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INSTRUMENTS FOR MEASURING THE AMOUNT OF MOISTURE IN THE AIR

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16. ABSTRACT

This report presents a summarization and discussion of the many systems available today for measuring moisture in the atmosphere. Conventional methods used in the field of meteorology and methods used in the laboratory are discussed. Performance, accuracies, and response of the instruments are presented as well as the advantages and disadvantages of each. Methods of measuring humidity aloft by instrumentation onboard aircraft and balloons are given, in addition to the methods used to measure moisture at the Earth's surface. Much of the information contained in this report has been summarized from books, papers, and documents available in the open literature which are included as references.

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INSTRUMENTS FOR MEASURING THE AMOUNT OF MOISTURE IN THE AIR

I. INTRODUCTION

This report presents a summary, based on a search of the literature, of all methods/instrumentation used through the mid-1970's in the measurement of atmospheric moisture content. Moisture in the form of water vapor is the parameter of interest. Obtaining a measurement of liquid or solid moisture states will not be considered here. The instrumentation for the measurement of the water vapor content of the air (generally called humidity or moisture content) is seldom as precise or accurate as is desired. As Middleton [1] states: "The measurement of humidity is one of the least satisfactory of instrumental procedures in meteorology, and in this field there is still a great opportunity for research and invention."

The humidity element (transducer) of any hygrometer is that part that quantitatively "senses" atmospheric water vapor. Six different types of moisture measuring methods are presented here. They are: (a) thermodynamic methods, (b) hygroscopic substances, (c) condensation methods, (d) absorption methods, (e) diffusion methods, and (f) optical methods.

The main moisture measuring instrumentation related to each of these methods in the field of meteorology will be discussed in detail, while all other types (laboratory) will be listed and defined. The first part of the discussion will concentrate on humidity measuring systems at the Earth's surface, including the principle of measurement and the accuracy and response of each instrument. Throughout this report accuracies of humidity measuring instruments will be referred to according to Wexler [2] and the Inter-Range Instrumentation Group (IRIG) standards [3]. Wexler [2] defines his uncertainty "as the estimated overall bounds to the systematic error plus three times the random error (standard deviation)." IRIG [3] defines its reliability values "as Root-Mean-Square (RMS) deviations about a mean value that is the best estimate of the measure of the quantity." References 1 through 17 were used in compiling the information presented in this report.

II. THERMODYNAMIC METHOD

The first type of humidity measuring instrument discussed uses the thermodynamic psychrometric method that incorporates the principle of adding water vapor to a gas to produce complete saturation. If water vapor is evaporated into a gas from a water source, the gas will cool and eventually reach a steady-state value. The initial gas temperature (dry bulb) and final steady-state air-over-water temperature (wet bulb) provide a measure of the humidity of the gas.

A. The Sling Psychrometer

The sling (or whirling) psychrometer is an instrument that obtains both of these temperatures (Fig. 1). It usually consists of two mercury-in-glass thermometers attached to a frame that is attached to a handle. One thermometer bulb is covered with a thin, wet cloth (muslin), and evaporation of water vapor from the wet bulb (which produces the cooling) is aided with forced ventilation. In this case, the sling psychrometer is whirled by hand, which produces the required ventilation rate. The muslin must be kept constantly wet, and the entire procedure of whirling the psychrometer is continued until the temperature falls to its lowest limit (usually this procedure lasts up to a couple minutes but depends on how dry the air is). Consecutive readings of the dry- and wet-bulb temperatures should agree to within 0.1°C [4].

The psychrometric formula [5] is given as:

$$e = e' - aP(t - t')$$

where

t = dry-bulb temperature

t' = wet-bulb temperature

P = atmospheric pressure

e' = saturated vapor pressure (corresponding to t')

e = vapor pressure

a = psychrometric constant $\left[a = 0.000367\left(1 + \frac{t' - 32}{1571}\right)\right]$.

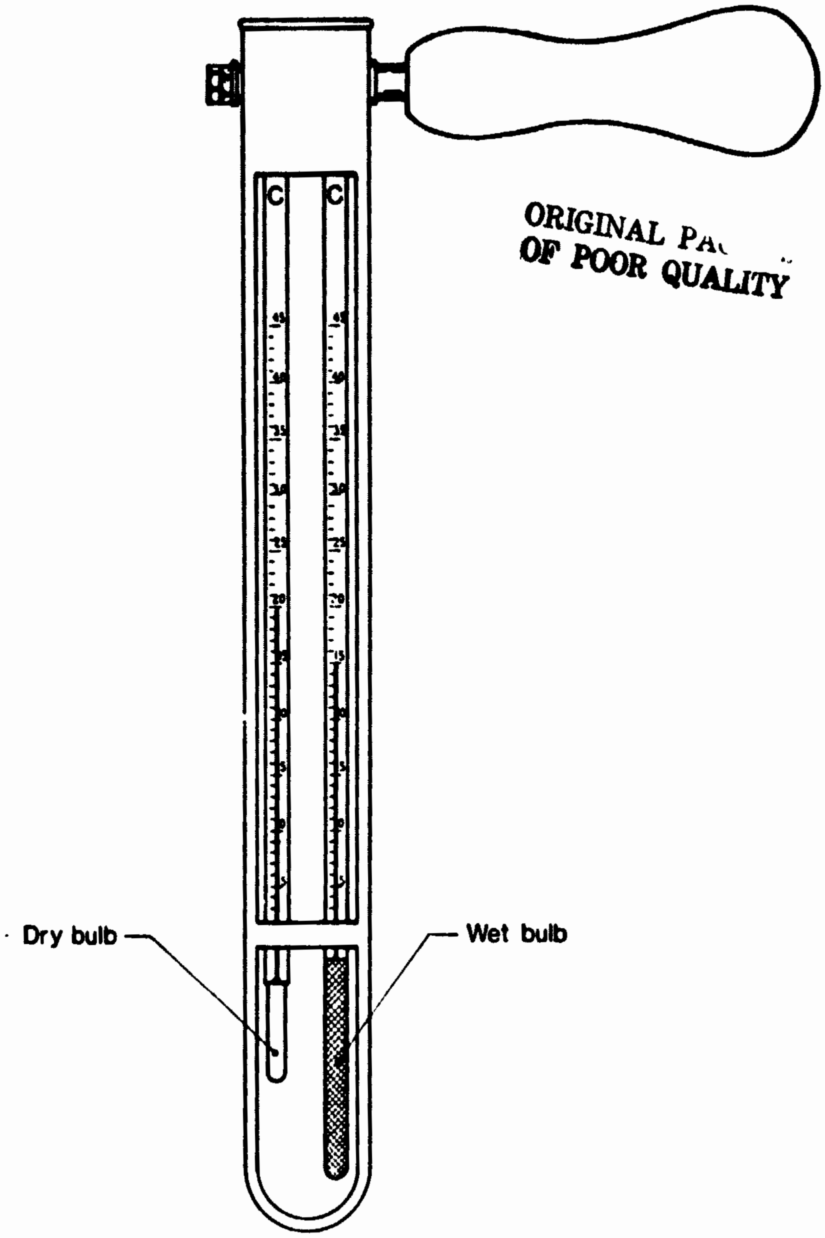

Figure 1. Sling or whirling psychrometer [6].

It should be noted that the psychrometric constant depends to some extent on the speed of the air past the wet bulb. It has been found that wind speeds greater than approximately 3 m/s allow the constant a to be steady [1]. Therefore, a 4 m/s flow rate or a sling rate of 3 rev/s is considered a standard rate of flow for the psychrometer.

B. The Assmann Psychrometer

The Assmann psychrometer employs a motor-driven (spring windup or electric) ventilation system (Fig. 2). A fan draws the air through the psychrometer rather than blowing it on the bulbs. This eliminates any motor heat blowing on the bulbs and affecting the temperature they measure. Also, it supplies a steady flow rate that eliminates any ventilation errors caused by insufficient ventilation of air past the wet bulb (as mentioned later).

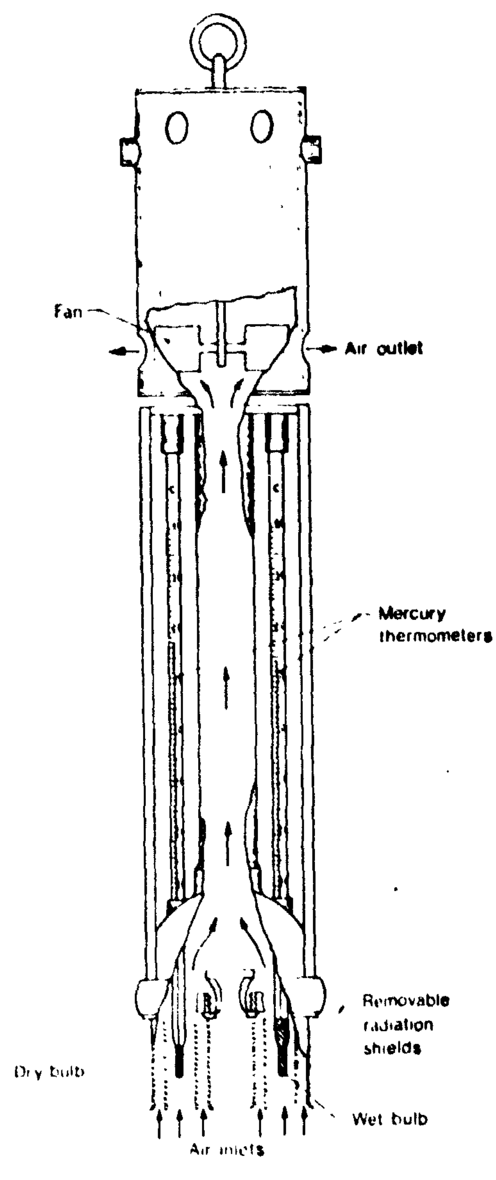

Figure 2. Assmann psychrometer [6].

C. Hand-Aspirated Psychrometer

The hand-aspirated psychrometer uses a venturi tube to produce a vacuum which allows the correct flow rate over the bulbs. Aspiration around the wet and dry bulbs is induced by a rubber bulb hand pump (Fig. 3).

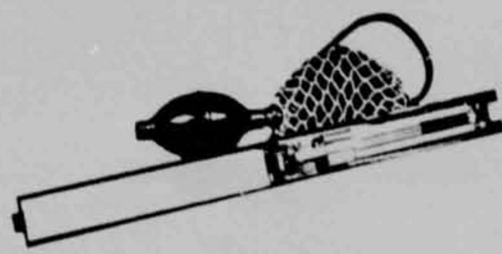

Figure 3. Hand-aspirated psychrometer (Bendix Model HA/2A).

D. Other Transducers Used

Resistance thermometers, thermocouples, and thermistors have all been used as the sensing elements (i.e., wet and dry bulbs) in psychrometers and offer a smaller required flow rate (0.7 m/s) and a response time on the order of seconds. Figure 4 shows some of the ways in which thermocouples are used as wet- and dry-bulb transducers. Also, mercury-in-steel thermometers [4] have been used in psychrometers. The main problem when using this type of thermometer is conduction of heat down the thermometer stem.

E. Sources of Error

Following are several sources of error which affect the performance of psychrometers [1,4,6]:

1) The sensitivity, accuracy, and agreement in reading thermometers. Low temperatures can cause problems in reading mercury-in-glass thermometers. That is, at -18°C, if an error of 0.6°C is made in reading the two temperatures, this will produce an error of ±33 percent in the relative humidity. Likewise, at 27°C an error of 0.6°C in reading will produce only an error of ±4 percent in relative humidity [1].

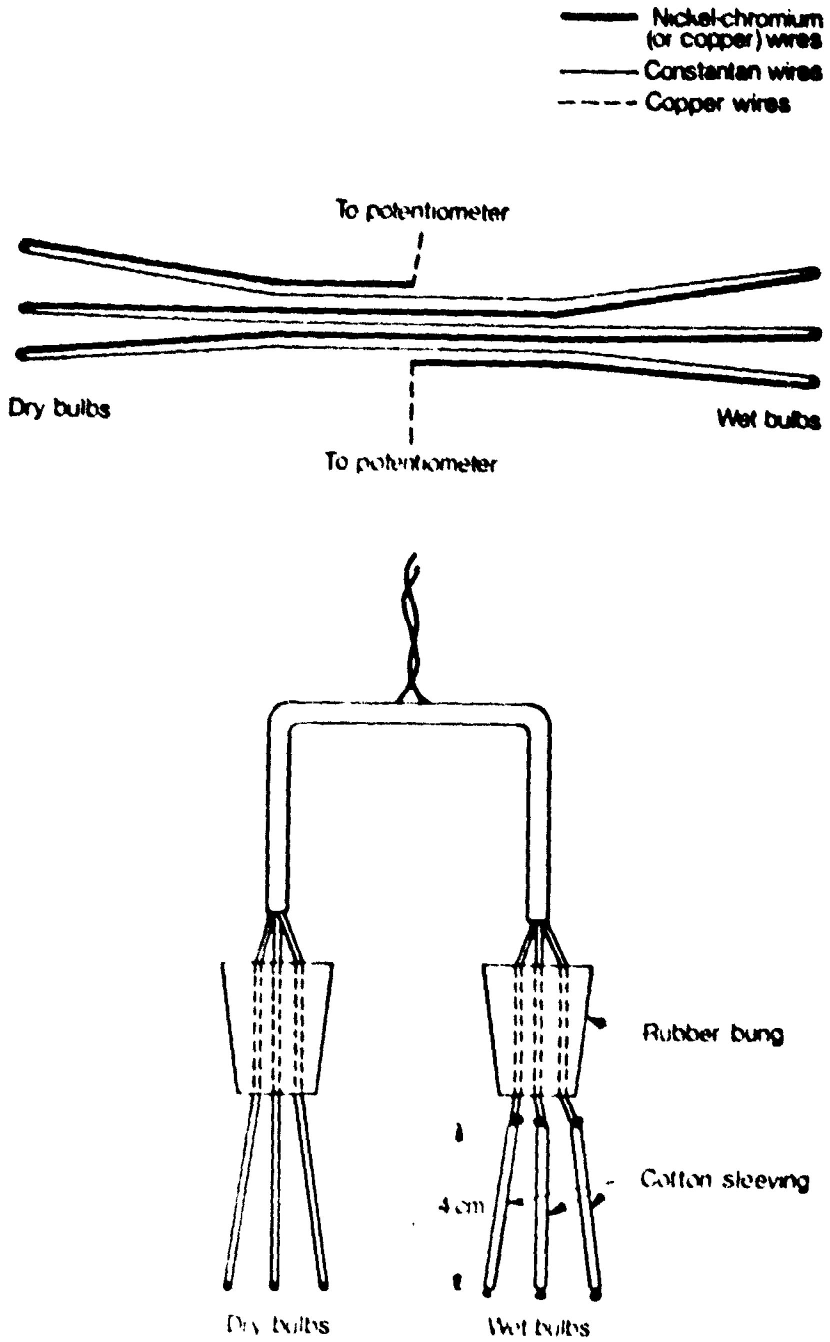

Figure 4. Thermocouples used in psychrometry [6].

2) Insufficient ventilation of air past the wet bulb. One should have greater than 3 m/s flow rate so that there will be no uncertainty in the value of the psychrometric constant. In using a sling psychrometer, the problem arises of using the wrong value of the psychrometric constant for the actual ventilation employed. Use of an aspirated psychrometer will eliminate thi- problem.

3) The size, shape, material, and wetting of the wick (muslin). Use thin cotton material, closely woven and fitting tight on the bulb. It should be changed once a week (keep muslin clean), or more often near a salt or desert atmosphere. Other materials that have been used as the wick have been handkerchief, linen, cotton corset lace, filter paper, or wet strength tissue paper (use paper products if dusty). The wetting of the bulb muslin should be complete, because a partially wet muslin introduces error. The muslin (or an ice covering on muslin) can be too thick, introducing error also. The muslin can be dipped in water, or water can be applied to the wet bulb using a rubber bulb. Water can also be continuously applied by capillary action from a reservoir along a wick into the wet-bulb muslin. Do not allow the reservoir water to affect the dry-bulb reading by flow of air past the wet bulb and reservoir. The relative positions of the dry and wet bulbs can be important.

4) Impure water, applied to the wet bulb, should not be used. Use only distilled water, or, if none is available, use rain water. Tap water should not be used because the chemicals it contains would soon become encrusted and form a deposit.

5) Water or snow on the dry bulb or radiation shield will produce a small error. The dry bulb will tend to act somewhat like a wet bulb, while moisture on the radiation shields will tend to humidify the air passing through the instrument.

6) Conduction of heat down the thermometer stem introduces error. This is taken into account (in the case of glass thermometers) in preparing the psychrometric tables [5], because the tables are based on experimental results using mercury-in-glass thermometers. Therefore, the error is not a factor in using glass thermometers; but when thermocouples are used in mercury-in-steel thermometers, a 0.6°C temperature gradient can exist across the thermometer bulb [1]. Usually one can cover the stem with wet muslin to eliminate the gradient.

7) Insufficient time in allowing the wet bulb to attain a steady temperature introduces an error.

8) Even the presence of the observer may cause error. One breath contains sufficient water vapor to saturate 0.001 m^3 at 20°C. Therefore, the observer should be screened away or downwind of the instrument.

9) Incident radiation on the thermometer, when read, also introduces some error. It should be noted that most of the preceding sources of error (except overventilation and reading errors) will tend to increase the reading of the wet bulb, thereby increasing the apparent humidity of the air.

F. Accuracy of the Psychrometer

Wexler [2] states that it is possible to achieve an accuracy in relative humidity within 1 percent over the range of approximately 5 to 65°C. But usually instruments are no better than within 2 percent, the sling psychrometer being of the order of 3 to 4 percent relative humidity. IRIG [3] states that for a humidity range from 5 to 100 percent relative humidity and temperatures above 0°C, relative humidity rms reliability is 3 percent (6 percent if below 0°C). Hickman [6] states that "to obtain relative humidities to 2 percent RH at about 20°C, the thermometers need to be calibrated to ±0.1°C or better." The adiabatic psychrometer [2] can obtain an accuracy within 0.25 to 0.50 percent relative humidity and can be used as a secondary standard.

The time constant (time required to indicate 63 percent of a step change in temperature with a known air flow speed) for a typical wet-bulb, mercury-in-glass thermometer is 20 to 25 s in 3 m/s flow, with temperatures approximately 20°C. The 3 mm wet-sleeve thermocouple (in 1 to 2 m/s flow) has a time constant of only 10 to 15 s [6]. Therefore, the thermocouple does have more application in micrometeorological work involving shorter time scales.

III. HYGROSCOPIC SUBSTANCES

Porous or cellular hygroscopic substances have been used to take up a quantity of water vapor equal to that given up by the air. This type of instrument is termed a mechanical hygrometer. When the moisture contant of the air varies, the hygroscopic substances change in dimension (e.g., hair stretches when in humid air).

A. Hair Hygrometer

Human hair has been used as a transducer to measure the moisture in the air since the 18th century and was one of the first type of humidity elements flown on an aircraft and a radiosonde [1]. At first, a change in weight of the substance with increased humidity was measured, but it was then determined that the change in length of a hair is a function of relative humidity and not a function of the actual amount of water vapor (absolute humidity) in the air. There is a total change of approximately 2.5 percent of the original hair length when the relative humidity increases from 0 to 100 percent. Also, for relative humidities above 20 percent, the elongation of the hair is approximately proportional to the logarithm of relative humidity. Besides changing length with moisture change, the hair also changes length with changing temperature, but its magnitude is approximately 1/15 as much per degree Centigrade as the change in length for 1 percent relative humidity.

A bundle of human hair (approximately 10 to 25 cm long) should be treated before using it as a transducer. Remove all fats and oils in the hair by soaking in ethyl ether for no longer than 1 h. It will deteriorate if kept longer. Wash in distilled water and air dry. Do not use electric heaters or lights to dry. Hairs should be washed once a week with distilled water applied with a camels hair brush. Wash more frequently if the element is exposed to a salty or dusty atmosphere.

B. Other Hygroscopic Materials

Hygroscopic materials other than human hair have been used. These include goldbeater's skin (outside membrane of the large intestine of an ox), horse hair, wood (cone) fibers, wool, cotton, silk, nylon, plastic, and paper. Horse hair is not often used because its response is much slower than human hair. Wood fiber has been used in Europe (not in the United States); however, it tends to mold since it is a wood product. Goldbeater's skin response is faster than hair but it also has many detrimental features.

C. Characteristics

Hair is very sluggish at low temperature (below 0°C), and its time constant approaches infinity at -40°C. If the relative humidity suddenly changed from 70 to 80 percent relative humidity under standard temperature conditions, it would take approximately 20 min for hair or goldbeater's skin to come within

2 percent of the final reading (40 min for cone fibers, horse hair, or paper). The time constant would be even greater at lower temperatures [6]. This puts a limitation on the usefulness of hair as an indicator of humidity for low ground temperatures or for upper air work. Hair is quite fast at higher temperatures, but if saturated conditions exist, the detailed behavior of hair is by no means simple. A hair wet with liquid water is, in fact, slightly shorter than the same hair in saturated conditions (it indicates approximately 96 percent) [1]. One should not use the hair hygrometer below 20 percent relative humidity or above 50°C because it may cause a permanent change in the hair length. Therefore, a recalibration may be necessary [6]. The hair hygrometer is a good instrument to use when humidity fluctuations are small or change slowly with time.

D. Description

The simple hair hygrometer is shown in Figure 5a [1,4,7]. The hair is attached between A and B under the tension supplied by the weight W. The arm WO is pivoted at zero with a pointer located there. Figure 5b indicates the three basic hygrograph mechanisms. Design (a) of Figure 5b indicates basically the same setup as shown in Figure 5a. It is simple in design and has one pivot point, but the output (pointer or recording pen) scale is not linear. The zero can also be changed without altering the magnification. Design (b) of Figure 5b shows that hook CB rotates about B, while arm AB rotates about A. Changes in the zero do alter the magnification somewhat. However, here the scale is approximately linear. Likewise, in design (c) of Figure 5b physical cams are used that force the scale to be linear. However, this design introduces functional resistance and the possibility of corrosion. It is usually left to the user to select the method he prefers.

E. Adjusting and Calibration

The conventional hair hygrometer may need two adjustments from time to time: (1) magnification and (2) zero. Magnification should rarely need adjusting. Only if the hairs acquire a permanent stretch with time will magnification adjustment be necessary. However, the zero is rarely stable and should be checked/reset at least once a week (particularly if the air has been dry too long). The zero is reset by dusting off the hair with a brush and then wetting the hair with distilled water and adjusting the pointer to read 96 percent with the use of the adjustable screw B in Figure 5a. The continuous recording hygrograph uses this third method and is illustrated in Figure 5c and 5d. The magnification procedure is tedious and involves the linkages in direct contact with the hair,

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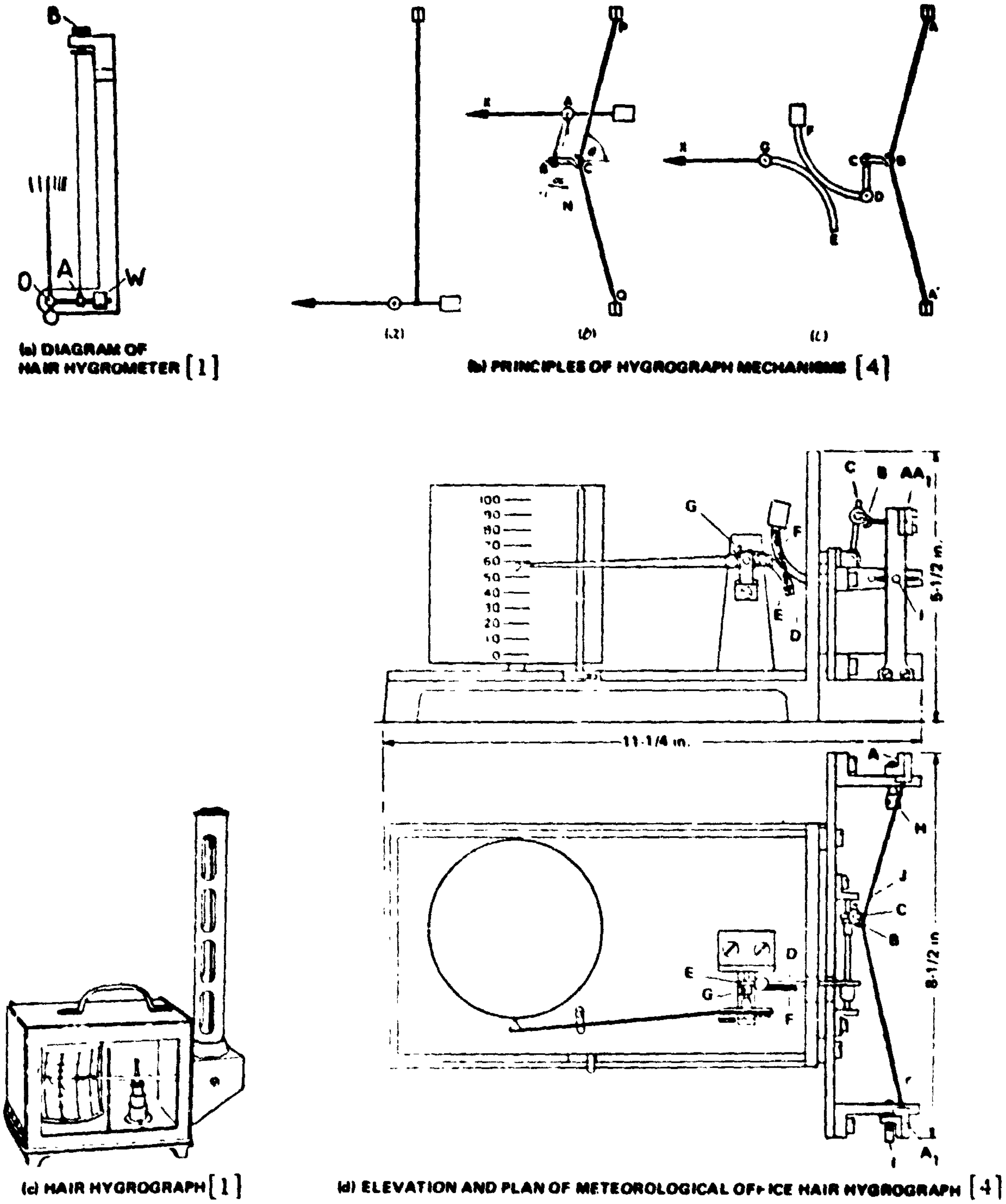
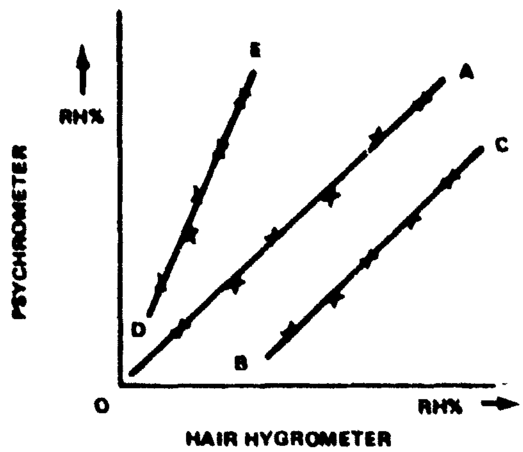


Figure 5. The hair hygrograph.

i.e., the hook in Figure 5d [6]. A way to check a hair hygrometer to see if it needs zero adjusting or magnification adjusting [4] is to keep a plot of the relative humidity calculated from the hygrograph as compared to the psychrometer measurement. A correct instrument will produce a 45 deg mean line (OA) as shown in the following graph:



If the zero needs adjusting, a straight line laterally displaced will be noticed (BC), while a line (DE) not at a 45 deg slope indicates the magnification needs adjusting.

When calibrating the hair hygrometer [1] a special humidity chamber is used similar to the one shown in Figure 6. However, if a humidity chamber is not available, one can use the fairly steady conditions of an ordinary room. The instrument should be covered with a wet cloth until the indicator has ceased to rise. This is the 100 percent relative humidity point. Then expose the instrument to the room air. Once the new indication is steady, a psychrometer should be used to take a number of readings. Make the necessary zero or magnification adjustments and repeat this test until no further adjustments are needed.

F. Accuracy of the Hair Hygrometer

Wexler [2] states that the hair hygrometer will measure relative humidity from 2 to 100 percent with an accuracy of 3 percent at temperatures as low as 0°C (approximately 8.5 percent accuracy at -20°C). IRIG indicates that the rms data reliability of the hair hygrometer is 10 percent throughout the range 5 to 100 percent relative humidity in use as a surface humidity instrument.

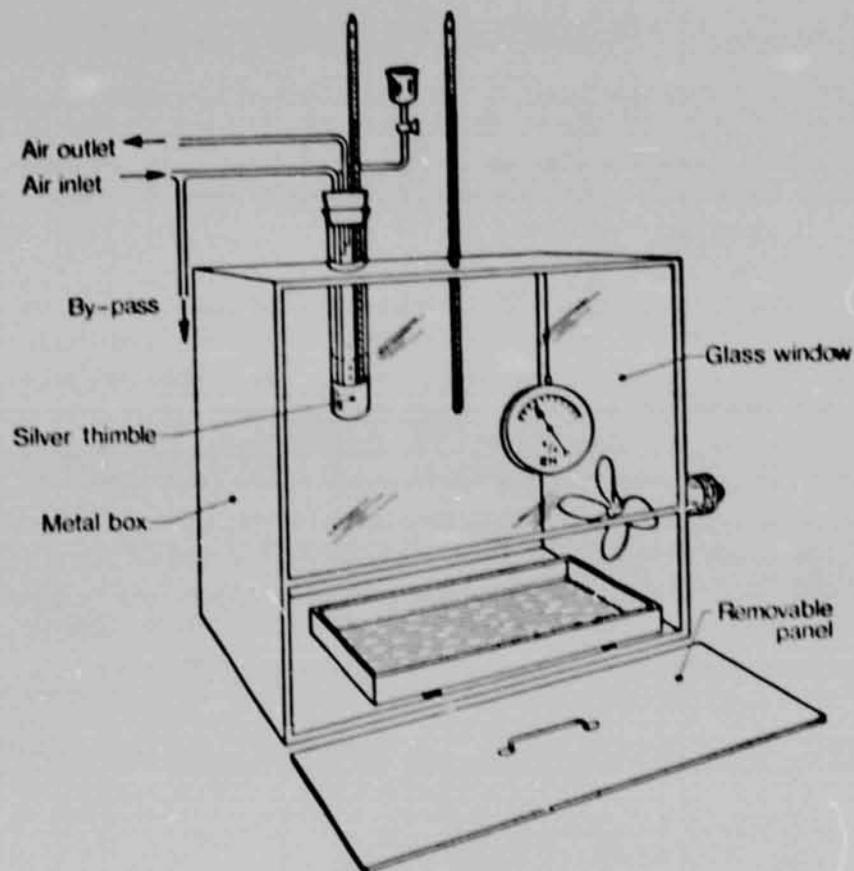


Figure 6. Instrument testing box [6].

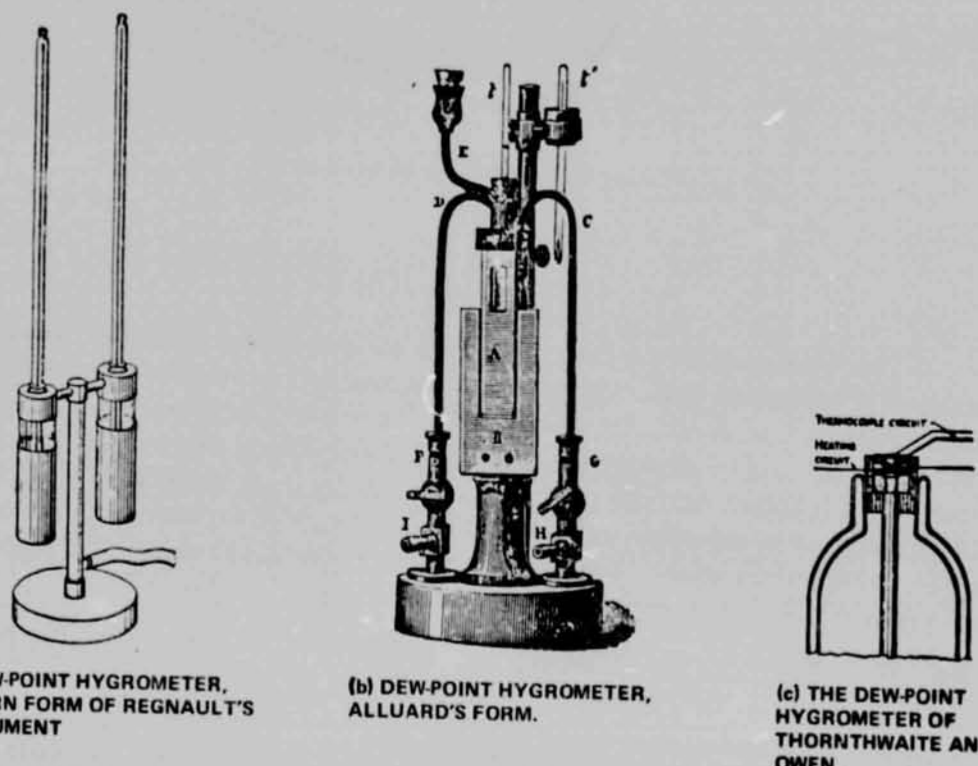
IV. CONDENSATION METHOD

The condensation method [1,2] is a method in which the dew-point temperature is observed when a moist gas is cooled and condenses on a cooled solid body. The surface is usually a polished mirror that is exposed to the moist air and is cooled until condensation occurs. A vapor-liquid or vapor-solid equilibrium is established, and the surface mirror reflections become dull. This method is used to measure low humidities and is ideal for use in the upper air where low temperatures (below 0°C) and low humidities exist. The transducer is usually a mercury thermometer or thermocouple.

A. Types of Dew-Point Apparatus

Over the years three basic forms of the "dew point" psychrometer have been used in meteorology. These will be discussed in the following paragraphs. The high-altitude, balloon-borne, frost-point hygrometer will not be discussed in this section but will be discussed in a later section concerning measuring humidity in the upper air.

1. Regnault Instrument. The modern form of the Regnault dew-point instrument is shown in Figure 7a. Two mercury-in-glass thermometers are mounted in two silvered tubes, one empty and the other containing ether. Air is simply bubbled through the ether, causing evaporation and causing the temperature to drop toward its dew point. The other silvered tube is used for a comparison when observing the formation of dew on the first (ether-filled) tube. The temperature read off the thermometer immersed in ether, when dew forms, is the dew-point temperature. Because it is difficult to see the precise beginning of condensation on the tube, it is the usual practice to take the average of two temperatures: (a) the temperature observed when dew forms (cooling surface) and (b) the temperature when dew disappears (warming surface) [1].



(a) DEW-POINT HYGROMETER, MODERN FORM OF REGNAULT'S INSTRUMENT

(b) DEW-POINT HYGROMETER, ALLUARD'S FORM.

(c) THE DEW-POINT HYGROMETER OF THORNTHWAITE AND OWEN.

Figure 7. Dew-point hygrometers [1].

2. Alluard Instrument. A similar but better form of dew-point hygrometer is the Alluard model [1] shown in Figure 7b. This instrument is based on similar principals, but the viewing surface A (for condensation) is much better located for making a comparison with surface B. Air is bubbled through ether by means of a suction bulb, and a telescope is usually used several feet from the instrument to eliminate false readings caused by the observer's breath.

3. Thornthwaite and Owen Instrument. Thornthwaite and Owen's hygrometer [1] uses an ordinary freezing mixture of solid CO_2 (dry ice) contained in a Dewar flask (Fig. 7c). A copper rod having a polished surface on its end is passed through the stopper. One junction of a thermoelectric circuit (thermocouple) is attached to it, with the other end being attached at a standard reference temperature. A small heating element is located beneath the polished circuit to keep the instrument from going below the dew-point temperature. This concept was developed and refined and is used today in upper-air humidity instrumentation [8]. Any volatile liquid, ether, acetone, methylated spirits, liquid or solid CO_2, or even mechanical refrigeration has been used as the cooling agent in dew-point hygrometers.

The two main problems encountered when using a dew-point apparatus are (a) it is difficult to measure the temperature of a cooled body exactly at its surface and (b) it is difficult to see the exact beginning of condensation. Consequently, the averaging method (mentioned previously) of observing dew formation and disappearance is employed. Recently, experimenters have used photoelectric cells to detect dew formation, because dew interferes with the specular reflection of a beam of light and hence interrupts the photocurrent. The temperature sensor (usually a bead thermistor) is embedded slightly beneath the surface. This method alleviates the previously mentioned problems. When using thermometers immersed in a volatile liquid, one should use "partial-immersion" thermometers [1] to avoid stem errors.

4. Cloud Chamber Hygrometer. With the cloud hygrometer [2], the formation of fog is the criterion for saturation. Either moist air samples are compressed and adiabatically expanded to atmospheric pressure, or moist air at atmospheric pressure is expanded into a lower pressure chamber until fog forms. The temperature of fog formation is the temperature of the dew point. This is mainly a laboratory type experiment in which the operator must develop a skill in forming fog within the chamber. He usually has to make repeated trials with air samples until he gets the pressure ratio at which fog barely forms. Condensation nuclei are introduced into the chamber usually from a radioactive source. The Alnor dew pointer [9] is an example of a small, portable type chamber. As can be seen from Figure 8, air is compressed into a

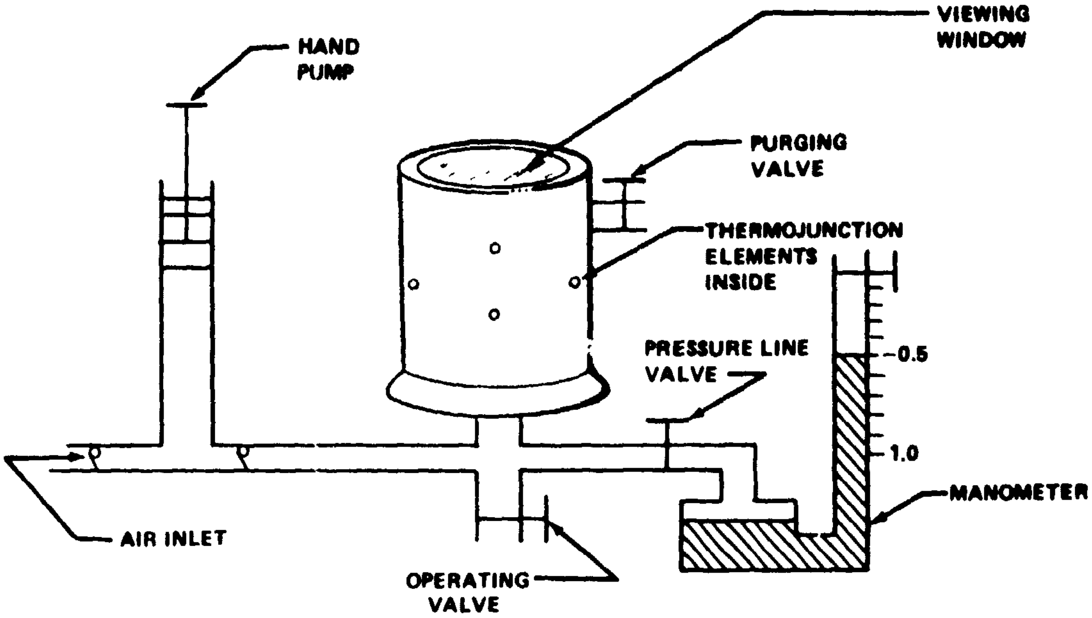


Figure 8. Alnor dew pointer.

chamber with a hand pump to a certain recorded pressure. This air is suddenly expanded out an operating valve, producing adiabatic cooling. This cooling, if lowered enough, will cause fog or dew to form in the chamber. Adjusting the pressure ratio in the chamber [knowing the initial chamber temperature (T_1) — measured with thermojunctions], one can arrive at a pressure ratio at which dew barely forms. These data can be used in the adiabatic expansion equation and solved for the dew-point temperature (T_D); i.e.,

The first law of thermodynamics for an adiabatic process is

$$du = -\delta\omega, \text{ or } c_v dt = -pdv = -RT\frac{dv}{v} \quad .$$

Integration with substitution gives Poisson's equation,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{R/c_p} = \left(\frac{P_2 \text{ atmos.}}{P_1 \text{ chamber pressurized}}\right)^{Q}$$

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or solving for T_2 (i.e., T_D)

$$T_D = (T_1 + 273.15)\,(\text{Press Ratio})^{0.2855} - 273.15 \qquad (°C) .$$

B. Accuracy of Dew-Point Methods

Wexler [2] states that the typical dew-point instrument has an uncertainty of the order of 1°C over the temperature range of -40 to 30°C. The most accurate dew-point hygrometers have inaccuracies in dew point of the order of 0.1°C over this range. These hygrometers have thermometers that can detect temperatures to 0.01°C and can be used as a satisfactory standard for checking and calibrating hygrometers with lesser accuracy. IRIG [3] states that the conventional dew-point hygrometer (Cambridge System, Inc.) has a data reliability of:

0.5°C → dew point above 0°C

1.5°C → 0°C to -40°C

3°C → -40°C to -60°C .

Wexler [2] indicates the inaccuracy of the cloud chamber hygrometer to be of the order of 3°C over the range of -30 to 30°C.

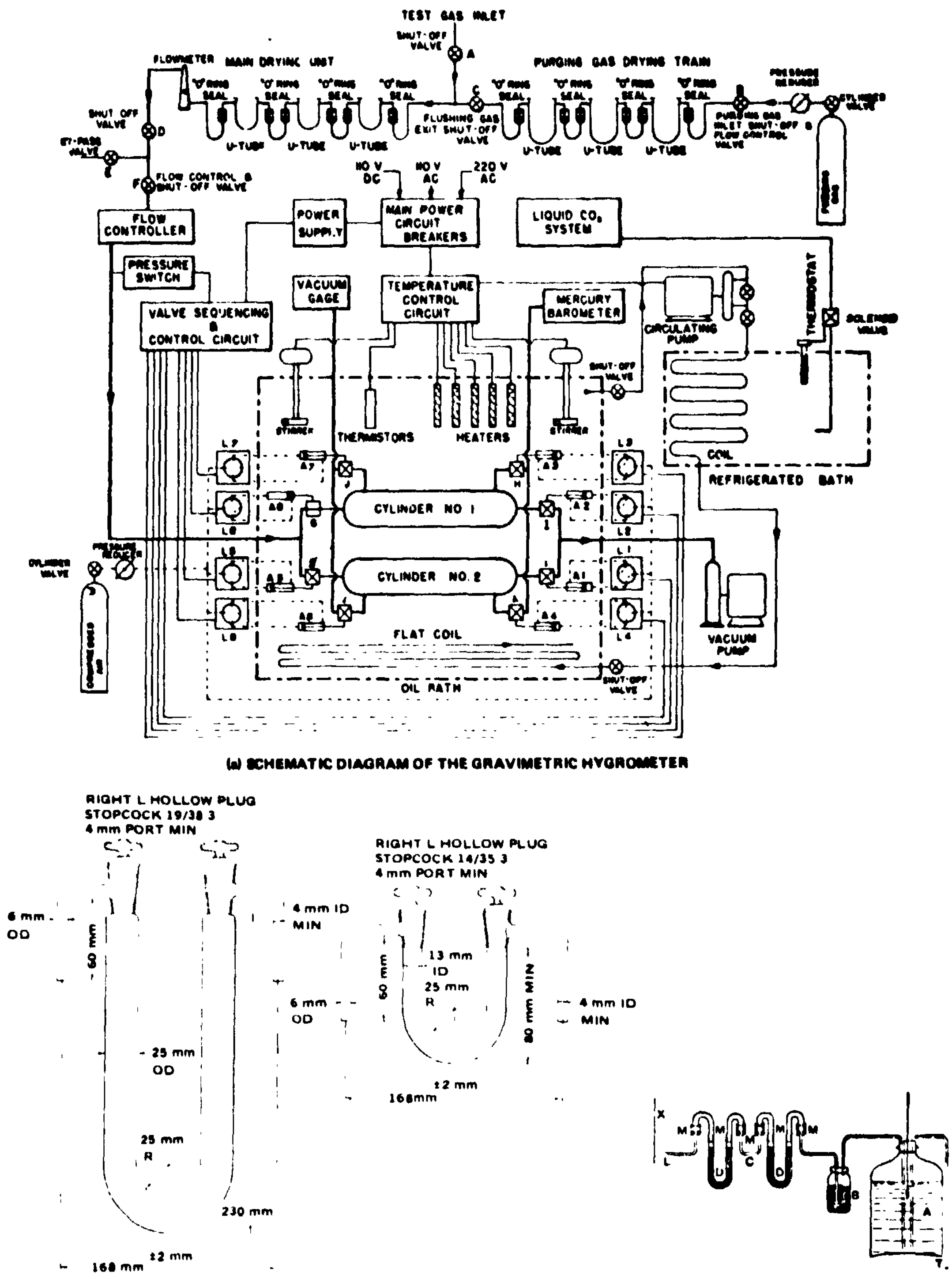
V. ABSORPTION HYGROMETERS

Absorption hygrometers are usually divided into two groups: the chemical and the electrical. The electrical method is used extensively in the field of meteorology, whereas the chemical method is strictly a laboratory method and is rarely used in meteorology.

A. Chemical Method

The chemical absorption method [2] uses the principle of removing water vapor from a gas by using a solid or liquid desiccant to absorb the water vapor. Cryogenic techniques also can be used to freeze out the water vapor.

1. Gravimetric Hygrometer. The gravimetric hygrometer (Fig. 9) is a very accurate moisture measuring device. It is used extensively in the laboratory and serves as the National Bureau of Standards (NBS) standard instrument for measuring the moisture content of gases on an absolute basis in terms of mixing ratio [10]. In the conventional gravimetric hygrometer, the water vapor in the air (given volume) is removed by a desiccant, and its mass is determined



(a) SCHEMATIC DIAGRAM OF THE GRAVIMETRIC HYGROMETER

(b) DRYING TUBES [FLUSHING GAS DRYING TRAIN U-TUBE (LEFT); MAIN DRYING TRAIN U-TUBE (RIGHT)]

(c) TWO DRYING CELLS USED IN SERIES

Figure 9. Gravimetric hygrometer [10].

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by direct weighing. From the increase in weight of the desiccant, the absolute humidity can be found. The desiccant (e.g., H_3PO_4 or $CaCl_2$) can reduce the relative humidity to zero. Two drying tubes, D, are used in series (Fig. 9c), with each being weighed separately before and after the test. The aspirator, A, initially full of wate., is allowed to empty slowly (100 cc/min). This provides the drawing of air through the drying tubes, D. The first drying tube should handle all the absorption, but the second tube is used in case the flow through the tubes is too rapid for the first tube to absorb all the moisture in the gas sample. The vessel, B, is filled with a desiccant and is used as a valve to prevent any moisture from reaching the tubes from the aspirator, A. The volume of gas is measured with a volume-measuring instrument. If the density of the dry gas is known, the measured volume can be converted into a mass, thereby allowing absolute humidity to be obtained. References 2, 7, 10, and 11 give good summaries on the gravimetric hygrometer.

2. Other Methods. Other chemical absorption techniques have been used, such as the volumetric method, pressure method, coulometric method, and the pneumatic bridge method. Again, these methods are suited for the laboratory and are accurate, but they are not as accurate as the gravimetric method. These techniques are described briefly in Section IX of this report.

B. Electrical Method

Humity sensors which indicate a change in an electrical parameter (usually resistance) when used in a measuring circuit are termed electrical hygrometers [2]. These hygrometers are used mainly in upper air humidity measurements and will be discussed in Section VIII of this report. However, the Dewcell [1,16], designed primarily for surface air conditioning control work, will be described here (Fig. 10). The Dewcell is an adaptation of the lithium chloride electrical-resistance hygrometer. It consists of two parallel electrical conductors with an ac potential of 25 V between them. These conductors are covered with a lithium chloride wicking (saturated salt solution). Water vapor from the air is absorbed, and the solution becomes a better conductor of electricity. This flow of electricity causes a heating up until moisture equilibrium is attained. The dew-point temperature is the temperature (not resistance) of the cell when the equilibrium is established between the vapor pressure over saturated lithium chloride and the ambient vapor pressure. A resistance thermometer is usually used to sense the temperature. The Dunmore and Gregory electrolytic hygrometers are similar types of humidity instruments [7] relying on the use of lithium chloride and a changing resistance (not temperature).

Figure 10. Automatic heated dewcell humidity sensor.

C. Accuracy of Absorption Hygrometers

Wexler [2] indicates that skilled operators can measure moisture in a gas with a gravimetric hygrometer, with a total uncertainty of approximately 0.1 percent. It is a laboratory method that is tedious, complicated, time consuming, and seldom used; however, it is the standard NBS hygrometer and gives a very accurate mean value of moisture in approximately 1 h.

The dewcell can operate between temperatures of -30 and 100°C and can measure humidity from 100 percent to the equilibrium value of a saturated solution of LiCl (at 50°C it is 11 percent relative humidity). The colder the ambient temperature, the higher this minimum relative humidity becomes. At -30°C, the minimum is approximately 100 percent relative humidity. High ventilation rates should be avoided since this would conduct too much heat away from the lithium chloride solution, affecting solution temperature. The dewcell has a dew-point uncertainty of approximately 1.5°C, with a response time of approximately 1 to 3.5 min for a 90 percent indication change. IRIG [3] states the data reliability of the remote surface dewcell (AN/TMQ-11, etc.) is 1.1°C between 0°C and 32°C, and 1.7°C between 0°C and -46°C.

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VI. DIFFUSION METHODS

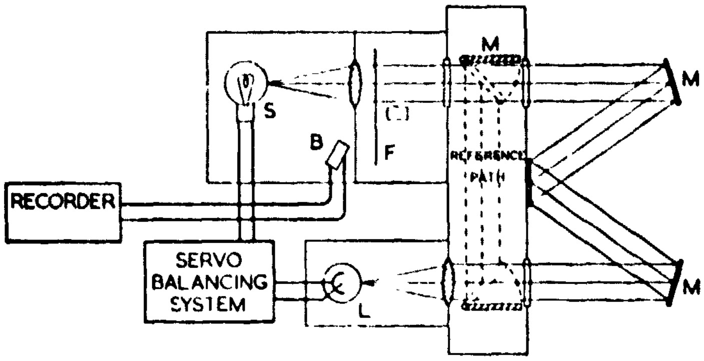
The diffusion hygrometer is sometimes considered a type of absorptive water vapor removal hygrometer [2]. There have been different adaptations of the diffusion hygrometer, but only one will be presented here [2,7]. Certain porous materials such as clay, marble, gypsum, alabaster, gelatin, and cellophane act as semipermeable membranes which allow air diffusion but prevent water vapor diffusion through the material. One such instrument consists of two vessels fitted with manometers, each of which has an open side in which a porous diaphragm is placed. One vessel contains water, and the other vessel contains a desiccant. The vessel containing water will exert a vapor pressure $(P+P_1)$ greater than the outside air (P). The other vessel containing the desiccant will measure a reduced water vapor pressure $(P-P_2)$ lower than the outside air (P). Therefore, the two manometers measure P_1 and P_2, giving the relative humidity of the outside air as: $RH = P_2 (P_1 + P_2)$. With this hygrometer the outside air pressure does not really need to be known in computing relative humidity. The instrument is very sensitive to quick changes in temperature, wind, dust, and solar radiation. The response is somewhat sluggish, but it is a low-cost humidity instrument with an uncertainty of approximately 5 percent relative humidity [2].

VII. OPTICAL HYGROMETERS

There are many different optical hygrometers which depend on the physical properties of a gas (e.g., refractive index, viscosity, thermal conductivity, density, and sonic velocity) all of which vary with the amount of water vapor present. Therefore, these are also called physical methods of hygrometry [2] because the measurement of such a property is an indication of the atmospheric moisture content. They tend to respond rapidly, and they neither add to nor subtract from the air sample, as other humidity methods do. Empirical calibrations are usually required.

A. Spectroscopic Hygrometer

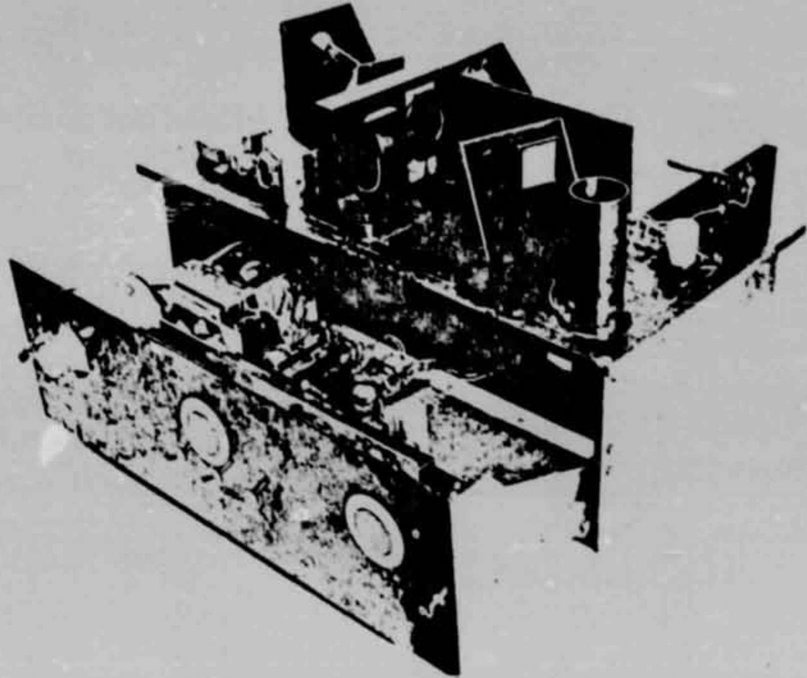
The optical hygrometer of interest to the meteorologist is the U.S. Weather Service's spectroscopic hygrometer, called either an infrared absorption hygrometer or an ultraviolet hygrometer, depending on the wavelengths employed [2, 12]. Figure 11 shows the structure of the instrument. It consists



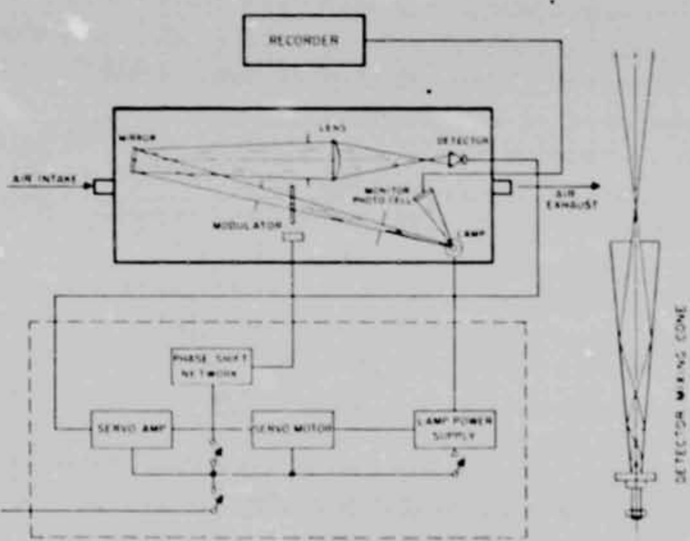
NOTE: S, RADIATION SOURCE; F, FILTER SECTOR WHEEL; M, MIRRORS; L, LEAD SULPHIDE CELL; B, SELENIUM CELL FOR MEASURING ENERGY OF SOURCE.

Figure 11. Spectroscopic infrared hygrometer [12].

of a projector with a tungsten lamp hot filament, S, that emits a continuous spectrum of radiation through a test gas and is received by a photocell, L. Because water vapor will attenuate this beam of radiation at selected wavelengths and not at others, this provides a method to measure humidity. More specifically, a set of eight glass filters is mounted as sectors of a wheel, F, which is rotated at 15 rps. Four of the filters, alternately spaced, transmit radiation in a narrow band centered near 1.37 μ, while the other four filters transmit near 1.24 μ. The 1.37 μ band is actually a very good water vapor absorption band, while at 1.24 μ the absorption is not appreciable. The radiation passes through the filters, reflects off the mirrors, M, and is received by a lead-sulphide photocell, L, with a signal consisting of two 60 cycles/s components with a 180 deg phase difference. When the flux through each set of filters is such that these two components are equal, the resultant combined signal is zero. If, however, water vapor is present in the test gas, the beam through the 1.37 μ filters will be attenuated so that the photocell gives an error signal indicating the lack of balance between the two components it receives. A servo-mechanism then changes the voltage which changes the temperature of the lamp, S, until balance is again obtained. Thus, the lamp temperature indicates a measure of the water vapor content of the air. The photocell, B, measures the energy of lamp emission when in balance. An internal reference path is also included as a check on calibration drift. The U.S. Weather Service has improved the original model [2, 13], as illustrated in Figure 12.



(a) PHOTO OF THE 1 m FOLDED-PATH INFRARED ABSORPTION HYGROMETER WITH HUMIDITY CHAMBER COVER OFF AND EQUIPMENT DRAWER EXTENDED.



(b) FUNCTIONAL DIAGRAM SHOWING GENERAL ARRANGEMENT OF OPTICAL AND ELECTRICAL COMPONENTS IN 1 m FOLDED-PATH INFRARED ABSORPTION HYGROMETER.

Figure 12. Infrared absorption hygrometer [13].

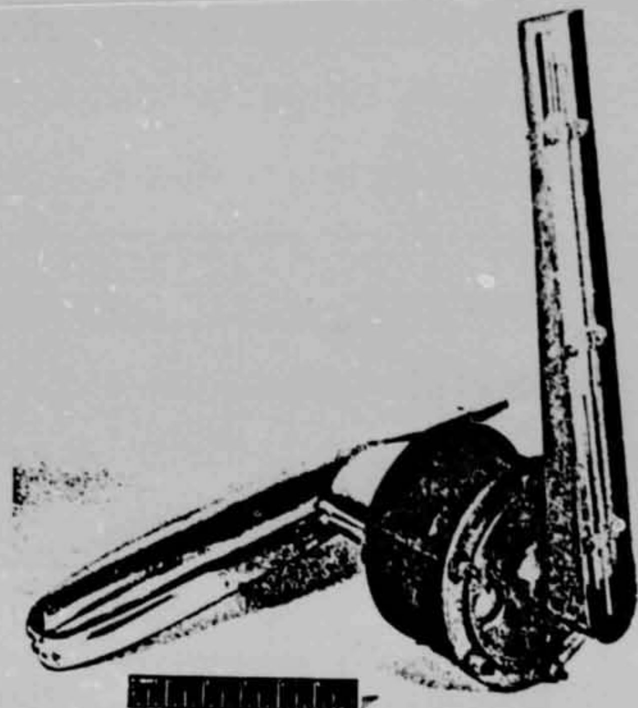
B. Characteristics and Accuracy

The advantage of the spectroscopic hygrometer is that it can determine the average water vapor content of a large sample of the atmosphere in one observation. The air itself is used in the measurement, not some intermediary material as with other hygrometers. The speed of response is limited only by the speed of the indicating instrument. The instrument is expensive and requires calibration. Short-term (1 week) stability is good, but long-term stability is variable. Atmospheric pressure changes affect the calibration as does temperature (to a lesser extent). The pressure effect will require further study. The instrument operates between -45 and 20°C dew point [2]. Wexler's uncertainty at -45°C is approximately 3°C, while at 20°C it is approximately 0.5°C.

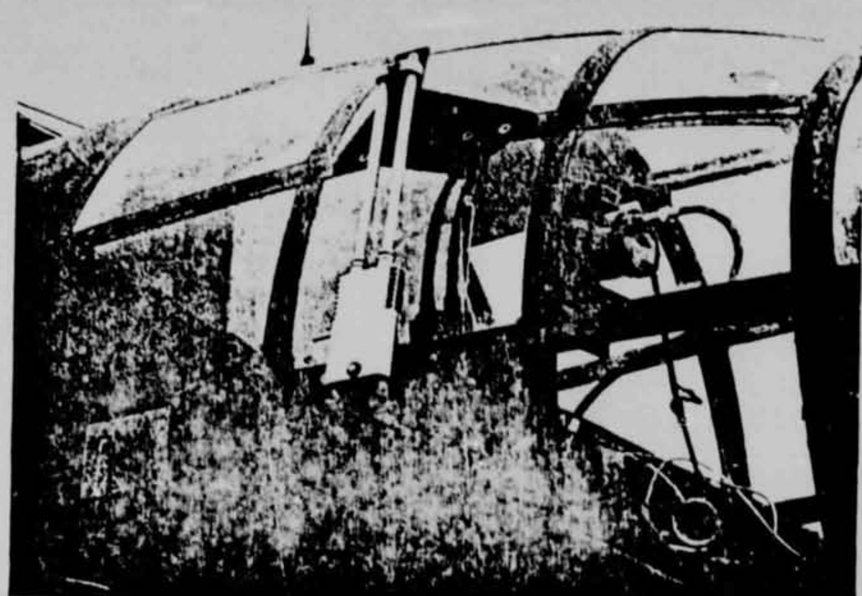
VIII. HYGROMETERS USED IN THE UPPER AIR

A. Aircraft Hygrometers

Aircraft hygrometers were used extensively prior to the advent of the instrumented balloon. They employed organic absorption methods which used hair and goldbeater's skin as elements. However, because of the extreme lag of hair at low temperatures and the loss of calibration which results when goldbeater's skin is covered with a thin water film, they were not suitable for measurements aloft. Wet- and dry-bulb thermometers have been used in the aircraft psychrometer [12] attached outside the craft (Fig. 13). All types of aircraft psychrometers have the disadvantage that the wet-bulb depression for a given relative humidity falls rapidly with a decrease in temperature, thereby giving unreliable measurements at low temperatures. At 0°C the wet-bulb depression must be known to 5/100 of a degree Centigrade to get an accuracy of ±2.5 percent in relative humidity. Frost-point hygrometers were introduced by Dobson [12], and modern versions are illustrated in Figure 14. The method of operation is similar to that of Mastenbrook's [8] balloone-borne, automatic, frost-point hygrometer which will be discussed in a later section. Dobson's device has been successfully used on aircraft to measure atmospheric temperature down to 190° absolute [1, 12]. At 500 mb it represents an accuracy of approximately 5 percent relative humidity [12].

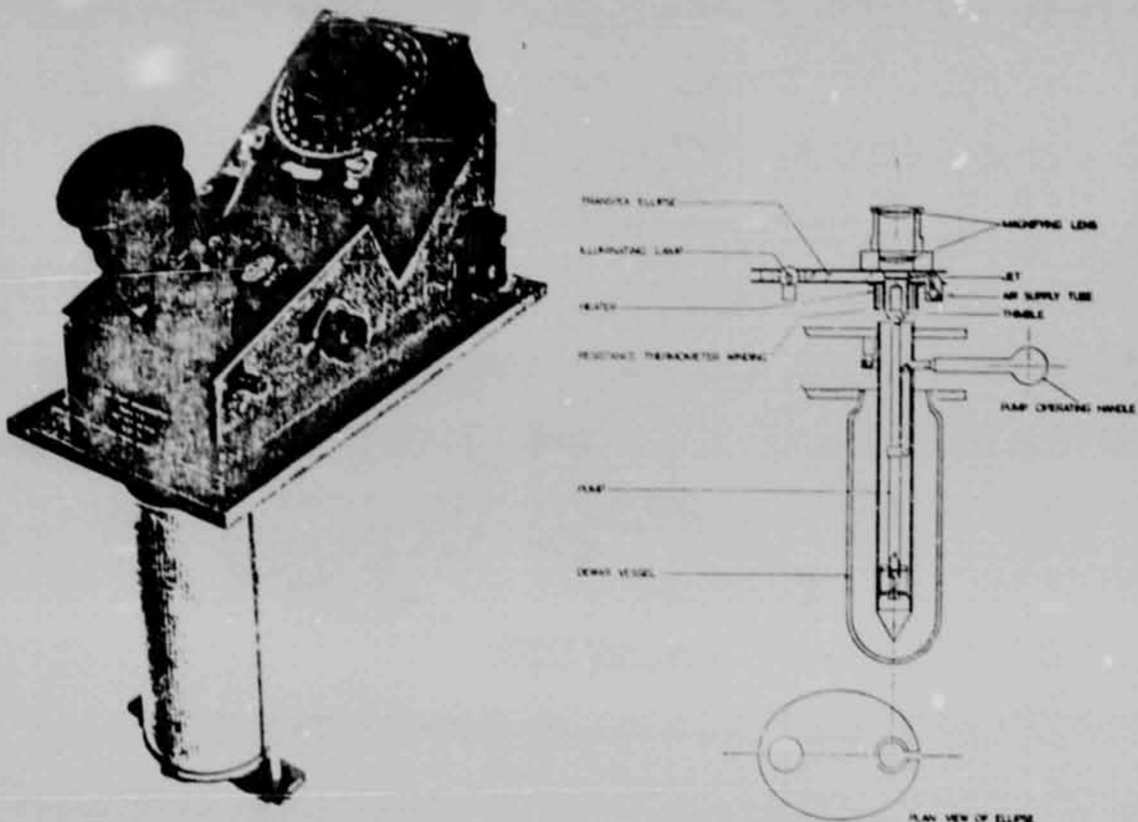


(a) U.S. SIGNAL CORPS AIRCRAFT PSYCHROMETER, TYPE ML-313/AM.



(b) INSTALLATION OF PSYCHROMETER, MARK 6, ON A BOSTON AIRCRAFT.

Figure 13. Aircraft psychrometers [12].



(a) METEOROLOGICAL OFFICE FROST-POINT HYGROMETER, MARK 2B.

(b) CONSTRUCTION OF METEOROLOGICAL OFFICE FROST-POINT HYGROMETER.

Figure 14. Aircraft frost-point hygrometer [12].

B. Radiosonde Hygrometers

1. Hair Hygrometer. The earliest type of balloon-borne humidity element was the hair hygrometer [1] using a cage of hairs connected by a lever system to a contact which moved along a wound resistor (Fig. 15a). But the hair hygrometer had the usual low temperature-high lag defects and was replaced by the electrical hygrometer.

2. Electrical Hygrometers. Dunmore developed the first electrical hygrometer [1]. It consisted of a bifilar winding in a moisture-sensitive film that contained lithium chloride which was coated on a nonconducting tube (Fig. 15b). The latest lithium chloride design (Fig. 15c) consists of a nonconducting

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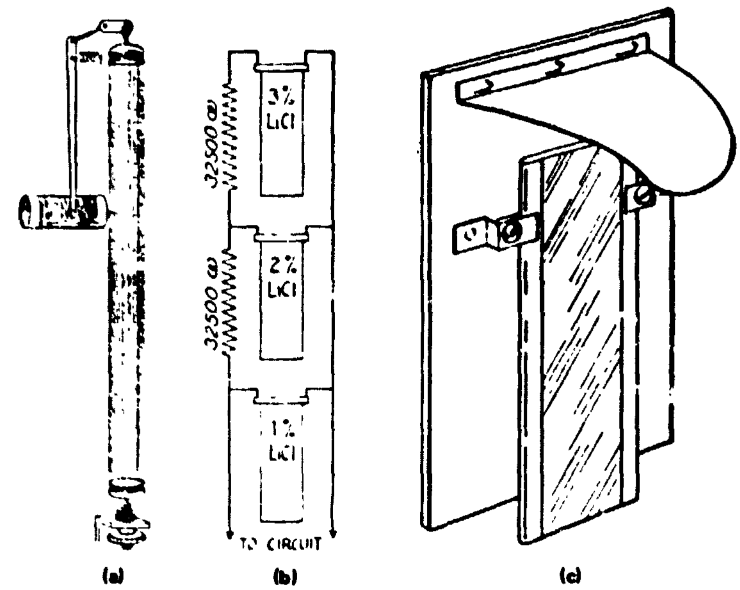


(a) HAIR HYGROMETER, (b) ELECTRICAL HYGROMETERS IN PARALLEL CIRCUIT, (c) LATER FORM OF ELECTRICAL HYGROMETER (FRIEZ), SHOWING MOUNTING.

Figure 15. Electrical hygrometers used in radiosondes [1].

plastic strip covered with lithium chloride and with metal strips along the edges. The electrical resistance of the lithium chloride film between the metal edges is used as an indicator of the air humidity. Since a salt solution is a good conductor, the resistance across the strip decreases with increasing relative humidity. The humidity element is physically attached (electrically) to the radiosonde unit. The unit is calibrated before liftoff with a helium-filled balloon. As it rises up through the air, the radiosonde sends humidity measurement signals periodically to the ground-based receiver. Before use, the element is sealed in a glass or plastic vial containing dry air.

A problem [14] encountered with the lithium chloride strip is that liquid water droplets may be picked up, producing a washout effect. It also becomes insensitive at high humidities. The response is faster than hair, but it is slow at sub-zero temperatures (high lag). Also, electrical dc circuit care must be taken to protect the element from a polarization effect. The resistance is temperature sensitive as well as humidity sensitive, and calibration curves relating resistance to temperature and humidity must be obtained. Middleton [1] states that the electrolytic strip can give relative humidity measurements with a probable error of ±2.5 percent at −10°C between 15 and 96 percent relative humidity. Barium fluoride has also been used [9] as a coating. It has a fast response, but problems with hysteresis and liquid moisture, together with rapid deterioration in storage, made it impractical for use.

In recent years the carbon humidity element strip [9, 14] has replaced the lithium chloride strip in radiosonde use. Carbon particles are suspended in a thin film of gelatin on a plastic strip. The particles touch one another, allowing for a small amount of resistance across the strip. If the relative humidity rises, the gelatin absorbs moisture and expands. The result of this expansion is that the carbon particles do not touch as firmly, thereby causing a resistance increase across the strip. Therefore, the resistance across the strip increases with increasing relative humidity. The opposite effect occurs when the lithium chloride strip is used. The carbon strip has been adopted by various U. S. agencies as the standard hygrometer element for use in radiosondes. The advantages that the carbon strip has over the lithium chloride strip are (a) no danger of dripping at high humidities (no washout), (b) smaller temperature correction factor, and (c) slightly faster response. Problems encountered with the carbon strip are (a) uniform production of the carbon element is difficult and (b) the element is sensitive to the storage environment.

The VIZ Manufacturing Company of Philadelphia produces three different carbon elements (ESSA, ML-476, and ML-630) for use in radiosondes [14]. They state that the resistance changes more than 100 times for a 90 percent relative humidity change. Element No. 476 has a resistance of 20 000 ohms at 33 percent and 25°C. The other two elements have a resistance of 10 000 ohms at those same conditions. Evaluators are to be used to convert recorder divisions to relative humidity. VIZ states that the change with temperature is small compared to the change with humidity. It is near zero at 33 percent relative humidity, and 0.2 percent relative humidity per degree Centigrade at 100 percent relative humidity. The VIZ Company specifications indicate an accuracy of ±5 percent relative humidity over a temperature range 40°C to -60°C and a humidity range of 10 to 100 percent. Over a 5 to 99 percent relative humidity range, IRIG [3] indicates a relative humidity data reliability for the ML-476 Hygristor of:

5 percent → Temperature > 0°C

10 percent → 0°C to -20°C

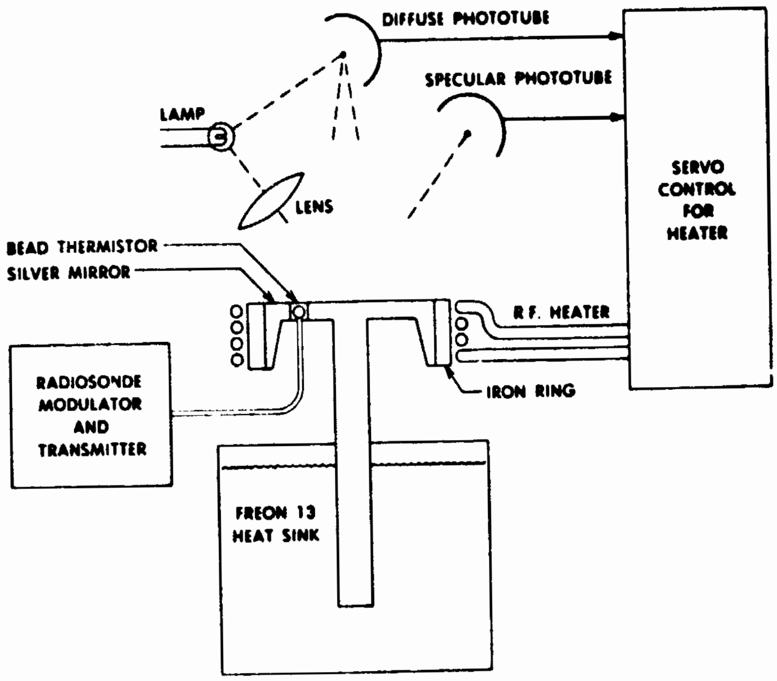
20 percent → -21°C to -40°C

Unreliable → Below -40°C.

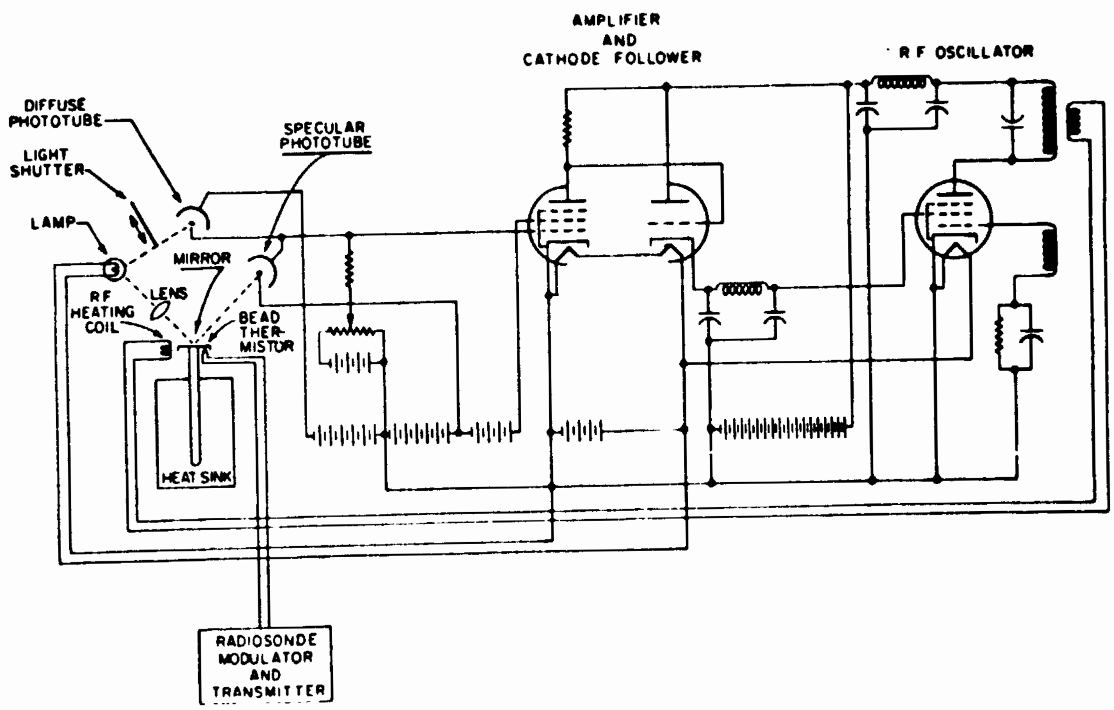
Other strip coatings have also been studied for use as an electrical hygrometer (e.g., plastic resins and aluminum oxide), but no field data are available [14].

3. Frost-Point Hygrometer [17]. The dew-point or frost-point hygrometer uses the same principle as the condensation dew-point method described previously. During the past 15 years, the Naval Research Laboratory (NRL) has developed a balloon-borne frost-point hygrometer which uses a mirror refrigeration system for measuring moisture in the upper atmosphere up to 30 km [8]. Air on a thermostated mirrored surface is cooled until dew (or frost) forms on the mirror. A stable dew formation is maintained by controlling the mirror temperature through the use of a sensing and control circuit (Fig. 16). The temperature of the mirrored surface is taken as the dew point of the air stream. The temperature is measured by a bead thermistor element (0.014 in. in diameter) embedded in the mirror. An optical-electronic-thermal servo loop is used to continuously control the mirror at the dew-point temperature. Two phototubes are used, one specular and one diffuse. The amount and optical characteristics of the condensation on the mirror determine the relative proportion of light that reaches the phototubes. The phototubes determine the output to the RF heating coil around the mirror. The heat sink of dry-ice balances the induction heating to control the size of the condensation spot on the mirror. Heat flowing toward the heat sink establishes a radial thermal gradient on the mirror surface, making it possible to control the condensation spot size. The bead thermistor is placed so that it is located at the periphery of the controlled condensation spot. A temperature-controlled bath is used for each embedded thermistor to determine a resistance-temperature curve (Fig. 17a). Before launch, resistance versus recorder-division data are obtained so that a temperature-recorder division calibration curve (Fig. 17b) is attained for each instrument.

Figure 18 was chosen as an example of an extreme frost-point sounding obtained by the frost-point hygrometer. This profile shows an extreme deviation of frost-point taken during ascent compared to that taken during descent. This result generated interest in the problem of moisture contamination, as reported by Mastenbrook [15]. It is believed that because the instrumentation is prepared in the moist troposphere and within an hour is at stratospheric levels where the moisture content is 5 or 6 orders of magnitude lower, moisture is probably carried into the stratosphere by the instrumentation, equipment, and the balloon. The sample inlet is located beneath the instrument, at the lowest point in the flight train. Therefore, it is believed that emphasis should be placed upon the descent portion of the flight data since the bottom inlet will be sampling the pure atmosphere on its downward journey. Other possible problems include the gradient of temperature across the face of mirror error, giving an error of approximately 1°C and the stoppage of blower, allowing moisture stagnation to build up.

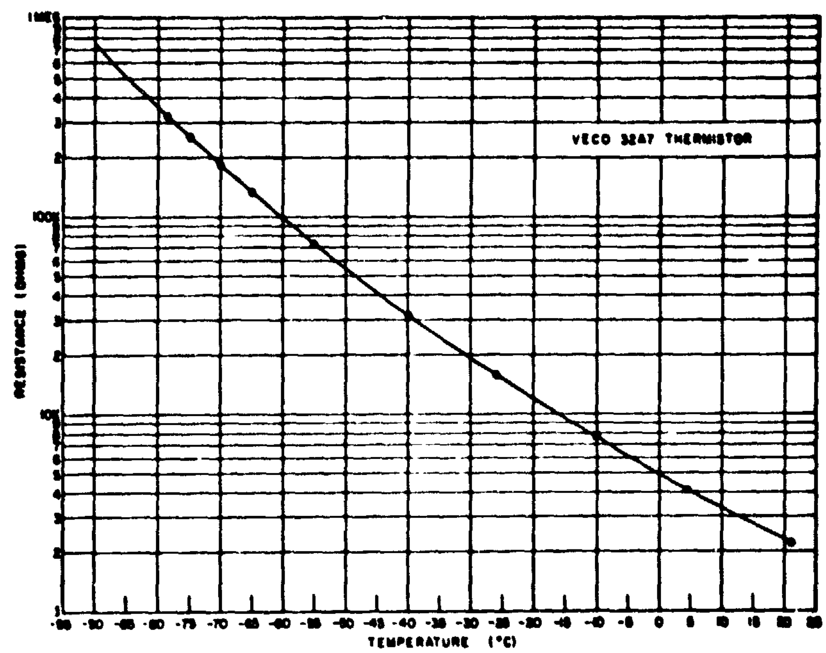


(a) OPERATION PRINCIPLES OF FROST-POINT HYGROMETER [17]

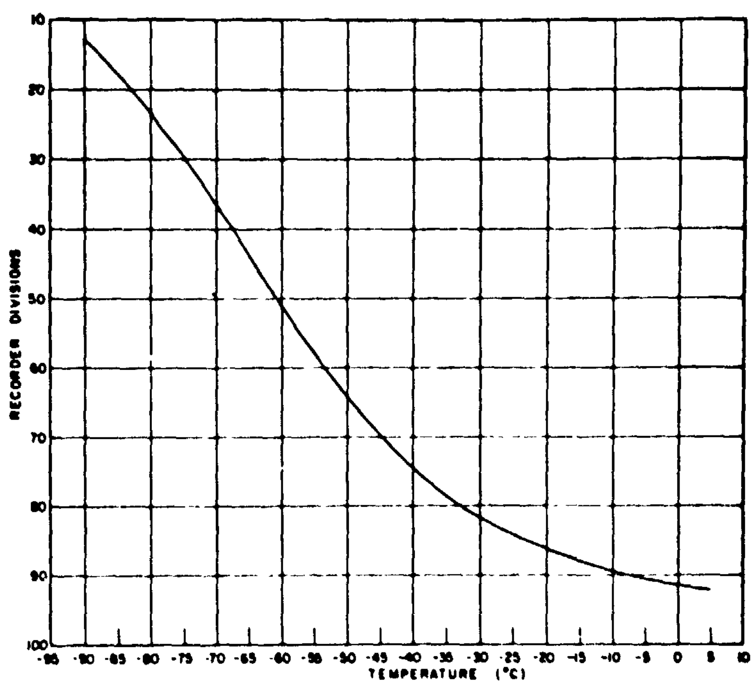


(b) SCHEMATIC DIAGRAM OF THE CONTROL CIRCUIT OF THE DEW-POINT RADIOSONDE. [8]

Figure 16. Frost-point hygrometer.



(a) TYPICAL CURVE SHOWING RESISTANCE-VERSUS-TEMPERATURE CHARACTERISTICS OF THE THERMISTOR USED TO MEASURE MIRROR TEMPERATURE.



(b) TYPICAL CURVE SHOWING CALIBRA~~ON OF FROST-POINT THERMISTOR IN TERMS OF THE RESPONSE OF THE RADIOSONDE-RECEIVER RECORDER.

Figure 17. Calibration curves for frost-point thermistor [8].

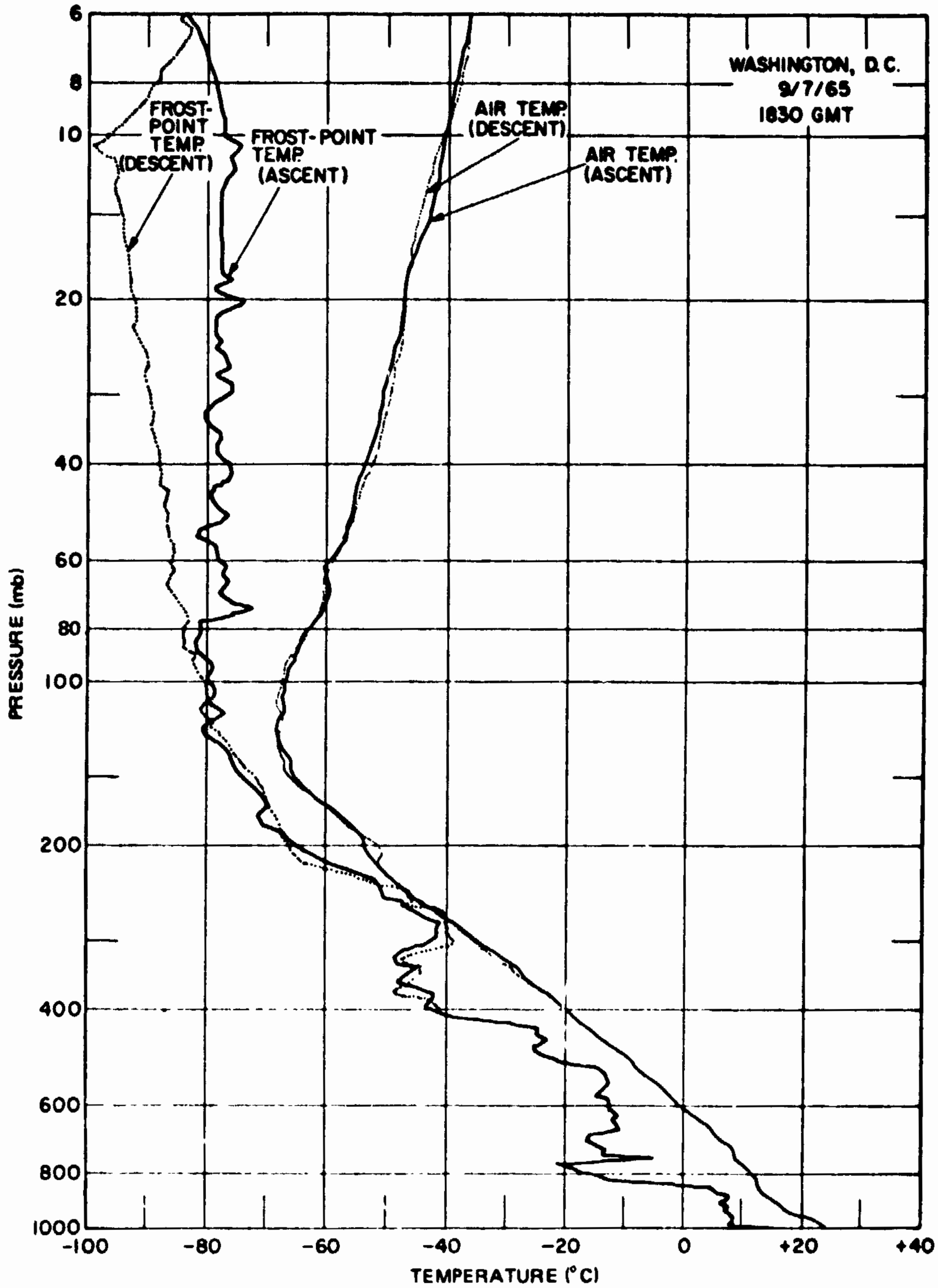


Figure 18. Temperature/frost-point sounding using frost-point hygrometer [17].

The NBS has tested [8] the NRL frost-point hygrometer over a range of 0.4 to -39.1°C, using air of a known frost point. The average reproducibility of measurements at any point was within 0.4°C (maximum was 0.8°C). At a frost-point temperature of -52°C, the errors averaged 1.2°C (range, -1.4°C to 3.0°C). Response time (1/e) for the instrument, if 3°C offset, is 0.36 min at -85°C and 100 mb and 0.60 min at -90°C and 45 mb.

IX. OTHER HYGROMETERS

This section briefly discusses other hygrometers that have been used to measure moisture. Most of these types are designed for the laboratory and are not used in conventional meteorological practice. Details will be omitted from the discussion; i.e., only title, classification, operating principle, and possibly accuracy will be mentioned. This report does not include a complete listing of all the humidity methods or instrumentation used today.

A. Volumetric Method

The volumetric method [2] is a water vapor removal method (chemical absorption) similar to the gravimetric approach, except that the change in volume of the gas sample at constant pressure and temperature, after desiccant moisture absorption, is a measure of the partial volume of the water vapor.

B. Pressure Method

The pressure method [2] is another water vapor removal method (chemical absorption). However, here the change in pressure at constant volume and temperature, after absorption, is a measure of the partial pressure of the water vapor. Uncertainty in these two methods is approximately 0.2 gm/kg (mixing ratio) over a range of 4 to 20 gm/kg. Response is in the order of minutes.

C. Coulometric Method

The coulometric water vapor removal method [2] works on the principle of removing water vapor from a stream of moist air and then electrolyzing it into gaseous hydrogen and oxygen. Faraday's Law indicates the mass of water electrolyzed per unit time is directly related to the electrolysis current. Therefore, the electrolysis current is a measure of the air humidity. An accuracy within 5 percent of the reading can be obtained between 20 to 1000 ppm (2 percent has been attained). Response time (1/e) is 1 to 2 min, depending on increasing or decreasing humidity, respectively.

D. Pneumatic Bridge

The pneumatic bridge instrument [2] removes water vapor. Four small flow nozzles are set up in a network analogous to a Wheatstone bridge, with the nozzles being the analog of the resistors; a differential pressure gage is analogous to the galvanometer. Test gas is taken in at the junction of the two upstream nozzles. The gas divides and flows through a separate arm of the bridge, comprising a set of two nozzles in series. The gas recombines and exits at the junction of the two downstream nozzles. When the bridge is balanced, the differential pressure across the bridge is zero. Putting a moisture-absorbing desiccant into an arm of the bridge between a pair of nozzles will remove water vapor from the gas and reduce the mass flow, decreasing the gas pressure at the downstream nozzle entrance. The difference in entrance pressure between these two downstream nozzles is a measure of the gas humidity. It is a very accurate instrument when calibrated. With a flow rate of 10 liters/min, the response is 0.75 min. The uncertainty in measurement is no greater than 0.05 gm/kg (0.25 percent) between a mixing ratio range of 0.15 to 20 gm/kg.

E. Weighing Hygrometer

The weighing hygrometer [2] utilizes the process of sorption, similar to the hygroscopic hygrometers. Using this method a change in weight (not length) due to sorbtion and desorbtion of water vapor with changing relative humidity takes place, and the hygroscopic material is actually weighed. This method is seldom used and is slow in response, with a large hysteresis and drift.

F. Colorimetric Method

The colorimetric method [2] is a sorption process in which chemicals such as cobaltous chloride and cobaltous bromide are put on cloth, paper, or other hygroscopic material and change color from pink to blue when exposed to increasing relative humidity. It is relatively inaccurate but for crude measurements is adequate.

G. Piezoelectric Hygrometer

The piezoelectric hygrometer [2] is a sorption instrument which works by coating the piezoelectric quartz crystal (in an oscillator circuit) with a hygroscopic material. The moisture in the air will attach to the crystal, and the change in the crystal's mass will change the crystal's resonant frequency, which is a measure of the air humidity. The instrument can cover a wide range of humidity and detects very low vapor concentrations. Inaccuracy is ±5 percent at humidities of 20 ppm and higher.

H. Heat of Sorption

The heat of sorption hygrometer [2] uses a hydrophilic material to sorb or desorb water vapor. This is accompanied by anexothermic or endothermic exchange of heat which will produce a temperature change (measured by thermometric means) in the material. This instrument can detect small traces of water vapor (i.e., 1 ppm). It is slow, it averages, and it requires calibration.

I. Refractive Hygrometer

The refractive hygrometer [2] uses physical methods (optical). Since the refractive index of a gas varies with moisture (also with pressure and temperature), it can be used to measure humidity. In addition to optical frequencies, radio and microwave frequencies are often used. The optical method will be described here. An interferometer is used, and monochromatic light is split into two identical path lengths. One path contains dry gas, while the other has the test gas. The light is recombined, producing interference fringes. Changes in water vapor content produce changes in the fringe count. It is a very accurate and sensitive instrument, with the microwave version appearing to be the best. Another type of optical instrument measures the change in the refractive index of glycerine [1,6] with the change in humidity. Cigarette paper is soaked in glycerine and exposed to the atmosphere. The refractive index of the glycerine is measured with an Abbé refractometer.

J. Thermal Conductivity Bridge

The thermal conductivity bridge instrument [2] uses a physical method in its measurement of humidity. The thermal conductivity of a gas mixture (air and water vapor) varies with composition. It serves as a useful indicator of the relative proportions of the two constituents. Therefore, humidity can be measured using the principle of heat transfer being proportional to the thermal conductivity of the gas.

K. Karl Fischer Method

The Karl Fischer method [2] is a chemical reaction laboratory method. A reagent chemical solution is used in titrimetric procedures with a test gas. Moisture is extracted from the test gas by bubbling through absolute methanol which is then titrated with the reagent. Accuracy within 2 percent has been measured as low as -45°C frost point but required 30 min to accomplish.

L. Water Vapor Conversion Method

The water vapor conversion method [2] is another chemical reaction method in which a sample of gas is passed continuously through a chemical reactant (e.g., calcium carbide) which converts the water vapor into a more easily detectable gas acetylene. The acetylene is then oxidized catalytically by an electrically heated platinum wire. The heat produces changes in the resistance of a platinum coil in a Wheatstone bridge. The bridge output is a measure of the gas water vapor content. Accuracy is within 2.5°C at -30°C and 0.25°C at 0°C. Response time is a few minutes.

M. Miscellaneous Hygrometers

References 7 and 14 describe other hygrometers; however, for brevity they are only listed here. These are the thermal hygrometer, paper hygrometer, sulphuric acid hygrometer, dielectric hygrometer, and solid hygroscopic salt hygrometer, as described in Reference 7. The Space Data Corporation [14] made a study of upper air hygrometers and, in addition to the ones previously mentioned, lists the Lyman-alpha hygrometer, which is a radiation-absorbing instrument to determine water vapor density. The Brady array humidity sensor's ac impedance varies with humidity. Vaisala Company in Finland has developed a thin-film sensor (Humicap) based upon the capacitance change in a thin-film capacitor with changing humidity.

X. COMPARISON OF HYGROMETERS

The purpose of this section is to offer the reader a comparison of the good and bad points of the major hygrometers in use today. Included are types, operating principles, moisture and temperature ranges of instruments, response times, and uncertainties. Wexler [2] presents a table which includes all these items (included as Table 1 in this report). Every instrument is not listed in

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TABLE 1. SUMMARY OF TECHNICAL CHARACTERISTICS OF SELECTED HYGROMETERS AT STANDARD ATMOSPHERIC PRESSURE [2]

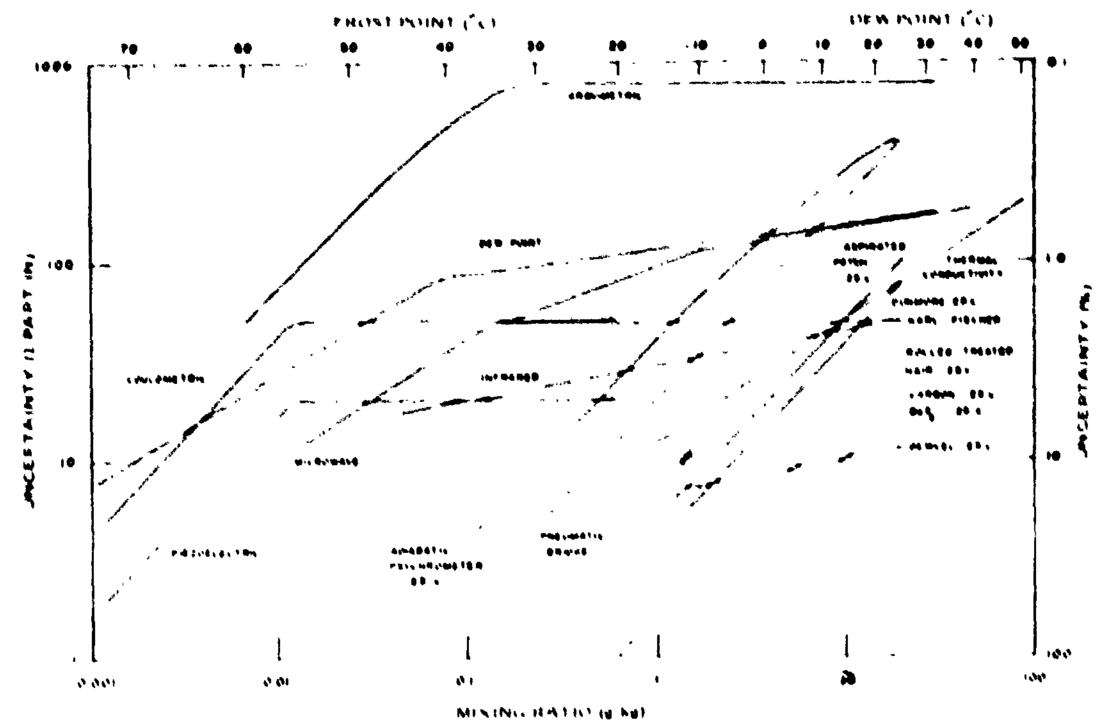
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Reading	Range	Dew point	[illegible]	Ambient operating temperature range (°C)	Measurement or response time	Sampling flow rate (liters/min)	Type of operation	Primary output parameter
Methods dependent on removal of water vapor from a moist gas													
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]				Room	Slow	[illegible]	Discrete manual	Mass and volume
[illegible]	[illegible]	[illegible]	[illegible]						Field	Medium	[illegible]	Continuous automatic	Electric current
[illegible]	[illegible]		[illegible]			[illegible]			Field	Medium	[illegible]	Continuous manual	Pressure
	[illegible]			[illegible]					[illegible]	Medium	5	Continuous manual	Pressure
Methods dependent on adding water vapor to a gas													
	[illegible]			[illegible]				[illegible]	[illegible]	Medium	[illegible]	Discrete manual	Temperature
	[illegible]			[illegible]				[illegible]	[illegible]	Medium to fast		Discrete continuous manual automatic	Temperature
[illegible]	[illegible]			[illegible]				[illegible]	[illegible]	Medium	5	Continuous manual	Temperature
Methods dependent on the equilibrium sorption of water vapor by a sensor													
[illegible]	[illegible]		[illegible]		[illegible]				Room	Fast	[illegible]	Discrete manual	Resistance
[illegible]	[illegible]			[illegible]				[illegible]	[illegible]	Fast	[illegible]	Continuous automatic	Resistance
[illegible]	[illegible]			[illegible]				[illegible]	[illegible]	Fast	[illegible]	Continuous automatic	Resistance
[illegible]	[illegible]			[illegible]				[illegible]	[illegible]	Fast	[illegible]	Continuous/automatic	Reactance
[illegible]	[illegible]			[illegible]				[illegible]	[illegible]	Fast	[illegible]	Continuous automatic	Resistance
[illegible]	[illegible]			[illegible]				[illegible]	[illegible]	Fast	[illegible]	Continuous operation [illegible]	Resistance
[illegible]	Measuring elongation [illegible]			[illegible]				[illegible]	[illegible]	Medium	[illegible]	Continuous manual/automatic	Elongation
Piezoelectric [illegible]	Measuring frequency change [illegible] quartz crystal [illegible] hygroscopic film	[illegible]	[illegible]			[illegible]			Field	Medium	[illegible]	Continuous automatic	Frequency

TABLE 1. (Concluded)

Type of hygrometer	Principle of operation	Range: Mixing ratio (g/kg)	Range: Dew (frost) point (°C)	Range: Relative humidity (%)	Uncertainty: Reading (%)	Uncertainty: Range (%)	Uncertainty: Dew point (°C)	Uncertainty: Relative humidity (%)	Ambient temperature range (°C)	Measurement or response time	Sampling flow rate (liters min⁻¹)	Type of operation	Primary output parameter
Methods dependent on measuring a physical property of a gas													
Infrared	Measuring attenuation of IR radiation	[illegible]	45 to +20				1 to 0.5		Field[b]	Fast	1	Continuous/automatic	IR radiation
Microwave	Measuring refractive index at microwave frequency	[illegible] to 49	55 to +40				0.2 to 0.1		Field[b]	Fast	10	Continuous/automatic	Frequency
Thermal conductivity	Measuring thermal conductivity	[illegible]	−18 to +50				1 to 0.1		Field[b]	Medium	0.2	Continuous/automatic	Temperature
Methods dependent on attaining a vapor-liquid or vapor-solid equilibrium condition													
Dew- and frost-point	Measuring temperature at which dew or frost forms	[illegible] to 633	−80 to +100				[illegible]		Field[b]	Medium to fast	1	Continuous/manual/automatic	Temperature
Cloud chamber	Measuring pressure ratio necessary to produce fog after adiabatic expansion	[illegible] to 20	−80 to +25				[illegible]		Field[b]	Medium	[illegible]	Discrete/manual	Pressure and temperature
Dew	Measuring equilibrium temperature of saturated salt solution	[illegible] to 622	−40 to +100				1.5		−30 to +100	Medium	[illegible]	Continuous/automatic	Temperature
[illegible]	Measuring equilibrium temperature of saturated salt solution	[illegible]	−15 to +20				0.05		Room	Fast	0.1 to 1.2	Continuous/automatic	Temperature
Methods dependent on chemical reactions and procedures													
Karl Fischer	Measuring extraction of water vapor and titration with reagent	0.045 to 35	−45 to +20		2				Room	Slow	[illegible]	Discrete/manual	Color change
Carbide	Reacting water vapor with calcium carbide to obtain acetylene	0.23 to 18	[illegible] to 0				2.5 to 0.25		Room	Medium	0.06	Continuous/automatic	Temperature

a At ambient temperature <0°C, the uncertainty gradually increases until at −40°C it may be of the order of 10 percent humidity.
b The instrument, with some precautions, can be used in the field over part of the atmospheric temperature range of meteorological interest.
c This instrument is whirled to produce an air speed in excess of 3 m s⁻¹.
d Thermometers with 1/4-in. diameter bulbs must be ventilated at an air speed > 3 m s⁻¹. Smaller diameter bulbs require lesser air speeds.
e The instrument is normally exposed directly to the test gas without ventilation.
f Temperatures as low as −20°C and as high as 100°C are feasible, but with a significant loss in accuracy.
g For dew (frost) points between −40 and 30°C. Below and above this range the accuracy degrades.
h For dew (frost) points between −30 and 30°C.
i The dew (frost) point range is a function of ambient temperature. See text.
j This instrument is used primarily in the mixing ratio of 0.0004 to 0.6 gm kg⁻¹, i.e., dew (frost) points −78 to −20°C.
k For frost points between −55 and −20°C.
l For dew (frost) points between −10 and 10°C.

Table 1, however, data on one or two of the more important from each classification method are presented. A response time of the order of seconds is defined "fast," one of the order of minutes is defined "medium," and one a half-hour or longer is defined "slow." The temperature range "room" implies that which is normally encountered indoors, while "field" implies the range encountered of meteorological interest. Figure 19 shows Wexler's [2] uncertainty chart versus humidity. The figure shows an instrument-by-instrument comparison in terms of uncertainty. One can see from Figure 19 that the NBS standard hygrometer, the gravimetric hygrometer, has the least uncertainty over all dew points. The dew-point method is also a good method to use over the entire moisture range.



NOTE THE CURVES ARE PLOTS OF THE RANGES AND UNCERTAINTIES OF SPECIFIC INSTRUMENTS AND METHODS FOR MEASURING HUMIDITY. EACH CURVE REPRESENTS THE UPPER LIMITS OF ACCURACY CURRENTLY ATTAINABLE

Figure 19. Accuracy chart [2].

XI. CONCLUSION

This report has summarized most of the humidity measuring instruments used in meteorology and in the laboratory. Classification, description, principle of operation, accuracy and response of the transducers, and associated equipment have been discussed. There is a wide range of techniques to use in measuring atmospheric humidity, and each has its advantages and disadvantages. As Wexler [2] states: "There is no single instrument that will be suitable for every type of measurement." This report was prepared to help the user understand better the different techniques used today in humidity measurement.

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APPROVAL

INSTRUMENTS FOR MEASURING THE AMOUNT OF MOISTURE IN THE AIR

By Dale L. Johnson

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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