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Icing-Tunnel Tests of a Glycol-Exuding, Porous Leading-Edge Ice Protection System

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A glycol-exuding, porous leading-edge ice protection system was tested in the NASA Icing Research Tunnel at Lewis Research Center. Test results showed that the system was very effective in preventing ice accretion (anti-ice mode) or removing ice from an airfoil. Minimum glycol flow rates required for anti-icing are a function of velocity, liquid water content in the air, ambient temperature, and droplet size. Large ice caps were removed in only a few minutes using anti-ice flow rates, with the shed time being a function of the type of ice, size of the ice cap, angle of attack, and glycol flow rate. Wake survey measurements showed that no significant drag penalty was associated with the installation or operation of the system tested.

Nomenclature

c	= chord
c_d	= section drag coefficient $= 2[(V_l/V)(1-V_l/V)]dx/c$
c_l	= section lift coefficient
H	= local stagnation pressure
H_0	= freestream stagnation pressure
LWC	= liquid water content, g/m^3
OAT	= outside air temperature
p_0	= freestream static pressure
T	= total temperature
V	= freestream equivalent airspeed
V_l	= local equivalent airspeed
WS	= wing station, in.
x, y	= position coordinates
α	= angle of attack

Introduction

AT the present time the only airframe ice protection system available from the U.S. light airplane manufacturers is a pneumatic boot system. While this concept has been relatively successful, there are some disadvantages. The boots are expensive and must be replaced periodically. The boots do not prevent ice but remove it after it has formed. This causes two problems: some ice may remain adhered to the boot, and premature actuation of the boot may only displace—not remove—the ice, making further removal difficult. Pilot judgment is therefore a factor that influences the performance of the system. Furthermore, any ice that forms on the wing aft of the active portion of the boot will not be removed. This may be substantial, especially at high angles of attack.

One alternative to the pneumatic boot is a liquid ice protection system that distributes a glycol solution onto the leading edge of a wing or control surface through a porous

skin. This concept was developed by T.K.S. (Aircraft De-Icing) Ltd., of England, and was subsequently employed on numerous airplanes.

There are several advantages associated with a porous leading-edge ice protection system.

- 1) Leading-edge airfoil contours can be retained with excellent tolerance.
- 2) No residual or runback ice is left on surfaces after system actuation.
- 3) The life of the system hardware is comparable to that of the airframe.
- 4) The system operates with a low power demand.
- 5) Little judgment is required by the pilot to operate the system safely.

A disadvantage is that the glycol solution must be carried onboard whenever the need for ice protection is anticipated. Furthermore, the duration of ice protection is limited by the finite supply of fluid. Obviously, it is desirable to establish the minimum fluid flow rates required to obtain the level of protection desired.

Relatively little is known about porous leading-edge ice protection systems in the United States, and no American-built airplanes employ such a system as factory-installed equipment. Thus there is a need to increase understanding of this option and to generate a data base for designers to use in the future.

The purpose of these tests is to determine the operating characteristics of a porous leading-edge glycol system on an advanced low-speed airfoil and to define minimum effective glycol flow rates at various flight conditions.

Tunnel Description and Test Conditions

The NASA Lewis Icing Research Tunnel (IRT) is a closed cycle, refrigerated wind tunnel with a rectangular test section 1.83 m (6 ft) high by 2.74 m (9 ft) wide by 6.1 m (20 ft) long (Fig. 1). Maximum tunnel airspeed is 134 m/s (300 mph). A natural icing cloud is simulated by injecting a water spray upstream of the test section.

The area of interest on the test model is confined to the region in the center of the test section, where the icing cloud is most uniform, covering a cross-sectional area of 0.9 m (3 ft) high by 1.5 m (5 ft) wide. The liquid water content (LWC) of the cloud can be varied from about 0.5 to over 2 g/m^3 with volume median droplet diameters in the range 10–20 μ . The tunnel airflow temperature can be varied from $-28.9^\circ C$ ($-20^\circ F$) to ambient.

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For this series of tests, two test section equivalent airspeeds were chosen, namely, 49.2 m/s (96 knots) and 90.3 m/s (175 knots). These speeds correspond to the best rate of climb speed and the cruise speed of an aircraft on which a NACA 64 series airfoil is typically used.

Since the LWC and water drop size ranges of the IRT icing cloud depended upon tunnel airspeed, operating envelopes for LWC and drop size were plotted for the given airspeeds of interest, 49.2 and 90.3 m/s (Fig. 2). From these two tunnel operating envelopes the extreme values and several midpoint values of LWC and drop size were chosen as the icing cloud test conditions (Fig. 2). The LWC and drop size varied then from 0.65 to 2.4 g/m³ and from 11 to 20 μ m, respectively. Figures 3 and 4 illustrate where the tunnel icing cloud test conditions are located on the continuous maximum and intermittent maximum icing condition curves specified in Federal Aviation Regulations, Part 25.¹

The type of ice (i.e., glaze or rime) that formed on the airfoil depended primarily on the tunnel total air temperature. To provide glaze ice, the tunnel total air temperature was set at -3.9°C (25°F); and to produce rime ice, it was set at -15°C (5°F). The ambient or outside air temperature (OAT) corresponds to the static air temperature in the tunnel test section. For the two airspeeds chosen, namely, 49.2 and 90.3 m/s, the OAT's for glaze ice were -5.1 and -7.8°C , respectively; and the OAT's for rime ice were -16.2 and -18°C , respectively. The true airspeeds were 43.7 and 85.3 m/s at $T = -15^\circ\text{C}$ and 44.7 and 86.9 m/s at $T = -3.9^\circ\text{C}$.

A translating wake-survey probe was used to measure the section drag coefficient, c_d , of the test model. The probe consisted of a single stagnation pressure tube which could be retracted behind a wind screen. When the airfoil was exposed to the tunnel icing cloud, the probe was retracted. After the icing cloud was turned off, the probe was inserted into the airstream and the wake survey was made. This probe, which was located about one chord length downstream of the airfoil at midspan, was installed as shown in Fig. 5 to yield the velocity decrement ratio (V_1/V) in the airfoil wake. By translating laterally through the wake, a plot of V_1/V vs position was obtained. Integration of the wake defect gave a measurement of model section drag coefficient.

Model Description

The wing section tested was taken from an actual single-engine, light airplane. The original wing tapered from a NACA 64₁A215 airfoil at the root (WS 0) to a NACA 64₁A412 airfoil at the tip (WS 216). The wing incorporated a modification proposed by Raymond Hicks^{2,3} of NASA Ames Research Center. This modification, which adds thickness to the forward 30% of the upper surface, increases $c_{l_{\max}}$.

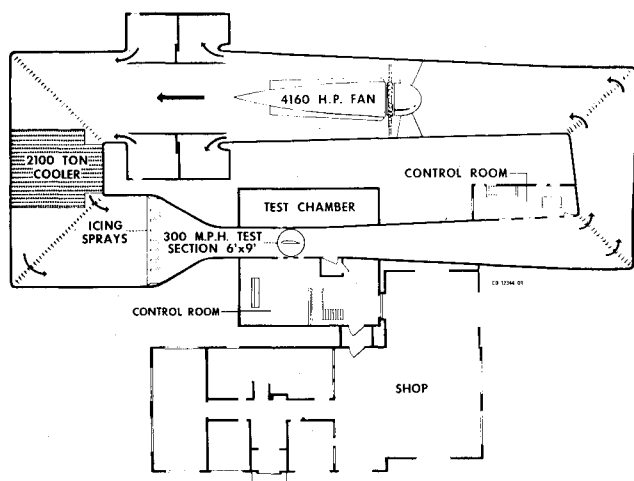


Fig. 1 NASA Lewis Icing Research Tunnel.

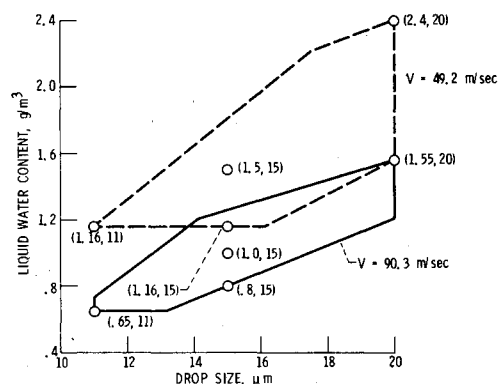


Fig. 2 IRT operating envelopes and test points.

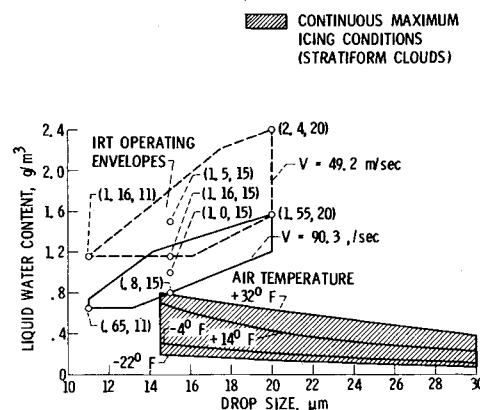


Fig. 3 Continuous maximum icing conditions¹ and IRT operating envelopes.

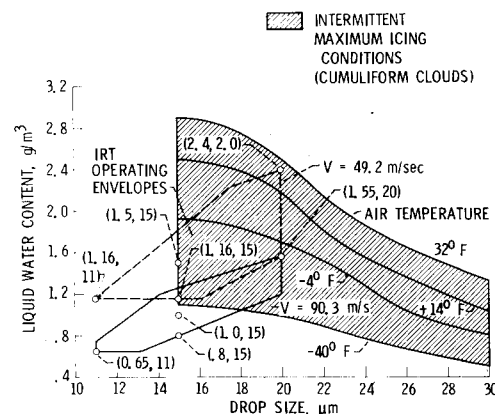


Fig. 4 Intermittent maximum icing conditions¹ and IRT operating envelopes.

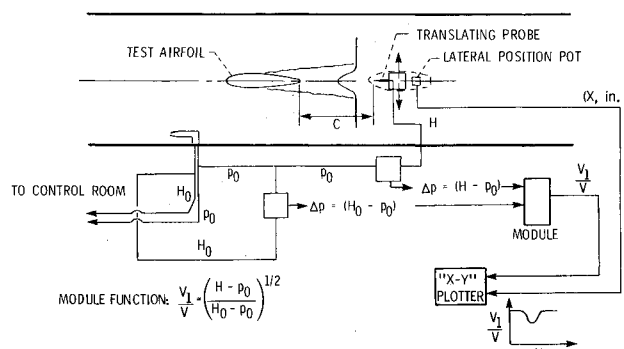


Fig. 5 Schematic of wake-survey probe instrumentation.

reduces c_d at high c_l , and improves stall characteristics. A typical "Hicks" modification is shown in Fig. 6.

The wing section tested was fastened securely to the turntable on the floor of the tunnel, using the spar fittings that are used to attach the wing to the fuselage of the airplane. A clearance of $\frac{1}{2}$ in. was allowed between the outboard end of the wing segment and the ceiling of the 6-ft-high test section of the tunnel. The centerline of the tunnel was at WS 58 of the original wing. Table 1 gives the airfoil coordinates at WS 58, where the wing chord is 63.25 in. The chord tapers 1.1 in./ft of span, and the wing is twisted 0.167 deg/ft of span (washout). Figure 7 shows the wing section installed in the NASA Lewis Icing Research Tunnel.

Ice Protection System Description

The system tested consists of a porous stainless steel panel attached to the leading edge of the wing, and a pump that distributes a glycol-based fluid from a tank to the panel through plastic tubing. The fluid exudes from the porous panel onto the surface of the wing, providing either an anti-icing capability by dissolving the supercooled water droplets and preventing the formation of ice, or a deicing capability by chemically breaking the bond of established ice. A significant feature of the system is that protection is obtained aft of the panel by the flow of the fluid along the chord to the trailing edge, thus preventing the formation of ice anywhere aft of the active leading edge.

The porous leading-edge panel used in this test was attached to the original wing leading edge, as shown in the cross-sectional drawing in Fig. 8. The width of the porous region is 8.7 cm. The panel is divided spanwise into three separate porous sections. Referring to the vertical position of the wing in the tunnel, the upper and lower sections are 20.3 cm long and the middle section is 30.4 cm long. The maximum thickness of the panel is 3.2 mm. The flow rate into each section was controlled independently by three variable positive displacement pumps.

The fluid reservoir behind the porous leading-edge skin consists of a solid stainless steel backing plate and a thin polyvinylchloride sheet that separates the fluid from the porous leading edge. The purpose of the polyvinylchloride sheet, whose porosity is much lower than that of the stainless steel, is to distribute the glycol evenly over the entire active portion of the panel, regardless of the chordwise pressure distribution changes that occur as angle of attack changes.

The porous stainless steel skin consists of two layers of wire cloth that are rolled, sintered, and then finish-rolled to thickness. The wire cloth is manufactured from an 18-8 austenitic stainless steel and nominally has 110 \times 20 wires/in. The two layers are oriented 90 deg with respect to each other. The system hardware was designed and manufactured by T.K.S. (Aircraft De-Icing) Ltd.

The fluid used in this test is composed of 80% monoethylene glycol and 20% deionized water.

The edges of the active portion of the panel must be placed such that extreme positions of the stagnation points for which icing protection is required are no closer to the edge than approximately 1 cm. This ensures that the fluid will always be distributed on both the upper and lower surfaces of the wing. Figure 8 shows the location of the stagnation points on the leading edge for each angle of attack used in this test.

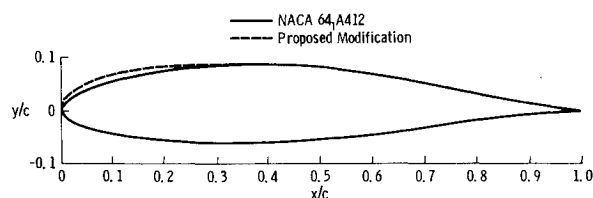


Fig. 6 Hicks modification on a NACA 64₁ A412 airfoil.

Table 1 Airfoil coordinates of wing section at centerline of the IRT (WS 58) in percent of chord

Upper surface		Lower surface	
x	y	x	y
0	-0.704	0	-0.704
0.015	-0.250	0.335	-1.474
0.648	0.791	0.723	-1.858
1.138	2.372	1.216	-2.193
2.055	3.447	2.451	-2.760
3.953	4.941	4.926	-3.545
6.324	6.008	7.407	-4.130
9.486	6.735	14.223	-5.371
11.352	7.036	19.197	-5.395
13.439	7.502	24.175	-6.359
22.024	7.565	29.157	-6.658
24.996	7.581	34.142	-6.816
30.126	7.597	39.129	-6.870
34.783	7.534	44.122	-6.718
39.428	7.426	49.115	-6.449
44.409	7.110	54.111	-6.114
49.387	6.591	99.741	-2.794
54.360	5.891		
59.331	5.047		
62.111	4.526		
99.744	-2.606		

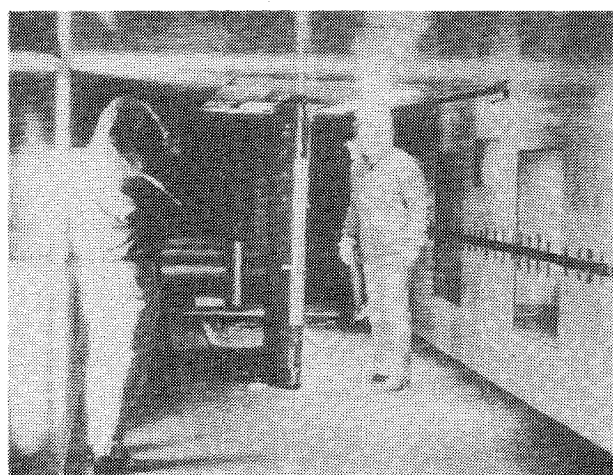


Fig. 7 Wing section installed in the NASA Lewis Icing Research Tunnel.

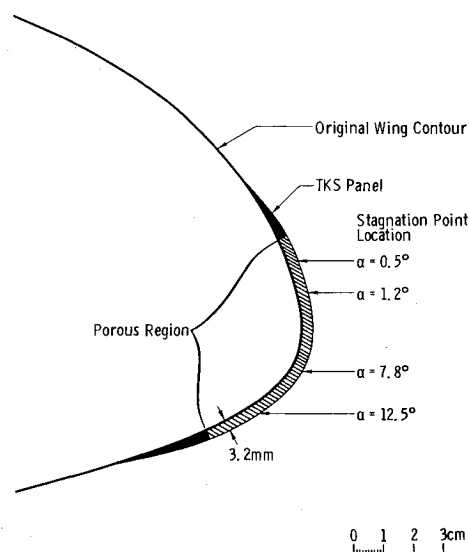


Fig. 8 Cross section of the porous panel installed on the test wing, WS 58.

Test Results

Anti-Ice Mode

Normal operation of the glycol-exuding, porous leading-edge system is in the anti-ice mode; that is, the glycol flow rate is sufficient to prevent any ice from forming on the wing. This is possible as long as the glycol-water solution on the surface maintains a freezing temperature below the ambient air temperature. The solution freezing temperature increases as the ratio of the water catch rate to the glycol flow rate increases. A series of runs was conducted in the Lewis IRT to determine the minimum glycol flow rate at which anti-icing could be maintained.

The method of determining the glycol flow rate corresponding with the anti-ice threshold was as follows. At a given flight condition, the flow rate was set to be well above the anti-ice threshold. The flow rate was then reduced in steps, allowing about 30 s for the system to stabilize at each point, until small flecks of ice began to appear on the leading edge in the vicinity of the stagnation point. At the anti-ice threshold, the small ice flecks, ranging up to about 3 mm in diameter, would form and then be swept downstream in only a few seconds. A glycol flow rate lower than the threshold value would cause the ice flecks to persist, gradually growing into larger patches before being shed from the wing.

To obtain the minimum anti-ice glycol flow rates, the upper and lower sections were used simultaneously during each run to establish independent flow rate values from each section while the center section was used to determine minimum flow rates for natural deicing (discussed in the next section). The data presented represent an average of the results from the upper and lower sections. As a general rule, the anti-ice threshold occurred at a lower flow rate on the lower section than on the upper section. This can be attributed to the larger leading-edge radius of the lower section, which results in a reduced water catch rate at the leading edge. The average should closely represent the anti-ice threshold on the center section. Flow rates are presented in terms of specific fluid flow: milliliters of glycol per square centimeter of active panel per minute.

Figures 9a-9d present the results of anti-ice tests at the two airspeeds and temperatures used for this study. Specific fluid flow is shown as a function of angle of attack for several liquid water contents at each flight condition. Minimum anti-ice fluid flows are not strongly affected by angle of attack, as long as the stagnation point is not too close to the edge of the porous skin. As seen in Fig. 8, the stagnation point for $\alpha = -0.5$ deg is closest to the edge. This angle of attack tends to require a higher flow rate, particularly at the higher airspeed. For $\alpha = 12$ deg, the stagnation point is not as close to the edge as for $\alpha = -0.5$ deg, and the effect of the edge is not evident in the data.

As one would expect, required glycol flow rates generally increase as LWC increases and as airspeed increases. However, the width of the threshold in terms of glycol flow rate, the subjective task of identifying the threshold, and the normal variations in LWC during a series of runs results in a sometimes broad band of uncertainty in the data, as shown in Fig. 9c.

One method to check for consistency in anti-ice threshold data is to plot glycol flow as a function of LWC, all other conditions being constant. To first-order accuracy, the result should be a straight line through the origin with positive slope, since an increase in water collection at the leading edge should require a proportionate increase in glycol to maintain a solution at the threshold of freezing.

Figures 10a-10d illustrate results for the anti-icing tests. In general, the fluid flow rates do increase monotonically as LWC increases, frequently approximating the straight line through the origin that would be expected. Obvious variances do appear, however, as a result of test points that probably were not run long enough to determine the flow rate at the lower end of the threshold. In virtually every case, the

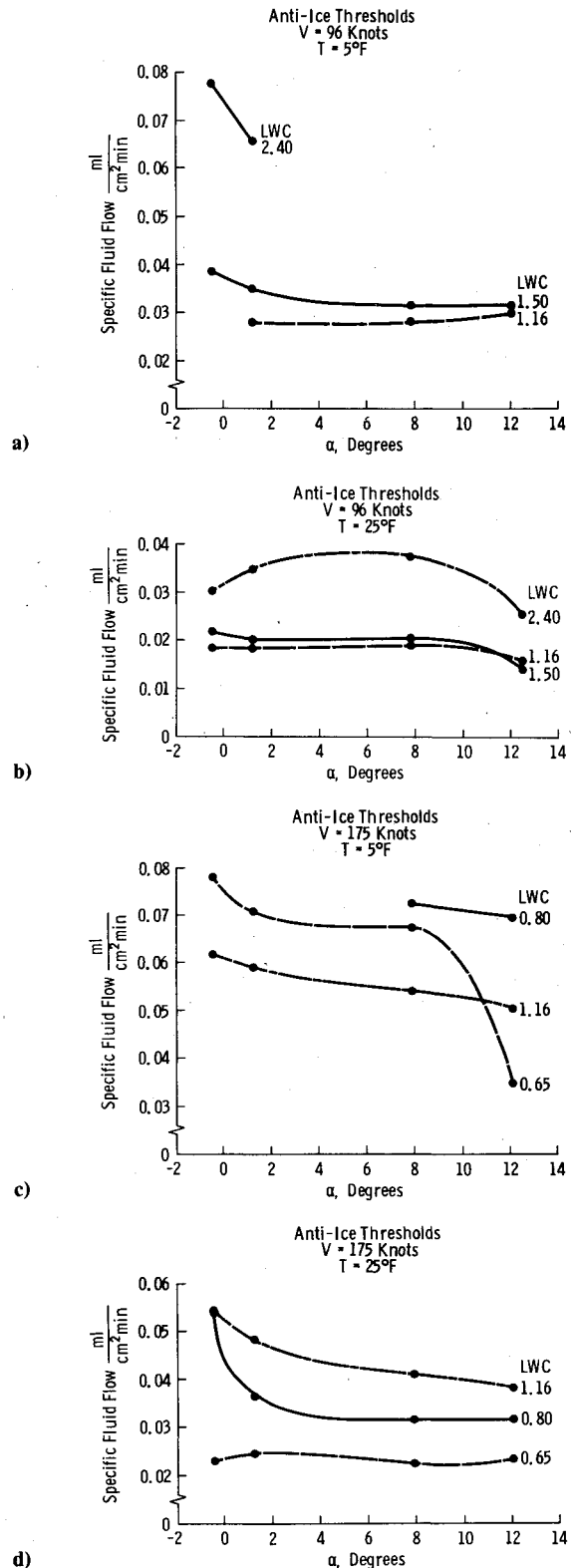


Fig. 9 Minimum glycol flow rates required to maintain anti-icing.

variance in flow rate appears to indicate a higher than expected value.

One other point needs to be made. One variable that does not appear explicitly in Figs. 10a-10d is the water droplet diameter. As the droplet size increases, the catch rate of the wing will increase also because of the higher inertia of each drop. This will require a higher glycol flow rate to maintain anti-icing at the same LWC. However, the data do not indicate that this effect is much greater than the uncertainty in the data over the range of 11-20 μ used in these tests.

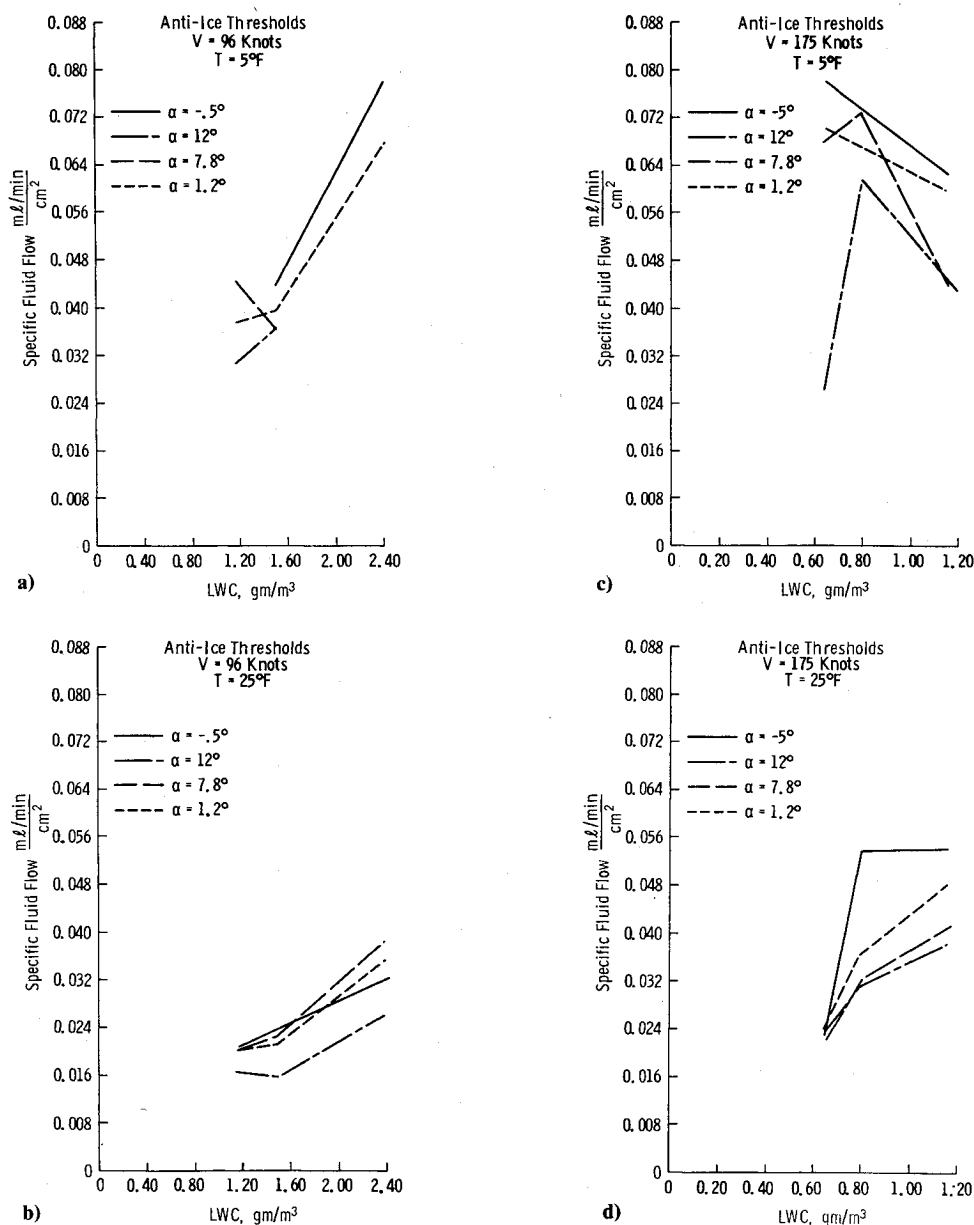


Fig. 10 Effect of liquid water content on minimum anti-ice glycol flow rate.

A designer might well be concerned whether these flow rates would be adequate to meet certification requirements. The maximum droplet size specified by Federal Aviation Regulations (FAR), Part 25, Appendix C,¹ is $50 \mu\text{m}$; and as droplet size increases from 20 to $50 \mu\text{m}$, the LWC decreases significantly. Further studies are now in progress to define more accurately the effect of droplet size on flow rate required and to develop a reasonably accurate analytical method of predicting minimum anti-ice glycol flow rates.

Natural Deice Mode

The natural deice mode occurred when the glycol flow rate was below the anti-ice threshold value but still high enough that no permanent ice accretions formed on the wing. It was subjectively identified by the formation of a continuous spanwise bar of ice along the stagnation line, about 3-7 mm thick and 5-10 mm wide, which would shed at intervals of approximately 2-7 min. The threshold was identified as the lowest specific fluid flow at which periodic shedding of the bar of ice would take place.

Results are presented in Figs. 11a-11d. Again, the required glycol flow rates are not a strong function of angle of attack

except at 175 knots and 5°F , where the flow rates increase significantly as the stagnation point approaches either edge of the porous panel. The band of uncertainty is observed to be near the variation caused by the differences in LWC.

The natural deice flow rates were substantially lower than those for anti-icing, often being as low as 25-50% of the anti-ice threshold. This implies that a system designed for anti-icing at a given LWC can safely withstand much more severe icing conditions, operating in the natural deicing mode.

Deicing Tests

It is possible that a pilot might fly in icing conditions for a period of time before becoming aware of the situation, particularly at night. Therefore it is of interest to determine the capability of the porous leading-edge system to shed ice after an initial buildup that has occurred with the flow pump turned off.

The test procedure was as follows. The center section glycol was turned off, and the upper and lower sections were provided a flow rate equal to or greater than the minimum required for anti-icing. This prevented the ends of the ice cap from adhering to an untreated portion of the leading edge, thus influencing the results. At each test condition the icing

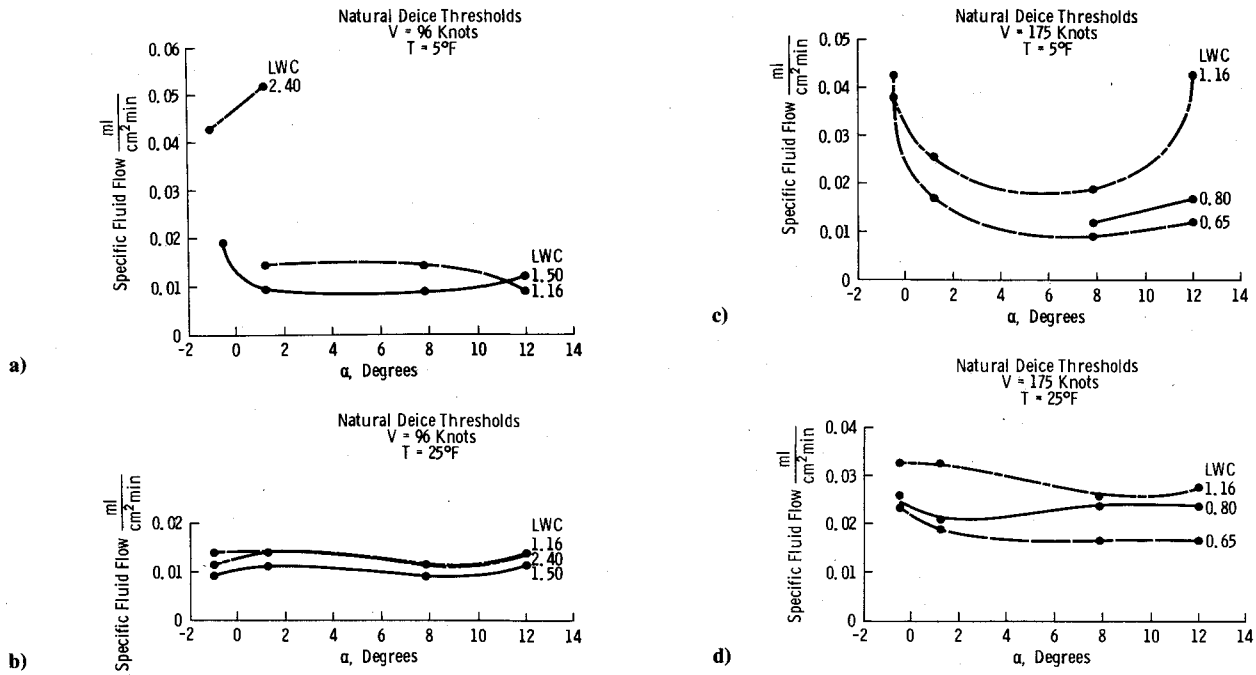


Fig. 11 Minimum glycol flow rates required to maintain natural deicing.

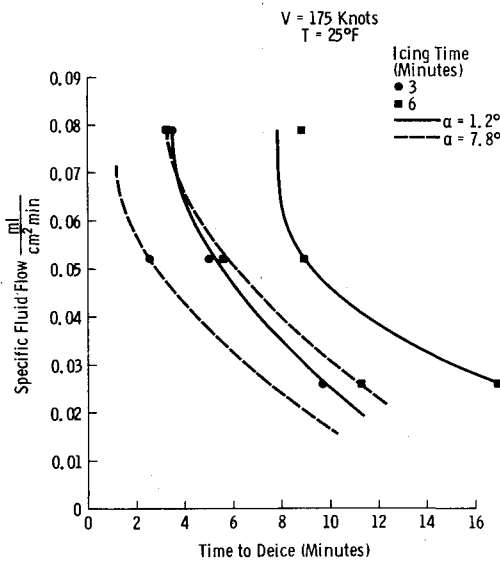


Fig. 12 Effect of angle of attack and glycol flow rate on time to deice.

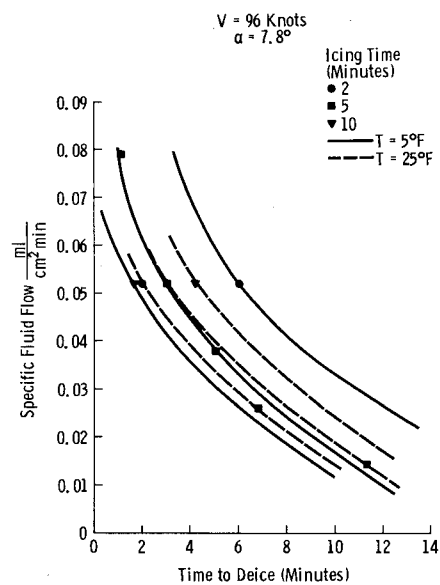


Fig. 13 Effect of temperature and glycol flow rate on time to deice.

spray was turned on for a specific period of time. After the spray was turned off, the center section glycol pump was turned on at a given rate and the time required to shed completely the cap of ice from the leading edge was determined.

Results of the deicing tests are presented in Figs. 12 and 13. General observations are that the higher the glycol flow rate, the shorter the time required to shed the ice (although very high flow rates bring diminishing returns), and reasonable ice shedding times can be achieved with glycol flow rates that are comparable to flow rates required for operation in the anti-ice mode.

Figure 12 shows that the deicing time is dependent on angle of attack. With $\alpha = 7.8$ deg, the deicing time may be as low as one-half that for $\alpha = 1.2$ deg. Extreme angles, where the stagnation point approaches the edge of the active panel, should be avoided.

An interesting phenomenon may be observed in Fig. 13. For a temperature of 25°F , the longer the ice is permitted to

build up, the longer it takes to remove it—a result that might have been expected. However, at 5°F a larger ice cap is shed more quickly than a smaller ice cap at the same specific fluid flow.

The explanation is that at 25°F glaze ice is formed, which is accompanied by runback icing and a wide ice cap. As the icing exposure time increases, the ice cap becomes more firmly attached to the leading edge, particularly at the edges of the porous skin. Therefore, as the icing time increases, so does the time required for the glycol to completely break the bond between the ice and the wing skin.

At 5°F , only rime ice forms. This ice freezes almost immediately on contact with the wing; thus the ice cap tends to remain concentrated near the stagnation point on the porous panel. In this case, the time required to shed the ice depends strongly on the aerodynamic forces acting on the ice. Since these forces are roughly proportional to the size of the cap, the larger caps tend to shed more quickly, at least for the icing durations used in these tests.

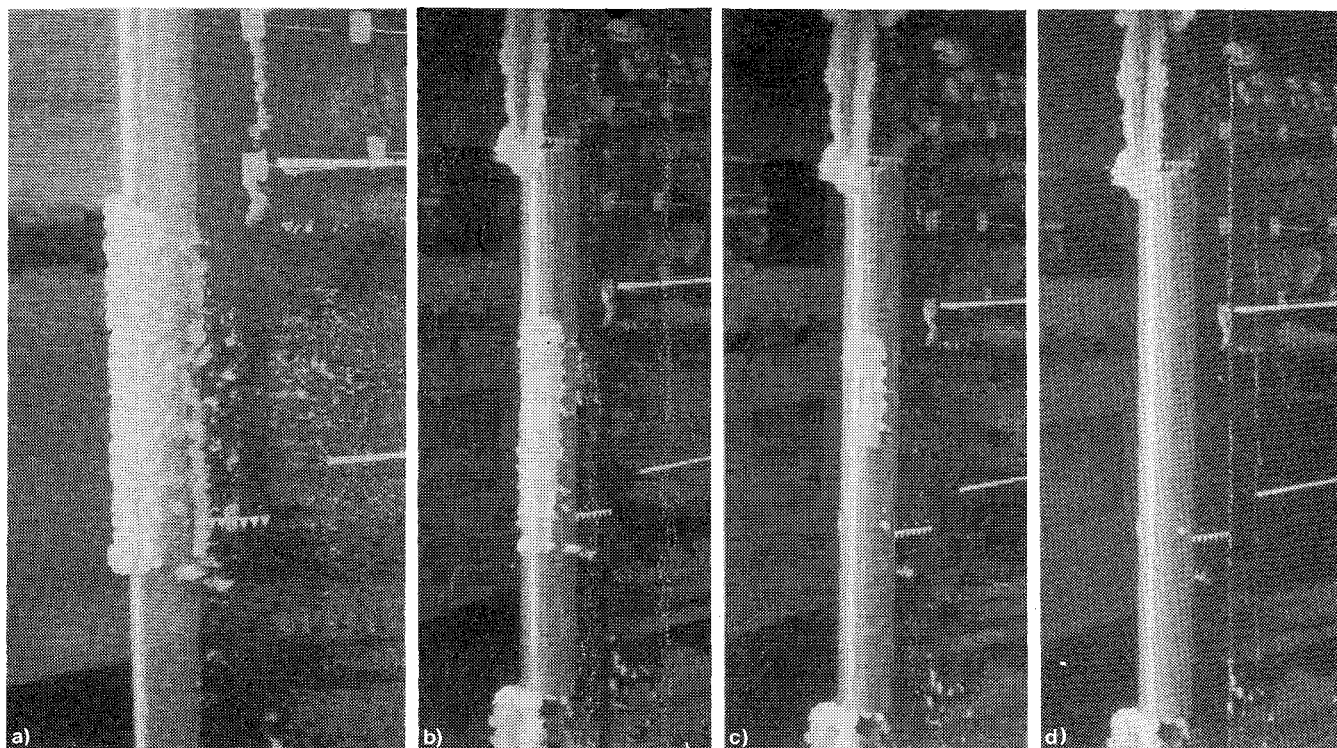


Fig. 14 Deicing time sequence for ice cap formed by 10-min exposure, with $LWC = 2.4 \text{ g/m}^3$, $V = 96 \text{ knots}$, $\alpha = 7.8 \text{ deg}$, $T = 25 \text{ deg}$. Specific fluid flow $= 0.052 \text{ ml/cm}^2/\text{min}$. a) 0 min, b) 2 min, c) 3 min, d) 4 min.

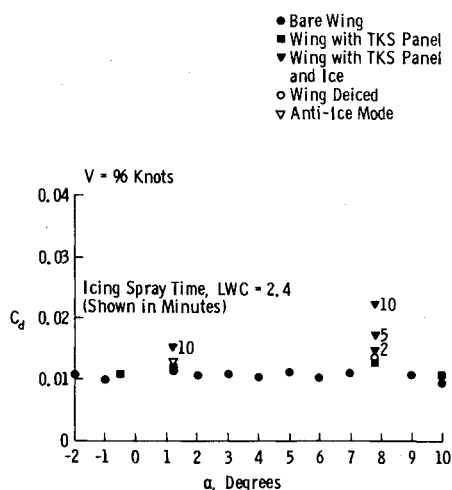


Fig. 15 Effect of icing system and various amounts of ice on section drag coefficient.

In several cases it was observed that a small change in angle of attack would precipitate the shedding of an ice cap because of the increased aerodynamic force on the ice caused by the altered flowfield.

Figure 14 is a sequence of photographs showing the progressive shedding of an ice cap formed at $T = 25^\circ\text{F}$, $V = 96 \text{ knots}$, $\alpha = 7.8 \text{ deg}$, and liquid water content $LWC = 2.40 \text{ g/m}^3$. The droplet mean size was 20μ . Icing spray time was 10 min. The glycol specific fluid flow was $0.052 \text{ ml/cm}^2/\text{min}$. The bottom surface of the wing is shown. Note that by the time the leading-edge ice is shed, the runback of glycol along the wing surface has substantially removed the frost and ice particles well behind the active portion of the leading edge.

Drag Measurements

The wake survey probe described previously was used to measure the effect of the porous panel, various modes of

operation, and different amounts of ice on the section drag coefficient of the wing. The results are shown in Fig. 15.

The porous panel adds less than 0.001 to the section drag of the wing, within the uncertainty band of the drag measuring system. The penalty of carrying ice is clearly seen in the 50-100% increase in c_d , depending on angle of attack, caused by a 10-min accumulation of ice.

After deicing, the drag is almost back to the clean level, except for the effect of some residual frost and ice particles on the lower surface of the wing. The anti-ice mode has practically no effect on the section drag.

Discussion and Conclusions

The data obtained in these tests provide useful information on the glycol flow rates required to obtain satisfactory ice protection performance from a porous leading-edge system. Although the data apply to only the airfoil tested, the range represented should be typical for most light airplane wings.

In most cases satisfactory performance can be obtained with much lower flow rates. As shown in Fig. 3, the extreme conditions tested represent a LWC three times higher than the upper boundary of the continuous maximum conditions defined by FAR, Part 25, Appendix C.¹ The upper boundary of the intermittent maximum conditions is just met. The results showed that extremely severe conditions can be handled by a liquid protection system if the condition is only temporary. The system merely reverts to the natural deicing or deicing mode until conditions permit a return to the anti-ice mode. It would be possible to operate the system at two different flow rates.

It would be desirable to be able to predict accurately the minimum flow rates required to achieve anti-icing at various flight conditions. Reference 4 provides an empirical method, but investigation showed that this method was limited in range and required assumptions that limited the accuracy of the prediction for this airfoil. In a follow-on study, methods are being developed to obtain reasonably accurate predictions of minimum flow rates, so that design evaluations of various configurations can be made without the necessity for icing-tunnel tests.

Additional icing-tunnel testing is also planned so that more data can be obtained for purposes of comparison, questionable data points can be resolved, and the effect of droplet diameter can be assessed.

As a result of the tests reported herein, the following conclusions have been made:

1) A glycol-exuding, porous leading-edge ice protection system is a very effective means of preventing ice accretion or removing ice from an airfoil.

2) The stagnation point may come within 1 cm of the edge of the porous surface without seriously degrading the performance of the system.

3) The system tested was able to remove large ice caps with glycol flow rates normally used in the anti-ice mode.

4) The type of ice formed and the angle of attack have a significant effect on the deicing time.

5) No significant drag penalty was associated with the installation or operation of the system tested.

Acknowledgment

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AERODYNAMIC HEATING AND THERMAL PROTECTION SYSTEMS—v. 59 HEAT TRANSFER AND THERMAL CONTROL SYSTEMS—v. 60

Edited by Leroy S. Fletcher, University of Virginia

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