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Review of the Aerodynamic Acceptance Test and Application to Anti-Icing Fluids Testing in the NRC Propulsion and Icing Wind Tunnel

Andy P. Broeren
Glenn Research Center, Cleveland, Ohio

James T. Riley
Federal Aviation Administration, William J. Hughes Technical Center, Atlantic City Airport, New Jersey

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

James T. Riley
Federal Aviation Administration
William J. Hughes Technical Center
Atlantic City Airport, New Jersey 08405

Abstract

In recent years, the FAA has worked with Transport Canada, National Research Council of Canada (NRC) and APS Aviation, Inc. to develop allowance times for aircraft operations in ice-pellet precipitation. These allowance times are critical to ensure safety and efficient operation of commercial and cargo flights. Wind-tunnel testing with uncontaminated anti-icing fluids and fluids contaminated with simulated ice-pellets had been carried out at the NRC Propulsion and Icing Wind Tunnel (PIWT) to better understand the flowoff characteristics and resulting aerodynamic effects. The percent lift loss on the thin, high-performance wing model tested in the PIWT was determined at 8° angle of attack and used as one of the evaluation criteria in determining the allowance times. Because it was unclear as to how performance degradations measured on this model were relevant to an actual airplane configuration, some means of interpreting the wing model lift loss was deemed necessary. In this report, the lift loss was related to the loss in maximum lift of a Boeing 737-200ADV airplane through the Aerodynamic Acceptance Test (AAT) performed for fluids qualification. This report provides a review of the research basis of the AAT in order to understand how this correlation was applied. A loss in maximum lift coefficient of 5.24 percent on the B737-200ADV airplane (which was adopted as the threshold in the AAT) corresponds to a lift loss of 7.3 percent on the PIWT model at 8° angle of attack. There is significant scatter in the data used to develop the correlation related to varying effects of the various anti-icing fluids that were tested and other factors. A statistical analysis indicated the upper limit of lift loss on the PIWT model was 9.2 percent. Therefore, for cases resulting in PIWT model lift loss from 7.3 to 9.2 percent, extra scrutiny of the visual observations is required in evaluating fluid performance with contamination. Additional research may result in future changes to this correlation.

Nomenclature

C_l	sectional lift coefficient
C_L	airplane lift coefficient
$C_{l,\max}$	maximum sectional lift coefficient
$C_{L,\max}$	maximum airplane lift coefficient
V_2	takeoff safety speed
V_{s1g}	1g stall speed
α_B	body angle of attack
α_w	wing section angle of attack
δ^*	boundary-layer displacement thickness
δ^*_{fluid}	boundary-layer displacement thickness of fluid in AAT at a given temperature

δ^*_{dry}	boundary-layer displacement thickness of dry flat plate in AAT
$\delta^*_{l\,@\,-20\,°C}$	boundary-layer displacement thickness limit define for AAT at –20 °C

Acronyms

AAT	Aerodynamic Acceptance Test
AEA	Association of European Airlines
AMIL	Anti-Icing Materials International Laboratory
APS	APS Aviation, Inc.
EG	ethylene glycol
FAA	Federal Aviation Administration
HOT	holdover time
IRT	Icing Research Tunnel
KEAS	equivalent airspeed, kn
NASA	National Aeronautics and Space Administration
NRC	National Research Council (Canada)
OAT	outside air temperature
PG	propylene glycol
PIWT	Propulsion and Icing Wind Tunnel
POI	Principal Operations Inspector
SEE	standard error of the estimate

1.0 Introduction

During the period from 1992 to 2004, many air carriers were allowed to operate in ice-pellet conditions provided that the flight crew did a contamination check of the wings within 5 min of takeoff although no holdover times (HOTs) existed for these conditions. This check was conducted from inside the aircraft in the case of most passenger aircraft, and from the outside for freighters (which had no windows in the cabin). This procedure for operation in ice-pellet conditions was incorporated into the deicing and anti-icing programs of many individual air carriers and approved annually by the FAA Principal Operations Inspector (POI) for those carriers.

In 2005, the FAA became concerned about operations in ice-pellet conditions after learning of questions raised relating to regional carriers operating in ice pellets with non-slatted aircraft and with less experienced flight crews than the major carriers. As a result of these concerns, the FAA issued three notices effectively disallowing operations in ice pellets in October 2005 (Refs. 1, 2, and 3). In the winter of 2005-2006, this action had a major impact at several airports during ice-pellet events. Due in part to concerns raised by these events, the FAA undertook a thorough reassessment of its policy with respect to operation in ice-pellet conditions.

HOTs are determined based on the results of endurance time testing of anti-icing fluids in natural or simulated icing conditions. Fluid failure occurs when the fluid is no longer able to effectively absorb the incoming precipitation. The endurance times are determined by applying failure criteria using visual cues for fluid failure, which vary depending on the icing conditions (snow, freezing drizzle, freezing rain).

Environmental chamber testing showed that ice pellets generally remain in the frozen state imbedded in Type IV anti-icing fluid, and are not absorbed by the fluid in the same manner as other forms of precipitation. Using the guidelines for determining anti-icing fluid failure, the presence of a contaminant not absorbed by the fluid (remaining imbedded) would be an indication that the fluid has failed. However, the imbedded ice pellets were generally not readily detectable by the human eye except through short range inspection. This indicated that a contamination check of the wings within 5 min of takeoff in operational conditions would be of little value. The difficulty in establishing visual cues for detecting fluid failure in ice-pellet conditions has thus far precluded the establishment of practical failure criteria for endurance time testing. Without endurance time testing, HOTs cannot be established and so the FAA has never provided HOTs for operations in ice-pellet conditions.

The environmental chamber testing did not indicate that the imbedded ice pellets were conducive to contamination adhering to the underlying surface. Researchers decided to examine whether this was also true during actual takeoff runs, and also whether the presence of the ice pellets somehow interfered with the flowoff of the fluid during a takeoff run. Adhering contamination or a significant amount of fluid remaining on the wing at takeoff would both represent a safety hazard.

The FAA Ground Icing Program and Transport Canada sponsored research conducted at the MacDonald Cartier International Airport, Ottawa, Canada, in March 2006 using a Dassault Falcon 20 aircraft belonging to and operated by NRC Canada. APS Aviation, Inc. was contracted to support this research. Ice pellets were simulated using crushed ice from blenders which was run through sieves to get a size distribution similar to natural pellets. Type IV fluids were applied to a designated portion of the Falcon 20 wing followed by the simulated ice pellets that were distributed in known quantities and rates using modified and calibrated hand held spreaders. The test segment of the wing was on the inboard half and had a trailing-edge flap, but no leading-edge slat. The flaps were not deployed until the start of the simulated takeoff. The Falcon 20 was operated through a simulated takeoff run excluding climbout. For most of the trials, the maximum speed ranged from 119 to 125 kn (61.2 to 64.3 m/s) that was attained in 23 to 27 s after brake release. The contaminated fluid flowoff behavior was visually observed and recorded, and no aerodynamic performance data were reported. These tests indicated that when the aircraft was protected with Type IV anti-icing fluid, the fluid contaminated with the simulated pellets would readily flow off prior to rotation for all but the most extreme conditions tested, and that no frozen contamination remained on the wing. Review of the research indicated that a 25 min allowance time after anti-icing in light ice pellets afforded a large safety margin. The FAA approved a 25 min allowance time for winter 2006-2007 after anti-icing in light ice pellets with undiluted Type IV fluid, giving air carriers adequate time to get off the ground at most airports. An allowance time differs from a HOT in that there is no provision for pre-takeoff contamination check if the time is exceeded, meaning that the allowance time cannot be extended by a visual cabin check or external tactile or visual check of the aircraft critical surfaces within 5 min of takeoff. Ordinarily pre-takeoff contamination checks are conducted from the cabin, and the research showed that such a check would be of little use in the case of ice pellets (Ref. 4).

Ice pellets often occur mixed with other forms of precipitation in North America (Ref. 5). Thus the FAA recognized a need for further testing for various mixed conditions and temperature ranges. The following winter (January-February 2007), again in cooperation with Transport Canada, ice-pellet contamination testing was conducted in a large, open-circuit wind tunnel. This facility, the Propulsion and Icing Wind Tunnel (PIWT) is owned and operated by NRC. A two-dimensional, single element, NACA 23012 airfoil model with 4.0 ft (1.2 m) chord was used for this test campaign (Ref. 6). An airplane takeoff acceleration profile and rotation was simulated in the wind-tunnel testing typically reaching a maximum speed of 100 kn (51.4 m/s) in 30 to 35 s. Allowance times were determined using the visual observations of the researchers. Limited aerodynamic measurements were also made, supplementing the observations of the researchers. However, the results did not show large effects of the contaminated fluids on the coefficient of lift, and no aerodynamic criteria were introduced for the determination of allowance times. The PIWT tests were also supplemented by environmental chamber tests whereby plates contaminated with ice pellets were be subjected to simulated freezing rain, freezing drizzle, and snow. Based on the results from the testing, the FAA published an allowance time table for winter 2007-2008 in Notice N 8900.19 (Ref. 7) and also in Notice N 8900.22 (Ref. 8). The table is reproduced as Table I of this report.

In February and March 2008, simulated takeoff testing (excluding climbout) was conducted using NRC's Dassault Falcon 20 and Lockheed-Martin T-33 airplanes. The primary purpose of this testing was further evaluation of the allowance times already provided (cf. Table I) to determine if any changes were needed. Therefore, methods were developed to provide simulated ice-pellet conditions and mixed conditions (ice pellets mixed with snow, freezing rain, freezing drizzle) on the runway. The methods and procedures used in the March 2006 Falcon 20 tests were generally followed in this campaign. The contaminated fluid flowoff behavior was visually observed and recorded, and no aerodynamic performance data were reported. In addition to the Falcon 20 inboard wing segment used in March 2006, fluid and contamination was also applied to an outboard section of the Falcon 20 wing. This allowed for observation of the effect of extended leading-edge slat on contaminated fluid flowoff behavior. The rotation speed was nominally 120 kn (61.7 m/s) at 25 s after brake release. The effect of rotation speed was also considered in this test campaign with trials conducted at a nominal speed of 80 kn (41.1 m/s) at 17 s after brake release. There were no changes to the allowance time table for winter 2008-2009 as a result of this testing.

TABLE I.—ICE PELLET ALLOWANCE TIMES FOR WINTER 2007-2008 (REFS. 7 AND 8)

	OAT –5 °C or warmer, min	OAT colder than –5 °C, min
Light ice pellets	50	30
Moderate ice pellets	25	10
Light ice pellets mixed with light or moderate snow	25	Operations not authorized
Light ice pellets mixed with light or moderate freezing drizzle, or light freezing rain (operations not authorized below –10 °C OAT)	25	10 (operations not authorized below –10 °C OAT)
Light ice pellets mixed with light rain (operations not authorized below 0 °C OAT)	25 (operations not authorized below 0 °C OAT)	Operations not authorized below 0 °C OAT)

The research returned to the NRC PIWT again in January-March 2009 using a 6.0 ft (1.8 m) chord LS(1)-0417 airfoil model. This model had a span of 7.9 ft (2.4 m) and was mounted in the tunnel between two end plates to minimize three–dimensional effects. This model had a single-element slotted flap deployed at 15°. Allowance times were again determined primarily using the visual observations of the researchers. Aerodynamic measurements were made, supplementing the observations of the researchers. However, the results did not show large effects of the contaminated fluids (never more than 5 percent loss of lift), and no aerodynamic criteria were explicitly introduced for the determination of allowance times. Based on the results, the FAA published an updated ice pellet allowance time table for Winter 2009-10 in Notice N 8900.98 (Ref. 9) reproduced here as Table II. An allowance time for light ice pellets mixed with rain was added, and changes were made to the rows for light ice pellets mixed with light snow and light ice pellets mixed with moderate snow.

TABLE II.—ICE PELLET ALLOWANCE TIMES FOR WINTER 2009-2010 (REF. 9)

<table>
<tr><th></th><th>OAT –5 °C and above, min</th><th>OAT less than –5 to –10 °C, min</th><th>OAT less than –10 °C, min</th></tr>
<tr><td>Light ice pellets</td><td>50</td><td>30</td><td>30</td></tr>
<tr><td>Moderate ice pellets</td><td>25</td><td>10</td><td>10</td></tr>
<tr><td>Light ice pellets mixed with light or moderate freezing drizzle</td><td>25</td><td>10</td><td rowspan="6">Caution: No allowance times currently exist</td></tr>
<tr><td>Light ice pellets mixed with light or freezing rain</td><td>25</td><td>10</td></tr>
<tr><td>Light ice pellets mixed with light rain[a]</td><td>25</td><td rowspan="2"></td></tr>
<tr><td>Light ice pellets mixed with moderate rain[a]</td><td>25</td></tr>
<tr><td>Light ice pellets mixed with light snow</td><td>25</td><td>15</td></tr>
<tr><td>Light ice pellets mixed with moderate snow</td><td>10</td><td></td></tr>
</table>

[a]Limited to OAT of 0 °C and above

Tests were continued in the NRC PIWT in January-February 2010 using a thin, high-performance airfoil model rigged with a single-element slotted flap fixed at 20°. The thin, high-performance section was regarded as typical of wings on regional jet transport airplanes. This model had a chord of 6.0 ft (1.8 m) and a span of 7.9 ft (2.4 m) and was mounted in the tunnel between two end plates. Clark and MacMaster (Ref. 10) provide further information regarding the January-February 2010 wind-tunnel testing conducted at the NRC PIWT. Aerodynamic measurements were again made, and effects on lift were significantly larger than in past years. Along with visual evaluation by the researchers, a criterion for percentage loss in lift at 8° angle of attack was explicitly used. This raised several concerns that are discussed in detail in Section 3.0 of this report. Based on the results, the FAA published an updated ice pellet allowance time table for winter

2010-2011 and 2011-2012, since it was not changed, on the FAA AFS-200 Ground Deicing Web site (Ref. 11) reproduced here as Table III. The allowance times for propylene glycol (PG) based fluids were reduced or eliminated in some cases. It was noted that ethylene glycol (EG) fluids tend to flow off more readily than PG fluids, especially when contaminated and for temperatures lower than –10 °C. The allowance times were eliminated for light ice pellets and moderate ice pellets for OAT less than –10 °C for PG fluids for aircraft with rotation speeds less than 115 kn (59.1 m/s), and were reduced from 25 to 15 min for moderate ice pellets for OAT greater than 0 °C for PG fluids.

TABLE III.—ICE PELLET ALLOWANCE TIMES FOR WINTER 2010-2011 (REF. 11)

	OAT –5 °C and above, min	OAT less than –5 to –10 °C, min	OAT less than –10 °C, min
Light ice pellets	50	30	30[a]
Moderate ice pellets	25[b]	10	10[a]
Light ice pellets mixed with light or moderate freezing drizzle	25	10	Caution: No allowance times currently exist
Light ice pellets mixed with light freezing rain	25	10	
Light ice pellets mixed with light rain[c]	25		
Light ice pellets mixed with moderate rain[c]	25		
Light ice pellets mixed with light snow	25	15	
Light ice pellets mixed with moderate snow	10		

[a]No allowance times exist for PG fluids, when used on aircraft with rotation speeds less than 115 kn. (For these aircraft, if the fluid type is not known, assume zero allowance time.)
[b]Allowance time is 15 min for PG fluids, or when the fluid type is unknown.
[c]Operations NOT authorized below 0 °C

Tests were continued in the NRC PIWT in January-February 2011 using the same thin, high-performance wing model used the previous year. There were no changes to the allowance times tables for winter 2011-2012 based on the testing. The evolution of the allowance time tables since their introduction is depicted in Table IV, which employs a common format to facilitate comparison of all the tables.

TABLE IV.—EVOLUTION OF ALLOWANCE TIME TABLES (ALL TIMES ARE IN MINUTES)

	Winter 2007-2008 and 2008-2009				Winter 2009-2010				Winter 2010-2011 and 2011-2012			
	OAT ≥ 0 °C	0 °C > OAT ≥ –5 °C	–5 °C > OAT ≥ –10 °C	–10 °C > OAT	OAT ≥ 0 °C	0 °C > OAT ≥ –5 °C	–5 °C > OAT ≥ –10 °C	–10 °C > OAT	OAT ≥ 0 °C	0 °C > OAT ≥ –5 °C	–5 °C > OAT ≥ –10 °C	–10 °C > OAT
Light ice pellets	50	50	30	30	50	50	30	30	50	50	30	30[b]
Moderate ice pellets	25	25	10	10	25	25	10	10	25[a]	25	10	10[b]
Light ice pellets mixed with light or moderate freezing drizzle	25	25	10	0	25	25	10	0	25	25	10	0
Light ice pellets mixed with light freezing rain	25	25	10	0	25	25	10	0	25	25	10	0
Light ice pellets mixed with light rain	25	0	0	0	25	0	0	0	25	0	0	0
Light ice pellets mixed with moderate rain	0	0	0	0	**25**	0	0	0	25	0	0	0
Light ice pellets mixed with light snow	25	25	0	0	25	25	**15**	0	25	25	15	0
Light ice pellets mixed with moderate snow	25	25	0	0	**10**	**10**	0	0	10	10	0	0

[a]Allowance time is 15 min for PG fluid.
[b]Allowance time is 0 min for PG fluid with rotation speed less than 115 kn.

Shading indicates that more time is allotted than in previous table.

Shading indicates that less time is allotted than in previous table.

The dissemination of the wind-tunnel testing results and subsequent changes to the ice-pellet allowance time tables have led to concerns regarding the fidelity and applicability of the measured lift degradation in the ice-pellet contamination fluid testing at the NRC PIWT. Given the potential operational safety implications associated with the measured performance degradations, it is even more important that these concerns be addressed appropriately. The list of potential issues includes the following:

- A two-dimensional model with endplates was used instead of a three-dimensional geometry more representative of an airplane wing.
- Lift degradations were measured at $\alpha_w = 8°$ on the two-dimensional model instead of at stall.
- Airplanes undergoing take-off accelerations and rotation experience ground effects that were not simulated in the PIWT testing.
- The chord Reynolds number was small relative to most airplane wing sections.
- The 6-ft (1.8 m) chord length model is small relative to most airplane wing sections.
- The large model size and proximity of the wind-tunnel walls resulted in uncorrectable effects on the aerodynamic data and performance.
- The rotation speed used in the PIWT tests was low relative to typical airplane rotation speeds.

The essence of these concerns is understanding how the performance degradations measured on the model in the NRC PIWT testing relate to an actual three-dimensional, full-scale airplane configuration. Therefore, some means of determining the significance of the measured lift degradations relative to a full-scale airplane is necessary.

It has been suggested that the measured lift degradation due to the uncontaminated, or pristine, fluids in the NRC PIWT tests could be compared to the loss in maximum lift that is associated with the Aerodynamic Acceptance Test (AAT). The AAT is described in SAE Aerospace Standard AS5900 (Ref. 12) and was developed as a means to qualify deicing and anti-icing fluids. The AAT fluid acceptance criterion for utilizing the flat-plate, boundary-layer displacement thickness, δ^*, is based upon a correlation with loss in maximum lift on a Boeing 737-200ADV configuration derived from flight and wind-tunnel testing. Therefore, δ^* data resulting from the AAT for a specific fluid correlate to a loss in maximum lift on the B737-200ADV airplane. Relating this information to the measured lift degradation in the corresponding NRC PIWT testing using the same fluid provides a means to “scale” the measured lift degradation in the NRC PIWT tests. In order to follow this approach, a detailed review of the research basis for the AAT must be conducted. It is important to understand how the AAT qualification criterion was established in order to understand how it may be applied to the present aerodynamic testing of anti-icing fluids.

Therefore, the purpose of this report is to review the research basis of the AAT and determine how it may be applied to the present aerodynamic testing of anti-icing fluids in the PIWT. A detailed review of the research basis of the AAT is performed in Section 2.0 of this report. Section 3.0 then provides a review of the anti-icing fluid aerodynamic testing conducted at the NRC PIWT with the uncontaminated fluid. These results were used in conjunction with results from the AAT performed for the same fluids to relate the aerodynamic degradation on the two-dimensional PIWT model to a B737-200ADV airplane. This relationship was then used to develop a lift loss criterion that could be used to establish allowance times for ice-pellet contamination. This report describes how this “scaling” method may address the concerns raised in regard to the NRC PIWT tests and implications for establishing ice-pellet allowance times.

2.0 Review of the Research Basis of the Aerodynamic Acceptance Test

2.1 Introduction

A major research program was conducted in the mid to late 1980s and early 1990s to characterize deicing/anti-icing fluid behavior and aerodynamic effects on transport airplanes. This work was led by

Eugene Hill and Thomas Zierten of the Boeing Commercial Airplane Group and is described in References 13 to 16. This research led to the development of the AAT that is described in Ref. 12. A flight test was conducted to establish the fluid effects on a full-scale Boeing 737-200ADV airplane. Following the flight test, wind-tunnel testing was conducted with both three-dimensional and two-dimensional subscale models based upon the B737-200ADV in the NASA Glenn (then Lewis) Icing Research Tunnel (IRT). The icing tunnel test results were correlated to the flight trials to determine the applicability of subscale wind-tunnel testing for deicing/anti-icing fluid effects. The IRT testing was extended to include boundary-layer measurements on the two-dimensional model. These measurements were subsequently correlated to boundary-layer measurements on a flat plate model to form the basic principles of the AAT. This review will describe each of these research efforts in more detail.

2.2 Flight Test Campaign

The flight test campaign was conducted during January 11 to 20, 1988, at Kuopio, Finland. The experiments were led by Boeing and supported by the Association of European Airlines (AEA) and three fluid manufacturers. *"The objectives of the flight test were to evaluate the aerodynamic effects of ground deicing/anti-icing fluids on a large jet transport and to establish a full-scale data base for extrapolating data from a planned, more comprehensive wind-tunnel investigation. The primary goal of the flight test was to obtain data for assessing the fluid effects on lift."* (Ref. 13) To carry out these objectives, a series of takeoffs were performed using an instrumented Boeing 737-200ADV airplane. In addition to the airplane and air data acquisition, video and photographic records of the fluid flow characteristics were also obtained. Only Type I and Type II fluids were tested. The fluids were applied using a two-step, in-service procedure: the wing and horizontal stabilizer were first deiced using a 50:50 mixture of Type 1 fluid and hot water and then anti-iced with undiluted, cold Type II fluid. When testing was conducted with only Type I fluid, the fluid was applied cold and undiluted without the deicing step. A picture of fluid application is shown in Figure 1. Four fluids were tested:

- Fluid 1: Hoescht Type I
- Fluid 2: Obsolete Type II (used because existing wind-tunnel data were available)
- Fluid 3: Hoescht Type II
- Fluid 4: Union Carbide Canada Type II

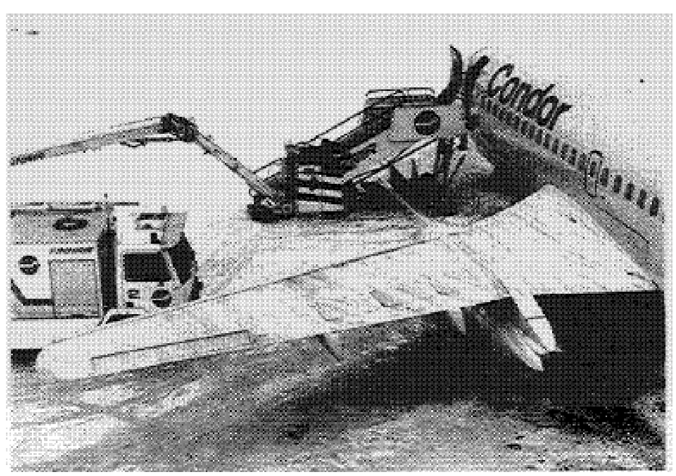

Figure 1.—Application of anti-icing fluid to B737-200ADV during flight test trials at Kuopio, Finland, in 1988, from Hill and Zierten (Ref. 13). Reprinted with permission of the American Institute of Aeronautics and Astronautics.

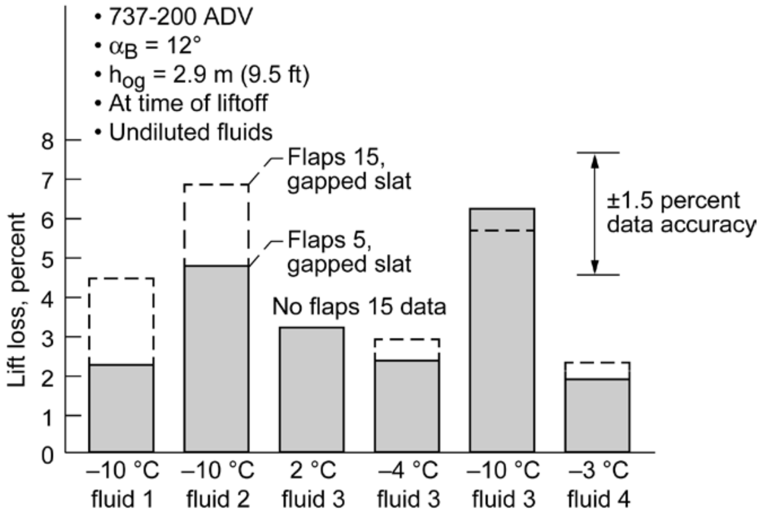

Figure 2.—Summary of fluid effects on lift coefficient from B737-200ADV flight test trials, from Hill and Zierten (Ref. 13).

Overall, the flight test results showed that the lift is lower with the fluids applied to the wing relative to the clean, dry baseline. A summary of the fluid effects on lift coefficient for a liftoff attitude of 12° is shown in Figure 2. Hill and Zierten (Ref. 13) note that the liftoff attitude, α_B = 12° was typical of the one-engine inoperative takeoff climb attitude for the B737-200ADV. They also estimated a ±1.5 percent uncertainty in the experimental data. The baseline lift coefficient for α_B = 12° corresponded to 75 percent of $C_{L,\max}$ for the clean, dry airplane. Flight test data were not gathered near $C_{L,\max}$ because this would have required stalling the airplane close to the ground (Ref. 16). The data in Figure 2 illustrates the effects of the four fluids at various temperatures and for both the flaps 5 and flaps 15 configurations. In general, the lift penalties due to the fluid were higher at flaps 15 than flaps 5, thus illustrating the effect of airplane configuration. The lift loss for the Type I fluid (Fluid 1) at –10 °C was less than that of a Type II fluid (Fluid 3) also at –10 °C. Hill and Zierten (Ref. 13) reported, *"Limited assessments of flow off time, liftoff speed and fluid exposure time revealed that reasonable variations of these parameters had no measurable effects on the test results."* Visual observations of the fluid flowoff characteristics were also performed and led to various hypotheses about the behavior of the instability waves in the fluids. Detailed discussion of fluid flowoff characteristics and instabilities is beyond the scope of this report.

Hill and Zierten (Ref. 13) reported the following general conclusions from the B737-200ADV flight test trials:

1. *"The neat fluids cause a measurable loss in lift, similar to the results of earlier Boeing and AEA wind-tunnel tests.*
2. *The fluid effects are configuration dependent.*
3. *Effects of the fluids on airplane handling qualities can be small.*
4. *A secondary fluid wave flows aft immediately after rotation for takeoff.*
5. *Fluid effects are transitory."*

References 13 to 16 provide more information supporting these conclusions.

2.3 Phase I IRT Test Campaign

Both Phase I and II IRT tests were cooperative efforts among Boeing who provided the models and conducted the test, NASA Glenn who provided use of the IRT and test support, various fluid manufacturers who provided the deicing/anti-icing fluids and the AEA who monitored the test to maintain continuity with their fluids research program at that time. The first IRT test campaign, Phase I, was conducted in early 1988, shortly after the conclusion of the flight test trials. According to Hill and Zierten, (Ref. 13) the primary objective of the Phase I test campaign was to validate the use of wind-tunnel tests for investigating the aerodynamic effects of deicing/anti-icing fluids.

The Phase I IRT campaign was conducted using an existing B737-200ADV model. This model was a 9.1 percent scale, half-plane model mounted to a splitter wall along the tunnel test-section sidewall as shown in Figure 3. The forces and moments on the model were measured with a balance located in the splitter wall. The average chord length for this model was 1.0 ft (0.305 m) and the wing was equipped with a leading-edge slat and a trailing-edge flap. The model was tested with and without a ground plane installed in the test section as shown in Figure 3. The detailed test procedures are described in References 13 and 16, and are summarized here. After the fluid application, a 5-min exposure time was used to allow the fluid temperature to equilibrate with the model and air temperature. The wind-tunnel flow velocity was linearly increased to 135 KEAS (69 m/s) in approximately 30 s. After 25 s of tunnel flow, the model was rotated from the taxi attitude ($\alpha_B = 0°$) to the desired angle of attack at rotation rate of 3°/s. The speed at rotation was approximately 120 to 125 KEAS (62 to 64 m/s), corresponding to typical rotation speeds for the full-scale B737-200ADV airplane. A comparison of the flight test and IRT test acceleration profile is shown in Figure 4. The desired attitude varied, but was up to and including wing stall in many cases. Using this method, the entire lift curve could be determined with a single run. This method for obtaining the entire lift curve in a single run was validated by performing a series of runs where the model was rotated to a fixed attitude to establish the lift curve in fixed increments. The aerodynamic performance data from both methods were comparable (Ref. 16).

Through the course of the initial IRT investigations, Runyan et al. (Ref. 16) considered the effect of the rotation speed, time to rotation and initial fluid depth on the aerodynamic performance. The effect of independent variations of these parameters on lift coefficient is shown in Figure 5 for Fluid 3 at $\alpha_B = 7°$. The first plot shows that there is an effect of the velocity at rotation with higher rotation speeds resulting in higher lift coefficients. The second plot shows that there was virtually no difference in lift coefficient for two different rotation times. In this case the rotation velocity was constant and the times were changed by changing the acceleration profile. Finally, the effect of the initial fluid thickness on lift coefficient was inconclusive due to the scatter in the data. Analogous plots for the percent increase in drag coefficient are shown in Figure 6. The drag data tend to follow the trends in the lift effects, with the possible exception of the effect of rotation time. The longer rotation time seemed to reduce the percent increase in drag coefficient slightly, but had little or no effect on lift coefficient. Based upon these results and the lift comparisons to be described in the following paragraph, no adjustment of the acceleration conditions was found to be necessary. That is, the time to rotation, rotation speed and rotation rate used in the IRT tests matched that used in the flight test campaign.

Runyan et al. (Ref. 16) provide a good discussion of the limitations involved in the fluids-related wind-tunnel testing. They discussed the tradeoff and effects of model scale, Reynolds number, local flow velocities and surface shear stresses, etc. It was certainly acknowledged that the small model scale (9.1 percent) and associated Reynolds number effects would result in serious questions about significance and applicability of the wind-tunnel data. That is why Phase I was conducted to gain confidence that the wind tunnel could be used to evaluate fluid effects on aerodynamic performance. Hill and Zierten wrote (Ref. 13): *"By testing the same deicing/anti-icing fluids used during the flight test program on the B737-200ADV three-dimensional model, the correlation between full- and model-scale fluid effects on lift…was obtained."* The authors refer to Figure 7 that shows the comparison between percent lift loss on the

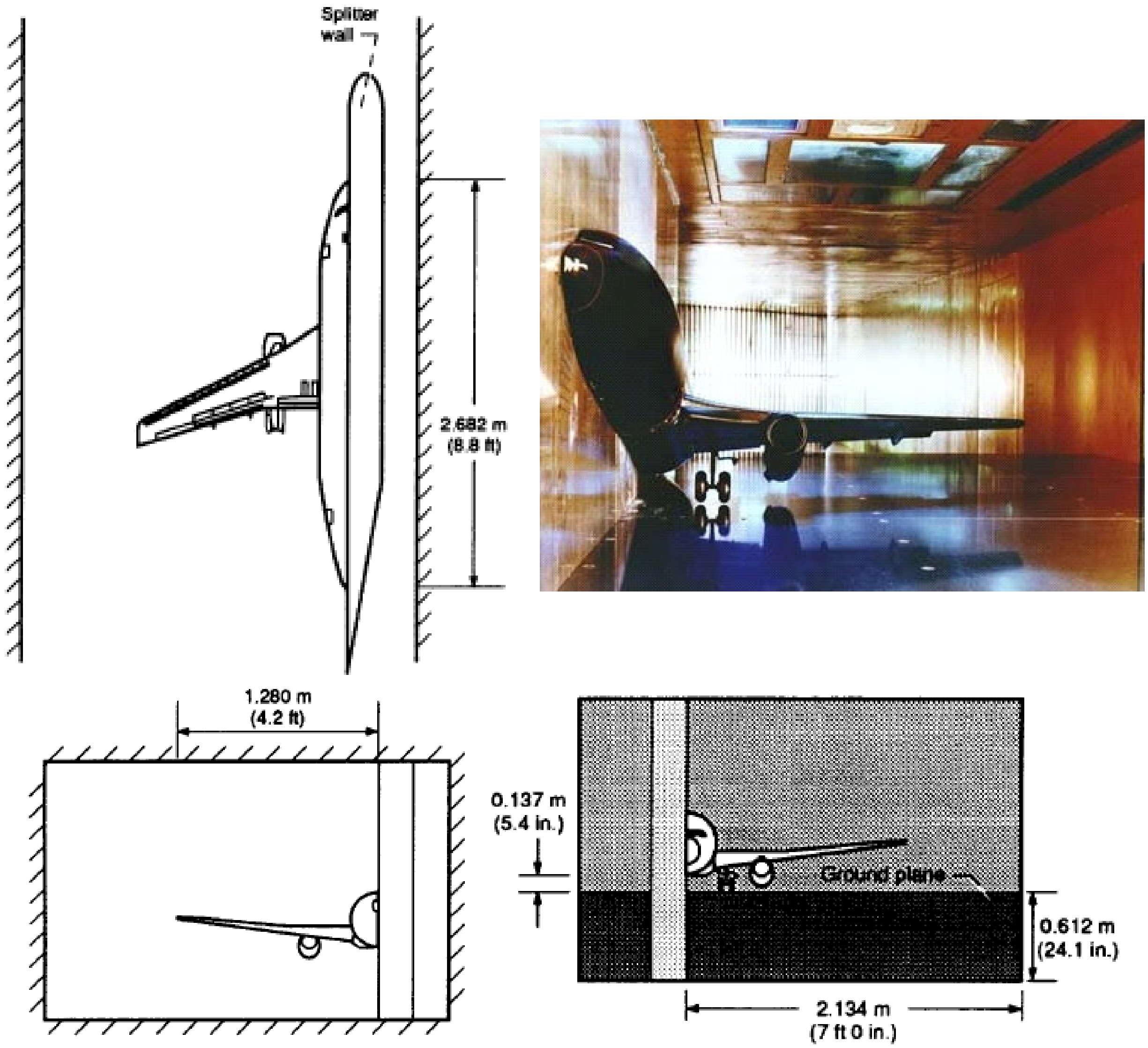

Figure 3.—9.1 percent scale, three-dimensional half-plane B737-200ADV model installed in NASA IRT, from Runyan et al. (Ref. 16).

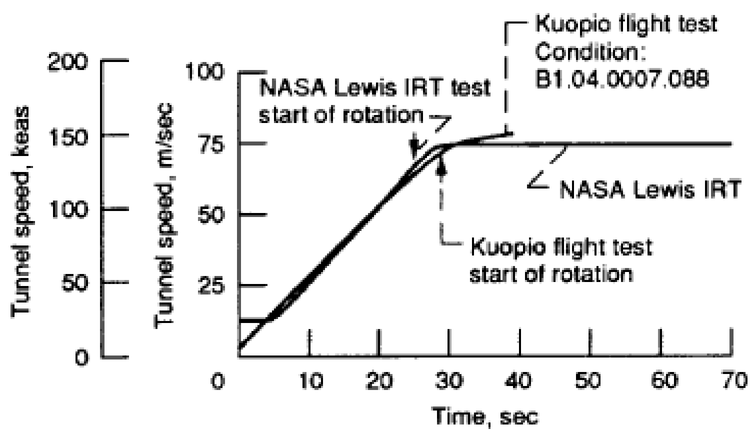

Figure 4.—Comparison of takeoff acceleration profiles between the flight test trials and the IRT test campaign, from Runyan et al. (Ref. 16).

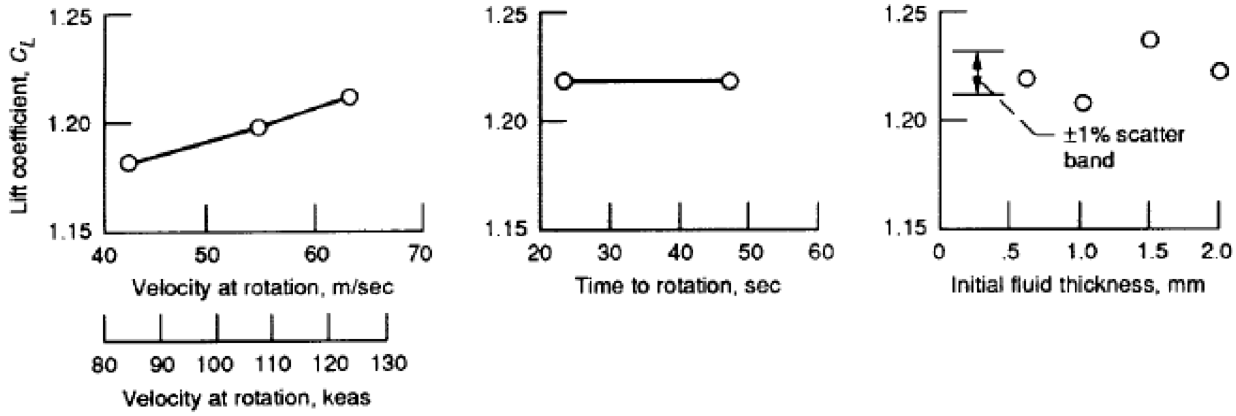

Figure 5.—Effect of acceleration parameters on lift coefficient at α_B = 7° on the 9.1 percent scale, three-dimensional half-plane B737-200ADV model with sealed slat, flaps 5 configuration, Fluid 3 at –10 °C air temperature with ground plane installed, from Runyan et al. (Ref. 16).

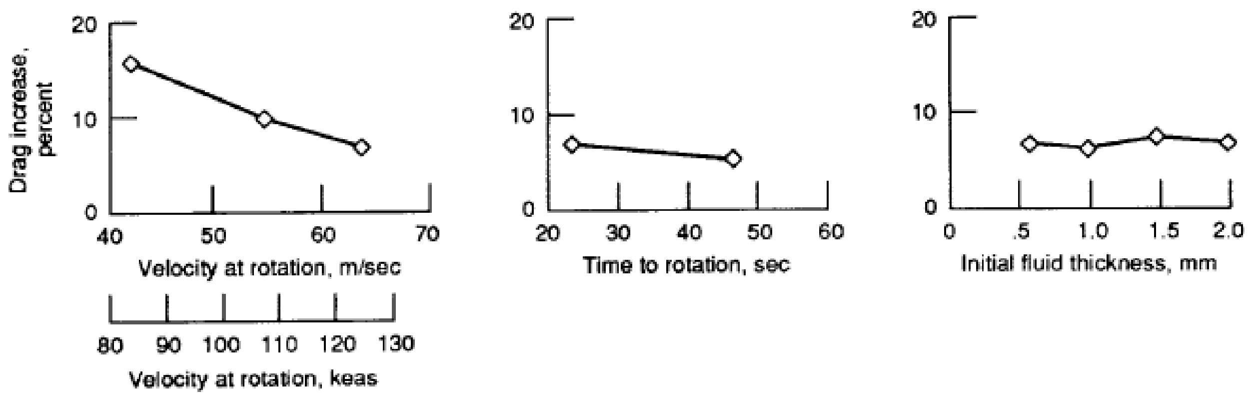

Figure 6.—Effect of acceleration parameters on percent increase in drag coefficient at α_B = 7° on the 9.1 percent scale, three-dimensional half-plane B737-200ADV model with sealed slat, flaps 5 configuration, Fluid 3 at -10 °C air temperature with ground plane installed, from Runyan et al. (Ref. 16).

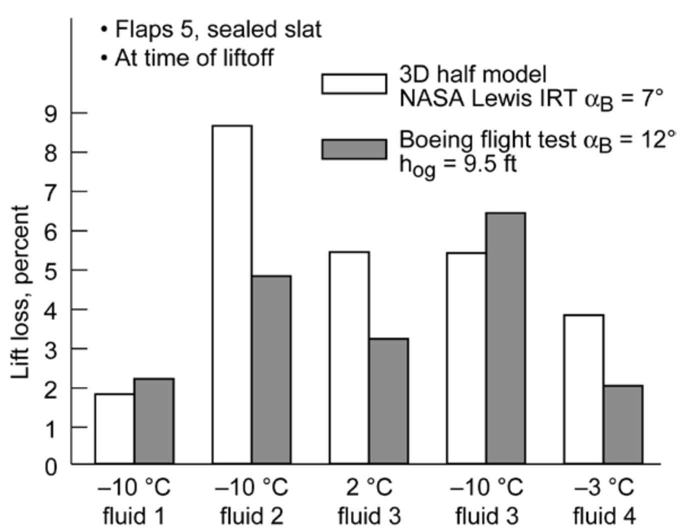

Figure 7.—Comparison of fluid effects on percent lift loss between the full-scale B737-200ADV airplane and the 9.1 percent scale, three-dimensional half-plane model in the IRT tests, from Hill and Zierten (Ref. 13).

full-scale airplane from the flight test trials and the 9.1 percent scale, three-dimensional half model in the IRT. An important note to Figure 7 is that the lift loss on the scale IRT model was calculated at $\alpha_B = 7°$ instead of the $\alpha_B = 12°$ used for the flight test data. The choice of $\alpha_B = 7°$ on the subscale model was made because this corresponded to 75 percent of the $C_{L,\max}$ on the clean model. The choice of 75 percent $C_{L,\max}$ as the comparison point was selected since the takeoff safety speed condition (one-engine-out climb) corresponds to about 75 percent of $C_{L,\max}$. Presumably, $\alpha_B = 7°$ on the subscale model was lower than $\alpha_B = 12°$ on the full-scale airplane due to Reynolds number effects. Hill and Zierten then came to this conclusion: *"Realizing the estimated ±1.5 percent data accuracy, the correlation [Figure 7] suggested that the wind-tunnel lift loss results could be extrapolated to full scale on a 1:1 basis."* The authors also go on to point out that similar results have been observed with distributed solid roughness on the wing. Therefore, the authors showed that the wind-tunnel testing of deicing/anti-icing fluids on a 9.1 percent scale, three-dimensional half-plane B737-200ADV model produced results that were comparable to the full-scale flight test without applying any scale factors or other corrections. This allowed for the expanded matrix of fluids effects testing that was conducted in the phase II IRT test campaign.

2.4 Phase II IRT Test Campaign

Having addressed the validity of the IRT testing with the three-dimensional half-plane model in Phase I, the test objectives were expanded in Phase II to include:

- Determining the effects of the fluid on maximum lift.
- Expanding the testing envelope in terms of fluids used, temperature ranges, aerodynamic and fluid-flow measurements.
- Acquisition of boundary-layer displacement thickness data that were subsequently used in the development of the AAT.

In order to accomplish these objectives further tests were conducted with the 9.1 percent scale, three-dimensional half-plane model described in previous section and illustrated in Figure 3. In addition, a two-dimensional model test set up was also introduced into the IRT test section. The two-dimensional model was an 18 percent scale (1.5 ft (0.457 m) chord) section of the B737-200ADV wing at 65 percent semispan station. It was mounted horizontally between two splitter walls as shown in Figure 8 and no ground plane was used. This section (at 65 percent semispan) was selected because it was "critical" relative to the stall progression on the baseline, clean, full-scale B737-200ADV airplane. The aerodynamic performance data were acquired from a force and moment balance mounted in the splitter walls. In addition to these measurements, the boundary-layer velocity profile was measured with a pressure rake mounted toward the aft end of the model, just upstream of the flap. The velocity profile was integrated to obtain the boundary-layer displacement thickness.

Since the flight test trials were conducted in close proximity to the ground, safety considerations prevented measurements of fluid effects near stall. That is why the lift loss results were reported at $\alpha_B = 12°$. Determining the fluid effects on maximum lift was accomplished safely in the wind tunnel and the results for a variety of fluids and air temperatures are shown in Figure 9 for the 9.1 percent scale, three-dimensional half-plane B737-200ADV model. These data show that percent lift loss was much larger at $C_{L,\max}$ that at $\alpha_w = 8°$. (Note that $\alpha_w = 8°$ corresponds exactly to $\alpha_B = 7°$) These large differences emphasized the importance of evaluating the effect of the fluids at stall. Since no full-scale data were available for the effects of the fluids on $C_{L,\max}$, it had to be assumed that the subscale model IRT results at $C_{L,\max}$ could be extrapolated to full-scale on a one-to-one basis. In further support of this assumption, Runyan et al. (Ref. 16) present aerodynamic data acquired on the 9.1 percent scale, three-dimensional half-plane B737-200ADV model with distributed solid roughness and simulated frost in the IRT. It was noted that the percent reductions in maximum lift agreed closely with flight test data for similar roughness configurations. Runyan et al. (Ref. 16) also describe a number of parametric studies designed to ascertain

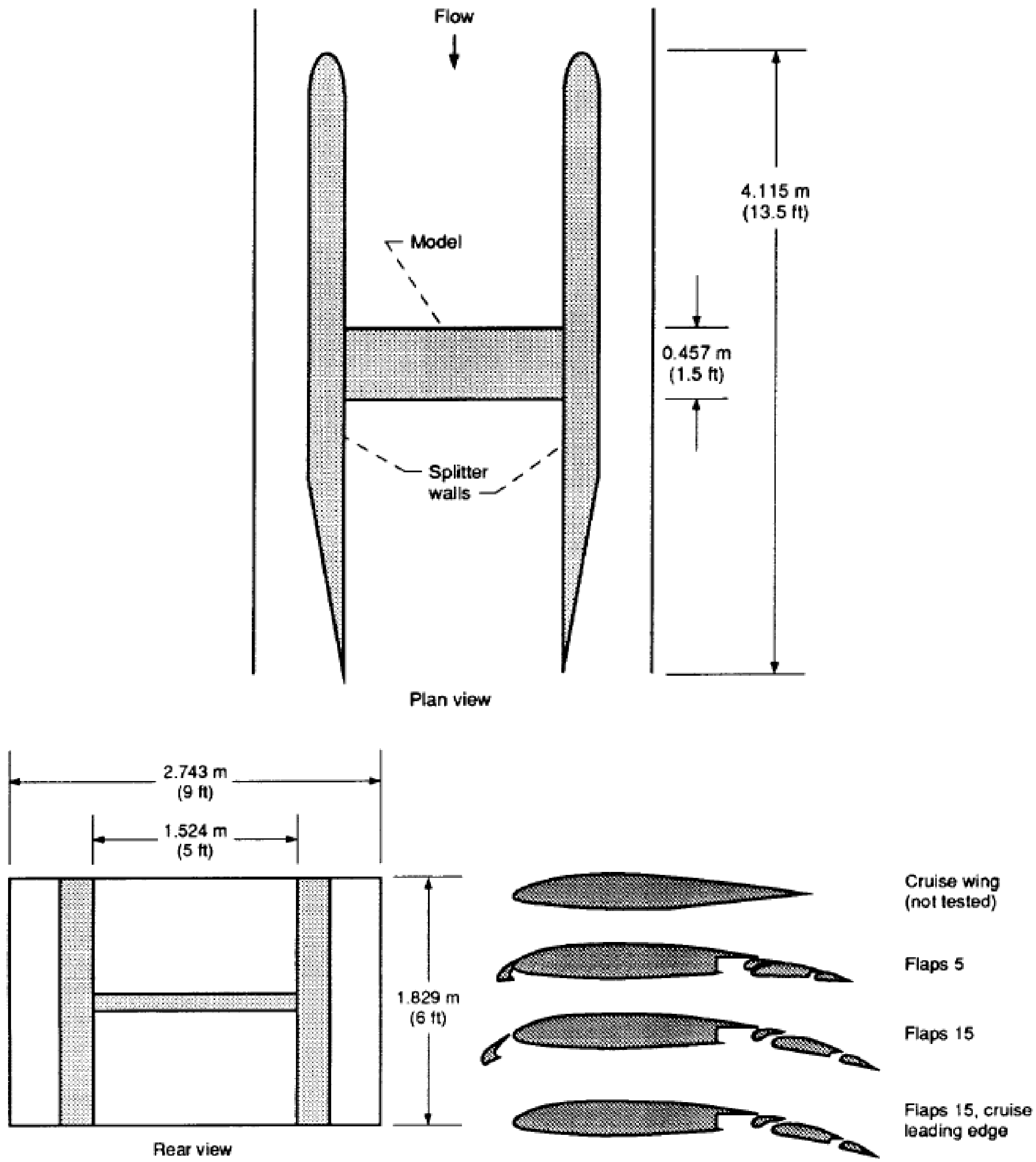

Figure 8.—18 percent scale, two-dimensional model of the B737-200ADV wing section installed in the NASA IRT, from Runyan, et al. (Ref. 16).

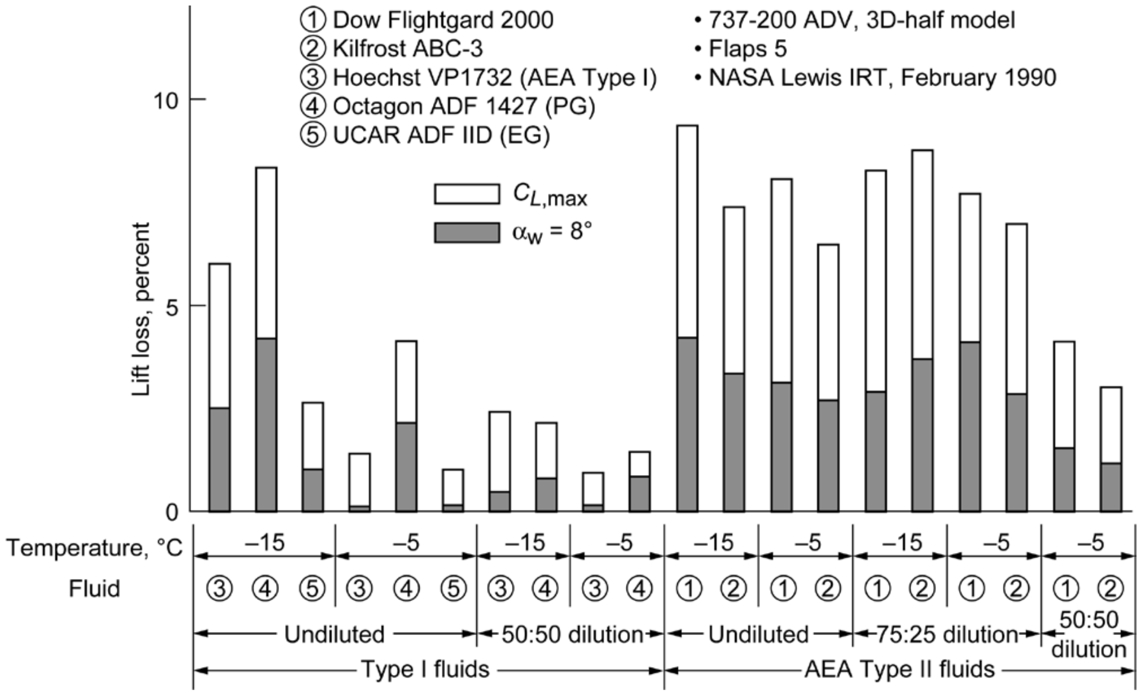

Figure 9.—Summary of the deicing/anti-icing fluid effects on percent lift loss at α_w = 8° (α_B = 7°) and at $C_{L,max}$ for the 9.1 percent scale, three-dimensional half-plane model in the NASA IRT, from Hill and Zierten (Ref. 13).

the effect of various slat and flap configurations on fluid flowoff and resulting aerodynamic performance effects. While it is beyond the scope of this report to review these results in detail, they were carefully analyzed to support the hypotheses regarding the fluid flow behavior and aerodynamic degradation.

Having concluded that the 9.1 percent scale, three-dimensional half-plane model results were representative of full-scale on a one-to-one basis, the next step was to evaluate lift degradation on the 18 percent scale, two-dimensional wing section. Numerous parametric studies were performed looking at the effects of the various fluids, air temperature and other factors. The lift degradation was measured at both α_w = 8° (α_B = 7°) and at stall. Some sample results are shown in Figure 10. Note here that $C_{l,max}$ (with lower case "*l*") is the two-dimensional sectional maximum lift coefficient. Hill and Zierten (Ref. 13) commented, *"Results shown in [Figure 10] for the two-dimensional model, indicate percentage lift losses at 8° angle of attack that are larger than those at maximum lift. This trend is different from that observed on the three-dimensional model and indicates the importance of three-dimensional testing."* Presumably, the authors meant that the importance of three-dimensional testing is relative to determining accurately the effects of the fluids at maximum lift. This is an important point because the authors conducted numerous other tests with the two-dimensional model. Runyan et al. (Ref. 16) offer a clarification on this point: *"…these two-dimensional results are useful for determining the relative fluid-to-fluid lift losses at a given temperature and temperature-to-temperature lift losses for a given fluid. However, since these are two-dimensional data, they cannot be used directly to estimate lift losses on the airplane."* Therefore, the two-dimensional model testing was useful for evaluating the relative effects of the fluids, temperature, contamination and other factors. This conclusion suggests that meaningful relative comparisons of fluid aerodynamic effects can be obtained in two-dimensional model testing. However, Hill and Zierten (Ref. 13) suggested that accurate absolute percentage lift losses were only obtained using the three-dimensional half-plane model.

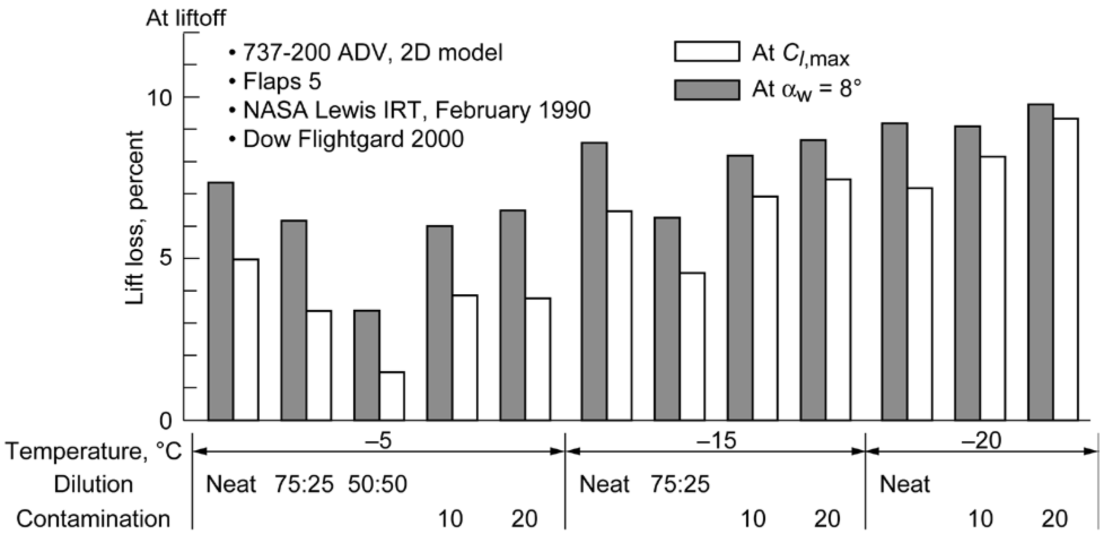

Figure 10.—Effect of fluid temperature, dilution and contamination (simulated precipitation) on lift loss at α_w = 8° and at $C_{l,max}$ for the 18 percent scale two-dimensional model in the NASA IRT, from Hill and Zierten (Ref. 13).

Through the course of this and previous investigations, hypotheses relating the fluid-flow-off behavior to the aerodynamic degradation were being developed and tested. It is beyond the scope of this review to describe these hypotheses, related experiments and observations with the exception of the hypothesis leading to the development of the AAT. Hill and Zierten (Ref. 13) suggested, *"If the hypothesis is valid that the mechanism of the fluid effect on the aerodynamics of the wing is premature growth of the boundary layer, then a correlation between the prematurely thickened boundary layer and the aerodynamic effect can be anticipated."* The authors quantified the boundary-layer displacement thickness through direct measurement and subsequent integration of the boundary-layer velocity profile. Their hypothesis was then supported by Figure 11 that illustrates the suggested correlation between the percent lift loss on the two-dimensional model at α_w = 8° and δ^* measured on the same model at the same condition. Since the data for the various fluids and air temperatures "collapse" onto the correlation curve, the conclusion is that the hypothesis is valid. Hill and Zierten continue: *"Because the two-dimensional model airfoil is the critical (relative to stall progression) 737-200ADV wing section and assuming that the thickened boundary-layer measured at 8-deg. angle of attack was an indicator of the effect of fluid at maximum lift, then an acceptable correlation between the two-dimensional model boundary-layer thickness and the three-dimensional model maximum lift loss can also be anticipated."* The suggested correlation is shown in Figure 12 that plots the three-dimensional model percent loss in maximum lift against δ^* measured on the two-dimensional airfoil model at α_w = 8° for the same fluids at the same conditions used on each model. All of the data for the various fluids at three different temperatures tend to collapse onto the curve shown in Figure 12, suggesting that the correlation is, as suggested, acceptable. Therefore, Hill and Zierten concluded that these results indicate that the fluid effects on the boundary-layer thickness (on the two-dimensional model at α_w = 8°) is an indicator of fluid effects on airplane performance.

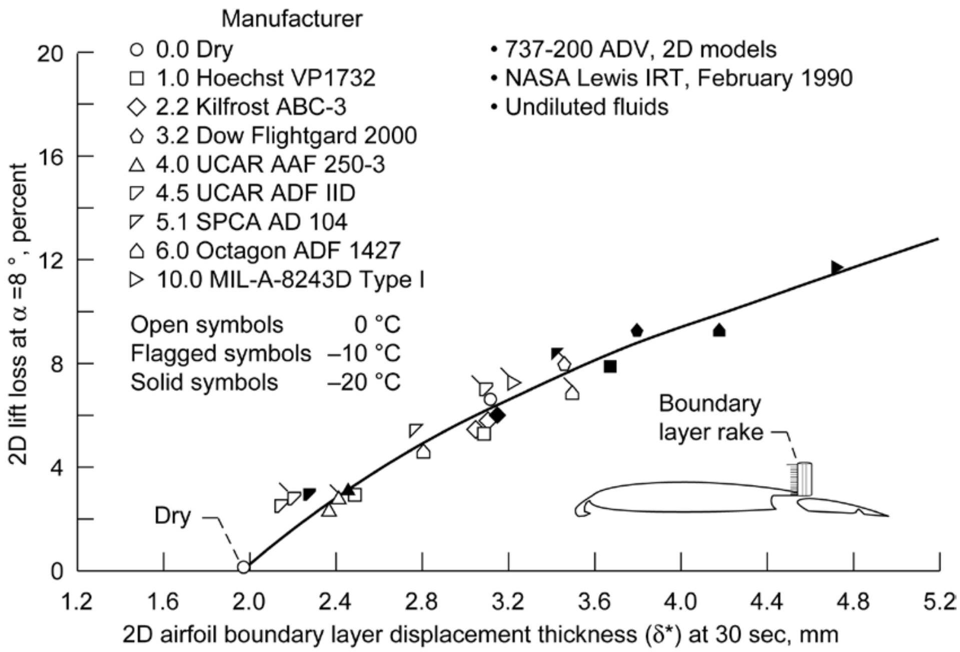

Figure 11.—Correlation between percent lift loss and boundary-layer displacement thickness as measured on the two-dimensional model at $\alpha_w = 8°$ for various fluids at air temperatures of 0, –10 and –20 °C, from Hill and Zierten (Ref. 13).

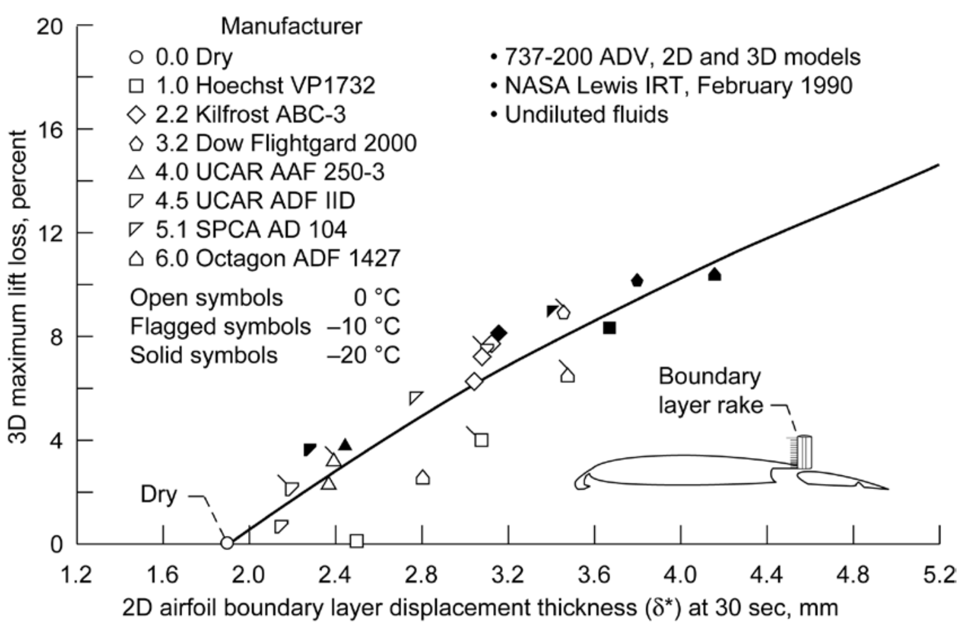

Figure 12.—Correlation between three-dimensional B737-200ADV model percent maximum lift loss and two-dimensional model boundary-layer displacement thickness at $\alpha_w = 8°$ for various fluids at air temperatures of 0, –10 and –20 °C, from Hill and Zierten (Ref. 13).

These correlations and the data plotted in Figure 11 and Figure 12 imply a direct relationship between the percent maximum lift loss measured on the three-dimensional model and the percent lift loss measured at $\alpha_w = 8°$ on the two-dimensional model for the same fluids tested on each model under identical conditions. These data were extracted from Figure 11 and Figure 12 and are plotted in Figure 13. This could be done because the δ* data plotted on the horizontal axis was common to both plots. In Figure 11, a measured value of δ* for a given fluid at a given temperature was associated with a percent lift loss on the two-dimensional model at $\alpha_w = 8°$. The same fluid at the same temperature was tested on the three-dimensional model as well, providing a specific percent loss in maximum lift. Thus, the same δ* measured in the two-dimensional test for the same fluid at the same temperature was correlated with percent maximum lift loss on the three-dimensional model, even though δ* was not measured on the three-dimensional model. The resulting correlation is shown in Figure 13 and a linear fit was constructed through the data. The *y*-intercept was forced through the origin because this is the limiting case for the dry wing. That is, the dry wing has no lift loss for either the two-dimensional or three-dimensional model, by definition. The slope of the line, 1.04 is very close to one which is consistent with the statement by Hill and Zierten that the two-dimensional wing section tested was the critical section relative to the stall progression. The data show that the implied correlation between the lift loss on the two-dimensional model at $\alpha_w = 8°$ and the maximum lift loss on the three-dimensional model was better for some fluids than for others. Note that there are three data points for each fluid corresponding to air temperatures of 0, –10 and –20 °C as in Figure 11 and Figure 12. Generally, the percent lift loss increases with decreasing temperature. The data for the Dow, UCAR AAF and SPCA fluids tend to match the correlation fairly well, whereas the data for the Hoeschst and Kilfrost fluids clearly had a different effect between the two-dimensional and three-dimensional models. This same "scatter" is represented in Figure 11 and Figure 12, however, the discrepancies do not appear to be as large due to the choice of scales on the plots. These data illustrate the potential variation in fluid behavior and their attendant effects on aerodynamic performance.

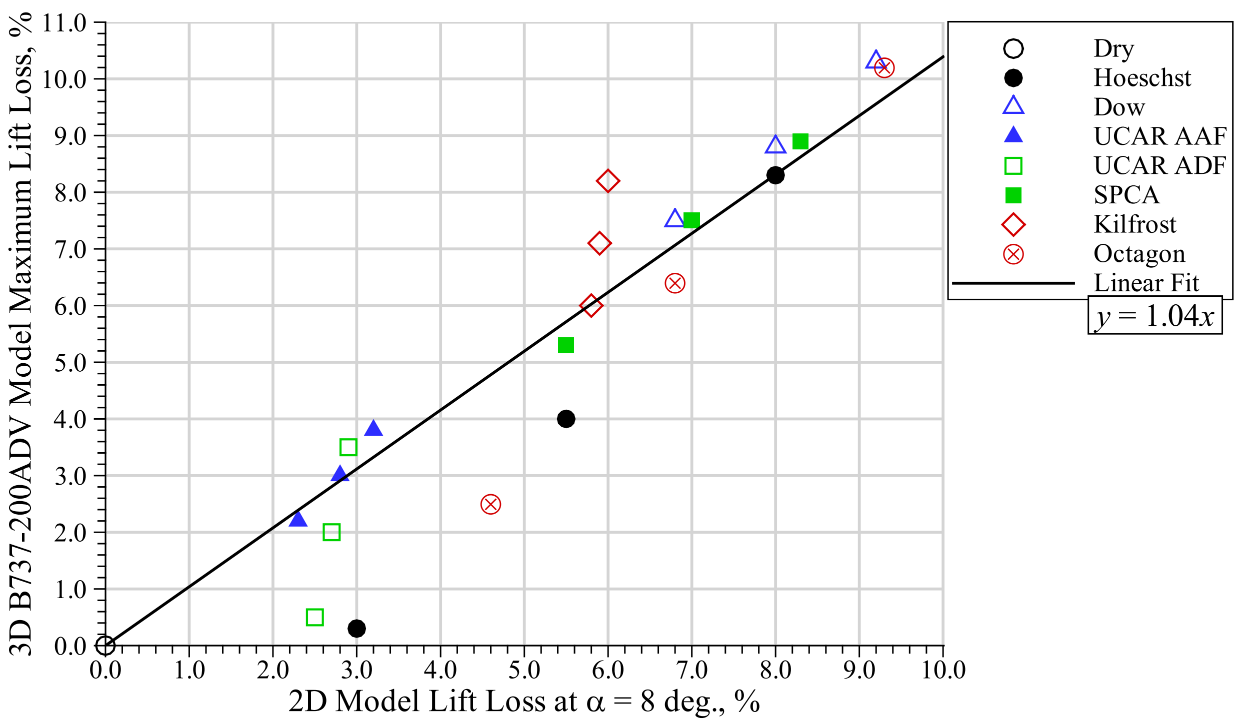

Figure 13.—Correlation between percent lift loss on the two-dimensional model at $\alpha_w = 8°$ and percent maximum lift loss on the three-dimensional B737-200ADV model for a given fluid at a given temperature in the Phase II IRT tests. Note that there are three data points for each fluid representing 0, –10 and –20 °C. Data extracted from Hill (Ref. 14)

Hill and Zierten (Ref. 13) summarized the main conclusions from both the Phase I and Phase II IRT test campaigns:

1. *"Fluid effects can be evaluated in the wind tunnel and the results can be extrapolated to full scale with reasonable confidence.*
2. *Dependent on temperature, Newtonian Type I and non-Newtonian Type II fluids produce measurable adverse aerodynamic effects.*
3. *For the B737-200ADV three-dimensional configuration, lift loss at maximum lift are greater than that at lower angles of attack.*
4. *Fluid aerodynamic effects are transitory.*
5. *The fluid effects vary with airplane configuration.*
6. *Aerodynamic effects of the fluids correlate well with boundary-layer thickening caused by the fluids.*
7. *Aerodynamic effects of the fluid vary with specific fluids and viscosity is not the only governing rheological parameter."*

2.5 Basis of the AAT

The research and findings regarding the potential transitory aerodynamic degradation due to fluids led an international working group to develop the AAT for the fluids. This working group was formed under the Aerospace Industries of America Transportation Committee and consisted of industry representatives and others members. This AIA TC 218-4 group worked with the von Karman Institute and the AEA to develop the AAT. Research performed at the von Karman Institute showed that the fluid flowoff behavior on a small flat plate in a wind tunnel capable of operational airspeeds and temperatures correlated to the flowoff characteristics observed on the two-dimensional B737-200ADV wing section tested in the NASA IRT. This correlation, plotted in Figure 14, suggests a quasi-linear relationship between the displacement thickness measured on the two-dimensional airfoil model and the flat plate testing that was conducted at the von Karman Institute.

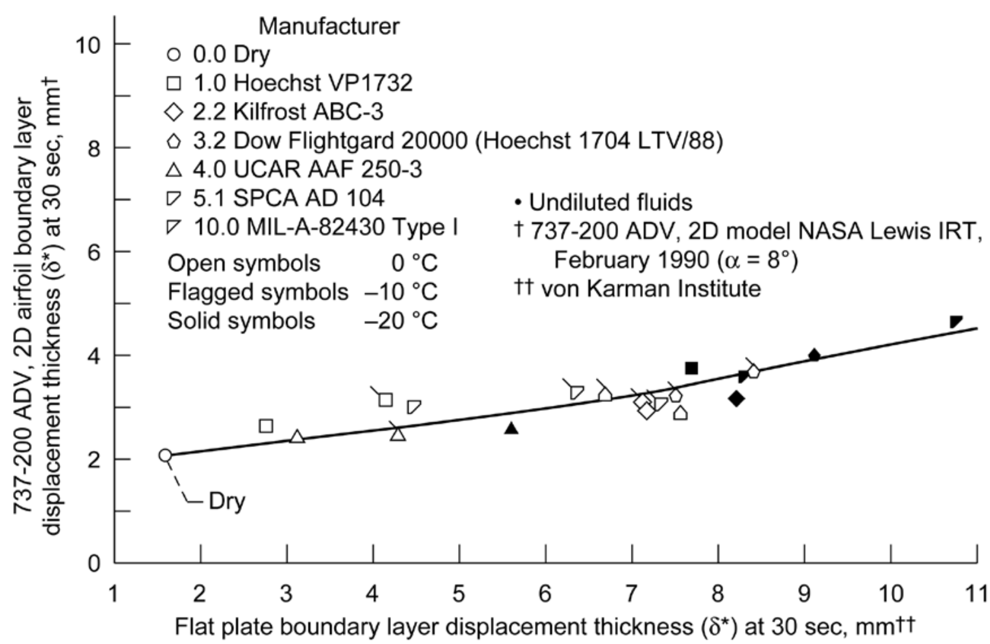

Figure 14.—Correlation between displacement thickness measured on the two-dimensional B737-200ADV wing section in the IRT and the displacement thickness measured on the flat plate in the von Karman Institute experiment, from Hill and Zierten (Ref. 13).

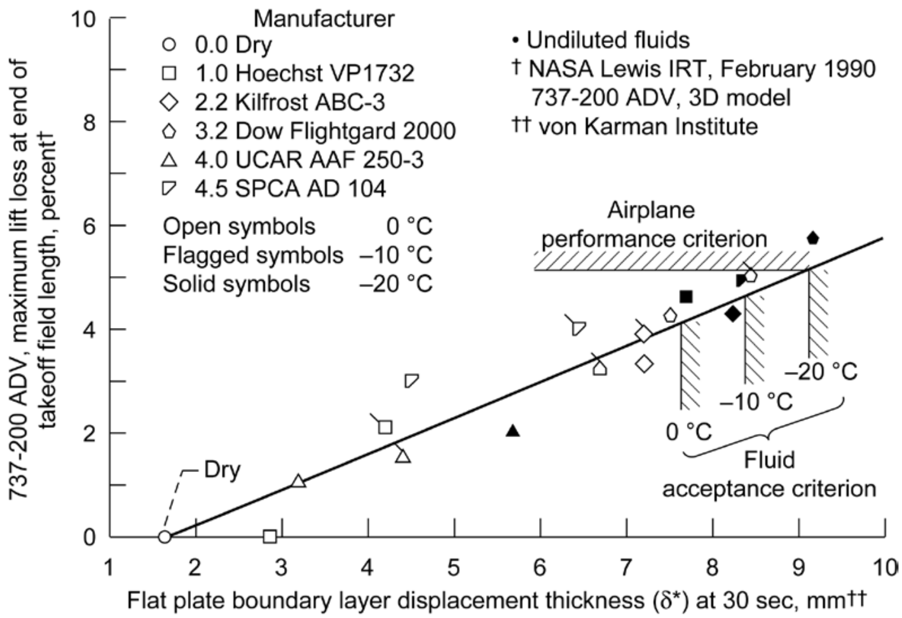

Figure 15.—Correlation between maximum lift loss on the full-scale B737-200ADV airplane and the displacement thickness measured on the flat plate at von Karman Institute, from Hill and Zierten (Ref. 13).

The typical flat-plate test apparatus and wind-tunnel requirements currently used in the AAT is detailed in Reference 12. In this case, the deicing/anti-icing fluid is applied uniformly to the horizontal floor of a rectangular duct having a width of 1.0 ft (0.3 m) and sufficient height and length to satisfy the dry-plate boundary-layer displacement thickness specifications. Operational temperatures of the plate, air and fluid are also maintained at the desired set point. The wind-tunnel airflow over the plate is accelerated to approximately 127 kn (65 m/s) in 25 s to simulate the takeoff profile. The displacement thickness is measured after 30 s at a location 5.0 ft (1.5 m) downstream from the leading edge. The displacement thickness is measured indirectly using static pressures to determine the local flow velocity, relating this to an area change and subsequently the displacement thickness. This is different from the more direct method measuring the boundary-layer velocity profile used in the IRT experiments. However, the details of the measurement methods should not affect the results if performed properly.

The series of correlations presented in Figure 11, Figure 12 and Figure 14 imply that there exists a final correlation between the maximum lift loss measured on the 9.1 percent scale three-dimensional B737-200ADV half-plane model in the IRT and the boundary-layer displacement thickness measured on the flat plate. This final correlation is shown as a linear relationship in Figure 15. To summarize, this correlation was developed through the following steps:

- Takeoff profile flight tests were performed on a B737-200ADV airplane to measure the effects of the fluid on lift. This was specifically documented at $\alpha_B = 12°$, corresponding to 75 percent of $C_{L,\max}$ on the clean, dry airplane.
- Subsequent tests performed in the NASA IRT on a 9.1 percent scale, three-dimensional B737-200ADV half-plane model using the same fluids and temperatures as in the flight tests showed that percentage lift losses at 75 percent $C_{L,\max}$ (corresponding to $\alpha_B = 7°$ on the subscale model) could be extrapolated to full-scale on a one-to-one basis (Figure 7).
- Furthermore, aerodynamic testing on subscale models and flight tests with simulated roughness and frost indicated that the percent maximum lift losses (i.e., $\Delta C_{L,\max}$) measured on the 9.1 percent scale three-dimensional B737-200ADV half-plane model could also be extrapolated to full-scale on a one-to-one basis.

- Therefore, the effect of fluids on full-scale airplane maximum lift was determined directly from IRT tests conducted on the 9.1 percent scale three-dimensional B737-200ADV half-plane model.
- IRT tests performed with the same fluids and temperatures on the 18 percent scale two-dimensional B737-200ADV wing section model showed that percent lift losses measured at $\alpha_w = 8°$ correlated with:
  - Boundary-layer displacement thickness on the 18 percent scale two-dimensional B737-200ADV wing section at $\alpha_w = 8°$ (Figure 11)
  - Percent maximum lift loss on the 9.1 percent scale three-dimensional B737-200ADV half-plane model (Figure 13).
  - Percent maximum lift loss on the 9.1 percent scale three-dimensional B737-200ADV half-plane model correlated with the boundary-layer displacement thickness on the 18 percent scale two-dimensional B737-200ADV wing at $\alpha_w = 8°$ (Figure 12).
- The displacement thickness measured on a small-scale flat plate at the von Karman Institute with the same fluids and temperatures correlated with the displacement thickness measured on the 18 percent scale two-dimensional B737-200ADV wing section at $\alpha_w = 8°$ (Figure 14).
- Therefore, the percent maximum lift losses on the full-scale B737-200ADV airplane correlated with the displacement thickness measured on the flat plate (Figure 15.)

This summarizes the development of the AAT for deicing/anti-icing fluids. The research showed that it was possible to conduct meaningful small-scale, flat-plate experiments to evaluate the potential aerodynamic effects of these fluids. The remaining step in the development of the AAT was to establish the acceptance criterion.

2.6 Fluid Acceptance Criterion

Having established a relatively low-cost and simple means of evaluating the fluid effects on performance through the flat-plate boundary-layer displacement thickness, Hill and Zierten developed an acceptance criterion based upon the allowable maximum lift penalty on the B737-200ADV airplane. This is described in References 13 and 15 and involved an evaluation five specific takeoff performance criteria following FAR 25 requirements. Hill and Zierten determined that the most critical of these five criteria was maintaining: adequate margin between the 1g stall speed and the takeoff safety speed, V_2. Hill and Zierten continue in Reference 15: *"To insure safe operation when the fluids are used, a criteria requiring V_2 speed to be $1.1V_{s1g}$ or greater was selected. The 10 percent V_2 speed margin to the 1g stall speed compares with a 13 percent margin requirement interpreted from FAR 25.107(b)(1) for the nominal dry, clean wing. For aircraft whose V_2 speed is at the minimum margin, 1.13 V_{s1g}, the acceptable lift loss resulting from the fluids is 5.24 percent.*" The algebraic analysis used to arrive at the 5.24 percent reduction in $C_{L,\max}$ is paraphrased from Reference 15:

$$V_2^{\text{Dry}} \geq 1.13V_{s1g} \tag{1}$$

$$V_2^{\text{Fluid}} \geq 1.10V_{s1g} \tag{2}$$

$$\frac{\Delta C_{L,\max}}{C_{L,\max}^{\text{Dry}}} = \frac{C_{L,\max}^{\text{Dry}} - C_{L,\max}^{\text{Fluid}}}{C_{L,\max}^{\text{Dry}}} \tag{3}$$

$$\frac{\Delta C_{L,\max}}{C_{L,\max}^{\text{Dry}}} = 1 - \frac{C_{L,\max}^{\text{Fluid}}}{C_{L,\max}^{\text{Dry}}} \tag{4}$$

$$\frac{\Delta C_{L,\max}}{C_{L,\max}^{Dry}} \leq 1 - \frac{\left(1.10V_{s1g}\right)^2}{\left(1.13V_{s1g}\right)^2} \tag{5}$$

$$\frac{\Delta C_{L,\max}}{C_{L,\max}^{\text{Dry}}} \leq 5.24\% \tag{6}$$

So, the 5.24 percent maximum lift loss ($\Delta C_{L,\max}$) defines an acceptance criterion based upon the minimum margin for the V_2 speed to $1.10V_{s1g}$. It is important to note again that this is specific to the B737-200ADV used in this development. There is reduced concern for airplanes with larger margin for the V_2 speed.

Returning to the context of the AAT, the 5.24 percent maximum lift loss criterion is shown in Figure 15 as the upper limit in lift loss and corresponding boundary-layer displacement thickness measured in the flat-plate experiment at von Karman Institute. The plot shows that the 5.24 percent cut-off correlates $\delta^* \approx 9.2$ mm for the fluid at –20 °C. Figure 15 also indicated that there are slightly lower maximum lift loss criteria for temperatures of –10 and 0 °C. Hill and Zierten (Ref. 13) explained that this was imposed because runways would be more likely to be contaminated at these warmer temperatures. Presumably the contaminated runways would also have an adverse impact on the airplane performance in addition to the presence of the deicing/anti-icing fluid. While this may be an important consideration for the AAT, it is important to realize the that reduced acceptance criteria (either in terms of $\Delta C_{L,\max}$ or δ^*) was not based upon a fluid-specific requirement, but concerns about additional adverse effects due to contaminated runways.

2.7 The AAT—Conclusions

This brief summary of the research basis of the AAT has shown how the potential adverse performance effects of deicing/anti-icing fluids on a B737-200ADV airplane were related to the boundary-layer displacement thickness measured on a flat plate. The relatively simple and low-cost flat-plate experiment has subsequently been used as a part of the qualification process for ground deicing/anti-icing fluids. As noted in the previous sections, the aerodynamic effects of these fluids are configuration dependent and can be influenced by other factors such as the takeoff speed. Quoting Hill and Zierten (Ref. 15) again, *"Compliance with the acceptance test is considered a minimum requirement since the test's acceptance criterion is derived from fluid effects on a specific aircraft design [B737-200ADV] and only considers adequate takeoff safety speed margins. An airframe manufacturer may impose additional requirements which reflect considerations for specific airplane designs and performance criteria not addressed by the acceptance test."*

3.0 Aerodynamic Evaluation of Anti-Icing Fluids in the NRC PIWT

3.1 Introduction

As described in Section 1.0, a cooperative effort among FAA, Transport Canada, NRC and APS has been undertaken to develop allowance times for ice-pellet conditions. The aerodynamic testing of the fluids with and without contamination was conducted at the PIWT facility on the NRC Montreal Road campus in Ottawa. One of the criteria used to evaluate the effectiveness of the fluid protection is the lift loss caused by the fluid/contamination as measured in the wind tunnel. The use of a lift loss performance criterion requires the establishment of some threshold value above which some safety level would be exceeded. (Such a threshold was developed for the AAT as described in Sec. 2.6.) Since the testing has employed a generic, thin, high-performance wing section, it is unclear what the appropriate lift loss threshold should be. Some means of relating the wind-tunnel model lift degradation to a real airplane configuration is needed in order to determine a reasonable lift loss threshold. This is important because of the potential operational safety implications associated with the measured performance degradations due to contaminated fluids.

It has been suggested that the measured lift loss due to the uncontaminated fluid in the PIWT tests can be compared to the B737-200ADV lift loss that is related to the AAT (as will be explained in this section). This approach provides a means to "scale" the measured lift degradation in the PIWT tests to equivalent maximum lift degradation on a full-scale B737-200ADV airplane. As reviewed in Section 2.5, Hill and Zierten (Ref. 13) showed that two-dimensional airfoil percent lift loss and boundary-layer displacement thickness correlated with the three-dimensional model maximum lift loss. Therefore, the thin, high-performance PIWT wing model lift loss may be correlated with the AAT results for tests with the same uncontaminated fluids at the same temperatures. Since the AAT results are directly related to percent maximum lift loss on the B737-200ADV airplane this correlation can be applied to establish an equivalent lift loss threshold for the thin, high-performance wing model in the NRC PIWT tests.

The purpose of this section is to demonstrate how this analysis was carried out. Samples of the fluids used during the 2010 and 2011 PIWT test campaigns were subjected to the AAT as described in Reference 12 at the University of Quebec at Chicoutimi Anti-Icing Materials International Laboratory (AMIL). The AAT was performed over temperature ranges that closely matched those used in the PIWT test campaigns. For each fluid, the boundary-layer displacement thickness variation with temperature was quantified according to the Reference 12 procedures. An analysis was then performed to determine the relationship between the measured AAT boundary-layer displacement thickness, the PIWT model percent lift degradation for the fluid and the corresponding percent maximum lift loss on the B737-200ADV airplane. This analysis was used to define a lift loss threshold for evaluating the fluid performance on the model in the PIWT test. This procedure and results are described in the Sections 3.3, 3.4, and 3.5. The experimental methods used in the PIWT tests are described first in Section 3.2.

3.2 PIWT Test Experimental Methods

The experimental methods used to evaluate the performance of fluids in the uncontaminated state and with ice-pellet contamination has been described elsewhere, so only a brief overview is given here. For example, Clark and MacMaster (Ref. 17) also provide a detailed description of the test set up, procedures and results. The PIWT is an open-return wind tunnel that draws air from the outdoors and is therefore naturally cooled. The fan is located in the wind-tunnel inlet and was driven by a gas turbine engine for these test campaigns. The test section measures 10 ft (3 m) across and 20 ft (6 m) in height. For these tests an insert was used that reduced the height to 16.4 ft (5 m) resulting in an increase in maximum test section speed. A two-dimensional airfoil section was mounted horizontally in the test section as shown in Figure 16. The model had a span of 7.9 ft (2.4 m) and was isolated from the wind-tunnel walls with end plates. Due to the large gaps between the end plates and the test-section walls (≈ 1 ft (0.3 m) on each side) and the small size of the end plates, the model installation is quasi-two-dimensional. Figure 17 shows the 6 ft (1.8 m) chord, thin, high-performance wing section with single-slotted flap deflected at 20°. The model had a fixed (or "hard") leading edge and was regarded as typical of wings on regional jet transport airplanes. The model was supported by a force balance at each end located outside of the test section walls. A drive motor and gearbox connected to the force balance provided the rotation for setting angle of attack. The lift data and angle of attack were corrected for wind-tunnel wall effects using the 2D airfoil methods described in Rae and Pope (Ref. 18).

Data from a typical simulated takeoff run are shown in Figure 18. Plotted is the model lift coefficient versus time. These data were acquired by accelerating the test section airflow from 20 kn (10.3 m/s) to 100 kn (51.4 m/s) in less than 31 s. The model was rotated from $\alpha_w = -2°$ to 8° when the speed reached 100 kn. The rotation rate was 2.7°/s. The wing was held at 8° for 1.5 s to gather more data at this angle of attack, then the angle was reduced. This was a typical profile. In other runs, the angle of attack was increased through stall along with other variations in rotation speed and time. The large rate of increase in C_l in Figure 18 corresponds to the model rotation from –2° to 8° angle of attack. During post processing, the C_l vs. α_w data were extracted and plotted as shown in Figure 19. There are data for three

Figure 16.—Photographs of thin, high-performance wing model installed in the NRC PIWT facility.

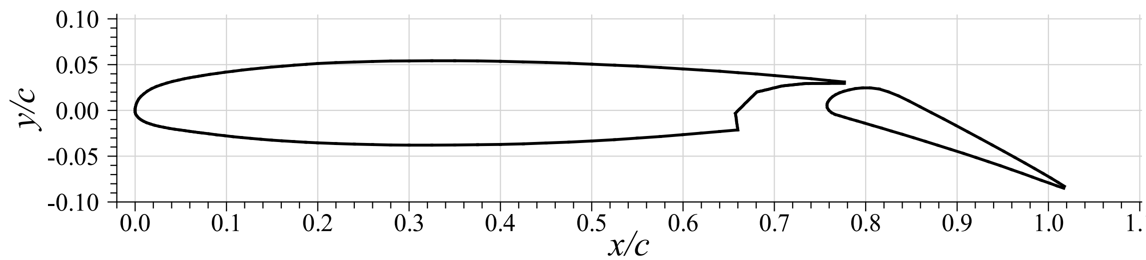

Figure 17.—Thin, high-performance airfoil section used in the PIWT testing, reference chord = 6.0 ft (1.8 m).

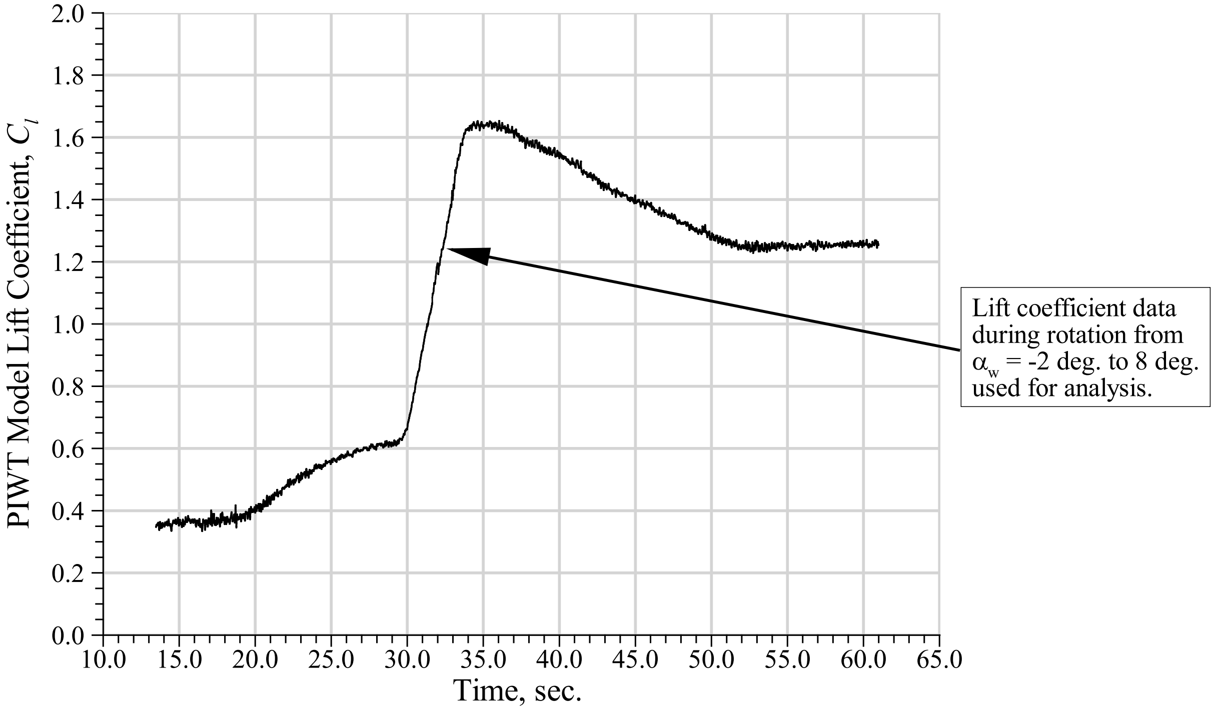

Figure 18.—Sample lift coefficient vs. time profile for the simulated takeoff acceleration and wing rotation used in the PIWT tests.

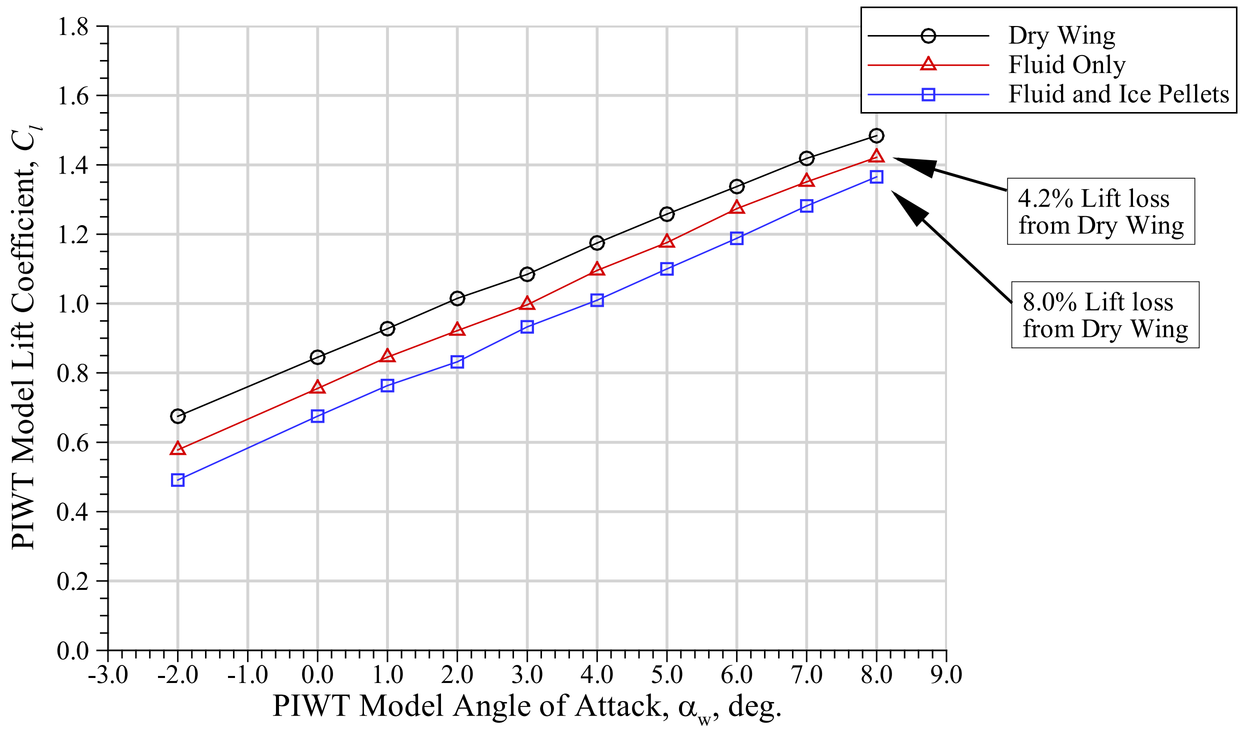

Figure 19.—Sample lift coefficient versus angle of attack data for three configurations—dry wing, uncontaminated fluid only and fluid with ice-pellet contamination.

configurations: the dry wing, the wing with uncontaminated fluid only and the wing with fluid plus ice-pellet contamination. These data illustrate typical deicing/anti-icing fluid effects on lift. The lift curves for the fluid only and fluid with ice pellets are shifted below and to the right of the "Dry Wing" lift curve. This effect is due to the presence of the fluid and contamination on the wing upper surface. The effect is to reduce the wing camber causing a shift in the zero-lift angle of attack. This effectively makes the profile more symmetric—and a symmetric airfoil has zero lift at zero angle of attack. The fact that the lift curves appear to be nearly parallel is not uncommon in fluids testing and has been reported in other studies (Ref. 16). It was determined that the percent lift loss on the model would be evaluated at $\alpha_w = 8°$. As shown in Figure 19, the fluid only configuration resulted in a 4.2 percent loss in lift from the dry wing at $\alpha_w = 8$ °. The addition of ice pellets to the fluid resulted in a further reduction in lift coefficient of 8.0 percent from the dry wing configuration. The objective of the analysis described in this report is to determine the significance of these percent lift loss values relative to a full airplane configuration.

3.3 Summary of 2010 and 2011 Uncontaminated Fluid Tests at NRC PIWT

A series of simulated takeoff runs were performed in both 2010 and 2011 PIWT test campaigns for uncontaminated fluid applied to the model. Many other runs were performed for contaminated fluids, but are not discussed in this report. For each simulated takeoff, the percent lift loss from the clean or dry wing was evaluated at $\alpha_w = 8°$ as described in Section 3.2. These data are summarized as a function of the test temperature in Figure 20. There were five different fluids tested:

- ABC-S Plus manufactured by Kilfrost,
- EG106 manufactured by Dow Chemical,
- AD-49 manufactured by Dow Chemical,

- Launch manufactured by Clarient,
- Max-Flight manufactured by Octagon Process.

Of these, all are PG fluids except for EG106 which is an EG fluid. The data show the expected variation of PIWT model lift loss measured at $\alpha_w = 8°$ with test temperature. In general, the percent lift loss increases with decreasing temperature. It was noted that EG fluids tend to flow off more readily than PG fluids, explaining the lower lift losses in Figure 20 for the EG106 fluid. It is important to note that all of these fluids are qualified fluids and as such, have passed the AAT. The variation in percent lift loss characteristics is due to the differences in the various fluids and the resulting flowoff behavior.

3.4 Summary of AAT Results

Samples of the fluids tested during the 2010 and 2011 PIWT test campaigns were sent to AMIL at University of Quebec at Chicoutimi. These fluids were tested according to the procedures for the high-speed ramp of the AAT. This procedure is described in detail in Reference 12 and was summarized in Section 2.5. The test temperature range was selected to correspond to the range used in the PIWT test campaigns that was illustrated in Figure 20. The AAT test results for these fluid samples is shown in Figure 21. The upper limit of boundary-layer displacement thickness at –20 °C ($\delta^* = 9.74$ mm) was determined according to Reference 12. The plot shows that all of the fluids tested passed the AAT since all of the δ^* data lie below the upper limit of 9.74 mm. The fluid samples tested were taken from the same batch used for the PIWT testing thereby eliminating any potential variations due to the manufacturing tolerances of the fluids. In the case of the Launch fluid, the same batch was used for both 2010 and 2011 test campaigns. The data presented in Figure 20 and Figure 21 were subsequently used to relate the PIWT model lift loss to the lift loss on a B737-200ADV airplane using the latter's relationship to the AAT.

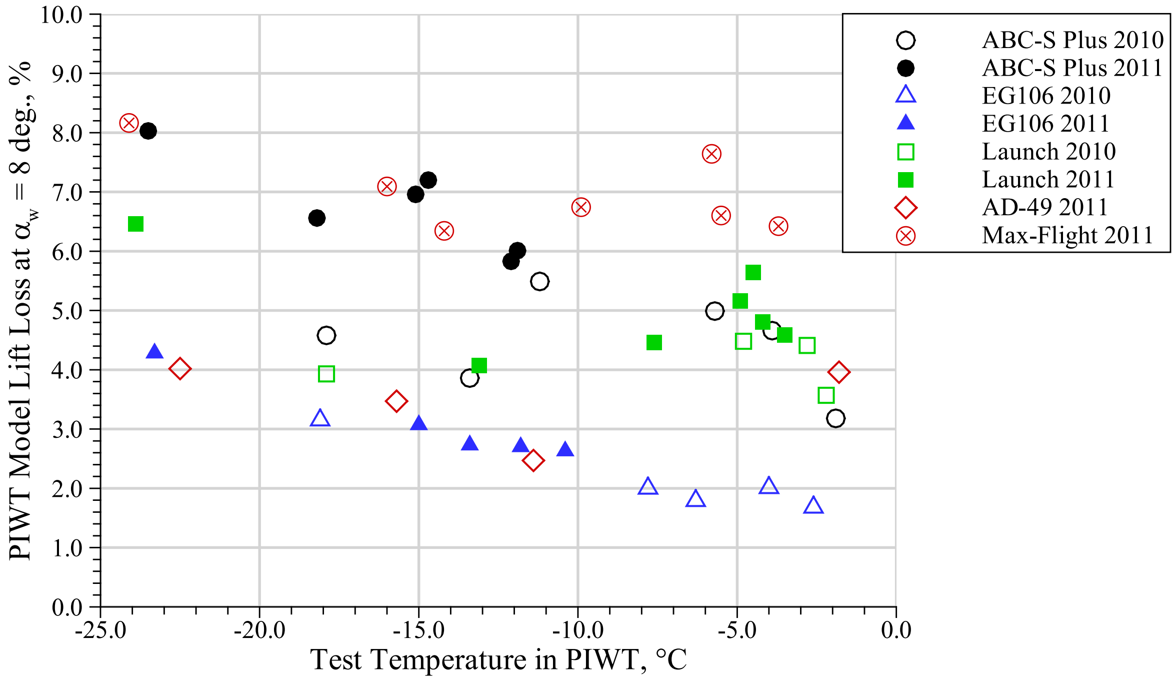

Figure 20.—Summary of uncontaminated fluid tests for PIWT test campaigns in 2010 and 2011.

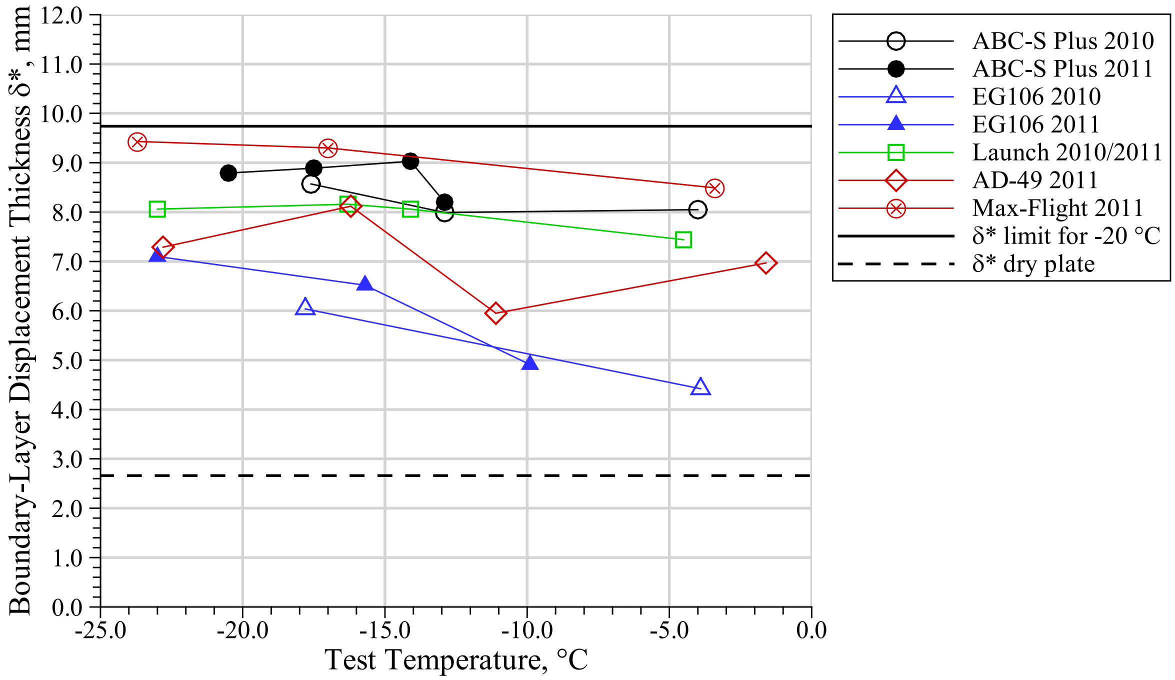

Figure 21.—Summary of AAT results for fluid samples used in the 2010 and 2011 PIWT test campaigns.

3.5 Establishment of a PIWT Model Lift Loss Criterion Via the AAT

As described in Section 2.5 (cf. Figure 15), the results of the AAT relate directly to the maximum lift loss on the B737-200ADV airplane. It is therefore possible to use the results of the AAT to relate the lift loss measured on the PIWT model to the maximum lift loss on the B737-200ADV airplane. The first step in the process was to associate values for displacement thickness with the temperatures used in the PIWT testing by two-point interpolation or extrapolation employing the temperatures and displacement thicknesses from the AAT results (cf. Figure 21). This step accounts for the fact that the test temperature of the runs conducted in the PIWT (cf. Figure 20) were not identical to the test temperatures for the AAT results (Figure 21). For example, three AAT runs were performed with the EG106 2011 fluid batch at temperatures of –9.9, –15.7 and –23.0 °C (cf. Figure 21). These temperatures and measured values of δ* are shown in Table V. The PIWT fluid tests using the same EG106 2011 batch were conducted at temperatures of –10.4, –11.8, –13.4, –15.0 and –23.3 °C. Two-point linear interpolation was performed to associate the δ* values with the PIWT temperatures. Since the PIWT test temperature of –23.3 °C was slightly lower than the AAT temperature value of –23.0 °C, a linear extrapolation was performed for this case using the nearest two temperatures (–15.7 and –23.0 °C). The PIWT temperatures and associated displacement thickness values are listed in Table VI. The same process was followed for the other fluids. The associated δ* values are plotted against the PIWT test temperatures in Figure 22.

TABLE V.—AAT RESULTS FOR
EG106 2011 FLUID BATCH

AAT test temperature, °C	Displacement thickness (δ*), mm
–9.9	4.91
–15.7	6.52
–23.0	7.10

TABLE VI.—DISPLACEMENT THICKNESS VALUES
CORRECTED FOR TEMPERATURE FOR PIWT
TEST OF EG106 2011 FLUID BATCH

PIWT test temperature, °C	Interpolated displacement thickness (δ*), mm
–10.4	5.05
–11.8	5.44
–13.4	5.88
–15.0	6.33
–23.3	7.12

Hill and Zierten (Ref. 13) suggested that there is a linear relationship between the maximum lift loss on the B737-200ADV airplane and the AAT boundary-layer displacement thickness. This line is shown in Figure 15 and is given by:

$$\Delta C_{L,\max} = 5.24\% \left[\frac{\delta^*_{\text{fluid}} - \delta^*_{\text{dry}}}{\delta^*_{l\,@-20\,^\circ C} - \delta^*_{\text{dry}}}\right] \quad (7)$$

This equation was used to calculate maximum lift loss on the B737-200ADV airplane using the data in Figure 22. As shown in Figure 22, all of the displacement thickness values are known:

- δ^*_{fluid} is given for each fluid batch as a function of test temperature;
- δ^*_{dry} is given from the AAT data, = 2.66 mm;
- $\delta^*_{l\,@\,-20\,^\circ C}$ is given from the AAT data, = 9.74 mm.

Using these data, all of the corresponding values for the B737-200ADV maximum lift loss were calculated for each fluid tested in the PIWT at each temperature and the resulting data are plotted in Figure 23. As noted previously in this section, all of these fluids passed the AAT so all maximum lift loss values lie below the 5.24 percent limit as indicated in Figure 23. The form of the data in Figure 23 is similar to that in Figure 22 because of the linear relationship given in Equation (7).

This analysis has generated the data required to relate the lift losses measured on the thin, high-performance wing model in the PIWT to the B737-200ADV maximum lift loss implied by the AAT. The PIWT model lift losses measured at $\alpha_w = 8°$ were plotted against test temperature in Figure 20 for tests with the fluids shown in the plot legend. The B737-200ADV airplane maximum lift losses were obtained from the AAT for the same fluids at the same test temperatures as shown in Figure 23. Therefore, the common independent variable of test temperature can be eliminated between Figure 20 and Figure 23 to yield a correlation between the B737-200ADV maximum lift loss and the PIWT model lift loss measured at $\alpha_w = 8°$. This correlation is shown in Figure 24 and reflects the appropriate trend of increasing B737-200ADV maximum lift loss for increasing PIWT model lift loss measured at $\alpha_w = 8°$. This plot is analogous to that shown in Figure 13 relating B737-200ADV three-dimensional model maximum lift losses to the lift losses on the corresponding two-dimensional model at $\alpha_w = 8°$. In both plots (Figure 13 and Figure 24) there is considerable scatter in the data that is indicative of the differences in the fluid flowoff

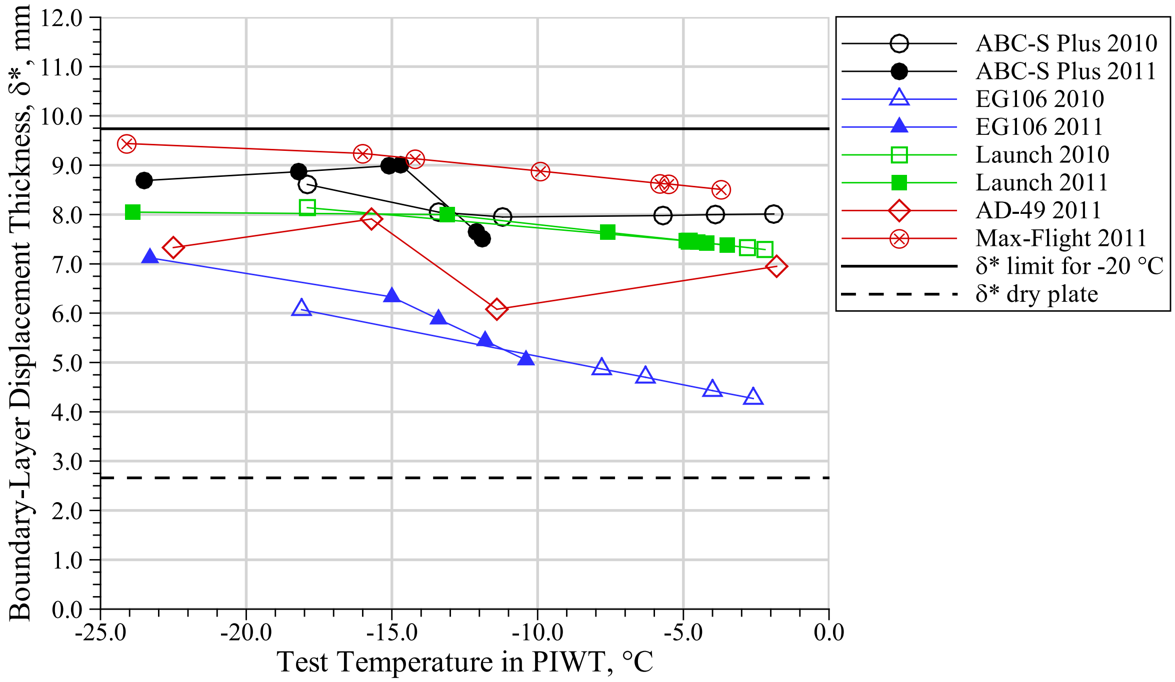

Figure 22.—Boundary-layer displacement thickness values associated with PIWT test temperatures.

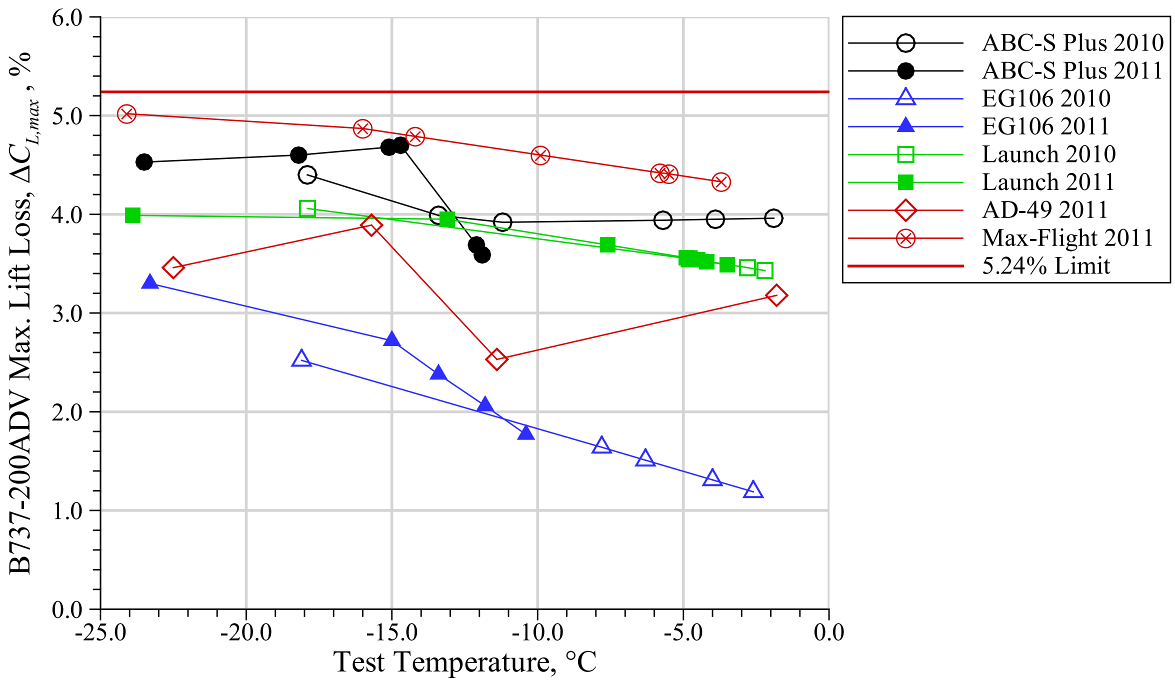

Figure 23.—B737-200ADV maximum lift loss for the PIWT test temperatures calculated using AAT data shown in Figure 22 using Equation (7).

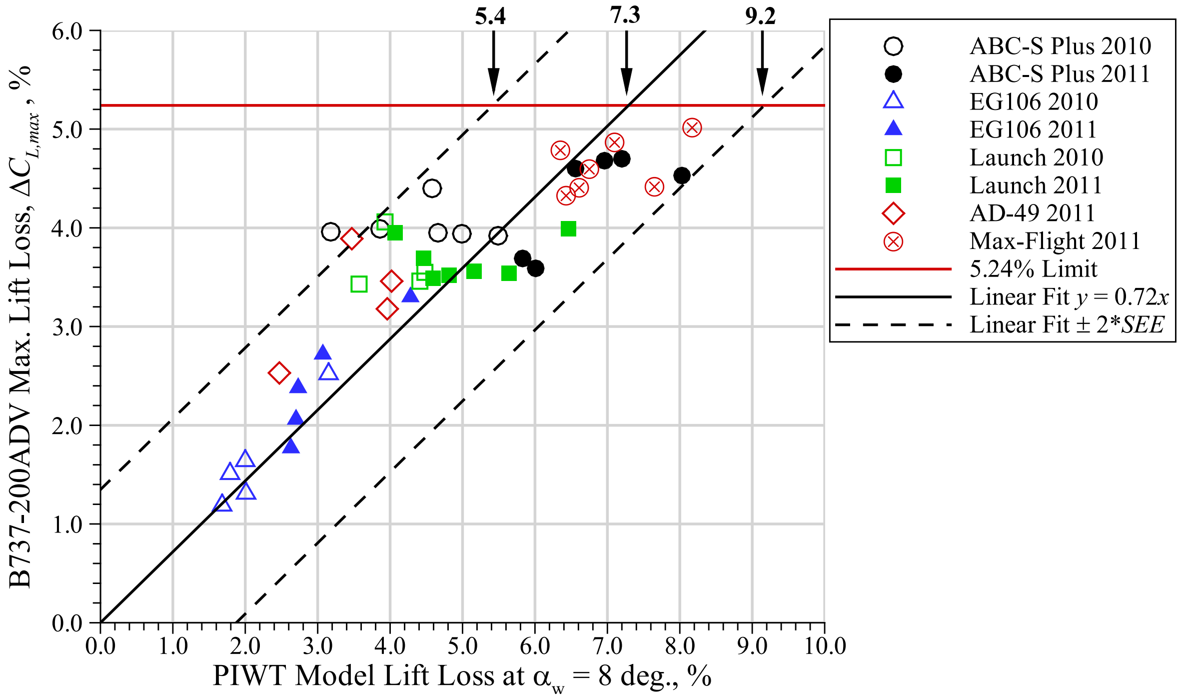

Figure 24.—Correlation between percent lift loss on the PIWT model at α_w = 8° and percent maximum lift loss on the three-dimensional B737-200ADV airplane for the uncontaminated fluid tests.

characteristics and resulting performance penalties. A linear regression curve fit was performed on the data in Figure 24. The regression was forced through the origin since this corresponded to the dry wing for each configuration. The percent lift loss on the dry wing was 0, by definition. The regression line had a slope = 0.72 whereas the slope in Figure 13 was 1.04. The most likely explanation for the difference in these slopes is that the thin, high-performance wing section used in the PIWT test had significantly different aerodynamic characteristics than the "critical" section of the B737-200ADV wing. There are other differences as well, such as the speed at model rotation, between the two tests. Therefore some difference in these slopes is expected. The data indicate that a $\Delta C_{L,\max}$ of 5.24 percent on B737-200ADV airplane is equivalent to a lift loss of 7.3 percent on the PIWT model measured at α_w = 8°. It is therefore suggested that an appropriate lift loss threshold for the tests conducted on the PIWT model is 7.3 percent measured at α_w = 8° since this is equivalent to a $\Delta C_{L,\max}$ of 5.24 percent on B737-200ADV airplane.

It is clear from inspection of Figure 24 that some means of accounting for the scatter in the data is needed. Furthermore, establishing an absolute lift loss threshold of 7.3 percent neglects the three data points in Figure 24 that have a PIWT model lift loss measured at α_w = 8° greater than 7.3 percent. These cases should not fail the criterion because they are qualified fluids having passed the AAT. Chapra and Canale (Ref. 19) define the *Standard Error of the Estimate* (*SEE*) as a means of quantifying the data spread about the linear regression line and is given by:

$$SEE = \sqrt{\frac{\sum_{i=1}^{N}(y_i - 0.72x_i)^2}{N-2}} \tag{8}$$

The *SEE* is a measure of the "goodness of fit" based upon the sum of the residuals about the regression line. For the data in Figure 24, *SEE* = 0.67 and has "units" of the *y*-variable—B737-200ADV airplane percent maximum lift loss. Plotted in Figure 24 are lines representing ±2**SEE* deviations from the linear regression line and all but two of the data points fall between these lines. In addition, the upper bound (+2**SEE*) captures the three PIWT data points with lift loss greater than 7.3 percent but have still passed the AAT. Therefore, it seems prudent to establish a lift loss threshold up to 9.2 percent for the PIWT model lift loss at $\alpha_w = 8°$. Since the evaluation of the fluid performance with ice-pellet contamination is also based upon visual observations of flowoff and failure, specifying a range of lift loss can help identify cases that may need more careful evaluation of the visual observations. For example, if the PIWT measured lift loss at $\alpha_w = 8°$ is greater than 7.3 percent, but less than 9.2 percent, then the fluid performance may still be acceptable based upon visual observations. However, if the PIWT measured lift loss at $\alpha_w = 8°$ is greater than 9.2 percent, this should be grounds for rejection since the upper limit has been surpassed. Additional data may result in future adjustments to the proposed criterion.

4.0 Comments on PIWT Model Tests and Results

As stated in Section 1.0, the dissemination of the PIWT test results with the thin, high-performance wing model and the subsequent changes to the ice-pellet allowance time tables have led to concerns regarding the fidelity and applicability of the measured lift degradation. Given the potential operational safety implications associated with the measured performance degradations, it is even more important that these concerns be addressed appropriately. The essence of these concerns is understanding how the performance degradations measured on the model in the NRC PIWT testing relate to an actual three-dimensional, full-scale airplane configuration. The review of the research basis of the AAT and the subsequent analysis in Section 3.0 was conducted to address the following specific concerns:

- A two-dimensional model with endplates was used instead of a three-dimensional geometry more representative of an airplane wing.
- Lift degradations were measured at $\alpha_w = 8°$ on the two-dimensional model instead of at stall.
- Airplanes undergoing take-off accelerations and rotation experience ground effects that were not simulated in the PIWT testing.
- The chord Reynolds number was small relative to most airplane wing sections.
- The 6-ft (1.8 m) chord length model is small relative to most airplane wing sections.
- The large model size and proximity of the wind-tunnel walls resulted in uncorrectable effects on the aerodynamic data and performance.
- The rotation speed used in the PIWT tests was low relative to typical airplane rotation speeds.

Interestingly, all but the last two of these concerns were also raised in the development of the AAT and were addressed by Hill and Zierten (Ref. 13) and Runyan et al. (Ref. 16). The experimental methods used in the aerodynamic evaluations of fluids in the PIWT closely follow the methods used in the two-dimensional model testing during the development of the AAT. Hill and Zierten (Ref. 13) and Runyan et al. (Ref. 16) showed the usefulness and applicability of two-dimensional model testing. In both research efforts, lift losses on the two-dimensional model were evaluated at an angle of attack well below stall. The PIWT model lift data were analyzed at $\alpha_w = 8°$. At this low angle of attack, the flow on the model was two dimensional based upon observations of the fluid flow. So analyzing the lift data at $\alpha_w = 8°$ minimized any three-dimensional effects and wall effects that may increase in magnitude with increasing angle of attack above 8°. In both research efforts, the wind-tunnel testing was performed without a ground plane (for the two-dimensional model). In the AAT research, the two-dimensional model was very small (1.5 ft (0.305 m) chord) relative to the full-scale wing. The small size of the wing meant that the chord Reynolds number ($\approx 1.5\times10^6$ at rotation) was also very low. The PIWT model was larger (6 ft chord) and therefore higher Reynolds numbers ($\approx 7.0\times10^6$ at rotation) were obtained in the wind tunnel. The effect of Reynolds number on aerodynamic performance of airfoils is usually insignificant above 6.0×10^6. This "critical" Reynolds number is much lower with any type of leading edge contamination on the wing (Refs. 20 to 23). The AAT research indicated model scale and Reynolds number effects were negligible—down to the small values used in that work. Therefore, the present PIWT model scale and Reynolds number should not introduce any additional concerns.

There is little reason for concern about the model size and wind-tunnel walls resulting in large and uncorrectable solid and wake blockage effects that would adversely affect the aerodynamic data. The model chord to test-section height ratio was 0.37, which is less than 0.40—the value recommended as the reasonable upper limit for two-dimensional model testing for accurate values of maximum lift (Ref. 24). Since the model was not oversized relative to the tunnel height, the effects of the walls should be minimal. These effects should be similar for all of the test runs and therefore should not affect the relative comparisons. Furthermore, wind-tunnel wall effects become more significant at higher angles of attack and lift coefficient approaching maximum lift. So measuring the PIWT model lift loss at $\alpha_w = 8°$, well below maximum lift, also mitigated these effects.

There are some differences between the B737-200ADV research effort used to develop the AAT and the present PIWT model research effort. However, these differences in the experimental methods, such as model size, geometry, installation and Reynolds number, should be accounted for in the correlation presented in Figure 24. This discussion has shown that the concerns listed at the beginning of this section do not compromise the applicability of the AAT scaling methodology for PIWT model lift loss. The PIWT testing was carried out in a manner consistent with the methods used in the AAT research and with standard wind-tunnel testing methods. The possible exception is the lower rotation speed, addressed in the following paragraph.

In the PIWT model tests, the speed at model rotation was limited to 100 kn (51.4 m/s) by the capabilities of the wind-tunnel facility. In the "high-speed ramp" procedures currently used for the AAT, the simulated rotation speed is 127 kn (65 m/s) (Ref. 12). This value is very similar to the rotation speed of 120 to 125 KEAS (62 to 64 m/s) that was used in the flight test trials and wind-tunnel testing on the B737-200ADV for the development of the AAT (Refs. 13 and 16). A similar rotation speed range was used in the Falcon 20 trials described in Section 1.0. The effect of rotation speed on lift coefficient was shown in Figure 5 and is significant. Higher rotation speeds resulted in higher lift coefficient, which in turn means lower percent lift loss due to the fluid. The relationship between rotation speed and lift coefficient appears to be linear over the range shown in Figure 5. If this relationship is linear, then the primary effect of low rotation speed on the PIWT aerodynamic data may already be accounted for in the "scaling" analysis described in the previous section. The low rotation speed in the PIWT tests could partly explain the lower slope of the regression line plotted in Figure 24. However, more data may be required to completely ameliorate this concern.

There are additional concerns not included in the list at the beginning of this section. For example, the AAT was developed prior to the current widespread use of Type IV anti-icing fluids, such as those used in the PIWT tests. If adjustment to the AAT acceptance criteria were required for Type IV fluids, then this may affect the proposed "scaling" methodology applied to the PIWT data. Beisswenger et al. (Ref.25) performed a series of flat-plate fluid tests comparing flowoff characteristics that showed similar behavior between Type II and Type IV fluids. The authors are unaware of any corresponding aerodynamic evaluation that would help confirm similarities between Type II and Type IV fluid effects and further research may be required.

Another concern that may be introduced by the proposed "scaling" methodology relative to the development of the ice-pellet allowance times is that the visual observations of the fluid flowoff and associated evaluation are still based upon the aerodynamics of the thin, high-performance wing while the lift loss criterion has been scaled to the effect on the full-scale B737-200ADV airplane. This represents some type of mixed evaluation that may or may not affect the development of the allowance times. For example, a key difference in the model geometries is that the B737-200ADV model had a leading-edge slat while the PIWT model had a hard leading edge. Hill and Zierten (Ref. 13) noted this "configuration dependency" in their work. It is unclear that similar ice-pellet contamination testing on the B737-200ADV model would lead to similar allowance times. Finally, it may be worthwhile revisiting the fluids research on commuter aircraft that was conducted shortly after the B737-200ADV IRT test campaigns, described in References 26 and 27. This may help to further mitigate concerns about the present PIWT model tests and results due to a higher degree of similarity in the model configurations and rotation speeds.

5.0 Summary and Conclusions

The FAA has worked with Transport Canada and others to develop allowance times for aircraft operations in ice-pellet precipitation. Wind-tunnel testing has been carried out to better understand the flowoff characteristics and resulting aerodynamic effects of anti-icing fluids contaminated with ice pellets. This testing has taken place at the National Research Council of Canada's Propulsion and Icing Wind Tunnel (PIWT) using a nominally two-dimensional wing with a thin, high-performance section and single-element slotted flap. The model, with either uncontaminated anti-icing fluid or fluid contaminated with simulated ice-pellet precipitation, was subjected to a simulated takeoff through rotation. Evaluation of the fluid performance was determined from visual observations of the flowoff and evaluation of the model lift degradation. The percent lift loss on the PIWT model was calculated at 8° angle of attack and used as one of the evaluation criteria in determining the allowance times in recent testing. The dissemination of the wind-tunnel testing results and subsequent changes to the ice-pellet allowance time tables led to concerns regarding the fidelity and applicability of the measured lift degradation in fluid testing at the NRC PIWT. Given potential operational safety implications associated with the measured performance degradations, it was important that these concerns be addressed. This report addresses these concerns and shows that the lift loss in the PIWT can be related to the loss in maximum lift of a Boeing 737-200ADV airplane through the Aerodynamic Acceptance Test (AAT) performed for fluids qualification.

The AAT was developed as a simple and relatively low-cost method to evaluate deicing and anti-icing fluids. Fluid samples are tested on a small, horizontal, flat plate at operational air temperatures and simulated takeoff speeds. The measured boundary-layer displacement thickness due to the fluid was shown to be directly proportional to the loss in maximum lift on a B737-200ADV airplane. Fluids with AAT displacement thickness values corresponding to less than 5.24 percent maximum lift loss are considered acceptable. Fluid samples used in the PIWT model testing were subjected to the AAT to develop the relationship for those samples between displacement thickness and B737-200ADV maximum lift loss. Samples of these same fluids were tested at the same temperatures on the thin, high-performance wing model in the PIWT and lift losses were determined at 8° angle of attack. This permitted the development of a correlation between the PIWT model lift loss at 8° angle of attack and lift loss at maximum lift on the B737-200ADV airplane.

The analysis presented in this report shows that a maximum lift loss of 5.24 percent on the B737-200ADV airplane corresponds to a lift loss of 7.3 percent for the thin, high-performance wing at $\alpha_w = 8°$ in the PIWT. There is significant scatter in the data used to develop the correlation related to varying effects of the various anti-icing fluids that were tested and other factors. A statistical analysis indicated that the upper limit of lift loss on the PIWT model was 9.2 percent. Therefore, a range of lift loss from 7.3 to 9.2 percent on the thin, high-performance wing at $\alpha_w = 8°$ in the PIWT suggests that extra scrutiny of the visual observations is required in evaluating fluid performance with contamination and establishing the allowance times. For example, if the PIWT model lift loss at $\alpha_w = 8°$ is greater than 7.3 percent, but less than 9.2 percent, then the fluid performance may still be acceptable based upon visual observations. However, if the PIWT model measured lift loss at $\alpha_w = 8°$ is greater than 9.2 percent, this should be grounds for rejection since the upper limit has been surpassed.

This review of the research basis of the AAT and the subsequent PIWT model analysis has shown that any differences such as model size, geometry, installation and Reynolds number, are accounted for in the correlation presented in Figure 24. Furthermore, this report shows that concerns about the thin, high-performance wing model testing in the PIWT do not compromise the applicability of the AAT scaling methodology for PIWT model lift loss determined at 8° angle of attack. The PIWT testing was carried out in a manner that was consistent with the methods used in the AAT research and with standard wind-tunnel testing methods. There are, however, some remaining concerns such as rotation speed, applicability to Type IV fluids and model configuration that could be addressed in future research.

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