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A HEATED-WIRE LIQUID-WATER-CONTENT INSTRUMENT AND RESULTS OF INITIAL FLIGHT TESTS IN ICING CONDITIONS

By Carr B. Neel

Ames Aeronautical Laboratory
Moffett Field, Calif.

NATIONAL ADVISORY COMMITTEE
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SUMMARY

In the conduct of research directed toward the development of a simple instrument suitable for the measurement of icing severity, a flight version of the NACA heated-wire liquid-water-content instrument was constructed and flight tested in natural icing conditions. Data obtained simultaneously with rotating multicylinders indicated that reliable flight measurements of liquid-water content could be made with the heated-wire instrument. The rate of response of the instrument to variations in water content was sufficiently high to enable a detailed study of cloud structure. Tests in a cloud duct during development of the instrument indicated that measurements could be performed at speeds up to at least 700 mph. Although the flight tests revealed certain deficiencies in the present form of the instrument, it appeared that, with the inclusion of several modifications, the heated-wire device could serve as a useful and practical flight instrument.

Results of the flight measurements in natural icing conditions substantiated the high values of liquid-water content predicted in a previous statistical analysis. The highest value measured was 3.7 grams per cubic meter.

INTRODUCTION

A twofold need exists for instruments suitable for the measurement of icing severity in flight. First, an instrument is required in the investigation of meteorological phenomena associated with aircraft icing. Research on the meteorology of icing serves to expand the knowledge applicable to the design of ice-protection equipment, and to increase the understanding of cloud composition to aid in the forecasting of icing conditions. Second, an instrument is desired for use on military and commercial airplanes which will provide a direct indication to the pilot of prevailing icing severity. This information can guide the pilot in the operation of ice-protection equipment and, if necessary, in the selection of an alternate flight path. Knowledge of the icing severity is also of immediate interest to the aircraft dispatchers.

An instrument which appears to be useful in meteorological research and which might also be adapted for direct indication of icing severity has been developed by the Ames Laboratory of the NACA. This investigation was a continuation of the initial development reported in reference 1. The instrument consists basically of a loop of resistance wire which is mounted in the air stream and is heated electrically by passing current through it. Its change in resistance from the clear-air condition, resulting from cooling due to evaporation of impinging water droplets, is used as a measure of the liquid-water content, or icing severity. Ground tests were performed to effect a number of improvements to the instrument developed in reference 1. Subsequently, two flight models of the instrument were constructed, one of which was flight tested in natural icing conditions. This report describes the flight instrument and presents data obtained during the flight and ground experiments. Also included is an analysis of measurements made in the most severe icing conditions encountered.

The flight tests were performed in cooperation with United Air Lines, Inc., during icing trials of a U.A.L. Convair Model 340 airplane (ref. 2). United Air Lines gave valuable aid in the conduct of this research and made possible these initial flight tests of the heated-wire instrument.

DESCRIPTION OF FLIGHT INSTRUMENT

The flight version of the heated-wire instrument was basically the same as that proposed in reference 1. However, certain improvements were incorporated into the flight models, as follows: (1) the power requirement for the wire loop was decreased, (2) the rate of response of the instrument to changes in liquid-water content was increased, and (3) simplification was achieved by eliminating the voltage regulator, which was found to be unnecessary.

A reduction in the power requirement was obtained by decreasing the wire diameter from 0.064 inch to 0.021 inch, allowing a reduction in the length of wire in the loop and a decrease in the maximum power required from about 400 watts to 31 watts. This decrease in wire size also resulted in a desirable increase in the rate of response of the instrument. Elimination of the voltage regulator was possible because the voltage from the airplane inverter, which provided the power for the wire, was sufficiently stable. Omission of the regulator to maintain the voltage at a specified value required, however, that the voltage be recorded.

The two flight models built were basically the same, but differed somewhat in the arrangement of components. The auxiliary equipment for the instrument from which the flight results presented herein were obtained was constructed first and, for reasons of expediency, was assembled in a rudimentary fashion. Since the two instruments were essentially the same, only the later, more compact, unit will be described.

Instrument Components

The instrument was composed of six components which are described in the following paragraphs:

Wire-loop sensing element.- The wire-loop sensing element and supporting strut are shown in figure 1. The wire-loop mounting assembly was constructed using a coaxial plug-in arrangement so that the entire sensing-element unit could be replaced in the event of its failure or damage.

Heating current for the wire loop passed from the inner pin of the plug, which was formed by the copper rod, through the wire loop, then out the copper tubing, which was connected to the outer shell of the plug. The heater element to prevent the formation of ice on the strut consisted of thin-walled stainless-steel tubing which formed the outer covering for the strut. Current for this heater passed from the outer case of the threaded connector, through the stainless-steel tubing, then out the copper tubing.

The wire was 0.021-inch diameter, as mentioned previously, and consisted of an alloy containing 72-percent nickel and 28-percent iron. The measured temperature-resistance characteristics of the wire are given in figure 2. It will be noted that the temperature-resistance curve is reasonably linear throughout the anticipated operating range of wire temperature. This is a desirable quality, as pointed out in reference 1.

Power supply.- Electrical power for heating the wire loop and supporting strut was supplied from the 400-cycle aircraft inverter, which is a standard part of airplane equipment. A step-down transformer was used to decrease the voltage from 115 to 1.37 volts to supply the required voltage at the loop. It was calculated that this voltage would allow measurement of water contents up to 2.5 grams per cubic meter before saturation of the wire occurred at the design conditions of 250 mph indicated airspeed, 6000 feet pressure altitude, and 0° F free-air temperature. The design conditions and calculated power requirements for the instrument are listed in table I.

In the measurement of liquid-water content, the increase in wire current above the clear-air condition is of primary importance. Consequently, a Wheatstone-bridge circuit containing the wire loop was employed to obtain zero suppression for the recording and indicating of water content. The fixed members of this bridge, together with the power transformer and other necessary equipment, were contained in the power-supply unit. Figure 3 shows the power supply and other pieces of the auxiliary equipment. The basic circuit used in the power supply and measuring apparatus is diagramed in figure 4.

Recording oscillograph.- An oscillograph which recorded on photographic film by means of galvanometer elements was utilized for recording wire-loop current and voltage, indicated airspeed, pressure altitude, and free-air temperature, all of which are required in the determination of liquid-water content. The oscillograph is shown in figure 3. To simplify the recording of current and voltage, no rectification of the 400-cycle current was provided for the galvanometer elements; hence, the current and voltage records appeared as envelope traces of the alternating-current sine-wave curves. A typical oscillograph record obtained with the earlier flight instrument during flight through an icing condition is shown in figure 5. In this case, the airspeed and altitude were recorded separately; consequently, traces for these quantities do not appear on the record.

Direct-reading meter.- A standard panel-type microammeter, shown in figure 3, was graduated to read directly in liquid-water content and was connected into the measuring circuit as noted in figure 4. Since the indication from the instrument varies with changes in airspeed, altitude, and air temperature, as well as in liquid-water content, the meter would read correctly for only one set of operating conditions. The conditions selected for graduation of the dial were 180 mph indicated airspeed, 10,000 feet pressure altitude, and 15° F free-air temperature. The range of liquid-water content chosen for marking was from 0 to 3 grams per cubic meter.

Airspeed and altitude transducers.- Strain-gage-type pressure transducers were used with the oscillograph to record airspeed and altitude. The transducers were housed in a separate box, which is shown in figure 3.

Free-air-temperature probe.- In order to provide a means for recording the free-air temperature, a probe was constructed which consisted of a resistance-wire sensing element contained in a shield designed to prevent the formation of ice on the element. The probe, which is illustrated in figure 6, was connected to the oscillograph in a bridge circuit.

Installation of Instrument on Airplane

Figure 7 shows the location in which the heated-wire sensing element and the free-air-temperature probe were mounted on the U.A.L. airplane. An NACA pressure-type icing-rate meter of the type described in reference 3 was also installed on the airplane, as indicated in figure 7(b). (The results obtained with the pressure instrument are presented in reference 2.) These instruments were located immediately above the airplane airspeed static-pressure vent, just forward of the propeller plane. The remainder of the components for the heated-wire instrument, with the exception of direct-reading meters, were mounted in the baggage compartment, adjacent to the sensing elements. Two direct-reading meters were employed in the tests, one located on the pilots' instrument panel and one at the observer's station.

DESCRIPTION OF TESTS

Cloud-Duct Tests

In the development of the flight model of the heated-wire instrument, it was recognized that a considerable saving in power and an increase in the rate of response of the instrument could be obtained by reducing the size of the sensing wire. Consequently, two series of experiments were made to investigate the performance of a smaller size of wire than utilized in the study of reference 1. In the first of these tests, a loop of the 0.021-inch-diameter wire subsequently used for the sensing element was mounted in the 5-inch-diameter cloud duct which had been employed in the investigation reported in reference 1. Wire loop 1[1] of reference 1 also was installed in the duct and served as the standard of comparison to determine the usability of the smaller wire. The tests were conducted at speeds of 160, 255, and 355 mph at various values of liquid-water content.

A second series of tests was performed to evaluate the operation of the smaller wire at high speeds. In these experiments, the 0.021-inch-diameter wire loop was mounted alone in the duct, which had been reduced in size to 3-1/2-inches diameter to enable the attainment of higher velocities. Measurements of water content were made at speeds from 150 to 700 mph, at which point choking occurred in the duct. The tests were performed at two wire-loop voltages.

Flight Tests

The flight tests were conducted in conjunction with an investigation by United Air Lines of the Convair Model 340 ice-prevention system. During the tests, continuous records of liquid-water content were obtained throughout most of the icing periods, and the heated-wire measurements were coordinated with measurements made with a rotating multicylinder apparatus (generally accepted as the standard for icing measurements) which had been installed in the airplane. (See ref. 2.) To fulfill the U.A.L. objective of the tests, conditions falling in the light icing bracket as defined in reference 4 were sought primarily. However, intermittent heavy icing was occasionally encountered, and these conditions produced the heated-wire results of most interest.

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[1] Wire diameter, 0.064 inch.

RESULTS AND DISCUSSION

Cloud-Duct Tests

The plan to utilize in the flight instrument a wire of a diameter smaller than had previously been tested necessitated a determination of the small-wire performance characteristics. There was the possibility, for example, that a reduction in wire diameter would also reduce the maximum range of water-drop size for which the wire would provide accurate readings. Tests of the smaller wire, therefore, were expected to reveal, among other qualities, any drop-size limitation occurring within the range normally encountered in icing conditions, since the cloud-duct spray produced sizes falling in this category (ref. 1).

Comparison of measurements with two wire sizes.- In the comparative tests conducted with two wire sizes to evaluate the performance of the smaller wire, two factors were investigated: (1) the ability of this wire to measure liquid-water content accurately, and (2) the saturation characteristics of the wire. Figure 8 presents the results of these tests, in which simultaneous measurements of water content were made with the two sizes of heated wires. Values of water content were computed from the data by use of the equations developed in reference 1. In all of the calculations of water content presented herein, experimental values of convective heat-transfer coefficient were employed. At the three test speeds, good agreement was obtained between the 0.021-inch wire and wire loop 1, which was used as the standard of measurement, up to the point of surface saturation for wire loop 1. These data indicated that the performance of the smaller wire was predictable within the range of water content measurable by wire loop 1 for the particular voltage employed. The saturation points noted in figure 8 for wire loop 1 were computed from the data of reference 1, and at speeds of 160 and 255 mph (figs. 8(a) and (b)) these points corresponded closely with the points of departure of the data from the line of perfect agreement, indicating that saturation of loop 1 occurred before saturation of the 0.021-inch wire. At 355 mph (fig. 8(c)), the saturation point for the smaller wire, which was taken as the value of liquid-water content above which there was no further decrease in wire resistance, coincided with the saturation value computed for loop 1. It should be noted that the saturation points, which limit the useful range of measurement, were established by the magnitude of voltages applied and could have been raised or lowered by increasing or decreasing the voltages.

In view of the fact that the saturation point for the 0.021-inch wire appeared to be well defined, and since the performance of the wire was found to be predictable up to this point, it was concluded that the smaller wire was suitable for use as the sensing element in the flight instrument. No drop-size limitation was evident from these tests.

Tests of 0.021-inch wire at high speeds.- Extension of the performance evaluation of the small wire to higher speeds was made possible through the knowledge gained on the means for detecting the saturation point. Since the operation of the wire appeared to be predictable up to the saturation point, only information on the saturation characteristics was obtained.

Measurements of the saturation liquid-water content for the 0.021-inch wire at velocities up to 700 mph are given in figure 9 for two wire-loop voltages. As would be expected, the water content at saturation decreased with increasing speed for constant voltage, and an increase in the wire voltage increased the measuring range of the instrument. The product of water content and speed appeared to be essentially constant for a given voltage. This would seem reasonable, since saturation is established primarily by the rate of water impingement. At a potential of 1.68 volts, the maximum range of measurement was approximately 2.5 grams per cubic meter at 700 mph. An increase in the voltage above this value should result in even a greater range of measurement. Thus, it is seen that the range of such an instrument can be made sufficiently high to enable the measurement of normally expected icing severity at speeds up to at least 700 mph. It should be noted that the limiting speed in these experiments was imposed by the test equipment; no speed limitation of the heated-wire instrument was evident. From these tests, it appears that the useful range of the instrument would not be limited by high values of water content or airspeed, as is the case with currently used icing instruments which operate on the principle of ice accretion (ref. 5).

In the design of a heated-wire instrument, the saturation point must be predictable in order to allow selection of the required wire voltage. In reference 1 it was shown that the saturation point could not be established from theory alone, but that experimental data were necessary to aid in the prediction of saturation. It was found that, due probably to the thermal lag of the impinging water droplets in reaching the wire temperature, the measured wire temperatures at saturation were always higher than the calculated values. This effect is illustrated for the 0.021-inch wire in figure 10, which shows the difference between the experimental and calculated saturation temperatures as a function of airspeed for the conditions noted in figure 9. The calculated temperatures were computed from the equations given in reference 1. The data presented in figure 10 may be used in the prediction of the saturation point as outlined in reference 1.

A decrease in temperature difference with increase in airspeed similar to that exhibited in figure 10 was also observed in the study of reference 1. However, the magnitude of the temperature difference obtained in reference 1 for wire loop 1 was considerably greater than for the smaller wire. This is shown in figure 11, which compares the temperature-difference curves for the two sizes of wire. From this figure it is apparent that, insofar as prediction of wire temperature at the saturation point is concerned, the performance of the smaller wire approached theory more closely than did the larger wire.

Flight Tests

Typical flight records.- Measurements of liquid-water content obtained with the heated-wire instrument during flight through several cumulus clouds are presented in figure 12. The geographical locations of each of the encounters are indicated in figure 13.

The records shown in figure 12 illustrate the extremely irregular nature of cumulus clouds, and the ability of the heated-wire instrument to indicate the water-content variations. This high rate of response makes the instrument an excellent research tool for the detailed study of the structure of clouds composed of liquid water.

Comparison of heated-wire and rotating-cylinder measurements.- The measurements made with the rotating cylinders during flight in natural icing conditions were presented in reference 2, together with the data from the heated-wire instrument. These results are analyzed herein to compare the heated-wire data with the values obtained by means of the commonly accepted rotating-cylinder method. Five measurements were taken with the rotating cylinders, but unfortunately, simultaneous records were obtained with the heated wire during only three of the cylinder runs. In order to compare the heated-wire data with these cylinder measurements, the curves of water content from the heated-wire records were averaged for each interval of exposure of the cylinders. Each of the values of water content from the cylinder measurements as given in reference 2 was modified to take into account the increase in air velocity, and hence in icing rate, over the top of the airplane fuselage where the rotating cylinders were exposed. Since the values presented in reference 2 were computed on the basis of airplane velocity, rather than local velocity, this modification was necessary to place both sets of measurements on an equal basis. (No corrections were made in the case of the heated-wire data, inasmuch as the wire loop was located in a region of ambient static pressure, wherein the local airspeed was equal to the airplane speed.) In modifying the cylinder data, it was necessary to assume a value for the increase in local velocity, since no measurements were made of the airspeed in the region of the cylinders. The value chosen was an increase of 12 percent of the airplane speed, and is based on data previously obtained for a similar airplane and cylinder configuration (ref. 6). A second modification to the rotating-cylinder values of reference 2 was necessary in two cases in which the effective icing period, used in the reduction of data, was less than the exposure period, due to the existence of areas of clear air or very light icing. In these cases, the cylinder measurements were decreased by the ratio of effective icing period to exposure period in order to place the cylinder and heated-wire values on a common basis.

The average values of liquid-water content as obtained with the heated-wire instrument are compared with the modified rotating-cylinder measurements in the following table:

Date	Cylinder-exposure time,[2] PST	Measured liquid-water content, g/m^3		Mean-effective drop diameter, microns (from cylinder measurements)
		Rotating cylinders	Heated wire	
Nov. 28, 1952	2:46:43 to 2:51:50	0.18	0.10	31
Nov. 28, 1952	3:53:30 to 3:57:30	.15	.12	17.5
Dec. 6, 1952	5:23:00 to 5:30:00	.28	.26	18

It is seen that the heated-wire results agreed very well with the rotating-cylinder measurements in the second and third cases. In the first case, also, the agreement is considered satisfactory, in view of the fact that the difference between the measured values represents only 2 percent of the estimated full-scale reading of 4 grams per cubic meter for the heated wire under the particular operating conditions, and therefore could reasonably be attributed to experimental error. Unusually large water drops were encountered in this case; hence, part of the discrepancy might also have been due to inability of the wire to evaporate the larger drops completely. Actually, the drop-size limitations are not definitely known, but it may be concluded from the above data that the heated-wire instrument provided reliable measurements of liquid-water content at drop sizes normally expected in icing conditions.

Comments regarding operation of heated-wire instrument.- The performance of individual components of the heated-wire apparatus will be discussed to evaluate the practicality of the instrument, and to indicate features requiring improvement.

In general, the recording-oscillograph system operated satisfactorily. Recording of the 400-cycle-envelope curves for current and voltage appeared to provide a simple and fairly reliable system. In this connection, two of the galvanometer elements failed during the flight tests; however, subsequent life tests of three samples of a different type of element produced no failures in over 1000 hours of operation. The major objection to this system is that reduction of the data to obtain a continuous curve of liquid-water content as a function of time is very difficult unless only half of the double amplitude of the trace is used, in which case the accuracy of measurement is decreased. For this reason, it appears that rectification of the alternating-current signal would be desirable.

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[2] The cylinder-exposure times presented for November 28 differ slightly from those given in reference 2. This is due to the fact that one of the synchronizing clocks apparently had been operating erratically, and the discrepancy in times was not discovered until after publication of reference 2.

During the flight-test program reported in reference 2, the direct-reading meter provided a useful indication of prevailing icing severity. As stated in reference 2, these indications aided in the selection of suitable test conditions. Although no provision was made to compensate for variations in airspeed, altitude, and air temperature, most of the flights were conducted sufficiently close to the flight conditions selected in the graduation of the meter dial that the resulting indications were usually fairly reliable. However, it was evident that compensation should be provided for cases where large variations in flight conditions would be expected. The meter response was rapid enough to indicate the high degree of nonuniformity of the icing clouds that was illustrated by the flight records. In general, however, a damped response which would give more of an average reading, as suggested in reference 2, probably would be preferable in an instrument intended as a guide for pilots.

The presence of snow appeared to have very little effect on the indication of the heated-wire instrument. Probably this was due to removal by aerodynamic forces of the snowflakes striking the wire before appreciable cooling could result. This feature is considered desirable, since the quantity of liquid water, rather than of frozen water, is of primary concern in determining the severity of an icing condition. Simultaneous observations of the performance of the airplane wing thermal ice-prevention system and of the heated-wire instrument substantiated this view. In general, no runback ice would form aft of areas of the wing which were marginally heated during flight through snow, when the meter indicated negligible liquid-water content; whereas, runback was nearly always observed on the wing when the meter gave a positive reading.

The wire loop proved vulnerable to damage, both from pieces of ice which broke loose from formations on the forward parts of the airplane during flight, and from ground crews during normal maintenance procedures. This situation could be alleviated either through appropriate location of the loop or by the provision of a heated protective shield.

In summary, then, it is believed that with the inclusion of several modifications, the heated-wire instrument could serve as a useful and practical flight instrument which would be well suited either to further research on the meteorology of icing or to assist in the safe operation of airplanes in icing conditions.

Analysis of the Most Severe Icing Conditions Encountered

The heated-wire measurements of greatest meteorological interest were presented previously in figure 12, which shows the variation of liquid-water content within four of the most severe icing conditions encountered. It will be noted that the peak values of water content are all above 2 grams per cubic meter, with the largest being 3.7 grams per cubic meter (icing encounter C). This was the highest value measured during the tests and is believed to be the third largest liquid-water content yet measured in icing conditions. The two highest values previously reported are 10.0 and 4.1 grams per cubic meter (refs. 7 and 8, respectively), although there appears to be some question as to the validity of the larger measurement.

It is of interest to compare the data of icing encounter C (fig. 12(c)) with the predictions of Lewis and Bergrun (ref. 9) for maximum values of liquid-water content likely to be encountered in Pacific coast cumulus clouds. Maximum values of the average water content existing in horizontal distances of 0.5, 1.0, and 1.9 miles were taken from the data of figure 12(c). The distance of 1.9 miles represents the maximum effective extent of the cloud; whereas, the distances of 0.5 and 1.0 mile were selected arbitrarily as a basis for comparison of the measurements with the probable maximum water concentration within the cloud. The measured averages are compared in the following table with values of water content obtained from reference 9 for the same horizontal extents and air temperature.

Horizontal extent, miles	Maximum of the average liquid-water content, g/m^3	
	Measured with heated wire (fig. 12(c))	Value from ref. 9 for P_e of 1 in 1000
0.5	3.3	3.3
1.0	3.1	3.1
1.9	2.5	2.8

The agreement is seen to be very good throughout the entire cloud. As noted, the values obtained from reference 9 are for an exceedance probability,[3] P_e, of 1 in 1000, which appears reasonable in this case, since the condition consisted of an isolated cumulus cloud that was flown through deliberately. Hence, the likelihood of encountering such a condition during a routine flight would be very small. The water-drop size in the cloud was not known, and since the predicted liquid-water content varies with drop diameter for a given exceedance probability, it was necessary to assume the drop size in taking the values from reference 9. The size chosen was 17 microns, which is suggested in reference 4 as a reasonable value to assign to cumulus clouds.

In view of the necessity for assuming drop size and exceedance probability, the remarkable agreement between measured and predicted values in the foregoing table may be partly fortuitous. However, the

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[3] The exceedance probability is the number of times a particular value is likely to be exceeded in a given number of icing encounters.

agreement would not be greatly altered if different assumptions were made, provided the figures taken were reasonable. These results, therefore, tend to substantiate the probability analysis of reference 9. The measured values of water content also are in general agreement with the values recommended for design in references 10 and 11.

CONCLUSIONS

As a result of an investigation to develop a flight version of the NACA heated-wire icing-severity instrument, the following conclusions were reached:

1. The instrument was shown to be suitable for the measurement of liquid-water content (icing severity) in flight at water-drop sizes normally encountered in icing conditions.

2. The rate of response of the instrument to variations in liquid-water content was sufficiently high to enable the detailed study of cloud structure.

3. Tests in a cloud duct indicated that the instrument could be used for the measurement of liquid-water content at speeds up to at least 700 mph.

4. Results of flight measurements in natural icing conditions substantiated the high values of liquid-water content predicted in a previous statistical analysis. The highest value measured was 3.7 grams per cubic meter.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Sept. 23, 1954

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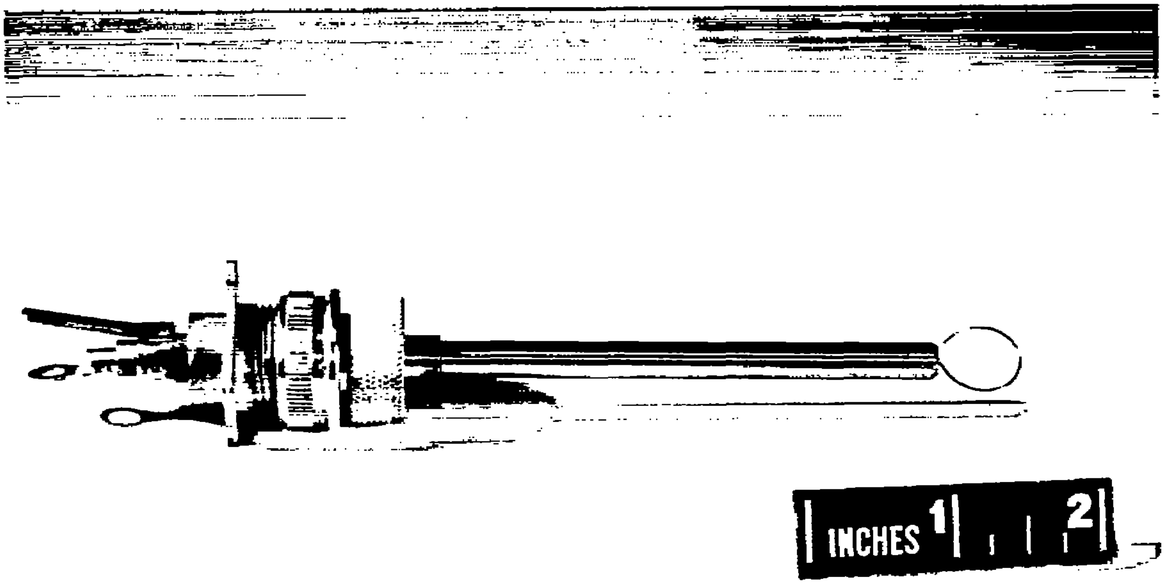
TABLE I.- DESIGN CONDITIONS AND CALCULATED POWER REQUIREMENTS FOR HEATED-WIRE INSTRUMENT

		Design conditions					Power requirements			
		True air-speed, mph	Pressure altitude, ft	Free-air temp., °F	LWC g/m^3	Surface temp., °F	Power, watts	Current, amps	Voltage, volts	Resistance, ohms
Wire loop	Maximum power	262	6,000	0	2.5	225	31.0	24.8	1.25	0.050
	Minimum power	259	30,000	0	0	650	17.2	13.2	1.30	.099
Supporting-strut heater		300	25,000	-10	1.27	[1]35	82	60	1.37	.023

[1] Stagnation-point temperature



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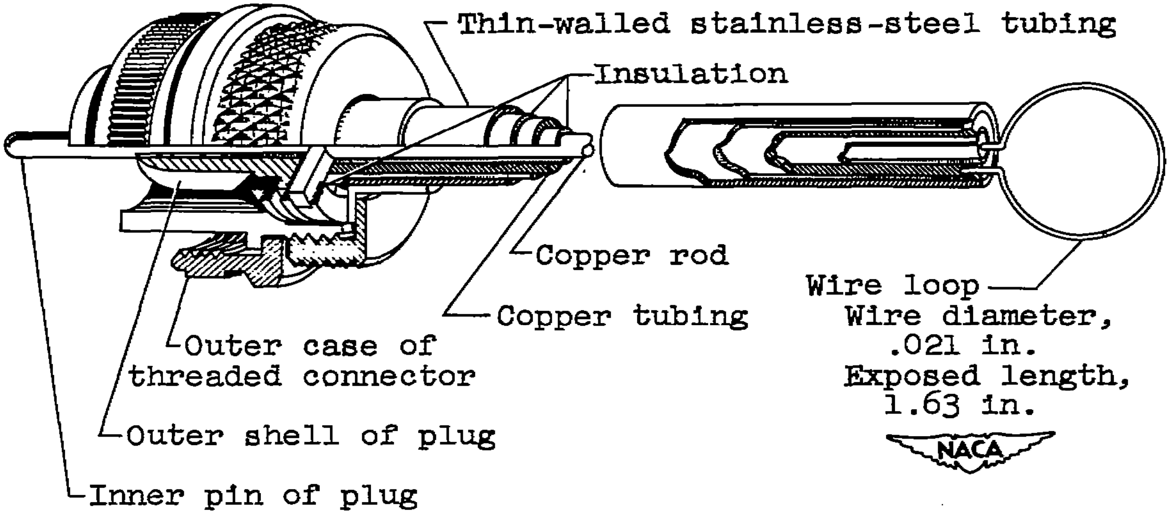
(a) Wire-loop and supporting-strut assembly.



(b) Construction details of wire-loop and supporting-strut assembly.

Figure 1.- Sensing element of flight model of heated-wire instrument.

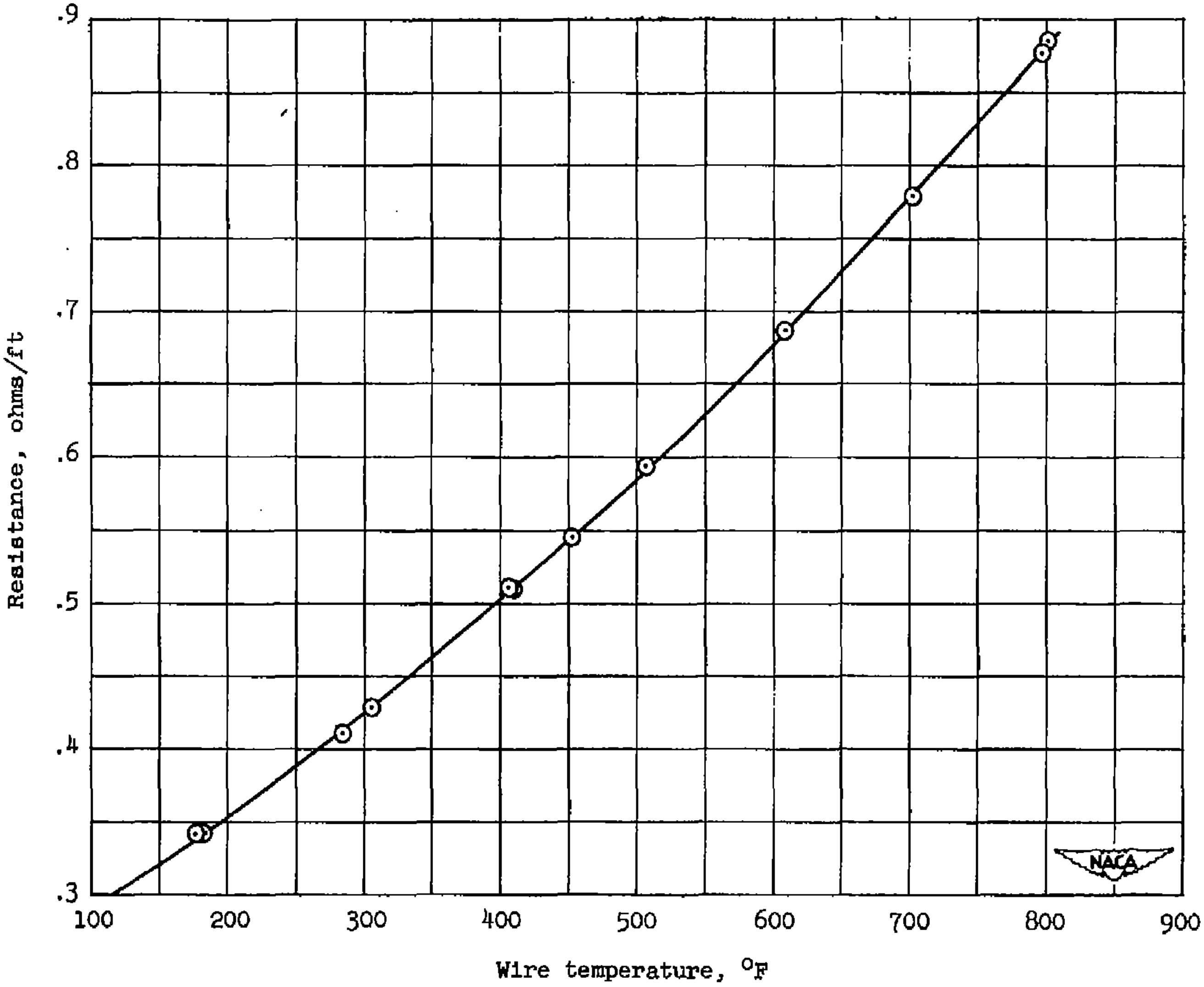


Figure 2.- Resistance as a function of temperature for wire used in heated-wire instrument.

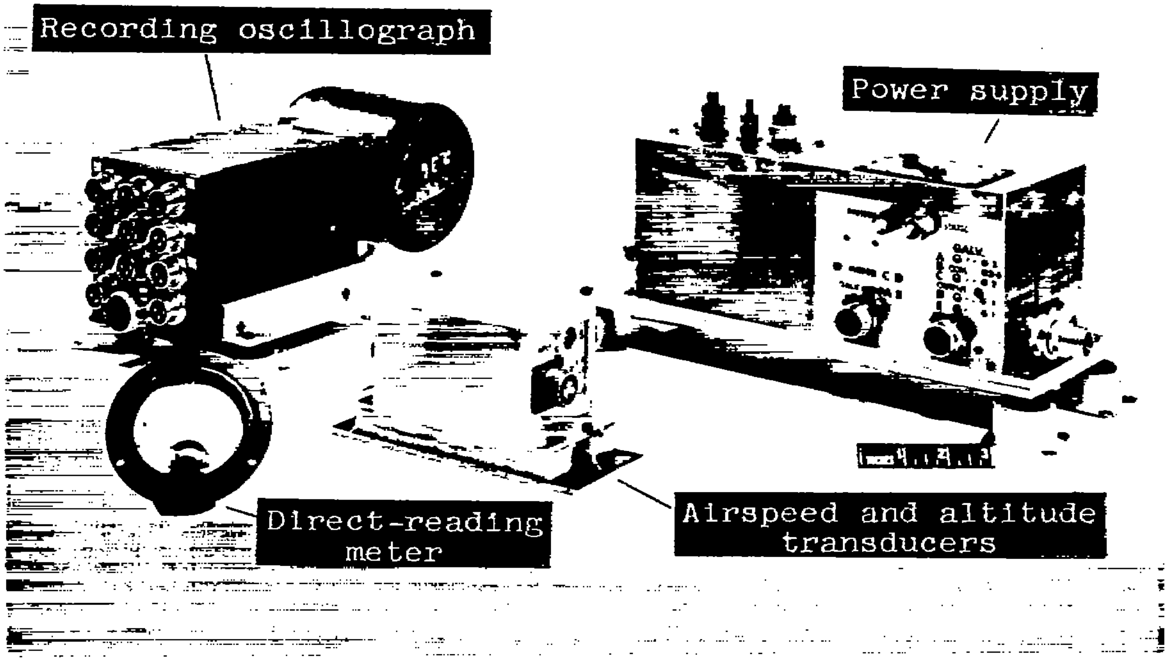


Figure 3.- Auxiliary equipment for heated-wire instrument.

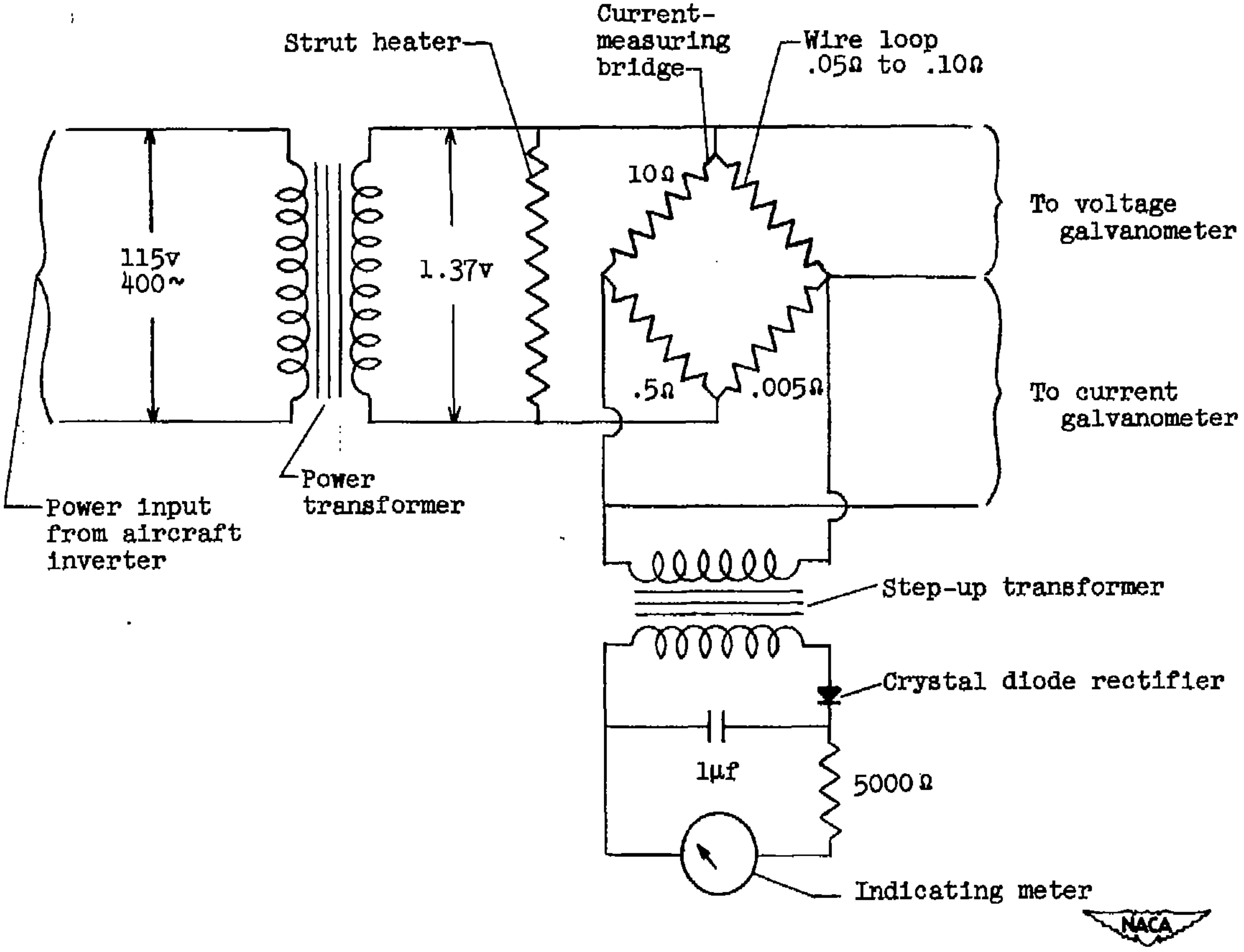


Figure 4.- Basic circuit employed in the measurement of liquid-water content with heated-wire instrument.

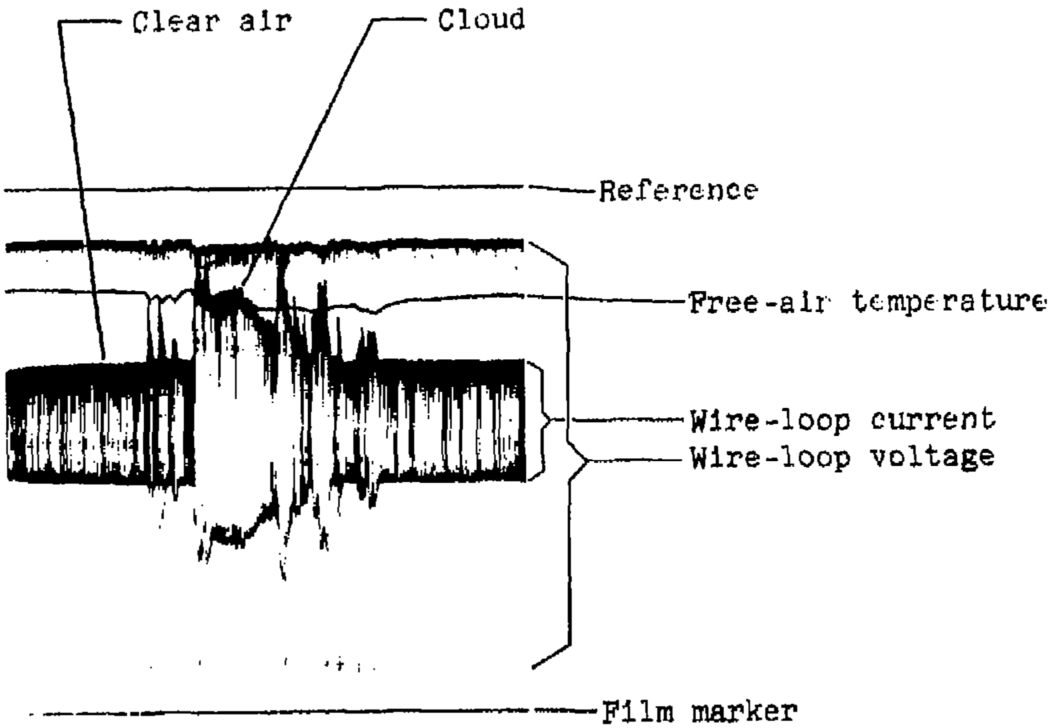


Figure 5.- Typical record obtained with heated-wire instrument during flight through icing clouds.

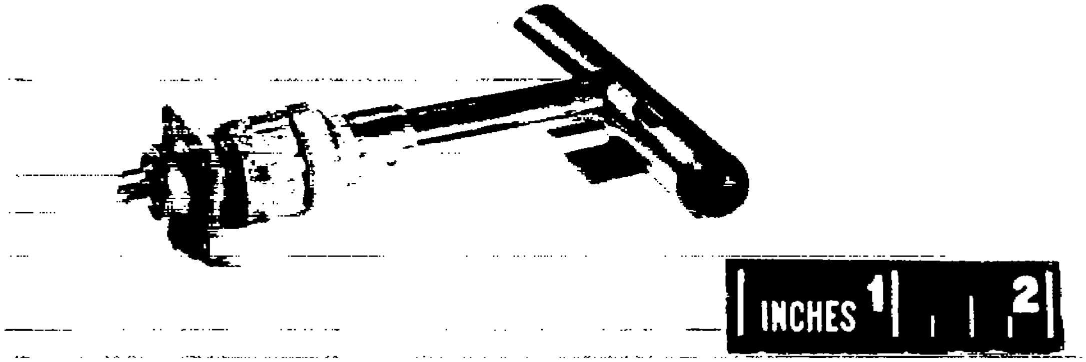
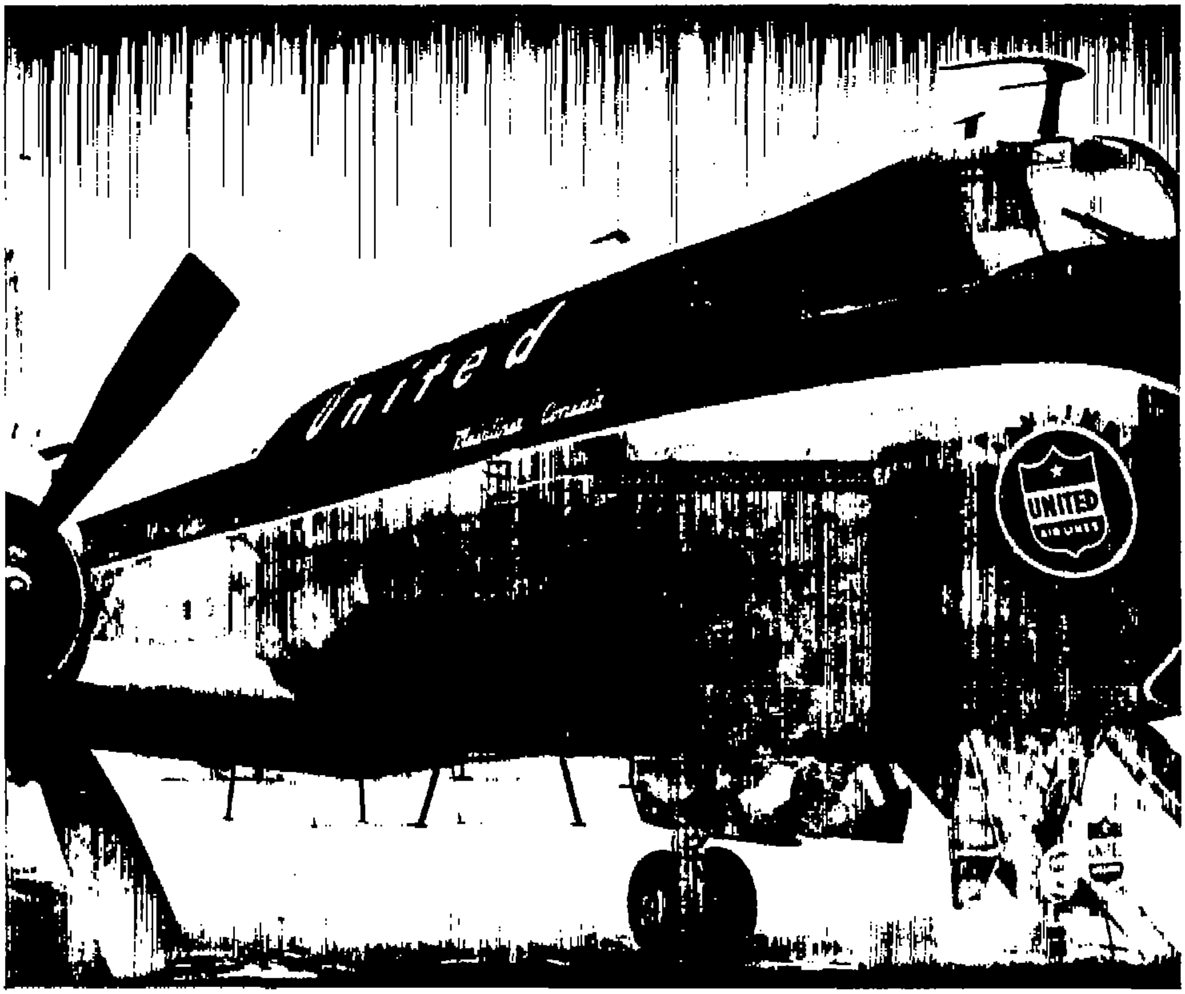


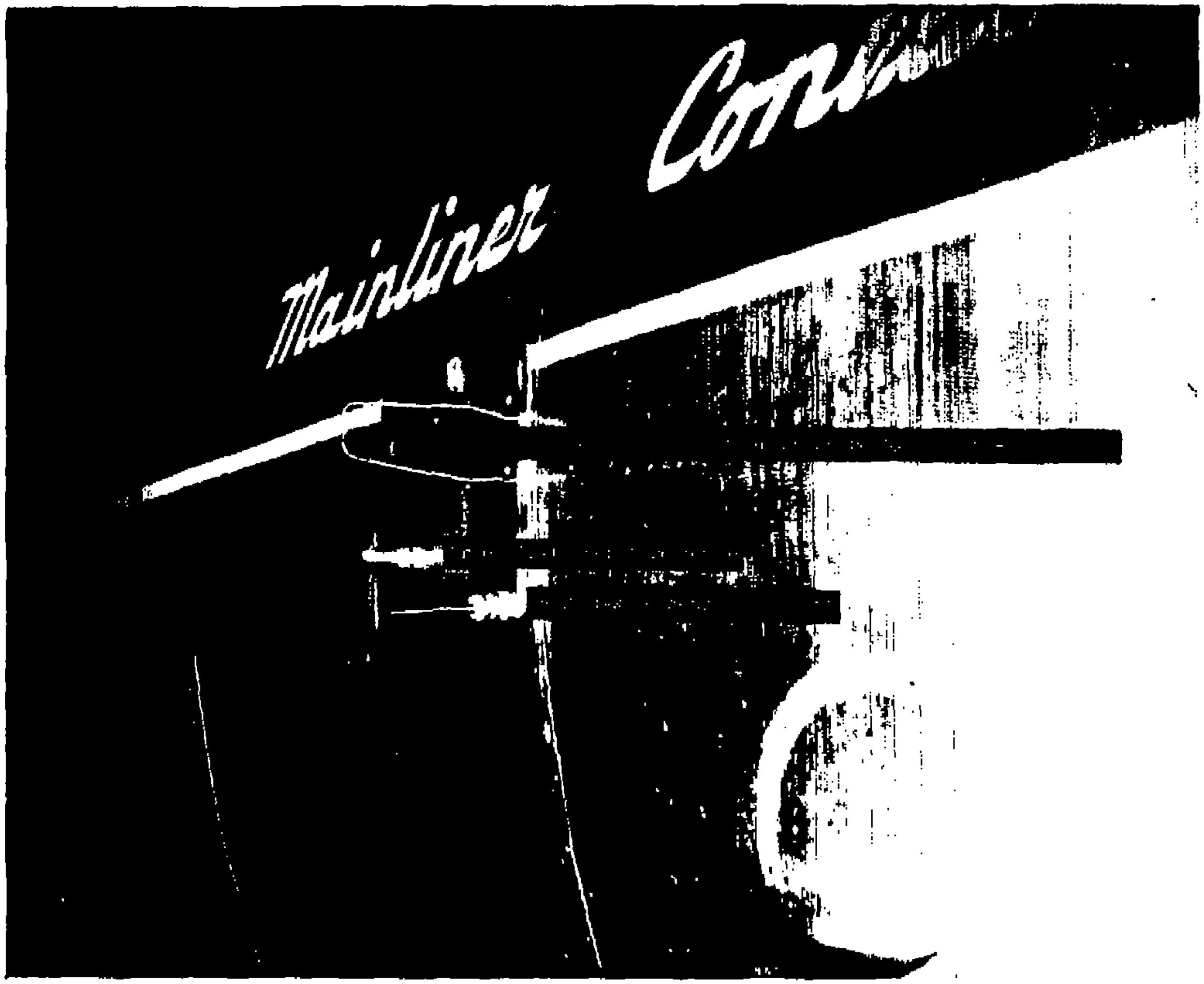
Figure 6.- Free-air-temperature probe.



A-19102.1

(a) General view of airplane and instrument sensing elements.

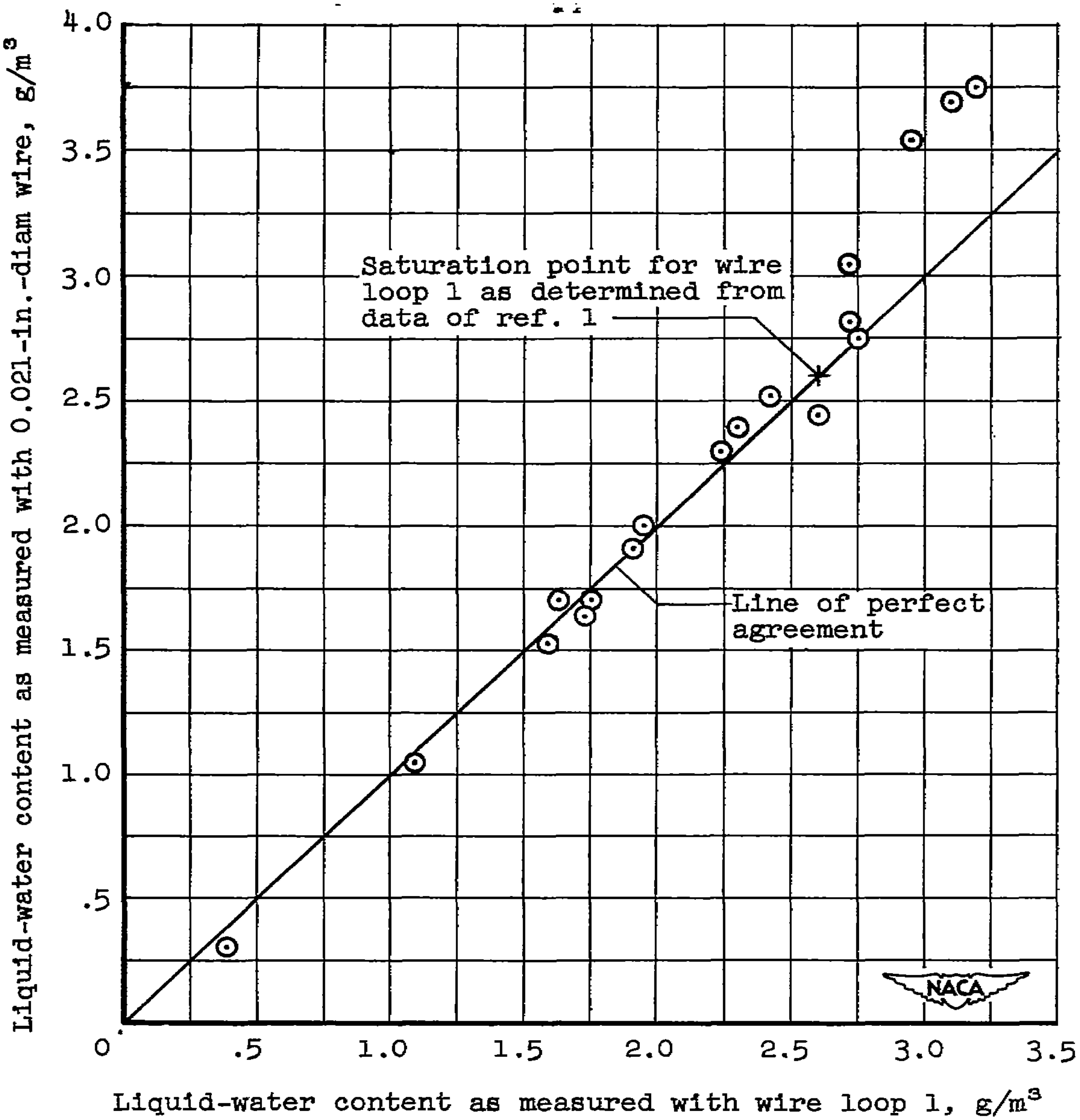
Figure 7.- Installation of NACA icing instruments on United Air Lines Convair 340 airplane. (Photographs obtained from reference 2.)



A-19103.1

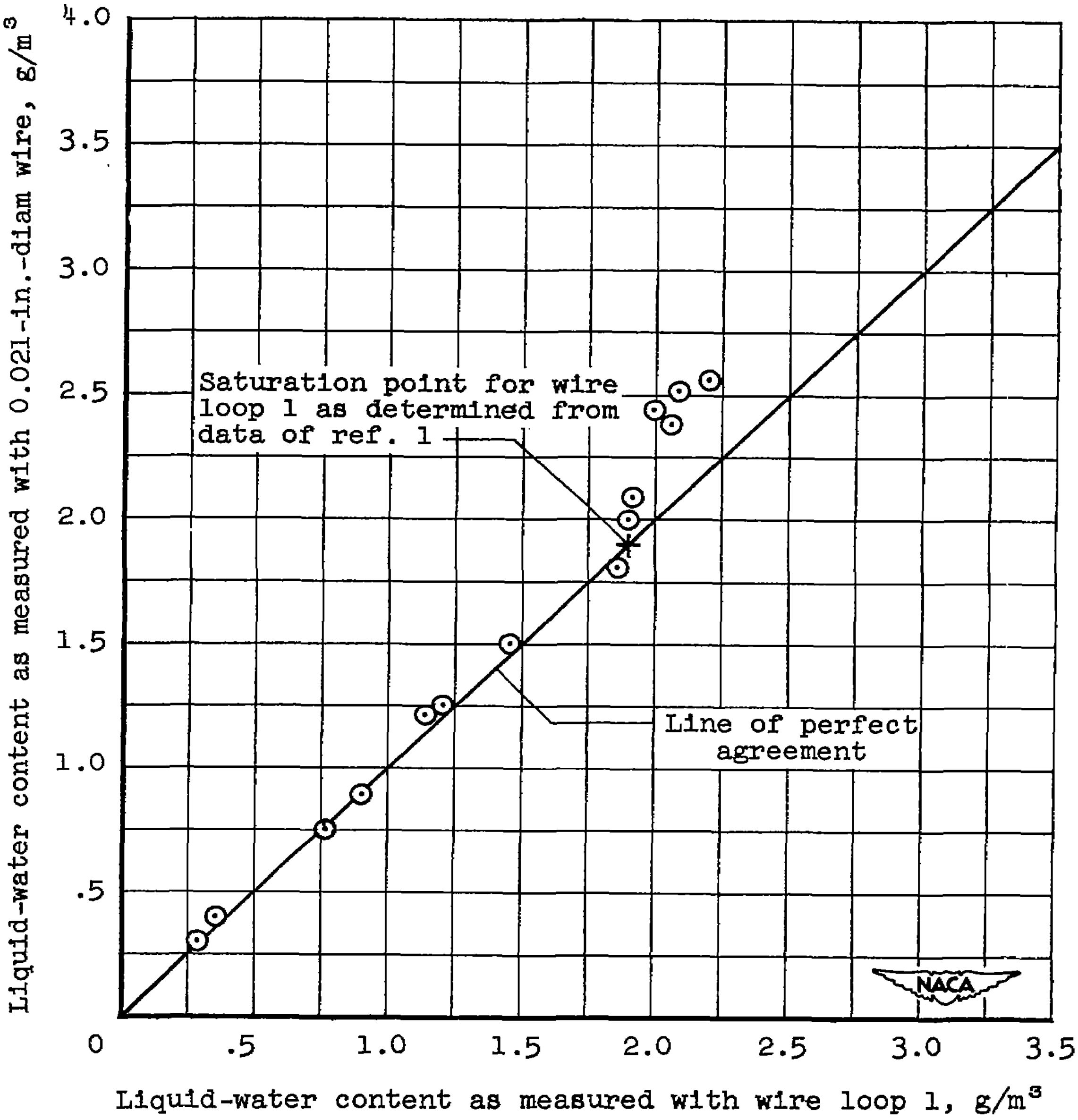
(b) Close-up view of instrument sensing elements.

Figure 7.- Concluded.



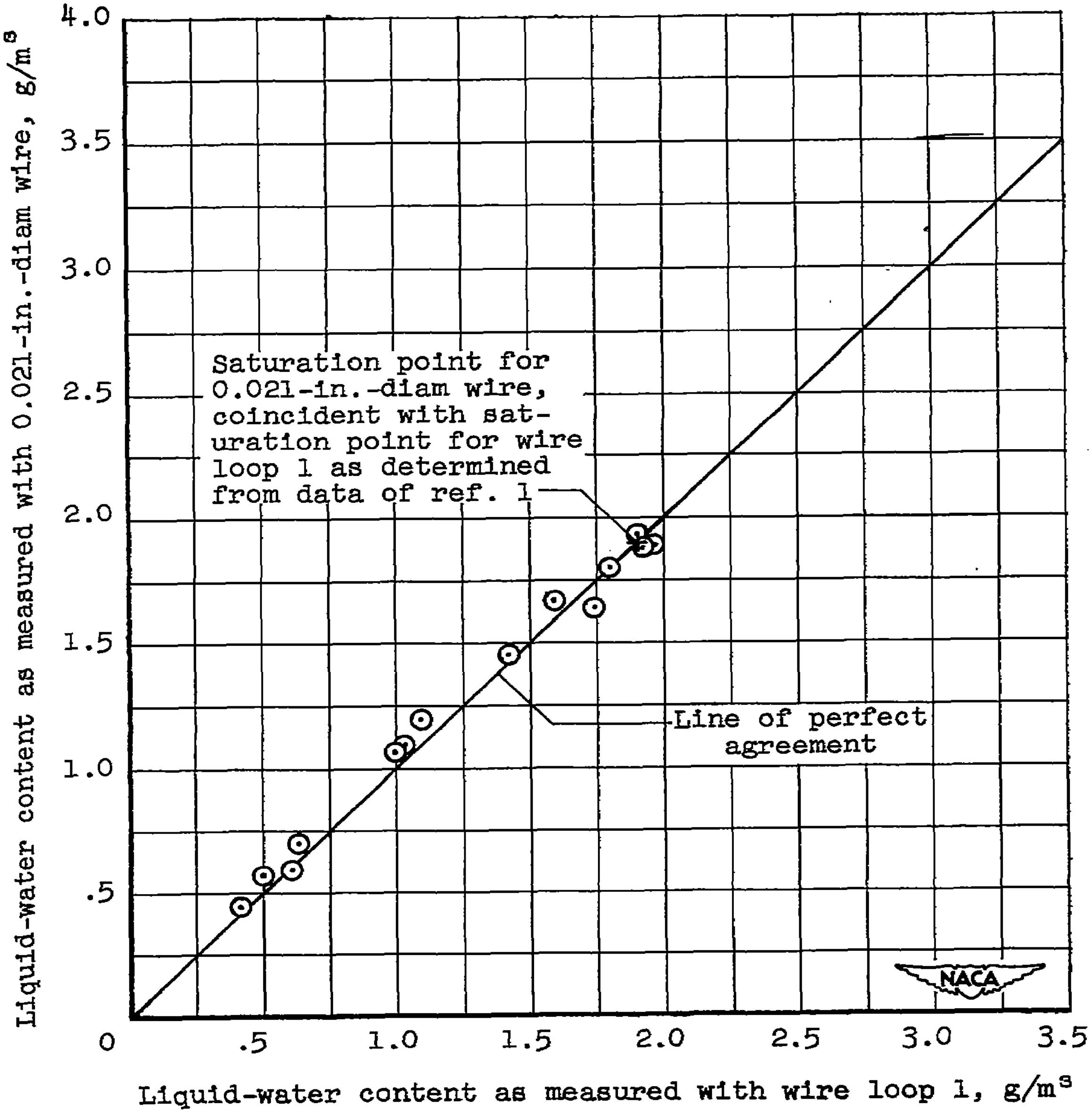
(a) True airspeed, 160 mph.

Figure 8.- Performance of 0.021-inch-diameter heated wire as compared with wire loop 1 of reference 1 for three speeds in cloud duct.



(b) True airspeed, 255 mph.

Figure 8.- Continued.



(c) True airspeed, 355 mph.

Figure 8.- Concluded.

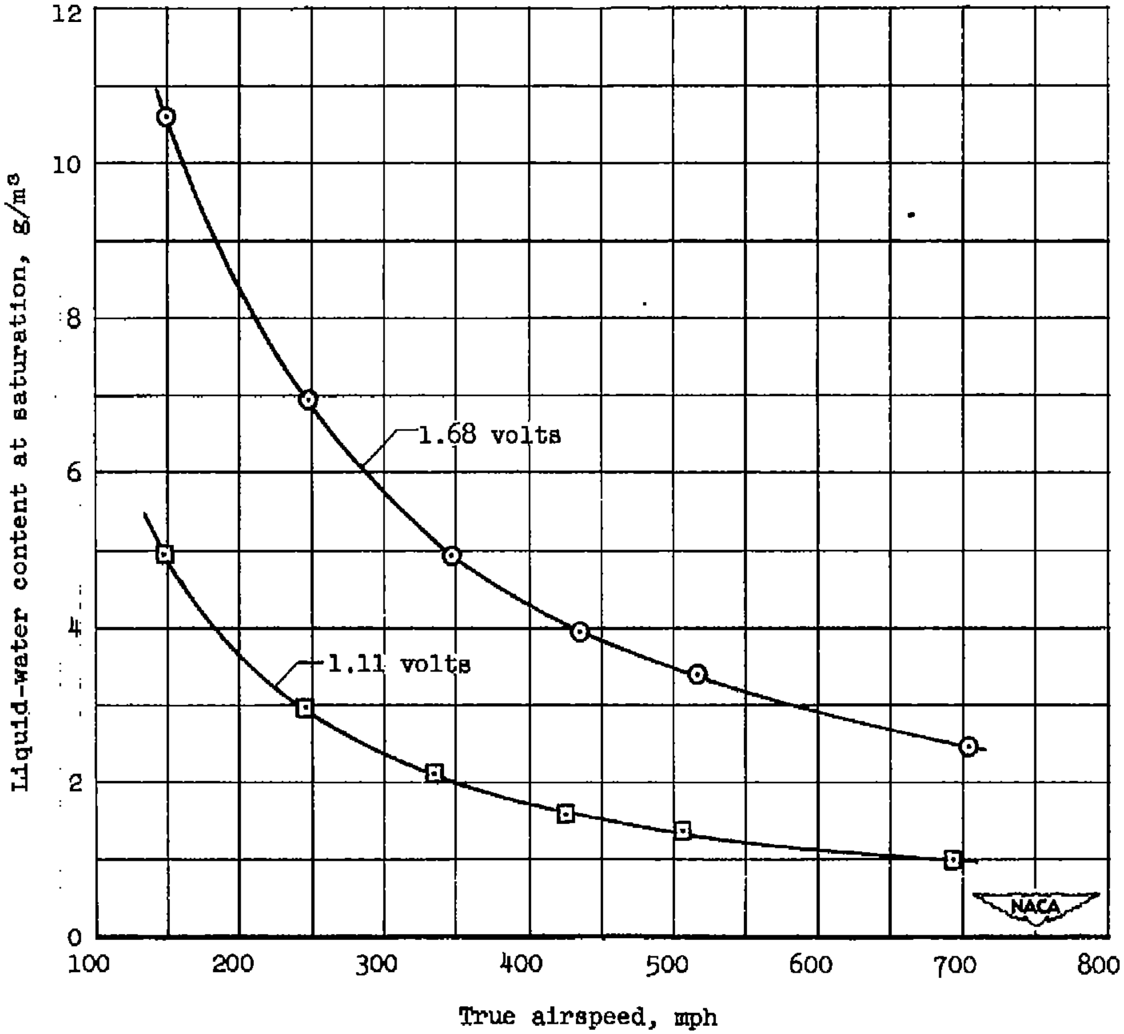
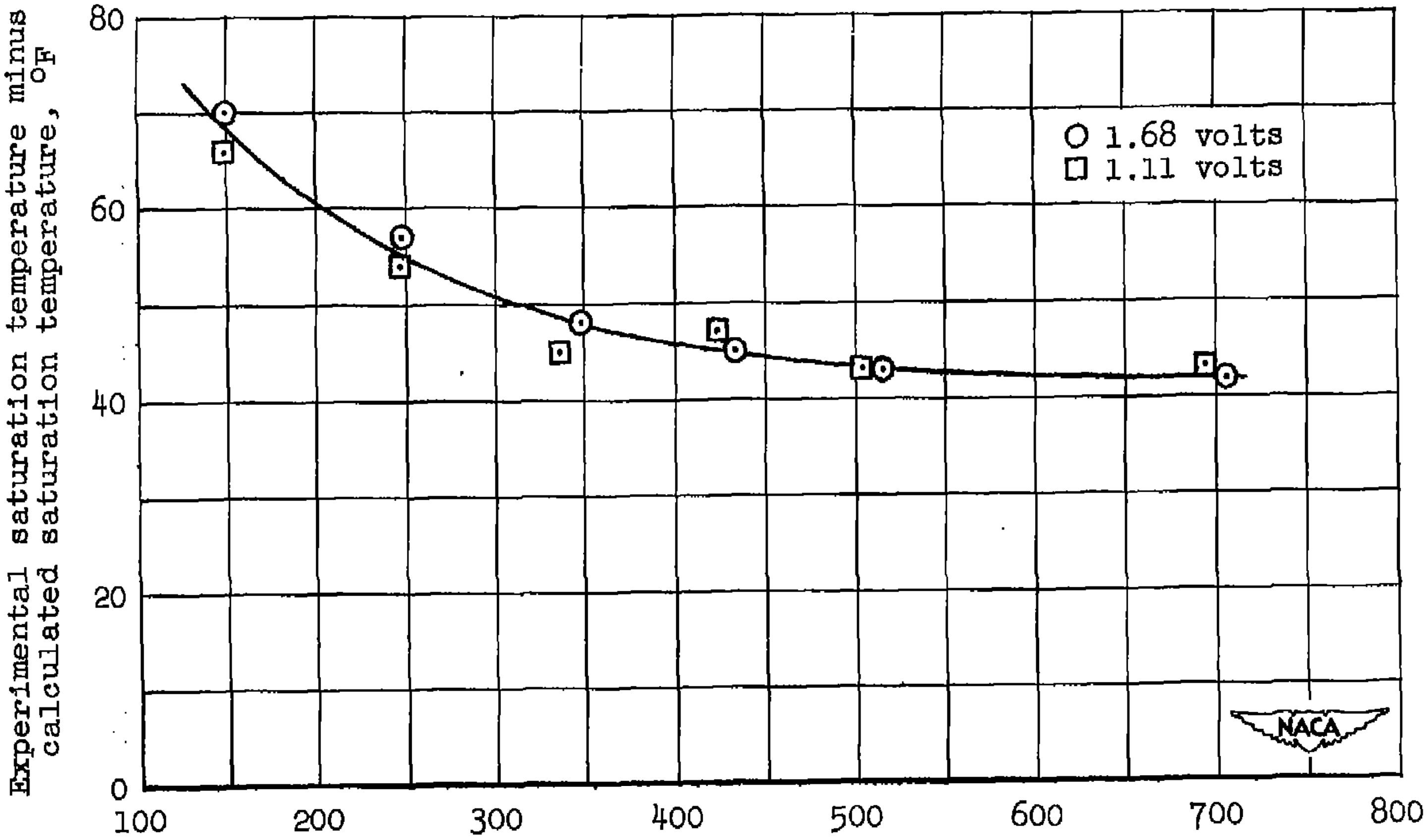


Figure 9.- Liquid-water content at saturation as a function of airspeed for 0.021-inch-diameter wire at two voltages in cloud duct. Length of wire, 1.70 inches.



True airspeed, mph

Figure 10.- Difference between experimental and calculated saturation temperatures as a function of airspeed for 0.021-inch-diameter wire in cloud duct. Average water-drop temperature, approximately 40°F.

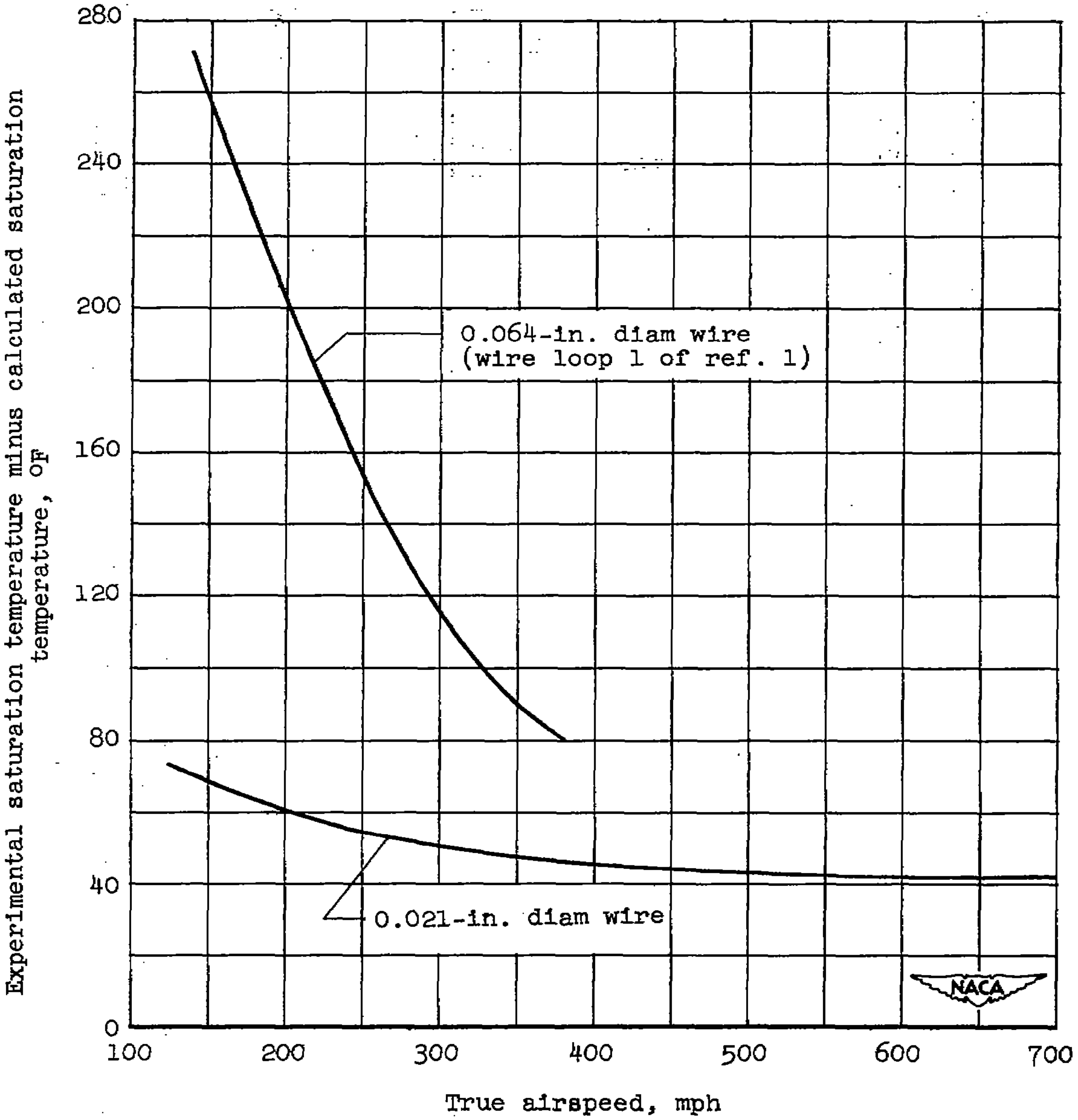
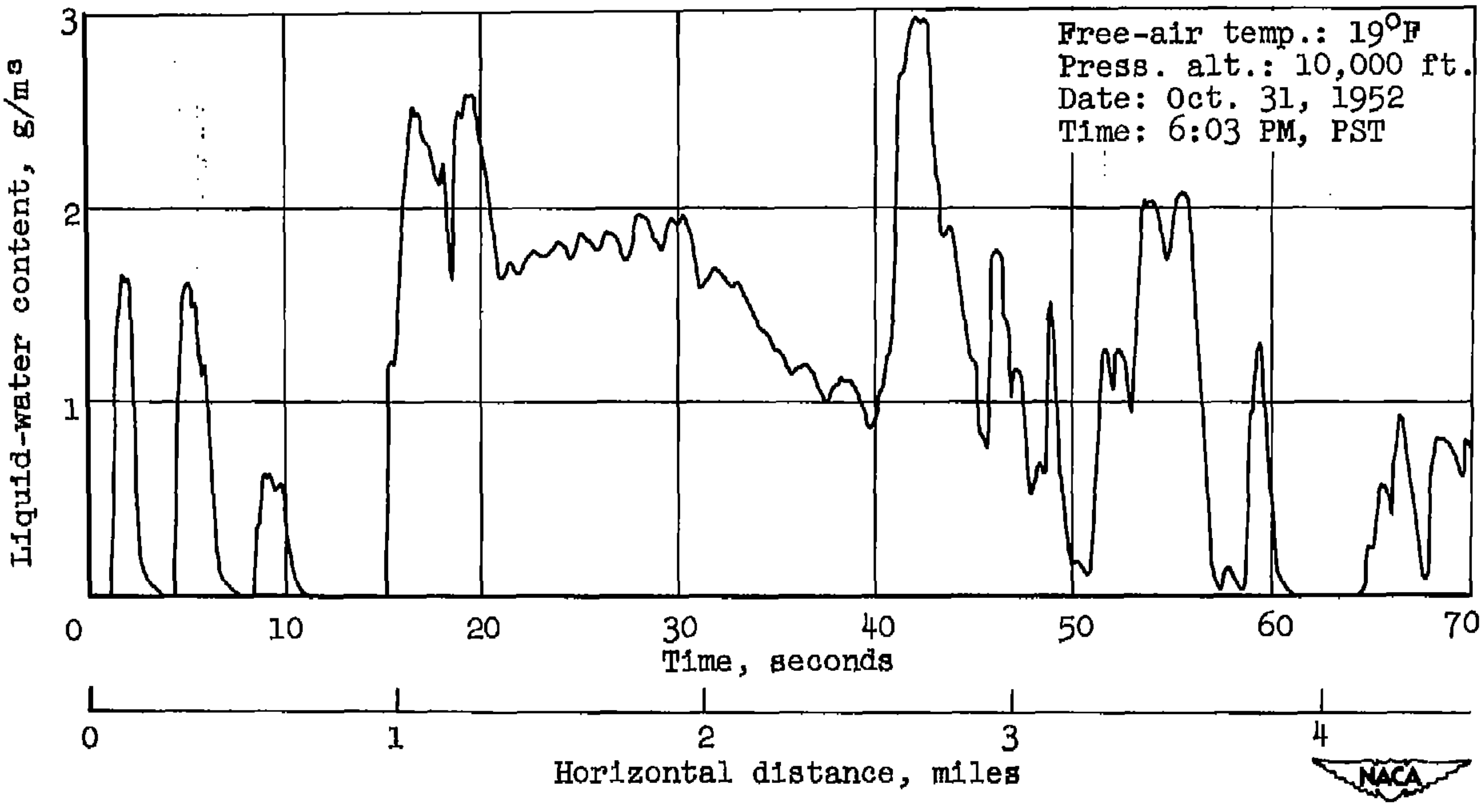
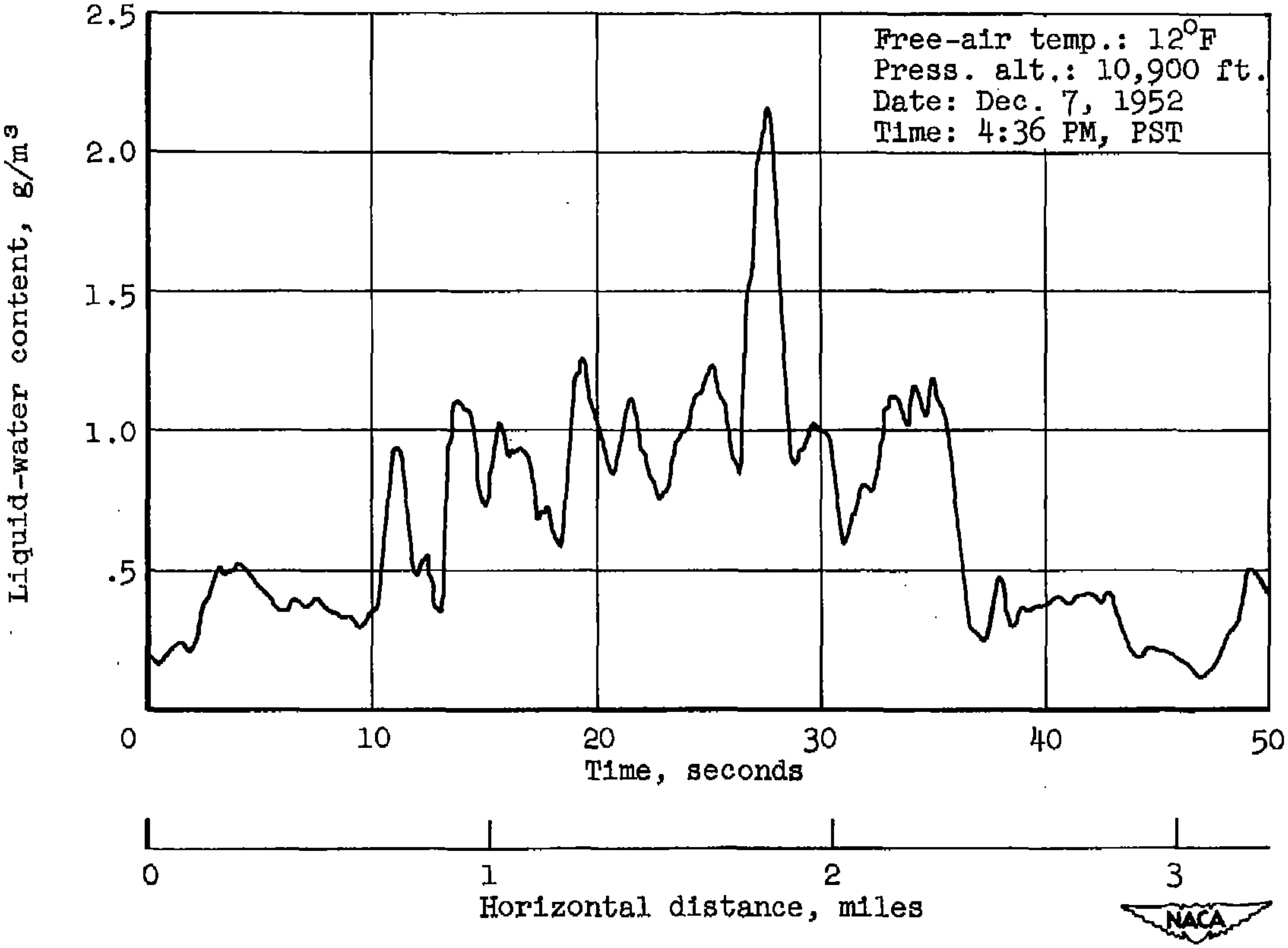


Figure 11.- Comparison of saturation-temperature-difference curves for two sizes of heated wires, as determined from tests in cloud duct.



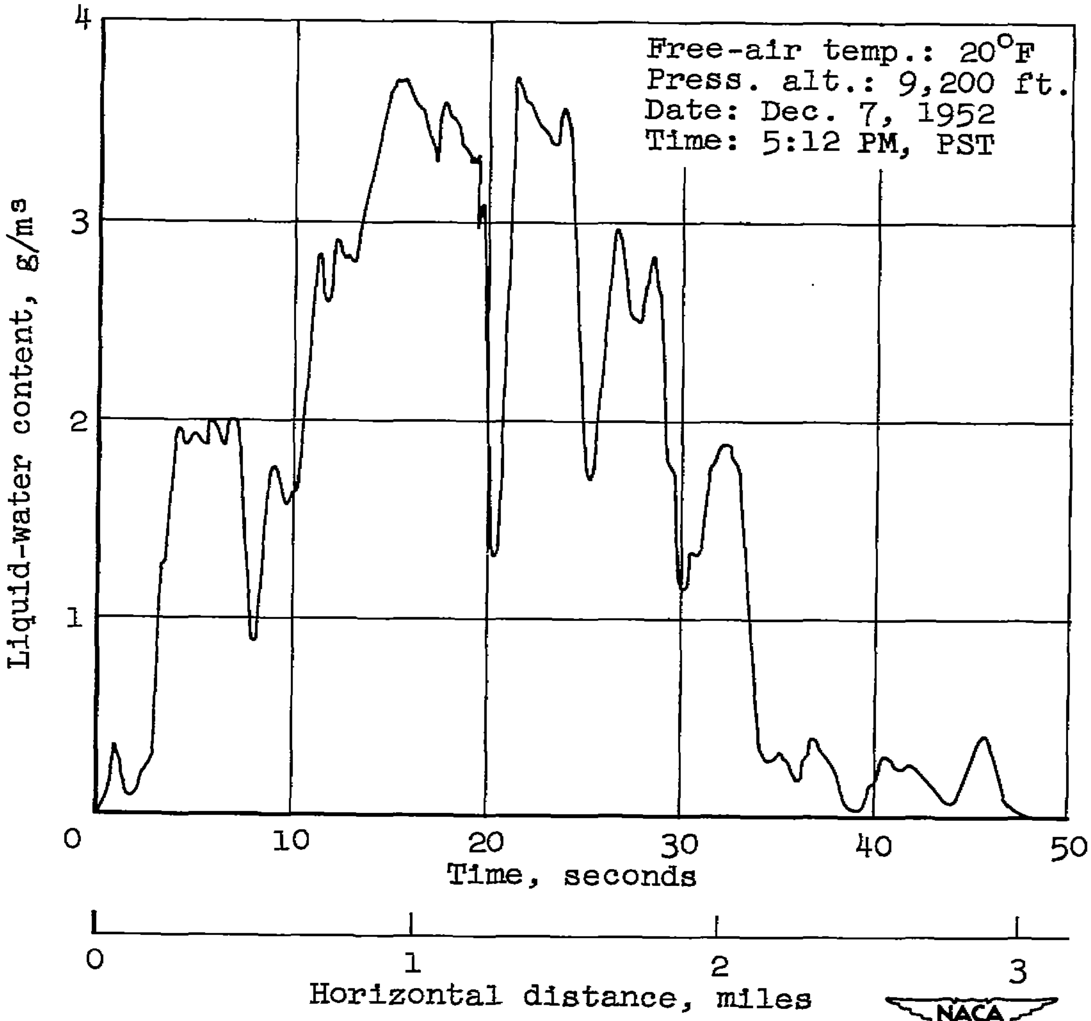
(a) Icing encounter A.

Figure 12.- Measurements of liquid-water-content variation through cumulus clouds as obtained with NACA heated-wire icing-severity instrument during United Air Lines Convair 340 tests. (See figure 13 for locations of encounters.)



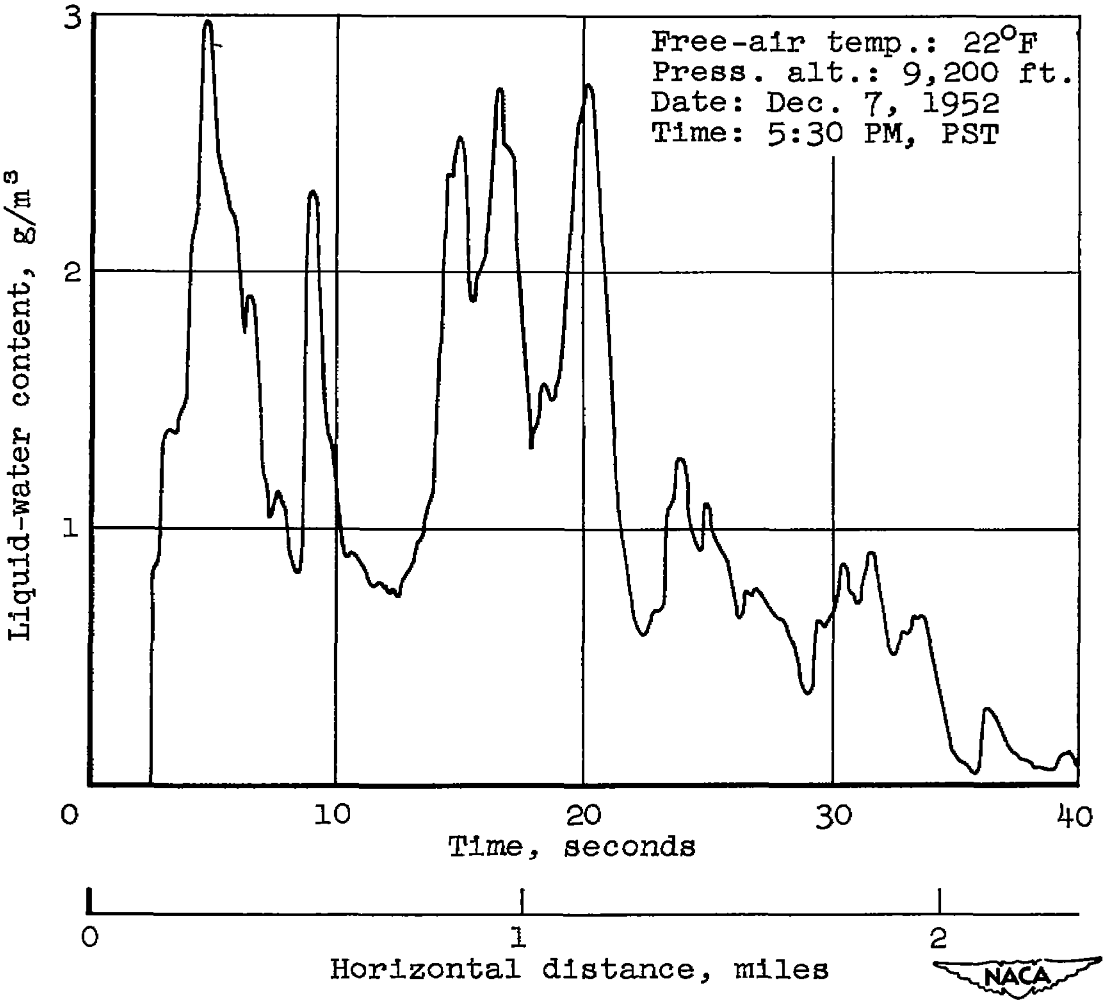
(b) Icing encounter B.

Figure 12.- Continued.



(c) Icing encounter C.

Figure 12.- Continued.



(d) Icing encounter D.

Figure 12.- Concluded.

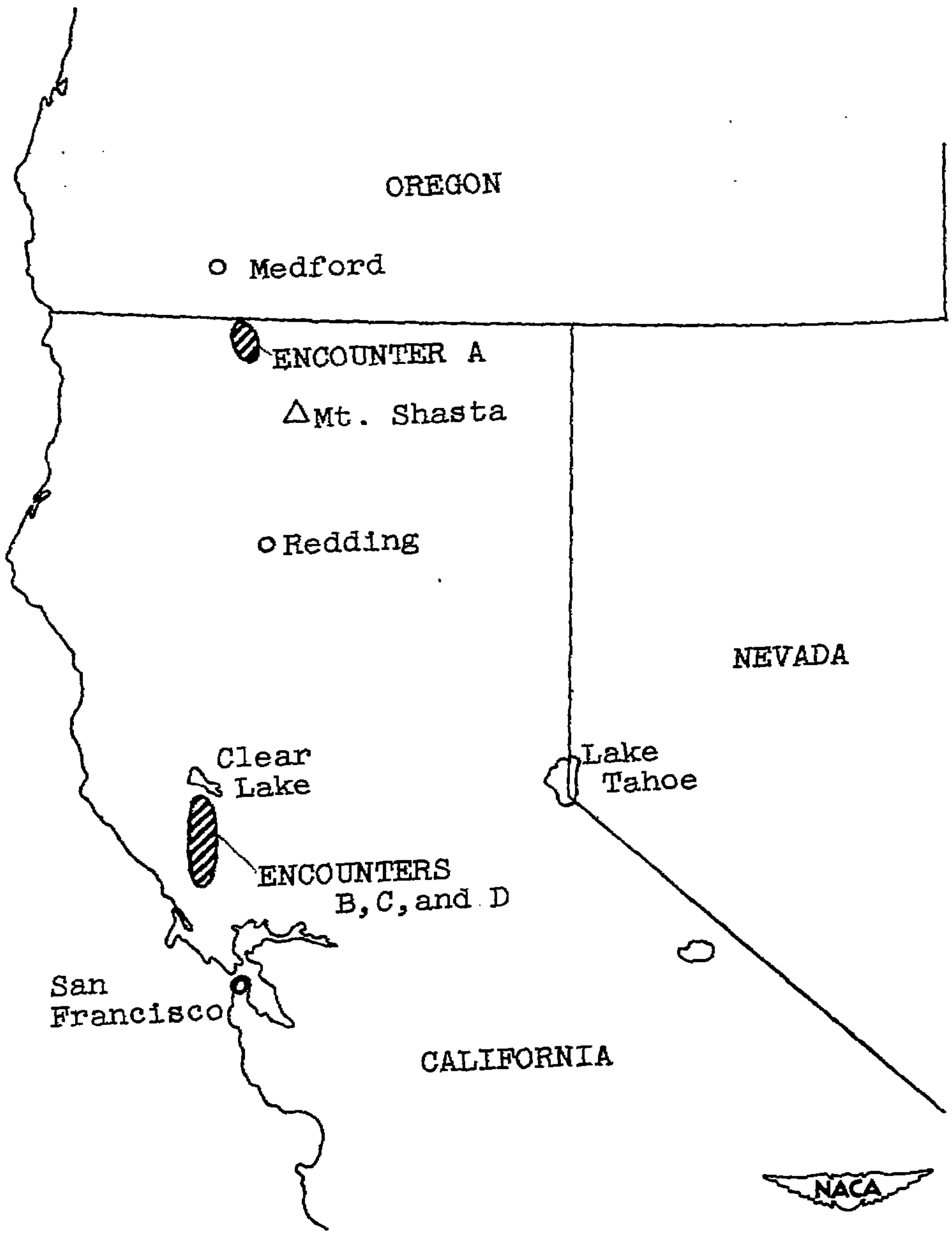


Figure 13.- Approximate geographical locations of icing encounters of figure 12.