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A Study of Large Droplet Ice Accretion in the NASA Lewis IRT at Near-Freezing Conditions; Part 2

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SUMMARY

Results of experiments designed to determine the effects of large droplet ice accretion on a NACA 23012 wing section are presented. Using primarily an icing condition with a median volumetric diameter droplet size of 160 µm and a liquid water content of 0.82 g/cm, the effects of various air temperatures, angles of attack, and de-icer boot cycle interval times on ice accretion were studied. Measurements of aerodynamic performance penalties due to the ice accretions were made. Results were also compared with similar tests conducted with a Twin Otter wing section in Part 1 of this study. The form of the ice from the large droplet cloud varied as a function of air total temperature; particularly at the near-freezing temperatures of 28 to 34 °F. Changing boot cycle interval time did not prevent formation of an ice ridge. The most detrimental aerodynamic effects occurred at an air total temperature of 28 °F.

INTRODUCTION

This investigation is part of a series of experimental large droplet icing tests conducted in NASA Lewis' Icing Research Tunnel (IRT) since late 1994 (ref. 1). Large droplet icing conditions are defined as icing clouds composed of water droplets which have a distribution of droplet sizes ranging from 40 to 400 µm in terms of Median Volumetric Diameter (MVD). The more common icing clouds consist of droplet distributions in the 10 to 40 µm MVD range. These IRT tests constitute the first comprehensive effort to study the effects of large droplet ice accretions on aircraft at near-freezing temperatures.

The atmospheric conditions which result in the creation of large droplet icing clouds are relatively rare. However, there is growing evidence that the frequency of aircraft encounters with large droplet icing clouds is higher than expected. This is of particular concern since the hazard to an aircraft flying in these conditions is also greater than what has been anticipated and is potentially catastrophic (ref. 2).

Earlier portions of this study found that aircraft ice formed from large droplet icing clouds accretes further aft on aircraft surfaces than that formed from the more common 10 to 40 µm droplet icing clouds (ref. 1). This is primarily due to the fact that large droplets impinge further aft on the airfoil surfaces than do small droplets. A significant amount of runback and secondary impingement has also been observed in these tests. Secondary impingement is a term used to describe the action of unfrozen water droplets blowing off the accreted ice, then impinging on the model further downstream. Whether this is characteristic of the large droplets or is due to high water loading has not been determined at this time.

In Part 1 of this study, (ref. 1) it was found that a significant amount of ice from a large droplet icing cloud can accrete aft of conventional ice protection equipment on an airfoil. If the ice protection equipment is activated during the icing encounter, only the ice on the protected portion of the airfoil is removed leaving a forward facing ridge of ice aft of the protected area. When the ice protection system is not activated during the encounter and the air is at a near-freezing temperature, ice will accrete until a large portion of it is blown off the leading edge by aerodynamic forces. The residual ice aft of the leading edge, again, has a forward facing ridge. These scenarios were studied in Part 1 of this investigation. In that part of the study, a Twin Otter wing section was mounted in the IRT and subjected to an array of large droplet icing conditions including variations

in temperature, airspeed, droplet size, angle of attack, pneumatic deicing boot cycle interval, and flap setting. Specific findings were:

- An ice ridge formed aft of the active portion of the deicer boot for every experimental test run in which ice was accreted. The location, height, and spanwise extent of the ridge varied considerably. This variability was caused by random shedding of the ice.
- Large droplet ice accretions were found to be sensitive to changes in total temperature. As the temperature was varied, the ice ridge reached a relative maximum at a total temperature of 28 °F for 125 mph and of 30 °F for 195 mph.
- An increase in droplet size moved the impingement limits further aft on the airfoil. In addition, runback and secondary impingement accreted ice aft of the impingement limits on the airfoil.
- Increasing the angle of attack caused more ice to accumulate on the pressure surface and less ice on the suction surface.
- As flap setting was increased, the extent and amount of ice accretion on the suction surface decreased.
- Variation in the boot cycling time did not appear to have a significant effect on the residual ice accretion.

Part 2 of this investigation is described herein. Tests similar to those conducted with the Twin Otter wing section in Part 1 were carried out using a NACA 23012 airfoil to expand the knowledge base about large droplet ice accretion.

Facility and Model Description Icing Research Tunnel

The NASA IRT is a closed loop refrigerated wind tunnel.[3] The test section is 6 ft high and 9 ft wide and contains a turntable assembly which allows for model angle of attack changes. A 5000 hp fan provides airspeeds up to 400 mph (empty test section). The refrigeration heat exchanger can control the air temperature from -40 °F to +40 °F.

Icing Cloud Spray System

The spray system that generates the icing cloud in the IRT is composed of eight spray bars containing a total of ninety-five spray nozzles. The spray bars are located in the settling chamber upstream of the test section. The spray nozzles used are air-assist type atomizers (ref. 3). Two different sets of nozzles are currently used in the IRT spray system and are designated Standard and Mod-1. The Mod-1 nozzles were used for the large droplet tests described in this report because they produce liquid water content (LWC) levels closer to those expected for large droplet icing clouds found in nature.

A droplet size of 160 μm MVD was used to simulate a large droplet icing cloud during most of the test runs in this part of the study. This droplet size is outside the normal operating envelope of 10 to 40 μm MVD for the IRT. In order to simulate a large droplet icing cloud, special tests were run in the tunnel to calibrate the cloud for droplet size distribution and for cloud uniformity. Results of these tests indicated that the 160 μm cloud generated in the IRT would be the best to simulate large droplet icing conditions (ref. 1). However, time did not permit calibration of the 160 μm MVD cloud at various LWC's at a given airspeed. Therefore, the effect of varying LWC was not investigated in this study.

Model

The test model was a 6 ft span, single element, NACA 23012 wing section which was mounted vertically in the IRT test section. It had a chord length which varied from 73.8 in. at the floor to 65.2 in. at the ceiling of the tunnel and was 68.6 in. at the model centerline. The leading edge of the model was outfitted with a full span pneumatic de-icer boot extending to approximately 6 percent chord on the suction surface and to 11 percent chord on the pressure surface. A photograph of the test model is shown in figure 1. Figure 2 shows the airfoil's cross section.

Parametric Investigation

As in Part 1, a primary objective of these tests was to study how parameters such as air temperature, droplet size, angle of attack, airspeed, and pneumatic deicer boot cycle time affect large droplet ice accretions. Table I lists the parameter values which were investigated.

Not all possible combinations of parameters were tested. To make more effective use of the test time, a particular value for each parameter was selected and designated as an anchor point value. The anchor point values were selected based upon representative flight operating conditions as well as knowledge of large droplet ice accretions which formed at near-freezing conditions. While the effects of one parameter were being investigated by varying it, the other parameters were held constant at their anchor point values. The anchor point values, which are also listed in Table I, were: 32 °F, 160 μm MVD, 0.82 g/m^3 LWC, 195 mph, 0° AOA, 3 min boot cycle, and an 18 min icing spray time.

The parameter array values vary slightly from those for the Twin Otter test matrix as reported in reference 1. However, many identical conditions were used with the NACA 23012 so that direct comparisons could be made. Several different values (24, 26, 35, and 37 °F) were added to the air total temperature array because it was found to be the dominant parameter in determining the characteristics of the ice accretion. This allowed the problem to be more thoroughly bounded. Two values (1.3° and 3.9°) were added to the angle of attack array to examine conditions typical of flight for this type airfoil. The value of 163 mph was dropped from the airspeed array because speed was found to have little effect on the ice accretion. The values for the droplet size and for the boot cycle interval time arrays remained the same as in the Twin Otter tests.

Ice Shape Repeatability

Since an important aspect of these tests is to document the ice shapes formed under the various parameters in this study, the repeatability of the ice shapes is significant. The capability of the IRT to accurately reproduce icing clouds is well established. Previous studies, including Part 1 of this effort, have documented this capability (refs. 1 and 4).

Even though the icing cloud in the IRT remains generally consistent and repeatable from test run to test run, it was discovered in Part 1 of this work that the ice shape formed due to a large droplet icing cloud at near freezing conditions is random and not repeatable in a quantitative way. The chordwise location, height, and spanwise extent and position of the ridge varied from run to run under icing cloud conditions intended to be the same. This was found to be primarily due to the random manner in which residual ice remained on the model after activation of the ice protection system or after an aerodynamically induced self shed.

This random shedding was observed during Part 2 of this work. At the same icing cloud conditions, the height, chordwise location, and spanwise extent and position of the ridge varied considerably for five separate test runs at the anchor point conditions. Figure 3 shows profiles of the ice remaining on the model for these test runs. All of these profiles were traced at the centerline of the model. It should be noted that there was more variability in the ice shape on the suction(upper) surface than on the pressure(lower) surface. On the pressure surface, the ridge usually began at the edge of the active portion of the boot (10 percent chord) and extended aft to 15 percent chord where the composite leading edge of the model intersected with the aluminum skin. The aluminum skin covered the aft 85 percent chord of the model. Some ice accreted on the model just aft of this intersection, most likely due to secondary impingement. On the suction surface, the ridge begins at some random point between 6 and 9 percent chord. The active portion of the boot ended at approximately 5 percent chord. Also, the ridge height can be seen to have varied considerably from run to run.

Temperature Effect

As in the previous large droplet study with the Twin Otter wing section, the total temperature of the air was found to have a very strong effect on the NACA 23012 ice accretion. For this large droplet investigation, tests were run at total temperatures from 5 to 37 °F while holding the other parameters constant at their anchor point values. The temperature of 37 °F was chosen to isolate the upper limit where no ice accretion formed, while the 5 °F temperature represented the lowest temperature at which the large droplet icing condition is believed to exist in nature (ref. 5).

The effect of total temperature on NACA 23012 ice accretions was essentially the same as that observed with the Twin Otter wing section. At 37 °F, all the impinging water ran back to the trailing edge and was blown off the model. At 34 °F, less runback was noted and ice formed. When the ice formed, there was a

distinct ridge just after the active portion of the boot on both the suction and pressure surfaces. The ice protection system was activated at three minute intervals for all of these test runs.

The effect of temperature on NACA 23012 large droplet ice accretions is illustrated in figure 4. Photographs of suction surface ice accretions are presented for total temperatures ranging from 34 to 5 °F. These photographs were taken at the conclusion of the eighteen minute icing spray. The ice protection system had last been activated at fifteen minutes into the spray, therefore, the photos show the condition of the ice accretion just prior to another pneumatic boot activation. The markings on the model indicate percent chord of the airfoil. The boot ends at 6 percent chord.

Perusal of figure 4 reveals that at the warmer temperatures (30 to 34 °F), the ice ridge behind the active portion of the boot had a tendency to randomly self shed. However, as the total temperature was decreased below 30 °F, the ice ridge appeared to "harden" and become more resistant to self shedding. Also, these photos show that as the temperature was successively decreased more ice froze on the boot surface. At 34 °F, a layer of ice is evident beginning at the 5 percent chord line, while at 28 °F, the ice layer appears to have moved forward to the stagnation line. This trend suggests that as the temperature was decreased more water froze forward on the boot, thereby reducing the amount of runback water available to "feed" the development of the ice ridge. Ice thickness measurements at the stagnation line corroborated this trend, because the thickness of ice on the boot increased as the temperature decreased.

Based on the above result, one would surmise that the ice ridge height would lessen as the temperature was decreased. This was not the case. In fact, for temperatures below 30 °F, substantial ice ridges developed aft of the active portion of the boot. The largest ice ridges occurred at temperatures in the range of 24 °F through 28 °F. Ice ridge heights of over 1 in. were observed on the suction and pressure surfaces at these temperatures. Clearly, runback is not the only mechanism affecting the development of the ridge. It is possible that increased structural strength at the colder temperatures facilitates the growth of the ice ridge farther into the flow, which then has the effect of increasing the collection efficiency of the ridge. Table II lists ice ridge heights and ice thickness at the stagnation point as well as calculated freezing fraction for the above temperatures.

Angle of Attack Effect

Tests were run at AOA's of -2°, 0°, 1.3°, 2°, and 3.9° while the other parameters were held at their anchor point values. As the AOA increased, the extent of ice aft of the boot on the pressure surface increased significantly. The front of the ridge on this surface was usually located at the end of the active boot, although there were some variations due to random shedding.

On the suction surface, as the AOA increased, the aft edge of the ice accretion moved forward and the total amount of ice decreased. Inspection of the photographs and tracings showed that there can be a high ridge at a high AOA condition, but that it is due to a random lump of ice stuck to the surface as opposed to a ridge with some spanwise extent. In general, a ridge is less likely to form because less ice accumulates. These trends were similar to those observed in the Twin Otter tests.

Boot Cycle Effect

The time interval between pneumatic boot activation was referred to as boot cycle time. Three different boot cycle times were used: forty-two seconds, three minutes, and six minutes. Also, for comparison purposes, a full eighteen minute spray was run with no boot activation.

Boot cycle tests were made at total air temperatures of 5, 28 and 32 °F. As was found in the Twin Otter model portion of the study, the total air temperature of 32 °F allows ice to form which was relatively weak and was prone to self shedding. A ridge formed on both the pressure and suction surfaces for all the boot cycle cases at 32 °F . For the cases with boot activation, the ridges formed in the vicinity of the edge of the active portion of the boot. In the no boot cycle run, the ridges were very random in location due to the random self shedding of the ice. No further correlation between ridge and boot cycle was observed at this temperature.

At air total temperatures of 28 and 5 °F, no self shedding of the ice was observed. Photos of the ice at 28 °F are shown in figure 5(a) and the corresponding centerline ice tracings are shown in figure 5(b). These photos and tracings were taken after eighteen minutes of icing just before the next boot activation was to occur. At 28°F, the ridges on the suction surface were similar for all three time intervals. However, on the pressure surface, no distinct ridge formed for the forty-two second interval run although significant ice did accrete aft of the boot. For the three and six minute intervals, a relatively high ridge formed on the pressure surface at the edge of the active portion of the boot. At 5 °F , as the boot cycle interval increased, it was observed that

the amount of residual ice left on the boot also increased. The forty-two second interval run left very little residual ice on the protected area. Both the three and six minute intervals left considerable residual ice. A photo of the three minute boot cycle case at 5 °F was shown in figure 4(h).

Aerodynamic Performance

In addition to documenting the characteristics of the ice formation on the model during an icing encounter, measurements of the change in lift and drag for the wing section due to the ice were also made. These changes in lift and drag were made using an external force balance system which had a significant limitation when used in this application. It measures aerodynamic effects over the entire wing section while the IRT's large droplet icing cloud does not uniformly cover the entire span of the model. In fact, the cloud has a uniform liquid water content at an MVD of 160 μm for about a one foot span at the model's center. The cloud tapers off in LWC over a significant length at each end of the wing section. Definitive, absolute measurements are difficult to make under these circumstances.

Despite this limitation, the aerodynamic performance data can be helpful if it is interpreted cautiously. Figure 6a shows the change in lift coefficient for the wing section as a function of air total temperature. The change in lift coefficient was defined as the difference between the clean wing lift coefficient and the iced wing lift coefficient. All of the data points shown as diamonds were run using a three minute boot cycle interval with the model set at a 0° angle of attack. These data suggested that air total temperature had a large effect on the ice accretion and the resulting decrease in aerodynamic performance. The highest lift loss was observed at an air total temperature of 28 °F.

Figure 6(b) shows the change in drag coefficient for the same set of test runs. The change in drag coefficient was defined as the difference between the iced wing drag coefficient and the clean wing drag coefficient. These data are also plotted as a function of air total temperature. As in the lift coefficient comparison, air total temperature had a significant effect on the resulting aerodynamic performance with the highest drag increase also occurring at an air total temperature of 28 °F.

The square in figure 6(a) indicates the highest measured lift loss. This resulted from the large droplet ice accretion at 28 °F with no boot cycle. The drag increase measured for this ice shape is shown in figure 6(b), also with a square. It is of interest to note that the large droplet ice accretion which results in the highest measured lift loss does not also result in the highest drag increase.

SUMMARY OF RESULTS

A parametric study of large droplet ice accretions at near freezing temperatures was conducted in the NASA Lewis IRT using a single element NACA 23012 wing section. Parameters studied were air total temperature, angle of attack, and boot cycle interval. In summary, the results of this portion of the study were:

• Similar to the Twin Otter wing section tests, an ice ridge formed aft of the active portion of the de-icer boot for nearly every test run. The location, height, and spanwise extent of the ridge varied due to random shedding of the accreted ice.
• Again, similar to the Twin Otter results, the large droplet ice accretions were found to be sensitive to changes in total temperature. At temperatures of 30 to 34 °F, the ice aft of the active boot randomly self shed quite frequently. At temperatures of 24 to 28 °F, the ice aft of the active boot was more resistant to shedding and resulted in the highest ridges.
• Increasing the angle of attack caused more ice to accumulate on the pressure surface and less on the suction surface. This was also found during the Twin Otter tests.
• Variation in boot cycling time did not have an effect on the residual ice at a total air temperature of 32 °F. At 28 and 5 °F, the forty two second boot cycle interval was more effective at removing ice, especially on the pressure surface. However, a ridge still formed on the suction surface for all temperatures and boot cycle intervals. Boot cycling was investigated only at 32 °F with the Twin Otter model and was found to have no effect on the ridge.
• The greatest measured lift loss was observed for an ice accretion at 28 °F for which the ice protection boot was not cycled.
• The greatest measured increase in drag was observed for an ice accretion at 28 °F for which the ice protection boot was cycled at three minute intervals.

CONCLUSION

While this series of tests has yielded valuable information as well as a substantial database on large droplet ice accretions, there is a great deal of work to be done. Since a relatively small amount of data is available to characterize naturally occurring large droplet icing conditions, a fairly rigorous flight program is warranted to gather cloud characteristics data. This data is needed to generate a realistic large droplet cloud envelope for the IRT and to help define tests to investigate the effects of varying LWC on large droplet ice accretions. This series of tests did not address the effect of LWC on large droplet ice accretions. Furthermore, tests at various angles of attack for a model with flaps extended needs to be performed such that approach configurations may be studied. The NACA 23012 model was a single element model therefore different flap settings could not be investigated. The Twin Otter model did have a movable flap, but it was not tested at various angles of attack with the flap extended due to concerns about wall effects. Lastly, more work needs to be done to further extend the computer ice accretion code as described by Wright, et. al. (ref. 6).

REFERENCES

1. Miller, D.R., Addy, H.E., and Ide, R.F., "A Study of Large Droplet Ice Accretions in the NASA Lewis IRT at Near-Freezing Conditions," AIAA Paper No. 96–0934, Jan. 1996.
2. Ashenden, R., Lindberg, W., and Marwitz, J., "Two-Dimensional NACA 23012 Airfoil Performance Degradation By Super Cooled Cloud, Drizzle, and Rain Drop Icing," AIAA Paper number 96–0870, Jan. 1996.
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5. Jeck, R., "Representative Values of Icing Related Variables Aloft in Freezing Rain and Freezing Drizzle," AIAA Paper No. 96-0930, Jan. 1996.
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TABLE I. —PARAMETER VALUES FOR LARGE DROPLET STUDY

Total temperature, °F	0, 5, 24, 26, 28, 30, 32, 34, 35, 37
Droplet size, μm (MVD)	40, 99, 160
Airspeed, mph	125, 195
Angle of attack, degrees	-2, 0, 1.3, 2, 3.9
Boot cycle interval, min.	none, .7, 3, 6
Anchor point conditions	32°F, 160 μm, 195 mph, 0° AOA. 3 min. Boot cycle, 18 min. spray

TABLE II. —MEASURED ICE THICKNESS AND CALCULATED FREEZING FRACTION
ON NACA 23012 WING SECTION

Run number	Total temperature °F	Ice Thickness, inches						
		Pressure surface ridge		Leading edge		Suction surface ridge		Freezing fraction
		max	min	max	min	max	min	
403	34	0.04	0.03	0.00	0.01	0.00	0.03	
404	33	0.25	0.08	0.05	0.56	0.04	0.59	
405	32	0.50	0.43	0.06	0.41	0.05	0.47	0.07
406	30	0.91	0.84	0.12	0.46	0.07	0.95	0.10
407	28	1.48	1.12	0.14	0.83	0.13	1.07	0.14
408	26	0.53	0.38	0.19	0.64	0.14	1.14	0.17
409	24	1.31	0.81	0.17	1.30	0.15	1.90	0.20

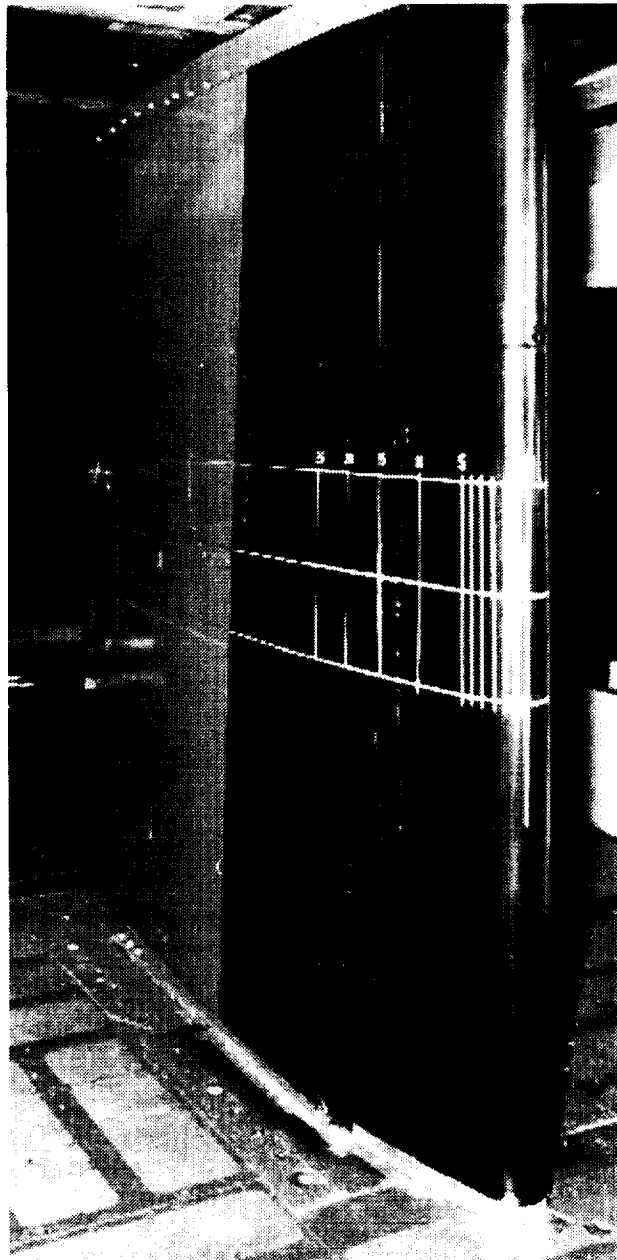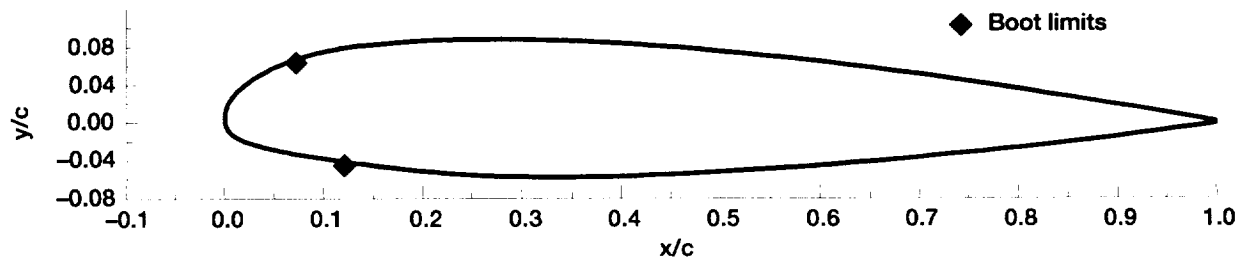Figure 1.—NACA 23012 wing section installed in Icing Research Tunnel.
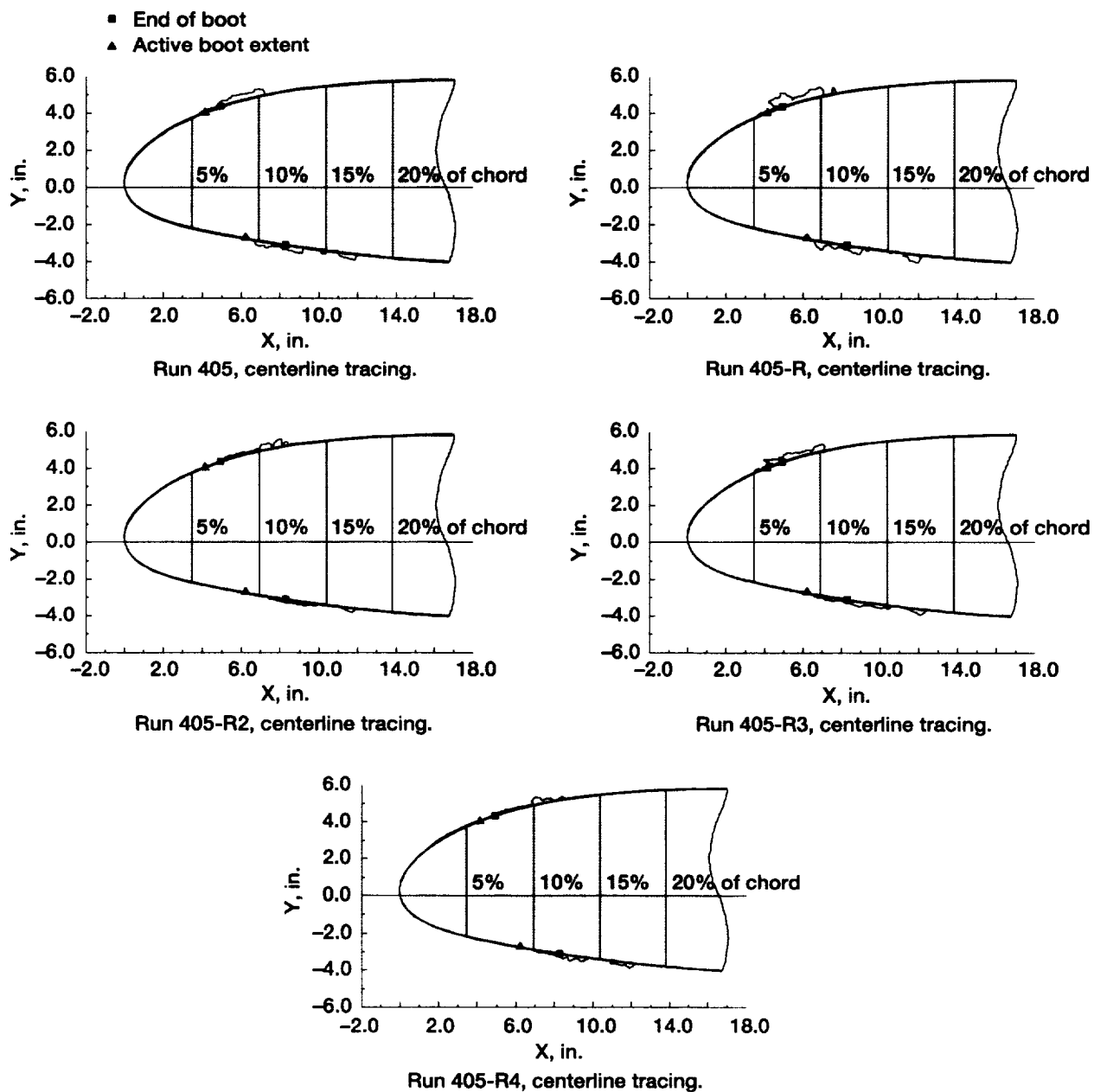

Figure 2.—NACA 23012 airfoil.

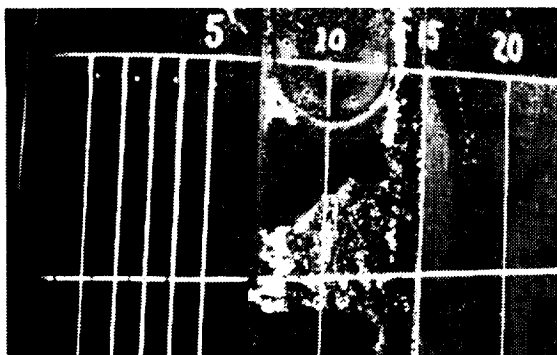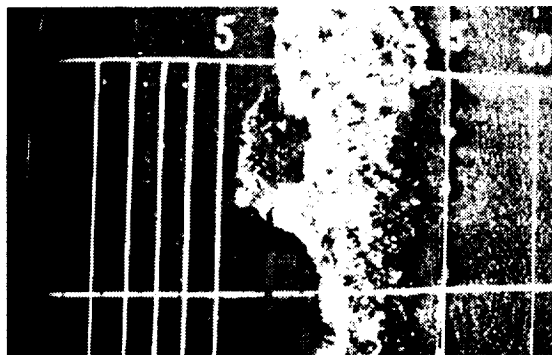- End of boot
- Active boot extent

Run 405, centerline tracing.

Run 405-R, centerline tracing.

Run 405-R2, centerline tracing.

Run 405-R3, centerline tracing.

Run 405-R4, centerline tracing.

Figure 3.—Run-to-run repeatability of large droplet ice accretions (Tt = 32 °F (0 °C), MVD = 160 μm, LWC = 0.82 g/m^3, AOA = 0°, V = 195 mph (170 kts), boot cycle = 3 min, spray = 3 min).

(a) Run 403, Tt = 34 °F (1.1 °C).

(b) Run 404, Tt = 33 °F (0.6 °C).
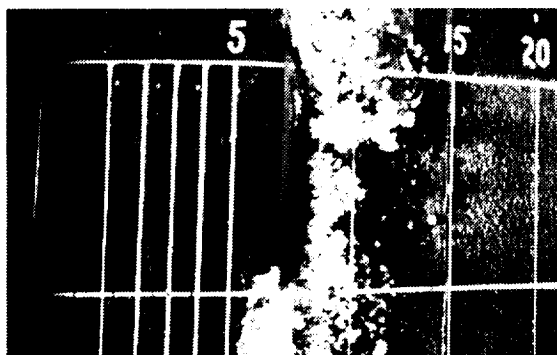
(c) Run 405, Tt = 32 °F (0 °C).
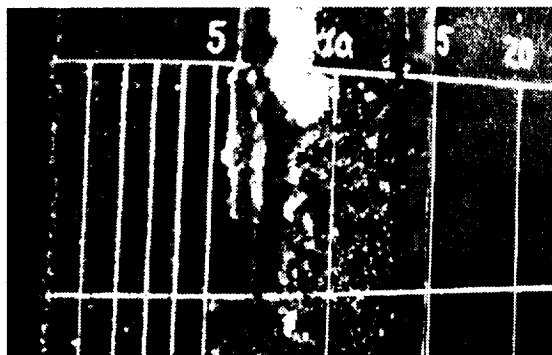
(d) Run 406, Tt = 30 °F (–1.1 °C).
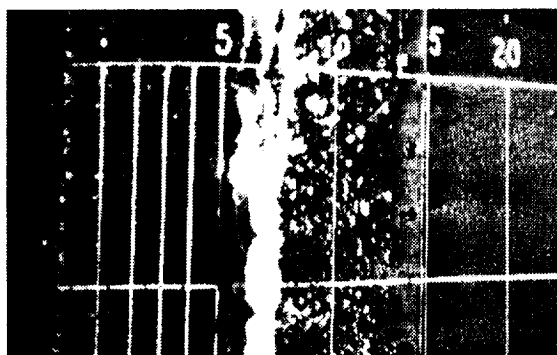
(e) Run 407, Tt = 28 °F (–2.2 °C).

(f) Run 408, Tt = 26 °F (–3.3 °C).

(g) Run 409, Tt = 24 °F (–4.4 °C).

(h) Run 417, Tt = 5 °F (–15 °C).

Figure 4.—Effect of total temperature on large droplet ice accretion (V = 195 mph (170 kts), MVD = 160 µm, LWC = 0.82 g/m^3, AOA = 0°, boot cycle = 3 min, spray = 18 min).
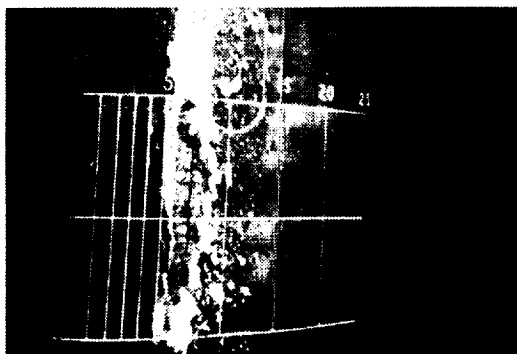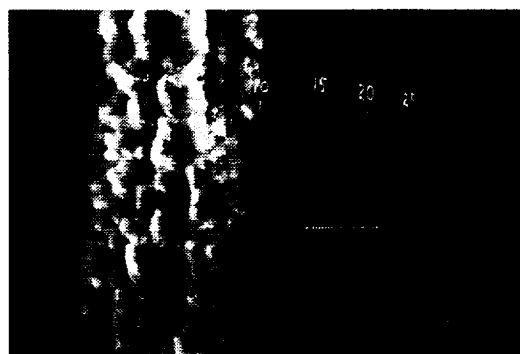
Run 413, boot cycle = 42 sec.
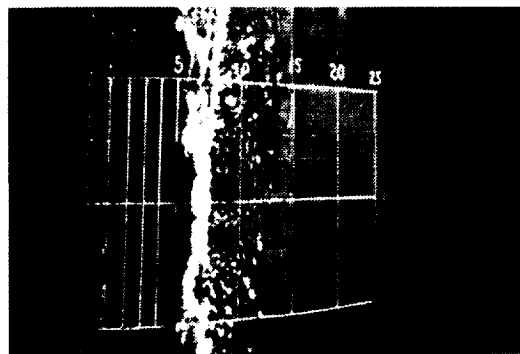
Run 407, boot cycle = 3 min.
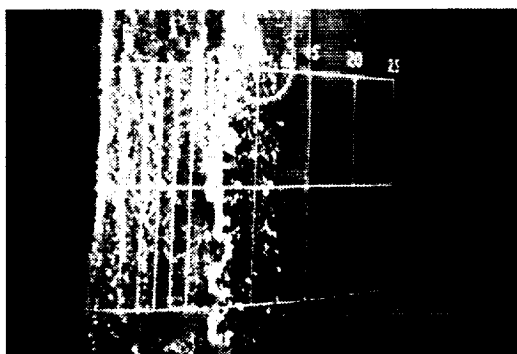
Run 414, boot cycle = 6 min.

Run 416, no boot cycle.

(a) Photos.

■ End of boot
▲ Active boot extent

Run 413, boot cycle = 42 sec.

Run 407, boot cycle = 3 min.
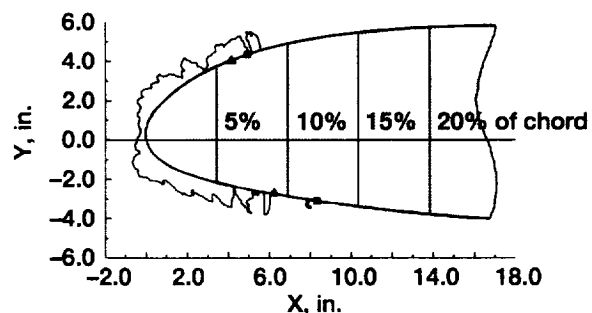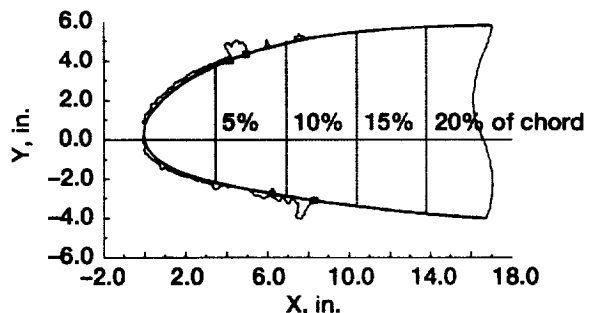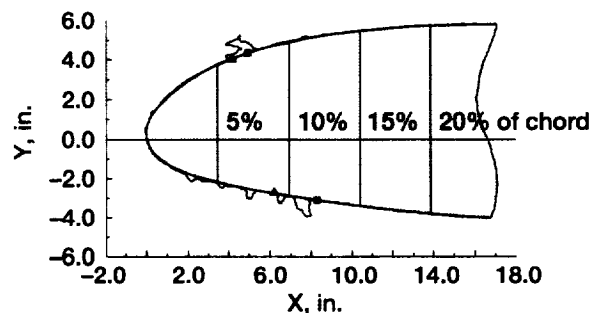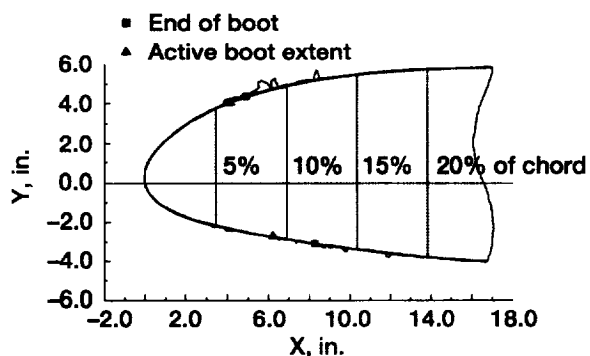
Run 414, boot cycle = 6 min.

Run 416, no boot cycle.

(b) Ice shape tracings.

Figure 5.—Boot cycle effect (Tt = 28 °F (–2.2 °C), MVD = 160 μm, LWC = 0.82 g/m³, AOA = 0°, V = 195 mph (170 kts), spray = 18 min).
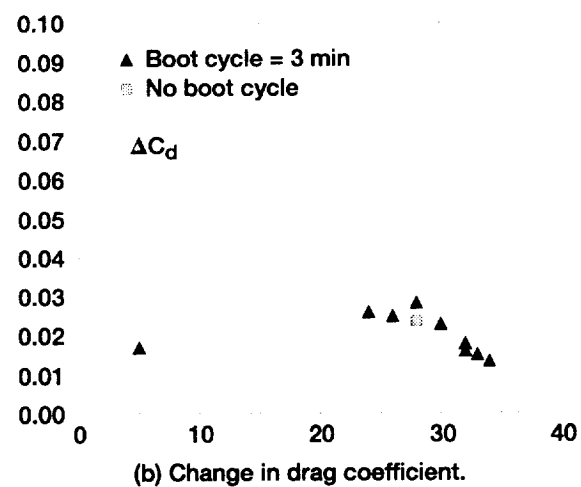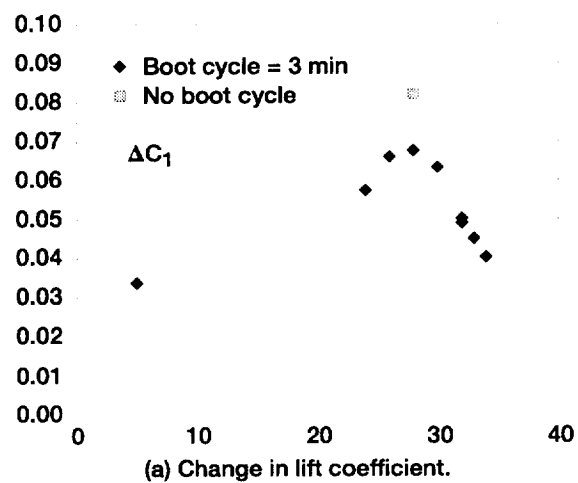
(a) Change in lift coefficient.

(b) Change in drag coefficient.

Figure 6.—Aerodynamic effects of large droplet ice
accretion on NACA 23012 wing section (Tt = 28 °F
(–2.2 °C), MVD = 160 μm, LWC = 0.82 g/m^3,
AOA = 0°, V = 195 mph (170 kts), spray = 18 min).

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)

Results of experiments designed to determine the effects of large droplet ice accretion on a NACA 23012 wing section are presented. Using primarily an icing condition with a median volumetric diameter droplet size of 160µm and a liquid water content of 0.82 grams per cubic meter, the effects of various air temperatures, angles of attack, and de-icer boot cycle interval times on ice accretion were studied. Measurements of aerodynamic performance penalties due to the ice accretions were made. Results were also compared with similar tests conducted with a Twin Otter wing section in Part 1 of this study. The form of the ice from the large droplet cloud varied as a function of air total temperature; particularly at the near-freezing temperatures of 28°F to 34°F. Changing boot cycle interval time did not prevent formation of an ice ridge. The most detrimental aerodynamic effects occurred at an air total temperature of 28°F.

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