TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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A PRELIMINARY STUDY OF THE PREVENTION OF ICE ON AIRCRAFT BY THE USE OF ENGINE-EXHAUST HEAT

By Lewis A. Rodert
Langley Memorial Aeronautical Laboratory

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SUMMARY

An investigation was made in the N.A.C.A. ice tunnel at air temperatures from 20° to 28° F. and at a velocity of 80 miles per hour to determine whether ice formations on a model wing could be prevented by the use of the heat from the engine-exhaust gas. Various spanwise duct systems were tested in a 6-foot-chord N.A.C.A. 23012 wing model.

The formation of ice over the entire wing chord was prevented by the direct heating of the forward 10 percent of the wing by hot air, which was passed through leading-edge ducts. Under dry conditions, enough heat to maintain the temperature of the forward 10 percent of the wing at about 200° F. above that of the ambient air was required for the prevention of ice formation. The air temperature in the ducts that was necessary to produce these skin temperatures varied from 360° to 834° F.; the corresponding air velocities in the duct were 152 and 45 feet per second.

Ice formations at the leading edge were locally prevented by air that passed over the interior of the wing surface at a velocity of 30 feet per second and a temperature of 122° F.

INTRODUCTION

The formation of ice on aircraft in flight remains a serious problem for both commercial and military operation. Although various means of preventing and removing ice have been proposed and tried, none has proved entirely satisfactory. The most successful method to date, which is in common use on airplanes in this country, employs the Goodrich deicer that removes ice from the leading edges of the wings and the tail surfaces by mechanical action. This device, however, fails to eliminate ice satisfactorily under some conditions, although its action is being constantly improved. Another method that has been proposed and studied to some extent is the use of heat from the engine exhaust (reference 1); but thus far the possibilities of this system have not been fully investigated or developed. Existing data indicate that sufficient heat is available; the problem is therefore to determine how this heat can be utilized to the best advantage or, in other words, the problem is one of distribution.

The present investigation, which was carried out in the N.A.C.A. ice tunnel, is concerned with the distribution of engine exhaust heat and its effectiveness in the removal and the prevention of ice on the airplane wing. An analysis of the distribution of heat over the wing indicates that, as the heat flows from the root toward the tip, only the quantity of heat needed for ice prevention at successive points along the span should be given up to the atmosphere at each point. This restriction will insure an adequate supply of heat for ice prevention at the wing tips and a minimum weight of the duct system. This investigation of heat distribution is therefore concerned with the chordwise distribution problem. Although the tests are preliminary in nature and should be extended to cover the topic more broadly, the present data appear to be of some interest.

APPARATUS

The investigation was conducted in the N.A.C.A. 7- by 3-foot ice tunnel at a minimum temperature of 20° F. The tunnel velocity for the test runs was 80 miles per hour. Natural precipitations were simulated by admitting water to the air stream through a spray nozzle. The tunnel test section with the model and the spray are diagrammatically shown in figure 1. A source of heated gas, such as would be available from an engine exhaust, was simulated by blowing air through a multitube electric heater.

An N.A.C.A. 23012 airfoil section having a 72-inch chord was used for the models. Three models, representing different duct systems, were used during the tests. The structure of the models simulated that of an all-metal wing insofar as the structure affects the distribution of heat along the chord. Forced circulation within the model was obtained by placing three small electric fans within the structure.

Model A, the thermocouple locations, and the duct that carries the heated air through the wing are shown in figure 2. The model ends were attached through an insulating material to the tunnel wall. The heated air was led from the heater to the tunnel wall and then through the model to the opposite tunnel wall where it was discharged to the atmosphere.

Model B, shown in figure 3, differs only in duct area and shape from model A.

Model C, shown in figure 4, has a tube 3-1/2 inches in diameter leading the heated air along the span. It will be noted that the wall of this tube was separated from the model surface covering by an air gap but that, in models A and B, a part of the duct wall constituted the airfoil skin over 10 percent of the chord at the leading edge.

TESTS AND RESULTS

Ice formations.- Preliminary to the investigation of the distribution of heat over the wing and the actual ice removal, a study was made of the various forms of ice that were obtainable with the spray equipment. The form of ice obtained was determined by the tunnel air speed and temperature, the drop size discharged from the spray nozzle, and the temperature of the waterdrops just prior to striking the model surface.

The range of control over the formation of ice was such that a simulation of all typical ice formations found in flight could be produced.

A photograph and a sketch shown in figure 5 illustrate a glaze-ice formation on the model. This formation is typical of ice encountered in precipitating clouds at temperatures about 28° F. The adjustment of the nozzle for this formation was such that large drops of water struck the model. Figure 6 illustrates a rime formation, which is typical of ice that would build up on a wing passing through a supercooled mist of very small waterdrops. The spray nozzle was adjusted so that only very small waterdrops struck the model. Rime ice formed only along or near a stagnation-pressure region. Other significant data are given on the sketches of figures 5 and 6.

After the ice-formation tests were made, it was concluded that the most severe condition that could be imposed on an ice-prevention system using heat was one representing the combination condition of a low temperature and an abundance of waterdrops. Such a condition results in an ice formation over the leading edge of the wing that extends to the after portion if sufficient time is allowed for the accretion to grow. A precipitating cloud with a temperature between 20° and 28° F. will give this condition. The heat-distribution and the ice-removal tests were therefore made within this range of temperature.

Chordwise heat distribution.- The release of heat from a gas to the walls of a duct through which it flows is a function of the mass flow of the gas and the temperature difference between the gas and the ducted walls. As a means of control, heated air was forced through the ducts at various temperatures and velocities. The mass of air passed was measured by an orifice meter in the air line to the heater. The temperature of the gas was measured by a thermocouple at the location T_{11}, as indicated in figures 2, 3, and 4. The locations of the thermocouples by which the skin temperatures were measured are also shown for the three models in the figures.

The observed data have been assembled in table I and are plotted in figures 7 to 11. It will be noted that the plotted temperatures are measured with reference to that of the tunnel air. Except as noted in table I, the tunnel air was dry during the heat-distribution tests.

An analysis of the distribution of the heat as it leaves the gas and enters the duct wall indicates that part is transmitted through the air in the after portion of the wing, part is conducted rearward by the skin and other chordwise structures, and the rest goes into the boundary-layer air adjacent to the duct wall. The transmission of heat rearward along the chord through the enclosed air depends upon the internal air circulation and will be small unless forced circulation is provided. An evaluation of the flow through the metal structure in a chordwise direction may be made on the basis of an assumed two-dimensional-flow condition existing rearward from the 10-percent-chord point on models A and B.

The temperature of the metal referred to that of the tunnel air at any point x measured from the 10-percent-chord point is given by the equation $T_x = T_{(x=o)} e^{-ux}$. The exponential coefficient u is obtained from $u^2 = \alpha/\lambda t$, in which α is the heat from the skin in [B.t.u./(sq. ft.-hr.)/°F.], λ is the conductivity of metal in [B.t.u./(sq. ft.-hr.)/(°F./ft.)], and t is the equivalent thickness of the skin in feet.

The temperature rise over the upper surface of the skin of the after portion that is due to transfer of heat through the structure has been calculated on the basis of this equation and the data from one test. The temperature at the 10-percent-chord point, $T_{(x=o)}$, is related to the temperature T_3 by the equation $T_{(x=o)} = T_3 - T_0$, where T_0 is the temperature of the tunnel air.

In the test chosen, $T_3 = 320°$ F. and $T_0 = 27°$ F.; by calculation, using the existing data, u = 7.5. The resultant values for several points along the chord of the wing gave values that are shown in the dotted line in figure 12.

The difference between the dotted curve and that drawn through the observed data is an indication of the relative effectiveness of heat transmission through the boundary layer.

Ice removal.- The general problem of ice removal and prevention was studied under the various conditions that may be encountered during flight. It was first assumed that ice had formed on the airplane wing before heated gas was admitted to the duct, in which case the problem was one of removal. The problem of removal may be confined to the leading-edge region or it may be extended to cover the entire chord. It was next assumed that the wing had been heated prior to the time that ice accretion started, in which case the problem was one of prevention. As in the case of ice removal, the problem of ice prevention may be concerned with the leading-edge region or the entire chord.

The tunnel velocity was 80 miles per hour and the flow of heated air through the ducts was 16 pounds per minute for all removal tests. The internal air-circulating fans were used during some of the tests. Other test conditions and results are given in table II.

DISCUSSION

Because of their preliminary and inconclusive nature, these results must be discussed with some qualification. Certain general remarks, however, seem justified.

The results indicate that the temperature of the skin at the leading edge which will prevent ice accretion there is obtained with a relatively low duct-air temperature. If ice prevention is to be extended, however, over the entire chord by the use of the duct systems tested, a higher temperature of the duct air is required. The flow of heat rearward within the boundary-layer air appears to be principally responsible for the temperature rise of the skin over the after portion. This conclusion is reached from a consideration of the significance of the heat flow through the enclosed air and the wing structure. The temperature rise due to transmission through the structure is analytically shown to be small by the dotted curve in figure 12. The temperature rise due to transmission and convection through the enclosed air even with fans operating is believed to be small, particularly with models A and B. It was observed that skin-temperature measurements made with the fans on and off differed by an amount within the average deviation of the data. With model C, it was evident from the slope of the curves in figure 11 that the chordwise transmission of heat within the wing had an appreciable effect on the skin temperatures.

It appears, therefore, that the principal source of heat transmission along the chord is within the boundary layer and that the results obtained in a given case will be dependent upon the nature of the boundary layer. The surface conditions, the scale, and the air-stream velocity would then be expected to have some effect on the heat distribution obtained. In the present case, the surface condition of the wing was typical of current metal-covered wings having smooth leading-edge sections.

In order to prevent the accretion of ice, sufficient heat was provided to maintain the temperature of the skin above freezing and also to supply waterdrops striking the wing with enough heat to remove any condition of supercooling that existed. These requirements remained unchanged for different points of the wing chord.

Ice removal at the leading edge of the wing was possible when sufficient heat was supplied to melt the ice at its contact with the skin faster than it formed and to replenish the heat carried away by the air stream. Ice was removed over the after portion of the wing when sufficient heat was provided to melt enough ice to form a film of water between the ice and the skin. After this water film was formed, the ice accretion was blown off by the air stream. An ice cap over the leading edge, however, would not blow off but had to be removed by melting. The problem of removal over the leading edge will therefore probably be more difficult than that of prevention if the removal is to be effected in a short time.

The type of ice formation did not alter the problem of ice prevention or removal because, with the skin temperature above 32° F., any ice that had existed on the leading edge prior to the application of heat melted and ran back over the after portion. If prevention was unsuccessful there, the resulting formation was always a glaze ice. No difference could be observed between removal of glaze ice and of rime ice from the leading edge. The quantity of water released by the spray is indicated by the rate of ice accretion when no attempt was made to prevent the formation. Under such conditions, ice formed at the rate of about 3 inches per hour over about 26 inches of the airfoil span.

Both removal and prevention were somewhat more difficult on the lower than on the upper surface. This increased difficulty may have been due either to a more turbulent flow over the under side of the model or to the fact that the stagnation point is on the under side of the nose. It will be noted from figures 7 to 10 that the temperature of the lower surface fell below that of the upper in all cases.

In order to avoid confusion in the interpretation of the results, it shoud be noted that the skin-temperature measurements were made when the tunnel air was dry, except as noted in table I. The same heating conditions were used in the ice-removal and the ice-formation tests.

In the ice-removal tests (see table II), it was found that a duct-air temperature of 890° F. produced skin temperatures over the entire chord which both removed ice from the leading edge and prevented any ice from forming on the trailing edge. During the skin-temperature investigation, a duct-air temperature of 834° F. gave skin temperatures over the forward 10-percent-chord part of the wing of about 200° F. It appears that heating this portion of the wing enough to maintain a temperature of about 200° F. above that of the ambient air under dry conditions will prevent ice from forming over the entire wing chord under icing conditions. These observations were made with a mass air flow of 16 pounds per minute, which corresponds to a velocity of about 45 feet per second for the temperatures noted.

Table I shows that the skin temperature is determined by both the duct-air temperature and the duct-air velocity and that, in cases such as model B for which the velocity is high, a skin temperature higher than 200° F. at the leading edge is obtained with a duct-air temperature of only 360° F., the corresponding duct-air velocity being about 152 feet per second.

Although a skin temperature of 200° F. over the forward 10-percent-chord part is required for the complete elimination of ice, a temperature lower than 200° F. above that of the ambient air at the skin may be expected to be satisfactory when a greater part of the chord is directly heated from within. The evidence is not conclusive, but this conclusion may be suggested by the results of ice-removal and temperature-distribution tests made with model C. It will be noted from table II that ice was eliminated over the entire chord with a duct-air temperature of 450° F. (velocity about 200 f.p.s.) and, from table I, that a duct-air temperature of 430° F. gave skin temperatures at the leading edge under 150° F. The duct system of model C possibly gave direct heating to a greater percentage of the chord.

By the extension of the chordwise proportion of the duct until the entire interior of the wing forms the passageway for the flow of heated gases, a system is established in which the lowest duct-air temperatures that prevent ice may be expected. The results from a test of model A given in table II indicate that ice is prevented from forming on the exterior of the skin if the temperature of the duct air on the inside is about 122° F. The actual velocity for this case is about 30 feet per second. Tests of model B indicate that an interior temperature of 94° F. will prevent ice. Here the velocity is nearly 100 feet per second. These results may give an indication of the temperatures and the velocities that will be required if heated air is to be circulated throughout the interior of the wing and if no concentration of heat is placed at the leading edge.

Practical considerations seem to indicate that the operation of a duct system having some concentration of heat at the leading edge, such as model C, augmented by forced internal-air circulation will meet most practical requirements. Although all duct systems tested prevented ice on the wing, a modification of model C meets the structural and the safety requirements common to airplane design. The air circulation within the wing will avoid the accumulation of explosive mixtures and will also prevent overheating the structure locally. In addition, such a system offers a simple solution to the problem of linear expansion and contraction of the exhaust-gas duct. A round spanwise tube could be supported in guides; it would thus have freedom to move lengthwise.

CONCLUSIONS

For the spray conditions existing during the tests, which produced typical ice formations at about 3 inches per hour, the following conclusions are drawn:

1. Ice formations over the wing of a 6-foot model were removed or prevented by a heating condition that would produce a skin temperature over the leading 10-percent portion of about 200° F. above tunnel air when the spray was not operating. The gas temperature in the duct that was necessary to produce this skin temperature varied from 360° to 834° F. with corresponding air-duct velocities of 152 and 45 feet per second, respectively.

2. Ice formations at the leading edge were locally prevented by air that passed on the interior of the wing surface at a velocity of 30 feet per second and at a temperature of 122° F.

3. The heating requirements for the after portion of

a wing chord are less stringent than at the leading edge because there it is only necessary to form a film of water between the ice and the wing to effect removal.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 15, 1939.

REFERENCE

1. 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. T.R. No. 403, N.A.C.A., 1931.

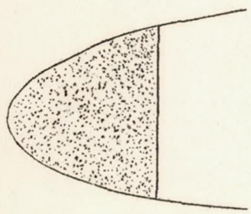
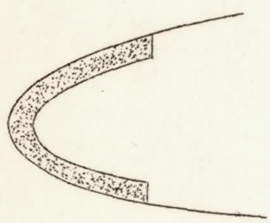
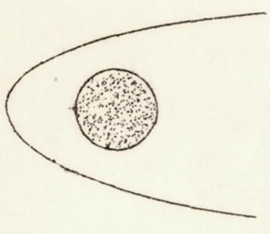
TABLE I.- TEMPERATURE DISTRIBUTION TEST RESULTS

[Tests 14, 15, 16, and 29D, fans on]

Test	Duct air (lb/min.)	Duct air temperature (°F.)	Model temperature (°F) (See figs. 2,3,and 4)										Tunnel air temperature (°F.)
			T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	
Model A, area 29 sq. in.													
4	25.8	750	215	540	300	198	124	103	540	156	87	90	26
5	22.4	820	264	570	320	205	130	106	577	158	87	90	27
7	16.0	900	131	378	208	141	86	78	436	117	78	78	27
8	16.0	834	131	438	226	141	84	77	359	115	63	63	27
9	22.4	725	153	420	243	145	105	94	282	135	--	--	28
10	25.8	630	118	350	195	111	48	45	248	92	53	42	28
11	25.8	534	92	223	122	80	45	38	152	64	45	38	28
12	22.4	632	92	190	106	78	36	36	140	60	39	33	27
13	16.0	738	90	184	102	65	35	--	133	53	34	--	27
[a]14	16.0	96	39	--	--	--	--	--	--	--	--	--	25
[a]15	16.0	890	--	--	--	--	--	--	--	--	--	35	25
[a]16	16.0	122	--	--	--	--	--	--	--	--	--	28	25
[a]Spray operating													
Model B, area 8.5 sq. in.													
26	16.0	360	205	--	272	130	68	55	350	104	48	40	26
Model C, area 7.1 sq. in.													
[a]28	16.0	95	32	--	--	--	--	--	--	--	--	--	20
[a]29A	16.0	105	43	--	39	39	23	23	28	50	32	22	20
[a]29B	16.0	430	117	--	77	117	65	55	75	155	71	33	20
[a]29D	16.0	450	108	--	--	--	--	32	--	--	--	32	20
[a]29E	16.0	230	95	--	80	95	42	42	80	107	37	--	20

Table II.- Ice-removal-test conditions and results.

-air
[Mass duct/velocity for all tests, 16 lb./min.]

Model	Tunnel-air temperature (°F)	Duct-air temperature (°F)	Test results
	25	8 90	A preformed glaze-ice cap, 3/8 inch thick, on the leading edge and other formations on the after-body were removed and re-freezing was prevented.
Model A	25	122	Ice formation was prevented over the leading-edge region. Glaze ice formed in unjoined chordwise ridges near the trailing edge.
	27	105	Glaze-ice formation over the leading-edge region was removed in 3 minutes. Ice continued to form near the trailing edge.
Model B	27	94	Ice formation was prevented over the leading-edge region. Ice formed on the after portion.
	20	[a] 450	Glaze ice removed from all parts of wing.
	20	[a] 95	Ice prevented over leading-edge region
Model C	20	250	Leading-edge glaze-ice cap removed from leading-edge region in 12 minutes.

[a] Internal circulating fans turned on.

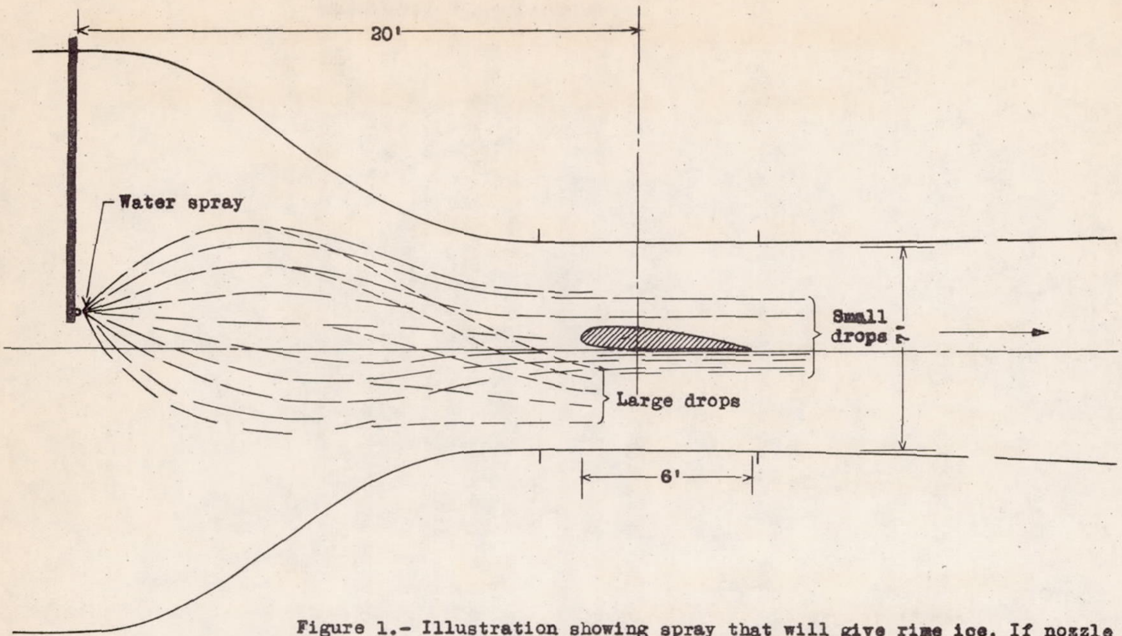
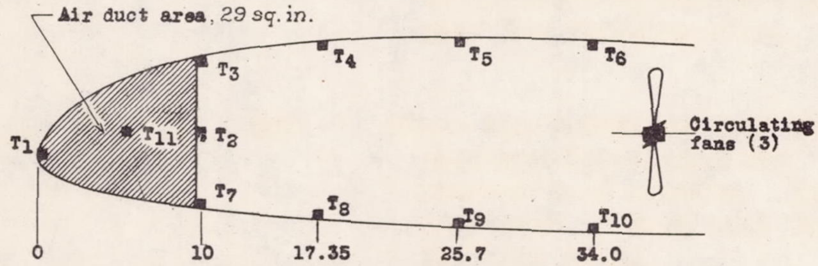


Figure 1.- Illustration showing spray that will give rime ice. If nozzle is raised, large drops will strike model, giving glaze ice.



Chord station location of thermocouples, percent

Figure 2.- Model A, heated wing.

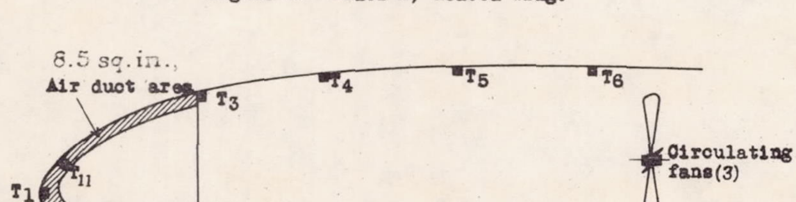


Figure 3.- Model B, heated wing.

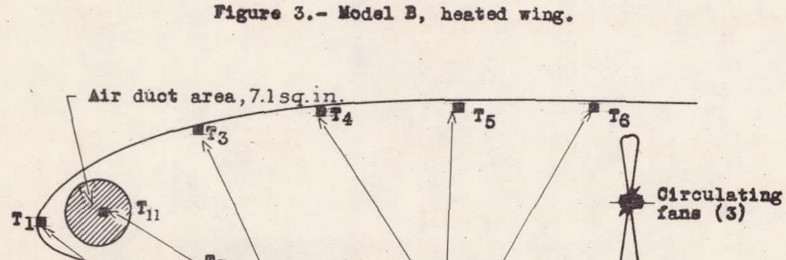


Figure 4.- Model C, heated wing.

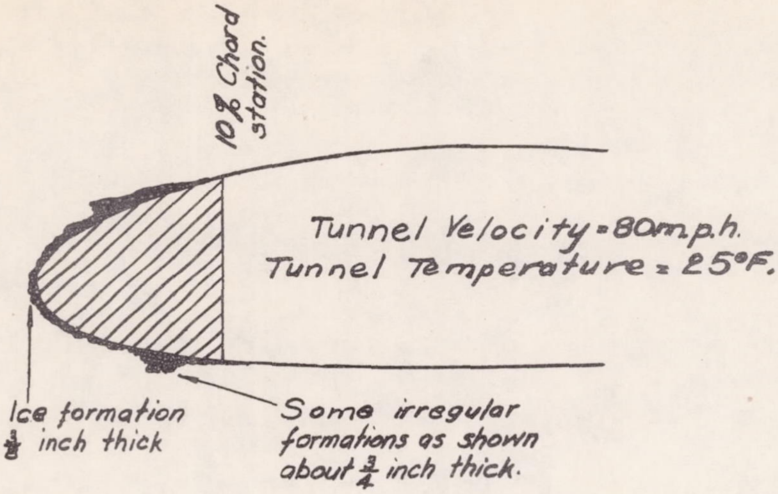
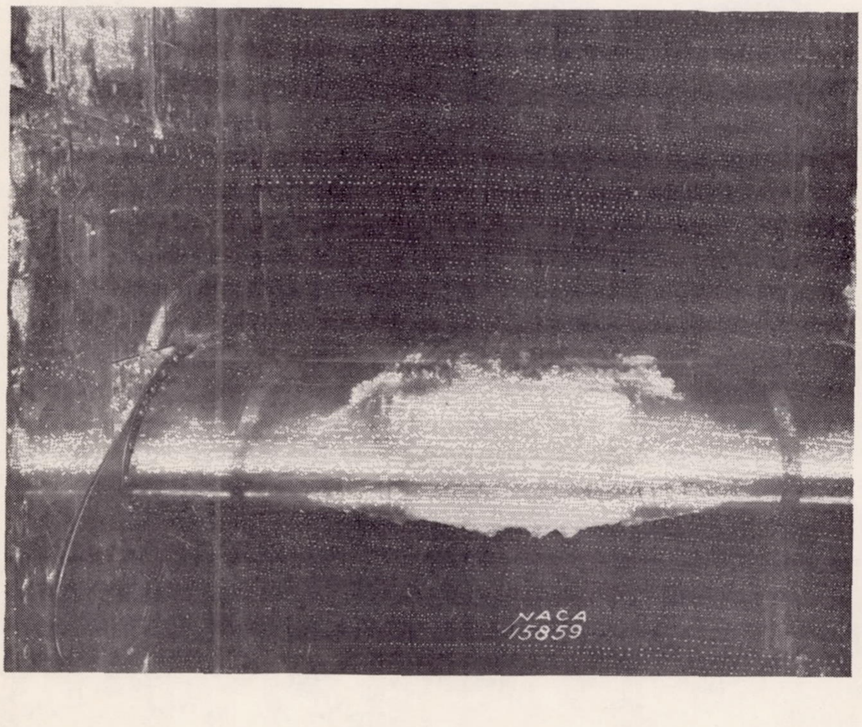


FIGURE 5 Glaze ice on plain wing.



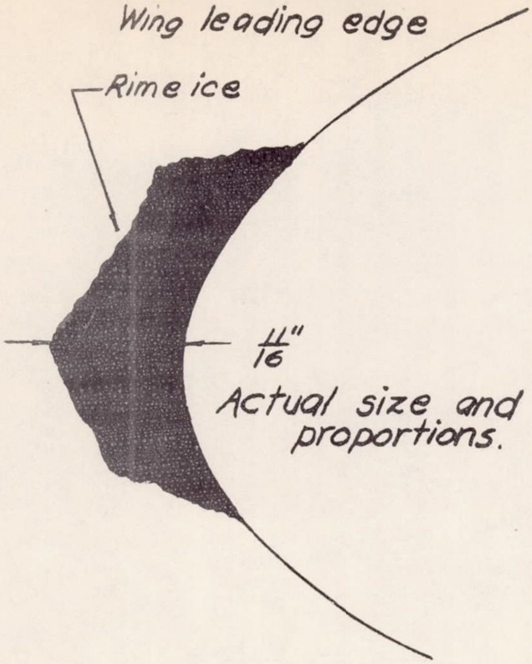
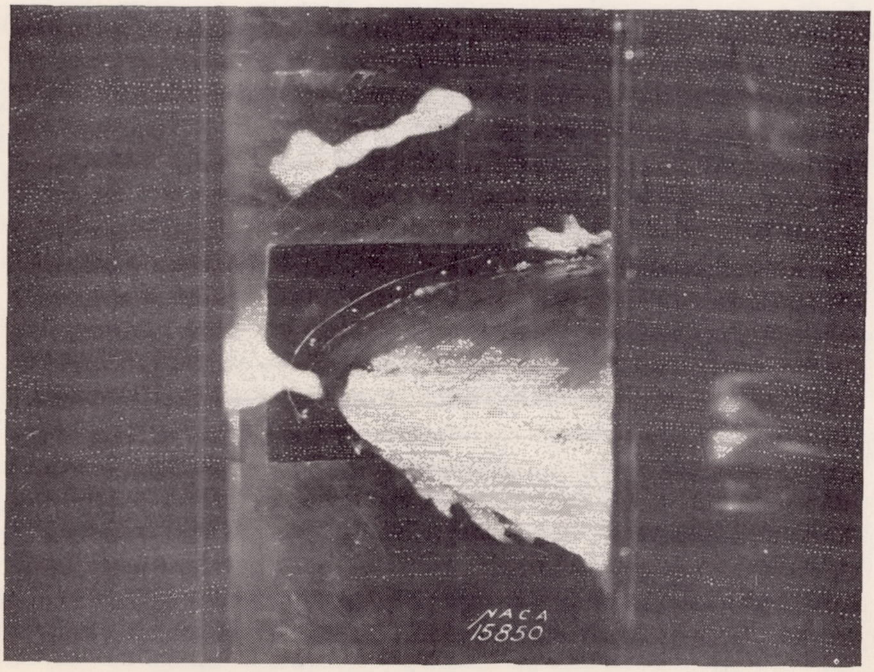


FIGURE 6 Rime ice on plain wing.



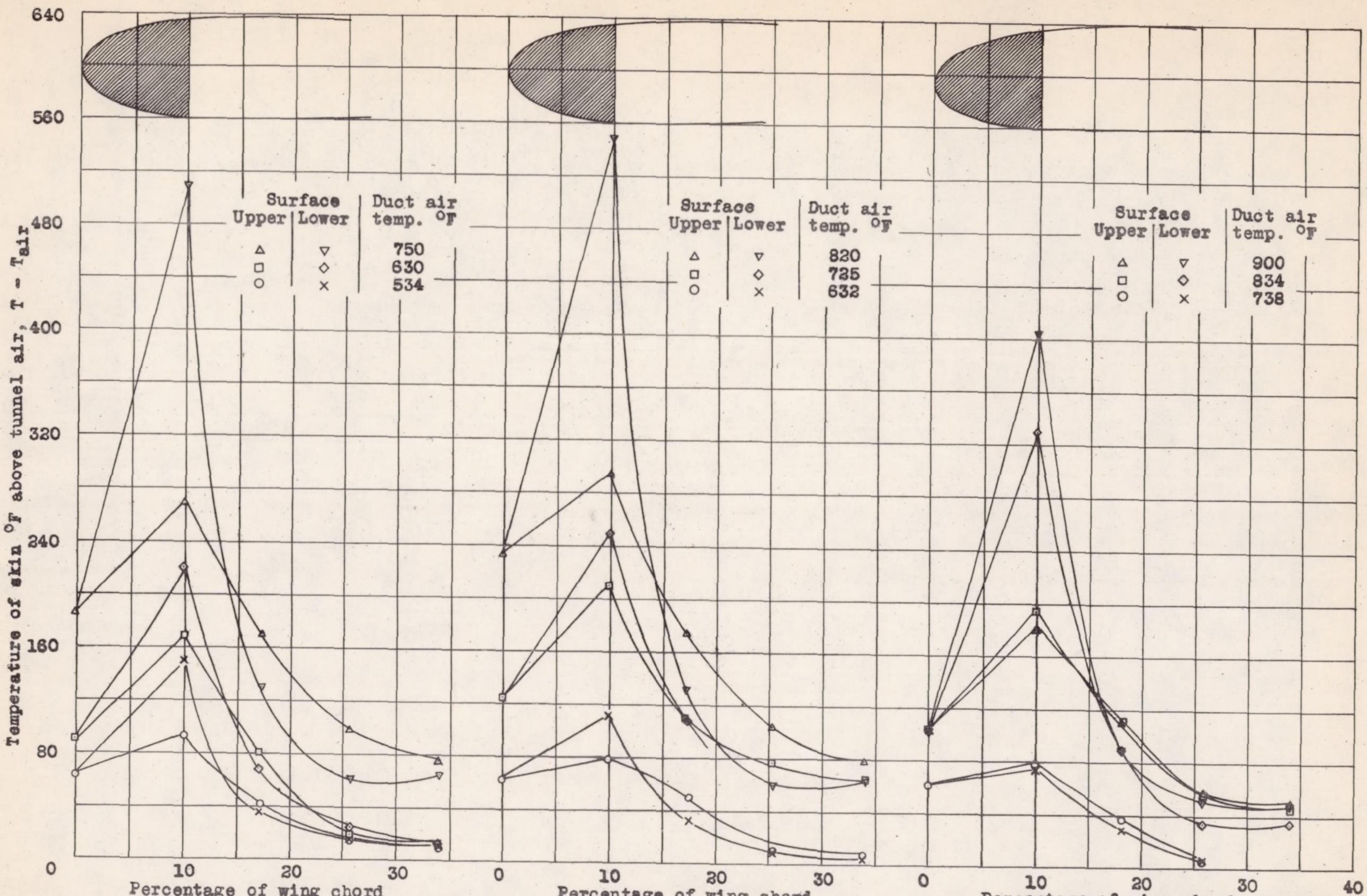


Figure 7.- Skin temperatures. Mass of air through duct = 25.8 lb./min. Model A.

Figure 8.- Skin temperatures. Mass of air through duct = 22.4 lb./min. Model A.

Figure 9.- Skin temperatures. Mass of air through duct = 16 lb./min. Model A.

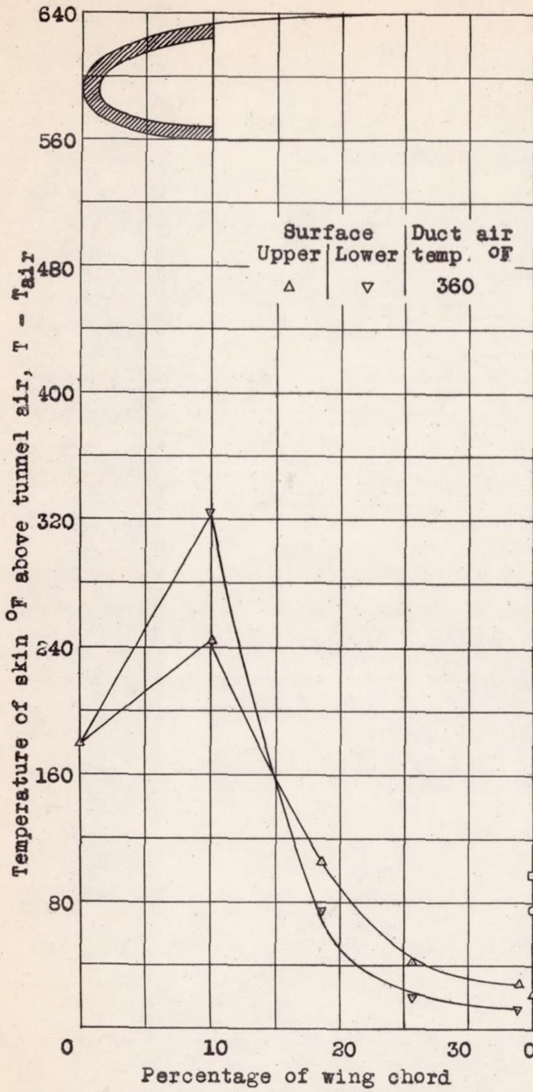


Figure 10.- Skin temperatures. Mass of air through duct = 16 lb./min. Model B.

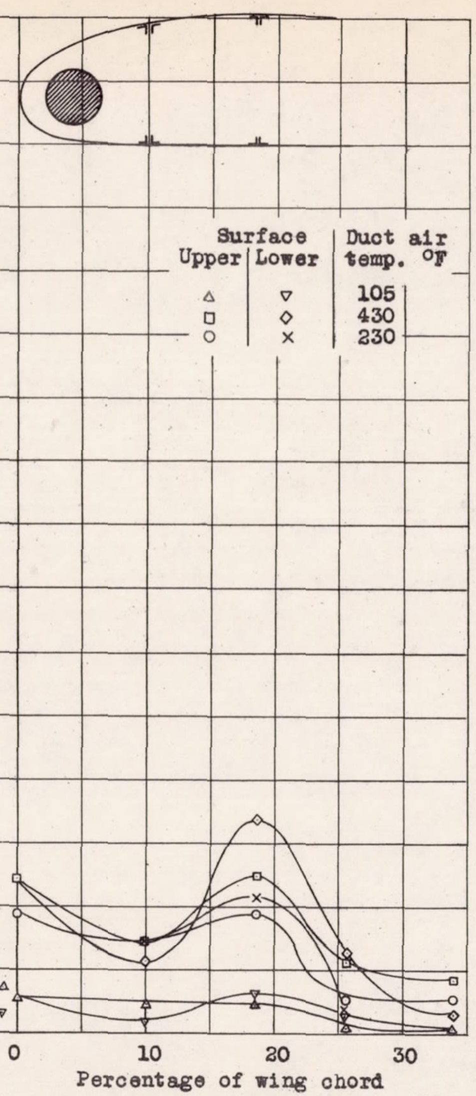


Figure 11.- Skin temperatures. Mass of air through duct = 16 lb./min. Model C.

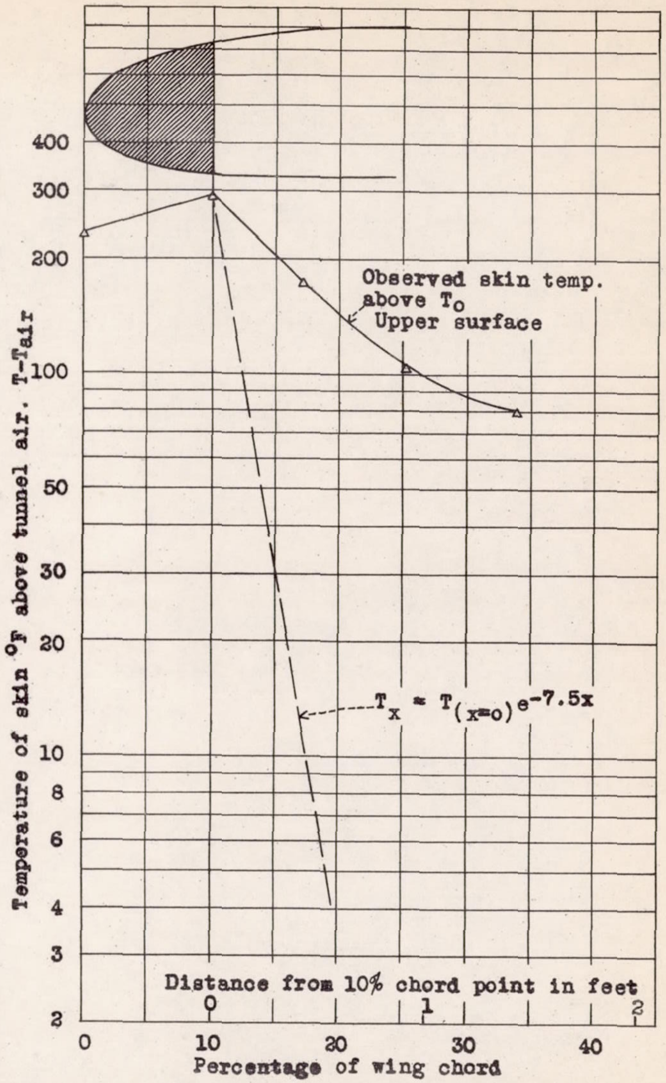


Figure 12.- Skin temperatures. Mass of air through duct = 22.4 lb./min. Model A.