



A Database of Supercooled Large Droplet Ice Accretions

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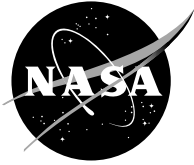
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Abstract

A unique, publicly available database regarding supercooled large droplet ice accretions has been developed in NASA Glenn's Icing Research Tunnel. Identical cloud and flight conditions were generated for five different airfoil models. The models chosen represent a variety of aircraft types from the horizontal stabilizer of a large transport aircraft to the wings of regional, business, and general aviation aircraft. In addition to the standard documentation methods of 2D ice shape tracing and imagery, ice mass measurements were also taken. This database will also be used to validate and verify the extension of the ice accretion code, LEWICE, into the SLD realm.

Introduction

The crash of an ATR-72 in Roselawn, Indiana on 31 October 1994 due to supercooled large droplet (SLD) icing focused attention on the need to better understand this condition. Still on the National Transportation Safety Board's (NTSB) #1 Most Wanted Transportation Safety Improvement in Aviation (ref. 1) is to

Reduce Dangers to Aircraft Flying in Icing Conditions
 Specifically to

Use current research on freezing rain and large water droplets to revise the way aircraft are designed and approved for flight in icing conditions.
Conduct additional research with NASA to identify realistic ice accumulations and incorporate new information into aircraft certification and pilot training requirements. [Italics added]

This work addresses part of NASA's effort to identify these realistic ice accumulations. Based on this, NASA and its partners developed an SLD Technology Roadmap (ref. 2). This map identified the need to provide a database of realistic SLD ice shapes, and to modify accretion codes to accurately model SLD conditions. The database work has been done in conjunction with SLD Sensitivity (ref. 3) and Methods studies, also conducted in the Icing Research Tunnel (IRT).

Methodology

Models

Five different models from the IRT livery were tested. An essential requirement for selection was that the

model be full span (72 in.) with a minimum chord of 36 in. Four of the five models were 2D. The fifth model, a Business Jet Wing, had slight sweep (9°), taper (from 66.8 to 55.3 in. over the 72 in. span) and twist. The model also had a thermal ice protection system to 8 percent chord. These models are described in table 1 and figure 1, and pictured as installed in the IRT in appendix A. Note, Entry A occurred in December 2004. The results from this test provided the impetus to improve the SLD cloud uniformity in the tunnel. Entries B to F occurred after IRT facility modification substantially improved the cloud uniformity.

Table 1. SLD database test identifier, model, centerline (CL) chord, characteristics and start dates.

Test Entry	Model	CL Chord (in.)	Model characteristics	Test start date
B	NLF 0414	36	2D, Fiberglass and wood	16 February 2006
C	NACA 23012	72	2D, Aluminum	02 March 2006
D	GLC 305	36	2D, Aluminum	28 March 2006
E	Commercial tail	36	2D, Fiberglass	22 May 2006
F	Business jet wing	61	3D, Aluminum, Thermal LE	17 January 2007

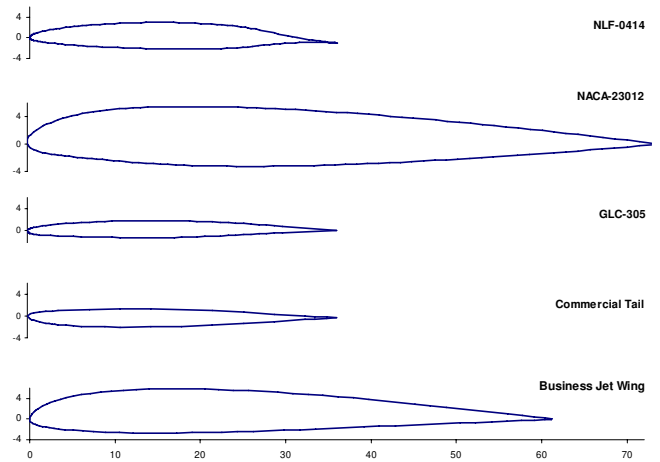


Figure 1. Model cross-sections in physical coordinates.

Models with imbedded pressure taps were aligned aerodynamically via comparison with existing experimental or theoretical CP curves (Entries B, C, and E). For Entry D, the IRT's force balance and wake survey systems were also installed. The model was aligned by finding the angle with minimum drag. The force and wake survey data are not included here. For Entry F, the model was aligned by comparing an ice shape (specifically, the suction horn location) to a previous tracing. Thermocouples on every model were used to ensure that the model was cold-soaked prior to spray.

Data Acquisition

For each accretion, generally three types of data were recorded. Besides the standard documentation methods of ice shape tracing and photography, the mass from a spanwise section was also captured and weighed (figs. 2 and 3). Of primary interest was the "main" leading edge ice shape, whether this included the suction and pressure horns or runback-type shapes. The aft feather region experienced random shedding.

Tracing

The ice shape tracing data, taken at centerline, and sometimes other locations, yielded horn heights and angles for both suction and pressure sides of the "main" ice shape, and leading edge minimum height (fig. 2(a)).

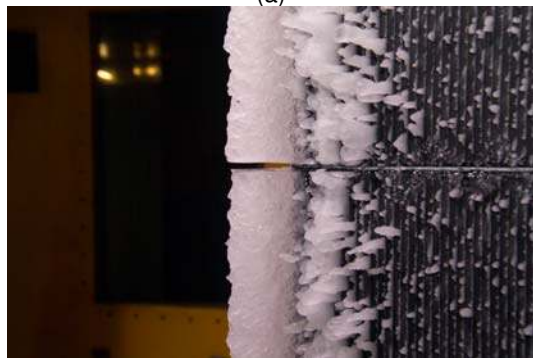
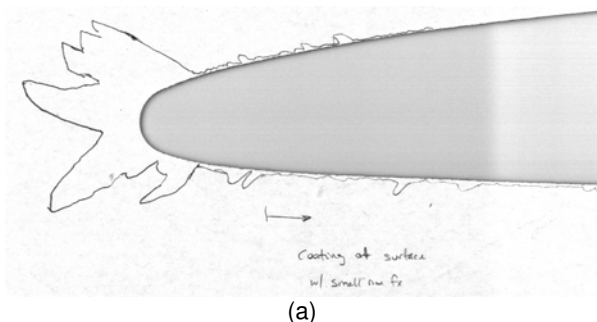


Figure 2. (a) Ice shape tracing sample, (b) and corresponding close-up of pressure surface. Heater placement and gap are also visible.

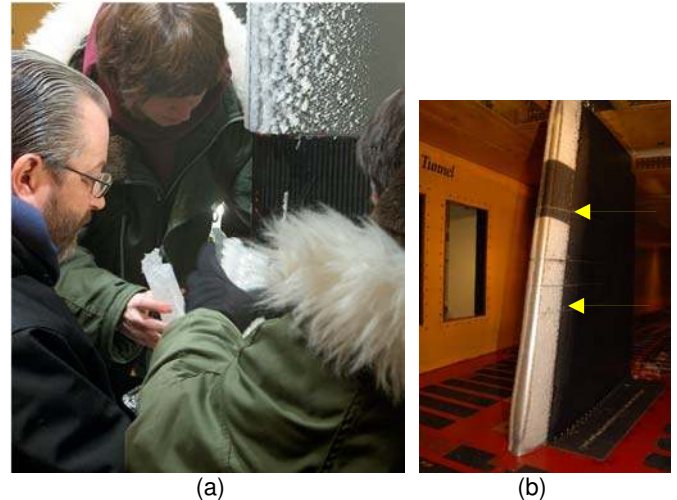


Figure 3. Ice collection process for mass measurement, (a) Procedures for Entries B to E; (b) for Entry F, ice was collected between top and bottom indicators.

These measures are used to compare to the computationally generated SLD ice shapes. The aft region of individual feathers was not always recorded and/or digitized in detail. Such a record was found to be problematic due to feather shedding and the artificial alignment of the feathers on the small ridges from the Minco heaters. To better understand the influence of these ridges, one day of testing (nominally 8 sprays) was conducted without the heaters for Entries C to E.

To obtain the tracing, an ice knife (1/8 in.-thick copper sheet) was heated to cut the ice to the airfoil surface (fig. 2(b)). A cardboard template that had been cut to the model coordinates was then inserted into this slot so that it was snug with the model. The researcher traced the ice shape according to Icing Branch established guidelines (ref. 4). Note the traced shape is always a pencil radius thicker than the actual ice. A horizontal table, adjusted to the model centerline, helped facilitate the ice cutting and tracing process.

Imagery

After the cut and tracing, at least five views were captured with a digital camera: close-ups of the pressure side, leading edge and suction side, as well as long-shots showing the entire span from both sides. A sampling of these types of images can be seen in appendix B.

Ice Mass

Ice mass measurements are a relatively recent option in the data collection process at the IRT. The ice mass, along with the area obtained from the 2D tracing (extruded over the collection span) can offer some

insight about an average ice density. For this article, only the mass measurements are reported. Without a valid area recorded and/or digitized in the feather region, no such density calculations were attempted.

To obtain the mass measurements, four 10 by 15 in. (or 9 by 11 in. for Entry D) Thermofoil (Minco, Minneapolis) heater elements were wrapped to capture the impingement limits (worst case) from the suction to pressure sides. Heaters were wrapped on either side of the centerline, with a 5 mm gap to accommodate the ice knife and template. There was no apparent effect on the ice shape due to this gap. After all other data were captured, the heaters were turned on just enough to debond the ice from the surface. The main ice shape and feathers were scraped or placed into a pan (fig. 3(a)). For each run, the pan was weighed with and without the ice on a scale with accuracy ± 0.5 g. The difference was the ice mass.

For the Business Jet wing, the internal thermal ice protection system was used in lieu of the heaters. Mass from the equivalent spanwise range, 20 in., was captured using two pans – one to catch the ice, the other as a dam to prevent the ice above from falling into the lower, measurement pan. As only the leading 8 percent of chord was heated, only the tops of the ice feathers aft of this region could be scraped into the pan – a thin layer of ice remained at the surface. This remaining mass is estimated to be less than 5 percent of the total.

Test Conditions

In the IRT, the researcher selects airspeed, model angle of attack, temperature, spray time, liquid water content (LWC) and median volume diameter (MVD) of the droplets. To reduce the SLD Database test matrix to a manageable size, several parameters were fixed. The spray time was set to 10 min. The temperature was fixed at one of two values so that it was as warm as possible without risking a shed of the main ice shape. The angle of attack was also essentially fixed to a low, non-zero, value, chosen to match that model's testing history. The target for LWC and MVD was to map a roughly evenly spaced grid. That is for MVD, the researcher targeted MVD values in increments of 50 μm : 50, 100, 150 and 200, and LWC values in increments of 0.25 g/m^3 : 0.25, 0.50, 0.75, 1.00, 1.25, and 1.50. The decision was also made to limit the matrix to IRT calibrated air speeds and spraybar pressures. The accuracies for the SLD cloud are subdivided into two droplet size ranges: for $40 < \text{MVD} < 100$: $\text{LWC} \pm 15$ percent, $\text{MVD} \pm 20$ percent; for $\text{MVD} > 100$: $\text{LWC} -10/+30$ percent, $\text{MVD} \pm 10$ percent (ref. 5). The test matrix was constructed with three central objectives. The bulk of the data was built with a "basic matrix" that explored the IRT's range for LWC and MVD in the SLD regime. Also investigated was the

capability of a "bimodal" spray condition. Finally, a hold or descent flight condition was represented.

Basic Matrix

The basic matrix is presented in table 2. It included the four calibrated airspeeds: $V = 100, 150, 200, 250$ kts, fixed AOA at a low positive angle: 2° for Entries B to E and 3° or -1° for Entry F. The selected total temperatures were $T_t = -5^\circ\text{C}$ for 100 and 150 kts, or -10°C for 200 and 250 kts. MVD and LWC values were limited to the SLD calibration points, and chosen to map as much of the IRT envelope as possible. In table 2, the grey-shaded boxes indicate points outside the IRT calibration. Due to the large range for the 100 kts case, a further down-selection was required; the more extreme cases were explored.

Table 2. Basic test matrix. For each speed/temperature, the reference number and resulting MVD and LWC values are listed. Grey-shaded blocks lie outside of calibrated areas.

Reference number/MVD, LWC					
$V = 100$ kts, $T_t = -5^\circ\text{C}$					
LWC	1.50		1995 119, 1.5	1997 139, 1.3	1999 225, 1.39
	1.25				
	1.00	1983 45, 0.97			
	0.75		1975 97, 0.85		
	0.50				
	0.25	1933 40, 0.32			
		50	100	150	225
$V = 150$ kts, $T_t = -5^\circ\text{C}$					
LWC	1.00		3985 119, 0.98		
	0.75	3973 45, 0.65	3975 82, 0.72	3977 139, 0.72	3979 225, 0.8
	0.50	3953 56, 0.55	3955 103, 0.55		
	0.25	3933 40, 0.2			
		50	100	150	225
		MVD			

V = 200 kts, T _t = -10 °C				
LWC	0.75	7575 119, 0.7		
	0.50	7555 97, 0.4	7557 139, 0.5	7559 225, 0.55
	0.25	7533 46, 0.23		
	50	100	150	225

V = 250 kts, T _t = -10 °C				
LWC	0.50	9555 119, 0.5	9557 168, 0.4	9559 225, 0.38
	0.25	9533 36, 0.24	9535 89, 0.25	9537 156, 0.3
	50	100	150	225

Bimodal

A condition that will be used in SLD certification is one that simultaneously contains both “small” and “large” droplets with an absence of droplet sizes in between. These are called bimodal conditions. In the IRT, this condition is simulated by spraying large then small droplets in an alternate manner. A key is to ensure that the freezing fraction for both clouds is the same. See Potapczuk and Miller (ref. 6) for further discussion.

For this study, a condition at V = 150 kts and T_t = -5 °C, that met all the IRT constraints and matched a distribution proposed by the Meteorological Services of Canada (MSC2) is specified below and shown in figure 4.

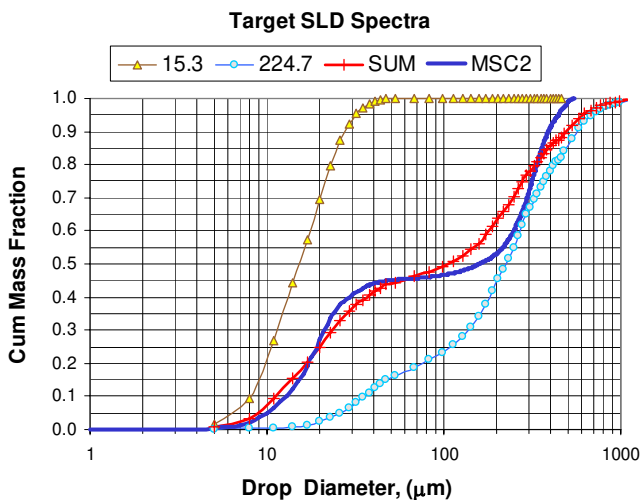


Figure 4. Target spectra for bimodal distribution (MSC).

Large: LWC = 0.79 g/m³, MVD = 225 μm for 70 percent of the spray time, and Small: LWC = 0.94 g/m³, MVD = 15 μm for the other 30 percent.

The 10-min bimodal spray (3979b) was achieved by alternating the large and small droplet conditions. The large droplet condition was sprayed three times for 2.33 min. each, and the small droplet condition was sprayed twice at 1.5 min. each. In addition, 10-min. sprays with only the small droplets (3979c) were run. Note the large droplet only spray was also run (3979). All bimodal conditions were run at the same model angle as the Basic Matrix.

Flight Condition

The flight condition was to simulate a relevant airspeed and AOA for a generic aircraft on which the wing section might be expected. When possible, this condition was repeated from an earlier database – mostly from the Modern Airfoils (ref. 7) database. Specifically, for Entries B and C this hold AOA was 3°, a descent AOA was 6° for Entry D, and -1° for E.

On occasion, additional data on temperature or angle of attack effects were gathered.

Data

A more comprehensive report and a DVD with the full SLD Database are available in other references (refs. 8 and 9). For each model, the spray conditions, ice mass, 2D tracing, ice shape characteristics and images are given for every valid spray.

In this article, a small cross-section of the results is given here. Appendix B presents the 7575 spray condition for each of the five different models: V = 200 kts, t = 10 min., T_t = -10 °C, LWC = 0.7 g/m³, MVD = 119 μm. This shape can be characterized by its well-defined “horns”. Specifically presented are the digital images, the ice shape tracing from the centerline, and a table with the ice mass and ice shape characteristic data consisting of suction horn height and angle, pressure horn height and angle, leading edge minimum thickness. Also presented in appendix B is a runback-like case, 1999: V = 100 kts, T_t = -5 °C, LWC = 1.39, MVC = 225. The ice shape for this condition is presented with and without the heaters.

The ice shape characteristic data was obtained by running THICK (ref. 10) on the 2D ice shape coordinates. THICK is an additional output file from NASA’s ice accretion code, LEWICE. Figure 5 illustrates how these measurements are calculated. Horn heights are measured

*There was no attempt to scale the cloud based on the model geometry.

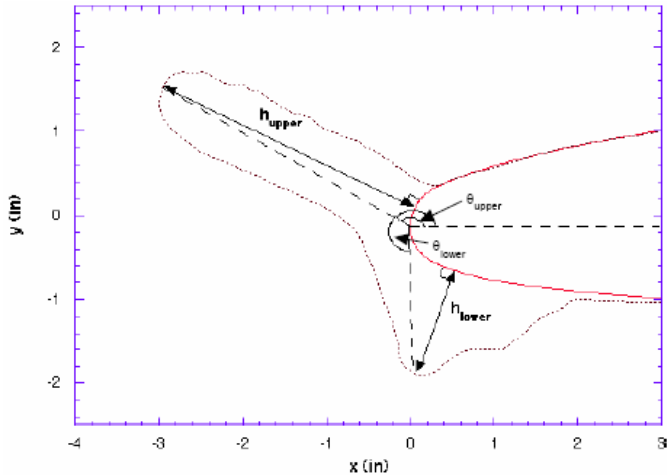
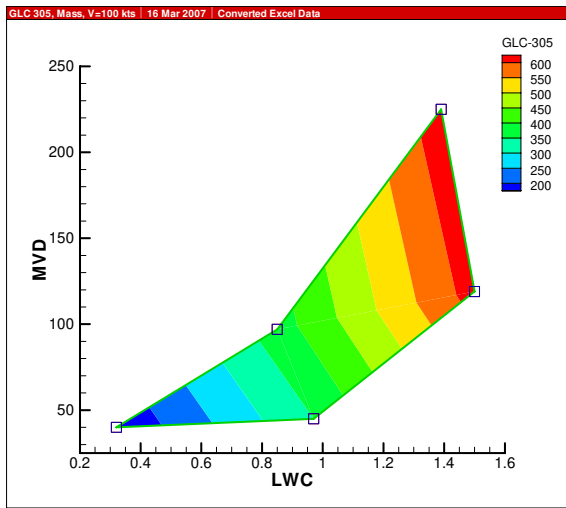


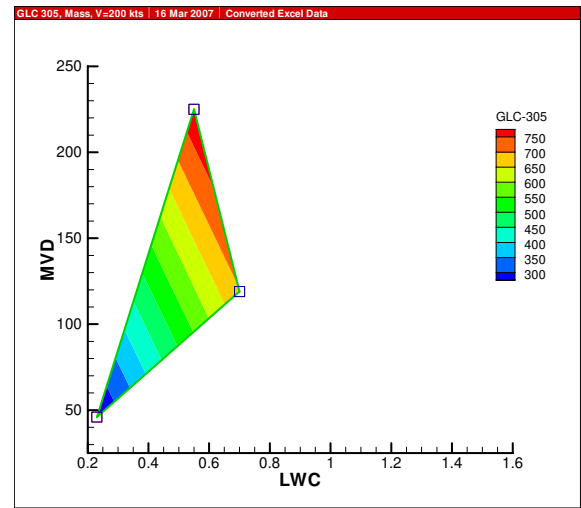
Figure 5. Sample ice shape illustrating the ice shape characteristics output by THICK.

from the surface normal to the peak height, whereas the horn angle is between the line straight aft of the leading edge and the line from the leading edge to the peak height. For this paper, the terms “pressure” and “suction” are used in lieu of “upper” and “lower” to reduce confusion when discussing the Commercial Tail. Also, note that the 2D tracing data are presented with the suction surface on top, regardless of how the model was installed in the tunnel.

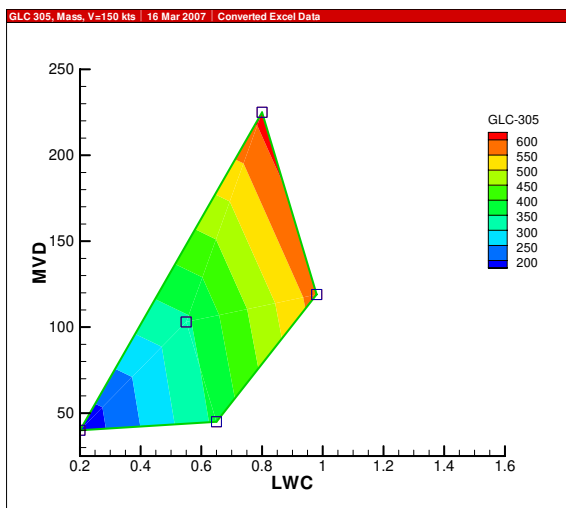
Sample ice mass measurements are presented here graphically. For repeat conditions, the mass is averaged. Figure 6 presents the mass obtained for one model, the GLC 305, at each speed. The squares indicate the measured or averaged mass values, depending on whether the point was repeated or not. The contour colors are linearly interpolated within a graphing package (TecPlot, Bellevue).



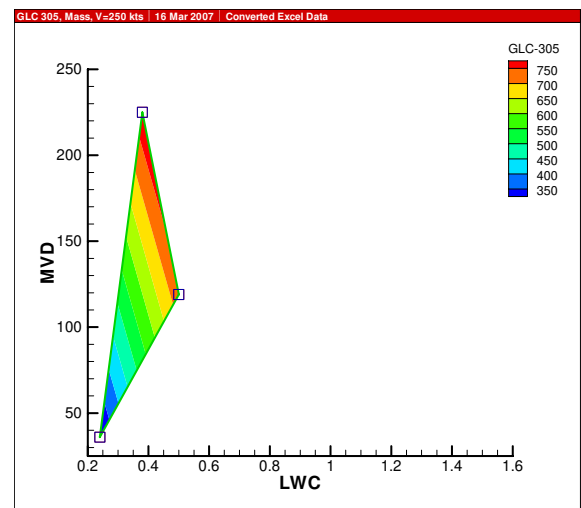
(a)



(b)



(c)



(d)

Figure 6. Mass (g) presented as a function of LWC and MVD for the GLC 305 model at $V =$ (a) 100 kts, (b) 150 kts (c) 200 kts, and (d) 250 kts. Note the different scales.

Conclusion

A database of SLD ice shape accretions has been generated in NASA Glenn's Icing Research Tunnel. Five different full-span models experienced the same set of SLD spray conditions. A small sample of ice

accretion images, 2D ice shape tracings and their characteristics, and ice mass data are presented here; a more complete data set is also available on a DVD included in the back of this document, and available from the NASA Center for Aerospace Information as NASA/CR—2007-215020/SUPPL.

Appendix A Models

Appendix A presents the five models as they were installed in the IRT. The pressure and suction sides are noted.



Figure A1. Entry B NLF 0414 airfoil in IRT (a = left) Pressure Side, (b = right) Suction Side.

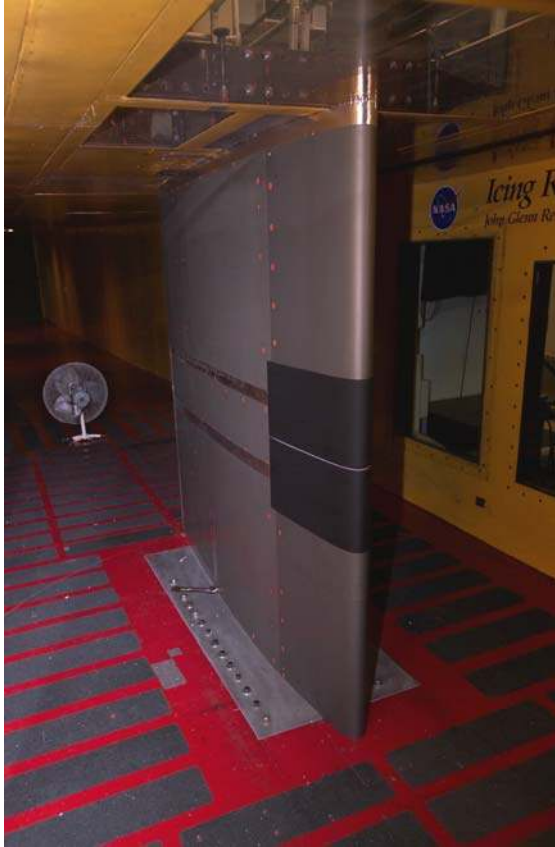


Figure A2. Entry C: NACA 23012 airfoil in IRT (a = left) Pressure Side, (b = right) Suction Side.



Figure A3. Entry D (and A) GLC 305 (a = left) Suction Side, (b = right) Pressure Side.



Figure A4. Entry E Commercial Tail airfoil in IRT (a = left) Pressure Side, (b = right) Suction Side.



Figure A5. Entry F Business Jet Wing (a = left) Suction Side, (b = right) Pressure Side. Note: a portion of the aluminum leading edge was painted black for an earlier test.

Appendix B

Data Sample

The images, centerline tracing, mass and ice shape data from the five different models from a high-repeat case are presented here. The case is 7575: $V = 200$ kts, $T_{\text{t}} = -10$ °C, $LWC = 0.7$ g/m³, $MVD = 119$ μm. Note: all heights are in inches, angles in degrees and mass in grams.

The first time a particular spray condition was run, it was denoted by its 4-digit reference number, e.g., 7575. Subsequent sprays were designated by appending 'r1', 'r2', etc., e.g., 7575r1. For Entries C, D and E, a day (nominally 8 sprays) was devoted to running without the heaters. This modified condition was noted by appending an 'm', e.g., 7575m. Mass could not be measured for these runs.

Images in the top row show the close-up shots of the pressure, leading edge and suction sides. The particular suction/pressure side orientation is noted for each model. Images in the second row show the long shots, along with the ice shape tracing data. Note that the 2D tracing data is presented with the suction surface on top, regardless of the model orientation in

the tunnel. Finally, a table with the ice shape characteristic data for each repeat is presented, along with their average. For case E-7575, these repeat conditions are co-plotted on the 2D tracing data.

The last page contains a runback-type ice shape on the NACA 23012 with and without the heaters, C-1999 and C-1999m: $V = 100$ kts, $T_{\text{t}} = -5$ °C, $LWC = 1.39$ g/m³, $MVD = 225$ μm. For the C-1999 case, the feather region was not captured and/or digitized in detail. After the notch around $x = 3.7$ in, which indicates the end of the "solid" ice, only the tops of the feathers were identified. As the accompanying images show, the feathers are aligned with the heater ridges, with bare surface visible in between. This approach was adopted partly due to the questionable value of recording this artificially-aligned aft feather data, and partly due to the extremely labor-intensive process to digitize and append each individual feather. The comparison with the C-1999m tracing, which was faithfully traced, shows the randomly-spaced feathers were roughly the same height as those on the heater.

B-7575: NLF 0414

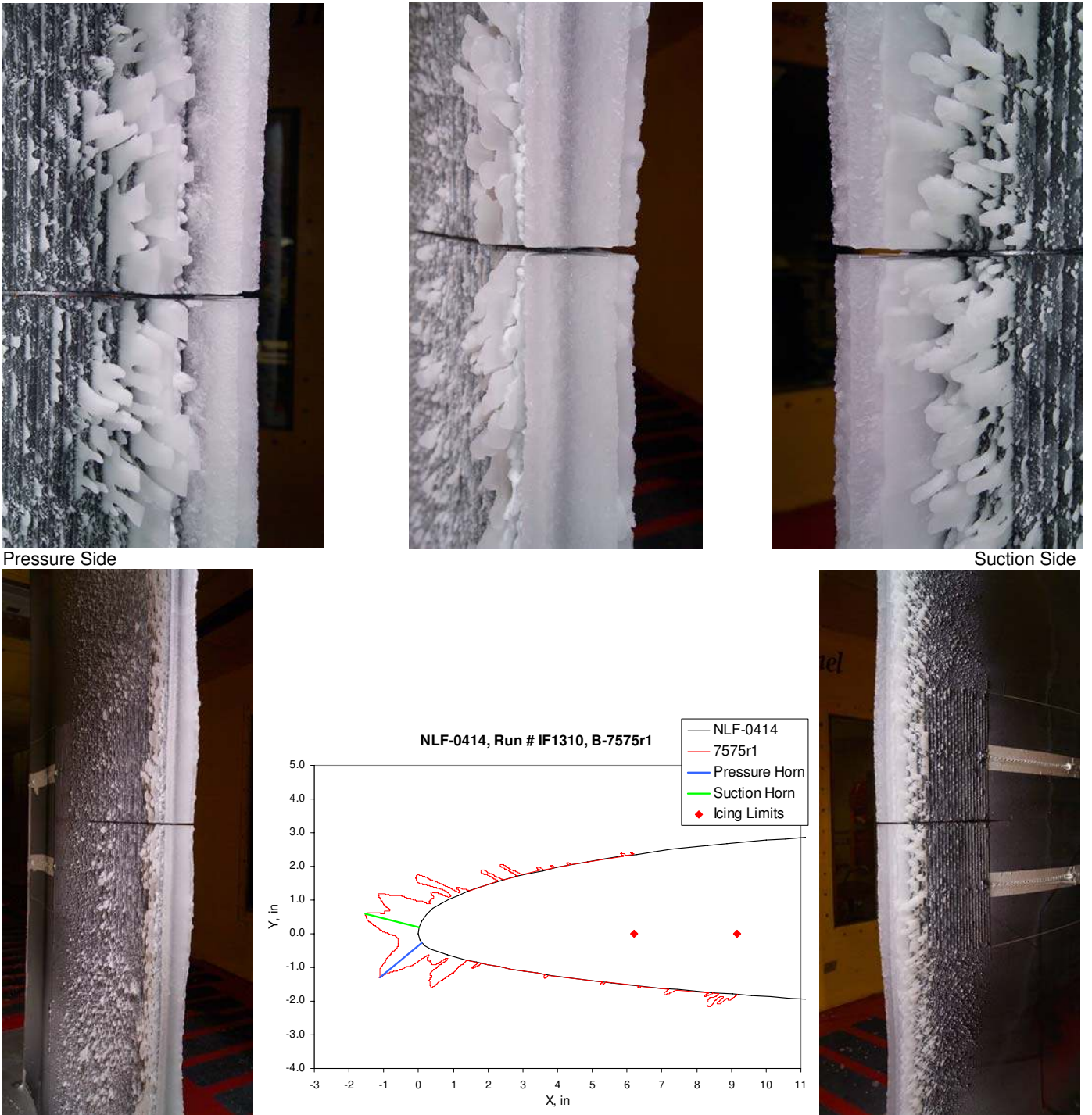


Figure B1. Case B-7575r1 ice accretion (a = top left) pressure side, (b = top center) leading edge, (c = top right) suction side, (d = bottom left) pressure long shot, (e = bottom center) tracing, (f = bottom right) suction long shot.

Table B1. Ice mass and shape characteristic data for the B-7575 repeat series.

NLF 0414, V = 200 kts, T _t = -10 °C, AOA = 2°								
Ref	LWC	MVD	Pressure Side Horn		Suction Side Horn		Mass	LE Min
			Thickness	Angle	Thickness	Angle		
B-7575r1	0.7	119	1.59	228.82	1.60	158.84	1123	0.600
B-7575r2	0.7	119	1.58	227.51	1.59	159.87	1129	0.621
<i>B-avg</i>	<i>0.7</i>	<i>119</i>	<i>1.585</i>	<i>228.16</i>	<i>1.595</i>	<i>159.355</i>	<i>1126</i>	<i>0.611</i>

Note: B-7575 did not spray properly, and therefore is excluded from analyses.

C-7575: NACA 23012

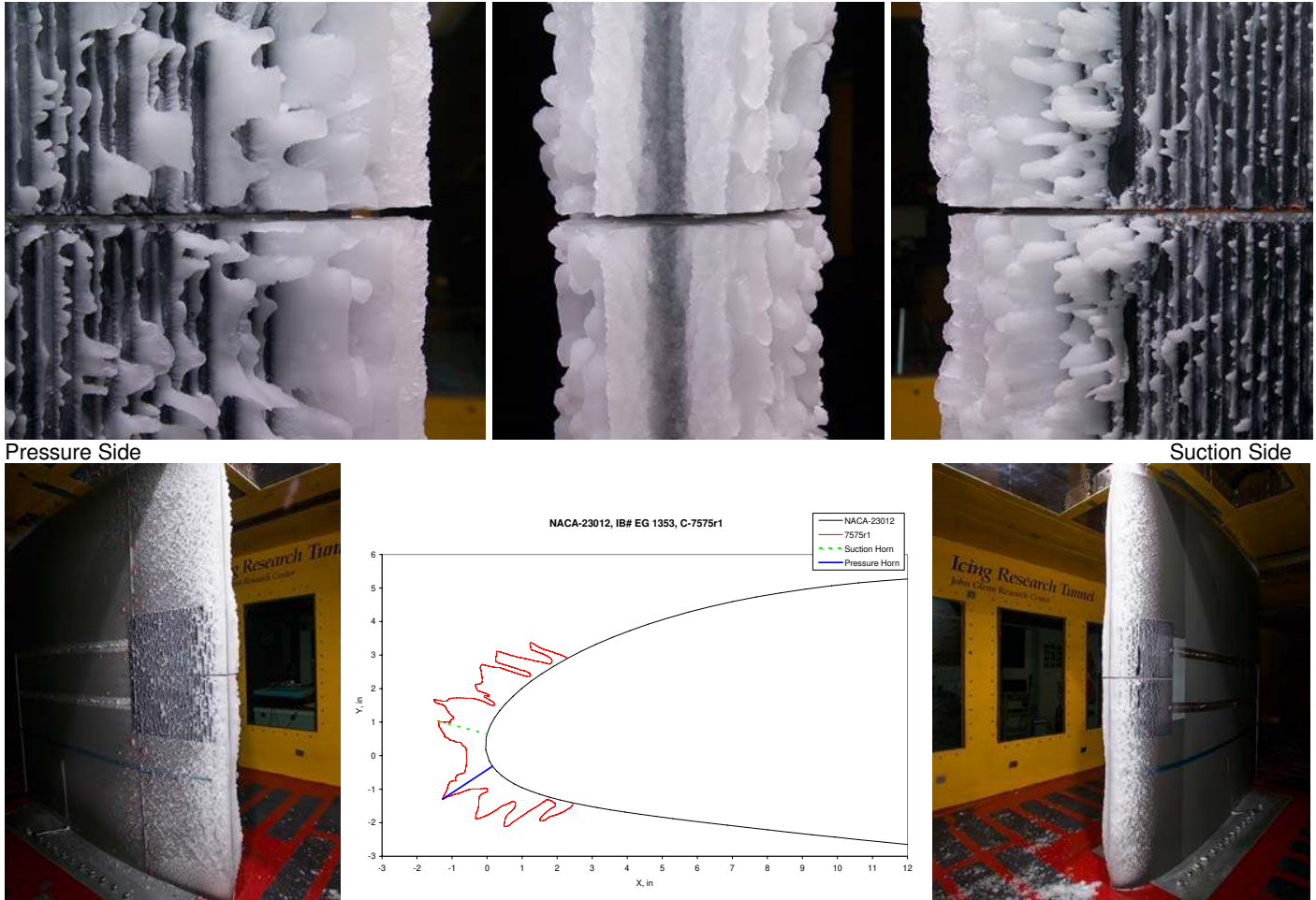


Figure B2. Case C-7575r1 ice accretion (a = top left) pressure side, (b = top center) leading edge, (c = top right) suction side, (d = bottom left) pressure long shot, (e = bottom center) tracing, (f = bottom right) suction long shot.

Table B2. Ice mass and shape characteristic data for the C-7575 repeat series.

NACA 23012, $V = 200$ kts, $T_t = -10$ °C, $AOA = 2^\circ$								
Ref	LWC	MVD	Pressure Side Horn		Suction Side Horn		Mass	LE Min
			Thickness	Angle	Thickness	Angle		
C-7575	0.7	119	1.519	228.9	1.36	148.9	1850	0.587
C-7575r1	0.7	119	1.731	230.0	1.44	147.7	1867	0.554
C-7575r2	0.7	119	1.525	230.8	1.31	145.7	1886	0.548
C-7575m	0.7	119	1.483	232.8	1.28	146.3	-	0.564
C-avg	0.7	119	1.565	230.6	1.35	147.1	1868	0.563

D-7575: GLC 305

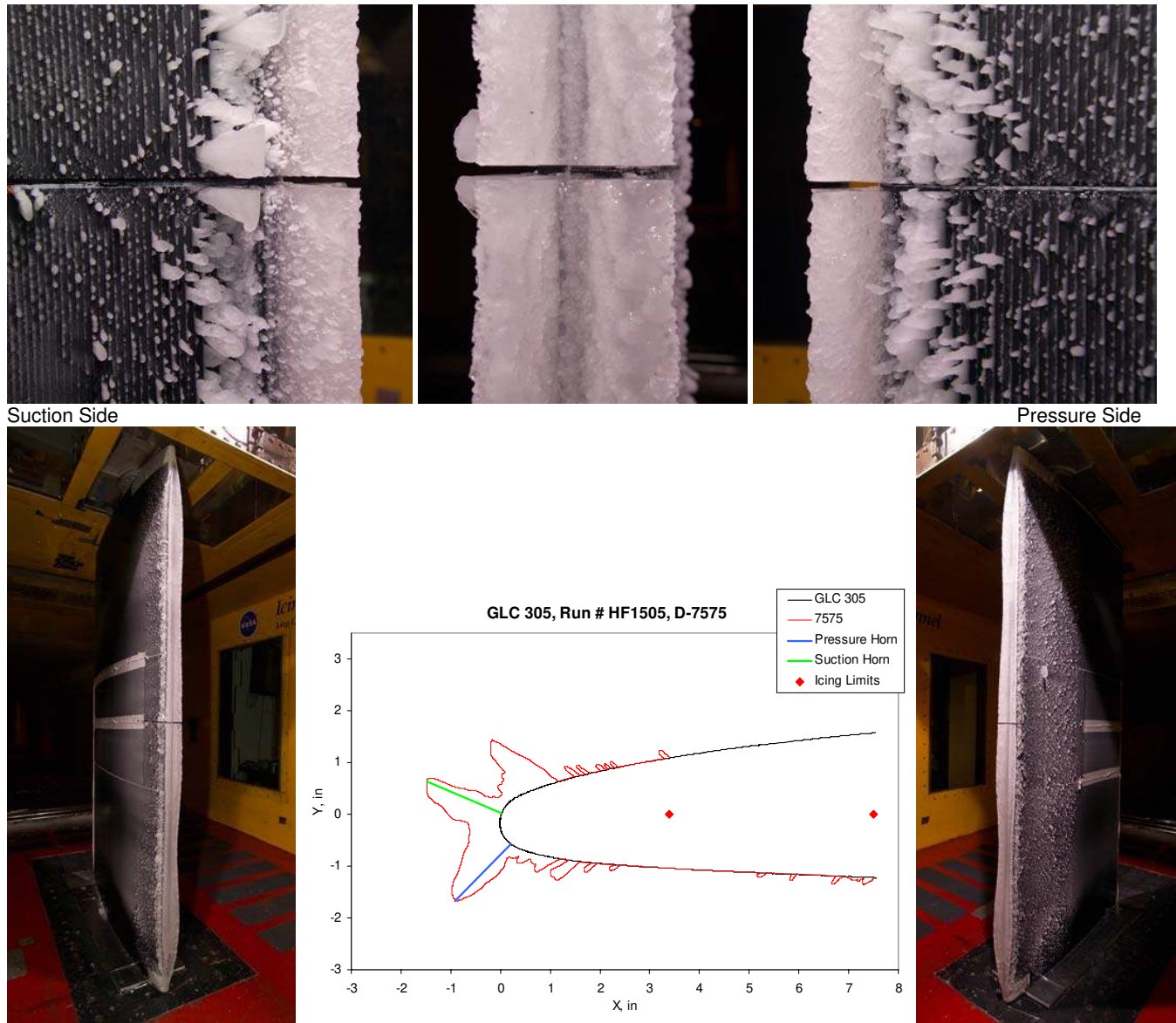


Figure B3. Case D-7575 ice accretion (a = top left) suction side, (b = top center) leading edge, (c = top right) pressure side, (d = bottom left) suction long shot, (e = bottom center) tracing, (f = bottom right) pressure long shot.

Table B3. Ice mass and shape characteristic data for the D-7575 repeat series.

GLC 305, $V = 200$ kts, $T_{\infty} = -10$ °C, $AOA = 2$ °								
Ref	LWC	MVD	Pressure Side Horn		Suction Side Horn		Mass	LE Min
			Thickness	Angle	Thickness	Angle		
D-7575	0.7	119	1.549	238.6	1.617	150.4	675	0.616
D-7575r2	0.7	119	1.477	231.2	1.535	157.8	730	0.673
D-7575m	0.7	119	1.868	224.4	1.930	160.4	-	0.675
<i>D-avg</i>	<i>0.7</i>	<i>119</i>	<i>1.631</i>	<i>231.4</i>	<i>1.694</i>	<i>156.2</i>	<i>702.5</i>	<i>0.655</i>

E-7575: COMMERCIAL TAIL



Pressure Side

Suction Side

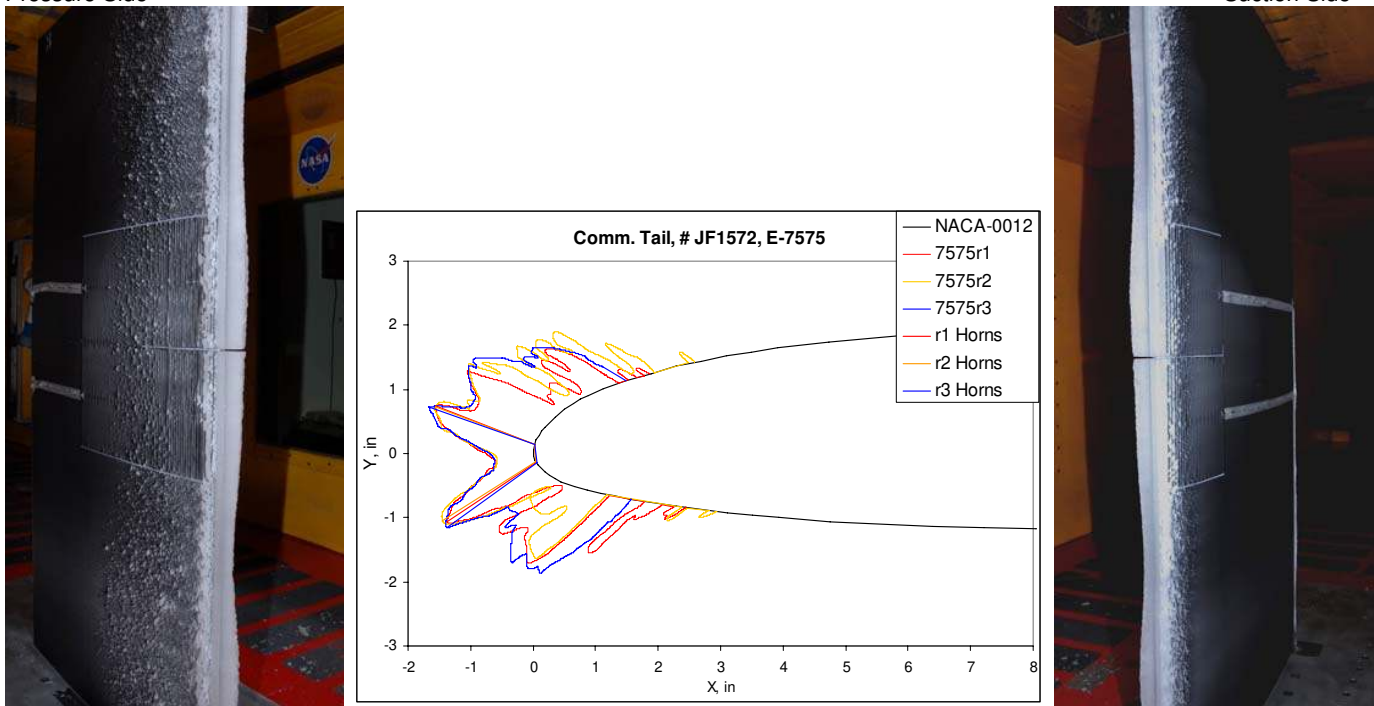


Figure B4. Case E-7575r1 ice accretion (a = top left) pressure side, (b = top center) leading edge, (c = top right) suction side, (d = bottom left) pressure long shot, (e = bottom center) multiple tracings, (f = bottom right) suction long shot.

Table B4. Ice mass and shape characteristic data for the E-7575 repeat series.

Commercial Tail, $V = 200$ kts, $T_t = -10$ °C, $AOA = 2^\circ$								
Ref	LWC	MVD	Pressure Side Horn		Suction Side Horn		Mass	LE Min
			Thickness	Angle	Thickness	Angle		
E-7575*	0.7	119	1.712	218.1	1.630	155.2	947*	0.587
E-7575r1	0.7	119	1.706	219.0	1.691	156.1	970	0.611
E-7575r2	0.7	119	1.757	217.3	1.692	156.9	977	0.580
E-7575r3	0.7	119	1.757	221.1	1.788	157.8	975	0.624
<i>E-avg</i>	<i>0.7</i>	<i>119</i>	<i>1.733</i>	<i>218.9</i>	<i>1.700</i>	<i>156.5</i>	<i>974</i>	<i>0.600</i>

*This was the first run of the night. Mass is expected to be up to 10 percent low, and is not included in the average.

F-7575: BUSINESS JET WING



Suction Side

Pressure Side

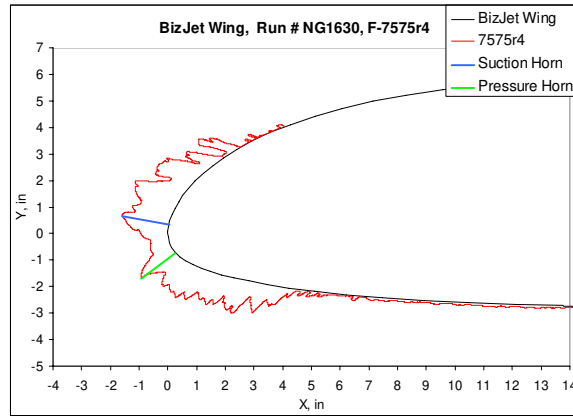


Figure B5. Case F-7575r4 ice accretion (a = top left) suction side, (b = top center) leading edge, (c = top right) pressure side, (d = bottom left) suction long shot, (e = bottom center) tracing, (f = bottom right) pressure long shot.

Table B5. Ice mass and shape characteristic data for the F-7575 repeat series.

Business Jet Wing, $V = 200$ kts, $T_t = -10$ °C, $AOA = 3^\circ$								
Ref	LWC	MVD	Pressure Side Horn		Suction Side Horn		Mass	LE Min
			Thickness	Angle	Thickness	Angle		
F-7575	0.7	119	1.513	241.2	1.400	132.9	1921	0.572
F-7575r1*	0.7	119	1.446	236.2	1.509	152.6	1872*	0.604
F-7575r2	0.7	119	1.364	243.1	1.541	140.0	1913	0.596
F-7575r3*	0.7	119	1.575	235.7	1.752	152.1	-	0.664
F-7575r4	0.7	119	1.511	240.5	1.671	156.1	-	0.614
<i>F-avg</i>	0.7	119	1.482	239.3	1.575	146.7	1917	0.610

*These were the first runs of the night. Mass is expected to be up to 10 percent low, and is not included in the average.

C-1999: NACA 23012 ($V = 100$ KTS, $T_{TOT} = -5$ °C, $LWC = 1.39$ G/M³, $MVD = 225$ μM)



Pressure Side

Suction Side

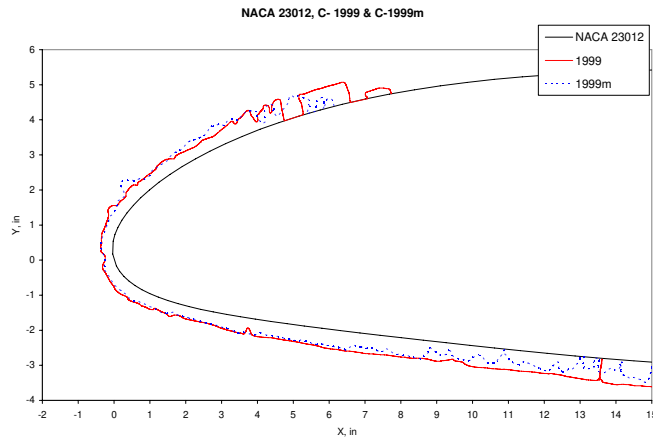


Figure B6. Case C-1999 ice accretion (a = top left) pressure side, (b = top center) leading edge, (c = top right) suction side, (d = middle left) pressure long shot, (e = middle center) tracing of C-1999 and C-1999m, (f = middle right) pressure long shot. (g = bottom left) Case C-1999m pressure long shot, (h = bottom right) C-1999m suction long shot.

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