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RESEARCH MEMORANDUM

FLIGHT INSTRUMENT FOR MEASUREMENT OF LIQUID-WATER CONTENT IN CLOUDS AT TEMPERATURES ABOVE AND BELOW FREEZING

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FLIGHT INSTRUMENT FOR MEASUREMENT OF LIQUID-WATER CONTENT IN CLOUDS AT TEMPERATURES ABOVE AND BELOW FREEZING

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SUMMARY

A principle formerly used in an instrument for cloud detection was further investigated to provide a simple and rapid means for measuring the liquid-water content of clouds at temperatures above and below freezing. The instrument consists of a small cylindrical element so operated at high surface temperatures that the impingement of cloud droplets creates a significant drop in the surface temperature.

The instrument is sensitive to a wide range of liquid-water content and was calibrated at one set of fixed conditions against rotating multicylinder measurements. The limited conditions of the calibration included an air temperature of 20° F, an air velocity of 175 miles per hour, and a surface temperature in clear air of 475° F. The results obtained from experiments conducted with the instrument indicate that the principle can be used for measurements in clouds at temperatures above and below freezing. Calibrations for ranges of airspeed, air temperature, and air density will be necessary to adapt the instrument for general flight use.

INTRODUCTION

Determination of the amount of liquid water contained in an atmospheric cloud is of considerable value in meteorology, particularly for investigating the necessary requirements for adequate protection of aircraft against the icing hazard. In connection with icing meteorology, much effort has been directed toward developing a suitable instrument for measuring the liquid-water concentration in clouds where the temperature is below the normal freezing point of 32° F. Because water below its normal freezing point will, upon striking a moving surface, usually freeze and adhere to that surface, a suitable ice-collecting body becomes a convenient means for measuring the amount of water in a below-freezing cloud. For many years, this principle has been used in an instrument utilizing the ice-collection characteristics of various size cylinders. The rotating multicylinder technique, as this method is called, is based on a theoretical treatment of the trajectories of cloud droplets about various size cylinders with axes normal to the air stream (reference 1).

Although a value of the liquid-water concentration of clouds can be obtained with a certain degree of accuracy by the multicylinder method, the difficulty of manipulating the multicylinder device and the inability to measure the liquid-water concentration in above-freezing clouds have emphasized the necessity of developing a more suitable instrument. Another method formerly used for measuring liquid-water concentration in above-freezing clouds employs a capillary-type water-collecting device where the collecting body is of porous material and the water is pulled in from the surface by capillary action (reference 2). These methods as well as any other water- or ice-collecting techniques involve bulky equipment and cannot be easily adapted to general flight application, particularly with regard to accurate measurement of the amount of water or ice collected.

An electric or thermal method for indicating the amount of water collected on a surface offers a medium for using sturdy and reliable instruments that can be readily adapted for flight use. A measure of the amount of electric energy necessary to evaporate water as it is collected on a surface can be utilized in an instrument to determine the liquid-water content of an icing cloud. A more direct and easier method, however, is to detect the amount of water striking a heated surface by measuring the degree of cooling caused by the water as it evaporates from the surface. The amount or rate of water collected can then be measured in terms of the temperature change of the collecting surface. This principle was originally used as a cloud detector to indicate entrance and exit from a cloud during flight (reference 3). The instrument was not used for the measurement of quantitative values of liquid water because the surface temperatures during operation were insufficient.

An instrument for measuring the liquid-water concentration of clouds utilizing the principle of the cooling effect of water striking a heated surface is described herein. The instrument, designed for flight measurements in above- or below-freezing clouds, was calibrated at a given set of air conditions for values of liquid-water concentration by the rotating multicylinder technique in the NACA Lewis icing research tunnel.

INSTRUMENT

Design considerations. - In order to determine the quantity of liquid water in a cloud from the amount collected on a moving body, the collection characteristics of the body must be known. Because the droplet trajectories around a cylinder with axis normal to the air stream have been analyzed, a suitable size cylinder was chosen as the collecting body for this instrument. Although a small cylinder will collect more water in proportion to its size than a larger cylinder (collection efficiency), which makes a small cylinder desirable for this instrument, a very small cylinder was found by experiment to have less cooling effect from water impingement than a large cylinder. A 5/16-inch-diameter cylinder, which would produce enough surface cooling for a high degree of sensitivity to water content, was therefore chosen.

The mass of the material was made small in order to minimize the cooling-time lag at the point on the surface of the cylinder where the temperature change was measured. A hollow tube with a wall thickness of 0.010 inch and length of about 1 inch proved satisfactory for the water-sensitive part of the instrument. A heating method that would satisfactorily combine the requirements of small mass and high surface temperatures necessary for the water-sensitive element was found to be that of generating heat by passing electric currents directly through the element. In order to minimize high currents necessary for sufficient heating, the element was constructed of a high electric-resistance material. The heating current was obtained through use of a short-circuit-type transformer connected as close to the element as possible and designed for 110-volt, 400-cycle power input.

The temperature of the surface of the element was measured by an iron-constantan thermocouple embedded in the element at the aerodynamic stagnation point. The element temperature was satisfactorily measured by several methods including a self-balancing-type recording potentiometer, a film-recording galvanometer, and thermocouple temperature gages.

Construction. - A photograph of the instrument is shown in figure 1 and figure 2 illustrates the pertinent details of construction for support in the free air stream. The water-sensitive element was welded to the end of a thick-wall brass tube about 9 inches long, which was in turn fastened to a base mounting plate. A coaxial-tube electric heater, surrounding and electrically insulated from the support tube, was used for protection from ice accretions. The transformer was mounted on the inside surface of the base plate, and electric connections were made to the element through a 1/8-inch-diameter copper wire inside the support tube and a ground connection to the base plate. The thermocouple leads were also extended through the support tube.

Power requirements. - The power required for the water-sensitive element is small for the conditions investigated, being about 250-volt-amperes input to the transformer. The ice-protection heater for the support tube requires a high current of about 40 amperes at 3.3 volts for adequate protection in icing conditions as severe as air temperature of 0° F, air velocity of 200 miles per hour, and liquid-water content of 1 gram per cubic meter.

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LIQUID-WATER-CONTENT CALIBRATION

The amount of surface cooling caused by liquid water striking the heated element varied greatly with the quantity of liquid water in the air stream. The variation of element surface temperature with increasing water content of the air stream is shown in figure 3. The plot indicates a large linear drop in surface temperature with increasing water content down to about 150° F. At about this temperature, the instrument becomes less sensitive to increasing water content and at a temperature of about 100° F becomes almost insensitive to any large quantities of liquid water. Observation of the sensitive element showed that the element provided sufficient heat to maintain a dry surface above 150° F, but that the surface remained wet below that temperature. In order to obtain a maximum variation of surface temperature with liquid-water content with a consistent temperature trend, it is therefore necessary to maintain a completely dry surface, a condition that requires a sufficient surface temperature to evaporate all the water on impingement. The operating liquid-water-content range of the instrument is therefore determined by the heating capacity of the instrument to maintain a dry surface.

The variation of the drop in surface temperature with the liquid-water content of the air stream was calibrated in terms of temperature by applying the values of liquid-water content as measured by the conventional multicylinder technique. The calibration was conducted at below-freezing conditions in the test section of the icing research tunnel where a simulated icing cloud is produced through use of accurately calibrated water sprays introduced upstream of the model. The multicylinder technique was slightly modified by inserting only one cylinder at a time to insure the same cloud distribution over the cylinders and the liquid-water-content meter. Separate cylinders were individually exposed at the same location followed by exposure of the liquid-water-content meter also at the same location. By this means, a calibration (fig. 4) was obtained up to liquid-water-content values of 1.1 grams per cubic meter.

The initial surface temperature of the element in water-free saturated air was 475° F. The maximum liquid-water content caused a surface temperature drop of over 250° F. The resulting surface temperature of 225° F was well above the minimum temperature necessary for complete evaporation on impingement for the conditions of the investigation. Because the temperature of the element was above the minimum of 150° F for all conditions of liquid-water content investigated (fig. 3), a straight-line calibration was assumed through the values established by the multicylinders. The straight-line relation provides a convenient calibration constant of 0.0046 gram per cubic meter per °F drop in surface temperature from a water-free condition for the conditions investigated.

Values of liquid-water content of a cloud obtained using the instrument should be considered to have an accuracy only within the accuracy of the measurements using the multicylinder technique (reference 4) because the multicylinder technique was used as a basis for calibration. The greatest advantage of the liquid-water-content meter, however, lies in its simplicity of structure and operation for obtaining results equal to those of the far more complicated multicylinder system.

A second calibration of the heated element was conducted in the icing research tunnel under the same conditions using a rotating-disk-type icing-rate meter to measure the liquid-water content. This meter had been previously calibrated against the multicylinder technique at flight icing condition. The rotating disk of the icing-rate meter was mounted within reasonably close proximity to the liquid-water-content meter. With the assumption that the distribution of liquid water was uniform within this area, a direct calibration of the heated element was made with the icing-rate meter. These results are also shown in figure 4. This calibration, of course, also contains the errors associated with the multicylinder technique.

Both calibrations were conducted using the same simulated-cloud conditions. The multicylinder technique indicated the droplet sizes in the simulated cloud varied with increasing quantity of water injected into the tunnel and ranged between Langmuir C to E size distributions with a volume median droplet size (reference 5) close to 10 microns diameter.

OPERATING CHARACTERISTICS

The surface temperature of the heated element is not only a function of the amount of liquid water striking the surface but also depends on air temperature, velocity, and density and on the power input or surface temperature in clear air. These variables must be known while measuring liquid-water content with the instrument. A complete calibration of the instrument requires the determination of the effect of each of these variables on surface temperature.

Several characteristics of the instrument were noted during the investigation conducted in the icing tunnel. In order to check the effects of above- and below-freezing temperatures on the liquid-water-content indications, a known value of water content at a below-freezing condition was held constant in the tunnel while the air temperature was raised above the freezing point. No change in the surface-temperature drop was observed between 20° and 40° F, which indicates a below-freezing calibration can be used within this range of temperatures. Large changes in air temperature need further investigation because of the vapor-pressure effect on the heat transfer from the surface.

The instrument was exposed to a cloud composed only of ice crystals to determine the effects of frozen particles on the surface temperature. The surface temperature was unaffected by the presence of the crystals, which indicates a surface-temperature drop occurs only with liquid droplets. A further investigation to explain this phenomenon was not undertaken.

Because the heated element has some thermal capacity, a certain amount of time lag exists during changing conditions. When suddenly exposed to the full range of liquid-water content, the surface temperature changes almost instantly but requires about 20 seconds to stabilize. For flight measurements in broken or scattered clouds where water contents are rapidly changing in the flight path, a heated element of considerably lower thermal capacity is needed for obtaining true values of the liquid-water content.

SUMMARY OF RESULTS

A small cylindrical element capable of being heated in clear air to temperatures in the order of 475° F was constructed and investigated to determine the feasibility of measuring the liquid-water content of an air mass by observing the temperature drop of the sensitive element during exposure to the wet air stream. The following results were obtained from experiments conducted with the instrument:

1. The instrument was very sensitive to a wide range of liquid-water content and could be used for measurements in above- and below-freezing clouds.

2. At the conditions investigated, the surface temperature of the sensitive element had to be maintained above 150° F during the measuring period to assure complete evaporation of the impinging water.

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3. A calibration of the instrument at an air temperature of 20° F, an air velocity of 175 miles per hour, and a surface temperature in clear air of 475° F was obtained using rotating multicylinders as a basis of measurement.

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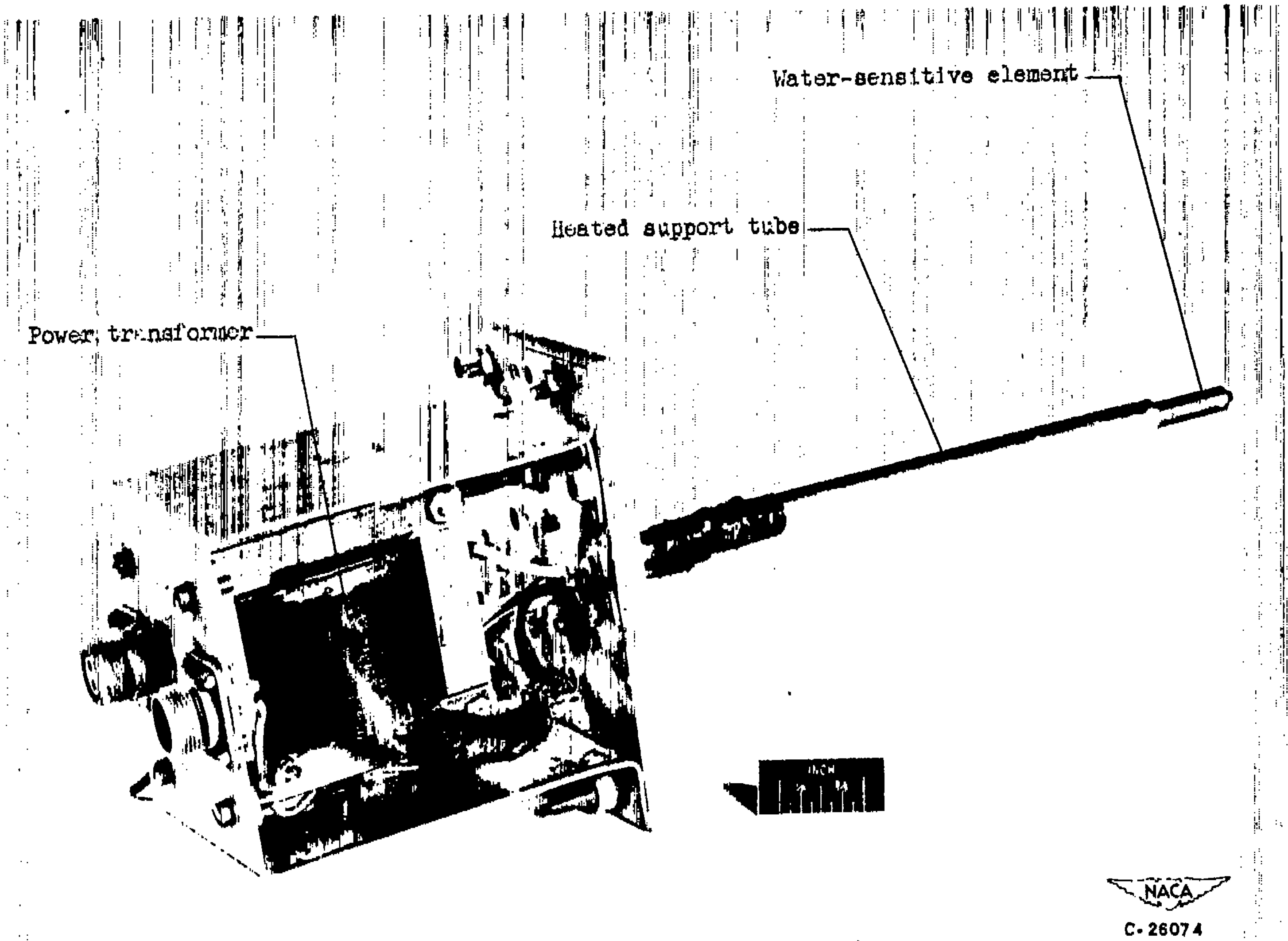

Figure 1. - NACA liquid-water-content meter.

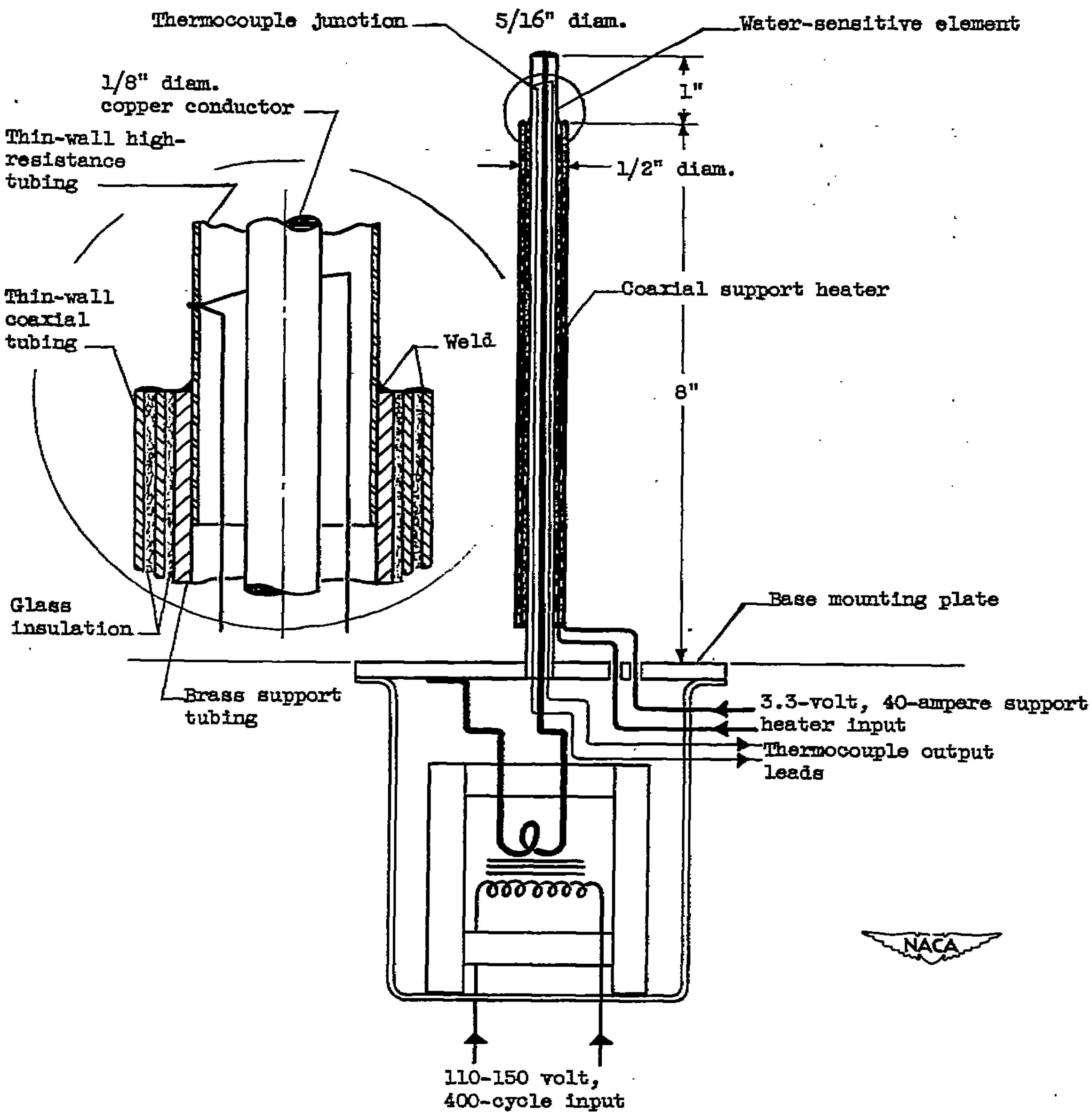

Figure 2. - Construction details of NACA liquid-water-content meter.

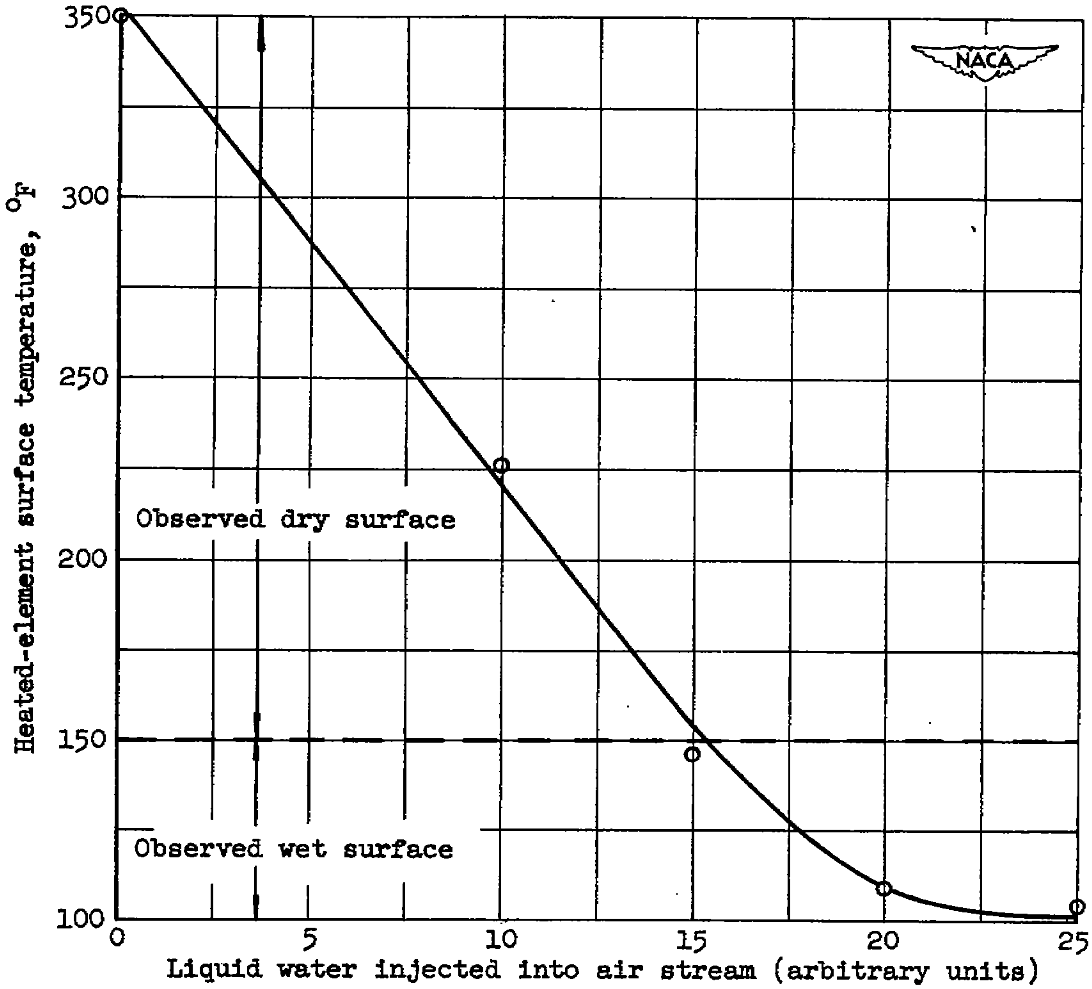

Figure 3. - Effect of liquid water in air stream on element surface temperature. NACA liquid-water-content meter; air temperature, -2° F; air velocity, 185 miles per hour; air density, 0.072 pound per cubic foot.

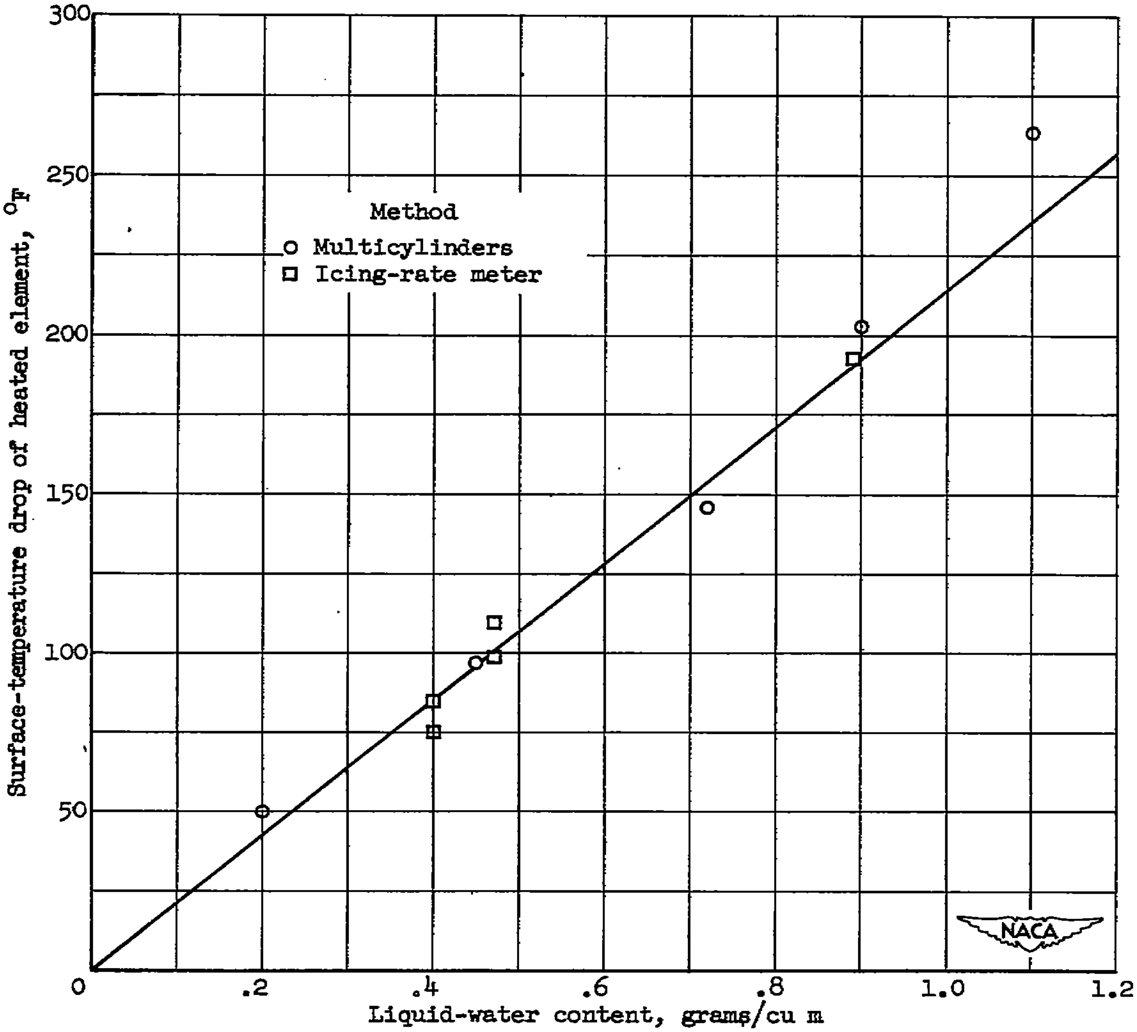

Figure 4. - Calibration of NACA liquid-water-content meter using rotating multicylinders and icing-rate meter. Air temperature, 20° F; air velocity, 175 miles per hour; air density, 0.077 pound per cubic foot; clear-air surface temperature of heated element, 475° F.

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