SAE INTERNATIONAL

AEROSPACE RECOMMENDED PRACTICE

ARP6852™ REV. D

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Superseding ARP6852C

Methods and Processes for Evaluation of Aerodynamic Effects of SAE-Qualified Aircraft Ground Deicing/Anti-Icing Fluids

RATIONALE

Text clarification at 4.4.3.2.1.2 to better representing industry practices.

New reference from FAA added.

Inclusion of middle speed ramp at 3.3.2, and wording harmonization with AS5900. Notes referring to development history of high-speed, low-speed, and middle-speed ramps added.

Minor editorial corrections.

Change in title of Figure A1.

FOREWORD

The qualification processes for SAE fluids are described in ARP5718 and the standards, including aerodynamic standards, with which the fluids must comply are given in AMS1424 (Type I) and AMS1428 (Types II, III, and IV). These standards require that the aerodynamic performance of all fluids be tested and qualified in accordance with AS5900. The purpose of the AAT is to ensure that new fluids have aerodynamic performance properties that are not worse than an established, accepted standard. In this way, the AAT provides a general screening of the aerodynamic effects of the fluids. Even with successful AAT qualification, however, there can be circumstances which require evaluation of the aerodynamic effect of the fluids on specific aircraft.

The intent of this SAE Aerospace Recommended Practice (ARP) is to provide guidance for the evaluation of aerodynamic effects of fluids on aircraft, if it is determined that an evaluation is required to ensure safe operation of an aircraft with fluids applied. This ARP describes previously used methods and methods under development. To evaluate fluid effects on a particular model, it should typically not be necessary to utilize more than one method described in this ARP; however, depending upon the circumstances, it may be advantageous to do so (e.g., similarity analysis combined with CFD).

The recommended practices and other information described herein are limited to the experiences of the members of the SAE G-12 ADF Aerodynamics Working Group. Thus, this ARP is not intended to be an exhaustive discussion of information from all possible sources. Should users of this ARP, or other entities with relevant experience, have additional recommendations or revision suggestions, they are encouraged to contact the SAE G-12 ADF Aerodynamics Working Group.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) describes methods that are known to have been used by aircraft manufacturers to evaluate aircraft aerodynamic performance and handling effects following application of aircraft ground deicing/anti-icing fluids (“fluids”), as well as methods under development. Guidance and insight based upon those experiences are provided, including:

- Similarity analyses.
- Icing wind tunnel tests.
- Flight tests.
- Computational fluid dynamics and other numerical analyses.

This ARP also describes:

- The history of evaluation of the aerodynamic effects of fluids.
- The effects of fluids on aircraft aerodynamics.
- The testing for aerodynamic acceptability of fluids for SAE and regulatory qualification performed in accordance with AS5900.
- Additionally, Appendices A to E present individual aircraft manufacturers’ histories and methodologies which substantially contributed to the improvement of knowledge and processes for the evaluation of fluid aerodynamic effects.

NOTE: This document is applicable for fluids that are “qualified” (i.e., have passed) to the tests and other standards prescribed in AMS1424 or AMS1428, and are properly used in accordance with AS6285.

NOTE: There are topics of potential interest not discussed in this document, such as re-hydrated gel residues (see 2.2).

CAUTION: The results and conclusions of the various test programs described herein should not be assumed to be universally applicable.

CAUTION: All methodologies presented in this ARP were created or developed considering solely glycol-based fluids.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AMS1424 Fluid, Aircraft Deicing/Anti-Icing, SAE Type I

AMS1424/1 Deicing/Anti-Icing Fluid, Aircraft SAE Type I Glycol (Conventional and Non-Conventional) Based

AMS1424/2 Deicing/Anti-Icing Fluid, Aircraft SAE Type I Non-Glycol Based

AMS1428 Fluid, Aircraft Deicing/Anti-Icing, Non-Newtonian (Pseudoplastic), SAE Types II, III, and IV

AMS1428/1 Fluid, Aircraft Deicing/Anti-Icing, Non-Newtonian (Pseudoplastic), SAE Types II, III, and IV Glycol (Conventional and Non-Conventional) Based

AMS1428/2 Fluid, Aircraft Deicing/Anti-Icing, Non-Newtonian (Pseudoplastic), SAE Types II, III, and IV Non-Glycol Based

ARP5718 Qualifications Required for SAE Type II/III/IV Aircraft Deicing/Anti-Icing Fluid

AS5900 Standard Test Method for Aerodynamic Acceptance of AMS1424 and AMS1428 Aircraft Deicing/Anti-Icing Fluids

AS6285 Aircraft Ground Deicing/Anti-Icing Processes

2.1.2 Other Documents and Publications

1. "Adverse Aerodynamic Effects Attributed to Old AEA Formulation (1987-88) Type II De-Ice/Anti-Ice Fluids," Advisory Notice No. 34, Boeing Canada, de Havilland Division, 1988.

2. "Aerodynamic Acceptance Test for Aircraft Ground Deicing/Anti-Icing Fluids," Document No. D6-55573, The Boeing Company, 1992.

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2.2 Definitions and Abbreviations

2.2.1 Definitions

HOLDOVER TIME (HOT): The time that anti-icing fluid is expected to prevent the formation of frozen contamination on the treated surfaces of an aircraft.

LOWEST OPERATIONAL USE TEMPERATURE OF A FLUID (LOUT): The lowest operational use temperature (LOUT) is the higher (warmer) of (a) the lowest temperature at which the fluid meets the aerodynamic acceptance test (according to AS5900) for a given type (high speed or low speed) of aircraft, or (b) the freezing point of the fluid plus the freezing point buffer of 10 °C (18 °F) for Type I fluid and 7 °C (13 °F) for Type II, III, or IV fluids.

THICKENED FLUID(S): SAE Types II, III, and IV, containing polymer thickeners for extended anti-icing protection relative to Type I; governed by AMS1428.

2.2.2 Abbreviations

AAT	aerodynamic acceptance test
AEA	Association of European Airlines
AFM	Airplane Flight Manual
AGL	above ground level
AIA TC	Aerospace Industries of America - Transport Committee
AMIL	Anti-Icing Materials International Laboratory, University of Quebec at Chicoutimi, Quebec, Canada
AMS	Aerospace Material Specification
AOA	angle-of-attack
AOM	aircraft operations manual
APU	auxiliary power unit
AS	Aerospace Standard
BLDT	boundary layer displacement thickness
CD	drag coefficient
Cf	coefficient of friction
CFD	computational fluid dynamics
CG, cg	center of gravity
cl	2D lift coefficient
CL	3D lift coefficient
clmax	2D maximum lift coefficient
CLmax	3D maximum lift coefficient
DGPS	differential global positioning system

ECS	environmental control system
FAA	United States Federal Aviation Administration
FWP	flight working paper
g	gravitational constant
HOT	holdover time
HP	pressure altitude
HSR	high-speed ramp
ITT	interstage turbine temperature
JAA	Joint Aviation Authorities
k_s	sand grain roughness
kts	knots
LAAT	lowest acceptable aerodynamic temperature
LOUT	lowest operational use temperature of a fluid
LSR	low-speed ramp
MAC	mean aerodynamic chord
NAE	National Aeronautical Establishment
NASA IRT	NASA Icing Research Tunnel, Glenn Research Center, Cleveland, OH, USA
NASA	National Aeronautics and Space Administration (USA)
NS2D	2-dimensional Navier-Stokes CFD code
OAT	outside air temperature
OEI	one engine inoperative
TCCA, TC	Transport Canada Civil Aviation
TDC	Transportation Development Centre, Canada
USC	United States Code of Federal Regulations
V2	takeoff safety speed
VMC	minimum control speed
VMU	minimum unstick speed
VR	rotation speed
VS1g	1-g stall speed

3. DEICING/ANTI-ICING FLUIDS AND THEIR EFFECT ON AERODYNAMICS

3.1 Deicing/Anti-Icing Fluid Types

The SAE Standards categorize fluids as Type I, II, III, or IV. The fluids are qualified to one of two SAE Standards, depending upon their physical performance. Type I fluids are qualified to AMS1424 and are Newtonian fluids. Historically, Type I fluids have essentially been mixtures of glycol, water, surfactants, dye, and corrosion inhibitors. More recently, Type I fluids utilizing freezing-point depressants other than glycol have been introduced. Type I fluids provide very limited holdover time (HOT).

Types II, III, and IV fluids are qualified to AMS1428 and are non-Newtonian, pseudo-plastic fluids. This means that as the shear stress on them increases, their viscosity decreases, so that they flow off as the airplane speed increases during takeoff ground roll. These fluid types contain thickening polymers which facilitate the fluid maintaining greater thickness on the airplane surfaces following application, thereby providing longer HOTs than Type I fluids. Type II fluids were developed to satisfy the desire for longer HOTs than are provided by Type I fluids. Type IV fluids were developed after Type II fluids to further lengthen HOTs. Most recently developed were Type III fluids, which provide longer HOTs than Type I fluids while maintaining acceptable aerodynamic effects for commuter-type aircraft with low takeoff rotation speeds, although they may be permitted on other types as well.

3.2 Aerodynamic Impacts

The application of fluids removes frozen contamination and/or prevents frozen contamination from forming on aircraft surfaces, maintaining “clean” surfaces. In this context, “clean” means that there is no frozen contamination adhering to the surfaces. However, the fluids themselves interfere with the boundary layer, disturbing the airflow over the surfaces and reducing their aerodynamic efficiency. The aerodynamic effects of fluids are transitory and decrease as the fluid flows off of the surfaces during taxi, ground roll, rotation, and climb. The wave roughness of the fluid surface introduced by the flow-off has a variety of adverse aerodynamic consequences. The thickened fluids (Types II, III, and IV) do not flow off of the surfaces as easily or completely as Type I fluids, and therefore thickened fluids have greater aerodynamic impacts.

It has been demonstrated that with wing leading-edge thermal anti-icing systems that can be operated on the ground, thickened anti-icing fluids on the leading edges may become dehydrated by the heat, affecting both the anti-icing protection capability and the aerodynamic properties of the fluid. It is recommended that such systems not be operated on the ground when Type II, III, or IV fluids have been applied.

3.2.1 Effects on Aerodynamic Performance

The presence of fluid on aircraft lifting surfaces reduces the lift generated by those surfaces. The adverse effect on lift is correlated to the boundary layer displacement thickness (BLDT). The BLDT is affected by the shearing of the fluid from the surface and the roughness introduced by the fluid flow-off surface waves.

At the time of rotation, not all of the fluid (particularly thickened fluid) has departed the aircraft surfaces, and the act of rotation results in additional fluid wave motion. The resulting lift loss during liftoff and initial climb can be measurable and may be significant. As a consequence, to maintain safe takeoff margins, it may be necessary to increase takeoff speeds.

The most critical point during a takeoff should be considered. The most critical point occurs at the maximum angle of attack achieved between liftoff and reaching initial climb speed (typically between V2 + 10 kts and V2 + 20 kts). Where it occurs depends in general on wing stall characteristics, high-lift configuration, fuselage geometry, rotation speed, initial climb speed, and time to accelerate to rotation speed and initial climb speed:

- The wing stall characteristics (leading-edge stall versus trailing-edge stall) and high-lift configuration determine how the effect of fluid varies as a function of angle of attack. The effect is very complex, but can be generalized as follows:
    - A wing with leading-edge stall characteristics is very sensitive to fluid on the leading edge and less affected by fluid aft of the leading edge. The lift decrease due to fluid is often constant at all angles of attack, and CLmax might be unaffected, but could be strongly affected.

- A wing with trailing-edge stall characteristics is sensitive to fluid on the leading edge and also to fluid aft of the leading edge. In this case, the boundary layer thickness gradually increases with increasing angle of attack until local flow separation occurs. The lift decreases due to fluid increases (more or less linear) with increasing angle of attack, and CLmax is often strongly affected.

- The high-lift configuration (leading-edge slats and/or trailing e-edge flaps) influences the local flow and thus changes the local effect of fluid. A conclusion from the Boeing 737-200ADV testing (see Appendix A; also refer to Reference 41) was that for a high-lift configuration with leading-edge devices, the fluid effect is largest at the maximum lift condition.

- If the aircraft is geometry-limited, then the rotation angle is limited to avoid a tail strike. In that case, a lower maximum angle of attack is reached during the rotation than if the aircraft was not geometry-limited. This should be considered when determining the most critical point.

- Speed and time to accelerate to rotation speed have an important effect on the fluid flow-off. Lower speed and shorter time means less fluid flow-off and thus more fluid remaining on the wing.

During the takeoff ground roll, continuing throughout rotation, liftoff, initial climb, and beyond, more and more fluid shears off of the wing, thus decreasing the aerodynamic effects caused by the fluid on the wings. This is referred to as the fluid effects being transient. Current data suggests that the fluid's transient behavior is similar for different types of aircraft. Examples include test data for the Boeing 737-200ADV, shown in the plot below from Reference 26 (also Reference 24 and possibly others), Saab 2000 (see Figure 2), and Bombardier Dash 8 (see Figure E4).

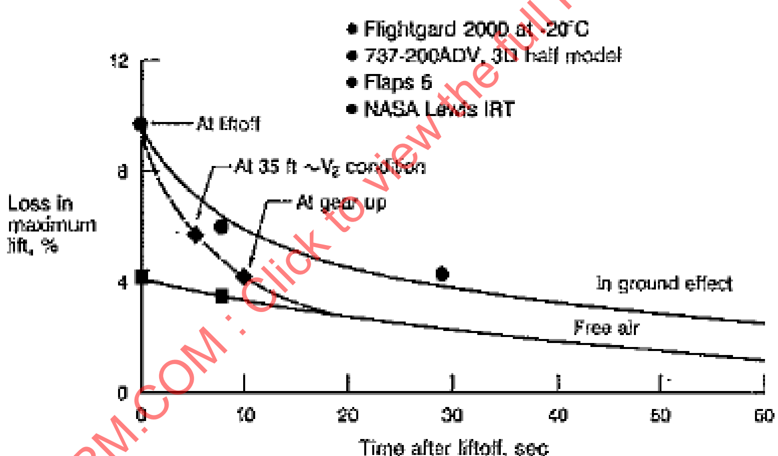

Figure 1 - Maximum lift loss variation with time (B737-200ADV)

The presence of fluids on the aircraft also increases drag, but the overall effect of this on aircraft takeoff performance has generally been found to be insignificant.

Aerodynamic effects typically increase with decreasing OAT due to the increase in fluid viscosity and the consequent increase in the time that it takes for fluid to flow off.

3.2.2 Effects on Handling Qualities

Most aircraft that have conducted testing have not exhibited noticeable fluid effects on lateral control; some have experienced detrimental, but acceptable, effects.

Some aircraft with unpowered pitch control surfaces have experienced rotation difficulties during takeoff due to increased stick/column forces that can be caused by the aerodynamic effects of fluids on the elevator and horizontal tail.

Several theories have been postulated for aircraft with unpowered pitch control surfaces, for example:

- It has been shown that fluids can flow down through the gap between the stabilizer and elevator and contaminate the leading edge of the elevator on the lower side with fluid roughness, affecting hinge moments.

- Fluid has also been observed to accumulate on top of the elevator balance nose during the takeoff ground roll. This fluid suddenly flows through the gap when the elevator is deflected for takeoff rotation, which can result in flow reversal and separation on the lower side of the elevator. This will affect the elevator control force, especially when the elevator is equipped with gear or spring tabs and may also reduce the effectiveness of the elevator.

- Another theory is that the fluids may partially obstruct air from flowing through the gaps between the stabilizer and elevator and/or elevator and tab, decreasing elevator and/or tab effectiveness.

As a result of the associated change in the hinge moment characteristics by flow separation, the sudden increase of force gradient will feel like the elevator has hit the stop and available elevator deflection seems insufficient for takeoff at a normal takeoff speed.

Increased rotation speeds or a decrease in takeoff flap setting, which also results in increased rotation speeds and times, has alleviated these effects on some aircraft. For the Mitsubishi YS-11, it was found that applying fluid to the lower surface of the horizontal tail eliminated the rotation difficulties.

A caution to be noted with regard to elevator and tab hinge moment effects is that every airplane model has a different configuration and different dependencies. Therefore, the physics and aerodynamics of the fluid behavior that have resulted in these rotation difficulties may also be different for each model. It would be misleading and potentially erroneous to assume that the cause(s) associated with increased rotation forces for one model are the same for other models.

3.3 AS5900 - the Aerodynamic Acceptance Test

3.3.1 History of the Aerodynamic Acceptance Test

See Appendices A and B for a description of research and testing that resulted in development of the aerodynamic acceptance test (“AAT”), AS5900.

3.3.2 Testing Conducted per the AAT

The AAT attempts to determine the aerodynamic acceptability of fluids relative to airplane lift loss. It measures the effect of the fluid on the boundary layer displacement thickness (“BLDT”) on a flat plate. To ensure safe operation when a fluid is used, V2 speed must be at least 1.10 VS1g. This requirement results in a maximum acceptable lift loss due to the fluid of 5.24% for a large jet aircraft and 8% for a commuter-type aircraft with wing-mounted propellers.

The test set-up consists of a duct inserted in the test section of a refrigerated wind tunnel. In this tunnel, the airflow and fluid can be maintained at a constant temperature, between 5 °C ± 1 °C and -45 °C ± 2 °C. The AAT protocol begins with applying a 2 mm layer of fluid to cover the duct floor. The fluid is then subjected to an accelerating air flow, simulating one of the following takeoff profiles:

- Large jet transport-type aircraft (high-speed ramp test):

  - BLDT is calculated from the static pressures measured in the tunnel and is the average of the measures between the 27th and the 33rd seconds after the beginning of the test.

  - The high-speed ramp test is used to evaluate fluids to be used on airplanes with takeoff rotation speeds exceeding 100 kts, with time from brake release to rotation speed greater than 20 seconds and time to lift-off greater than approximately 25 seconds. This is a general takeoff scenario for large jet aircraft.

- Large turbo-prop aircraft (middle-speed ramp test):
    - BLDT is calculated from the static pressures measured in the tunnel and is the average of the measures between the 20th and the 22nd seconds after the beginning of the test.
    - The middle-speed ramp test is used to evaluate fluids to be used on airplanes with takeoff rotation speeds between 80 kts and 100 kts, with time from brake release to rotation speed between 16 seconds and 20 seconds. This is a general takeoff scenario for large turbo-prop aircraft.
- Propeller-type commuter aircraft (low-speed ramp test):
    - BLDT is calculated from the static pressures measured in the tunnel and is the average of the measures between the 19th and 21st seconds after the beginning of the test.
    - The low-speed ramp test is used to evaluate fluids to be used on airplanes with takeoff rotation speeds between 60 kts and 100 kts, with time from brake release to rotation speed between 15 seconds and 20 seconds. This is a general takeoff scenario for commuter-type aircraft with wing-mounted propellers.

NOTE: When compensating measures, such as increased rotation speed, are used in a particular airplane's takeoff procedure, the high-speed ramp can apply.

The test acceptance criteria is calculated for each fluid qualification using results from dry tests, performed without fluid, and reference fluid tests, for which BLDT results are well documented. This was done to take into account the tunnel variations between facilities, although, to date, only one facility conducts this testing. For dry and reference fluid tests, the BLDT values are recorded at four temperatures: 0 °C, -10 °C, -20 °C, and -25 °C. A candidate fluid is acceptable at a test temperature if none of the independent BLDT measurements is greater than the acceptance criteria. This test temperature is the average of the three lowest temperatures of the acceptable data points. The test is performed at decreasing temperatures until the lowest temperature at which the fluid is aerodynamically acceptable is found. Each fluid is tested at temperatures including 0 °C, -10 °C, and -20 °C, and to the lowest acceptable aerodynamic temperature (LAAT) identified by the fluid manufacturer (if lower than -20 °C), in approximately 10 °C increments.

A detailed description of this test protocol is presented in AS5900.

Before introduction of the middle-speed ramp, Type I and III fluids were often tested to both the high-speed and low-speed ramps; Type II and IV fluids were generally only tested to the high-speed ramp. This may change after introduction of the middle-speed ramp.

NOTE: History of Boeing development, which resulted in the aerodynamic acceptance test and the high-speed ramp is presented at Appendix A.

NOTE: History of Bombardier development, which resulted in the low-speed ramp, is presented at Appendix B.

NOTE: History of the middle-speed ramp is presented at Appendix C of AS5900 (from Revision E onward).

3.4 Evaluation of Aerodynamic Effects on Specific Aircraft

As described in Appendix A, development of the AAT was conducted using the Boeing 737-200ADV airplane configuration with the Type I and II fluids that were available at that time. This research resulted in many important conclusions. With respect to the AAT, Hill and Zierten (Reference 26) state that:

Compliance with the acceptance test is considered a minimum requirement for acceptable aircraft ground deicing/anti-icing fluids. An airframe manufacturer may impose additional requirements which reflect considerations for airplane designs that are different than the 737-200ADV and for performance criteria not addressed by the acceptance test.

It is therefore important to note that the AAT is a basic requirement, and there can be differences between the implications of the AAT results and the applicability to specific airplanes. As discussed in 3.2, there are some operational examples of events that have occurred with fluids qualified to AS5900 that resulted in a need for airplane-specific evaluation, such as:

- Reports of high stick or wheel forces during rotation on some airplane types with unpowered flight controls.
- Takeoff speed corrections needed to compensate for lift losses caused by fluids.

There are a number of factors, both airplane-configuration based and operationally based, that should be considered relative to fluid-related performance that are beyond the AAT evaluation. For example:

- There is a large variation in wing designs (external lines/configuration, high-lift systems, sweep, taper, and twist distributions) across the spectrum of airplanes in operation. These variations can affect the flow-off of fluids and the resulting aerodynamic effect relative to the results of the AAT.
- Rotation speeds and takeoff acceleration profiles for some airplane types are different from those used for the AAT.

These factors can necessitate the evaluation of fluid aerodynamic effects on specific airplanes.

4. RECOMMENDED METHODOLOGIES

There is more than one way to do the evaluations described below. This section presents both methodologies that have been used, as well as some that are in development.

4.1 Evaluation Process Flow Chart

The flow chart below provides items to consider when evaluating the effects of thickened fluids on aircraft (see Figure 2).

The first option presented is to determine if thickened fluids been approved for use on a similar aircraft model. Items to be considered in a similarity analysis are provided in 4.2.1. If the effects of thickened fluids are well known on an existing aircraft model and the “new” model is found to be sufficiently similar, then the thickened fluids can be approved on the new model. Any special takeoff procedures in use for the existing aircraft model should, at a minimum, also be used for the model being evaluated. This methodology has been successfully utilized.

If the new model is not found to be similar to a model that has been previously approved for operation with thickened fluids, then there are multiple things to consider prior to utilize one of the methodologies presented in the following sections. One of the primary considerations is whether or not the “new” airplane has powered flight controls. Some airplanes that have unpowered flight controls have experienced increased rotation forces on takeoff (see 3.2.2). Some airplanes have also experienced issues with lift loss (see 3.2.1). These issues have typically been resolved with adjustments to the takeoff procedure when thickened fluids have been applied (see Section 5).

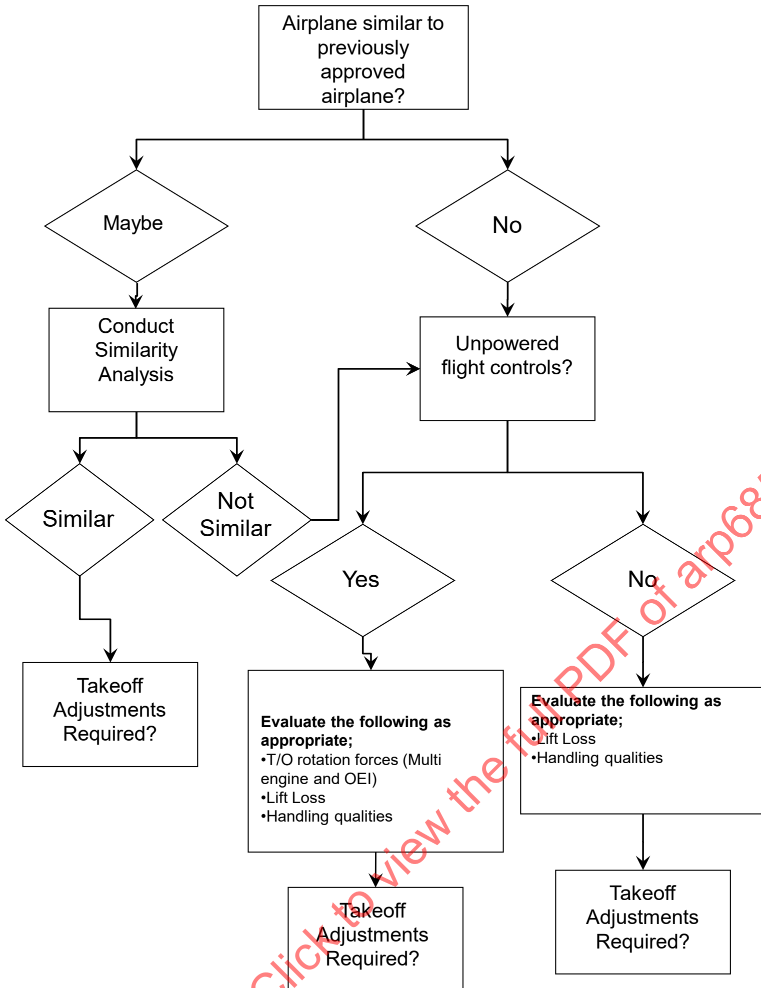

Figure 2 - Flow chart for evaluating the aerodynamic effects of deicing/anti-icing fluids

4.2 Similarity Analysis

If the characteristics of a “high-speed” aircraft are similar to those of the B737-200ADV, it follows that AS5900-compliant fluids should be acceptable for use on that aircraft as well. A similarity analysis may be used to compare any aircraft with the B737-200ADV to consider whether they are different enough that further analysis or tests may be required.

If the characteristics of a “low-speed” aircraft can be shown to be similar to those of the DHC-8, it follows that AS5900-compliant Type I and Type III fluids (which are tested to the low-speed ramp of AS5900) should be acceptable for use on that aircraft as well. A similarity analysis may be used to compare any aircraft with the DHC-8 to consider whether they are different enough that further analysis or tests may be required.

It should be noted that the B737-200ADV and the DHC-8 do not necessarily have to be used as the “reference aircraft” for an analysis of similarity. If the aerodynamic effects of fluids have been established for another aircraft by some means, that aircraft may be used as the reference aircraft against which the similarity of a new aircraft is assessed.

Similarity analysis is known to have been used by one aircraft manufacturer, which flight tested a previous model and made an analytical comparison with a new model, using numerical tools (i.e., CFD) to extend the previous test results to the new model.

It should also be noted that the acceptability of the AAT results is limited to the effect on wing lift; other issues may need to be addressed.

4.2.1 Considerations

An important consideration is the service history of existing aircraft models, i.e., whether or not similar models have experienced in-service events attributable to the use of fluids.

The following features and characteristics of an aircraft should be considered when assessing its similarity to a reference aircraft:

- Geometry of the wing, particularly:
    - Design of 2D airfoil(s) or 3D wing (note: several relevant airfoil cuts may be needed to evaluate a 3D wing).
    - High-lift configuration.
    - Incidence during the takeoff roll.
    - Chord.
    - Type of stall (e.g., leading-edge or trailing-edge) and CLmax sensitivity to roughness.
- Geometry of the horizontal tail.
- Geometry of any other lifting surfaces (e.g., vertical tail, canards, winglets).
- Takeoff acceleration profile and speed schedule, including which takeoff performance requirements define or limit the takeoff speed (i.e., VS1g, VMU, or VMC).
- Design of flight controls and flight-control systems, such as their actuation method (i.e., powered versus unpowered).

It may be necessary to understand how any differences in aircraft geometry and takeoff performance may affect the fluid effects and therefore the ability to demonstrate an acceptable level of similarity. The following information should be considered when determining the impact of any differences:

- The local skin friction coefficient (CF) distribution in the takeoff configuration(s) will influence the speed at which fluids will flow off the aircraft. Local differences should be considered, in addition to the average CF over the chord. A region of high localized CF may cause the fluid to be removed from that region more quickly. In contrast, a region of low localized CF may cause the fluid to flow off more slowly from that location and may even create a temporary increase of fluid thickness during the initial flow-off. The CF distribution characteristics will therefore affect the quantity and distribution of fluid over wing at rotation and therefore the disturbance that the fluid creates. Consideration should also be given to the change in the CF distribution that occurs following rotation, since previous experience has shown that the movement of the stagnation point and the increase of shear forces around the leading edge may create a secondary wave of fluid flowing aft following rotation.
- Fluids may flow off of a wing that has a larger chord more slowly than from a smaller-chord wing due to the larger distance over which the fluid has to travel.
- A faster takeoff profile, resulting either from a more rapid acceleration or a lower rotation speed, will allow less time for the fluid to flow off of the wing and will cause a larger quantity of residual fluid to be present on the wing at rotation.
- Differences in airfoil profiles or the nature of the high-lift systems may change the sensitivity of a wing to the effects of fluids, either due to changes in the sensitivity to roughness or due to changes in the distribution of shear forces (CF distribution).
- Although the aerodynamic characteristics of the wing are typically the primary focus, the characteristics of the horizontal and vertical tail surfaces should also be considered.

It may be appropriate to perform suitable analyses to evaluate the degree of similarity. CFD may be used to determine the CF distribution for the reference aircraft and the aircraft that is being evaluated. Recent studies have also explored the possibility of modeling fluid transportation using thin-film fluid mechanics theory to model the flow characteristics of a fluid under the influence of the predicted shear forces (see 4.5.1.3). CFD may also be used to evaluate the relative sensitivity of the aircraft to arbitrary quantities of roughness, used to simulate the disturbances caused by the flow-off of fluids, as described in 4.5.1.2.

If analyses are performed and are inconclusive in evaluating similarity, it may be necessary to consider other methods, such as wind tunnel testing or flight testing, to supplement the similarity analysis.

4.2.2 Applicability

This method is suitable only for aircraft that are similar to another aircraft (the reference aircraft), for which the effects of fluids are known.

4.2.3 Pros and Cons

4.2.3.1 Pros

- Relatively low cost (little or no physical testing is required).

4.2.3.2 Cons

- If differences are identified, it may be difficult to determine their impact.

4.3 Wind Tunnel Tests

4.3.1 Historical Testing

See Appendices A and B for descriptions of wind tunnel testing conducted by Boeing and Bombardier (then Boeing Canada, de Havilland Division), which were primarily research oriented to understand physics behind the aerodynamic effects of fluids.

4.3.2 Recommended Procedures for Wind Tunnel Testing

Based upon consideration of the historical practices, the following are recommended procedures to be considered:

- Start with a clean, dry model.
- Bring the tunnel and model to test temperature.
- Apply fluid to the model until there is complete coverage and the fluid actively drips off of the model, e.g., applying 3 L of Type IV per square meter is a good rule of thumb.
- Linearly increase the tunnel speed at the appropriate rate until reaching the target speed.
- Rotate the model per the takeoff profile.
- Continue the run for 30 seconds past the end of model rotation.

4.3.3 Boundary Layer Tripping

For the wind tunnel tests conducted by Boeing, boundary layer tripping was used (refer to Reference 41; also see Appendix A).

To assure that turbulent flow existed on as much of the wing as possible and to better simulate the shear stress to which the fluid is subjected in full-scale fight, a trip strip was applied near the wing leading edge.

4.3.4 Pros, Cons, and Considerations

4.3.4.1 Pros

- Ability to determine the maximum lift coefficient degradation due to the fluids, which is not possible from flight testing.
- Ability to determine the drag increase due to the fluids, which is less accurate from flight testing.
- Ability to economically test a matrix of various fluid formulations and concentrations, at different temperatures, and on different configurations, which would otherwise be cost-prohibitive.
- Flow visualization capability.
- Boundary layer measurement capability.

4.3.4.2 Cons

- It is necessary to correlate the model wind tunnel data to airplane flight test data. Without flight test data, or at least prior experience with such a correlation for fluids testing, it is unlikely that correct interpretation of the wind tunnel data is possible.
- The conduct of fluid tests in aerodynamic wind tunnel facilities is very uncommon and there are only a small number of facilities where such testing with fluids is permitted (presumably only two are available for commercial use).

4.3.4.3 Considerations

- Fluid cannot be scaled and the effect of this is unknown. However, for the Boeing tests, it was not believed to be an issue after comparing wind tunnel and flight test data (see Appendix A).
- The small wind tunnel scale models' short chord lengths provide a shorter distance for the fluid to travel for flow-off than on the full-scale wing. In addition, there is a greater fluid-depth-to-chord ratio. The effects of these aspects may be insignificant (see Appendix A).

4.4 Flight Tests

Flight tests can be used to determine the aerodynamic effects of fluids on aircraft performance (lift and drag) and flying qualities.

4.4.1 Instrumentation

Aircraft instrumentation should include an inertial reference system (IRS) and a data acquisition system (e.g., inputs for calculations of gross weight and center of gravity, engine parameters, airspeed, accelerations, ground speed, distance, and IRS angular data). An onboard engineering data analysis system can also be useful.

Video and photographic equipment may be set up in the aircraft cabin. Typically, two fixed video cameras mounted at an over-wing window are used to provide full and clear coverage of one wing. Additional fixed cameras or a hand-held video camera can be used to record the fluid flow-off behavior. For aircraft with high wings or without windows, the video cameras would need to be located externally, looking down at the wings.

4.4.2 Fluid Selection and Application

A fluid should be chosen whereby it can be used at a temperature as close to the aerodynamic acceptance limit as practicable. In order to accomplish this, obtain an AAT result report from the fluid manufacturer (refer to AS5900, Figures 11 and 12).

Review the aerodynamic acceptance limit graph and note the temperature range below -20 °C where the fluid is closest to the acceptance limit. This will be the preferred aircraft flight test temperature range.

Since different fluids have somewhat different aerodynamic behavior, the best practice will be to review a number of fluids to find one or more closest to the aerodynamic acceptance limit near the desired test temperature range.

Although it may not be practical to choose the fluid closest to the acceptance limit, an effort should be made to choose one that closely approaches the limit. This may require using a fluid that is not normally available at the chosen flight test airport.

Since all thickened fluids are qualified to the same aerodynamic acceptance specification (refer to AS5900), flight testing with a fluid that is close to the aerodynamic acceptance test limit allows the airframe manufacturer to approve all thickened fluids based upon the results of the flight-tested fluid. However, consideration should be given to the fluid's BLDT versus time characteristics in relation to the aircraft's takeoff speed schedule, especially time to liftoff. If the aircraft to be tested with fluid lifts off before approximately 25 seconds, then the BLDT characteristics at the actual times should be considered.

Fluid should be applied to the airplane in accordance with SAE and aircraft manufacturer recommended procedures, or as appropriate for the purpose of the testing.

NOTE: Some propylene glycol fluids present an increase in viscosity as they dilute from a neat concentration to roughly 65 to 75% dilution, bringing the fluid closer to the BLDT limit than the undiluted fluid, even for higher temperatures (above -20 °C). In this case, it could be possible to perform the flight tests with the diluted fluids in a temperature range above -20 °C.

4.4.3 Airplane Performance and Handling Tests

4.4.3.1 Purpose

Takeoff performance testing can provide sufficient information to determine the amount of lift loss (ΔC_L) due to residual fluid at or after liftoff[1], or at another point of interest; the takeoff acceleration drag and in-flight drag increases (ΔCD) due to the fluid; and whether the presence of residual fluid after takeoff causes noticeable effects on handling qualities.

4.4.3.2 Test Procedures

4.4.3.2.1 Lift

4.4.3.2.1.1 General Information

The aircraft should be flown by an experienced flight test air crew to safely and efficiently perform handling and performance tests.

This testing is typically conducted away from an aircraft manufacturer's flight test center; thus, a full off-site instrumentation and maintenance team with appropriate equipment are recommended. A portable ground station should be used to record outside air temperature and wind data.

The aircraft should be configured at the lightest weight practical for these tests, corresponding to a low operational takeoff weight with low takeoff speeds. The most critical aircraft weight regarding fluid effects on lift is the highest of the minimum operational weight and the weight when VR is just limited by VMC. A means to determine accurate gross weight and center-of-gravity data should be available at the test location.

Analysis of comparable test data for the aircraft with and without fluid applied, at similar weight and center-of-gravity conditions will show the effects, if any, of the fluid on takeoff characteristics and airplane performance. Typical data comparisons include control inputs, control forces, control-surface positions, altitude, speed, pitch angle, pitch rate, angle-of-attack, and time to rotation and liftoff.

[1] Recent flight tests have focused on obtaining ΔCL at liftoff or during rotation, whereas the AAT fluid-acceptance limit is based upon ΔCLmax at V2. The difference is because the AAT was developed based upon the determination that the V2 margin is the single most critical safety criterion around which a fluid-acceptance test should be established.

4.4.3.2.1.2 Performance Checks - Normal and “Fixed-Pitch” Takeoffs

Comparisons of lift data with and without fluid application should be made to check whether the effects of the fluid are minor or are significant. If they are not minor, it may be necessary to determine takeoff performance adjustments that need to be made when fluids are used.

Back-to-back normal takeoffs should be conducted with and without the application of the test fluid to the wings and horizontal stabilizer. Direct comparison should be made of the flight data with and without fluid to determine if there are any significant effects on the lift coefficients and takeoff performance. Normally, the maximum angle of attack during takeoff does not occur at liftoff but rather, at the end of the rotation and may be higher than the stabilized angle of attack at V2 speed.

“Fixed-pitch” takeoff tests have historically been performed to establish stable pitch attitudes during normal, clean-wing (no fluid) takeoffs to facilitate the accurate estimation of an aircraft's lift characteristics. However, fixed-pitch takeoffs with fluids applied involve early rotation to high pitch angles, which can cause greater accumulation of residual anti-icing fluid on the wing at liftoff than that which occurs during normal takeoffs. This can cause larger lift losses at liftoff than occur during normal takeoffs. Aircraft with rotation-force issues cannot rotate early and therefore cannot perform fixed-pitch takeoffs. Due to uncertainties and associated concerns, performing fixed-pitch takeoffs is not recommended.

All-engines-operating normal and abuse takeoffs may be conducted to assess any deviations from normal behavior. For abuse takeoffs, the regulatory criterion without fluids applied is VR (10 kts) or VR (7%), whichever is higher. For tests with fluids, considering that the V2 margin is 1.10 VS1g rather than 1.13 VS1g for a clean wing, it is considered adequate to conduct abuse takeoffs with rotation at VR (7 kts) or VR (3.5%).

4.4.3.2.2 Drag

In general, the additional drag due to fluid is not significant for the takeoff distance required (TODR, distance to 35 feet) and may be ignored. Even when aircraft performance corrections are needed when operating with fluids, the additional drag due to fluid is still not significant for the TODR.

The aerodynamic effect of fluid is transitory and diminishes quickly after liftoff. Therefore, additional drag due to fluid may not have to be considered for the climb performance.

For example, Saab determined the additional drag due to fluid by flight testing with an instrumented test aircraft (see Appendix C). Normal Flaps 0 and Flaps 15 takeoffs with and without fluid were performed. The lift loss due to fluid, and thus additional drag, peaks after liftoff at the maximum angle of attack during rotation and decreases rapidly after that due to the lower angle of attack and fluid flow-off. Below is an example of measured lift loss as a function of time after liftoff on the Saab 2000 Flaps 0:

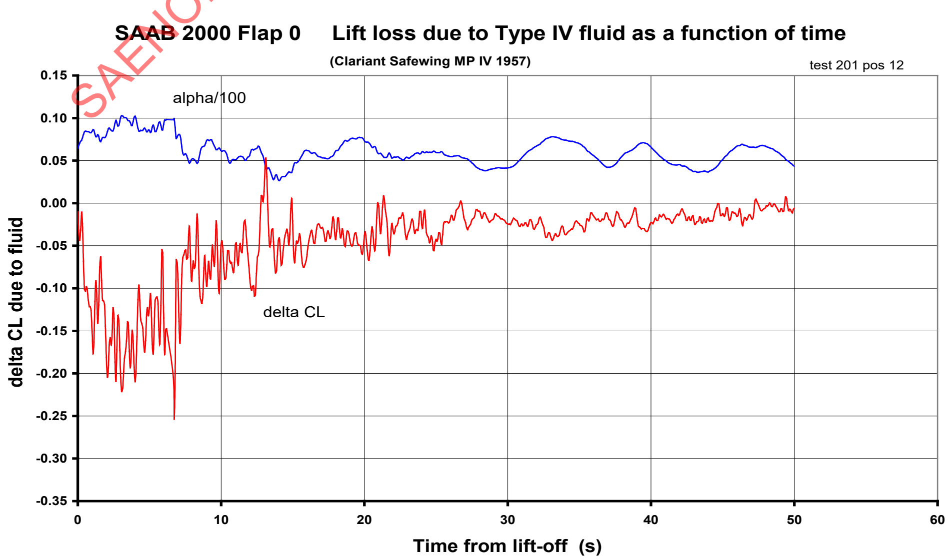

Figure 3 - Lift loss as a function of time - Saab 2000 (Flap 0)

The measured additional drag due to fluid is presented in Figure 4:

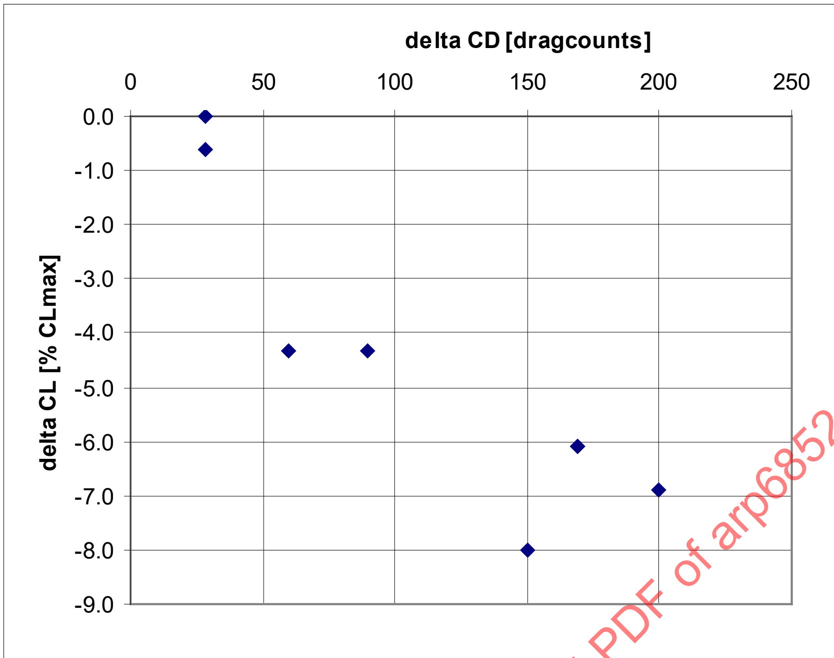

Figure 4 - Drag due to the fluid - Saab 2000 (Flap 0)

The highest values occurred at the maximum angle of attack during rotation. The data points with values close to zero are from a climb, i.e., after significant fluid flow-off. Based on these results, Saab decided to use in the aircraft performance calculations a conservative average drag increment of 75 drag counts during the whole takeoff distance (i.e., up to 35 feet) when a takeoff speed correction due to fluid is required.

It should be noted that in this example, the additional drag due to fluid was analyzed from transient flight test data directly after liftoff and thus the accuracy is likely an order of magnitude lower than drag data obtained from dedicated, well-stabilized flight tests.

4.4.3.2.3 Handling Qualities

It should be sufficient for handling qualities flight testing to be qualitative in nature. The purpose of the tests is to evaluate airplane handling during the takeoff and climb, as well as to evaluate the control forces after fluid application. Additionally, simulated one-engine inoperative (OEI) takeoffs can be used to evaluate climb performance with fluid applied. If it is desired to assess directional controllability, then fluid must also be applied to the vertical tail for the testing.

The following maneuvers to assess the aircraft’s longitudinal and lateral control characteristics after fluid application have been required of some aircraft manufacturers by some authorities and are included here for completeness. However, whether these maneuvers are of value is questionable since it is believed that no abnormalities have ever been found.

- ±40-degree bank excursions (±30 degrees for simulated OEI takeoffs).

- Normal load factor variation between 0.5 g and 1.5 g (or between 0.8 g and 1.3 g for simulated OEI takeoffs).

While it is desirable that maneuvers be performed soon after takeoff such that there is representative residual fluid remaining for the evaluation, it must be acknowledged that high-risk maneuvers must only be performed at an altitude that will ensure flight safety. Flight test pilots or engineers can establish appropriate limits.

4.4.3.2.3.1 Control Forces

It is desired that the stick forces required to rotate and control an aircraft during takeoff should be essentially the same with and without the application of thickened anti-icing fluids. An undue and unexpected increase in stick force can mislead the pilot into believing that there is a problem with the flight controls. A rejected takeoff at speeds above VR can be hazardous. Therefore, a qualitative as well as quantitative assessment of the stick forces should be made during a flight test evaluation of anti-icing fluids.

Some aircraft equipped with unpowered elevator flight control surfaces have experienced large increases in stick force during the takeoff rotation following application of thickened anti-icing fluids (see 3.2.2 for additional information). If the stick force increase is excessive, it may be necessary to either increase the takeoff rotation speeds or use a reduced flap deflection to alleviate the effects of the fluids.

Degradation of aerodynamic performance or control characteristics due to the presence of fluids, as indicated by lift loss and/or control force increases, may require adjustments to takeoff speeds (e.g., increases to VR and/or V2) to ensure adequate safety margins. While normally a successful solution, speed increases have not mitigated increased control forces in every case.

If the takeoff speeds are adjusted, other aspects of takeoff performance will need to be re-evaluated, such as required takeoff field length. Corrections may also be necessary for takeoff weight and distances, as well as brake energies. Different takeoff techniques can also be necessary (e.g., change of pitch rate or target pitch attitudes).

Some aircraft types with unpowered ailerons have also experienced minor increases in lateral control forces.

4.4.4 Evaluation of Fluid Behavior

Flight tests can also be used to evaluate the behavior of fluids during the takeoff ground roll, liftoff, and climbout. Flow visualization techniques, such as ultraviolet photography, have been utilized to capture images of fluid flowoff, wave action, etc. It may be beneficial to conduct flow visualization testing at night to enhance image resolution.

4.4.5 Flight Test Considerations

- Calm and stable air with no precipitation or active frost conditions is recommended.
- Wind speed should not be greater than 10 kts.
- Wind speed and ambient air temperature measurement facilities (wind station) are recommended.
- Testing should be conducted on a cloudy day with no precipitation. A cloudy day will help ensure that the aircraft skin temperature is closer to the ambient air temperature. Flight testing on a clear, sunny day has shown that there can be a large variance between the skin temperature and the ambient temperature. Skin temperature should be monitored with spot measurements using a hand-held probe to ensure that the skin temperature does not vary greatly from the outside air temperature.
- Flight test quality control should be implemented to ensure repeatability of the test and the integrity of the test results. At a minimum, the following measures should be taken:
    - Fluid samples should be taken to determine the viscosity of the fluid in the application vehicle. To confirm that the fluid's viscosity is above the lowest on-wing viscosity for that fluid, fluid samples should also be taken directly from the application nozzle of the truck and from fluid applied to the wing. These samples should be taken at the start of each test day and again whenever the truck is refilled with fluid.

- To ensure appropriate and repeatable fluid thicknesses, flood the surface with fluid (about 2 to 4 L/m²) and allow the fluid to settle (when the rate of the fluid dripping off decreases). A visual inspection should be carried out by a trained individual to verify the proper application of fluid. This inspection should ensure a uniform and adequate coverage of fluid. In addition, fluid thickness measurements should be taken near the leading edge, on top of the wing, and on the aft portion of the wing to confirm uniform fluid coverage. At a minimum, measurements should be taken for the first and final test points; however, it is recommended that measurements be taken for every test point. It may be good practice to initially measure and record the fluid thickness 5 minutes after application to allow fluid to settle and to minimize variability during the settling process; the thickness decreases the most during the first 5 minutes while it is settling. After gaining experience with the fluid application process, the settling of the fluid may be judged empirically rather than applying a 5-minute wait time. The amount of fluid applied for each test should be documented.

- It is recommended that each test begin with a clean wing. Before each test, the wing should be cleaned to remove any residual fluid from a previous test flight. This can be accomplished by using a squeegee for smaller aircraft; however, for larger aircraft, a two-step fluid application process as per AS6285 is recommended. During the first step, deicing, the fluid may be used to "wash" the aircraft surfaces prior to applying the thickened test fluid during the second step. When using a two-step process, the methods employed should be as close to normal operations as possible. It is important to purge any Type I from the surface with the second-step fluid. It should be noted that extensive application of heated Type I may increase the wing skin temperature.

- Alternatively, it can also be acceptable to not remove residual fluid between tests (so long as the fluid has not frozen during the flight and the same fluid is being used). Applying thickened fluid on top of the residual fluid from a previous test will give conservative aerodynamic results. It also eliminates the potential for dilution of the test fluid by the fluid used for cleaning. Testing time constraints may also be a factor favoring this approach. This procedure is similar to the one-step fluid application procedure currently utilized in Europe.

- It is recommended to ensure that the fluid and equipment used for the fluid application are appropriate and within the fluid manufacturer's specifications.

- For small aircraft, a single application vehicle may be sufficient for application and inspection. For larger aircraft, it may be desirable to have additional vehicles that can be dedicated to fluid application, inspections, and fluid measurements.

- It is recommended that the same personnel conduct the entire test to ensure consistency.

4.4.5.1 Pros and Cons

4.4.5.1.1 Pros

- Real airplane data.
- Flight-control hinge moments can be evaluated.
- Flow visualization capability.
- Operational aspects of using fluids can be evaluated (e.g., APU ingestion, accumulation in aerodynamically quiet areas).

4.4.5.1.2 Cons

- Very expensive.
- Weather dependent (need cold temperatures, low winds, no precipitation, ideally cloudy skies).
- Flight test maneuvers close to the ground are high risk. For example, it is (hopefully) not feasible to determine the CLmax degradation.

- Logistics - Most manufacturers find it necessary to do this testing at a remote location. An airport is needed that has a long runway, low traffic, and fluid application and recovery (if necessary) equipment available. It may be necessary to provide the desired fluid for the testing. It is possible that the airplane will be cold-soaked in the morning and testing may need to wait for the airplane to warm up.

4.5 Computational Fluid Dynamics and Other Numerical Analyses

4.5.1 Procedures

4.5.1.1 Overview

Computational fluid dynamics (CFD) and other numerical modeling methods can potentially be used to estimate the fluid flow-off behavior, and/or the aerodynamic degradation caused by the presence of fluids on the wing surface.

CFD methods have been used in different ways by several aircraft manufacturers. The maturity of the CFD analyses performed is varied. In some cases, CFD has already been used as part of the aircraft design and certification process to evaluate the fluid effects. In other cases, the use of CFD and other numerical modeling techniques has been investigated only as part of on-going research studies.

Furthermore, the precise application of CFD has varied. Some aircraft manufacturers have used CFD to determine the aircraft CLmax loss due to fluids by using CFD to extrapolate flight-measured lift losses (lift losses in the linear part of the lift curve) that were measured at the highest angle of attack during rotation. Other aircraft manufacturers have begun to investigate whether it is feasible to use numerical analyses to model fluid flow-off, either to support similarity assessments or to obtain residual fluid data for subsequent CFD assessments of the aerodynamic effects. There may be other ways in which CFD and numerical methods may be used, but this document intends only to describe how some aircraft manufacturers have used CFD in the past or envisage how CFD may be used in the future.

The flow chart in Figure 5 illustrates possible uses of CFD and other numerical methods. The processes shown in Figure 5 are described in more detail in 4.2, 4.5.1.2, and 4.5.1.3. It should be noted that it is not necessary to perform the activities shown in both the red box and the blue box, but only one or the other. Furthermore, Figure 5 illustrates only two examples of how CFD and numerical analyses may be used; there may be other ways in which numerical analysis may be used to help evaluate fluid effects. For both of the processes shown in Figure 5, the final goal of the analysis is to determine the effect of the fluid on the aircraft CLmax. In addition, other aerodynamic and takeoff performance characteristics may be of interest.

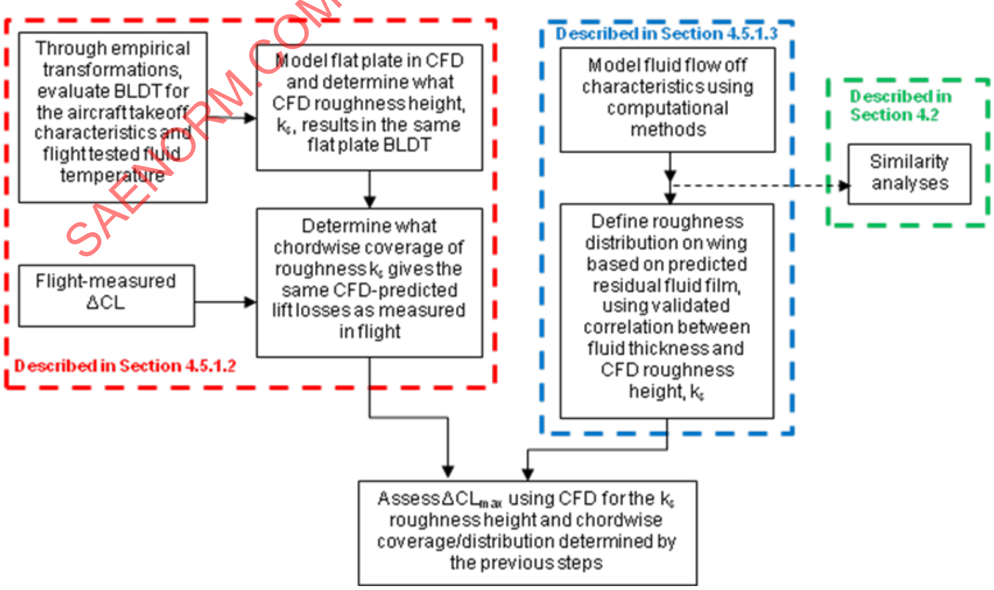

Figure 5 - Flow chart example of the possible use of CFD and other numerical methods for evaluating the aerodynamic effect of fluids

4.5.1.2 Use of CFD to Model Aerodynamic Effects

CFD methodologies can be used based upon the AAT BLDT constraints for fluid qualification and the aircraft's takeoff acceleration profile. Critical data for this methodology are the AAT results for the specific fluid being evaluated. However, this methodology can be used for a generic, non-fluid-specific, worst-case evaluation by adopting the AAT BLDT "limit of acceptance" as the "CFD standardized roughness" when time to liftoff is 25 seconds or more; otherwise, the maximum BLDT during rotation should be considered.

Starting with the fluid's AAT test results (BLDT versus fluid temperature on a flat plate for a standardized acceleration profile, or "speed ramp") and the aircraft acceleration profile, it is possible to correct the BLDT variation on a flat plate as a function of the fluid temperature for the actual aircraft acceleration profile through an empiric transformation process. CFD analyses are then used to make a correlation between the corrected flat-plate BLDT variation and a respective numerical roughness height that matches this BLDT variation. The numerical roughness is equivalent to a sand grain roughness (k_s). Hence, a numerical roughness that matches the fluid influence on the flat plate BLDT, denoted by "CFD standardized roughness," can be determined. The next step is to extend these data to the aircraft.

With the CFD standardized roughness height determined, the result of the roughness distribution over the wing surface is calibrated against flight test or wind tunnel test results, both qualitatively and quantitatively. The chord-wise extent of numerical roughness is varied until the reference lift loss (flight test and/or wind tunnel test data) is matched. The CFD standardized roughness can be used with either a 2D or 3D CFD code to determine the 3D maximum lift deviation due to roughness. If a 2D code is used, it is essential that 3D data (wind tunnel or flight) are available to calibrate the 2D results. One aircraft manufacturer has used a 2D critical section method, which assumes that the wing is at its maximum lift when any individual spanwise element or section (2D) is at its maximum lift coefficient.

For calibration purposes, the specific fluid's AAT BLDT data must be used, as opposed to the generic "Limit of Acceptance" data. However, once calibrated, this methodology may be extended to other aircraft models besides those used for the calibration process.

Appendix C describes how CFD methodology has been used by another aircraft manufacturer to extrapolate flight test data to CLmax.

4.5.1.3 Use of Computational Methods to Model Fluid Flow-Off

Theoretical methods are being developed that aim to model the fluid flow-off and/or the subsequent effect of any residual fluid on the aerodynamic performance. Either or both of these two elements of the theoretical method may be used evaluate the relative effects between two different aircraft to provide further supporting evidence of similarity, as discussed in 4.2. Furthermore, in principle at least, it may be possible to evaluate theoretically the flow-off and aerodynamic effects of an aircraft in isolation, to determine the aerodynamic effects of a fluid that complies with the AS5900 flow-off criteria.

- Fluid flow-off modeling: Current efforts to model fluid flow-off are using thin-film theory to model the transportation of the fluid over the wing. The wing surface is discretized, and the transportation of the fluid under the influence of the air shear stress from one control volume to the next is modeled using an explicit numerical scheme. The air shear stress may be obtained from a Navier-Stokes CFD code or from an inviscid CFD method that is coupled to integral boundary layer analysis. Current studies have focused on modeling 2D airfoils, but a theoretical method such as this is also capable of modeling the flow-off on a 3D wing or aircraft surface.

- Residual-fluid modeling: Current studies are investigating the feasibility of evaluating the effect of the residual fluid, as predicted by a flow-off analysis, on the aerodynamic performance. A suitable CFD code, such as a Navier-Stokes code, would be used to model the aerodynamic performance (although it is necessary for the CFD code to model surface roughness). Another method that has been used is to model or estimate the effect of residual fluid using wind tunnel test and/or flight test data with artificial roughness.

In any case, it would be necessary to establish and validate a correlation between the residual fluid thickness distribution and an artificial surface roughness distribution that causes an equivalent effect on the aerodynamic behavior.

The use of CFD codes to predict the aerodynamic performance in this manner is also discussed in 4.5.1.2; although, in those cases, the required roughness height is obtained by correlating lift loss in the linear part of the lift curve with measurements from flight testing.

4.5.2 Applicability

As shown in Figure 5, CFD and other numerical methods may be used in a variety of ways to evaluate the effects of fluids. The applicability of CFD and other numerical methods depends upon how a particular method is being used, but might include the following:

- Determination of maximum lift coefficient degradation due to fluid effects.

- Supporting a determination of similarity between aircraft and quantifying the impact of any differences.

4.5.3 Pros, Cons, and Considerations

4.5.3.1 Pros

- Allows evaluation of aerodynamic fluid effects for the “worst scenario,” i.e., using the AAT BLDT “limit of acceptance” values.

- Allows estimation of maximum lift coefficient degradation due to the fluids, which is not possible from flight testing.

4.5.3.2 Cons

- Before use, it is necessary to calibrate the CFD methodology. Flight test or wind tunnel data should be used to calibrate the methodology.

4.5.3.3 Considerations

- The capability to determine hinge-moment effects on flight-control surfaces may be feasible but has not been validated.

- The methodologies would benefit from application on a broader sample of aircraft for calibration/validation.

5. POTENTIAL PERFORMANCE ADJUSTMENTS

Degradation of aerodynamic performance or control characteristics due to the presence of fluids, as indicated by lift loss and/or control force increases, may require adjustments to takeoff speeds (e.g., VR and/or V2 increases) and/or procedures to ensure adequate safety margins. The corrections will be different for specific aircraft based upon their takeoff performance. In some cases, the lift loss caused by fluids will not impact the airplane’s normal performance schedule (when the takeoff speeds are already sufficiently greater than stall speeds).

If the takeoff speeds are adjusted, other aspects of takeoff performance will need to be revisited. Corrections may also be necessary for takeoff weight and distances, as well as braking energies. Different takeoff techniques can also be necessary (e.g., change of pitch rate or attitude).

6. SYNOPSIS

This section presents a synopsis of the recommended methodologies described in Section 4, as well as the effects on aerodynamics and handling qualities.

6.1 Recommended Methodologies

Table 1 presents the recommended methodologies, comparing the main pros and cons of each one.

Table 1 - Recommended methodologies

Methodology	Pros	Cons
Similarity Analysis	• Low cost	• Difficult to determine impact in case of differences
Wind Tunnel Tests	• Maximum lift coefficient degradation determination • Drag increase determination • Evaluation of a matrix of various fluid formulations and concentrations, at different temperatures, and on different configurations • Flow visualization capability • Boundary layer measurement capability	• Correlation of wind tunnel data to airplane flight test data required • Small number of facilities where fluid tests can be conducted (presumably only two are available for commercial use)
Flight Tests	• Real airplane data • Flight-control hinge moments evaluation • Flow visualization capability • Evaluation of operational aspects of using fluids (e.g., APU ingestion, accumulation in aerodynamically quiet areas)	• Very expensive • Weather dependent • High-risk maneuvers • Logistics
Computational Fluid Dynamics and Other Numerical Analyses	• Aerodynamic effects evaluated at the worst scenario • Maximum lift coefficient degradation estimation	• CFD methodology calibration is required

6.2 Effects of Fluids on Aerodynamic Performance

See below the list of aerodynamic performance characteristics affected by anti-ice fluids:

- Aircraft lift during liftoff and initial climb.
    - Potentially reducing takeoff safety margins.
- Aircraft drag (usually not significant).
- Takeoff climb gradient (deemed acceptable; see Appendix B).

The practical actions to overcome the characteristics presented above are:

- Increase takeoff speeds (see Appendix C).

6.3 Effects of Fluids on Handling Qualities

See below the list of handling qualities characteristics affected by anti-ice fluids:

- Takeoff rotation difficulties (due to increased stick/column forces).
- Lateral control force changes (detrimental, but acceptable; see example in Appendix C).

NOTE: Fluids will reduce the effectiveness of the controls. Both elevator and aileron control forces are an issue for manual controls.

The practical actions to overcome the characteristics presented above are:

- Increase takeoff speeds (see example on Appendix B).
- Decrease takeoff flaps setting.

7. NOTES

7.1 Revision Indicator

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY SAE G-12ADF AIRCRAFT DEICING FLUIDS COMMITTEE

APPENDIX A - BOEING HISTORY - EVALUATIONS OF THE EFFECTS OF DEICING/ANTI-ICING FLUIDS ON AIRCRAFT AERODYNAMICS AND DEVELOPMENT OF AN AERODYNAMIC ACCEPTANCE TEST

A.1 INTRODUCTION

Throughout the 1980s and into 1990, Boeing performed wind tunnel and flight test evaluations of the aerodynamic effects of deicing/anti-icing fluids ("fluids"). These tests were initially research oriented and aimed at quantifying the aerodynamic performance effects and understanding the fluid dynamic behavior causing those effects. Later, as part of the international Aerospace Industries of America Transport Committee (AIA TC) 218-4, one of the ultimate results of Boeing's efforts was the development of a wind-tunnel test methodology and aerodynamic acceptance criteria for fluids. Several reports of this work were published and are available to the public.

Boeing conducted its first tests with fluids, Types I and II, in 1982. In the Boeing Icing Wind Tunnel, a 0.25-m (10-inch) chord airfoil model was utilized for flow visualization studies of the fluid flow-off characteristics. In the Boeing Research Wind Tunnel, both force and flow data were obtained on a 0.61-m (25-inch) chord 2D model. From 1984 through 1987, the Association of European Airlines (AEA) and the von Karman Institute for Fluid Dynamics sponsored a three-phase research program which generally validated the results of Boeing's 1982 testing. To understand model-scale and 3D effects, the AEA requested that Boeing perform flight testing.

In January of 1988, Boeing and the AEA conducted flight-test evaluations of four fluids (one then-current Type I, one obsolete Type II that was wind-tunnel tested in 1982, and two then-current Type IIs) at Kuopio, Finland, on a Boeing 737-200 Advanced provided by Lufthansa Airlines. Aircraft instrumentation included an inertial reference system (IRS); a data acquisition system for recording gross weight, center of gravity, engine parameters, airspeed, acceleration, ground speed, distance, and IRS angular data; an onboard engineering data analysis system; video and photographic equipment.

For Type I testing, cold, neat fluid was applied with a one-step procedure. For Type II fluids, the AEA two-step procedure was utilized to apply 50:50 Type I and cold, neat Type II. Fluid was applied to the upper surfaces of the wing and horizontal stabilizer. Fluid samples were taken to establish rheological properties. The testing was conducted in cloudy, non-precipitation weather conditions. Ambient test temperatures ranged from 2 °C (36 °F) to -10 °C (14 °F).

Figure A1 - Fluid application during flight tests
Photo source references: Nos. A.8, A.9, A.11, and A.15

To establish lift curves in ground effect with and without fluids, a series of constant-attitude takeoffs was performed at Flaps 5 (sealed slats) and Flaps 15 (gapped slats). The aircraft was rotated early to a specific attitude and then accelerated at that attitude through initial climb. Normal, continuous-rotation takeoffs were also performed to confirm that the constant-attitude technique did not affect results. Thrust and weight were varied to keep ground-roll time to liftoff and the takeoff speed approximately constant such that the fluids were subject to the same shear stress and flowoff time (except when shear stress and flowoff time were varied to ascertain their effects). Assessments were made at the liftoff attitude corresponding to one-engine-inoperative climb (12 degrees). The fluids caused an increase in takeoff acceleration drag, but it was not possible to accurately measure in-flight drag due to atmospheric conditions. Small variations in liftoff speed, fluid flow off time, and fluid exposure time showed no measurable effect on results.

Qualitative handling characteristics were evaluated by performing ±30-degree bank turns. For one flight, Type II fluids were applied to the left wing only. There were no noticeable effects on handling qualities.

Flow visualization imagines were acquired using ultraviolet photography and back-scatter laser techniques. A fluorescent dye was added to the fluids[2] to enhance visibility and provide for the measurement of fluid depth and roughness. A camera mounted on the vertical tail was focused on the 65% semi-span region of the wing. Photographs were taken every 2 seconds via synchronization of the camera with ultraviolet strobe lights located in cabin window cutouts. The flow visualization testing was conducted at night for better image resolution. The photographs showed an initial fluid wave flowing aft from the leading edge, as well as roughness of the fluid surface behind the wave, during the takeoff roll. This was consistently followed by a secondary wave immediately after takeoff.

Figure A2 - Ultraviolet fluorescent photograph of a fluid 8 seconds after brake release

Figure A3 - Ultraviolet fluorescent photograph of a fluid at liftoff
Photo source references: Nos. A.8, A.9, A.11, and A.15

Results and conclusions of the flight tests included the following:

- The fluids cause measurable lift losses and drag increases, with the lift losses of the neat fluids being similar to those seen in the 1982 wind-tunnel testing.
- Fluid effects are configuration dependent, insignificant for handling qualities, and transitory.
- Fluid flowoff characteristics include a secondary wave commencing immediately after takeoff rotation, which results in greater lift losses at higher angles of attack.

The 1988 flight tests were followed by two evaluations in the NASA IRT. Phase I was conducted in 1988, and Phase II in 1990. The tests were a team effort: Boeing supplied the models; NASA IRT provided and operated the tunnel; fluid manufacturers supplied the fluids; AEA monitored the tests; Boeing and NASA IRT conducted and documented the tests.

[2] The dye that was added to the fluids also dyed the white wings of the airplane pink, earning it the nickname, “The Pink Pussycat”—a bit of historical trivia that ought not be lost.

Both a 0.46-m (1.5-feet) chord 2D, 0.18-scale model of the 65% semi-span 737-200ADV airfoil and a 0.091-scale 3D half-model of the 737-200ADV were utilized (see Figures A4 and A5). Again, the Flaps 5 and Flaps 15 configurations were tested, as well as Flaps 15 with retracted (cruise) leading edge. For the 3D half-model testing, a ground plane was in place for most of the runs. To ensure that the flow would be turbulent on the entire wing and to improve simulation of the full-scale shear stresses, a trip strip of No. 50 microbeads was applied near the wing leading edge.

The Phase I testing established that wind-tunnel lift loss results could be directly extrapolated to full scale (1:1) with reasonable confidence. In addition to the configuration dependency established during flight testing, aerodynamic effects of the fluids were found to be strongly influenced by operational speeds and time to liftoff. The purpose of testing Flaps 15 with a cruise leading edge was to investigate the effects of fluids on a commuter-type aircraft. For this configuration, the highest lift loss occurred at taxi attitude rather than at maximum lift. The high leading-edge flow velocities caused high shear stresses and reduced fluid viscosity, resulting in less residual fluid and no secondary waves.

The effects of three different Type I fluids and four Type II fluids were further examined in the Phase II testing. Lift and drag were most adversely impacted at colder temperatures. The transitory nature of the fluid effects was again evident. The initial thickness of the fluid did not significantly affect results. For two of the Type II fluids, dilutions of 75:25 and 50:50 were also tested, and the 25% dilution had lift losses similar to the neat fluid. In many cases, the 2D model data, particularly for the Flaps 5 sealed-slat configuration, showed greater lift losses at 8-degree wing angle of attack (α_w) than at clmax. The 3D model data, however, consistently showed greater lift losses at CLmax than at 7-degree angle of attack, indicating the importance of 3D effects.

The second entry also incorporated investigation of the effects of precipitation on Type II flow-off characteristics. For this testing, water equivalent to 10% and 20% dilutions were sprayed over the model to simulate active precipitation (a variation of this procedure later became the Water Spray Endurance Test of AS5901). At the colder temperatures, lift losses were either higher or similar to those with the water mixed to dilute the fluid. Video recordings revealed that the sprayed water froze into a sheet of ice on top of the fluid layer rather than being absorbed by the fluid.

There were some concerns relative to the validity of the wind tunnel testing (refer to Reference A.16), particularly scale effects due to the small-scale models, and the fact that the model chord lengths were limited due to height of the tunnel test section, which resulted in both reduced relative fluid flow-off distance compared to a full-scale airplane and lower chord Reynolds number producing higher shear stress than on a full-scale airplane. However, comparison with flight data showed that corrections to the wind tunnel data and test parameters for these effects were not needed.

- Airfoil at 65% semi-span
- 18% scale
- Chord = 0.457m (1.5 ft)

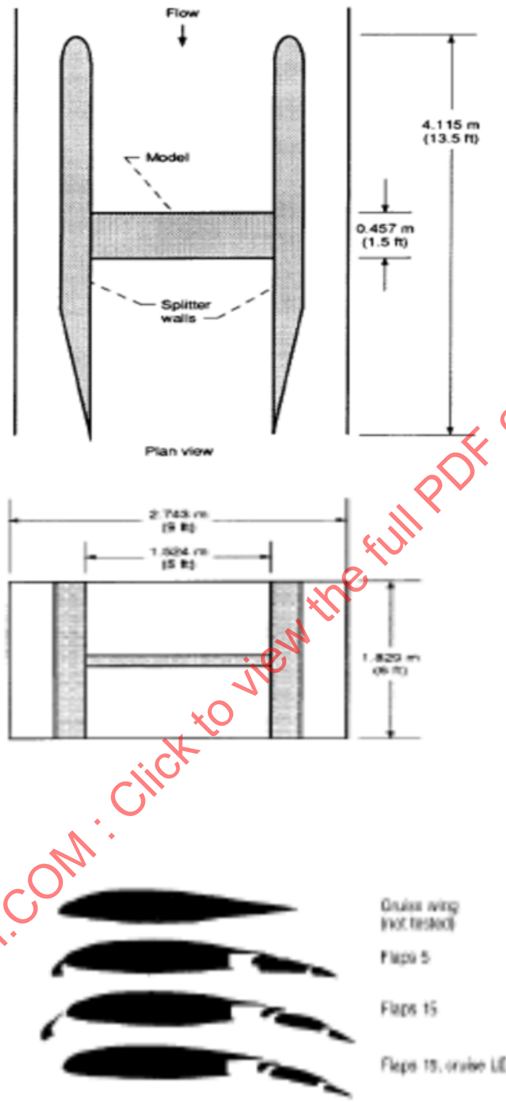

Figure A4 - 2D model

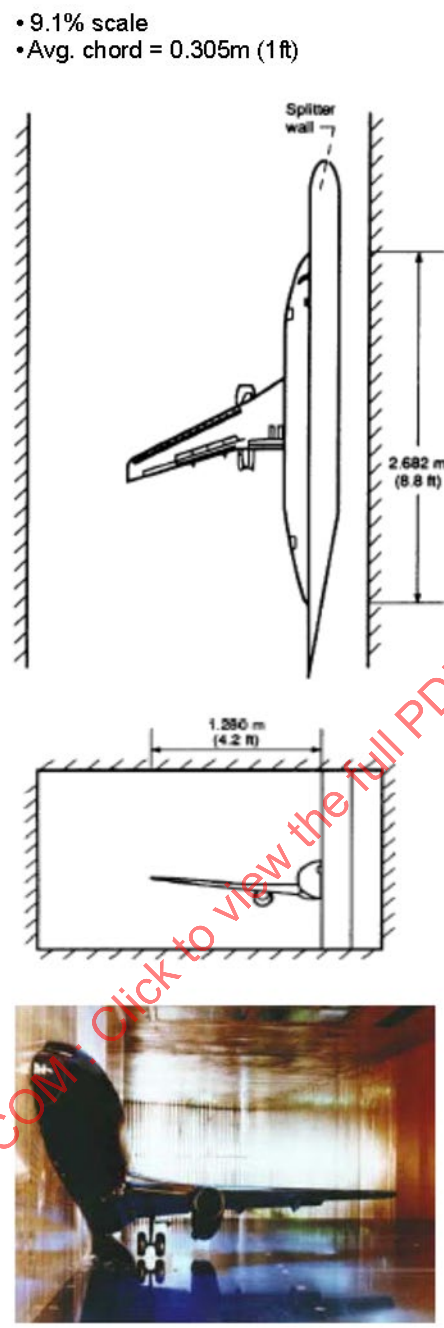

Figure A5 - 3D model

[Diagram/photo source references: Nos. A.8, A.9, A.11, A.14, and A.15 (and possibly more)]

Boundary layer data, gathered utilizing a rake of 10 total and one static pressure probe located at the trailing edge of the 2D model, clearly showed the effect of the fluids. The boundary layer displacement thicknesses were calculated from these data and correlated to the 3D maximum lift losses. This correlation between fluid effects on the boundary layer displacement thickness (BLDT, or δ*) and effects on airplane performance made possible one of the primary Phase II test objectives: development of a methodology for a test to determine aerodynamic acceptance of specific fluids.

In 1988 the AIA TC 218-4 group (which included Airbus, Boeing, British Aerospace, Fokker, McDonnell Douglas, AEA, and the von Karman Institute for Fluid Dynamics) had begun considering the aerodynamic effects of fluids. Results of the Boeing tests were supplemented by research conducted at the von Karman Institute. The von Karman testing established that fluid flow-off characteristics could be replicated on a flat plate in a wind tunnel operating at takeoff speeds and temperatures, and that a correlation existed between the flat-plate BLDT and the lift loss on a 2D wind tunnel model. By measuring a fluid's BLDT on a flat plate in a small, cooled wind tunnel, a direct correlation to 3D lift losses due to fluids could be made, and therefore a relatively simple aerodynamic acceptance test was possible.

Several considerations laid the foundation for an aerodynamic acceptance test, the most important of which was that airplane safety is paramount. Other considerations included the transitory nature of fluid effects and the history of safe fluid use. Five criteria based upon airplane takeoff performance were identified:

1. Takeoff safety speed margin to 1-g stall speed.

2. Liftoff speed margin to minimum unstick speed.

3. Aft body runway clearance.

4. Takeoff acceleration and climb capability.

5. Maneuver capability to stall warning.

The first was deemed most critical. A 10% speed margin was applied (V2 = 1.10 VS1g). For a V2 speed equal to the minimum regulatory requirement of 1.13 VS1g for a clean, dry wing, the resultant maximum acceptable CLmax loss due to fluid, reducing the V2 speed to 1.10 VS1g, is 5.24%.

The test correlations showed that a 5.24% lift loss resulted in a maximum acceptable fluid BLDT of 9.15 mm. However, the data indicated that at warmer temperatures, the fluid BLDT was thinner. The proposed BLDT acceptance criterion was therefore set at a constant 9.15 mm for temperatures up to -20 °C and then linearly decreased with increasing temperature. This was the origin of the aerodynamic acceptance Test (refer to AS5900).

A.2 APPENDIX A REFERENCES

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APPENDIX B - BOMBARDIER HISTORY - EVALUATIONS OF THE EFFECTS OF DEICING/ANTI-ICING FLUIDS ON AIRCRAFT AERODYNAMICS

B.1 INTRODUCTION

What are now classified as SAE Type I fluids, primarily ethylene-glycol based, have been used for many years to remove accumulated ice prior to flight without reported aerodynamic degradation. In the early 1980s, a new class of fluids was developed: non-Newtonian, “thickened” fluids (initially SAE Type II, followed by Types IV and III). These thickened fluids absorb incoming precipitation, delaying the accumulation of frozen contamination for significant periods. In 1988, several European DHC-8 operators reported difficulty during rotation, which resulted in an increase in rotation speeds under certain conditions when Type II fluids were applied. Bombardier (then Boeing Canada, de Havilland Division) issued an Advisory Notice (refer to Reference B9) to alert operators to adverse aerodynamic effects attributable to fluid formulations from 1988 and earlier, and a limited ambient temperature qualitative wind tunnel test of a particular fluid in question was conducted. The test was performed at the National Aeronautical Establishment (“NAE”) 9 x 6 feet low-speed wind tunnel on a 0.25-scale DHC-8 empennage.

The results of the test were qualitative since the balance system was designed to measure only static loads. The video records of these tests showed that when the elevator was deflected, the fluid migrated from the upper surface of the tail plane through the gap ahead of the elevator to the lower, aerodynamically active, surface of the elevator. The resulting wave-induced roughness was expected to significantly degrade the elevator performance and possibly the ability to rotate the aircraft. Figure B1 shows the model set-up.

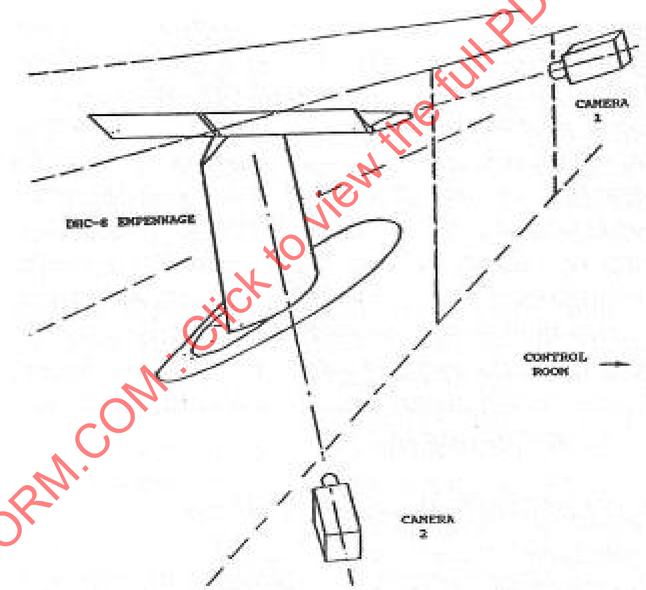

Figure B1 - 0.25-scale DHC-8 empennage model set-up

At the same time, Boeing performed flight and wind tunnel tests with fluids (see Appendix A). Boeing identified lift losses and drag increases for their jet aircraft, which could be expected to affect turbo-prop commuter aircraft as well. A more comprehensive investigation of the effects of these fluids for turbo-prop commuter aircraft types was necessary.

A test of the wing/flap and tailplane/elevator models in an icing wind tunnel was selected as the most appropriate approach to determine the aerodynamic effects of thickened fluids for two model configurations (a wing with a flap and a tailplane with an elevator) at rotation speeds and times typical of commuter aircraft operations. Although testing with relatively small models in a wind tunnel raises the question of scale effects, flight-testing, because of the transient presence of the fluid, is not appropriate for examining the critical cases of CLmax loss and single-engine climb gradient. Also, flight testing a matrix of various fluid formulations and concentrations at different temperatures, configurations, and rotation speeds would not have been economically viable. Finally, previous Boeing tests (refer to Reference B.10) showed a good correlation between flight test and wind-tunnel test data at climb angles of attack, in spite of the small model scale.

The primary objective of the de Havilland test was to obtain data that would contribute to understanding the aerodynamic effects of ground deicing/anti-icing fluids on aircraft, particularly for the commuter and larger general aviation types. The test provided a basis for providing advice to operators regarding the use of these fluids. The results of this test also contributed to the database for establishing an aerodynamic acceptance standard for fluids applicable to the lower takeoff rotation speeds of commuter and general aviation types of aircraft.

B.2 WIND TUNNEL TEST

The wind tunnel test was conducted at the NASA IRT in the early part of 1990 with a new formulation of fluids. This test was a joint effort among Boeing Canada, de Havilland Division (BCDD); Transport Canada Transportation Development Centre (TDC); and NASA IRT. Ten fluid manufacturers assisted in the test by providing fluids. BCDD built, instrumented, and installed the models; planned and conducted the test; and analyzed the data. TDC shared with BCDD the cost of building and testing the model. NASA IRT provided and operated the tunnel, assisted with the model installation, the conduct of the test, and recording of the data. The test was conducted immediately following Boeing's second entry (Phase II) in the IRT, discussed in Appendix A.

The models tested had the wing/flap and the tailplane/elevator configurations as shown in Figure B2. The scale of the wing/flap model is 0.2 and the tailplane/elevator model is 0.35. The wing/flap configuration is a 2D section of the DHC-8 wing at the MAC with the highest takeoff flap setting (15 degrees). The tailplane/elevator model is a simulated DHC-8 tailplane section with both a nose-balanced and a round-nose elevator.

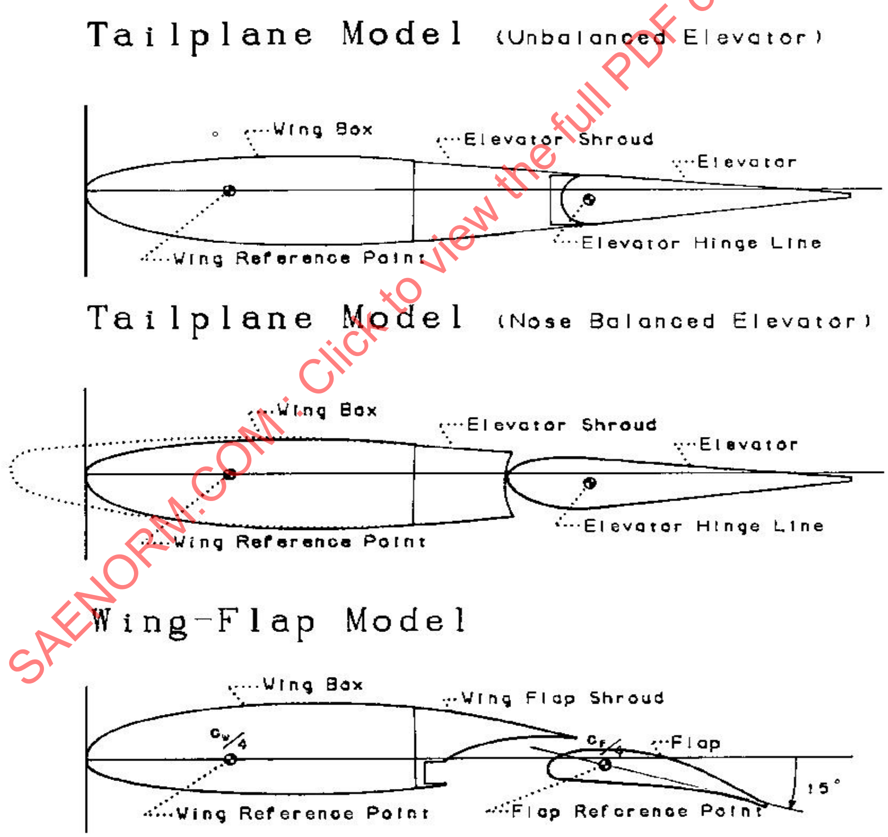

Figure B2 - Geometry of DHC-8 wing/flap and tailplane/elevator 2D models

The test parameter matrix as presented in Table B1 shows the Type I, Type II, and the Type III (then called Type I.5, or "turbo-prop fluids") at different concentration, temperature, configuration, and rotation speeds were tested for the wing/flap model and, where appropriate, for the tailplane/elevator model.

Table B1 - Test parameter matrix

AIRCRAFT GROUND DE-ICING/ANTI-ICING FLUIDS WIND TUNNEL TEST

2ND ENTRY IN NASA LEWIS IRT (PHASE II)

Test Description	V_{ROT} (KT)	Dry /SS	Type I					Turbo-Prop Prod.		Turbo-Prop Exp.			Type II Production				Type II Experimental				
			1	2	3	4	19	5	6	7	8	9	10	11	12	13	14	15	16	17	18
		Codes	4.5	1	8	9.1	10	3.3	5.3	4.6	5.2	2.4	3.2	4	2.2	5.1	4.3	7.1	7.2	5.1	8.1
Wing/Flap Model (δ_F = 15°, α ramp 0 to 20°)																					
Ambient Temperature Baseline	60	1/1																			
Temperature 0°C Full Strength	60 & 80	14/2	~~2~~ **1**	2	2	2		2	2	2	2	2	2	2	2	2	2	2	2	2	2
75:25 Dilution	60 & 80	2/0						2		~~2~~ **1**	2		2	2						**2**	
50:50 Dilution	60 & 80	2/0											2	2	**1**						
10% and 20% Contamination	60 & 80	2/0											~~4~~								
Temperature -10°C Full Strength	60 & 80	4/0						2		2	2		2	2							
75:25 Dilution	60 & 80	2/0											2	2							
50:50 Dilution	60 & 80	0/0											2	2							
10% and 20% Contamination	60	2/0															~~2~~ **3**				
Temperature -20°C Full Strength	60 & 80	6/0						2	**2**	2	2	**2**	2	2	2		**2**			**2**	**2**
Temperature -29°C Full Strength	60 & 80	4/2	2	2	2	2	**2**														
50:50 Dilution	60 & 80	2/0	2	2	2																
Tailplane/Nose Balanced Elevator Model, α = 0°																					
Ambient Temperature Baseline, δ_e ramp 0 to -30°	60	1/1																			
Temperature 0°C Full Strength, δ_e ramp 0 to -30°	60 & 80	2/2						2					2								
Full Strength, δ_e ramp 0 to -20°	60 & 80	2/0						2					2								
Temperature -20°C Full Strength, δ_e ramp 0 to -30°	60 & 80	2/2						2					2	**1**							
Full Strength, δ_e ramp 0 to -20°	60 & 80	2/0						2					2								
Temperature -29°C Full Strength, δ_e ramp 0 to -30°	60 & 80	2/2	2		2																
50:50 Dilution, δ_e ramp 0 to -30°	60	2/0	1		1																
Full Strength, δ_e ramp 0 to -20°	60 & 80	2/2	2		2																
50:50 Dilution, δ_e ramp 0 to -20°	60	2/0	1		1																
Tailplane/Round Nose Elevator Model, α = 0°																					
Ambient Temperature Baseline, δ_e ramp 0 to -30°	60	1/1																			
Temperature 0°C Full Strength, δ_e ramp 0 to -30°	60 & 80	2/2						~~2~~ **3**					2								
Full Strength, δ_e ramp 0 to -20°	60 & 80	2/0						2					2								
Temperature -20°C Full Strength, δ_e ramp 0 to -30°	60 & 80	2/2						~~2~~ **3**					2								
Full Strength, δ_e ramp 0 to -20°	60 & 80	2/0						2					2								

Legend: plain type (eg. 2) ... Number of runs planned and tested
struck through or crossed out (eg. ~~2~~ or ~~4~~) ... Number of runs planned but either dropped or count revised.
bold and underlined (eg. **3**) ... Number of runs added or count revised

100% Program:

Wing/Flap Model:	100 wet runs,	32 dry runs,	146 total runs
Wing/Elevator Model:	44 wet runs,	46 dry runs,	76 total runs
Model Test Program:	144 wet runs,	78 dry runs,	222 total runs

Takeoff acceleration profiles for both the DHC-6 (lower rotation speed of 60 kts) and DHC-8 (higher rotation speed of 80 kts) were tested.

To simulate a takeoff, the takeoff acceleration profile as shown in Figure B3 was used.

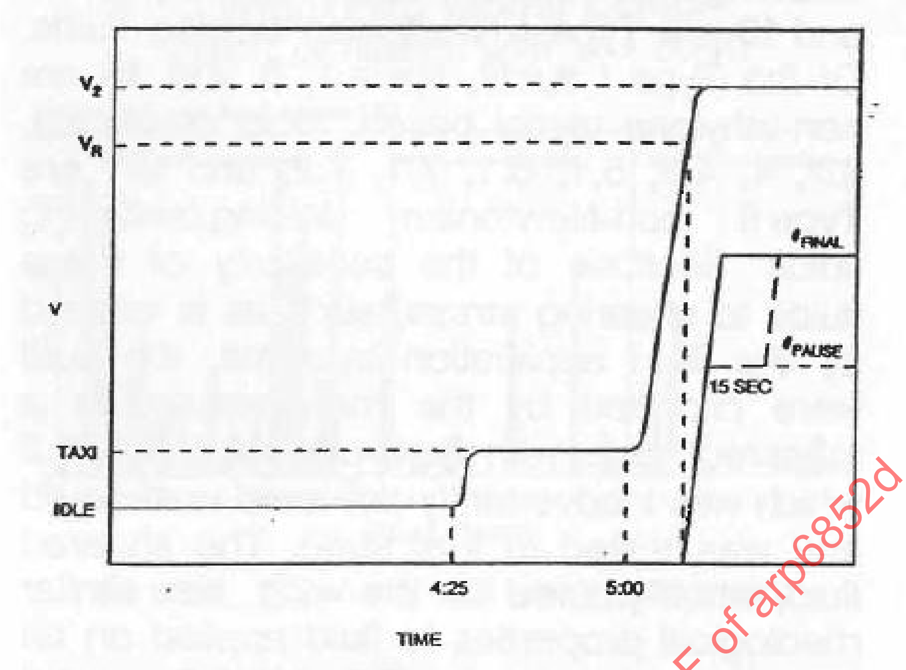

Figure B3 - Wind tunnel takeoff acceleration profile

The tunnel was idle at a speed of 6.2 m/s (12 kts) for about 4 minutes and 30 seconds; it was then run at 12.3 m/s (24 kts) for 30 seconds to simulate taxi. The time spent at these speeds was not long enough to cause significant clearing of the fluid. The tunnel was then linearly increased to a V2 speed of 36 m/s (70 kts) at an acceleration rate of 2.1 m/s^2 (4 kts/s), or 45.3 m/s (88 kts) at 2.6 m/s^2 (5 kts/s), as appropriate, for a rotation speed of 30.9 m/s (60 kts) comparable to the DHC-6, or 41.2 m/s (80 kts) comparable to the DHC-8. After 15 seconds, the wing/flap model was rotated from 0 to 20 degrees at 4 degrees/s; or, for the tailplane/elevator model, the elevator trailing edge was deflected up from 0 degrees to the desired deflection at the rate of 24 degrees/s. The run was continued for 30 seconds past the end of the model rotation or elevator deflection.

The fluids tested are summarized in Table B2.

Table B2 - Test fluids

TEST FLUIDS

Type I Deicer Fluids	Code	Fluid Base[1]	Fluid Status[2]
1. Union Carbide (USA) UCAR ADF IID	4.5	(EG)	Production
2. Hoechst VP 1732	1	(DG/PG)	Production
3. Octagon ADF-1427	6	(PG)	Production
4. Technoshield Airborne 99	9.1	(EG)	Production
19. MIL-A-8243D	10	(PG/EG)	Production
Turbo-Prop Deicer/Anti-icer Fluids			
5. Hoechst VP 1788	3.3		Production
6. SPCA (France) AD 106	5.3		Production
7. Union Carbide Canada 5.3	4.6		Experimental
8. Octagon ADF Plus	6.2	(PG)	Experimental
9. Kilfrost (Arco)	2.4		Experimental
Type II Deicer/Anti-icer Fluids			
10. DOW FLIGHTGARD 2000	3.2		Production
11. Union Carbide Canada AAF 250-3	4		Production
12. Kilfrost (Arco) ABC3	2.2		Production
13. SPCA AD 104	5.1		Production
14. Union Carbide Canada 5.1	4.3		Experimental
15. Texaco TWD P5	7.1	(PG)	Experimental
16. Texaco TWD E5	7.2	(EG)	Experimental
17. Octagon	6.1		Experimental
18. BASF Aerex 21173	8.1	(PG)	Experimental

Notes:

- DOW Flight Guard 2000 is Hoechst 1704 LTV/88 sold under license
- Kilfrost products sold under license by Arco
- EG ... Ethylene Glycol Base
- DG ... di-Ethylene Glycol Base
- PG ... Propylene Glycol Base

[1] Fluid base as understood at time of test
[2] Fluid status as understood at time of test

Detail descriptions of the IRT, models and installation, data system and measurement, test procedures, and limitations are presented in Reference B.7.

B.3 TEST RESULTS

The fluids are classified in the following figures with fluid codes, as indicated in Table B2. Because of the sensitivity of the fluids to shearing stress, such as is caused by the fluid application systems, the fluids were provided by the manufacturer in a “sheared” state, with the exception of fluid 3.2, which was inadvertently delivered unsheared and was tested in that state. The sheared fluid, when poured on the wing, has similar rheological properties to fluid applied on an aircraft. Since the test, fluids 2.4, 4.6, 5.3, 7.1, and 7.2 (an experimental fluid) were discontinued. For Figures B4, B5, B7, and B9, a line is shown at 8% lift loss, which represents an acceptable transient loss of clmax. Similarly, for Figures B6, B8, and B10, a line is shown at 0.008, which is considered to represent an acceptable transient loss of climb gradient. A more detailed discussion can be found in the Performance Considerations section below. Figures B4 and B5 show the effects of temperature on the lift losses at maximum lift for the undiluted fluids. Most of the Type II fluids and the turbo-prop fluids have lift losses greater than 10% at some temperature. For the Type I fluids containing non-ethylene glycol, where viscosity increases sharply with decreasing temperature, the lift losses at -29 °C (-20 °F) are well above 20%. The data for Figures B4 and B5 are at rotation speeds of 30.9 m/s (60 kts) and 41.1 m/s (80 kts), respectively, and the time to rotate to those speeds from the beginning of acceleration to rotation is 15 seconds. The lift loss does not seem to be affected very much by the two different rotation speeds.

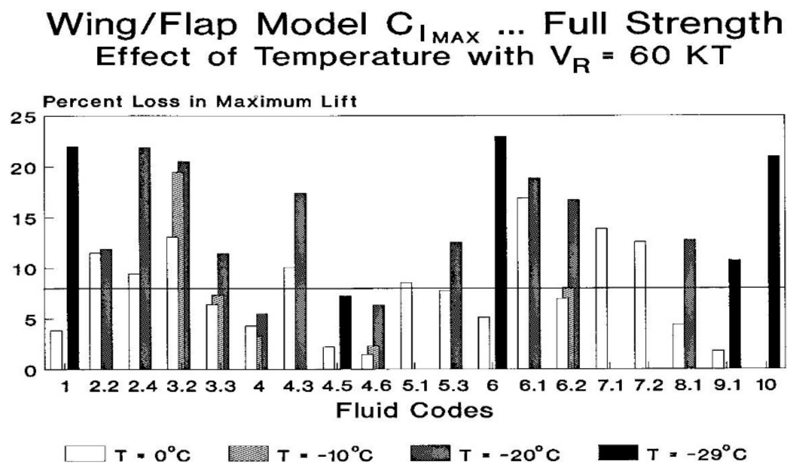

Figure B4 - Wing/flap model decrement in clmax, undiluted fluids, V_{rot} = 60 kts

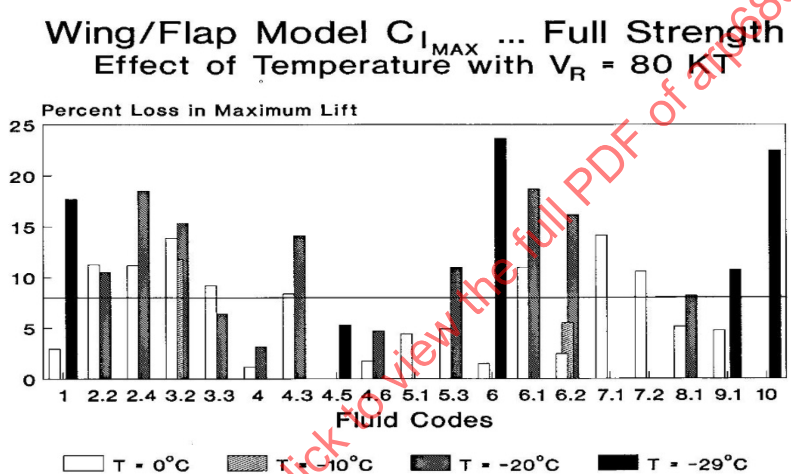

Figure B5 - Wing/flap model decrement in clmax, undiluted fluids, V_{rot} = 80 kts

The results for a rotation speed of 80 kts in Figure B6 show that climb gradient losses at minimum climb-out speed correlate well with the lift losses at maximum lift in Figure B5. This is also true for a rotation speed at 60 kts.

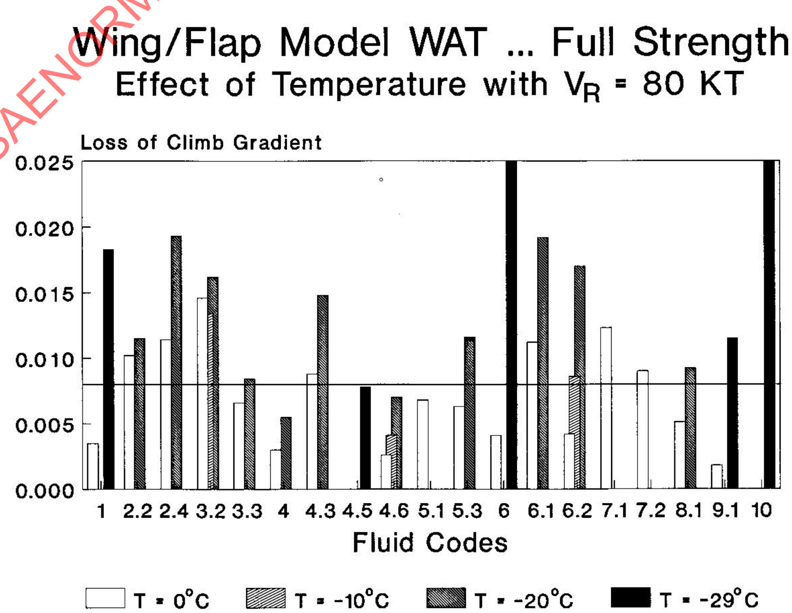

Figure B6 - Wing/flap model decrement in climb gradient at V2, undiluted fluids, V_{rot} = 80 kts

The effect of fluid dilution on lift losses at maximum lift and loss of climb gradient are shown in Figures B7 and B8 (for rotation speed of 80 kts). Both the lift loss and the loss of climb gradient are reduced as the fluids become more diluted, with the exception of one fluid (No. 3.2); this is also true for a rotation speed of 60 kts. For that fluid at a 75:25 dilution (fluid:water), the losses remain fairly similar to those of a 100% fluid concentration. This is to be expected, as this fluid has a peculiar behavior in which viscosity increases as the fluid is diluted to 75:25 concentration and then subsequently decreases with further dilution. Although most diluted fluids have reduced lift loss and loss of climb gradient relative to neat fluids, the holdover times are also reduced.

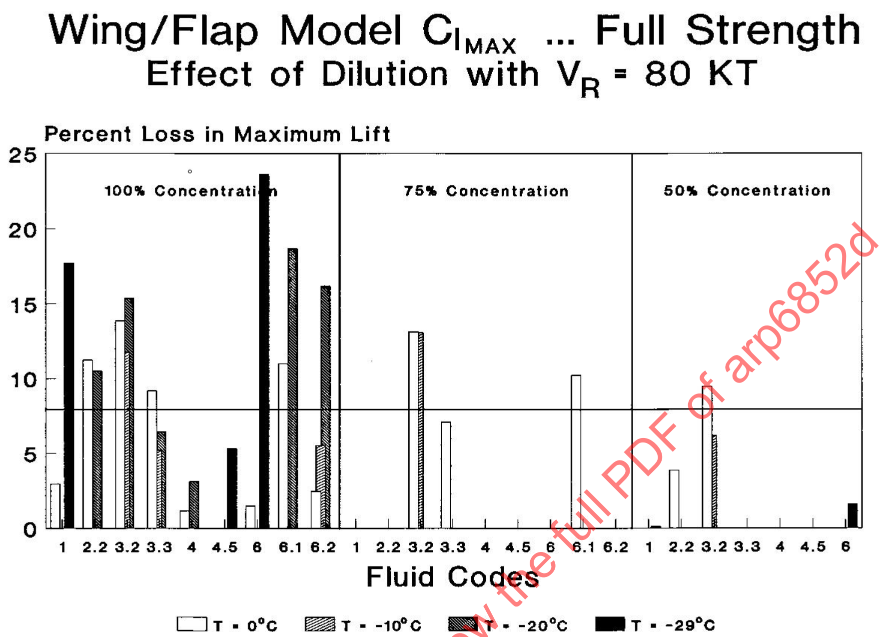

Figure B7 - Wing/flap model decrement in clmax, fluid dilution = Vary, V_{rot} = 80 kts

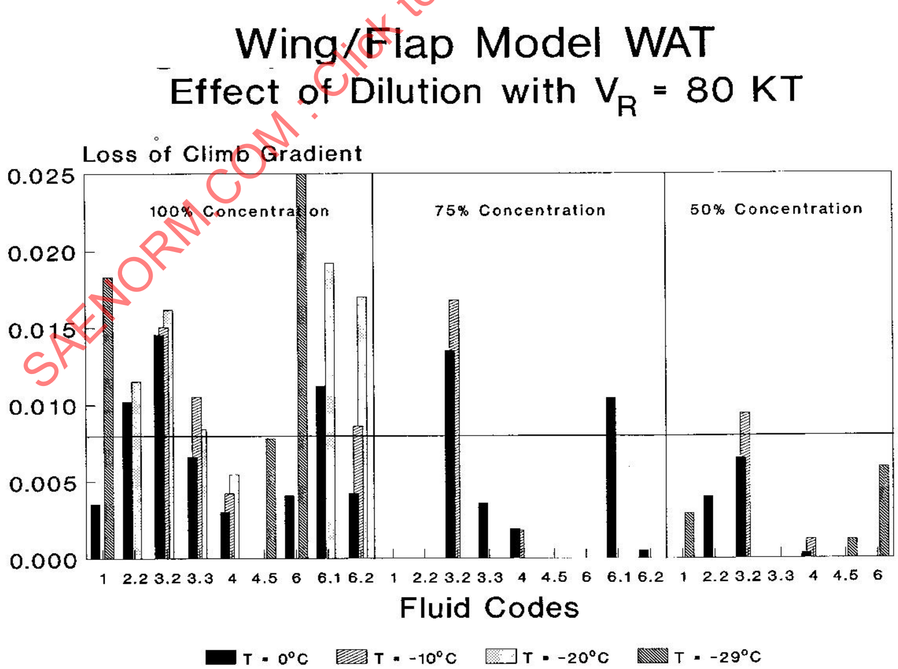

Figure B8 - Wing/flap model decrement in climb gradient at V2, fluid dilution = Vary, V_{rot} = 80 kts

The effect of increasing the time to rotation is presented in Figures B9 and B10. This shows that an increase from 15 to 30 seconds results in a substantial reduction in both lift losses at maximum lift and the loss of climb gradient. The extra time, as evident from viewing the motion of the fluid during the tests, allows a considerable amount of the fluid to be cleared from the model whereas very little, if any, is cleared from the model for the shorter rotation time.

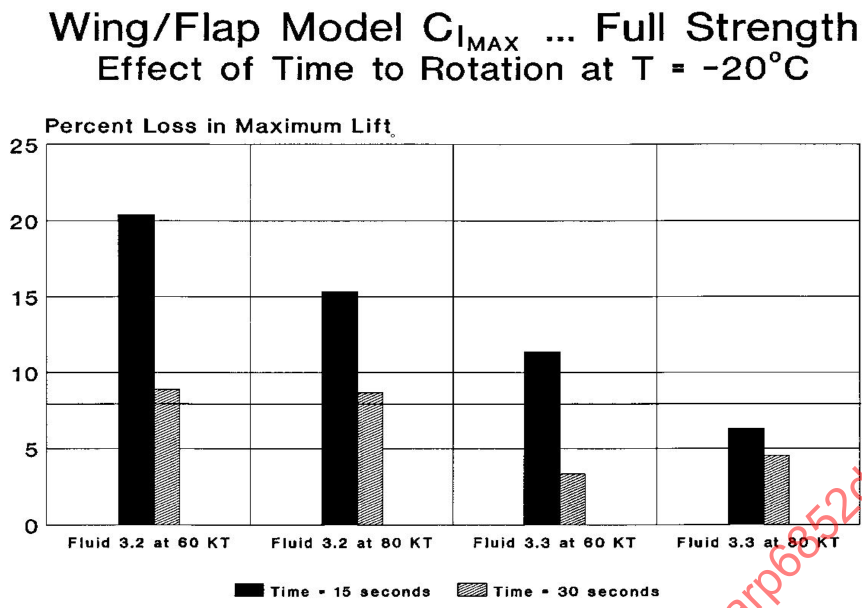

Figure B9 - Wing/flap model decrement in clmax, undiluted fluids

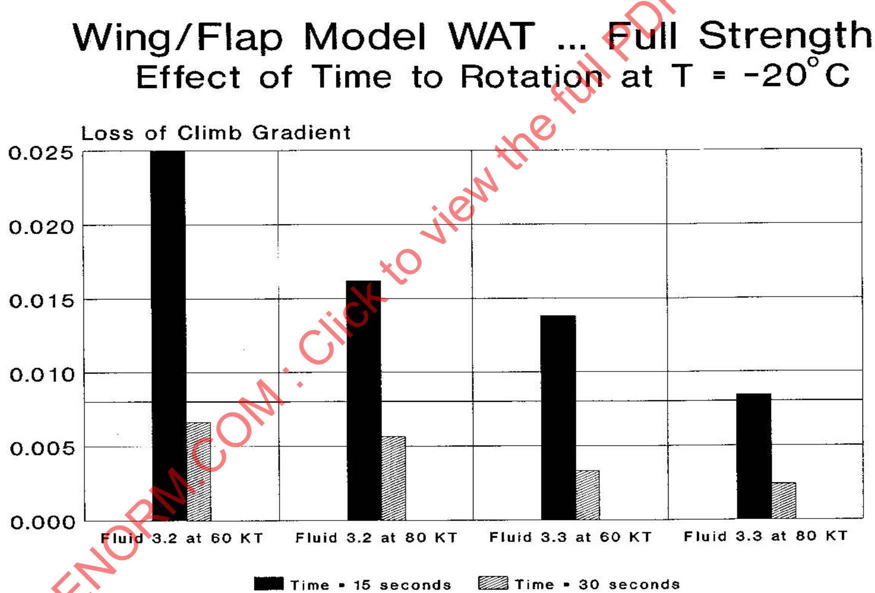

Figure B10 - Wing/flap model decrement in climb gradient at V2, undiluted fluids

B.4 SUMMARY OF TEST RESULTS

The magnitude of the degradation in the maximum lift and climb gradient at climb-out for the wing/flap model appears to differ for each fluid, rotation speed and time to rotation, range of temperature, and fluid dilution.

The most significant finding is the effect of increasing the time to rotation. Tests showed that one fluid (No. 3.2, a Type II) had no significant clearing of the fluid from the wing/flap model for a rotation time of 15 seconds, resulting in a large aerodynamic penalty which is considered unacceptable. When the same fluid was exposed to a 30 second rotation time, there was a significant improvement even with a lower rotation speed; most of the degradation caused by reducing the rotation speed was gained back. This phenomenon undoubtedly exists for most of the fluids tested. Therefore, this substantial improvement with the longer time to rotation would make those fluids acceptable as well.

From the results of this test, it is clear that deicing/anti-icing fluids have a more significant impact on commuter-type aircraft operating with a shorter time to rotation and lower rotation speed than large jet aircraft.

These results also provide a database for the aerodynamic acceptance testing of future fluids.

A full summary of the test results, including those of the tail plane/elevator model, is presented in Reference B.7.

B.5 PERFORMANCE CONSIDERATIONS

When scheduling airplane takeoff performance, criteria for ensuring adequate safety margins with one engine failure and with the degradation due to deicing/anti-icings fluids must be considered. The major concern is the increased potential of inadvertently stalling the wing.

The first criteria, and the most critical, are an adequate margin to stall and the maneuver capability to stall warning. For the DHC-8 type of aircraft, a loss of 8% in maximum lift, as presented in References B.8 and B.7, would leave the aircraft capable of 30-degree banked turns with no margin to stall remaining. This reduced margin may be acceptable for the short period between liftoff and further clearing of the fluids, when the following mitigating circumstance for two-engine, propeller-driven aircraft is considered: A sizeable portion of the wing (about 30%) is immersed in the propeller slipstream from the moment of power application and will thus have substantially more fluid cleared than the rest of the wing. Even in the case of an engine failure, a portion of the wing will provide powered lift from the remaining engine and will increase the margin to stall.

The test correlations showed that an 8% lift loss resulted in a maximum acceptable fluid at a constant BLDT of 10.6 mm as discussed in Reference B.12. This is the basis of the aerodynamic acceptance test (low-speed ramp) (refer to AS5900) for a commuter-type aircraft with wing-mounted propellers.

The second criterion is the ability of the aircraft to climb with the aerodynamic performance degradation caused by fluids. For two-engine airplanes, airworthiness regulations require a 0.8% margin between the gross and net climb gradient. A reduction of 0.8% from the net climb gradient will leave the airplane with no margin between gross and net gradient. This may be deemed acceptable because the reduction is temporary due to the transient presence of the fluid. Also, the climb capability of the airplane is at its minimum performance level under hot and high conditions, not at lower temperatures where these fluids are applied. Therefore, some margin will likely exist.

As for the effect of degradation in elevator effectiveness at the liftoff speeds for the Dash 8, as discussed in Reference B.11, lift degradation of 10% for the tail plane was considered insignificant.

B.6 APPENDIX B REFERENCES

B.1 "Adverse Aerodynamic Effects Attributed to Old AEA Formulation (1987-88) Type II De-Ice/Anti-Ice Fluids," Advisory Notice No. 34, Boeing Canada, de Havilland Division, 1988.

B.2 Carbonaro, M., Locatelli, C., Mantegazza, C., McSpadden, C., and Moller, I., "Experimental Study of the Flow of a Film of Aircraft De-Icing Fluid during a Simulated Take-off at Subfreezing Temperature," Report No. 1985-02, von Karman Institute for Fluid Dynamics, 1985.

B.3 Carbonaro, M., "Experimental Study of the Aerodynamic Characteristics of a Two-Dimensional Wing Model Covered with De/Anti-Icing Fluid during a Simulated Take-off at Subfreezing Temperatures," Report No. 1986-22, von Karman Institute for Fluid Dynamics, 1986.

B.4 Carbonaro, M., "Further Study of the Aerodynamic Performance of a Two-Dimensional Wing Model Covered with Simulated Frost or with De/Anti-Icing Fluid During a Wind Tunnel Simulated Take-off at Subfreezing Temperature," Report No. 1987-29, von Karman Institute for Fluid Dynamics, 1987.

B.5 Cruse, D.L. and Zierten, T.A., "Boeing/Association of European Airlines (AEA) Evaluation of the Aerodynamic Effects of Aircraft Ground De-/Anti-Icing Fluids," Society of Flight Test Engineers Nineteenth Annual Symposium, 1988.

B.6 "De/Anti-Icing Fluid, Aircraft," Material Specification, Association of European Airlines.

B.7 Ellis, N.D. and Lim, E., "Effects of Anti-icing/Deicing Fluids on the Take-off Performance of Commuter Aircraft," Report No. TP 10838E, DHC-TDC 90-1, Canadian Transportation Development Centre, 1991.

B.8 Ellis, N.D. Lim, E., Teeling, P., and Zhu, S., "Wind Tunnel Tests of Aerodynamics Effects of Type I & II Ground De/Anti-icing Fluids on Small Transport & General Aviation Aircraft During Takeoff," Paper No. AIAA-91-0763, 1991.

B.9 Hendrickson, G.S. and Hill, E.G., "Effects of Aircraft De-/Anti-Icing Fluids on Airfoil Characteristics," von Karman Institute for Fluid Dynamics Lecture Series, "Influence of Environmental Factors on Aircraft Performance," 1987.

B.10 Hill, E.G. and Zierten, T.A., "Flight and Wind Tunnel Tests of the Aerodynamic Effects of Aircraft Ground Deicing/Anti-Icing Fluids," Paper No. AIAA-91-0762, 1991.

B.11 Lim, E., Ellis, N., Teeling, P., and Zhu, S., "Aerodynamic Impact of Deicing/Anti-Icing Fluids on Commuter Aircraft," SAE Technical Paper 911026, 1991, https://doi.org/10.4271/911026.

B.12 Louchez, P., Laforte, J.-L., and Bouchard, G., "Boundary Layer Evaluation of Anti-Icing Fluids for Commuter Aircraft," Report No. TP11811E, Transport Canada, 1994.

APPENDIX C - SAAB AB METHODOLOGY - DETERMINING AIRCRAFT PERFORMANCE CORRECTIONS WHEN DEICING/ANTI-ICING FLUIDS ARE APPLIED

C.1 METHODOLOGY

This appendix describes the methodology used by Saab AB to determine aircraft performance corrections when aircraft ground deicing/anti-icing fluid ("fluid") is applied.

SAE Type I, II, III, and IV fluids, qualified according to AMS1424 and AMS1428, are approved for use on the Saab 340 and Saab 2000, provided that the procedures in AOM Supplement No. 1 (Operations in cold weather and icing conditions) are used. The AOM supplement presents the recommended aircraft performance corrections when fluid is applied.

During 1989 to 1990, the Aerospace Industry of America (AIA) Transport Committee (TC) Project 218-4 established criteria which defined acceptable flow-off behavior for fluids. The AIA TC Project 218-4 was chaired by Boeing, and the active members included representatives from Airbus Industry, British Aerospace, Fokker, McDonnell Douglas, and with contributions from the Association of European Airlines. Based on research performed by Professor Mario Carbonaro at the von Karman Institute for Fluids Dynamics and Boeing 737-200ADV wind tunnel results in the NASA IRT, a fluid acceptance predicated on fluid flow-off characteristics over a flat-plate at operational temperatures and airspeed was selected. Fluid flow-off behavior is defined by measuring the fluid effect on the Boundary Layer Displacement Thickness (BLDT) on a flat-plate. Acceptability of the fluid flow-off behavior is determined by comparing the BLDT with that found to produce acceptable airplane performance on the Boeing 737-200ADV. The premise of the acceptance test is that the BLDT is a valid indicator of the fluid's aerodynamic effects; increased BLDT caused by the fluid results in increased adverse aerodynamic effects (increased lift loss and drag increase). Reference C2 presents information that forms the technical basis of the AAT for fluids. The AAT is described in AS5900 and is required by AMS1424 and AMS1428 to qualify a fluid for aerodynamics. The AAT is also included in the ISO specifications for fluids.

In 1992, Professor Mario Carbonaro at the von Karman Institute for Fluids Dynamics continued the above investigation with a study of aerodynamic effects of fluids for commuter airplanes (refer to Reference C.4). One figure of that report is copied to show the linear correlation of lift loss with BLDT (see Figure C1).

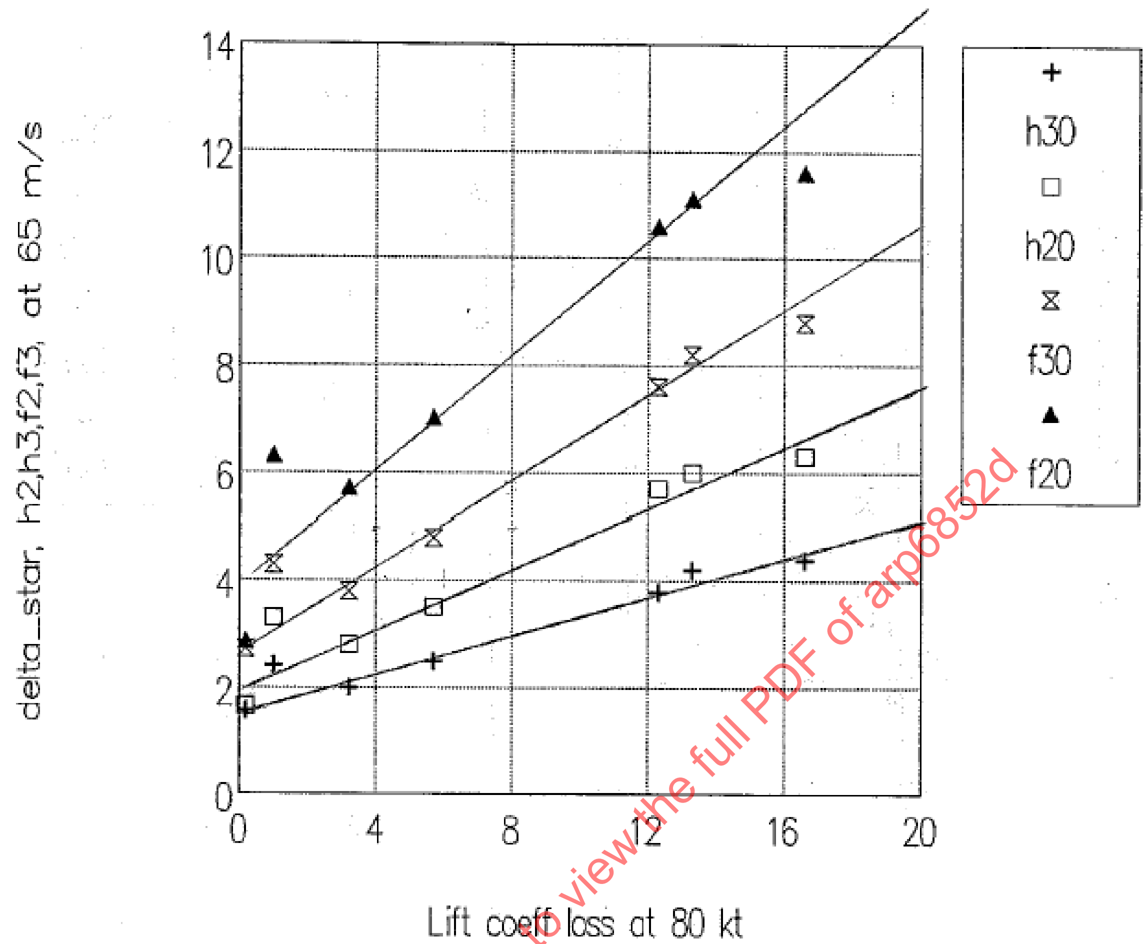

FIG. 15 LIFT COEFFICIENT LOSS CORRELATIONS

Legend: delta_star is equal to BLDT
h2 = h20 BLDT measured at half the flat-plate length after 20 seconds
h3 = h30 BLDT measured at half the flat-plate length after 30 seconds
f2 = f20 BLDT measured at end of the flat-plate after 20 seconds
f3 = f30 BLDT measured at end of the flat-plate after 30 seconds

"Lift coeff loss at 80 kts" is the percentage lift loss due to several fluids from measurements in NASA IRT with the 45% semi-span section of the De Havilland Canada DHC-8 Series 100 with flaps 15 degrees. The model scale was 20%.

Figure C1 - Correlation of lift loss with BLDT
Copied from Reference C.2

The methodology used by Saab AB to determine the aircraft performance corrections for fluids is primarily based on the principle behind the AAT, i.e., a linear correlation of lift loss with BLDT.

Saab has performed flight tests with and without fluid to determine the effect of the fluid on aircraft performance and handling. The flight tests were performed in 1998 and 1999.

The Saab 340 and Saab 2000 aircraft performance corrections, when fluids are applied, have been determined as follows:

- Determination of the reference case:

  1. Flight test with and without fluid.

  2. Analysis of flight test data to determine the lift loss and additional drag due to fluid.

  3. AAT wind tunnel data.

     a. AMIL AAT wind tunnel data for fluid used during flight test.

     b. Additional flat-plate wind tunnel tests at Saab 340 and Saab 2000 takeoff speed schedules with fluid used during flight tests.

  4. Calculate delta BLDT = (BLDTfluid - BLDTdry) for the flight test condition based on AMIL AAT wind tunnel data and additional flat-plate wind tunnel data.

  5. Numbers 2 and 4 give the reference case for the determination of Saab 340 and Saab 2000 performance corrections due to fluid.

- Determination of three-dimensional loss in CLmax due to fluid:

  1. Extrapolate the lift loss from flight test to two-dimensional Δclmax by two-dimensional Navier-Stokes CFD calculations with roughness.

  2. Determine three-dimensional ΔCLmax with extended lifting line theory.

- Determination of ΔCLmax for other flight conditions:

  1. Determine the rotation speed as a function of aircraft weight, temperature, altitude, and flap angle.

  2. Determine the time from brake release to maximum angle of attack during rotation as a function of aircraft weight, temperature, altitude, and flap angle.

  3. Numbers 1 and 2 give the rotation speed and time from brake release to maximum angle of attack during rotation for each new flight condition.

  4. AAT Wind Tunnel Data

     a. AMIL AAT wind tunnel data for reference fluid and several other fluids.

     b. Additional flat-plate wind tunnel tests at Saab 340 and Saab 2000 takeoff speed schedules with fluid used during flight tests.

  5. From Numbers 3 and 4, determine (BLDTfluid - BLDTdry) for each new flight condition.

  6. Scale the lift loss from flight test (i.e., maximum lift loss during rotation) with the ratio of (BLDTfluid - BLDTdry) for each new flight condition and (BLDTfluid - BLDTdry) for the reference case.

  7. Extrapolate the lift loss during rotation to ΔCLmax by two-dimensional Navier-Stokes CFD calculations with roughness and extended lifting line theory.

C.2 INITIAL CHECK

The VR (rotation speed) and time from brake release to maximum alpha during the rotation for the various takeoff conditions were compared with the AAT high-speed ramp speed schedule. The VR speed fits well with the HSR AAT speed schedule, but the time from brake release to maximum alpha during the rotation at sea level varies between 16 seconds and 29 seconds, i.e., it is always less than the 30 seconds where the BLDT is checked in the AAT. This indicates that the Saab 2000 might need performance corrections due to fluids.

When comparing the maximum angle of attack during rotation with and without fluids, a difference of about 1 degree was found. Thus, a further assessment of the effect of fluids was initiated.

C.3 FLIGHT TESTS

Flight tests were performed with and without fluid to determine the effect of the fluid on aircraft performance and handling qualities. These tests were performed on a Saab 2000 instrumented prototype and on a Saab 340 series aircraft.

C.3.1 Flight Tests for Flight Handling Qualities

Handling-qualities flight tests were performed to investigate the effect of fluid on:

- Aileron characteristics, by performing rolls immediately after liftoff.

- Elevator characteristics, especially stick force during rotation and required takeoff trim.

Stall-speed flight tests with fluid were not performed since stalls cannot be performed immediately after liftoff due to obvious safety reasons, and if the stalls would be performed at a safe altitude, the fluid would have flown-off significantly.

Handling-qualities flight test results:

- The Saab 2000 is equipped with a manual aileron control system. The aileron control forces were increased by the presence of fluid, but still acceptable.

- The Saab 2000 has a powered elevator control system. Thus, a change in elevator control forces due to fluids is not important. The elevator efficiency during rotation was not affected by fluids.

- The Saab 340 has a manual elevator and aileron control system. The Saab 340 aileron controls have less aerodynamic balance than the Saab 2000 ailerons. Thus, the effect of fluids is less on the Saab 340 compared to the Saab 2000. The required Saab 340 elevator control forces during rotation and elevator trim in takeoff were not significantly changed due to fluids.

C.3.2 Flight Tests for Performance Corrections

Takeoff flight tests with and without fluid were performed to determine the effect of the fluid on aircraft performance. These tests were performed on a Saab 2000 instrumented prototype. The AFM takeoff procedure was used (i.e., normal takeoff with AFM rate of rotation). Normal takeoff runs were preferred to constant-pitch runs to avoid uncertainties regarding validity of fluid flow-off behavior during the constant-pitch runs. Tests were performed with both Flaps 0 and Flaps 15. All tests were performed at about the same aircraft weight (and above minimum control speed limited takeoff weight).

The purpose of the takeoff tests without fluid was to obtain a reference lift curve (CL versus alpha).

The takeoff tests with fluid to determine the performance corrections were performed with neat Clariant Safewing MP IV 1957. This fluid has BLDT characteristics close to the allowed limit according to the AAT, also at higher temperatures (see Figure C2). Thus, lift degradations due to the fluid were obtained close to the maximum allowable BLDT limit. This is important in order to minimize the amount of extrapolation for the most critical flight conditions as the testing was performed at temperatures between -8 °C and +4 °C.

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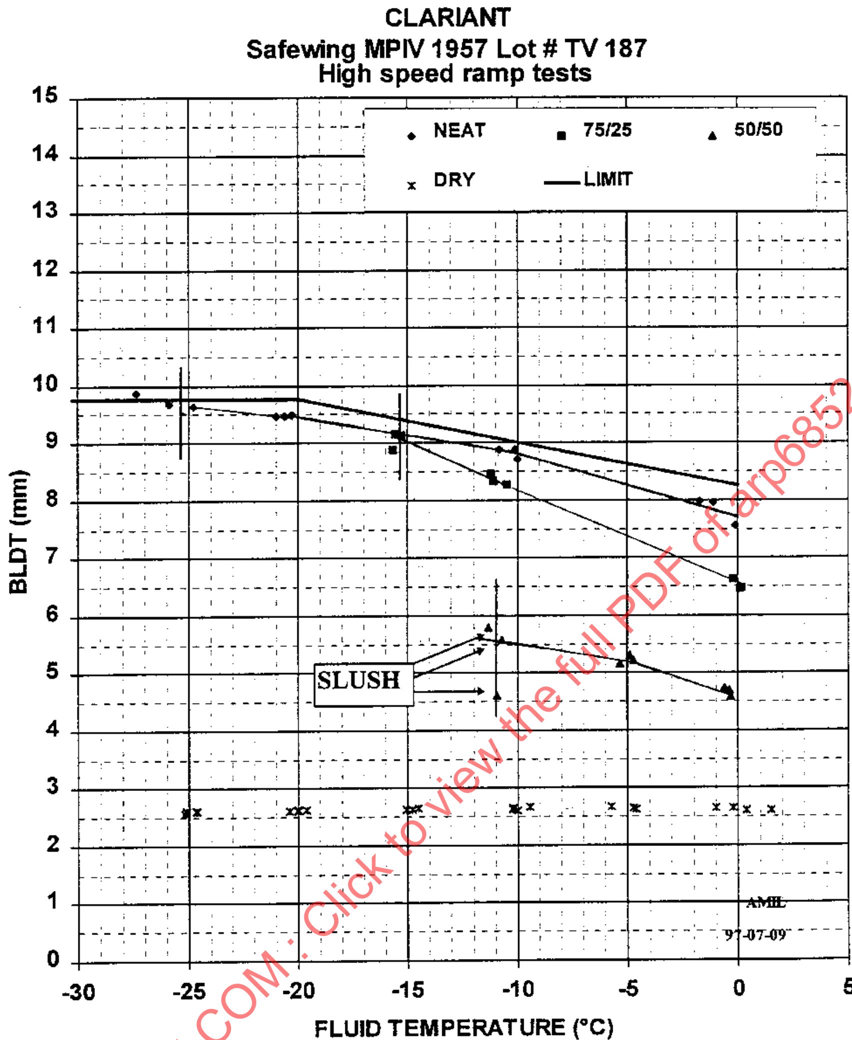

Figure 1 - Aerodynamic Test Results

FP-97-32 *AMIL* *97-07-15*

Figure C2 - BLDT as a function of temperature for Clariant Safewing MP IV 1957
Copied from Reference C.6

Figure C3 presents an example of the lift during takeoff (all data points from liftoff are shown) as a function of angle of attack with and without fluid. This figure clearly indicates that the lift is affected by fluid; however, it is not possible to determine from this figure how much the lift is affected. Therefore, the time-dependent lift contributions due to ground effect, elevator deflection, and pitch rate have to be removed. This was done for all takeoff flight tests, both with and without fluid, by correcting the CL test results to:

- No ground effect.
- Neutral elevator deflection.
- Zero pitch rate.

The correction to no ground effect, neutral elevator deflection, and zero pitch rate also removes the variations in ground effect, elevator deflection (important), and pitch rate between different flights. It is assumed that the lift contribution from ground effect, elevator deflection, and pitch rate is unaffected by fluid.

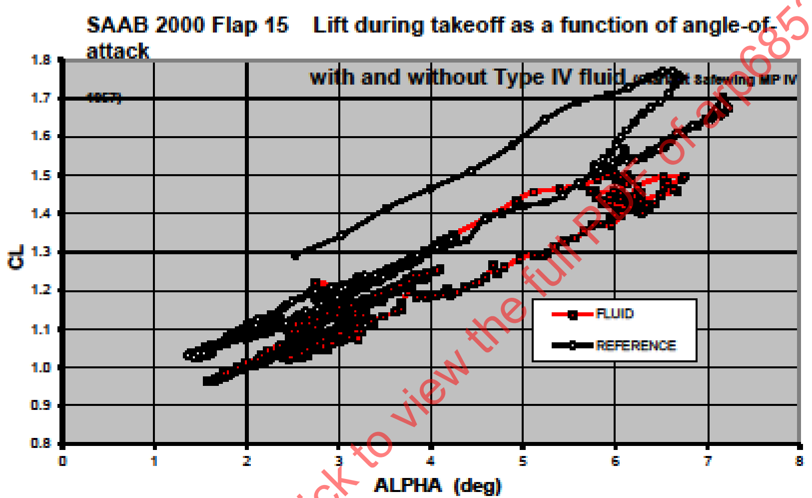

Figure C3 - Lift during takeoff as a function of angle of attack with and without Type IV fluid (Clariant Safewing MP IV 1957)

For the reference cases, i.e., without fluid, a least-square regression line was used to obtain straight CL-alpha curves (using all data points from liftoff). Whether the CL-alpha curve was a correct representation of the measured data was checked. This was done by subtracting the straight CL-alpha curve from the measured CL data, corrected as mentioned above, and this delta CL was plotted as a function of time to check that no time-dependent residues were present. The average of several CL-alpha curves, without fluid, has been used as the “reference CL-alpha curve.”

The lift degradation due to the fluid was obtained by subtracting the “reference CL-alpha curve” from the measured CL data, corrected as mentioned above. This delta lift was plotted as a function of time to determine the highest lift degradation during rotation.

Figure C4 presents an example of the lift loss due to fluid as a function of time. This figure clearly shows that the lift loss is maximum at the highest angle of attack reached during rotation rather than at liftoff, i.e., the first data points at time = 0.

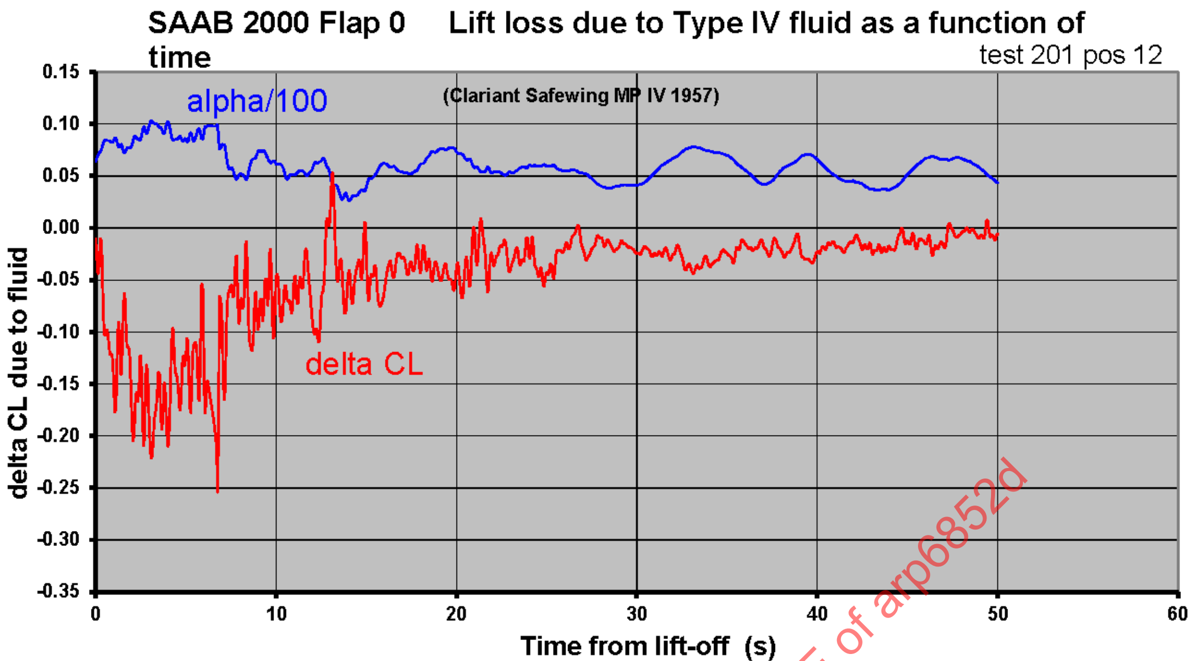

Figure C4 - Lift loss due to Type IV fluid as a function of time

Figure C5 presents a summary of the Saab 2000 lift loss during rotation due to neat Clariant Safewing MP IV 1957. The flight tests were performed at various temperatures, and this confirmed the linear relationship between lift loss and the AAT BLDT.

NOTE: The lift loss presented in Figure C5 is at maximum angle of attack during rotation and not yet corrected to CLmax.

From this data the reference cases for Flaps 0 and Flaps 15 are selected.

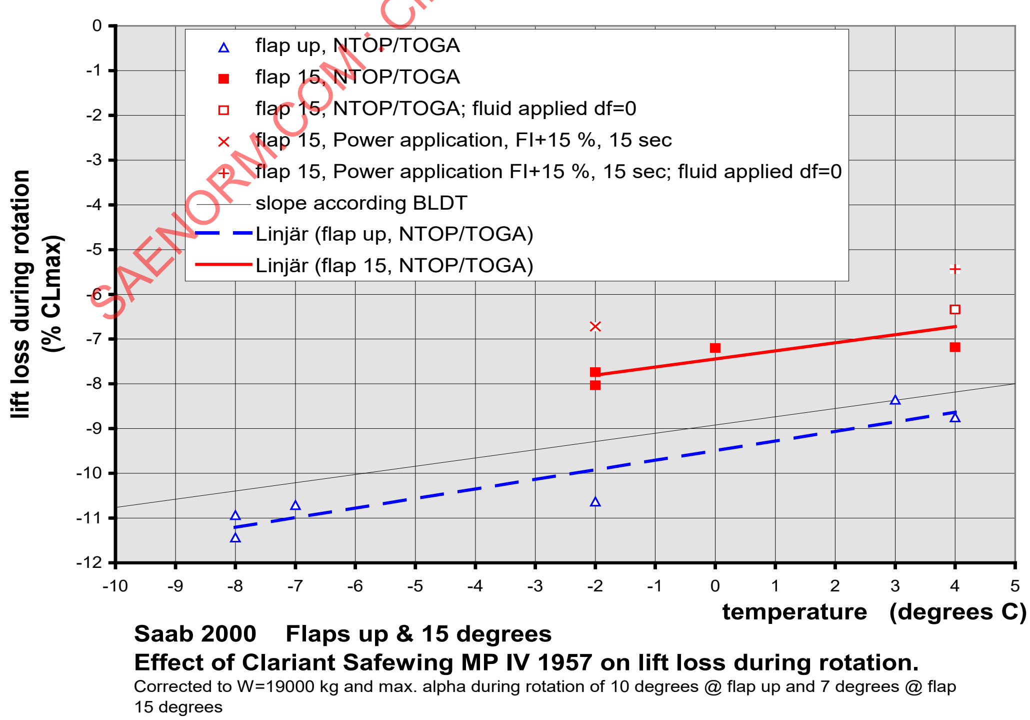

Figure C5 - Lift loss during rotation due to Clariant Safewing MP IV 1957

C.4 AERODYNAMIC ACCEPTANCE TEST

The flat-plate AAT is described in AS5900, as well as in 3.3 of this document. The AAT is required by AMS1424 and AMS1428 to qualify a fluid for aerodynamic acceptability. The AAT is performed by AMIL. The AAT is performed according to the high-speed ramp (HSR) and/or low-speed ramp (LSR) protocol. The HSR AAT is intended for large transport-type jet aircraft and the LSR AAT is intended for commuter-type propeller aircraft. Refer to Reference C.4 for the AMIL aerodynamic qualification test report for Clariant Safewing MP IV 1957. Figure C6 shows the digitized HSR BLDT versus time curves from this report. This data has been used to determine the reference cases and to calculate the performance corrections.

Clariant performed additional flat-plate tests to determine the effect on BLDT for accelerations and final speeds which match the Saab 340 and Saab 2000 takeoff speed schedules. Clariant performed these additional flat-plate tests both for Type IV (Clariant Safewing MP IV 1957) and Type III (Clariant Safewing MP III 2031 ECO) (refer to References C.8 and C.9).

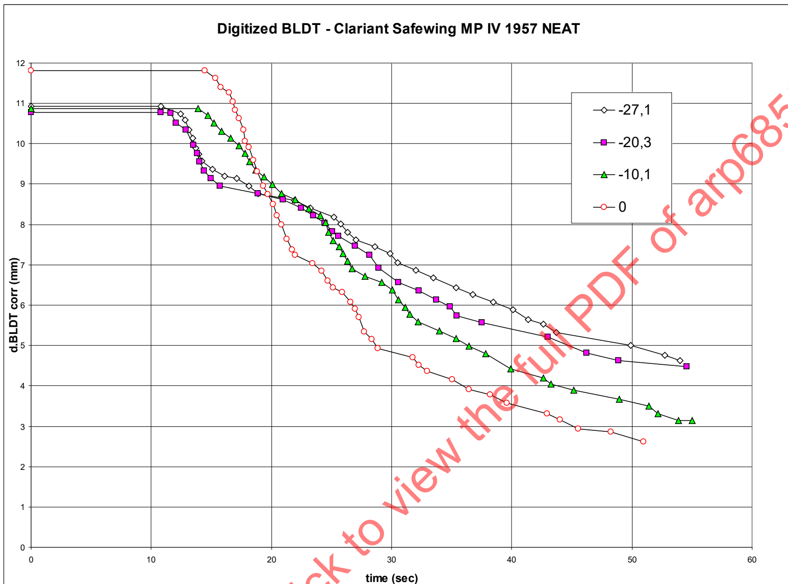

Figure C6 - Digitized BLDT versus time curves for several temperatures
d.BLDT = (BLDTfluid - BLDTdry)
Clariant Safewing MP IV 1957 neat
Data from Reference C.6

Based on the additional AAT results, it has been concluded that AAT results for Clariant Safewing MP IV 1957 according to takeoff speed schedules of the Saab 340 and Saab 2000 can be approximated by correcting the AMIL HSR AAT results for Clariant Safewing MP IV 1957 as follows:

- The delta BLDT (BLDTfluid - BLDTdry) as a function of time for Clariant Safewing MP IV 1957 for another acceleration time to the same final airspeed can be approximated by correcting the time of the AMIL HSR AAT results by (-0.65) times (25 minus the actual acceleration time) seconds. For instance: accelerating in 15 seconds instead of 25 seconds to the same final airspeed means that the delta BLDT curve of the AMIL HSR AAT result is shifted in time by (-0.65)*(25-15) = -6.5 seconds.

- The delta BLDT as a function of time for Clariant Safewing MP IV 1957 for another final airspeed obtained with the same acceleration time can be approximated by correcting the delta BLDT of the AMIL HSR AAT result by 0.8 mm per 10 m/s lower final airspeed.

However, the additional AATs with Clariant Safewing MP III 2031 ECO resulted in different corrections:

- The delta BLDT as a function of time for Clariant Safewing MP III 2031 ECO for another acceleration time to the same final airspeed can be approximated by correcting the time of the AMIL HSR AAT results by (-0.3) times (25 minus the actual acceleration time) seconds.

- The delta BLDT as a function of time for Clariant Safewing MP III 2031 ECO for another final airspeed obtained with the same acceleration time can be approximated by correcting the delta BLDT of the AMIL HSR AAT result by 0.35 mm per 10 m/s lower final airspeed.

The results of Clariant Safewing MP IV 1957 are used for all Type II and IV fluids.

The results of Clariant Safewing MP III 2031 ECO are used for all Type I and III fluids.

C.5 EXTRAPOLATION OF LIFT LOSSES DUE TO FLUID DURING ROTATION TO LOSSES AT CLMAX

Two-dimensional CFD calculations and extended lifting line theory have been used to extrapolate the lift losses at rotation to lift losses at CLmax.

The two-dimensional Navier-Stokes code (NS2D) has been used at Saab to extrapolate to two-dimensional clmax. The NS2D code is a two-dimensional, time-dependent, compressible, Reynolds-averaged Navier-Stokes solver. The surface roughness has been modeled by a modification of the wall distance in the Chien's κ-ε model (refer to References C.5 and C.7). The NS2D calculations have been performed on the most critical section for wing stall. Calculations have been performed for several roughness heights, roughness locations, and roughness lengths. From these calculations, it was concluded that the degradation in clmax was in principle only a factor of BLDT and not of the position of the roughness and/or location, and thus was in agreement with the basic idea behind the AAT, i.e., linear correlation of lift loss with BLDT.

The extended lifting line theory has been used for the conversion of two-dimensional lift losses to three-dimensional lift losses. The two-dimensional lift curves of the sections other than the most critical section have been obtained by modifying them in the same way as the most critical section by applying the same delta cl and delta clmax.

Figure C7 shows the relationship between the lift loss at maximum angle of attack during rotation and the lift loss at CLmax that has been used to determine the speed corrections. For the Saab 340 and Saab 2000, the extrapolation of lift loss due to fluid during rotation to lift loss at CLmax is not significant for the flaps retracted configuration. However, for Flaps 15, the extrapolation becomes significant above about 7% lift loss during rotation.

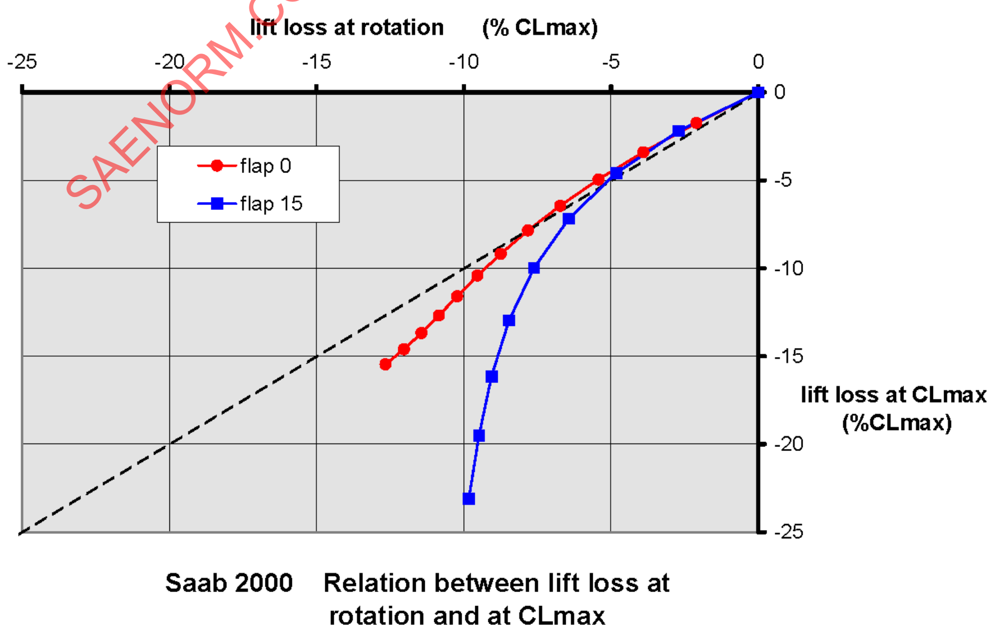

Figure C7 - Relationship between lift loss at rotation and at CLmax determined with two-dimensional Navier-Stokes CFD calculations with roughness and extended lifting line theory