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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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Special Report #155

A FLIGHT INVESTIGATION OF EXHAUST-HEAT DE-ICING

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September 1940

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SUMMARY

The National Advisory Committee for Aeronautics has conducted exhaust-heat de-icing tests in flight to provide data needed in the application of this method of ice prevention. The capacity to extract heat from the exhaust gas for de-icing purposes, the quantity of heat required, and other factors were examined. The results indicate that a wing-heating system employing a spanwise exhaust tube within the leading edge of the wing will make available for de-icing purposes between 30 and 35 percent of the exhaust-gas heat. Data are given by which the heat required for ice prevention can be calculated. Sample calculations have been made, on a basis of existing $\frac{\text{engine power}}{\text{wing area}}$ ratios, to show that sufficient heating can be obtained for ice protection on modern transport airplanes.

INTRODUCTION

Previous NACA investigations (references 1 and 2) have indicated that the use of exhaust heat offered a practical means for providing ice protection to the airplane wing, but it has been found that additional data were necessary before full-scale application of this means could be undertaken. Tests have been made to determine how much heat can be taken from the exhaust gas and how much heat is required for ice protection. In addition, observations were made on the temperature-distribution characteristics of model wings, the nature of the mechanics of ice prevention and removal, and methods of control in exhaust heating systems. Calculations were made to determine the applicability of the present result to several modern transport airplanes.

APPARATUS

The tests were conducted in flight on a model wing which was mounted between the wings on an XBM Navy biplane. Figure 1(a) shows the model on the airplane while figure 1(b) illustrates the interior construction. The construction was similar to that used in all-metal wings having two spars and stressed skin. End plates were employed in order to preserve, as much as possible, two-dimensional air-flow characteristics.

In the tests conducted to determine how much heat could be extracted from the exhaust gas, an exhaust tube was placed inside the wing running along the leading edge. (See fig. 1(b).) The principles involved in the heat exchange for the model in this form are explained with the aid of figure 2. Heat is transmitted from the exhaust tube to the wing skin by radiation and convection. The transmission by convection is controlled by changing the circulation of air through the model interior. Heat is picked up by the air between points A and B. (See fig. 2.) As the air follows a circuitous path through the after portion of the wing a large part of the heat in the air is transmitted to the skin while the remainder is lost at the trailing edge in the circulated air.

The heat-transmission and de-icing tests were made with the model adapted for the use of hot air. Air was heated by an exhaust heater separated from the model as shown in figure 3. A photograph of the model when hot-air heated is shown in figure 4. The heated air flows along the leading edge of the model and thence through the after portion the same as when the exhaust tube was used. The heat-transmission and de-icing tests were made with the hot-air-heated model because of the more precise measurements which were possible with this method of heating.

The exhaust gas from two of the cylinders from the airplane's engine was used as a source of heat in all of the tests. The rates of flow of exhaust gas and air involved in the experiments were measured by the use of orifice meters. Temperature difference measurements were made with thermocouples, while the ambient air temperature was read from a strut mercury thermometer. The temperature changes were measured in the exhaust gas and circulated air, which, with the gas and air-flow measurements, permitted a definition of the heat exchange in the model.

The nature of the heat distribution was observed from temperature measurements at numerous points on the model skin. The positions of the skin thermocouples are shown in figures 2 and 3.

The wing was mounted on a support tube running spanwise at the 25-percent chord point and at the trailing-edge midpoint as is shown in figure 1(a). The angle of attack of the model could be changed in flight by the rotation of the threaded rod extending upward from the lower airplane wing to the trailing edge of the model. Since all of the tests were made at zero degrees angle of attack, the attitude of the model was adjusted by equalizing the pressures of two static orifices at geometrically similar positions on the upper and lower surfaces.

Visual records of the ice-prevention and removal tests were obtained by photographing the de-icing tests with a 35-mm motion-picture camera. The camera and mounting are shown in figure 5(a). Icing conditions were simulated by the discharge of water from spray nozzles in front of the model. The desired temperatures were obtained by flying at the proper altitude. The spray nozzles in operation are shown in figure 5(b).

Other apparatus for making the measurements, such as millivoltmeter, pressure recorders, heating controls, and thermocouple selector switches, were located in the observer's cockpit.

PROCEDURE

All of the tests were made at 100 miles per hours air speed and, as has been noted above, at zero degree angle of attack. The heat transmission tests were made in dry air and in misty cloud formations. The tests in clouds were taken to be representative of actual icing conditions, except that the temperature of the air was above 32° F, instead of below that point. Since the tests were for purposes of measuring heat transmission in which temperature difference was observed, this is believed to be a valid procedure. No attempt was made, therefore, to conduct these flights at any particular air temperature.

De-icing tests were made with air temperatures between 17° and 25° F and with the spray nozzles producing a waterdrop content in the air stream comparable to that in a very severe icing condition. A distinction was made in the testing procedure between ice prevention and ice removal. Ice-prevention tests were made to measure the heating requirements for the prohibition of any ice on the model wing. The removal tests were made to observe the operation of, and to measure the heat required for, the removal of ice formed prior to turning on the heat. Motion pictures were taken during ice-prevention and removal tests.

RESULTS AND DISCUSSION

Characteristics of Exhaust Tube System

The results of tests to determine the capacity to remove heat from the exhaust gas are given in table I. The data indicate that from 30 to 35 percent of the exhaust-gas heat normally discharged at the engine can be applied to the prevention of ice by the use of an exhaust tube in the leading edge of the wing.

It was further observed that by reducing the amount of air circulated within the wing, the capacity to extract heat from the exhaust gas was reduced only slightly and that a larger portion of the heat was dissipated from the leading-edge 30-percent portion of the wing. Accordingly, the temperature rise of the leading-edge region was increased and the temperature rise of the after portion was decreased when the circulation of air was discontinued. The temperature rise of the after portion of the wing when air circulation is stopped is due largely to the transfer of heat from the leading edge in a rearward direction through the boundary air. While a chordwise distribution of heat may be obtained by the air convection over the outside of the wing, the heat given to the boundary-layer air forward can be only partially recovered by the wing surface aft and therefore heat is wasted. The most efficient use of the heat is obtained when the distribution results in a uniform temperature rise over the region which is to be protected. Although reducing the quantity of air circulated through the wing may result in a reduction of the efficiency of the heating of the entire wing surface, a consideration of other factors indicates that the concentration of heat at the leading edge may be desirable. Some provision for increasing the quantity of heat which can be directed to the leading edge is desirable when extremely severe ice storms are encountered. The leading edge should always be kept free from ice even though accretions may form on the after portion because, as is shown by reference 3, surface protuberances over the leading-edge 20 percent of the wing are of greater harm to the aerodynamic efficiency than are protuberances on the after portion. Recent flight tests on a wing which was equipped with an inflatable de-icer emphasized the conclusions of reference 3.

The flight tests showed that simulated ice formations one-half inch high in the vicinity of the de-icer attachment strips, which are about 7 percent back from the leading edge, resulted in a profile-drag increase of over 350 percent and a decrease in $C_{L\ max}$ of 59 percent.

Meteorological observations indicate that ice storms of great severity usually occur only over limited geographical area and altitude range. A de-icing system, therefore, which can concentrate heat on the leading edge of the wing at the expense of the trailing-edge region is believed to be of particular value in storms of great severity because the leading edge can be kept continuously clear and the ice which may form near the trailing edge of the wing can be removed after the storm center has been passed.

Heat-Transmission Tests

The transmission of heat from the model wing is given in coefficient form in table II. A comparison of the results obtained in the present investigation with those given in reference 2 is made possible by the inclusion in the table of a calculated heat-transfer coefficient based on the wing chord and air-stream velocity during the present tests. It is noted that the dry-air coefficient obtained in the present tests is about 82 percent of the calculated values from reference 2. The fact that the present tests were made with an NACA 0006 airfoil while the previous work was done on a Clark Y section may explain the difference. The present measurements are believed to be accurate to within ±5 percent.

The tests made to determine the heat required for ice protection were made in dense clouds from which a mist was falling. The free-moisture content of the air during these tests was believed to have been capable of producing a severe ice storm had the air temperature been below freezing.

From reference 2 and the results of the heat transmission tests with a wet wing the coefficient of heat transfer from an airfoil whose profile drag is comparable with that of the NACA 0006 is given by the equation

$$\alpha = \alpha_0 \frac{C_0}{C} \left(\frac{V \times C}{V_0 \ C_0} \right)^n \tag{1}$$

in which

α	heat transfer coefficient, Btu/sq ft, hr, °F
C	wing chord, ft
V	velocity in mph
n	exponent depending on angle of attack
o	subscript denoting present test conditions

At cruising angles of attack n is approximately 0.8. By substituting in the above equation the values for α_0, V_0, and C_0 from the present tests, the following equation is written:

$$\alpha = 0.6 \frac{V^{0.8}}{C^{0.2}} \tag{2}$$

If it can be assumed that a uniform temperature rise has been obtained over the entire airplane wing, then the minimum heat required to prevent ice formations is given by

$$Q = \alpha(32 - T)(\text{area}), \text{ Btu/hr} \tag{3}$$

in which T is the ambient air temperature in °F and the area is the actual wing area heated. (Both the upper and lower surfaces must be considered since α is given in terms of square feet of exposed surface.) If the temperature rise over the wing is not uniform, the required heat according to equation (3) will be in error, the extent of which will depend upon the temperature variation over the wing.

Ice-Prevention Tests

The temperature rise during the ice-prevention tests over the model wing surface varied rather widely from leading edge to trailing edge and therefore it was expected that the heat expended for ice prevention would be in excess of the calculated heat required.

The results of the ice-prevention and removal tests are given in table III. The results from two different ice-prevention tests are shown. In the first, the heat supplied was gradually reduced until ice formations were noted and then increased slowly until all ice was removed. In the second, the heat was reduced until ice started to form but did not spread beyond a small region near the trailing edge. The residual ice on the wing during a typical test of this kind is shown in figure 6.

On a basis of the heat-transmission tests the heat input of 567 Btu/(sq ft, hr) corresponds to an average temperature rise of about 30° F. Since the outside air temperature was 24° F, a temperature rise of 8° F was all that was required. Thus, without uniform temperature rise, the quantity of heat required would be several times as great as would be predicted from equation (3).

The results obtained from the removal tests indicate the pre-formed ice on the leading edge of a wing can be removed. Several removal tests were made in order to observe, by way of the motion-picture camera, the manner in which the ice was eliminated. In each instance the ice covering the leading edge was removed in less than 30 seconds and, as shown by the results in table III, in as low as 10 seconds. Figure 7 shows the type of ice formation which was removed, and figure 8 shows the same formation a few seconds after the heated air was admitted to the wing. The blurred regions on the photograph are pieces of ice being blown away from the wing. Ice formations on the after portion of the wing were readily removed when heated air was circulated throughout the interior of the wing. When the exhaust-tube-heated model was tested without internal air circulation, the removal of ice from regions near the trailing edge was slow, and a greater total quantity of heat was employed than during other successful ice-removal tests.

Application of Test Results

The design of ice-prevention equipment which makes use of exhaust heat is principally a problem of heat distribution. The important considerations in the problem are: (1) ambient-air-temperature range over which protection is desired; (2) ratio of exhaust thermal energy to the surface area to be protected; and (3) the extent to which a uniform temperature rise can be obtained over the heated region.

For any particular geographical location, the temperature range common to ice storms is a factor which can be defined only by statistics. While the information regarding the temperatures at which ice storms have occurred on the North American continent is meager, on a basis of reports on air-line operations within the United States, severe ice storms occur with the greatest frequency at temperatures above 15° F. Reports have been received which indicate that in Canada severe ice storms occasionally occur at still lower temperatures. Inasmuch as the most common ice storm occurs just slightly under freezing temperature and the largest amount of water is encountered at the higher temperatures, it will be assumed, for purposes of this analysis, that the temperature rise over the protected area must be not less than 17° F. This would, assuming a uniform plain temperature rise, give ice protection at air temperatures of 15° F or above. An analysis has been made on the basis of the characteristics of 12 modern transport airplanes to determine what temperature rise might reasonably be expected if 30 percent of the available exhaust heat is applied to wing heating. While several assumptions and qualifications must be made in such an analysis, it is believed a good indication is given of the applicability of the exhaust heating system. The assumptions have been made that the available heat for use in the wing-heating system is equal to the engine power at maximum speed, and that this heat will be applied to the entire wing area. Actually the exhaust-gas energy wasted by the modern engine is in excess of the useful power and, therefore, if the heat is used economically, the first assumption will be valid. The second assumption also appears to be valid, since areas in the regions of the fuselage or engine nacelles may not require protection from ice formations. It may be shown by reference 3 that a large part of the lifting surface in the trailing-edge region could be covered with ice and not produce a great loss in aerodynamic efficiency of the airplane, provided that the leading-edge region is protected.

On the basis of these assumptions and the results of the present investigation, the temperature rise resulting from the use of an exhaust tube inside the wing leading edge has been calculated. An approximation of the applied energy per square foot is given by the equation

$$q = \frac{P}{2S} \times E, \quad \text{Btu/(sq ft, hr)}$$

in which P engine power at V_{max}, Btu/hr

S wing area, sq ft.

and E exchange efficiency of heating system

The transmission coefficient has been calculated for the 12 transport airplanes referred to above on a basis of the average wing chord and the maximum velocity, using equation (2). From a knowledge of the heat applied, q, and the coefficient, α, an average temperature rise ΔT for the lifting surfaces has been calculated by the use of the equation

$$\Delta T = \frac{q}{\alpha}$$

The results of these calculations are shown plotted on figure 9, which indicates that a satisfactory temperature rise can be obtained. The plotted points which show the greatest wing surface temperature rise, ΔT, refer to the most recent airplane designs, which indicates that the present design trend is toward a greater potential heating capacity for the wing surface.

Although it is doubtful that the results shown in figure 9 can be achieved without experience, it is believed that a satisfactory heat distribution can be obtained over the vital areas from existing data on heat-exchanger design. (See reference 4.) Experience in the design and operation of this type of equipment should bring improvements in the uniformity of heat distribution and economical refinements resulting from a more accurate knowledge of just where protection is required. In view of the favorable results of NACA investigations on the application of heat, and also of reports which have been received describing the successful application of this method on numerous four-engine transport airplanes in Germany, it is believed that full-scale application should be undertaken at an early date in this country. A full-scale application is planned by the NACA in cooperation with the Army Air Corps, which it is hoped will give added data on the application and operation of the heating method.

CONCLUSIONS

1. A wing with an exhaust gas tube running spanwise inside the leading edge has the capacity to apply from 30 to 35 percent of the exhaust heat to the prevention or removal of ice.

2. Heat transmission tests in misty-cloud formations indicated that the heat required for ice prevention may be calculated from the equation

$$q = 0.60 \frac{V^{0.80}}{C^{0.20}} (32 - T)$$

in which q in Btu/sq ft, hr

V the velocity, mph

and C the wing chord, ft

T ambient air temperature, °F

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2. Theodorsen, Theodore, and Clay, William C.: Ice Prevention on Aircraft by Means of Engine Exhaust Heat and a Technical Study of Heat Transmission from a Clark Y Airfoil. Rep. No. 403, NACA, 1931.

3. Jacobs, Eastman N.: Airfoil Section Characteristics as Affected by Protuberances. Rep. No. 446, NACA, 1932.

4. McAdams, William H.: Heat Transmission. McGraw-Hill Book Co., Inc. 1933.

TABLE I.- HEAT-EXCHANGE DATA FROM EXHAUST-TUBE-MODEL TESTS

Air circulated through model (lb/sec)	Heat content of exhaust gas entering model wing above ambient air (Btu/hr)	Heat removed from exhaust gas by model (Btu/hr)	Heat transmitted through skin of model (Btu/hr)	Percent of heat entering wing removed by model system	Percent of heat removed and transmitted through model skin	Efficiency of exhaust-tube model
0.19	259,000	100,500	89,000	39	89	35
.16	251,000	86,000	74,500	35	82	30
0	284,000	96,000	96,000	34	100	34

TABLE II.- HEAT-TRANSMISSION DATA FROM HOT-AIR-MODEL TESTS

Weight of air circulated (lb/sec)	Heat added to circulated air (Btu/hr)	Heat transmitted from model skin, Q (Btu/hr)	Efficiency of model heat exchange (percent)	Average temperature rise of model skin above ambient air (Δ T, °F)	Heat transmission coefficient, α (Btu/sq ft, hr, °F)	Calculated heat transmission coefficient from reference 2 (Btu/sq ft, hr, °F)	Surface condition of wing
0.18	44,500	30,500	69	78.3	16.2	19.7	dry
.19	45,000	29,900	66	65.3	19.1		wet

Additional data: Area of model, 24 sq ft

Formula for the calculation of transmission coefficient: $\alpha = \dfrac{Q}{\Delta T \times \text{area}}$

TABLE III.- ICE-PREVENTION DATA (HOT-AIR MODEL WING)

Air circulated (lb/sec)	Heat dissipated through model skin (Btu/hr, sq ft)	Outside-air temperature °F	Type of tests	Remarks
0.08	917	23	prevention	Ice prevented over entire wing
.046	567	24	prevention	Ice formed along the trailing edge (See fig. 7)
.176	1300	24	removal	Ice removed over leading edge in 10 seconds

Note: Several flights in which the above observations were repeated for photographic purposes, ice formations on leading edge varying from 1/2 to 1 inch in thickness were removed in from 10 to 30 seconds after the heat was admitted to model.

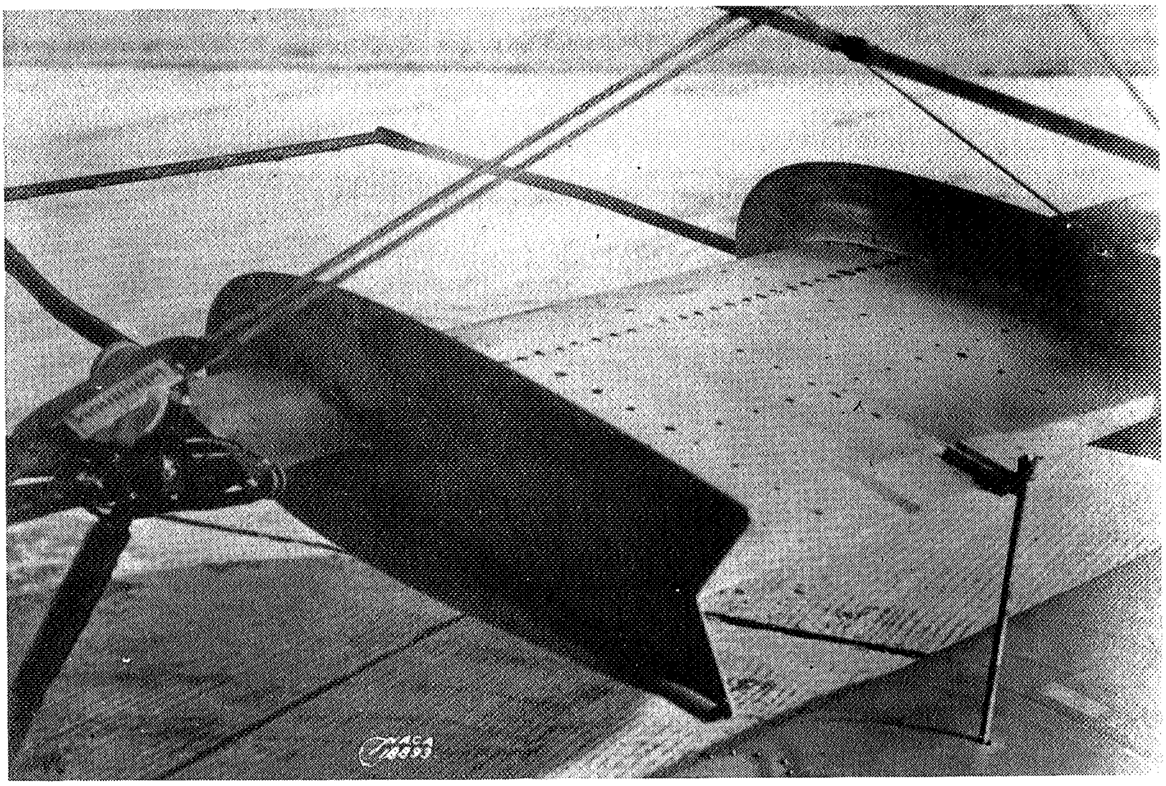

Figure 1a.- Model wing heated by exhaust tube and mounted on XBM airplane for flight tests.

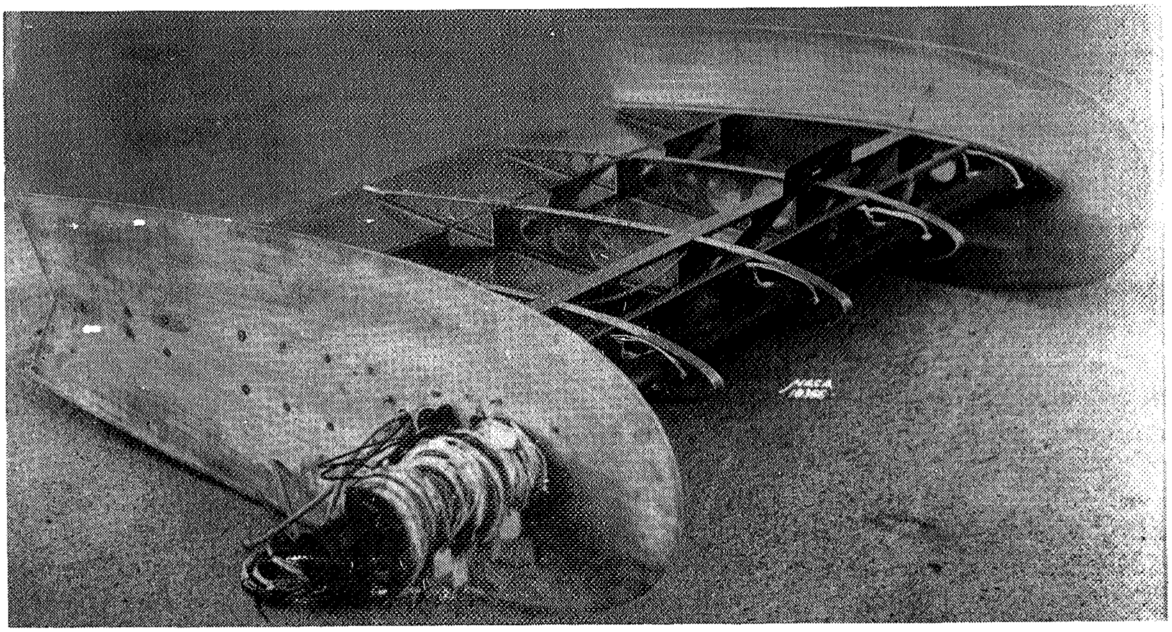

Figure 1b.- Model wing in construction showing exhaust tube along interior of leading edge.

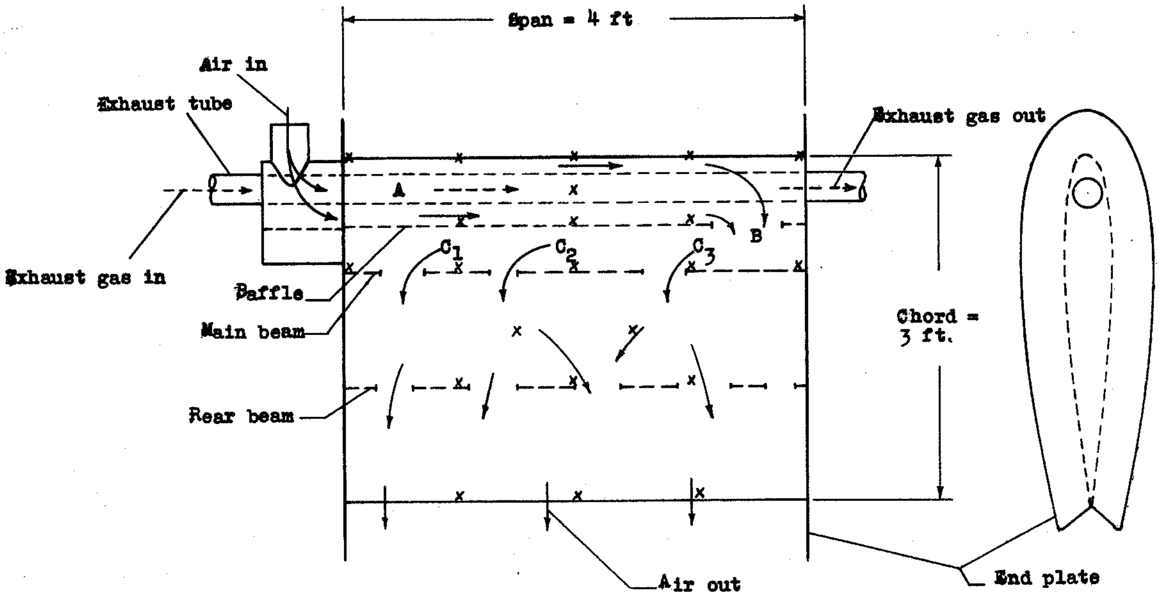

Figure 2.- Set-up of wing heated by exhaust tube, showing path of exhaust gas and air through the model and the location of skin-temperature thermocouples, x.

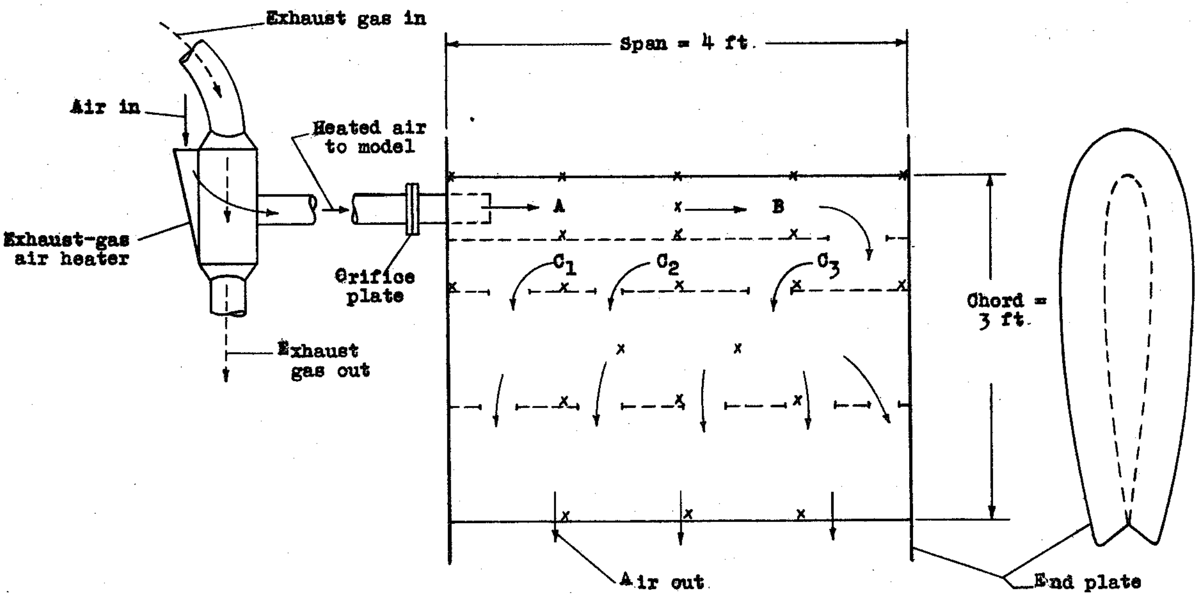

Figure 3.- Set-up of wing heated by hot air, showing path of heated air through the model and the location of skin-temperature thermocouples.

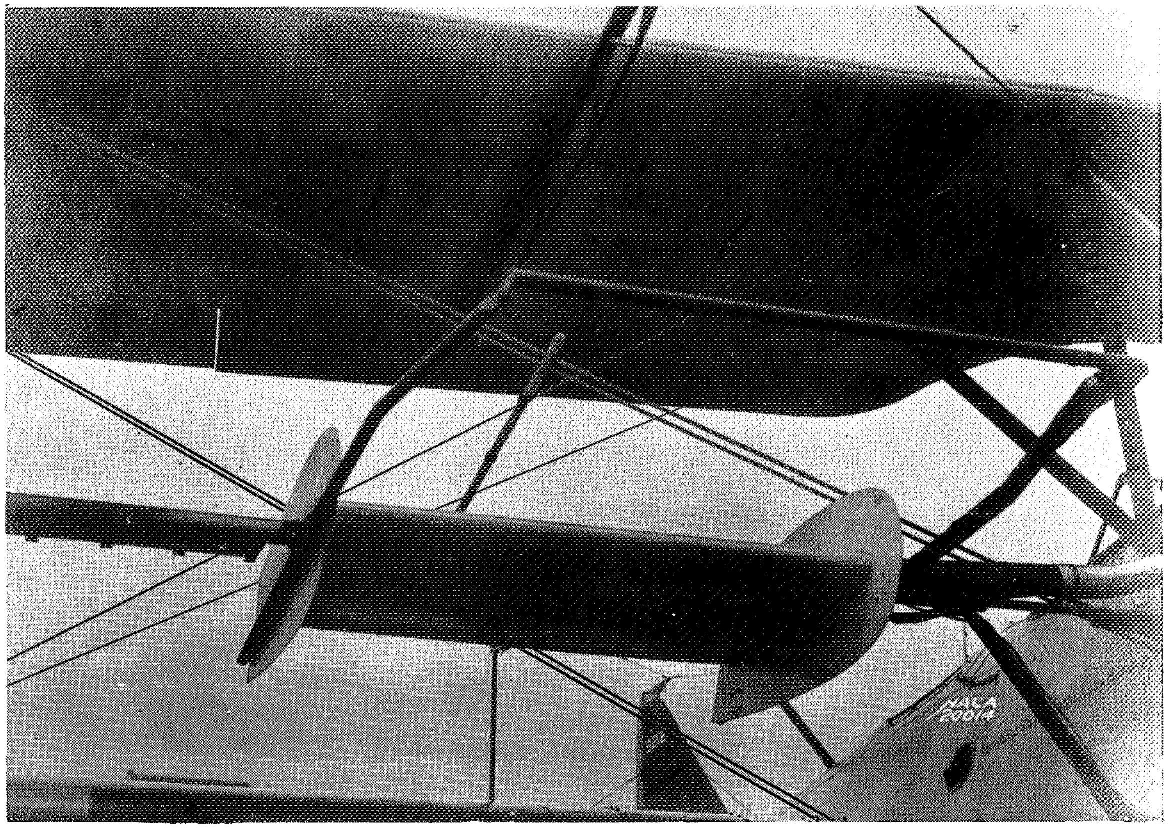

Figure 4.- Wing, heated by hot air, mounted on XBM airplane for flight tests.

Figure 5(a).- General view of XBM airplane, showing wing heated by hot air, and motion-picture camera mounted above and in front of the model wing.

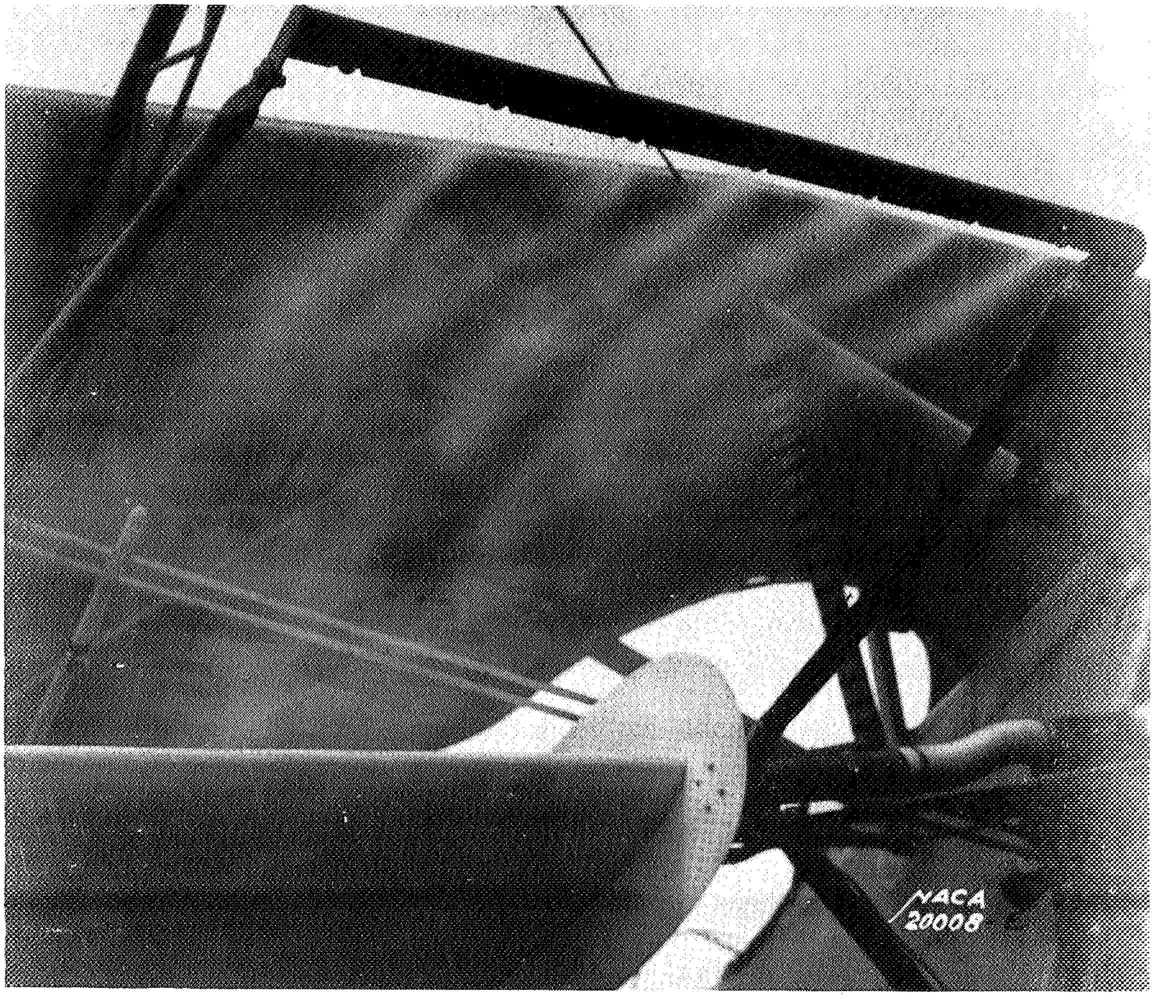

Figure 5(b).- Spray nozzles in operation.

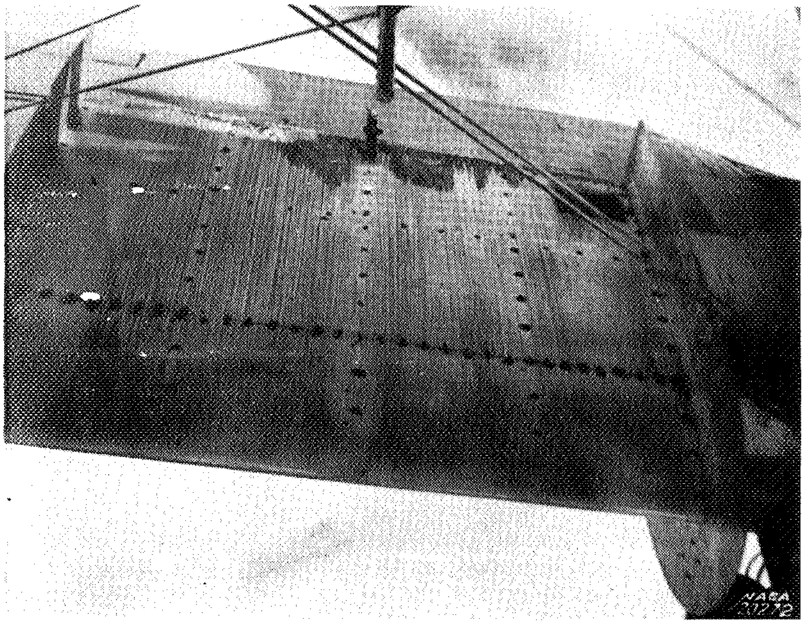

Figure 6.- Model wing with ice along trailing edge. The quantity of heat required for prevention of ice over rest of model was reduced to the minimum.

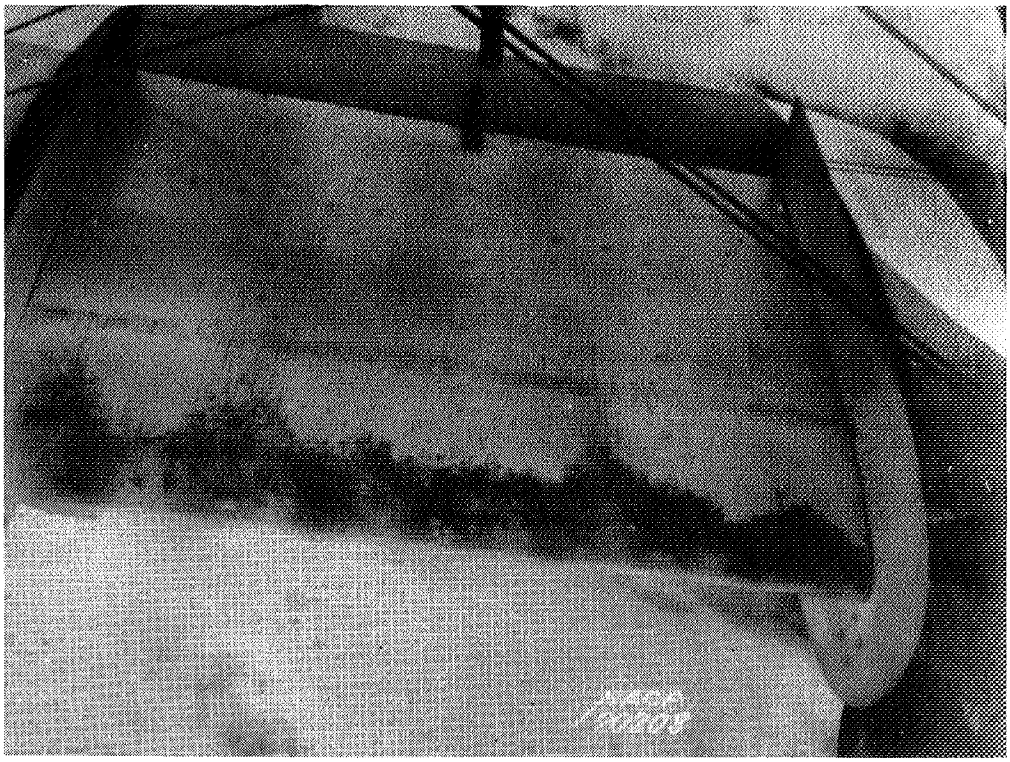

Figure 7.- Nature of ice formation on model wing prior to application of heat.

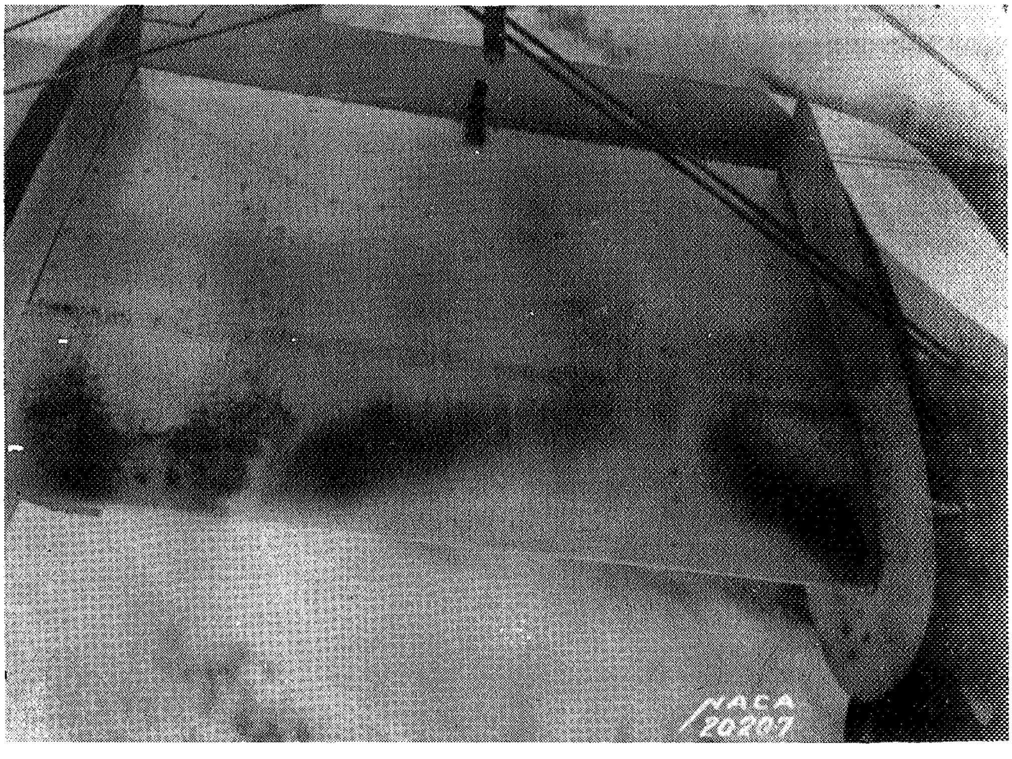

Figure 8.- Large pieces of ice being blown away less than 10 seconds after hot air was admitted to the wing

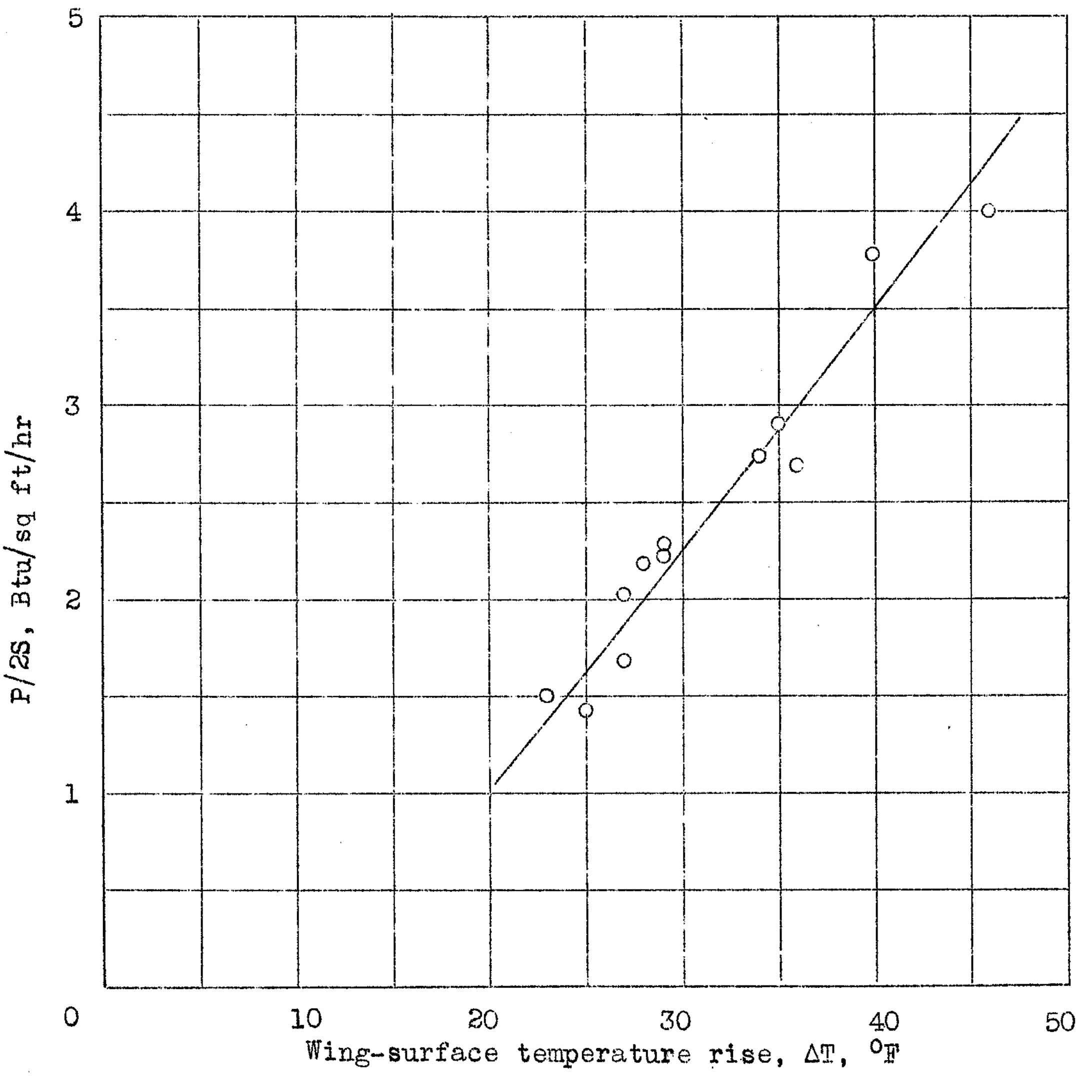

Figure 9.- The calculated temperature rise for 12 modern transport airplanes.