NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2615

THE CALCULATED AND MEASURED PERFORMANCE CHARACTERISTICS

OF A HEATED-WIRE LIQUID-WATER-CONTENT METER

FOR MEASURING ICING SEVERITY

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NACA

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SUMMARY

Ground tests have been made of an instrument which, when assembled in a more compact form for flight installation, could be used to obtain statistical flight data on the liquid-water content of icing clouds and to provide an indication of icing severity. The sensing element of the instrument consists of an electrically heated wire which is mounted in the air stream. The degree of cooling of the wire resulting from evaporation of the impinging water droplets is a measure of the liquid-water content of the cloud. Determination of the value of the liquid-water content from the wire temperature at any instant requires a knowledge of the airspeed, altitude, and air temperature.

An analysis was made of the temperature response of a heated wire exposed to an air stream containing water drops. Comparisons were made of the liquid-water content as measured with several heated wires and absorbent cylinders in an artificially produced cloud. For one of the wires, comparative tests were made with a rotating-disk icing-rate meter in an icing wind tunnel. From the test results, it was shown that an instrument for measuring the concentration of liquid water in an air stream can be built using an electrically heated wire of known temperature-resistance characteristics, and that the performance of such a device can be predicted using appropriate theory.

Although an instrument in a form suitable for gathering statistical data in flight was not built, the practicability of constructing such an instrument was illustrated. The ground-test results indicated that a flight heated-wire instrument would be simple and durable, would respond rapidly to variations in liquid-water content, and could be used for the measurement of water content in clouds which are above freezing temperature, as well as in icing clouds.

INTRODUCTION

In the investigation of means for protecting aircraft from icing in flight, the meteorological structure of icing clouds is an important consideration. Studies of clouds require the development of instruments for measuring such quantities as liquid–water content, droplet size, and air temperature. A discussion of some of these instruments is given in reference 1.

Recent development of icing instruments has been concentrated on simple instruments designed for the purpose of obtaining statistical data on the severity of icing conditions. The NACA has conducted research on several instruments for this purpose. One of these instruments, which is described in reference 2, is being used in a cooperative program with airlines and the U. S. Air Force for obtaining statistical information regarding frequency, extent, and intensity of icing conditions. This instrument measures the rate of ice accretion on a small-diameter cylinder. From simultaneous recordings of ice–accretion rate and airspeed the liquid–water content of the icing cloud is evaluated. The icing severity is then established by the reasoning advanced in reference 3 that the effect of droplet size is secondary and that liquid-water content can be considered to give a good first approximation of icing severity.

Another instrument, which is described herein, has been developed by the Ames Laboratory of the NACA. This instrument also utilizes the principle that, at temperatures below freezing, liquid-water content is a good approximation of icing severity. The liquid-water content of the cloud is determined from the rate of interception of water by a small–diameter heated cylinder. Since first suggested in 1944 by Mr. J. K. Hardy of the R.A.E. as a means for measuring liquid-water content, the heated cylinder, until recently, had been used only for detecting the presence of liquid water in flight (reference 4). In 1946, a design was proposed for an instrument of this type to measure water concentration (reference 5). In a recent investigation (reference 6), a heated-cylinder instrument was developed and was calibrated over a limited range of conditions. Although this instrument is less complicated and more easily arranged for direct indication than any of the other types of instruments mentioned previously, certain disadvantages still remained. For example, the sensing element is somewhat fragile and complicated in construction, and the response to changes in water content is not as rapid as is desirable. This instrument, as well as the other types mentioned previously, does not readily lend itself to theoretical treatment, and, hence, must be calibrated for a wide range of values of liquid-water content, airspeed, and altitude to be usable.

The instrument investigated at the Ames Laboratory, which constitutes the subject of this report, overcomes these disadvantages while retaining the advantage of being easily adaptable for direct indication of liquid-water content. The sensing element consists simply of a loop of electrical resistance wire which is heated by passing current through it.

Its change in resistance, resulting from cooling due to evaporation of impinging water droplets, is used as a measure of the liquid-water content. Equations were developed which predict the performance of a heated wire in a cloud composed of water droplets. In order to provide data suitable to evaluate these equations, tests of several resistance wires were performed in an artifically produced cloud within a duct at above freezing temperatures, wherein a wide range of values of airspeed and liquid-water content could be obtained. In addition, tests over a limited range of conditions were conducted at subfreezing temperatures with one resistance wire in the Lewis Laboratory Icing Research Tunnel. Presented in this report are the results of these tests, together with an analysis of the heated-wire-type instrument. Comparisons are made of values of water content obtained with the heated wires and those measured by means of absorbent cylinders. In addition, the performance characteristics of the instrument are illustrated. Although an instrument was not built in a form suitable for installation in an airplane, sufficient information is included to indicate the practicability of constructing a complete instrument for gathering statistical flight icing data.

SYMBOLS

A_p projected frontal area of cylinder, square feet

A_s surface area of cylinder, square feet

c_p specific heat of air at constant pressure, Btu per pound, °F

c_{p_w} specific heat of water at constant pressure, equal to 1 Btu per pound, °F

C concentration factor for water drops impinging at any location on the cylinder surface; defined, considering the two-dimensional flow field, as the ratio of the differential distance, normal to flow direction, of two adjacent trajectories of water drops at free-stream conditions to the differential distance along the cylinder surface measured between the points of impingement of the water drops, dimensionless

d diameter of absorbent cylinder, inches

D diameter of heated cylinder, feet

e_{o_k} saturated water-vapor pressure at temperature t_{o_k}, millimeters of mercury

e_s saturated water-vapor pressure at temperature t_s, millimeters of mercury

E electrical potential across ends of resistance wire, volts

E_M water-drop collection efficiency, dimensionless

g acceleration due to gravity, equal to 32.2 feet per second, second

h convective surface heat-transfer coefficient at any point on cylinder surface, Btu per hour, square foot, $^\circ$F

h_{av} mean convective surface heat-transfer coefficient, average for periphery of cylinder, Btu per hour, square foot, $^\circ$F

h_g enthalpy of saturated water vapor at temperature t_s, Btu per pound

I electrical current flow through resistance wire, amperes

J mechanical equivalent of heat, equal to 778 foot-pounds per Btu

m liquid-water concentration, grams of water per cubic meter of air

M_a weight-rate of water-drop impingement per unit of surface area, pounds per hour, square foot

M_T total weight-rate of water-drop impingement, pounds per hour

p local barometric pressure, millimeters of mercury

Q rate of heat flow, Btu per hour

r measured rate of ice accretion on rotating disk, inches per minute

R electrical resistance of wire at temperature t_s, ohms

t_o ambient-air temperature, $^\circ$F

t_{o_k} kinetic-air temperature adjacent to any point on the cylinder surface, $^\circ$F

$t_{o_{k_{av}}}$ mean kinetic-air temperature (average temperature of air adjacent to periphery of cylinder), $^\circ$F

t_s cylinder-surface temperature, $^\circ$F

T_f average of cylinder-surface temperature t_s, and ambient-air temperature t_o, $^\circ$F absolute

V free-stream velocity, feet per second

W_T total weight of water intercepted by absorbent cylinder, grams

γ specific weight of air at temperature T_f and prevalent pressure, pounds per cubic foot

ρ density of ice formed on rotating disk, grams per cubic centimeter

τ duration of exposure of absorbent cylinder, seconds

φ central angle measured from forward stagnation point of cylinder, degrees

ANALYSIS

Operation of a Heated Cylinder in a Cloud

A heated cylinder placed transversely in an air stream containing water droplets is cooled by convection, by the transfer of heat to the water drops striking the cylinder, by the evaporation of the water on the cylinder surface, and by radiation. In general, the transfer of heat due to radiation is small, and in the subsequent analysis this heat loss will be neglected. A circular cylinder of infinite length and of uniform surface temperature is assumed.

If the cylinder is heated sufficiently to evaporate all impinging water, the flow of heat from its surface due to convection, water-drop impingement, and evaporation can be expressed as

$$Q = h_{av} A_s \left(t_s - t_{o_{k_{av}}} \right) + M_T \left[h_g + (32 - t_o) c_{p_w} \right] \qquad (1)$$

The rate of water-drop impingement is

$$M_T = 0.225 \, V A_p \, E_M \, m$$

If the cylinder is in the form of an electrical resistance wire, and the wire is heated by passing current through it, the power input is equal to the product of the current and the voltage at the wire terminals, and the value of Q equals $3.41 \, EI$. Substituting in equation (1) for Q and M_T and assigning c_{p_w} the value of 1 Btu per pound, $^\circ F$, the liquid-water concentration of the air stream is given as follows:

$$m = \frac{3.41 \, EI - h_{av} A_s \left(t_s - t_{o_{k_{av}}} \right)}{0.225 \, V \, A_p \, E_M \, (h_g + 32 - t_o)} \qquad (2)$$

When the wire is composed of a material the resistance of which
increases with increasing temperature, cooling of the wire due to
impinging water droplets will cause its resistance to decrease. Thus,
by use of equation (2), and from the temperature-resistance character-
istics of the wire, the liquid-water content can be obtained simply by
measuring the voltage and current, in addition to the airspeed, alti-
tude, and ambient-air temperature. If the voltage across the wire
terminals is held constant, the current flow through the wire will
increase with increasing liquid-water content, due to the decreasing
resistance resulting from the lowered temperature. In this manner, the
change in current can be used to indicate liquid-water concentration
directly.

Evaluation of Average Heat-Transfer Coefficient

The value of the average heat-transfer coefficient, h_{av}, in equa-
tion (2) can be obtained either by calculation or by measurement during
flight in clear-air conditions. The value may be computed from the
following equation, which is taken from reference 7:

$$h_{av} = 0.211 \ T_f^{0.43} \frac{(V\gamma)^{0.6}}{D^{0.4}} \tag{3}$$

Saturation of a Heated Cylinder

The previously discussed theory is not applicable beyond the point
of surface saturation. The saturation point is reached when the rate of
water impingement on the cylinder just equals the maximum possible rate
of evaporation of the water. At this point, the surface is just becoming
wet. It is possible to establish the temperature at which saturation
theoretically will begin for a given liquid-water content by analyzing
the evaporation process around the cylinder surface. At the inception
of saturation, the relationship between rate of water impingement and
maximum possible rate of evaporation at any point around the cylinder
surface can be derived from equations presented in reference 8, as
follows:

$$M_a = \frac{0.622 \ h}{p \ c_p} \left(e_s - e_{o_k} \right)$$

where

$$M_a = 0.225 \ Vm \ C$$

The saturation vapor pressure at the surface, then, is

$$e_s = e_{o_k} + 0.361 \frac{Vm\ Cp\ c_p}{h} .$$ (4)

The value of the heat-transfer coefficient, h, can be calculated for any location on the forward half of the cylinder surface from the following expression, which is taken from reference 7:

$$h = 0.194\ T_f{}^{0.49} \left(\frac{V\gamma}{D}\right)^{0.5} \left[1 - \left(\frac{\varphi}{90}\right)^3\right]$$ (5)

By solving for e_s in equation (4) for a particular liquid-water content, the temperature corresponding to the value of e_s can be obtained from water-vapor-pressure tables. This temperature is the saturation temperature for any point on the forward half of the surface of the cylinder. By use of equations (4) and (5), it can be shown that the saturation temperature is highest at the stagnation point of the cylinder. Thus, the saturation point for the cylinder as a whole is the saturation temperature at the stagnation point.[1]

DESCRIPTION OF EQUIPMENT

Heated-Wire Loops

Three heated-wire loops were tested in the cloud duct and are shown in figure 1, which gives the designation number for each loop. Wire loop 2 consisted of the same wire material as loop 1; whereas loop 3 was made of a different material. Tests in the Lewis Icing Research Tunnel were conducted using a circular loop identical to loop 2. Since extensive tests were made with loop 1 under various conditions, but for only one condition with loops 2 and 3, pertinent descriptive information will be presented for wire loop 1 only. Details of construction of the loop and method of installation are shown in figure 2. The temperature-resistance characteristics of the wire material as determined in a temperature-controlled oven are presented in figure 3.

[1]Actually, the saturation point for the cylinder as a whole would be at a value slightly below this temperature, since that portion of the water not evaporated would tend to run aft around the cylinder and be evaporated in the areas not yet saturated. This process is not easily analyzed, but is believed to be of such small consequence as to be negligible.

Power Supply and Measuring Equipment

In the cloud-duct tests, the heating current for the wires was obtained through use of a step-down transformer designed for a 115-volt 60-cycle power input. A variable autotransformer was used to allow manual adjustment of the voltage. Values of voltage and current were recorded with an oscillograph in order to obtain records of the variation of these values during each test. Similar equipment was used in the tests conducted in the icing tunnel.

Cloud Duct

A general view of the cloud duct in which the tests were performed is presented in figure 4. A schematic diagram of the duct and equipment is shown in figure 5. The duct was insulated on either side of the plastic section to minimize the heat transfer from the air in the duct to the surrounding air. This was done in an attempt to maintain an adiabatic expansion of the air entering the duct so as to facilitate the computation of the duct-air temperature from measurements of the surrounding-air temperature.

A commercial paint gun, shown in figure 4, was used to spray water into the duct entrance to create an artificial cloud. The drop-size distribution was assumed to be uniform; however, a variation in drop size with water-flow rate through the spray gun was noted. This variation is presented in figure 6. These data were obtained with a 1-inch-diameter cylinder using the technique described in reference 1 for the fixed cylinder.

Absorbent Cylinders

In order to measure the amount of liquid water contained in the duct air stream, small absorbent cylinders about 1/4 inch in diameter which would collect a sample of the water were used. One of the absorbent cylinders is shown in figure 7. The cylinders consisted of blotter material wrapped around a 1/8-inch-diameter steel tube and bound with fine wire. Clear cellulose tape was placed around each end of the blotter, leaving a 3-inch length exposed, so as to provide a water-drop collection sample representative of conditions existing in the central 3-inch-diameter region of the duct. This arrangement was found desirable to eliminate boundary effects near the sides of the duct.

A discussion of the use of absorbent cylinders for measuring liquid-water content and tests of the characteristics of the cylinders are presented in appendix A.

Rotating-Disk Icing-Rate Meter

In the tests of the heated wire in the icing tunnel, a rotating-disk icing-rate meter was used as the reference instrument for measuring the liquid-water content in the tunnel. A brief description of the rotating-disk instrument is given in reference 2.

TEST PROCEDURE

Tests in Cloud Duct

With voltage of a previously established amount applied across the wire-loop terminals, the water spray into the duct was adjusted to enable a predetermined value of current to flow through the loop, the value representing a certain calculated liquid-water content. An absorbent cylinder which had been weighed was then inserted into the duct air stream, while a record of wire-loop voltage and current was obtained on the oscillograph. During exposure of the cylinder, it was rotated at a speed of approximately one revolution per second to assure even absorption of water over the entire cylinder surface. Immediately upon removal of the cylinder from the duct, it was weighed to determine the amount of water collected. Measurements were made of the duct-air velocity, water-flow rate to the spray gun, and ambient-air temperature.

Preliminary measurements of the change in relative humidity of the air in the cloud duct due to the water spray had indicated that only a comparatively small increase in humidity resulted from evaporation of water from the spray. Since in most cases the duct air was not saturated, a small amount of the water impinging on the absorbent cylinders was removed by evaporation during exposure. To determine the quantity of water evaporated, the absorbent cylinder which had been exposed to the duct air stream and water spray was again inserted into the duct with the water spray off. The wet cylinder was exposed for the same length of time as previously, then removed and again weighed. The difference in cylinder weight resulting from this exposure provided a measure of the amount of water which had been evaporated during the initial exposure.

To establish the value of the wire heat-transfer coefficient, h_{av}, measurements of the voltage and current to the wire loop were made periodically in clear-air conditions. In general, a clear-air measurement was made immediately prior to each test.

Tests in Icing Tunnel

With the voltage at the wire-loop terminals maintained constant, measurements were made of current and voltage supplied to the loop while a record was obtained of the rate of ice accretion on the rotating disk. Readings were also taken of the velocity, temperature, and pressure of the air in the tunnel. As in the experiments in the cloud duct, measurements of the pertinent variables were made in clear air prior to each icing test.

TEST CONDITIONS

Tests in Cloud Duct

The various conditions under which tests of the performance of the heated wires were made are given in the following table:

Test condition No.	Study effects of	Wire loop No.	Air-speed (mph)	Wire voltage	Clear-air wire temperature (^oF)	Average duct-air temperature (^oF)
1	wire size and material	1	265	2.94	460	60
		2		2.75	460	
		3		4.07	620	
2	airspeed variation at constant voltage	1	200	2.94	500	60
			315		430	45
3	airspeed variation at constant clear-air wire temperature	1	150	2.55	460	60
			365	3.28		35
4	large increase in wire temperature	1	150	3.08	600	60
			265	3.58		50

Tests in Icing Tunnel

Tests were conducted at airspeeds of 200, 275, and 305 miles per hour, and at temperatures ranging from -2° to 23° F. The liquid-water

content of the air stream was varied up to the maximum output of the
spray system in use in the tunnel at the time of the experiments. A
constant potential of 2.97 volts was maintained at the wire-loop ter-
minals under all conditions of test.

RESULTS

Cloud-Duct Data

The results presented are for loop configuration 1 since only
limited tests were made of configurations 2 and 3. Results of measure-
ments made simultaneously with the heated-wire loop and absorbent
cylinders are given in tables I through IV. Comparisons of the liquid-
water concentrations calculated from the data of tables I through IV
for the wire loop and the absorbent cylinders are presented in fig-
ures 8 through 11 for test conditions 1 through 4, respectively. The
calculated liquid-water concentrations at saturation and corresponding
saturation temperatures for all but the last test condition are given.
The precision of the liquid-water-content measurements with the heated
wire and absorbent cylinders is discussed in appendix B.

Reduction of heated-wire data.- The values of liquid-water content
presented which are based on measurements with the heated-wire loop were
calculated by use of equation (2). The heated-wire temperature, t_s, was
obtained from the resistance of the wire, as determined from the measure-
ments of current and voltage, using the curve of figure 3. As is implied
in equation (2), the temperature of the water droplets was assumed to be
at the same temperature as the air in the duct. The collection effi-
ciency, E_M, was computed from the data of reference 9, using values of
water-drop size from figure 6. Due to limitations of the technique
employed to obtain the data of figure 6, no measurements of drop size
were made at speeds above 265 mph. In the reduction of data above 265 mph,
the water-drop-size data for 265 mph were used. Inasmuch as the collec-
tion efficiency was high, any likely errors in the determination of drop
size for the higher-speed data would cause only very small errors in the
calculated value of collection efficiency.

Because the heated-wire and absorbent-cylinder measurements were
made simultaneously, the liquid-water content of the air downstream from
the absorbent cylinder was depleted by the amount of water intercepted
by the cylinder. Corrections for this reduction in water content were
applied to values obtained from measurements with the wire loops. A
discussion of these corrections is given in appendix A.

Calculations showed the wire-temperature reduction due to conductive
heat loss from the wire ends to be negligible.

Reduction of absorbent-cylinder data.- In the computation of
values of liquid-water content from the data obtained with the absorbent
cylinders, the following equation was used:

$$m = 1696 \frac{W_T}{Vd\ E_M \tau}$$ (6)

The effective absorbent-cylinder length of 3 inches is included in
the constant of equation (6). The value of W_T includes the measured
weight of water evaporated from the absorbent cylinders during exposure.
The collection efficiency, E_M, was evaluated from the information con-
tained in reference 9, using the water-drop-size data of figure 6. As
in the reduction of the heated-wire data, for the tests above 265 mph,
the measurements of water-drop size at 265 mph were used.

Rate of response of heated wire.- Results of a test of the rate
of response of the wire loop are presented in figure 12, which shows an
oscillograph record of the rate of increase and decrease in current
through the wire loop when the water spray was turned on and off. Since
the indicated water content is a direct function of current under the
conditions of this test, the values of indicated liquid-water content
corresponding to the values of current are presented. Also included is
the record of voltage across the ends of the wire obtained during the
tests. The fluctuations in voltage occurring when the spray was started
and stopped resulted from difficulty in maintaining the voltage constant
by manual adjustment of the variable-voltage transformer as the current
changed.

Icing-Tunnel Data

Presentation of results.- The results of the simultaneous measure-
ments with the heated-wire loop and rotating disk are presented in
table V. A comparison of the water contents calculated from the indica-
tions of the heated wire and the rotating disk is shown in figure 13.
An explanation of this figure is given in the following section.
Reduction of the heated-wire data was performed as described for the
cloud-duct tests.

Reduction of rotating-disk data.- The values of liquid-water
content presented in figure 13 were computed, from the measured icing
rate on the disk and the airspeed, from the formula

$$m = 1390 \left(\frac{r}{V}\right)\left(\frac{\rho}{E_M}\right)$$ (7)

From equation (7) it is seen that the value of liquid-water content as
indicated by the disk is a function of the ratio of the ice density to
the collection efficiency of the disk. In calibrations of a rotating-
disk instrument with rotating cylinders, it has been shown that the
ratio of ρ to E_M can vary considerably (reference 4). For this
reason the rotating disk cannot be used to give precise values of liquid-
water content. The data points shown in figure 13 were computed from the
rotating-disk results using a value of the ratio of ρ to E_M which is
an average of the extreme variations of each factor as noted in previous
investigations. Since E_M may be influenced by the disk design, only
data from tests in the Lewis Laboratory icing tunnel were considered in
the determination of the average value of this factor. In reference 2,
the collection efficiency was specified as ranging from 0.5 to 0.7, and
in references 4 and 10 the density of the ice was taken as 0.75 and 0.9,
respectively. Therefore, average values of 0.6 for E_M and 0.83 for ρ
were used in computing the data points in figure 13. As an indication
of the possible spread of the data points resulting from the extreme
possible combinations of E_M and ρ, two additional lines have been
added to figure 13. These two lines, therefore, represent the extremes
of the rotating-disk data, while the data points represent the most
probable values.

DISCUSSION

Performance of Heated Wire

Comparison of experiment and theory.- Figures 8 through 10 show
good agreement between the values of liquid-water content computed from
theory incorporating the measurements with heated-wire loop 1 and those
values measured in the duct with the absorbent cylinders up to a point
of apparent saturation of the heated wire.[2] Beyond this point, the
heated-wire measurements exhibit lower values of water content than the
absorbent cylinders, indicating that not all impinging water was being
evaporated. The value of water content at the point of apparent satura-
tion was in all cases considerably less than the computed saturation
liquid-water content. Apparently, the theory for the prediction of the
operation of the heated wire, which assumes that all impinging water is
evaporated, is adequate in the range where this evaporation can be
achieved, but appears to be inadequate for the prediction of the satura-
tion point.

Comparison of calculated and apparent saturation temperatures.- In
order to examine the possible reasons why the saturation point was not
predictable, the data were analyzed to compare the calculated and appar-
ent saturation temperatures, since the evaporation process is primarily

[2]Equally good agreement was obtained in the tests of loops 2 and 3 to
the point of apparent saturation.

a function of temperature. To determine the wire temperature at apparent saturation, the wire temperatures were plotted against the liquid-water-content values as measured with the absorbent cylinders for each test condition. From curves faired through these data, the measured saturation temperatures were established as the wire temperatures at the values of liquid-water content at apparent saturation, which were taken from figures 8 through 10. A comparison of the wire temperatures at apparent saturation and those calculated using equation (4) for the liquid-water-content value at apparent saturation is given in table VI. The wire temperatures at apparent saturation are shown to be considerably higher than the calculated values. A possible explanation of this difference is that, in the theory of operation and saturation of a heated wire, no allowance is made for the time required for the water droplets impinging on the wire to respond to the large increase in temperature to which they are subjected.

All impinging droplets are assumed to be evaporated completely, which could occur only if the droplets remained on the wire a sufficient length of time. In the actual case, aerodynamic forces on the drop tend to remove part of the water before it is entirely evaporated. The heated-wire performance still will follow theory as long as each entire drop impinging on the wire is evaporated. When the temperature lag of the droplet allows sufficient time for part of it to be carried away by the air stream before evaporating, the performance of the wire will no longer follow theory and apparent saturation will have been reached. It appears, then, that the difference between calculated and apparent saturation temperatures shown in table VI is a measure of the temperature lag of the water droplets, since this difference represents the increase in wire temperature above the calculated saturation temperature necessary to raise the droplet temperature rapidly enough to ensure complete evaporation.

Effect of airspeed.- A study of table VI shows that as the airspeed is increased, the difference between the measured wire temperature at apparent saturation and the calculated saturation temperature decreases. This relationship is illustrated in figure 14, where it is evident that the effect of speed is a dominant factor influencing the evaporation process. Since the temperature response of the water drops determines the rate of evaporation and the apparent saturation point of a heated wire, the velocity of the drops as they impinge on the wire must affect their rate of temperature response. This effect on the temperature response probably is caused by an increased tendency for the drops to spread as they strike the wire at higher velocities, thereby presenting a greater area to receive the heat from the wire and allowing a more rapid increase in temperature. This mechanical spreading action of the drops appears to be a large enough factor to dominate the saturation picture, completely masking the effect on saturation of the various influencing factors as predicted from theory.

Effect of wire temperature.- Provided the foregoing argument is correct regarding saturation of the heated wires, an increase in the operating wire temperature should result in a more rapid increase in the temperature of the impinging water drops, thus ensuring more rapid evaporation and increasing the value of liquid-water content at saturation. This effect is demonstrated in figure 11, where good agreement is shown between the heated-wire and absorbent-cylinder measurements of liquid-water content up to approximately 2.6 and 3.3 grams per cubic meter at velocities of 150 and 265 mph, respectively, for a clear-air wire temperature of about 600° F. Since the values of water content represent the upper limits of the tests, the saturation points under these conditions were not obtained. From these data, then, it is apparent that by increasing the operating temperature of a heated wire the range of water concentration for which its performance is predictable by theory can be increased.

Selection of wire temperature.- An indication of the amount by which the wire temperature at saturation should be increased above the calculated value can be obtained from figure 14. It appears from this figure that, in the design of a heated-wire-type liquid-water-content instrument consisting of a wire about 1/16-inch diameter and operating under the conditions of the tests, the wire temperature at the desired saturation value of water content should be maintained from about 100° to 250° F above the calculated saturation temperature, depending on the air-speed. It should be noted that the average duct-air temperature for the data of figure 14 was about 60° F. Since this was also the average water-droplet temperature, the droplets would have reached the temperature required for complete evaporation upon contact with the wire sooner than if they had been at a lower temperature, which would be the case in icing conditions. It is suggested, then, that in determining the design saturation temperature of a heated wire, the difference between 60° F and the design air temperature be added to the difference between apparent and calculated saturation temperatures shown in figure 14.

Comparison of Heated-Wire and
Rotating-Disk Measurements

Figure 13 shows good agreement between the heated-wire and rotating-disk measurements of liquid-water content when average values of ice density and collection efficiency are used in computing the water content from the disk indications. The data points follow the line of perfect agreement reasonably well, and fall approximately in the middle of the region bounded by the extreme possible mean-line locations for the disk data. Although these results do not give a precise check on the theory of operation of a heated wire due to uncertainty as to the exact values of the disk collection efficiency and ice density, nevertheless they provide an indication of the degree of accuracy of the heated-wire instrument in icing conditions.

Rate of Response of Heated Wire

A rapidly responding instrument for recording the presence of large concentrations of liquid water of short extent is desirable from the standpoint of supplying information on the severity of meteorological conditions which could affect the operation of certain parts of an airplane, such as turbine-engine induction systems, where a sudden large mass of super-cooled water might be critical. According to reference 11, such a cloud composed of a high concentration of liquid water might extend horizontally only 1/2 mile, in which case the duration of the condition would be only about 7 seconds for flight at 265 mph. Thus, in order to provide an accurate indication of such a condition, an instrument must have a more rapid response to sudden changes than 7 seconds. The response curve of figure 12 shows that the instrument reacts rapidly to sudden changes in liquid-water content. The wire reached an equilibrium condition 4 to 5 seconds after the water spray was turned on or off, and gave an indication of about 80 percent of the final value within 2 seconds after the sudden changes in condition. It appears, then, that this wire has sufficiently rapid response to provide reliable information on the severity of icing clouds of short extent.

Possible Limitations of Heated-Wire-Type
Liquid-Water-Content Instrument

In the tests of the heated wire loops, the largest diameter of water droplet obtained in the duct was about 25 microns. For this size of drop and for all smaller sizes, the heated wires proved capable of evaporating the entire drop. It is possible that wires of the size tested would not be able to evaporate completely drops considerably larger than 25 microns before part of the water would be carried away by the air stream. For this reason, heated wires in the order of 1/16-inch diameter may not be usable for accurate measurement of water content in clouds composed of large drops; it is improbable, in fact, that this size of wire could completely evaporate drops of the size of raindrops (above about 1000-microns diameter). One means of alleviating the possible difficulty of measuring the water content in clouds with large drops present may be to increase the diameter of resistance wire, thereby presenting a larger surface area for evaporation of the impinging drops. No information is available on this point, however.

In the case of heated wires of the size tested, errors in the measurement of liquid-water content resulting from the possible incomplete evaporation of water drops larger than 25 microns would not be serious insofar as use of the data for statistical analysis is

concerned. Clouds composed of water droplets with a mean-effective diameter[3] larger than 25 microns are unusual, and are not likely to have high values of water content (references 3, 4, 12, 13, and 14). Thus, errors from this source would not be frequent and would occur mostly at low values of liquid-water content, and hence would not have an important influence on the frequency distribution of maximum values. A discussion of a proposed application of a heated-wire-type instrument for obtaining statistical meteorological data in flight is contained in appendix C.

Although the rate of response of the heated-wire-type instrument is greater than that of any device currently available for the statistical determination of liquid-water content in flight, the response rate would prove a limitation in the measurement of instantaneous values of water content in clouds in which large changes in water content occurred in less than 4 or 5 seconds. This limitation, at the present at least, is not considered to be serious.

Remarks on the Use of a Heated Wire for Direct Indications of Liquid-Water Content

It was mentioned previously that by maintaining the voltage constant across the terminals of a heated-wire-type liquid-water-content meter, the ammeter measuring the wire current can be used to indicate water concentration directly. With this arrangement, the indications of the ammeter would represent values of liquid-water content accurately only for the conditions of airspeed, altitude, and air temperature for which the operating voltage was selected. (An example of the procedure to be followed in the calculation of operating voltage and in the use of a heated-wire instrument is given in appendix D.) Some variation from the design conditions could be tolerated, however, with only small error in the indicated values of liquid-water content. This is illustrated in figure 15 which presents calculated curves of current as a function of water content, for the wire of loop 1, showing the effect of variations of airspeed, altitude, and air temperature for constant voltage. These data show that for the same ammeter indication a variation of about ±10 mph in the true airspeed represents a variation of ±0.1 gram per cubic meter in actual water content. Likewise, for the same ammeter reading, a variation of about ±3000 feet in altitude is representative of a difference of ±0.1 gram per cubic meter, and a variation in air temperature of about ±20° F represents the same liquid-water-content variation.

In order to obtain a more versatile arrangement for the direct indication of liquid-water content, it is possible that the ammeter could be

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[3]The mean-effective diameter of water drops in a cloud which contains a variety of drop sizes is the diameter of drop for which there are equal volumes of water existing in drops larger and smaller than the drop.

provided with either a manually adjustable scale for variations in air-
speed, altitude, and air temperature, or with a means for automatically
compensating for such variations, so that accurate indications of water
content could be obtained under operating conditions other than those
for which the design voltage was established.

Selection of Wire and General Configuration
for a Heated-Wire-Type Instrument

Selection of wire.- An important factor influencing the selection
of wire for use in a heated-wire liquid-water-content meter is the
temperature-resistance characteristics of the wire. It is desirable
that the temperature-resistance curve for the wire have a fairly high
slope and be linear throughout the operating range. The slope of the
temperature-resistance curve for the wire of loop 1 (shown in fig. 3) up
to a temperature of about 500° F appears to be adequate and provides a
good degree of sensitivity of the resulting instrument for changes in
water content. The decrease in slope of the curve above 500° F is
undesirable, however, since the sensitivity of the instrument and, cor-
respondingly, its accuracy decrease accordingly in this region of opera-
tion. For example, consider the curves of figure 15 which were computed
for the wire of loop 1. A marked decrease in the sensitivity is evident
for values of liquid-water content below about 0.6 gram per cubic meter.
This illustrates the desirability of selecting a wire having linear
temperature-resistance characteristics over the entire anticipated oper-
ating range of wire temperature.

Configuration of wire.- Concerning the configuration of the wire,
it should be pointed out that the cross-shaped form of the loop of wire
was tested to determine whether this shape would provide a more compara-
ble sampling of conditions in the duct to that of the absorbent cylinders
than the circular shapes. Although no significant differences were noted,
the bulk of the tests were performed with this configuration. In the
case of a heated-wire liquid-water-content instrument to be used in
flight, a cross-shaped loop would have no advantage over a circular one.
Inasmuch as a circular shape is desirable from the standpoint of sim-
plicity of construction, it is suggested that this configuration be
embodied in the design of a heated-wire liquid-water-content meter.

Advantages of Heated-Wire-Type Liquid-
Water-Content Instrument

It has been shown that a heated resistance wire can be used to
measure the quantity of liquid water contained in an air stream, and the
performance of the wire can be predicted using appropriate theory. Thus,
a major advantage of the heated-wire-type instrument over existing icing

instruments is that no calibration is required to establish its perform-
ance, aside from that needed to determine the temperature-resistance
characteristics of the wire. The sensing element is extremely simple and
durable, containing no fragile temperature-measuring devices, such as
thermocouples, or moving parts, such as ice-thickness feelers. An indi-
cation of icing severity is obtained directly from the easily measured
quantity, electrical current. Response of the instrument to changes in
water content is considerably more rapid than that of any of the existing
instruments which are usable for obtaining statistical data. A final
advantage is that it can be used for measurements of liquid-water content
in clouds which are above freezing temperature, as well as in icing
clouds. Consequently, this type of instrument may be useful in the study
of all clouds, regardless of temperature.

CONCLUSIONS

An investigation of the practicability of utilizing the temperature-
resistance characteristics of an electrically heated wire as the basis
for an instrument to measure liquid-water concentration in clouds has
resulted in the following conclusions, which apply to wires of approxi-
mately the same size as those tested:

1. A simple, durable, direct-indicating device for measuring
liquid-water content can be built using an electrically heated wire of
known temperature-resistance characteristics for the sensing element.

2. The performance characteristics of a heated wire when subjected
to various values of liquid-water concentration and airspeed are in
agreement with predicted characteristics as long as all impinging water
is evaporated, that is, provided the water concentration is less than
the value required to saturate the wire.

3. The present theory for calculating the concentration of water
required to saturate the wire is inadequate, and predicts values which
are considerably larger than the observed values at apparent saturation.
An empirical relationship has been established, however, which allows
adequate evaluation of the concentration of water required to saturate
the wire.

4. By supplying sufficient voltage, the wire temperature can be
raised to a point where the performance of the wire is predictable for
practically the entire liquid-water-content range associated with icing
conditions.

5. Response of the instrument to variations in liquid-water
content is considerably more rapid than that of existing instruments
which are usable for obtaining statistical meteorological data.

6.   The principle of. this instrument can be used for measuring liquid-water content in clouds at temperatures either above or below freezing.

Ames Aeronautical Laboratory,
     National Advisory Committee for Aeronautics,
          Moffett Field, Calif., July 30, 1951.

APPENDIX A

USE OF ABSORBENT CYLINDERS FOR MEASURING

LIQUID-WATER CONTENT

Characteristics of Absorbent Cylinders

Porous cylinders composed of an absorbent material have been used previously for the measurement of liquid-water content in clouds at temperatures above freezing (reference 15). The basic requirements for cylinders used for this purpose are that they possess the ability to absorb all impinging water (exclusive of a small amount lost through evaporation) and the ability to remain relatively undistorted when subjected to a high-velocity air stream.

Observation of the absorbent cylinders used in the present investigation revealed no noticeable distortion when inserted into the duct air stream. In order to obtain information on the absorption characteristics of the cylinders, tests were made to determine the effect of duration of exposure on the weight of water absorbed. Results of these tests, conducted for two values of liquid-water concentration, are presented in figure 16. This figure shows the absorption of the cylinders to be directly proportional to the duration of exposure up to an absorbed weight of about 0.9 gram, at which point the cylinders became saturated. The characteristic of a proportional increase in water absorbed with increase in duration of exposure indicates that all impinging water is absorbed. Because saturation of the cylinders occurred at an absorbed weight of about 0.9 gram, an attempt was made to limit the duration of exposure during the tests of the heated wires so as to maintain the absorbed weight under 0.9 gram.

Interference Effect of Absorbent Cylinders

Since, in the tests of the heated wires, the absorbent cylinders were inserted upstream with respect to the heated wires, a depletion of water concentration at the wire-loop location was anticipated. Evidence of this depletion was shown by a reduction in the wire-loop current as a cylinder was inserted into the air stream. The magnitude of the depletion of water content as indicated by the reduction in current was found to be equal to the quantity of water intercepted by the absorbent cylinder. Thus, it was apparent that complete mixing of the air and water drops had occurred upstream of the wire loops. The interference effects of the absorbent cylinders, therefore, were accounted for by applying corrections to the values of liquid-water content as indicated by the wire loops considering complete mixing.

APPENDIX B

PRECISION OF MEASUREMENTS OF LIQUID-WATER CONTENT

The precision of measurement of the liquid-water content in the cloud duct using the absorbent cylinders is a function of the precision with which each of the terms in equation (6) was determined. Likewise, the precision of the indications of liquid-water content as computed from measurements with the heated wire is a function of the precision with which each of the terms in equation (2) was established. In order to evaluate the precision of the measurements, the estimated maximum errors in the determination of water content will be considered.

Due to large variations in quantities measured with both the heated wire and absorbent cylinders, the maximum error in water content would be different for each observation. For this reason, the average of the maximum errors for the observations probably would provide a useful index of the over-all precision of the data, and accordingly these values were computed for both the heated wire and absorbent cylinders. Inasmuch as interest lies only in the values of liquid-water content where agreement should exist between measurements with the heated wire and absorbent cylinders, only data below the apparent saturation point of the heated wire were considered. Since only comparative values of the water content as obtained by the two methods are of interest, and since the water content as obtained by both methods is inversely proportional to the airspeed, errors in airspeed measurement would affect both values equally, and, hence, were neglected.

Errors in Heated-Wire Measurements

The primary source of error in determining the liquid-water content with the heated wire is in the measurement of the voltage and current. The estimated maximum error in each of these terms in the test data is as follows:

$$\Delta E \ \pm 0.02 \ \text{volt}$$
$$\Delta I \ \pm 0.5 \ \text{ampere}$$

Calculations were made of the maximum error for each observation in tables I through IV for values of water content below the apparent saturation point, using these deviations. The average of the maximum errors for the heated wire was computed to be approximately 0.06 gram per cubic meter.

Errors in Absorbent—Cylinder Measurements

The estimated maximum errors in each of the terms of equation (6), with the exception of the free—stream velocity, are as follows:

$$\Delta W_T \quad \pm 0.02 \text{ gram}$$
$$\Delta d \quad \pm 0.01 \text{ inch}$$
$$\Delta E_M \quad \pm 0.01$$
$$\Delta \tau \quad \pm 0.2 \text{ second}$$

Calculations similar to those for the heated wire, using these estimated errors, showed the average maximum error for the absorbent—cylinder observations to be approximately 0.14 gram per cubic meter.

APPENDIX C

PROPOSED APPLICATION OF HEATED-WIRE PRINCIPLE IN

AN INSTRUMENT FOR OBTAINING STATISTICAL

METEOROLOGICAL DATA IN FLIGHT

The soundness of the principle of utilizing a heated wire as the sensing element·of an instrument for the measurement of liquid-water content has been illustrated. It was suggested that in the application of the principle, the voltage to the heated wire be maintained constant so that measurement of. the current would provide a measure of the liquid-water concentration. The practicability of utilizing the heated-wire principle in an instrument which could be installed in a large number of airplanes· for the purpose of gathering sufficient water-content data for statistical analysis, then, depends primarily on the ease with which accurate voltage regulation and current measurement can be effected, and the size and weight of the required equipment. The value of liquid-water content as determined by the heated-wire method also is a function of the prevailing airspeed, altitude, and air temperature, but the technique for measuring these quantities is well established and will not be discussed further.

In order to illustrate the practicability of constructing a complete heated-wire instrument for obtaining statistical flight data, a typical application will be outlined. Information concerning the equipment required for voltage regulation and for recording the pertinent quantities will be based on knowledge of available equipment and straightforward circuit design. Three units of equipment are involved: These are (1) the power supply, (2) the recording apparatus, and (3) the control panel. It will be assumed that the heated wire has approximately the same resistance and temperature coefficient of resistance as the wire used in the tests. The current, then, would vary from about 80 to 120 amperes for a variation in water content from 0 to 2 grams per cubic meter under a normally expected range of airplane operating conditions.

Power Supply

It is proposed that current for the heated wire be taken from a 115-volt 400-cycle inverter, which is standard equipment on most aircraft. Approximately 400 watts of power would be required. A commercially available voltage regulator would be used in combination with a step-down transformer to provide constant voltage of the required amount (approximately 3.5 volts) to the wire loop. With this equipment, regulation in voltage could be maintained within ±0.2 percent. The

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regulator and transformer would occupy a space approximately 13 by 8 by 6 inches and would weigh about 16 pounds.

Recording Apparatus

Zero suppression.- Since in the measurement of water content interest lies only in the increase in current above a given datum value (approximately 80 amperes), it is desirable to balance out the datum value of current by means of a zero-suppression circuit so that deflections of the recorder are indicative only of changes in current from the datum value. A suppressed-zero circuit with good stability characteristics could be obtained utilizing the source of regulated voltage supplied to the heated wire. A maximum variation of about ±1 percent in zero-suppression current would thus result.

Current recording.- Recording of the current variation could be effected using a current recorder incorporating a commercially available galvanometer element. The accuracy of such a recorder would be approximately ±1 percent.

Size and weight.- The combined equipment for zero suppression and recording of current, airspeed, altitude, and air temperature would be approximately 10 by 8 by 6 inches in size and would weigh about 10 pounds.

Control Panel

A control panel containing the necessary switches and other equipment, including an ammeter for direct indication of water content, would be about 6 by 4 by 2 inches in size and would weigh approximately 1 pound.

Recording Accuracy of Values of
Liquid-Water Content

The over-all accuracy with which values of liquid-water content could be recorded using the arrangement outlined is a function of the accuracy of the voltage regulation, the variation in the zero-suppression current, and the accuracy of the current recorder. Variations of ±0.2 percent in voltage regulation would result in approximately ±0.2 ampere current variation. A variation of ±1 percent in zero-suppression current would cause a variation of ±0.8 ampere in the recorded current for a suppressed-current value of 80 amperes. An accuracy of the current recorder of ±1 percent would result in a

variation of ±0.4 ampere for a full-scale deflection of 40 amperes. Thus, the over-all accuracy of recording the absolute value of current would be ±1.4 amperes, which represents an accuracy in the liquid-water-content determination of approximately ±0.1 gram per cubic meter at moderate flight speeds. Thus, it appears that recording of values of liquid-water content to a reasonable degree of accuracy is possible using a heated-wire instrument, and furthermore that from the standpoint of size and weight, such an instrument would be suitable for installation in a large number of airplanes for the purpose of gathering statistical icing data.

APPENDIX D

EXAMPLE OF PROCEDURE TO BE FOLLOWED IN THE USE

OF A HEATED-WIRE LIQUID-WATER-CONTENT METER

To provide an example of the procedure to be followed in the use of a heated wire for measuring the liquid-water content of a cloud, a typical case will be illustrated with numerical values. The meter will be assumed to consist of a loop of wire of the material used in the construction of loop 1.

The length of wire will be taken as 8 inches. For the purpose of this example, the average flight conditions for operation of the heated wire are assumed to be:

True airspeed	250 mph
Pressure altitude	5,000 ft
Ambient-air temperature	0° F

Establishment of Saturation Temperature

It will be assumed that performance of the wire is to be predictable up to a selected saturation value of liquid-water content of 2 grams per cubic meter for the above operating conditions. The theoretical saturation temperature is obtained by solving equation (4) for conditions existing at the stagnation point. To evaluate the term e_{o_k} in equation (4), the value of the kinetic-air temperature at the stagnation point must first be obtained. This temperature is obtained from the following expression:

$$t_{o_k} = t_o + \frac{V^2}{2Jgc_p} \tag{8}$$

For the conditions chosen

$$t_{o_k} = 0 + \frac{367^2}{2 \times 778 \times 32.2 \times 0.24}$$

$$= 11° \text{ F}$$

and

$$e_{o_k} = 1.9 \text{ mm Hg}$$

The value of the heat-transfer coefficient, h, at the stagnation point
is computed from equation (5). Since the heat-transfer coefficient
varies only slightly with the temperature of the wire, an average
operating wire temperature of 450° F will be assumed in the evaluation
of h. Then

$$h = 0.194 \times 685^{0.49} \left(\frac{367 \times 0.0482}{0.0053}\right)^{0.5}$$

$$= 274 \text{ Btu/hr ft}^2 \, {}^\circ F$$

The value of the concentration factor, C, is obtained from the data of
reference 9, and is computed to be 0.99. (The concentration factor at
the stagnation point is designated as β_0 in reference 9.) For the
conditions chosen

$$V = 367 \text{ ft/sec}$$
$$m = 2.0 \text{ g/m}^3$$
$$p = 632 \text{ mm Hg}$$
$$c_p = 0.24 \text{ Btu/lb } {}^\circ F$$

Then

$$e_s = 1.9 + \frac{0.361 \times 367 \times 2.0 \times 0.99 \times 632 \times 0.24}{274}$$

$$= 147 \text{ mm Hg}$$

The temperature corresponding to this vapor pressure is 139° F. This
is the theoretical saturation temperature for these conditions. From
the data of figure 14, the wire temperature at the selected saturation
water content should be about 150° F above the calculated saturation
temperature at the design speed of 250 mph. Since the data of figure 14
were obtained for an air temperature of about 60° F, the difference
between 60° F and the design air temperature of 0° F should be added to
the increase in calculated saturation temperature obtained from
figure 14, as previously suggested. Thus, the wire temperature at satu-
ration should be about 350° F.

Calculation of Operating Voltage

The design operating voltage is obtained by solving equation (2)
for the term E for conditions at saturation. The current, I, in
equation (2) is determined from Ohm's Law using the appropriate value of
wire resistance. The resistance is taken from figure 3 for a length of
8 inches and a temperature of 350° F, and is found to be 0.0304 ohm.

Then

$$I = \frac{E}{R}$$

$$= \frac{E}{0.0304}$$

The value of h_{av} is computed from equation (3) as follows:

$$h_{av} = 0.211 \times 685^{0.43} \frac{(367 \times 0.0482)^{0.6}}{0.0053^{0.4}}$$

$$= 160 \text{ Btu/hr ft}^2 \text{ }^\circ F$$

As in the previous evaluation of h, an assumed average operating wire temperature of 450° F was taken.

In the calculation of the water-drop collection efficiency, E_M, 20-micron droplets will be assumed. The value of E_M, then, from reference 9 is 0.98. The term $t_{o_{K_{av}}}$ is taken, using the data of reference 16 as a basis, as

$$t_{o_{K_{av}}} = t_o + 1/2 \frac{V^2}{2Jgc_p} \tag{9}$$

and is computed to be 6° F. Substituting the above values in equation (2), inserting the appropriate constants, and solving for E results in

$$E = \sqrt{\frac{0.0304}{3.41} \left[2.0 \times 0.225 \times 367 \times 0.00353 \times 0.98(1217+32-0) + 160 \times 0.0111(350-6) \right]}$$

$$= 3.43 \text{ volts}$$

Thus, if the voltage at the wire terminals is maintained constant at 3.43 volts, the heated wire will be capable of evaporating all impinging water in a cloud containing 2 grams per cubic meter in flight at 250 mph, 5,000 feet, and 0° F air temperature.

In calculating the operating voltage for a heated-wire instrument, it is suggested that conditions be selected to give the highest value of voltage to prevent saturation of the wire at other than design conditions. Those conditions requiring a high voltage are high airspeed, low altitude, low air temperature, and high water concentration.

Calculation of Liquid—Water—Content
from Current.Measurement

Assume that the heated wire is being used for measurement of the
liquid—water content under the following conditions of flight:

True airspeed   230 mph
Pressure altitude   10,000 ft
Ambient—air temperature $10°$ F

Upon entering a cloud, assume the current in the wire, which is main-
tained at a constant potential of 3.43 volts, is 90 amperes. Using the
current measurement and the voltage, the wire resistance is determined
from Ohm's Law and is computed to be 0.0381 ohm. Thus, $t_s = 565°$ F
from figure 3. The value of h_{av} for the above conditions is obtained
using equation (3), and is calculated to be 133 Btu per hour, square
foot, $°$F. The average kinetic-air temperature, $t_{Ok_{av}}$, is computed from
equation (9), and, for the conditions specified, is found to be $14°$ F.
Substituting these values into equation (2) gives

$$m = \frac{3.41 \times 3.43 \times 90 - 133 \times 0.0111(565 - 14)}{0.225 \times 337 \times 0.00353 \times 0.98(1319 + 32 - 10)}$$

$$= 0.68 \ g/m^3$$

It should be noted that in the use of the equations for computing
the performance of a heated wire, the velocity represented by the term
V is the free—stream velocity in the region of the wire. Therefore, if
the wire is mounted on the wing or fuselage of an airplane, where the
velocity is somewhat higher than the airplane forward speed, the veloc-
ity in this region must be known. For this reason, it may be desirable
to determine the average heat—transfer coefficient, h_{av}, for various
operating conditions from measurements during flight in clear air after
installation of the heated—wire instrument.

In locating a heated—wire loop on an airplane, attention should be
given to placing it in a region of uniform flow where a representative
sample of the cloud will pass over the wire. For example, if the loop
is to be installed on the fuselage, it should be mounted outside the
boundary layer and consideration should be given to the water—drop-
deflecting action of the large fuselage.

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TABLE I.— RESULTS OF MEASUREMENTS MADE WITH HEATED-WIRE LOOP 1 AND ABSORBENT CYLINDERS IN CLOUD DUCT FOR TEST CONDITION 1

Water flow rate from spray gun (lb/min)	Absorbent cylinder diameter (in.)	Duration of exposure of absorbent cylinder (sec)	Weight of water absorbed by cylinder (grams)	Weight of water evaporated from cylinder (grams)	Air velocity (mph)	Air density (lb/cu ft)	Surrounding air temperature (°F)	Wire-loop current (amps)	Wire-loop voltage (volts)
0	—	—	—	—	262	0.0708	73	77.8	2.93
.08	0.245	20.9	0.19	0.04	262	.0708	73	80.6	2.92
.11	.250	20.7	.35	.05	263	.0706	74	83.4	2.91
.16	.240	15.8	.47	.04	263	.0705	75	85.0	2.93
.19	.245	15.9	.51	.04	264	.0700	79	86.4	2.93
0	—	—	—	—	266	.0693	84	77.4	2.93
.22	.240	16.0	.60	.05	265	.0693	84	87.0	2.94
.24	.235	10.8	.43	.03	264	.0693	84	88.8	2.95
.25	.240	10.8	.59	.04	266	.0693	84	92.0	2.94
.30	.235	10.8	.70	.03	266	.0692	85	94.6	2.94
.34	.245	6.3	.55	.01	264	.0693	84	95.6	2.94
.42	.245	5.8	.70	.02	266	.0692	85	102.2	2.95
.34	.245	7.8	.67	.02	266	.0693	84	95.8	2.93
.29	.240	7.8	.60	.01	266	.0692	85	95.2	2.91
.25	.240	7.9	.42	.02	265	.0692	85	92.2	2.93
0	—	—	—	—	264	.0724	61	78.5	2.93
.39	.240	6.7	.59	.01	264	.0724	60	99.8	2.93
.48	.240	6.6	.68	.01	263	.0723	61	102.2	2.95
.49	.250	6.2	.54	.01	265	.0722	61	101.8	2.98
0	—	—	—	—	263	.0721	62	78.1	2.93
.54	.235	5.6	.60	.01	264	.0721	62	102.4	2.98
0	—	—	—	—	264	.0718	66	77.8	2.93
.45	.240	6.6	.62	.01	264	.0716	66	99.8	2.98
0	—	—	—	—	267	.0723	60	77.5	2.93
1.18	.235	5.5	.87	.01	267	.0723	60	110.6	2.95
0	—	—	—	—	266	.0723	60	77.8	2.93
1.18	.245	5.8	.89	.01	266	.0723	60	109.2	2.93
0	—	—	—	—	261	.0730	56	78.4	2.93
.71	.250	6.8	.80	.01	261	.0730	56	105.3	2.98

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TABLE II.- RESULTS OF MEASUREMENTS MADE WITH HEATED-WIRE LOOP 1 AND ABSORBENT
CYLINDERS IN CLOUD DUCT FOR TEST CONDITION 2

Water flow rate from spray gun (lb/min)	Absorbent cylinder diameter (in.)	Duration of exposure of absorbent cylinder (sec)	Weight of water absorbed by cylinder (grams)	Weight of water evaporated from cylinder (grams)	Air velocity (mph)	Air density (lb/cu ft)	Surrounding air temperature (°F)	Wire-loop current (amps)	Wire-loop voltage (volts)
0	---	---	---	---	196	0.0735	65	74.0	2.93
.21	0.235	15.7	0.50	0.01	196	.0735	65	83.0	2.94
.24	.240	15.8	.72	.01	196	.0735	65	85.6	2.95
.30	.240	10.9	.71	.01	198	.0734	65	90.4	2.96
.29	.245	10.7	.69	.01	197	.0735	65	89.8	2.95
.26	.255	15.9	.88	.01	196	.0735	65	88.0	2.95
.34	.245	8.8	.75	.01	197	.0735	65	92.2	2.95
.30	.250	8.7	.57	.01	198	.0734	65	91.0	2.95
.11	.235	20.6	.25	.03	198	.0733	66	78.0	2.93
0	---	---	---	---	312	.0702	62	80.1	2.93
.31	.245	10.4	.75	.02	312	.0702	62	97.0	2.95
.36	.240	8.3	.65	.01	313	.0702	62	100.0	2.94
0	---	---	---	---	313	.0702	62	80.2	2.93
.44	.245	8.5	.80	.01	313	.0702	62	103.8	2.94
0	---	---	---	---	312	.0702	62	80.3	2.93
.53	.240	6.8	.69	.01	313	.0702	62	104.6	2.94
.62	.235	6.6	.80	.01	315	.0699	63	106.5	2.89
.20	.245	15.6	.68	.02	317	.0702	62	90.4	2.95

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TABLE III.— RESULTS OF MEASUREMENTS MADE WITH HEATED-WIRE LOOP 1 AND ABSORBENT CYLINDERS IN CLOUD DUCT FOR TEST CONDITION 3

Water flow rate from spray gun (lb/min)	Absorbent cylinder diameter (in.)	Duration of exposure of absorbent cylinder (sec)	Weight of water absorbed by cylinder (grams)	Weight of water evaporated from cylinder (grams)	Air velocity (mph)	Air density (lb/cu ft)	Surrounding air temperature (°F)	Wire-loop current (amps)	Wire-loop voltage (volts)
0	---	---	---	---	151	0.0746	65	67.2	2.55
.06	0.235	30.6	0.10	0.03	151	.0746	65	69.8	2.55
.08	.245	30.8	.25	.03	151	.0746	65	71.0	2.55
.12	.250	30.6	.41	.03	151	.0746	65	72.9	2.55
.13	.235	30.7	.62	.04	152	.0746	65	74.7	2.55
.19	.250	20.3	.56	.03	152	.0746	65	75.8	2.55
.24	.255	20.7	.77	.03	152	.0746	65	77.8	2.55
.26	.235	15.5	.56	.02	152	.0745	65	79.6	2.55
.30	.240	10.5	.72	.01	152	.0745	66	80.8	2.55
.33	.245	10.4	.68	.02	152	.0744	66	82.4	2.55
.29	.240	10.5	.72	.01	152	.0744	66	81.7	2.55
.35	.240	10.2	.70	.01	151	.0744	66	83.1	2.55
0	---	---	---	---	151	.0744	66	67.6	2.55
.21	.245	20.3	.70	.02	151	.0746	65	77.6	2.55
0	---	---	---	---	151	.0746	65	66.6	2.55
.23	.240	15.3	.72	.01	152	.0745	65	78.2	2.54
.23	.235	15.2	.69	.01	152	.0744	66	78.2	2.57
.32	.250	10.3	.75	.01	151	.0744	66	83.4	2.55
0	---	---	---	---	145	.0801	59	66.4	2.55
.11	.235	30.0	.44	.03	145	.0801	59	72.6	2.55
.30	.240	10.8	.61	.01	146	.0803	58	82.0	2.57
0	---	---	---	---	366	.0687	59	85.3	3.28
.11	.245	20.7	.27	.03	360	.0684	61	89.6	3.28
.12	.235	20.3	.50	.03	360	.0690	59	91.2	3.28
.21	.245	15.8	.58	.03	360	.0691	58	96.6	3.31
0	---	---	---	---	360	.0690	59	85.7	3.28
.25	.240	10.9	.50	.02	366	.0690	59	99.0	3.33
.39	.235	10.3	.76	.03	364	.0687	59	105.7	3.28
.39	.240	10.5	.80	.04	366	.0688	58	106.1	3.34
.44	.250	8.4	.80	.03	365	.0687	58	108.0	3.28
.62	.245	6.7	.82	.02	365	.0688	60	114.7	3.28
0	---	---	---	---	360	.0688	58	85.5	3.28
.81	.240	5.5	.74	.02	358	.0688	60	117.6	3.35
0	---	---	---	---	358	.0683	60	85.1	3.28
1.19	.240	4.2	.83	.01	358	.0683	60	121.6	3.28
.59	.240	5.5	.63	.01	358	.0685	58	114.8	3.28
.69	.240	5.4	.72	.01	358	.0685	58	117.2	3.28
0	---	---	---	---	358	.0687	58	85.3	3.28
.73	.245	5.8	.84	.01	358	.0687	58	116.0	3.28
1.19	.250	4.8	.87	.02	358	.0687	58	119.8	3.28

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TABLE IV.— RESULTS OF MEASUREMENTS MADE WITH HEATED-WIRE LOOP 1 AND ABSORBENT CYLINDERS IN CLOUD DUCT FOR TEST CONDITION 4

Water flow rate from spray gun (lb/min)	Absorbent cylinder diameter (in.)	Duration of exposure of absorbent cylinder (sec)	Weight of water absorbed by cylinder (grams)	Weight of water evaporated from cylinder (grams)	Air velocity (mph)	Air density (lb/cu ft)	Surrounding air temperature (°F)	Wire-loop current (amps)	Wire-loop voltage (volts)
0	—	—	—	—	151	0.0746	65	73.2	3.08
.20	0.240	25.8	0.85	0.03	152	.0746	65	80.0	3.08
.25	.245	15.6	.75	.02	151	.0747	64	83.5	3.08
.29	.255	10.7	.67	.01	151	.0747	64	86.6	3.09
.33	.240	8.6	.63	.01	151	.0747	65	89.4	3.08
0	—	—	—	—	146	.0801	60	72.8	3.08
.11	.235	30.4	.50	.03	145	.0801	60	76.2	3.08
0	—	—	—	—	262	.0729	54	84.4	3.58
.74	.240	5.0	.77	0	261	.0728	58	117.0	3.63
1.18	.235	3.5	.57	0	262	.0727	58	123.0	3.59
0	—	—	—	—	264	.0714	67	84.7	3.58
.38	.245	5.5	.52	0	264	.0714	67	101.8	3.58
.39	.245	5.7	.48	.01	264	.0715	67	103.0	3.58
0	—	—	—	—	261	.0717	66	84.9	3.58
.45	.235	5.4	.54	0	261	.0717	66	103.6	3.58
.49	.235	5.4	.50	.01	264	.0716	66	103.8	3.58
0	—	—	—	—	267	.0722	60	84.4	3.58
1.18	.245	5.0	.87	.01	267	.0722	60	121.6	3.64
.52	.245	4.7	.58	.01	265	.0723	60	109.6	3.58

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TABLE V.- RESULTS OF MEASUREMENTS MADE WITH HEATED-WIRE LOOP
AND ROTATING DISK IN LEWIS LABORATORY
ICING RESEARCH TUNNEL

Icing rate (in./min)	Air velocity (mph)	Air density (lb/cu ft)	Air temperature (°F)	Wire-loop current (amps)
0	202	0.0759	22	80.4
.0334	202	.0759	22	82.4
.0608	201	.0757	23	84.0
.0922	201	.0759	22	85.6
.1158	201	.0761	21	87.6
0	202	.0756	20	80.8
.0393	202	.0756	20	83.6
.0648	201	.0758	19	84.8
.0903	201	.0758	19	86.4
.1257	201	.0758	18	88.8
.1512	201	.0759	20	90.0
0	198	.0790	5	82.0
.0440	198	.0790	5	85.2
.0557	199	.0786	5	86.0
.0919	198	.0790	5	88.4
.1080	198	.0790	5	89.2
.1130	198	.0790	5	90.0
0	274	.0765	-4	87.6
.0244	274	.0762	-2	88.4
.0392	280	.0756	2	89.6
0	311	.0745	-2	89.2
.0228	302.5	.0767	1	90.0
.0360	308	.0741	0	90.8

NOTE: Wire-loop voltage maintained constant at
2.97 volts. Mean-effective drop diameter, 15 to 18
microns; drop-size distribution, type C (reference 9).

TABLE VI.-COMPARISON OF CALCULATED AND APPARENT SATURATION TEMPERATURES
FOR HEATED-WIRE LOOP 1 UNDER VARIOUS TEST CONDITIONS

True Airspeed (mph)	Apparent saturation liquid-water content (g/cu m)	Calculated saturation temperature at apparent saturation (^{o}F)	Measured wire temperature at apparent saturation (^{o}F)	Difference between apparent and calculated saturation temperatures (^{o}F)	Data figure number
150	1.1	118	369	251	10a
200	1.7	137	348	211	9a
265	1.6	142	289	147	8
315	1.6	145	242	97	9b
365	1.8	151	244	93	10b
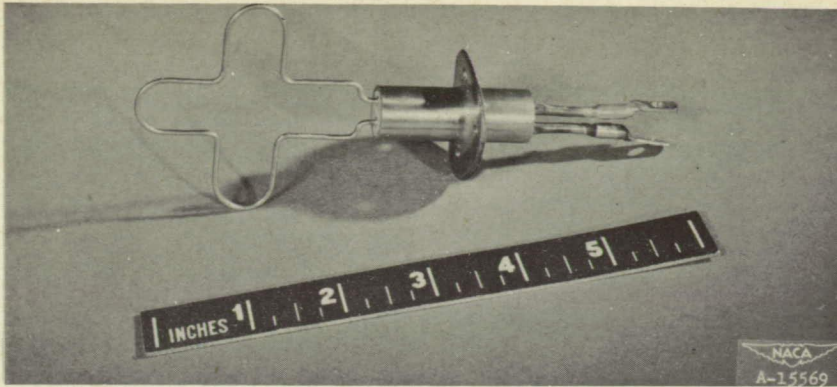
(a) Loop 1; wire diameter, 0.0635 inches.
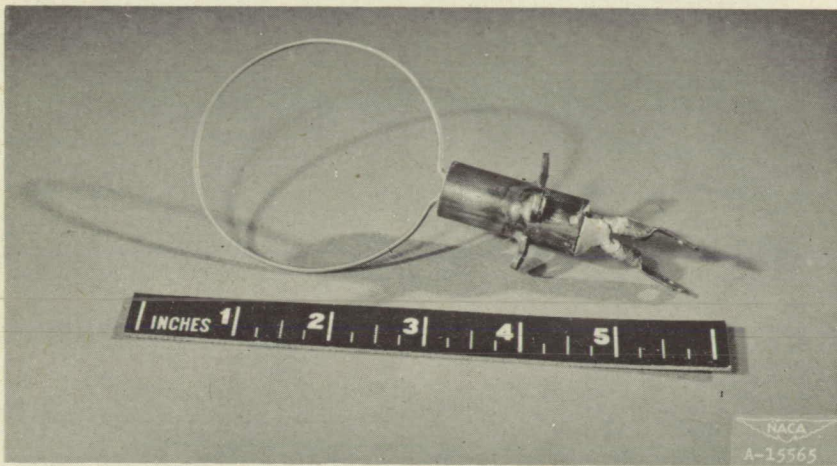
(b) Loop 2; wire diameter. 0.0635 inches.
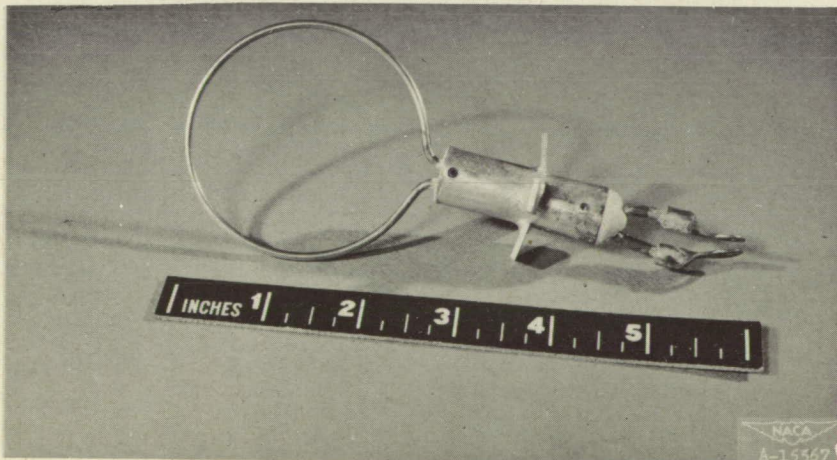
(c) Loop 3; wire diameter, 0.093 inches.

Figure 1.— Wire loops tested.
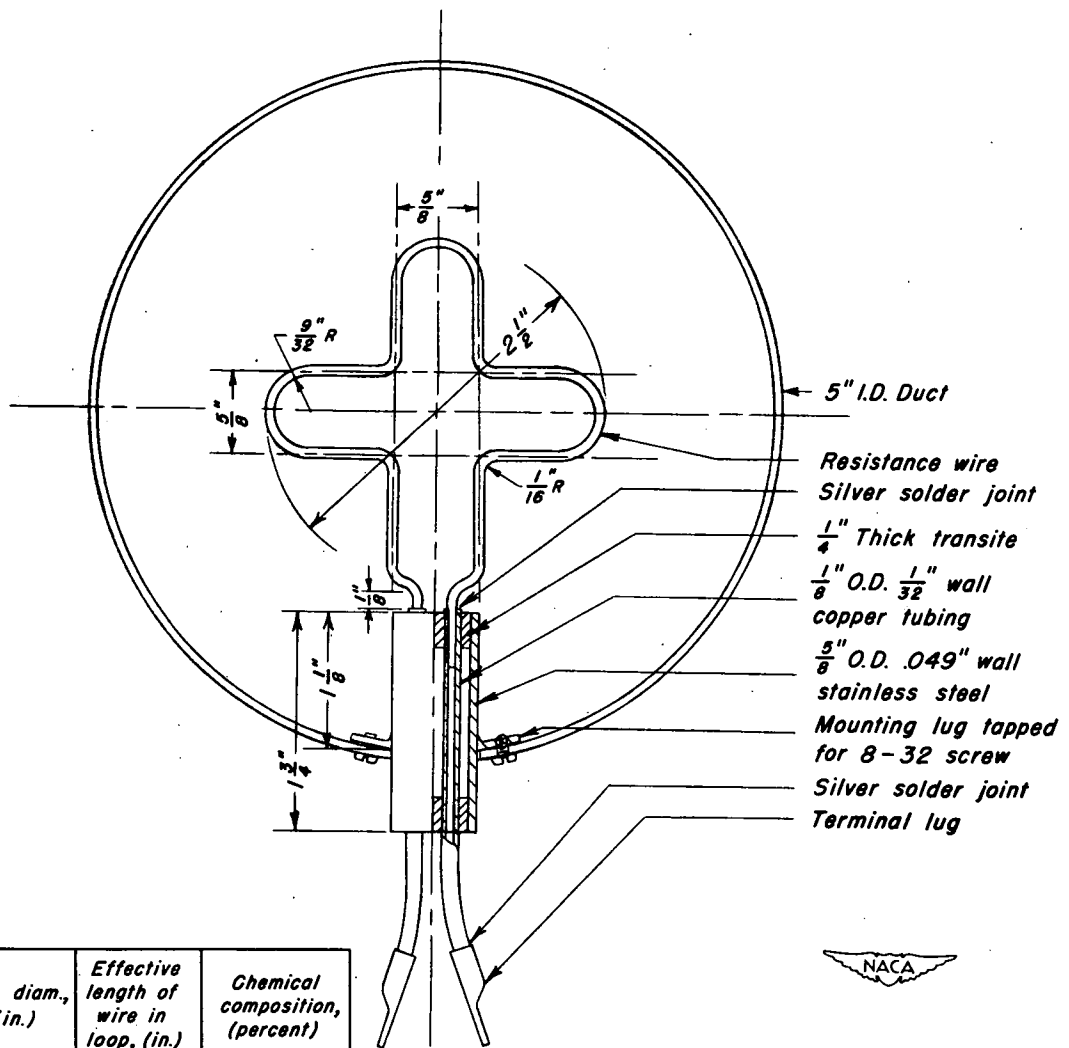
Wire diam., (in.)	Effective length of wire in loop, (in.)	Chemical composition, (percent)	
0.0635	8.59	Ni	95
		Mn	4
		Si	1

5" I.D. Duct

Resistance wire
Silver solder joint
$\frac{1}{4}$" Thick transite
$\frac{1}{8}$" O.D. $\frac{1}{32}$" wall copper tubing
$\frac{5}{8}$" O.D. .049" wall stainless steel
Mounting lug tapped for 8-32 screw
Silver solder joint
Terminal lug

Figure 2.- Dimensions, mounting details, and other data for wire loop 1.
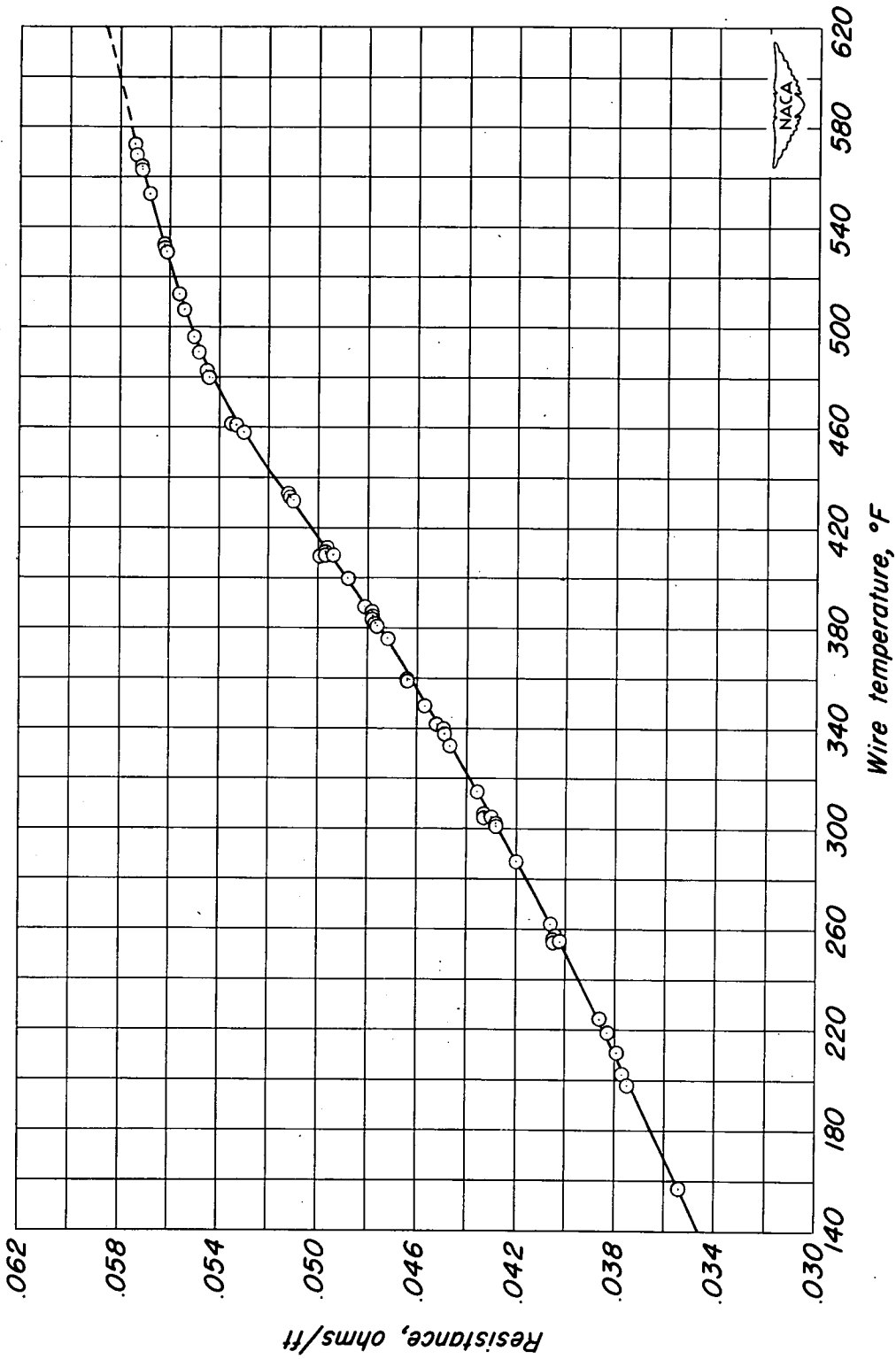
Figure 3.- Temperature - resistance characteristics of wire of loop I. Length of wire calibrated, 32 feet.
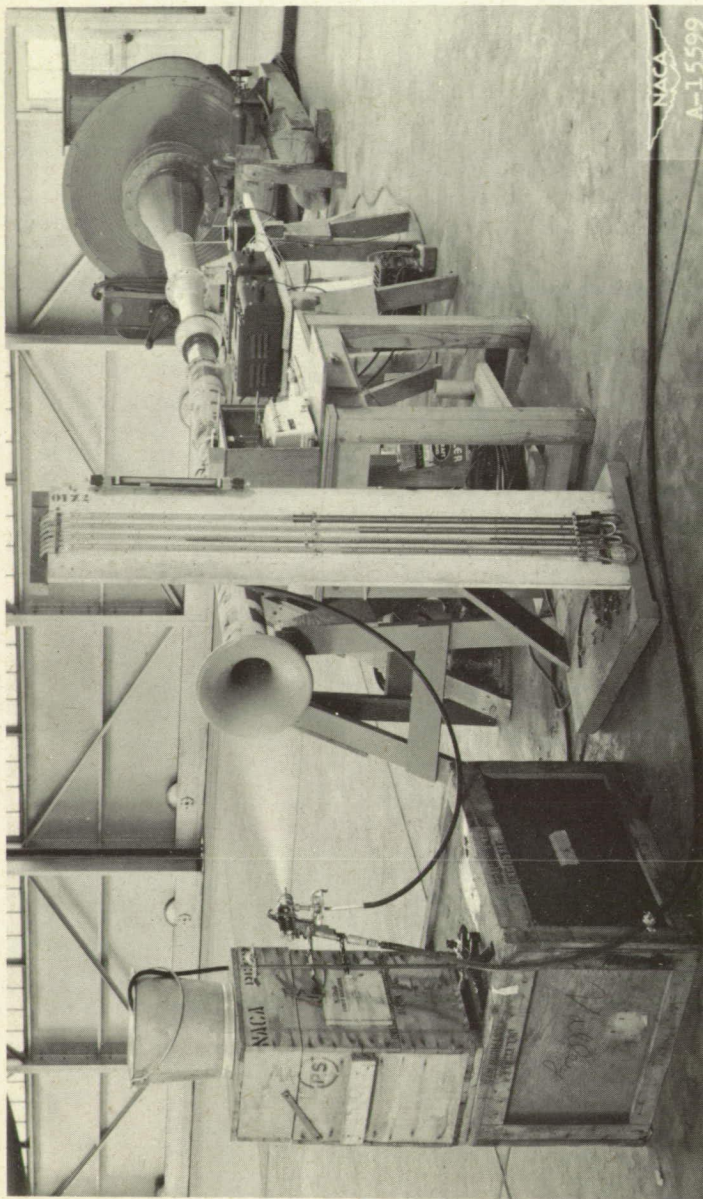
Figure 4.- General view of cloud duct showing blower and water-spray setup used in tests of heated wires.
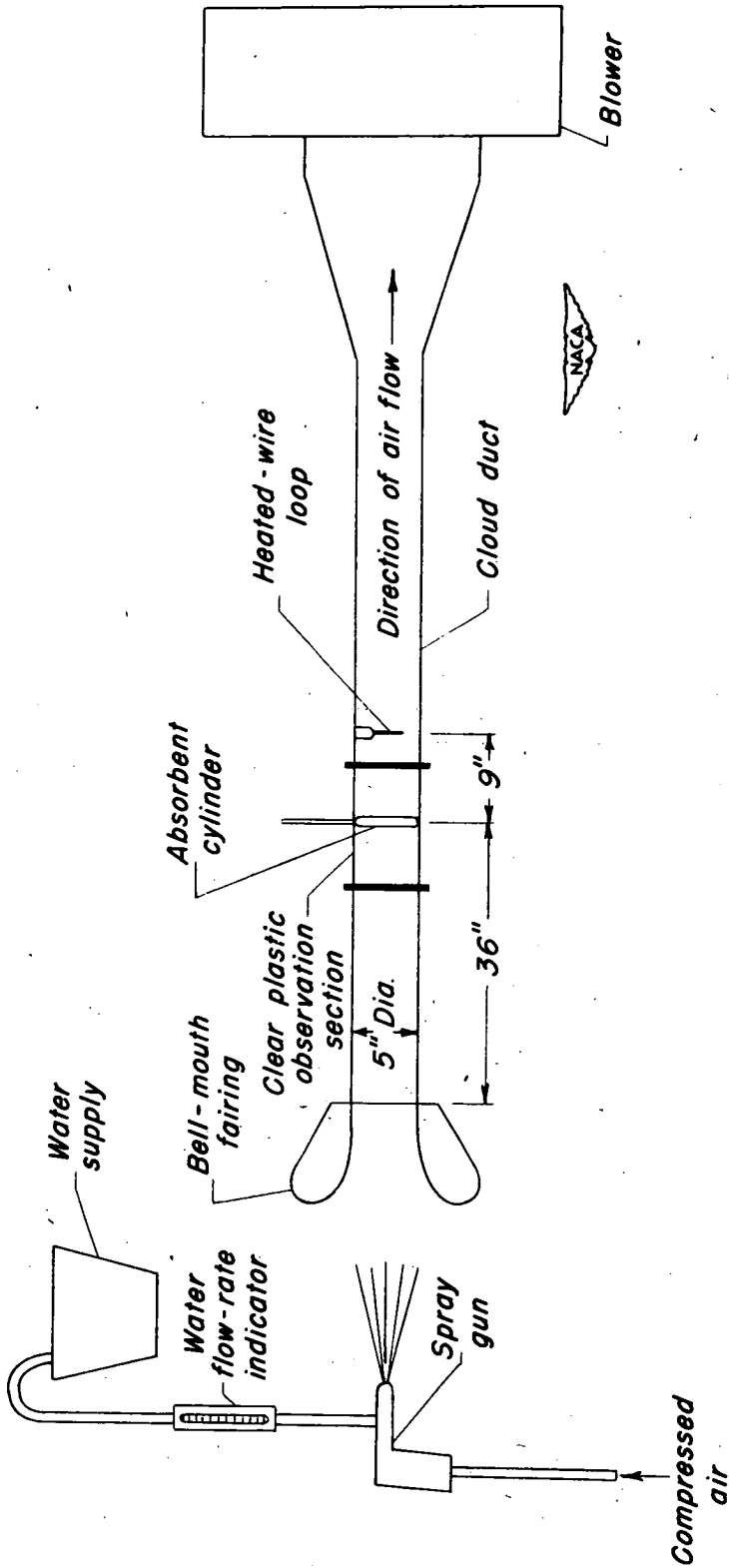
Figure 5.- Schematic diagram of cloud duct and water-spray equipment.

(a) True airspeed, 150 mph.

(b) True airspeed, 265 mph.
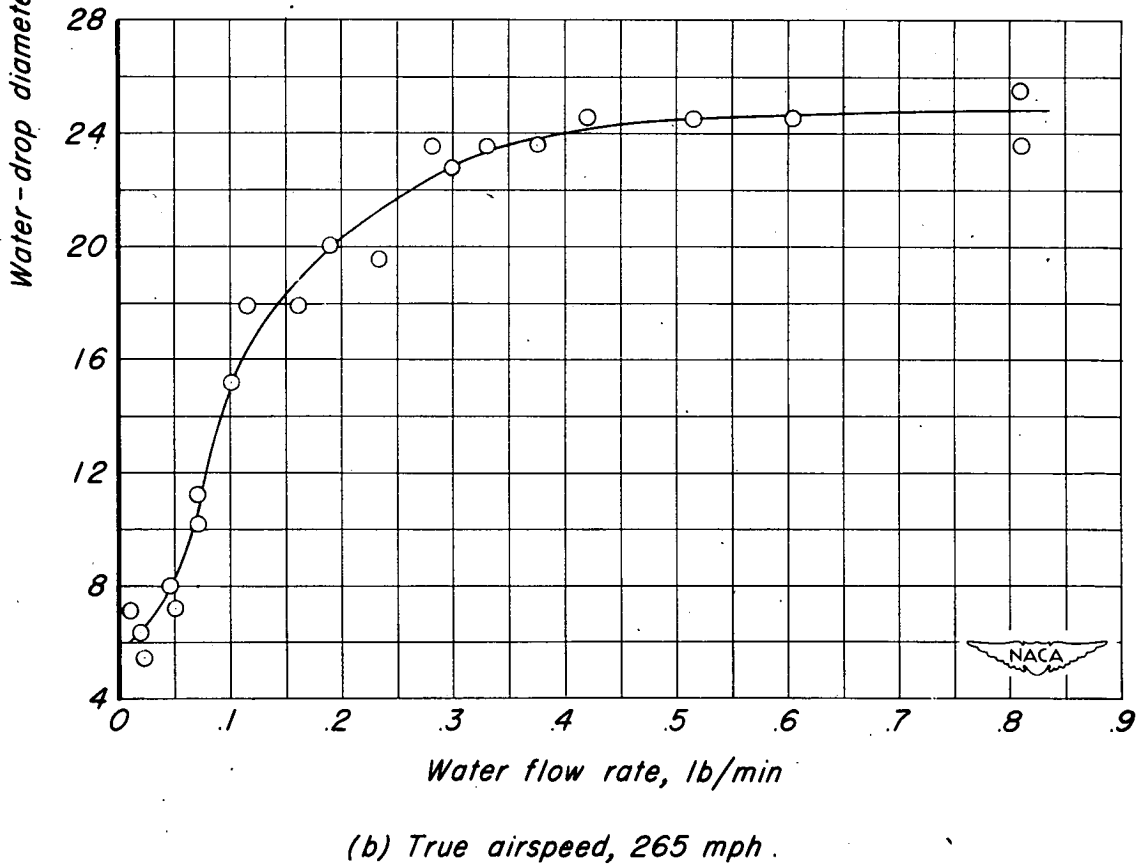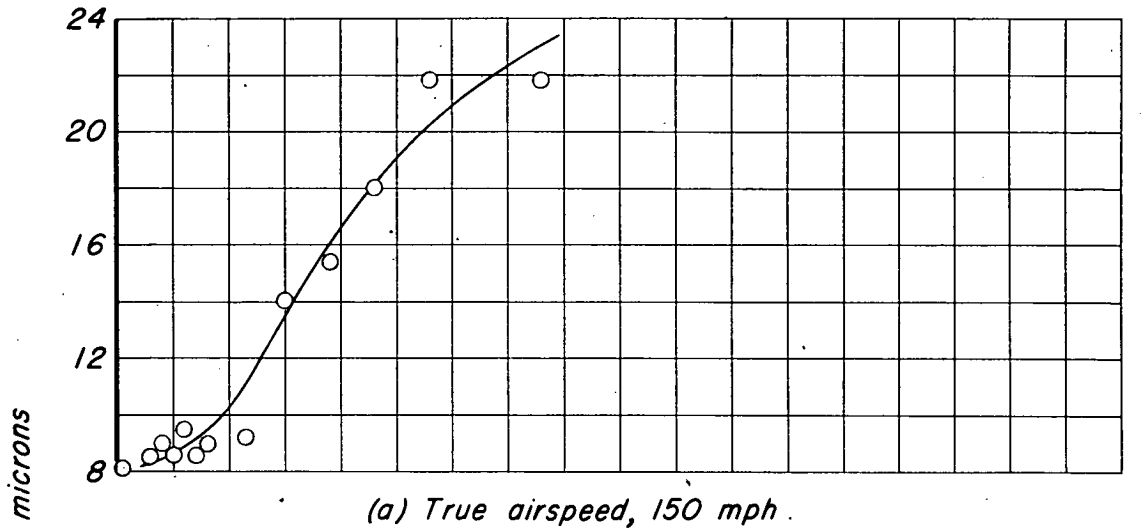
Figure 6.– Results of measurements of water-drop size as a function of
water flow rate in the cloud duct.
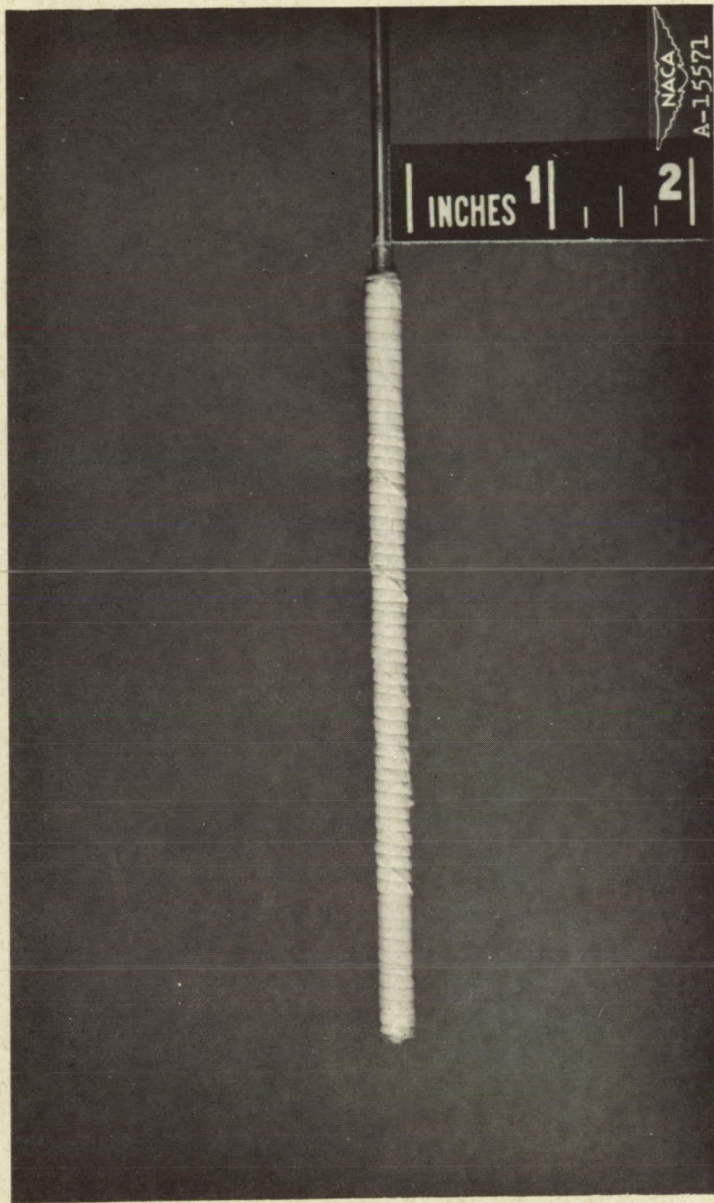
Figure 7.— Absorbent cylinder used in the measurement of liquid-water content in the cloud duct.
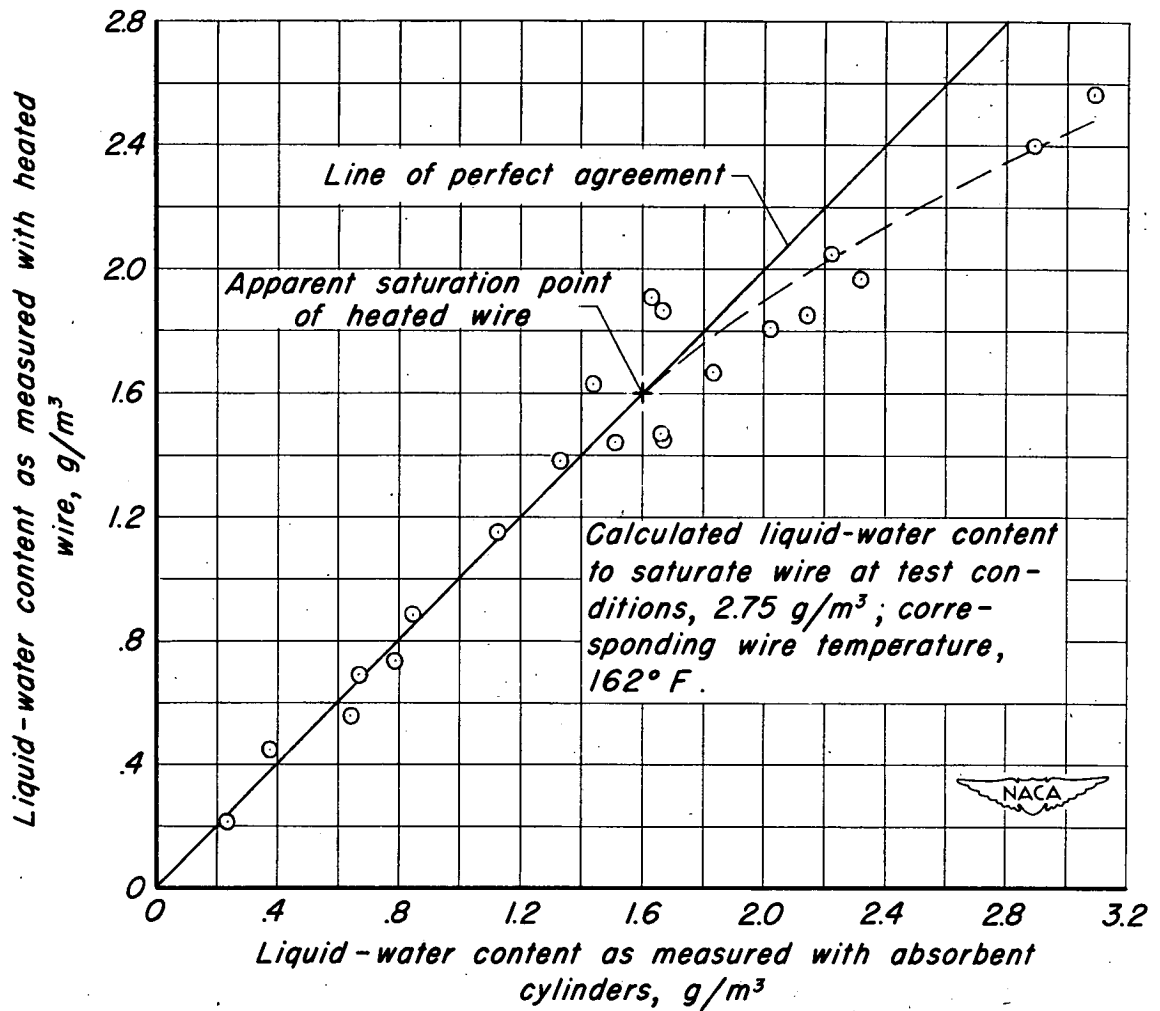
Figure 8.- Performance of heated-wire loop I at 265 miles per hour true airspeed. Wire-loop voltage, 2.94 volts. Clear-air wire temperature, 460° Fahrenheit. (Test condition I).

Apparent saturation point of heated wire

Line of perfect agreement

Calculated liquid-water content to saturate wire at test conditions, 3.76 g/m³; corresponding wire temperature, 167° F.
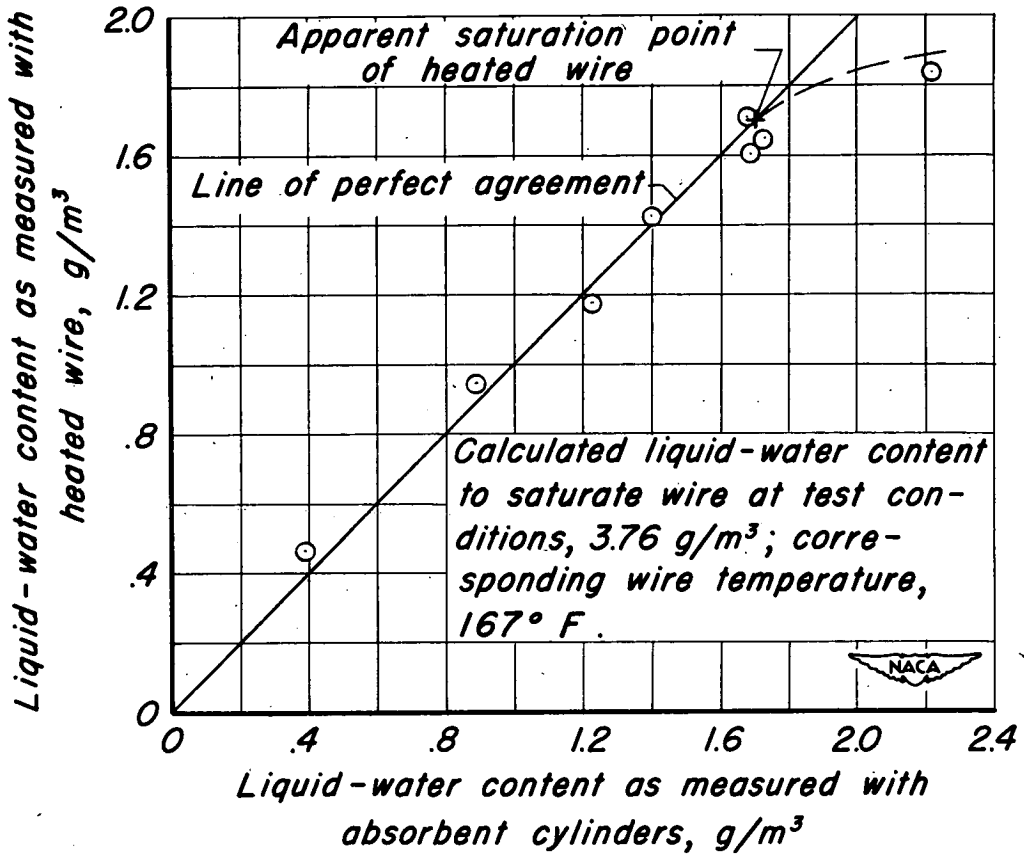
(a) True airspeed, 200 miles per hour. Wire-loop voltage, 2.94 volts. Clear-air wire temperature, 500° Fahrenheit.

Figure 9.—Comparison of the performance of heated-wire loop I for a variation in airspeed while maintaining constant voltage. (Test condition 2).
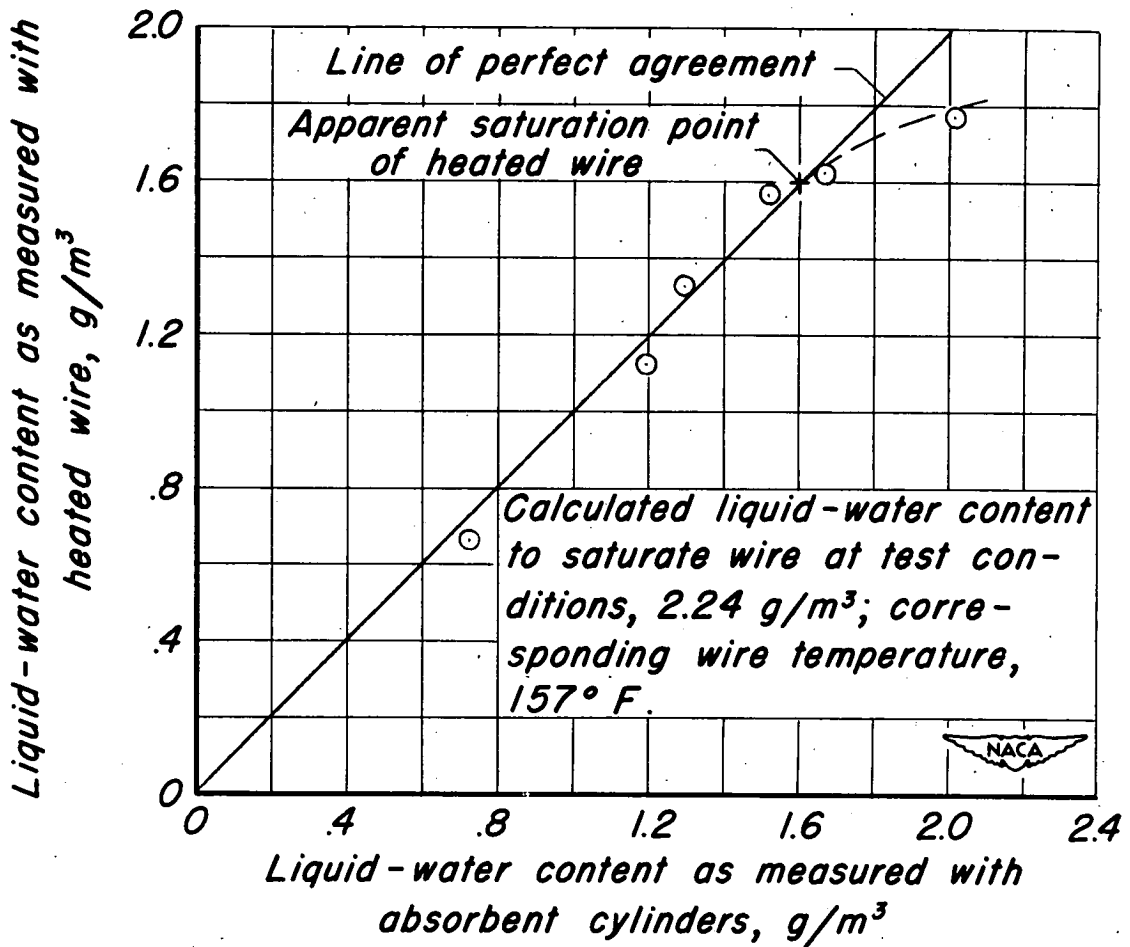
(b) True airspeed, 315 miles per hour. Wire-loop voltage, 2.94 volts. Clear-air wire temperature, 430° Fahrenheit.

Figure 9.- Concluded.
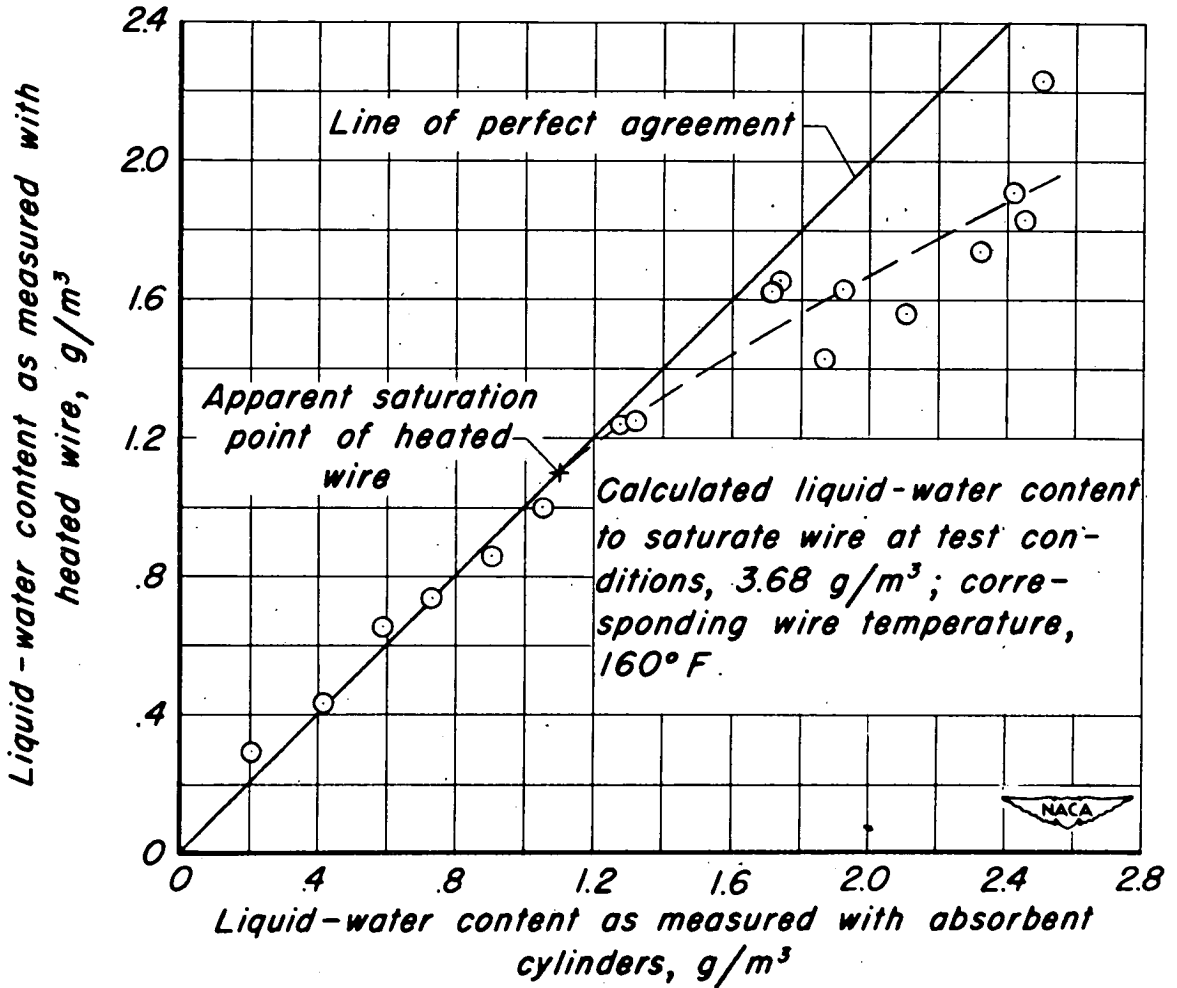
(a) True airspeed, 150 miles per hour. Wire-loop voltage, 2.55 volts.

Figure 10.— Comparison of the performance of heated-wire loop 1 for a variation in airspeed while maintaining the clear-air operating temperature constant. Clear-air wire temperature 460° Fahrenheit. (Test condition 3).
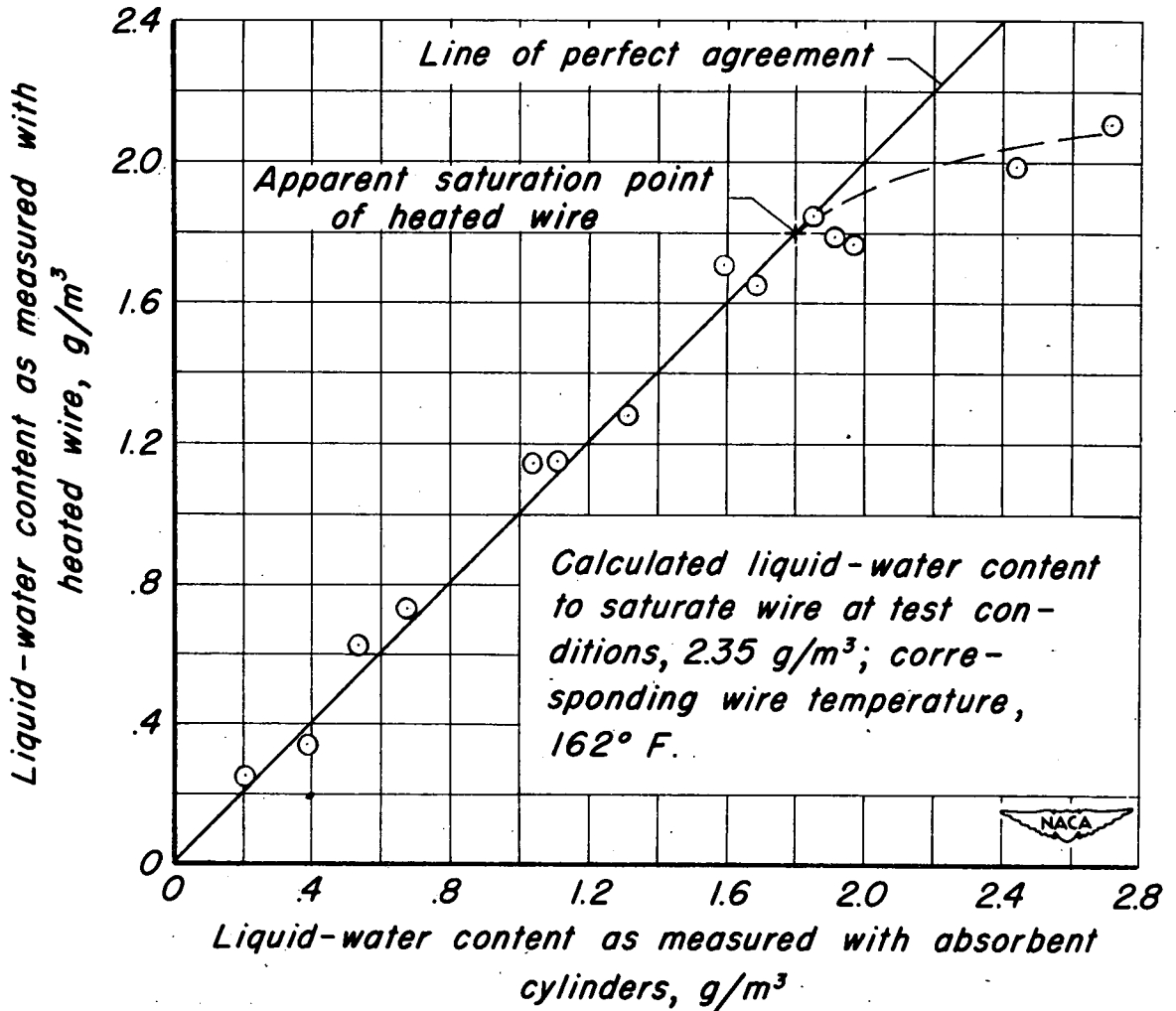
(b) True airspeed, 365 miles per hour. Wire-loop voltage, 3.28 volts.

Figure 10. – Concluded.
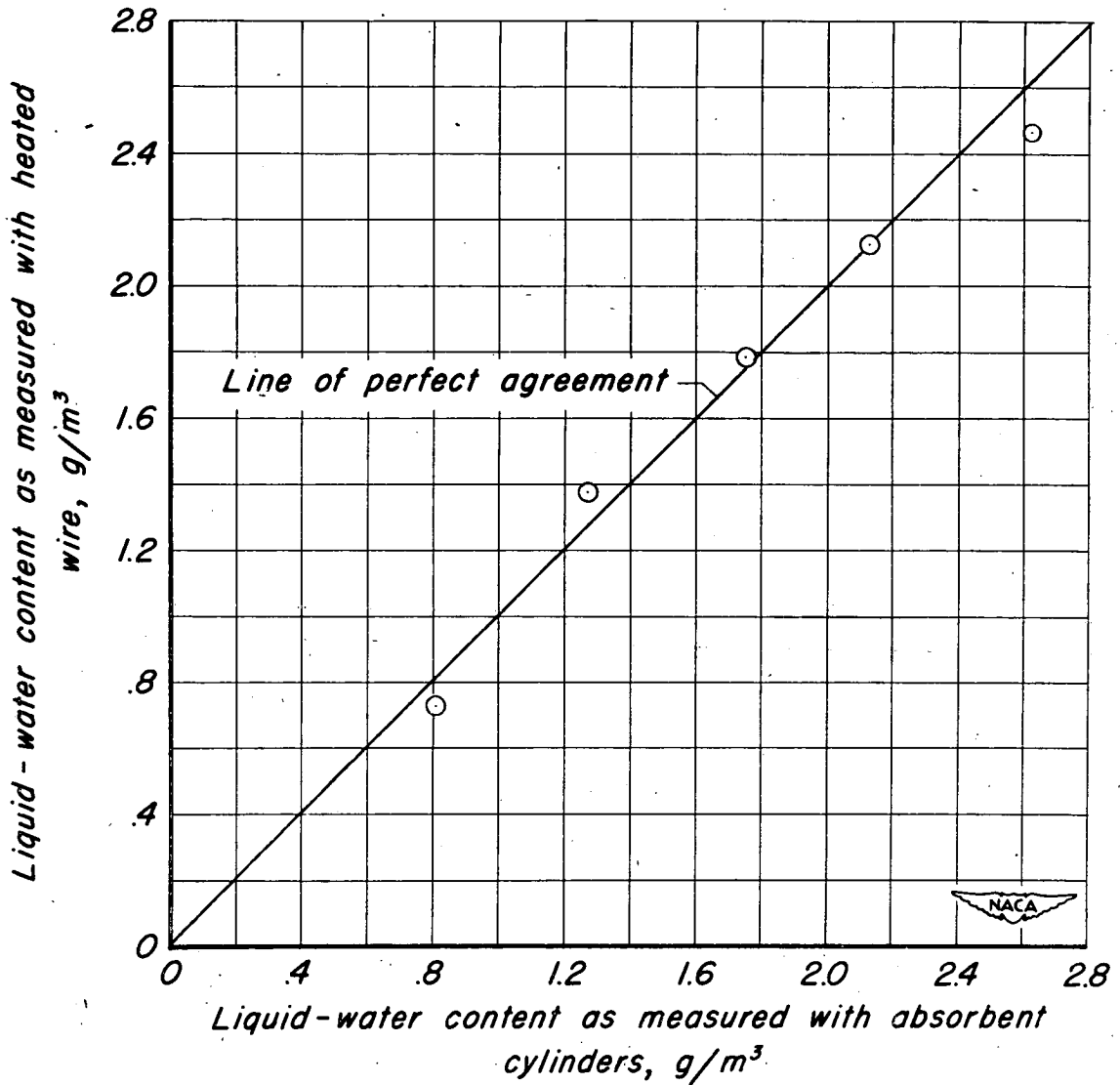
(a) True airspeed, 150 miles per hour. Wire-loop voltage, 3.08 volts.

Figure 11.- Results of tests of the performance of heated-wire loop 1 while operating at increased temperature for two airspeeds. Clear-air wire temperature, 600° Fahrenheit. (Test condition 4).
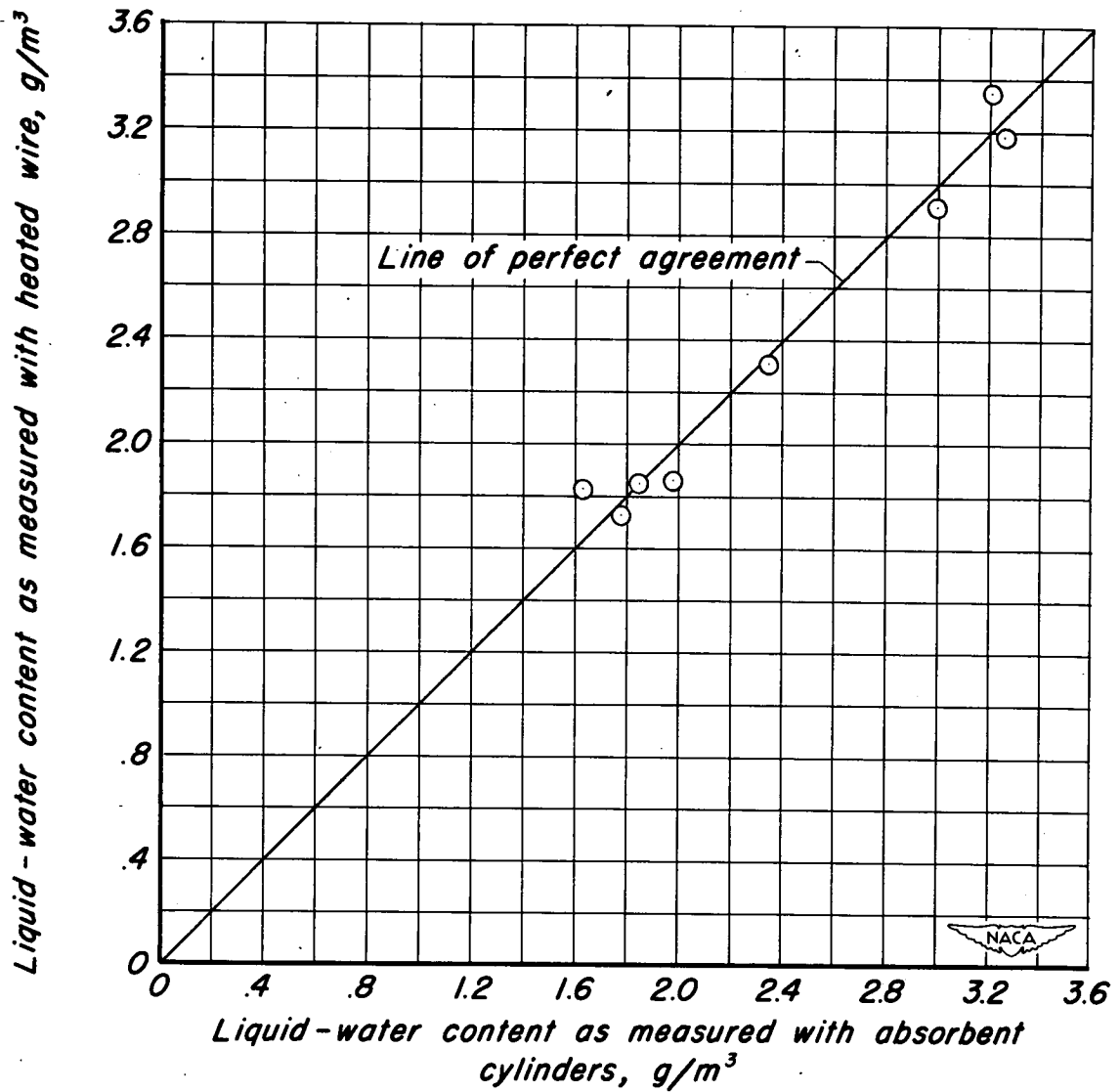
(b) True airspeed, 265 miles per hour. Wire-loop voltage, 3.58 volts.

Figure 11.- Concluded.
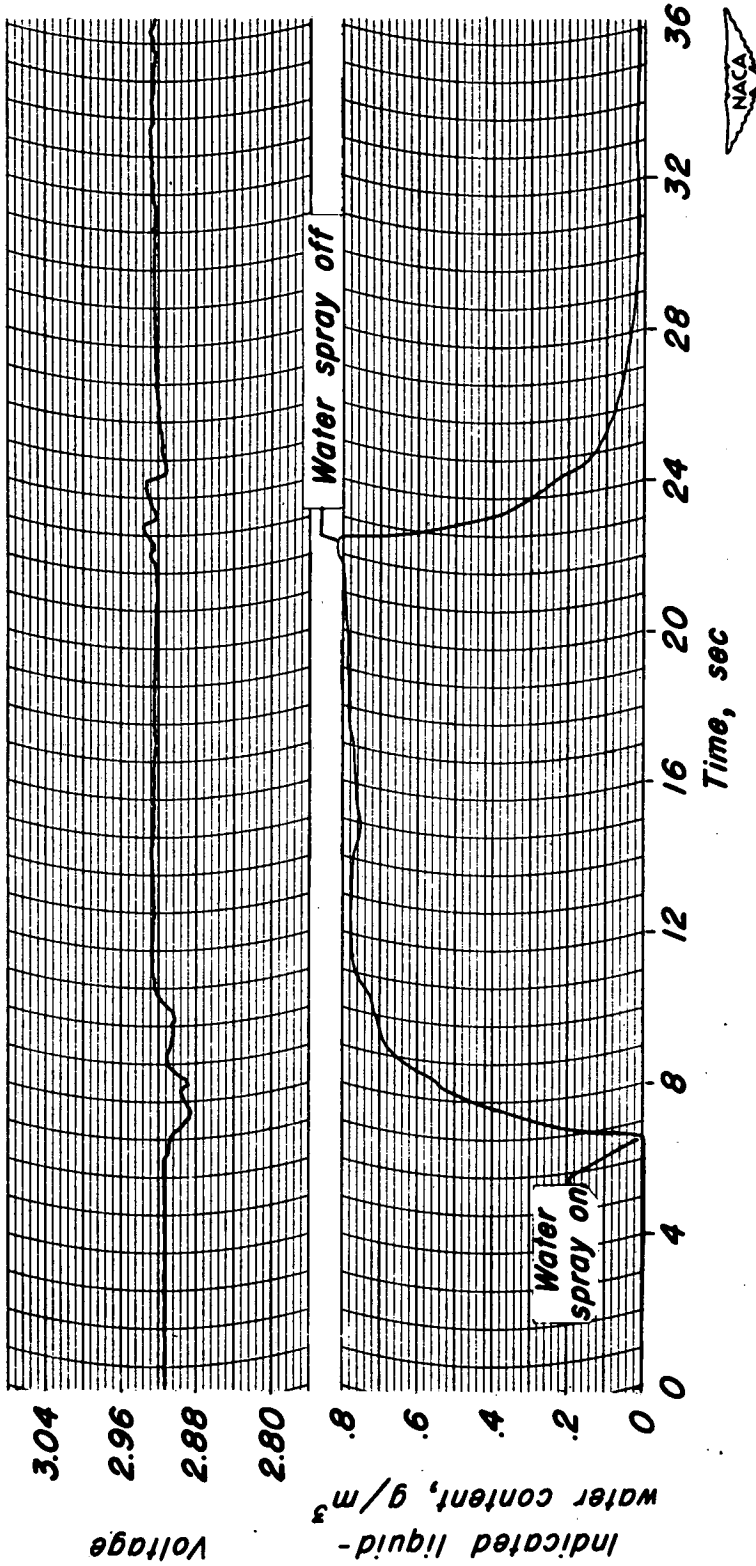
Figure 12.- Oscillograph record showing rate of response of heated-wire loop I when subjected to sudden changes in liquid-water content. True airspeed, 265 miles per hour.
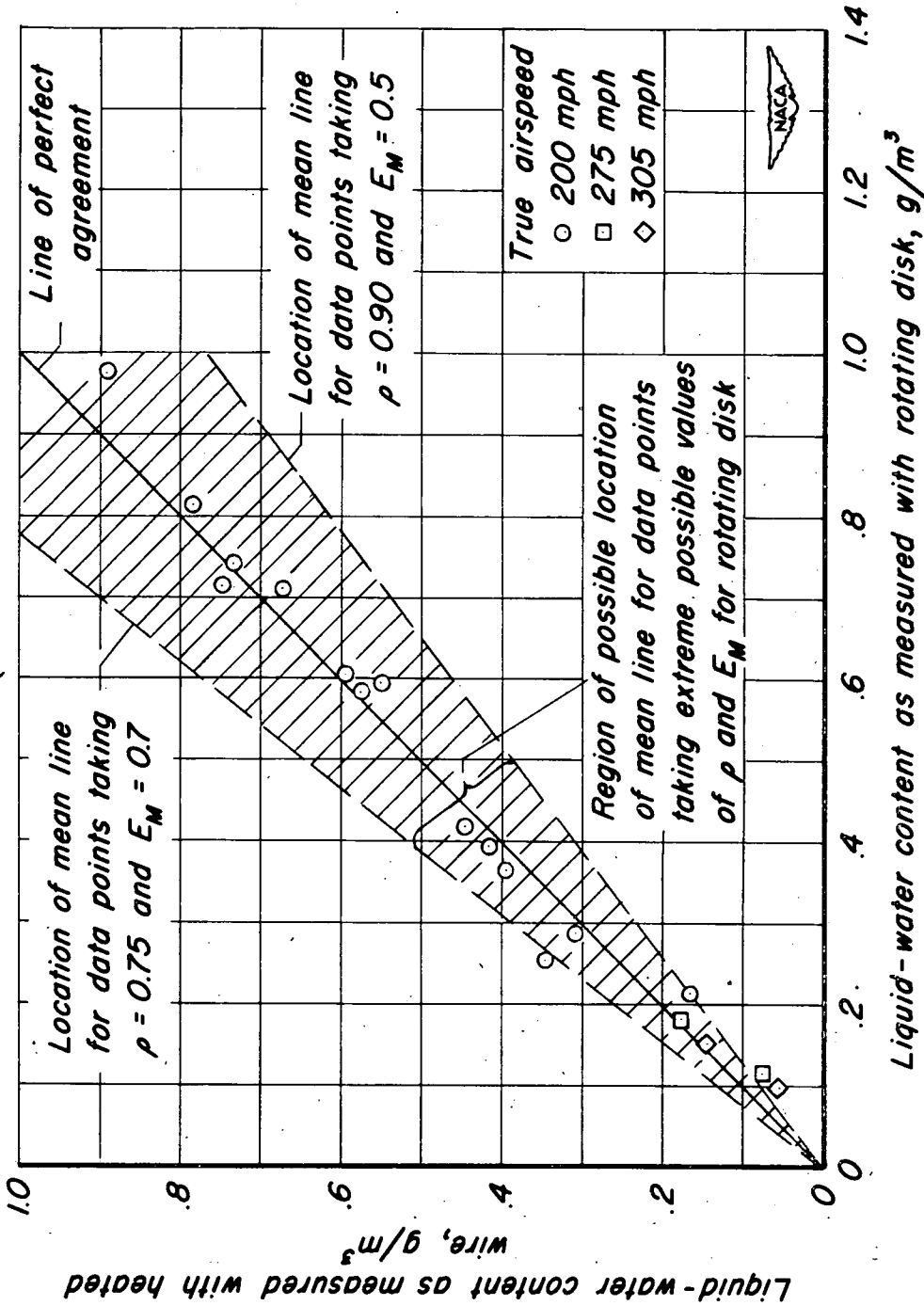
Figure 13.—Comparison of measurements of liquid-water content as obtained with rotating disk and heated wire in Lewis Laboratory Icing Research Tunnel, taking $\rho = 0.83$ and $E_M = 0.6$ for disk.
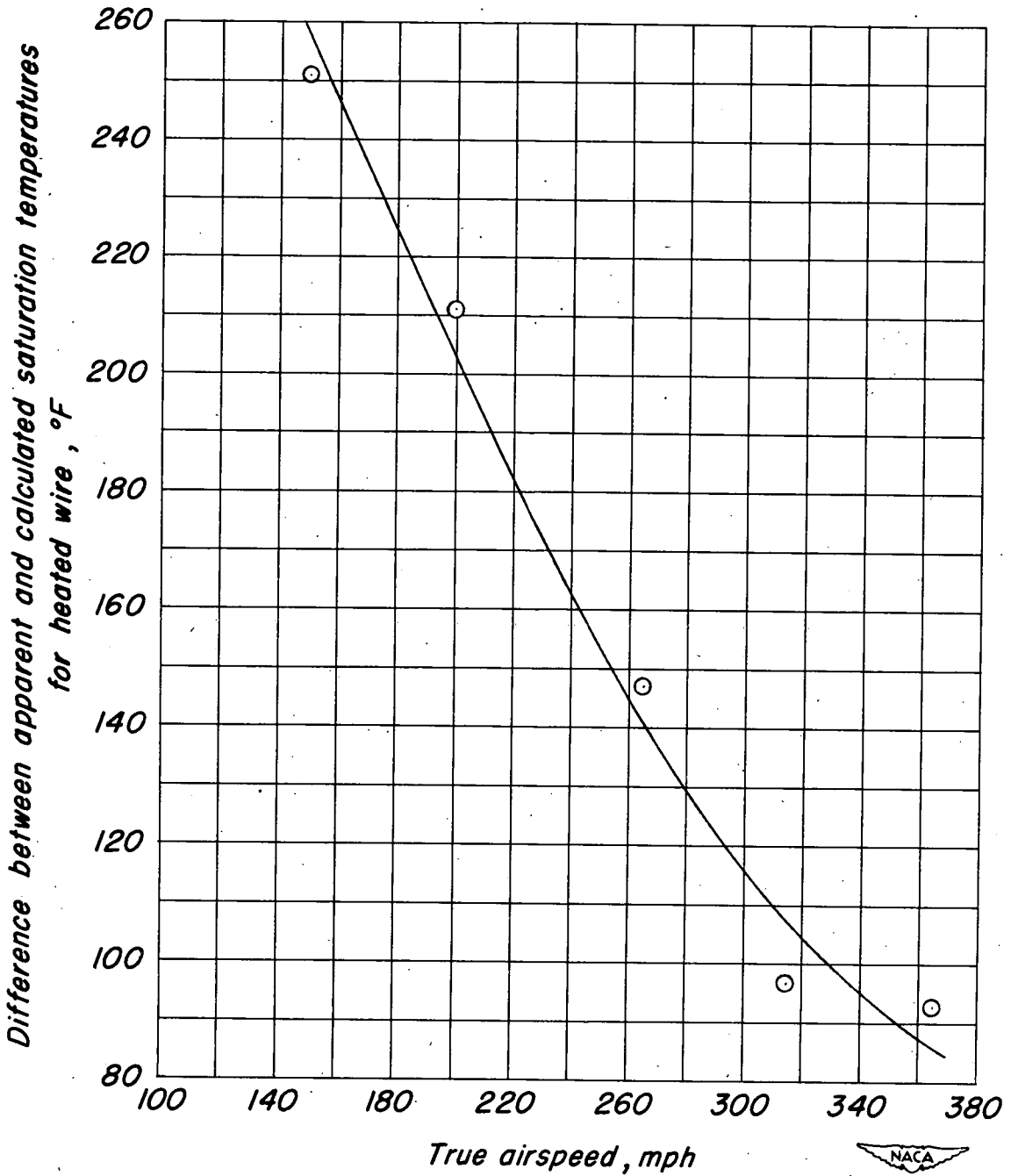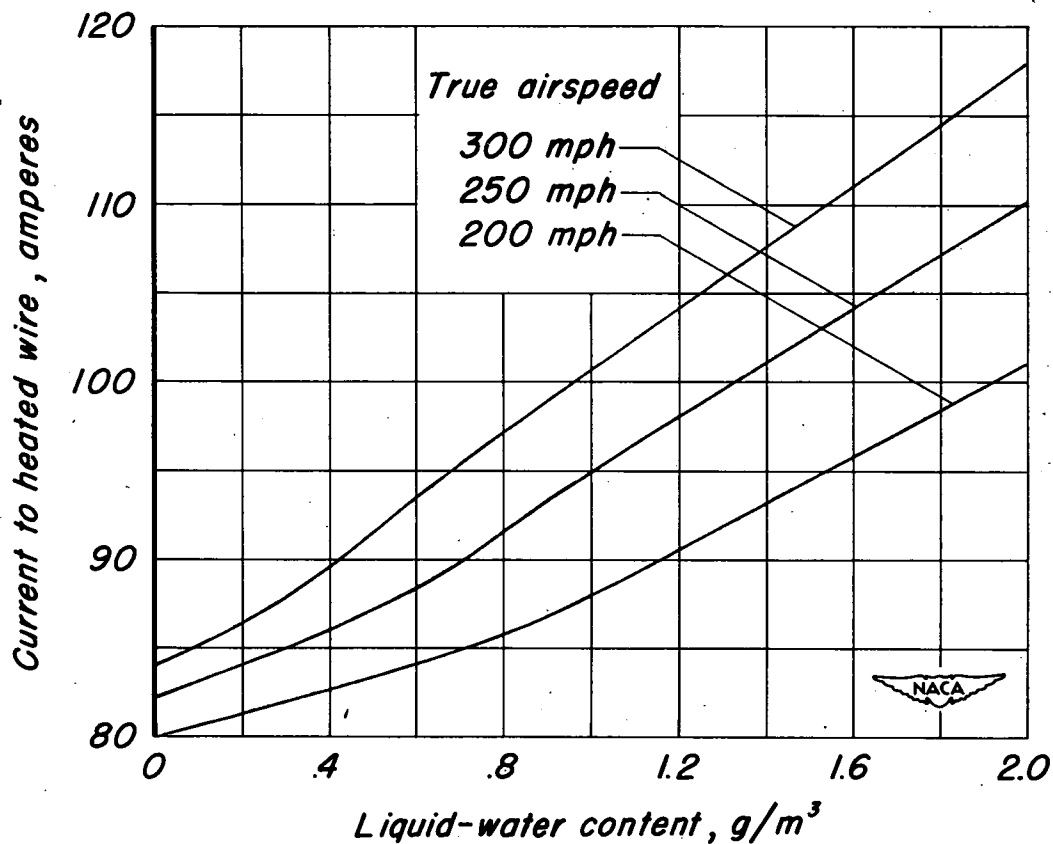
Figure 14.- Effect of airspeed on difference between apparent and calculated saturation temperatures for heated-wire loop 1. Average duct-air temperature, approximately 60° Fahrenheit.
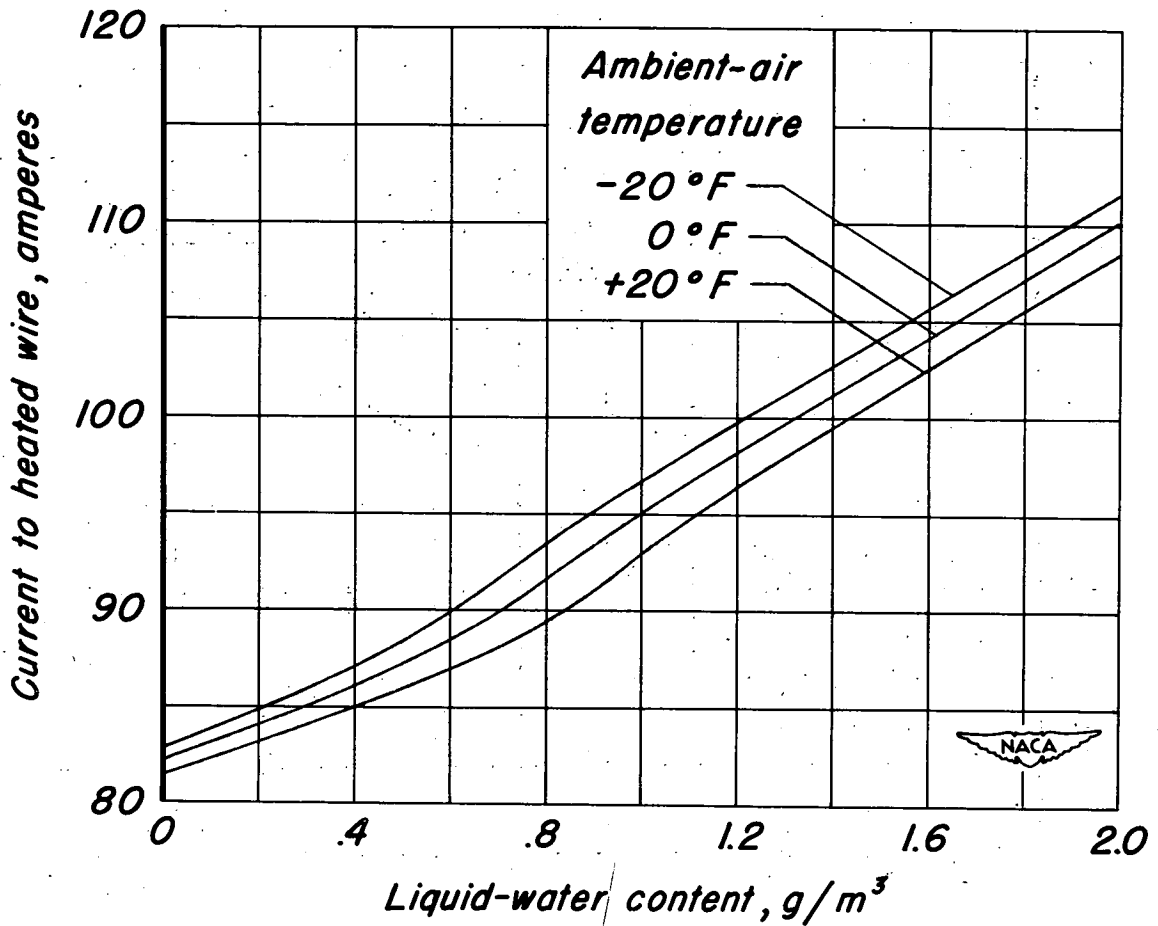
(a) Variation in airspeed. Altitude, 10,000 feet.
Air temperature, 0° Fahrenheit.

Figure 15.- Relationship between liquid-water content and
current to heated wire of loop I computed for various
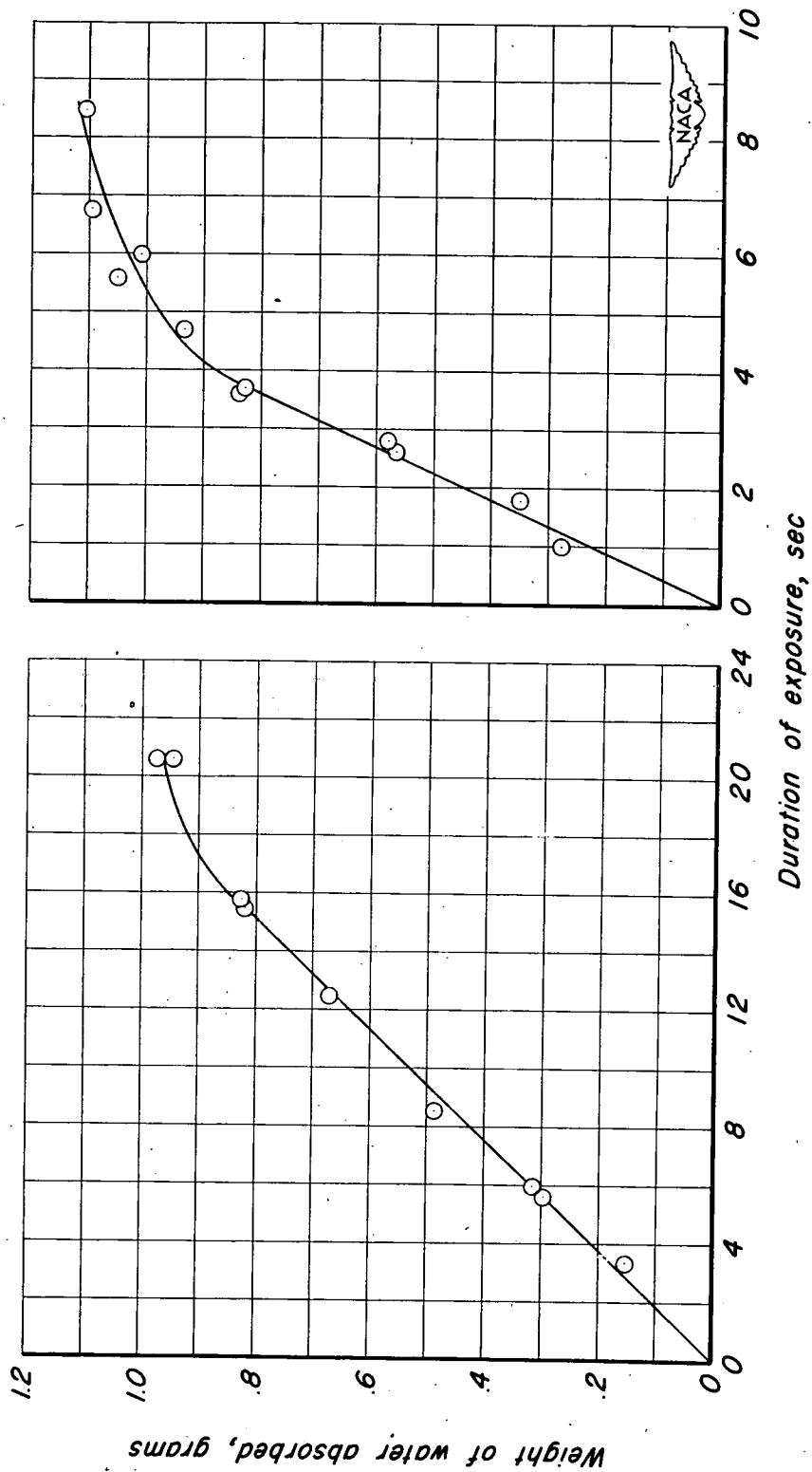operating conditions.
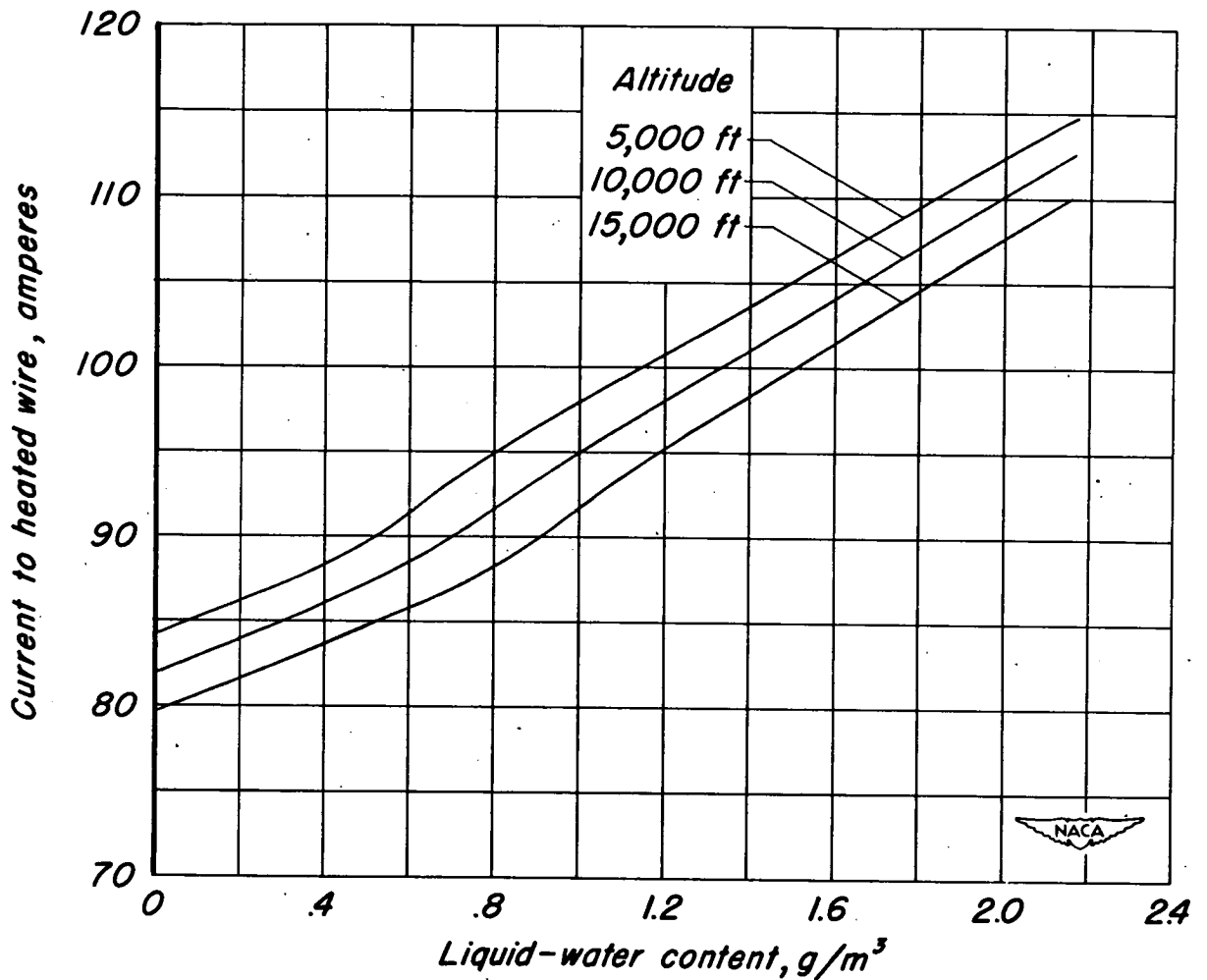
(b) Variation in altitude. Airspeed, 250 miles per hour. Air temperature, 0° Fahrenheit.

Figure 15.- Continued.

(c) Variation in air temperature. Airspeed, 250 miles per hour. Altitude, 10,000 feet.

Figure 15.– Concluded.

(a) Liquid-water content, 1.05 g/m³

(b) Liquid-water content, 4.22 g/m³

Figure 16.- Measurements of the amount of water absorbed by absorbent cylinders as a function of exposure time. True airspeed, 265 miles per hour.