TP15232E

WIND TUNNEL TRIALS TO EXAMINE ANTI-ICING FLUID FLOW-OFF CHARACTERISTICS AND TO SUPPORT THE DEVELOPMENT OF ICE PELLET ALLOWANCE TIMES, WINTERS 2009-10 TO 2012-13

Volume 1

Prepared for
Transportation Development Centre

In cooperation with

Civil Aviation
Transport Canada

and

The Federal Aviation Administration
William J. Hughes Technical Center

Prepared by:

APS Aviation Inc.

November 2013
Final Version 1.0

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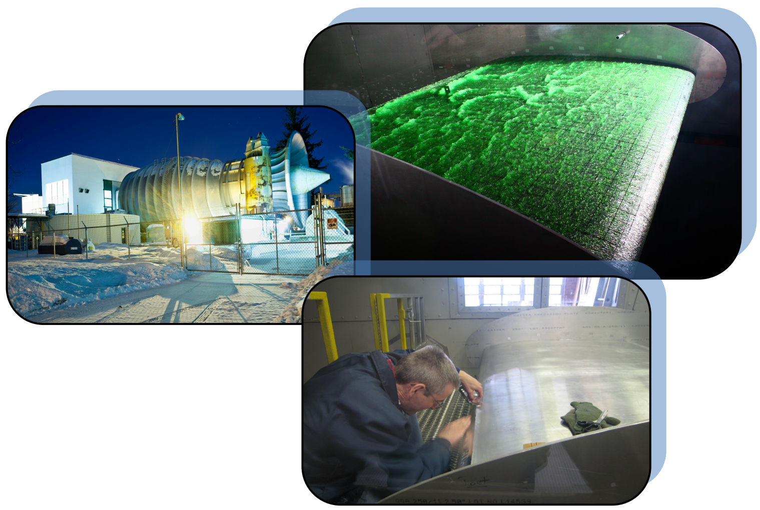

By:

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APS Aviation Inc.

November 2013

Final Version 1.0

The contents of this report reflect the views of APS Aviation Inc. and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

The Transportation Development Centre does not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

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Oct 23, 2020

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Un sommaire français se trouve avant la table des matières.

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PREFACE

Under contract to the Transportation Development Centre of Transport Canada with support from the Federal Aviation Administration, APS Aviation Inc. has undertaken a research program to advance aircraft ground de/anti-icing technology. The specific objectives of the APS Aviation Inc. test program are the following:

- To develop holdover time data for all newly-qualified de/anti-icing fluids and update and maintain the website for the holdover time guidelines;
- To evaluate weather data from previous winters that can have an impact on the format of the holdover time guidelines;
- To conduct general and exploratory de/anti-icing research;
- To conduct tests to evaluate the effect of deployed flaps and slats prior to anti-icing;
- To conduct tests and research on surfaces treated with ice phobic products;
- To conduct tests to evaluate holdover times in heavy snow conditions;
- To develop an SAE AIR for the evaluation of aircraft coatings;
- To support the evaluation of the National Research Council Canada Propulsion Icing Wind Tunnel to determine its flow characteristics;
- To develop holdover time guidance for operation in ice crystal conditions;
- To continue research for development of ice detection capabilities for pre-deicing, engine deicing and departing aircraft at the runway threshold;
- To develop a performance specification for electronic holdover time applications;
- To investigate pre-takeoff contamination check 5-minute allowance;
- To conduct full-scale general aviation aircraft windshield washer fluid deicing testing to substantiate and support flat plate testing results;
- To update the regression coefficient report with the newly-qualified de/anti-icing fluids; and
- To develop Type II/IV holdover times in light and very light snow conditions.

The research activities of the program conducted on behalf of Transport Canada during the winter of 2012-13 are documented in seven reports. The titles of the reports are as follows:

- TP 15227E Winter Weather Impact on Holdover Time Table Format (1995-2013);
- TP 15228E Aircraft Ground De/Anti-Icing Fluid Holdover Time Development Program for the 2012-13 Winter;
- TP 15229E Regression Coefficients and Equations Used to Develop the Winter 2013-14 Aircraft Ground Deicing Holdover Time Tables;
- TP 15230E Aircraft Ground Icing General Research Activities During the 2012-13 Winter;
- TP 15231E Cold Climate Technologies – Investigation of Sensor Technologies as an Alternative Means of Detecting Aircraft Icing (Year 2 of 3);

- TP 15232E Wind Tunnel Trials to Examine Anti-Icing Fluid Flow-Off Characteristics and to Support the Development of Ice Pellet Allowance Times, Winters 2009-10 to 2012-13; and
- TP 15233E Exploratory Wind Tunnel Aerodynamic Research Examination of Contaminated Anti-Icing Fluid Flow-Off Characteristics Winter 2012-13.

In addition, the following two interim reports are being prepared:

- *Investigation of Ice Phobic Technologies to Reduce Aircraft Icing in Northern and Cold Climates (Year 2 of 3); and*
- *Evaluation of Endurance Times on Extended Flaps and Slats.*

This report, TP 15232E has the following objective:

- To conduct research in the Propulsion Icing Wind Tunnel with a thin-high performance wing section to calibrate and characterise the facility and wing section, and to further develop and expand ice pellet allowance times.

This objective was met by conducting a series of full-scale tests using a thin high-performance wing model in the National Research Council Canada Propulsion Icing Wind Tunnel with the cooperation of National Aeronautics and Space Administration, Transport Canada and the Federal Aviation Administration.

PROGRAM ACKNOWLEDGEMENTS

This multi-year research program has been funded by Transport Canada with support from the Federal Aviation Administration, William J. Hughes Technical Center, Atlantic City, NJ. This program could not have been accomplished without the participation of many organizations. APS Aviation Inc. would therefore like to thank the Transportation Development Centre of Transport Canada, the Federal Aviation Administration, National Research Council Canada, the Meteorological Service of Canada, and several fluid manufacturers.

APS Aviation Inc. would also like to acknowledge the dedication of the research team, whose performance was crucial to the acquisition of hard data. This includes the following people: Yelyzaveta Asnytska; Brandon Auclair; Steven Baker, Stephanie Bendickson, Kirby Bennett; Patrick Caines; John D'Avirro, Jesse Dybka, Derek Foebel; Benjamin Guthrie, Dany Posteraro, Marco Ruggi, James Smyth, Fillipo Suriano; David Youssef and Victoria Zoitakis.

Special thanks are extended to Howard Posluns, Yvan Chabot, Doug Ingold and Warren Underwood, who on behalf of the Transportation Development Centre and the Federal Aviation Administration, have participated, contributed and provided guidance in the preparation of these documents.

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Several research reports for testing of de/anti-icing technologies were produced for previous winters on behalf of Transport Canada. These are available from the Transportation Development Centre. Several reports were produced as part of this winter's research program. Their subject matter is outlined in the preface. The work described in this report was, in part, co-sponsored by the Federal Aviation Administration.

16. Abstract

This report documents the series of full-scale tests conducted in the National Research Council Canada 3 m x 6 m Open-Circuit Propulsion Icing Wind Tunnel using a thin high-performance wing model to determine the flow-off characteristics of anti-icing fluid with and without mixed precipitation conditions with ice pellets.

Since 2009-10, a significant amount of work and analysis has been performed to support the development of the ice pellet allowance times. As the work has been ongoing, the reports were only compiled as "Interim" and therefore never officially published. The purpose of having this summary report with each of the previous interim reports included as volumes is to have an official documentation of the work completed; the individual projects are documented in detail in four separate reports included as Volumes to this report. This also requires a lesser level of effort as compared to a consolidated report; all interim reports have been included as volumes in "as-is" format. In the future, a report consolidating all the ice pellet work from 2005-06 onwards would be beneficial to provide a full-spectrum analysis of the data used to develop the ice pellet guidance material.

The documentation of this project has been divided into five separate volumes: one summary report, and four detailed reports on each of the respective testing years' activities. The volumes are as follows:

- Volume 1: Summary Report
- Volume 2: 2009-10 Testing Report
- Volume 3: 2010-11 Testing Report
- Volume 4: 2011-12 Testing Report
- Volume 5: 2012-13 Testing Report

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Antoine Lacroix pour Barry Myers

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Plusieurs rapports de recherche sur des essais de technologies de dégivrage et d'antigivrage ont été produits au cours des hivers précédents pour le compte de Transports Canada. Ils sont disponibles auprès du Centre de développement des transports. Plusieurs rapports ont été rédigés dans le cadre du programme de recherche de cet hiver. Leur objet apparaît à l'avant-propos. Les travaux décrits dans ce rapport ont été en partie coparrainés par la Federal Aviation Administration.

16. Résumé

Le présent rapport documente la série d'essais pleine grandeur réalisés dans la soufflerie de givrage à propulsion et à circuit ouvert de 3 m sur 6 m du Conseil national de recherches Canada, au moyen d'un modèle d'aile haute performance à profil mince, afin de déterminer les caractéristiques de ruissellement du liquide d'antigivrage avec et sans conditions de précipitations mixtes comprenant des granules de glace.

Depuis 2009-2010, un nombre important de travaux et d'analyses ont été effectués afin de déterminer les marges de tolérance dans des conditions de granules de glace. Puisque les travaux sont toujours en cours, les rapports ont seulement été compilés de façon provisoire, et n'ont donc jamais été officiellement publiés. Le présent rapport sommaire est regroupé avec chacun des rapports provisoires sous forme de volumes afin de disposer de documents officiels sur les travaux réalisés ; les projets individuels sont documentés de façon détaillée dans quatre rapports distincts, inclus au présent rapport. Cette approche nécessite moins d'efforts qu'un rapport consolidé, les rapports provisoires ayant tous été inclus « tels quels ». Il serait éventuellement utile de disposer d'un rapport regroupant tous les travaux sur les granules de glace réalisés depuis l'année 2005-2006 afin de fournir une analyse globale des données utilisées dans l'élaboration des lignes directrices concernant les granules de glace.

Les documents relatifs à ce projet ont été divisés en cinq volumes distincts : un rapport sommaire et quatre rapports détaillés, chacun traitant des activités de recherche d'une année donnée. Les volumes sont les suivants :

- Volume 1 : rapport sommaire
- Volume 2 : rapport d'essais 2009-2010
- Volume 3 : rapport d'essais 2010-2011
- Volume 4 : rapport d'essais 2011-2012
- Volume 5 : rapport d'essais 2012-2013

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Détecteur, prévisions immédiates, ROGIDS, lignes directrices sur les durées d'efficacité, gel, détection de givre, LOUT, recherche et développement, applications, neige légère, neige très légère, avant décollage, contamination, lave-glace, soufflerie, visibilité, OEPP

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EXECUTIVE SUMMARY

Under contract to the Transportation Development Centre (TDC), with financial support from the Federal Aviation Administration (FAA), APS Aviation Inc. (APS) has undertaken research activities to further advance aircraft ground de/anti-icing technology. As part of a larger research program examining de/anti-icing fluid flow-off during simulated aircraft takeoff, APS conducted a series of full-scale tests in the National Research Council Canada (NRC) 3 m x 6 m Open-Circuit Propulsion Icing Wind Tunnel (PIWT) using a thin high-performance wing model to determine the flow-off characteristics of anti-icing fluid with and without mixed precipitation conditions with ice pellets.

Since 2009-10, a significant amount of work and analysis has been performed to support the development of the ice pellet allowance times. As the work has been ongoing, the reports were only compiled as "Interim" and therefore never officially published. The purpose of having this summary report with each of the previous interim reports included as volumes is to have an official documentation of the work completed; the individual projects are documented in detail in four separate reports included as Volumes to this report. This also requires a lesser level of effort as compared to a consolidated report; all interim reports have been included as volumes in "as-is" format. In the future, a report consolidating all the ice pellet work from 2005-06 onwards would be beneficial to provide a full-spectrum analysis of the data used to develop the ice pellet guidance material.

Conclusions and Future Recommendations for Testing

The following conclusions and recommendations have been compiled based on the most recent work conducted during the winter of 2012-13; as testing conducted each year builds on the previous years, the 2012-13 results are the most relevant and current.

During the winter of 2012-13, the clean, dry wing aerodynamic repeatability was confirmed in comparison with previous data and the additional data collected in 2012-13 helped in substantiating these findings. The stalling characteristics of the wing with fluid (or fluid with contamination) appeared to be driven by secondary wave effects near the leading edge; these effects were difficult to interpret on the two-dimensional model relative to a fully three-dimensional wing and therefore should not be used in developing allowance times. Additional lift-loss scaling correlation data with different fluids at colder temperatures confirmed that previous lift loss limits were still valid. Forty ice pellet allowance time tests were conducted to validate and possibly expand the current guidance material. The data validated the current allowance times with new fluids and also indicated a potential to expand the allowance times for light ice pellets mixed with light snow and moderate snow.

Possible future areas of research for the winter of 2013-14 may include:

- Allowance time testing to expand the guidance for mixed conditions including light ice pellets with light or moderate snow conditions;
- Investigation of the higher lift losses observed at lower temperatures close to the fluid lowest operational use temperature (LOUT) to determine the aerodynamic effects of ice pellet contamination at these colder temperatures;
- Further substantiation of the ice pellet allowance times with new fluids, or fluids previously tested but with limited data;
- Evaluation of the effect of fluid viscosity on aerodynamics; and
- Additional testing and analysis to further develop the PIWT results correlation to the boundary layer displacement thickness (BLDT) test.

SOMMAIRE

Dans le cadre d'un contrat avec le Centre de développement des transports (CDT) et avec l'appui financier de la Federal Aviation Administration (FAA), APS Aviation Inc. (APS) a entrepris des activités de recherche visant à faire progresser les technologies associées au dégivrage et à l'antigivrage d'aéronefs au sol. Dans le cadre d'un plus vaste programme de recherche étudiant le ruissellement du liquide de dégivrage et d'antigivrage durant le décollage simulé d'un aéronef, APS a mené une série d'essais pleine grandeur dans la soufflerie de givrage à propulsion et à circuit ouvert de 3 m sur 6 m du Conseil national de recherches Canada (CNRC), au moyen d'un modèle d'aile haute performance à profil mince, afin de déterminer les caractéristiques de ruissellement du liquide d'antigivrage avec et sans conditions de précipitations mixtes comprenant des granules de glace.

Depuis 2009-2010, un nombre important de travaux et d'analyses ont été effectués afin de déterminer les marges de tolérance dans des conditions de granules de glace. Puisque les travaux sont toujours en cours, les rapports ont seulement été compilés de façon provisoire, et n'ont donc jamais été officiellement publiés. Le présent rapport sommaire est regroupé avec chacun des rapports provisoires sous forme de volumes afin de disposer de documents officiels sur les travaux réalisés ; les projets individuels sont documentés de façon détaillée dans quatre rapports distincts, inclus au présent rapport. Cette approche nécessite moins d'efforts qu'un rapport consolidé, les rapports provisoires ayant tous été inclus « tels quels ». Il serait éventuellement utile de disposer d'un rapport regroupant tous les travaux sur les granules de glace réalisés depuis l'année 2005-2006 afin de fournir une analyse globale des données utilisées dans l'élaboration des lignes directrices concernant les granules de glace.

Conclusions et recommandations pour les futurs essais

Les conclusions et recommandations qui suivent ont été compilées à partir des plus récents travaux réalisés durant l'hiver 2012-2013. Comme les essais réalisés chaque année s'appuient sur les activités des années précédentes, les résultats de 2012-2013 sont les plus récents et les plus pertinents.

Durant l'hiver 2012-2013, la répétabilité des données obtenues aux essais aérodynamiques sur des ailes propres et sèches a été confirmée par rapport aux données précédentes ; les données supplémentaires recueillies en 2012-2013 ont contribué à étayer ces constatations. Les caractéristiques de décrochage de l'aile recouverte de liquide (ou de liquide contaminé) semblaient suscitées par des effets d'onde transversale près du bord d'attaque ; ces effets étant difficiles à interpréter sur le modèle bidimensionnel comparativement à une aile en trois dimensions, ils ne devraient pas être utilisés dans l'élaboration des marges de tolérance. D'autres

données de corrélation sur l'échelle des pertes de portance avec différents liquides par temps froid ont confirmé la validité des limites précédentes concernant la perte de portance. Quarante essais sur les marges de tolérance dans des conditions de granules de glace ont été réalisés afin de valider et, possiblement, d'élargir les marges actuelles. Les données ont permis de valider les marges de tolérance actuelles avec de nouveaux liquides et ont aussi démontré la possibilité élargir les marges de façon à inclure les conditions mixtes de granules de glace légers avec de la neige légère et modérée.

Voici certains éléments qui pourraient être étudiés à l'hiver 2013-2014 :

- Essais sur les marges de tolérance visant à élargir les lignes directrices concernant les conditions mixtes de façon à inclure les conditions de granules de glace légers avec de la neige légère ou modérée ;
- Analyse des pertes de portance supérieures observées à basse température se rapprochant de la température minimale d'utilisation opérationnelle du liquide (LOUT) afin de déterminer les effets aérodynamiques de la contamination par des granules de glace à ces températures plus froides ;
- Corroboration supplémentaire des marges de tolérance dans des conditions de granules de glace avec les nouveaux liquides, ou avec les liquides déjà testés, mais pour lesquels les données sont limitées ;
- Évaluation de l'effet de la viscosité des liquides sur les propriétés aérodynamiques ; et
- Essais et analyses supplémentaires visant à établir une corrélation entre les résultats obtenus dans la soufflerie de givrage à propulsion et ceux des essais sur l'épaisseur de déplacement de la couche limite (EDCL).

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GLOSSARY

AAT	Aerodynamic Acceptance Test
APS	APS Aviation Inc.
BLDT	Boundary Layer Displacement Thickness
EG	Ethylene Glycol
FAA	Federal Aviation Administration
HOT	Holdover Time
LOUT	Lowest Operational Use Temperature
MSC	Meteorological Service of Canada
NASA	National Aeronautics and Space Administration
NRC	National Research Council Canada
OAT	Outside Air Temperature
PG	Propylene Glycol
PIWT	3 m x 6 m Open-Circuit Propulsion Icing Wind Tunnel
SAE	Society of Automotive Engineers
TDC	Transportation Development Centre
UPS	United Parcel Service

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1. INTRODUCTION

Under winter precipitation conditions, aircraft are cleaned with a freezing point depressant fluid and protected against further accumulation by an additional application of such a fluid, possibly thickened to extend the protection time. Aircraft ground deicing had, until recently, never been researched and there is still an incomplete understanding of the hazard and of what can be done to reduce the risks posed by the operation of aircraft in winter precipitation conditions. This "winter operations contaminated aircraft – ground" program of research is aimed at overcoming this lack of knowledge.

Since the early 1990s, the Transportation Development Centre (TDC) of Transport Canada (TC) has managed and conducted de/anti-icing related tests at various sites in Canada; it has also coordinated worldwide testing and evaluation of evolving technologies related to de/anti-icing operations with the co-operation of the United States Federal Aviation Administration (FAA), the National Research Council Canada (NRC), the Meteorological Service of Canada (MSC), several major airlines, and deicing fluid manufacturers. The TDC is continuing its research, development, testing and evaluation program.

Under contract to the TDC, with financial support from the FAA, APS Aviation Inc. (APS) has undertaken research activities to further advance aircraft ground de/anti-icing technology.

NOTE: The documentation of this project has been divided into five separate volumes: one summary report, and four detailed reports on each of the respective testing years' activities. The volumes are as follows:

Volume 1:	*Summary Report*
Volume 2:	*2009-10 Testing Report*
Volume 3:	*2010-11 Testing Report*
Volume 4:	*2011-12 Testing Report*
Volume 5:	*2012-13 Testing Report*

This report is Volume 1 of 5.

1.1 Background

Prior to the winter of 2006-07, Holdover Time (HOT) guidance material did not exist for ice pellet conditions; however, aircraft could still depart during ice pellet conditions following aircraft deicing and a pre-takeoff contamination check. This protocol was feasible for common air carrier aircraft that provided access to emergency exit windows overlooking the leading edge of the aircraft wings; however, it posed a significant problem for cargo aircraft that have limited visibility of the wings from the cabin.

On December 22, 2004, United Parcel Service (UPS) aircraft in Louisville were grounded for several hours due to extended ice pellet conditions. Due to cargo aircraft configuration, pre-takeoff contamination checks by the onboard crew were not possible. Fed-Ex had been faced with similar problems in Memphis. Following this event, in October 2005, the FAA issued two notices restricting takeoffs in ice pellet conditions.

As a result of this costly incident, UPS set out to obtain experimental data to provide guidance and allow operations to continue in ice pellet conditions. During the winter of 2004-05, aerodynamic and endurance time testing were conducted in simulated ice pellet conditions. APS also conducted some preliminary flat plate research [see TC report, TP 14718E, *Preliminary Endurance Time Testing in Simulated Ice Pellet Conditions*, (1)]. Based on the preliminary data, an allowance of 20 minutes in light ice pellet conditions was proposed; however, no changes to the HOT Guidelines were made.

During the following winter of 2006-07, the FAA provided a 25-minute allowance as a preliminary guideline; TC issued a note indicating that no changes would be made to the HOT Guidelines. This allowance was based on the previous research conducted during the winter of 2005-06, primarily as a result of the Falcon 20 aerodynamic research [see TC report, TP 14716E, *Falcon 20 Trials to Examine Fluid Removed from Aircraft During Takeoff with Ice Pellets* (2)]; these results were presented at the Society of Automotive Engineers (SAE) meeting in Lisbon in May 2006. To address the option of a pre-takeoff contamination check, the 20-minute targeted allowance was extended to 25 minutes; pre-takeoff contamination checks would no longer apply. This allowance was followed by a list of conditions; one restriction was that operations would be limited to ice pellets alone (no mixed conditions).

Due to the high occurrence of ice pellets combined with freezing rain or snow, the industry requested additional guidance material for operations in mixed ice pellet conditions. Additional endurance time testing and aerodynamic research was conducted in simulated ice pellet conditions during the winter of 2006-07.

During the winter of 2007-08, TC and the FAA provided allowance time guidance material for operations in mixed conditions with ice pellets. These allowance times were based on the research conducted during the winter of 2006-07 [see TC report, TP 14779E, *Development of Allowance Times for Aircraft Deicing Operations During Conditions with Ice Pellets* (3)]. The recommended allowance times were based on aerodynamic research conducted using the 3 m x 6 m Open-Circuit Propulsion Icing

Wind Tunnel (PIWT) and the NRC Falcon 20 aircraft; these results were presented at the SAE meeting in San Diego in May 2007. These allowance time guidelines were followed by a list of restrictions based on the results obtained through the research conducted and on the lack of data in specific conditions.

During the winter of 2007-08, additional endurance time testing and aerodynamic research were conducted to support and further expand the ice pellet allowance times [see TC report, TP 14871E, *Research for Further Development of Ice Pellet Allowance Times: Aircraft Trials to Examine Anti-Icing Fluid Flow-Off Characteristics Winter 2007-08,* (4)]. Full-scale testing with the NRC Falcon 20 and T-33 aircraft was conducted in mixed conditions with ice pellets and in non-precipitation conditions. Testing was primarily geared towards simulating low rotation speed aircraft. No changes to the allowance times were made as a result of this work as aerodynamic data was not available.

During the winter of 2008-09, testing was conducted in the PIWT using a National Aeronautics and Space Administration (NASA) LS-0417 airfoil to validate and potentially expand the allowance times. As a result of this testing, a reduction to the light ice pellets mixed with moderate snow allowance time was issued for outside air temperature (OAT) above -5ºC: the allowance time was reduced from 25 minutes to 10 minutes. The testing conducted also allowed the expansion of the table to include a new 25-minute allowance time for light ice pellets mixed with moderate rain for above -5ºC conditions, as well as a new 15-minute allowance time for light ice pellets mixed with light snow for -5ºC to -10ºC conditions. A newly updated version of the Type IV allowance time table was developed and adopted for the 2009-10 version of the HOT Guidelines. It was recommended that additional testing be conducted in the PIWT during the winter of 2009-10 using a supercritical airfoil to validate the allowance time for use with newer generation aircraft.

A series of tests were designed and carried out during the winter of 2009-10 using a newly constructed thin high-performance airfoil. In general, higher lift losses were observed with the thin high-performance wing as compared to previous wings tested. Although initially 5 percent lift loss was used as the cut-off for evaluating each test, this was expanded to 8 percent based on the data collected; 8 percent lift loss correlated well with the visual observations recorded. More specifically, lift losses greater than 8 percent on the 2D model were recorded during light ice pellet and moderate ice pellet conditions below -10ºC. The data was re-analysed and extrapolated, indicating that the allowance times would be acceptable for rotation speeds of 115 knots or greater (compared to 100 knots or greater). It was recommended that a footnote restricting the use of propylene glycol (PG) fluids to aircraft with rotation greater than 115 knots during light ice pellet and moderate ice pellet conditions below -10ºC be included in the allowance time table for the winter of 2010-11.

In addition, fluid failure issues with the thin high-performance wing were observed with PG fluids during moderate ice pellets above -5ºC. The relatively flat surface of the wing had less fluid flow-off and resulted in an earlier fluid failure for PG fluids. Data collected indicated that an allowance time of 15-minutes would be more appropriate. It was recommended that a footnote reducing the allowance time to 15 minutes for PG fluids during moderate ice pellet conditions above -5ºC be included in the allowance time table for the winter of 2010-11. Additional analysis paired with wind tunnel testing was recommended for the winter of 2010-11 to develop a correlation between the lift losses observed in the wind tunnel and those used as the basis of the aerodynamic acceptance tests (AATs) for fluid certification.

Results from the 2010-11 testing demonstrated similar results to the 2009-10 testing in that the results indicated fluid flow-off issues with the thin high-performance wing when using PG fluids at the lower temperatures. The results indicated that the changes to the guidance material made the previous winter were still relevant and should remain in the allowance time table for the winter of 2011-12. However, a large part of the 2010-11 work was focused on developing a correlation between the PIWT and the AAT. Based on the work that was conducted by NASA and APS, it was determined that a maximum lift loss of 5.24 percent on the B737-200ADV airplane is equivalent to a lift loss of 7.29 percent on the PIWT model. Due to the scatter in the data, the standard error of the estimate determined an upper limit of lift loss on the PIWT model of 9.2 percent and a lower limit of 5.4 percent. Currently, the scatter in the "review" range is somewhat large and causes ambiguities when analysing the data collected. It is anticipated that as future testing progresses and as more data is collected, a narrower range or single-value pass/fail cut-off may be developed similar to the AAT and B737-200ADV airplane tests.

Due to industry concern with the validity of the results obtained, and the relevance of the test methods to operational aircraft, it was recommended that testing during the winter of 2011-12 focus on surveying and characterizing the wind tunnel to obtain a better sense of the repeatability of the results. With the support and under the direction of NASA, a large series of test runs (both dry and with fluid) were planned to better understand the performance characteristics of the wind tunnel and airfoil.

During the winter 2011-12 testing, the back-to-back fluid only runs demonstrated excellent repeatability of test methods, and this was reflected in the aerodynamic data collected. Variation in year-to-year fluid only test runs demonstrated some differences that can be attributed to differences in ramp-up time, temperature, and fluid viscosity. The additional variable of contamination generated slightly more variation in the test results; however, it is considered acceptable given the number of variables such as temperature, ramp-up time, fluid viscosity, and contamination. The repeatability of the testing was considered acceptable for this type of aerodynamic testing work and was not indicative of systematic errors in procedures or equipment. Repeatability or integrity of data was not affected by the larger end plate configurations, but the lift loss measured at $\alpha = 8$ degrees was greater than for the smaller end plates. The scatter and dynamic nature of the stall tests demonstrated the difficulties with using 2D model stall data for evaluating allowance times.

The testing results from the 2011-12 winter demonstrated that the PIWT and thin high-performance wing model are appropriate for the testing and comparative evaluation of de/anti-icing fluid flow-off with and without contamination. It was recommended that testing continue using the existing methodologies with an outlook to continue improving testing protocols and procedures. As such, the testing initiatives for the winter of 2012-13 were re-focused on the further development and validation of the ice pellet allowance times.

During the winter of 2012-13, the clean, dry wing aerodynamic repeatability was confirmed in comparison with previous data, and the additional data collected in 2012-13 helped in substantiating these findings. The stalling characteristics of the wing with fluid only (or fluid with contamination) appeared to be driven by secondary wave effects near the leading edge; these effects were difficult to interpret on the 2D model relative to a fully 3D wing and therefore should not be used in developing allowance times. Additional lift loss scaling correlation data with different fluids at colder temperatures confirmed that previous lift loss limits were still valid. Forty ice pellet allowance time tests were conducted to validate and possibly expand the current guidance material. The data validated the current allowance times with new fluids and also indicated a potential to expand the allowance times for light ice pellets mixed with light snow and moderate snow.

Table 1.1 describes the timeline of the developed allowance time guidance material and respective documents.

1.2 Program Objectives

The primary objective of this program has been to examine anti-icing fluid flow-off characteristics in the NRC PIWT with the aim of supporting the development of ice pellet allowance times.

1.3 Overview of 2009-10 to 2012-13 Testing

Tables 1.2 to 1.5 demonstrate the groupings for the global set of tests conducted at the NRC PIWT during the winters of 2009-10 to 2012-13. The focus of the testing may have shifted from year to year, and therefore these tables help identify the level of effort dedicated to the different objectives. Only tests pertaining to the dry wing and fluid calibration and characterization work and to the ice pellet allowance time testing are described in this report.

Table 1.1: Timeline of Developed Allowance Time Guidance Material

Winter Testing	Research Conducted	FAA Allowance Time	TC Allowance Time	Report TP #	Related Winter HOT Guidelines
2004-05	UPS Research APS PMG Research	October 2005 Notices 8000.309 and 8000.313 (no takeoff in IP)	No Changes to Guidelines	Data available through UPS & TP 14718	2005-06
2005-06	APS Falcon 20	20 minutes targeted, 25 minutes recommended *(to include 5 min PTCC)*	Note include indicating no changes to guidelines	TP 14716E	2006-07
2006-07	APS Wind Tunnel & Falcon 20	Allowance Time Table 1st Version	Allowance Time Table 1st Version (October 2007)	TP 14779E	2007-08
2007-08	APS Falcon 20	Allowance Time Table 1st Version	Allowance Time Table 1st Version	TP 14871E	2008-09
2008-09	APS Wind Tunnel	Allowance Time Table 2nd Version	Allowance Time Table 2nd Version	TP 14935E	2009-10
2009-10	APS Wind Tunnel	Allowance Time Table 3rd Version	Allowance Time Table 3rd Version	TP 15232E (Vol. 2)	2010-11
2010-11	APS Wind Tunnel	No Changes to Guidelines	No Changes to Guidelines	TP 15232E (Vol. 3)	2011-12
2011-12	APS Wind Tunnel	No Changes to Guidelines	No Changes to Guidelines	TP 15232E (Vol. 4)	2012-13
2012-13	APS Wind Tunnel	No Changes to Guidelines	No Changes to Guidelines	TP 15232E (Vol. 5)	2013-14
				TP 115232E (Vol. 1)	

Table 1.2: Summary of 2009-10 Wind Tunnel Tests by Objective

Objective	# of Runs
Dry Wing Calibration	3
Fluid Only Calibration	24
Ice Pellet Allowance Times	58
Exploratory Research Tests (multiple objectives)	33
Total	***118***

Table 1.3: Summary of 2010-11 Wind Tunnel Tests by Objective

Objective	# of Runs
Dry Wing Calibration	8
Fluid Only Calibration	42
Ice Pellet allowance times	61
Exploratory Research Tests (multiple objectives)	37
Total	***148***

Table 1.4: Summary of 2011-12 Wind Tunnel Tests by Objective

Objective	# of Runs
Dry Wing Calibration and Characterization Tests	125
Fluid Calibration and Characterization Tests*	40
Exploratory Research Tests (WWF, S- and S--, Heavy Contamination)	40
Total	***185***

Note: Ice pellet testing only conducted as part of fluid calibration and characterization tests

Table 1.5: Summary of 2012-13 Wind Tunnel Tests by Objective

Objective	# of Runs
Wing and Tunnel Calibration and Characterization	125
Ice Pellet Allowance Times	40
Exploratory Research Tests (Ice Phobic Coatings, Airfoil Performance Monitor)	48
Total	***213***

1.4 Report Format

This report provides a summary of each of the four years of testing conducted as part of the research program. The individual projects are documented in detail in four separate reports included as additional volumes to this report. The goal of this report is to provide a brief overview of the research completed to support the development of ice pellet allowance times during the winters of 2009-10 to 2012-13. Figure 1.1 demonstrates the relationship of each of the detailed project reports with respect to this report.

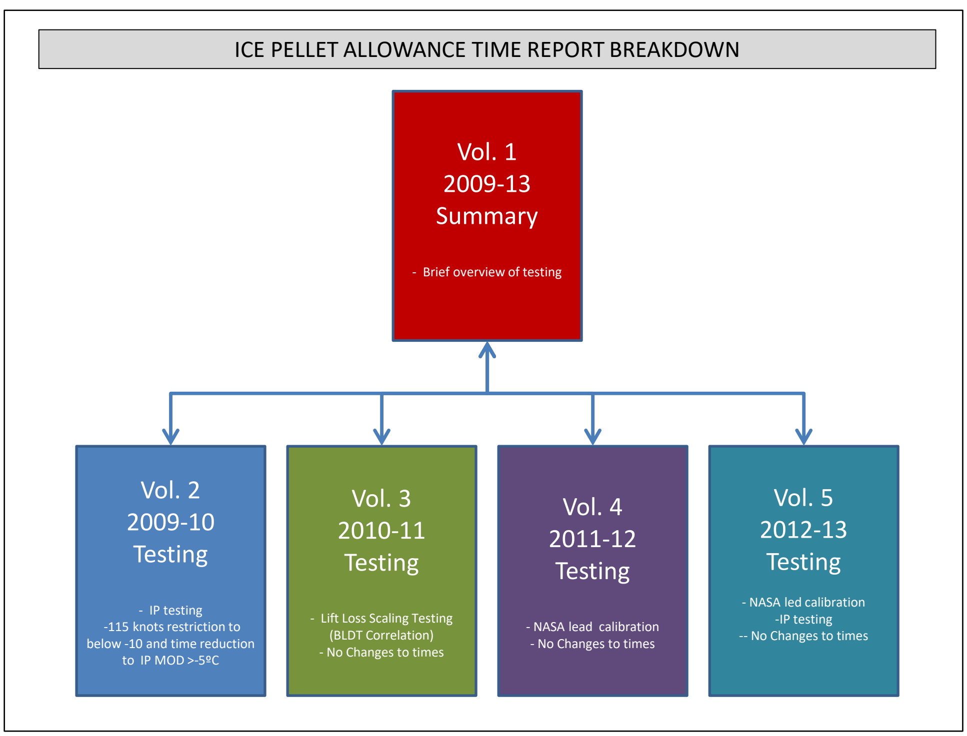

Figure 1.1: Report Relationship Schematic

Each of the following sections summarizes one of the four research years completed as part of the ice pellet allowance time development program. The content of the sections is as follows:

- Section 2: Summary of 2009-10 Testing;
- Section 3: Summary of 2010-11 Testing;
- Section 4: Summary of 2011-12 Testing;
- Section 5: Summary of 2012-13 Testing; and
- Section 6: Recommendations for future testing.

The sections of the TDC work statement pertaining to the work described in this report are provided in the separate detailed reports.

1.5 Purpose of Summary Report

Since 2009-10, a significant amount of work and analysis has been performed to support the development of the ice pellet allowance times. As the work has been ongoing, the reports were only compiled as "Interim" and therefore never officially published. The purpose of having a summary report with each of the previous interim reports included as volumes is to have an official documentation of the work completed. This also required a lesser level of effort compared to a consolidated report; all interim reports have been included as volumes in "as-is" format. In the future, a report consolidating all the ice pellet work from 2005-06 onwards would be beneficial to provide a full-spectrum analysis of the data used to develop the ice pellet guidance material.

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2. SUMMARY OF 2009-10 TESTING

A series of tests were designed and carried out during the winter of 2009-10 to validate the current guidance material in ice pellet and mixed conditions for newer generation aircraft with supercritical wing designs. Testing was conducted with and without contamination. Research was conducted to validate and develop allowance times for Type IV Fluid – High-Speed Ramp.

The details of this testing can be found in TC report, TP 15232E, *Wind Tunnel Trials to Examine Anti-Icing Fluid Flow-Off Characteristics and to Support the Development of Ice Pellet Allowance Times, Winters 2009-10 to 2012-13* (Vol 2.) (5).

2.1 Overview of Results

2.1.1 Type IV High-Speed Allowance Times

In comparison to previous tests on other airfoils, fluid flow-off issues with the supercritical wing were observed with PG fluids at the lower temperatures. More specifically, lift losses greater than 8 percent on the 2D model were recorded during light ice pellet and moderate ice pellet conditions below -10ºC; visual observations supported the lift loss data collected. As a result, rather than restrict the allowance times to ethylene glycol (EG) fluids only, the PG data collected was re-analysed simulating higher rotation speeds. The analysis indicated that the allowance times would be acceptable for rotation speeds of 115 knots or greater (compared to 100 knots or greater). It was recommended that a footnote restricting the use of PG fluids to aircraft with rotation greater than 115 knots during light ice pellet and moderate ice pellet conditions below -10ºC be included in the allowance time table for the winter of 2010-11.

In addition, fluid failure issues with the supercritical wing were observed with PG fluids during moderate ice pellets above -5ºC. The relatively flat surface of the wing had less fluid flow-off and resulted in an earlier fluid failure for PG fluids. Data collected indicated that an allowance time of 15 minutes would be more appropriate. It was recommended that a footnote reducing the allowance time to 15 minutes for PG fluids during moderate ice pellet conditions above -5ºC be included in the allowance time table for the winter of 2010-11.

In general, it was found that the tests conducted in all other conditions generated acceptable lift losses based on the current evaluation criteria: i.e., lift loss less than 5 percent was considered "good" and between 5 percent and 8 percent was considered "ok" (acceptable), whereas tests with lift losses above 8 percent were considered “bad” and required further review. Typically, the EG fluids performed better, especially in the colder temperature, and generated lower lift losses as compared to the PG fluids.

In general, higher lift losses were observed with the supercritical wing compared to previous wings tested. Although 5 percent was used as the initial cut-off for evaluating each test, this was expanded to 8 percent based on the data collected; 8 percent lift loss correlated well with the visual observations recorded. Additional analysis paired with wind tunnel and full-scale aircraft testing is recommended to develop a correlation between the lift losses observed in the wind tunnel and those seen on an operational aircraft with newer generation supercritical wings.

2.1.2 Comparison of Fluid Certification BLDT Results vs. NRC Wind Tunnel Lift Loss Results

The preliminary 2D results from this analysis indicate that 5 percent lift loss may not be appropriate as the lift loss cut-off. When correlating to the fluid certification results, a higher lift loss cut-off may be more appropriate based on the Launch, ABC-S Plus, and EG106 data. It is recommended that future testing be done to simulate fluid certification results in the NRC wind tunnel at specific temperatures to substantiate the correlation observed in this preliminary analysis.

2.1.3 Flap Retracted (UP) vs. Flap Extended (DOWN)

In general, the results indicated that a heavily contaminated flap could have adverse effects on aerodynamic performance. On average, the test results showed an average 1.4 percent improvement in lift loss (with a maximum of 3.4 percent) when the flap was up (retracted) during the contamination period. It can be assumed that the flap will fail faster compared to the main wing section by a factor of less than 60 percent (likely closer to 50 percent of the main wing section protection time); however, data comparing equal levels of contamination on the main wing section and on the flap is required to provide a proper estimate.

3. SUMMARY OF 2010-11 TESTING

A test program was developed for the winter of 2010-11 in an attempt to continue the previous winter's work and to substantiate and possibly expand the current ice pellet allowance times. In addition, testing was conducted to develop a correlation between the lift losses observed in the wind tunnel and those used as the basis of the AATs for fluid certification.

The details of this testing can be found in TP 15232E (Vol. 3) (5).

3.1 Overview of Results

3.1.1 Type IV High Speed Allowance Times

Results from the 2010-11 testing demonstrated results similar to the 2009-10 testing in that the results indicated fluid flow-off issues with the supercritical wing when using PG fluids at the lower temperatures. During the winter of 2009-10, greater lift losses on the 2D model were recorded during light ice pellet and moderate ice pellet conditions below -10ºC, and changes to the guidance material were made to address this.

During the winter of 2010-11, similar results were obtained, and the data collected indicated that the footnote in the guidance material restricting the use of PG fluids to aircraft with rotation greater than 115 knots during light ice pellet and moderate ice pellet conditions below -10ºC was still relevant and should remain in the allowance time table for the winter of 2011-12.

It should be noted that three moderate ice pellet tests conducted at 115 knots and at the very low end of the temperature range demonstrated lift loss results that were marginally above the upper acceptable limit of 9.2 percent; however, the visual observations demonstrated satisfactory results. It was agreed that changes would not be made until some additional testing could be conducted to support this work and until the lift loss limits were further investigated.

The testing conducted during the winters of 2009-10 and 2010-11 supported the potential expansion of the light ice pellets mixed with light or moderate snow cells. More specifically, the results indicated that for light ice pellets mixed with light snow in above -5ºC conditions, the allowance time could potentially be increased from 25 minutes to 40 minutes; for light ice pellets mixed with moderate snow in above -5ºC conditions, the allowance time could potentially be increased from 10 minutes to 20 minutes; and a new allowance time of 7 minutes could potentially be added for light ice pellets mixed with moderate snow in the -5ºC to -10ºC condition. It was agreed that changes would not be made until some additional testing could be conducted to support this work and until the lift loss limits were further investigated.

3.1.2 Correlation of Fluid Certification BLDT Results with NRC Wind Tunnel Lift Loss Results

Based on the work that was conducted by NASA and APS, it was determined that a maximum lift loss of 5.24 percent on the B737-200ADV airplane is equivalent to a lift loss of 7.29 percent on the PIWT model. Due to the scatter in the data, the standard error of the estimate determined an upper limit of lift loss on the PIWT model of 9.17 percent and a lower limit of 5.41 percent.

The scatter in the “review” range is still large and causes complications when analysing the data collected. It is anticipated that as future testing progresses and as more data is collected, a single-value pass/fail cut-off will be developed similar to the AAT and B737-200ADV airplane tests.

4. SUMMARY OF 2011-12 TESTING

Due to industry concern with the validity of the results obtained during previous years' ice pellet testing campaigns, and with the relevance of the test methods to operational aircraft, it was recommended that testing during the winter of 2011-12 focus on surveying and characterizing the wind tunnel to obtain a better sense of the repeatability of results. With the support and under the direction of NASA, a large series of test runs (both dry and with fluid) were planned to better understand the performance characteristics of the wind tunnel and airfoil.

The details of this testing can be found in TP 15232E (Vol. 4) (5).

4.1 Overview of Results

4.1.1 Wind Tunnel Facility Calibration

As reported by the NRC, the year-to-year equipment and facility upgrades have increased the integrity of the aerodynamic data produced, and the wind tunnel can closely simulate aircraft takeoff profiles.

4.1.2 Dry Wing Calibration and Characterization

As reported by NASA, the characterization of the current dry wing model with original end plates demonstrated appropriate aerodynamic behaviour.

4.1.3 Fluid and Contamination Testing - Calibration and Characterization

The back-to-back fluid only runs demonstrated excellent repeatability of test methods, and this was reflected in the aerodynamic data collected. Variation in year-to-year fluid only tests runs demonstrated some differences that can be attributed to ramp-up time, temperature, and fluid viscosity. The additional variable of contamination generated slightly more variation in the test results; however, it is considered acceptable given the number of variables such as temperature, ramp-up time, fluid viscosity, and contamination.

The repeatability of the testing was considered acceptable for this type of aerodynamic testing work and was not indicative of systematic errors in procedures or equipment. Repeatability or integrity of the data was not affected by the larger end plate configurations, but the lift loss measured at $\alpha = 8$ degrees was greater than for original smaller end plates. The scatter and dynamic nature of the stall tests demonstrated the difficulties with using 2D model stall data for evaluating allowance times.

4.1.4 Type IV High-Speed Allowance Times

Testing was not conducted during the winter of 2011-12 with the objective of further developing or substantiating the current ice pellet allowance times. No changes were made to the values in the Type IV allowance time table; however, additional guidance was included to explicitly indicate that guidance material is for SAE Type IV undiluted fluid only and that all fluids are PG-based with the exception of the Dow Chemical EG106 fluid. The updated table was published in the July 2012 Revision 1.0 version of the Transport Canada HOT Guidelines, and a similar table has been published by the FAA.

5. SUMMARY OF 2012-13 TESTING

The primary focus of the testing was aimed at completing the outstanding calibration and characterization testing in the wind tunnel in dry conditions and with fluid with the support and direction of NASA experts. In addition, testing initiatives for the winter of 2012-13 were re-focused on the further development and validation of the ice pellet allowance times.

As secondary research objectives, testing was conducted to investigate the aerodynamic impacts of ice phobic coatings during icing conditions with and without fluid, as well as the evaluation of an airfoil performance monitor and the ability to detect airflow separation (stall).

The details of this testing can be found in TP 15232E (Vol. 5) (5).

5.1 Overview of Results

5.1.1 Wing Calibration and Characterization

During the winter of 2012-13, the clean, dry wing aerodynamic repeatability was confirmed in comparison with previous data, and the additional data collected in 2012-13 helped in substantiating these findings. The stalling characteristics of the wing with fluid only (or fluid with contamination) appeared to be driven by secondary wave effects near the leading edge; these effects were difficult to interpret on the 2D model relative to a fully 3D wing and therefore should not be used in developing allowance times. Additional lift loss scaling correlation data with different fluids at colder temperatures confirmed that previous lift loss limits were still valid. Forty ice pellet allowance time tests were conducted to validate and possibly expand the current guidance material.

5.1.2 Type IV High-Speed Allowance Times

The data validated the current allowance times with new fluids and also indicated a potential to expand the allowance times for light ice pellets mixed with light snow and moderate snow.

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6. RECOMENDATIONS FOR FUTURE TESTING

The following sections describe higher priority areas of possible future research for the winter of 2013-14 wind tunnel testing plan, and they were compiled based on the most recent work conducted during the winter of 2012-13. These areas of future research have been determined based on consultations with TC, the FAA, and NASA, and through industry discussions, and as such they may not be directly linked to the research described in this report. These areas of research have been listed below for ease of reference and to maintain continuity in the year-to-year reporting.

6.1 Allowance Time Expansion of Mixed Light Ice Pellets and Light and Moderate Snow Conditions

Historical winter weather data has indicated that a significant portion of light ice pellets mixed with light snow precipitation occurs below -10°C and light ice pellets mixed with moderate snow precipitation occurs below -5°C to -10°C where no allowance times currently exist. Some additional data has been collected in 2012-13 that supports potential guidance in these conditions. A detailed analysis of the data collected to date in this condition should be conducted to determine the possibility of issuing guidance material and to determine any possible future research needs, if necessary.

6.2 Lift Losses at LOUT

Previous testing has shown that lift losses in general significantly increase at the lower temperatures. Limited data is available at (or very near) the fluid Lowest Operational Use Temperature (LOUT). Additional testing is recommended to obtain data close to the fluid LOUT to determine the aerodynamic effects of ice pellet contamination at these colder temperatures.

6.3 Substantiation of Ice Pellet Allowance Times with New Fluids

Testing should continue to investigate different Type IV fluids to further substantiate the ice pellet allowance times. Testing should consider new fluids or fluids previously tested but with limited data (i.e., Max Flight, Polar Guard).

6.4 Evaluate Effect of Fluid Viscosity on Aerodynamics

Limited testing should continue to investigate the effect of fluid viscosity on aerodynamics. Testing could look at the high and low ends of production fluid viscosities and possibly also investigate mechanically or chemically degraded fluids.

6.5 Lift Loss Scaling with NASA LS-0417 and NACA 23012 Wing Sections

The extensive work conducted with the thin high-performance wing section has led to the development of a methodology for evaluating aerodynamic performance based on a lift loss scaling between the model results and the AS5900 AAT. If research capacities are available, it is recommended that limited testing be conducted with the wing sections previously tested in 2006-07 and 2008-09 to better understand the sensitivity of these models used in the development of the ice pellet allowance time tables.

6.6 Development of Consolidated Report of All Ice Pellet Data Collected to Date

A report consolidating all the ice pellet work from 2005-06 onwards would be beneficial to provide a full-spectrum analysis of the data used to develop the ice pellet guidance material. This report would provide a fresh perspective on older data, as analysis methodologies have evolved since the early inception of this program and because the test models have changed over the years.

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