



AEROSPACE RECOMMENDED PRACTICE

ARP6852™**REV. D**Issued 2015-12
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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

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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 $V_2 + 10$ kts and $V_2 + 20$ 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 CL_{max} 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 CL_{max} 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).

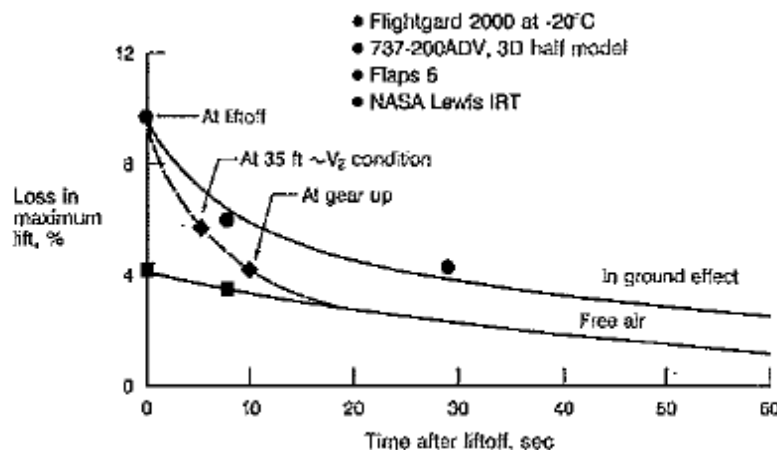


Figure 1 - Maximum lift loss variation with time (B737-200ADV)

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, V_2 speed must be at least $1.10 V_{S1g}$. 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 $5\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ and $-45\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$. 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).

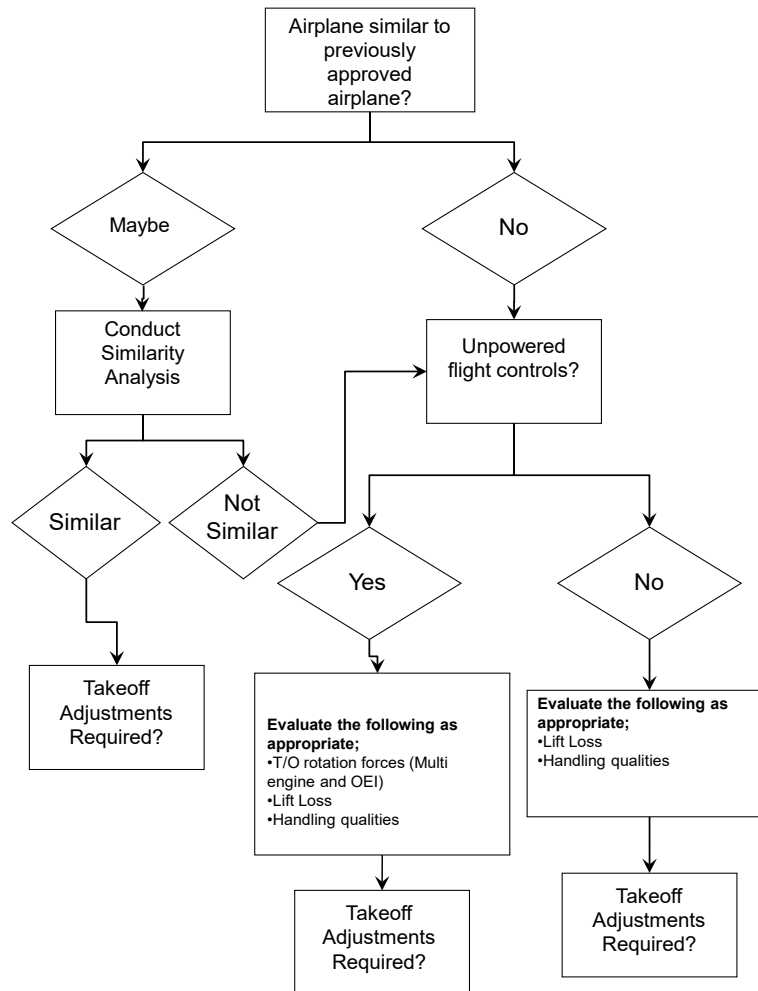


Figure 2 - Flow chart for evaluating the aerodynamic effects of deicing/anti-icing fluids

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 CL_{max} 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 flight, 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 liftoff¹, 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 ΔC_L at liftoff or during rotation, whereas the AAT fluid-acceptance limit is based on ΔC_L 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 V_2 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 V_2 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:

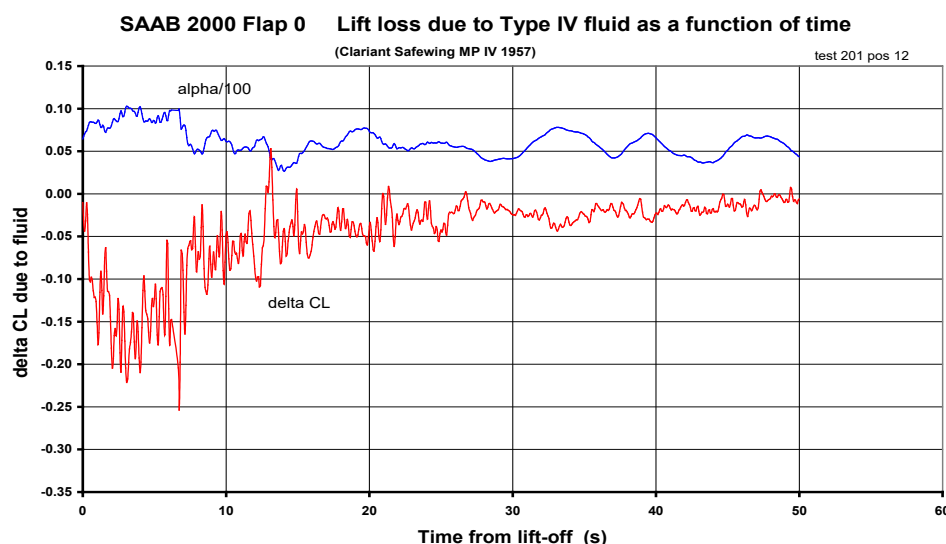


Figure 3 - Lift loss as a function of time - Saab 2000 (Flap 0)

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

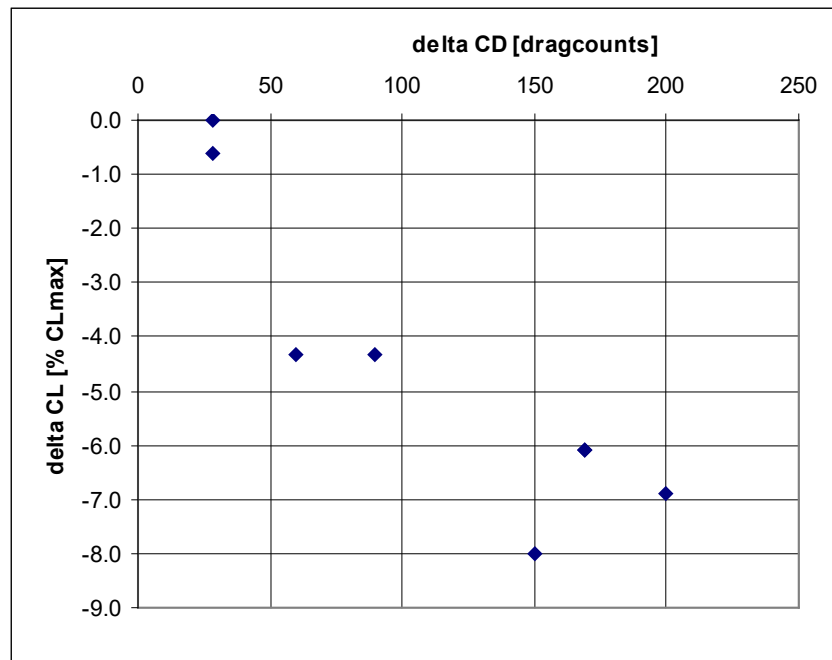


Figure 4 - Drag due to the fluid - Saab 2000 (Flap 0)

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.