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RESEARCH MEMORANDUM

A SIMPLIFIED INSTRUMENT FOR RECORDING AND INDICATING FREQUENCY AND INTENSITY OF ICING CONDITIONS ENCOUNTERED IN FLIGHT

By Porter J. Perkins, Stuart McCullough, and Ralph D. Lewis

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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A SIMPLIFIED INSTRUMENT FOR RECORDING AND INDICATING FREQUENCY AND INTENSITY OF ICING CONDITIONS ENCOUNTERED IN FLIGHT

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SUMMARY

An instrument for recording and indicating the frequency and intensity of aircraft icing conditions has been developed by the NACA Lewis laboratory to obtain statistical icing data over world-wide air routes during routine airline operations. An accumulation of data of this type is needed to provide pertinent meteorological information necessary for the optimum design of ice-protection systems.

The operation of the instrument is based on the creation of a differential pressure between an ice-free total-pressure system and a total-pressure system in which small total-pressure holes vented to static pressure are allowed to plug with ice accretion. At a fixed value of ice accretion, the differential pressure operates an electrical heater that de-ices the total-pressure holes. The resulting cyclic process varies with the intensity of the icing and serves as a measure of the icing rate. The simplicity of this operating principle permits automatic operation upon encountering an icing condition, and relative freedom from maintenance and operating problems. The complete unit weighs only 18 pounds. Icing rate, airspeed, and altitude are recorded on photographic film providing $4\frac{1}{2}$ hours of continuous data. Visual indications of the icing intensity are made available to the pilot by periodic flashing of a light on the instrument panel.

The indications of icing rate from the instrument were calibrated against the rotating-disk type of icing-rate meter. Recorded values of icing rate and airspeed provide a means of obtaining values of cloud liquid-water content based on the multicylinder method for measuring supercooled cloud quantities.

INTRODUCTION

A large accumulation of statistical data concerning the probabilities of occurrence, extent, and severity of icing conditions during routine flight operations is essential for determining the optimum design of ice-protection systems. A measure of the concentration of liquid water in a supercooled cloud is of considerable value in determining the severity of aircraft icing conditions. The maximum rate of ice accretion on aircraft components is principally a function of the amount of supercooled water in a cloud. Flight measurements of the liquid-water content of icing clouds can therefore be used to determine the intensity of an icing encounter and thereby provide pertinent information for the design of adequate ice-protection systems.

In considering an instrument for accumulating data on icing conditions encountered on regularly scheduled airlines or other flight operations, emphasis must be directed toward lightness of weight together with rugged construction and simplicity of operation. The instrument having these features reported herein was designed and constructed by the NACA Lewis laboratory for the purpose of obtaining statistical icing data over the air routes of the world. The instrument is called a pressure-type icing-rate meter. The rate of icing measured by the instrument was calibrated in terms of liquid-water content of icing clouds.

OPERATING PRINCIPLE

The instrument operates on differential pressure created when small total-pressure holes plug with ice accretions, as illustrated in the sketch of figure 1. The small total-pressure holes in the ice-collecting element, which are vented to static pressure through a small orifice, are balanced against a nonvented, ice-free total pressure in a differential pressure switch. When these small total-pressure holes plug from ice accretion, the pressure in the corresponding side of the pressure switch approaches static by bleeding through the static orifice and a differential pressure is created between the iced and ice-free systems. Continuous operation is obtained by allowing the differential-pressure switch to energize an electric heater that de-ices the ice-plugged total-pressure holes. The pressures in the two systems then tend to equalize, opening the pressure switch and allowing the cycle to be repeated. The heat-off time of this cyclic process is used as a measure of the period of time required to plug the holes. This period is a function of the rate at which ice accumulates on the element containing the holes because the amount of ice accretion required for plugging is a constant value. The duration of the heat-off period is calibrated against a measured icing rate in order to obtain a measure of icing rate from the heat-off period. The rate of icing thus measured is a function of cloud liquid-water content and air velocity. In order to obtain cloud liquid-water content, the air velocity is measured simultaneously with the heat-off or icing period.

An NACA flight-type film recorder is used to record continuously the duration of the heat-off or icing period, the heat-on or de-icing period, the indicated airspeed, and the altitude. The recorder is semiautomatic in that the initial plugging starts the recorder, which operates continuously until turned off manually after an icing encounter. The recorder may be supplemented with a remote panel equipped with indicating lights that can be installed in the pilots' compartment for visual indications of the icing intensity and the operation of the recorder during flight. An icing encounter is indicated by periodic flashing of a light parallel with the heating circuit; thus, the time between flashes can be used as an indication of the icing intensity. Another light on this panel indicates the operation of the recorder, and a third light indicates when the recording film is exhausted.

DESCRIPTION OF INSTRUMENT

Construction. - The instrument is composed of three separate units: (1) the ice-collecting unit, (2) the film-recorder unit, and (3) the remote indicating panel. A photograph of these three units, which have a combined weight of approximately 18 pounds, is shown in figure 2.

The ice-collecting unit (close-up in fig. 3) is a "U"-shape tubular construction with 10 small total-pressure holes (0.014-in. diam.) drilled in the side of a small phosphor-bronze tube (0.100-in. diam.) attached at the bottom of the "U". The multiple number of holes is considered necessary to prevent erratic plugging from large droplets or foreign material. The larger tubes of nickel alloy at the sides of the "U" support this small tube about 6 inches from a brass plate that fastens to the skin of the aircraft. Figure 3 shows this unit mounted on the left side of the fuselage ahead of the propeller plane of a twin-engine research aircraft. The "U"-shape unit is mounted normal to the air stream with the total-pressure holes in the small tube on the upstream side.

A 400-cycle, step-down transformer is mounted on the inboard side of the base plate of the ice-collecting unit and is protected by a metal cover. The transformer provides a large electric current (70 amperes) for de-icing the complete tube. The current is conducted directly through the metal tubing exposed to the airstream. The tubing materials selected are of such electrical resistance that the support tubes will de-ice before the small tube containing the total-pressure holes.

The film-recorder unit operates on 28 volts d.c. and contains the film-recording mechanism, airspeed and altitude cells, pressure switch, and electrical components for the complete operation of the instrument. The film-drive motor is governor-controlled to provide a constant film speed of about 1 inch per minute. The film drums containing 20 feet of $2\frac{7}{16}$-inch-wide roll film are easily replaceable and are provided with an electrical switch that automatically operates the indicating light when the film supply is exhausted. The airspeed and altitude cells consist of metal bellows each separately enclosed in sealed capsules. Differential pressures from the airspeed and altitude pressure taps actuate the bellows. The movement of the bellows is magnified by a light beam and mirror system, which records these deflections on the film. The deflections are calibrated in terms of dynamic pressure and pressure altitude for the airspeed and altitude cells, respectively. The pressure switch is a metal diaphragm type that can be adjusted to operate at various differential pressures. An electrically operated marker solenoid, which is energized when the pressure switch closes, records the icing and de-icing periods on the film.

A complete wiring diagram for the instrument is given in figure 4. The 115-volt, 400-cycle power required for de-icing the ice-collecting unit and the 28-volt d.c. power required to operate the film-recorder unit enter at the side of the film-recorder unit. Each power input is fused separately within the recorder unit. The 400-cycle power to the ice-collecting unit is conducted through a 28-volt d.c. relay controlled by the pressure switch. This same relay closes a second 28-volt d.c. relay that energizes the film recording mechanism.

The pressure connections to the instrument are shown in the diagram of figure 5. The total pressure from both the ice-collecting unit and the ice-free system (conventional total-pressure system of aircraft) are connected to the differential-pressure switch in the film-recorder unit. The total pressure from the ice-collecting unit is vented to static pressure through an orifice (0.018-in. diam) connected to the static side of a pitot static-pressure tube or to a static-pressure tap on the side of the aircraft fuselage. The conventional static-pressure system of the aircraft should not be used as a source for this static pressure because of the higher pressures introduced through the orifice. This static-pressure tap is unnecessary in unpressurized aircraft where the cabin pressure is approximately equal to outside static pressure. The static orifice is located within a tube fitting on the pressure switch. The conventional total- and static-pressure systems of the aircraft are connected to the airspeed and altitude cells on the recorder unit.

Operation. - If both the 115-volt 400-cycle, and the 28-volt d.c. power are supplied to the instrument, operation will automatically start upon entering an icing condition. The small total-pressure holes, when plugged from the initial ice accretion, will create a differential pressure across the pressure switch. The switch will operate when the differential pressure reaches a fixed value and close the 28-volt d.c.

circuit to the first or "heater" relay. Two sets of contacts on this relay will close, one set operating the 115-volt 400-cycle power to the ice-collecting unit, and the other set operating the second or "recorder" relay. The recorder relay locks itself in and energizes the 28-volt d.c. film-recording mechanism. Both the "heat" and "recorder" indicating lights on the remote panel will glow and the marker solenoid in the film recorder will be displaced.

After the heating power has cleared the total-pressure holes, the pressures in the pressure switch will tend to equalize, which causes the switch to open when the differential pressure drops to a fixed value slightly lower than that required to close the switch. The "heater" relay will then open, turning off the heating power and causing the "heat" indicating light to go out and allowing the marker solenoid to return to its original position. When the total-pressure holes are again plugged with ice, the cycle is repeated. After the icing has ceased, the push-button on the remote panel or on the recorder must be depressed to open the "recorder" relay and stop the film-recording mechanism.

This operating principle thus provides several features that make the instrument desirable for use during routine airline operations. These features include (1) simplicity of operation, (2) freedom from maintenance and operating problems, (3) automatic operation upon encountering an icing condition, (4) visual indications of icing intensity available to the pilot, and (5) a total weight of 18 pounds.

CALIBRATION

Rate of icing. - If it is assumed that the ice collecting on the tube with the total-pressure holes builds up to the same thickness during each icing cycle regardless of the rate of ice accretion, the rate of icing as measured by the instrument can be expressed by the relation

$$R = \frac{k}{P}$$

where

R icing rate, (in./min)

k constant ice thickness, (in.)

P icing period or heat-off time required to accumulate ice to thickness k, (min)

The icing period as indicated by the instrument includes the time required for the ice-collecting element to cool to the icing temperature and, therefore, an icing rate determined by the above relation would be smaller than the true value. The low thermal-time constant of the element makes this a small and nearly constant error that permits a calibration against a known icing rate.

The total-pressure holes were made small in order to obtain practical icing periods for the range of icing rates usually encountered in flight. These short periods of icing are not enough to allow a sufficient thickness of ice accretion to be conveniently measured. Because of this limitation, the instrument cannot be used as a fundamental means of measuring icing rate and, therefore, must depend on a calibration against a known icing rate. A rotating-disk type icing-rate meter was used for this calibration, which was conducted in the NACA icing research tunnel.

The rotating-disk type meter for measuring the rate of icing, first developed by the Massachusetts Institute of Technology (reference 1), consisted of a rotating disk edgewise to the air stream, a feeler to measure the thickness of the ice collected on the edge of the disk, and a scraper to remove the ice after its thickness has been measured. A photograph of the meter and a close-up taken during operation (figs. 6(a) and 6(b)) illustrate this operating principle. The meter can be seen mounted on the side of the fuselage of the research aircraft in figure 3.

The pressure-type meter was calibrated in the tunnel for rate of icing by varying the liquid-water content and the velocity of the air stream. Both meters were mounted so that the ice-collecting elements were within 2 inches of each other to assure the same icing conditions for both instruments. The results of this calibration (fig. 7) show that the icing period or heat-off time varies between 0.21 to 0.07 minute (13 to 4 sec) for an icing-rate range of 0.055 to 0.22 inch per minute (3 to 13 in./hr). The variation of slope of the calibration curve provides the greatest reading accuracy at the low icing rates, but the accuracy decreases as the icing rate becomes greater to a point where the icing period becomes almost insensitive to large changes of icing rate. The maximum limit of operation occurs at the point where the heat must stay on continuously to keep the total-pressure holes ice-free. The reading error varies from ±2 percent at the low icing rate to ±20 percent at the measurable high icing rates. The reading accuracy of the disk-type meter varies between ±12 percent at the low icing rate to ±6 percent at the high icing rate, thus providing a total maximum error in the calibration of about ±14 percent at the low icing rates to ±26 percent at the high icing rates. No effects of air temperature on the icing-rate calibration were noted between 0° and 20° F.

Liquid-water content. - The reciprocal of the icing period was used in the plot shown in figure 8 to obtain a linear relation to liquid-water content, which was calculated from the values of air velocity and icing rate using the results of previous studies of the ice-collecting characteristics of the rotating disk. These investigations were conducted by the NACA during a series of icing research flights from the Lewis laboratory. It was found that the disk-type icing-rate meter collects between 50 and 70 percent of the liquid-water content as measured by the multicylinder technique (reference 2). The accuracy of this technique cannot be completely evaluated because of the unknown magnitude of errors resulting from blow-off, otherwise failure of the cloud droplets to adhere to the cylinders, and the validity of the theoretical analysis used to determine the droplet trajectories that intercept the cylinders. Values of liquid-water content used in this plot were calculated from the indications of icing rate from the disk-type meter using a 60-percent water-collection relation based on the multicylinder comparison. The plot of figure 8 is for an air velocity of 250 miles per hour. Values of liquid-water content may be obtained from this graph at other air velocities by using the following relation:

$$LWC_1 = \frac{250}{V_1} LWC_0$$

where

LWC_1 liquid-water content (grams/cu m) at desired air velocity V_1 (mph)

LWC_0 liquid-water content (grams/cu m) at 250 miles per hour (from graph)

This calibration was verified at 180 miles per hour in flight icing conditions using both the disk-type meter and the multicylinder method installed on the research aircraft shown in figure 3.

OPERATING CHARACTERISTICS

Deposition efficiency. - The errors in the liquid-water content indications of the instrument, which result from assuming no changes in the rate of collection of ice on the small tube because of variations in droplet size, air velocity, and air density, were investigated by calculating the collection efficiency of the tube as a function of these variables using the theoretical cloud-droplet trajectories as calculated in reference 3. One reason for using a small-diameter tube for the ice-collecting element was to obtain a high collection efficiency and thereby reduce the possible errors to a minimum. The diameter of the total-pressure holes centered on the stagnation line of the tube is small enough to consider only the droplet deposition at the stagnation line of the tube. The enlarged sketch of the tube given in figure 9(a) shows the relative size of the total-pressure holes to the diameter of the tube. The hole diameter includes an angle of only ±8° about the stagnation line, which permits the use of the droplet deposition at stagnation without introducing any appreciable error in the calculations. The deposition efficiency at the stagnation point β_0, defined as the amount of ice collected at the stagnation point relative to that which could be intercepted if there were no deflection of the droplets, was calculated for a range of droplet diameters at various air velocities and altitudes. It can be seen from these calculations as plotted in figure 9(b) that for the range of droplet sizes between 5 and 50 microns the deposition efficiency is above 0.80 and for droplets above 10 microns in diameter the deposition efficiency is above 0.93. Air velocity and altitude are shown to have only a slight effect on the deposition efficiency. From this analysis a deposition efficiency of 0.95 was considered as an average value for the most probable ranges of droplet size, air velocity, and density that would be encountered in flight.

Icing of total-pressure holes. - The plugging characteristics of the total-pressure holes from ice accretions were investigated by recording the change in differential pressure, as a result of plugging, with respect to time during the operation of the instrument. It was found from these records that the differential pressure between the iced and ice-free system is not created suddenly but instead has a variable rate of change while the total-pressure holes are plugging with ice. This fact is illustrated by some typical records shown in figure 10 where the differential pressure Δp is plotted against time for several cycles of operation. As the total-pressure holes collect ice, the differential pressure increases gradually at first, then more rapidly, as it approaches the full dynamic pressure of the airstream. The differential-pressure switch was set, in this case, to go on before full dynamic pressure was reached and, therefore, de-icing prevented the differential pressure from becoming the full dynamic pressure. It will be noted that the differential pressure rapidly decreases following de-icing at the maximum value.

A minimum differential pressure of 2 to 4 inches of water exists in an ice-free condition because of air flow through the static orifice created by the static-pressure tap. The switch is set to go off at a differential pressure about 3 to 5 inches of water above this minimum value to assure a safe margin of operation and to allow as much heating time as possible for complete de-icing of the element.

The differential-pressure records shown in figure 10 were taken at both a high and low icing rate to show the variation in the differential-pressure changes at each condition and the resulting traces that are recorded on the standard data film. The length of the heat-off line can be used as a direct measure of the icing rate provided the speed of the film travel is known. The heat-on or deicing period does not change appreciably with icing rate but is affected more by air temperature and velocity.

Research flights were conducted in snow and rain to check the operation of the instrument in atmospheric conditions other than supercooled clouds. The instrument was not affected by these conditions, which indicates that the small total-pressure holes respond only to ice accretions.

Static-pressure bleed. - The static-pressure bleed was investigated to determine whether its characteristics influenced the indications of icing rate. The volume of air in the ice-collecting side of the total-pressure system must be exhausted in less time than that required for the holes to plug with ice to prevent any effects from the static-pressure bleed. The time required to bleed the air from this system is a function of the pressure difference across the orifice, which is a function of the air velocity and altitude. The bleed time was determined by measuring the time interval required to bleed the system from total pressure to the pressure at which the pressure switch turns on, this interval being simultaneous with the icing period. The results of these measurements for various air velocities and altitudes are plotted in figure 11. It can be seen that the bleed time decreases with increasing velocity and increases with increasing altitude, but within the operating ranges the bleed time is less than the icing period for the highest icing rate calibrated for the instrument. It can therefore be concluded that the bleed-orifice characteristics have little or no effect on icing-rate indications and also that the indications are independent of altitude.

TYPICAL DATA

After the development and calibration of the instrument, arrangements were made to install several of these units on commercial airliners. Part of a typical data film obtained from an icing condition encountered during a routine airline flight is shown in figure 12. Airspeed, altitude, icing rate, and duration of the icing condition can be obtained from this record. With notations by the pilot of time, data, temperature, and geographic location, this record gives sufficient information for a complete meteorological analysis of the particular icing encounter. Values of liquid-water content can be obtained from the icing rate and airspeed records using the calibration previously described. Each film roll usually contains several encounters in sequence, which must be correlated with the pilot's log.

CONCLUDING REMARKS

An instrument for recording and indicating the frequency and intensity of aircraft icing conditions has been developed by the NACA Lewis laboratory for obtaining statistical icing data over world-wide air routes from routine airline operations. The instrument operates on differential pressure created when small total-pressure holes in a static-pressure vented system, which is balanced against an ice-free total-pressure system, are allowed to plug with ice accretions.

The features that make the instrument desirable for use during routine airline operations are: (1) simplicity of operation, (2) freedom from maintenance and operating problems, (3) automatic operation upon encountering an icing condition, (4) visual indications of icing intensity available to the pilot, (5) total weight of 18 pounds, and (6) continuous recorded data. Recorded values of icing rate and airspeed provide a means of calculating cloud liquid-water content based on the multicylinder method for measuring supercooled cloud quantities.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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2. Anon.: The Multicylinder Method. The Mount Washington Monthly Res. Bull., vol. II, no. 8, June 1946.

3. Langmuir, Irving, and Blodgett, Katherine B.: A Mathematical Investigation of Water Droplet Trajectories. Tech. Rep. No. 5418, Air Materiel Command, AAF. Feb. 19, 1946. (Contract No. W-33-038-ac-9151 with Gen. Elec. Co.)

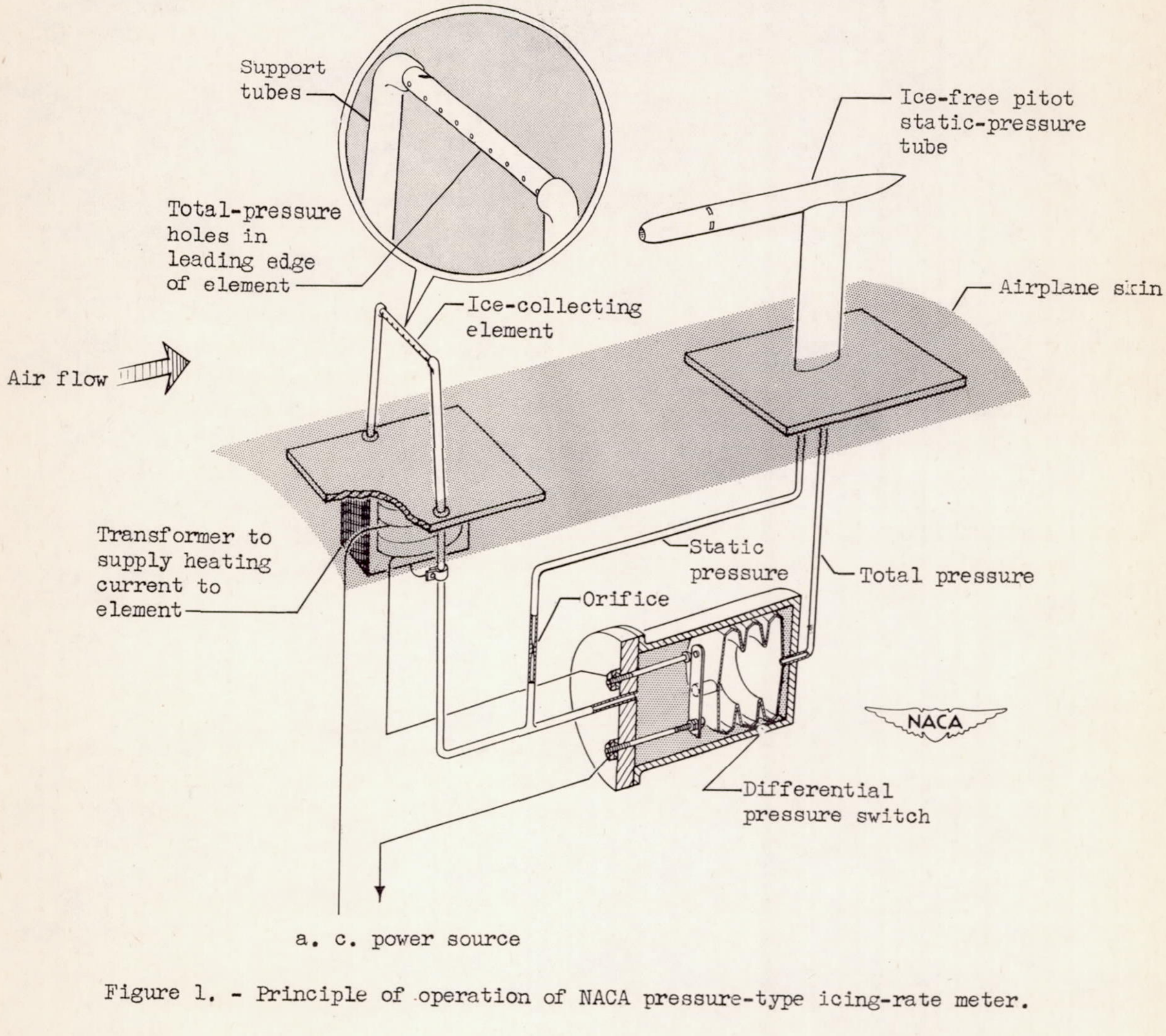


Figure 1. - Principle of operation of NACA pressure-type icing-rate meter.

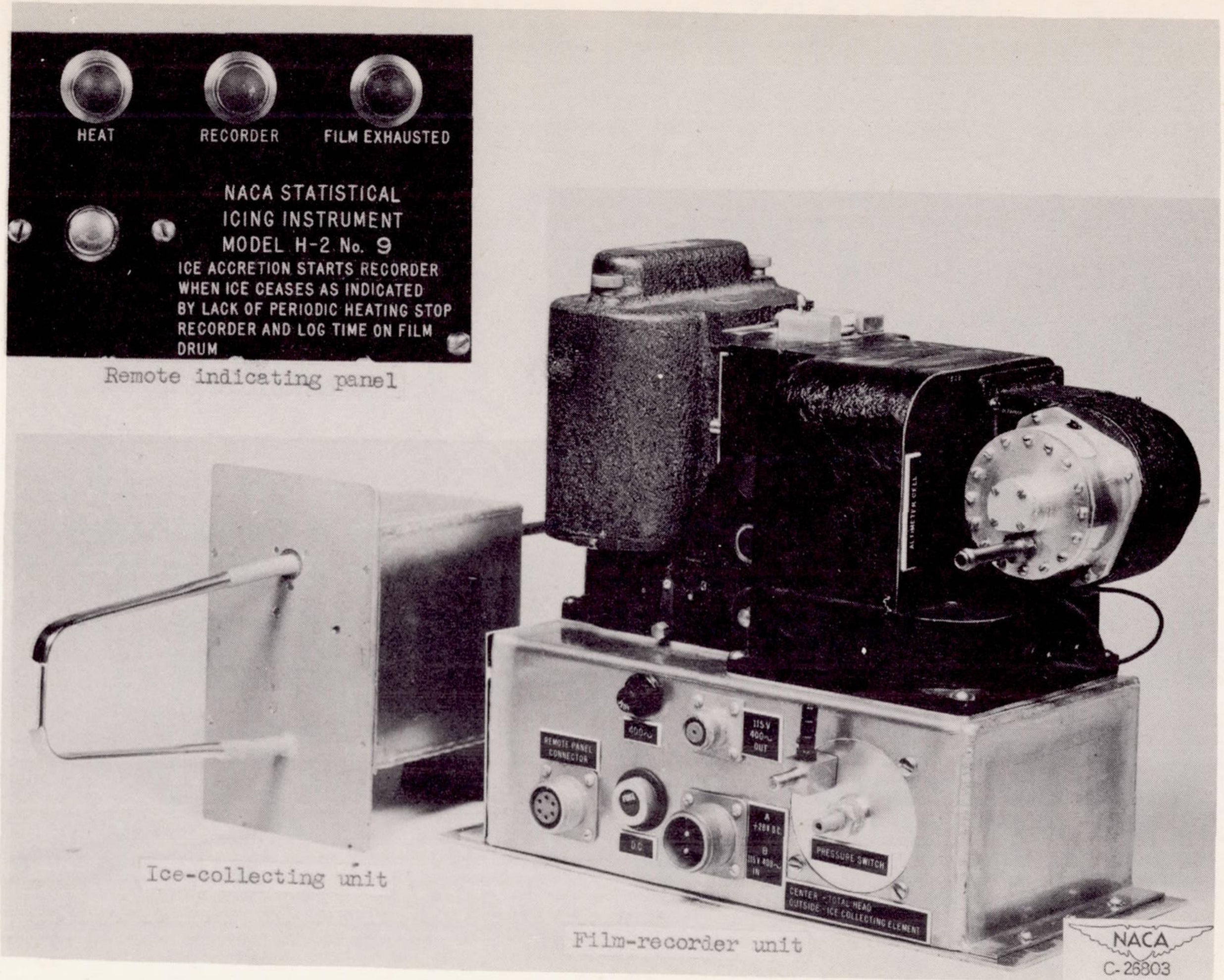
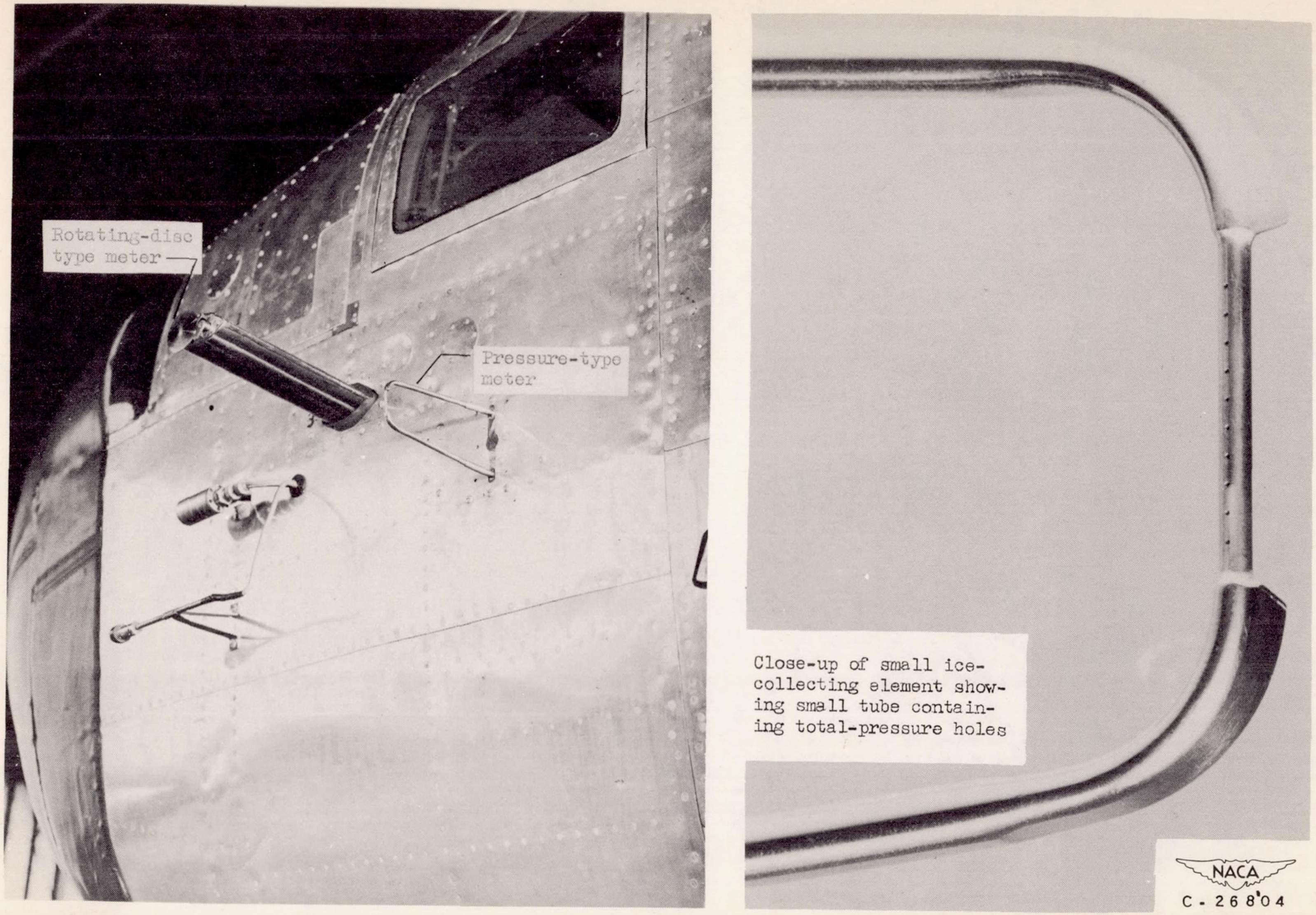


Figure 2. - NACA pressure-type icing-rate meter.



Close-up of small ice-collecting element showing small tube containing total-pressure holes

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Figure 3. - Ice-collecting element of NACA pressure-type icing-rate meter mounted on fuselage of research aircraft.

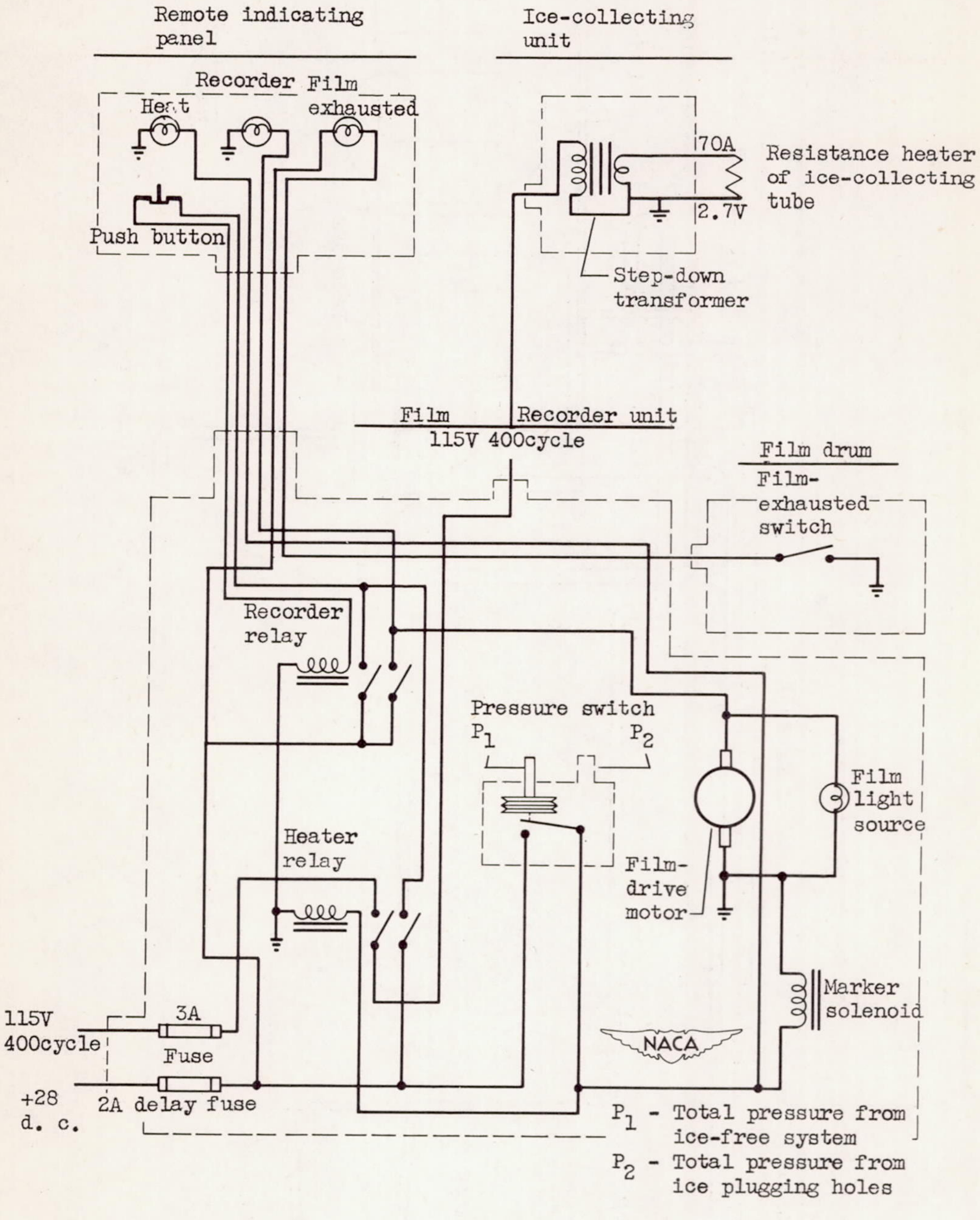


Figure 4. - Wiring diagram for NACA pressure-type icing-rate meter.

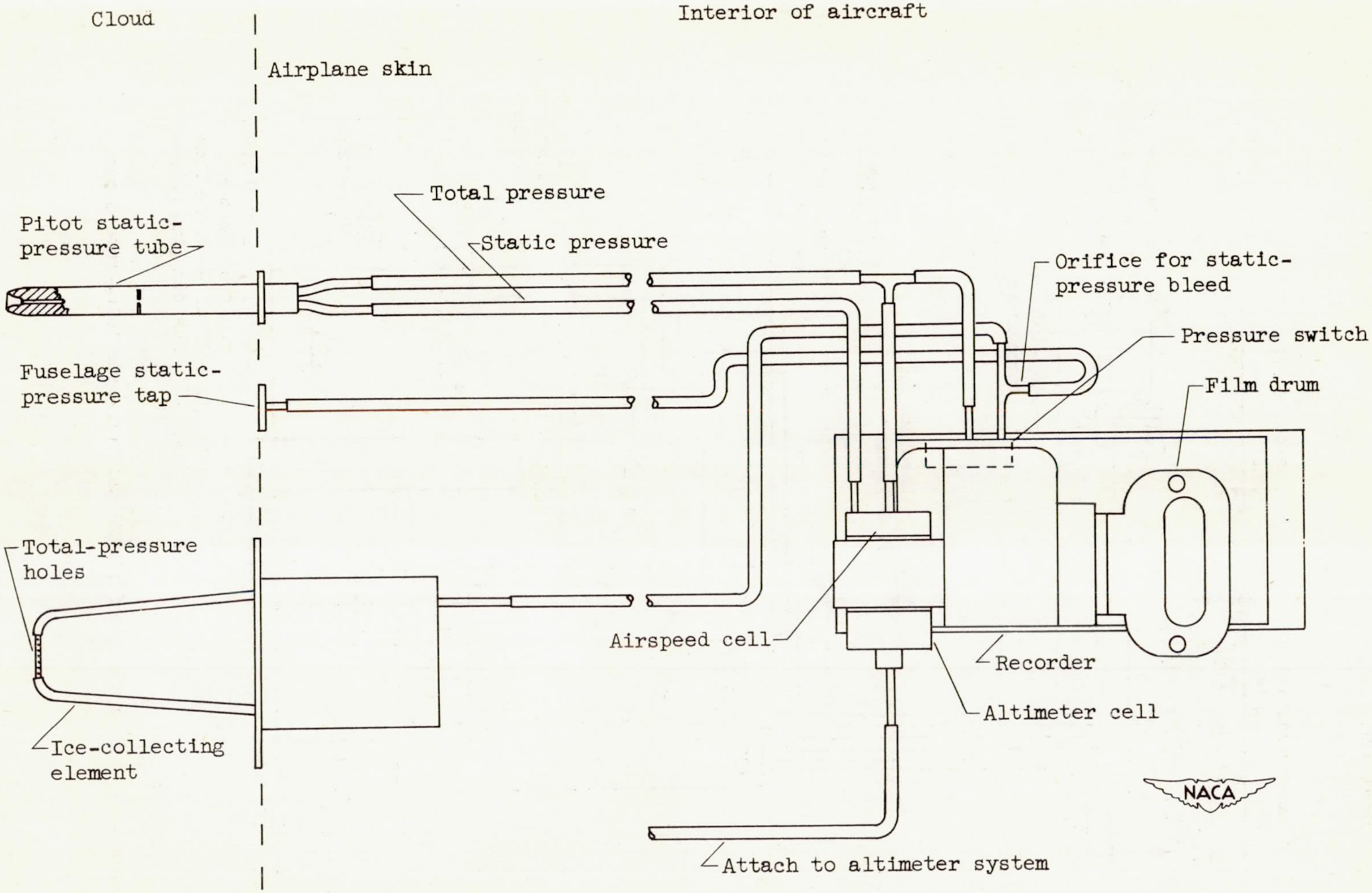
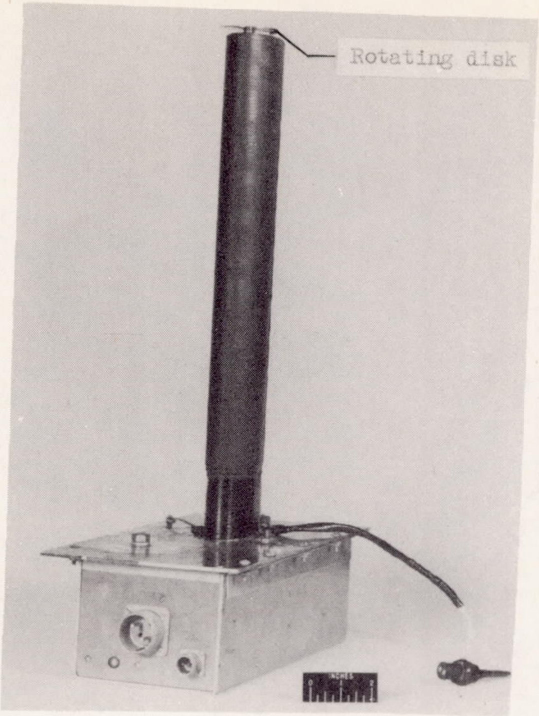


Figure 5. - Pressure diagram for NACA pressure-type icing-rate meter.



(a) Over-all view of rotating-disk type icing-rate meter.

(b) Close-up of face of rotating disk illustrating operating principle for measuring icing rate.

Figure 6. - Rotating-disk type icing-rate meter.

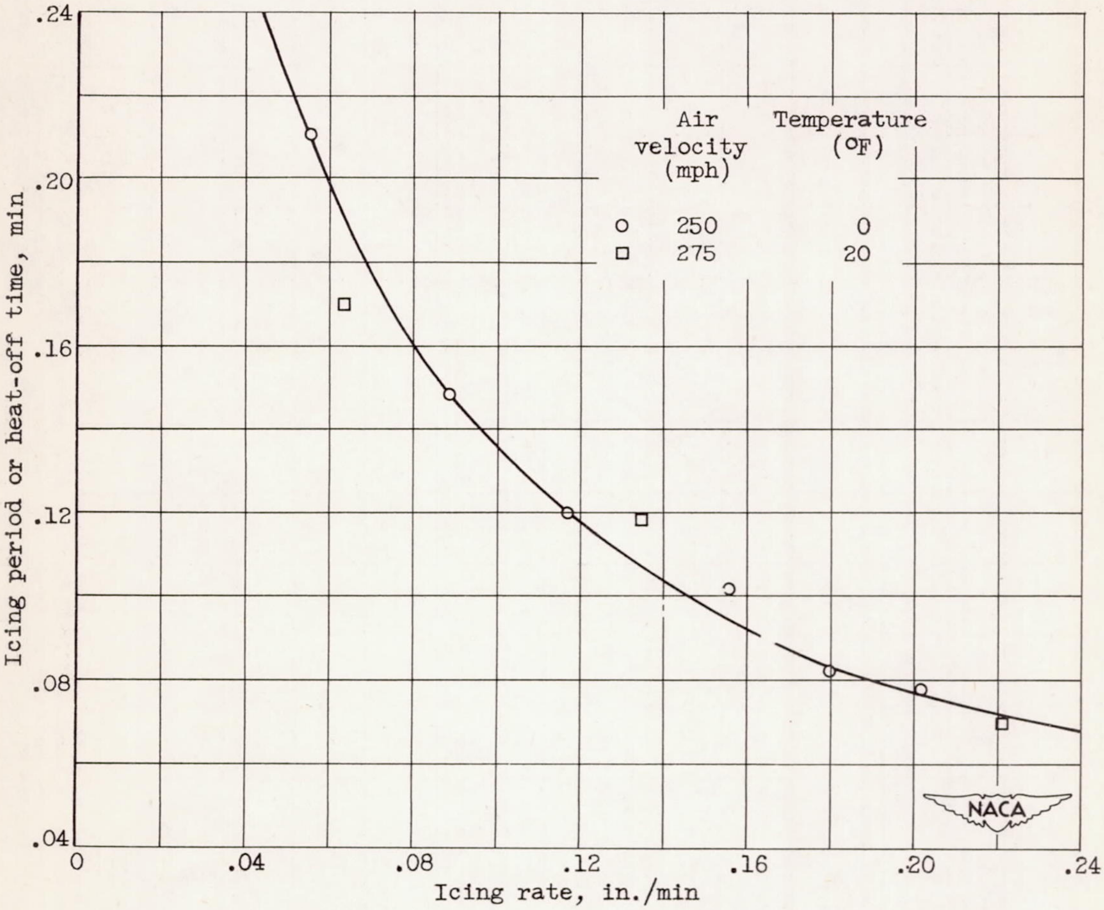


Figure 7. - Calibration of pressure-type icing-rate meter against rotating-disk type icing-rate meter in NACA icing research tunnel.

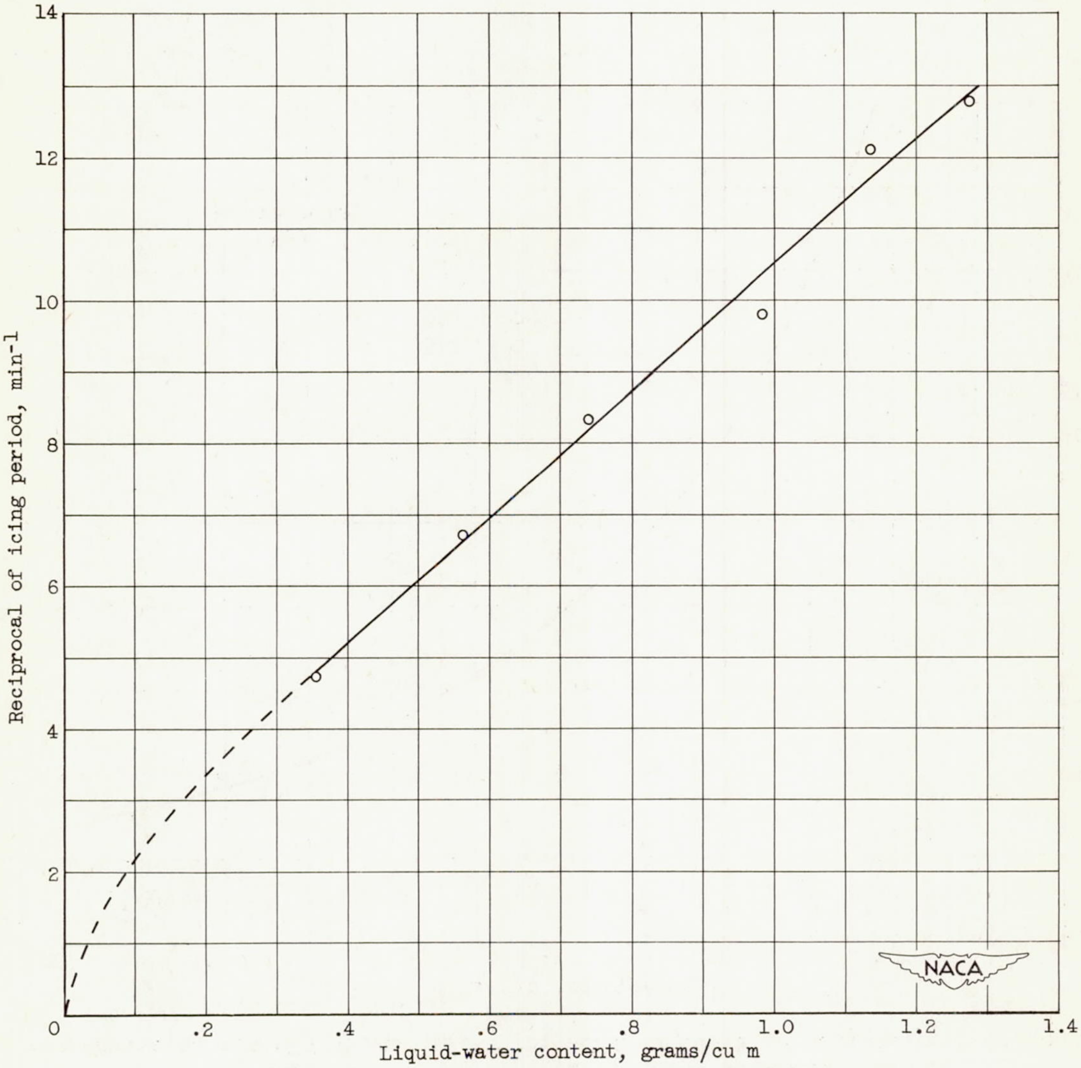
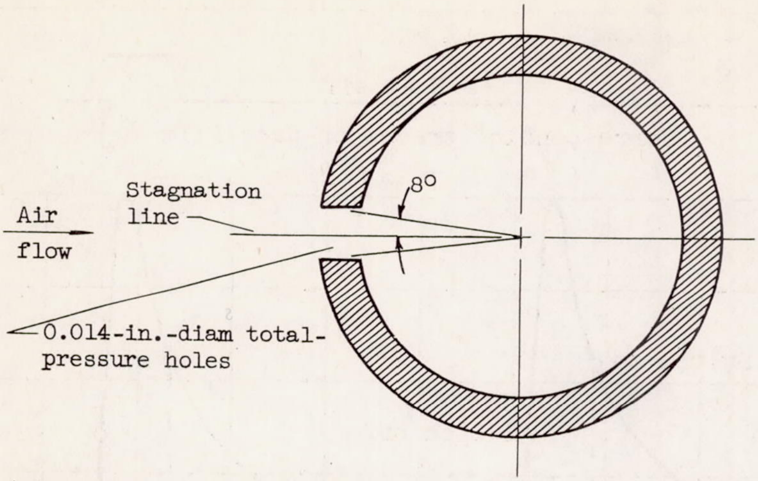
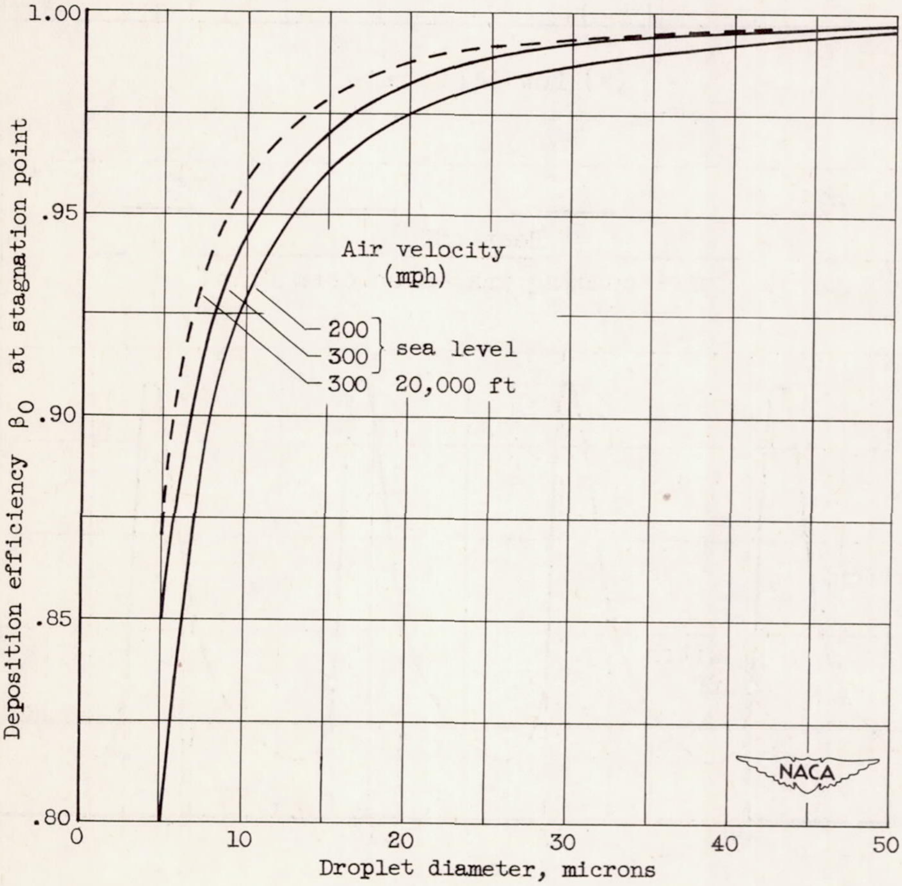


Figure 8. - Graph for obtaining cloud liquid-water content from indications of pressure-type icing-rate meter at 250 miles per hour. Values of liquid-water content based on calibration of disk-type icing-rate meter against multicylinder method.

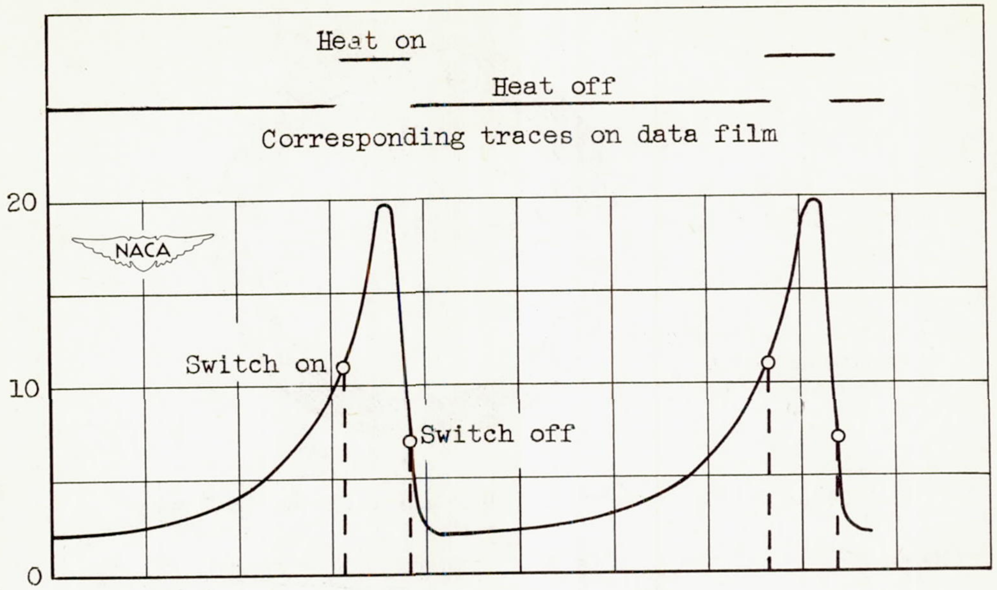


(a) Ice-collecting element of 0.100-inch diameter (25X scale).

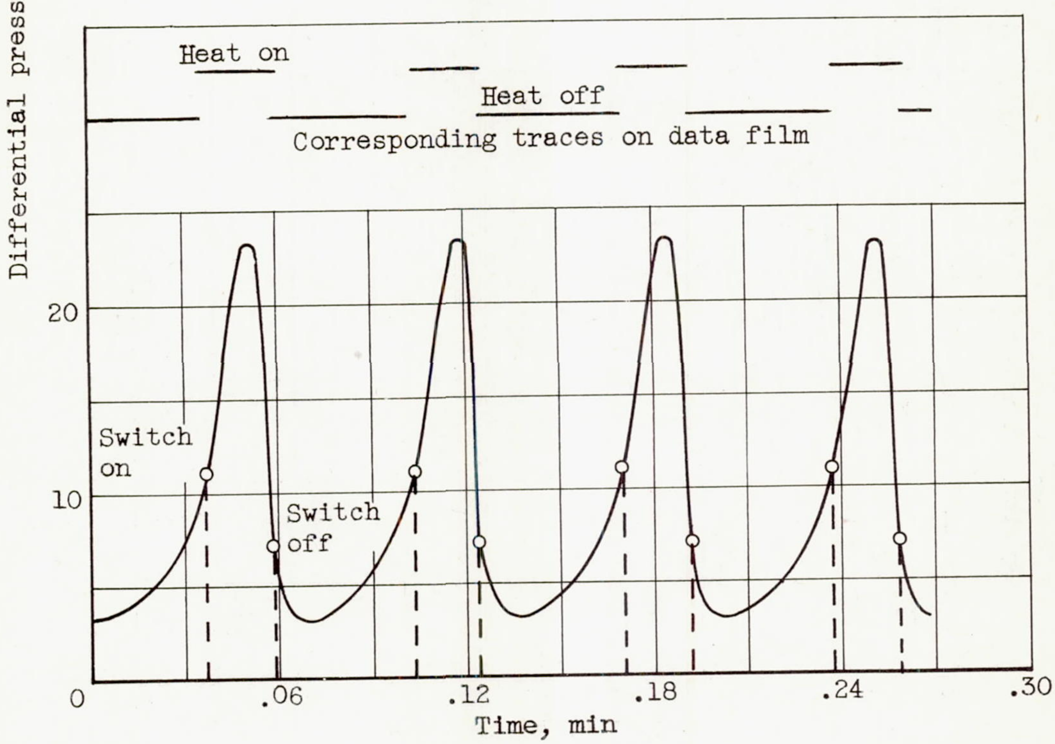


(b) Deposition efficiency at stagnation point.

Figure 9. - Deposition efficiency of pressure-type icing-rate meter. Sketch shows considerations for calculating deposition only at stagnation point.



(a) Low icing rate



(b) High icing rate.

Figure 10. - Typical records of differential pressure for several cycles of operation of pressure-type icing-rate meter showing relation to icing-rate indications as recorded on data film.

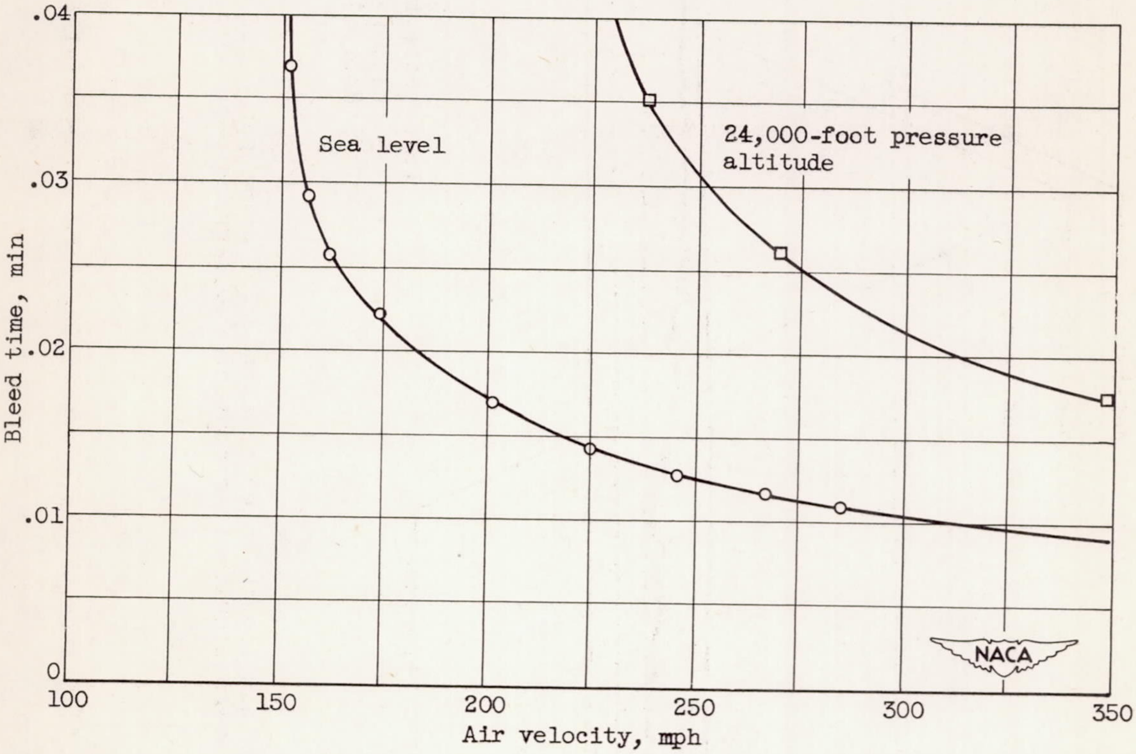
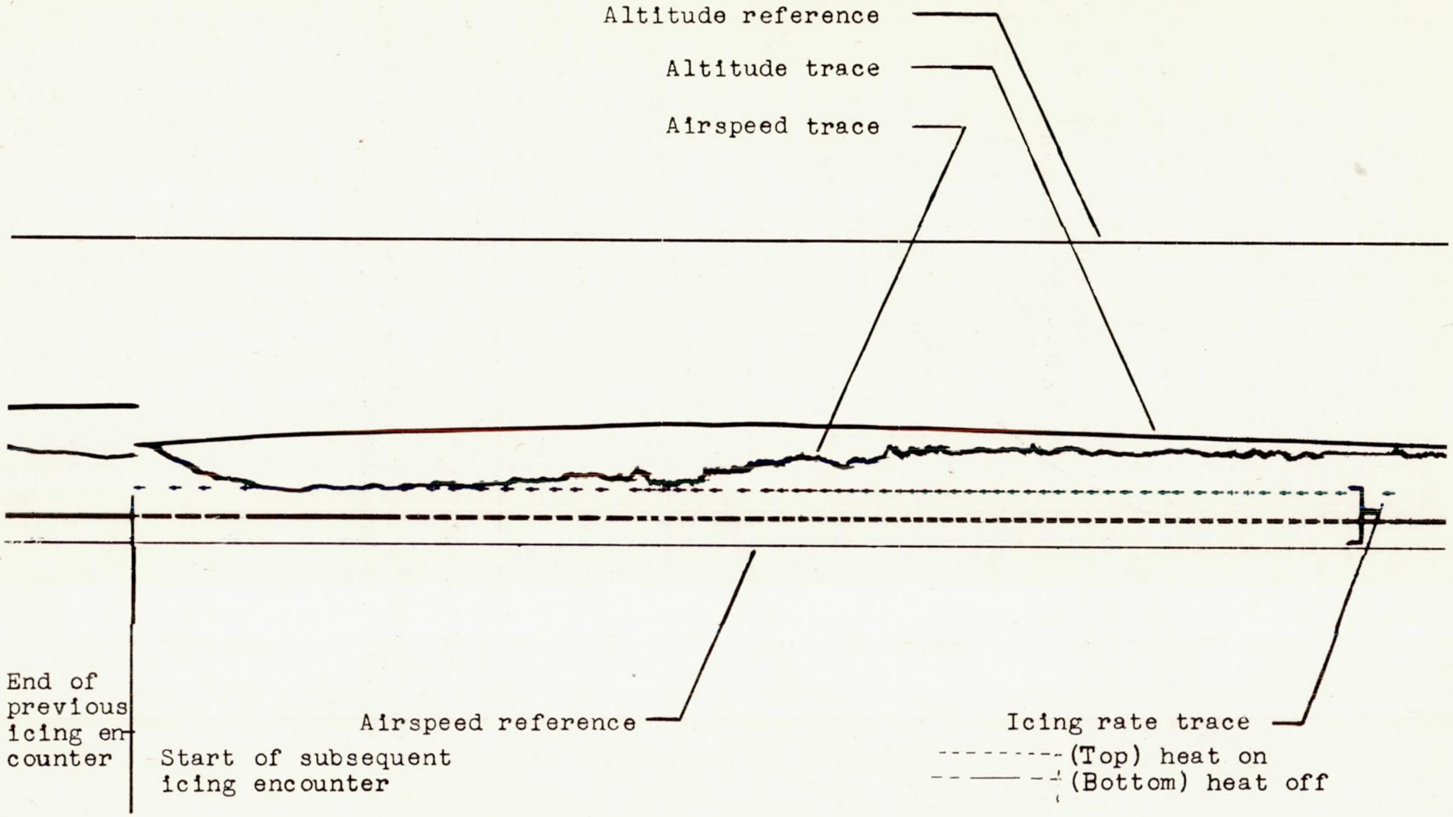


Figure 11. - Time interval required to approach static pressure through bleed orifice during icing period of pressure-type icing-rate meter.



Film analysis: Maximum liquid-water content - 1.3 grams per cubic meter
Average liquid-water content - 0.87 grams per cubic meter

Figure 12. - Portion of data film from pressure-type icing-rate meter obtained during routine airline flight operations.

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