THE DEVELOPMENT OF A DIRECT READING RELATIVE HUMIDITY INSTRUMENT

by

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INTRODUCTION

The ratio of the actual vapor pressure in the air to the vapor pressure of saturated air at the same temperature is the accepted definition of the scientific term "relative humidity" (1). A more everyday meaning is the amount of water vapor in the atmosphere as compared to the amount of water vapor that the air could hold at the same temperature. Human comfort is affected to a great extent by the water vapor present in the air, thus it is often included in the discussion of the weather by the layman. Relative humidity is a much more complicated subject than the average person realizes, and the effects are far more reaching than an individual's comfort.

Modern science has studied atmospheric vapor for many years. The early Greek meteorologists probably made moisture content measurements of the air, along with the other properties such as temperature and barometric pressure (2). Ever since that time meteorologists, as well as scientists of many fields, have made similar measurements. The advancements in the techniques and instruments for taking temperature and barometric pressure measurements have far exceeded those for relative humidity measurements. The meteorologists were the only people concerned with the problem for many years, but in the last forty or fifty years the advancements made in the fields of air conditioning, refrigeration, industrial drying, agricultural crop processing, etc. have made the humidity measurement problem one offar wider and more urgent interest.

In spite of the progress and the expanding applications to fields involving the manufacturing of almost all the necessities of our modern living, including items from bread to steel, and in spite of the research that has been carried out on the problem of humidity measurement, the methods employed today for most humidity instruments are the same basic methods that have been used for many years. These classical methods are the measurement of wet and dry-bulb temperatures, measurement of dewpoint temperature, and the hygroscopic properties of materials. A large and varied assortment of devices and instruments has been developed from each of these methods. Other basic principles have been employed and some very unique instruments have been developed, but none of these have come into popular usage.

For some applications, the instruments that are available do not satisfactorily meet the requirements for humidity measurements. (3,4). This is especially true in the field of agriculture. The need for a relative humidity sensing device in agricultural research and practice has increased as farm crop processing methods have developed. Researchers in this field have employed many of the available instruments, but many of these devices have been found to be inadequate due to the inherent difficulties in making moisture determinations plus the severe conditions sometimes encountered in agricultural applications. Crop drying and curing equipment often produce dust conditions that render most sensing elements ineffective after a very short time. Although agricultural research and development presents the greater demand for a good humidity instrument, the farmer needs a similar instrument to aid in the proper application of his process equipment. Especially is this true from the standpoint of a sensing element for control circuits. Any element which would be successful for agricultural applications must be equally adaptable to measuring and control functions.

As was stated above, many branches of science are concerned with humidity measurements and have, to some extent at least, developed or adapted instruments to suit their specific needs. Each general field of application will require an instrument which has the characteristics to meet the special problems encountered. For example, the meteorologists must obtain humidity readings over a very large temperature range - from 100°F to as low as perhaps - 75°F, or aviation oxygen supply cylinders must be tested for moisture content at about 10 atmospheres pressure. Likewise the instruments to be used in agricultural applications must be selected or designed to meet the special problems found in farm installations. All humidity instruments must have some of the same general characteristics such as accuracy, good speed of response, sensitivity over a wide humidity and temperature range, and the adaptability to remote indications, but the special requirements of an agricultural instrument are freedom from frequent recalibration, no influence from dust accumulations, simplicity of construction but rigid in nature, little or no maintainance for the convenience of the farm operator, adaptibility to control circuits, and a low initial cost. An instrument with these qualifications would meet the needs of the agricultural worker and would strengthen his control over another element of nature.

In view of the many fields of research that have studied atmospheric moisture, the possibility was considered that an instrument had been perfected in another branch of research that could be useful to the agricultural scientist, yet unknown to him because the device was not in general usage. What was perhaps a more realistic possibility was also condidered. Since no existing device appeared satisfactory, a study of humidity instruments could result in the selection of a feasible method from which a suitable instrument could be developed. Either possibility would involve the testing or developing of the instrument in the laboratory to determine if the instrument was of sufficient value to be tested in the field.

The laboratory equipment required would undoubtedly be similar to that which had been used by others. Therefore with this three-fold purpose, a literature survey was made and is included herein.

Because no instrument could be located which would be satisfactory for agricultural applications, the developement of an electric hygrometer was undertaken. Based on the theory that the electrical resistance of a porous ceramic material will change with the relative humidity, an instrument was constructed with a ceramic sensing element and a vacuum tube voltmeter as the indicating device. This instrument was tested in the laboratory by placing the sensing element in chambers containing specific relative humidities. Later the procedure was altered by replacing the vacuum tube voltmeter with a circuit which had a milliammeter and a constant alternating current voltage supply in series with the ceramic sensing element. The method and results of the tests conducted on the electric hygrometer are reported herein.

ATMOSPHERIC AIR AND RELATED TERMS

Air is a physical mixture of gases and vapors comprising three groups (5). In general, the gases of the first group are always present in the air in almost constant proportions. These gases and the approximate proportions present in dry air are:

	BY WEIGHT (5)	BY VOLUME (5)
Nitrogen	75.5%	78.1%
Oxygen	23.1%	21.0%
Argon, neon, helium and other gases in very small amounts	1.4%	0.9%

The second group of gases are those that are present due to some local condition, and therefore the presence and proportions of these gases are not fixed. Gases such as ozone, ammonia, sulphur dioxide, etc. are included in these accidental gases.

The third group consists of water vapor, carbon dioxide, and dust. These are present in widely varying proportions. The measurement of the proportion of water vapor, usually referred to as the percent relative humidity, is the subject of this paper.

In the mixture of air and water vapor, the water vapor is either saturated or superheated because if the vapor were wet, drops of water would be present that would cause the mixture to be nonhomogeneous. However, if given sufficient time, the drops of water would settle out. Therefore, the vapor in the atmospheric air can be studied independently from the dry air as saturated or superheated steam (6). The temperature of the water vapor is the same as the temperature of the mixture, but the pressure is not the same. According to Dalton's law, the total pressure exerted by a mixture of gases is the sum of the pressures which each gas would exert were it to occupy the vessel alone (6). Therefore, the pressure of the water vapor is that part of the atmospheric pressure known as the partial pressure of the vapor.

Figure 1 is a temperature-entropy diagram with the saturated liquid and vapor lines for water. Consider a sample of air containing water vapor; that is, a mixture of dry air and superheated water vapor, thus the condition of the vapor can be represented by point 1 on figure 1, where the pressure of the vapor is p_{v1} and the temperature is t_1. Next consider a process in which the mixture is maintained at a constant pressure and is cooled. If the gases are perfect gases, the partial pressure of the water vapor will remain constant in accordance with the kinetic theory of gases. If the cooling continues until the temperature t_3 is reached, the point representing the condition of the vapor on the T-S diagram will move along the constant pressure line from point 1 to point 3. Point 3 is on the saturated vapor line, therefore the steam is now saturated. Should the temperature be decreased below t_3, some of the vapor will condense because if a vapor is saturated at any temperature

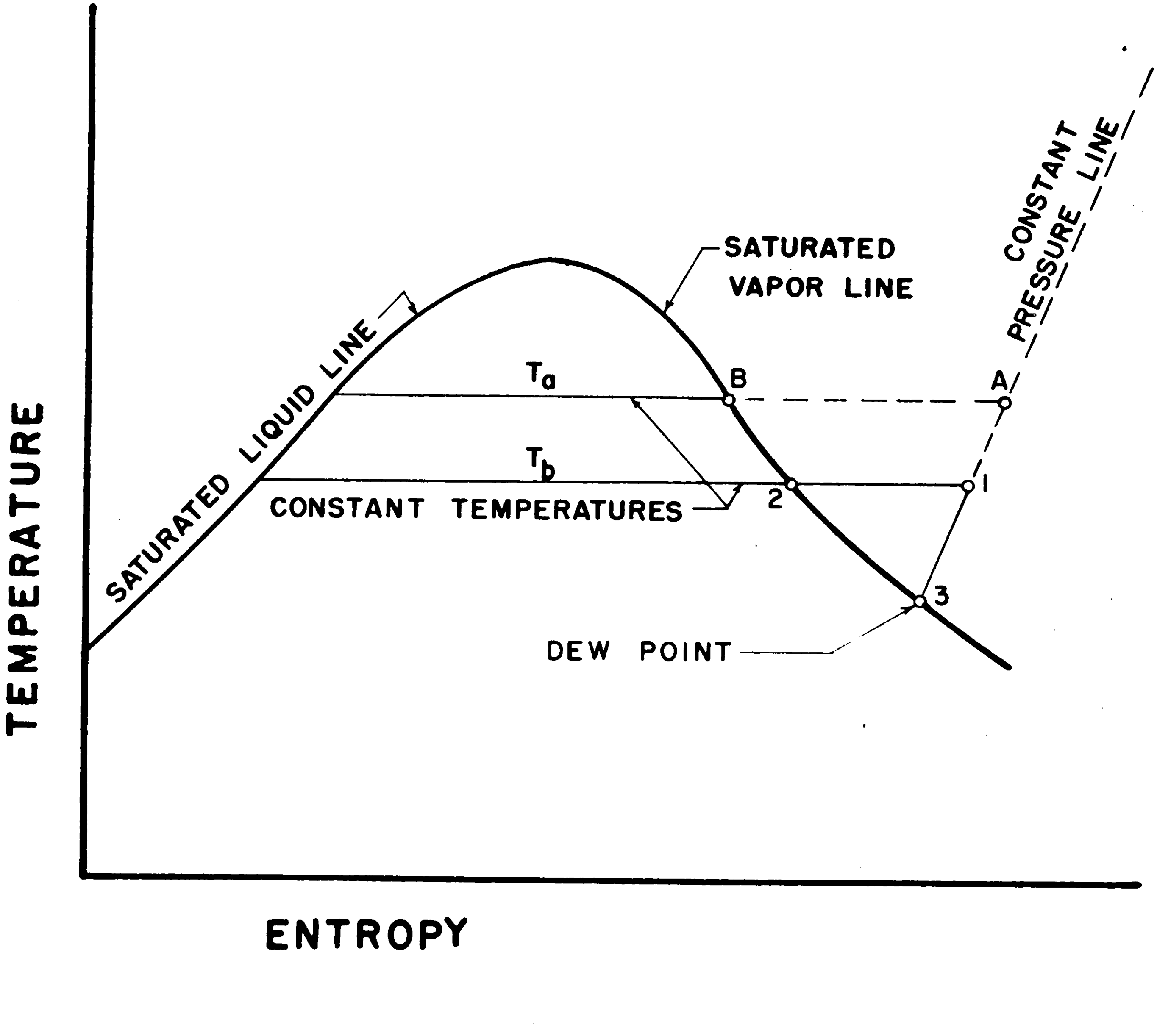


FIGURE 1. TEMPERATURE — ENTROPY DIAGRAM FOR WATER.

and heat is abstracted, some of the vapor must condense. Although the vapor partial pressure was constant during the cooling process from point 1 to 3, any further cooling of the mixture will cause condensation and thus a decrease in the vapor pressure since the remaining vapor must be saturated. The total pressure of the mixture remains constant due to the nature of the process. Since water will be condensed from the atmospheric air as it is cooled below the point 3, this point is called the dew point and the temperature t_3 is the dew point temperature. A common example of water being condensed is often seen in the winter when water or ice forms on the warm side of a windowpane that is exposed to air temperatures that are below the dew point of the inside air.

Referring again to figure 1 with the mixture represented by point 1, consider a second process in which the temperature and the total pressure of the mixture remain constant. Let a liquid evaporate so that its vapor diffuses into the mixture, but allow the mixture to expand to maintain the constant total pressure. As vapor is added to the mixture at temperature t_1, that portion of the mixture which is vapor increases, and the vapor partial pressure must also increase. As the pressure of the vapor in the mixture increases, the point representing the vapor moves along the constant temperature line from point 1 towards point 2, and when sufficient vapor has been added, the vapor will be represented by point 2 which is on the saturated vapor line. Since the mixture contains saturated vapor, the mixture is also considered to be saturated because the amount of saturated vapor present in any space cannot be increased as long as the temperature is constant (6).

The universal term, relative humidity, has come to mean an index which indicates the condition of the vapor in air, the rate that water will evaporate into the air, or the amount of moisture present in the air. The term is defined as the ratio of the partial vapor pressure of a vapor and the partial vapor pressure of a saturated vapor when both vapors are at the same temperature. This ratio is expressed as a percentage and is often referred to as the percent relative humidity. From figure 1, the percent relative humidity, % R. H., is shown as:

$$\%\text{ R. H.} = \frac{p_{v1}}{p_{v2}} \times 100\%$$

Where: p_{v1} = partial vapor pressure at point 1

p_{v2} = partial vapor pressure at point 2

With a very slight variation, which is not serious, the same ratio can be expressed as:

$$\text{R. H.} = \frac{\text{Vapor density, Point 1}}{\text{Vapor density, Point 2}} \times 100\%$$

Either definition can be derived from the other provided the vapors are assumed to behave as perfect gases. This is a good assumption for steam pressures below 1 pound per square inch, and partial vapor pressures are within this range for atmospheric temperatures up to slightly more than 100° F.

Referring to figure 1, if the mixture is maintained at a constant pressure and the temperature is raised from t_1 to t_A, the condition of the vapor will move from point 1 along a constant pressure line to point A, thus p_{v1} equals p_{vA}. If point B represents the saturated vapor pressure at the temperature t_A, the relative humidity for the mixture is:

$$\% \text{ R. H.} = \frac{p_{vA}}{p_{vB}} \times 100\%$$

However, the relative humidity at t_1 will not equal the relative humidity at t_A because the saturated vapor pressure at the higher temperature is greater than the saturated pressure at the lower temperature. This is true because more vapor is present in a saturated mixture at the higher temperature creating a higher vapor pressure. Therefore, as the temperature of a mixture is increased, the percent relative humidity will decrease provided no vapor is added. Likewise, if the temperature is decreased, the percent relative humidity will increase provided no vapor is lost.

One of the earliest means of measuring the relative humidity, and still one of the most used methods, is that of determining the wet-bulb temperature. The wet-bulb temperature is the temperature of a mixture after it has been adiabatically saturated. Such a measurement can be made by using an ordinary thermometer that has the bulb covered with a wet gauze. A stream of the mixture is passed over the wet gauze. A cooling effect due to the evaporation of the water on the gauze causes the indicated temperature to be less than the dry-bulb temperature which is the temperature of the mixture measured with an ordinary thermometer. The heat required for the evaporation is taken from the mixture and the water adjacent to the thermometer bulb, thus causing the temperature depression in the wet-bulb thermometer. The lower temperature limit is reached and taken as the wet-bulb temperature when the mixture passing over the wet-bulb becomes saturated and no more water is evaporated from the wet-bulb.

The rate of evaporation of water from the wet-bulb, which determines the wet-bulb reading, depends upon the amount of moisture already in the mixture. If the air is saturated, none of the water on the gauze will evaporate because the mixture is already saturated and cannot take on any more vapor. Thus the wet-bulb temperature will be equal to the dry-bulb temperature. The less moisture in the mixture, the more that must be evaporated to saturate the mixture. Hence, the rate of evaporation being greater, the wet-bulb temperature will be lower. Similarly, a mixture with a high relative humidity will result in a slow rate of evaporation and a relatively high wet-bulb reading.

Based on the relation between the wet-bulb temperature, the dry-bulb temperature, and the relative humidity, charts have been made showing these relationships graphically for atmospheric air. These charts, known as psychrometic charts also include the relationships of the above quantities with the dewpoint temperature and sometimes with the specific volume, the specific humidity, and the absolute humidity. The specific volume is the volume of one unit weight of the mixture. The specific humidity is often used in air conditioning work and is the weight of water vapor in air per unit weight of the dry air. The absolute humidity is the weight per unit volume of water vapor.

Carrier PSYCHROMETRIC CHART Normal Temperatures

Barometric Pressure
29.92 inches of Mercury

ADDITIVE CORRECTIONS FOR W, h, AND v WHEN BAROMETRIC PRESSURE DIFFERS FROM STANDARD BAROMETER

Wet Bulb Temp.	Sat. Vapor Press.	APPROXIMATE ALTITUDE IN FEET													
		−900		900		1800		2700		3700		4800		5900	
		$\Delta p = +1$		$\Delta p = -1$		$\Delta p = -2$		$\Delta p = -3$		$\Delta p = -4$		$\Delta p = -5$		$\Delta p = -6$	
t'	In. Hg	$\Delta W'_s$	Δh	$\Delta W'_s$	Δh	$\Delta W'_s$	Δh	$\Delta W'_s$	Δh	$\Delta W'_s$	Δh	$\Delta W'_s$	Δh	$\Delta W'_s$	Δh
20	.1027	−0.5	−0.08	0.5	0.08	1.1	0.17	1.7	0.26	2.3	0.36	3.0	0.46	3.8	0.58
21	.1078	−0.5	−0.08	0.5	0.08	1.1	0.17	1.8	0.27	2.4	0.37	3.2	0.49	4.0	0.61
22	.1130	−0.5	−0.08	0.6	0.09	1.2	0.18	1.9	0.29	2.6	0.40	3.4	0.52	4.2	0.64
23	.1186	−0.6	−0.09	0.6	0.09	1.3	0.19	2.0	0.30	2.7	0.41	3.6	0.55	4.4	0.67
24	.1243	−0.6	−0.09	0.6	0.10	1.3	0.20	2.1	0.32	2.8	0.43	3.7	0.57	4.6	0.71
25	.1303	−0.6	−0.10	0.7	0.10	1.4	0.21	2.2	0.33	3.0	0.46	3.9	0.60	4.9	0.75
26	.1366	−0.7	−0.10	0.7	0.11	1.4	0.22	2.3	0.35	3.1	0.48	4.1	0.63	5.1	0.78
27	.1431	−0.7	−0.11	0.7	0.11	1.5	0.23	2.4	0.37	3.2	0.50	4.3	0.66	5.4	0.83
28	.1500	−0.7	−0.11	0.8	0.12	1.6	0.24	2.5	0.38	3.4	0.52	4.5	0.69	5.6	0.86
29	.1571	−0.8	−0.12	0.8	0.12	1.7	0.26	2.6	0.40	3.6	0.55	4.7	0.72	5.8	0.89
30	.1645	−0.8	−0.12	0.8	0.13	1.7	0.27	2.7	0.42	3.8	0.58	4.9	0.75	6.1	0.92
31	.1723	−0.8	−0.13	0.9	0.13	1.8	0.28	2.8	0.44	3.9	0.60	5.1	0.78	6.3	0.95
32	.1803	−0.9	−0.13	0.9	0.14	1.9	0.29	3.0	0.45	4.1	0.63	5.3	0.82	6.6	1.01
33	.1878	−0.9	−0.14	1.0	0.15	2.0	0.30	3.1	0.47	4.3	0.66	5.5	0.85	6.9	1.06
34	.1955	−0.9	−0.14	1.0	0.15	2.1	0.32	3.2	0.49	4.4	0.68	5.7	0.88	7.2	1.11
35	.2034	−1.0	−0.15	1.0	0.16	2.1	0.33	3.4	0.51	4.6	0.71	6.0	0.92	7.5	1.16
36	.2117	−1.0	−0.15	1.1	0.17	2.2	0.35	3.5	0.53	4.8	0.74	6.2	0.96	7.8	1.20
37	.2202	−1.0	−0.16	1.1	0.17	2.3	0.36	3.6	0.56	5.0	0.77	6.5	1.00	8.1	1.25
38	.2290	−1.1	−0.17	1.2	0.18	2.4	0.37	3.8	0.58	5.2	0.80	6.8	1.05	8.4	1.30
39	.2382	−1.1	−0.18	1.2	0.19	2.5	0.39	3.9	0.61	5.5	0.85	7.1	1.09	8.8	1.36
40	.2477	−1.2	−0.18	1.3	0.20	2.6	0.41	4.1	0.63	5.7	0.88	7.4	1.14	9.2	1.42
41	.2575	−1.2	−0.19	1.3	0.20	2.7	0.42	4.3	0.66	5.9	0.91	7.7	1.19	9.6	1.48
42	.2676	−1.3	−0.20	1.4	0.21	2.8	0.44	4.4	0.69	6.1	0.94	8.0	1.23	10.0	1.54
43	.2781	−1.3	−0.21	1.4	0.22	3.0	0.45	4.6	0.71	6.4	0.99	8.4	1.29	10.4	1.61
44	.2890	−1.4	−0.22	1.5	0.23	3.1	0.47	4.8	0.74	6.7	1.04	8.7	1.34	10.8	1.67
45	.3002	−1.4	−0.22	1.6	0.24	3.2	0.49	5.0	0.77	6.9	1.07	9.1	1.40	11.3	1.75
46	.3119	−1.5	−0.23	1.6	0.25	3.3	0.51	5.2	0.80	7.2	1.11	9.4	1.45	11.7	1.81
47	.3239	−1.6	−0.24	1.7	0.26	3.4	0.53	5.4	0.84	7.5	1.16	9.8	1.52	12.1	1.87
48	.3363	−1.6	−0.25	1.8	0.27	3.6	0.56	5.6	0.87	7.8	1.21	10.2	1.58	12.6	1.95
49	.3491	−1.7	−0.26	1.8	0.28	3.7	0.58	5.8	0.90	8.1	1.25	10.5	1.63	13.1	2.03
50	.3624	−1.7	−0.27	1.9	0.29	3.9	0.60	6.1	0.94	8.4	1.30	10.9	1.69	13.6	2.11
51	.3761	−1.8	−0.28	2.0	0.30	4.0	0.63	6.3	0.97	8.7	1.85	11.3	1.75	14.1	2.18
52	.3903	−1.9	−0.29	2.0	0.32	4.2	0.65	6.5	1.01	9.0	1.40	11.8	1.83	14.7	2.28
53	.4049	−1.9	−0.30	2.1	0.33	4.4	0.68	6.7	1.05	9.3	1.44	12.2	1.89	15.2	2.36
54	.4200	−2.0	−0.31	2.2	0.34	4.5	0.70	7.0	1.09	9.7	1.50	12.7	1.97	15.8	2.45
55	.4356	−2.1	−0.32	2.3	0.35	4.7	0.73	7.3	1.13	10.1	1.57	13.2	2.05	16.4	2.54
56	.4518	−2.2	−0.34	2.4	0.37	4.9	0.76	7.6	1.18	10.5	1.63	13.7	2.13	17.1	2.66
57	.4684	−2.3	−0.35	2.4	0.37	5.1	0.79	7.9	1.22	10.9	1.69	14.2	2.21	17.7	2.75
58	.4856	−2.3	−0.37	2.5	0.39	5.3	0.82	8.2	1.27	11.3	1.76	14.7	2.28	18.4	2.86
59	.5033	−2.4	−0.38	2.6	0.41	5.4	0.85	8.5	1.32	11.7	1.82	15.3	2.38	19.1	2.97
60	.5216	−2.5	−0.40	2.7	0.42	5.7	0.88	8.8	1.37	12.2	1.90	15.9	2.47	19.9	3.09
61	.5405	−2.6	−0.41	2.8	0.44	5.9	0.91	9.2	1.43	12.7	1.98	16.5	2.57	20.7	3.22
62	.5599	−2.7	−0.43	2.9	0.46	6.1	0.95	9.5	1.48	13.2	2.05	17.1	2.66	21.4	3.33
63	.5800	−2.8	−0.44	3.0	0.48	6.3	0.98	9.9	1.54	13.7	2.13	17.7	2.76	22.3	3.47
64	.6007	−2.9	−0.46	3.2	0.49	6.5	1.02	10.2	1.59	14.2	2.21	18.4	2.87	23.1	3.60
65	.6221	−3.1	−0.48	3.3	0.51	6.8	1.06	10.6	1.65	14.7	2.29	19.1	2.98	23.9	3.73
66	.6441	−3.2	−0.50	3.4	0.53	7.1	1.10	11.0	1.72	15.3	2.38	19.8	3.09	24.8	3.87
67	.6668	−3.3	−0.51	3.5	0.55	7.3	1.14	11.4	1.78	15.8	2.47	20.5	3.20	25.7	4.01
68	.6902	−3.4	−0.53	3.7	0.57	7.6	1.18	11.8	1.84	16.4	2.56	21.3	3.32	26.7	4.16
69	.7143	−3.5	−0.55	3.8	0.59	7.9	1.23	12.2	1.90	17.0	2.65	22.1	3.45	27.7	4.32
70	.7392	−3.7	−0.57	3.9	0.61	8.1	1.27	12.7	1.98	17.6	2.75	22.9	3.58	28.7	4.48
71	.7648	−3.8	−0.59	4.1	0.64	8.4	1.32	13.1	2.05	18.2	2.84	23.7	3.70	29.7	4.64
72	.7911	−3.9	−0.61	4.2	0.66	8.7	1.36	13.6	2.13	18.8	2.94	24.6	3.84	30.9	4.82
73	.8183	−4.1	−0.63	4.4	0.69	9.0	1.41	14.1	2.20	19.5	3.05	25.5	3.99	31.9	4.99
74	.8463	−4.2	−0.66	4.6	0.71	9.4	1.46	14.6	2.28	20.2	3.16	26.4	4.14	33.1	5.18
75	.8750	−4.4	−0.68	4.7	0.74	9.7	1.52	15.1	2.36	20.9	3.27	27.4	4.28	34.3	5.37
76	.9047	−4.5	−0.71	4.9	0.77	10.0	1.57	15.7	2.46	21.7	3.39	28.3	4.42	35.5	5.56
77	.9352	−4.7	−0.73	5.1	0.79	10.4	1.63	16.3	2.55	22.5	3.52	29.4	4.61	36.9	5.77
78	.9667	−4.9	−0.76	5.2	0.82	10.8	1.69	16.9	2.65	23.3	3.65	30.5	4.77	38.2	5.98
79	.9990	−5.0	−0.79	5.4	0.85	11.2	1.75	17.5	2.74	24.2	3.79	31.6	4.95	39.6	6.20
80	1.032	−5.2	−0.82	5.6	0.88	11.6	1.82	18.1	2.84	25.1	3.93	32.7	5.13	41.0	6.43
81	1.067	−5.4	−0.85	5.8	0.91	12.0	1.88	18.8	2.95	26.0	4.08	33.9	5.32	42.5	6.66
82	1.102	−5.6	−0.88	6.0	0.94	12.5	1.96	19.5	3.06	27.0	4.24	35.1	5.51	44.0	6.90
83	1.138	−5.8	−0.91	6.2	0.97	12.9	2.02	20.2	3.17	28.0	4.39	36.4	5.71	45.6	7.15
84	1.175	−6.0	−0.94	6.4	1.00	13.3	2.10	20.9	3.28	28.9	4.54	37.7	5.92	47.2	7.41

t = Dry bulb temperature (F)
t' = Wet bulb temperature (F)
p = Barometric pressure (in. of Hg)
Δp = Pressure difference from standard barometer (in. of Hg)
W = Moisture content of air (gr per lb of dry air)
W'_s = Moisture content of air saturated at wet bulb temperature t' (gr per lb of dry air)
ΔW = Moisture content correction of air when barometric pressure differs from standard barometer (gr per lb of dry air)
$\Delta W'_s$ = Moisture content correction of air saturated at wet bulb temperature when barometric pressure differs from standard barometer (gr per lb of dry air)

NOTE: To obtain $\Delta W'_s$ reduce $\Delta W'_s$ by 1% where $t - t' = 24$ F

Correct proportionally, when $t - t' =$ is other than 24 F

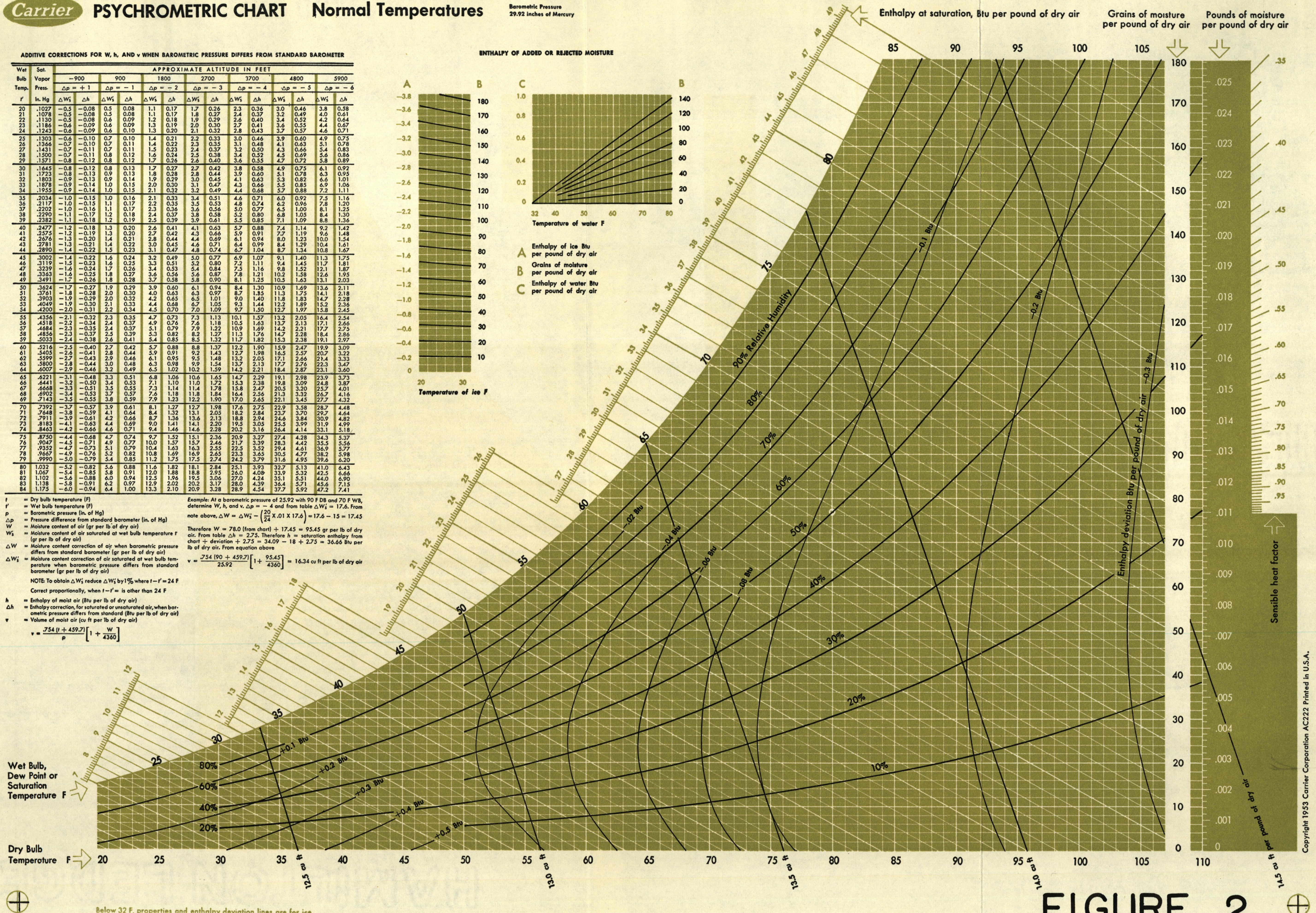
h = Enthalpy of moist air (Btu per lb of dry air)
Δh = Enthalpy correction, for saturated or unsaturated air, when barometric pressure differs from standard (Btu per lb of dry air)
v = Volume of moist air (cu ft per lb of dry air)

$$v = \frac{.754\,(t + 459.7)}{p}\left[1 + \frac{W}{4360}\right]$$

Example: At a barometric pressure of 25.92 with 90 F DB and 70 F WB, determine W, h, and v. $\Delta p = -4$ and from table $\Delta W'_s = 17.6$. From note above, $\Delta W = \Delta W'_s - \left(\frac{20}{24} \times .01 \times 17.6\right) = 17.6 - .15 = 17.45$

Therefore $W = 78.0$ (from chart) $+ 17.45 = 95.45$ gr per lb of dry air. From table $\Delta h = 2.75$. Therefore h = saturation enthalpy from chart + deviation $+ 2.75 = 34.09 - .18 + 2.75 = 36.66$ Btu per lb of dry air. From equation above

$$v = \frac{.754\,(90 + 459.7)}{25.92}\left[1 + \frac{95.45}{4360}\right] = 16.34 \text{ cu ft per lb of dry air}$$



Below 32 F, properties and enthalpy deviation lines are for ice

FIGURE 2

THE CLASSICAL METHODS OF MEASUREMENT

The three classical methods of humidity measurements are the wet-and dry bulb temperatures, the dew point temperature, or the hygroscopic properties of materials. These methods have been employed through the years without any fundamental improvement. The actual apparatus and techniques have been greatly improved, and instruments based on these principles make up by far the larger number of humidity measuring devices in use today.

PSYCHROMETERS. The earliest use of the wet-bulb temperature was made by Baume in 1758, for the purpose of measuring the "evaporative power" of air (7). In 1792, Dr. James Hutton, of Edinburgh, dipped a thermometer in water after both the thermometer and the water had been brought to the temperature of the surrounding air, and then exposed the wet-bulb to a current of air. He noted the depression of the mercury in the thermometer and then estimated the "dryness" of the air. This was the first known use of the wet-bulb temperature in measuring the humidity (7). An equation for the psychrometric chart was derived by J. Ivory from an analysis of Hutton's work in 1822. Soon thereafter, in 1825, E. F. August introduced the name psychrometer. "Psychro" is taken from the Greek and means cold, while the suffix "meter" means an instrument for measuring. Thus, the word "psychrometer", when translated, is an instrument for measuring cold, or, probably as August thought of it, an instrument for measuring the cooling effect produced by the evaporation of moisture from the wet-bulb thermometer (7). Therefore, a psychrometer is an instrument for measuring the relative humidity consisting of a wet-and a dry-bulb thermometer and any other accessories required to produce the wet- and dry-bulb temperatures. The science involving the thermal properties of moist air, the measuring and control of moisture content of air, and the effect of atmospheric moisture on materials, processes, and human comfort, may properly be termed psychrometrics (1).

The term hygrometer includes all instruments with which the relative humidity is determined (3,8). Generally, the use of the term hygrometer is restricted to those instruments which give a direct reading of relative humidity, thereby excluding such devices as the psychrometer and the dewpoint temperature indicators. Hygrometers which record the relative humidity are known as hygrographs.

The basic simplicity and fundamental calibration have made the wet-and dry-bulb psychrometer the dominant means for measuring the moisture content of air. The elementary form of the psychrometer consists of two thermometers, one covered with a moistened cloth wick and the other bare. Some means is generally used to ventilate the thermometers, and to supply water to the wet-bulb. Perhaps the most common type psychrometer is the universal sling psychrometer. The wet-bulb thermometer is mounted on a staff so that it can be twirled to produce a minumum air velocity of 900 feet per minute (3). The dry-bulb temperature is taken simultaneously with a second thermometer which is usually stationary. The sling psychrometer is used by meteorologists, engineers, and scientists for humidity measurements, and it is very often used in experimental work as a standard (9), however its value as such is questionable (2).

Assmann or aspiration psychrometers provide the necessary air stream for stationary thermometers. The bulbs are carefully shielded from radiation effects, and the air stream of sufficient velocity is drawn over the bulbs by motor driven suction fans. The wetting of the wick for the wet-bulb is done very adequately by capillary action when the wick is extended into a reservoir of pure water. This type of psychrometer is replacing the sling psychrometer to some extent because of its features which tend to increase its accuracy, and because of its self-contained operation (2).

The psychrometer is only a special application of the thermometer, and most temperature measuring devices can be adapted for psychrometric use. Resistance thermometers, thermocouples, thermistors, bimetal thermometers, and liquid-, vapor-, and gas filled thermometers can all be employed as the temperature sensing elements for psychrometers (2, 3, 10, 11). Thermocouples and thermistors are of special interest where there is very little ventilation (10, 11), where standard recording instruments are available, and where the point of measurement is removed from the location of the indicating instruments. Psychrometers have many advantages as instruments for measuring humidity, and very accurate instruments have been developed that are often used as standards in laboratory work. On the other hand, disadvantages are also present. The necessity of having to refer to a psychrometric chart after the temperatures are taken is the primary disadvantage. The automatic combination of the two temperatures to give a direct reading of relative humidity would be a distinct improvement, but this has never been satisfactorily accomplished (3). The curvature and dissymmetry of the basic psychrometric curves have proven a serious obstacle to such a translating device.

Two other major problems involved in the operation of a psychrometer are the means of providing moisture for the wet-bulb, and the means of providing an air stream of a sufficient velocity. Moisture supply has been accomplished in many satisfactory ways, but it still limits the flexibility and adaptability of the instrument. The correct air velocity, 900 to 1200 feet per minute (2, 3), requires special equipment and design to assure accuracy, and thereby decreases the overall usefulness. Other problems and sources of error are present such as the effect of radiation, corrosion of the wet-bulb, and the sensitivity, accuracy and agreement in reading the thermometers.

As have been pointed out, the psychrometer has many limitations. The application of this instrument for field work has not been satisfactory, and it is not easily adapted to control installations. Since a direct reading is not given, plus the moisture and air velocity requirements, the possibilities for improving the psychrometer are also very limited. With the possible exception of the use of thermocouples or thermistors requiring very little ventilation, the psychrometer presents no foreseeable improvement which would justify further study.

DEWPOINT INDICATORS. The dewpoint indicator has been successfully used since early in the last century and theoretically is the soundest of the three classical methods of humidity measurement (2). J. F. Daniell, in 1819, invented a dewpoint apparatus which has had no fundamental improvement, though, of course, technical improvements have been made. About 1845, V. Regnault developed a dewpoint instrument consisting of a thin polished thimble containing ether through which air was passed to cause evaporation and hence, cooling of the thimble. The temperature of the ether at the appearance of condensation on the outside of the thimble was taken as the dewpoint. A thermometer in a second thimble, near the first, gave the ambient temperature. With these two temperatures the relative humidity could be determined either by calculations or from a psychrometric chart.

Most of the early models used ether for cooling and mercury thermometers for temperature measurement. The more modern dewpoint indicators employ cooling methods such as compressed carbon dioxide, dry ice, liquid air, and mechanical refrigeration. Temperatures can be obtained with any of the popular temperature sensing devices, but the thermocouple has been used principally because of its small size and its fast temperature response. Metal mirrors, on the surface of which the condensation takes place, are used. A photoelectric cell can be used to indicate the instant at which the condensation forms on the mirror, thereby changing the manual dewpoint indicator to an automatic instrument. With further electronic manipulations, a dewpoint indicator can be converted into a recording instrument or into a control device.

The dewpoint indicators have been found to be very accurate for laboratory work and are often used as reference standards. However, the use of these instruments would not be successful under conditions often encountered in industrial or agricultural applications. Although automatic recording and control are possible with a dewpoint temperature indicator, the devices are not rugged or fool-proof enough for field operation. The operation of the indicator usually requires some skill, and the accuracy of a manual indicator is directly dependent on the ability of the operator to recognize the instant condensation forms. The most general use of a dewpoint apparatus is for special situations or under the conditions of high pressures or low temperatures. It is for such specialized laboratory applications that the dewpoint indicator has become popular.

HYGROSCOPIC HYGROMETERS. The group of relative humidity measuring instruments generally referred to as hygrometers are based on the third classical method of humidity measurement - the hygroscopic properties of materials. One of the earliest humidity instruments described in scientific literature is of this type. In the middle of the Fifteenth Century, Cardinal Nicolous de Cusa used a piece of cotton wool balanced against weights on a scale, and the change of moisture-content of the wool due to changes of atmospheric moisture caused variations in the scale balance (2). Oddly enough, the description of several hygrometers can be found in literature of this century which are very similar. Since this very early apparatus, scientists have used their imaginations to make many ingenous measuring devices operating on the changes produced in a material by the variation of the humidity of the surrounding atmosphere.

Many materials, especially organic materials, are hygroscopic in nature and exhibit the ability to absorb moisture from the air, or to give-off moisture (2, 3, 5). As the moisture content varies, the materials undergo certain physical changes, such as, changes in dimensions, electrical resistance, weight, color, strength, etc. Using the magnitude of the physical change as a direct indication of the relative humidity, a device can be made which will register the change of the physical property as the relative humidity. Thus, hygroscopic hygrometers indicate relative humidity directly, a most desirable characteristic for any humidity measuring instrument. However, it is a thoroughly empirical instrument and does not bear close theoretical examination.

Most hygroscopic hygrometers can be classed in one of three categories- mechanical, electrical, or gravimetrical - depending on the physical property of the material that is utilized to give an indication of humidity. All hygrometers with sensing elements which function on a change of dimension or strength are mechanical due to the mechanical linkage necessary to translate the physical change into an indication of relative humidity. Others, having a change of electrical resistance or weight, would be grouped as electrical and gravimetrical hygrometers, respectively, due to the nature of the indicating apparatus. Instruments have been developed employing a wide selection of materials, both organic and inorganic (4, 9), but no one material combines all desirable properties of the ideal hygroscopic sensing element. Some of these requirements are (5):

1. A relationship between the humidity and the physical

change of such a form that it could be expressed by a mathemathical equation.

2. Quick response and high sensitivity.

3. Low hysteresis (difference between the indications when humidity is being raised and when humidity is being lowered).

4. Permanent calibration- no aging, fatique, or deterioration.

5. Unaffected by temperature variation.

The best known mechanical hygroscopic hygrometer, which has given fairly satisfactory results for many years, is the instrument employing a human hair sensing element. This hygroscopic material changes in length with humidity variations. Human hair, under moderate tension, will elongate nearly 3 percent from dry to saturated air (5). de Saussure developed a very modern-looking instrument of this type in 1783. His instrument, as well as those in use today, consisted of a group of matched hairs held in tension between a fixed point and a mechanical lever. Any change in the length of the hairs is translated through the mechanical lever to a scale calibrated in percent relative humidity; or the mechanical lever is equipped with a pen, in the case of the hygrograph, which traces the change of humidity on a clock driven chart, thereby affording a continuous record of the humidity.

Hair hygrometers and hygrographs have been very popular in this country, and are used for many applications where simple and inexpensive devices are required. Meterological agencies, including the U. S. Weather Bureau, often use hair hygrographs in obtaining weather data (5) because of the simplicity of the recording devices. The hair element, with suitable accessories, is very well adapted to control applications for household air conditioning. However, the operator often uses this very versitile hygrometer without being fully aware of the many inaccuracies, faults, and errors that can be present.

The shortcomings of the human hair sensing element are the result of the material failing to fullfill the requirements for an ideal material as listed above. The chief defect is the lack of stability of calibration under usual conditions of use, meaning that frequent recalibration is necessary. The response is very slow, often trailing a change of humidity by more than 5 minutes. The response may be even slower if conditions are taken to extremes such as 100 percent relative humidity, and may not recover at all when ambient temperatures go below freezing. Dust collection on the hair element destroys the accuracy of the instrument. These failings, plus the fact that the instrument is not suited to remote readings, leaves the hair hygrometer far short of being a desired instrument for agriculture.

Many other materials have been used as the sensing elements for mechanical hygrometers. Goldbeater's skin, wood fibers, biplastic strips (12), and cotton torsion elements have been employed with success similar to that of the hair hygrometer (3). A German instrument, composed of a thin membrane of wood fibers firmly cemented to a metal (5) or plastic (2) strip and wound into a spiral, operates in a manner similar to the familiar bimetallic temperature spring. Considerable torque is produced under the influence of humidity changes. It is claimed that this type of instrument is very stable, hysteresis effects and aging effects are almost eliminated, and the response is very rapid (5). The instrument has been used in this country for several decades, especially for control, however, it is not in very general usage at this time.

The most modern idea for hygrometers was initiated during the period of World War I as a means of measuring the moisture content of gun powder (13). The moisture content was related to the electrical resistance through the powder. Shortly thereafter, the same approach to measuring relative humidity was made by measuring the change of the electrical resistance through a hygroscopic material as the humidity varied. Thus, the electric hygrometer was introduced to the field of hygrometry, bringing with it the characteristics of direct readings and adaptibility to electrical control circuits. However, the same shortcomings that are apparent in the other types of hygrometers are present.

By far the most popular electric hygrometer that has been developed is known as the Dunmore cell (14, 15). Named after its inventor, the Dunmore cell was developed during 1938-39 to furnish continuous humidity records for weather ballons. The cell was connected to appropriate radio signalling equipment, and as the ballon made its ascent, radio signals were transmitted to the ground receiver establishing a record of the humidity corresponding to the travel of the ballon. The cell was soon adapted with an indicator for industrial use (3, 16, 17).

The sensing element consists primarily of two parallel wires wound upon a hollow plastic cylinder approximately three-eights of an inch in diameter and two inches long. A hygroscopic coating of dilute lithium chloride solution is placed between the wires. With the appropriate electrical measuring instruments, the resistance between the two parallel wires can be measured. If the cell is exposed to changing humidity, the moisture-content of the lithuim chloride will change, thereby changing the resistance between the two wires. At constant temperature, the logarithm of the electrical resistance between the wires varies approximately linearly with the logarithm of the relative humidity (3).

The electric resistance is highly dependent on the ambient temperature, thus the instrument must be calibrated for the temperatures at which it is expected to be used. The calibration is not permanent, and must be checked at intervals. However, the Dunmore cell is very useful under low temperatures and pressures for which it was actually designed. The response is good, it has very good sensitivity when used with appropriate electrical measuring devices, and the hysteresis effect is small. The cell is easily adapted to control circuits. A disadvantage, from the standpoint of agricultural usage, is the initial cost of the cell and indicating equipment

Measuring the change of electrical resistance can be applied to almost any substance. Cotton impregrated with several chemical solutions has been used as a sensing element with fair success. Cotton wool and human hair have been tested, and the logarithms of the resistancy of these materials is proportional to relative humidity (3). Small blocks of underfired clays have been investigated and developed to the extent that the element has been patented, but no commercial productions are known to be on the market (9, 18). All of these materials, plus many others, present possibilities for further research and study in the development of an electric hygrometer suitable to agricultural applications.

Gravimetric hygrometers, based on the change of weight of a material, are accepted as the most accurate method for determining the amount of water vapor in a gas (3). The passage of an air stream over a moisture absorbing material located on a delicate balance will give an indication of the relative humidity by the deflection of the balance. Materials, such as cotton, human hair, and some chemicals, have been used. The weight of the material must be affected by the relative humidity only. Although this type of hygrometer has been in existance for centuries (2), the primary application has been for laboratory standards and no commercial models are known to be in use (2, 3).

OTHER METHODS OF MEASUREMENTS

Instruments, other than the three classical types, have been developed that employ entirely different approaches to the problem of measuring relative humidity. Several of these have been perfected to the extent that they are used successfully for very accurate humidity determinations in laboratory work. Others have been introduced through scientific literature, but have been developed neither commercially nor for research.

VAPOR PRESSURE MEASUREMENT. The pressure of a constant volume of air can be measured; and after the moisture is absorbed by a drying agent, the pressure of the dry air is determined. The difference in the two pressures is the vapor pressure of the initial sample of air. The relative humidity is easily determined from the measured vapor pressure and the saturated vapor pressure at the recorded temperature of the air sample.

One apparatus of this type provides a means for taking a sample of air into a closed chamber where a manometer indicates the pressure. The air is then passed over a sulfuric acid solution which absorbs the moisture leaving the air dry. The dry air is returned to the same closed chamber and another pressure reading is taken from the manometer. The difference in the manometer readings is the vapor pressure of the air sample (20). A similar apparatus is designed so that a constant volume of air is brought into contact with a drying agent without any change of pressure due to the sampling procedure. As the moisture is absorbed, a gage is provided to indicate the decrease of the pressure. The difference in the barometric pressure and the dry air pressure is the vapor pressure of the air sample (21). A third vapor pressure hygrometer applicable to certain measurements, such as the relative humidity over a chemical solution, consists of a flask connected to a manometer. If a solution is placed in the flask and the system is evacuated with a vacuum pump, the reading of the manometer after some 30 minutes is the vapor pressure created by the chemical solution (22).

Many more hygrometers of this type could be mentioned (3), but the principles involved are the same with only a variation in design and operation. Most of the devices have been built for some specific laboratory determination, and they do not have sufficient merit to justify further development due to several distinct disadvantages. These instruments require a skilled operator, a long period of time for each determination, a rather bulky apparatus including a means of maintaining at least part of the apparatus at a constant temperature, plus the undesirable necessity of making a calculation to actually arrive at a value for relative humidity. The outstanding attribute is the accuracy usually obtained.

CHANGE OF VOLUME MEASUREMENT. If the volume of an air sample is measured, the change of volume when the air is dried will be equal to the amount of moisture that was present in the sample, provided both measurements are made at the same pressure. The relative humidity can then be determined if the temperature of the air sample is recorded. One apparatus of this type has provisions for admitting small amounts of sulfuric acid into an air chamber. Sufficient acid is admitted to maintain the air at a constant pressure as indicated by a manometer. The amount of acid added is then equal to the amount of moisture that was present in the sample (3). A slightly different device provides for the intake of an air sample of a given volume. The sample is then brought into contact with sulfuric acid, thus removing the moisture. The dry air is returned to its original chamber, and the initial pressure, as indicated by a manometer, is maintained by the introduction of a small quantity of mercury. The amount of mercury required is equal to the moisture that had been present.

Hygrometers of this type are very similar to the vapor pressure instruments; and in some cases an instrument can be operated on either principle. The usefulness of the change of volume devices is limited due to disadvantages that are the same as those for the vapor pressure instrument (23).

THERMAL CONDUCTIVITY. The development of an instrument for quantitative gas analysis based on the difference of the thermal conductivity of two gases has led to the use of this type of instrument for the determination of the moisture content of gases (24). Because air with different relative humidities also has different thermal conductivity, the use of the thermal cell, or katharometer, is applicable. The instrument consists of two cells, each with a winding of small wire connected as the adjacent arms of a wheatstone bridge circuit. One cell, termed the reference cell, is filled with a gas of known analysis, and sealed. Circulation of the mixture being tested is allowed through the other cell and around the exposed winding. If a small fixed current is passed through the windings, the temperature of the windings will increase, thereby changing the electrical resistance. If the thermal conductivity of the gas in the two cells is different, the temperature varies and the resistance will be different, thus causing an unbalanced condition in the bridge circuit. The unbalance of the bridge is an indication of the conductivity of the gas, thus it is an indication of the relative humidity.

For relative humidity measurements, the reference cell has been filled with dry air (25), or has had a continuous supply of saturated air (26). Both arrangements are satisfactory, but more development has been done on an instrument with the reference cell filled with dry air. Very good accuracy over wide temperature and humidity ranges, fast response, and easy adaptability to recording instruments, are the outstanding advantages. Limitations are due to the variations of other components of the air that would influence the thermal conductivity, plus the cost of such an instrument for general applications. The development so far as is known is for laboratory instruments.

VARIATIONS OF AIR DENSITY. The difference in density of saturated air and partially saturated air has been used to measure atmospheric humidity (3). A column of atmospheric air is balanced against a column of saturated air, but due to the difference in the density of thetwo columns, the lighter saturated air diffuses upward into the atmosphere, and likewise, the heavier atmospheric air diffuses downward into a saturation chamber where it, in turn, becomes fully humidified. The deflection of a vane suspended in the air column is directly proportional to the vapor pressure of the atmospheric air. It is claimed that this method is effective over a wide temperature range, is continuously indicating, and is portable. Possible limitation would be the effect on the density of the air due to changes of other components of the air, especially dust, and the lack of ruggedness of such an apparatus. Very little development has been done, and no commercial instruments are known.

DIFFUSION HYGROMETERS. Based on the difference of the diffusion of water vapor and air through a semipermeable membrane, a hygrometer has been developed which registers a pressure drop that is directly proportional to the vapor pressure (3, 27). A porous clay plate is cemented to an opening in the wall of an enclosed vessel containing a drying agent. The clay plate allows the air to diffuse through but prevents water vapor diffusion, or nearly so. The drying agent in the vessel removes any water vapor that does enter the vessel. A differential manometer is connected to register the pressure drop P_1 between the vessel and the atmosphere. The pressure drop P_1 is theoretically the vapor pressure of the atmosphere, but due to unknowns, P_1 is considered directly proportional to the vapor pressure. To avoid consideration of the constant of proportionality for the apparatus, a similar vessel with an identical porous clay plate and manometer, but containing water instead of the drying agent, is employed. The pressure drop P_2 indicated by the latter arrangement is directly proportional to the difference between the saturation vapor pressure and the ambient partial vapor pressure. Therefore, the saturated vapor pressure is the sum of P_1 and P_2, and the relative humidity is the ratio of P_1 to the sum of P_1 and P_2. All readings must be taken at constant temperature.

The basic theory of such an apparatus is sound, but study has shown that the clay plates are not too satisfactory (27). Development of this method could give a good laboratory instrument, but for a field instrument, too many factors, such as dust, temperature variations, ruggedness, etc. indicate that this hygrometer would not be successful. No commercial models are on the market.

DIELECTRIC CONSTANT. Since the dielectric constant of air varies with the water-vapor content (3), an instrument capable of indicating the dielectric constant of a stream of air could be used to measure relative humidity. A recording microwave refractometer of high sensitivity and fast response (about one-half second for discrete changes) has been developed that will continuously sample and record the dielectric constant of a stream of air (28). Although not developed specifically for humidity measurements, there does appear to be a possibility for the use of such a device in the laboratory. For agricultural field work, the cost of the equipment is entirely out of line, not to mention other obvious limitations for such applications.

CHEMICAL METHODS. A rough estimate (within ten or fifteen percent) of the relative humidity can be obtained from an indicator consisting of cloth or paper impregnated with cobaltous chloride (3). If the indicator is exposed to varying humidities, the color will vary from blue to pink, and by reference to a color comparison scale, a humidity sensing can be made. Such gages are seldom, if ever, used for measurements of any importance. Other chemical methods have been suggested but are, in general, restricted to applications of moisture determinations in special cases and not for atmospheric air (29).

MISCELLANEOUS METHODS. Several of the above mentioned methods have not been developed to any extent, but in most cases, the theory of the proposed instrument appears to be sound. There are other methods that have been tried, or at least, the ideas for possible instruments have been considered that do not appear to be of sufficient value to justify further development. Some of these ideas are listed with only a brief explanation concerning the basic theory.

1. Spectroscopic Method. A comparison of the measurements of radiant energy received from infrared bands passing through a stream of atmospheric air and a stream of dry air (3).
2. Index of Refraction. Some research has been done on the variation of the index of refraction of a thin film of glycerine with a water vapor content that is the same as the vapor content of the ambient air (3).
3. Thermal Rise. The increase of the temperature of dry cotton wool when exposed to atmospheric air has been studied as a means for indicating relative humidity (3).
4. Mobility of Ions. The variation in the mobility of ions, due to alpha rays and gamma rays, has been studied in relation to the presence of water vapor (3).
5. Critical Flow. A proposed means of measurement utilizes critical flow through small nozzles. Two sets of two nozzles in series are arranged in parallel with critical

flow maintained through all nozzles, thus the mass flow through each nozzle is independent of the downstream pressures, and is directly proportional to the entrance pressure. If a drying agent is placed between one series pair of nozzles, the mass flow, and hence, the entrance pressure to the downstream nozzle are reduced. The difference in downstream entrance pressure at the downstream reference nozzle, and the temperature of the air, will determine the relative humidity of the air flowing (3, 30).

6. Thermoelectric Hygrometer. Two dissimilar metals are separated by only a very thin block of ceramic material. Due to moisture adsorbed by the ceramic, a small thermal e. m. f. would be introduced in the circuit between the two dissimilar metals (9).

No doubt more ideas have been explored as methods for humidity measurements, but it is felt that a rather complete review of literature has been made, and all of the basic methods have been mentioned. The literature survey was aided to a very large degree by the National Bureau of Standards Circular 512 (3). This circular reviews many of the same methods covered herein, and lists 157 references on humidity instruments. Although some of these references were not readily available, many of them were reviewed and the material covered in this paper .

MAINTAINING ATMOSPHERES OF KNOWN HUMIDITIES FOR TESTING AND CALIBRATING HYGROMETERS

For the purpose of conducting tests on various types of hygrometers, the use of atmospheres of known humidities provides a means for obtaining better and more accurate test data. If nature has to be depended upon to produce the necessary humidity conditions, the testing period may be long and drawn out, plus the introduction of possible errors from the determinations of the natural conditions by an instrument of questionable reliability. Several systems have been used on previous studies, and a review of these aided in the selection of the method used.

DIVIDED - FLOW. A simple apparatus in theory, but complicated in actual construction, operates on the principle of mixing a known amount of dry air with a known amount of saturated air (31, 32). In general, such an apparatus functions as follows: a flow of dry air is divided by a proportioning valve into two parts of a known ratio. One part is saturated by passing through a saturator, and then it is returned to a chamber and mixed with the other portion of dry air. By knowing the proportion of dry air that was saturated, it can be proved by applying the perfect gas laws that the relative humidity of the final mixture is equal to that portion of dry air that was saturated.

The precision required in the construction, and the accurate temperature and pressure control required, makes this apparatus very expensive. A device of this type was observed during a visit to the National Bureau of Standards. It was stated that it had required some three years for the Bureau to perfect the apparatus.

TWO TEMPERATURE METHOD. A somewhat simpler apparatus was perfected by the Bureau of Standards as a supplement to the divided-flow apparatus (33). The fundamental method of producing known humidities is to saturate a stream of air with water vapor at a given temperature, and then to raise the temperature of the air to a specified higher value. The relative humidity of the air at the higher temperature is equal to the ratio of the saturated vapor pressure at the lower temperature and the saturated vapor pressure at the higher temperature, provided the absolute pressure remains constant. Although the operation is fundamental and relatively simple, the actual apparatus required very accurate temperature control as well as expert design and construction. Several years were required for its development by the Bureau, and is, therefore, not practical for this problem.

TWO-PRESSURE METHOD. Another Bureau of Standards development is an apparatus which employs another fundamental principle-pressure (34, 35). In this device, air is saturated at a high pressure, and then expanded to some lower pressure. The relative humidity is then equal to the ratio of the lower pressure to the higher pressure, assuming the perfect gas laws are followed, and that the air at both pressures is at the same temperature. Once again, this apparatus is simple in theory, but the functional model requires precision design and construction, limiting its application as a means of furnishing controlled humidities.

WATER - SULFURIC ACID MIXTURES. A very inexpensive and convenient method for producing atmospheres of known humidities is the use of mixtures of water and sulfuric acid. If such a liquid is exposed in a sealed chamber, the equilibrium vapor pressure of water in the space above the solution will depend on the acid concentration and temperature. Also, the air could be bubbled or otherwise brought into intimate contact with the liquid to establish a certain humidity (36). The advantages of this method are simplicity, adaptability to many conditions, and the low cost of equipment and materials. Several sources, such as the Chemical Engineering Handbook and the International Critical Tables, lists the equilibrium vapor pressure for different concentrations and temperatures.

The sulfuric acid method was considered a very good means to be used for the proposed hygrometer tests. However, the use of chemical solutions, the method that was used in this problem and is discussed next, appeared to have the same advantages plus an additional advantage. Saturated solutions are easier to obtain than are solutions which have a very accurately measured concentration of acid. The concentration of acid by weight must be determined very accurately to insure the desired humidity.

SATURATED SALT SOLUTIONS. The method selected to furnish known humidities is believed to be the simplest of all methods described in the literature. A saturated salt solution enclosed in a chamber will establish an equilibrium water vapor pressure with the air that is above the solution (22, 37). The vapor pressure will remain constant for a given chemical salt so long as the temperature of the chamber remains constant. Some salts are roughly independent of temperature, while others will vary as much as eight percent relative humidity for a change of 25 degrees Fahrenheit. This method is used frequently for calibrating mechanical type hygrometers, and for maintaining constant humidities in chambers for certain product testing (3).

A large amount of work has been done on the determination of the vapor pressures corresponding to certain chemical salts (37). The values that have been obtained vary over a wide range. The published data of the more recent work of two organizations, the Bureau of Standards and the American Paper and Pulp Association, shows very close agreement of the values obtained for the same salts. Figures 3 and 4 (page 54 and 55) are the relative humidity vs temperature curves for the salts that were used in this problem based on the data published by the organizations mentioned above.

THE POSSIBILITIES OF THE ELECTRIC HYGROMETER USING A CERAMIC SENSING ELEMENT

Many of the problems involved with the operation of existing humidity instruments are of a nature that even good solutions would not necessarily produce satisfactory devices. For example, the hair element for a hygrometer would remain sensitive to temperature changes even if it could be developed to the point that it was free from the necessary recalibration. Likewise, a psychrometer would still require a water and air supply though the device be made to read directly. Other instruments could be treated in a similar manner with the same results, thus the selection of a method of humidity measurement that would justify further development was rather difficult.

The electric hygrometer has some characteristics which indicate that it could be a most versatile instrument. The simplicity of the fundamental theory, a change of electrical resistance accompanies a relatve humidity change of the atmosphere surrounding the sensing element, makes the electric hygrometer readily adaptable to many electrical circuits. Measurements, control applications, and remote indications are all possible with a minimum of effort when used with a well designed circuit. With a sensing element that would provide a large change of resistance for a given change of humidity, but still operate in a range of resistance less than one megaohm, the necessary circuity could be built into an indicating instrument at a reasonably low cost. A wheatstone bridge, or other resistance measuring circuits, would be simple to construct and of sufficient ruggedness to withstand the treatment that would more than likely result during field tests (38). The operation if any, of such an instrument would be very simple, and the maintainance would be no more than any layman's care of an electrical appliance.

The above mentioned characteristics have all been the results of the means used for measuring the physical change of a sensing element. When the sensing element is considered, the limitations of the electric hygrometer are soon discovered. The accuracy, response, sensitivity, freedom from recalibration, and no affect from dust, are necessary requirements of a good hygrometer, and are functions of the sensing element of the electric hygrometer. Many materials have been used for the elements and some very good ones have been developed (3, 9, 14). The Dunmore cell, described earlier, is by far the best known cell that has been developed. As such, the element still has limitations. The manufacture of the element is a precision job requiring very careful workmanship. Each cell is useful over only a limited humidity range; eight separate cells being required for readings ranging from 6 to 99 percent relative humidity (17). Also, the cells are sensitive to temperature changes, and must be furnished with temperature calibration curves. Although the necessity for recalibration has been decreased, the cells must be recalibrated at intervals.

Based on these facts concerning the Dunmore cell, the possibility for a satisfactory humidity instrument of the electric hygrometer type depends on the selection of a sensing element that does not have the limitations mentioned, yet fullfills the requirements completely. The use of ceramic materials for sensing elements was introduced in 1944 when this type of element was patented (18). The inventor used, primarily, the highly porous fired clays, such as pottery clays. Although no good elements of this type have been fully developed, the idea of using a ceramic material seems to have advantages.

The change of electrical resistance of any material under changing water vapor conditions depend mainly on the amount of water vapor adsorbed by purely physical means; that is, the adhering of particles on the surface of the material. This concept makes the ratio of the total surface area to the volume of any sensing element of extreme significance. Ceramic materials can be selected with very large area to volume ratios due to the porosity of the material. A few other materials, especially some chemicals, could also be used, but ceramic materials can be made into more usable forms and still maintain the highly porous structure.

The material used as a sensing element must be able to release moisture as readily as it adsorbs it. A ceramic material, even though it may be very porous, will generally meet this requirement since the attachment of the water molecules to the surface is purely a physical attachment. Any element must be chemically inert so no chemical action would be set-off by the moisture that would tend to hold the moisture by more than a physical means. Many ceramic materials could be selected that would be chemically inert, but any ceramic material selected should be tested to ascertain the moisture adsorbing and releasing characteristics.

Perhaps the most important advantage expected from ceramic elements is stability of calibration. In almost all hygroscopic elements for the various types of hygrometers, this has been the most significant failure. Although it is not definitely established that a ceramic element will overcome this difficulty, earlier research indicates that certain clays possess this quality (4, 9). Another objective in the testing procedure should be to determine the permanency of the calibration.

Therefore, the development of a humidity measuring instrument, based on the principles of an electric hygrometer utilizing a ceramic element, was selected because of the apparent possibilities of this type of device. The advantages of the necessary electrical measuring circuit, plus the capabilities that the ceramic element is believed to possess, means that a good, rugged instrument can be developed to meet fully the requirements outlined for an instrument suitable to agricultural field work.

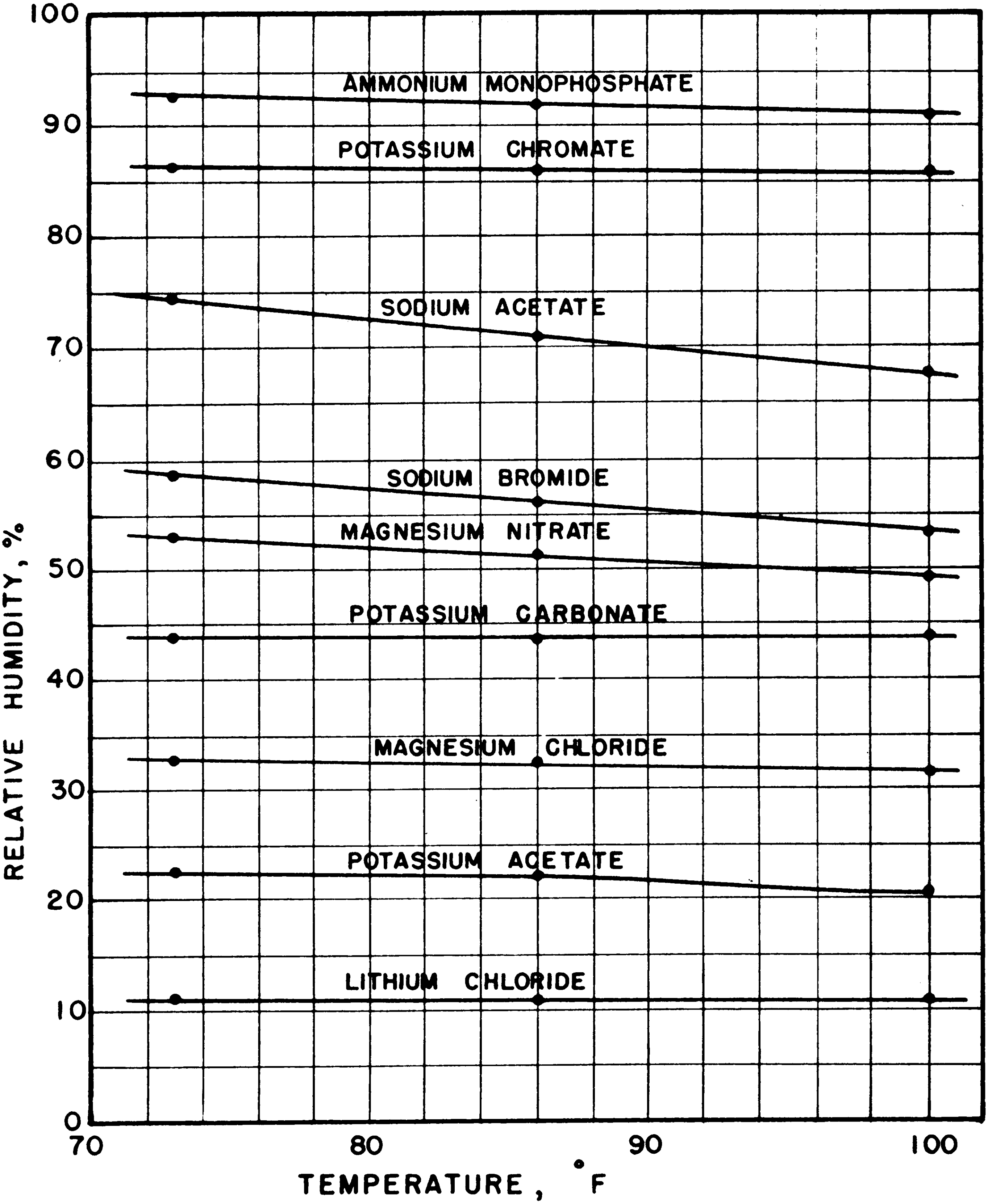
PROCEDURE

To better determine the value of the ceramic sensing element for electric hygrometers, and to develop an instrument of this type for use in the field of agriculture, a laboratory research program was planned. With a satisfactory laboratory set-up, it was planned to study various ceramic materials, the size, shape, density, or any other characteristics that would appear to affect the desired properties of each material. As a material to begin with, the Ceramic Engineering Department suggested a very light composition, consisting mostly of aluminum oxide mixed with a suitable binding material. The desired shaping and sizing of an element could be done since the material could be cut, drilled, and filed with relative ease. Several samples were furnished, each with a different porosity and thus a different density since the density is inversely proportional to the porosity. Only one ceramic material was furnished at this time because it was thought that a better selection could be made after some of the characteristics of the aluminum oxide were established.

In the perparation of a laboratory set-up for the study of ceramic sensing elements, it was necessary to provide the means for preforming two operations: Atmospheres of known humidities had to be provided for testing the various elements, and an instrument was necessary to measure the resistance of an element when it was located in a humidity chamber. The atmospheres of known humidities were furnished by a very simple means, but the instrumentation developed into a problem of such magnitude that the success of the entire study was somewhat limited due to the lack of dependable resistance measurements.

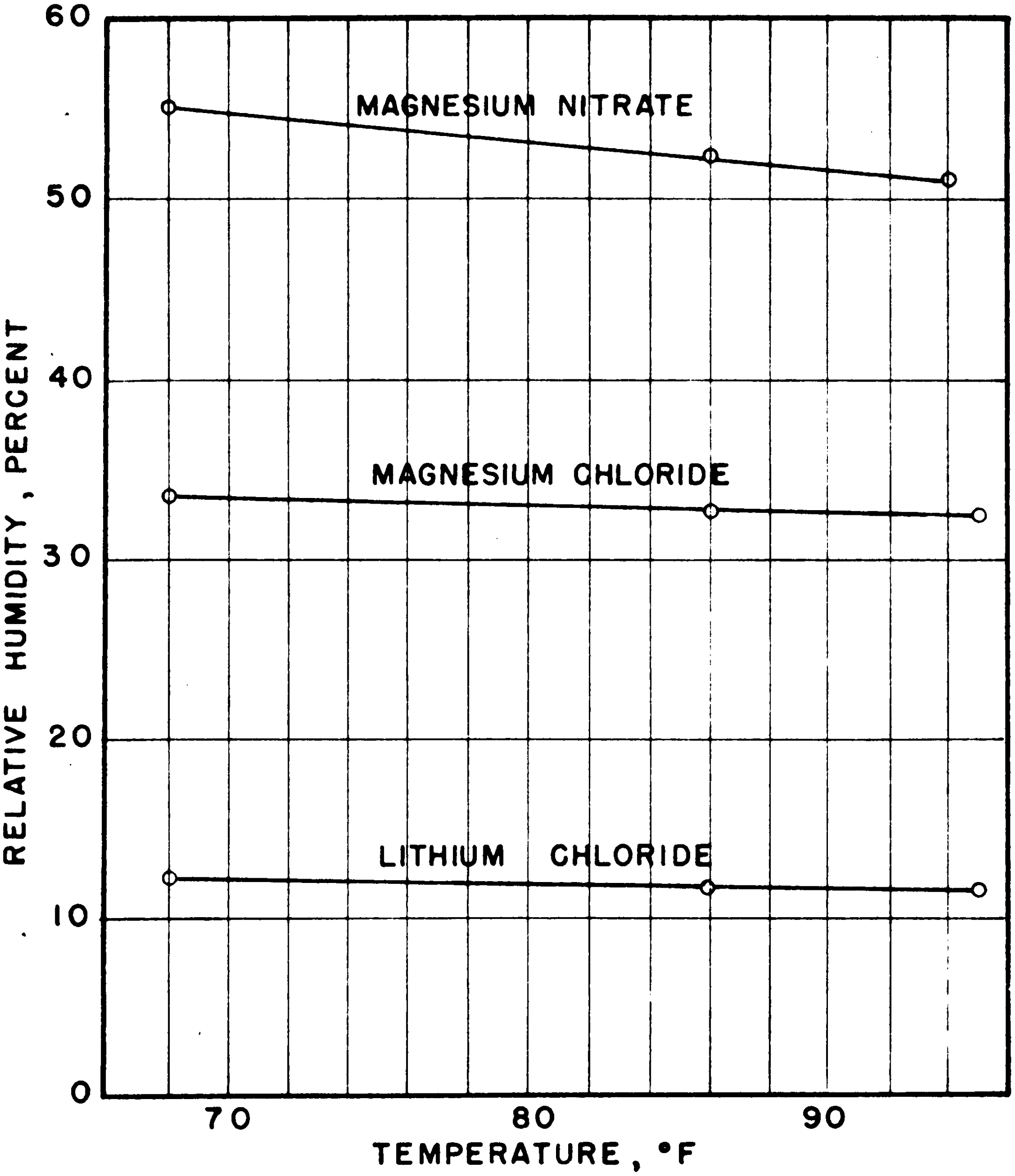
As described earlier, saturated salt solutions were used to maintain constant humidity conditions. Nine solutions were selected from the published data so that relative humidities from approximately ten percent to ninety percent, in steps of ten percent, could be used (3, 22, 37). Chemical salts of a commercially pure grade were obtained and used to saturate approximately one pint of distilled water. The solutions were then placed in individual, one-half gallon, wide-mouth fruit jars, and the chamber sealed with the two piece, self-sealing top. No means of stirring the air inside the jar was provided, and it is possible the vapor pressure throughout the jar was not uniform due to stratification; therefore, excessive time was allowed before recording data to allow for a better distribution of the water vapor. Also, the elements were placed very close to the surface of the liquid since the air immediately above the solution should be at the predetermined vapor pressure.

Table 1 (page105) gives the data as published in (22 and 37) for all solutions used for the three temperatures at which the determinations of vapor pressure were made. Figures 3 and 4 show the relative humidity vs. temperature curves for



VARIATION OF EQUILIBRIUM RELATIVE HUMIDITY WITH TEMPERATURE OVER SATURATED SALT SOLUTIONS (22).

FIGURE 3



VARIATION OF EQUILIBRIUM RELATIVE HUMIDITY WITH TEMPERATURE OVER SATURATED SALT SOLUTIONS(37).

FIGURE 4

the solutions used. The data from (37) do not include all of the solutions used, but the agreement for the solutions covered in both references is very satisfactory.

As shown in figures 3 and 4, temperature has an effect on the humidity in the chamber. Therefore, a thermocouple was used to measure the temperature on the inside of the jar. It was also necessary that the leads to the sensing element go into the jar. To facilitate the entry of these wires into the chamber, a top was designed utilizing the standard screw-rim with a plexiglas lid. The plexiglas was to prevent any current leakage between the two element leads. Figure 7 is a sketch of the lid assembly which provides terminals for each of the leads, and a small tube for a thermocouple that was sealed with wax. It was later determined that it would be an advantage to measure the temperature of the element. A second thermocouple was taken through the same opening. The nine humidity chambers were located in a partitioned box insulated with fiber board in an attempt to maintain a more constant temperature within the solution containers.

The measuring instrument required for the determination of the change of electrical resistance of a ceramic element exposed to atmospheres of varying humidities, was a very necessary part of the laboratory equipment. Such a device had to be capable of measuring resistance as high as 500 megaohms, or as low as 500,000 ohms. No equipment approaching this

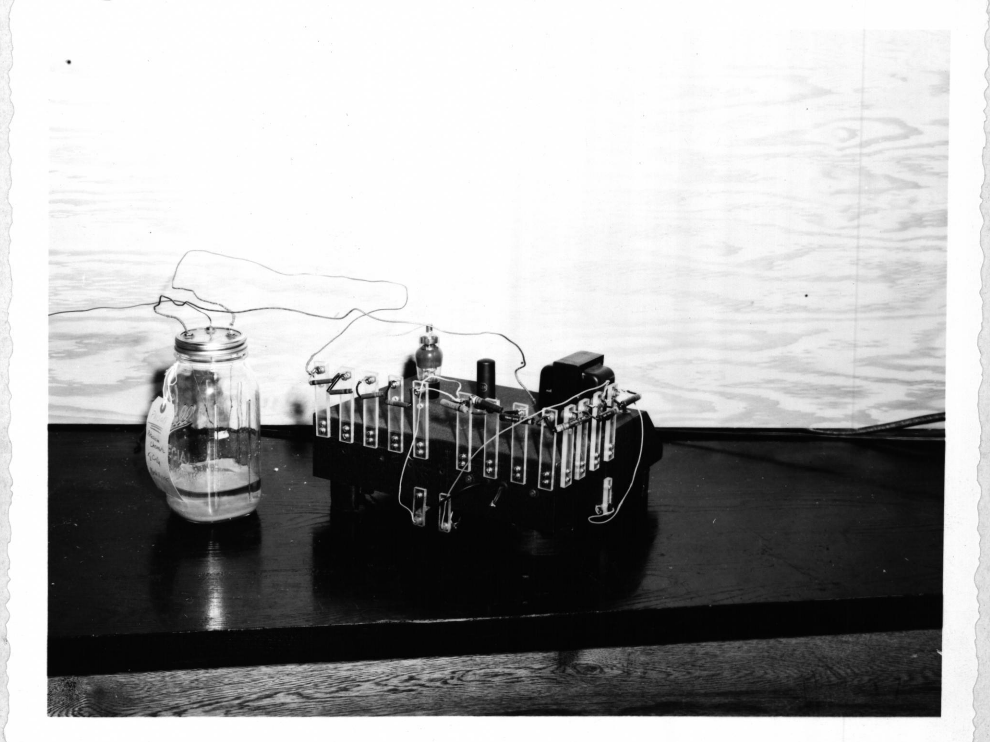


Figure 5. Vacuum Tube Voltmeter Connected to Element A which is Located in a Constant Humidity Chamber. Thermocouple Enters the Chamber from the Left.

capacity was available, so a simple, inexpensive measuring circuit was fabricated based on a circuit diagram suggested for this purpose by Mr. Fred Lichtgarn, the "father" of the ceramic element (19). Essentially, this instrument was a vacuum tube voltmeter that did not indicate resistance directly, but rather the current through the sensing element which was in direct proportion to the resistance of the sensing element. A circuit diagram is shown in figure 9.

Once the instrument had been assembled, the next problem encountered was the means of attaching the electrical leads to the ceramic element. Two rectangular elements were being considered at this time, one was 3/16 x 1/2 x 1 inches, and the other was 3/8 x 3/8 x 1 inches. For the thinner element, a 1/8 inch hole was drilled through the smaller dimension near each end of the element. The holes were then filled with hot-rosin-core solder and a lead wire dipped into the metal, As the metal cooled, the solder shrank, pulling away from the walls of the drilled holes. However, it was possible to secure some of the leads in this manner and still maintain what was believed to be a good electrical contact. For the larger element, a circular groove was cut in each end, leaving a small cone in the center. Hot solder was placed in the groove, and a lead wire inserted. As the solder shrank, it drew tighter on the ceramic cone. It is believed that this method gave better electrical contact, and it was very apparent that

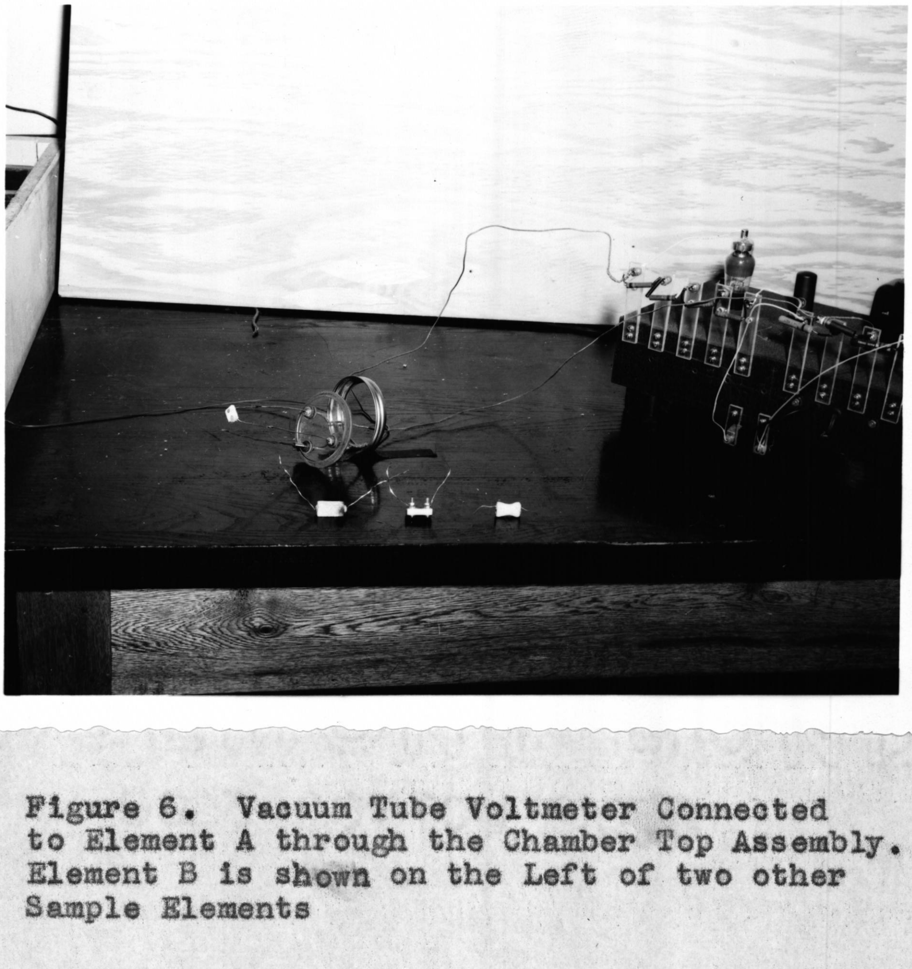
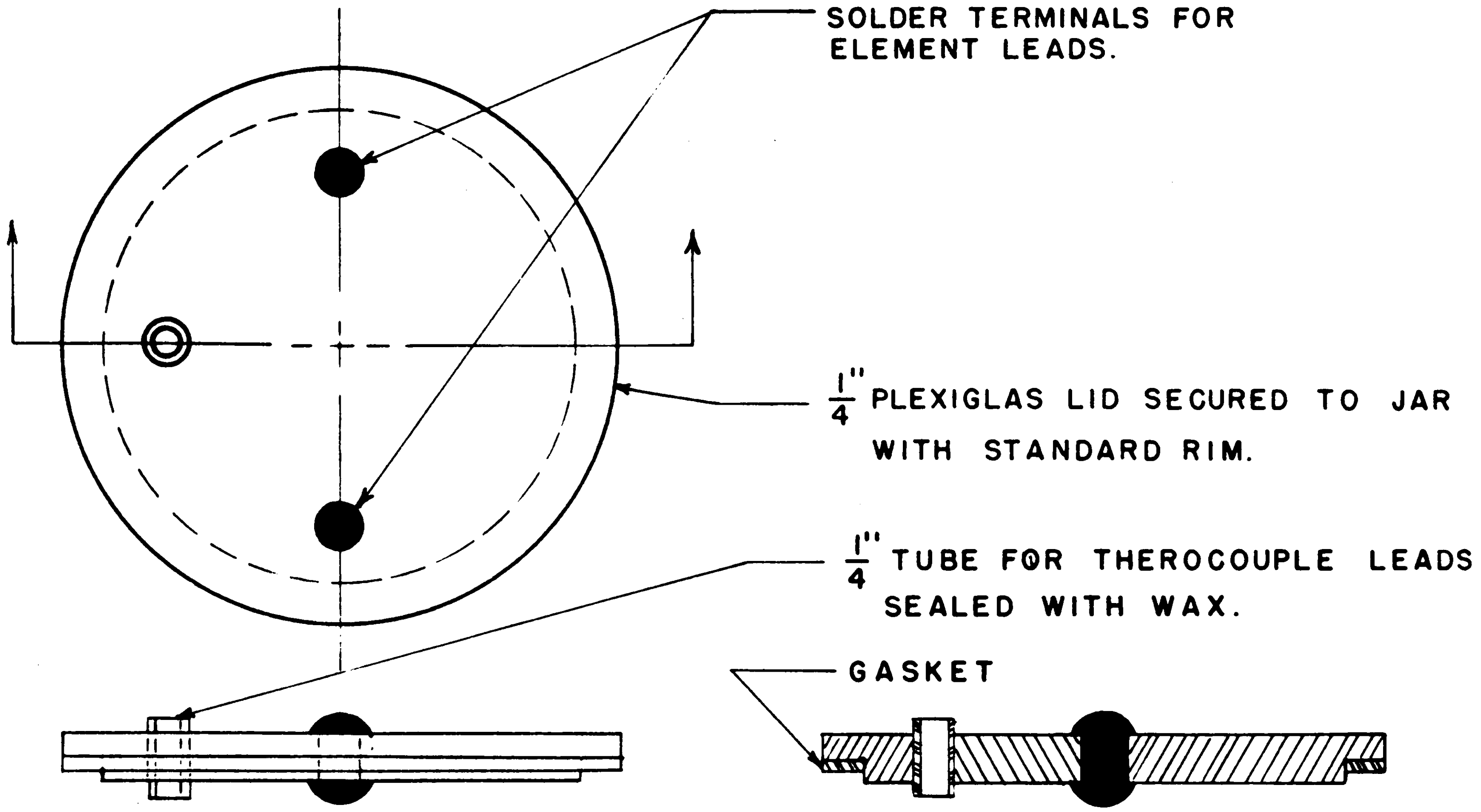


Figure 6. Vacuum Tube Voltmeter Connected to Element A through the Chamber Top Assembly. Element B is shown on the Left of two other Sample Elements



TOP ASSEMBLY FOR HUMIDITY CHAMBERS

FIGURE 7

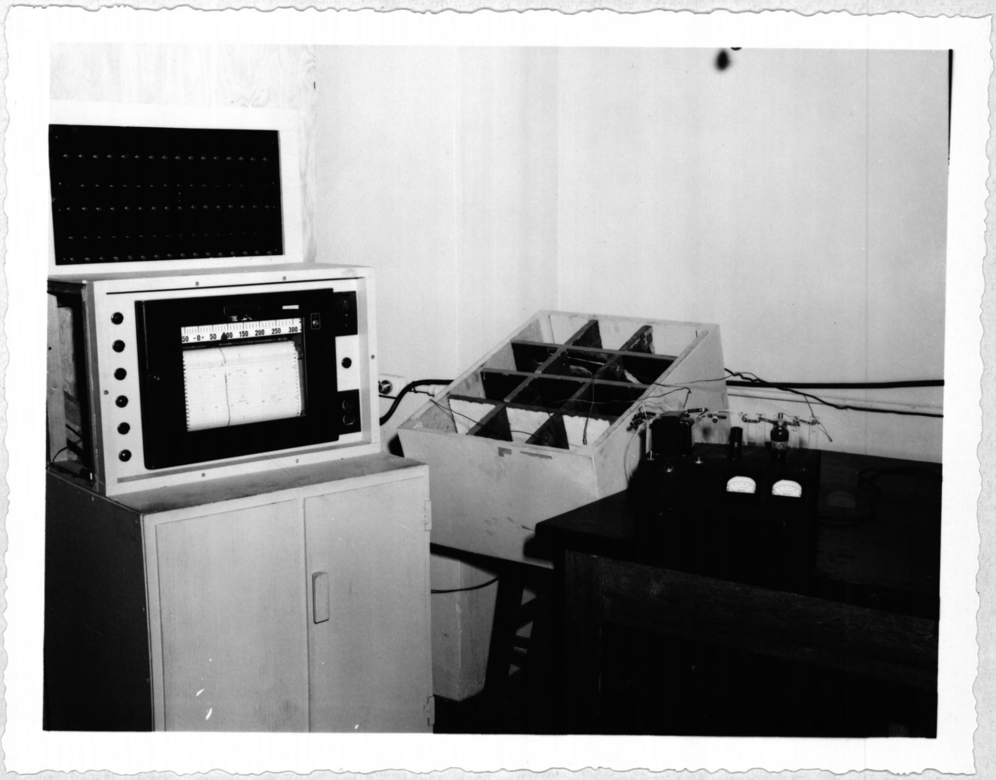
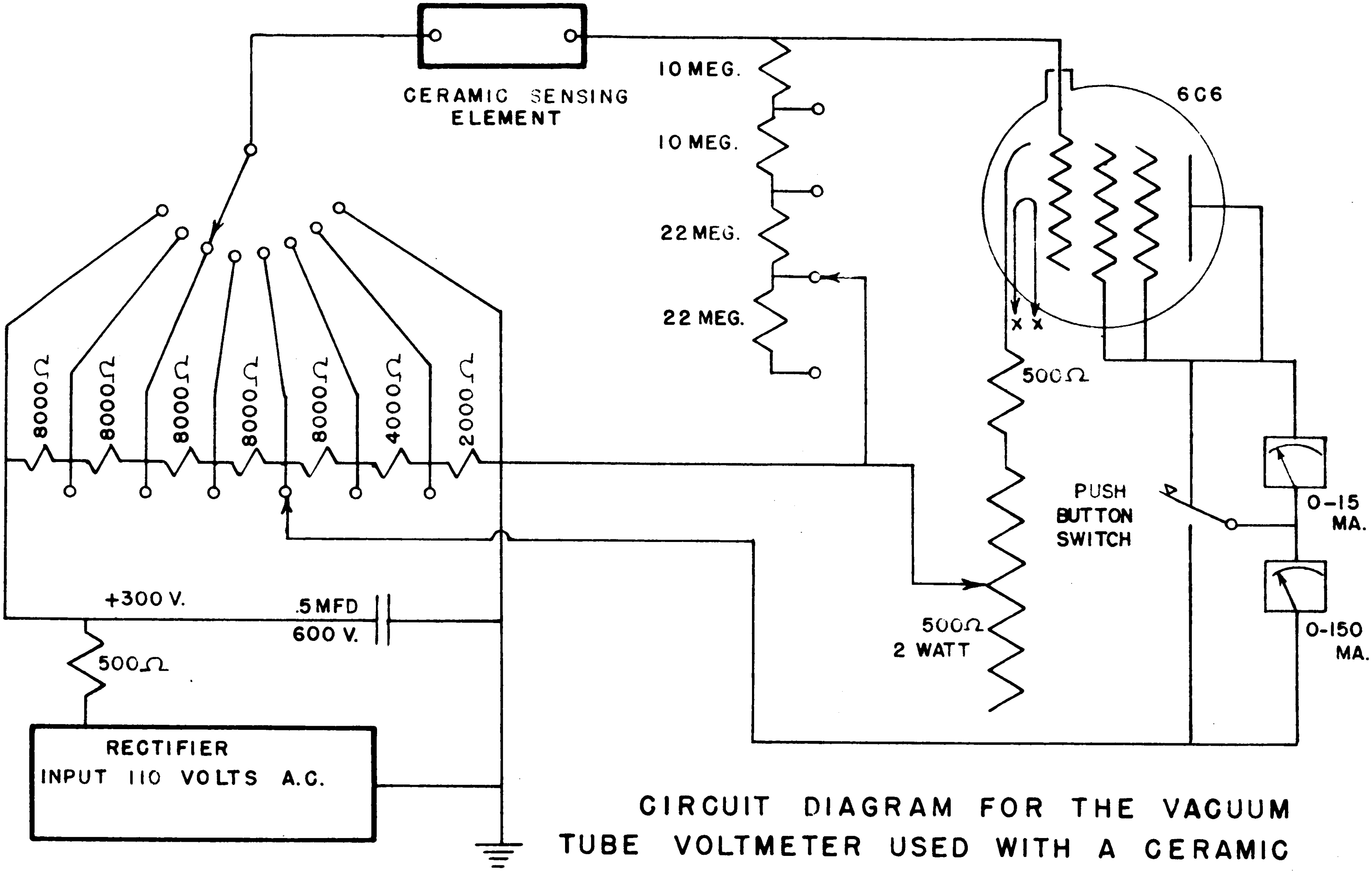


Figure 8. Vacuum Tube Voltmeter Connected to Element Located in Humidity Chamber which is Housed in an Insulated Box. Recording Potentiometer used with Thermocouples to Record Temperatures is Shown on the Left.

a better physical connection was made.

Preliminary tests were made to determine the overall operation of the apparatus using the small element described above, hereafter referred to as element A. Initial tests involved the moving of the element from one chamber to another and recording the current reading. As can be seen from the circuit diagram, figure 9, there were many possible settings of the switches which would influence the magnitude of the current readings. Also, it was possible to select a zero reading for any given setting of the other switches by switching the element out of the circuit and adjusting the current with the variable resistor that was in series with the cathode of the amplifying tube. Much time was spent in an attempt to establish a procedure for the operation of the vacuum tube voltmeter to provide on-scale readings for all the relative humidities being used and for one zero setting of the instrument.

Regardless of the care taken, the readings over a period of time with the element continuously exposed to constant conditions, varied as much as 0.45 milliamperes. Table II, page 108, shows these variations for several of the humidity chambers. Along with these variations, there was also present a constant movement of the needle on the milliammeter making it very difficult to read. A third trouble was that the zero setting would



CIRCUIT DIAGRAM FOR THE VACUUM TUBE VOLTMETER USED WITH A CERAMIC SENSING ELEMENT TO INDICATE PERCENT RELATIVE HUMIDITY.

FIGURE 9

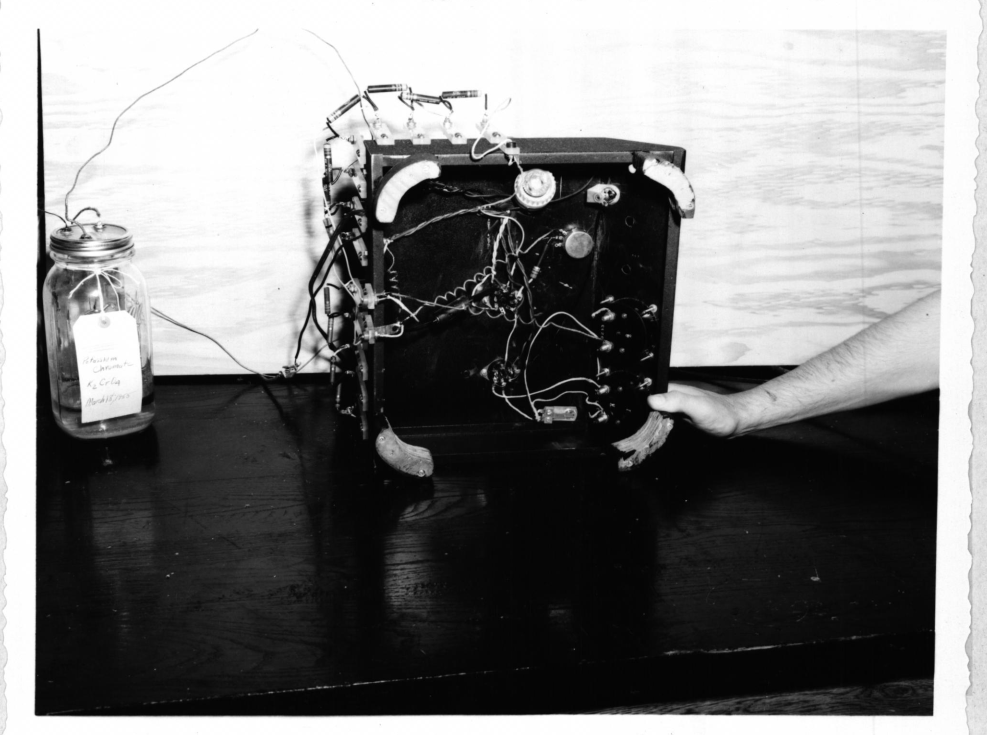


Figure 10. Underside View of the Vacuum Tube Voltmeter.

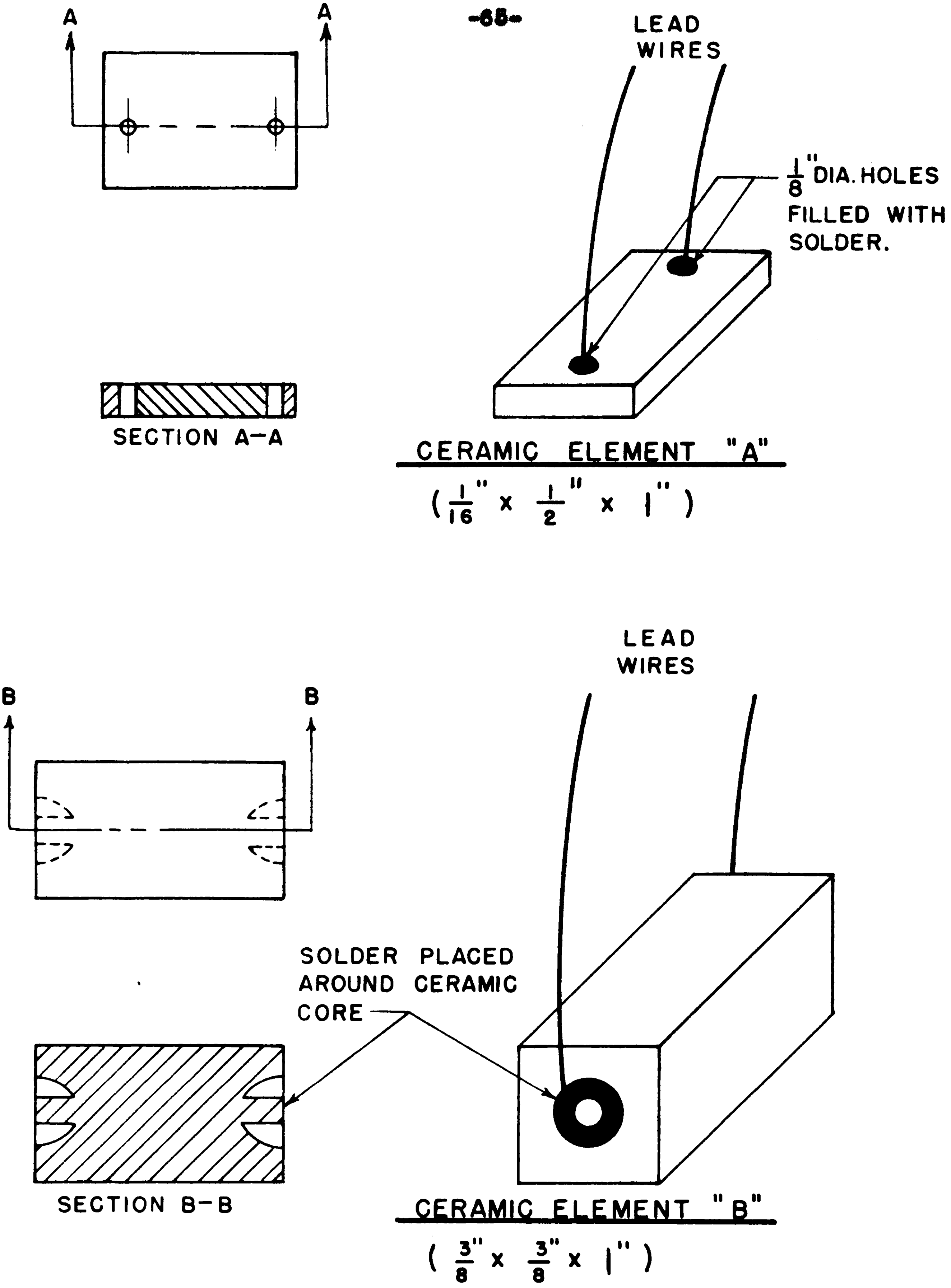

A
A
SECTION A–A
LEAD WIRES
1/8" DIA. HOLES FILLED WITH SOLDER.
CERAMIC ELEMENT "A"
(1/16" x 1/2" x 1")
LEAD WIRES
B
B
SOLDER PLACED AROUND CERAMIC CORE
SECTION B–B
CERAMIC ELEMENT "B"
(3/8" x 3/8" x 1")

FIGURE 11

drift from the initial setting after a rather short time. Because of these difficulties, the entire instrument was disassembled. The two rotating contact switches were eliminated. To replace these switches, leads from the various components were mounted on plexiglas strips, and switching was accomplished by soldering jumpers from one terminal to another. Therefore, all connections in the rebuilt instrument were soldered in an attempt to eliminate contact resistance in the switches. All soldering was done with rosin-core solder, and the parts being soldered were always heated sufficiently to melt the new solder, thus the soldering copper never came into direct contact with the solder. All lead wires were spaced as far from each other as was practical to protect against the break-down of the wire insulation.

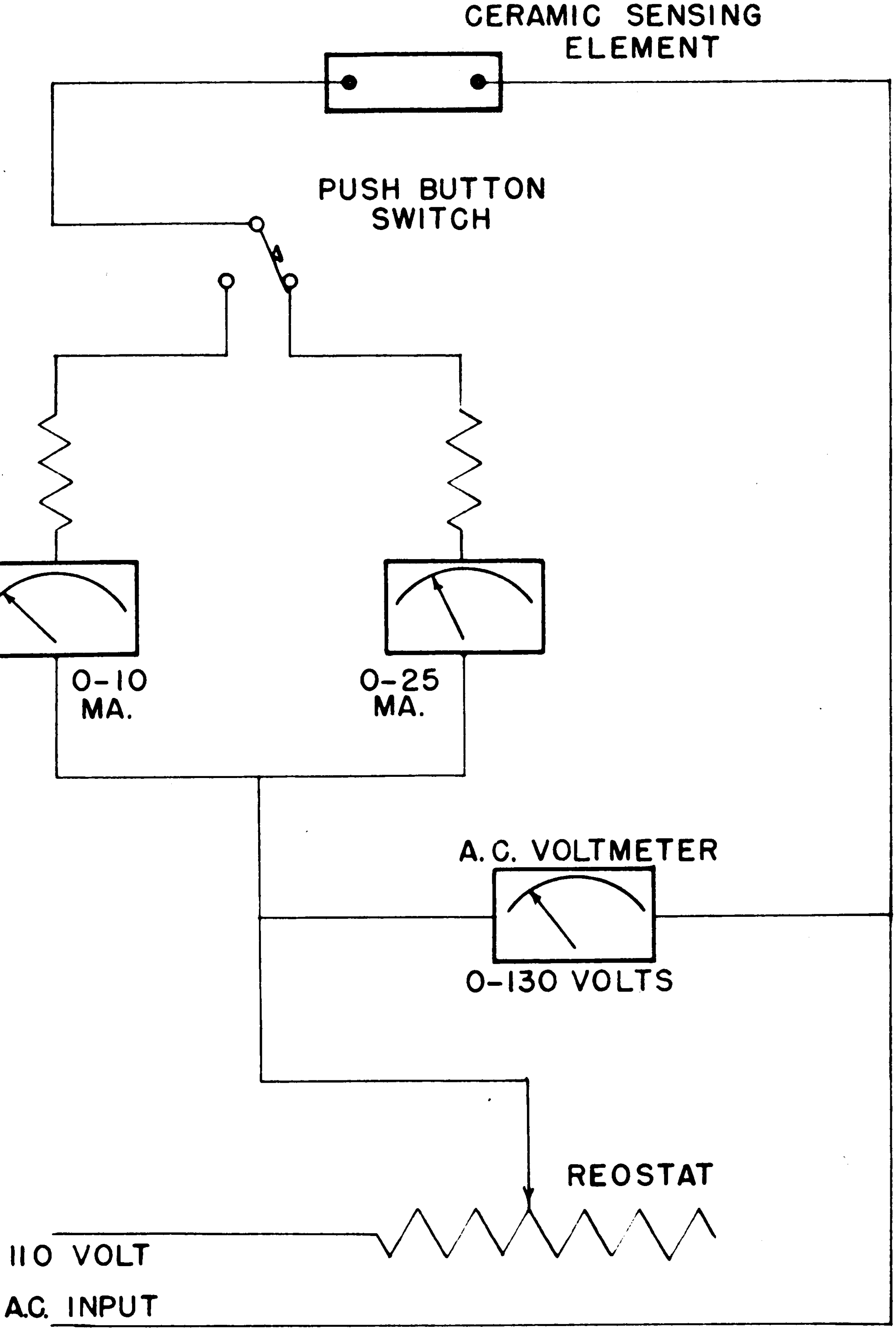
Further tests with the modified instrument indicated the same troubles that had been present in the beginning. However, considerable data was obtained using the instrument and element A. (Table III, page 107). The element was suspended in each of the chambers for some period of time and readings were recorded at various intervals. No definite test procedure was set up because it was still felt that the instrument was not adequate. For the same reason, no other elements were tested to any extent, although the operation of the instrument was observed for the large element described above, here-

Figure 12. Reostat and Voltmeter Used to Maintain a Constant Input Voltage to the Vacuum Tube Voltmeter.

after referred to as element B. Using element B, the instrument performed the same as with element A. Because of the lack of confidence in the vacuum tube volt meter fabricated in the laboratory, consideration was given to the use of other means for making the electrical measurements.

It was realized that it was necessary to keep the current through the element very small to prevent any heating of the element, and thus, a driving-off of moisture adsorbed by the element. However, based on work at the General Electric Laboratories where the heating effect was utilized to modify the characteristics of a hygrometer element, it was decided to apply a voltage directly across the sensing element (39). With a milliammeter in series with the element, the current could be read directly. Figure 13 is a diagram of the circuit used for these tests. The voltage supply was A-C to prevent polymerization, and could be varied from 0 to 130 volts. The apparatus was arranged so that a milliammeter of the proper range could be placed in the circuit at any time, but each meter had to have a series resistor added to maintain a constant resistance for the circuit, excluding the sensing element. The temperature of the element was recorded with a thermocouple inserted into a small opening approximately in the center of the element.

All of the testing done with the direct method involved the use of element B after it had been soaked for several days in a saturated solution of lithium chloride, and then dried



CIRCUIT FOR APPLYING AN A.C. VOLTAGE ACROSS A CERAMIC SENSING ELEMENT.

FIGURE 13

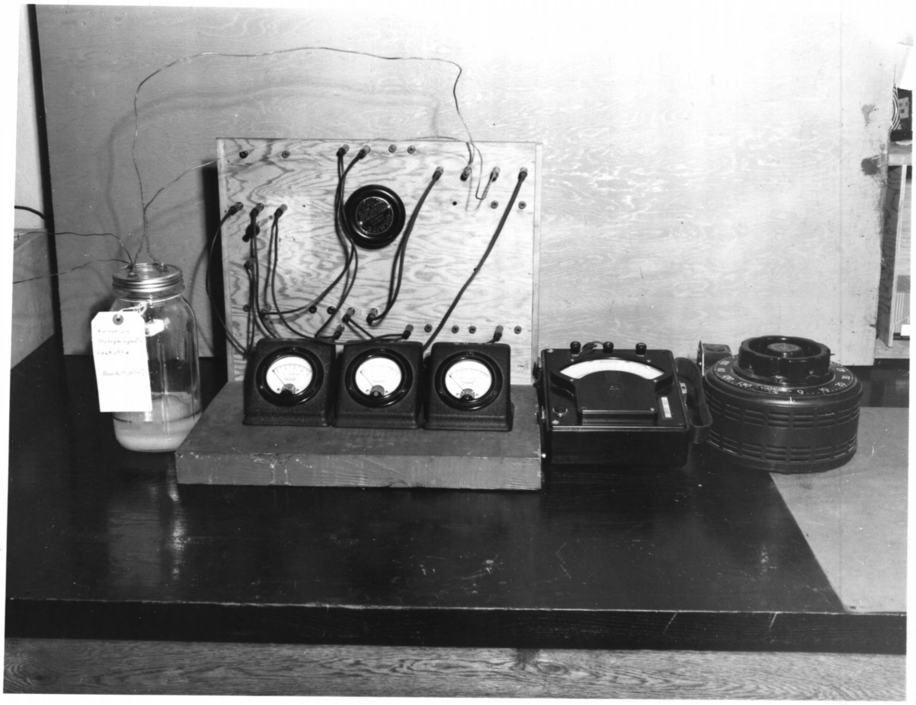


Figure 14. Arrangement of Components Used for Applying AC Voltages across the Sensing Element. The Reostat and Voltmeter were used to Control Voltage, and three milliammeters were available for measuring the current-0 to 100 ma., 0 to 25 ma., and 0 to 10 ma.

in an oven at 150°F for several more days. The first test was to show the relationship between conduction, temperature, and time. The element was suspended in the humidity chamber for at least 2 hours before a voltage was applied across the element. Current and temperature readings were recorded every 30 seconds until the readings became constant. The test was conducted for 60, 80, and 130 volts (Table IV, page 109).

Using the same equipment, a test was conducted wherein the voltage was adjusted to maintain a current of one milliampere through the sensing element. The voltage required was considered an indication of the relative humidity. This method was used for each of the humidity chambers in an attempt to keep the element heating as low as possible. The voltage, chamber temperature, and element temperature were recorded for each chamber (Table V, page 110).

Again using the same apparatus and sensing element, the element was exposed in individual humidity chambers and the applied voltage varied from 0 to 130 volts in 10 volt steps. The element current, chamber temperature, and element temperature were recorded for each voltage. The duration of exposure in each chamber was not specified, nor were the time intervals for making readings. Test data were collected over a period of about five months, with the element being exposed in each chamber several times to provide comparative data for the same conditions after a time lapse. (Table VI, page 111).

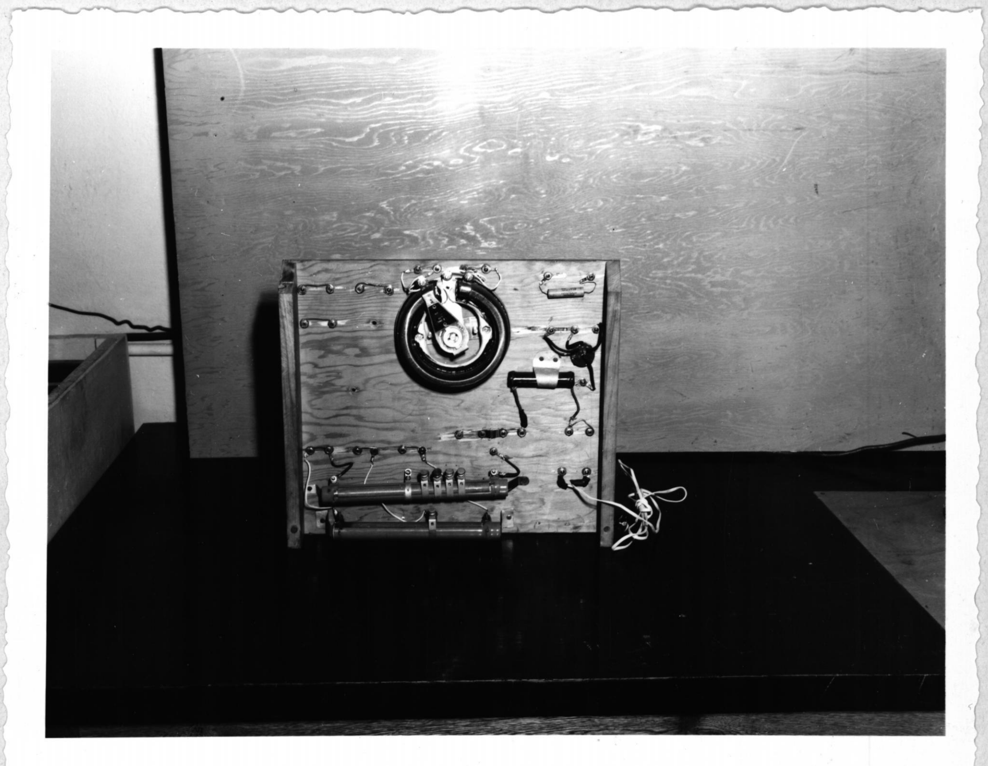


Figure 15. Rear View of the Apparatus for Applying AC Voltages Directly to the Element.

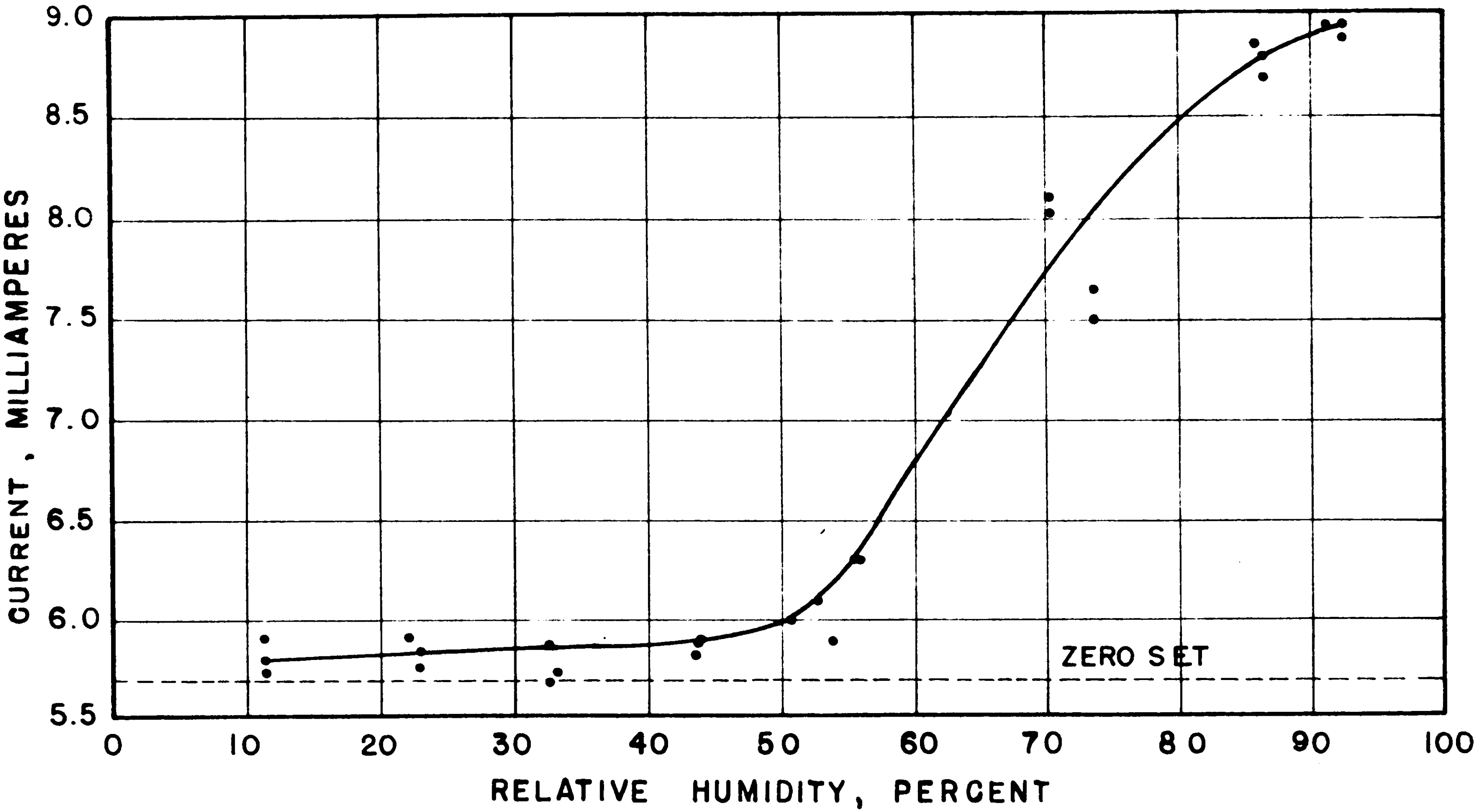
Using the data obtained from the test just described to calibrate the apparatus, the sensing element was exposed to the atmosphere. A constant voltage of 130 volts was applied, and the element current, atmospheric temperature, and element temperature were recorded. An Assmann psychrometer was used to obtain wet-and dry-bulb temperatures from which the atmospheric relative humidity could be determined, thus furnishing sufficient information to provide a comparison of the two humidity measuring instruments (Table VIII, page 115).

RESULTS OF LABORATORY RESEARCH

The tests were designed and conducted for a two-fold purpose: to evaluate the indicating instrument, and to determine some of the characteristics of the ceramic elements. A summary of the recorded data is given in the Appendix, and the results are presented and shown graphically in this section.

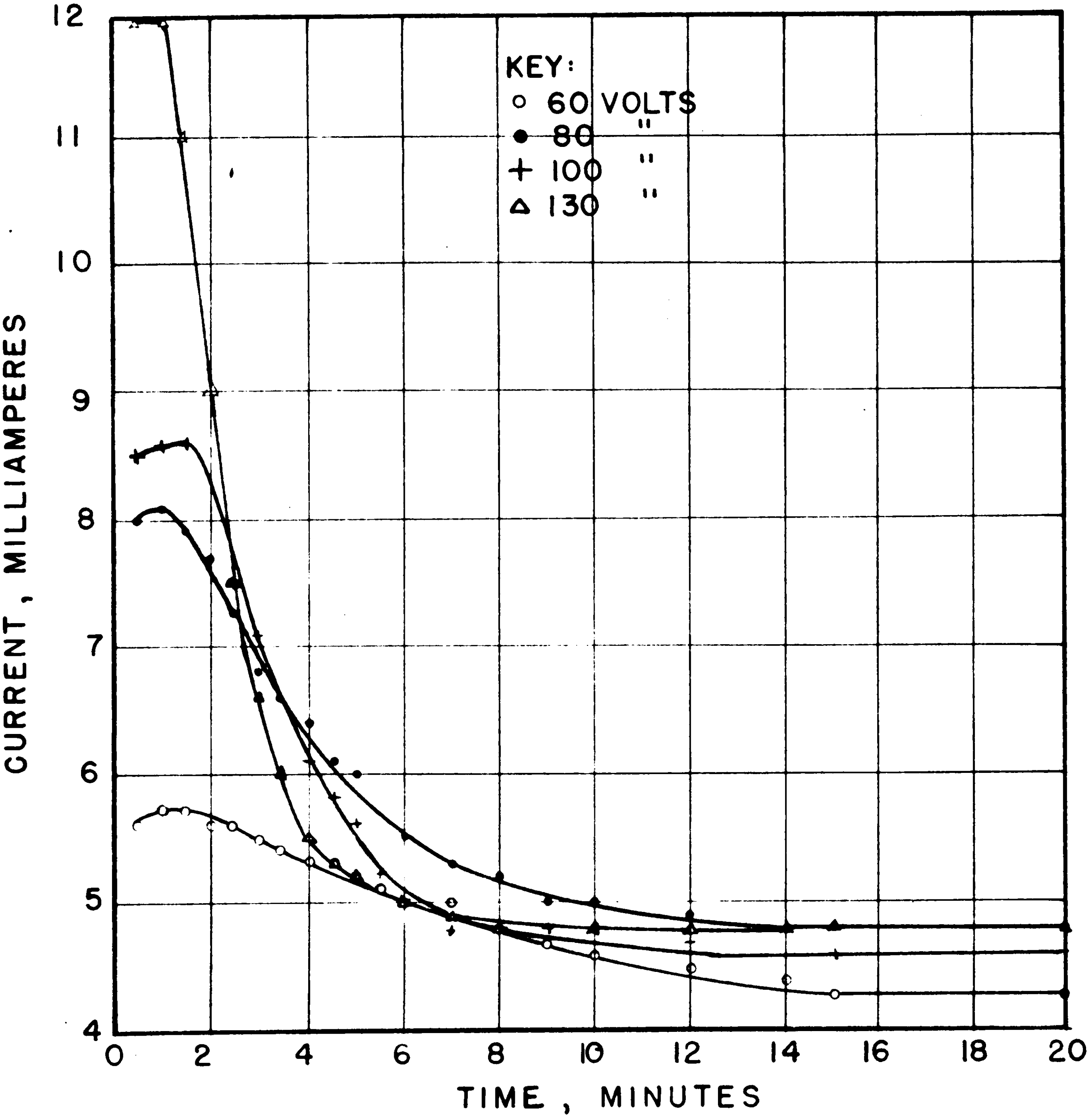
Figure 16, current vs. relative humidity, is the calibration curve plotted from data obtained with the vacuum tube voltmeter and element A after that instrument was modified (Table III, page 107). The curve indicates a very large change of resistance between 50 and 100 percent relative humidity, but a small change of resistance below 50 percent. The sudden change of the slope of the curve at about 52 percent, variations of the collected data, drifting of the zero set, and fluctuations of the indicator, all for approximately the same conditions, give reason to question the reliability of the indicating instrument; and therefore, the operation of the instrument was not considered satisfactory.

The effect of heating element B by the use of sufficient current is shown in figures 17 and 18. The data (Table IV, page 109), were obtained with a voltage applied to element B suspended in a chamber at approximately 92.5 percent relative humidity and 80°F, and are believed to be very accurate. Figure 17, current vs. time, indicates that ten minutes is



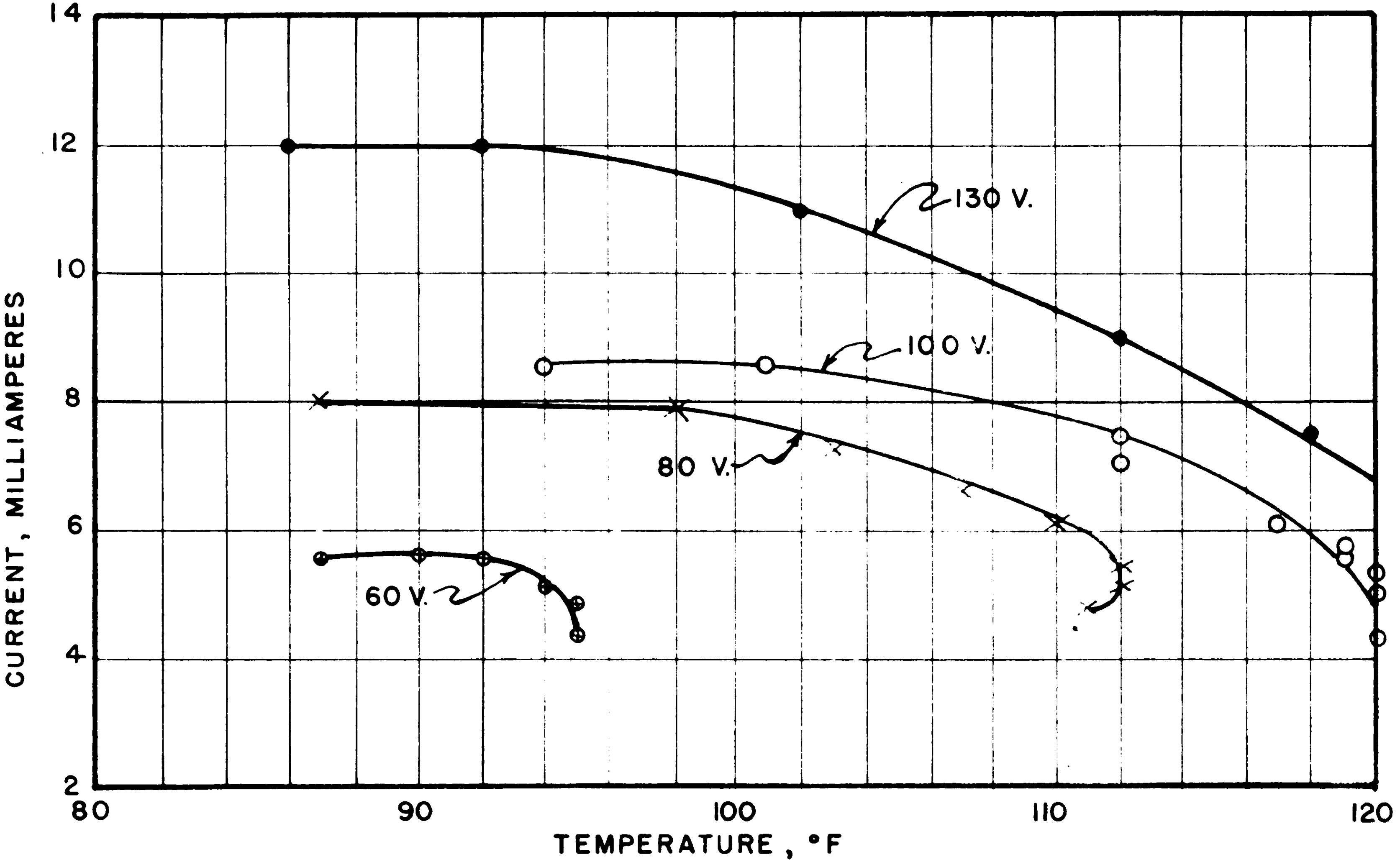
THE CALIBRATION CURVE FOR THE VACUUM TUBE VOLTMETER

FIGURE 16



THE EFFECT ON THE CONDUCTANCE OF ELEMENT B DUE TO THE HEAT PRODUCED BY THE CURRENT WHEN A CONSTANT VOLTAGE IS APPLIED ACROSS THE ELEMENT.

FIGURE 17



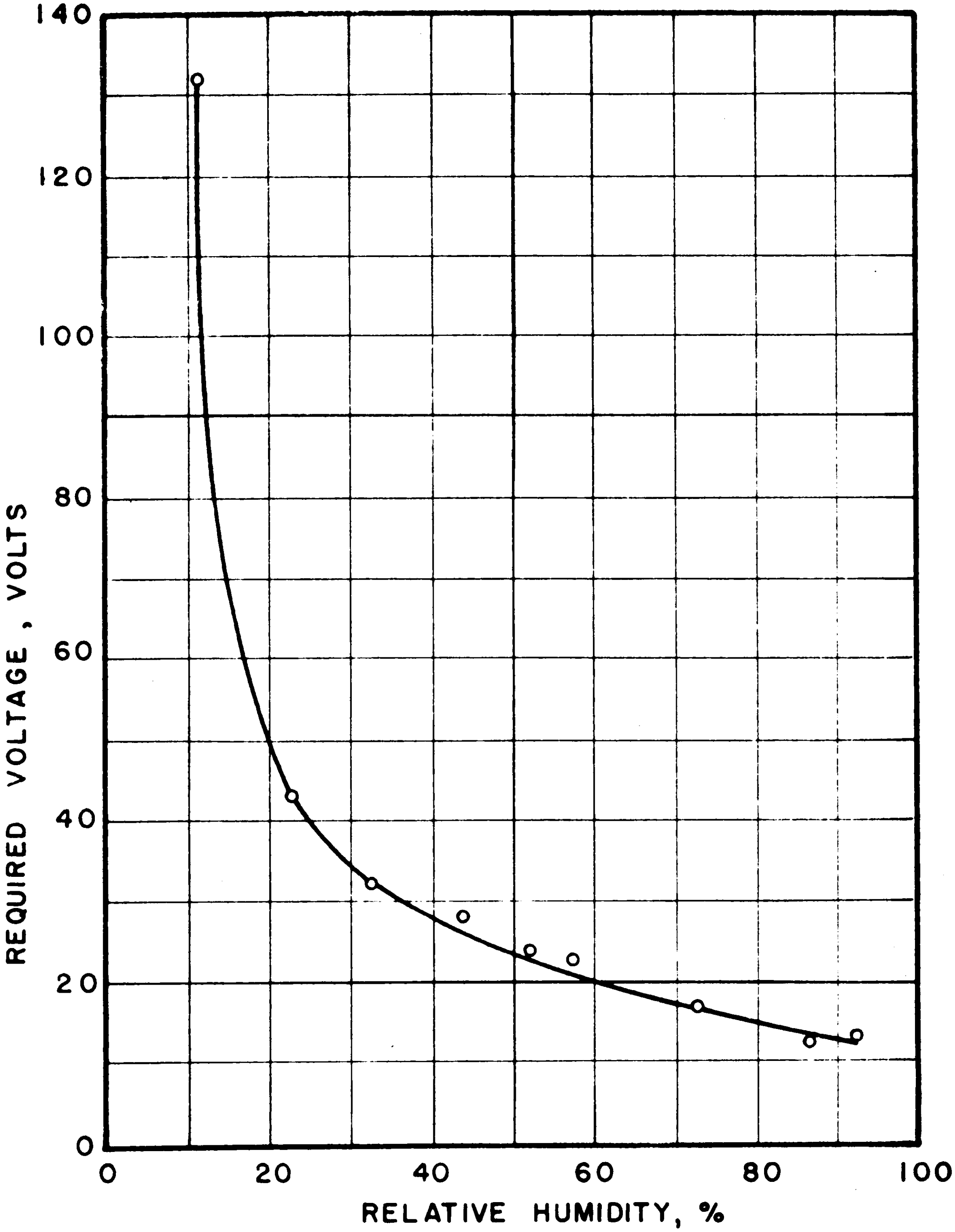
THE RELATION OF ELEMENT CONDUCTANCE TO THE TEMPERATURE OF THE ELEMENT

FIGURE 18

sufficient time for an element to reach an equilibrium condition after a voltage is applied. The curve also indicates that after the initial heating affect, that is, when the element has reached an equilibrium condition, a constant current will be obtained for a given voltage, and nearly a constant current for any of the four voltages tested since the variation is less than seven-tenths of a milliampere. Thus, a possible conclusion is that a similar instrument could be operated on line voltage without being seriously affected by the usual line voltage fluctuations.

Figure 18, current vs. temperature, indicates nearly a constant current until approximately one-half of the increase of element temperature has taken place, and figure 17 indicates the same constant current for one to one and one-half minutes after the voltage is initially applied. However, after the initial temperature rise, the current drops off very rapidly until the temperature and current reach an equilibrium condition, represented by the final point for the curves on Figure 18.

In order to hold to a minimum the heating of element B, the directly applied voltage was adjusted to maintain a constant current of one milliampere. Figure 19, voltage vs. percent relative humidity, was plotted from the data obtained (Table V, page 110). The curve indicates a very rapid change of resistance from 10 to 22 percent, a rather uniform change from 22 to 86 percent, and practically no change from 86 to 93

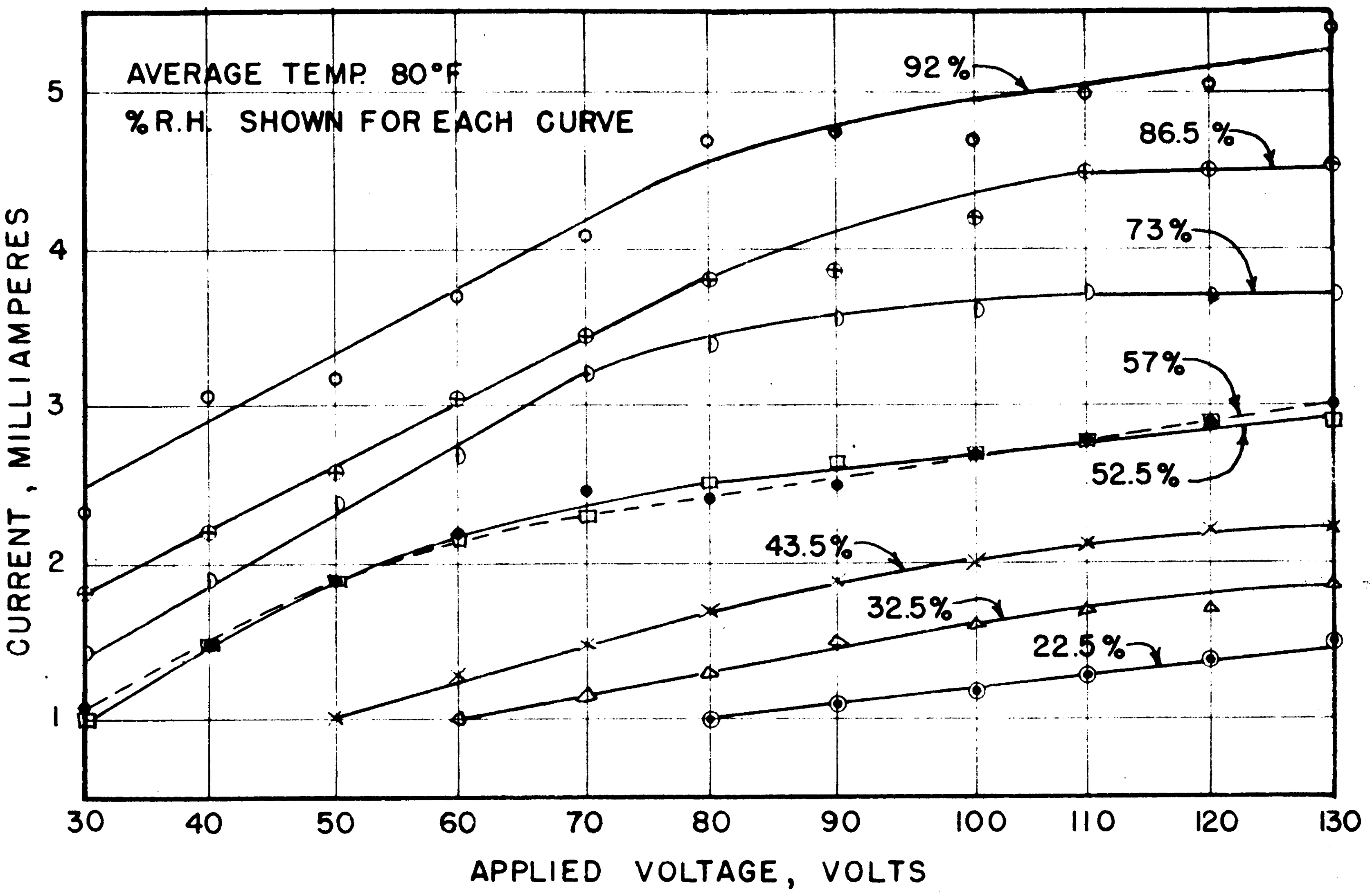


VOLTAGE REQUIRED TO MAINTAIN CURRENT OF 1 MA. THROUGH ELEMENT B FOR ALL HUMIDITY CHAMBERS.

FIGURE 19

percent relative humidity. However, a comparison of the chamber and element temperatures recorded for each humidity chamber revealed that the element heated a measurable amount for the six chambers containing the lower humidities, the temperature being raised the most for the lowest humidity.

Disregarding the heating effect, the voltage applied to element B was varied in steps of 10 from 10 to 130 volts and the corresponding current recorded. The data collected over a five month period was condensed, and two readings for each humidity chamber and each voltage were selected to plot the curves, figure 20, giving the relationship between the applied voltage and the current for each of the nine available humidities (Table VI, page111). The selection of the data to be used was based on an average of the recorded element current for a chamber temperature of 80°F, or thereabouts. Consideration was also given to the length of time that the element had been exposed in a chamber, the longer time being considered the best. The curves of figure 20 indicate a fairly uniform change of resistance throughout the humidity range with perhaps a tendency for the curves to flatten out for the higher voltages. The larger current increases the heating since the heating effect is proportional to the square of the current. Thus, the increased element temperature causes an increase in the resistance, and, thereby, the current is controlled not only by the voltage applied, but also by the temperature



CURRENT THROUGH ELEMENT B FOR VOLTAGES VARIED FROM 30 TO 130 V. IN STEPS OF 10 V. FOR EACH TEST HUMIDITY.

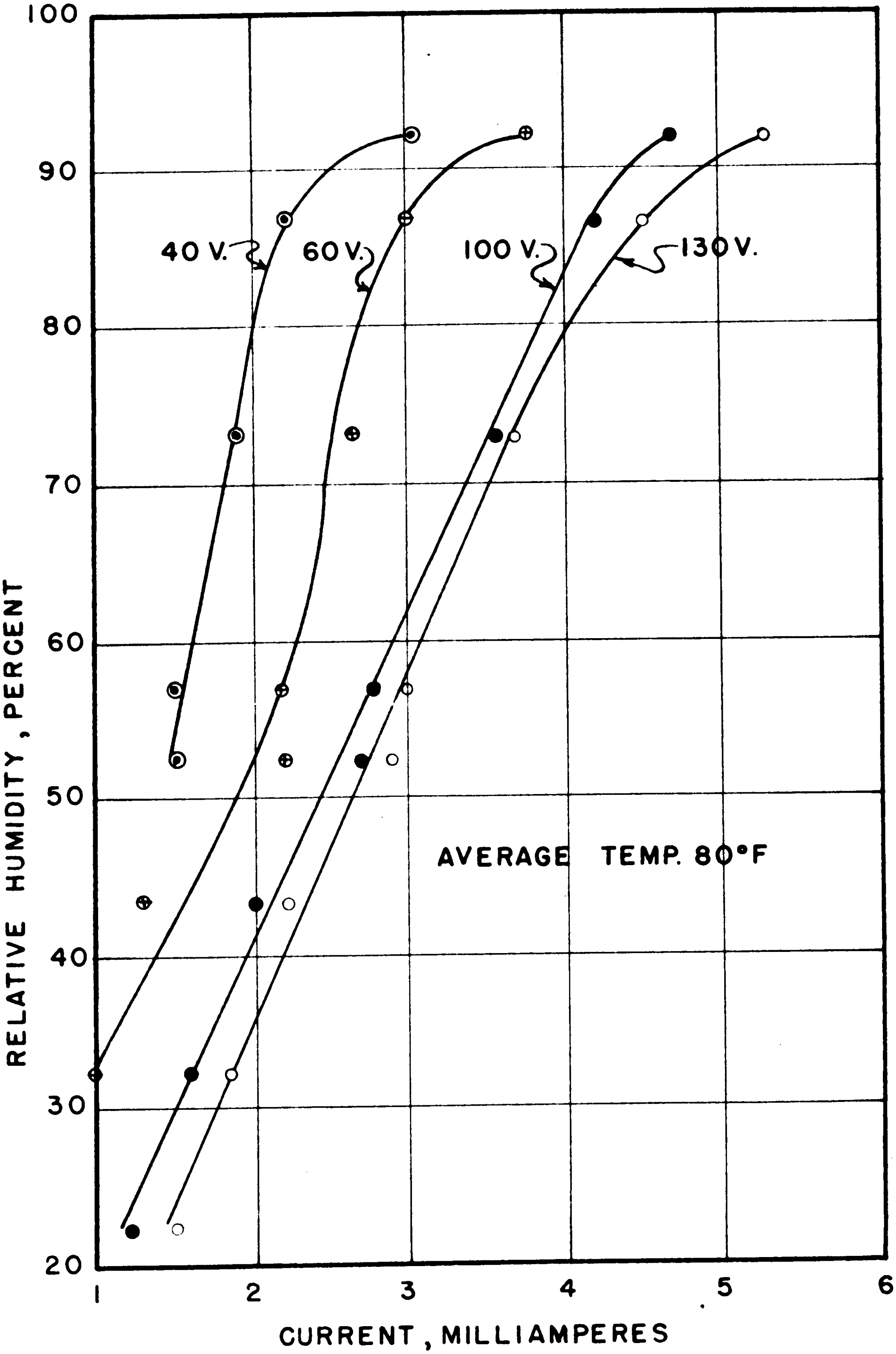
FIGURE 20

of the element.

Note that the curve for the lithium chloride chamber, 11.1 percent relative humidity, does not appear on figure 20. Since a 0 to 10 milliammeter was used, the current could not be measured below one milliampere. Therefore, the current could not be read when the element was in the lowest humidity chamber.

Figure 21, plotted from the same data as figure 20 described above, gives the relationship of the element current to the percent relative humidity. These curves, plotted for a given voltage and an average temperature, are the calibration curves for the direct-voltage method used for indicating the changes of resistance. Because the current could not be recorded below one milliampere, the lower range of the relative humidity that can be measured is a function of the applied voltage. For 130 volts, the highest voltage used, the humidity could be detected in the chamber having 22.5 percent relative humidity, but for 40 volts, the lowest detected was 52.5 percent.

While collecting the data for the test just described, all humidity chambers were used several times. In some cases, a time interval of two or more months seperated the tests for the same chambers. A comparison of the data collected for a given humidity for the first test run and that collected later indicates a very significant change between current readings for the same voltages. A comparison of several



CALIBRATION CURVES FOR THE DIRECTLY APPLIED VOLTAGE METHOD.

FIGURE 21

sets of data are shown in the appendix (Table VII, page114). Such an occurrence could be termed "aging" of the element, and could be due to a chemical change of the element. Data recorded from the same chamber after the element had been in use for two months, agrees closely.

The final test was a comparison of element B exposed in the atmosphere and the humidity determinations made with an Assmann psychrometer. A comparison of the readings is given in Table VIII (page115). Approximately one-third of the values determined with the ceramic element are within two percent, while the remaining two thirds disagree by as much as 30 percent relative humidity. Every determination with the electric hygrometer was low, even when agreement was within two percent relative humidity. Also, all of the dry bulb temperatures (equal to chamber temperatures) were below 80°F., the average temperature for the calibration of the electric hygrometer. If the surrounding temperature affects the resistance of the element, then the low dry-bulb temperatures may have, in part, caused the low readings. However, if the resistance of an element exposed to water vapor increases with temperature of the element due to the increased heating, then the determinations with the electric hygrometer at the lower temperatures should have been high instead of low. Considering the electrical resistance of a ceramic material free from moisture, it is possible that the electrical resistance increases with a decrease in temperature, that is, the material has a negative temperature coefficient of resistance. Although this investigation did not establish this fact, it is known that some ceramic materials possess this property (40). Should this be true of the element tested, then it is at least a partial explanation for the low values obtained.

All of the determinations compared in the atmosphere were for relative humidities below 60 percent. This was not the intended range, but was determined by the natural conditions within the laboratory. It is thought that for higher humidities the electrical instrument will function better because of the larger current through the element. Most of the data recorded for the directly applied voltage tests appear to be more consistent when the current is above three milliamperes.

DISCUSSION OF RESULTS

The vacuum tube voltmeter, although not successful in the research completed appears to be the most suitable type of instrument for an indication of the change of resistance of a ceramic sensing element. Tests with the applied voltage method show very readily the effect of heating on the conductance of the element. The heating counteracts the fundamental characteristics of the ceramic material - the adsorption of water on the surface. The change of resistance of the element is a function of the adsorbed moisture, but driving - off some of the moisture by heating partially destroys the natural phenomenon, and causes the humidity indication to be a function of the decreased adsorption. The vacuum tube volt-meter employs a current so small in magnitude that the temperature of the element is not increased and the change of resistance remains proportional to the surrounding humidity. It is felt that the troubles involving the use of the vacuum tube volt-meter were created by the design and construction of the device, plus the possibility that the instrument was not adjusted properly.

The results obtained with the vacuum tube voltmeter indicate a change of resistance for element A that would be readily measurable for any humidity changes over 50 percent. The results do not, however, eliminate the use of the ceramic element for lower humidities because insufficient testing was conducted for this range.

The other method of indication, a directly applied voltage, gave results indicating successful determinations of humidity as low as 22.5 percent. However, the use of voltages above the maximum of 130 V. that was used, would perhaps extend the useful range to lower humiditties.

In the tests where the applied voltage was adjusted to maintain an element current of one milliampere, the heating effect was partially eliminated for the higher humidities, but it was still measurable for the lower humidities. Since element heating occured and since an automatic instrument to maintain the proper current would be more difficult to construct, this method does not appear to justify further consideration.

From the data obtained with both instruments indicating that a ceramic material can be used as a sensing element for humidity measurements, the most significant problem remaining is the effect that temperature has on the resistance of the ceramic element. Since the resistance of all materials is affected to some extent by temperature changes, the magnitude of the effect on the ceramic material should be determined. For the tests conducted, the total resistance change was indicated, and therefore the change can not be broken down to the change due to humidity, and the changed due to temperature. Because no means were provided for temperature control, all results were obtained at natural temperature conditions, and for comparison, the results had to be selected from the recorded data where the temperatures were nearly the same. Thus, the curves showing the various relationships are based on an average temperature of 80°F.

Where the element was heated, the effect of resistance due to temperature changes could be expected to be the greatest. This factor definitely limits the conclusions that might be obtained as to element characteristics from the data obtained with the directly applied voltage.

The comparison of the electric hygrometer and the Assmann psychrometer was not completely satisfactory, but it does give reason to believe that when perfected, the ceramic element will perform adequately. Several reasons for the poor comparison between some of the measurements with the two instruments can be given. First, the temperature of the element was as much as 20°F below the average temperature of the calibration curve. Also, the element could not be located at the same position as the wet - and dry-bulbs due to the enclosure surrounding the thermometers. The circulating fan on the psychrometer created an air movement, thus making it necessary to locate the element away from the psychrometer. These conditions do not justify the large differences between the humidities measured, although they do at least, give a partial explanation for the variations.

The original plan for testing included tests to determine the value of coating the ceramic element with a hygroscopic solution. As explained earlier, element B was coated with lithium chloride, but no tests were conducted to ascertain the usefulness of such a treatment. It was noted with element B, that an apparent aging took place. This is, the conductance of element B changed for approximately the first two months, and then was constant for the remainder of the tests. Readings were obtained after the initial period which were duplicated several times during the last three months of testing. Test data does not indicate that element A underwent similar aging, therefore the cause of the aging may be due to the lithium chloride coating.

CONCLUSIONS

Any conclusions resulting from the laboratory research are those that can be based on general observations made during the testing of the two ceramic elements, and to a lesser degree, on the results of the tests. Thus, from these two sources, the foremost deduction is that the possibilities of using a ceramic material for the sensing element of an electric hygrometer are as good as were expected before the tests were begun.

The results of tests conducted with two methods for obtaining indications, which involved the use of a very small electrical current and the use of a current sufficient to cause heating of the element, leads to the conclusion that for the most successful instrument, the small current is an essential requirement. Heating of the element alters the fundamental adsorption of the moisture by the ceramic material and decreases the overall effectiveness of the element.

From the voltage applied across element B and the measured current resulting, the resistance of the element at a specific humidity can be calculated. Using Ohm's law, it was determined that the resistance for element B varied from 132,000 ohms at 132 volts and 11.2 percent relative humidity to 11,800 ohms at 20 volts and 92.6 percent relative humidity. This range of resistance is much lower than expected. However, since element B was coated with lithium chloride, the hygroscopic salt may have increased the adsorption of moisture, and thereby greatly decreased the resistance of the element. No comparison with an uncoated element was made, however, the current observed with the vacuum tube voltmeter and element B was very small even after some amplification. This would indicate the resistance for a plain ceramic element was much greater than the resistance of an element coated with some hygroscopic salt.

Based on the current-humidity relation established for a given voltage, a ceramic element, such as element B, could be used as a humidity control element. Using element B as an example, a current of 1.7 ma. correspondes to a voltage of 110 volts and a humidity of 32.5 percent for an average temperature of 80^{o}F. If the temperature remains nearly constant, but the humidity increases to 73 percent, the current for the same voltage is 3.7 ma. If a relay capable of operating on 3.7 ma., but not operating on 1.7 ma., is placed in the circuit with the element, the relay could be used to control the operation of dehumidification equipment. Thus, the equipment would operate when the humidity was above 73 percent, but would not function for lower humidities. With the element as described in this paper, it would be difficult to maintain a very close control, but rather within a range of from 10 to 20 percent relative humidity. The operating range, the desired current, and other elements of the system could be varied by the choice of the applied voltage and the ceramic element. It is, therefore, concluded that an element made from a ceramic material could be applied to humidity control applications where very close control would not be required.

RECOMMENDATIONS

During this investigation, many obstacles were encountered which hindered the progress of the project and limited the findings. Therefore, the following are recommendations made to aid the success of any similar project.

The means of maintaining atmospheres of known humidities was considered adequate for the basic investigation. It is felt, however, that a more reliable means should be used for the accurate calibration of a hygrometer. It is recommended very strongly, that in any future use of the saturated solutions as a means for producing known humidities, that a method be adapted for maintaining the solutions and chambers at a constant temperature. It is further recommended that at least two additional chambers be used - one containing water to give 100 percent relative humidity, and one containing a desiccant to give dry air or zero percent relative humidity.

The importance of obtaining a satisfactory instrument for measuring the change of electrical resistance can not be over emphasized. Likewise, such an instrument should use a small current to eliminate any heating of the element.

The methods of attaching the electrical leads to the element should be studied to determine the best available means. Although the methods used herein appeared to be satisfactory, no evaluation of the connections was made.

The investigation as to suitable elements should include studies such as the effect of material, size, shape, porosity, and the use of coatings of hygroscopic salts. The experiments should be designed to determine the sensitivity to humidity and temperature, speed of response for both increasing and decreasing humidities, stability of calibration, effect of dust accumulations, and ruggedness of the sensing element.

The preparation for a future project should include a survey of literature concerning ceramic materials. Undoubtedly, information can be found concerning properites of common ceramic materials which would aid greatly in the selection of materials to be tested.

SUMMARY

The first objective of this problem - thorough literature review - was conducted on all available references concerning humidity measurement, and visits were made to the American Instrument Company in Silver Springs, Maryland, and the National Bureau of Standards. The survey evaluated the instruments in use today and also explored many of the ideas and concepts that have been suggested in past years as possible means for humidity measurement. A summation of the survey indicated that the electric hygrometer with a ceramic element was a good basic theory for a humidity instrument, but still required development before it would be of any practical use.

The second objective - development of a useful hygrometer - was directed towards the development of the electric hygrometer using a ceramic element. The study that resulted included the evaluation of two methods for determining the change of resistance of the ceramic element, as well as a preliminary investigation of the characteristics of a ceramic element when employed as the sensing element for an electric hygrometer.

The element intended for the initial tests, a porous ceramic containing mostly aluminum oxide, was the only material tested, but the tests included elements of the pure ceramic material and the same material after it was soaked in a saturated solution of lithium chloride. With the instruments used, the indications were that both elements were suited for determining the high humidities. The pure element had a lower limit of 50 percent relative humidity, and the coated element a lower limit of 20 percent.

Two instruments were used for indicating the change of relative humidity. A vacuum tube voltmeter type instrument was tested, but found unsatisfactory due to variations of readings under the same conditions, drifting of the zero set, and excessive fluctuations of the indicating meter. The other instrument or method used was to apply an A-C voltage across the element, and to measure the resulting current flow. Because the current was maintained above 1 milliampere, heating of the element was caused, resulting in a change of element resistance. However, results with this instrument were sufficient to establish a calibration curve for the apparatus. A comparison of this device and a psychrometer indicated the usefulness of such an instrument, but confirmed that the development was not complete.

The overall result of the research indicates that the selection of the ceramic sensing element for an electric hygrometer has merit, but more development is necessary. Two phases of any future work on the problem should be the development of the indicating instrument, and the selection and design of the sensing element. The need for a satisfactory instrument still exists, and the successful development of the type instrument described herein, would undoubtedly meet the requirements.

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APPENDIX

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TABLE I

Relative Humidity Over Saturated Salt Solutions

Chemical*	Determination Temperatures		
	73°F	86°F	100°F
	% R. H.	% R. H.	% R. H.
Ammonium Monophosphate	92.9	92.0	91.1
Potassium Chromate	86.5	86.3	85.6
Sodium Acetate	74.8	71.4	67.7
Sodium Bromide	58.5	56.3	53.7
Magnesium Nitrate	53.5	51.4	49.0
Potassium Carbonate	43.9	43.5	43.4
Magnesium Chloride	32.9	32.4	31.9
Potassium Acetate	22.9	22.0	20.4
Lithium Chloride	11.1	11.2	11.1

* The relative humidity over saturated salt solutions at the specified temperatures as given in Report No. 40, The American Paper and Pulp Association, 1945.

Chemical**	Determination Temperatures		
	68°F	86°F	95°F
	% R. H.	% R. H.	% R. H.
Magnesium Nitrate	55.2	52.5	51.2
Magnesium Chloride	33.6	32.8	32.5
Lithium Chloride	12.4	11.8	11.7

** The relative humidity over saturated salt solutions at the specified temperatures as given in Research Paper 2512, Journal of Research of the National Bureau of Standards, July, 1954.

TABLE II

Variation of Current Readings with Vacuum Tube Voltmeter

Solution in Chamber	% R. H.	Current, ma.	Chamber Temp., °F
Ammonium Monophosphate #9*	92.2	8.45	82
	92.2	8.60	82
	92.2	8.70	82
	92.2	8.85	82
	92.5	8.90	82
Sodium Acetate #7	72.6	7.70	81
	72.6	8.50	81
	72.6	7.50	81
	72.6	8.80	81

* Reference number for solution.

The selected data above is taken from tests made with the vacuum tube voltmeter before it was modified. Note the variations of current readings for the same conditions of temperature and relative humidity.

TABLE III

Data Obtained With the Modified Vacuum Tube Voltmeter and Element A

Solution	Current, ma.	Chamber Temp., °F.	Percent Relative Humidity
Ammonium Monophosphate	8.95	91	91.5
	8.95	77	92.7
#9*	8.95	91	91.5
	8.90	78	92.6
Potassium Chromate	8.85	90	86.0
	8.85	90	86.0
#8	8.80	77	86.5
	8.70	77	86.5
Sodium Acetate	7.50	78	73.5
	8.10	90	70.3
#7	8.05	90	70.3
	7.65	78	73.5
Sodium Bromide	6.30	90	55.5
	6.30	90	55.5
#6	6.30	78	57.7
	6.30	78	57.7
Magnesium Nitrate	6.00	90	50.7
	6.00	90	50.7
#5	6.10	78	52.7
	5.90	72	53.7
Potassium Carbonate	5.90	90	43.5
	5.85	90	43.5
#4	5.90	73	43.8
	5.85	77	43.8
Magnesium Chloride	5.75	78	32.7
	5.85	80	32.6
#3	5.70	90	32.3
	5.85	82	32.5

TABLE III (continued)

Solution	Current, ma.	Chamber Temp., °F.	Percent Relative Humidity
Potassium Acetate	5.75	78	22.5
#2	5.80	79	22.4
	5.80	79	22.4
	5.90	90	21.8
Lithium Chloride	5.90	80	11.1
#1	5175	74	11.1
	5,80	76	11.1
	5.80	76	11.1

* Reference number for solution.

This table gives values of current indicated by the modified vacuum tube voltmeter for element A during tests in each humidity chamber. The zero set of the instrument was 5.7 ma.

TABLE IV

The Effect on the Conductance of the Ceramic Element Due to Heating

Total Time,	60 Volts		80 Volts		100 Volts		130 Volts	
Min. + Sec.	ma.	°F	ma.	°F	ma.	°F	ma.	°F
0 + 0	0	86	0	84	0	89	0	81
0 + 30	5.6	87	8.0	87	8.5	94	12.0	86
1 + 0	5.7		8.1		8.6	101	12.0	92
1 + 30	5.7	90	7.9	98	8.6	107	11.0	102
2 + 0	5.6		7.7		7.5	112	9.0	112
2 + 30	5.6	92	7.3	103	7.1	112	7.5	118
3 + 0	5.5		6.8				6.6	121
3 + 30	5.4	93	6.6	107			6.0	122
4 + 0	5.3		6.4		6.1	117	5.5	123
4 + 30	5.3	94	6.1	110	5.8	119	5.3	123
5 + 0	5.2		6.0		5.6	119	5.2	123
5 + 30	5.1	94			5.4	120		
6 + 0	5.0		5.5	110	5.2	120	5.0	123
7 + 0	5.0	94	5.3	110	5.0	120	4.9	123
8 + 0	4.8	95	5.2	110	4.8	120	4.8	123
9 + 0	4.7	95	5.0	110	4.8	120	4.8	123
10 + 0	4.6	95	5.0	110	4.8	120		
12 + 0	4.5	95	4.9	109	4.7	120		
14 + 0	4.4		4.8	109	4.6	120		
15 + 0	4.3	95	4.8	109	4.6	120	4.8	123
20 + 0	4.3	95	4.8	109	4.6	120		

Tests were conducted with element B suspended in the ammonium monophosphate chamber which maintained a humidity of approximately 92.5%. The temperature shown was obtained with a thermocouple located at the center of the element.

TABLE V

Voltage Applied to Maintain Current of One Milliampere

Chamber Ref. #	Volts	Element Temp. °F	Chamber Temp. °F	Percent R. H.
#9	13	80	80	92.5
#8	12	81	81	86.4
#7	17	82	82	72.4
#6	22.5	80	79	57.5
#5	24	84	83	51.8
#4	28.5	82	80	43.8
#3	32	84	83	32.4
#2	43	82	79	22.5
#1	132	88	83	11.2

To reduce the element heating, the voltage across element B was varied to maintain a constant current of one ma. when the element was exposed in each of the humidity chambers. Temperature of the chamber and element were recorded to indicate the heating effect.

TABLE VI

Element Current for Controlled Voltages

Applied Voltage, Volts	Chamber Reference Numbers					
	#1		#2		#3	
	ma.	°F	ma.	°F	ma.	°F
10	1 *	82	1 *	82	1 *	80
20	1 *	82	1 *	82	1 *	80
30	1 *	82	1 *	82	1 *	80
40	1 *	82	1 *	82	1 *	80
50	1 *	82	1 *	82	1 *	80
60	1 *	82	1 *	82	1.0	77
70	1 *	82	1 *	82	1.1	80
					1.2	81
80	1 *	82	1.0	82	1.3	85
					1.3	83
90	1 *	82	1.1	82	1.5	84
					1.5	85
100	1 *	82	1.2	82	1.6	84
					1.6	81
110	1 *	82	1.3	82	1.7	83
					1.7	84
120	1 *	82	1.4	82	1.7	85
					1.7	83
130	1 *	82	1.5	82	1.9	84
					1.8	85

* Current was below 1 ma. and could not be read.

Data was obtained with element B suspended in each of the humidity chambers and the voltage varied from 10 to 130 V. Temperature was recorded inside of each chamber with a thermocouple.

TABLE VI (continued)

Element Current for Controlled Voltages

Applied Voltage, Volts	Chamber Reference Numbers					
	#4		#5		#6	
	ma.	°F	ma.	°F.	ma.	°F.
10	1 *	79	1 *	82	1 *	78
20	1 *	79	1 *	81	1 *	78
30	1 *	79	1.0 1.0	83 81	1.0 1.1	85 84
40	1 *	79	1.5 1.5	85 82	1.5 1.5	84 84
50	1.0	78	1.9 1.9	82 83	1.9 1.9	84 83
60	1.3	84	2.2 2.1	84 86	2.1 2.3	88 83
70	1.5	85	2.3 2.3	86 86	2.4 2.5	81 83
80	1.7	85	2.5 2.5	86 84	2.4 2.4	81 85
90	1.9	85	2.7 2.6	82 86	2.5 2.5	81 80
100	2.0	83	2.7 2.7	82 78	2.7 2.7	81 81
110	2.1	82	2.8 2.7	79 78	2.8 2.8	82 84
120	2.2	75	2.9 2.9	72 74	2.9 2.9	84 85
130	2.2	83	2.9 2.9	79 74	3.0 3.0	84 82

* Current was below 1 ma. and could not be read.

Data was obtained with element B suspended in each of the humidity chambers and the voltage varied from 10 to 130 V. Temperature was recorded inside of each chamber with a thermocouple.

TABLE VI (continued)

Element Current for Controlled Voltages

Applied Voltage, Volts	Chamber Reference Numbers					
	#7		#8		#9	
	ma.	°F	ma.	°F	ma.	°F
10	1 *	80	1 *	79	1 *	77
					1 *	78
20	1 *	80	1.3	76	1.7	78
			1.4	71	1.7	75
30	1.5	80	1.7	79	2.4	74
	1.5	80	1.9	66	2.3	80
40	1.9	79	2.3	75	3.1	80
	1.9	79	2.1	69	3.0	84
50	2.4	76	2.7	80	3.1	80
	2.4	80	2.5	67	3.2	78
60	2.7	81	3.0	79	3.8	78
	2.7	82	3.1	74	3.6	81
70	3.2	86	3.5	81	4.2	78
	3.2	86	3.4	82	4.0	82
80	3.4	86	3.8	80	4.7	80
	3.4	84	3.8	81	4.7	77
90	3.5	86	3.9	78	4.8	79
	3.5	86	3.9	68	4.7	83
100	3.6	80	4.3	81	4.7	82
	3.6	80	4.1	76	4.7	78
110	3.7	80	4.5	81	5.0	81
	3.7	79	4.5	84	5.0	77
120	3.7	80	4.5	78	5.1	80
	3.7	83	4.5	84	5.0	80
130	3.7	82	4.5	86	5.5	79
			4.5	82	5.3	80

* Current was below 1 ma. and could not be read.

Data was obtained with element B suspended in each of the humidity chambers and the voltage varied from 10 to 130 V. Temperature was recorded inside of each chamber with a thermocouple.

TABLE VII

Change of Current with Element Age

Chamber Ref. #	Applied Voltage, V.	Current, Ma.	Date
#9	20	3.2	8/6/55
		2.5	8/9/55
		1.7	9/26/55
		1.7	10/3/55
#5	130	3.8	8/18/55
		3.6	8/23/55
		2.9	12/14/55
		2.9	12/14/55
#3	100	2.3	8/11/55
		1.6	1/24/56
		1.6	1/25/56

The above data was selected from that recorded for the directly applied voltage tests. Note the apparent decrease of current as the element is in use for a longer period of time. Such an effect has been termed "ageing".

TABLE VIII

Comparison of Electric Hygrometer and Assmann Psychrometer in the Atmosphere

Electric Current, ma.	Hygrometer % R. H.	Assmann Psychrometer	
		D. B. Temp °F	% R. H.
1.0	22.5 *	79.5	18
1.1	22.5 *	66.0	50
1.3	22.5 *	65.5	30
1.1	22.5 *	69.5	24
1.1	22.5 *	67.0	41
2.6	47	70.5	48
2.4	43	73.5	44
3.0	54	73.5	56
1.6	26	71.5	31
1.3	22.5 *	72.5	27
1.6	26	68.5	33
1.9	36	66.5	38
1.8	31	64.0	38
2.0	35	60.0	44
2.2	39	60.0	50
1.3	22.5 *	69.0	27
1.5	22.5	62.0	35
1.7	28	61.5	37
2.2	39	77.0	41

* Since 22.5% R. H. is the lowest humidity on the Calibration curve, no estimation could be made for currents below that corresponding to 22.5% R. H.

The ceramic element of the electric hygrometer was placed in the atmosphere, and a voltage of 130 V applied. Using the recorded currents and the calibration curve at that voltage, % R. H. was estimated. Determinations of % R. H. were made with the Assmann psychrometer for comparison.