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Application Information on Typical Hygrometers Used in Heating, Ventilating and Air Conditioning (HVAC) Systems

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
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Prepared for
Civil Engineering Laboratory
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James Y. Kao
William J. Snyder

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U.S. DEPARTMENT OF COMMERCE, **Malcolm Baldrige**, ***Secretary***
NATIONAL BUREAU OF STANDARDS, **Ernest Ambler**, ***Director***

ABSTRACT

This report provides hygrometer selection information for application in heating, ventilating, and air-conditioning (HVAC) systems. A general review of hygrometer literature has been provided and the most commonly used ones for HVAC are discussed. Typical hygrometer parameters are listed to indicate the type of performance that can be expected. Laboratory test results of self-regulating, salt-phase transition hygrometers are presented and discussed in detail.

Key words: building energy monitoring; heating, ventilating, and air conditioning controls; humidity; humidity control; humidity measurement; humidity sensor; hygrometer.

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1. Introduction

A wide variety of hygrometers are available to the engineer who is designing or retrofitting HVAC systems. Unfortunately, there is no single hygrometer on the market today that maintains high accuracy and fast response over the full range of humidity. Thus, the engineer must examine the measurement problem in terms of performance criteria such as span, accuracy, response time, sensor lifetime, contamination effects, maintenance and recalibration requirements.

Several excellent handbooks and references [1-10]* address the general problem of hygrometer selection but do not emphasize the HVAC application. Therefore, the intent of this report is to describe realistic performance requirements, to establish correct maintenance schedules, and to identify sensor development areas for humidity sensors in HVAC applications. This report will primarily be concerned with humidity measurements, but will briefly discuss temperature measurement, since temperature is often a hygrometer's output signal. Because of the myriad of hygrometers available, only those hygrometers currently used in HVAC applications will be discussed in detail.

The energy consumption of buildings, depends to a large extent, on the proper design and operation of the HVAC systems. Hygrometers used for controlling outside air economizer cycles and for controlling humidifiers may affect the building energy usage substantially.

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* Numbers in brackets indicate references cited at the end of the report.

In this report, a general literature survey of hygrometers is presented to develop a background and create an awareness of sensor types, characteristics and problems. The detailed characteristics of hygrometers currently being used in HVAC systems are discussed with regard to performance. Finally, information for hygrometer selection and maintenance is presented.

2. General Humidity Sensor Survey

2.1. Classification of Hygrometers

Most hygrometers use the principle of changing physical characteristics caused by the absorption and desorption of water molecules on a surface. A change in electrical impedance, ion exchange capacility, dielectric strength, density, or polarizability can be used to indicate the sorption of water molecules.

There are many types of resistive hygrometers. Some depend on the change in resistance or conductivity of an ionizable hygroscopic salt with humidity. The most commonly used salt is lithium chloride (usually less than 5% by weight).

Capacitive hygrometers use a thin film of hygroscopic material as a dielectric of a capacitator. The capacitance of the hygrometer changes with the humidity of the air (actually changes with the partial pressure of water in the air). Impedance hygrometers such as aluminum oxide are based on the change of electrical impedance (both resistive and capacitive) of the sensor with humidity.

Mechanical sensors rely on a change in dimension with sorption of water molecules. Organic materials such as nylon, paper, organic skin membranes and hair are commonly used. As an example, human hair (under a one-gram tensile load) expands in a nonlinear manner with increasing humidity at approximately 1.3 x 10^{-6} to 10 x 10^{-6} meter per meter for 1% of relative humidity change [10].

Spectroscopic hygrometers do not require a surface to sense humidity since they depend on the absorption of electromagnetic radiation by water molecules in the vapor state. The radiation may be infrared, ultraviolet, visible or in the microwave region.

Piezoelectric detectors consist of a crystal coated with a hygroscopic material. As the hygroscopic material absorbs water from the ambient, the oscillating frequency of the crystal changes. This frequency change is detected and is used as a measure of ambient relative humidity.

Measurement of humidity by a gravimetric method is considered as a primary standard [5] because only mass and volume are measured. Although gravimetric methods have the greatest accuracy (approximately 1% mass and volume), this method is difficult to use as a continuous measure of moisture in air conditioning systems.

Psychrometers give an indication of humidity from a measurement of wet-bulb and dry-bulb temperatures. They depend upon the cooling of a wetted temperature sensor by an air stream. To obtain accurate readings the air stream should flow across the wet wick at 3 to 5m/sec. The main advantage of psychrometers is simplicity but the data must be reduced by using the psychrometric equation or tables. The psychrometer accuracy deteriorates at high dry-bulb temperature and low relative humidity, unless precautions are made to reduce the wet-bulb measurement errors caused by radiation and conduction. The accuracy also decreases if the wick becomes contaminated but can be regained by cleaning or replacing the wick. Although the psychrometer can be used in most ambient conditions, it is difficult to obtain measurements with good accuracy when the wet-bulb is below 0°C.

The last category of hygrometer is the condensation-type dew-point detector. This hygrometer uses thermoelectric, mechanical or other means to cool a mirror until the water vapor in the ambient or sampling air condenses. The temperature of the mirror surface is measured and this temperature is the dew-point temperature of the air. The observation of condensation forming on the mirror is done visually, by optical instruments, or by other means. The accuracy of this hygrometer is within ± 1°C in the temperature and humidity range of HVAC application. Automated systems are available.

2.2. Hygrometer Characteristics

There are a vast number of humidity-measuring devices. They are generally classified as aluminum oxide, carbon, cellulose, chromatographic, Dacro thread, dew point, Dunmore, Goldbeater skin, gravimetric, hair, ion exchange, magnetic, nylon, piezoelectric, Pope, psychrometric, salt-phase transition, semiconductor, single ionic crystal, and spectroscopic. The important parameters for hygrometer selection are humidity span, temperature range, accuracy, drift, hysteresis, response time, contaminant effects and maintenance.

Currently, no single hygrometer is available which will operate over the complete humidity range with a constant high accuracy. Also, all humidity sensors are susceptible to contamination, which changes accuracy, response time and life expectancy. This change may be irreversible depending on the the concentration level and exposure time to the contaminant.

Psychrometers, self-regulating saturated salts, dimensional change, and most electrical impedance-type humidity sensors are generally useful for mid-range temperature and humidity applications. Electrolytic hygrometers are suitable for low dew point ranges. Condensation dew-point hygrometers cover a wide range of temperature and humidity. The gravimetric method gives the most accurate measurement. Condensation dew-point hygrometers generally yield more accurate results than most other sensors, such as electrical impedance, saturated salt, or dimensional change type. In actual practice, accuracies are also affected by contaminants on the sensor or in the sample lines where air sample lines are used. In addition, the desired accuracy determines the required maintanance and recalibration schedule. Effects of typical contaminant levels on sensor response times are usually negligible in HVAC operations unless sensor damage is involved.

3. HVAC Applications

3.1. Self-Regulating Salt-Phase Transition Hygrometer

Operating Principles. A thin-walled metal tube is wrapped with a cloth sleeve impregnated with a hygroscopic salt such as lithium chloride. A bifilar winding of two electrodes is wound outside the cloth sleeve and is connected to low voltage alternating current. An equilibrium temperature is reached when the rate of moisture absorption of the salt equals the moisture evaporation due to the heat generated in the salt by the electric current.

This temperature is related to the partial pressure of the water vapor content and the dew point of the air. Therefore, this temperature is measured to relate the dew point. Theoretically, this hygrometer does not need calibration if the salt is not contaminated.

Performance. The operating range of this hygrometer is between -40°C and 70°C dew point and is limited to relative humidity above 11%. The typical error is ±1.5°C dew point above -5°C; it may go as high as 3.5°C below -5°C. The response time depends on the dew point of the air. For dew points above 5°C, the response time (63%) is usually below 3 minutes.

Calibration and Maintenance. Like any other measuring equipment, the hygrometer should be calibrated prior to purchase acceptance. Most hygrometers need to be calibrated periodically after they are installed. The interval of calibration of this type depends on the quality and the stability of the thermometer, and the quality of the air the sensor is required to measure. The calibration includes calibrating the temperature sensor and checking the salt element temperature against the temperature-dew point curve. When its salt element is exposed to humid air, the hygrometer should always be energized (element heated) so that the element will not absorb excess amounts of moisture causing the salt solution to run off. Retreatment of the salt element is necessary if sensor current is interrupted for a prolonged period of time, since the salt element may absorb excess moisture or become contaminated. The retreatment intervals depend on the air quality the element senses and may range from 100 days to twice a year. Retreatment usually is done by washing off the contaminated salt, applying fresh salt solution and drying off at approximately 85°C.

Installation Precautions. Excessive air velocity, above 15 meters per minute, at the salt element may reduce the temperature at the thermometer and give lower dew point readings [3]. Some manufacturers recommend using shields. When installed outdoors, a weather hood should be provided to protect the sensor from contacting rain water. Condensation on the salt element may change the calibration. Sensor locations should be avoided where the following contaminates are present in the air: hydrogen sulfide, sulfur dioxide, acid vapor, chlorine, ammonia, alkaline vapors, acetylene, ethylene oxide, salt-contaminated air, alcohols, and glycol vapors.

Failure Modes. Total failure of this hygrometer is not frequent but drifting of readings due to salt element contamination is common.

Building HVAC Suitability. Since the dew point is actually measured by temperature, this type of hygrometer is easily used in HVAC systems to sense the outdoor dew point. The lower range of 11-15% rh of the instrument should not be a limiting factor in building HVAC applications. Since the response time is slower than some other hygrometers, it may not be suitable for space dew point monitoring where the humidifier response needs to be fast, such as for the dry steam type humidifier. Frequent maintenance is required.

3.2. Impedance Type Hygrometer

Operating Principles. There are various arrangements and materials in construction of this kind of hygrometer. Some are based on the principle that the electrical resistances and/or capacitances of certain hygroscopic materials change with the concentrations of the material. Others are based on the fact that the electrical resistances and/or capacitances of the surfaces of certain materials vary with the moisture they absorb. Since the moisture absorption and adsorption are functions of the relative humidity of the space, the electrical impedance is measured to indicate the space relative humidity. The effect of temperature must be corrected for in some transducers, because temperature variations usually also change the electrical impedance. However, some sensors are practically independent of temperature in the temperature range of HVAC application. Multiple sensors covering different ranges and wide range single sensors are available. Alternating current circuitry is often used in the measurement to avoid polarization of the sensors.

Performance. The performances vary widely among the sensors of this type because of the diversified arrangements and materials used. Individual hygrometer performances should be examined for each application. Sensors covering the general range of 10% to 99% rh and in the HVAC application range of dry bulb temperature are numerous. The response time is much shorter than the salt-phase transition type hygrometer, ranging from a few seconds to less than a minute (63% change) with an adequate ventilation rate at the sensor. Dunmore type (electrolytic) hygrometers may be used in the range of 2% to 99% rh and have accuracies of ± 1.5% rh. Aluminum oxide (surface resistance and capacitance) hygrometers may be used between 5% and 100% rh with accuracies of ±3% rh. These sensors are not significantly affected by temperature. Dielectric film (capacitance) hygrometers are usually in the range of 20% to 80% rh. The accuracy may be no better than ±5% rh. The errors in impedance type hygrometers are due mainly to repeatability and hysteresis.

Calibration and Maintenance. Performance of these types of hygrometers is determined empirically, and they must be calibrated individually to ensure their accuracy. As with the salt-phase transition type hygrometers, the recalibration period depends on the air quality and sensor handling techniques. A proper calibration schedule should be established by observing the drift characteristics with short calibration intervals at the beginning. Calibration in laboratories can be done by: (a) generating humidity at known levels, such as two-pressure systems; or (b) using saturated salt solution chambers where the humidity level is known for a certain temperature. Calibration services for transfer standards are available from the National Bureau of Standards and other standards laboratories. Field calibration, which may be more suitable for HVAC systems, may be performed by using a recently laboratory calibrated hygrometer as a transfer standard. Some hygrometers have temperature sensors for correcting temperature effects. They should be calibrated according to their requirements. Other than calibration and maintenance of any filter equipment, these sensors require little maintenance.

Installation Precautions. Humidity sensors should be handled carefully so that they will not be damaged or contaminated. Chemical contamination by acids, sulfur compounds, or certain solvents may damage the sensors or shift their calibrations. In locating hygrometers for outdoor air humidity sensing, locations near cooling towers, boiler stacks or other chemical exhausts should be avoided. Since condensation or water may shift the calibration of some sensors of this type, rain protection should be provided.

Failure Modes. Total failure is not frequent but drifting of readings due to sensing element contamination is common.

Building HVAC Suitability. Depending on the humidity range, some sensors are not suitable for outdoor use, such as the dielectric film capacitance type. The wide-range Dunmore type can be used in either outdoor, duct, or space sensing. The fast response of these hygrometers allows them to be used for any type of building humidification control.

Some operating characteristics of often-used impedance-type hygrometers are detailed below.

3.2.1. Dunmore Relative Humidity Sensor

This hygrometer is often made up of several humidity sensing elements. Each element has electrodes and is painted with hygroscopic material such as lithium chloride. The hygroscopic material responds to the change of the ambient humidity and changes the electrical resistance. Since each element can cover only a narrow range of humidity, the elements are usually combined and electrically conditioned to cover a wide humidity range to suit its specific application. The electrical resistance of the sensors are usually also sensitive to ambient temperature change, some hygrometers have temperature compensation arrangements to reduce temperature influence. Hygrometers of this kind may be found to cover the humidity range between 2% rh and just below saturation and in a temperature range of the entire HVAC applications. The accuracy is ± 1.5°rh and is subject to the direction and magnitude of the ambient air humidity changes. The calibration may change 1 to 2% rh per year operating in a clean environment. This drift may be corrected by recalibration and adjusting of transducers. If the sensor is calibrated with a psychrometer, agreement should not be expected to be less than ± 3%. Temperature fluctuations in the dry or wet bulb, and humidity gradients (stratifications) can result in variations of 10% rh. A secondary transfer standard should be used for calibration accuracy less than ± 2%.. Lead wires should be included with the hygrometer during calibration.

In moving air the response time (63% change) to a step input in rh at 25°C is approximately 40 seconds. The response time increases with decreasing temperature and is approximately 3-5 minutes at 5°C or 10 minutes at -18°C. This type of sensor will lose its accuracy if subject to saturated humidities. Therefore, applications which may subject the sensor to condensation should be avoided.

3.2.2 Aluminum Oxide Sensor

A porous metal surface absorbs and desorbs water molecules when the ambient vapor pressure changes, and this in turn changes the electrical capacitance and resistance of the metal surface. This principle may be used to measure the ambient air dew point. Aluminum oxide sensor uses a strip of anodized aluminum where the porous surface is created. One manufacturing process is to deposit a thin film of gold over the oxide layer, thus the aluminum core and the gold flim form the two electrodes. When water vapor diffuses through the gold flim into or out of the aluminum oxide, the impedance is changed and this output is calibrated to indicate the air dew point.

The performance varies between manufacturing processes and makes. Generally, these hygrometers may be used below a dew point of 70°C to much lower (-100°C frost point). The response time (63%) is on the order of seconds. At high relative humiditiy (say over 90% rh), the response is slower. The user should consult manufacturers on the details of other properties.

3.3. Dimensional Change Hygrometer

Operating Principles. Many hygroscopic materials change length or volume when responding to the relative humidity level of the air. Examples are hair, wood, paper, and cellulose.

In one group of hygrometers, using a coating of carbon particles or impregnating carbon particles in such materials, a change in the electrical resistance of the sensor (corresponding to the change of its dimensions) results with a change in humidity. Since the electric conductivity is due to electronic rather than electrolytic effects, there is little polarization of the sensor and either AC or DC excitation may be used. The following discussion concerns this type of carbon sensor.

Performance. The sensitivity is low at low relative humidity. It increases gradually after approximately 40% rh. The useful range is somewhere between 20% and 90% rh. Hysteresis averages about ± 3% rh with higher values in the lower humidity range. Typical accuracy is no better than ± 5% rh and the response time (63% of change is typically less than one minute.

Calibration and Maintenance. Calibration should be performed frequently, perhaps every three to six months. Since the resistance of the carbon sensor is also temperature dependent to some extent, the hygrometer should be calibrated for the existing site temperature range. No other maintenance is required.

Installation Precautions. General installation precautions for all humidity sensors should be observed, i.e., avoiding locations where temperature variation is large and air quality is poor.

Failure Modes. Similar to other type of hygrometers in that total failure of the hygrometer is not frequent but drifting of readings due to sensing element contamination, such as from dust, is common.

Building HVAC Suitability. This type of hygrometer is suitable for space and return duct installations because of its fast response and relatively maintenance free (except for calibration) characteristics.

4. Sensor Performance

4.1. Factors Affecting Performance

How close a given moisture-in-air level can be measured and maintained depends upon how good the existing instrumentation techniques are. In general, moisture is measured by wet and dry bulb temperatures, dew point temperature or relative humidity. Instrumentation accuracy depends on the method employed and varies with the inherent accuracy of the measurement of temperature, position, and/or electrical resistance or capacitance. The accuracy of the humdity sensor system is a combination of the inherent accuracy of the method and the operational error, i.e., drift of readout instrument, sensor history, temperature/humidity range, excitation voltage changes, noise, contaminant effects, air flow, and geometric parameters (heat and mass transfer). A convenient classification of these variables is shown in table 1. Figure 1 shows a typical sensor system from the sensor to the indicator and all its intermediate stages.

To aid in the identification of sensor development areas for research, the characteristics of an "ideal" sensor are listed in table 2 (partly adapted from reference [11]). Currently there is no commercial sensor which can satisfy all of these requirements.

4.2. Definition of Performance Terms

In assessing the performance of hygrometers, it is useful to state some important definitions that relate to their characteristics [12].

Accuracy - The degree of conformity of the measurement to a primary standard reference. An estimate of accuracy is usually made by summing the known sources of error such as drift, precision and reproducibility measurements.

Calibration Precision - The variance of calibration data about the best fit calibration curve.

Calibration Reproducibility - The variance between calibration data obtained at different times during the instrument operational period.

Drift - A gradual deviation from a set position.

Drift Rate - The time rate of change of a signal from a set position.

Effective Range - The instrument range over which a single calibration curve gives sufficient calibration precision.

Error - The difference between the instrument reading and the reading of a calibrating standard.

Non-Linearity - The maximum deviation between an actual instrument reading and the reading predicted by a straight line calibration drawn over the extent of its range.

Precision - The degree of exactness of the instrument expressed as the reproducibility that can be demonstrated by repeated measurement of the same sample. Specifically the degree of agreement between repeated measurement of the same sample expressed as the standard deviation of the single results from the mean.

Range - The maximum and minimum mensuration limits of humidity.

Reproducibility - The ability to obtain the same output for a fixed input measured at intervals over a period of time. Estimates of reproducibility are influenced by the reproducibility of the calibration.

Response Time - The time for an instrument to reach a new equilibrium or steady-state value.

Sensitivity - The instrument output per unit input performance.

Span Drift - The change in instrument sensitivity at full range over a stated period of time normally determined together with zero drift.

Stability - A measurement of the instrument drift over a short time or long time period.

Temperature Coefficient - The change in instrument ouput per unit temperature change.

Tolerance - Permissible error that is acceptable, normally specified as a percent of the full scale reading.

Zero Drift - The change in instrument output at zero input over a stated time period obtained through unadjusted continuous operation or by a comparison of successive calibration data.

4.3. Measured Performance of Lithium Chloride Self-Regulating Salt-Phase Transition Dew Point Sensors

In order to obtain more application information on hygrometers used in HVAC, two of the commonly used sensors (LiCl self-regulating, salt-phase-transition, designated as sensor numbers 1 and 2) was studied to determine typical values of the parameters affecting performance. The results of these measurements are discussed in this section.

4.3.1 Calibration Procedure

A self-regulating, lithium chloride dew-point sensor (sensor number 1) was calibrated in the NBS two-pressure generator [6]. Table 3 shows the dry-bulb temperatures, relative humidities, and corresponding dew points in the calibration chamber, and the millivolt outputs of the sensing bobbin cavity temperature as measured by a type T thermocouple. Table 4 shows a second calibration of the same sensor after 55 days of exposure to various static humidity conditions and low levels of sulfur dioxide and ammonia contamination, which will be discussed later. The second calibration was also performed using the same method. Comparison of tables 3 and 4 indicates that the sensor output has decreased after the 55-day exposure period. Figure 2 shows the bobbin cavity temperature and dew point curves for these calibrations. The thermocouple sensing junction was located at 3.8 cm from the bottom of the bobbin cavity. This thermocouple location gave the highest temperature readings within the cavity. More discussion of the cavity temperature measurement is given in the next paragraph and in paragraph 4.3.4.

4.3.2. Temperature Sensing Location Test

As discussed previously, the self-regulating lithium chloride dew point sensor is based on the principle that the water vapor pressure in the ambient air balances the water vapor pressure of the salt solution reflected by the temperature of the salt. Therefore, it is important to measure the salt solution temperature as close by as possible. The most feasible location for the temperature measurement, of course, is inside the bobbin cavity. It should be noted that there is a temperature gradient along the longitudinal axis of the cavity ranging between the close-to-salt temperature and the atmospheric temperature. This temperature difference may reach 50°C when the atmospheric temperature is high and close to saturation. A test was performed by using two thermocouples to compare the temperature differences at the bobbin bottom wall and 0.038 m distance from the bottom inside the bobbin cavity. This 0.038 m- distance was determined by preliminary tests to locate the highest temperature location inside the bobbin. Figure 3 shows the millivolt output differences of the thermocouples between these two locations as compared to atmospheric dew points at a relative humidity of approximately 70%.

4.3.3 Static Humidity Drift Test

To measure sensor stability and response time in clean and contaminated environments, a static humidity apparatus (figures 4, 5, 6) was constructed. Various saturated salt solutions (tables 5 and 6) were agitated by a magnetic stirrer and maintained at a constant temperature [13]. Two identical bell jars with different salt solutions were used to provide step changes in humidity to determine response times. The static humidity test apparatus was placed in an environmental chamber with temperature and humidity controls to minimize the effect of temperature and humidity conditions between the inside and outside of the bell jars. The humidity level, exposure time, air temperature inside the bell jar, saturated salt solution temperature, and environmental temperature and humidity were recorded. The static test apparatus included an injection port for introducing sulfur dioxide or amonia as contaminants. The results of the tests are discussed in paragraph 4.3.4.

4.3.4. Results and Discussion of Sensor Tests

The sensor characteristics determined from the NBS calibrations, the temperature-sensing location test, and the static humidity tests are presented in terms of the sensor parameters.

(a) Temperature Effect and Accuracy

There should be no marked temperature effect on self-regulating lithium chloride sensors as the vapor pressure of the atmospheric air determines the salt solution temperature. The apparent temperature effect shown in figure 2 was probably caused by failure to fine-tune the precise location of the cavity temperature-sensing location and by the thermocouple wire conduction loss. When the bobbin was new (first calibration), figure 2 indicates that the indicated dew point temperature was within 1°C of the calibration curve.

(b) Hysteresis

No clear trend of hysteresis may be concluded from the test data. As shown in tables 3 and 4, the cavity temperature of the new sensor was slightly higher for decreasing humidity than for increasing humidity, and the trend was reversed when the sensor were contaminated, but the magnitude of the differences was well within the experimental error.

(c) Response Time

Response times (63%) in still air were determined by moving the sensor from one bell jar to another at different humidity levels. The response times are summarized in tables 7, 8, and 9, which show that at different dry-bulb temperatures and relative humidity the response time are much scattered. The average values of rising humidity changes were 2.65 minutes for sensor number 1 and 4.01 minutes for sensor number 2, and the average values of falling humidity changes were 3.41 and 6.93 minutes, respectively.

In most cases, the response time for decreasing humidity was longer than for rising humidity change. The considerable response-time difference between the two sensors tested was probably caused by the bobbin retreating procedures. Comparing data of table 7 and 9, it does appear that the response times were altered considerably by the introduction of contaminants. It should be mentioned that the effect on the response time by exposing the sensors at room humidity for a very short time between the two jar humidity levels was not investigated.

(d) Drift

Figure 2 shows the difference between the two calibrations for sensor number 1 which was exposed to 55 hours of cycling humidities of 11 to 97% rh and less than 5 ppm sulfur dioxide and ammonia. The slope of the calibration curve changed in such a way that higher errors occurred at higher dew-point temperatures. The drifts were approximately 1.7°C, 2.3°C, and 3.0°C at 10°C, 20°C, and 30°C dew-point temperature, respectively. Assuming that this drift is uniformly distributed over the 55 days, a drift rate of 0.07°C/day at 20°C dew point is expected. This result would be considered a short-range drift. The sensor exposure times are shown in table 10.

(e) Location of Temperature Sensing

Figure 3 indicates that at approximately 70% rh and 26.7°C dew-point temperature, the difference in millivolt output of the microvoltmeter between the two thermocouple junctions (one at the bobbin bottom wall and the other at 3.8 cm from the bottom) was .46 mv, which was equivalent to 11.2°C in cavity temperature and 7.6°C in dew point. Resistance thermometers and filled bulbs are also commonly used for these temperature measurements. These higher thermal mass devices average the cavity temperature over a larger space, thus reducing the importance of the temperature-sensor location. On the other hand, they compromise the measurement accuracy and response time.

4.4. Temperature Measurement

Many humidity sensors have a temperature output which is related to humidity. For example, an optical dew-point hygrometer indicates the condensation temperature; a psychrometer indicates wet and dry-bulb temperatures; a self-regulating lithium chloride sensor uses a thermocouple or a resistance thermometer for cavity temperature measurement as discussed above. Thus, the errors associated with temperature measurement are coupled to the errors in humidity measurement. Discussion of these errors may be found in many temperature measurement publications and should be consulted for the evaluation of humidity sensors having temperature as output.

5. Sensor Selection and Maintenance

In selecting a sensor for HVAC applications, the required accuracy, initial purchase cost, maintenance, and calibration costs must be considered. For example, optical condensation hygrometers have a high initial cost of approximately $2,000 - $4,000, but provide high accuracy. Only a cost-effective study can determine the correct sensor alternative for the application. Most selections are often based on the initial cost alone (usually related to degree of accuracy) and do not consider the cost of energy, maintenance and calibration. Because the life-cycle cost difference can easily be greater than the purchased cost difference, the correct sensor should be chosen by a benefit/cost analysis. With this principle as a basis, a sensitivity analysis should be performed to evaluate the energy consumption difference caused by possible sensor errors. Although energy consumption of HVAC systems are building, system and climate dependent, it is probably true that better quality sensors should be used for humidifying and dehumidifying controls. On the other hand, humidity sensors used for enthalpy control may be of lesser quality, since the yearly energy effect of these sensors is generally less than those for humidifying controls.

Psychrometers are usually the lowest cost instruments, followed by saturated-salt dew-point hygrometers, electrical rh sensors, aluminum oxide, electrolytic, optical condensation hygrometers, and finally infrared, which is the highest cost.

All humidity sensors require routine maintenance, the periodicity depends on the environment and the type of the device. For example, a psychrometer needs wick changes periodically and a routine inspection of the water supply system. Otherwise, contaminated wick gives higher wet-bulb readings. Aluminum oxide, electrical rh sensors (Dunmore, Pope) must be periodically recalibrated or have the elements replaced. Most lithium chloride cells lose their calibration after exposure to high humidity or excessive contaminants. Some sensors can be cleaned and resensitized. Since the performance of most of the humidity sensors is affected by the amount of particulate and pollutants in the local air where the sensors are located, it is important that an estimate of the air quality be made in establishing initial maintenance and calibration schedules. Permanent maintenance schedules may be determined when a calibration history is established.

6. Conclusions

A literature search and a laboratory investigation have been conducted to provide information for the application of humidity sensors for HVAC systems. The following conclusions, specifically with regard to a self-regulating lithium chloride dew-point sensor, can be stated:

A. The laboratory tests indicated that between approximately -10°C and 30°C dew-point, the self-regulating lithium chloride dew-point sensors exhibited errors of ± 1°C when new and over ± 3.0°C after 55 days of operation and exposure to low level of contamination. There was no clear trend on hysteresis. The average response time (63%) of the sensors tested in still air was about four minutes.

B. The location of temperature sensors in the bobbin cavity of self-regulating lithium chloride dew point sensors is very important. Error of over 7°C of dew-point may result if the temperature sensor is not appropriately located.

C. Humidity sensor selections should be based on life-cycle costing, including accuracy and energy sensitivity analysis.

D. It is important that humidity sensors be calibrated and maintained periodically to reduce possible errors.

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Table 1. Classification of Factors Affecting Humidity Sensor Performance

Intrinsic

- Response Time
- Temperature Coefficient
- Hysteresis
- Drift
- Age

Operational

- Internal Heat and Mass Transfer
- Air Flow
- Maintenance
- Sensor Orientation
- System Geometry
- Temperature
- Pressure
- Humidity
- Time (History)
- Direction of Change in Operational Variables
- Excitation Level
- Calibration Method
- Type of Output Device, Signal Conditioning, and Transmission

Environmental

- Vibration and Shock (thermal and mechanical)
- Contamination
- Condensation

Table 2. An "Ideal" Humidity Sensor

1. Error of less than the equivalent of 0.3°C in dew point temperature.
2. Stability (remain in calibration) for several months.
3. Immune to common atmospheric contaminants.
4. Continued unattended operation for months.
5. Lag independent of temperature.
6. Output
    a. Directly in terms of dew point temperature
    b. Independent or insensitive of temperature and pressure changes
    c. Satisfactory output form for data acquisition
7. Fast response.
8. Dew point range +30 to -65°C at temperatures of +50 to -60°C.
9. Few or no moving parts and complete temperature compensation.
10. Low weight and power requirements (less than 2 watts).
11. Packaging should not be moisture sensitive.
12. Long lifetime, easy maintenance, replacement and recalibration.
13. Remote capability.
14. Compatible with control strategy or objective function of control system.
15. Easy verification or debug system.
16. Insensitive to vibration.
17. Low Cost

Table 3

First Calibration of Self-Regulating Lithium Chloride Dew-Point Sensor Number 1

Temp. °C	RH %	Dew Pt. °C	Output Reading mv
32.8	18.8	6.0	1.690
32.8	32.2	14.1	2.130
33.0	54.8	22.7	2.657
33.1	74.2	27.9	3.127
33.1	94.8	32.1	3.494
32.3	93.7	32.1	3.497
33.2	74.1	27.9	3.138
33.1	54.6	22.7	2.678
32.9	32.2	14.1	2.140
25.7	33.3	8.3	1.780
25.8	54.7	16.0	2.235
25.9	73.8	20.9	2.643
25.8	95.0	24.9	3.007
25.9	75.4	21.2	2.668
25.9	57.4	16.8	2.352
25.7	33.3	8.3	1.785
25.7	33.2	8.3	1.784
25.5	33.6	8.3	1.776

Table 4

Second Calibration of Self-Regulating Lithium Chloride Dew-Point Sensor Number 1

(55 Days After First Calibration)

Temp. °C	RH %	Dew Pt. °C	Reading mv
5.10	19.43	-16.39	.427
5.08	33.61	- 9.64	.685
5.10	75.36	1.11	1.254
5.10	98.49	4.89	1.505
5.10	75.55	1.14	1.258
5.09	33.63	- 9.62	.693
5.10	11.22	-22.79	.291
25.06	19.31	0.06	1.291
25.06	32.66	7.53	1.619
25.06	32.69	7.54	1.622
25.06	57.62	16.12	2.109
25.06	75.16	20.36	2.381
25.06	97.40	24.62	2.693
25.06	75.19	20.36	2.379
25.06	57.61	16.12	2.105
25.06	32.66	7.53	1.617
25.06	11.10	- 7.32	1.077
32.10	19.21	5.75	1.600
32.10	32.16	13.42	1.950
32.10	55.27	22.01	2.476
32.10	74.78	27.06	2.807
32.11	96.68	31.52	3.128
32.11	75.04	27.12	2.789
32.10	55.30	22.02	2.472
32.10	32.12	13.40	1.949

Table 5

Equilibrium Relative Humidity of Saturated Aqueous Salt Solutions @ 25°C

SALT	% RH
LiCl	11.3
KF	30.9
$Mg(NO_3)_2$	52.9
NaCl	75.3
KCl	84.3
K_2SO_4	97.3

Table 6

Typical Static Humidity Test Conditions

Air Temp. °C	Salt Temp. °C	Type of Salt	Relative Humidity %
31.1	32.5	LiCl	11.3
28.4	26.2	KF	32.4
24.5	30.1	$Mg(NO_3)_2$	51.4
26.3	24.9	NaCl	75.3
28.2	33.3	KCl	83.2
28.2	34.2	K_2SO_4	96.8

Table 7

Response Time Summary for Static Humidity Test - Sensor #1 before Exposure to Sulfur Dioxide or Ammonia

Step Change in % Relative Humidity		Response Time (min) at Dry-Bulb Temperature of		
From	To	5°C	25°C	35°C
11	53	3.32		
53	11	4.98		
31	53		1.89*	
53	31		2.75*	
53	75	3.99		
75	53	8.24		7.40
75	84			1.71
84	75		1.88	2.30
31	75	1.75*		1.87
75	31	2.60*		1.99
11	75			7.73
75	97	2.44*		1.89*
97	75	2.73		2.03*

* Average of two tests.

Table 8

Response Time Summary for Static Humidity Test - Sensor #2

Step Change in % Relative Humidity		Response Time (min) at Dry-Bulb Temperature of	
From	To	5°C	35°C
11	75	7.73	
75	11	14.87	
31	75	9.58	1.67
75	31	9.28	3.56
53	75	4.16	0.48
75	53	8.24	3.22
75	97	2.39	2.07
97	75		2.39

Table 9

Response Time Summary for Static Humidity Test - Sensor #1 after Exposure to Sulfur Dioxide or Ammonia

Step Change in % Relative Humidity		Response Time (min) at Dry-Bulb Temperature of	
From	To	35°C	Contaminants
75	97	1.77	5 ppm SO_2
97	75	2.14	5 ppm SO_2
97	75	1.82	5 ppm NH_3

Table 10

Sensor #1 History in Hours of Exposure in Static Humidity Test

Air Temperature	Approximate % RH							
	11%	30%	50%	52%	75%	84%	97%	Contaminants
25°C	0	310	21	8	44	1	4	No
33°C	0	1	0	1	22	1	1	No
10°C	2	1	0	1	22	0	1	No
25°C							85	SO_2
33°C							25	
33°C							2	NH_3

Notes:

Contaminates were less than 5 ppm.

During the remaining time of 55 days, the sensor was stored at room temperature at approximately 50% rh.

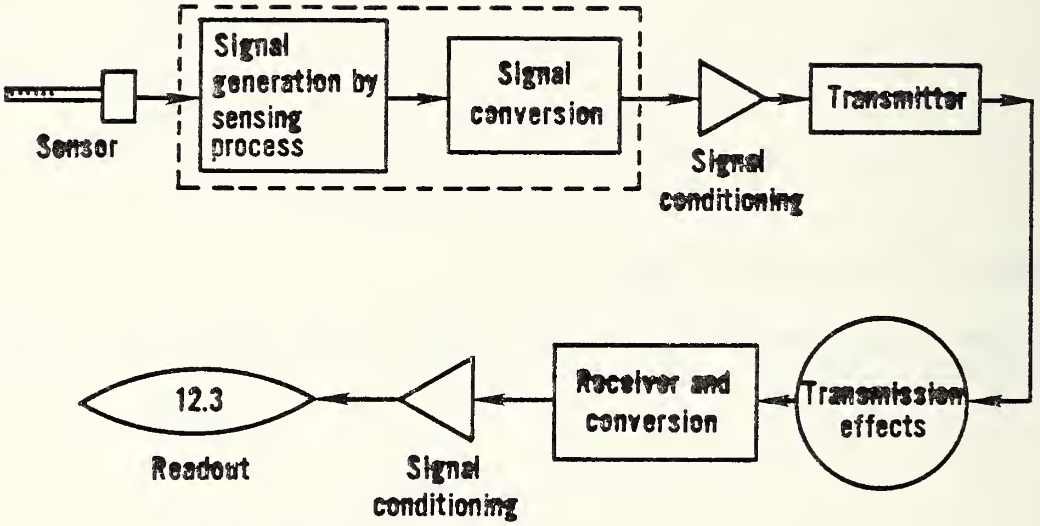

Figure 1. Block diagram of a sensor system

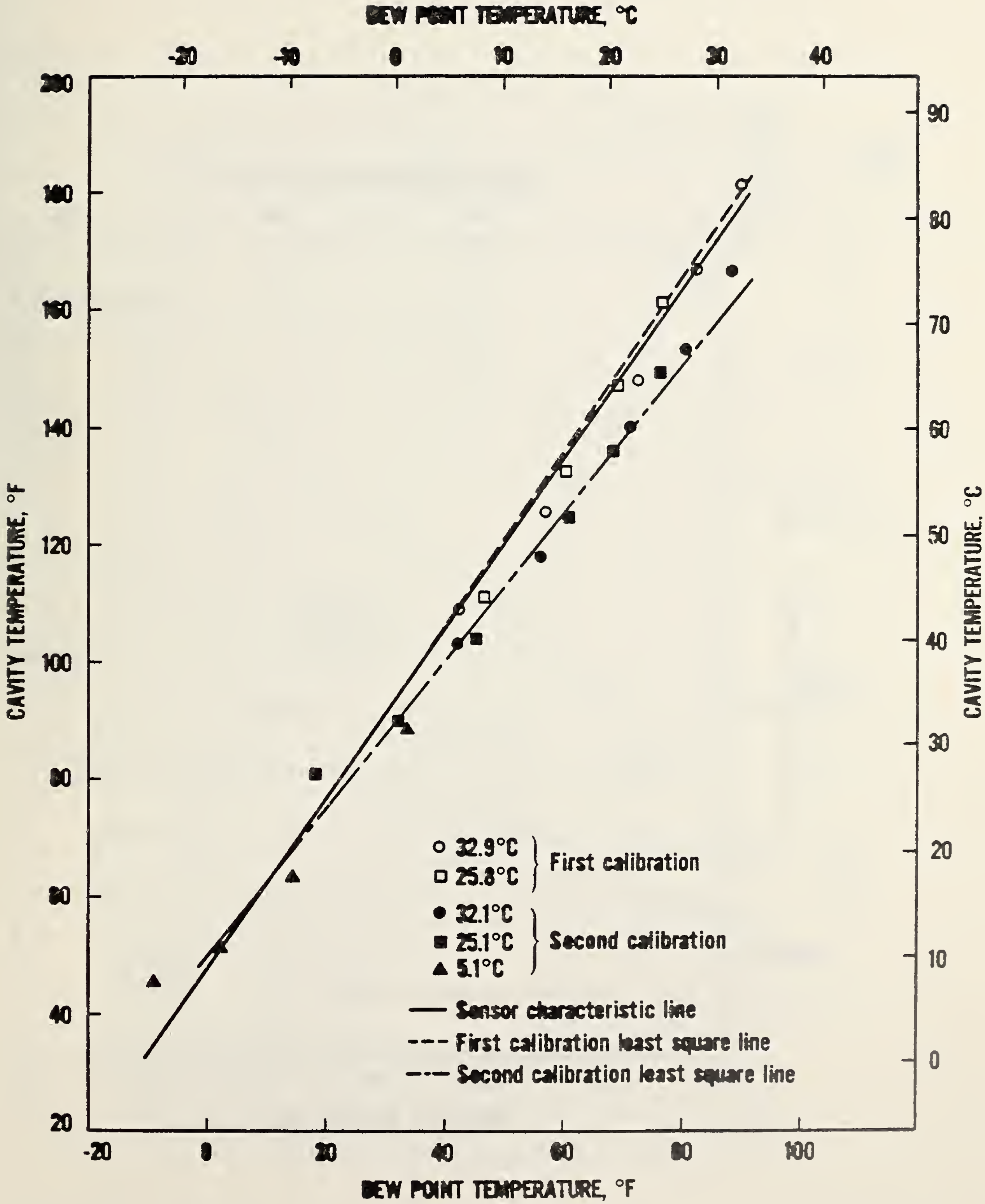

Figure 2. Sensor no. 1 calibration

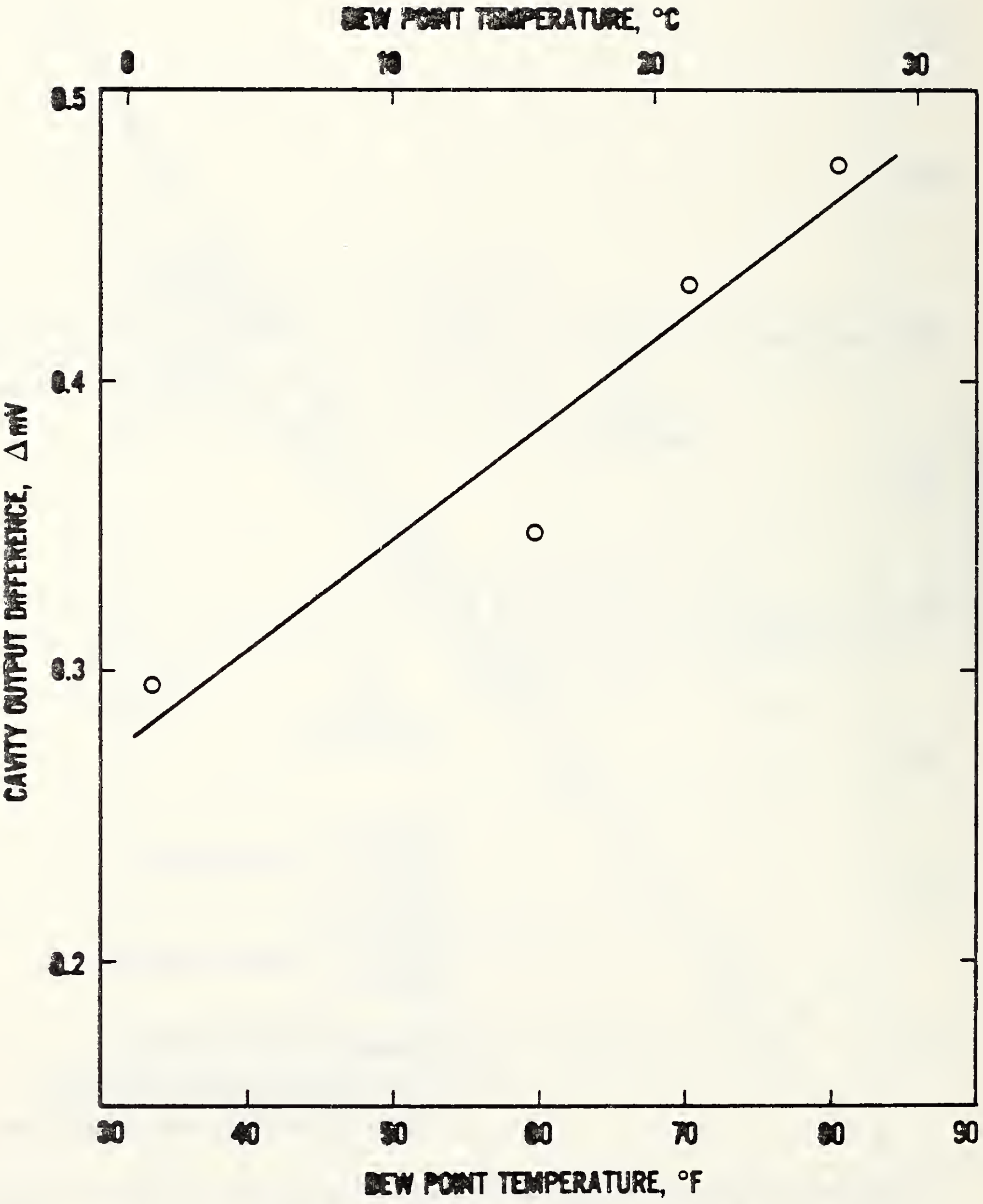

Figure 3. Temperature sensor location effect

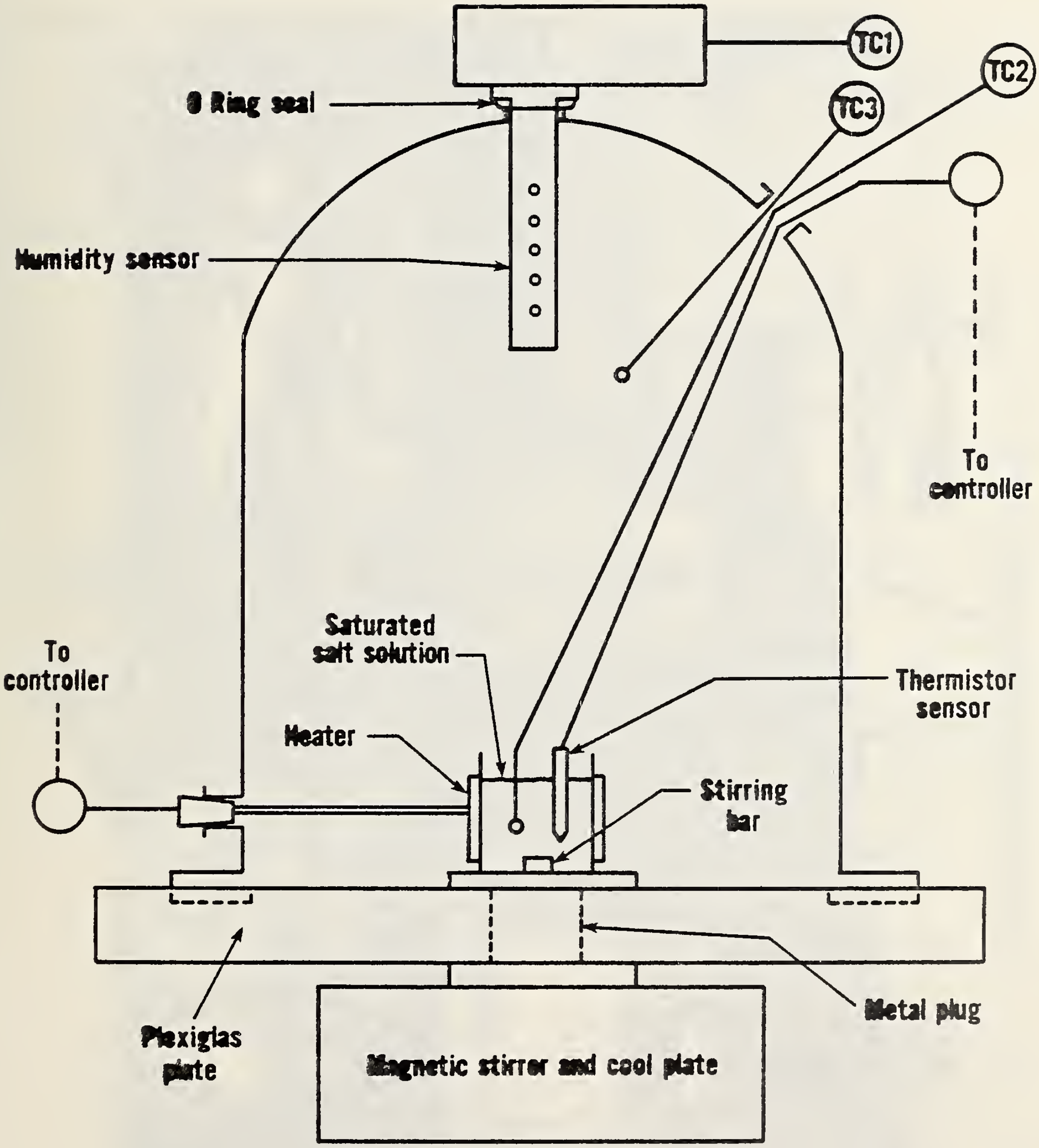

Figure 4. Schematic of the static humidity drift test apparatus

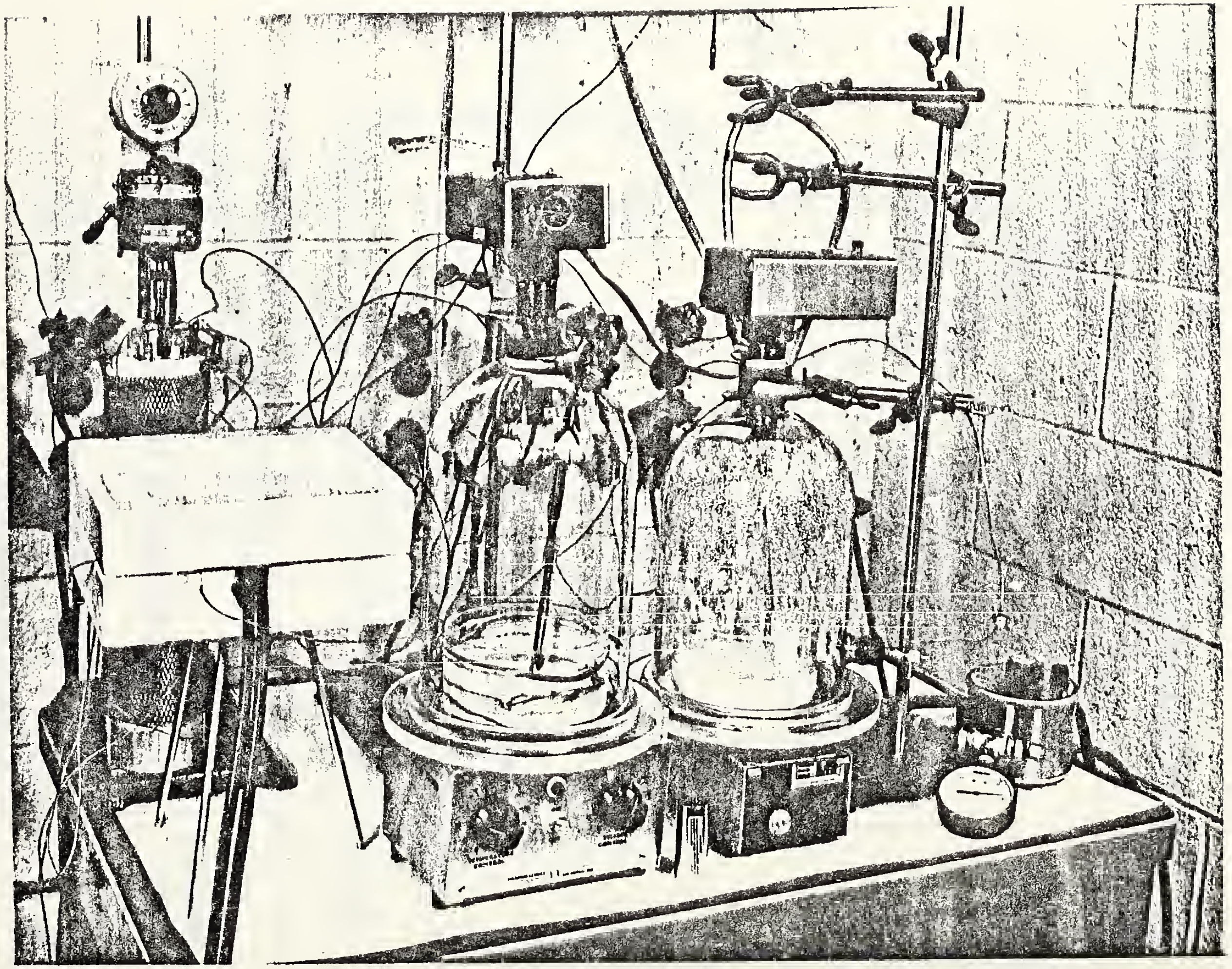

Figure 5. Static humidity drift test apparatus

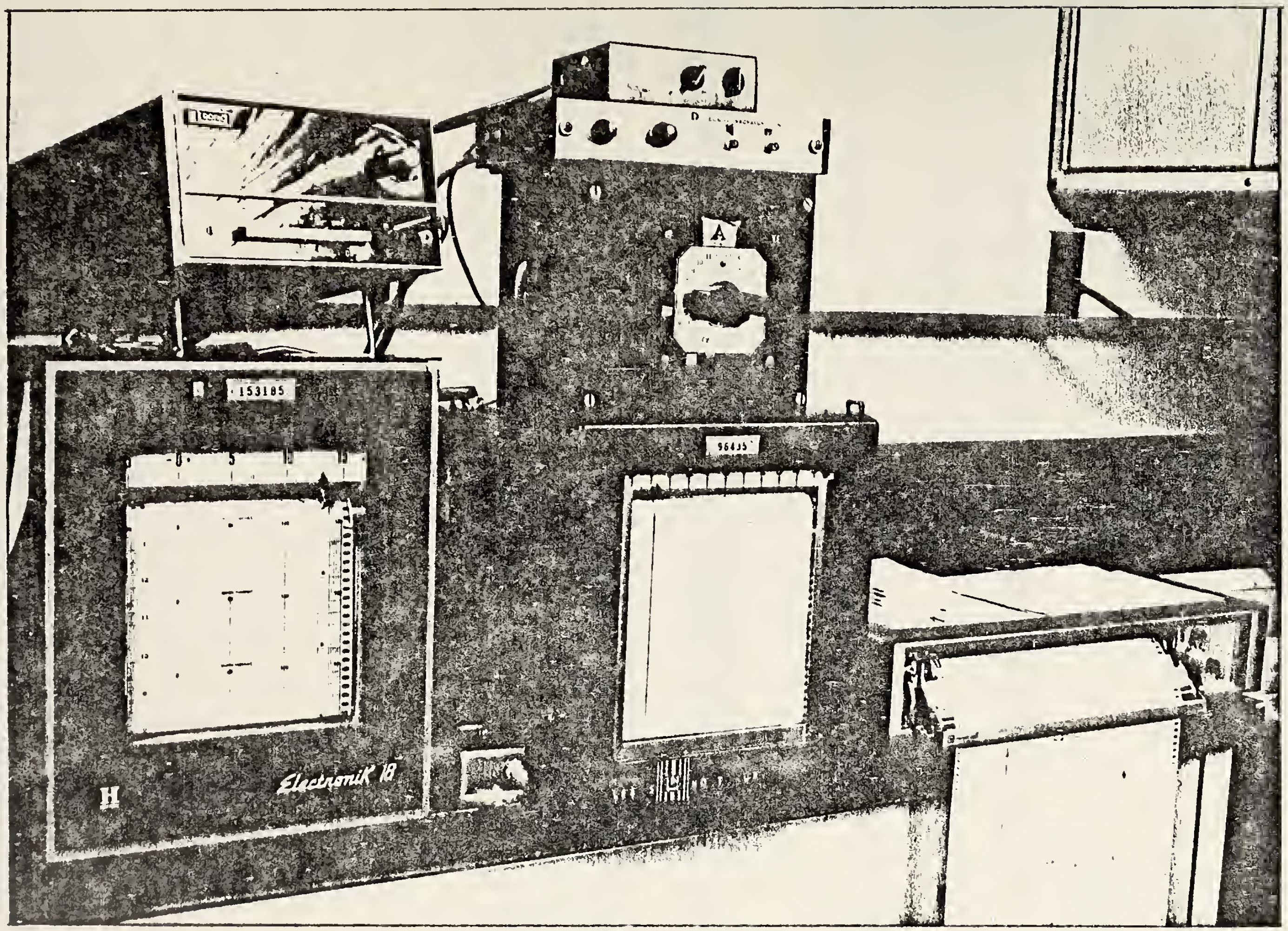

Figure 6. Instrumentation for static drift test

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report provides hygrometer selection information for application in heating, ventilating and air-conditioning (HVAC) systems. A general review of hygrometer literature has been provided and the most commonly used ones for HVAC are discussed. Typical hygrometer parameters are listed to indicate the type of performance that can be expected. Laboratory test results of self-regulating, salt-phase transition hygrometers are presented and discussed in detail.

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

Building energy monitoring; heating, ventilating and air-conditioning controls; humidity; humidity control; humidity measurement; humidity sensor; hygrometer

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