Vol. 7, No. 5

Royal Meteorological Society

HUMIDITY MEASURING INSTRUMENTS

H. H. BINDON

CANADIAN
BRANCH

25¢

Vol. 7 A Publication of the No. 5

Royal Meteorological Society, Canadian Branch

Additional copies of this publication are available at a price of 25 cents each. All enquiries and correspondence concerning the Canadian Branch of the Royal Meteorological Society and its publications should be addressed to:

The Secretary
Royal Meteorological Society, Canadian Branch
315 Bloor Street West
Toronto 5, Ontario

HUMIDITY MEASURING INSTRUMENTS

by

H. H. Bindon

Chief, Instrument Division
Meteorological Services of Canada

An address presented to the
Royal Meteorological Society, Canadian Branch
at Toronto on November 29, 1956

HUMIDITY MEASURING INSTRUMENTS

by H. H. Bindon

Water substance is the only component of the atmosphere that may exist as a solid, liquid, or gas within the normal atmospheric temperature range and is, consequently, the only constituent that may vary from point to point. The variation from point to point necessitates special measurements of the quantity of water vapour in the atmosphere.

Due to its nature and spatial variation, water, in the vapour phase, is of considerable importance as a modifying agent in the atmospheric energy regime. As a vapour, water may absorb a considerable proportion of the infra-red radiant energy. Water in the solid form reflects and absorbs a large proportion of the incident solar radiation as cloud. In the form of water or snow on the surface, it may markedly vary the albedo of the earth's surface. Dynamically water vapour may act as a trigger and as a propogating agency in large scale instability. In fact, if water was absent from the earth's surface, the general dynamic behaviour of the atmosphere might be radically different.

Because of the obvious importance of humidity measurements, the World Meteorological Organization has set up a Working Group on Hygrometry. This group concerns itself with methods of observing humidity in the atmosphere, the types of instruments best suited for meteorological observations of humidity, and the establishment of appropriate formulae for converting the indications of the instrument into humidity parameters. The group must draft recommendations for presentation at the next meeting of the Commission. As a member of this group and Acting Chairman, I thought it appropriate to undertake a survey of the instruments used to measure atmospheric humidity.

The Thermodynamic Method

The thermodynamic method of humidity determination is probably the oldest quantitative method, with a history extending back to the 18th century. It was first used in a quantitative manner by August in 1825.

The method is based on the depression below ambient atmospheric temperature of the temperature assumed by a body with a moist surface from which water is continually evaporating into the air. A steady thermodynamic state is set up when the loss of heat due to evaporation of the water on the surface exactly balances the gain of heat by the body from the surrounding atmosphere.

The generally accepted theoretical-empirical formula for a wet and dry bulb psychrometer is of the form

$$e = e' - A_p \, (T_a - T_w)$$

e = The ambient vapour pressure

e' = The saturation vapour pressure at the wet bulb temperature

p = The atmospheric pressure

T_a = The ambient air temperature

T_w = The wet bulb temperature

The theoretical and practical problem is to determine the value of the so-called psychrometric constant in terms of known parameters.

"A" is chiefly a function of the following parameters:

(1) The ventilation
(2) The covering of the bulb (water or ice)
(3) Shape and geometry of the wet bulb
(4) Radiation exchange between the bulb and surrounding objects (generally at the ambient temperature of the air).

A theoretical formulation of the value of A was derived by August and later by Maxwell.

The August theory was based on the assumption that the air in motion passes over the wet bulb and loses heat until it ultimately attains the wet bulb temperature and becomes completely saturated. The Maxwell theory was based on an analysis of the heat and moisture transfer between the moist surface of the wet bulb and the ambient air, with the assumption that the transfer took place only by conductive processes in the case of heat, and molecular diffusion in the case of water. Both of these theories were based on assumptions that are not in accordance with the practical facts. However, the Maxwell theory gave acceptable values of A when the ventilation speeds were low or zero, while the August theory gave numerically correct value for A at high wind speeds.

Arnold, in 1933, formulated a theory based on assumptions that were more closely related to reality, and by the application of the appropriate modern heat and vapour exchange theory was able to obtain an expression for A which is qualitatively in accord with observations. The August and Maxwell theories are, as might be expected, limiting cases of the Arnold theory.

Arnold was able to give some qualitative experimental confirmation of the fundamental correctness of his theory by using liquids that are fundamentally different from water in the values of their heat and vapour exchange coefficients.

The Arnold theory, while substantially correct from a qualitative standpoint, does not take into account the geometry of the wet bulb which has an important effect upon the ventilation, and consequently the exchange mechanism. Theoretical attempts to take into account the dimensional factors generally concern themselves with a cylindrical body and have been only partially successful.

Experiments along this line have been carried out by Wylie in which he makes use of differential wet bulbs, or two wet bulbs of different diameters maintained under similar ventilation conditions. In Figure (1) Wylie's results of a comparison between differential thermometers are illustrated. In Figure (2) the final results of the experiments are shown. It may be noted that 300 cm. per second may be considered as a lower ventilation limit. For ventilation above this speed the geometry of the bulbs become of secondary importance. It follows therefore that a ventilation of at least 300 cm. per second is desirable if comparable results are to be obtained from wet bulb thermometers of miscellaneous diameters. Below this ventilation speed it is necessary to reduce the diameter of the bulb to a minimum in order to get reliable results. Thermocouples are ideal when a psychrometer is to be used under calm conditions, or in investigations where it is not desirable to disturb the ambient air.

The wet and dry bulb psychrometer has certain advantages, the chief of which is the apparent simplicity of the equipment. The method must however be classified as secondary with its theory based on semi-empirical formulae. At temperatures below freezing, the difficulty in the correct handling of the ice bulb outweighs the advantages that the method otherwise has. The obvious difficulty is to provide an adequate coating of ice on the bulb. In addition to this, the actual depressions of the wet bulb become increasingly small and, to avoid errors, extreme accuracy in temperature measurement is necessary. The wet bulb psychrometer is at best a difficult instrument at temperatures below freezing, and at temperatures below $0^{o}F$ it is most desirable to utilize other methods. Figure (3) illustrates the various types of psychrometers.

Hygroscopic Type Involving Change of Length

This type of humidity element depends upon the property of certain organic and synthetic materials to absorb water. The absorption of water causes mechanical swelling to take place in the material. The materials generally used, e.g. human hair, goldbeaters' skin, or nylon, swell longitudinally to an appreciable extent and this property is utilized to indicate or record humidity through a mechanical magnifying linkage or by electrical amplification.

In this type of detector water vapour continues to penetrate into the material until, at a specific relative humidity, a vapour pressure equilibrium is set up between the ambient water vapour pressure in the air and the vapour pressure within the material. At this point, the intake of water stops and consequently the swelling. The behaviour of the hair in the presence of water is in many ways analogous to water vapour in equilibrium with a non-saturated salt solution. However, the actual physical cause of the phenomenon occuring inside the hair is not clearly established.

It has been suggested that the portion of the hair called the cortex, which lies just below the outer fatty coating, consists of a thread like material with capillary like entrances into which the water may penetrate. This assumption is probably substantially correct but the mechanism whereby the swelling takes place and the phenomena connected with lag in varying humidity situations have not been clearly explained

At the present time the substances used in meteorological instruments are human hair and goldbeaters' skin. Goldbeaters' skin is important as it is used in a number of designs of radiosondes. This skin responds many times more rapidly than the normal untreated hair and retains its sensitivity to low temperatures where the normal hair becomes useless. Frankenburger in Germany has discovered that normally prepared human hair, if rolled flat, becomes extremely active and it is claimed to be superior to goldbeaters' skin for radiosonde use. A difficulty with the rolled hair however is that its tensile strength is reduced by the flattening process and there is considerable difficulty in getting the mechanical performance out of it that might be desired.

Figure (4) illustrates the normal hair hygrograph. Figure (5) illustrates the magnification of the motion of the goldbeaters' skin by means of a linear differential transformer. An apparatus of this type has been devised by the Instrument Division of the Meteorological Branch and it has been found to be an excellent method for reading humidity remotely at the surface where humidity changes are slow.

The Absorption Methods Involving Electrical Characteristics

Most materials absorb or give off water vapour as ambient relative humidity increases or decreases. Associated with this absorption there is usually a corresponding change in the electrical resistance of the material. Materials exhibiting a humidity dependent change in resistance may be utilized as humidity sensors. Such sensors when coupled to suitable measuring circuits constitute the electrical class of hygrometric instruments.

General Principles

The various sensors as defined above may be conveniently categorized into instruments based on the following principles:

(a) Conductivity of aqueous electrolytic solutions.
(b) Surface resistivity of impervious solids.
(c) The resistivity of dimensionally variable materials.
(d) The temperature of saturated salt solutions.

Conductivity of Aqueous Electrolytic Solutions

This type of sensor depends upon the fact that the solution of most salts in water reduces the water vapour pressure below the vapour pressure over pure water. Thus, if a deliquescent salt, e.g., dry lithium chloride, is placed in an atmosphere with a relative humidity of 50%, it will take up water and form a non-saturated solution. The dilution of this solution will be increased by the addition of water until the proportion of lithium chloride in solution has come to the point where the equilibrium pressure over the solution is equal to 50%. The dilution will at this point stop, and the solution will hold constant. This solution will have an associated conductivity which is a measure of the ambient humidity.

Probably the most important sensor of this type used in meteorology is the Dunsmore Hygrometer which is utilized in the United States Type Radiosonde. In the radiosonde element a flat strip of polystyrene 3 x 11/16 x 1/32" with tin electrodes affixed to the two long edges is utilized. The element is coated by dipping in a binder of lithium chloride solution in the form of a mixture. The calibration characteristics of such an element are shown in Figure (6). The response of this element is reasonably rapid. At normal temperatures it has a 90% response in 25 - 35 seconds. At -20°C it has a 63% response in 50 - 150 seconds. Actually, the speed of response is an involved function of temperature, magnitude and direction of the relative humidity changes, etc.

The element does provide a humidity variable resistance that will allow it to be easily incorporated into U.S. Audio modulated radiosondes as it modulates the frequency as it varies. The element has, however, a number of serious drawbacks that make it far from ideal. The deficiencies of the element may be tabulated as follows:

(a) Its large temperature coefficient. (b) Its tendency to polarize. (c) It becomes inactive at humidities below 12%, and completely useless below -30°C. (d) Its speed of reaction while tolerable at high temperatures is not satisfactory at low temperatures.

Another type of sensor in this category is the Gregory Hygrometer. In this instrument, a cotton fabric is used to hold a lithium chloride solution and conductivity of the electrolytic solution is measured between two suitable electrodes. This instrument has the same type of problems common to the Dunsmore sensor but its reaction is considerably slower due to the great absorption times required in the cotton absorbent.

Surface Resistivity of Impervious Solids

In this type of instrument a salt solution is placed on a surface impervious to water vapour, such as smooth glass, and the resistance measured between suitable electrodes. If the layer of salt is thin enough an element of this type may be quite fast in response.

Wexler has devised a radiosonde sensor by depositing a film of potasium metaphosphate on a thin glass slide. The thickness of the film is 3 microinches. The resistivity of this element varies from 4×10^4 to 10^{13} ohms. At room temperature with ventilation speeds of 800 feet per minute its response is 0.1 to 0.4 seconds for 63% change of relative humidity and at -2 0°C 2 - $3\frac{1}{2}$ seconds. These very rapid changes are desirable in radiosondes or for investigations of extremely variable conditions of humidity, but the element has all the difficulties of the Dunsmore instrument.

Resistivity of Dimensionally Variable Materials

Many materials are dimensionally variable with relative humidity. If these materials are coated or impregnated with conductive substances, these substances will also expand or contract with the basic material and, if properly chosen, will change conductivity with dimensional variation.

Smith and Hcaflick have described the development of a carbon film hygrometer element which uses a plastic binder as the material that is dimensionally variable with relative humidity. A polystyrene strip 100 mm. long and 18 mm. wide and 1.2 mm. thick serves as a blank on which the sensitive film is placed. Two tin electrodes are located along the edges. A mixture composed of 45% carbon, 32% hydroxyethyl cellulose, 16% polyoxy ethylene sorbitol, and 7% alkyl anyl polyesten alcohol is sprayed on the blank. The calibration is shown in Figure (7). Although this element has good stability and would prove useful in radiosonde work, it is difficult to standardize in production.

Temperature Controlled Saturated Salt Solutions

Principle

A saturated solution of salt, e.g. lithium chloride, has a vapour pressure which is the function of the solutions temperature only. If the vapour pressure of the ambient air is, for example, 10^1mm. of Hg. at $5^{\circ}C$, the corresponding vapour pressure over a saturated solution of lithium chloride at $5^{\circ}C$ will be 10^0mm. of mercury. As a result, water will flow from the ambient air into the saturated solution. If however, the saturated solution is heated to $41^{\circ}C$ it will have a vapour pressure of 10^1 mm. of Hg. and will be in equilibrium with the ambient air, and no water vapour will flow into or out of the solution from the air.

The dewcell is a very ingenious instrument based on this principle. In this sensor a thermometer bulb, generally of the electric type, is surrounded by a glass wool wick impregnated with a saturated solution of lithium chloride. Two silver wire electrodes are wound around the wick in the bifiler coil. A 25 volt AC current is set up across the electrodes. When the vapour pressure over the saturated solution is less than the ambient vapour pressure in the air, the solution is conductive and is heated by the current passing between the electrodes. The solution will continue to heat until the saturated solution reaches a temperature where its vapour pressure is equal to the ambient vapour pressure in the air. At this point, it will start to give off water to the ambient air and will suddenly have a higher resistance which will cause the heating to stop. Natural cooling will drop the temperature and the instrument will hunt about this temperature point. Thus the ambient vapour pressure or dew point may be obtained directly from the dewcell. The instrument will work best where there is very little ventilation as ventilation carries away the heat too rapidly and vitiates the calibration. The instrument cannot be used below $-30^{\circ}F$ or when the humidity at normal temperatures falls below 12% relative humidity. It is, however, a very intriguing instrument and operates over a very wide atmospheric range.

Wylie in Australia has used the same principle in an instrument that he has devised that measures the conductivity over a single crystal. He conditions the temperature of the air as it comes into the test chamber containing the crystal. Provision is made to cool or heat the air and, as a result, the instrument can be used over a wider range of humidity with considerable accuracy claimed for its indications.

The Dew Point or Condensation Method

The dew point or frost point hygrometer has the advantage of requiring only a temperature calibration. It is based on the principle that the dew or condensation point may be determined directly by observing the formation of dew on a surface that may be cooled in a controlled manner.

The dew point is expressed by the equation

$$e_w\ (T_d) = \frac{r}{0.622 + r} \quad P$$

or

$$e_f\ (T_f) = \frac{r}{0.622 + r} \quad P$$

WHERE T_d is the dew point

T_f is the frost point

e_w is the saturation vapour pressure at temp. T_d.

r is the mixing ratio

In its general form a dew point instrument consists of a highly polished metal observing surface. Provision is made to alter the temperature of the surface and to detect the formation of water deposit, or frost deposit, on the surface visually by means of a photoelectric cell. The temperature of the surface corresponding to the first detection of dew or frost is carefully measured and designated as equivalent to the dew point.

The advantages of the method is that it gives absolute values of the dew point directly and may be used for determining humidity over the entire atmospheric range.

The disadvantages lie chiefly in the difficulties of building a practical instrument. In the first place it is necessary to provide controlled heating and cooling. Cooling may be accomplished in a number of ways but for a practical operational instrument the use of a refrigerated system is probably the only answer. Furthermore, it is necessary to be able to rapidly control the cooling by hand or by automatic means so that the dew surface temperature may be held very accurately.

The possibility of doing this depends upon the accuracy with which the formation of the dew can be detected and the device for control by feed back to regulate the temperature of the polished surface. The control must raise the temperature immediately on detection of the dew, and must be replaced by cooling as soon as the dew deposit disappears. The hunting about the dew point must be reduced to a minimum. The instrument leads to a very interesting and instructive exercise in control but is extremely difficult to arrange in practice. In addition to the control difficulties, there is a problem in correctly measuring the temperature of the polished surface, as gradients exist in the metal below the surface as well as in the film of test air blown over the surface. If the above mentioned problems are solved there are a number of residual questions that must be answered; for example; (a) does the formation of dew depend upon the material of the surface, (b) how does the response depend upon the jet speed of the sampled air?

Optical Methods

Optical methods in general depend upon measuring the absorption of light in certain water absorbing bands of the spectrum. Some of the best work on this method has been carried out by the Instrument Section of the U.S. Weather Bureau. They have developed an automatic infra-red absorption hygrometer. This instrument makes use of the high water absorption properties of a band at 1.37 /u. Absorption in this band is compared with absorption in a neighbouring band at 1.25/u , where water vapour does not absorb radiation. In this instrument it is necessary to obtain essentially monochromatic light beams centering around 1.37 and 1.2 /u, pass them through a metre length of air, and then detect the variation of intensity by means of an infra-red sensitive sulfide cell. The monochromatic beams are ingeniously obtained by the use of the newly developed transmission type narrow-band-pass light filters consisting of two highly reflecting but partially transmitting films of silver separated by a transparent spacer. The two filters are rotated in a disk in front of the light causing an alternating beam of light to pass through. The variability of light alternations are detected and ingeniously removed to a null value by a variation of the current in the light source bulb. The output is recorded on a recording potentiometer and indicates surprising variations on humidity. It is claimed that the instrument increases sensitivity at the low humidities encountered at low temperatures.

There are numerous other methods that are presently being used, for example, the microwave hygrometer in which the refractive index of moist air is measured by means of radio waves. A method based on water decomposition, by electrolysis of water withdrawn from sampled air by phosphorous pentoxide, shows considerable promise.

References

(1) R. G. Wylie "Psychrometry", National Standards Laboratory, Division of Physics, Australia, 1933.

(2) H. L. Penman "Humidity" Inst. of Physics Monograph 1955.

(3) Arnold Wexler "Electric Hygrometers" (unpublished)

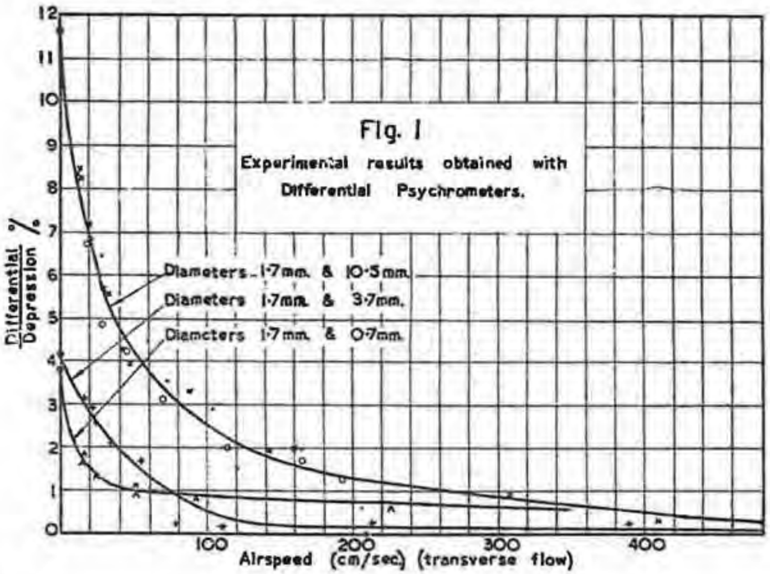


Fig. 1
Experimental results obtained with Differential Psychrometers.

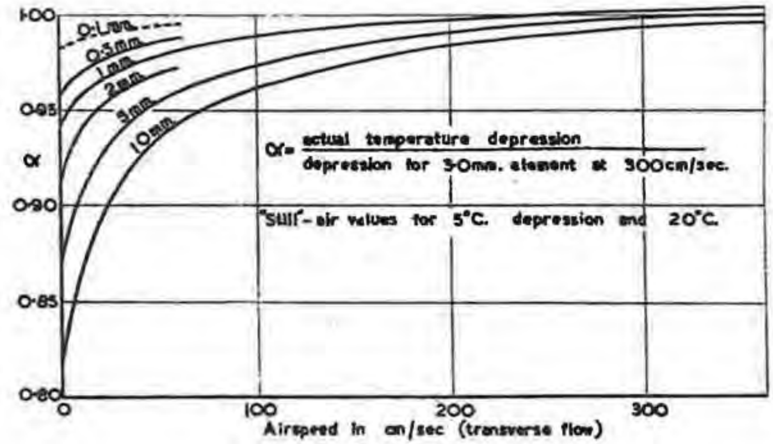
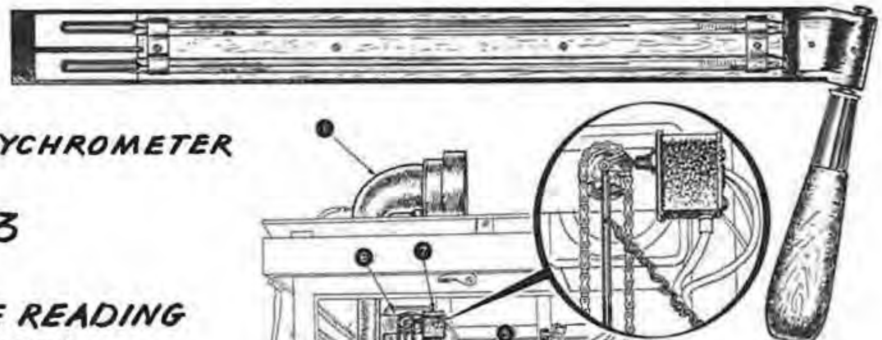


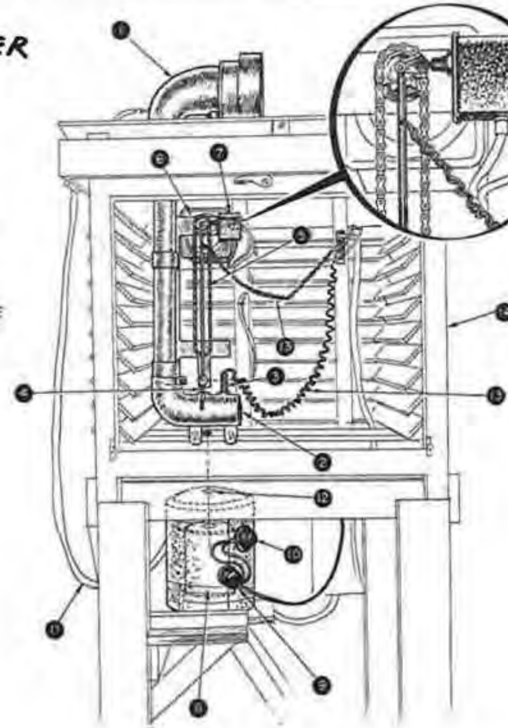
Fig. 2
Curves Showing the Effect of Airspeed and Diameter on the Temperature Depression of a Wet Element.



M.S.C. SLING PSYCHROMETER

Fig. 3

M.S.C. REMOTE READING PSYCHROMETER



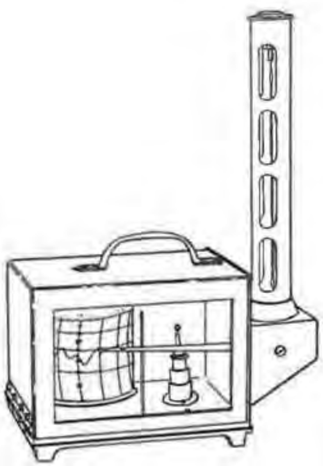


Fig. 4

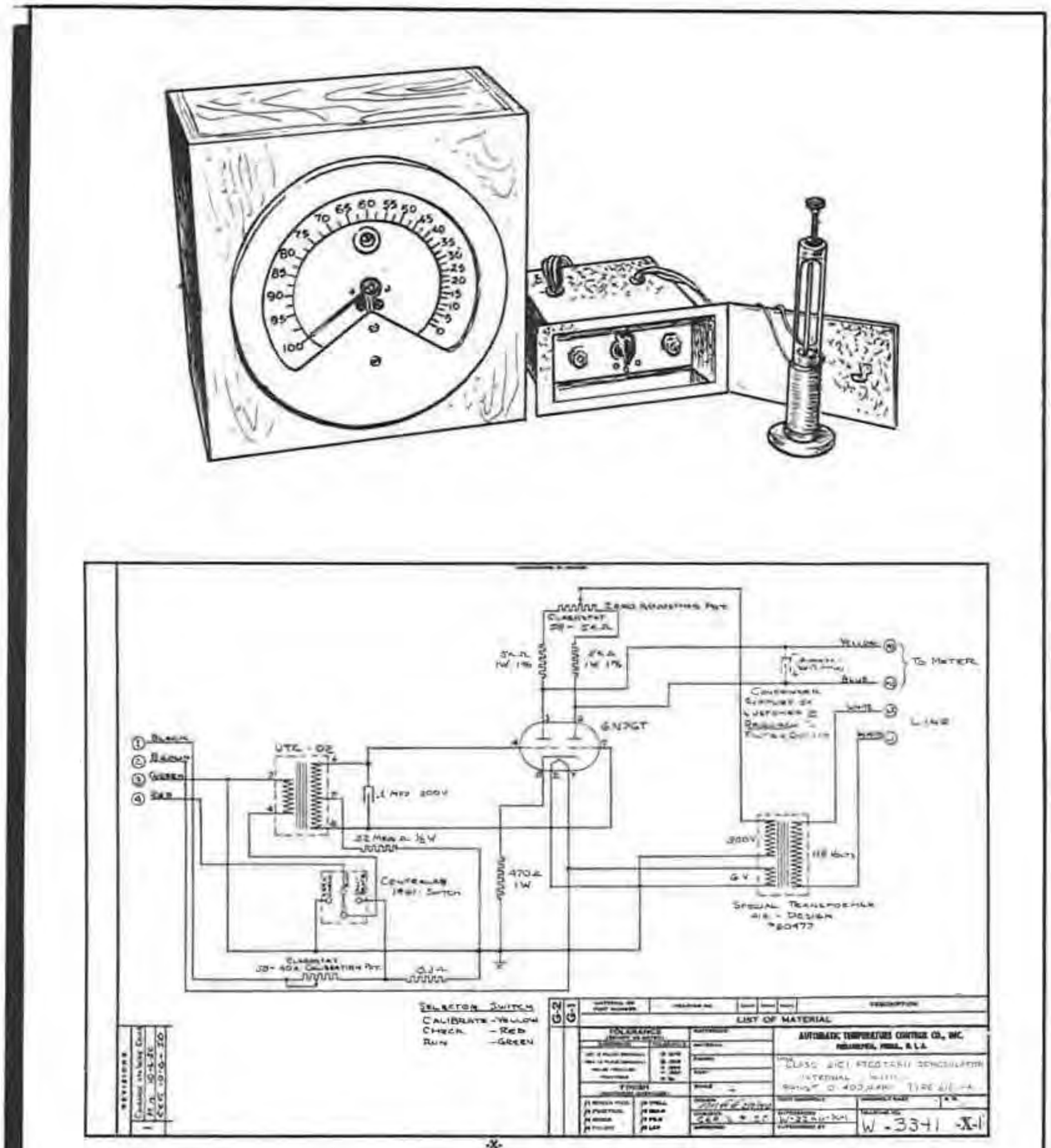


Fig. 5

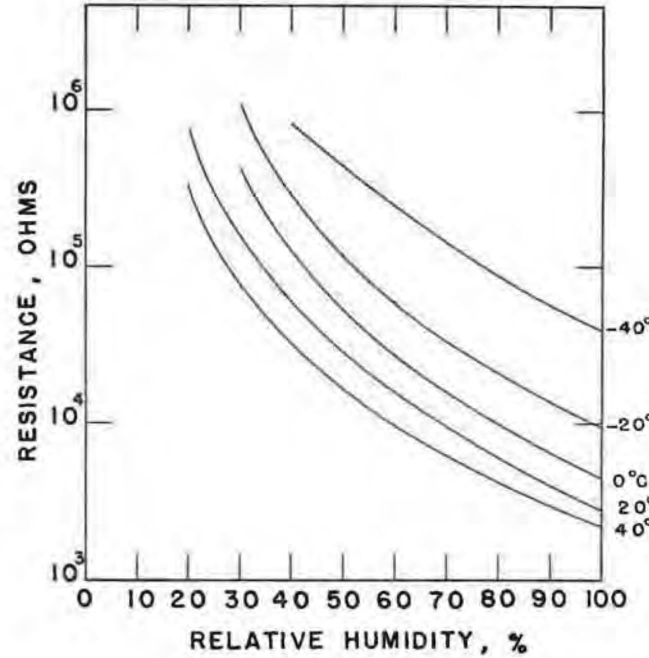


FIGURE 6

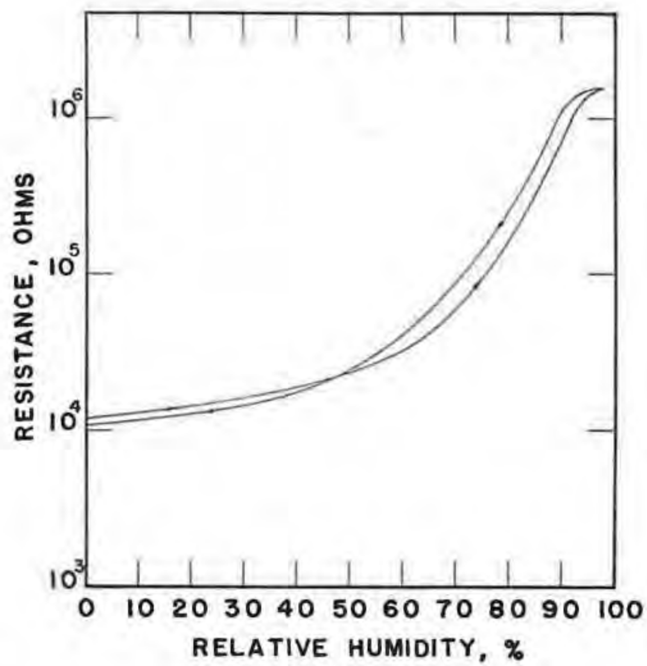


FIGURE 7