THERMAL ICE PREVENTION

DE-ICING RESEARCH

James Selna or
Jackson R. Stalder

Over a period of several years the NACA has conducted research on the problem of ice formations on airplanes. The initial phase of the program consisted of a study of the manner in which ice forms on an airplane in flight and the resultant effect on safe and efficient operation of the airplane. This study indicated that the dangers of ice formations were not associated with the added weight, but rather were the result of aerodynamic disturbances, closure of air intakes, loss of visibility and other factors. We will now examine a few photographs which illustrate these effects.

(Fig. 7 (b)). Here we see ice accretions on the air inlets for the induction and intercooler air of a Boeing B-17F airplane. These air inlets are located in the wing leading edge inboard of the inboard nacelle. Guide vanes not shown, located inside the inlets, were subject to severe icing with attendant loss of engine power. (Fig. 7 (c)). Air inlets located in the cowl leading edge are particularly susceptible to ice accumulations, as shown here. This opening is sufficiently large to prevent closure, but narrow openings should be avoided. Propeller ice accretions form at a rapid rate because of the sharp leading edge and large swept area. (Fig. 7 (d)). Under cold enough conditions propeller ice formations will extend to within a few inches of the tip as shown in this

photograph. (Fig. 7 (e)). Protuberances from the airplane are very susceptible to icing. Formations such as the one shown here on an airspeed mast can effect the static pressure and cause erroneous readings in airspeed and altitude of considerable magnitude. (Fig. 7 (f)). The ice shown here formed over the windshield of a B-17F airplane in a very few minutes to a thickness of one inch. The photograph shows the outside of the windshield and was taken from the bombardier's compartment in front of and below the windshield. The undesirability of such formations is obvious. (Fig. 7 (g)). Ice will form on an antenna wire at a very rapid rate, particularly when the wire is installed perpendicular to the line of flight. The increase in drag is frequently enough to cause failure of the antenna wire and thus cause a loss in radio communication at a time when it is most urgently needed. (Fig. 7 (h)). In research flights a small-diameter rod is sometimes installed beside the pilot's window to collect representative ice accretions. Such a rod, and one typical accretion obtained in flight, are shown here. (Fig. 7 (i)). A 5-inch-thick ice formation is shown here on the air intake scoop. The selection of the location of any auxiliary air inlets should be influenced by factors such as this.

To overcome the operational problems associated with aircraft icing such as you have just observed, the NACA undertook an investigation of the use of heat to prevent ice formations. A series of wind-tunnel and flight tests with models showed encouraging

results, and the first full-scale heated wing to be flown in this country was designed by this Laboratory and tested on a Lockheed 12A airplane in 1941. The success of this airplane led to the revision of a Consolidated B-24D Liberator, a Boeing B-17F Flying Fortress, and a Curtiss-Wright C-46 Commando airplane at this Laboratory and their subsequent testing in natural icing conditions. These tests proved conclusively that the use of heat for aircraft ice prevention is practicable and provides better protection than any previously employed means. The NACA ice-prevention systems all used heated air as a heat transfer medium. The general features of these NACA thermal ice-prevention systems were the same in all of the airplanes revised at the Laboratory and will now be illustrated for you in detail through the medium of an animated moving picture.

Dialogue	Scene
None.	(Title) - Details of NACA Thermal Ice-Prevention System.
Our present research airplane, the Curtiss-Wright C-46 shown here, will be used to illustrate the manner of operation of the NACA thermal ice-prevention system.	Movie of airplane in flight.
The heat to be used for de-icing is transferred from the exhaust gas to air in 4 heat exchangers located as shown by the arrows.	Still of airplane in flight. Arrows appear at heat exchanger locations.

Dialogue	Scene
The heat-exchanger installation which has been encircled will be examined at closer range to observe the method of operation.	Circle with arrow. Circle only. Close-up of nacelle. Close-up of nacelle with cowl removed.
The heat delivered by each heat exchanger is sufficient to heat about 6 5-room houses in New York City in the winter time.	
The engine exhaust gases are gathered in the conventional collector ring and directed to the heat-exchanger installation.	Exhaust gas arrows flow through collector up to exchanger.
The heat exchanger consists of a series of flat plates with alternate air and exhaust gas passages.	Exhaust gas arrows flow through exchanger and out discharge stack. Arrow appears with word "discharge."
Free-stream air is rammed to the exchanger air scoop, passes through the alternate exchanger passages, and is directed to the wing leading-edge heating system.	Airflow into scoop, large arrow only. Flow in scoop, through exchanger, and to wing leading-edge. Arrow shows flow to leading edge.
The heated air from the outboard exchangers is used to protect the wing outer panels. The air is distributed spanwise by a duct in the leading edge.	Still of airplane heat exchangers red. Wing leading edge gets red.
The chordwise flow will be shown in detail for the station indicated by the arrow.	Arrow appears pointing out station for which chordwise flow will be shown.
An inner skin spaced about ½ of an inch from the outer skin extends to the 10 percent chord point. The heated air enters the gap between the two skins through an opening at the leading edge and flows chordwise.	"D" duct area becomes red. Heated air flow through corrugations.

Dialogue	Scene
After the double-skin region, the air circulates through the wing interior and is discharged at the aileron or flap slots.	Airflow through wing interior. Air discharge.
The entire outer panel, including the wing tips, is heated in this manner.	Red leading edge extended to tip. Resultant heating of outer panels.
A part of the heated air from the inboard exchangers is used to heat the inboard section leading edge.	Arrows point out inboard exchangers. Wing inboard leading edge becomes red.
The majority of the heated air from the inboard exchangers is used to prevent ice on the tail surfaces.	Air flow from inner panel to junction. Air flow from junction to empennage.
The heating system employed for the tail surfaces is identical to that which has been shown for the wing.	Empennage surfaces get red. Resultant heating.
Another portion of the heated air from the inboard exchangers is used for windshield heating.	Airflow from junction to windshield.
In the windshield ice-prevention system heated air is passed between an inner and outer surface in the same manner as for the wing heating system.	Pilot's windshield - no air flow. Air flow to windshield gap.
The warm air passes through the gap between the windshield panels and is discharged into the pilot's compartment.	Air flow through gap. Air discharging into cockpit.
Air directly from the heat exchangers is not used for this purpose because of the possibility of carbon monoxide poisoning.	Resultant heating.

Dialogue	Scene
In summary, the NACA thermal ice-prevention system provides protection for the wings, tail surfaces, and windshields.	Complete airplane with wings, tail surfaces, and windshield shown red.

All of the thermal ice-prevention systems designed and fabricated at this Laboratory were also tested by members of the staff in actual flights through natural icing conditions. Instrumentation was installed in the airplanes to measure the performance of the thermal system and also to obtain meteorological information in icing conditions. We will now show you a brief moving picture of a typical icing research flight with the C-46 airplane.

Dialogue	Scene
None.	(Title) - Scenes from a typical NACA icing research flight.
The research group studies an icing forecast prepared by a meteorologist assigned to the project by the Weather Bureau.	Group around map.
Warm humid air from the Pacific has been elevated by the coast range of mountains with icing predicted as shown.	Far view of map. Close view of map - pilot traces course.
The flight course through the icing region is traced by the pilot.	
Flight gear is assembled and the crew boards the airplane.	Crew entering airplane.
The engines are warmed thoroughly and carefully checked to insure perfect operation during the hazardous flight ahead.	Engine warm-up and start of taxying.

Dialogue	Scene
The test airfoil mounted on the fuselage has an electrically heated leading edge and is used to determine the amount of heat necessary for ice prevention.	Takeoff. Airplane in level flight.
Arriving in the icing region the airplane circles the icing clouds. The airplane is now entering an icing cloud for a test run. This is an ice-removal test and the wings are not heated. The pictures were taken through one of the airplane's windows. Note the ice that has formed on the leading edge of the wing.	Airplane above clouds. Enters cloud - view of wing from inside airplane.
Now the heat has been turned on and soon you will see the first ice being removed near the tip. -- Now watch the ice near the nacelle. -- In most cases complete removal can be effected in 30 to 45 seconds. The strip in the center of the airfoil is an electrically heated test section used to determine wing heating requirements.	Ice on wing and removal.
In the airplane the crew are busy adjusting the electrical test heating equipment, recording temperatures, taking photographs, and making meteorological observations.	Crew taking data.
An interesting ice accretion has formed on the rod outside the pilot's window, so he brings it into the cockpit for close examination.	Pilot brings ice into cockpit.

Dialogue	Scene
The meteorologist assembles a system of rotating cylinders which are projected into the airstream. By measuring the amounts of ice collected by the various sizes of cylinders he obtains an indication of the amount of liquid water in the cloud and also the size of the cloud droplets.	Lewis assembles cylinders and pushes them out of fuselage. Outside view of cylinders projecting from cabin. Cylinders retracted and disassembled.
Electrical heating shoes were installed on the propeller blades for ice protection. In this scene the propeller is feathered, showing the ice that was accumulated with the heating shut off. Ice formations such as this have been observed to cause losses in airspeed as large as 16 miles per hour.	Propeller feathering.
The icing runs having been completed, the wings are cleared for the return flight to the base.	Clear left wing. Clear right wing.
The icing flight ends as the airplane returns to the field of operations.	Landing.

DESIGN REQUIREMENTS

Norman Bergrun or
Donna C. Look, Jr.

All of the heated wings which have been designed, fabricated, and tested by the NACA have been designed on an empirical basis which specifies a certain surface temperature rise under dry-air conditions. This specification is not arbitrary but is based on several years of experience by the NACA in wind-tunnel and flight tests.

The empirical NACA design requirements for heated airfoils are shown graphically on this chart (fig. 7 (j)). These specifications require an average surface-temperature rise of at least 100°F forward of the 10-percent-chord point under the flight conditions of dry air, 0°F ambient air temperature, 15,000 feet pressure altitude, and at cruising speed or about 60 percent of rated engine power. Aft of 10 percent chord the heated air circulates through the wing interior and provides some heating of the surface in this region. Wing-heating installations which satisfied the design requirements shown on this chart provided satisfactory protection against ice formations in all conditions encountered. Frequently flights extended as long as 3 or 4 hours in icing conditions and no flight was terminated because of ice accretions on or behind the heated regions.

The objective of current icing research at the Ames

Laboratory is to replace the present empirical design practice with a more rational method based on an investigation of the fundamental meteorological and heat transfer processes that govern the operation of a heated wing.

In order to visualize the various factors influencing heated-wing design, let us consider the simple case of a heated airfoil passing through a cloud of uniform drops as shown here (fig. 7 (k)). If the drops are small enough, practically all of them will pass around the airfoil and very little ice accretion will result. For the usual case, however, those drops are sufficiently large so that all of the drops in a region such as is shown shaded here strike the leading edge of the airfoil. The area of catch, or region in which the drops strike the surface, can be calculated for the case of a cylinder with reasonable accuracy, but the application of the calculations to the leading-edge cylinder of an airfoil requires further investigation.

In order to avoid freezing, the temperature of the water striking the airfoil leading edge must be raised to 32°F. What happens to the water from this point on is a matter of considerable speculation at the present time. It is claimed by some that all of the water striking the wing must be evaporated in order to avoid afterfreezing, or runback, which is freezing of the water on the surface behind the directly heated region. Others believe that the water will run or be blown from the wing and need only be maintained in the liquid state. All are in agreement that the

heated area should extend beyond the area of catch to some point such as indicated here.

The quantity of heat removed from the airfoil surface in the heated region consists of three distinct portions as follows:

(1) Heat required to raise the temperature of the water from free-stream temperature to the airfoil surface temperature.

(2) Heat required to evaporate all, or a portion, of the water caught.

(3) Heat removed by convection.

Equations are available for calculating the effects of moisture on the temperature distribution over a heated leading edge, provided several qualifying assumptions are made. As an example, let us examine the change in temperature distribution of a leading edge, initially heated to a temperature rise of 100°F in dry air, under the conditions of 15,000 feet pressure altitude, 0°F ambient air temperature, and the surface completely wetted to 10 percent chord. (Fig. 7 (1)). We see here that heating of the water has effected a small reduction in temperature and that evaporation of water has reduced this surface temperature by approximately 60 percent. For this condition, therefore, the 100°F temperature rise in dry air becomes a rise of from 40 to 50°F in an icing cloud, or a rise of only 8 to 18°F above freezing.

Although the ability to obtain this limited picture of the fundamental operation of a heated wing is encouraging, a great deal more research is required before the empirical, clear air method of design can be replaced by the rational, wet air method.

The objectives of this research include the determination of such factors as drop size and drop distribution, liquid water content, free-air temperature, area and rate of water catch, and evaporative requirements.

These factors are presently being investigated by the NACA. You have just seen the manner in which the C-46 airplane was employed last winter and will be used this winter, to further investigate these factors I have discussed. We will now make a brief inspection of the C-46 airplane and its research facilities (fig. 7 (m)), and also some examples of heat exchanger (fig. 7 (n)) and heated wing leading edge (fig. 7 (o)) constructions and a heated propeller.

(a) General view.

Figure 7.- Ice prevention exhibit.

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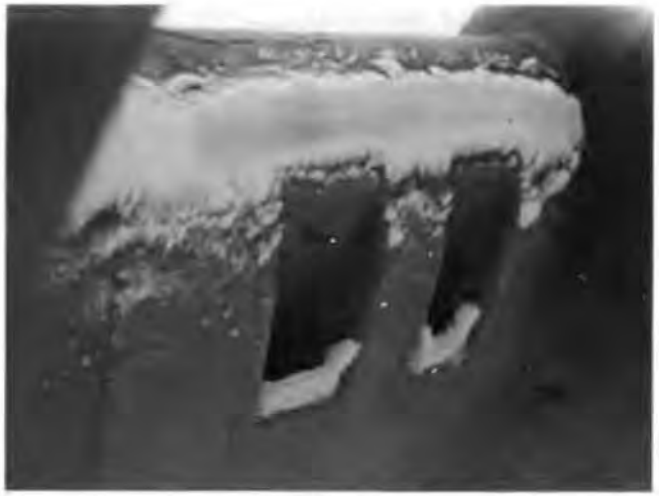
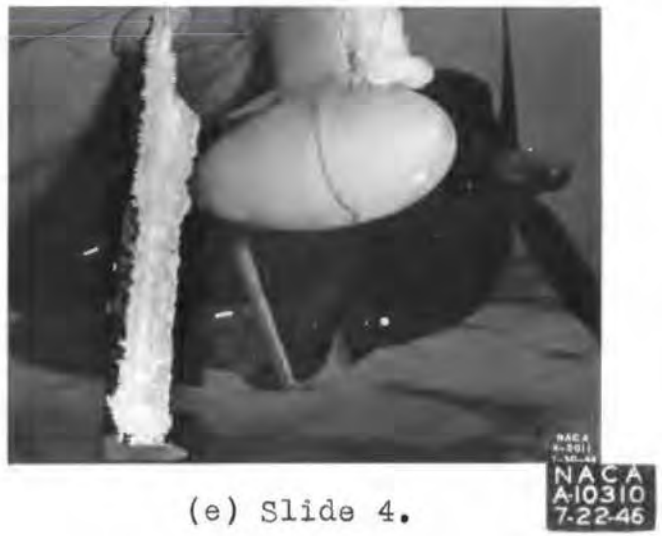


(b) Slide 1.

(c) Slide 2.

(d) Slide 3.



(e) Slide 4.

Figure 7.- Continued.

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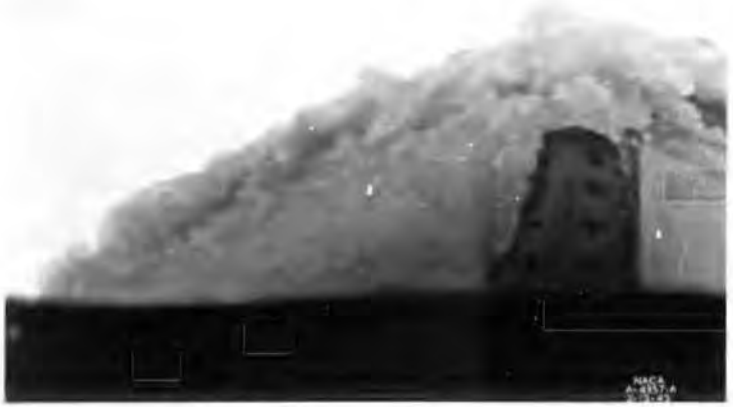

(f) Slide 5

(g) Slide 6.

(h) Slide 7.

(i) Slide 8.

Figure 7.- Continued

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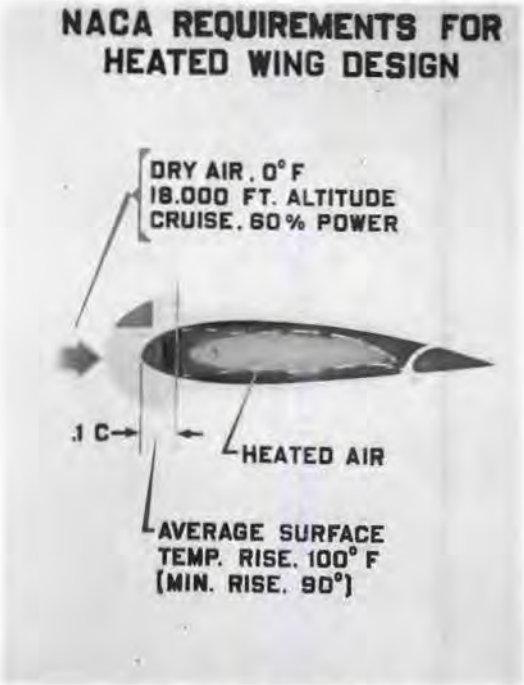
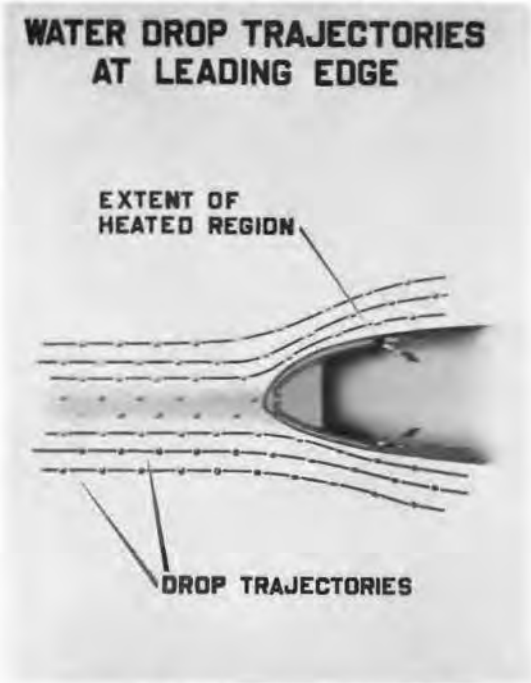
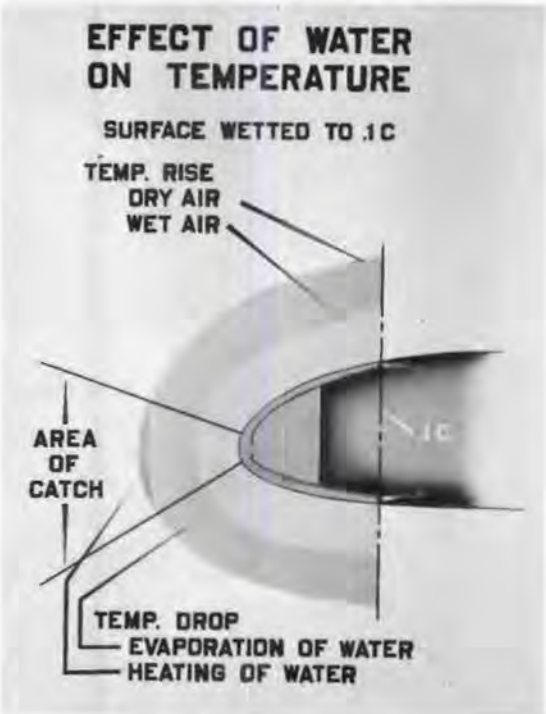


(j) First chart.



(k) Second chart.



(l) Third chart.

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Figure 7.- Continued.

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(m) Curtiss C-46 airplane used for de-icing research.

Figure 7.- Continued.

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(n) Heat exchangers.

(o) Heated wings.

Figure 7.- Concluded.

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