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AN ELECTRIC HYGROMETER AND ITS APPLICATION TO RADIO METEOROGRAPHY

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ABSTRACT

In radio meteorography the accuracy in measuring humidity has been considerably less than in measuring temperature. This is due to the serious time lag in the response of the hair hygrometer to sudden humidity changes encountered by a rapidly-ascending balloon. This lag increases with a decrease in temperature, so that the accuracy of this type of hygrometer becomes progressively less with increasing altitude.

This paper, which is in the nature of a progress report, deals with the development of an electrical-type hygrometer without moving parts or appreciable lag. Such an instrument makes possible a more rapid rate of ascent, and humidity measurements can be made at higher altitudes. The unit is in the form of a resistor which is connected to the input of the audio oscillator used in the radio meteorograph. The variations in the resistance of this unit with humidity are translated into audio frequencies which are received and recorded on the ground on a graphic audio-frequency recorder. The humidity-controlled resistor consists of the roughened glass surface between a dual winding on a thin-walled glass tube. The characteristics of such a unit with the roughened glass surface coated with various salts and acids are given. It was found that units so coated have a long- and short-period aging characteristic.

The effect of temperature on 11 units with different coatings is shown. The results indicate that a family of humidity-resistance curves for different temperatures may be established for a unit of standardized design. Knowing the temperature, the proper curve may be used when determining humidity from the received audio frequency.

Circuit arrangements are given showing the possibility of connecting one or more units into the oscillator circuit.

A method of expanding the humidity scale, not possible with the hair hygrometer, is shown, whereby if two or more units are used with different percentages of salt or acid coatings, each unit may be made to cover the full frequency (humidity) scale of the graphic frequency recorder for different temperature ranges.

A satisfactory unit appears to be one consisting of a dual winding of size 38 AWG tinned copper wire, 20 turns per inch, on a 0.3-mm wall Kimble flint-glass tube, 10 mm in diameter and 12.7 cm long. A coating of from 0 to 10 percent of a saturated solution of lithium chloride and water [1] may be used, depending on the aging time and the number of units necessary to cover the full temperature range. If used a day or so after coating, a unit coated with 0.5 percent LiCl would be satisfactory, or if two units are used, one should be coated with 0.25 percent and the other with 1.0 percent LiCl. A flight test using two units coated with 0.5 and 2.0 percent LiCl, respectively, in comparison with the hair-type hygrometer, indicated marked changes in humidity which the hair unit could indicate only slightly about 2 minutes later. As an ascent rate of 1,100 ft per minute was used, the hair unit was actually some 2,200 ft above the point where the real change in humidity occurred.

[1] Hereafter where percentage of coating is given, it refers to the percentage by volume of a saturated solution and water.

CONTENTS

I. INTRODUCTION

In the measurement of humidity in the upper atmosphere with the radio meteorograph developed by Diamond, Hinman, and Dunmore,[2] temperature inversions have indicated the probability of sudden changes in moisture content of the atmosphere encountered by the rapidly-ascending balloon, which the hair-type hygrometer failed to record. Such lag, which is a generally acknowledged defect of the hair-type hygrometer, manifests itself in incorrect humidity indications at any given altitude, depending upon the rate of ascent of the balloon, the sharpness of the humidity front, and the air temperature. The capillary-tube electrolytic type of temperature indicator responds to small temperature changes much quicker than the hair hygrometer will respond to humidity changes. It has been necessary, therefore, to limit the rate of ascent of a balloon carrying a hair-type hygrometer in order to give the hygrometer sufficient time to respond. Furthermore, the hair hygrometer ceases to function below temperatures of −20° C (approximately 25,000-ft. altitude). The hair hygrometer also requires mechanical linkages and moving parts in order to translate humidity changes into resistance variations necessary to alter the radio-meteorograph signal. Because of these limitations in the hair-type hygrometer, an investigation was started to develop a humidity indicating device which should function electrically, without moving parts or appreciable lag, and operate at stratosphere temperatures. A high rate of ascent is preferable in most instances as the data are obtained more quickly and the balloon does not drift as far away. This results in a stronger signal and greater chance of recovery.

No unit was found which would maintain a satisfactory calibration when exposed to varying humidities for long periods. Weaver and Ledig had the same experience in their work on electrical-type hygrometers.[3] The present paper, which is in the nature of a progress report, describes the development of a type of unit which, if held at a fixed humidity and subsequently checked within a few days before being used, should serve to indicate a relative humidity with an approximate

[2] H. Diamond, W. S. Hinman, Jr., and F. W. Dunmore, *A method for the investigation of upper-air phenomena and its application to radio meteorography.* J. Research NBS **20**, 369 (1938) RP1082.

[3] E. R. Weaver and P. G. Ledig. *Detector for water vapor in closed pipes.* Tech. Pap. BS **17**, 637 (1923) T242.

accuracy of ±5 percent. The speed of response of this unit is equivalent to that of the capillary-tube electrolytic thermometer, and its electrical resistance varies inherently with humidity. The effect of aging and low temperatures, and a comparison of its speed of response with that of the hair hygrometer, are described. The application of the dual-coil unit to the radio meteorograph previously mentioned is discussed. Flight records, both independently and with the hair hygrometer, are shown.

II. GENERAL DESIGN DETAILS

After experimenting with many types of electrical hygrometer resistor designs, a unit was made consisting of two fine copper wires spirally wound simultaneously on an etched glass tube. The wires were spaced about [illegible] mm apart and the glass surface between them was found to have a resistance which varied greatly with the moisture content in the air. Tests with this unit showed it to be superior to any types previously tried, so an extensive series of experiments were made to study and improve the operation of this dual-coil glass hygrometer device. Studies were made of different kinds of glass and various types of glass surfaces, such as sandblasted, ground, and etched. The effect of varying the size and wall thickness of the glass tubing was also studied. Various types of wire were tried, such as copper and tinned and amalgamated copper. Thin adsorbent surface coatings, such as bentonite, zeolite, silica gel, clays, doucile, aluminum oxide, and gelatin were tried on the glass. Cellulose acetate; polyvinyl alcohol and acetate; hydrogel; and sodium silicate were also tried. These materials were used with different binders, such as spar varnish, shellac, paraffin, collodion, balata, instrument lacquer, and resins. The adsorbent coatings were also applied over these materials as a base. Of the salts, only the more hygroscopic were tried, such as calcium, zinc, and lithium chloride. Sulfuric and phosphoric acid were tried. Some of the above materials were used in combination with one another to lower the crystallizing point, such, for example, as a 4-percent solution of zinc chloride and a 0.35-percent solution of sulfuric acid.

III. METHODS OF MEASURING THE RESISTANCE OF THE HYGROMETERS

A study of all units under different conditions of humidity and temperature was made by measuring their resistance. Some of the measurements extended over a period of several months in order to study the effect of aging.

In making resistance measurements of a device of this type, a counter-electromotive force is developed which gives an apparent resistance of the unit greater than its true value. In studying the performance of the units, an a-c bridge or a d-c bridge or ohmmeter provided with a mechanical reversing switch, may be used to measure the true ohmic resistance. Even with this arrangement the resistance is still a function of the current flowing through the sample while making the resistance measurement. For the purpose for which this unit is designed, however, small differences between a-c and d-c resistance values are not important.

A method of measurement can be employed in which the current through the sample is pulsating direct current and is kept very small, i. e., less than a few microamperes, and the voltage impressed on the sample during measurement is large relative to the counter-electromotive force. This method consists in putting the unit in the control grid of a relaxation oscillator circuit, and from the frequency of oscillation the resistance can be determined by the substitution method. In this method the hygrometer unit is used in a circuit similar to that in which it is used in practice.

Another method (and the one used in measurements described in this paper) made use of a direct-reading ohmmeter with a scale reading from 500 ohms to 25 megohms. A motor-driven reversing switch was used in series with the circuit from the ohmmeter to the hygrometer resistor unit. While resistance readings taken on two different scales of the ohmmeter were not entirely in agreement when measuring some units, because of different currents through the unit, the two could be averaged for the purpose of the study being made.

For measuring the resistance of units of the nature here described, a proper instrument would be direct-reading, in which alternating current is applied to the sample with means for holding the same current through the sample under all conditions of measurement. The value of current adopted should be of the same order as that used in actual service.

IV. TYPES OF DUAL-COIL HYGROMETER UNITS

1. ADSORBENT COATINGS ON NONADSORBENT SURFACES

Although glass had been found to be a very effective medium for water-vapor adsorption, some preliminary experiments were made in which the glass was used merely as a coil form and did not enter into the functioning of the unit.

In these experiments, several glass tubes (smooth surface) were coated with different water-resistant substances in order to find the best coating for covering the glass to insulate it from water vapor. The tubes were then wound with the standard dual-coil winding and placed in a damp chamber and resistance readings taken at intervals. Table 1 shows the results of these measurements. The figures shown are inversely proportional to the resistance of the units. It will be noted that after 23 hours in damp air the balata (rubber) unit maintained the highest resistance. Paraffin and spar varnish came next, followed by collodion, shellac, Bakelite resin, instrument lacquer, Cellophane, glyptal rosin, and soda-lime glass, in the order given. This table shows what a good conductor (relatively) glass is, when exposed to moisture. It will be seen that balata formed the best coating. This substance was therefore dissolved in benzene and painted on the glass surface in order to keep the glass dry. Then an overcoat of adsorbent materials, such as bentonite, etc., was applied. The unit was then sanded and wound. None of the units so constructed took on enough water vapor to lower the resistance to a measurable value at the lower humidities, so work along this line was discontinued and future experiments made with the glass as the conducting surface.

TABLE 1.—*Relative variation in conductivity of various substances when exposed to moisture. Absorption characteristics (arbitrary units)*

Elapsed time	Coating on glass									
	Balata	Shellac	Paraffin	Glyptal rosin	Cellophane	Unetched soda-lime glass	Spar varnish	Collodion	Bakelite rosin	Instrument lacquer
Hours										
0	0.45	0.47	0.47	0.65	0.45	0.60	0.47	0.50	0.47	0.50
0.5	.47	.50	.47	.67	.80	80.00	.52	.62	1.30	1.00
1.0	.60	.60	.55	.85	2.00	210.00	.65	.83	3.50	1.90
2.0	.72	.80	.75	1.80	2.60	400.00	.95	1.20	5.00	5.00
4.0	1.00	1.30	1.20	4.50	4.80	----------	1.30	1.90	2.70	4.40
23.0	4.7	9.50	5.00	70.00	22.00	3,400.00	5.00	5.50	14.00	16.00

2. GLASSES AND COATINGS

Since a roughened glass surface was found to take on water vapor very readily, dual coils were wound on glass tubing with surfaces roughened by grinding, by sandblasting, and by etching with hydrofluoric acid. No appreciable difference could be noted in the behavior of units so treated, except that roughening is quite necessary. Such roughening lowers the resistance of the sample by exposing a greater area of glass to the water vapor and by exposing a part of the glass that has not previously aged because of exposure to air. It also tends to hold any coating which may be applied to the surface.

Different types of glass were found to behave quite differently, so a study was made of dual coils wound on Kimble standard flint glass, Pyrex, Corning 0.015 glass, and soda-lime glass. The Kimble standard flint glass was found to give the most consistent results under changing temperature conditions. Since the glass tubing must be at the temperature of the surrounding air to give a true relative-humidity indication, it is necessary to use a very thin-walled tubing. Such a tubing was found as a special product of a leading glass manufacturer. It has an outside diameter of about 10 mm, a wall thickness of 0.3 mm, and a length of 12.7 cm. The outer surface of each tube was roughened by sandblasting.

These tubes were wound with size 38 AWG tinned copper wire by setting a lathe to cut a 20-turns-per-inch thread and guiding the two wires (from separate spools) through two slots in a brass fixture held in the tool post. The two slots should be approximately $\frac{1}{40}$ inch apart. The two wires are held in position at the start and finish by tying them to the tube with thread. After the unit is wound, the two wires at each end are pulled around the tube slightly in order to separate them. The thread and ends of winding are coated with a good insulating binder, such as balata or collodion. The two wires at one end of the tube are cut off close to the tube. The ends at the other end of the glass tube are soldered to terminal leads anchored to a small wooden stick supporting the glass tube. This type of construction allows free passage of the air both inside and outside of the glass tube, so that it may quickly come to the air temperature. Figure 1 (at the left) shows a unit constructed as described above. The tinned wire was adopted after experimenting with units wound with copper and amalgamated copper wire. Platinum wire would be preferable, but it is too costly. Tin is less subject to corrosion than copper or mercury, and will therefore keep a better electrical contact with the glass.

It was first thought that the ability of the glass to adsorb water vapor might be accentuated by covering its roughened surface with some highly-adsorbent materials, such as silica gel, aluminum oxide, doucile, bentonite, clay zeolite, gelatins, etc. These were each painted on different glass units before winding, after being finely powdered and mixed with various binders, such as spar varnish, shellac, collodion, balata dissolved in benzene, and rosins. After drying the coating, the surface was rubbed with fine sandpaper in order to take off the top surface of the binder.

After testing all of these combinations, it was found that they offered no improvement over the glass used alone, and, moreover, reduced the rapidity of response to humidity changes. The same was also true for coatings of cellulose acetate, polyvinyl alcohol, polyvinyl acetate, hydrogel, and others. Sodium silicate (water glass) had a very marked effect in producing a more sensitive unit but was found very unstable and had serious temperature effects.

V. CHARACTERISTICS OF GLASS UNITS COATED WITH HYGROSCOPIC SALTS AND ACIDS

In order to study the behavior of glass units coated with various salt and acid-water mixtures in different concentrations, different units were made up, using the thin-walled Kimble glass tubing previously mentioned (except for unit 84). These were studied for the effect of aging, speed of response, and temperature. The details of the construction of these units are given in table 2.

TABLE 2.—*Detail of construction of units*

Unit	Winding (tpi=turns of wire per inch)	Coated (1937)	Coating [1]	Remarks
KIMBLE SODA LIME GLASS TUBING, 17 MM DIAM, 0.5-MM WALL, GROUND-GLASS SURFACE				
84	16 tpi size 32 AWG tinned copper.	May 7	1 coat 1% LiCl	Outdoor exposure for 3 months.
KIMBLE FLINT GLASS, 10 MM DIAM, 0.3-MM WALL, SAND-BLASTED SURFACE				
101	16 tpi size 38 AWG copper.	June 24	1 coat 5% LiCl	Indoor exposure.
102	do	June 24	1 coat 10% LiCl	Do.
106	20 tpi size 38 AWG tinned copper.	June 26	1 coat 4% $ZnCl_2$; 1% of a 1.3 sp gr solution of H_2SO_4.	Do.
107	do	June 28	1 coat 4% LiCl, 4% $ZnCl_2$, 1% of a 1.3 sp gr solution of H_2SO_4.	Do.
108	do	June 28	1 coat 4% LiCl; 0.5% $LiNO_3$	Do.
113	16 tpi size 38 AWG tinned copper.	July 7	1 coat 10% LiCl; then coated with collodion and washed.	Washed after winding and coating. Indoor exposure.
114	do	July 7	1 coat 10% LiCl; then coated with balata dissolved in benzene; then washed.	Do.
118	20 tpi size 38 AWG tinned copper. Wound Oct. 8.	July 1	None	Indoor exposure.
119	20 tpi size 32 AWG tinned copper. Wound Oct. 8.	July 1	Powdered Corning 0.015 glass fused into surface of Kimble flint glass at 550° C; then washed.	Washed before winding; indoor exposure.
120	do	July 1	Powdered Li_2CO_3 fused on surface of flint glass at 550° C; then washed.	Do.

[1] Where percentage of coating is given, it refers to the percentage by volume of a saturated solution and water.

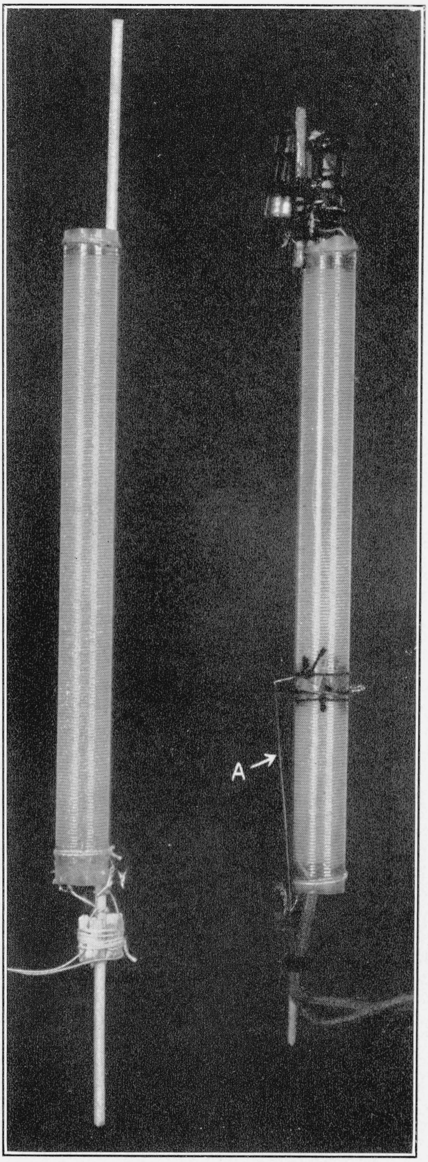

FIGURE 1.—*Final type of dual-coil hygrometer using thin-walled glass tubing, each coil having 20 turns per inch.*

The unit at the right has a temperature-operated range-expansion switch, shown at *A*.

1. EFFECT OF AGING

Figure 2 shows the effect of aging on the resistance of five of the Kimble flint-glass samples coated as indicated. The units were exposed to varying humidities during the interval from 0 to 160 days,

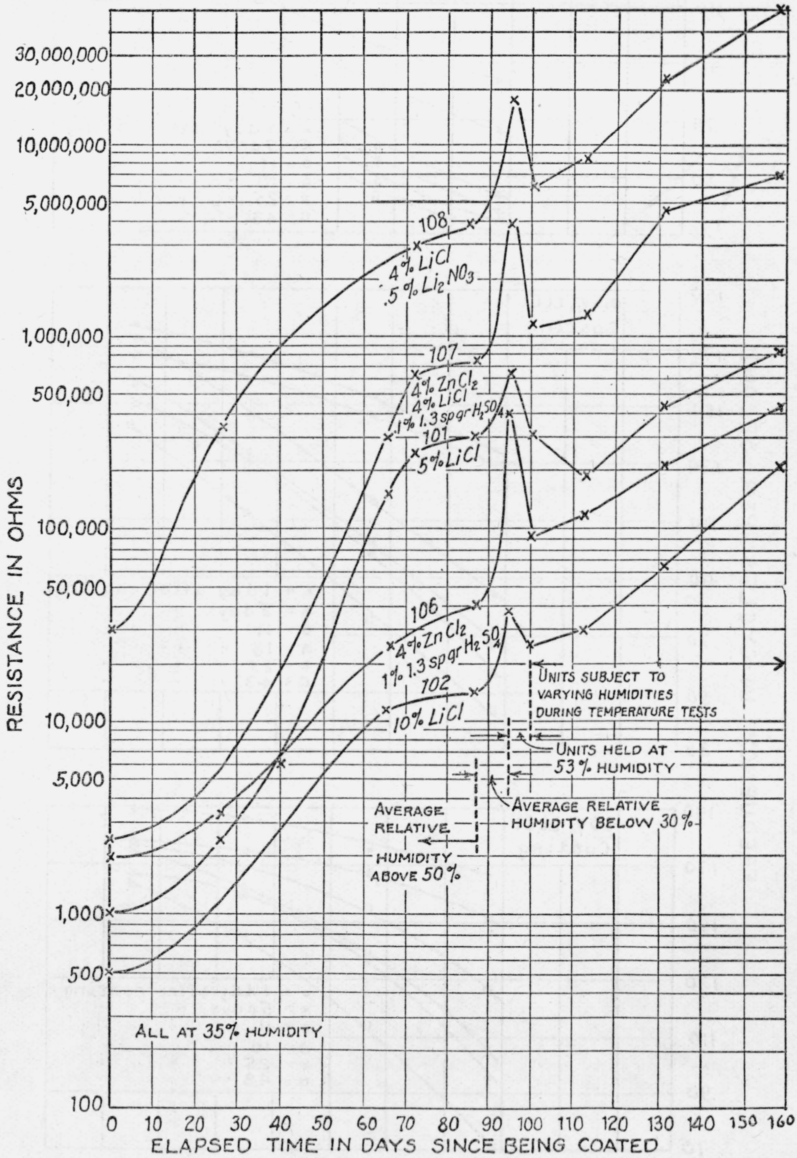

FIGURE 2.—*Effect of aging on the resistance at 35-percent relative humidity of five dual-coil hygrometers.*

but the measurements for the curves were always made after the units had been exposed to air of 35-percent humidity for several hours. The general increase in resistance indicates a long-period

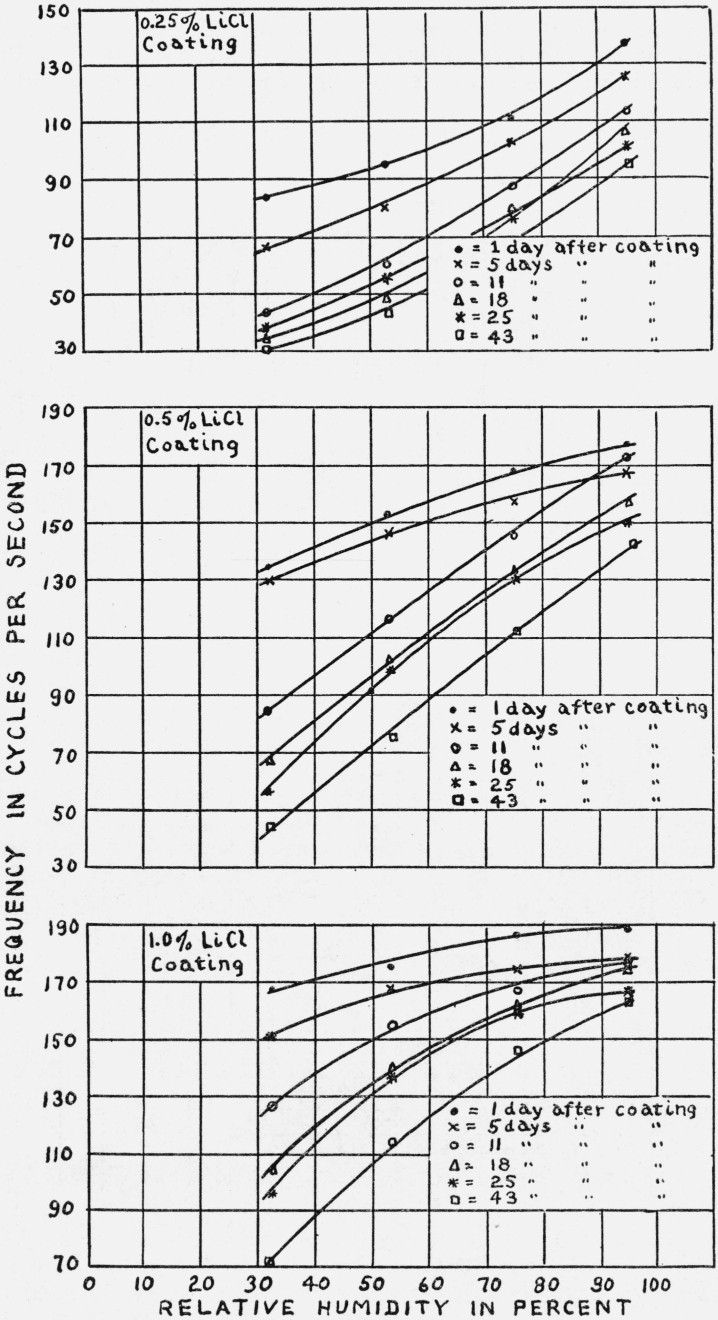

FIGURE 3.—*Effect of aging on dual-coil hygrometer units with different percentages of coatings of* LiCl.

aging phenomenon. Since all the units show the same general trend, i. e., resistance increase with time, the aging phenomenon might be due to a physical or chemical change in the exposed glass surface. It might be possible to find a more stable type of glass not subject to this phenomenon. The increase in resistance may be due to a gradual movement of the coating toward the wires forming the dual coil, or to oxidation on the wire at the point of contact with the glass. A secondary effect, which might be considered apart from the long-period aging and superimposed on it, is a slow period of either taking on or giving off of water vapor by the glass when exposed to different humidities for short periods, which are however still long relative to the time of exposure when in use. This effect is shown in figure 2 by the sudden jumps in the curves at the 95-day point when the units were subjected for 7 days to humidities below 30 percent, whereas previously the average humidity had been above 50 percent. Between the 95- and 100-day points the units were held at a 53-percent humidity. Beyond the 100-day point, the units were held at various humidities for the temperature tests.

Figure 3 shows the behavior over a period of 43 days of six Kimble flint-glass units similar to the unit at the left in figure 1. Two of the units had a 0.25-percent coating of LiCl, the second two a 0.5-percent coating, and the third two a 1.0-percent coating. Each curve represents the average for two units with coatings of similar percentage. Before each measurement the units were held at each humidity, without air circulation, for about 30 minutes. During the interval between measurements the units were kept dry in a container with calcium chloride.

The curves indicate the necessity for aging the units by holding them for a definite length of time at some arbitrary fixed humidity before calibrating and using them, or for coating and calibrating the units, not more than a few days before using them. In the second instance, a more dilute solution of the coating would be used. If coated and placed in a container over a saturated solution of magnesium chloride, which produces a relative humidity of approximately 32 percent at 24° C, the true drift in resistance can be established so that the proper time corresponding to the proper value of resistance for calibration and use of the units can be found.

If it is found that the ratio of the resistance at two different relative humidities, 45 and 100 percent, remains substantially constant, then a one-point calibration just before a flight should suffice.

2. RAPIDITY OF RESPONSE

An indication of the speed with which the various dual-coil units respond to humidity changes is shown in figures 4 and 5. These curves were obtained by placing the units (which had been at approximately 50 percent relative humidity for 4 days), together with a hair hygrometer and wet cotton, under a Cellophane cover for 1 hour. The resistance of each unit was then measured and the humidity obtained from previous calibrations. The average humidity indication for all 10 units was 68 percent. The hair hygrometer read 65 percent. The covering and wet cotton were then removed and air at the room humidity of 28 percent was circulated at a rate of approximately 150 ft per minute over the hair hygrometer and all of the units. Their resistances were measured (as rapidly as possible at first) for a period of 50 minutes. The curves of figures 4 and 5 show the results. It will be noted that even with this low air velocity (normal balloon ascent rate is 600 ft per min), sample 101 (coated with 5 percent LiCl) indicated a drop from 68-percent relative humidity to 32 percent (28 percent being the final value) within 40 seconds. Other units responded with varying speeds depending upon their makeup.

The hair hygrometer was more sluggish than any of the units. The slow response of the hair hygrometer, as compared with unit 101, for

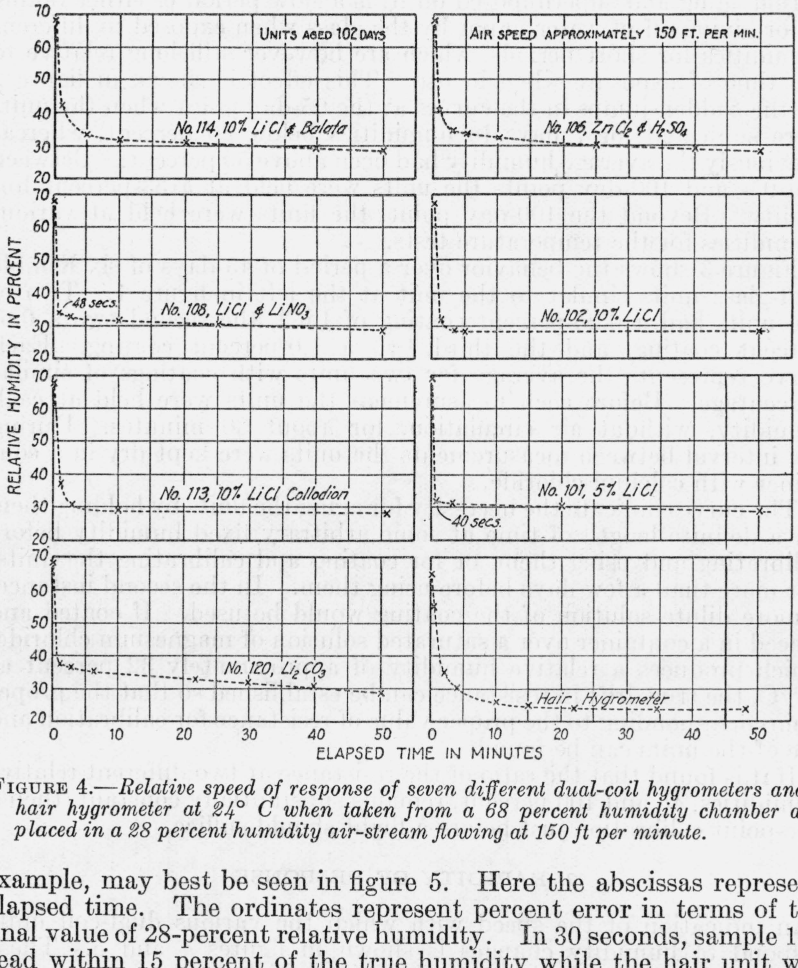

FIGURE 4.—*Relative speed of response of seven different dual-coil hygrometers and a hair hygrometer at 24° C when taken from a 68 percent humidity chamber and placed in a 28 percent humidity air-stream flowing at 150 ft per minute.*

example, may best be seen in figure 5. Here the abscissas represent elapsed time. The ordinates represent percent error in terms of the final value of 28-percent relative humidity. In 30 seconds, sample 101 read within 15 percent of the true humidity while the hair unit was 65 percent in error. These results indicate an approximate time-lag constant of 4.5 seconds in an air stream of 150 ft per minute for glass hygrometer unit 101, as compared with 42 seconds for the hair hygrometer. The capillary-tube electrolytic thermometer has a time-lag constant approximately equal to that of the glass hygrometer. From the standpoint of time lag, it is clearly evident that the dual-coil hygrometer is far superior to the hair-type hygrometer in giving a truer picture of the humidity structure of the upper atmosphere when used on a rapidly ascending balloon.

The relative rapidity with which the various units took on water vapor when the moist cotton was put into the Cellophane container with them, is shown in the curves in figure 6. These curves do not indicate the true rate of response, as the humidity was gradually increasing from 35 to 63 percent during the hour indicated. Also, there was no air circulation in the chamber.

While unit 108 (LiCl and $LiNO_3$) seems to respond to the absorption of water most rapidly, its curve for giving up water vapor (see fig. 4) shows considerable lag. From the point of view of quick response both with respect to taking on and giving off water vapor, sample 101

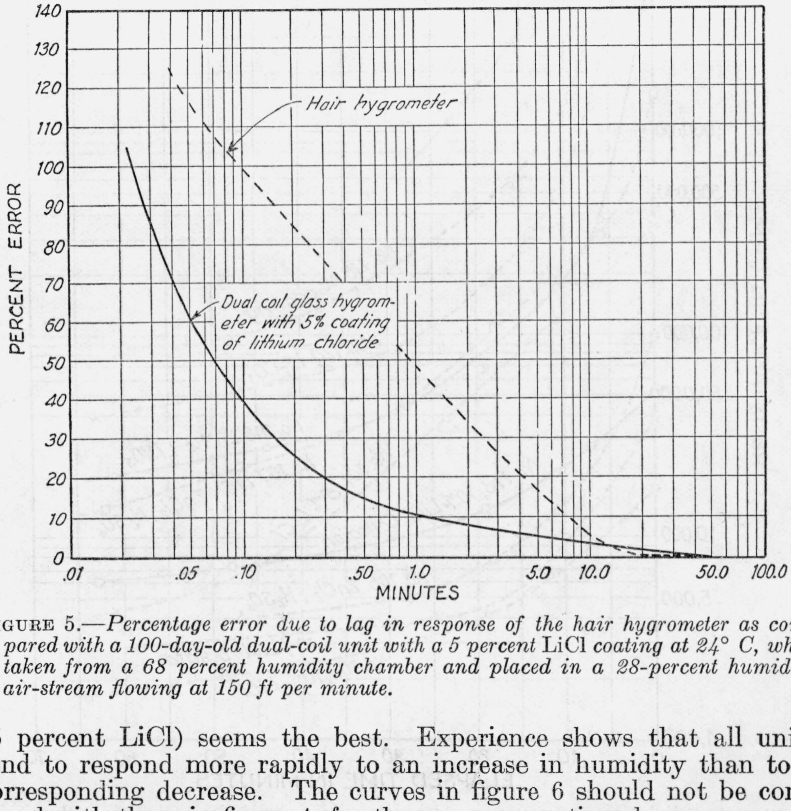

FIGURE 5.—*Percentage error due to lag in response of the hair hygrometer as compared with a 100-day-old dual-coil unit with a 5 percent* LiCl *coating at 24° C, when taken from a 68 percent humidity chamber and placed in a 28-percent humidity air-stream flowing at 150 ft per minute.*

(5 percent LiCl) seems the best. Experience shows that all units tend to respond more rapidly to an increase in humidity than to a corresponding decrease. The curves in figure 6 should not be compared with those in figure 4, for the reasons mentioned.

3. DETERMINATION OF TEMPERATURE CORRECTION

Through the cooperation of the Bureau's aeronautic instrument section, a study of the effect of temperature on the operation of the dual-coil glass hygrometer was made. The 11 units which had been coated for about 100 days were put into an airtight chamber with a large pan full of certain salts partially dissolved in water. The humidity produced at different temperatures by each of these four salts used separately in the airtight chamber had been previously determined. Before making the set of humidity-temperature measurements, the units were held at 53 percent relative humidity and 25° C for 4 days. With each salt in the chamber the resistance readings of each unit were taken at +30, +15, and 0° C; and at −10 and −20° C with two salts, giving approximate humidities of 88 and 50 percent at −10° C, and 87 and 54 percent at −20° C. The chamber was held for 1 hour at each new temperature before measuring the resistance of the units. During the interval overnight when not under test, the units were held at 15 to 20° C and at the humidity to be used next. The temperature runs were made with the different

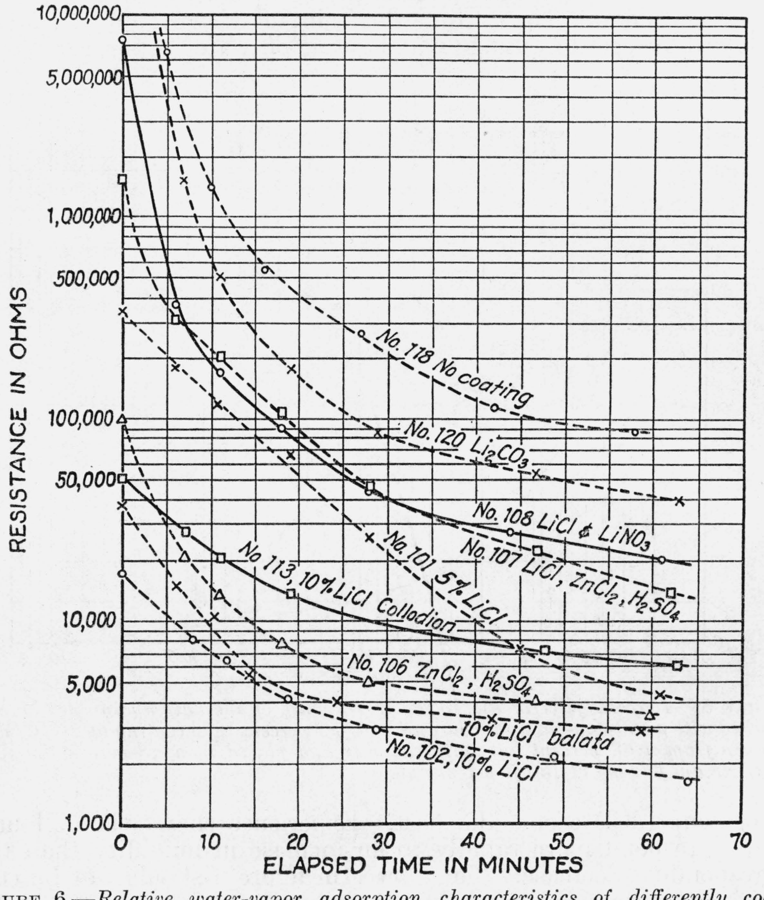

FIGURE 6.—*Relative water-vapor adsorption characteristics of differently coated dual-coil hygrometers.*

humidities in the following order: 53, 75, 94, 33, and 87 percent. Between the 94-percent run and the 33-percent run, the samples were left for 2½ days at 33 percent and 30° C.

The curves in figures 7 and 8 represent the results of these tests. The results for units 84 and 119 are omitted as these showed an erratic behavior. The curves for unit 120 are also omitted as they were quite similar to those for unit 108. Up to the time of writing this paper, measurements below 54-percent humidity at temperatures of −20° C or below had not been made, as salts for establishing low humidities at low temperatures had not been calibrated. From the trend of the curves and from flight tests, the indications are that these

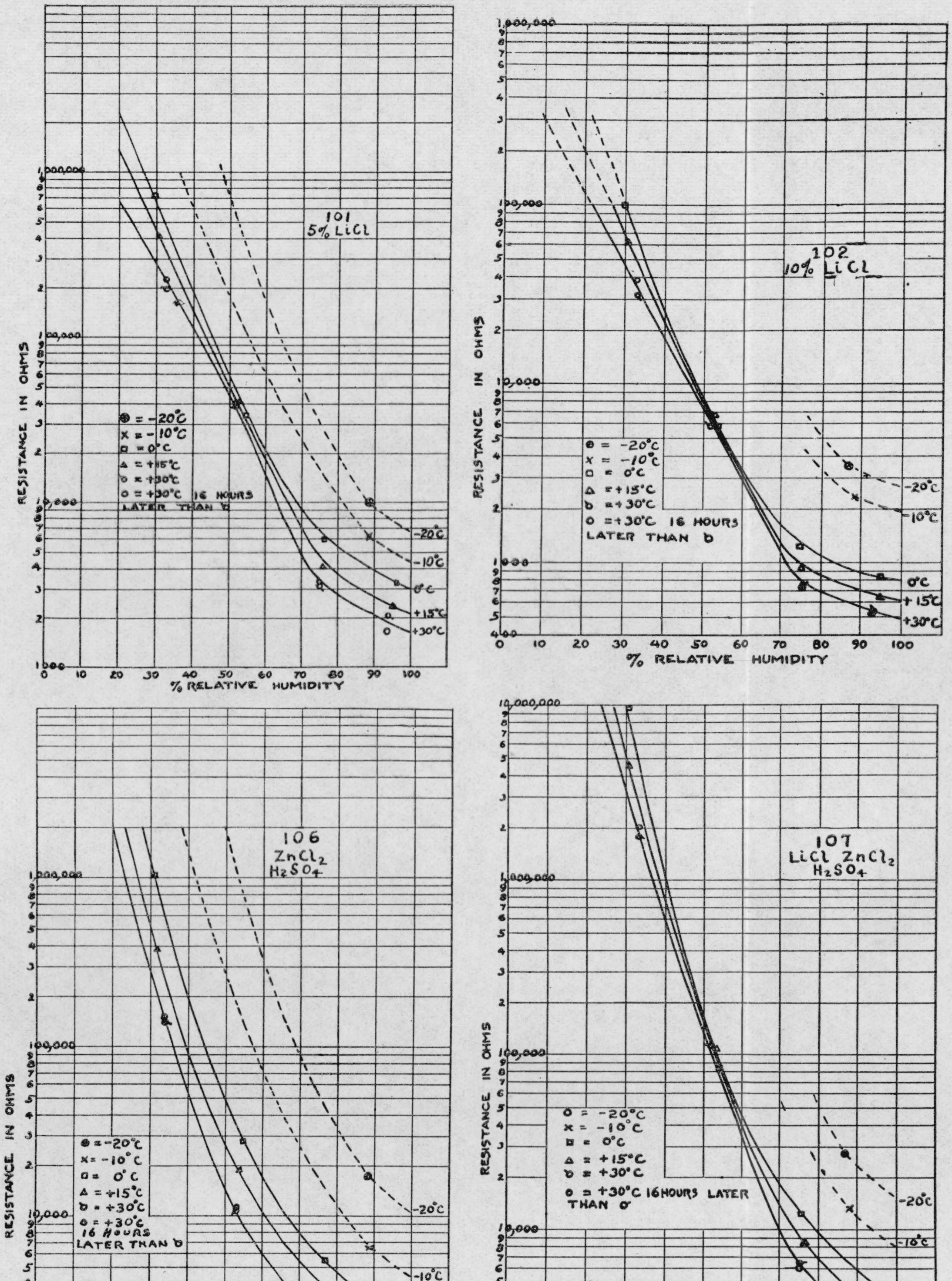

FIGURE 7.—*Variation in resistance with humidity at different temperatures of dual-coil hygrometers 101, 102, 106, and 107.*

See table 2.

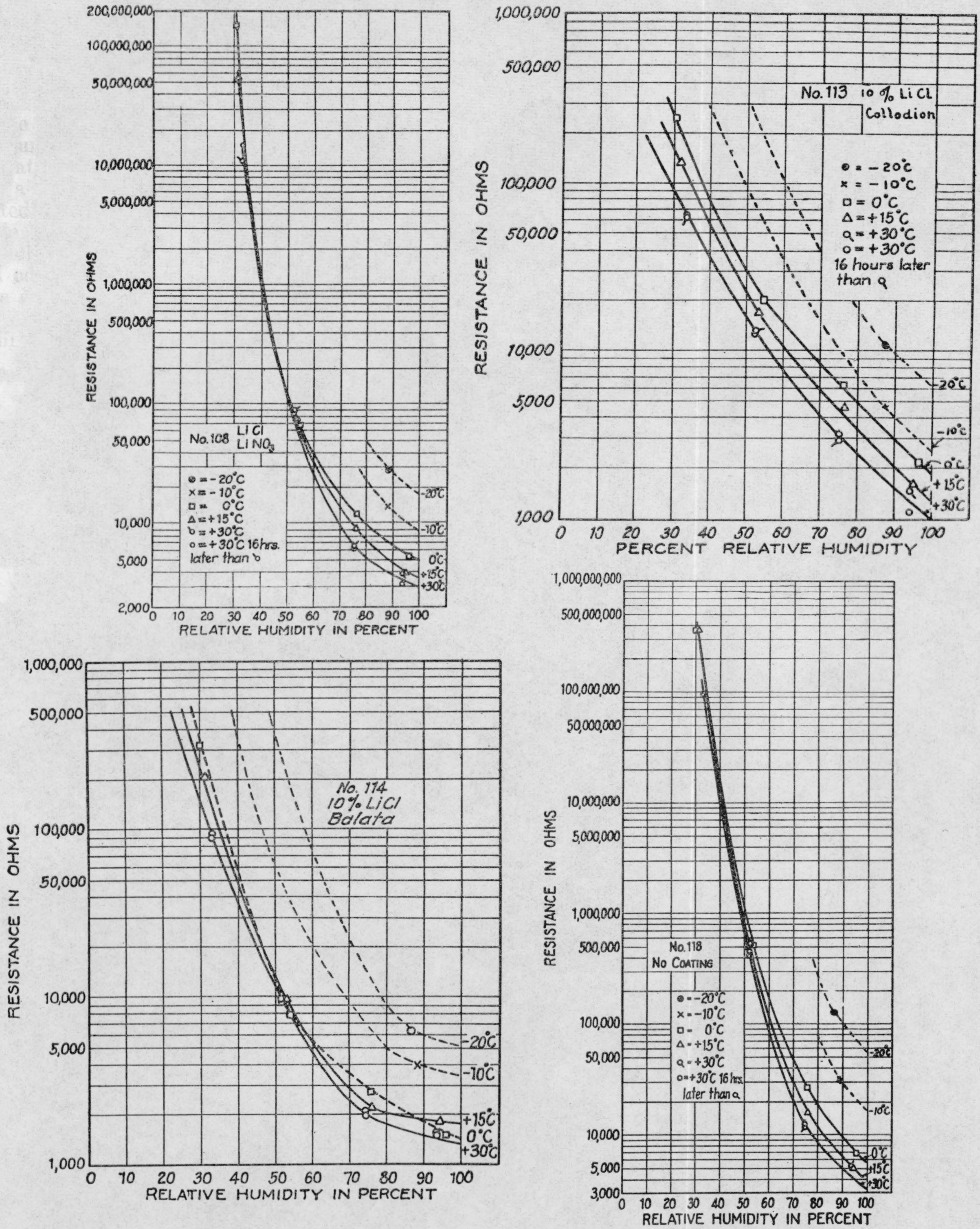

FIGURE 8.—*Variation in resistance with humidity at different temperatures of dual-coil hygrometers 108, 113, 114, and 118.*

See table 2.

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units continue to function down to stratosphere temperatures. From figures 7 and 8 it will be noted that temperature correction is greater for some of these units than for others and varies with the humidity.

The effect of temperature at 90-percent relative humidity is shown in figure 9. In this figure the full line represents the average error in indicated values of relative humidity when using the +30° calibration. The average is for units 101, 102, 107, 108, 113, 118, and 120. The dotted lines represent the maximum deviation above and below this average. The greatest deviation is about 9-percent relative humidity. The above units were all different, having various types of windings and coatings. It is to be expected that had the above seven units been identical in construction, each with a coating of, say, 5 percent LiCl, and had they been aged the same length of time, that the maximum deviation would have been less than 3 percent. The data in

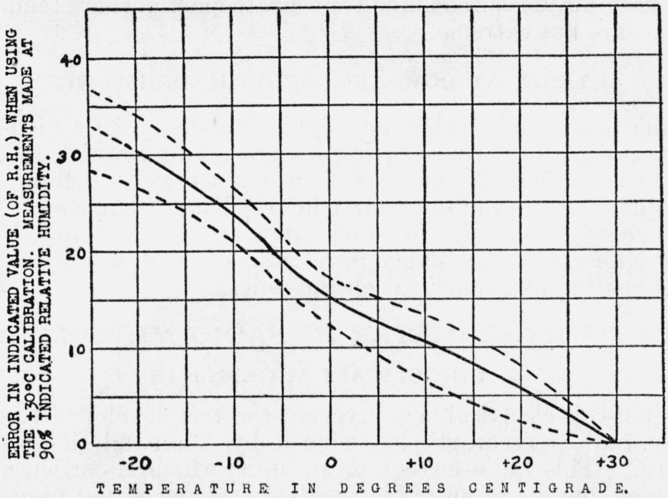

FIGURE 9.—*Average deviation in percentage relative humidity (figs. 7 and 8) of the indicated humidity readings (based on a +30° C calibration) from the true 90-percent value of relative humidity for units 101, 102, 107, 108, 113, 118, and 120.*

figures 7, 8, and 9 would indicate that it should be possible to establish the proper temperature-correction factor for a standardized design of unit which should apply to all units similarly constructed. A check at three or four humidities at room temperature should then be sufficient. Any deviation from normal at room temperature in this check could be applied throughout the temperature range.

In radio meteorography it is customary to measure temperature when measuring humidity, so the proper temperature curve of the family of humidity-resistance curves may be used to obtain the true relative humidity.

From the data shown in figures 7 and 8 it would appear that a good unit would be one similar in mechanical construction to unit 118, i. e., one having a winding of 20 dual turns per inch of size 36 or 38 AWG tinned copper wire. The coating should be LiCl, unless further measurements at temperatures below −20° C show some of the other coatings to be superior. The percentage strength of LiCl to be used for coating each unit will be dependent upon the aging period adopted, the temperature range to be covered, the method of applying the coating, and the portion of the humidity scale of most interest. In all cases the coatings were applied with a camel's-hair brush, using just enough of the liquid mixture to moisten the glass surface. If two units are to be used and are coated a day or so before use, a good coating is 0.25 percent LiCl on one unit and 1.0 percent on the other. A coating of 0.5 percent gives a good range of resistance variation from 0- to 100-percent humidity at temperatures down to -15 or $-20°$ C.

It has been noted when testing freshly coated units between 0 and $+30°$ C, that the change in resistance with humidity relative to the change due to temperature is greater the less the percentage of LiCl. Thus an uncoated unit is least affected (relatively) by temperature change, while a unit freshly coated with 3 percent LiCl or more has a marked temperature correction. A 3-percent unit would, however, only be used for measurements in the stratosphere, where temperature variations are not extreme.

4. TESTS AT LOW ATMOSPHERIC PRESSURES

In order to determine whether there is a tendency for a LiCl coating to evaporate at low atmospheric pressures, a unit which had had a coating of 2 percent LiCl for 3 weeks was put under a bell jar and the pressure held at 159 millibars for 1 hour. The resistance of the unit was measured before the low-pressure test and immediately afterwards. No appreciable change in resistance was noted, showing that the LiCl coating had remained on the unit.

VI. USE OF HYGROMETER IN RADIO METEOROGRAPH

1. CIRCUIT ARRANGEMENTS

The dual-coil electrical-type hygrometer was developed to operate with the radio meteorograph designed by Diamond, Hinman, and Dunmore.[4] This radio-meteorograph unit, which is carried aloft by the balloon consists of an audio oscillator the generated frequency of which is a function of the resistance across the input grid and filament. This resistance is made up of the electrolytic thermometer, hair-controlled resistor, or photoelectric cell. The audio frequency produced by the variation in resistance of each of these units is a function of the phenomenon they are measuring.

A circuit arrangement (described in reference 2) for adapting the dual-coil hygrometers to the radio meteorograph is shown in figure 10. In this circuit, one or more dual-coil hygrometers may be successively connected to the relaxation-oscillator input circuit in addition to the other measuring devices. A motor- or fan-operated switch serves to make the necessary connections so that each measurement is transmitted three times a minute or faster.

The usable range of resistance variation of any unit is limited by the fact that the relaxation oscillator will not function properly with less than 40,000 ohms across its input. The relaxation-oscillator circuit is so adjusted that this value of resistance produces a frequency of 200 cycles, which is the upper scale limit of the audio-frequency meter used at the receiving station. The lower limit used on the frequency meter is 20 cycles. The relaxation oscillator is limited to this lower frequency by shunting its input with a fixed resistor of

[4] J. Research NBS **20**, 369 (1938) RP1082.

350,000 ohms. These limitations require the use of two units in order to measure humidities at temperatures as low as −70° C, as the resistance of a unit designed to work at the higher temperatures would become too high at low temperatures to function in this circuit.

Figure 11 shows the variation of the relaxation-oscillator frequency as a function of the resistance of the dual-coil hygrometer or other device. The grid-circuit resistance consists of the device with 40,000 ohms in series and 350,000 ohms in shunt. In this figure, R_H is the hygrometer unit and R_0 is the resultant resistance across the input terminals A and B of the relaxation oscillator. From figure 11 it will be seen that the actual usable range of variation of resistor R_H is from

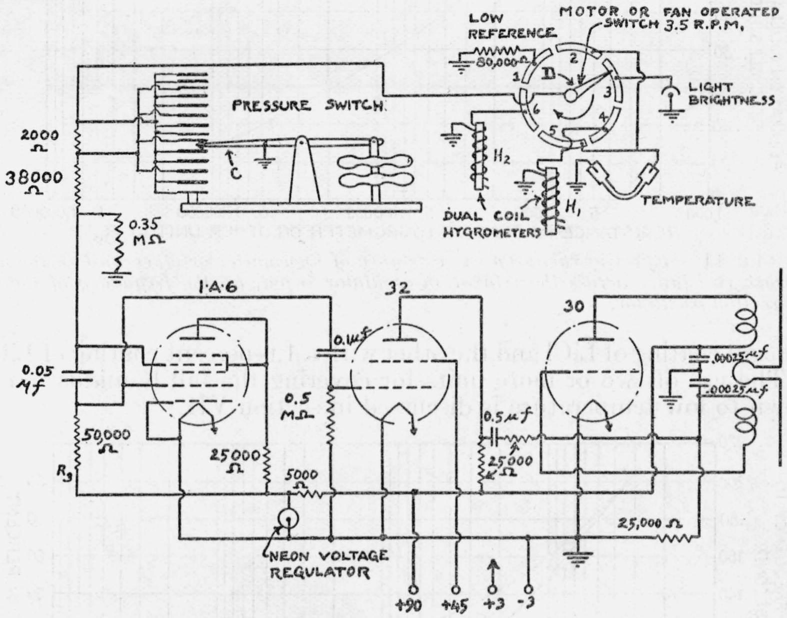

FIGURE 10.—*Radio-meteorograph circuit arrangement, showing pressure-shorting switch and motor-operated selector switch for six different measurements.*

about 3,500 ohms to 4.0 megohms. Since the resistance of R_H does not vary linearly with humidity, figure 11 does not give the relationship for converting humidity into frequency. Data for converting humidity into frequency variations are shown in figure 12. The lower curve shows the effect on the frequency of the relaxation oscillator when a unit varies in resistance from 3,500 ohms to 4 megohms. For a unit with a very small percentage of the LiCl coating, this might correspond, as shown by the upper curve, to a change in humidity at 30° C, from 100 to 45 percent.

In figure 13 is shown the results of frequency measurements with dual-coil units having different percentages of the LiCl coatings, and used in the standard radio-meteorograph circuit shown in figure 10. The measurements at 24° C (lower set of graphs) were made the day after coating, and those at 0° C (upper set of graphs) were made 3 days after coating. From the trend (due to temperature) of these curves, it appears that a 0.5-percent coating should give good humidity

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indications from +24° C to approximately −20° C. In order to cover the full temperature range (+30° C to −70° C) it would appear from these graphs that two units should be used, one having a 0.25-

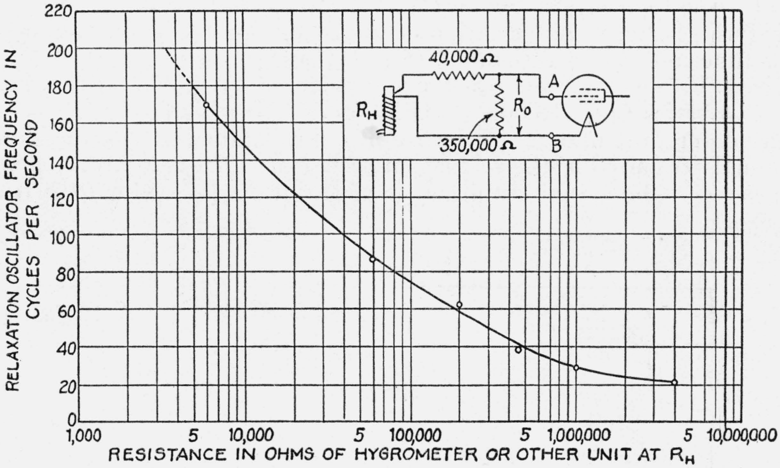

FIGURE 11.—*Effect of variation in resistance of hygrometer or other unit in the network resistance across the relaxation-oscillator input, on the frequency of the relaxation oscillator.*

percent coating of LiCl and the other with a 1.0-percent coating of LiCl.

The use of two or more units for covering the full humidity range down to low temperature is discussed in section VII.

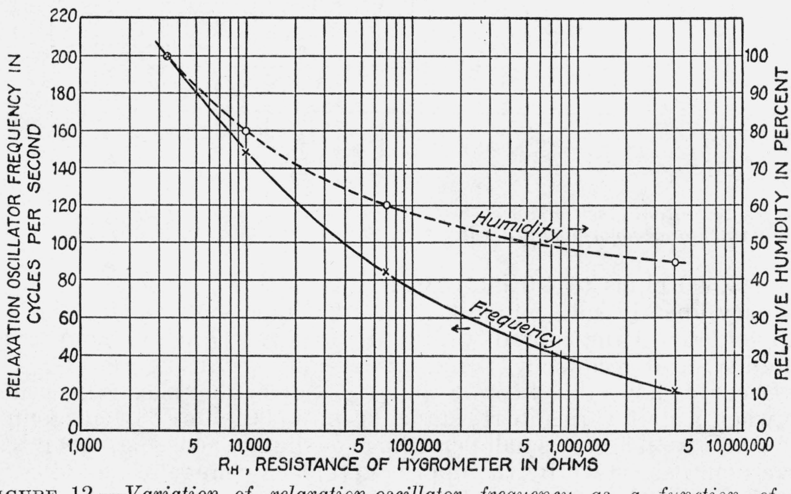

FIGURE 12.—*Variation of relaxation-oscillator frequency as a function of the resistance of a hygrometer unit at R_H in the circuit network shown in figure 11.*

Referring again to figure 10, the lower half of the figure represents the relaxation oscillator, modulation amplifier, and 65-megacycle oscillator with doublet antenna. The pressure- and motor-switching units are shown above. The circuit is such that when arm *C* of the atmospheric pressure-operated switch is on an insulated segment, the rotation of arm *D* of the motor-operated switch serves to connect the various measuring units to the input of the relaxation oscillator with the 38,000 and 2,000 ohms (40,000) in series and the 350,000 ohms in shunt. As the balloon rises from the ground, arm *C* first contacts the top No. 1 conducting segment of the pressure switch and all of the measuring units are shorted, leaving the 38,000 and 2,000-ohm resistors

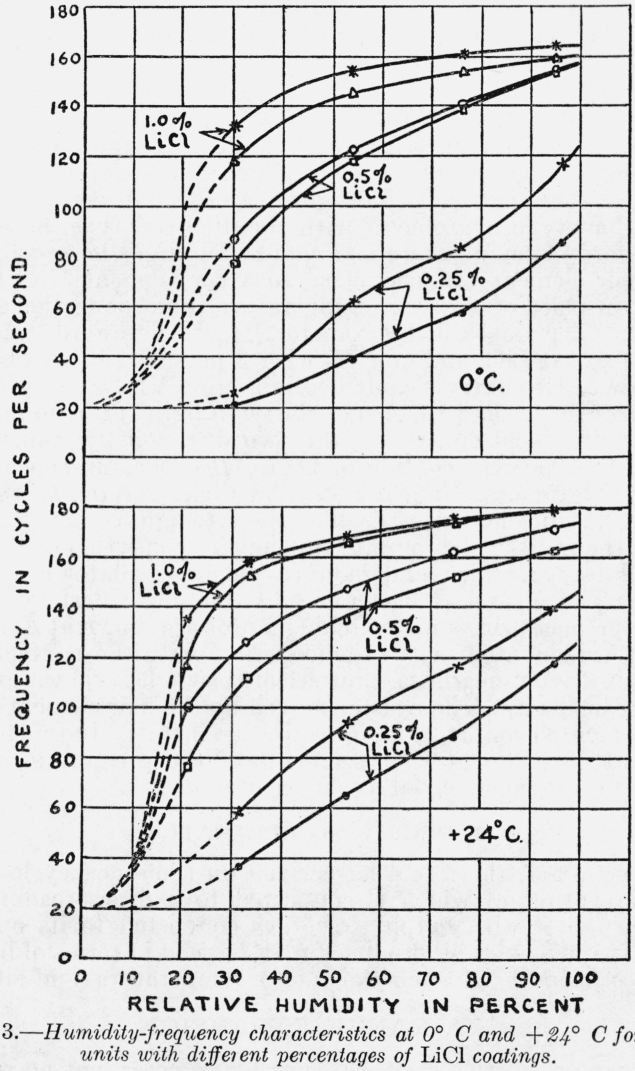

FIGURE 13.—*Humidity-frequency characteristics at 0° C and +24° C for dual-coil units with different percentages of* LiCl *coatings.*

in series across the input to the relaxation oscillator. This is the case for segments 1 and 2, 4 and 5, 7 and 8, etc. This fixes definite altitude points and gives a check on the relaxation-oscillator frequency calibration at the high end of the range. When arm *C* touches conducting segments 3, 6, 9, etc., counting from the top, a slightly different note is transmitted, as the 38,000-ohm resistor only is thrown into circuit. This change in note facilitates contact identification. The conducting segments are much narrower than the insulated segments so that the recording units are shorted out of circuit for as small a percentage of the time as possible—something like 15 percent, depending upon the segment width and number of conducting segments used. If each of six effects is transmitted three times a minute, the loss of a measurement of one or two of the effects for half a minute in each two or three minutes is not serious. If the temperature unit is connected to two opposite commutators, as shown in figure 10, the temperature measurement should always be repeated at least three times a minute and six times a minute during parts of the ascent.

2. DETAILS OF CONSTRUCTION

A radio-meteorograph instrument built according to the circuit arrangement in figure 10 is shown in figures 14 and 15. Figure 16 shows the instrument ready for flight. As this unit was built to compare the hair-type hygrometer with the dual-coil type, as well as to give a record of temperature and cloud structure, the resistor varied by the hair element was connected to extra segment 5 on the commutator, in place of the extra temperature tube connection shown in figure 10. The dual-coil hygrometer, H_1, in figure 10, was coated with 0.5 percent LiCl and unit H_2 with 2 percent LiCl. The reason for the use of two units is explained in section VIII.

In figures 14, 15, and 16, *A* (not shown in fig. 15) is a double-walled sun and rain shield containing the two dual-coil hygrometers with the 0.5- and 2-percent coating of LiCl. *B* is the sun shield housing the hair hygrometer and the capillary electrolytic thermometer. *G*, figure 16, is the photoelectric cell exposed to light coming from below it. *D* is the radio-meteorograph transmitter consisting of the relaxation-oscillator, amplifier, and radio-frequency oscillator in a shielded housing. The *A* and *B* batteries and the single flashlight cell for running the measuring unit switching motor are shown at *E*, figure 14. The pressure-operated switch is shown at *F* with the contact arm *C*. The motor-driven measuring unit selector switch is shown at *H* with the motor below it. The resistor moved by the hair element is shown at *I* with pivoted contact arm, *J*, resting against it. In this particular instrument only the 14 wide segments of the pressure switch were used. They were connected as shown in figure 10.

3. RECEIVING APPARATUS

On the ground, the signal is received on a 65-megacycle receiver, the audio output of which is connected to a direct-reading audio-frequency meter with graphic recorder connected to its output, so that the frequency graph produced may be read in terms of humidity, brightness (cloud height and thickness), temperature, and altitude.

VII. RANGE EXPANSION

An advantage of this electrical-type hygrometer, not possible with the hair unit, is the ability to expand the humidity scale by the use of two or more units of different sensitivity, each coated to vary over approximately the same resistance range but within different temperature ranges. The extra units may be switched into circuit by a bimetallic temperature-operated switch or by a pressure-operated switch, after the unit has reached a certain low-temperature point or a certain altitude. A temperature-switched unit is shown at the right in figure 1. The bimetallic strip shown at *A* short-circuits the lower insensitive portion of the unit when a temperature of −20 or

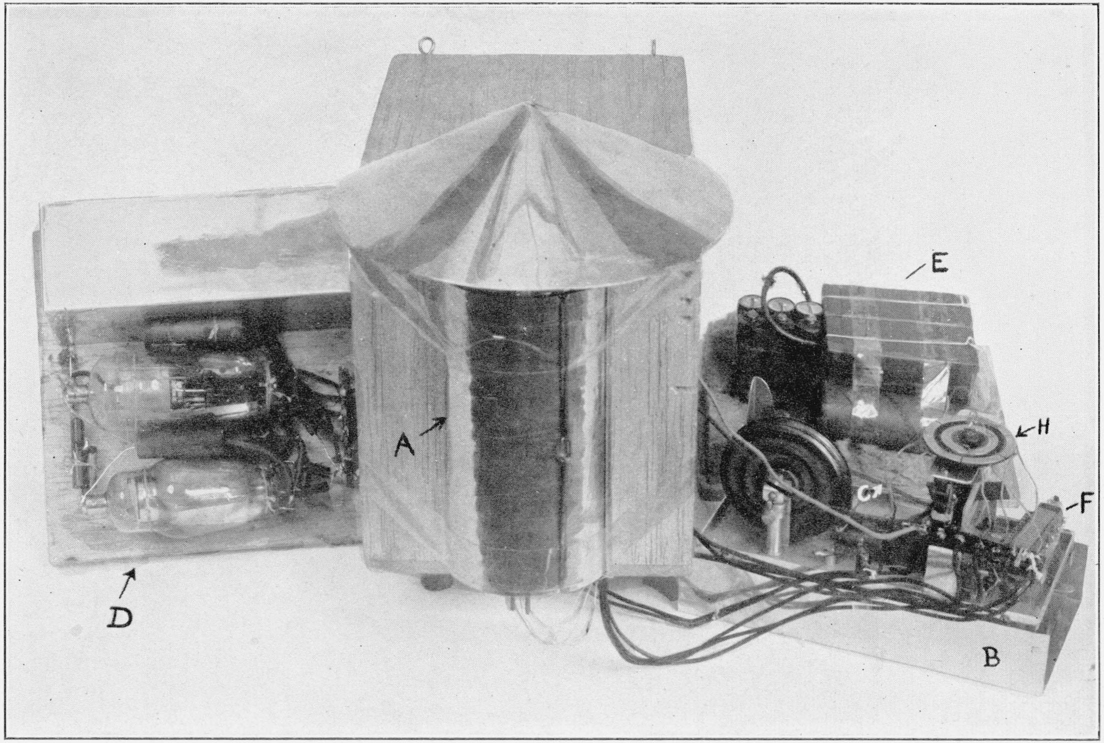

FIGURE 14.—*The radio meteorograph constructed according to the circuit arrangement shown in figure 10, except that a hair-hygrometer operated resistor was connected to the extra electrolytic-thermometer segment.*

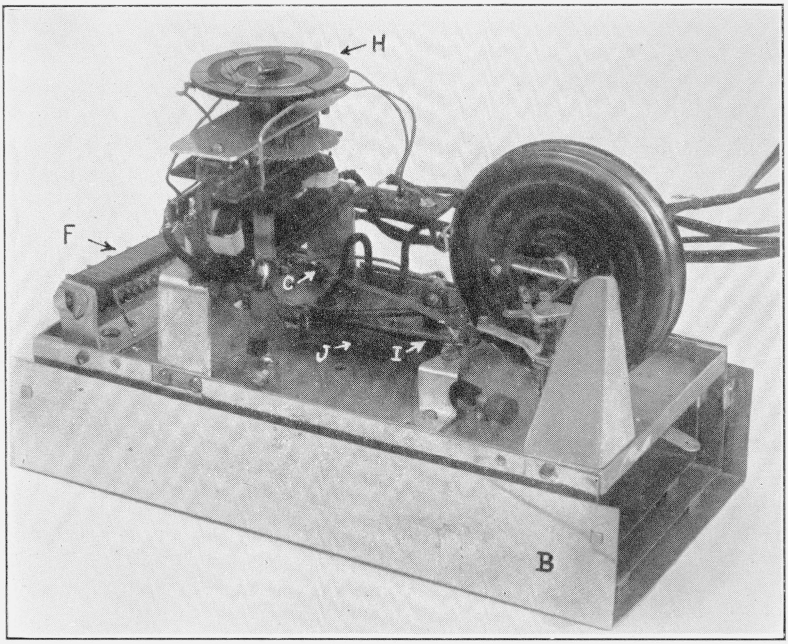

FIGURE 15.—*The radio-meteorograph pressure-operated switch for giving altitude, and motor-operated selector switch for connecting each of the six different measuring units for 3.5 seconds to the relaxation oscillator.*

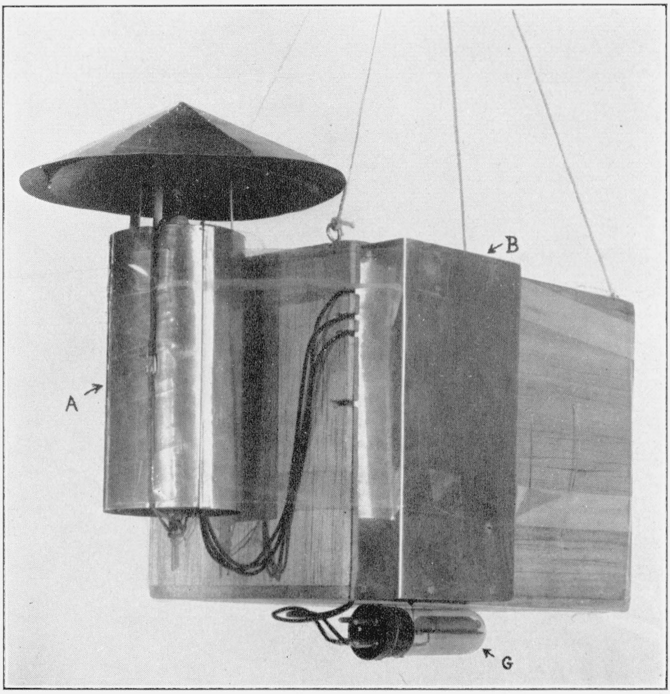

FIGURE 16.—*The multi-purpose radio meteorograph ready for use.*

This unit contains an electrolytic thermometer, hair-hygrometer operated resistor, two dual-coil hygrometers, and a photoelectric cell.

−30° C is reached. The resistors at the top are in shunt with the upper coil section and serve to indicate when the temperature switch closes, should it close when the resistance of both sections is extremely high. Another method of switching two different humidity units into circuit would be to use a simple single-pole double-throw relay-operated switch, the relay being caused to function by a circuit of proper time constant. In cases where a motor-, fan-, or clock-operated switch is used as described under section VI, to throw the temperature-, pressure-, and light-intensity measuring units into the relaxation-oscillator circuit, a number of extra contacts on the commutator may by provided, for as many humidity units as desired. As the measurement of temperature, humidity, etc., is not a function of the speed of

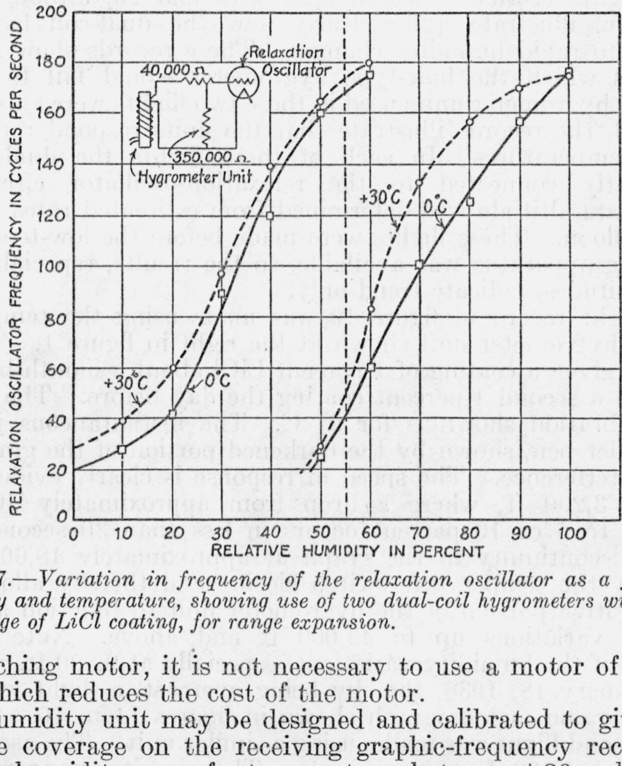

FIGURE 17.—*Variation in frequency of the relaxation oscillator as a function of humidity and temperature, showing use of two dual-coil hygrometers with different percentage of LiCl coating, for range expansion.*

the switching motor, it is not necessary to use a motor of constant speed, which reduces the cost of the motor.

One humidity unit may be designed and calibrated to give nearly full-range coverage on the receiving graphic-frequency recorder for the whole humidity range for temperatures between +30 and −10° C, while a second unit with more turns and a higher percentage coating of the LiCl or other coating may be made to give the same coverage on the recorder for the whole humidity range for temperatures between −10 and −40° C, and a third unit, if desired, coated to cover the humidity range at temperatures from −40 to −70° C. Or it may be found possible with the proper choice of coatings, as mentioned in section VI, to use two units, one for temperatures from +30 to −30° C and the other from −30 to −70° C.

For high sensitivity, where one is concerned only with a total temperature range of 40° C or less, two units may be made to cover the full humidity scale. One unit might cover 0- to 50-percent humidity and the other 50 to 100 percent. Two such families of frequency-humidity curves are shown in figure 17, the curves at the left being for a unit with a higher percentage of LiCl than those at the right.

In figure 18 are shown two humidity units mounted in a double shield for protection against the sun's heat and from direct rain. It is important in recording relative humidity that the glass hygrometer unit be at the same temperature as the air, the humidity of which is to be measured. This is the reason for using a glass tube with a wall thickness of only 0.3 mm and for constructing and mounting the tube so that the air may circulate over both of the inside and outside wall.

VIII. FLIGHT TESTS

The flight records shown in figures 19 and 20, although purely qualitative, illustrate quite clearly how the dual-coil hygrometer responds to rapid humidity changes. These records show humidity variations which the hair-type hygrometer would fail to register. While the hygrometer units used in these two flights were only roughly calibrated, the records illustrate that the units respond rapidly and at low temperatures. In each of these flights the dual-coil was permanently connected to the relaxation-oscillator circuit, and approximate altitude was determined from estimated rates of ascent of the balloon. These flights were made before the low-temperature calibrating apparatus was available, so the results, especially at the higher altitudes, indicate trend only.

The flight record of figure 19 was made using the temperature-switched hygrometer unit shown at the right in figure 1. This unit had been given a coating of 1 percent LiCl about a month before the flight and a second 1-percent coating the day before. The approximate calibration shown is for 0° C. The instantaneous jumps of the recorder pen, shown by the darkened portion of the graph, were due to interference. The speed of response is clearly evident, especially at 3,200 ft, where a drop from approximately 40-percent humidity to 5 or 10 percent occurs in less than 30 seconds. The sudden discontinuity in the graph at approximately 18,600 ft was caused by the temperature switch closing and thereby allowing the more sensitive portion of the hygrometer unit to function and show humidity variations up to 43,000 ft and above. Note the fine structure of the humidity variations, especially at 9,800 ft.

On January 18, 1938, the sky being overcast, a flight was made, using the radio meteorograph shown in figures 14 to 16. 2¼ hours later a second flight was made, using a similar unit. The ascent rates were about 1,100 feet per minute. The circuit arrangement was that shown in figure 10, except that a hair-hygrometer unit was connected to segment 5 in place of the second temperature tube connection. In these flights the arm, *D*, of the six-segment commutator, figure 10, rotated at about 3.5 rpm. Each effect was therefore transmitted for about 3 seconds on an average of 3.5 times per minute. The dual-coil hygrometer unit, H_1, was coated with 0.5 percent LiCl and unit H_2 with a 2.0-percent coating. Each was coated the day before using. The graph shown in figure 21 is a photographic copy (reduced in size) of the actual first-flight record, as traced by the graphic frequency recorder at the receiving station. The full- and dotted-line traces of the envelopes of temperature, light, and three humidity records, were added to make the record more intelligible. In this graph the short dotted line is a record of brightness as received from

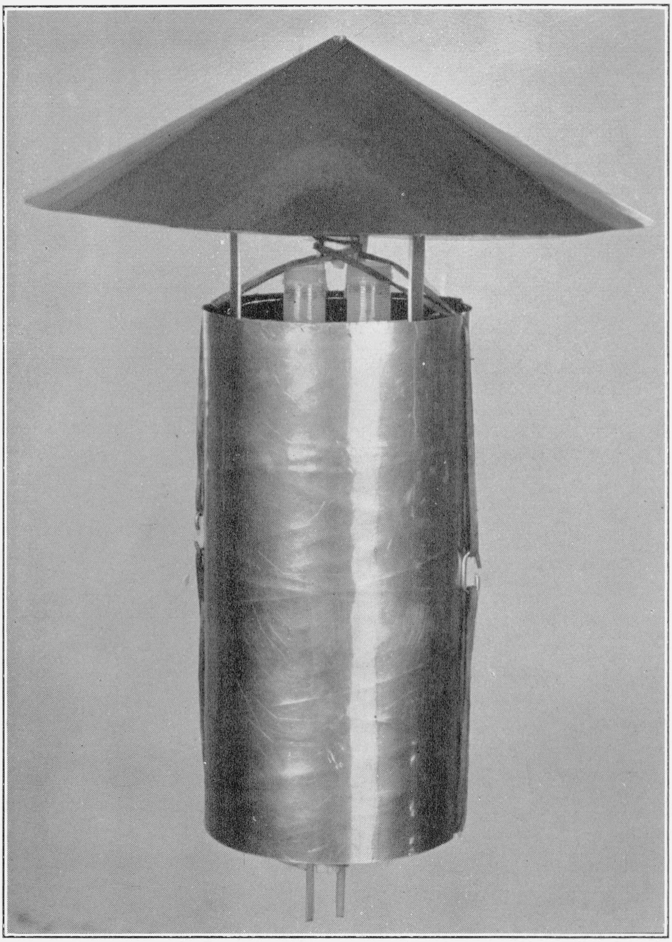

FIGURE 18.—*Double-walled sun and rain shield housing for two dual-coil hygrometers.*

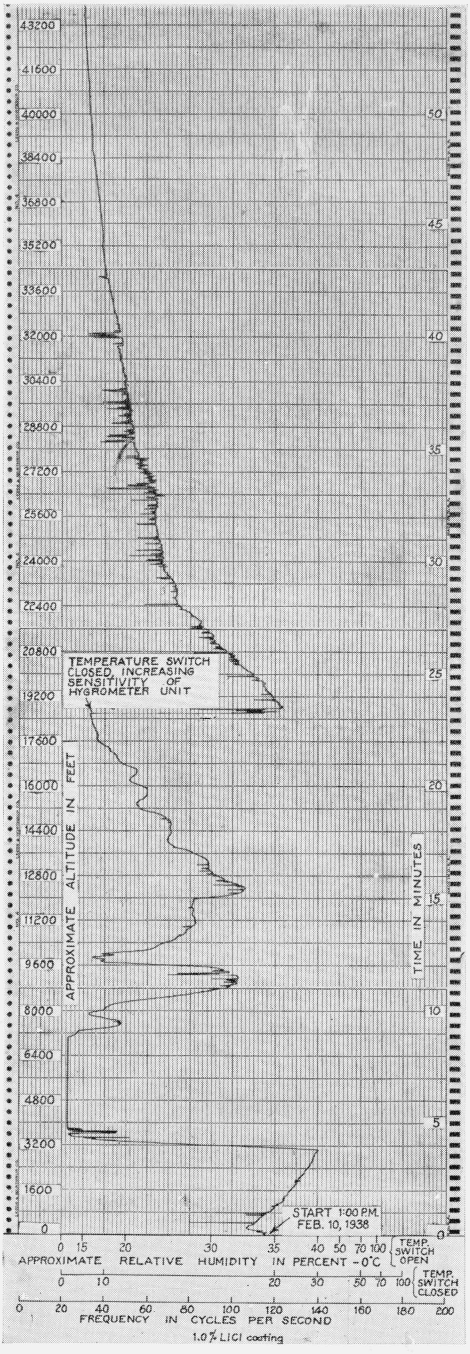

FIGURE 19.—*Humidity flight record using the dual-coil* LiCl *coated hygrometer, with temperature switch shown in figure 1.*

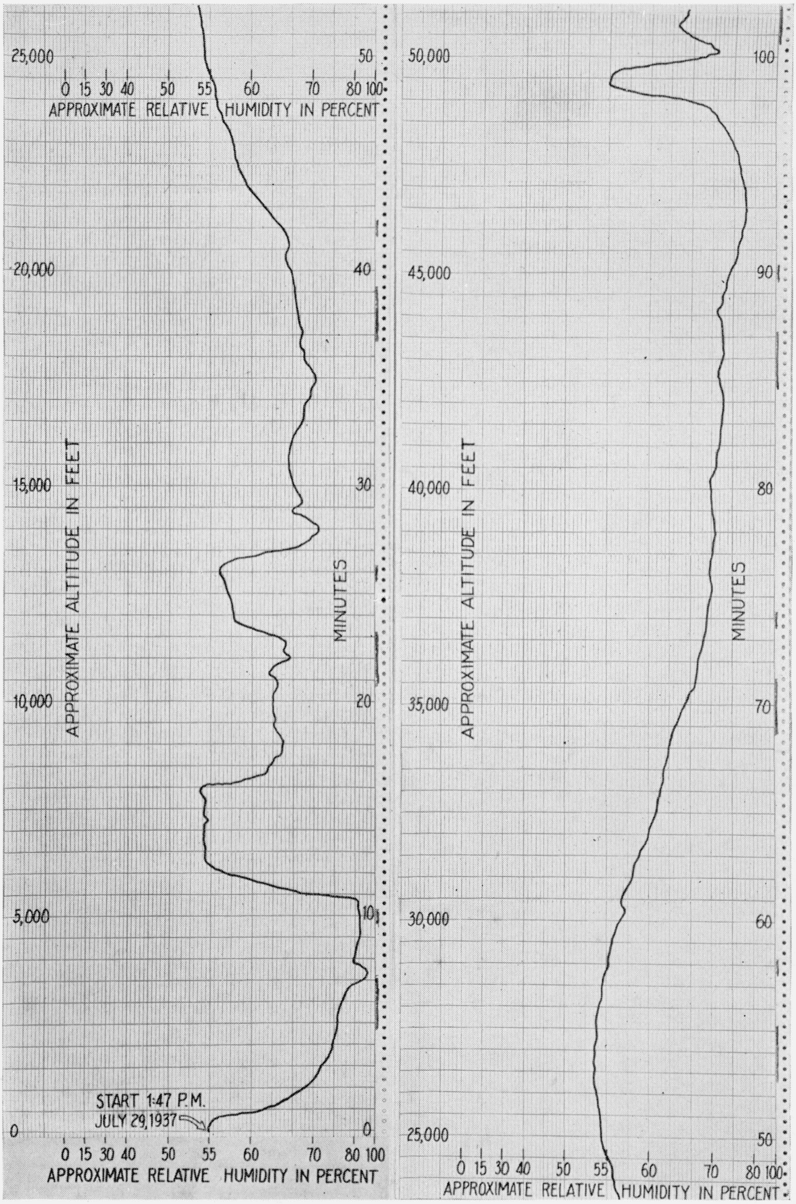

FIGURE 20.—*Humidity flight record using dual-coil hygrometer showing response at high altitudes.*

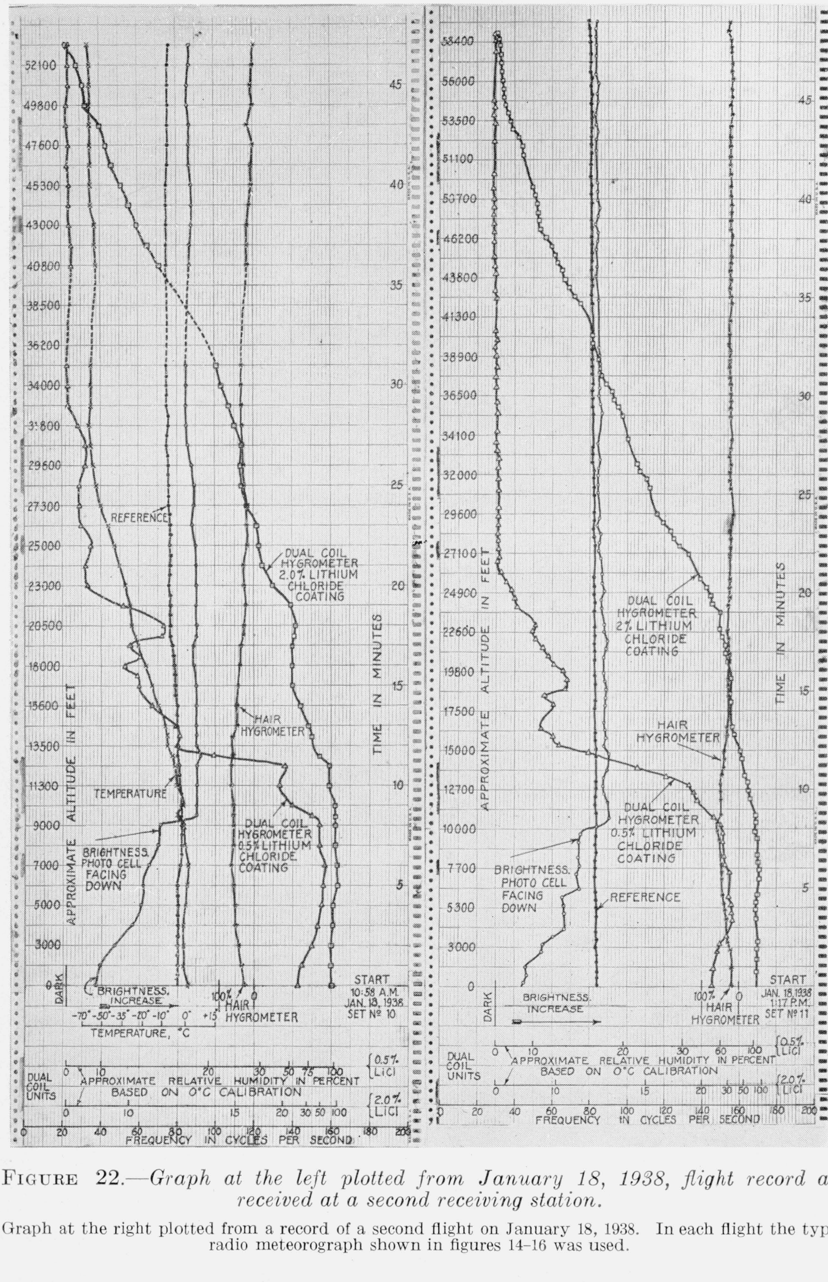

FIGURE 22.—*Graph at the left plotted from January 18, 1938, flight record as received at a second receiving station.*

Graph at the right plotted from a record of a second flight on January 18, 1938. In each flight the type radio meteorograph shown in figures 14–16 was used.

FIGURE 21.—*Flight record obtained on January 18, 1938, using the radio-meteorograph unit shown in figures 14, 15, and 16.*

below the radio meteorograph. The long dotted-line trace is that for temperature. The dash-dot line is a record of the humidity variations as given by the hair hygrometer. The full lines to the left and right are the humidity traces for the dual-coil hygrometers with 0.5 and 2.0 percent LiCl, respectively. It should be noted that the graph for the hair unit is the reverse from that of the two dual-coil units.

While all the measurements are more or less qualitative because of the difficulty of calibrating the dual-coil units at low temperatures, the results are comparative. Because of lack of calibration of the units, no correction is made in the humidity scale for temperature. Actually, the humidities indicated are higher, in a degree depending upon how much the ambient temperature is below 0° C. Figure 22 at the left shows graphs plotted from a record of the first flight obtained at a second receiving station. It is interesting to note that above an altitude of 35,000 ft (temperature of approximately −60° C) the 0.5 percent LiCl coated hygrometer unit ceased to function, while the 2 percent coated unit continued to show a decrease in humidity up to 55,000 ft where it became too dry for it to register. The major humidity changes above 10,000 ft recorded by the H_1 (0.5-percent coating) unit are also indicated by the H_2 (2-percent coating) unit at approximately the same altitudes. While the scale of humidity indications for the hair hygrometer is contracted in comparison with the electrical hygrometer units, nevertheless, close examination will show that it does not indicate many of the variations shown by the latter.

Major changes, such as those registered by unit H_1 between 12,000 and 13,500 ft, were not shown by the hair until a minute or so later. The temperature was approximately −6° C. This lag, which is equivalent to 1,100 ft, becomes greater at lower temperatures. A humidity drop indicated by both H_1 and H_2 units occurring between 20,500 and 23,000 ft is not indicated by the hair graph until 2 minutes later, occurring between 23,000 and 25,000 ft. The temperature in this instance was approximately −28° C.

A continuous record such as that shown in figure 21 and at the left in figure 22, produced practically simultaneously by three devices measuring temperature, humidity, and brightness, respectively, without appreciable lag in their response, makes possible a more intelligent analysis of the data than is possible where only temperature and humidity measurements are obtained at infrequent intervals. For example, note the correlation of the light variations with temperature and humidity changes, particularly at 9,500 ft, where the brightness graph shows that the balloon was just rising out of the last cloud layer, between 9,000 and 9,500 ft. Both temperature and humidity show sudden changes.

The full flight record shown in figure 21 indicates that the balloon reached an approximate altitude of 70,000 ft. The 14 pressure-contact signals shown to the right in the graph give the rate of ascent up to 35,000 ft. A previous calibration in a pressure chamber gave the approximate height corresponding to each pressure contact. From the rate of ascent the approximate maximum altitude of 70,000 ft was determined. Except for minor temperature variation, the humidity and light graphs show little variation above 55,000 ft. The discontinuities in the graph below 43,000 ft during the descent were caused by low battery voltage due to extreme cold.

The record for the second flight made 2¼ hours after the first one is shown at the right in figure 22. The sky was still overcast. The same general humidity variations are registered in this flight and at approximately the same altitudes as were shown in the first flight record. This record is therefore helpful in that it shows that the dual-coil units may be relied upon to give a true indication of the humidity structure of the atmosphere, even in the present stage of development.

IX. CONCLUSION

The electrical-type hygrometer appears to offer a new tool for the measurement of humidity in the upper atmosphere.

Further flight tests and development of means for calibrating this type of device at low temperatures seem to be all that is now necessary to adapt it to routine measurements in the upper atmosphere.

The author expresses his appreciation to H. Diamond for many helpful suggestions during the progress of this work; to E. G. Lapham and W. S. Hinman, Jr., of the Bureau's radio section, for assistance in the electrical design of the radio meteorograph and the flight tests; to L. L. Hughes, of the radio section, for his skillful construction and contribution to the mechanical design of the radio-meteorograph units used in the flight tests; to C. P. Saylor, E. R. Smith, and E. Wichers, of the Bureau's Chemistry Division, for assistance in choice of coatings for the hygrometer units; to E. O. Sperling, of the glass blowing shop, for ground-glass samples. Special acknowledgment is due to W. G. Brombacher, W. A. Wildhack, and B. W. Woolard, of the aeronautic instrument section, for the temperature-humidity measurements.

WASHINGTON, *March 14, 1938.*

[AUTHOR'S NOTE.—Recent experiments with a dual-coil unit wound with platinum wire showed very little change in resistance of the unit with time. This indicates that the long-period aging is due to a resistance film on the wire where it contacts the glass. A less corrosive wire than tinned copper should therefore be used. It is expected that noncorrosive materials, such as palladium, michrome, nickel, or Alleghany electric metal might be found satisfactory.]