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DEW POINT HYGROMETER WITH CONSTANT
RESISTANCE HUMIDITY TRANSDUCER

by

Curtis B. Campbell

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Meteorology

UTAH STATE UNIVERSITY
Logan, Utah

1969

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ABSTRACT

Dew Point Hygrometer with Constant
Resistance Humidity Transducer

by

Curtis B. Campbell, Master of Science

Utah State University, 1969

Major Professor: Dr. Gaylen L. Ashcroft
Department: Soils and Meteorology

The hygroscopic and electrical resistance characteristics of lithium chloride are investigated. Then an evaluation is made of the lithium chloride characteristics that would be suitable in development of a dew point hygrometer with measurement accuracy of ± 0.3 C.

The development of a 12 volt battery-powered hygrometer is presented with circuit details and performance characteristics. Lithium chloride phase transition hygrometers tend to oscillate under certain conditions. A damping control is presented as part of the circuit details and recordings of the response characteristics and effectiveness of damping are presented showing effective control of the oscillations with a wide range of humidity transients.

(93 pages)

INTRODUCTION

While studying snow pack conditions with Dr. Ben L. Grover in central Utah, an interesting moisture transport phenomena was noted. On many bright spring days snow was melting at lower mountain levels; whereas, the moisture content of the snow was actually increasing at higher elevations even though the skies were cloudless.

A study was initiated to elucidate the causes of this phenomena. To carry out the moisture transport study, it was necessary to measure the moisture status of the air as it moved up the mountain slope. Attempts to measure this atmospheric moisture, however, were fraught with many difficulties.

Dew-point measurements with wet and dry bulb psychrometers were quite unsatisfactory because the temperatures were often below freezing. A dewcell was tried but was not satisfactory because the necessary electrical power was not available and the accuracy was less than required.

These experiences pointed out the need for a piece of equipment that was accurate and had low electrical power requirements so that it could be operated from batteries in remote areas. The development of a dew point hygrometer for field use offered an interesting challenge and was selected as a thesis problem.

LITERATURE REVIEW

Historical note

The hair hygrometer is the first recorded instrument for measuring the amount of moisture in the air. About the year 1500 Leonardo da Vinci described a device whereby the quantity of moisture in the air was noted from the change in weight of a ball of wool or hair.

In 1783 De Saussure developed the hair hygrometer into its present style, i. e., measurement of changes in hair length. Since that time the hair hygrometer has probably been the most widely used instrument for humidity measurement and control. Numerous innovations have been tried, but after over 175 years the hair hygrometer is essentially unchanged; more is known about it technically, but attempts to improve it have been ineffective (Davey, 1965).

State of the art

Mechanical hygrometers. Hair and other mechanical hygrometers operate on the principle that absorption and desorption of water from the air by an organic material causes a physical change in the material: change in weight, change in length, change in volume, or a rotational effect. Through suitable simple lever systems these dimensional changes may be made to actuate a pointer or move a pen across a chart. They can be calibrated in terms of relative humidity

by appropriate techniques (Beyers, 1959, p. 70).

The main virtues of the mechanical hygrometer are its simplicity of design and construction and its low cost. It indicates relative humidity directly over a moderate range of temperatures. Its reliability decreases with decreasing temperature. Its chief defects are a lack of stability under normal conditions of use and an appreciable hysteresis.

Some of the materials that have been used as the variable humidity elements are hair, cotton, wool, silk, wood, goldbeater's skin, nylon, plastic, paper, and whalebone. Of these, hair is probably the most widely used material (Wexler, 1963).

Prior to the introduction of precision hygrometry, the hair hygrometer was the standard for general design and use. Some basic limitations, such as the fragile nature of the hair and very small changes in hair length, have led to considerable investigation into other types of humidity-sensitive materials.

Psychrometers. In its elemental form, the psychrometer is comprised of two thermometers. The bulb of one thermometer is covered with a moistened wick and is referred to as the "wet-bulb." The bulb of the other thermometer is left bare and is called the "dry-bulb." When adequately ventilated, evaporative cooling depresses the temperature of the wet-bulb thermometer below that of the dry-bulb thermometer. Using psychrometric tables, slide rules, nomograms or equations, the vapor pressure and relative humidity can be

determined from the wet- and dry-bulb temperatures, and the ambient pressure (Beyers, 1959, p. 71).

Some of the factors influencing the performance and accuracy of the psychrometric method are: (a) the sensitivity, accuracy, and agreement in reading of the thermometers, (b) the speed of air past the wet-bulb thermometer, (c) the incident radiation on the thermometers, (d) the size, shape, material, and wetting of the wick, (e) the relative positions of wet- and dry-bulb thermometers, and (f) the temperature and purity of the water used to wet the wick (Wexler, 1963).

The psychrometer is a simple relatively inexpensive instrument which can be used for either intermittent indication or continuous recording of wet- and dry-bulb temperatures. Since it does not yield the moisture content of a gas directly, it must be determined from equations, tables, charts, nomograms, or curves. These computational aids are available only for water vapor-air mixtures. Under normal operating conditions the accuracy of ± 4 percent relative humidity can be achieved.

Dew point hygrometers. When water vapor is cooled, a temperature is reached at which condensation (or sublimation) occurs. The dew-point method provides a convenient technique for ascertaining this temperature. The procedure is to alter the temperature, pressure, or volume of the gaseous mixture, of which water vapor is a component, in such a fashion that condensation occurs.

The temperature at which condensation is initiated for a given pressure and volume is defined as the dew-point temperature (Beyers, 1959, p 73).

The condensation may be on a surface in the form of dew or frost, or it may take place in the air to form a fog or cloud. The most common method of inducing condensation is to lower the temperature of a mirror and to detect the condensation thereon by observing changes in reflected or scattered light. However, condensation may be produced on a metal mirror maintained at a constant temperature by isothermally increasing the pressure of the gas sample under test. One interesting way of precipitating a fog or cloud is by cooling a gaseous mixture by adiabatic expansion into a closed chamber to a lower pressure. By repeating trials, a pressure ratio can be obtained so that a fog or cloud is just formed when the reduced pressure is suddenly released. The dew point is computed from the initial temperature and the ratio of initial to final pressure (Bridgeman, 1966).

The formation of dew or frost on a mirror surface can be detected visually or electrically. Cooling of the mirror may be achieved by evaporation of a liquid with a high latent heat of vaporization, by dry ice, or by the Peltier-type refrigeration. Through suitable electronic circuitry the mirror surface can be maintained at the dew-point temperature by adjusting the heat balance at the mirror to produce a constant dew film thickness or percent coverage.

In theory, the dew-point method may be considered a fundamental technique for determining vapor pressure or humidity. However, the certainty of the dew-point measurement is influenced by several factors which are of such indeterminate nature as to make an estimate of the accuracy difficult:

1. It is not always possible to measure the temperature of the mirror at the surface or to assure that no gradients exist across the surface.

2. The visual detection of the inception of condensation cannot be made with complete assurance nor is it probable that two different observers can detect dew or frost at the same instant. It is usual practice for the dew point to be taken as the average of the temperature at which dew is first detected on cooling of the mirror and the temperature at which dew or frost vanishes on warming the mirror. This procedure does not assure a correct dew-point temperature, however, unless care is taken to locate the thermometer so that no temperature gradient exists from the cold source to mirror surface or to the gas as a whole.

3. The automatic photoelectric detection of the dew point usually depends upon achieving an equilibrium condition on the surface during which the amount of dew or frost remains constant. This is difficult to achieve.

4. At temperatures below freezing, the initial formation of a condensate on a mirror may be either liquid or ice. Condensates

of supercooled water have been observed as low as -27°C . At extremely low temperatures, the ice deposition assumes a glossy appearance which is difficult to detect visually (Martin, 1965).

Electric hygrometers. Instruments of this type consist of two parts: a humidity-responsive resistor, usually called a sensor, and an electrical or electronic circuit for detecting and indicating the magnitude of the resistance of the sensor.

The most common form of sensor is one in which an aqueous electrolytic solution serves as the variable resistor. The electrical resistance of this type of sensor is a function of the ambient relative humidity and temperature. The solution can be applied directly to an impervious insulating surface on which electrodes have been affixed. This combination, however, is relatively unstable so that frequent calibration is needed to assure accuracy of indication. Stability of calibration can be achieved by mixing the solution with a binder, usually organic, that has adhesive properties and by applying the mixture to an insulating surface containing electrodes. Alternatively, organic fibers or porous ceramics may be impregnated with the solution (Mathews, 1965; and Rogers, 1965).

Another form of sensor utilizes the surface resistivity of selected impervious material like glass, porcelain, and plastics. Water is adsorbed on the surface of these materials and retained by physical bonding forces, forming a thin film whose thickness, and possibly continuity, is a function of relative humidity. This film of

moisture provides a leakage path for current flow. There probably are minute quantities of soluble salts or gases present on the surface which contribute to the conductivity of the film. The net effect is that as the relative humidity changes from 0 to 100 percent, the surface resistivity may decrease six or more decades. One interesting version of this sensor comprises an insulating surface on which a thin film is deposited whose surface is converted into a film of ion exchange resin.

In an analogous manner, the variation of the surface resistivity of some porous materials can be used for humidity sensing. There are many substances which adsorb water vapor, but relatively few that do so with sufficient reversibility and reproducibility. Highly porous substances--for example, underfired clays, natural fibers, and textiles--have a high capacity for moisture adsorption. Water vapor diffuses and permeates into the pores and capillaries of these substances, greatly affecting their volume resistivities. Unfortunately, the porous nature of these materials, which makes them so highly hygroscopic, often contributes undesirable characteristics that seriously detract from their usefulness as sensors. For example, the time involved for a porous material to reach equilibrium with change in relative humidity is often excessively long. Also, a porous material too often possesses appreciable hysteresis and drift. In spite of their shortcomings, porous solids find some application as sensors. Typical of this class of sensors are sintered

ceramics, underfired clays, and Plaster of Paris.

There is a class of electric hygrometer sensors that depends on dimensional changes to produce changes in resistance. Such materials as hair, vegetable fibers, and wood may be coated or impregnated with conductive substances. As the hygroscopic material expands and contracts, the material used for the coating or impregnation also expands and contracts. By the proper choice of the conductive substance, a measurable change in resistance is achieved.

The electric hygrometer has certain features which make it useful for a wide variety of applications. The sensor is usually small and relatively inexpensive, although the measuring circuit may be expensive. The output is an electrical signal so that remote indicating or recording is feasible. On the other hand, the electric hygrometer is an empirical device that requires calibration. It has an appreciable temperature coefficient and thus requires an auxiliary temperature measurement. To a limited extent, circuitry can be designed to correct or compensate for the temperature coefficients.

The performance of a sensor may be influenced by polarization, exposure to fog, clouds, or saturated gas, and contamination of the sensitive surface. Those sensors that use an aqueous solution without binder or an impervious surface are inherently faster in response but less stable than the binder type or the impregnated fiber, fabric, or ceramic. All of the sensors require special

circuitry and handling. Sensors that operate on a volume-based resistivity tend to be very sluggish in response and to exhibit hysteresis and drift. The carbon element usually displays a "hump" or reversal in its relative humidity vs. resistance characteristics. This results in relative humidity indications that are too high at high resistances (Wexler, 1963; and Amdur, Nelson, and Foster, 1965).

Gravimetric hygrometers. The gravimetric method of water vapor measurement is generally considered the most precise and accurate in hygrometry. In this method the water vapor admixed with a given volume of dry gas is adsorbed by a desiccant and weighed and then the volume of the dry gas is measured. Since mass and volume are fundamental quantities, this method yields an absolute measure of the humidity. Because it is absolute and relatively accurate, the gravimetric method is often used as a reference standard with which other methods and instruments are compared. To achieve the potential accuracy of the gravimetric method, however, there must be careful attention to details. Measurements are time consuming, especially those involving low moisture content. The results are average values for the time intervals of the tests. The gravimetric method is seldom used for routine humidity determinations, but finds its principal utility as a standard for making fundamental calibrations or for research work of the highest accuracy (Harrison, 1965; and Wexler, 1963).

Spectroscopic hygrometers. Certain spectral bands of electromagnetic radiation when projected through water vapor are attenuated in intensity. This adsorption of spectral energy may be correlated with the amount of water vapor present in the path of the projected beam. Instruments for measuring the moisture content of a gas, based on the attenuation of the intensity of emission spectral energy, are referred to as spectroscopic hygrometers. The near-infrared spectrum has bands of radiation capable of attenuation by water vapor. Instruments based on infrared energy adsorption are usually called infrared hygrometers.

Some of the advantages of the spectroscopic hygrometers are as follows: It is capable of very rapid response, the time being limited only by the speed of the associated electronic and servo systems and the flushing rate of the sample gas. The adsorption function is of such a nature that the instrument does not add or subtract water vapor, nor induce a change in state.

The instrument in its present state of development is a complicated optical-electronic device, relatively expensive to build or produce and requires calibration (Wexler, 1963; and Johns, 1965).

Absorption hygrometers. The absorption hygrometer is an instrument in which the water vapor of a gas sample is chemically absorbed and removed, yielding either a change in pressure or a change in volume. This type of hygrometer is simply a specialized version of chemical gas analysis apparatus.

Condensing hygrometers. One instrument of this type used two identical vessels, one containing dry gas and the other the gas sample of unknown water content. These vessels are sealed, connected through a differential manometer, immersed in a liquid bath, and gradually cooled until the differential manometer registers a pressure difference indicating condensation of water vapor from the moist sample. At this point, the temperature and pressure differential are read. From the saturation vapor pressure at the observed temperature and from the pressure difference, the initial water vapor content is computed.

An alternative procedure involves drawing a known volume of gas through a liquid-air trap and freezing out all moisture. The apparatus is then allowed to warm up in a thermostated bath, and the vapor pressure within the closed system, whose volume has been predetermined, is measured. With this method there should be no other condensable gases or vapors that will freeze out at the temperature that will be used.

These hygrometers are laboratory devices and not suitable for general use. They utilize discrete samples of test gas, and require considerable skill and manipulation on the part of an observer (Wexler, 1963).

Thermal hygrometers. Associated with the physical sorption or desorption of water vapor by a hydrophilic material is an exothermic or endothermic exchange of energy in the form of heat.

This heat of absorption results in a temperature change that can be detected and measured by thermometric means. An instrument in which the heat of adsorption is used as an indication of the water vapor concentration in a gas stream is classified as a thermal hygrometer.

One method of utilizing the heat of adsorption involves splitting the test gas stream into two equal streams and drying one part completely by a chemical drying train, liquid-air trap, or regenerative adsorption column. The dried and the undried streams are brought to the same temperature and passed through separate columns of desiccant, such as silica gel. Water vapor will be removed from the moist stream which will liberate heat and raise the temperature of the column of desiccant; whereas, the dry stream will desorb water vapor from its column of desiccant and decrease the desiccant temperature. With a sensitive thermopile the temperature difference between the two columns is measured. After a short interval, the flows through the two desiccant columns are reversed so that dry gas now passes through the partially wet column and the moist gas through the desorbed column.

It has been reported that a thermal hygrometer has been made with a sensitivity of a fraction of a part per million by volume. Thus, it has a capability of detecting extremely small traces of water vapor. The cycling rate limits the speed of response. Consequently, it is a slowly responding instrument. The measurement

obtained is an average for each half cycle (Cherry, 1965; and Wexler, 1963).

Refractive hygrometers. The refractive hygrometer utilizes the change in refractive index with change in water vapor concentration to indicate the moisture content of the gas. This is defined as the ratio of the velocity of a given electromagnetic radiation in vacuum to that of the same radiation in the gas. Since the velocity of electromagnetic radiation in vacuum is constant, only the velocity in the gas needs to be measured. Radiation at optical, radio, or microwave frequencies may be used.

At optical frequencies an interferometer is used to measure wave length. Monochromatic light is split and projected through two paths identical in length, one containing dry gas and the other the gas sample to be measured. The two beams are then recombined producing interference fringes. Changes in refractive index of the sample gas produce shifts of the interference fringes that are related to the vapor pressure.

At radio frequencies a small capacitor is used in a resonant circuit of a variable oscillator. Changes in refractive index, and hence in dielectric constant, are reflected as changes in the resonance frequency of the circuit. The variable frequency is compared with a reference frequency and the small difference is detected, measured, and related to vapor pressure.

At microwave frequencies two identical cavity resonators are

employed. Into one of these cavities the test sample is introduced; into the other, dry gas. The resulting difference in resonance frequency between the two cavities is then a measure of the vapor pressure.

The refractive hygrometer is capable of detecting the vapor pressure with high sensitivity. By using an appropriate servo system, the instrument may be made completely automatic and recording with a speed of response limited only by the flushing time and the lags in the electronic and recording devices. Its basic limitation arises from the fact that it may be used only with gas mixtures containing one variable, for it does not uniquely distinguish changes in water vapor content from changes in content of other vapors and gases (Wexler, 1963; Foster, Volz, and Foskett, 1965; Tillman, 1965; and Wood, 1965).

Electrolytic hygrometer. Water is electrolyzed into gaseous oxygen and hydrogen by the application of a voltage in excess of the thermodynamic decomposition voltage, i. e., more than two volts. The mass of water electrolyzed per unit time is directly related to the electrolysis current by Faraday's law. Thus, it can be shown that the current flow is directly proportional to the volume ratio of water vapor to air and to the mass flow of gas. Therefore, given a constant mass flow rate, the current uniquely determines the water vapor concentration.

The electrolytic hygrometer continuously and quantitatively

electrolyzes the water vapor of a water vapor-gas mixture and indicates its magnitude. It does this by maintaining a constant mass flow rate of the test gas through an electrolysis cell. Within the cell the water vapor is adsorbed by partially hydrated phosphorus pentoxide. Voltage is applied to spirally wound platinum wires embedded in the absorbent, and the electrolysis current is measured on a microammeter.

Vapor concentration of 1 ppm can be detected. The commercial instrument normally has scale ranges of 10 to 1000 ppm, although with special techniques higher concentration can be reliably determined (Jones and Peterson, 1965; and Czuha, 1965).

Dewcell hygrometers. The equilibrium vapor pressure of a saturated salt solution is a function of the solution temperature. When such a solution is exposed to a moist gas the solution temperature can be adjusted until its equilibrium vapor pressure equals the vapor pressure of the ambient gas. This is the principle of the dewcell hygrometer.

Hedlin and Trofimenkoff (1965) describe one form of the dewcell hygrometer. Their description is similar to descriptions contained in literature published by the Foxboro Company (1966) and Honeywell (1968). The dewcell hygrometer is described as a thermometer surrounded by a gas wool wick impregnated with a solution of lithium chloride. Two electrodes of noble metal wire are wound on the outside of the wick to form a bifilar coil.

Alternating current is impressed across the electrodes through a ballast tube. The flow of current through the solution generates heat which raises the temperature of the solution. As the solution temperature increases, water evaporates from the solution. The evaporation reduces the amount of solution available to carry current and, consequently, the resistance increases and the current decreases. This lessens the heat generated by the current flow. The solution thus attains a temperature at which the solution and ambient vapor pressures are equal. This equilibrium solution temperature is converted to vapor pressure or dew-point values by use of appropriate tables, graphs, or equations.

Wylie (1965), describes another type of hygrometer which uses a single crystal or group of crystals on which a thin film of saturated solution forms. The crystal, or group of crystals, is mounted between electrodes in an isothermal metal enclosure. Through resistance-heating or refrigeration the enclosure is brought to and maintained at the temperature that produces a fixed or predetermined solution resistance. A resistance thermometer wound on the enclosure, or a thermocouple attached thereto, is used to measure the temperature.

The range of vapor pressure, or dew points, measurable with the dewcell hygrometer depends upon the salt used to impregnate the wick. Provided the vapor pressure-temperature relationship is known, the dewcell hygrometer requires no calibration. It can

be instrumented to give continuous indication or recording. The temperature of the solution depends, in part, on the rate of gas flow across its surface. For highest accuracy the gas velocity must be kept low.

A tabulated list of humidity measuring instruments is contained in the appendix.

Limitations of current instruments

Mr. Albert Showalter (1965), Chief of the United States Weather Bureau Instrument Development Section, Washington, D. C., comments on the available techniques.

A review of presently available techniques points up problems and inadequacies:

- (A) Meteorologists have traditionally used the wet- and dry-bulb psychrometer as a basic humidity measuring device in making surface observations.
 - (1) Automation and telemetering are complicated.
 - (2) Use at below-freezing wet-bulb temperatures requires special techniques and care. The result is that data obtained at low temperatures are erratic and at times very inaccurate.
 - (3) Under extremes of relative humidity, special techniques are required and in the case of high humidity at least required accuracy is difficult if not impossible to achieve.

- (B) The infrared hygrometer is an instrument currently under development by instrument engineers of the Weather Bureau and others. (Mr. Foskett and his colleagues report on this instrument in Volume 1.) It is a sensitive and accurate instrument, but its routine use in meteorology presents problems.

- (1) The intricacy of the instrument may result in unfavorable cost and maintenance demands if its output is to be directly converted to dew-point temperatures.
 - (2) Weight and power demands may be high.
 - (3) The form of the measurement (i. e., absolute humidity) is not conservative with respect to adiabatic compression and expansion and is therefore not commonly used by meteorologists. To convert the output of the infrared hygrometer into dew point requires complicated calculations or precise graphical computation. These computations require knowledge of the ambient air temperature.
 - (4) For high relative humidities at moderate and high temperatures the accuracy of measurement may not be adequate.
 - (5) Since the instrument has instantaneous response (i. e., no lag), the readout must have an integrator to obtain representative meteorological measurements and filter out the higher frequency variations which, for the purpose of most meteorological measurements, constitute meteorological noise.
- (C) The Lyman-Alpha humidimeter shows interesting possibilities but is still a laboratory type instrument and requires further development.
- (D) With development in Peltier cooling, the technique based on the change of light reflectivity of a mirror as it is cooled to the dew-point temperature is being tested by meteorologists. However,
- (1) Until the tests are completed it will not be possible to assess the value of this type of sensor.
 - (2) For some meteorological applications (Upper air measurements), weight is too great and power requirements are too high.
- (E) The dewcell has been adopted as an interim standard for automated humidity measurement at the surface by the U. S. Weather Bureau, the U. S. Air force, and the U. S. Navy.

- (1) This device converts a lithium chloride "dew-point" temperature to a direct-reading equivalent water vapor dew-point temperature.
 - (2) The dewcell does not have satisfactory accuracy for many meteorological purposes, and its range is completely inadequate.
 - (3) The instrument may become unstable and may, without prior indication, begin giving completely erroneous measurements.
 - (4) Power requirements, weight, and its highly critical ventilation rate preclude the use of the sensor for upper air measurements.
- (F) Tests are being conducted on organic sensors which change physical form or dimensions with changes in humidity. Sensors included in this classification include the hair hygrometer, the Frankenberger hair, gold-beater's skin, the xerometer, etc.
- (1) All sensors of this class have accuracy and reproducibility limitations that make them unsatisfactory for precise meteorological purposes. They are most useful as trend indicators at temperatures well above freezing.
 - (2) There are also problems with automation of these sensors since an intermediate transducer to convert motion (produced by change of length or form) to an electrical parameter is necessary. This characteristic also complicates the use of such sensors in upper air measurements by a balloon-borne radio-sonde.
 - (3) In these sensors the lag is a function of temperature and becomes intolerably large especially for radio-sonde work at low temperatures.
- (G) Humidity to electrical resistance transducers have common problems of accuracy and reproducibility.
- (1) The lithium chloride strip has unsatisfactory accuracy, particularly with very high or very low humidity. It has excessive lag at low temperatures. If it is washed by rain its accuracy is completely destroyed.

- (2) Aluminum oxide sensors (Jason Hygrometers) have been found to have unsatisfactory accuracy at high relative humidities.
- (3) Ion-exchange sensors have not yet demonstrated sufficient accuracy for many meteorological purposes.
- (4) The carbon element which is still under development responds well at high humidities, but it appears difficult to mass-produce units with stable calibration properties.
- (5) The potassium metaphosphate hygrometer is highly temperature-sensitive and has unsatisfactory lag and accuracy characteristics at low temperatures.
- (6) The barium fluoride has good accuracy and very satisfactory lag characteristics but will not hold calibration more than a few days.
- (7) In all sensors of this class, the lag is a function of temperature and, as is true of sensors which depend on deformation or change of dimensions, the lag becomes intolerably large for upper air work at low temperatures.
- (8) Sensors of this type have a limited range when used in conjunction with available readout devices. For example, it is impossible for the radiosonde using the lithium chloride sensor to measure relative humidities less than 40 percent at temperatures of -40 C or less. (Showalter, 1965, p. 442-444)

Desirable specifications
for future work

Showalter (1965) further states that the sensor for the surface observation program should:

- (1) Have an overall accuracy equivalent to less than 0.3 C error in dew-point temperatures.
- (2) Be stable in calibration and remain within the above specified accuracy for periods of several months. These must include immunity to common atmospheric contaminants.

- (3) Be capable of continuous unattended operation for weeks or even months.
- (4) Have lag independent of temperature.
- (5) Read directly in terms of dew-point temperature.
 - (a) The dew-point is independent of temperature changes if pressure is constant.
 - (b) It varies only slightly with pressure changes which might occur at the earth's surface. For example, assume $P = 1010$ mb, $T = 10$ C and $DP = 5$ C. Assume further that the pressure falls under adiabatic conditions to $P = 960$ mb, then $T = 6$ C and the dew-point then becomes 4.5 C.
- (6) Have a lag coefficient of not less than 30 seconds.
- (7) Have a dew-point range of $+30$ to -65 C with temperature between $+50$ and -60 C.
- (8) Have few or no moving parts and have complete temperature compensation.
- (9) Have an output form that is satisfactory for use as input to an automatic data acquisition system. (Showalter, 1965, p. 444)

Showalter (1965, p. 445) concludes:

" . . . it is pointed out that in spite of the ingenuity, skill and technical know-how which has gone and is still going into meteorological instrumentation, present day sensors are far from ideal and in most instances something short of satisfactory. Future progress in meteorology will be dependent to a large degree on the obtaining of better and more representative data on the state of the atmosphere and in particular the moisture content of the atmosphere . . ."

From the foregoing material there was no obvious solution to the atmospheric moisture measurements desired. To get a better understanding of the problem of moisture and measurement a better understanding of fundamental theory is required.

Water in the atmosphere

From a meteorological viewpoint, the atmosphere is a mixture of dry air of almost constant composition and water. Water occurs in the atmosphere in all three of its phases (gas, liquid, and solid), and is the only major constituent of the atmosphere which varies markedly in time and space. The atmospheric water readily changes from one phase to another in response to changing atmospheric conditions. Each change of phase is accompanied by some exchange of latent and sensible heat. Consequently, the state of the atmosphere is controlled to a large degree by the content and form of water within it even though water vapor usually constitutes less than 3 percent of its total composition.

Dalton's law of partial pressures states that the pressure exerted by water vapor is independent of the pressure exerted by other atmospheric gases. The behavior of water vapor and of other atmospheric gases can be closely approximated by the equation of state for an ideal gas provided there is no condensation or evaporation taking place in the volume under consideration. Under these conditions the vapor pressure of water can be represented by

$$e = \frac{P_v}{M_w} RT \quad [1]$$

where P_v is the density of water vapor in g/cm^3 , M_w is the molecular weight of water (18 g/mole), R is the universal gas constant (8.31×10^7 erg/mole/deg. K), T is the absolute temperature of the

water vapor, and e is the water vapor pressure expressed in dyne/cm^2 .

The water vapor temperature may be taken to be the same as that of the air of which the vapor is one component.

The condition of saturation defines the limits between water vapor and the condensation of atmospheric humidity. Consider an enclosed container at constant temperature which is partially filled with pure water with a plane liquid surface. We now know that the equilibrium established is the same whether or not there is any other gas in the space above the liquid. At equilibrium the number of water molecules leaving the liquid surface per second due to thermal excitation will be the same as the number of vapor molecules being recaptured per second. The vapor pressure is then the maximum possible for that particular temperature. Thus, the saturation vapor pressure is a unique function of temperature. The rapid increase of the saturation vapor pressure of water with temperature is illustrated in Figure 1. List (1963)¹ tabulated values for this in the Smithsonian Meteorological Tables, pages 351-352. Figure 1 could alternatively be interpreted as the variation of the boiling point, (the abscissa), with the external atmospheric pressure, (the ordinate).¹

¹Atmospheric pressure at sea level is of the order of 10^6 dyne/cm^2 . In meteorology, the multiple of the absolute unit, known as a millibar, is used where the following relations hold: 1 bar = 10^6 dyne/cm^2 ; 1 mb = 10^3 dyne/cm^2 .

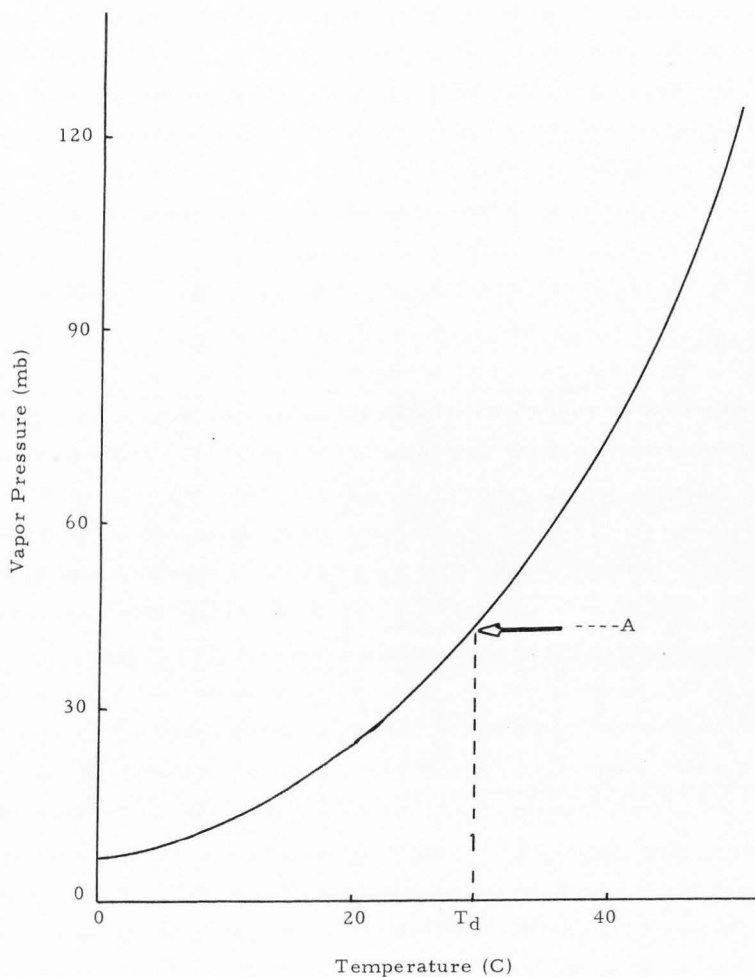


Figure 1. Saturation vapor pressure of water over a plane surface of water as a function of temperature

The vapor pressure, e , and the vapor density, P_v , introduced in equation [1] are two ways of measuring atmospheric humidity. Other measures of atmospheric humidity are sometimes more convenient. The saturation deficit is given by the differences $e_s - e$ where e is the actual vapor pressure and e_s is the saturated vapor pressure, i. e., the vapor pressure that would exist if it were saturated at the same temperature.

The relative humidity, h_r , is defined as the non-dimensional ratio.

$$h_r = \frac{e}{e_s} \quad [2]$$

This fraction is commonly multiplied by 100 to obtain relative humidity as a percentage, rh.

$$rh = 100 h_r = \frac{100 e}{e_s} \quad [3]$$

Neither e or e_s can be calculated from the ratio e/e_s nor the difference $e - e_s$. Thus, other information (air temperature, for example) must be given before any humidity condition is fully defined.

The dew-point temperature, as discussed by Rose (1966), is illustrated by reference in Figure 1. Let a parcel of air with humidity condition A be cooled at constant pressure without any gain or loss of water vapor. (Radiative cooling of air on a calm, clear night could fulfill these conditions provided there is no dew formation.) The horizontal line extending to the left of A represents the state path of this change. The intersection of this path with the saturation vapor

pressure curve defines the temperature at which the air would be saturated with water vapor. This temperature is called the dew point, T_d , since dew would form on any surface in contact with the vapor if the surface were cooled below this temperature.

Lithium chloride as a
hygroscopic agent

Nelson and Amdur (1965) presented an excellent discussion of salt solution phase transition hygrometry. Acheson (1965) pointed out the importance of knowledge of vapor pressure of inorganic salt solutions in hygrometry.

Martin (1965), Wylie (1965), Hedlin and Trofimenkoff (1965), and Acheson (1965) have examined several aspects of hygroscopic characteristics of various salts. Lithium chloride is one of the most active hygroscopic salts and from the writing of the above authors further examination of LiCl is warranted.

Figure 2 is a plot of water vapor pressure over a saturated LiCl solution as a function of temperature. This clearly shows the exponential nature of the energy required to separate water from the LiCl salt.

Dissolving LiCl salt in water lowers the vapor pressure of the water over the solution. This occurs due to the increased attraction between molecules in the solution. Increasing the amount of LiCl added to the water will continue to decrease the vapor pressure until the amount of salt added exceeds the amount that will dissolve. At

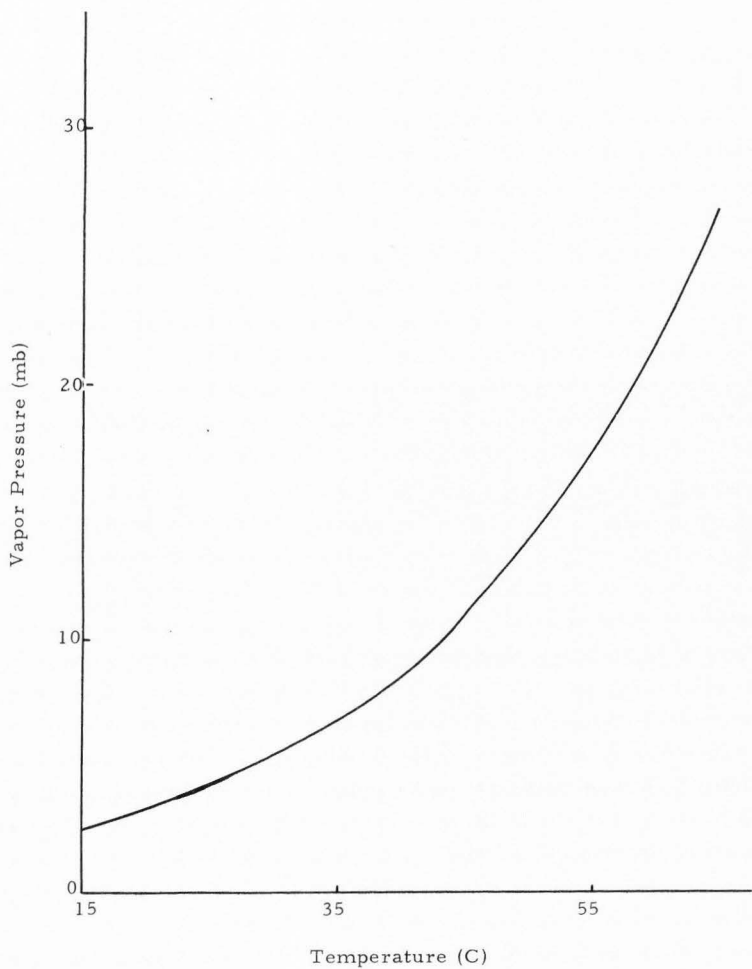


Figure 2. Plot of water vapor pressure over aqueous lithium chloride as a function of temperature

this point the vapor pressure becomes independent of concentration and is a function of temperature only.

When water contains all of the salt that it can dissolve, it is called a saturated solution. This condition is often accomplished by adding more salt than will dissolve to assure continuation of the saturated condition.

Figure 3 contains the curves of Figure 1 and Figure 2 for comparison and shows the vapor pressure vs. temperature curves over a pure water surface (curve A) and over a saturated lithium chloride solution (curve B). The condition at points A, D and F are selected to illustrate the vapor pressure and temperature relationships.

If the vapor pressure of the space is decreased to point D, the water will evaporate and the dry salt will remain. In order to maintain the salt solution phase at equilibrium when the vapor pressure is changed to D, the system must be cooled to the temperature which places the new vapor pressure on the equilibrium curves at point F.

If the vapor pressure is increased from point A to point F by adding water vapor, moisture will be absorbed into the solution, the solid salt will dissolve, and a solution will remain. When the vapor pressure is changed to F, equilibrium may be re-established by heating to G.

The temperature at which equilibrium is established indicates the vapor pressure at the new vapor phase condition. This

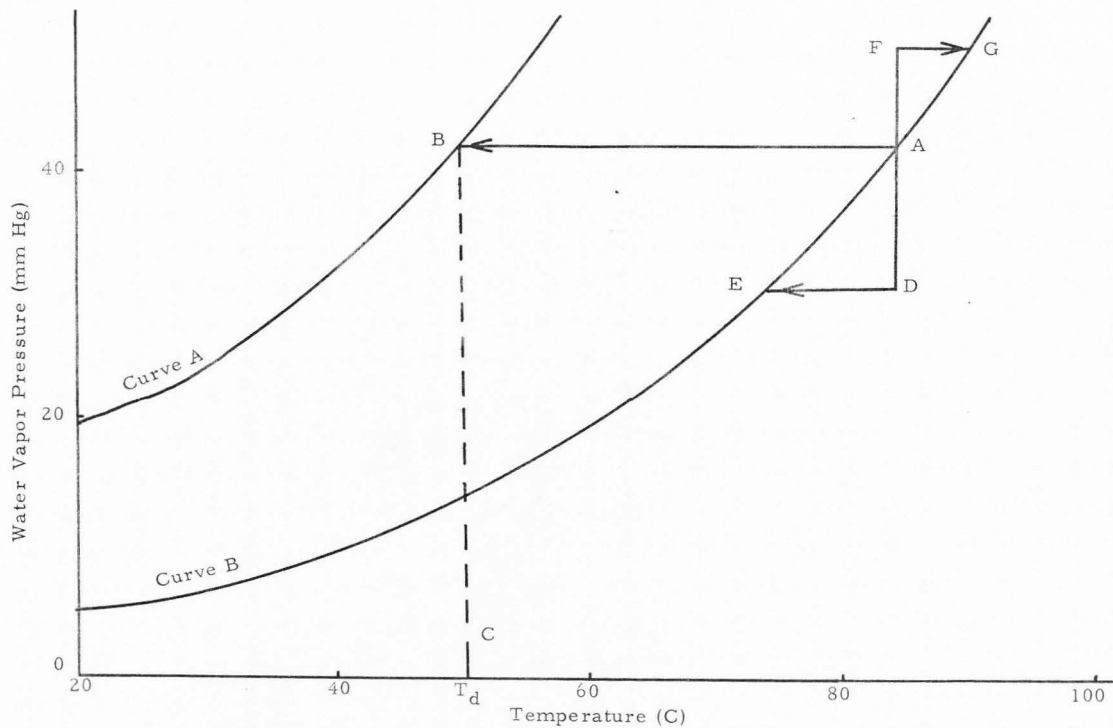


Figure 3. Comparative plot of water vapor pressure over water, Curve A, and over aqueous lithium chloride, Curve B, as a function of temperature

temperature may be readily converted to the conventional dew-point temperature as illustrated in Figure 3 by proceeding on a constant vapor pressure from A to B until intersecting the curve for pure water and then proceeding down to C on the temperature axis. The point of intersection on the temperature axis is the dew-point temperature, T_d .

Definition of the lithium chloride problem

The literature review left several questions unanswered. In particular, answers were needed for the following:

1. How rapidly will LiCl attract water from the atmosphere?
2. What conditions are required for measurement of LiCl electrical resistance?
3. How does the electrical resistance change as a function of solution concentration?
4. How does temperature affect the electrical resistance of an LiCl solution?
5. How do temperature and environment relate together in affecting the electrical resistance of LiCl?
6. Of what importance, if any, is the positioning or spacing of electrodes in making LiCl electrical resistance measurements?
7. Are answers to the above questions predictable and repeatable?

Since answers to these questions were not evident in the literature, experiments were designed and conducted to obtain answers.

ELECTRICAL AND HYGROSCOPIC PROPERTIES
OF LITHIUM CHLORIDE

Lithium chloride salt is a very active hygroscopic agent, but answers to the questions in the previous section are required if it is to be used effectively. Therefore, an evaluation was conducted to determine if LiCl could be used to achieve the accuracy and reliability desired for hygrometers.

Some observations

A sample of dry salt was placed on a flat surface in a dew-point environment of 0 C. When observed after a few hours, the dry salt had disappeared and solution remained on the surface. In the upper part of Figure 4 is a view of a saturated LiCl drop as it was placed on a glass surface. In the lower part of Figure 4 is a similar drop of LiCl solution which has been exposed to a high humidity environment for a few hours. The increase in size is caused by the moisture absorbed from the air. Coloring was added to the saturated solution to improve visibility.

Electrical resistance of lithium
chloride as a function of solution
concentration

Dry LiCl salt is a non-conductor of electricity. The dry salt

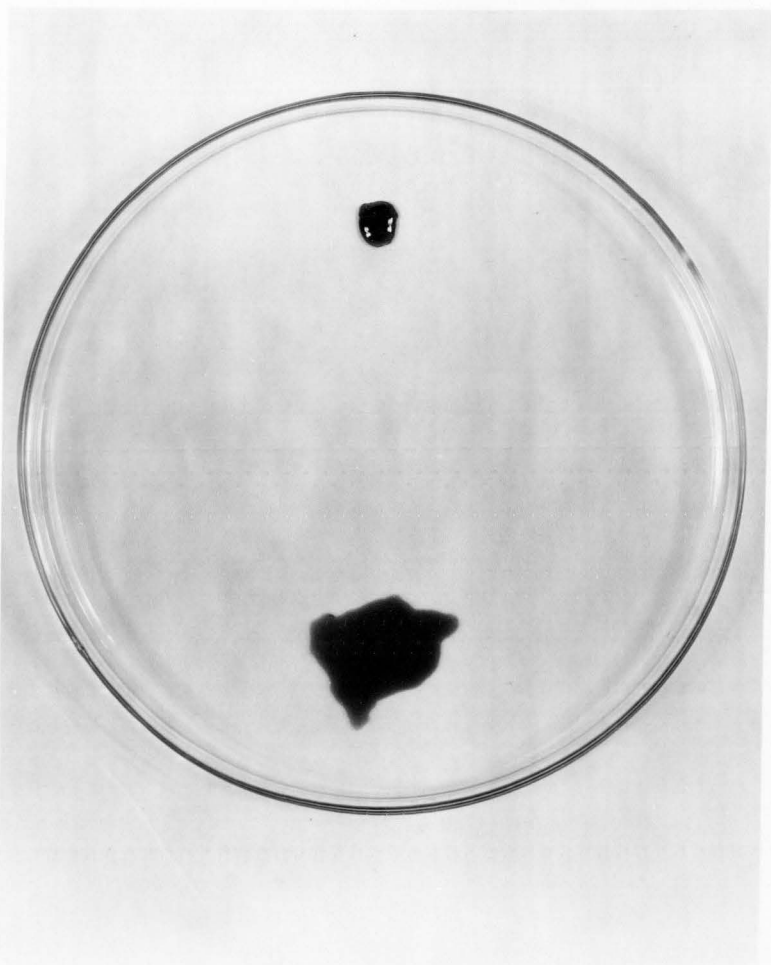


Figure 4. Photograph of two drops of lithium chloride solution.

The lower view shows the result of exposure to high humidity environment for an extended period of time.

shows a high electrical resistance which falls rapidly as solution begins to form. Because of polarization at the electrodes, resistance must be measured with a-c methods.

Figure 5 shows the test setup used for evaluating the electrical resistance of LiCl as a function of solution. This equipment combination will give a good resistance measurement to 10,000,000 ohms and indications to 10 times this value. It consists of:

1. A ten volt a-c supply
2. A 1,000 ohm series current limiting resistor
3. An a-c meter with current ranges for full scale deflection to 0.000015 to 0.005 amperes.
4. A tray for LiCl and electrodes

The procedural steps for this test are:

1. Place 10 drops of saturated LiCl solution on a glass tray surface at room temperature.
2. Connect the 10 volt a-c supply with the 1,000 ohm resistor in one lead and the a-c current meter in the other and place the electrodes in the LiCl solution.
3. Add drops of distilled water to the solution until it increases in volume 500 times.
4. Repeat step 3 and modify by heating the solution with a heat lamp at the initial condition, then repeating the heating at dilution of 300 and 500. After each heating return the temperature to ambient before continuing.

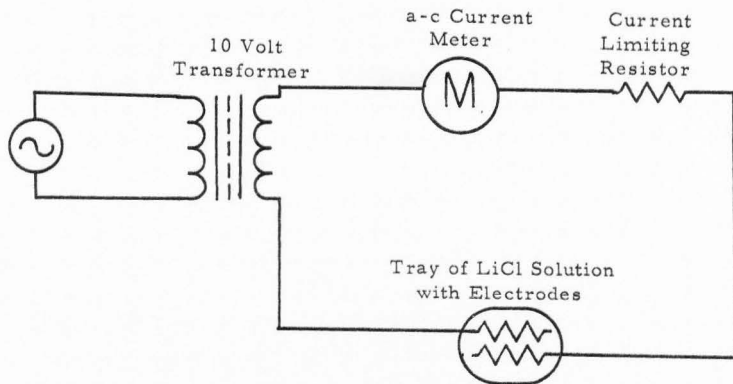


Figure 5. Schematic of test setup for measuring the electrical resistance of lithium chloride as variation of water content takes place

5. Remove the solution and repeat step 1. The operation now is to remove the water from the solution progressively until dry salt remains. This is accomplished by applying heat with a heat lamp in a series of steps and between steps allowing the temperature to return to ambient. Data are taken in the heated condition and at ambient. Weighing the sample between steps provides data for the ratio plot of $H_2O/LiCl$ vs. resistance.

Test results are shown in Figure 6, which is a plot of electrical resistance of LiCl salt as a function of solution concentration. For dilute solutions, a semi-log plot of resistance vs. concentration is linear at $H_2O/LiCl$ ratios greater than 100.

There is an increase in resistance, however, as the $H_2O/LiCl$ ratio drops below 0.01. The four important points learned from this are:

1. The resistance increases dramatically as the moisture content of the salt approaches zero.
2. The minimum resistance value is relatively constant for a wide variation in concentration. (0.01 to 100).
3. The minimum resistance value is greatly reduced when the LiCl solution is heated.
4. Curve B of Figure 3 represents a condition at which the electrical resistance of the salt solution is at a minimum.

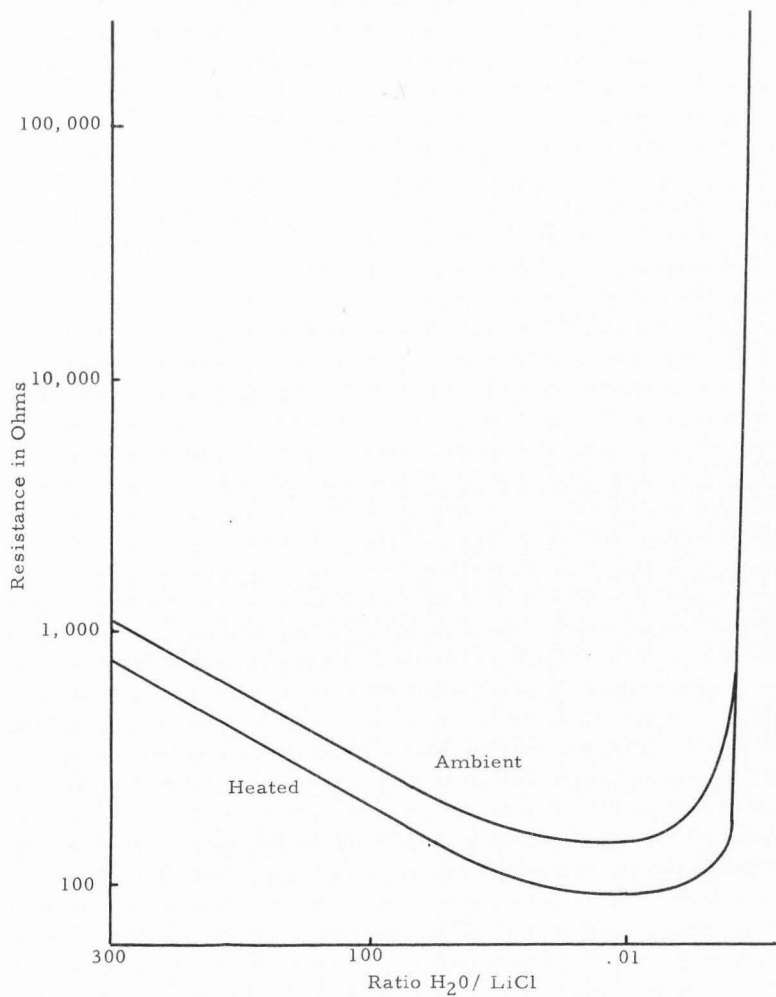


Figure 6. Plot of variation of electrical resistance of lithium chloride as concentration of solution varies

Electrical resistance of lithium
chloride solution as a function
of temperature

The test setup for measuring the electrical resistance of the LiCl solution as a function of temperature is shown in Figure 7.

The equipment consists of:

1. An a-c supply (10 volt).
2. A d-c supply (0 to 50 volt and 0 to 1.5 amp).
3. A current limiting resistor (1000 ohm)
4. An a-c current meter (15 to 10^{-6} amp to 1.5 amp)
5. An environmental chamber
6. A humidity transducer with cable (see Figure 15)
7. A d-c resistance bridge

The numbers associated with the humidity transducer schematic leads in Figure 7 correspond with the pin connections shown in Figure 15.

The test procedure follows:

1. The fiber glass wrapped on the humidity transducer is wetted with a 50 percent saturated solution of LiCl. This should be applied with a dropper taking care not to get solution on other parts of the equipment.

2. The d-c power supply is connected to pins 3 and 6 of the transducer to heat it. The current is adjusted to 5 ma to prevent salt movement when the transducer is placed in the environmental chamber. By varying the amount of current in the resistor, the

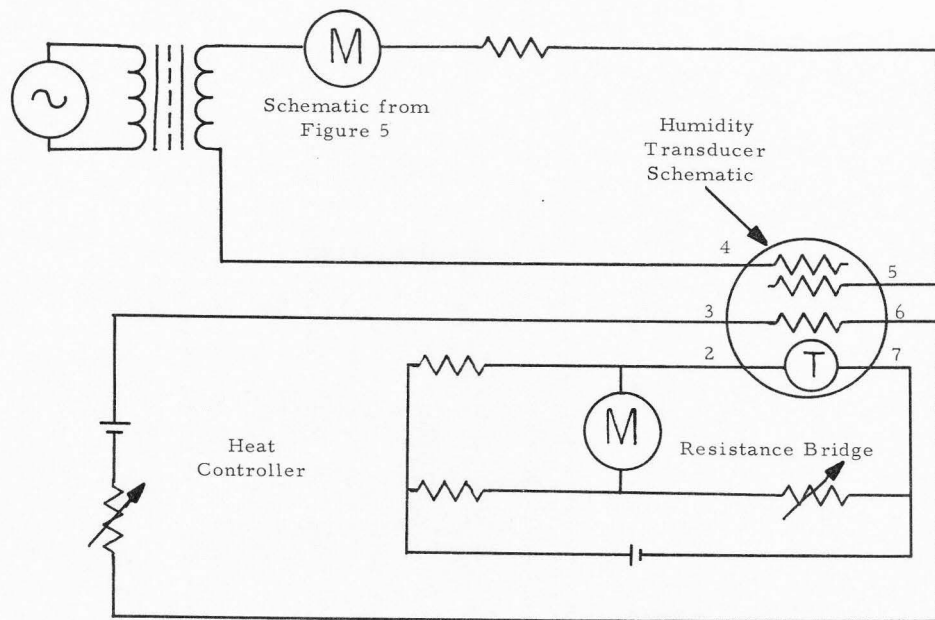


Figure 7. Schematic of test setup for measuring the electrical resistance of a lithium chloride surface as a function of temperature when enclosed in a constant dewpoint environment

temperature of the resistor will vary.

3. Place the humidity transducer in the environmental chamber which has a dew point of 25 C.

4. Connect the d-c bridge to pins 2 and 7 of the humidity transducer to measure the resistance of a YSI 44006 thermister inbedded in the heat sink compound within the 51 ohm resistor. This resistance converts to the temperature measurement of the transducer.

5. Connect the 10 volt a-c supply through the 1000 ohm resistor and the current meter to leads 4 and 5 of the humidity transducer. This is to measure the electrical resistance of the LiCl film on the transducer.

6. Slowly adjust the d-c current in the 51 ohm resistor until its temperature stabilizes near 40 C.

7. Observe the resistance of the LiCl film. When the resistance has remained constant for an hour, evaluation may begin. This step is to make sure the environment has reached equilibrium after inserting the transducer.

8. Proceed now to take data for the plot. Increase the heat in small steps and at each step allow the system to completely stabilize before taking LiCl film resistance and thermister resistance readings.

The curve in Figure 8 shows the resistance of an LiCl solution as it is elevated to higher temperatures and held there until equilibrium is achieved. The equilibrium is achieved by driving off some

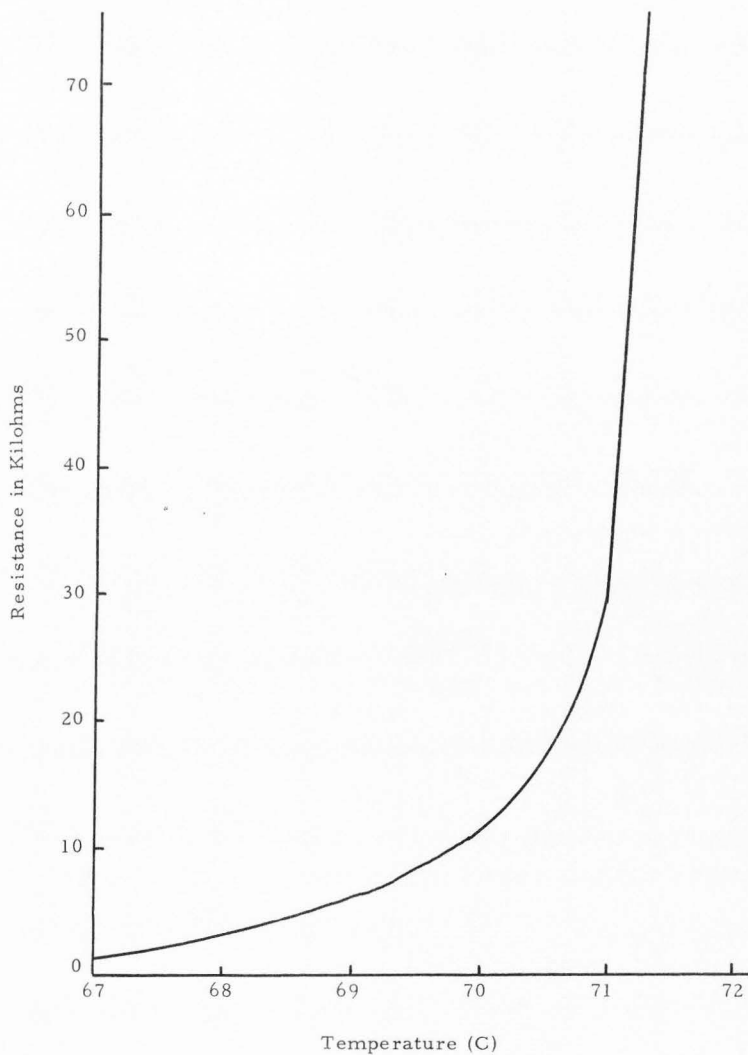


Figure 8. Plot of variation of electrical resistance of lithium chloride film as a function of temperature

of the water which, in turn, increases the salt concentration. The data for Figure 8 were obtained in an environment of a constant 25 C dew-point temperature.

In most dewcell hygrometers the resistance of the LiCl solution is utilized to heat the unit until it reaches equilibrium. This equilibrium condition is a function of ambient temperature and dew point. Thus the resistance point at which equilibrium will be reached, according to Hedlin and Trofimenkoff (1965), will usually be somewhere between 500 ohms and 5000 ohms resistance. By referring to Figure 8 we see that this represents about 4 C spread in temperature due to heat load requirements without any regard to dew point.

The important points learned from this are:

1. The resistance of the LiCl film is a function of temperature and humidity environment.
2. The vapor pressure-resistance relation has a temperature dependence.
3. The resistance at which a dewcell will operate in a given environment is a function of its heat dissipation requirements.
4. At a 25 C dew-point environment and at 10,000 ohm LiCl film resistance, the LiCl temperature will be about 6.9 C higher than if it were at equilibrium and minimum resistance.

Hygroscopic characteristics of dry lithium chloride

The test setup for measuring the wetting characteristics of

dry LiCl is the same as shown in Figure 5. About 20 ml of saturated solution of LiCl were placed on the tray as shown in Figure 5. Then heat was applied with a heat lamp until the electrical resistance of the LiCl exceeded 10 megohms, at which time the heat was removed. Figure 9 shows the appearance of the dry salt after it cooled to room temperature. The electrical resistance had continued to increase to greater than 50 megohms.

The data used to plot Figure 10 were obtained as the dry LiCl collected moisture from the air. As soon as the salt resistance decreased to 1 megohm, the resistance was noted at periodic intervals. The ambient environment had approximately a 0 C dew point and a 25 C temperature.

From Figures 9 and 10 it was concluded that if the electrodes of a dewcell became coated with dry LiCl salt it would not be useable for an extended period of time. This condition can and sometimes does exist if adequate care is not exercised when servicing the equipment.

The important points from this special study are:

1. For resistance to indicate the presence of moisture in the atmosphere the electrodes must be on the surface of the LiCl film which is in contact with the atmosphere.
2. Any operation or handling that would allow the salt to migrate would cause questionable or false resistance indications.

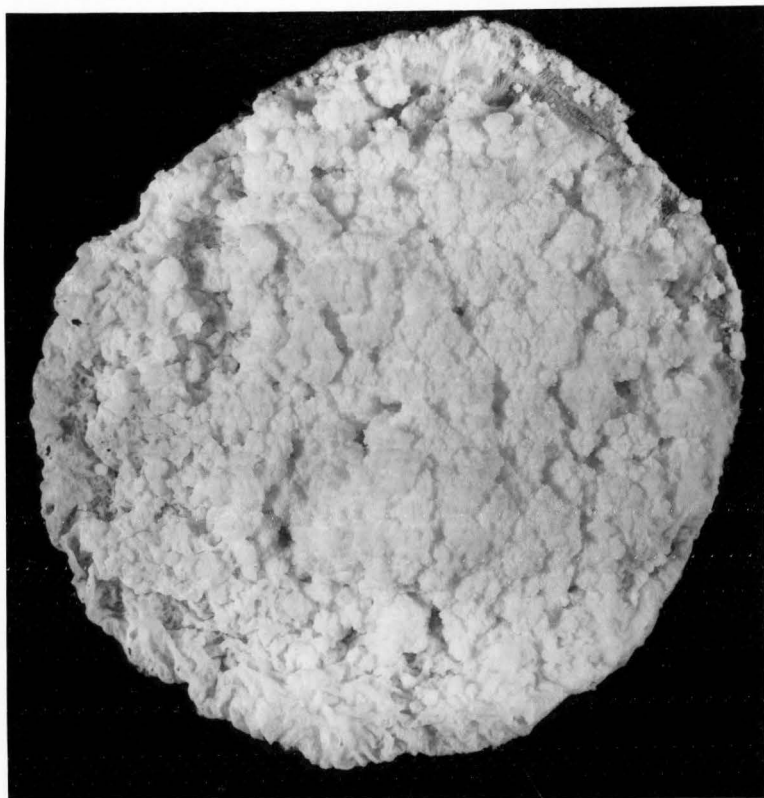


Figure 9. Photograph of dry lithium chloride from which water has been evaporated

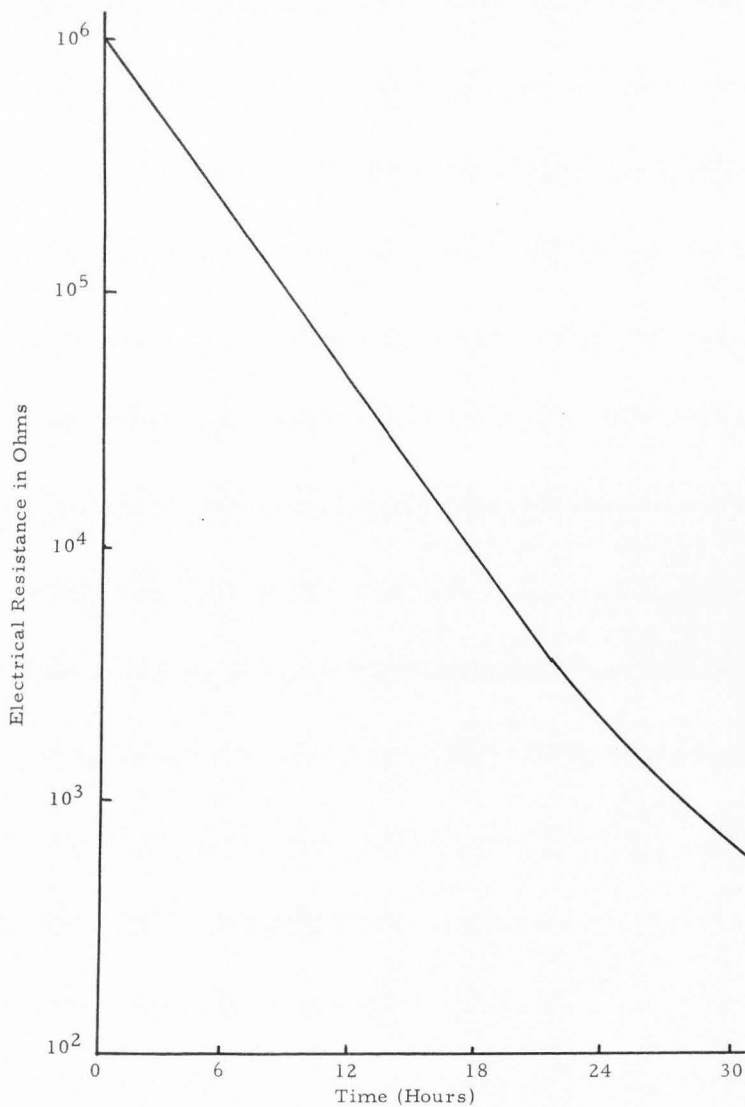


Figure 10. Plot of the wetting characteristics of lithium chloride salt in a 0 C dew-point environment

Summary of resistance factors

In this work several factors have been observed that affect the resistance of the LiCl film. These are:

1. Temperature of the LiCl
2. Concentration of solution
3. Hydrate status of the salt
4. Purity of the salt
5. Salt density (quantity or thickness)
6. Time
7. Environment

Analysis and comparison

It is now possible to see how well LiCl met the requirements set up by Showalter (1965).

Showalter's requirements

1. Have an overall accuracy equivalent to less than 0.3 C error in dew-point temperatures.
2. Be stable in calibration and retain the above specified accuracy for periods of several months. This must

Comparison and analysis (degree of achievement)

1. To meet this requirement it is necessary to operate the LiCl at a constant resistance as indicated in Figure 8.
2. Not tested directly, but from the data obtained in the preceding tests, this requirement is feasible.

include immunity to common atmospheric contaminants.

3. Be capable of continuous unattended operation for weeks or even months.

4. Have lag independent of temperature.

5. Read directly in terms of dew-point temperature.

6. Have a lag coefficient of not less than 30 seconds.

3. If the equipment shown in Figure 7 can be automated, it will meet this requirement except where the relative humidity drops below 11 percent. Additional equipment would be required to cool the air so that the relative humidity would exceed 11 percent.

4. This requirement appears to be achievable. Some changes in lag will occur with variations in dew-point environment, but this should not be confused with temperature dependence.

5. This requirement is achievable with proper calibration procedures.

6. This requirement can be met by properly sizing the transducer assembly.

7. Have a dew-point range of +30 to -65 C with temperature between +50 and -60 C.

8. Have few or no moving parts and have complete temperature compensation.

9. Have an output form satisfactory for use as input to an automatic data acquisition system.

7. This requirement was not met with the above equipment in the lower temperature region. There are hydrate changes in the salt structuring, and at the hydrate change point the uncertainty may exceed 0.3 C. No tests were made below -30 C dew point.

8. The equipment shown in Figure 7 are adaptable to this requirement.

9. Output from the humidity transducer shown in Figure 7 is adaptable to this requirement.

From the comparison and analysis made above, I will accept Showalter's requirements as the basis for hygrometer design except item 7. I will revise item 7 to read: "Have a dew-point range of +30 to -10 C with temperature between +50 and -10 C."

I have chosen to change Showalter's item 7 requirement for two reasons: (1) I do not have equipment available for adequately testing at the lower temperatures, and (2) the work that initiated this project does not require measurement of dew-point temperatures below -10 C or temperatures below -10 C.

In addition to the above requirements, further consideration will be given for operation at remote sites with battery power.

With this background, we shall now proceed to the problem of developing a practical hygrometer.

DEFINITION OF HYGROMETER PROBLEM

Performance characteristics
desired

To meet our needs for a remote location hygrometer, the following characteristics are required:

1. Have a dew-point range of -10 C to +30 C.
2. Be capable of operation from 12 volt battery power.
3. Have a power requirement of less than 0.75 watt.
4. Have an accuracy of ± 0.3 C for dew-point sensing.

To meet the above requirements, we chose to use LiCl salt solution phase transition for humidity sensing. LiCl characteristics which make it desirable for dew-point measurement are:

1. It is highly hygroscopic.
2. It can be maintained at a constant resistance when in an atmosphere with a relative humidity greater than 11 percent.

Functional characteristics to
be developed

To achieve the characteristics required above, the following functions are selected:

Performance required

1. Have a dew-point range

Physical features necessary to
meet performance requirements

1. From the preceding tests,

-10 C to + 30 C

2. Operate from a 12 volt battery.

3. Have power requirement of less than 0.75 watts.

4. Have an accuracy of ± 0.3 C for dew-point sensing

LiCl appears well suited to this range of operation.

2. Tests with LiCl solution showed that polarization takes place if direct current is applied to it; therefore, a means of converting from d-c to a-c is required for the humidity transducer.

3. When operating at temperatures considerably above ambient, radiative loss of heat could be excessive. Therefore, the physical size must be kept small to prevent excessive loss of heat through radiation. This will also reduce loss of heat by convection. Convective heat loss must be controlled to prevent temperature gradients from developing within the transducer.

4. This can be achieved by operating the LiCl film at a near constant resistance on the steep part

of the curve. (See Figure 8.)

Also, an accurate temperature-sensing device is required which will give high precision and will not present excessive thermal load on the humidity transducer operation.

Physical units discussed above which are necessary to give the required performance are:

1. A heater
2. A d-c to a-c converter
3. A humidity transducer
4. A resistance error detector and control
5. A temperature-sensing device

The functional relationship among these units are displayed in Figure 11.

Since a unique feature of this hygrometer is its operation of the LiCl film at a constant resistance, we shall name this hygrometer the Constant Resistance Hygrometer, identified as a C-R Hygrometer.

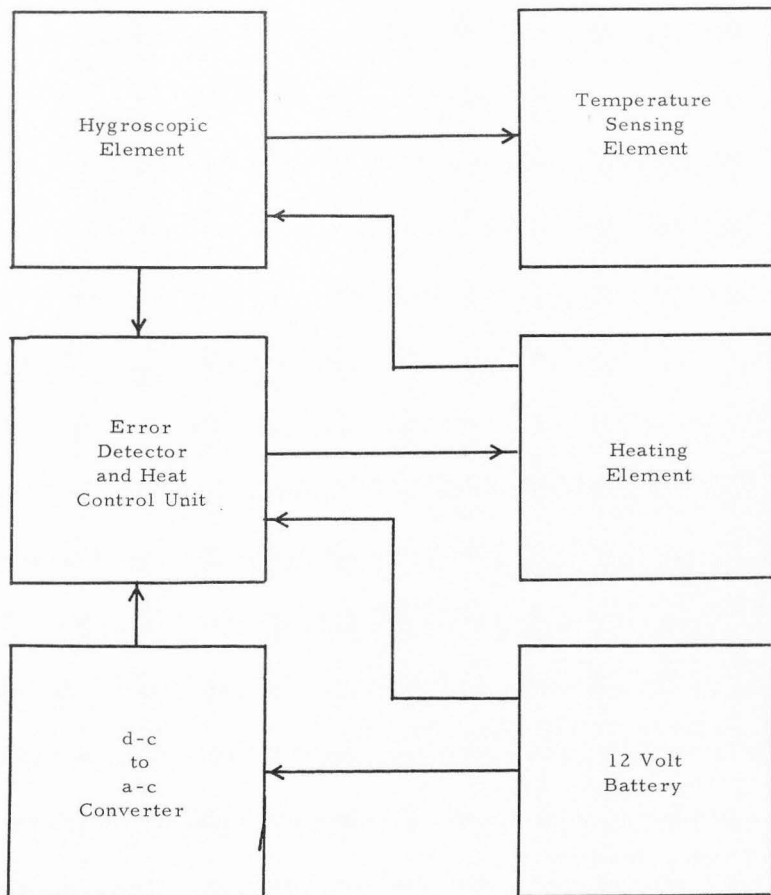


Figure 11. Block diagram showing functional parts required in the hygrometer with arrows indicating the direction of power flow and control

HYGROMETER DESIGN

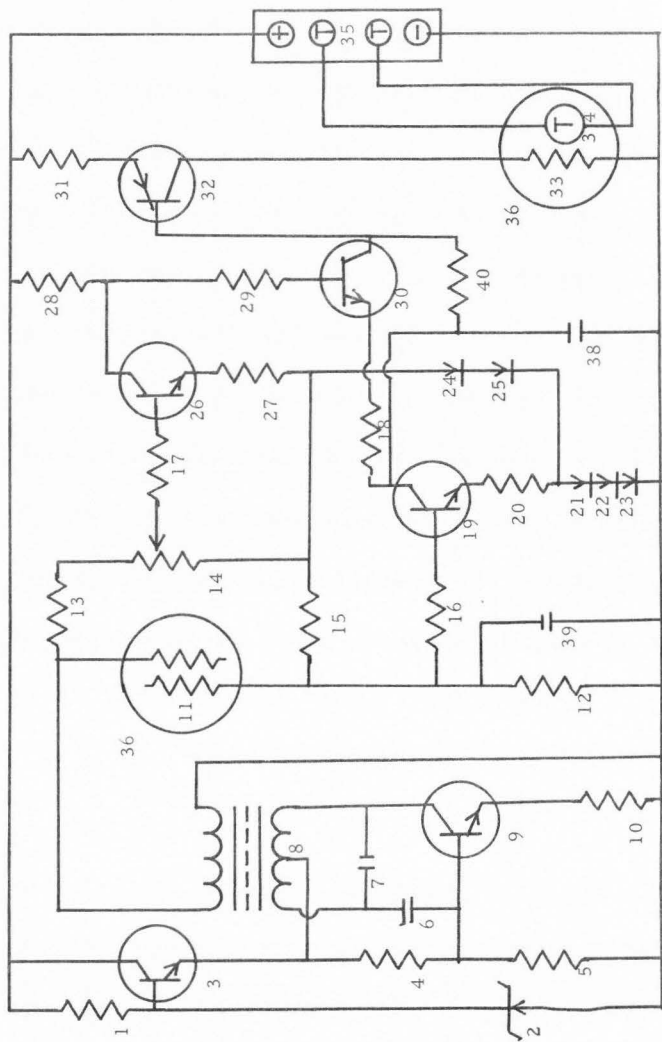
Introduction

A schematic and a parts list for the hygrometer are shown in Figure 12. The function served by each part is given in the following discussion. The use of trade names is not intended as an endorsement or recommendation; equivalent parts from another manufacturer would be equally suitable. All voltages are referenced to the negative supply.

Figure 11 includes two items not included in Figure 12. They are a twelve volt battery and a temperature readout device. Since these are usual laboratory items and not unique to this use, they are omitted.

Discussion

Parts 1, 2, and 3 constitute a regulated voltage source for the oscillator stage. Part 1 is a voltage-dropping resistor through which the current is passed for the zener diode (part 2) operation and for the base of the regulator transistor (part 3). The regulator transistor then functions as an emitter follower with its base voltage fixed by the zener diode, and its emitter voltage is held constant at about 0.5 volts less than the zener diode operating voltage. Thus a constant voltage is provided for the oscillator circuit as the supply



- | | | |
|---------------------------------------|-------------------------------|--|
| 1. 7.5 k 1/2 watt resistor | 15. 4.7 k 1/2 watt resistor | 29. 4.7 k 1/2 watt resistor |
| 2. 9.1 volt 0.4 watt zener diode | 16. 1 k 1/2 watt resistor | 30. 2N3704 NPN transistor |
| 3. 2N3704 NPN transistor | 17. 3 k 1/2 watt resistor | 31. 4.7 ohm 1 watt resistor |
| 4. 27 k 1/2 watt resistor | 18. 2 k 1/2 watt resistor | 32. GE D27D1 PNP power transistor |
| 5. 7.6 k 1/2 watt resistor | 19. 2N3704 NPN transistor | 33. 51 ohm 3 or 5 watt resistor |
| 6. 0.1 ufd mylar capacitor | 20. 220 ohm 1/2 watt resistor | 34. YSI precision thermister part #44005 |
| 7. 0.1 ufd mylar capacitor | 21. IN626 silicon diode | 35. Cinch - Jones 4-140-Y barrier blocks |
| 8. Triad TY 34X transformer | 22. IN626 silicon diode | 36. Humidity transducer including parts 11, 33, 34, 37 |
| 9. 2N3704 NPN transistor | 23. IN626 silicon diode | 37. Keystone octal base relay case (not shown) |
| 10. 330 ohm 1/2 watt resistor | 24. IN626 silicon diode | 38. 0.02 ufd mylar capacitor |
| 11. Lithium Chloride hygroscopic unit | 25. IN626 silicon diode | 39. 0.01 ufd mylar capacitor |
| 12. 10 k 1/2 watt resistor | 26. 2N3704 NPN transistor | 40. 27 k 1/2 watt resistor |
| 13. 10 k 1/2 watt resistor | 27. 10 ohm 1/2 watt resistor | |
| 14. 25 k 1/2 watt potentiometer | 28. 47 k 1/2 watt resistor | |

Figure 12. C-R Hygrometer schematic showing functional design and parts list

voltage is varied from 11 to 16 volts.

Parts 4, 5, and 10 are resistors for establishing the d-c operating conditions for the oscillator transistor (part 9). Parts 6, 7, and 8 are the additional items required to complete the conventional resonant feedback oscillator circuit. A prerequisite to accurate humidity measurements with this equipment is a constant voltage output from the secondary of the oscillator transformer (part 8). The choice of components and the design of the regulator circuit were for this purpose.

The a-c output from the oscillator transformer secondary is fed to the network consisting of parts 11, 12, 13, 14, and 15. Part 11, which is a part of part 36, consists of two electrodes wound over a LiCl solution absorption pad. This unit (part 11) connects into the circuit to sense the LiCl film resistance. Parts 13, 14, and 15 are in parallel with part 11 and their function will be discussed later.

Parts 20, 21, 22, 23, 40, 30, and 18 establish the normal d-c conditions for the transistor (part 19). Part 19 is normally non-conducting until a signal of sufficient amplitude and with proper polarity appears across part 12. The polarity of this signal must be positive with respect to the negative supply line for conduction to take place.

A unit known as the "Humidity Transducer" consists of parts 11, 33, 34, and 37, which are packaged together and referred to collectively as part 36. The resistance of the LiCl film is controlled

by the hygroscopic characteristics of LiCl and the heat applied to it.

In operation, as the LiCl attracts moisture from the air its resistance is decreased and the voltage across it decreases, causing the voltage across part 12 to increase. This increases the signal drive through the base series resistor (part 16) to part 19. Part 19 is the error signal amplifier which causes current to increase through parts 18, 30, and 40 to the base of the heat control amplifier (part 32).

The increase in base current of the heat control amplifier causes an increased current flow through parts 31 and 33. Part 31 provides series feedback for the heat control amplifier, making it less sensitive to variations in individual transistor characteristics. The increased current in part 33 produces heat which is directly applied to parts 11 and 34. This increased heat of the LiCl causes its resistance to increase, thus closing the feedback loop and correcting the resistance error that started the cycle.

When the LiCl film resistance is low, part 30 is biased to act as a low resistance path for error signals from part 19. However, as the LiCl film resistance increases, the voltage across the series combination of parts 13, 14, and 15 increases. This increases the voltage applied through part 17 to the base of damping control transistor (part 26). This in turn applies a signal through part 29 to the base of the drive limiting transistor (part 30) and limits the drive signal to the heat control amplifier.

Parts 24 and 25 are silicon diodes whose junction voltage characteristics set the reference to which the damping control transistor (part 26) can control the current flow through the drive-limiting transistor (part 30). Experience and particular applications may make it desirable to increase or decrease the number of diodes that are used in this way.

Adjustment

The voltage output of the transformer secondary is 4.8 volts. The damping control adjustment (part 14) is adjusted until 2.5 volts a-c are maintained across the LiCl film as measured across part 11. This adjustment should be made in an environment that has a dew point near the mean environment of the dew-point range in which the unit will operate. The lab proto-type unit has been adjusted at a dew-point environment of +10 C and then operated from -15 to +30 C. From the 2.5 volt setting the voltage increases to 2.7 volts at a -15 C and decreases to 2.4 volts at +30 C. This change in voltage is a function of the change in energy requirements necessary to establish an equilibrium condition. The voltage values have considerable leeway in their generation and application, but measurement accuracy is dependent on voltage stability and repeatability.

The circuitry and operation discussion above can readily be adapted to different d-c supply voltages or to an a-c power source.

Figure 13, left hand view, is a photograph of the assembled

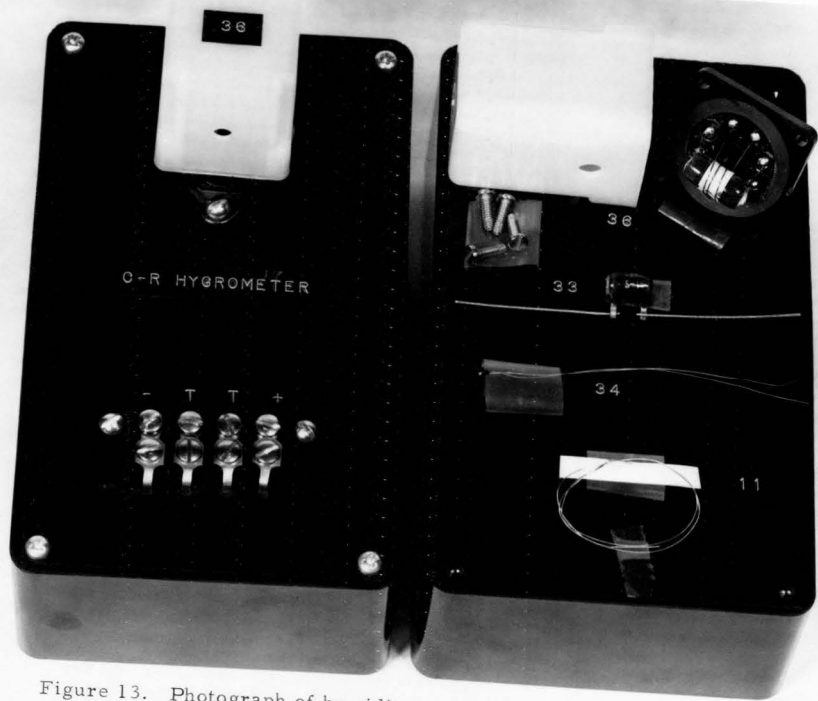


Figure 13. Photograph of humidity transducer details and C-R Hygrometer

C-R Hygrometer shown in Figure 12. The humidity transducer (part 36) is shown plugged into the oscillator and control unit. The right hand view shows the parts and assembly of the humidity transducer. The numbers by the parts refer to the parts list, Figure 12.

Humidity transducer

Parts of the humidity transducer are shown separately in Figure 13 for easy visualization of their relationship.

The assembly of the transducer may be accomplished as follows:

1. Install the ohmite 51 ohm (part 33) resistor in pins 3 and 6 of the octal plug (part of 37) and solder leads.
2. Spread the leads of the YSI 44005 thermister (part 34) 180 degrees apart, then install the thermister in the hollow core of the 51 ohm resistor. The thermister bead should be near the center of the resistor. The thermister leads are then inserted into pins 2 and 7 and soldered. The thermister leads should not be stressed at any time.
3. Place the fiber glass (part of part 11) on the 51 ohm resistor and hold it in place with an alligator clip while connecting the electrodes.
4. Connect the end of one electrode of the bifilar electrodes (part of part 11) to pin 1 of the octal plug; wrap one complete turn around the resistor and connect the other end to pin 4. Connect the

second electrode to pin 8 and wrap around the resistor in the opposite direction to the first, terminating in pin 5. Care must be taken to insure that the two electrodes are adequately spaced from each other. The only electrical connection that exists between them is through the salt film. Solder the electrodes in place.

5. Apply a good heat sink compound to the thermister to insure thermal equilibrium with the resistor temperature. Then seal the ends of the resistor core with a silicon rubber sealer.

This completes the assembly of the humidity transducer and it is now ready for servicing preparatory for use.

The salt density tolerance is quite broad for phase transition hygrometers, but errors of several degrees have been observed with insufficient or excessive salt. This condition is controlled by developing and following uniform procedures for handling and servicing. The following procedure has proved to be close to optimum for this transducer.

A saturated solution of LiCl should be prepared in advance of the time it is to be used. For treating the transducer, mix 1 part by volume of saturated LiCl solution and 1 part distilled water. Using a dropper, apply enough to wet the fiber glass. Care should be taken to insure that the solution does not get on other parts of the transducer.

Ventilation of the transducer may be controlled by installing the ventilation shield (part of part 37). A hole is drilled through

opposite sides of the shield as shown in Figure 13. The amount of ventilation depends on the size and orientation of these holes. Usually the transducer is mounted so that the holes are in the vertical plane; thus temperature gradient within the unit will induce ventilation.

Periodically the transducer must be cleaned and retreated with LiCl. Before adding new LiCl solution, perform the following check to see if the cleaning is adequate. After washing, plug the wet transducer into the oscillator and control unit and observe the results. If the unit is clean, it will heat up until dry, then it will return to ambient temperature. If it does not return to ambient temperature, it is not clean.

CALIBRATION AND RESPONSE

Test method and calibration

The C-R Hygrometer operating characteristics are shown in Figure 14 which relates the dew-point temperature (the abscissa) to the transducer temperature (the ordinate). Data for Figure 14 were obtained by using an ice and water system in a closed chamber where temperature-rise throughout the range from -15 C to +30 C was less than 1 C per hour. Under these conditions the air was regarded as having reached the saturation vapor pressure condition at the temperature read by the thermometer.

The closed chamber contained:

1. A quartz thermometer temperature-sensing element
2. A humidity transducer
3. A pump for circulating the water as it became available from ice melt
4. An immersion-type electric heater
5. An air circulating fan
6. Truncated cones of ice made by freezing ice in 5 ounce paper cups.

The closed chamber was a military surplus freezer that had been used to store aluminum rivets for airplane construction or

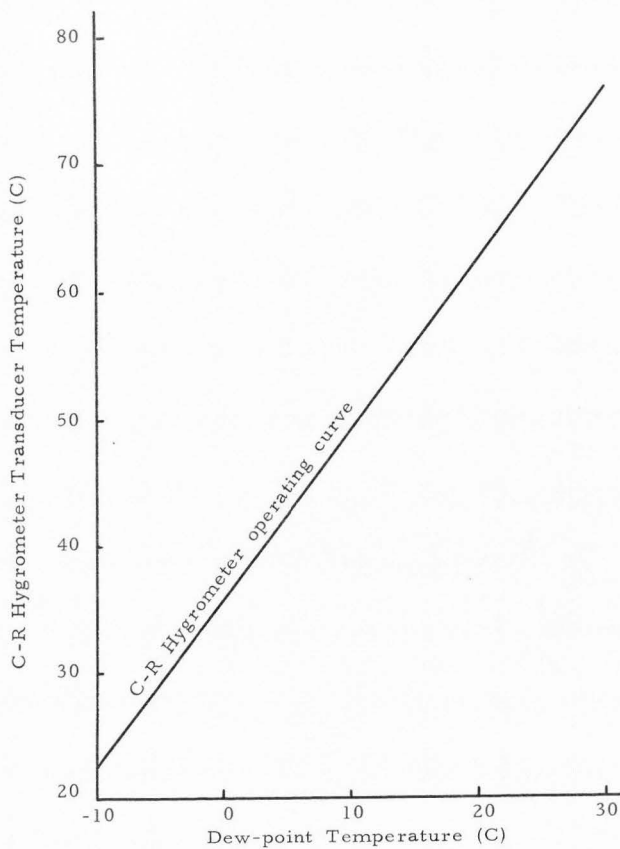


Figure 14. C-R Hygrometer characteristic curve showing relationship of hygrometer transducer temperature and the dew point of the environment in which it is operating

repair and was capable of producing temperatures as cold as -40 C .

The fan was placed to draw air from the bottom of the ice pack past the thermometer sensor and the humidity transducer, then blowing it back to the far end of the chamber. The thermometer was located so that it was in the air stream during the ice phase and immersed in the water as the ice melted. The humidity transducer was placed above the thermometer sensor just enough to be above the water when the ice melted.

The heater and pump were placed in the chamber at the beginning so that it would not require opening at any time during the calibration period.

Testing was started by cooling the chamber to -30 C , then allowing it to gradually warm. The results are reported above.

Hygrometer response

Figure 15 is the warm-up response curve for the hygrometer with the humidity transducer in a 0 C dew-point environment. The equipment had been turned off for a period of 15 minutes before starting this response curve.

Figure 16 was recorded under the same conditions as Figure 15 except the dew-point environment was 25 C . It was of particular interest to me to note that at the higher humidity (25 C dew point) the equipment required a longer time to warm up than at lower humidity (0 C dew point).

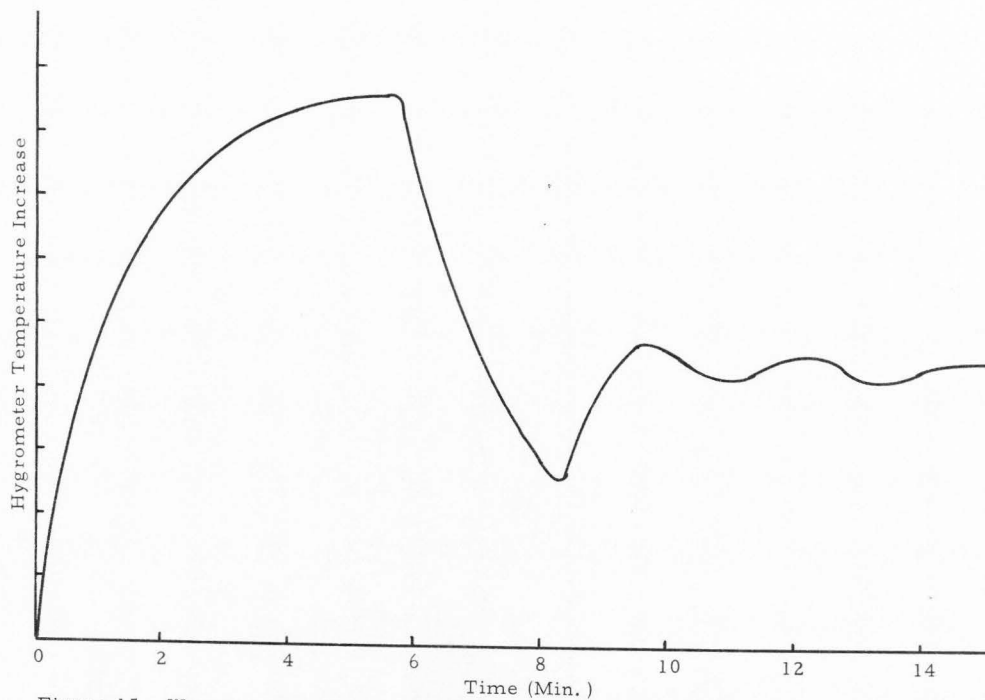


Figure 15. Warm up response curve for C-R Hygrometer with the humidity transducer in a 0 C dew-point environment

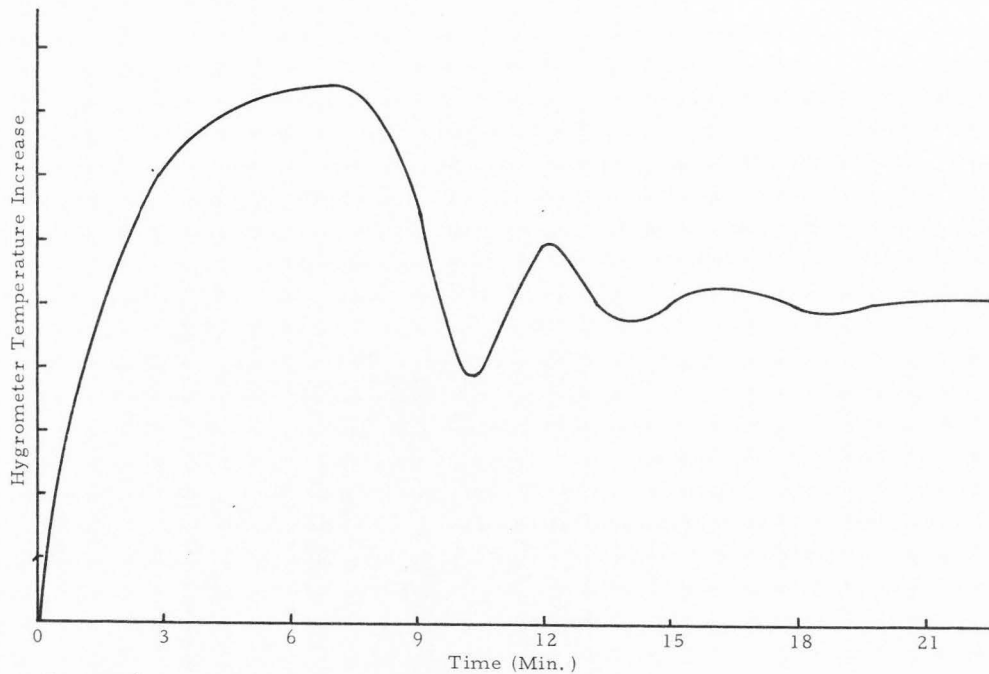


Figure 16. Warm up response curve for C-R Hygrometer with the humidity transducer in a 25 C dew-point environment

Figure 17A was obtained by turning off the power to the hygrometer until the resistance of the LiCl film was reduced to one-half its operating value. At this point the power was turned on and the time was indicated as time zero. Stability was achieved within four minutes. The curve in Figure 17 B was obtained by turning off the hygrometer power at time zero and leaving it off for 15 seconds. During this time the LiCl film resistance dropped to 80 percent of its operating value. The power was then turned on and stabilization was achieved within four minutes. Within this range of humidity transients the response time is more dependent on the transducer characteristics than on the magnitude of humidity transient.

Figure 18 is a transient response curve obtained with the humidity transducer in a 14 C dew-point environment. At time zero hygrometer power was turned off until the voltage across the LiCl film had dropped from 3 volts to 1.2 volts at Point A, at which time power was turned on. The sensor then heated to drive the excess moisture from the LiCl pad with thermal overshoot followed by cooling until it was able to attract enough moisture to start heating again. At that time the moisture content was low enough to follow a well damped path to the operating temperature. The voltage across the LiCl film at Point B was 2.7 volts.

Figure 19 was obtained with conditions identical to those for Figure 18 except the damping circuit was disabled. At time zero the power and damping circuit were turned off. At Point A the

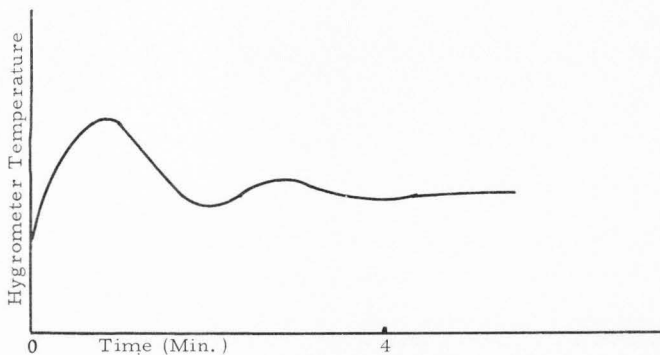


Figure 17 A. Transient response curve for C-R Hygrometer with humidity transducer in a 0 C dew-point environment

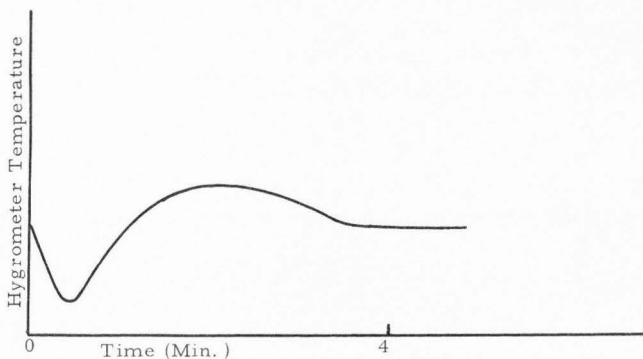


Figure 17 B. Transient response curve for C-R Hygrometer with the humidity transducer in a 0 C dew-point environment

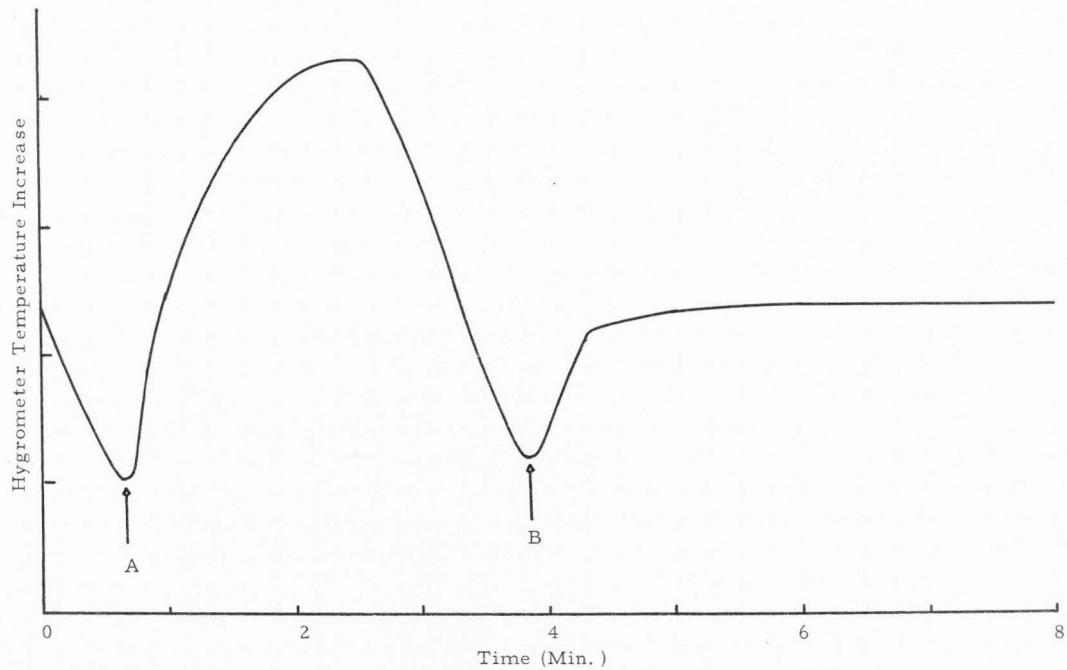


Figure 18. Transient response curve for C-R Hygrometer with the humidity transducer in a 14 C dew-point environment

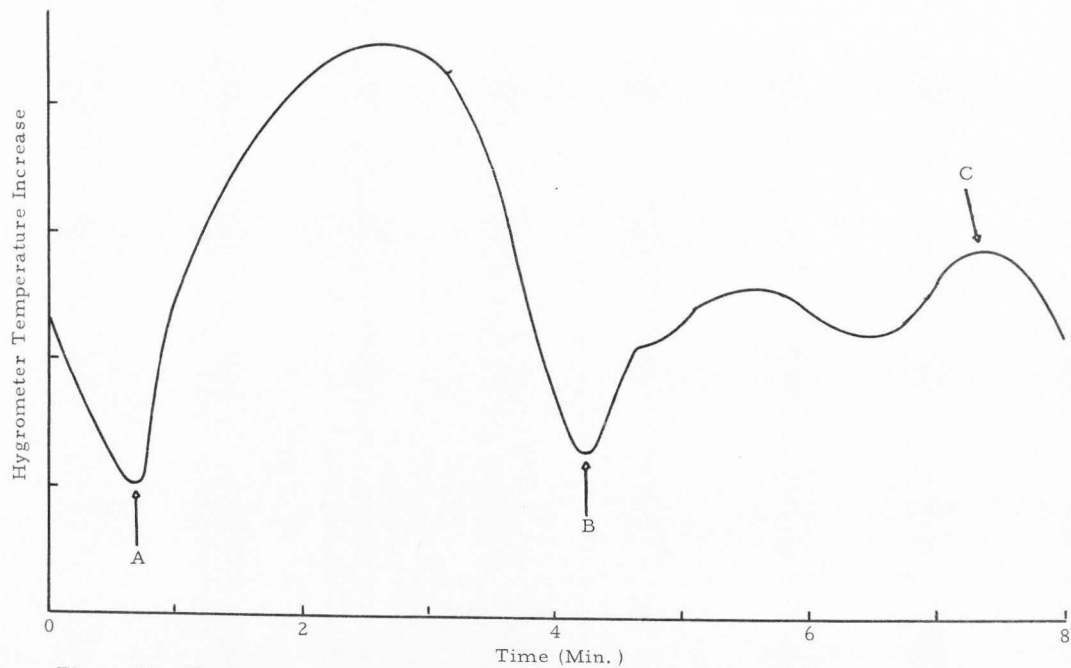


Figure 19. Transient response followed by oscillations in a lithium chloride phase transition hygrometer

voltage across the LiCl film had dropped to 1.2 volts as in Figure 18. Power was then turned on leaving the damping circuit disabled. The response was similar to Figure 18 except the initial heat-up lasted longer and the voltage at Point B was 3.1 volts instead of 2.7. The hygrometer oscillated with the LiCl voltage reaching 3.3 volts at Point C.

Figure 20 is a continuation of Figure 19. At Point D the voltage was 3.1 volts and at Point E the damping circuit was enabled, which promptly suppressed the oscillation.

To appreciate the condition causing oscillation, refer to Figure 8. In normal operation most self heating hygrometers operate with a LiCl film resistance below 5000 ohms and will have a ± 2 C tolerance on measurement accuracy. For high accuracy, however, operation on a steeper portion of the curve is desirable.

Moisture is driven outward through the LiCl pad. If an overshoot is encountered, a vapor deficit with respect to stable operation occurs. As soon as cooling starts the vapor deficit on the inside will take moisture from the surface, causing cooling below the stable operating point. This may be of such magnitude that stable operation cannot be achieved without a suitable damping device.

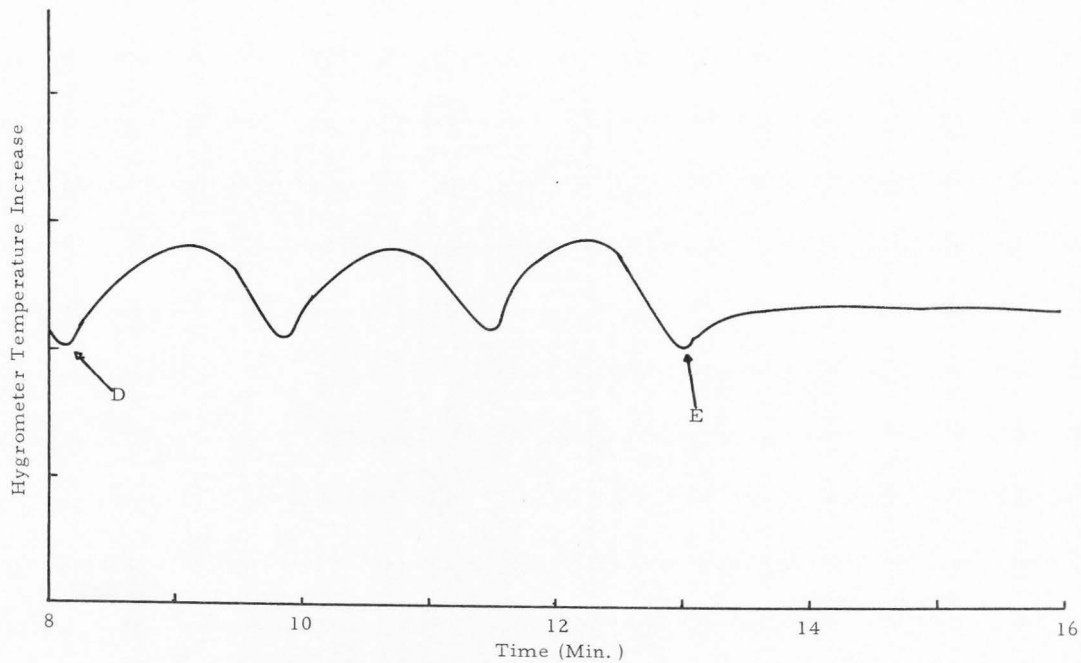


Figure 20. Recovery from oscillations in a lithium chloride phase transition hygrometer

SUMMARY AND COMPARISON

The performance characteristics selected for this project have been achieved as shown below in the comparison.

<u>Requirements</u>	<u>Achievements</u>
1. Dew-point range -10 to +30 C	1. The hygrometer provides stable operation in this range provided the relative humidity is not less than about 7 or 8 percent.
2. Operate from a 12 volt battery	2. This was accomplished. In addition, the unit has been operated from 120 volts a-c and 6 volts d-c with some simple modifications.
3. Power requirements of less than 0.75 watts	3. In a dew-point environment of 25 C the power required is 0.72 watts and decreases at lower temperatures.
4. Accuracy of ± 0.3 C dew-point sensing	4. This was accomplished. However, care in servicing and handling of the equipment is very important. Carelessness can

easily introduce 1 or 2 degrees error.

In addition to the achievements given above, we will now refer to Showalter's requirements and compare performance with the requirements for each item that he listed.

<u>Requirement</u>	<u>Comparison</u>
1. Have an overall accuracy equivalent to less than 0.3 C error in dew-point temperatures.	1. This item was tested and the equipment met the requirement.
2. Be stable in calibration and retain the above specified accuracy for periods of several months.	2. This was tested in field use for four months with 10 units. Calibration was checked on return to the laboratory. Nine units were within tolerance and one had thermister failure due to LiCl corrosion of the lead. This requirement was met.
3. Be capable of continuous unattended operation for weeks or even months.	3. This requirement was demonstrated.
4. Have lag independent of temperature.	4. This requirement was demonstrated in the response curves shown in Figures 15 through 20.

5. Read directly in terms of dew-point temperature.

6. Have a lag coefficient of not less than 30 seconds.

7. Have a dew-point range of +30 to -65 C with temperature between +50 and -60C.

8. Have few or no moving parts and have complete temperature compensation.

9. Have an output form satisfactory for use as input to an automatic data acquisition system.

5. This is a readout equipment choice and not part of the hygrometer design problem.

6. This requirement was demonstrated in the response curves shown in Figures 15 through 20.

7. This requirement as modified is shown in Figure 14.

8. This requirement was achieved as shown in the design of the equipment.

9. This requirement was accomplished in the design of the equipment and has been used with automatic data acquisition system. However, care at this point is essential if the accuracy designed into the hygrometer is to be retained.

FUTURE WORK

Extension of this work to provide greater accuracy and range present some very interesting and challenging problems. Some thoughts that have occurred to me are:

1. Could digital control techniques be adapted to this purpose?
2. Can stable operation be achieved in the LiCl film resistance range above 30,000 ohms?
3. Could a phase transition hygrometer be used in environment above 11 percent relative humidity and also adapt to a high resistance humidity sensor at lower relative humidity values?
4. What would be required to extend the range of this equipment to -65 C dew point? Or is this a good way to go?

With the vital role played by atmospheric moisture, its measurement and control are very elusive and much remains to be accomplished.

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APPENDIX

A variety of hygrometers were compiled and explained by Wexler (1963), and are summarized here. The identification he used is retained for reference purposes.

ISA NUMBER	MEASURAND	MEASURAND RANGE	OPERATING PRINCIPLE	OUTPUT CHARACTERISTICS	EXICATION
13-001	Relative humidity	5 to 99% R. H. in bands	Electrolytic solution	Resistance 20 K to 20 M	115 V, a-c
13-002	Relative humidity	1.5 to 99% in limited ranges	Electrolytic solution	Resistance 20 K to 20 M	115 V, a-c
13-003	Relative humidity	5 to 99%	Electrolytic solution	Resistance 20 K to 20 M	115 V, a-c
13-004	Relative humidity	0 to 100%	Dielectric constant	Voltage 0 to 50 mV	115 V, a-c
13-005	Relative humidity	0 to 100% R. H.	Ion exchange resin	Resistance 1 K to 50 M	20 V, a-c
13-006	Relative humidity	0 to 100% R. H.	Hair hygrometer	Pneumatic 3 to 15 psig	20 psig air
13-007	Dew point	-80 to +50 F	Dew point	Optical	Pressurized CO ₂

ISA NUMBER	MEASURAND	MEASURAND RANGE	OPERATING PRINCIPLE	OUTPUT CHARACTERISTICS	EXICATION
13-008	Dew point	-100 to +212 F dew-point temperature	Hygrometer platinum resistor sensor	Resistance	115 V, a-c
13-009	Dew point	-20 to +265 F dew-point temperature	Electrolytic solution	Resistance	25 V, a-c
13-010	Relative humidity	0 to 100%	Psychrometer	Resistance	5 ma
13-011	Dew point	-115 to +125 F	Thermo-electric	Thermocouple or Thermister	+12 V, d-c 16 W or 115 V, a-c
13-012	Dew point	-50 to +142 F	Dewcell	Resistance	24 V, a-c
13-013	Dew point	-50 to +142 F	Dewcell	Temperature	24 V, a-c 2 to 28 W
13-014	Dew point	-30 to +60 C	Dewcell	Resistance	30 V, a-c
13-015	Relative humidity	2 to 98%	Psychrometer	Resistance	110 V, a-c

ISA NUMBER	MEASURAND	MEASURAND RANGE	OPERATING PRINCIPLE	OUTPUT CHARACTERISTICS	EXICATION
13-016	Relative humidity	0 to 90%	Capacitance/ resistance change in porous coating	Impedance	a-c
13-017	Volume fraction	1 to 1000 ppm	Electrolysis	Voltage 0 to 100 mV	115 V, a-c
13-018	Volume fraction	1 to 1000 ppm	Electrolysis	Voltage 0 to 100 mV	115 V, a-c
13-019	Volume fraction	1 to 1000 ppm	Electrolysis	Voltage 0 to 100 mV	115 V, a-c
13-020	Volume fraction	0 to 1000 ppm	Electrolysis	Voltage 0 to 100 mV	115 V, a-c
13-021	Volume fraction	0 to 10 ppm and 0 to 1000 ppm	Heat of adsorption	Voltage 0 ± 1 mV	115 V, a-c
13-022	Weight fraction	1 to 1000 ppm	Electrolysis	Voltage 0 to 10 mV	115 V, a-c
13-023	H ₂ O by weight	1 to 100 mg/g	Electrolysis	Voltage 0 to 10 mV	115 V, a-c

ISA NUMBER	MEASURAND	MEASURAND RANGE	OPERATING PRINCIPLE	OUTPUT CHARACTER- ISTICS	EXICATION
13-024	Relative humidity	5 to 99% R. H.	Electrolytic solution	Resistance 20 K to 20 M	115 V, a-c