chamber will reach an equilibrium relative humidity, determined by the type of salt and the temperature. Humidity sensors which do not require a forced flow of gas across their sensing elements can be placed in the chamber and calibrated. Table B in appendix B lists some common salts, the relative humidities their saturated solutions will maintain, and the applicable temperatures. The uncertainties shown in this table are for ideal conditions, and cannot be realized in the field. For further information see reference [9]. A wide range of humidities may be generated in a reasonable time for calibration purposes through this simple method. A more detailed discussion of the method and precautions is given in section 6.4.

### 5.2 CALIBRATION BY COMPARING WITH A STANDARD DEVICE

The methods which may be used for intercomparing with a standard device are as numerous as ingenuity permits. For clarity, the types of standards will be divided into two types. The first type includes devices which require or use a gas flow, such as some dew point (cooled mirror) and psychrometric (wet-dry bulb) devices. Dew point devices and psychrometers may be most easily used to calibrate instruments which have been allowed to equilibrate with either room or outdoor temperature and humidity. These conditions usually, but not always, vary slowly enough to permit equilibrium to be achieved, yet rapidly enough to provide several closely-spaced points in a reasonable period of time. Buildings often have rooms controlled at different temperatures and/or humidities, thus providing stable calibration points. Note: Only your standard will tell what the room RH is at its current temperature. Do not assume the room specifications are being met!

It may be convenient to build a simple humidity generator for which the output may not be predictable, but for which the moisture output in a gas can be made constant within the required accuracy. The moist gas then can be led through a calibration chamber which contains both a standard to determine the moisture content and instruments to be calibrated by comparison with the standard. A generalized schematic diagram of such a system is shown in figure 1. The rate of flow of the moist gas across the standard and the instruments must fall within the specified limits given by the manufacturer of each device.

The generator may not contain all of the elements listed, but any generator of this type will have a gas supply, a throttling valve, moisture source, and calibration chamber. The degree of sophistication is a matter of need and choice. The moisture source, for example, can be a flat surface of water over which the gas flows, or a water supply with a wick exposed to the gas flow.

The moisture sources may be provided with a heater to raise the moisture level in the gas. Two flow paths with separate valves as shown in figure 1 might be used to proportion the moist and dry gas to vary the relative humidity output. If there is much turbulence over the moisture source, a droplet trap (such as a bottle stuffed loosely with glass wool or metal mesh) would be desirable as shown in figure 1. The heat exchanger might be needed if heaters are used in the moisture source to bring the temperature of the moist gas from the generator back to the temperature of the calibration chamber which contains the devices under test. A calibrated hygrometer can be used to monitor the sample gas flow through the calibration chamber. A flow-meter is included because the flow-rate must be measured during the use of many commercially available dew point devices and psychrometers.

If the instrumentation is located in a return air duct, the temperature and relative humidity of the air passing through it should be very close to those of the air in the room or hall near the intake port. One can therefore measure the intake conditions with a standard, see whether or not the duct instrumentation reads the same value (within uncertainty limits, see section 7), and adjust it accordingly. Disagreement in results may arise from sources other than a mis-calibrated instrument, and that possibility must be checked carefully before adjusting the device in the duct. Ambient temperature and moisture changes caused by the persons adjacent to the standard and performing the calibration are typical examples.

The second type of standards mentioned in section 5 do not require an air flow past their elements, although such flows may be used. These standards can be any convenient device whose humidity indication as a function of RH and temperature is known. Thus, in addition to the methods discussed above for generating moist atmospheres, closed calibration chambers may be used. A pan of water can be placed in the chamber, left long enough for the humidity to achieve some nominal level as determined by the standard, and then removed or covered (see figure 2) to allow general equilibration to occur. However, it is often just as easy, and indeed perhaps desirable, to use saturated salt solutions (see section 6.4).

This section has pointed out some general calibration techniques which may serve as guides for individual calibration schemes. The following section will discuss some of the details and precautions associated with the above calibration methods.

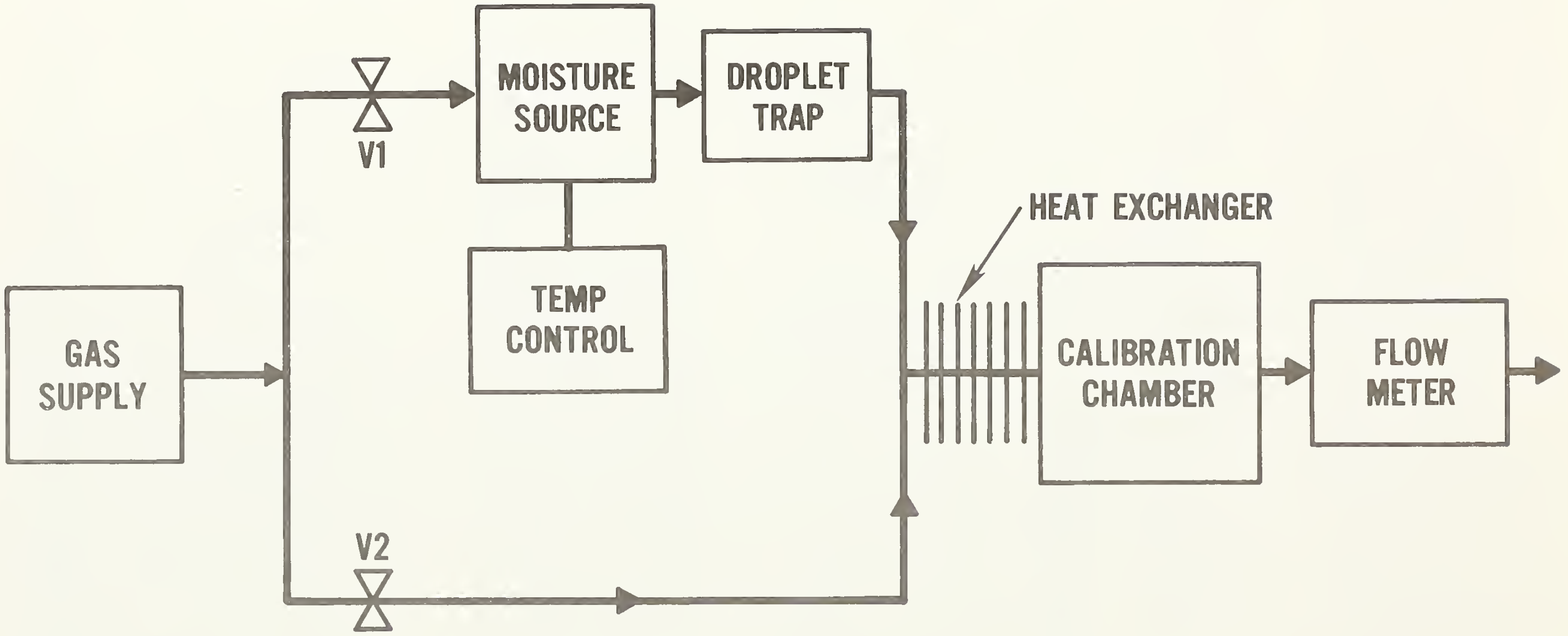

Figure 1. Schematic diagram of a generalized humidity generator for providing a flow of moist air

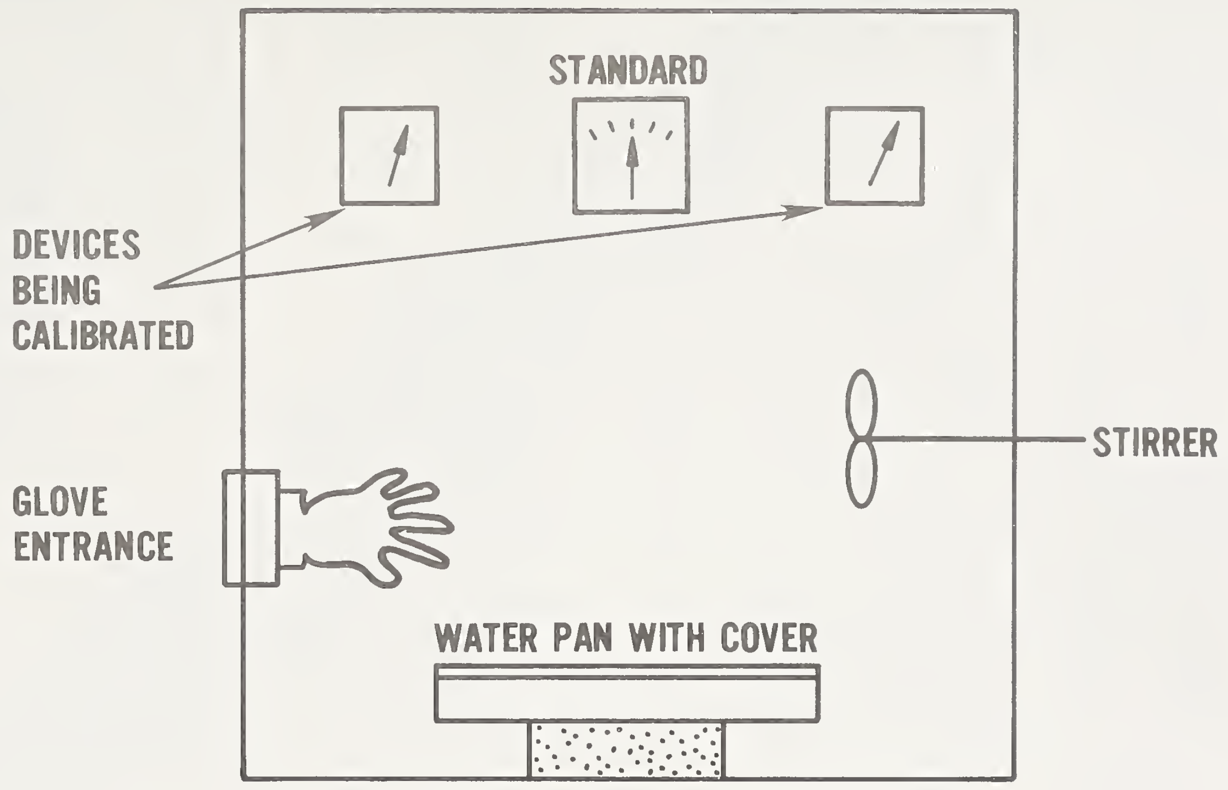

Figure 2. A simple humidity generator for calibrations which do not require large flow rates

## 6. SUGGESTED METHODS AND PRECAUTIONS IN CALIBRATING AND USING SEVERAL APPLICABLE DEVICES

This section will consider the use of forced air psychrometers, true dew point (cooled surface) devices, and the lithium chloride dew point indicator. The final paragraphs will cover use of saturated salt solutions as humidity generators.

One general comment can be made which applies to any device one may use. Read and understand the manufacturer's instructions. If questions remain, ask the manufacturer for assistance, and consult any literature which he might suggest.

### 6.1 FORCED-AIR PSYCHROMETERS AND THE PSYCHROMETRIC CHART

There are two kinds of forced-air psychrometers; motor driven and hand-held (sling) psychrometers. The instruments contain two temperature sensors in close proximity, one of which must be kept wet. This is accomplished by surrounding one sensor by a moistened wick. As the air whose moisture content is being measured is drawn across the sensors, the dry one simply records the moist air temperature. If the air happens to be saturated, no water will evaporate from the moist element once the wicking is at the same temperature as the moist air. If the air is not saturated, water will evaporate from the wicking, cooling it in the process. The cooling continues until equilibrium is established with the moist air. The dryer the air, the higher the rate of evaporation must be, and therefore the cooler the wet element will become before equilibrium is reached. The wet-bulb temperature depression relative to the dry bulb temperature is therefore a measure of the relative humidity, as will be discussed.

It is surprising how often the user will fail to keep the wick wet and that is therefore the most important rule. Rule number two is that the water which is used should be distilled. The solid particles, usually salts, found in non-distilled water will lower the saturation vapor pressure of the water and the rate of evaporation and the cooling of the wick will be less than it should be. Also, the wick itself will absorb these salts and, if not cleaned or changed before the next usage, the salts will go back into solution even if distilled water is used next. The third rule, therefore, is to rinse or change the wicks often, even if distilled water is used.

The instruments are used either by turning on the motor, or swinging by hand to cause air to pass over the wicks. Every 10-20 seconds, read the wet-bulb temperature (the dry bulb should not change significantly). This should reach a minimum value after several readings, at which point both temperature sensors are read. Be sure that the wet-bulb temperature has reached a minimum, and that the wick is still wet. If the air is very dry, the initial water temperature warm, and the water mass in the wicking small, the wick may dry out before the equilibrium temperature is reached. If so, note the minimum temperature achieved then re-wet the wick with water which has nearly that temperature (or at least is cooler than on the initial attempt), and continue taking readings. Psychrometric charts, such as figures 3 and 4, allow the user to determine the relative humidity by knowing the wet and dry sensor temperatures (usually called wet and dry bulb temperatures).

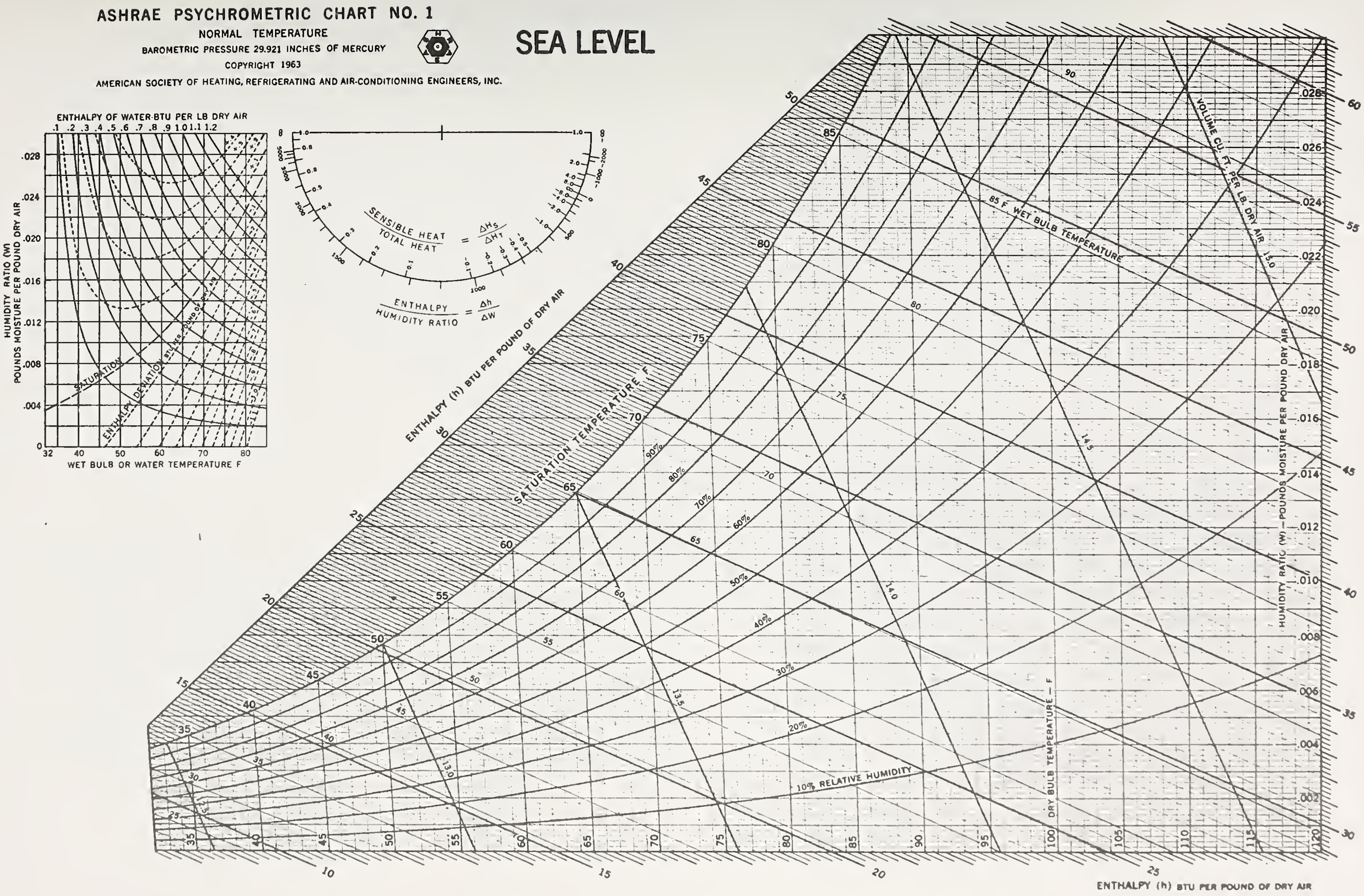

Figure 3. Psychrometric Chart No. 1
(Reprinted by permission from ASHRAE)

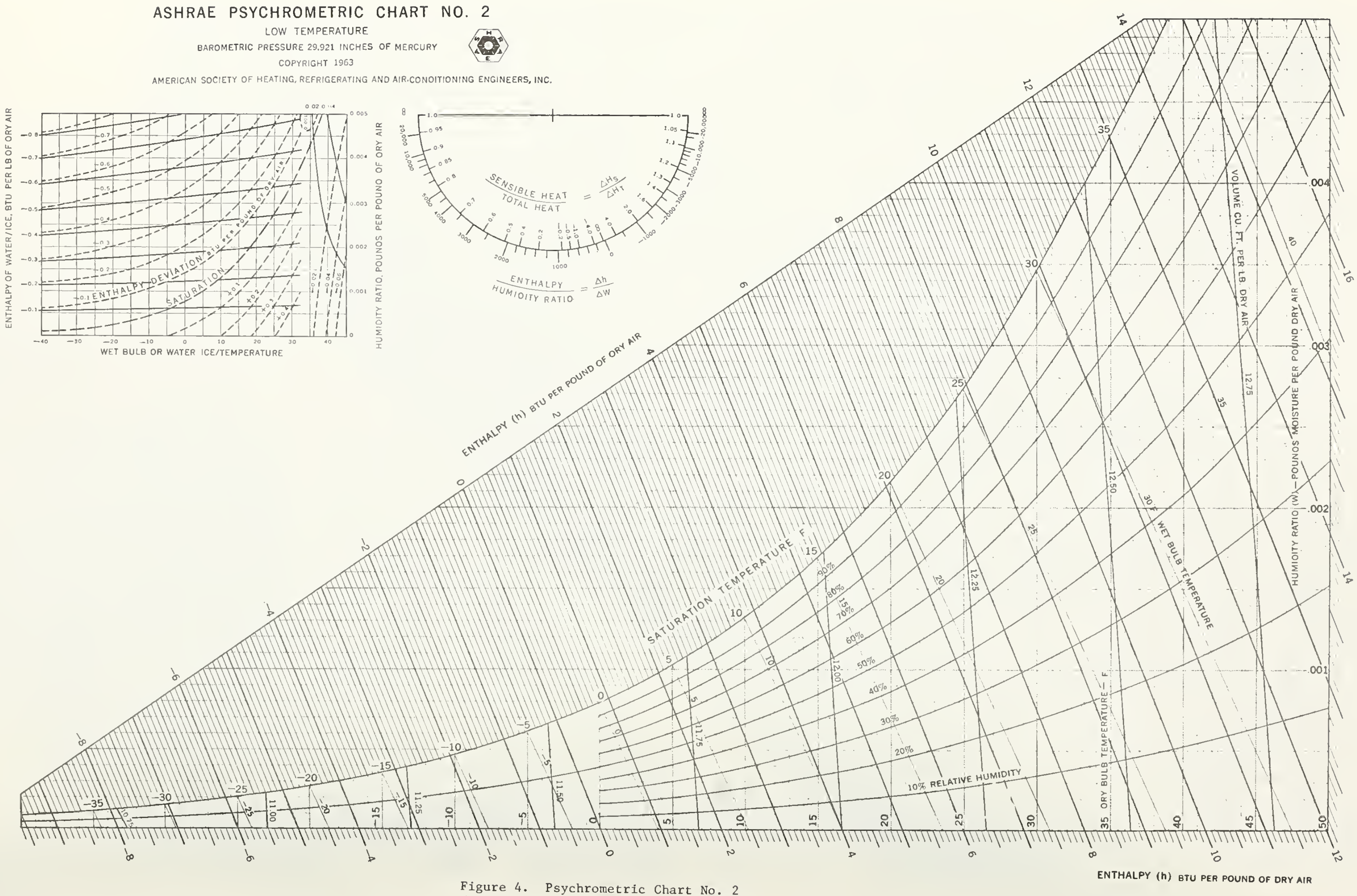

Figure 4. Psychrometric Chart No. 2
(Reprinted by permission from ASHRAE)

The ASHRAE (American Society of Heating, Refrigerationg, and Air-Conditioning Engineers) psychrometric charts (figures 3 and 4) display, at standard barometric pressure, relationships among the following parameters which relate to moist air: relative humidity, wet and dry bulb temperatures, humidity (mixing) ratio, specific enthalpy, and the volume of moist air per pound of dry air. Knowledge of any two of these parameters permits determination of the others. For example, in figure 3 if the dry bulb temperature is 77°F (25°C) and the wet-bulb temperature is 58°F (14.4°C) then the relative humidity is 31 percent, the specific enthalpy is 25 Btu/lb dry air, the humidity ratio is .0064 pounds of moisture per pound of dry air, and there are 13.65 cubic feet of moist air per pound of dry air.

The wet-bulb temperature is not the same as dew point temperature unless the air is saturated and therefore the RH is 100%. The reader should realize that the two terms are not synonymous except under these very special conditions. For example, if the relative humidity is 100% at 70°F (23.7°C), the wet-bulb and dew point temperatures are also 70°F (23.7°C). If the relative humidity is 50% at 70°F (23.7°C), the wet-bulb temperature is about 58.7°F (14.4°C) and the dew point temperature is about 50°F (10°C). If one uses a dew point device and measures a dew point of 45°F (7.2°C), then the humidity ratio is .0064 lbs/lb = .0064g/g. If the moist air temperature before cooling to the dew point was 68°F (20°C), then the relative humidity at 68°F (20°C) was 44%. This result can also be obtained from equations (10) and (13) and table A-2. Using the pressure in psia,

$$.0064 = \frac{.622\ P_w}{14.687\ P_w}$$

which yields $P_w$ = .1497 psia. Since the air before cooling was at 68°F (20°C), table A-2 shows that the saturation vapor pressure, e, is 0.339 psia. The relative humidity, from eq (13), is .1493/.339 = 44%. A final precaution; be sure that the temperature sensors read correctly, either by calibration or by comparing them with temperature sensors which are known to be reliable.

More details regarding the theory and use of psychrometers can be found in references [10] and [11]. More details in the use of the psychrometric charts can be found in reference [14]. The reader should read ASHRAE Standard ANSI/ASHRAE 41.6-1982, section 8, before using a psychrometer [15].

## 6.2 DEW POINT DEVICES

A true dew point (cooled surface) device cools a surface whose temperature can be measured until the relative humidity immediately above the surface is 100% and condensation just begins. As with psychrometers, the temperature sensors must be known to be reliable. The saturation temperature is called the dew point temperature (or frost point temperature, if the saturation temperature and conditions are such that ice is the condensate). Equilibrium is reached when cooling of the surface, which is usually a mirror, causes the observed area of condensation to grow, while heating the mirror causes the condensation to shrink. In other words, the desired temperature is such that the area of condensation observed on the mirror is approximately constant. Precision dew point instruments electronically sense a light being reflected from the mirror and scattered by the condensate. The temperature of the mirror is maintained constant to keep the intensity of the scattered light constant, meaning that the temperature of the scattering surface is not changing. Manually operated devices require practice to obtain stable areas of condensation. A method of visually observing the mirror surface must be provided, since it is the only way to distinguish whether the condensate is ice or water. Either may exist for dew point temperatures between about -22°F (-30°C) and 32°F (0°C). Initial undercooling to assure frost formation is sometimes used since automatic systems do not distinguish between supercooled water and frost. See reference [11] for further details.

All materials used to connect the dew point temperature device to the moisture source must neither absorb nor give off water vapor. Of course, there will be a layer of surface water molecules which will vary as conditions change and time must be allowed for this layer to come to equilibrium. However, water must not enter or exit the bulk material. Clean metal, glass, and Teflon tubing meet this criterion. Polyvinyl chloride (Tygon) does not.

If a pump is used to pull the moisture through the tubing, it must be located downstream of the mirror. Further, it should not cause a flow fast enough to introduce a pressure drop greater than .5% of the source pressure between the source and mirror chamber.

The mirror must be cleaned from time to time to avoid a buildup of surface contaminants which can cause a lowering of the equilibrium vapor pressure. The cleaning schedule can be established by noting changes in readings before and after cleaning (assuming the same conditions can be sampled). Otherwise, the mirror should be cleaned before each use.

The length of time required to establish equilibrium in a dew point device depends on the moisture content, since at very low dew or frost points it will take a long time for enough condensate to accumulate to permit visual operation. Approximate times for equilibration to occur as a function of dew point are listed below:

| Dew Point | Equilibration Time |
|---|---|
| 32°F (0°C) | 5 min |
| -4 to + 32°F (-20 to 0°C) | 5-20 min |
| -40 to -4°F (-40 to -20°C) | 20 min to 1 hr |
| -76 to -40°F (-60 to -40°C) | 1-2 hr |
| -94 to -76°F (-70 to -60°C) | 2-6 hr |

The estimated accuracy of the dew point hygrometer, as shown in figure 5, is valid only for "constant" ambient humidity. The estimated accuracy varies from ±0.7°F (±0.4°C) for condensation temperatures above freezing to ± 3.6°F (±2°C) at a condensation temperature of -94°F (-70°C). All uncertainties are at the 95% confidence level (see section 7). The following criteria should be used to determine whether the ambient humidity is "constant." If the standard deviation (section 7) of the dew point temperature is equal to or less than the values listed below, the ambient humidity is assumed to be sufficiently "constant" so that the accuracy curve given in figure 5 is valid.

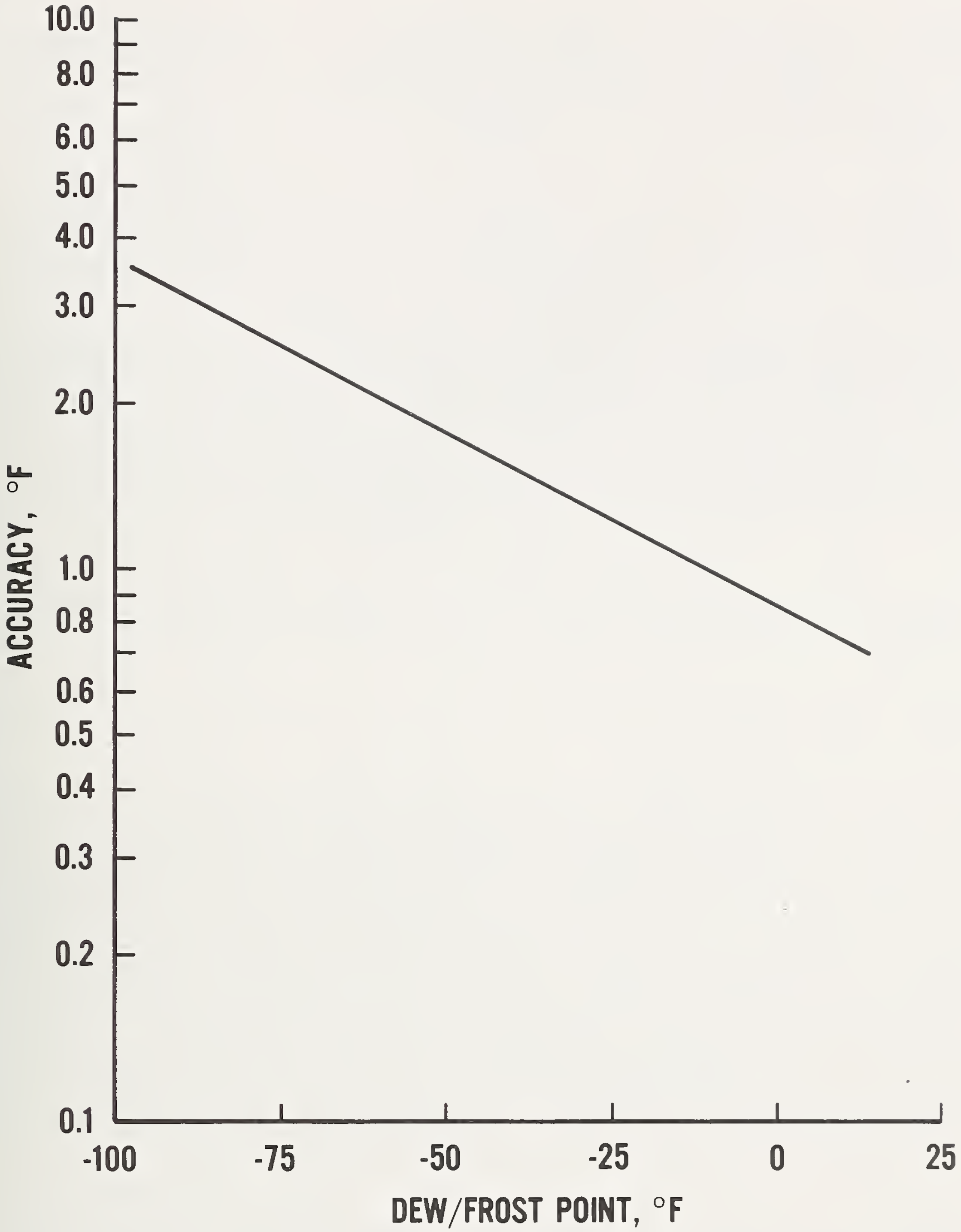

Figure 5. The estimated accuracy of a chilled mirror dew point hygrometer as a function of the measured dew point temperature. The above curve is valid only when the hygrometer is properly operated and the ambient humidity is constant

| Condensation Temperature (°C) | Duration of Sampling Time (min) | Number of Readings Taken Over Equally Spaced Time Intervals | Calculated Standard Deviation |
|---|---|---|---|
| -94°F (-70°C) | 120 | 10 to 25 | ±0.9°F (±0.5°C) |
| -76°F (-60°C) | 90 | 10 to 25 | ±0.72°F (±0.4°C) |
| -58°F (-50°C) | 60 | 10 to 25 | ±0.54°F (±0.3°C) |
| -40°F (-40°C) | 30 | 10 to 25 | ±0.36°F (±0.2°C) |
| -13°F (-40°C) | 20 | 10 to 25 | ±0.27°F (±0.15°C) |
| 14°F (-10°C) | 15 | 10 to 25 | ±0.18°F (±0.1°C) |
| 140°F (60°C) | 15 | 10 to 25 | ±0.18°F (±0.1°C) |

The following is an example of the use of the above table: If the indicated condensation temperature is -58°F (-50°C), take 10 to 25 readings at equally spaced time intervals for a period of approximately 60 minutes. Compute the average value, in this case -58°F (-50°C), and the standard deviation. If this calculated standard deviation is equal to or less than ±0.54°F (±0.3°C), the ambient humidity is assumed to be "constant" and the expected accuracy of the reading at -58°F (-50°C) is ±2.16°F (±1.2°C) (figure 5).

Once the dew point or frost point temperature has been determined, refer to table A-1 or A-2 in appendix A to determine the saturation vapor pressure at that temperature. The relative humidity in the sampled air is determined from the equation:

$$RH(\%) = \frac{P_a \quad e(t_d)}{P_c \quad e(t_a)} \times 100 \qquad (14)$$

where $P_a$ and $t_a$ are respectively the pressure and temperatures of the air being sampled, $t_d$ is the measured dew point temperature, $P_c$ is the pressure in the mirror chamber (which should not differ by more than .5% from $P_a$), and $e(t_d)$ and $e(t_a)$ are the saturation vapor pressures at temperatures $t_d$ and $t_a$. Between 32°F (0°C) and roughly -22°F (-30°C), the condensate may be either supercooled water or ice. Visual inspection is required to avoid errors in using table A-1 to find the vapor pressure since the vapor pressure curves for saturated water over ice and over supercooled water are significantly different. The presence of supercooled water is usually temporary and an initial undercooling of the surface to ensure frost formation can be used (see references [11] and [14] for further details. For further information on the use of dew point hygrometers, consult ASTM D4230 [16].

## 6.3 THE LITHIUM CHLORIDE DEW POINT INDICATOR (DEWCELL)

One of the most popular devices in the EMCS field is the lithium chloride dew point indicator. This device is attractive for use either as a sensor or standard. This section will describe its operation, some precautions for its use, and a simple calibration technique.

The equilibrium vapor pressure over a saturated lithium chloride salt solution is a known function of temperature. If the solution temperature is monitored and adjusted so that the water vapor pressure over its surface is in equilibrium with the vapor pressure in the ambient air, then the vapor pressure in the ambient air is known. If, in addition, the temperature of the air is known, its dew point can be determined.

The electrical resistance of the salt solution at a given temperature decreases if there is not enough salt to keep the solution saturated, and increases if the solution begins to dry out. This characteristic, along with the dependence of the equilibrium vapor pressure over the salt as a function of temperature, is used in the construction of the LiCl dew point device.

A bobbin is wrapped with a wick that is impregnated with LiCl and bifilar electrical current leads are wrapped around the wick. The bobbin, along with a thermometer, is inserted into an open structured cavity which permits ambient air to bathe the bobbin. Current from a constant voltage source passes through the leads and then through the salt solution, and the heat generated in the wick causes the cavity and salt solution temperature to change until equilibrium is reached. The cavity temperature is displayed and the operator reads tables or a graph (or uses a computer program) to determine the dew point of the surrounding air. If this dew point is to be used to convert to the relative humidity in the ambient air, the temperature of the ambient air before it enters the cavity must also be known. To obtain the relative humidity, the vapor pressure at the dew point is divided by the saturation vapor pressure at the temperature of the ambient (unheated) air and multiplied by 100, as shown in eq (13).

There are many contaminants which must be avoided with this device; the most obvious being substances such as other salts or alcohols which will readily dissolve in water to change the equilibrium vapor pressure or those which will create explosive atmospheres. Since EMCS are used in commercial and industrial settings, there may be contaminants of these types in the air. If so, consult the manufacturer of the instrument before use. Other considerations concerning the use of these devices include the response time, which is a function of the air flow past the sensor and the control circuit. Under high flows and/or high moisture conditions, the heating and cooling may not be rapid enough to permit either a proper response to changing RH or to prevent excessive wetting of the wick, while for very low flows it may take an excessively long time for the probe to react to changes. A guard may be placed around the part of the sensor facing the moving gas to prevent direct exposure to high flows. Flow must be within manufacturer's specs. It should be clear that exposure to moisture conditions which cause excessive wetting and dripping can damage the bobbin - the salt solution can be washed away or become non-uniform on the wick. At least one manufacturer places on the bobbin a heater which is automatically activated if exposure to excess moisture occurs, but this clearly cannot help if the drenching occurs too quickly for the heater to respond. Even with care, the bobbin will eventually become contaminated and have to be replaced or reactivated. The manufacturer will supply instructions on how the bobbin can be reactivated, if that step is practical.

The ultimate accuracy which can be expected from field devices is approximately 3°F (1.5°C) at dew points between 10°F and 93°F (-12°C and +34°C). At dew points from -29°F and 10°F (-34°C and -12°C) and again from 93 and 106°F (34°C and 41°C) the expected uncertainty increases to about ±6.3°F (3.5°C) because of possible changes in the hydration phase of the LiCl solution.

Many types of LiCl dew point sensors are currently available. Each has its own optimum operating and maintenance specifications which should be consulted before installation, reactivation or calibration. A more detailed discussion of this device can be found in reference [12].

## 6.4 USE OF SATURATED SALT SOLUTIONS

Saturated salt solutions may be used as generators of known relative humidities. These may be used as calibration standards in two ways. One method is to calibrate one device at a time over each of several salt solutions. In this case, a different saturated salt solution is put in a tray on the bottom of each of several small volume test chambers. Provision must be made for reading the temperatures in the chambers. The sensor is sealed into each chamber and time is allowed for temperature and relative humidity equilibration. The sensor is read and compared to the value (table B-1) known to be generated by the salt solution at the indicated temperature.

The second method is to use a test chamber large enough to accommodate a group of sensors. As above, one salt solution at a time is used. Temperature measuring devices are placed at several points in the chamber to monitor any gradients and to determine when equilibrium has been reached. Circulation systems may be added; but one must be careful that a fan doesn't induce unwanted heating, either by the motor itself or by the blade churning the air. Moving the motor away from the wall of the container solves the first problem, but the second is not so easy. Often the components are arranged as shown in figure 6 where the circulating fan is outside of the insulated calibration chamber. Downstream of the fan, the air passes through a heat exchanger to return it to the temperature of the calibration chamber. In general, some air circulation will be required. However, too much circulation will cause spray or droplets to deposit salt throughout the system; a situation which can damage some sensors. The need to insulate the test chamber from the room will depend on how well the room temperature is controlled, and the temperature homogeneity of the chamber interior. The chamber temperature can be raised by putting a heater in the circulation system as shown in figure 6 or by automatically controlling the entire volume with thermostats. Similarly, chilled water can be circulated around the chamber walls for cooling if desired.

It will require some experimentation to set up a calibration chamber which is best for a particular purpose and which bypasses problems arising from temperature gradients and salt spray. Commercial units are also available.

Tables in appendix B, taken from reference [9], list numerous salt solutions and the relative humidities they generate as functions of temperature. Also given are estimated uncertainties in those relative humidities as actually generated by the solutions under ideal conditions. The uncertainties shown are not the accuracies with which one ordinarily can calibrate field instruments. In general, one can expect to prepare atmospheres whose relative humidities are known within approximately ±4%. The actual accuracy of a particular calibrated sensor will, or course, depend upon the sensor itself and the calibration accuracy.

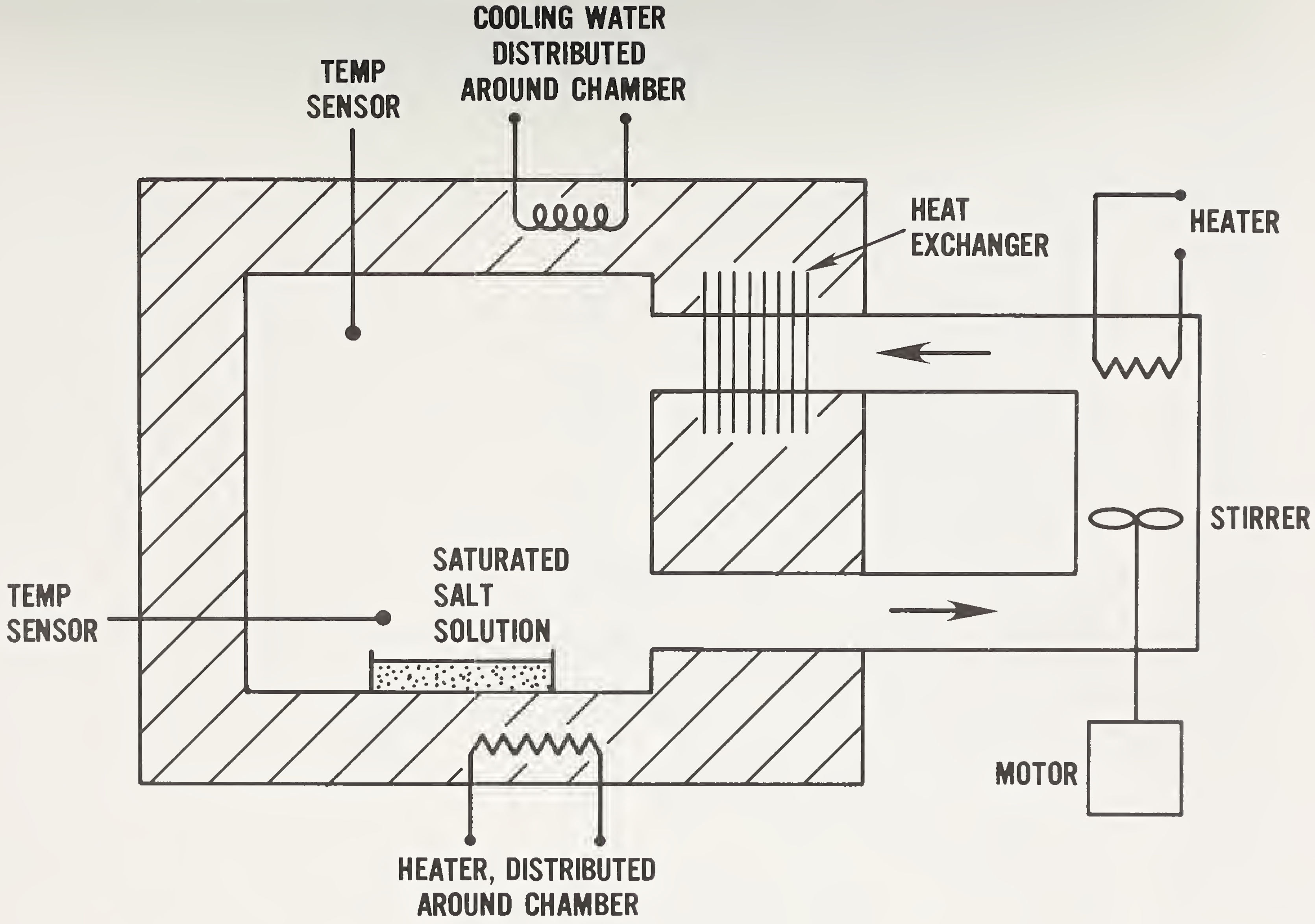

Figure 6. Schematic diagram of a saturated salt solution calibration chamber. All of the various components shown may not be necessary, depending on the particular calibration facilities

## 6.5 GENERAL

When instruments are being compared with standards for calibration, the primary concern must be that they are all sampling air at the same temperature and pressure, and that the moisture content of the air is the same at the location of each device being calibrated. While this may seem obvious, it bears repeating because it is easy to ignore simple precautions which may lead to significant errors.

Consider the use of devices such as motor driven psychrometers or dew point devices, which must draw an air sample past a sensor. It has already been indicated that their use as standards will be limited to situations where there is sufficient gas flow or the sample volume is large enough to permit the psychrometer to sample the volume of moist air without upsetting the pressure/temperature conditions at the device being calibrated. Suppose a humidity sensor were located on the interior wall of a duct as sketched in figure 7. To illustrate the effect of improper location, a valve has been added to permit a motor-driven psychrometer to draw air out of the duct but right next to the sensor being checked. When the valve is opened and the psychrometer turned on, the pressure immediately drops in the vicinity of the sensor. By the ideal gas law, each partial pressure will be lowered, and the relative humidity will decrease in proportion to the total pressure change. If the valve offers a restriction to the flow out, a second effect occurs; namely, the valve will cool the air as the air expands across it. The magnitudes of these effects on the sensor being calibrated will be highly dependent on the particular situation. However, this type of problem is easily avoided by placing the sampling port far away from the sensor to avoid the problem. Choosing the best location may require some experiments with placing pressure/temperature sensors along a laboratory duct.

Finally, when comparing or calibrating dial-type devices, it is wise to tap the instruments lightly before reading to reduce the errors caused by the vast differences in the static and kinematic friction coefficients in the mechanical parts.

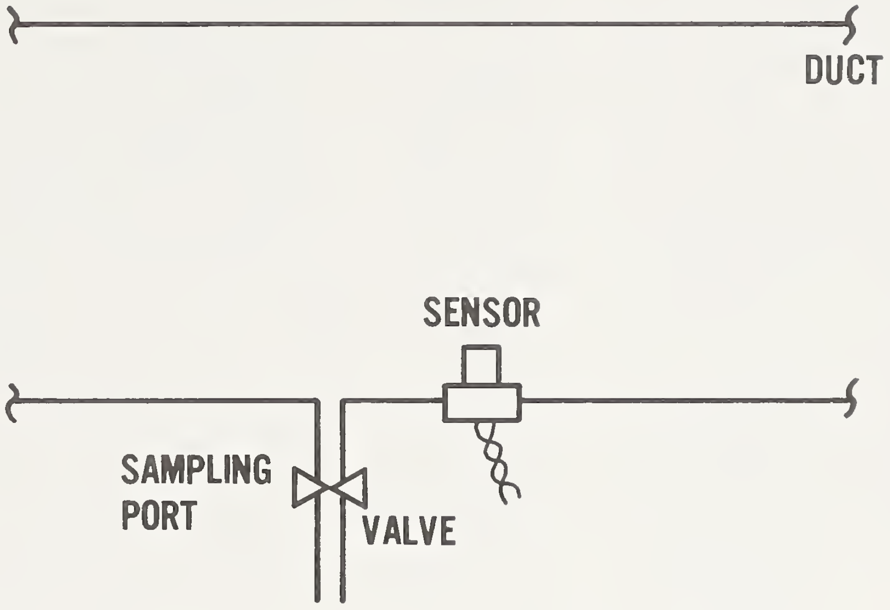

Figure 7. An example of poor placement of sampling port with respect to sensor position in a duct

## 7. ASSIGNING ERRORS TO THE CALIBRATED DEVICES

A calibration task has not been completed until the associated errors and uncertainties have been assessed and reported. This section will indicate how the error and uncertainty determinations might proceed. It is understood that the instruments or devices being calibrated are relative humidity indicators, although the principles discussed in this section are general.

### 7.1 RANDOM UNCERTAINTIES AND PRECISION

Random uncertainties arise because instruments and people possess limited resolving power and are subject to influences which either change the operation being used to make the measurement, or cause the relative humidity being measured to vary, or both. Random variations are always present to some degree. However, if the instrument making the measurement is capable of detecting changes of only ± 5% RH and the actual variations which are taking place are only ±.1% RH, the actual variations probably will not be noticed. The smallest meaningful change that an instrument can detect is often referred to as its resolution. The precision which is reported after a calibration reflects all random errors associated with repeated measurements and will depend on the stability of the relative humidity being measured (and therefore on the stability of moisture content, temperature, and pressure) and on the skill of the operator, as well as the fundamental instrument resolution. The reported precision is simply an estimate, and will not likely be the same from one calibration to the next.

A statistical quantity called the estimated standard deviation of the measurement, designated as $\hat{s}$, can be computed to give information on the random variations. For the moment, let us assume that any actual variations in the generated humidity (or in the standard against which a device is being calibrated) are small compared to the variations observed in the device itself. The calculation of $\hat{s}$ then proceeds as follows:

At each RH, a series of n separate readings $N$, $N_2$, ----$N_n$ is taken using the instrument being calibrated, and the average indicated value $\bar{N}$ is calculated. The differences $(N_1 - \bar{N})$, $(N_2 - \bar{N})$, etc. between each individual reading N and $\bar{N}$ are computed, and those differences are squared. These squared differences are then added to obtain a sum $\Sigma$, that is, $\Sigma = (N_1 - \bar{N})^2 + (N_2 - \bar{N})^2 + .. + (N_n - \bar{N})^2$. This quantity is then divided by one less than the number of readings, giving a number $\Sigma/(n-1)$. The estimated standard deviation of the series of measurements, $\hat{s}$, is the square root of this number. The value of $\hat{s}$ is such that if a known RH is measured again and again, approximately 68 percent of the measurements would lie within the range $\bar{N} \pm \hat{s}$. The more readings used to compute $\hat{s}$, the closer it becomes to representing the true random processes in the calibration.

The expected random uncertainty, or instrument precision, at each $\bar{N}$ is given by $\hat{s}$ or some multiple of $\hat{s}$, and this number should be stated in any documentation of the calibration. It is not good practice to use $\bar{N} \pm \hat{s}$ for the random uncertainty since one expects about 32 percent of the readings to lie outside of this range. The use of either $2\hat{s}$ or $3\hat{s}$ is common; the latter generally being considered conservative. The value $2\hat{s}$ is often used as an approximation to the 95 percent confidence interval. The multiple of $\hat{s}$ to be used is the calibration choice but it must be clearly stated in the calibration document.

When the calibration has been completed, and if $\hat{s}$ is almost the same at each of the $\bar{N}$ values, then one may use the largest of these as representative of the instrument's precision over its range of calibration, remembering that the statement of precision should preferably be made in terms of $2\hat{s}$ or $3\hat{s}$. If $\hat{s}$ varies, the instrument precision may be reported at each individual $\bar{N}$.

## 7.2 SYSTEMATIC ERRORS - FIRST TYPE

Systematic errors are the difference between $\bar{N}$ and the "true" value of the relative humidity being measured. There are two types of systematic errors. The first type is the difference between the $\bar{N}$ values of the device being calibrated and the corresponding value as indicated (or generated) by the standard. Evaluating and reducing these differences is the main object of performing the calibration. The second type of systematic error is discussed in section 7.4.

## 7.3 PRESENTATION OF RESULTS

Let us review an example of how the results of a calibration might be presented to indicate the magnitude of systematic errors of the first type as well as the instrument precision at different values of RH of the calibrated instrument. An instrument was calibrated over salt solutions at 68°F (20°C) and the standard deviations of the calibration readings were determined at each value. The calibration data are presented in table 3. Columns A and B, respectively, show the relative humidities known to be generated by the salts and the average values, $\bar{N}$, determined by the instrument being calibrated. Column C gives the value of $3\hat{s}$ at each point, N, and column D gives the difference between the average instrument reading and the salt solution value. Column E results from adding and subtracting Column C from Column D. The table by itself will not tell the entire story, but a plot such as the one shown in figure 8 shows all details at a glance. The differences (column D of the table) have been plotted against the values of $\bar{N}$ (column B), and a curve (solid line) has been drawn to indicate the systematic differences between the instrument being calibrated and the standard (salt solutions in this case) as a function of the indicated RH. The question should immediately arise, "How do we know that these differences aren't within the expected random variation of the instrument readings at the respective points, and therefore not really systematic?" This question may be answered by including the vertical random error bars which range between $\bar{N} \pm 3\hat{s}$ at each point. All readings which lie within the limits of the random error bars cannot be considered as being actually different from each other. We see that for the first four points, these random errors overlap the zero difference line, indicating that systematic errors of the first type are smaller than the precision of the device below about 20% RH. After that, however (with one exception), a systematic deviation is obvious. Note that the sample data have a point at about 27% RH which simply doesn't fit the curve. It is often hard to recognize such a point from a table. In this particular example, a single point like this is usually considered as a human error and is ignored in the evaluation of the instrument. However, if the data were not spaced as closely as this example shows, or if the instrument were to be used often near 35% RH (that is, near an indicated 20% RH) the user might want to check the calibration of the instrument at this questionable calibration point, or add another one close to it.

Table 3

Results of a hypothetical calibration of a device, using saturated salt solutions at 68°F (20°C)

| A | B | C | D | E |
|---|---|---|---|---|
| Rel. Hum. over salt % | Measured Rel. Hum. % | $3\hat{s}$ %RH | Difference %, B-A | Expected range of difference, % |
| 6.61 | 8.5 | 3.0 | 1.89 | -1.11 to 4.89 |
| 11.31 | 10.0 | 2.5 | -1.31 | -3.81 to 1.19 |
| 18.56 | 18.2 | 2.2 | - .36 | -2.56 to 1.84 |
| 23.11 | 24.0 | 2.1 | .89 | 01.21 to 2.99 |
| 33.07 | 27.5 | 1.2 | -5.57 | -6.77 to -4.37 |
| 43.16 | 47.0 | 2.5 | 3.84 | 1.34 to 6.34 |
| 54.38 | 60.0 | 1.9 | 5.62 | 3.72 to 7.52 |
| 59.14 | 65.2 | 2.1 | 6.06 | 3.96 to 8.16 |
| 69.90 | 73.3 | 3.0 | 3.4 | .4 to 6.4 |
| 79.23 | 80.0 | 3.0 | .77 | -2.23 to 3.77 |
| 85.11 | 82.0 | 2.2 | -3.11 | -5.31 to -91 |
| 97.59 | 89.8 | 3.1 | -7.79 | -10.89 to -4.69 |

If, upon recalibration of the device, a curve such as the one shown by the dashed line in figure 8 were to be obtained (lying within the precision [random error bars] of the individual points from the first calibration), then one would say that the instrument has not significantly changed between the calibrations.

Please note: This example was stated to be for a calibration temperature of 20°C. The calibration is not complete unless similar sets of data are obtained at enough different temperatures to permit correlation to be made over the entire temperature range in which the device is to be used. Some instruments, such as dew point devices which do not read relative humidity but moisture content, can be used with only a single set of curves.

## 7.4 SYSTEMATIC ERRORS - SECOND TYPE

Also shown in figure 8 are reasonable systematic error limits to be expected when using salt solutions (see section 6.4). These limits of uncertainty remain even after the corrections obtained from the curve have been applied, and represent a second type of systematic error. In the case of saturated salt solutions, table B-1, appendix B, shows that the best obtainable values under ideal conditions are uncertain by magnitudes on the order of tenths of a percent RH, depending upon the salt and its temperature. The "true" value over the salt solutions cannot be any better than this value. To this value, one must add the possible effects of the uncertainties in the temperature and temperature gradients as well as to account for the non-uniformity of moisture distribution throughout the calibration chamber and any other effects that may exist. This must be done realistically, and requires no small amount of thought. Obviously, if the error source(s) and effect(s) are known, a correction can be applied. However, here the "what if" types of errors are being considered which were not revealed in the calibration experiments. These sources of error will be present in any calibration procedure, not just when using salt solutions.

When all imaginable sources of systematic error have been listed and estimates made of their possible effects on the relative humidity, these must now be totaled in some way. If most of the effects listed would cause the RH which is believed to have been generated and measured by the standard to read high (or low), then one would add them algebraically to obtain the maximum possible systematic error in the "true" RH. It is more often the case that most of these possible sources could cause errors in either direction. In this case it is perfectly reasonable to compute the square root of the sum of the squares of the error magnitudes, and assign this number as the possible systematic error in the "true" RH. This error will remain even after the calibration is completed. Referring again to figure 8, it is therefore possible for the entire curve to be shifted up or down by 4% RH.

The 4% RH number is considered to be a reasonable estimate of residual unknown systematic errors when reasonably careful calibrations are performed using saturated salt solutions, and has been obtained by the process just described. Systematic errors should not be taken for granted; each source must be considered. In fact, the possible systematic error sources for any process being used to generate or determine a "true" or "known" relative humidity for calibration purposes must be considered. The calibration curve and random error bars of figure 8 are not sufficient descriptions of final errors. A statement concerning

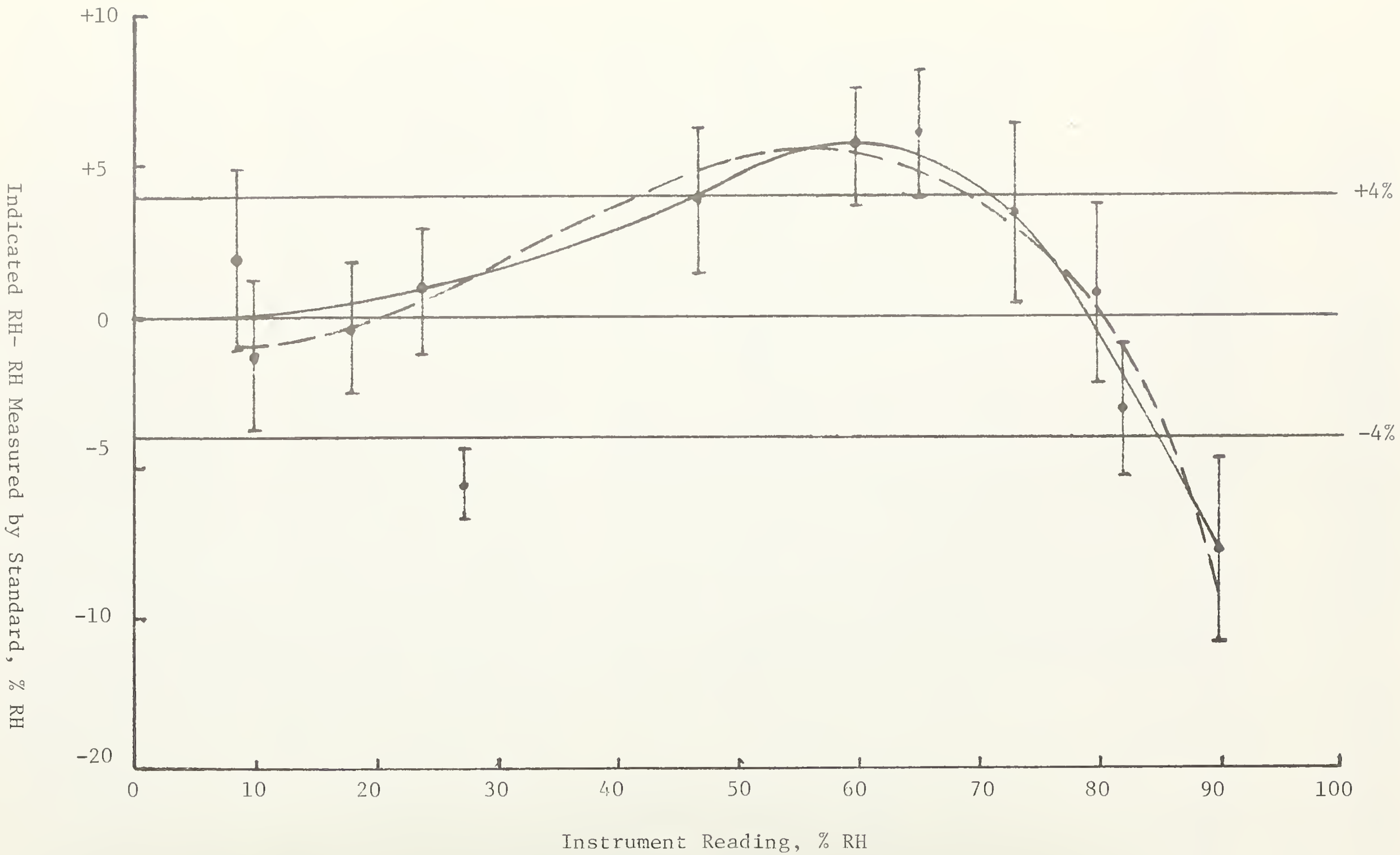

Figure 8. Plot of calibration results showing instrument error as a function of its indicated reading (solid line). The vertical bars are $3\hat{s}$ uncertainties at each point. The dashed line indicates the results of a second calibration, the results of which are insignificantly different from the first

possible residual systematic errors should also be included with the calibration report. Of course, it is possible that they may be completely negligible, but even this must be documented.

## 7.5 ADDITIONAL FACTORS

When the instrument being calibrated and the standard both have significant random variations, one other situation must be considered. Suppose the standard happens to be a device with a precision which is similar to the instrument being calibrated. That is, suppose the use of two hair hygrometers, one of which has been calibrated elsewhere and is now the standard. Now the random variations of the standard are not negligible with respect to those of the device being calibrated as was the case in section 7.1. Measurements made using the device being calibrated will be designated with the subscript x while the standard is designated by the subscript y.

Suppose one is measuring a relative humidity which is near 25% RH at some temperature. The residual systematic errors were discussed in section 7.4 above and won't be considered here. Suppose for then that five repeated pairs of measurements $RH_x$ and $RH_y$ were made and that the respective results are listed in table 4. Compute the difference x-y for each of the five readings, as well as a column of values $(x-y)^2$. Find the totals of each column. In this example, the mean values $\overline{\overline{RH}}_x$ and $\overline{\overline{RH}}_y$ and their respective estimated standard deviations have been computed for comparisons, but their values would not be used in the calibration report. Compute the quantity C, which is the square root of the average value of $\Sigma(x-y)^2$, and the quantity d, which is the average value of x-y. The quantity d is the systematic difference between the two instruments at this particular value of $\overline{\overline{RH}}$ as determined by the standard (25.4% RH). Finally, compute $\hat{s} = \left(\frac{C^2-d^2}{2}\right)^{\frac{1}{2}}$. The value of the estimated standard deviation, x, for the calibration test readings of the two instruments lies between the estimated value for $\hat{s}_x$ and $\hat{s}_y$. Therefore, the value of s for this calibration should be reported since the residual random errors of both instruments are reflected in this value.

## 7.6 CALIBRATION RECORDS

The maintenance of calibration records is often neglected in the field. However, the value of a complete file on the calibration of each instrument and each standard used in EMCS cannot be over emphasized. The date and source of the calibration of a standard being used to calibrate other instruments in the system is a good place to start. The time interval for returning the standard to a qualified laboratory for recalibration can be determined by reviewing the dates and the status of the standard when it was examined by the calibrating laboratory. Calibration records of standards should be made available to the laboratory performing the subsequent calibrations on the standard. Complete records on the use and calibrations of a standard can often reveal factors which require particular attention in a calibration process.

Similar record keeping is applicable to the calibration of each instrument in the EMCS. The calibration records of the instruments monitoring the moisture in an EMCS can reveal the source of many differences in the computation of a heat

## Table 4

Example for calculation of overall uncertainties when repeated measurements of the same relative humidity are made with two instruments which have nearly equal random uncertainties

| Reading No. | RH x | RH y | x-y | $(x-y)^2$ |
|---|---|---|---|---|
| 1 | 22.3 | 25.6 | -3.3 | 10.89 |
| 2 | 22.6 | 25.4 | -2.8 | 7.84 |
| 3 | 22.2 | 25.8 | -3.6 | 12.96 |
| 4 | 22.3 | 25.1 | -2.8 | 7.84 |
| 5 | 22.6 | 25.3 | 02.7 | 7.29 |
| Totals | 112.0 | 127.2 | -15.2 | $46.82 = \Sigma(x-y)^2$ |

$\overline{RH}_x = 22.4, \hat{s}_x = .19$ $\quad$ $\overline{RH}_y = 25.4, \hat{s}_y = .27$

$C = \sqrt{\frac{46.82}{5}} = 3.06$ $\quad$ $d = -15.2/5 = -3.04$

$$\hat{s} = \left(\frac{C^2 - d^2}{2}\right)^{\frac{1}{2}} = .25 \text{ (single system standard deviation)}$$

balance being performed on a heat exchange system or a particular portion of the system. One of the most important items to be included in calibration records are any possible effects of the uncertainties in the temperatures being recorded during calibration. Ambient conditions and any other factors which may affect the calibration should be noted. Systematic errors cannot be determined without this information.

Records on the calibration of LiCl dew point temperature sensors are often used to indicate the need for reactivating the bobbin. The contamination of the bobbin is often slow. However, a review of the calibration records can often point out when the need for replacement will occur and, as well, indicate the need for replacing the LiCl sensor with a sensor of another type which is less susceptible to contamination.

Calibration files should contain the individual readings of the points measured at each temperature during the calibration and include identification of the instruments used as standards in the calibration process. Calibration records on all devices should include detailed information such as that shown in tables 3 and 4 in addition to any plots made to improve the recognition of points that are off scale such as that shown in figure 8.

## REFERENCES

[1] Hasegawa, S. and Little, J.W., The NBS Two-Pressure Humidity Generator, Mark 2, J. Res. Nat. Bur. Stand. (U.S.), 81A, No. 1, 81, 1977.

[2] Harrison, L.P., Fundamental Concepts and Definitions Relating to Humidity, Humidity and Moisture, Vol. 3, A. Wexler and W. Wildhack (Eds.), Reinhold Publishing Corp., N.Y., 1964.

[3] Harrison, L.P., Imperfect Gas Relationships, Humidity and Moisture, Vol. 3, A. Wexler and W. Wildhack (Eds.), Reinhold Publishing Corp., N.Y., 1964.

[4] Wexler, A., Vapor Pressure Formulation for Water in the Range 0 to 100°C, A Revision, J. Res. Nat. Bur. Stand. (U.S.), 80A, 775, 1976.

[5] Wexler, A., Vapor Pressure Formulation for Ice, J. Res. Nat. Bur. Stand. (U.S.), 81A, 5, 1977.

[6] Wexler, A., Measurement of Humidity in the Free Atmosphere Near the Surface of the Earth, Meteorological Monographs, Vol. II, No. 33, 262, 1970 (American Meteorological Society).

[7] Kao, J.Y., and Snyder, W.J., Application Information on Typical Humidity Sensors Used in Heating, Ventilating, and Air Conditioning (HVAC) Systems, NBSIR 81-2460, January 1982.

[8] Kao, J.Y., and Baker, D.W., A Commentary on the Instrumentation for Building Energy Monitoring and Control Systems (EMCS), NBSIR 80-2104, September 1980.

[9] Greenspan, L., Humidity Fixed Points of Binary Saturated Aqueous Solutions, J. Res. Nat. Bur. Stand. (U.S.) 81A, 1977.

[10] Harrison, L.P., Some Fundamental Considerations Regarding Psychrometry, Humidity and Moisture, Vol. 3., A. Wexler and W. Wildhack (Eds), Reinhold Publishing Corp., N.Y., 1964.

[11] ASHRAE, Brochure on Psychrometry, ASHRAE, 1791 Tullie Circle, N.E., Atlanta, GA, 1977.

[12] Nelson, D.E., and Amdur, E.J., The Mode of Operation of Saturation Temperature Hydrometers Based on Electrical Detection of a Salt-Solution Phase Transition, Humidity and Moisture, Vol. I, R.E. Ruskin, (Ed.) Reinhold Publishing Corp., N.Y., 1964.

[13] Wexler, A., Humidity and Moisture, ISA Transducer Compendium, 2nd Edition, Part 3, G.F. Harvey, (Ed.), Instrument Society of America, 1972.

[14] ASHRAE Fundamentals Handbook, ASHRAE, 1791 Tullie Circle, N.E., Atlanta, GA, 1981.

[15] ASHRAE Standard Measurement Guide: Section on Standard Methods of Measuring Humidity with Cooled Surface Condensation (Dew Point) Hygrometer, ASHRAE Standard 41.6-1982, ASHRAE, 1791 Tullie Circle, NE, Atlanta, GA, 1983

[16] ASTM D4230 - Standard Method for Measurement of Moist Air Properties, ASTM, 1916 Race Street, Philadelphia, PA, 1983

# Appendix A

## Tables of Saturated Vapor Pressures

(Tables in this appendix were selected from reference 11)

## Table A-1

## Saturation Pressures of Water Vapor Over Ice as a Function of the Temperatures

| Fahr. Temp. t(F) | Absolute Pressure $P \times 10^5$ | |
|---|---|---|
| | Lb/Sq In. | In. Hg |
| -160 | 0.004949 | 0.01008 |
| -155 | 0.009040 | 0.01840 |
| -150 | 0.01620 | 0.03298 |
| -145 | 0.02850 | 0.05803 |
| -140 | 0.04928 | 0.1003 |
| -135 | 0.08380 | 0.1706 |
| -130 | 0.1403 | 0.2856 |
| -125 | 0.2312 | 0.4708 |
| -120 | 0.3757 | 0.7649 |
| -115 | 0.6019 | 1.226 |
| -110 | 0.9517 | 1.938 |
| -105 | 1.486 | 3.025 |
| -100 | 2.291 | 4.664 |
| -95 | 3.491 | 7.108 |
| -90 | 5.260 | 10.71 |
| -85 | 7.841 | 15.96 |
| -80 | 11.57 | 23.55 |
| -75 | 16.89 | 34.39 |
| -70 | 24.43 | 49.74 |
| -65 | 35.01 | 71.28 |
| -60 | 49.72 | 101.2 |
| -55 | 70.01 | 142.6 |
| -50 | 97.76 | 199.0 |
| -48 | 111.5 | 227.0 |
| -46 | 127.0 | 258.5 |
| -44 | 144.4 | 294.0 |
| -42 | 164.1 | 334.0 |
| -40 | 186.1 | 379.0 |
| -38 | 211.0 | 429.5 |
| -36 | 238.8 | 486.2 |
| -34 | 270.0 | 549.7 |
| -32 | 304.9 | 620.8 |
| -30 | 0.3440 | 0.7003 |
| -28 | 0.3876 | 0.7891 |
| -26 | 0.4363 | 0.8882 |
| -24 | 0.4905 | 0.9987 |
| -22 | 0.5509 | 1.122 |
| -20 | 0.6181 | 1.259 |
| -19 | 0.6545 | 1.333 |
| -18 | 0.6928 | 1.410 |
| -17 | 0.7332 | 1.493 |
| -16 | 0.7757 | 1.579 |
| -15 | 0.8204 | 1.670 |
| -14 | 0.8676 | 1.766 |
| -13 | 0.9172 | 1.867 |
| -12 | 0.9694 | 1.974 |
| -11 | 1.024 | 2.086 |
| -10 | 1.082 | 2.203 |
| -9 | 1.143 | 2.327 |
| -8 | 1.207 | 2.457 |
| -7 | 1.274 | 2.594 |
| -6 | 1.344 | 2.737 |
| -5 | 1.419 | 2.888 |
| -4 | 1.496 | 3.047 |
| -3 | 1.578 | 3.213 |
| -2 | 1.664 | 3.388 |
| -1 | 1.754 | 3.572 |
| 0 | 1.849 | 3.764 |
| 1 | 1.948 | 3.966 |
| 2 | 2.052 | 4.178 |
| 3 | 2.161 | 4.400 |
| 4 | 2.276 | 4.633 |
| 5 | 2.396 | 4.878 |
| 6 | 2.521 | 5.134 |

Table A-1, Continued

## Saturation Pressures of Water Vapor Over Ice as a Function of the Temperatures

| Fahr. Temp. t(F) | Absolute Pressure P | |
|---|---|---|
| | Lb/Sq In. | In. Hg |
| 7 | 0.02653 | 0.05402 |
| 8 | 0.02791 | 0.05683 |
| 9 | 0.02936 | 0.05977 |
| 10 | 0.03087 | 0.06286 |
| 11 | 0.03246 | 0.06608 |
| 12 | 0.03412 | 0.06946 |
| 13 | 0.03585 | 0.07300 |
| 14 | 0.03767 | 0.07669 |
| 15 | 0.03957 | 0.08056 |
| 16 | 0.04156 | 0.08461 |
| 17 | 0.04363 | 0.08884 |
| 18 | 0.04581 | 0.09326 |
| 19 | 0.04808 | 0.09789 |
| 20 | 0.05045 | 0.1027 |
| 21 | 0.05293 | 0.1078 |
| 22 | 0.05552 | 0.1130 |
| 23 | 0.05823 | 0.1186 |
| 24 | 0.06105 | 0.1243 |
| 25 | 0.06400 | 0.1303 |
| 26 | 0.06708 | 0.1366 |
| 27 | 0.07030 | 0.1431 |
| 28 | 0.07365 | 0.1500 |
| 29 | 0.07715 | 0.1571 |
| 30 | 0.08080 | 0.1645 |
| 31 | 0.08461 | 0.1723 |
| 32 | 0.08858 | 0.1803 |
| 32 | 0.088586 | 0.18036 |

## Table A-2

### Saturation Vapor Pressures of Water as a Function of the Temperature

| Fahr. Temp. t(F) | Absolute Pressure P[3] | |
|---|---|---|
| | Lb/Sq In. | In. Hg |
| 33 | 0.092227 | 0.18778 |
| 34 | 0.095999 | 0.19546 |
| 35 | 0.099908 | 0.20342 |
| 36 | 0.10396 | 0.21166 |
| 37 | 0.10815 | 0.22020 |
| 38 | 0.11249 | 0.22904 |
| 39 | 0.11699 | 0.23819 |
| 40 | 0.12164 | 0.24767 |
| 41 | 0.12646 | 0.25748 |
| 42 | 0.13145 | 0.26763 |
| 43 | 0.13660 | 0.27813 |
| 44 | 0.14194 | 0.28899 |
| 45 | 0.14746 | 0.30023 |
| 46 | 0.15317 | 0.31185 |
| 47 | 0.15907 | 0.32387 |
| 48 | 0.16517 | 0.33629 |
| 49 | 0.17148 | 0.34913 |
| 50 | 0.17799 | 0.36240 |
| 51 | 0.18473 | 0.37611 |
| 52 | 0.19169 | 0.39028 |
| 53 | 0.19888 | 0.40492 |
| 54 | 0.20630 | 0.42003 |
| 55 | 0.21397 | 0.43564 |
| 56 | 0.22188 | 0.45176 |
| 57 | 0.23006 | 0.46840 |
| 58 | 0.23849 | 0.48558 |
| 59 | 0.24720 | 0.50330 |
| 60 | 0.25618 | 0.52160 |
| 61 | 0.26545 | 0.54047 |
| 62 | 0.27502 | 0.55994 |
| 63 | 0.28488 | 0.58002 |
| 64 | 0.29505 | 0.60073 |
| 65 | 0.30554 | 0.62209 |
| 66 | 0.31636 | 0.64411 |
| 67 | 0.32750 | 0.66681 |
| 68 | 0.33900 | 0.69021 |
| 69 | 0.35084 | 0.71432 |
| 70 | 0.36304 | 0.73916 |
| 71 | 0.37561 | 0.76476 |

| Fahr. Temp. t(F) | Absolute Pressure P | |
|---|---|---|
| | Lb/Sq In. | In. Hg |
| 72 | 0.38856 | 0.79113 |
| 73 | 0.40190 | 0.81829 |
| 74 | 0.41564 | 0.84626 |
| 75 | 0.42979 | 0.87506 |
| 76 | 0.44435 | 0.90472 |
| 77 | 0.45935 | 0.93524 |
| 78 | 0.47478 | 0.96666 |
| 79 | 0.49066 | 0.99900 |
| 80 | 0.50701 | 1.0323 |
| 81 | 0.52382 | 1.0665 |
| 82 | 0.54112 | 1.1017 |
| 83 | 0.55892 | 1.1380 |
| 84 | 0.57722 | 1.1752 |
| 85 | 0.59604 | 1.2136 |
| 86 | 0.61540 | 1.2530 |
| 87 | 0.63530 | 1.2935 |
| 88 | 0.65575 | 1.3351 |
| 89 | 0.67678 | 1.3779 |
| 90 | 0.69838 | 1.4219 |
| 91 | 0.72059 | 1.4671 |
| 92 | 0.74340 | 1.5136 |
| 93 | 0.76684 | 1.5613 |
| 94 | 0.79091 | 1.6103 |
| 95 | 0.81564 | 1.6607 |
| 96 | 0.84103 | 1.7124 |
| 97 | 0.86711 | 1.7655 |
| 98 | 0.89388 | 1.8200 |
| 99 | 0.92137 | 1.8759 |
| 100 | 0.94959 | 1.9334 |
| 101 | 0.97854 | 1.9923 |
| 102 | 1.0083 | 2.0529 |
| 103 | 1.0388 | 2.1149 |
| 104 | 1.0700 | 2.1786 |
| 105 | 1.1021 | 2.2440 |
| 106 | 1.1351 | 2.3110 |
| 107 | 1.1688 | 2.3798 |

Table A-2 (continued)

## Saturation Vapor Pressure of Water as a Function of the Temperature

| Fahr. Temp. t(F) | Absolute Pressure $p^3$ | |
|---|---|---|
| | Lb/Sq In. | In. Hg |
| 108 | 1.2035 | 2.4503 |
| 109 | 1.2390 | 2.5226 |
| 110 | 1.2754 | 2.5968 |
| 111 | 1.3128 | 2.6728 |
| 112 | 1.3510 | 2.7507 |
| 113 | 1.3902 | 2.8306 |
| 114 | 1.4305 | 2.9125 |
| 115 | 1.4717 | 2.9963 |
| 116 | 1.5139 | 3.0823 |
| 117 | 1.5571 | 3.1703 |
| 118 | 1.6014 | 3.2606 |
| 119 | 1.6468 | 3.3530 |
| 120 | 1.6933 | 3.4477 |
| 121 | 1.7409 | 3.5446 |
| 122 | 1.7897 | 3.6439 |
| 123 | 1.8396 | 3.7455 |
| 124 | 1.8907 | 3.8496 |
| 125 | 1.9430 | 3.9561 |
| 126 | 1.9966 | 4.0651 |
| 127 | 2.0514 | 4.1768 |
| 128 | 2.1075 | 4.2910 |
| 129 | 2.1649 | 4.4078 |
| 130 | 2.2237 | 4.5274 |
| 131 | 2.2838 | 4.6498 |
| 132 | 2.3452 | 4.7750 |
| 133 | 2.4081 | 4.9030 |
| 134 | 2.4725 | 5.0340 |
| 135 | 2.5382 | 5.1679 |
| 136 | 2.6055 | 5.3049 |
| 137 | 2.6743 | 5.4450 |
| 138 | 2.7446 | 5.5881 |
| 139 | 2.8165 | 4.7345 |
| 140 | 2.8900 | 5.8842 |
| 141 | 2.9651 | 6.0371 |
| 142 | 3.0419 | 6.1934 |
| 143 | 3.1204 | 6.3532 |

| Fahr. Temp. t(F) | Absolute Pressure P | |
|---|---|---|
| | Lb/Sq In. | In. Hg |
| 144 | 3.2006 | 6.5164 |
| 145 | 3.2825 | 6.6832 |
| 146 | 3.3662 | 6.8536 |
| 147 | 3.4517 | 7.0277 |
| 148 | 3.5390 | 7.2056 |
| 149 | 3.6282 | 7.3872 |
| 150 | 3.7194 | 7.5727 |
| 151 | 3.8124 | 7.7622 |
| 152 | 3.9074 | 7.9556 |
| 153 | 4.0044 | 8.1532 |
| 154 | 4.1035 | 8.3548 |
| 155 | 4.2046 | 8.5607 |
| 156 | 4.3078 | 8.7708 |
| 157 | 4.4132 | 8.9853 |
| 158 | 4.5207 | 9.2042 |
| 159 | 4.6304 | 9.4276 |
| 160 | 4.7424 | 9.6556 |
| 161 | 4.8566 | 9.8882 |
| 162 | 4.9732 | 10.126 |
| 163 | 5.0921 | 10.368 |
| 164 | 5.2134 | 10.615 |
| 165 | 4.3372 | 10.867 |
| 166 | 5.4634 | 11.124 |
| 167 | 5.5921 | 11.386 |
| 168 | 5.7233 | 11.653 |
| 169 | 5.8572 | 11.925 |
| 170 | 5.9936 | 12.203 |
| 171 | 6.1328 | 12.487 |
| 172 | 6.2746 | 12.775 |
| 173 | 6.4192 | 13.070 |
| 174 | 6.5666 | 13.370 |
| 175 | 6.7168 | 13.676 |
| 176 | 6.8699 | 13.987 |
| 177 | 7.0259 | 14.305 |

## Table A-2 (continued)

### Saturation Vapor Pressure of Water as a Function of the Temperature

| Fahr. Temp. t(F) | Absolute Pressure p3 | |
|---|---|---|
| | Lb/Sq In. | In. Hg |
| 178 | 7.1849 | 14.629 |
| 179 | 7.3469 | 14.959 |
| 180 | 7.5119 | 15.295 |
| 181 | 7.6801 | 15.637 |
| 182 | 7.8514 | 15.986 |
| 183 | 8.0258 | 16.341 |
| 184 | 8.2035 | 16.703 |
| 185 | 8.3845 | 17.071 |
| 186 | 8.5688 | 17.446 |
| 187 | 8.7565 | 17.829 |
| 188 | 8.9476 | 18.218 |
| 189 | 9.1422 | 18.614 |
| 190 | 9.3403 | 19.017 |
| 191 | 9.5420 | 19.428 |
| 192 | 9.7473 | 19.846 |
| 193 | 9.9563 | 20.271 |
| 194 | 10.169 | 20.704 |
| 195 | 10.386 | 21.145 |
| 196 | 10.606 | 21.594 |
| 197 | 10.830 | 22.050 |
| 198 | 11.058 | 22.515 |
| 199 | 11.290 | 22.987 |
| 200 | 11.526 | 23.468 |
| 201 | 11.767 | 23.957 |
| 202 | 12.011 | 24.455 |
| 203 | 12.260 | 24.961 |
| 204 | 12.513 | 15.476 |
| 205 | 12.770 | 26.000 |
| 206 | 13.031 | 26.532 |
| 207 | 13.297 | 27.074 |
| 208 | 13.568 | 27.625 |
| 209 | 13.843 | 28.185 |
| 210 | 14.123 | 28.754 |
| 211 | 14.407 | 29.333 |
| 212 | 14.696 | 29.921 |

# Appendix B

## Tables of Equilibrium Relative Humidity of Selected Saturated Salt Solutions from 32°F to 212°F (0°C to 100°C)

(Tables in this appendix were selected from reference 9)

Table B-1. Equilibrium Relative Humidity of Selected Saturated Salt Solutions from 32°F to 212°F (0°C to 100°C)

| Temperature | | Relative Humidity, % | | | | | | |
|---|---|---|---|---|---|---|---|---|
| °F | °C | Cesium Fluoride | Lithium Bromide | Zinc Bromide | Lithium Chloride | Calcium Bromide | Potassium Acetate | Potassium Fluoride |
| 32 | 0 | | 7.75 ± 0.83 | | 11.23 ± 0.54 | | | |
| 41 | .5 | 5.52 ± 1.9 | | 8.86 ± 0.89 | 11.26 ± 0.47 | | | |
| 50 | 10 | 4.89 ± 1.6 | 7.14 ± 0.69 | 8.49 ± 0.74 | 11.29 ± 0.41 | 21.62 ± 0.13 | 23.38 ± 0.53 | |
| 59 | 15 | 4.33 ± 1.4 | 6.86 ± 0.63 | 8.19 ± 3.61 | 11.30 ± 0.35 | 20.20 ± 0.12 | 23.40 ± 0.32 | |
| 68 | 20 | 3.83 ± 1.1 | 6.61 ± 0.58 | 7.94 ± 0.49 | 11.31 ± 0.31 | 18.50 ± 0.12 | 23.11 ± 0.25 | |
| 77 | 25 | 3.39 ± 0.94 | 6.37 ± 0.52 | 7.75 ± 0.39 | 11.30 ± 0.27 | 16.50 ± 0.12 | 22.51 ± 0.32 | 30.85 ± 1.3 |
| 86 | 30 | 3.01 ± 0.77 | 6.16 ± 0.47 | 7.62 ± 0.31 | 11.28 ± 0.24 | | 21.61 ± 0.53 | 27.27 ± 1.1 |
| 95 | 35 | 2.69 ± 0.63 | 5.97 ± 0.43 | 7.55 ± 0.25 | 11.25 ± 0.22 | | | 24.59 ± 0.94 |
| 104 | 40 | 2.44 ± 0.52 | 5.80 ± 0.39 | 7.54 ± 0.20 | 11.21 ± 0.21 | | | 22.68 ± 0.81 |
| 113 | 45 | 2.24 ± 0.44 | 5.65 ± 0.35 | 7.59 ± 0.17 | 11.16 ± 0.21 | | | 21.46 ± 0.70 |
| 122 | 50 | 2.11 ± 0.40 | 5.53 ± 0.31 | 7.70 ± 0.16 | 11.10 ± 0.22 | | | 20.80 ± 0.62 |
| 131 | 55 | 2.04 ± 0.38 | 5.42 ± 0.28 | 7.87 ± 0.17 | 11.03 ± 0.23 | | | 20.60 ± 0.56 |
| 140 | 60 | 2.03 ± 0.40 | 5.33 ± 0.25 | 8.09 ± 0.19 | 10.95 ± 0.26 | | | 20.77 ± 0.53 |
| 149 | 65 | 2.08 ± 0.44 | 5.27 ± 0.23 | 8.38 ± 0.24 | 10.86 ± 0.29 | | | 21.18 ± 0.53 |
| 158 | 70 | 2.20 ± 0.52 | 5.23 ± 0.21 | 8.72 ± 0.30 | 10.75 ± 0.33 | | | 21.74 ± 0.56 |
| 167 | 75 | 2.37 ± 0.62 | 5.20 ± 0.19 | | 10.64 ± 0.38 | | | 22.33 ± 0.61 |
| 176 | 80 | 2.61 ± 0.76 | 5.20 ± 0.18 | | 10.51 ± 0.44 | | | 22.85 + 0.69 |
| 185 | 85 | | 5.22 ± 0.17 | | 10.38 ± 0.51 | | | 23.20 ± 0.80 |
| 194 | 90 | | 5.26 ± 0.17 | | 10.23 ± 0.59 | | | 23.27 ± 0.93 |
| 203 | 95 | | 5.32 ± 0.16 | | 10.07 ± 0.67 | | | |
| 212 | 100 | | 5.41 ± 0.17 | | 9.90 ± 0.77 | | | |

Table B-1. Equilibrium Relative Humidity of Selected Saturated Salt Solutions from 32°F to 212°F (0°C to 100°C) (continued)

| Temperature | | Relative Humidity, % | | | | | | |
|---|---|---|---|---|---|---|---|---|
| °F | °C | Magnesium Chloride | Potassium Carbonate | Magnesium Nitrate | Sodium Bromide | Cobalt Chloride | Strontium Chloride | Sodium Nitrate |
| 32 | 0 | 33.66 ± 0.33 | 43.13 ± 0.66 | 60.35 ± 0.55 | | | | |
| 41 | .5 | 33.60 ± 0.28 | 43.13 ± 0.50 | 58.86 ± 0.43 | 63.51 ± 0.72 | | 77.13 ± 0.12 | 78.57 ± 0.52 |
| 50 | 10 | 33.47 ± 0.24 | 43.14 ± 0.39 | 57.36 ± 0.33 | 62.15 ± 0.60 | | 75.66 ± 0.09 | 77.53 ± 0.45 |
| 59 | 15 | 33.30 ± 0.21 | 43.15 ± 0.33 | 55.87 ± 0.27 | 60.68 ± 0.51 | | 74.13 ± 0.06 | 76.46 ± 0.39 |
| 68 | 20 | 33.07 ± 0.18 | 43.16 ± 0.33 | 54.38 ± 0.23 | 59.14 ± 0.44 | | 72.52 ± 0.05 | 75.36 ± 0.35 |
| 77 | 25 | 32.78 + 0.16 | 43.16 + 0.39 | 52.89 + 0.22 | 57.57 ± 0.40 | 64.92 ± 3.5 | 70.85 + 0.04 | 74.25 + 0.32 |
| 86 | 30 | 32.44 ± 0.14 | 43.17 ± 0.50 | 51.40 ± 0.24 | 56.03 ± 0.38 | 61.83 ± 2.8 | 69.12 ± 0.03 | 73.14 ± 0.31 |
| 95 | 35 | 32.05 ± 0.13 | | 49.91 ± 0.29 | 54.55 ± 0.38 | 58.63 ± 2.2 | | 72.06 ± 0.32 |
| 104 | 40 | 31.60 ± 0.13 | | 48.42 ± 0.37 | 53.17 ± 0.41 | 55.48 ± 1.8 | | 71.00 ± 0.34 |
| 113 | 45 | 31.10 ± 0.13 | | 46.93 ± 0.47 | 51.95 ± 0.47 | 52.56 ± 1.5 | | 69.99 ± 0.37 |
| 122 | 50 | 30.54 ± 0.14 | | 45.44 ± 0.60 | 50.93 ± 0.55 | 50.01 ± 1.4 | | 69.04 ± 0.42 |
| 131 | 55 | 29.93 ± 0.16 | | | 50.15 ± 0.65 | 48.02 ± 1.4 | | 68.15 ± 0.49 |
| 140 | 60 | 29.26 ± 0.18 | | | 49.66 ± 0.78 | 46.74 ± 1.5 | | 67.35 ± 0.57 |
| 149 | 65 | 28.54 ± 0.21 | | | 49.49 ± 0.94 | 46.33 ± 1.9 | | 66.64 ± 0.67 |
| 158 | 70 | 27.77 ± 0.25 | | | 49.70 ± 1.1 | 46.97 ± 2.3 | | 66.04 ± 0.78 |
| 167 | 75 | 26.94 ± 0.29 | | | 50.33 ± 1.3 | 48.80 ± 2.9 | | 65.56 ± 0.91 |
| 176 | 80 | 26.05 ± 0.34 | | | 51.43 ± 1.5 | 52.01 ± 3.7 | | 65.22 ± 1.1 |
| 185 | 85 | 25.11 ± 0.39 | | | | | | 65.03 ± 1.2 |
| 194 | 90 | 24.12 ± 0.46 | | | | | | 65.00 ± 1.4 |
| 203 | 95 | 23.07 ± 0.52 | | | | | | |
| 212 | 100 | 21.97 ± 0.60 | | | | | | |

Table B-1. Equilibrium Relative Humidity of Selected Saturated Salt Solutions from 32°F to 212°F (0°C to 100°C) (continued)

| Temperature | | Relative Humidity, % | | | | |
|---|---|---|---|---|---|---|
| °F | °C | Sodium Chloride | Ammonium Chloride | Potassium Bromide | Ammonium Sulfate | Potassium Chloride |
| 32 | 0 | 75.51 ± 0.34 | | | 82.77 ± 0.90 | 88.61 ± 0.53 |
| 41 | 5 | 75.65 ± 0.27 | | 85.09 ± 0.26 | 82.42 ± 0.68 | 87.67 ± 0.45 |
| 50 | 10 | 75.67 ± 0.22 | 80.55 ± 0.96 | 83.75 ± 0.24 | 82.06 ± 0.51 | 86.77 ± 0.39 |
| 59 | 15 | 75.61 ± 0.18 | 79.89 ± 0.59 | 82.62 ± 0.22 | 81.70 ± 0.38 | 85.92 ± 0.33 |
| 68 | 20 | 75.47 ± 0.14 | 79.23 ± 0.44 | 81.67 ± 0.21 | 81.34 ± 0.31 | 85.11 ± 0.29 |
| 77 | 25 | 75.29 ± 0.12 | 78.57 ± 0.40 | 80.89 ± 0.21 | 80.99 ± 0.28 | 84.34 ± 0.26 |
| 86 | 30 | 75.09 ± 0.11 | 77.90 ± 0.57 | 80.27 ± 0.21 | 80.63 ± 0.30 | 83.62 ± 0.25 |
| 95 | 35 | 74.87 ± 0.12 | | 79.78 ± 0.22 | 80.27 ± 0.37 | 82.95 ± 0.25 |
| 104 | 40 | 74.68 ± 0.13 | | 79.43 ± 0.24 | 79.91 ± 0.49 | 82.32 ± 0.25 |
| 113 | 45 | 74.52 ± 0.16 | | 79.18 ± 0.26 | 79.56 ± 0.65 | 81.74 ± 0.28 |
| 122 | 50 | 74.43 ± 0.19 | | 79.02 ± 0.28 | 79.20 ± 0.87 | 81.20 ± 0.31 |
| 131 | 55 | 74.41 ± 0.24 | | 78.95 ± 0.32 | | 80.70 ± 0.35 |
| 140 | 60 | 74.50 ± 0.30 | | 78.94 ± 0.35 | | 80.25 ± 0.41 |
| 149 | 65 | 74.71 ± 0.37 | | 78.99 ± 0.40 | | 79.85 ± 0.48 |
| 158 | 70 | 75.06 ± 0.45 | | 79.07 ± 0.45 | | 79.49 ± 0.57 |
| 167 | 75 | 75.58 ± 0.55 | | 79.16 ± 0.50 | | 79.17 ± 0.66 |
| 176 | 80 | 76.29 ± 0.63 | | 79.27 ± 0.57 | | 78.90 ± 0.77 |
| 185 | 85 | | | | | 78.68 ± 0.89 |
| 194 | 90 | | | | | 78.50 ± 1.0 |
| 203 | 95 | | | | | |
| 212 | 100 | | | | | |

Table B1. Equilibrium Relative Humidity of Selected Saturated Salt Solutions from 32°F to 212°F (0°C to 100°C) (continued)

| Temperature | | Relative Humidity, % | | | |
|---|---|---|---|---|---|
| °F | °C | Strontium Nitrate | Potassium Nitrate | Potassium Sulfate | Potassium Dichromate |
| 32 | 0 | | 96.33 ± 2.9 | 98.77 ± 1.1 | |
| 41 | 5 | 92.38 ± 0.56 | 96.27 ± 2.1 | 98.48 ± 0.91 | |
| 50 | 10 | 90.55 ± 0.38 | 95.96 ± 1.4 | 98.18 ± 0.76 | |
| 59 | 15 | 88.72 ± 0.28 | 95.41 ± 0.96 | 97.89 ± 0.63 | |
| 68 | 20 | 86.89 ± 0.29 | 94.62 ± 0.66 | 97.59 ± 0.53 | |
| 77 | 25 | 85.06 ± 0.38 | 93.58 ± 0.55 | 97.30 ± 0.45 | 97.88 ± 0.49 |
| 86 | 30 | | 92.31 ± 0.60 | 97.00 ± 0.40 | 97.08 ± 0.41 |
| 95 | 35 | | 90.79 ± 0.83 | 96.71 ± 0.38 | 96.42 ± 0.37 |
| 104 | 40 | | 89.03 ± 1.2 | 96.41 ± 0.38 | 95.89 ± 0.37 |
| 113 | 45 | | 87.03 ± 1.8 | 96.12 ± 0.40 | 95.50 ± 0.40 |
| 122 | 50 | | 84.78 ± 2.5 | 95.82 ± 0.45 | 95.25 ± 0.48 |

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The control of the moisture content in the air in buildings directly affects the comfort of the building occupants and is one of the more important tasks of an energy management and control system (EMCS). Unfortunately, a lack of understanding of the principles of operation and calibration of the various instrumentation used in monitoring the moisture content of air often makes this one of the most difficult and most neglected tasks for those assigned the responsibility of maintaining and operating building heating, ventilating and air-conditioning (HVAC) control systems.

This report was written for the purpose of assisting the managers and operators of EMCS in buildings in the understanding and use of various techniques for on-site measurement of the moisture content in the air. In addition, various methods of on-site calibration of typical types of moisture monitoring instruments are also discussed.

The ideal gas law is reviewed because of its direct application in converting the various humidity units. Relative humidity and dew point temperature are defined and their relationship described. Typical types of moisture monitoring instruments are described together with their method of operation. Several calibration techniques are discussed together with their typical advantages and disadvantages. The last section of this report is devoted to the assessing and reporting of the errors or uncertainties associated with the calibration and functioning of various moisture monitoring instruments. This very important area is often neglected and can result in excessive operating and maintenance costs.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

chilled mirror hygrometer; dew point temperature; humidity generator; humidity sensors; lithium chloride humidity sensors; moisture content of building air; relative humidity; saturated salt solutions; sensor calibration; sensor precision; specific humidity; wet-bulb temperature

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