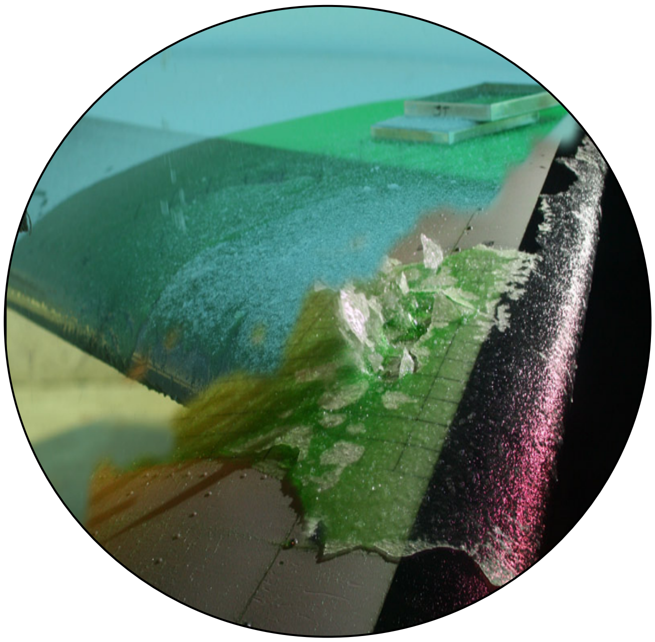
TP 14778E

Flow of Contaminated Fluid from Aircraft Wings: Feasibility Report



Prepared for
Transportation Development Centre

In cooperation with

Civil Aviation
Transport Canada

And

The Federal Aviation Administration
William J. Hughes Technical Center

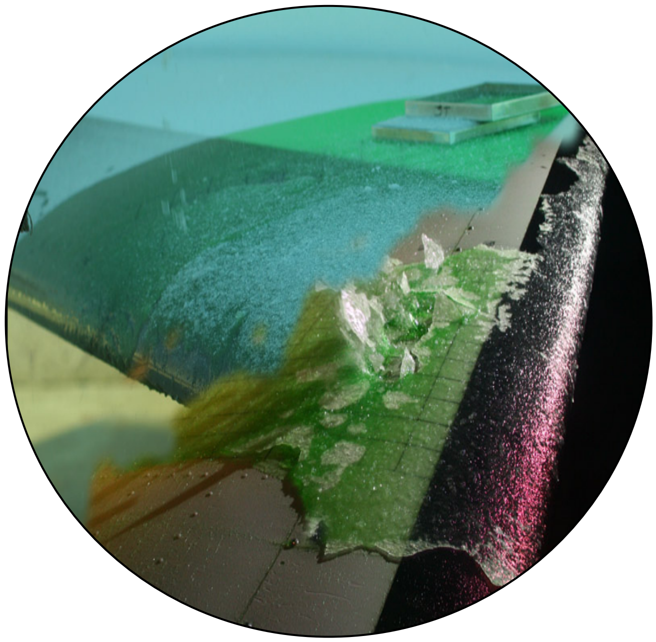
Prepared by

APS Aviation Inc.

January 2008
Final Version 1.0

TP 14778E

Flow of Contaminated Fluid from Aircraft Wings: Feasibility Report



by:

George Balaban

APS Aviation Inc.

January 2008
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.

DOCUMENT ORIGIN AND APPROVAL RECORD

Prepared by: **

George Balaban — Date
Junior Engineer

Reviewed by: Aug 24, 2021

John D'Avirro, Eng., PBDM — Date
Program Manager

Approved by: **

Jack Rigley, P.Eng. — Date
Vice President, Communications Engineering

Un sommaire français se trouve avant la table des matières.

This report was first provided to Transport Canada as Final Draft 1.0 in January 2008.
It has been published as Final Version 1.0 in August 2021.

***Final Draft 1.0 of this report was signed and provided to Transport Canada in January 2008. A Transport Canada technical and editorial review was subsequently completed and the report was finalized in August 2021; George Balaban and Jack Rigley were not available to participate in the final review or to sign the current version of the report.*

PREFACE

Under contract to the Transportation Development Centre of Transport Canada, 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;
- To evaluate whether holdover times should be developed for ice pellet conditions;
- To examine the effect of heated fluids on Type II, III and IV fluid endurance times;
- To evaluate weather data from previous winters to establish a range of conditions suitable for the evaluation of holdover time limits;
- To assist in the testing of flow of contaminated fluid from aircraft wings during takeoff;
- To assist in the testing of flow of contaminated fluid from simulated aircraft wings during takeoff;
- To validate the laboratory snow test protocol with Type II and IV fluids;
- To develop performance specifications for an integrated weather system that measures holdover time;
- To provide support for the development of a standard that evaluates remote on-ground ice detection systems;
- To conduct general and exploratory de/anti-icing research;
- To conduct endurance time tests on non-aluminum plates;
- To conduct endurance time tests in frost on various test surfaces;
- To conduct preliminary wind tunnel endurance time tests in heavy snow;
- To compile historical data for calculation of holdover times based on a small number of inputs;
- To examine the use of non-glycol tempered steam technology to deice aircraft; and
- To assist Department of National Defence Canada in evaluating the effects of slipstream on anti-icing fluid.

The research activities of the program conducted on behalf of Transport Canada during the winter of 2006-07 are documented in eight reports. The titles of the reports are as follows:

- TP 14452E Feasibility of ROGIDS Test Conditions Stipulated in SAE Draft Standard AS5681;
- TP 14776E Aircraft Ground De/Anti-Icing Fluid Holdover Time Development Program for the 2006-07 Winter;
- TP 14777E Winter Weather Impact on Holdover Time Table Format (1995-2007);
- TP 14778E Flow of Contaminated Fluid from Aircraft Wings: Feasibility Report;

- TP 14779E Development of Allowance Times for Aircraft Deicing Operations During Conditions with Ice Pellets;
- TP 14780E Evaluation of Tempered Steam Technology (TST) for Aircraft Deicing Applications;
- TP 14781E Aircraft Ground Icing General Research Activities During the 2006-07 Winter; and
- TP 14782E Regression Coefficients Used to Develop the Winter 2007-08 Type I Generic and Dow UCAR Endurance EG106 Holdover Time Tables.

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

- *Preliminary Aircraft Deicing Research in Heavy Snow Conditions;*
- *Endurance Time Testing in Snow: Comparison of Indoor and Outdoor Data for 2006-07;*
- *Substantiation of Aircraft Ground Deicing Holdover Times in Frost Conditions;*
- *Effect of Heat on Fluid Endurance Times Using Composite Surfaces;*
- *Effect of Heat on Endurance Times of Anti-Icing Fluids; and*
- *Regression Coefficients Used to Develop Aircraft Ground Deicing Holdover Time Tables: Winter 2007-08.*

In addition, the following report was written for Department of National Defence as part of this contract; this report does not have a TP number:

- Support for Testing to Ascertain the Effects of SAE Type IV De/Anti-Icing Fluids on CC-130 Hercules and CP-140 Aurora Aircraft Takeoff Handling.

This report, TP 14778E, has the following objective:

- To document the tools that are available to study aerodynamic flow-off and relate it to fluid failure on aircraft wings.

This objective was met by performing a series of wind tunnel and full-scale aircraft tests.

PROGRAM ACKNOWLEDGEMENTS

This multi-year research program has been funded by the Civil Aviation Group, 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: George Balaban, Katrina Bell, Stephanie Bendickson, Ryan Brydges, Michael Chaput, John D'Avirro, Peter Dawson, Dany Posteraro, Marco Ruggi, Joey Tiano, and David Youssef.

Special thanks are extended to Barry Myers, Frank Eyre and Yagusha Bodnar, who on behalf of the Transportation Development Centre, have participated, contributed and provided guidance in the preparation of these documents.

This page intentionally left blank.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 14778E	2. Project No. 5498-5501 (a-d)	3. Recipient's Catalogue No.
4. Title and Subtitle Flow of Contaminated Fluid from Aircraft Wings: Feasibility Report		5. Publication Date January 2008 6. Performing Organization Document No. CM2020.002
7. Author(s) George Balaban		8. Transport Canada File No. 2450-BP-14
9. Performing Organization Name and Address APS Aviation Inc. 6700 Côte-de-Liesse Rd., Suite 105 Montreal, Quebec, H4T 2B5		10. PWGSC File No. MTB-5-21166 11. PWGSC or Transport Canada Contract No. T8200-055516/001/MTB
12. Sponsoring Agency Name and Address Transportation Development Centre Transport Canada 800 René-Lévesque Blvd. West, Suite 600 Montreal, Quebec, H3B 1X9		13. Type of Publication and Period Covered Final 14. Project Officer Antoine Lacroix for Barry Myers

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

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. Eight reports (including this one) were produced as part of this winter's research program. Their subject matter is outlined in the preface. This project was co-sponsored by the Federal Aviation Administration.

16. Abstract

This report documents the feasibility of using wind tunnel and Falcon 20 tests to examine the fluid of contaminated de/anti-icing fluids from aircraft wings. Full-scale aircraft tests using the National Research Council Canada (NRC) Falcon 20 research aircraft have been conducted by APS Aviation Inc. since 1997 to study the effect of freezing precipitation on de/anti-icing fluids. Wind tunnel testing at the NRC wind tunnel in Ottawa complemented the Falcon 20 tests for the first time during the winter 2006-07. The purpose of the testing was to study aerodynamic flow-off of de/anti-icing fluids from aircraft wings.

The wind tunnel controlled environment proved to be a very good test platform to study the effects of freezing precipitation on de/anti-icing fluid. The wind tunnel tests showed that it is possible to simulate indoor takeoff runs with freezing rain, ice pellet and snow contamination. The feasibility of Falcon 20 testing has been demonstrated over the past 10 years of testing.

Additional testing is recommended to simulate takeoff runs with different airfoils and lower rotation speeds. The freezing precipitation dispersion and distribution requires further refinement. The low-light environment encountered in the wind tunnel was challenging for the photographic documentation of the testing. Better lenses and flashes could optimize the results.

17. Key Words Anti-icing, Deicing, Deicing Fluid, Holdover Times, Precipitation, Endurance Times, Type I, Type II, Type III, Type IV, Aircraft, Ground, Test, Winter		18. Distribution Statement Limited number of copies available from the Transportation Development Centre		
19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages xviii, 46 apps	23. Price —

CDT/TDC 79-005
Rev. 96

Canada

Transports Canada / Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. Nº de la publication de Transports Canada TP 14778E	2. Nº de l'étude 5498-5501 (a-d)	3. Nº de catalogue du destinataire
4. Titre et sous-titre Flow of Contaminated Fluid from Aircraft Wings: Feasibility Report		5. Date de la publication Janvier 2008 6. Nº de document de l'organisme exécutant CM2020.002
7. Auteur(s) George Balaban		8. Nº de dossier - Transports Canada 2450-BP-14
9. Nom et adresse de l'organisme exécutant APS Aviation Inc. 6700, Chemin de la Côte-de-Liesse, Bureau 105 Montréal (Québec) H4T 2B5		10. Nº de dossier - TPSGC MTB-5-21166 11. Nº de contrat - TPSGC ou Transports Canada T8200-055516/001/MTB
12. Nom et adresse de l'organisme parrain Centre de développement des transports Transports Canada 800, Boul. René-Lévesque Ouest, Bureau 600 Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final 14. Agent de projet 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. Huit rapports (dont celui-ci) ont été rédigés dans le cadre du programme de recherche de cet hiver. Leur objet apparaît à l'avant-propos. Ce projet était coparrainé par la Federal Aviation Administration.

16. Résumé

Le présent rapport documente la faisabilité de l'utilisation d'essais en soufflerie et sur le Falcon 20 afin d'examiner le ruissellement de liquides de dégivrage et d'antigivrage contaminés des ailes d'un aéronef. APS Aviation Inc. mène des essais pleine grandeur sur l'aéronef expérimental Falcon 20 du Conseil national de recherches Canada (CNRC) depuis 1997 afin d'étudier l'effet des précipitations givrantes sur les liquides de dégivrage et d'antigivrage. Des essais menés dans la soufflerie du CNRC à Ottawa sont venus compléter les essais menés sur le Falcon 20 pour la première fois au cours de l'hiver 2006-2007. Ils avaient pour but d'étudier le ruissellement aérodynamique des liquides de dégivrage et d'antigivrage des ailes d'un aéronef.

L'environnement contrôlé en soufflerie s'est avéré une très bonne plateforme d'essai pour étudier les effets des précipitations givrantes sur les liquides de dégivrage et d'antigivrage. Les essais en soufflerie ont démontré qu'il est possible de simuler des courses de décollage à l'intérieur avec des contaminations par la pluie verglaçante, les granules de glace et la neige. La faisabilité des essais sur le Falcon 20 a été démontrée au cours des dix dernières années.

Des essais supplémentaires sont recommandés afin de simuler des courses de décollage avec différentes surfaces portantes et à des vitesses de rotation plus basses. La dispersion et la répartition des précipitations givrantes doivent être affinées davantage. Le faible éclairage dans la soufflerie a compliqué la documentation photographique des essais. Les résultats pourraient être optimisés par l'utilisation de lentilles et de flashs de meilleure qualité.

17. Mots clés Antigivrage, dégivrage, liquide de dégivrage, durées d'efficacité, précipitation, temps d'endurance, Type I, Type II, Type III, Type IV, aéronef, sol, essai, hiver	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xviii, 46 ann.	—

CDT/TDC 79-005
Rev. 96

Canada

EXECUTIVE SUMMARY

Under contract to the Transportation Development Centre (TDC) of Transport Canada (TC), with support from the Federal Aviation Administration (FAA), and several fluid manufacturers, APS Aviation Inc. (APS) has undertaken a testing and research program to further advance aircraft ground de/anti-icing technology. The program has a number of objectives, and work completed to address these objectives is documented in a series of related reports. The objective of the project documented in this report was to examine the behaviour of ice pellet-contaminated anti-icing fluid at takeoff.

Background and Objective

Aircraft departure regulations in icing conditions require that no takeoff be attempted as long as any form of contamination (ice, frost, snow or slush) is adhering to the lift-critical surfaces of an aircraft. The method of identifying that some form of contamination does exist on the aircraft surface generally relies on visual indications, as perceived by personnel on the ground or by flight crew from flight decks and/or aircraft cabins. When the fluid's failure to absorb ice crystals is identified, it can only be assumed that this contamination is adhering.

Previous studies have shown that visual failure of a fluid does not always indicate adherence. Tests in the National Research Council Canada (NRC) wind tunnel and with the NRC Falcon 20 research aircraft are being conducted to link adherence to aerodynamic flow-off in an attempt to extend current holdover times.

The objective of this report was to document the tools that are available to study aerodynamic flow-off and relate it to fluid failure on aircraft wings.

Falcon 20 Testing

APS has been conducting full-scale aircraft testing with the NRC Falcon 20 since 1997. The purpose of these tests has been to study the effect of freezing precipitation on de/anti-icing fluids. Specifically, the Falcon 20 has been used to study aerodynamic flow-off and relate it to fluid failure on aircraft wings.

Wind Tunnel Testing

Wind tunnel testing was conducted by APS for the first time in the winter of 2006-07. The wind tunnel testing is a complement to the Falcon 20 tests and similarly studies aerodynamic flow-off of de/anti-icing fluids from aircraft wings.

Conclusions

The wind tunnel controlled environment proved to be a very good test platform to study the effects of freezing precipitation on de/anti-icing fluid. The wind tunnel tests showed that it is possible to simulate takeoff runs with freezing rain, ice pellet and snow contamination. The feasibility of Falcon 20 testing has been demonstrated over the past 10 years of testing. It can be concluded that full-scale aircraft tests with the Falcon 20 can be used to support the wind tunnel tests.

Recommendations

Additional testing is recommended to simulate takeoff runs with different airfoils and lower rotation speeds. The method of freezing precipitation dispersion and distribution requires further refinement. The low-light environment encountered in the wind tunnel was challenging for the photographic documentation of the testing. Better lenses and flashes could optimize the results.

SOMMAIRE

En vertu d'un contrat avec le Centre de développement des transports (CDT) de Transports Canada (TC), avec l'appui de la Federal Aviation Administration (FAA) et de plusieurs fabricants de liquides, APS Aviation Inc. (APS) a entrepris des essais et un programme de recherches visant à approfondir la technologie de dégivrage et d'antigivrage d'aéronefs au sol. Le programme poursuivait plusieurs objectifs et les travaux effectués pour atteindre ces objectifs sont documentés dans une suite de rapports connexes. Le projet dont il est question dans le présent rapport avait pour objectif d'examiner le comportement de liquides d'antigivrage contaminés par des granules de glace au moment du décollage.

Contexte et objectif

La réglementation relative aux décollages d'aéronefs dans des conditions de givrage interdit toute tentative de décollage tant qu'une quelconque forme de contamination (glace, givre, neige ou neige fondante) adhère aux surfaces essentielles à la portance d'un aéronef. La contamination des surfaces de l'aéronef est généralement décelée par des signes visuels perçus par le personnel au sol ou par l'équipage depuis le poste de pilotage ou la cabine de l'aéronef. L'adhérence des contaminants ne peut qu'être présumée lorsque le liquide ne peut plus absorber les cristaux de glace.

Des études antérieures ont démontré qu'une perte d'efficacité visuelle d'un liquide n'est pas toujours signe d'adhérence. Des essais sont effectués dans la soufflerie du Conseil national de recherches Canada (CNRC) et sur l'aéronef expérimental Falcon 20 afin d'établir une corrélation entre l'adhérence et le ruissellement aérodynamique pour tenter de prolonger les durées d'efficacité actuelles.

Le présent rapport vise à documenter les outils disponibles pour étudier le ruissellement aérodynamique et établir une corrélation entre celui-ci et la perte d'efficacité des liquides sur les ailes d'un aéronef.

Essais sur le Falcon 20

APS mène des essais pleine grandeur sur l'aéronef Falcon 20 du CNRC depuis 1997. Ces essais visent à étudier l'effet des précipitations givrantes sur les liquides de dégivrage et d'antigivrage. Plus précisément, le Falcon 20 a été utilisé pour étudier le ruissellement aérodynamique et établir une corrélation entre celui-ci et la perte d'efficacité des liquides sur les ailes d'un aéronef.

Essais en soufflerie

APS a réalisé des effets en soufflerie pour la première fois au cours de l'hiver 2006-2007. Ces essais viennent compléter ceux menés sur le Falcon 20 et étudient eux aussi le ruissellement aérodynamique des liquides de dégivrage et d'antigivrage des ailes d'un aéronef.

Conclusions

L'environnement contrôlé en soufflerie s'est avéré une très bonne plateforme d'essai pour étudier les effets des précipitations givrantes sur les liquides de dégivrage et d'antigivrage. Les essais en soufflerie ont démontré qu'il est possible de simuler des courses de décollage à l'intérieur avec des contaminations par la pluie verglaçante, les granules de glace et la neige. La faisabilité des essais sur le Falcon 20 a été démontrée au cours des dix dernières années. Il est possible de conclure que les essais pleine grandeur menés sur le Falcon 20 peuvent servir à étayer les essais en soufflerie.

Recommandations

Des essais supplémentaires sont recommandés afin de simuler des courses de décollage avec différentes surfaces portantes et à des vitesses de rotation plus basses. La dispersion et la répartition des précipitations givrantes doivent être affinées davantage. Le faible éclairage dans la soufflerie a compliqué la documentation photographique des essais. Les résultats pourraient être optimisés par l'utilisation de lentilles et de flashs de meilleure qualité.

CONTENTS Page

LIST OF APPENDICES

LIST OF FIGURES Page

LIST OF TABLES Page

LIST OF PHOTOS Page

This page intentionally left blank.

GLOSSARY

APS	APS Aviation Inc.
CDU	Cockpit Display Unit
CEF	Climatic Engineering Facility
CSA	Canadian Space Agency
DAT	Digital Audio Tape
DND	Department of National Defence
DVD	Digital Versatile Disk
FAA	Federal Aviation Administration
GPS	Global Positioning System
HOT	Holdover Time
ILS	Instrument Landing System
IP	Ice Pellets
LPM	Litre per Minute
LSI	Large Scale Integration
MSC	Meteorological Service of Canada
MSDS	Material Safety Data Sheet
MLS	Microwave Landing System
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NRC	National Research Council Canada
OAT	Outside Air Temperature

PIV	Particle Image Velocimetry
PIWT	3 m x 6 m Open-Circuit Propulsion Icing Wind Tunnel
PSP	Pressure Sensitive Paint
SAE	Society of Automotive Engineers
SN	Snow
TDC	Transportation Development Centre
VOR	VHF Omnidirectional Range
ZR	Freezing Rain

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.

1.1 Background

Aircraft departure regulations in icing conditions require that no takeoff be attempted as long as any form of contamination (ice, frost, snow, or slush) is adhering to the lift-critical surfaces of an aircraft. The method of identifying that some form of contamination does exist on the aircraft surface generally relies on visual indications, as perceived by personnel on the ground or by flight crew from flight decks and/or aircraft cabins. When the fluid's failure to absorb ice crystals is identified, it can only be assumed that this contamination is adhering.

In some situations, a tactile test may be conducted, either in response to regulations or as a voluntary practice to provide additional information on the wing condition. This test consists of passing a bare hand over an area of the wing surface, such as the leading edge, or scraping the surface with fingernails to detect the presence of a very thin ice film.

Previous studies have shown that the visual failure of a fluid does not always indicate adherence. Tests in the NRC wind tunnel and with the NRC Falcon 20 research aircraft are being conducted to link adherence to aerodynamic flow-off in an attempt to extend current holdover times (HOTs).

1.1.1 Wind Tunnel Testing

Testing to simulate aircraft ground icing conditions was attempted in the NRC open-circuit wind tunnel for the first time during the winter of 2006-07. The tests were conducted to address the effects of ice pellets mixed with snow and/or freezing rain and heavy snow. This research is documented in detail in two reports written by APS for TC:

1. TC report, TP 14779E, *Development of Allowance Times for Aircraft Deicing Operations During Conditions with Ice Pellets* (1); and
2. An interim report documenting aircraft deicing research in heavy snow conditions, which was provided to TC and the FAA. A final report is expected to be published once the research is completed in a future winter.

1.1.2 Falcon 20 Full-scale Aircraft Testing

Previous tests to examine the elimination of failed Society of Automotive Engineers (SAE) Type IV fluid from aircraft wings during takeoff were conducted during the 1997-98 and 1998-99 winter seasons. These tests, based on simulated takeoff runs using the NRC Falcon 20 aircraft, showed that the test approach was a viable one. The Falcon 20 test program conducted during the winters of 2001-02 and 2002-03 addressed the effects of unshed anti-icing fluid on aircraft takeoff performance.

As part of a larger research program examining aircraft operations in ice pellet conditions, APS conducted tests with the NRC Falcon 20 in 2005-06 to determine the maximum amount of ice pellet contamination that will flow-off an anti-iced aircraft at takeoff and in 2006-07 to study the effects of ice pellets mixed with snow and/or freezing rain.

This research is documented in detail in a series of six reports written by APS for TC:

1. TC report, TP 13316E, *Contaminated Aircraft Takeoff Test for the 1997/98 Winter* (2);
2. TC report, TP 13479E, *Contaminated Aircraft Takeoff Tests for the 1998-99 Winter* (3);

3. TC report, TP 13666E, *Contaminated Aircraft Simulated Takeoff Tests for the 1999-2000 Winter: Preparation and Procedures* (4);
4. TC report, TP 13995E, *Aircraft Takeoff Test Program for Winter 2001 02: Testing to Evaluate the Aerodynamic Penalties of Clean or Partially Expended De/Anti-Icing Fluid* (5);
5. TC report, TP 14147E, *Aircraft Takeoff Test Program for Winter 2002-03: Testing to Evaluate the Aerodynamic Penalties of Clean or Partially Expended De/Anti-Icing Fluid* (6); and
6. TC report, TP 14716E, *Falcon 20 Trials to Examine Fluid Removed from Aircraft During Takeoff with Ice Pellets* (7).

1.2 Program Objectives

A program for Falcon 20 and wind tunnel testing was developed for the winter of 2006-07 to substantiate and possibly expand the current allowance time of 25 minutes in ice pellets only conditions. Research was conducted in the following simulated precipitation conditions:

- Light Freezing Rain and Light Ice Pellets (ZR-/IP-);
- Light Ice Pellets Only (IP-);
- Moderate Ice Pellets Only (IP mod);
- Snow (SN) and Light Ice Pellets (IP-); and
- Heavy Snow (SN+).

The detailed objectives of the Falcon 20 and wind tunnel test program are provided in an excerpt from the TC statement of work in Appendix A. Two reports have been written for this test program:

1. This report, TP 14778E, documents the tools that are available to study aerodynamic flow-off and its relation to fluid failure on aircraft wings; and
2. TP 14779E (1), documents the data collected in the wind tunnel and Falcon 20 test program.

As this report was not requested by TC until testing was completed, it is not specifically included in the work statement.

1.3 Report Format

The following list provides short descriptions of subsequent sections of this report:

a) Section 2 describes the feasibility of wind tunnel testing;

b) Section 3 describes the feasibility of Falcon 20 full-scale aircraft testing;

c) Section 4 presents conclusions derived from testing; and

d) Section 5 lists recommendations for future testing.

2. WIND TUNNEL TESTING FEASIBILITY

2.1 Wind Tunnel

2.1.1 Description of the Wind Tunnel

The 3 m x 6 m Open-Circuit Propulsion Icing Wind Tunnel (PIWT) is a facility that bridges the gap between a conventional wind tunnel and an engine test cell. Photo 2.1 shows an overall view of the NRC wind tunnel, and Photo 2.2 shows its interior and test area. The wind tunnel has several unique features that lend themselves to a variety of applications.

The open-circuit layout, with fan at entry, permits contaminants associated with the test arrangements (such as heat, combustion products, wakes, jets, and lost lubricants) to discharge directly, without recirculating or contacting the fan. Additionally, a high-solidity fan attenuates unsteadiness from atmospheric wind. The fan is normally driven electrically, but high-speed operation can be accommodated by a gas turbine drive system.

The working section floor may be raised to within 0.46 m of the centreline to facilitate work on test installations, to simulate varying ground effects, or to modify floor boundary layer characteristics. The floor may be solid or porous, and in the normal lowered position, it forms the upper surface of a 1.22 m deep steel plenum extending the full width and length of the working section.

Working section velocity non-uniformities are generally less than 0.5 percent of mean velocity, and over most of the working section, flow direction is within 1° of the longitudinal axis. A test section insert is available to further increase wind speed.

Currently, the PIWT is being used in icing research. The open-circuit design of the wind tunnel means a naturally cold test section is available in the winter. This capability, combined with the working section height, results in the ability to simulate larger water droplets than most icing wind tunnels can support. Small cloud droplets have been simulated in the wind tunnel, and the potential exists to do a freezing drizzle simulation.

The freezing precipitation sprayer (Photo 2.3) used for HOT testing at the NRC Climatic Engineering Facility (CEF) was installed at the wind tunnel and used to produce freezing rain for the 2006-07 test session. It was uncertain whether the sprayer would produce the proper precipitation rate, distribution, and droplet size given the significant height difference between the NRC CEF and the wind tunnel.

APS allocated one week in January 2007 to test the feasibility of testing in the wind tunnel and to calibrate the test parameters. The preparatory week was a success, and testing was conducted using the knowledge acquired during this week. Twenty-nine tests were conducted in 2006-07. A typical test took approximately two hours to complete.

Ice pellets and snow were dispensed by APS personnel using hand-held devices.

2.1.2 Wind Tunnel Specifications

The characteristics of the NRC PIWT are given in this section.

2.1.2.1 Tunnel Geometry

- Test section: 3.1 m wide x 6.1 m high x 12.2 m long (3.1 m x 4.9 m x 6.4 m with insert)
- Test section area: 18.9 m^2 (15.2 m^2 with insert)

2.1.2.2 Tunnel Characteristics

- Fan power:
  - Electric = 750 kW
  - Gas turbine = 6,000 kW
- 18.9 m^2 test section max speed:
  - Electric = 40 m/s
  - Gas turbine = 54 m/s
- 15.2 m^2 test section max speed:
  - Electric = 50 m/s
  - Gas turbine = 67 m/s
- Speed uniformity: $\pm 0.5\%$

2.1.2.3 Auxiliary Systems

- Computer-controlled icing-spray rig
- Compressed air: up to 14.5 kg/s at 700 kPa
- Flow traverse rigs: several, automated

2.1.2.4 Data System and Instrumentation

- Software: test specific MatLab & LabView
- Model mounts: pitch rig and custom mounts available
- Pressure measurements: Scanivalve ZOC™, Kulite
- Anemometry: hot-film/hot-wire
- Balances: internal (TASK, NRC, various) and external (cruciform, various)
- Photography: Digital Versatile Disk (DVD), Super-Video Home System (S-VHS), 35 mm
- Flow visualization: Particle Image Velocimetry (PIV), Acoustic Array, Pressure Sensitive Paint (PSP), laser light sheet, smoke, surface oil, and fluorescent mini-tuft

2.1.3 Wind Tunnel Diagrams

The NRC wind tunnel setup used for the Winter 2006-07 testing is shown in Figure 2.1 (top view) and Figure 2.2 (side view).

2.1.4 Wind Tunnel Flight Profile

The wing section used for testing was supported on either side by 2-axis weigh scales capable of measuring drag and lift forces generated on the wing section. The wing section was attached to servo-systems capable of pitching the wing section to a static angle or generating dynamic movements.

The flight profile chosen for the 2006-07 wind tunnel tests was based on the flight profile data obtained with the Falcon 20 research aircraft in previous years. The simulated takeoff run, including rotation, was replicated in the wind tunnel with the following characteristics:

- Accelerate from 0 to 100 knots in 35 seconds;
- At 100 knots, pitch wing section from 0º to 8º in 3 seconds;
- Hold wing position for 1 second;
- Reduce angle of attack from 8º to 4º in 16 seconds;
- Hold wing position for 60 seconds; and
- Stop test.

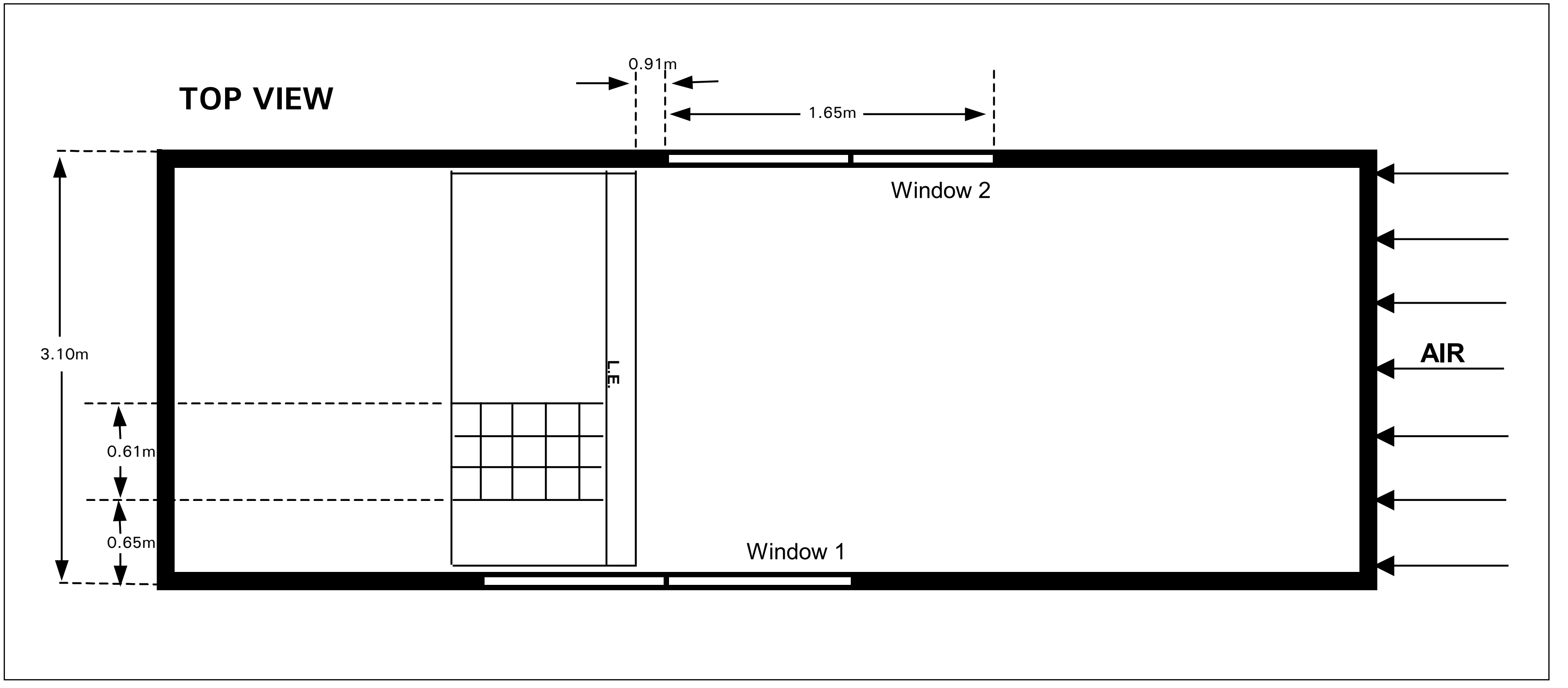


Figure 2.1: Top View of the NRC Wind Tunnel

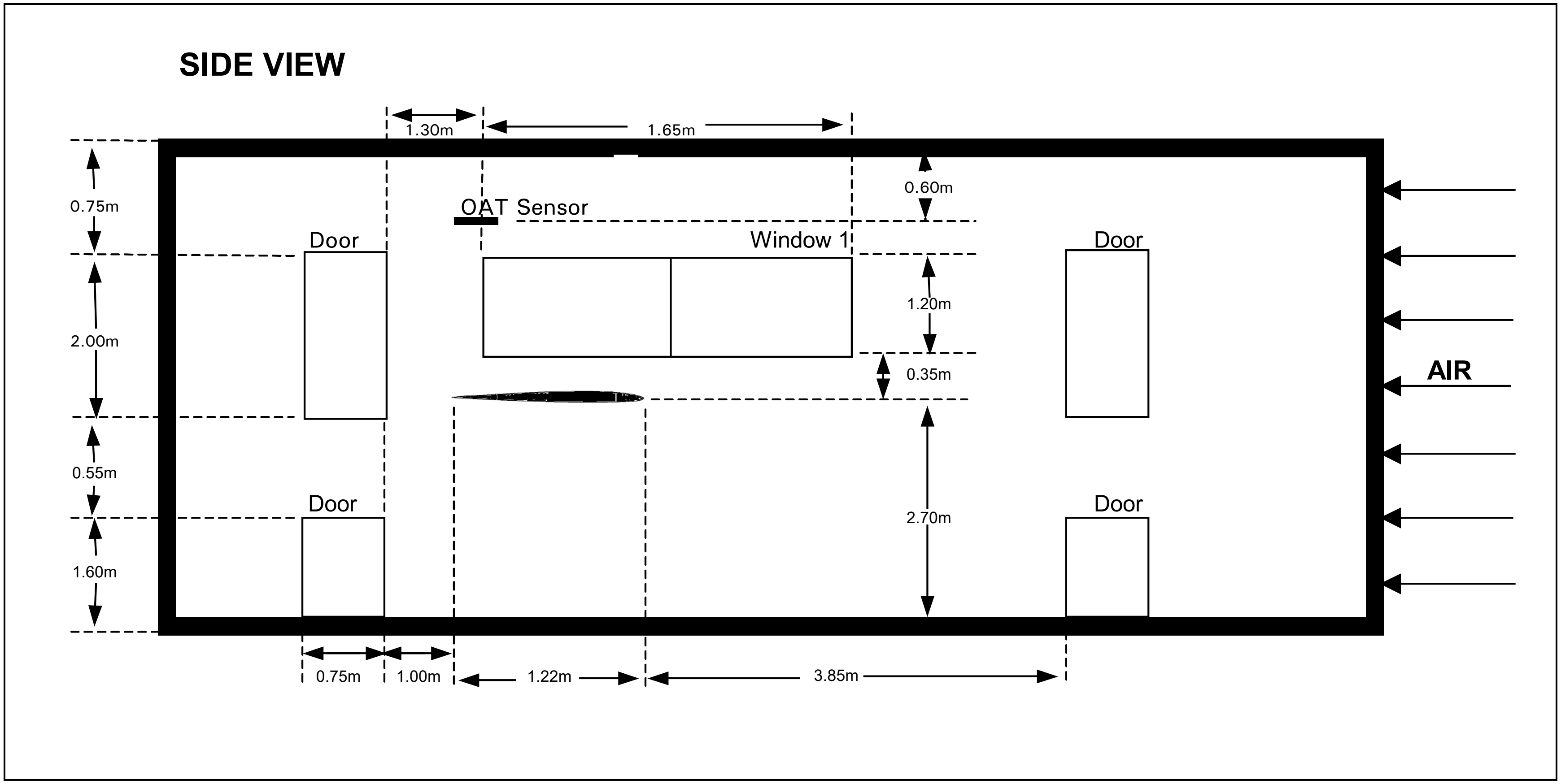


Figure 2.2: Side View of the NRC Wind Tunnel

2.1.5 Airfoil

The wing section used for testing was an NACA 23012 acquired by the NRC. Figure 2.3 shows the wing section used for testing. The wing section used was a hard wing similar to the airfoil of a Cessna Caravan. The NACA 23012 wing section had been used in recent years by the NRC for airborne icing experiments; this was the first time the wing section was used for ground icing simulation tests.

2.1.5.1 NACA 23012 Design Characteristics

A cross sectional view of the NACA 23012 wing section used for testing has been included in Figure 2.3. Some of the pertinent dimensions of the wing section are:

a) Wing chord: 1.2 m (4 ft.);
b) Length: 3.0 m (10 ft.); and
c) Wing surface area: 3.6 m^2 (39 $ft.^2$).

The wing section used did not have slats or flaps. No moveable devices were available on the wing section.

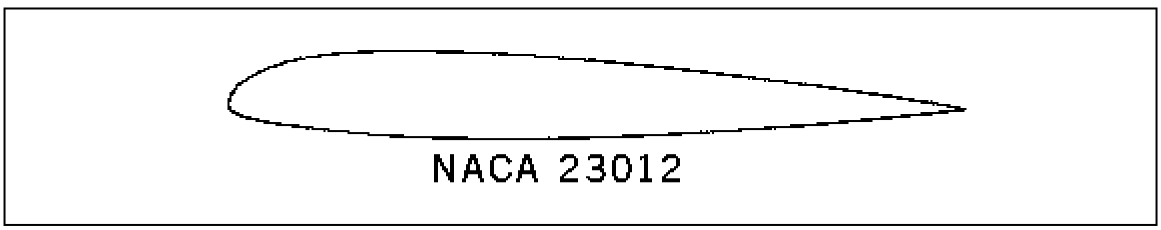


Figure 2.3: Schematic Cross Sectional View of NACA 23012 Wing Section

2.1.6 Test Area

The wing section (Photo 2.4) used for testing has the same width as the wind tunnel. The entire surface of the airfoil was contaminated during the tests performed in February 2007.

The wind tunnel airflow near the walls is affected by the boundary layers forming in these areas. For this reason, the test area analysed during the wind tunnel tests did not consider the wing surface less than 0.3 m from each of the wind tunnel walls.

Prior to the testing, APS personnel used markers to draw a grid with dimensions of 0.61 m x 1.22 m (2 ft. x 4 ft.) along a chord approximately 0.65 m (2 ft.) from the tunnel wall (see Figure 2.1). Smaller grids with dimensions of 5.1 cm x 5.1 cm (2 in. x 2 in.) were then drawn inside the larger grid, perpendicular and parallel to the leading edge. The grid was used to facilitate observations of the fluid shearing off the wing and the movement of contamination during takeoff.

2.1.7 Test Area Access

The NRC wind tunnel walls have rails at approximately 0.3 m (1 ft.) below the height of the wing section. NRC personnel built two platforms that could be moved on the rails and locked in position close to the test area and at the exhaust end of the wind tunnel. One platform was used to access the leading edge of the wing, while the other was positioned behind the trailing edge.

The platforms are accessed via two ladders, one for each platform. The platforms have removable railings for safety reasons. The railings and ladders are used to access the test area and are removed from the tunnel during the wind tunnel test.

2.1.8 Typical Test Procedure

To satisfy the program objective, simulated takeoff and climb-out runs were performed with the wing section, and different parameters, including fluid thickness, wing temperature, and fluid freezing point, were recorded at designated times during the tests.

The procedure for each run was as follows:

a) The wing section was treated with Type IV fluid, poured in a one-step operation (no Type I fluid was used during the tests);
b) Contamination, in the form of simulated ice pellets, freezing rain, and snow, was applied to the wing section. Test parameters were measured at the beginning and end of the exposure to contamination; and
c) At the end of the contamination period, the tunnel was cleared of all equipment and scaffolding.

The wind tunnel was subsequently operated through a simulated takeoff and climb-out run. The behaviour of the fluid during takeoff and climb-out was recorded with digital video cameras and digital high-speed still cameras.

To validate the results, test results were compared to those obtained with the Falcon 20 aircraft.

2.1.9 Test Sequence

The length of each test (from start of setup to end of last measurement) varied largely due to the length of exposure to precipitation. Time required for setup and teardown as well as preparing and configuring the wind tunnel stayed relatively the same from test to test. Figure 2.4 demonstrates a sample timeline for a typical wind tunnel run. A precipitation exposure time of 60 minutes is used in Figure 2.4 for demonstration purposes; this time varied for each test depending on the objective.

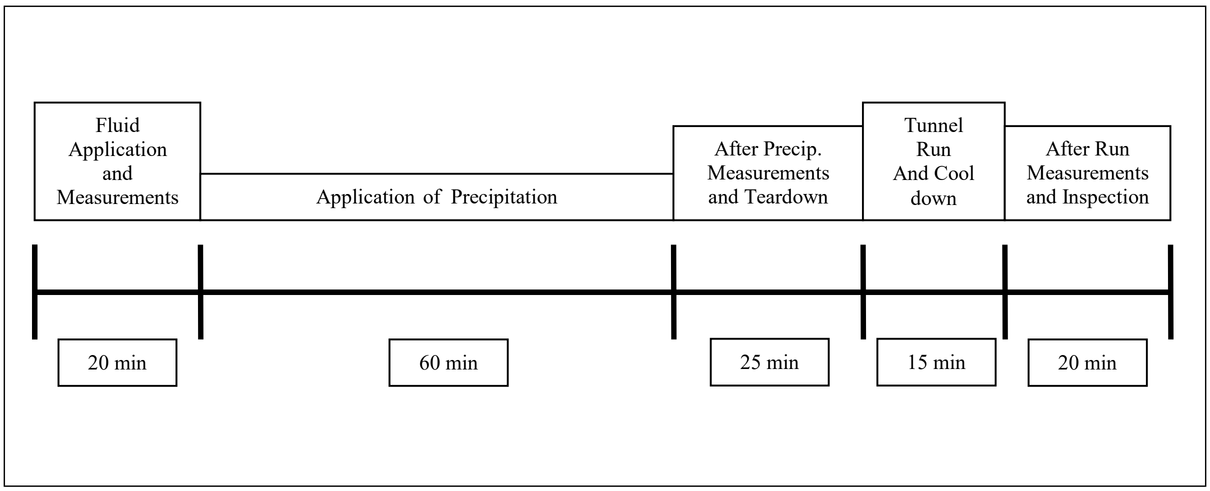


Figure 2.4: Typical Wind Tunnel Run Timeline

2.1.10 Safety

The test area is located 2.7 m above the wind tunnel floor. Even though the platforms have an anti-slip design, they can become slippery when the freezing precipitation accumulates. The tunnel floor and ladder become very slippery in the presence of deicing fluid and icing precipitation. For these reasons, several safety concerns need to be addressed to prevent accidents:

- All personnel must be familiar with Material Safety Data Sheets (MSDS) for fluids;
- Particular attention is required when working inside the tunnel as the floor and ladder are very slippery;
- Caution must be exercised when walking under the wing as fluid from the wing will drip;
- Prior to operating the wind tunnel, loose objects should be removed from the vicinity;

- When the wind tunnel is operating, ensure ear plugs are worn and personnel keep safe distances from moving equipment;
- When working on ladders, ensure equipment is stable;
- Appropriate footwear and clothing for frigid temperatures are to be worn by all personnel;
- Safety goggles must be used when working with or around fluids;
- If fluid comes into contact with skin, rinse hands under running water; and
- If fluid comes into contact with eyes, flush with the portable eyewash station.

2.2 Simulated Precipitation

The three types of simulated precipitation used during the Winter 2006-07 tests were:

- Freezing rain;
- Ice pellets; and
- Snow.

2.2.1 Freezing Rain

Simulated freezing rain was generated by the NRC freezing rain sprayer system installed on the top of the wind tunnel (Photo 2.3). The same sprayer head and scanner used for HOT testing at the NRC CEF was employed. The sprayer system uses compressed air and water to produce freezing rain. Four hypodermic needles are mounted onto a sprayer head whose movement is controlled by a 2-axis scanner.

During the 2006-07 test session, freezing rain rates of 5, 20, and 25 $g/dm^2/h$ were successfully simulated in the wind tunnel. NRC personnel used an Alicat Scientific 7 Litre per Minute (LPM) liquid flow controller to regulate the water supplied to the sprayer to achieve these rates. The 1.2 mm mean volume diameter droplet size measured in the tunnel replicated natural precipitation very well. The settings used are shown in Table 2.1.

Table 2.1: Freezing Rain Sprayer Settings Used in 2006-07

Target Precipitation Rate (g/dm²/h)	Actual Precipitation Rate (g/dm²/h)	Sprayer Settings						Mean Volume Diameter (mm)
		Translation		Nozzles	Speed	Water Flow Rate (mL/min/nozzle)	Air Pressure (psi)	
		x	y					
5	6.5	Full	Partial	2x#23, 2x#24	Low	37.5	27	1.2
20	19.8	Full	Partial	2x#23, 2x#24	Low	157.5	30	1.2
25	25	Full	Partial	2x#23, 2x#24	Low	232.5	30	1.2

The freezing rain distribution across the test area was considered even, with variations of a maximum 10 percent from the mean across the test area. Figure 2.5 shows the rates measured at six locations on the test area for the wind tunnel test performed on February 14, 2007. Figure 2.5. shows that the precipitation rate across the test area varies by a maximum 7 percent from the mean of 28.2 g/dm²/h.

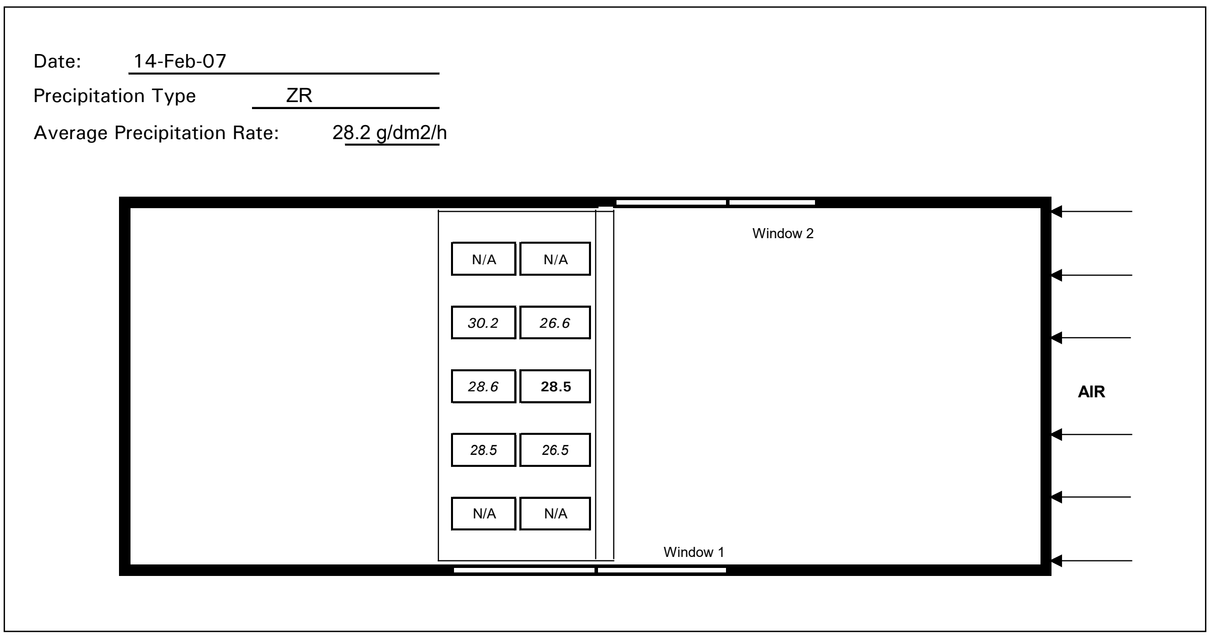


Figure 2.5: ZR Precipitation Rate Summary for Test 4 (2006-07)

2.2.2 Ice Pellets

Ice pellets were manufactured from ice cubes inside a rented refrigerated truck. The process required the use of blenders, calibrated sieves, colourant, and large Styrofoam containers.

Once produced, the ice pellets were stored in Styrofoam containers. They were applied over the test area using special hand-held dispensers. The ice pellets were applied from the leading edge only using two dispensers (Photo 2.5).

Ice pellet rates ranging from 5 to 73 g/dm^2/h were replicated in the wind tunnel. A typical ice pellet distribution across the test area is shown in Figure 2.6.

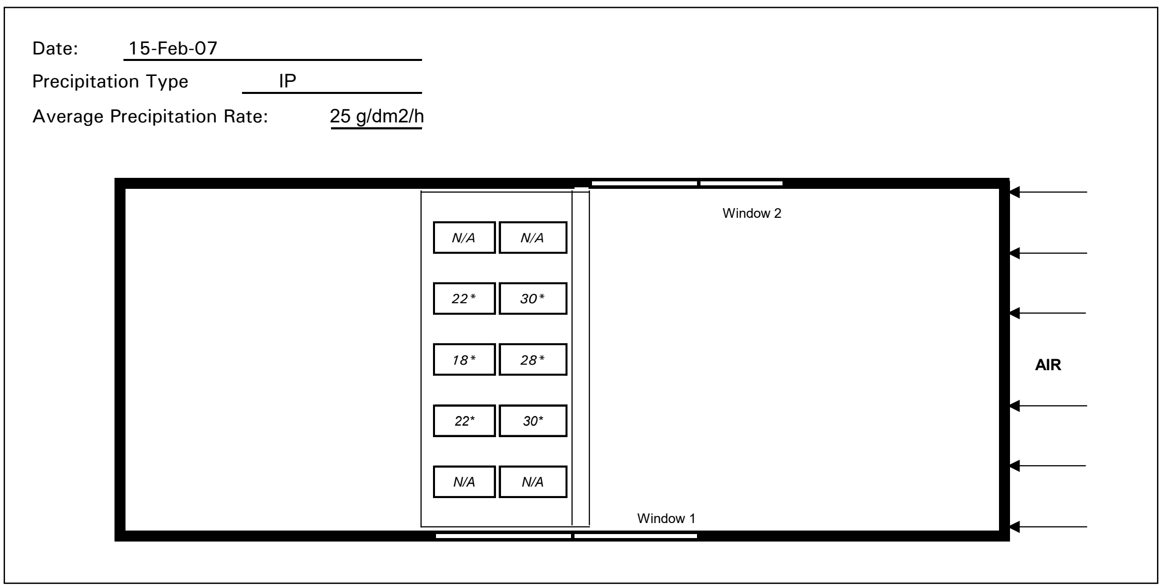


Figure 2.6: IP Precipitation Rate Summary for Test 5

2.2.3 Snow

Snow was manufactured using a similar process as used for the ice pellets. Once produced, the snow was stored in Styrofoam containers until applied over the test area using the ice pellet dispensers, modified to account for the finer snow particles.

The snow was applied using four dispensers, two on the leading edge and two on the trailing edge. Precipitation rates ranging from 4 to 77 g/dm^2/h were reproduced in the wind tunnel. A typical snow distribution is presented in Figure 2.7.

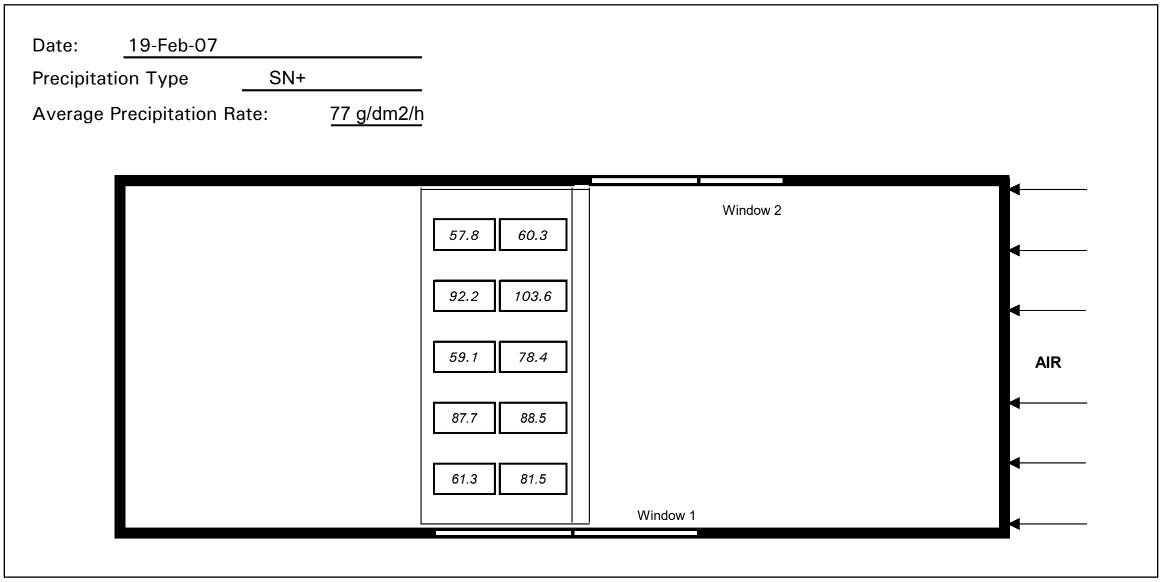


Figure 2.7: Snow Precipitation Rate Summary for Test SS4

2.3 Wind Tunnel Temperature

2.3.1 Variation between Outside Air Temperature and Wind Tunnel Temperature

The wind tunnel test area is enclosed in the wind tunnel building. The test temperature inside the wind tunnel is one of the critical parameters of the testing. The tunnel temperature is not a controlled variable because it depends on the outside air temperature (OAT), outside sky conditions and solar radiation, as well as the temperature inside the wind tunnel building. It is essential to maintain the air temperature inside the tunnel below freezing during the tests. The temperature inside the wind tunnel test area increased during the preparation of a typical wind tunnel test when workers were emanating heat in this area. The temperature inside the wind tunnel can be lowered by leaving the wind tunnel doors open and thus permitting outside air to circulate through the tunnel. However, the outside airflow reduces the effectiveness of freezing precipitation dispersion over the test area.

The wind tunnel test area was warmer than the OAT, on average, by 7ºC. The average OAT during all 2006-07 wind tunnel tests was -9.5ºC, while the average wind tunnel temperature was -2.8ºC.

For future testing, it is recommended that weather forecasts be monitored so that tests are conducted when OAT is below -8ºC. This parameter becomes even more sensitive if sunny weather is present. In 2006-07, extreme cases occurred when the tunnel temperature was up to 13ºC above the OAT.

2.3.2 Wind Tunnel Air Temperature Analysis

Air temperature data inside the wind tunnel was monitored and logged by NRC personnel. The data was analysed to characterize the test temperature of each wind tunnel test. The data is presented in Figures 2.8 and 2.9.

Four temperature parameters were considered in the analysis:

- Instantaneous tunnel OAT before run;
- Average tunnel OAT during last 10 minutes of precipitation;
- Average tunnel OAT from fluid application to start of takeoff run; and
- Average tunnel OAT from end of precipitation to start of takeoff run.

The analysis showed that the instantaneous tunnel temperature value might not be the correct temperature to be associated with the test. The temperature inside the wind tunnel varied considerably throughout the test. Also, the critical time of the precipitation phase usually takes place during the last minutes of precipitation when the fluid is failing. Therefore, a better and more conservative alternative is to consider the average temperature during the last 10 minutes of precipitation as the reference temperature for a typical test. This temperature value is usually one of the highest and most conservative temperatures, as shown in Figures 2.8 and 2.9.

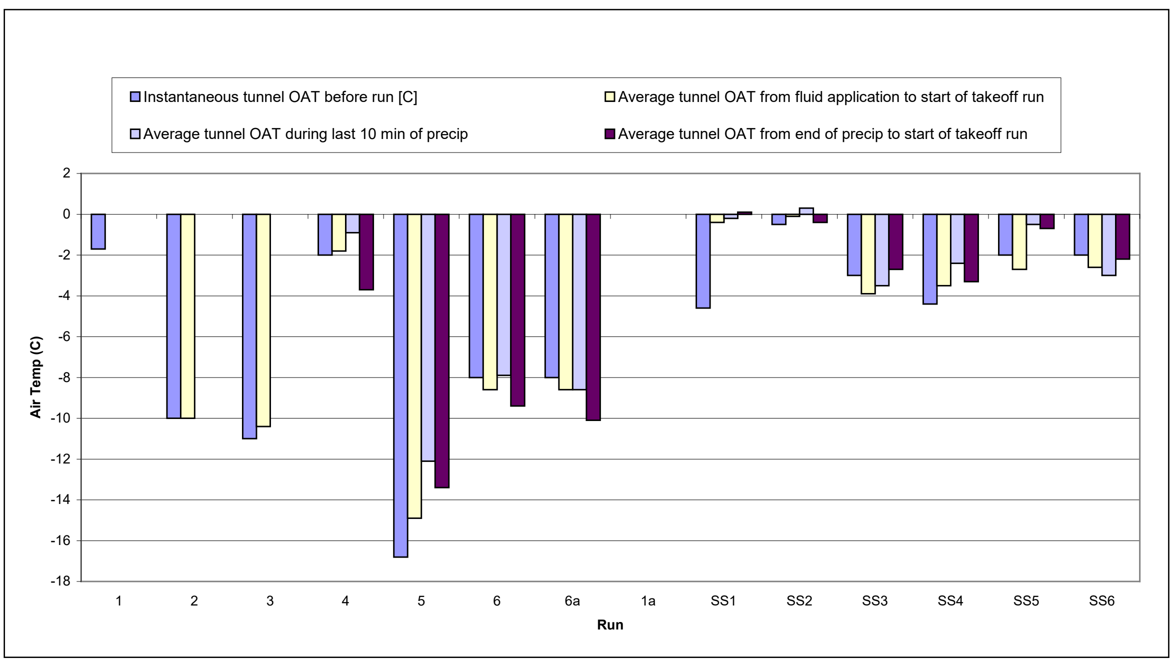


Figure 2.8: Wind Tunnel Temperature Analysis Chart for Runs 1 - SS6

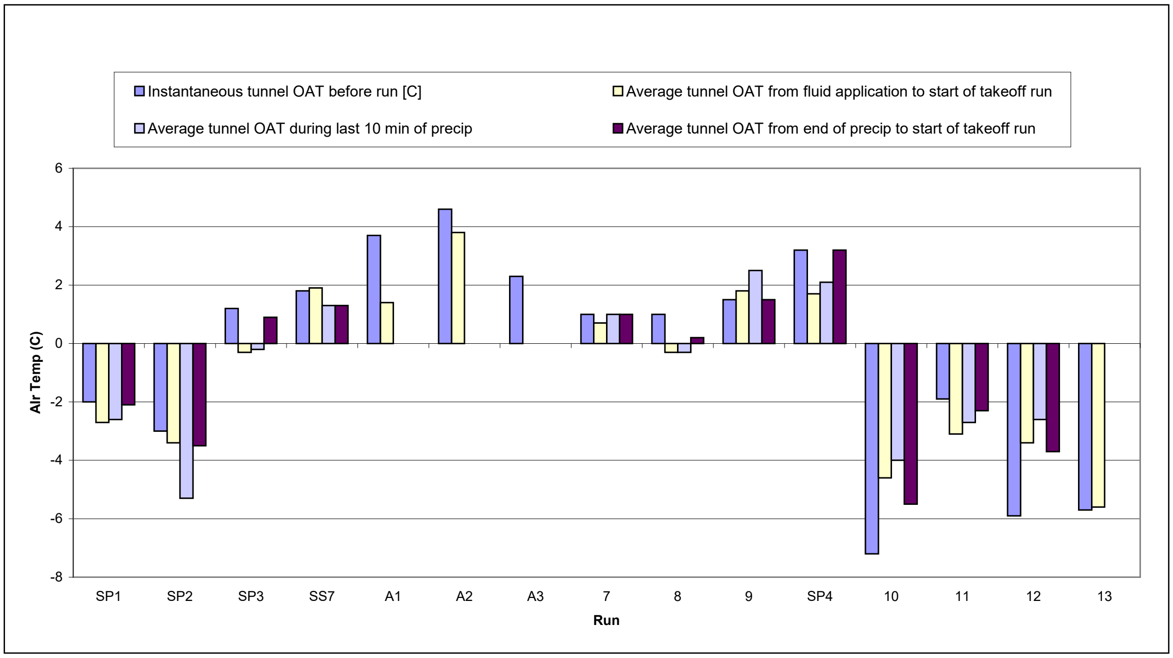


Figure 2.9: Wind Tunnel Temperature Analysis Chart for Runs SP1 - 13

2.3.3 Wing Skin Temperature Analysis

The wing skin temperature was measured at three locations during a typical wind tunnel test:

- On the leading edge;
- Mid-chord; and
- Under the wing.

An analysis similar to the air temperature study presented in Subsection 2.3.2 was conducted to select the proper wing skin temperature associated with each test. The results are shown in Figures 2.10 and 2.11. For this purpose, three parameters were compared:

- Approximate average wing temperature before run (average of the measurements recorded on the top surface of the wing);
- Approximate leading edge temperature before run; and
- Approximate under-wing temperature before run.

It was noted that the average wing skin and leading edge temperatures were close for all tests. Therefore, the average wing skin temperature can be associated with the reference wing skin temperature for each wind tunnel run.

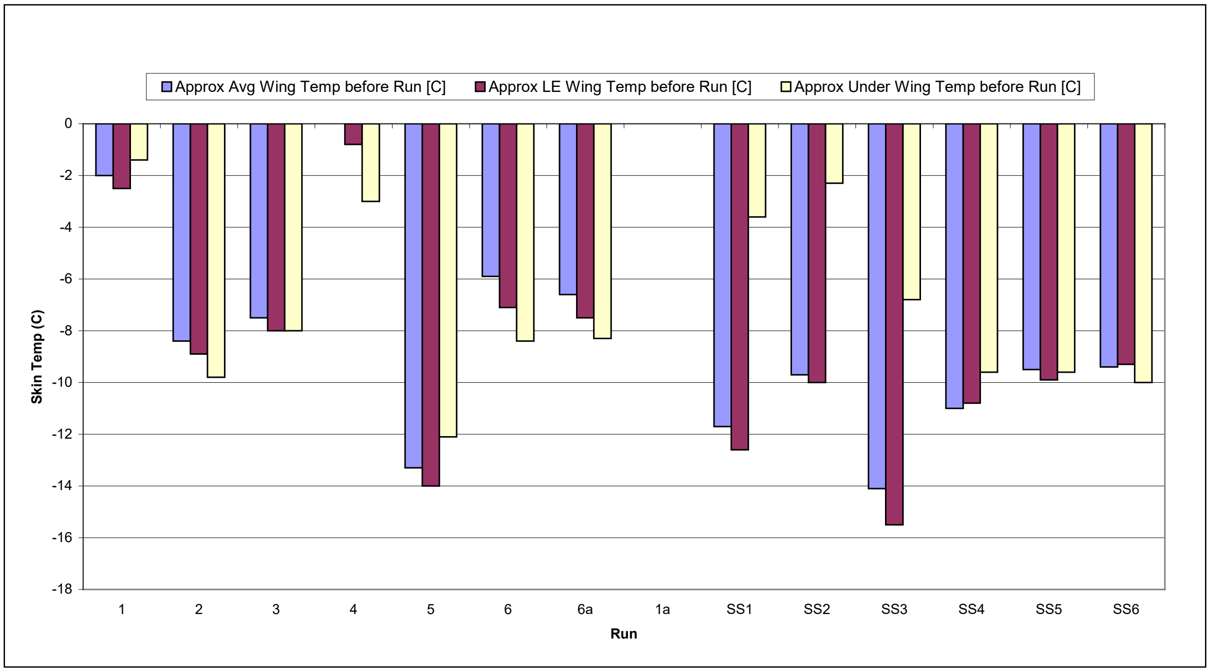


Figure 2.10: Wing Skin Temperature Analysis Chart for Runs 1 - SS6

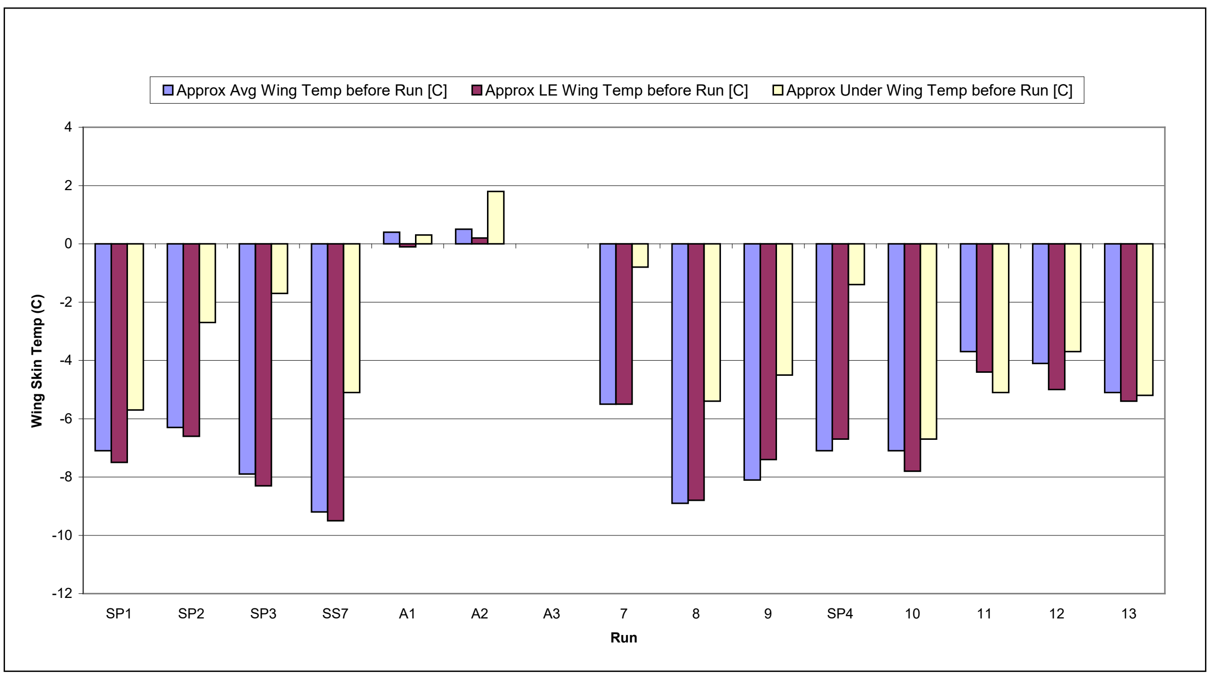


Figure 2.11: Wing Skin Temperature Analysis Chart for Runs SP1 - 13

2.3.4 Temperature Inside Wing Section

During the 2006-07 wind tunnel tests, APS installed surface temperature probes inside the wing section to monitor the wing skin temperature throughout all test phases. The purpose of this installation was to record the temperatures and to see if there was a correlation with the surface temperatures measured with the hand-held probe.

The wing section used in 2006-07 had a detachable leading edge that permitted access inside the wing (Photo 2.6). The temperature probes were passed through the axis supporting the wing and connected to a temperature logger placed outside the wind tunnel test area. Six temperatures were logged in this process:

- Temperature of the upper surface of the leading edge (denoted LU);
- Temperature of the lower surface of the leading edge (denoted LL);
- Air temperature inside the leading edge wing section (denoted LOAT);
- Temperature of the upper mid-chord surface (denoted MU);
- Temperature of the lower mid-chord surface (denoted ML); and
- Air temperature inside the mid-chord wing section (denoted MOAT).

Because of other priorities, only two runs (11 and SS3) were studied. An example of temperature logged during Run 11 is presented in Appendix B. The individual wing skin temperature measurements with the hand-held probe are denoted by dots of the same colour as the LU and MU measurements.

The limited analysis of the correlation of wing skin temperatures showed promising results. For Run 11, the temperature profiles logged for the upper surface of the wing on the leading edge and mid-chord locations follow closely the instantaneous measurements recorded with a hand-held temperature probe.

2.4 Fluid Application

The Type IV fluids were stored outside the wind tunnel and were kept at ambient temperature. The fluids were poured rather than sprayed so that application would not change the fluid viscosity. This methodology was appropriate given the relatively small test area and the goal of minimizing the amount of fluid flowing off the wing.

Type IV fluids were applied to the wing section by pouring directly from the 20 L fluid containers or from smaller 3 L containers. A total of 20 L of fluid were applied to the wing section for each test.

2.5 Photo and Video Recording

Two Canon Digital Rebel XT digital still cameras were used to obtain high-speed, high-resolution photographs of the testing. The 8 mega-pixel resolution cameras can take up to three pictures per second in continuous shooting mode. The cameras had two different lenses available:

a) 18-55 mm standard lens for wide angle pictures; and
b) 105 mm macro lens for close-ups (not used in 2006-07).

To create a consistent and stable setup for the cameras, APS mounted the cameras in the observation window overlooking the wing section. The flashes, operated through infrared sensors, were positioned in the opposing observation window (Figure 2.12); this created a shadow effect, which could be used to measure and calculate the magnitude of the fluid waves and protruding contamination. Photos 2.7, 2.8, and 2.9 demonstrate the camera setup used for the testing period. Video cameras, operated by NRC personnel, were positioned directly above the wing section. The cameras were zoomed in to observe the behaviour of the fluid and contamination on the wing.

In addition, a professional photographer used a digital still camera to take pictures of the test setup and all phases of the test runs.

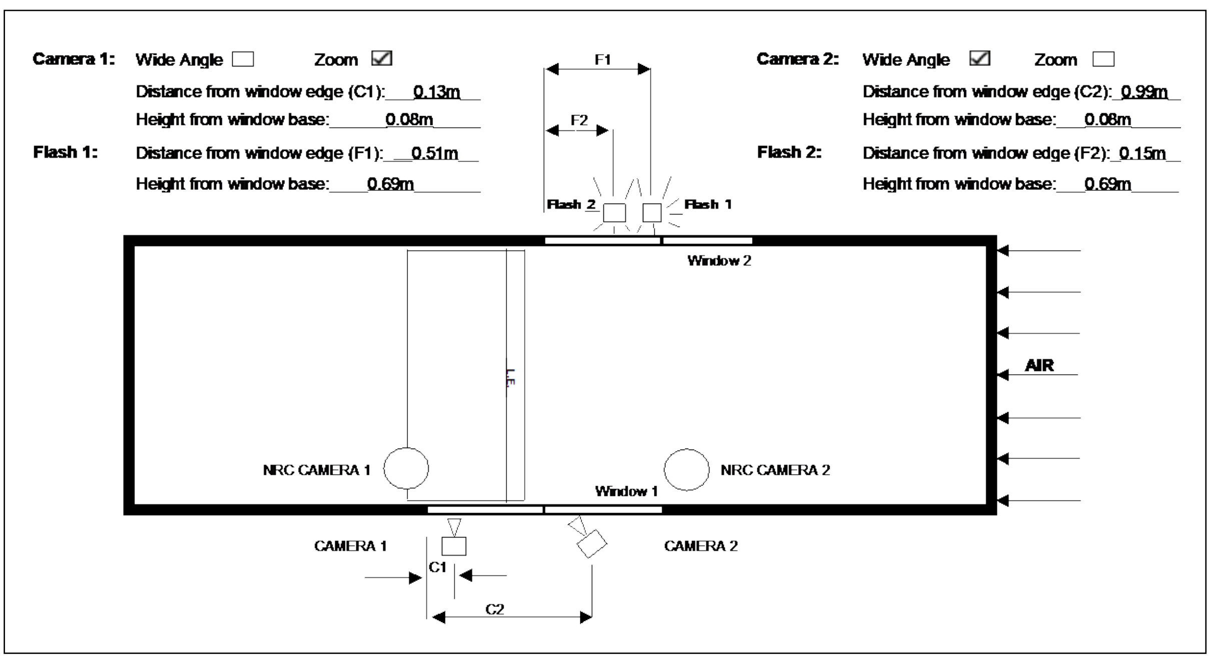


Figure 2.12: Wind Tunnel Camera and Flash Setup

This page intentionally left blank.

Photo 2.1: Overall View of the NRC Wind Tunnel

Photo 2.2: Interior View of the NRC Wind Tunnel

Photo 2.3: Freezing Rain Sprayer

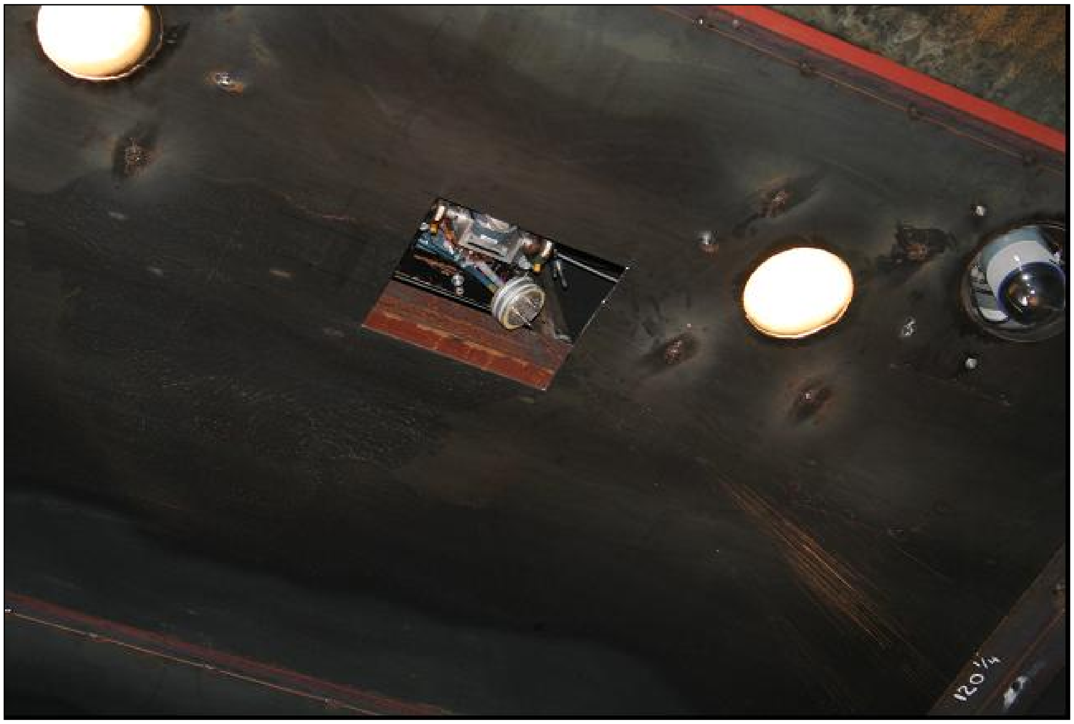


Photo 2.4: Wing Section Used in Wind Tunnel Tests

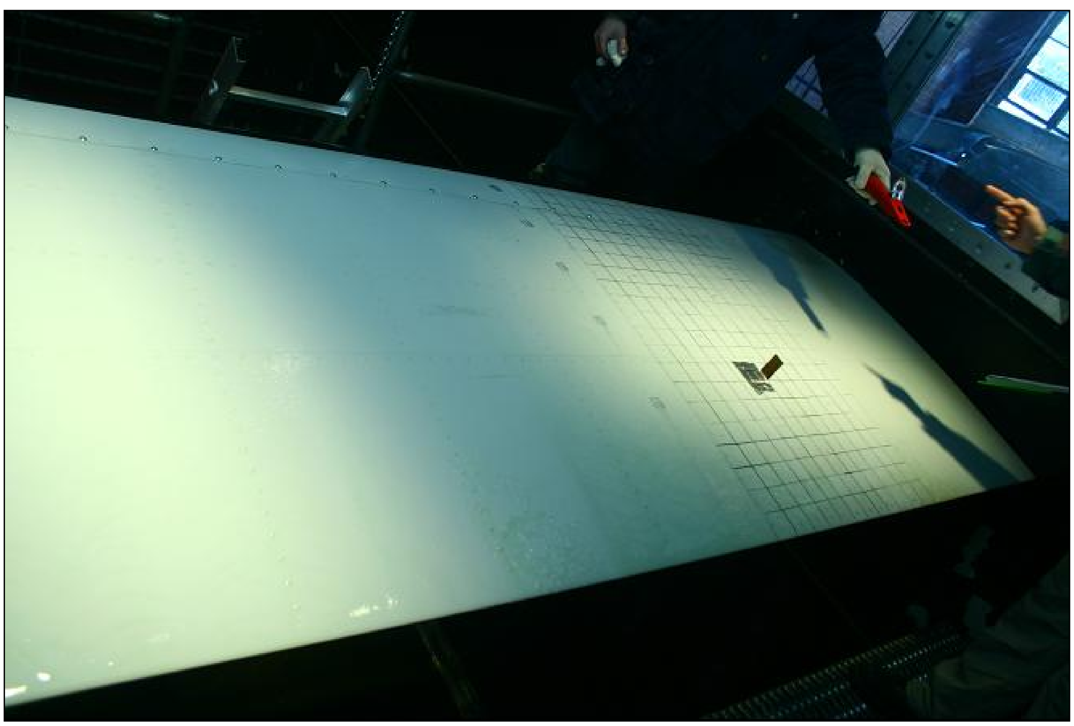


Photo 2.5: Ice Pellet/Snow Application during Wind Tunnel Tests

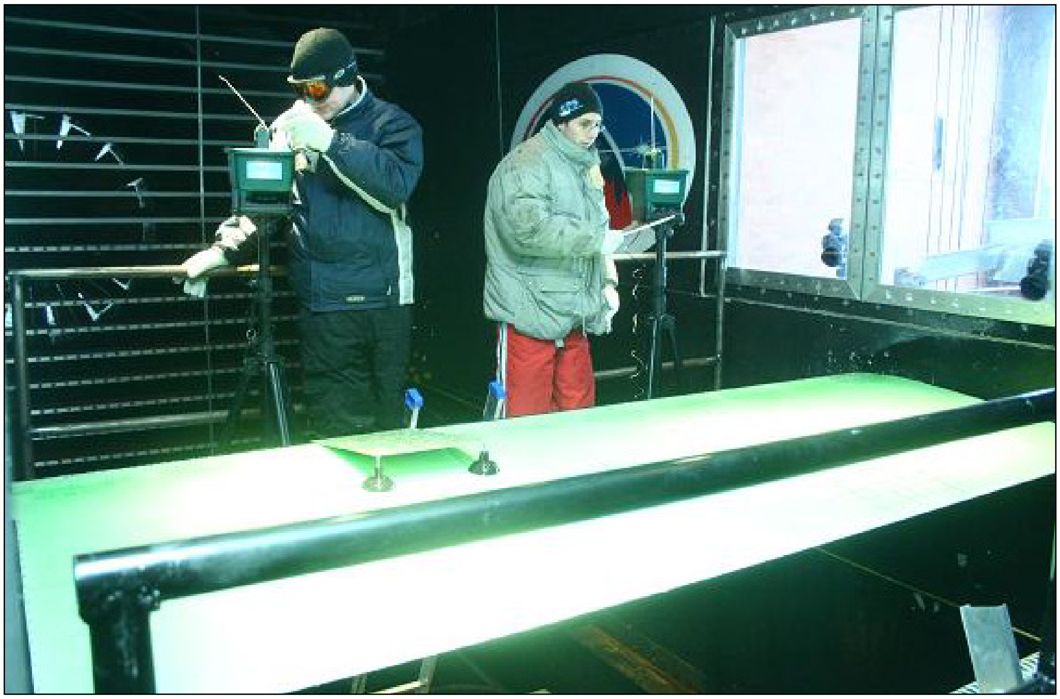


Photo 2.6: Temperature Probes Inside Wing Area

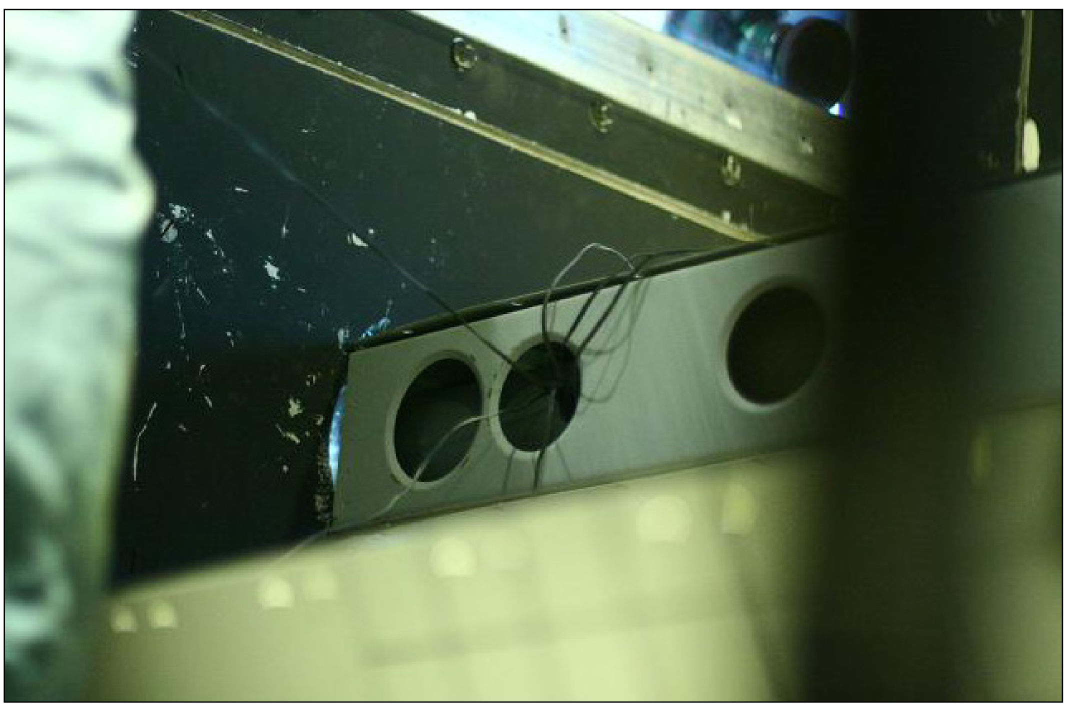


Photo 2.7: Camera Setup in Wind Tunnel

Photo 2.8: Camera 2 Overlooking the Leading Edge

Photo 2.9: Flash Setup in Wind Tunnel

This page intentionally left blank.

3. FALCON 20 TESTING FEASIBILITY

3.1 NRC Falcon 20

3.1.1 Description of the Falcon 20 Aircraft

The aircraft used for testing was a Dassault Falcon 20 twin-engine, mid-size business jet, operated by the NRC (see Photo 3.1). The aircraft is a multipurpose platform that has been used in recent years for two major research programs:

a) The testing and evaluation of precision instrument approaches using augmented Global Positioning Systems (GPS) for guidance; and

b) The determination of aircraft performance characteristics on runways contaminated by winter precipitation.

With an extensive onboard data acquisition system, the aircraft can also be used for airborne geoscience studies, avionics research, and aircraft-based sensor research.

NRC acquired the Falcon 20 from the Department of National Defence (DND) in 1991. In partnership with the Canadian Space Agency (CSA) and TC, NRC originally instrumented the aircraft to support micro-gravity research and curved path (area navigation) capabilities and procedures. These capabilities still exist with the modified aircraft fuel and hydraulic systems in place to allow the aircraft to fly “zero-G” parabolic manoeuvres and with the modified aircraft guidance systems available to fly curved path precision approaches using GPS-based receivers.

In partnership with TC, National Aeronautics and Space Administration (NASA), and DND, the NRC Falcon 20 was used in a five-year research program directed at standardizing runway friction reporting procedures for winter contaminated runways and at determining aircraft landing and takeoff performance changes as a result of runway contaminants.

3.1.2 Falcon 20 Characteristics

A three-view diagram of the Falcon 20 aircraft has been included in Figure 3.1. Some of the pertinent dimensions of the Falcon 20 are:

a) Wing span: 16.32 m (53 ft. 7 in.);

b) Wing surface area (both wings): 41 m^2 (441.33 $ft.^2$); and

c) Length: 17.15 m (56 ft. 3 in.).

The Falcon 20 has slotted slats outboard of the fence on each wing; the wing section inboard of the fence contains no moveable devices.

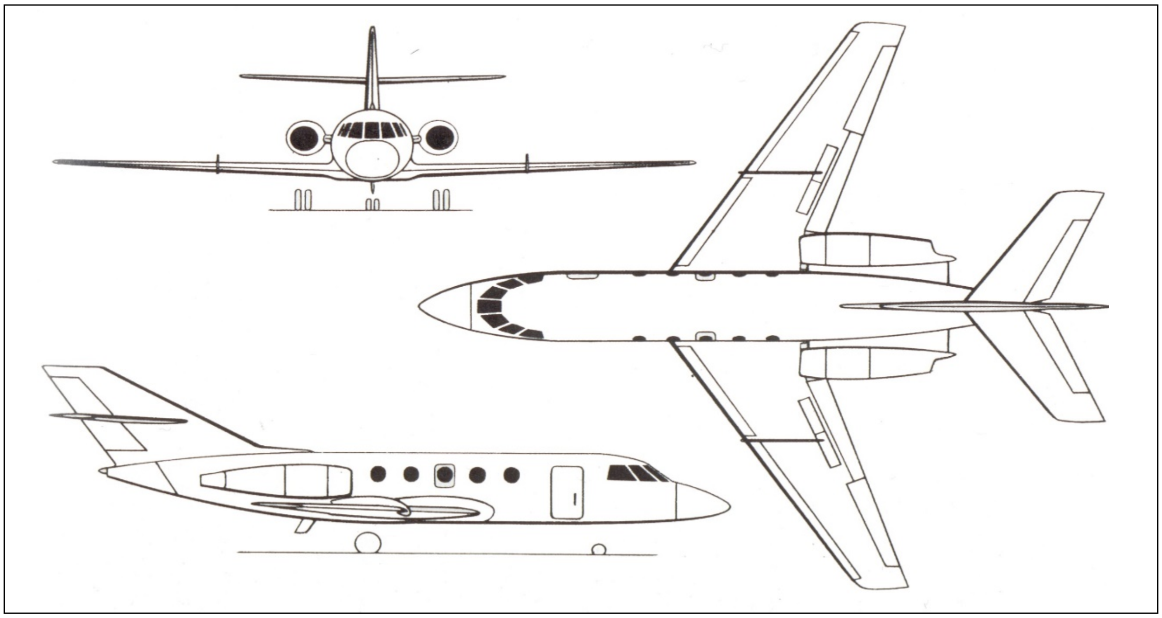


Figure 3.1: Schematic View of Dassault Falcon 20

3.1.2.1 Falcon 20 Onboard Installations

The NRC Falcon 20 research aircraft is equipped with the following onboard installations:

a) Engineering workstation containing computer with GPS receiver card, display, and interface with the data acquisition system;

b) Data acquisition system based on Large Scale Integration (LSI) 11/73 digital computer, with Digital Audio Tape (DAT) and/or hard disk recording medium;

c) Multiple navigation sensors including VHF Omnidirectional Range (VOR), Instrument Landing System (ILS), Microwave Landing System (MLS), GPS, flight test differential GPS, and modified flight director; and

d) Cockpit mounted Cockpit Display Unit (CDU) to initiate GPS approaches and monitor selected test parameters.

3.1.2.2 Falcon 20 Measurement Capabilities

The NRC Falcon 20 research aircraft has the following measurement capabilities:

a) 3-axis accelerations and rates;
b) Aircraft attitude and heading;
c) Three-dimensional positions and velocities;
d) Static and dynamic pressures;
e) OAT; and
f) Flight director system signals.

3.1.3 Falcon 20 Test Profile

Simulated takeoff runs can be performed with the Falcon 20 aircraft to study the effects of freezing precipitation on aircraft wings. The recent Falcon 20 tests excluded climb-out; however, actual takeoffs with the Falcon 20 have been performed in the past. A typical simulated takeoff run, including rotation, has the following characteristics:

- Accelerate from 0 to 120 knots;
- Cut engine power at 120 knots;
- Pitch nose up at 125 knots;
- Keep nose up until 914 m (3000 ft.) of runway remains; and
- Apply brakes.

3.1.4 Falcon 20 Test Area

Both wings of the aircraft can be used for testing. In the past, APS performed tests with the Falcon 20 aircraft using one or both wings at a time.

For example, in 2005-06, a single area on the port wing just inboard of the fence was selected to serve as the test surface on the Falcon 20 (Figure 3.2). The test area was made large enough to be representative of the entire wing and, at the same time, to enable a freezing precipitation production rate that was reasonably achievable.

Both wings were used for testing in 2006-07. The same 2.7 m^2 test area used for Runs 5 to 9 in 2005-06 (Figure 3.2) was selected for both port and starboard wings.

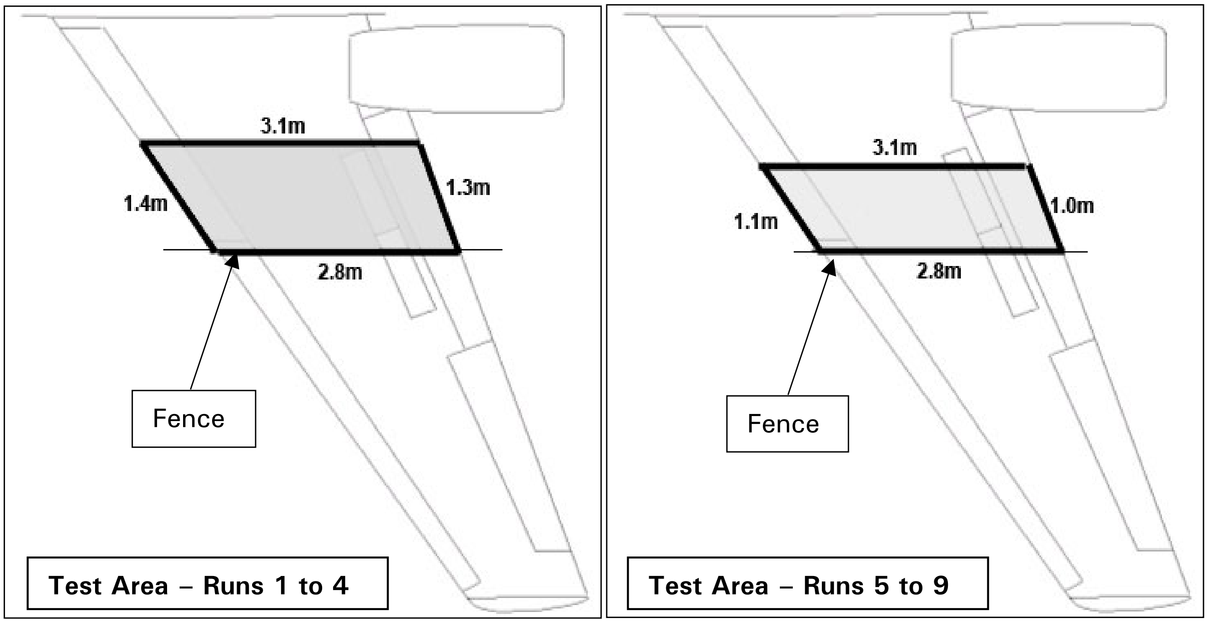


Figure 3.2: Test Areas Used in 2005-06 Testing

3.1.4.1 Test Area Grid

Prior to the testing, NRC personnel used markers to draw a grid with dimensions of 0.61 m x 0.61 m (2 ft. x 2 ft.) just inside the fence on the wing(s) of the Falcon 20 (Photo 3.2). Smaller grids with dimensions of 5.1 cm x 5.1 cm (2 in. x 2 in.) were then drawn inside the larger grid, perpendicular and parallel to the fence. The grid was used to facilitate observations of the fluid shearing off the wing and the movement of ice pellets during takeoff.

3.1.5 Typical Test Procedure

To satisfy the program objective, simulated takeoff runs were performed with the NRC Falcon 20 research aircraft, and different parameters, including fluid thickness, wing temperature, and fluid freezing point, were recorded at designated times during the tests.

The procedure for each run is outlined below.

a) The designated test area on the port and starboard wings was treated with Type IV fluid, poured in a one-step operation outside the NRC hangar.

b) Contamination, in the form of simulated ice pellets, freezing rain, and snow, was applied to one wing section; the other wing section was left uncontaminated and used as a baseline comparison test. Test parameters were measured at the beginning and end of the exposure to contamination.

c) At the end of the contamination period, the aircraft was taxied to the selected runway. Once at the button, APS personnel conducted an inspection of the contaminated wing section and measured selected test parameters.

d) The aircraft was subsequently operated through a simulated takeoff run, excluding climb-out. The behaviour of the contaminated and uncontaminated fluid during the takeoff run was recorded with digital video cameras and digital high-speed still cameras.

Tests results were compared to the results obtained in the NRC open-circuit wind tunnel to validate the results previously obtained in the wind tunnel.

3.1.6 Test Sequence

The Falcon 20 and wind tunnel tests followed the same critical path. The length of each test (from start of setup to end of last measurement) varied largely due to the length of exposure to precipitation. Time required for setup and teardown as well as preparing the Falcon 20 aircraft stayed relatively constant from test to test. Figure 3.3 demonstrates a sample timeline for a typical Falcon 20 run. It should be noted that a precipitation exposure time of 60 minutes was used for demonstration purposes; this time varied for each test depending on the objective.

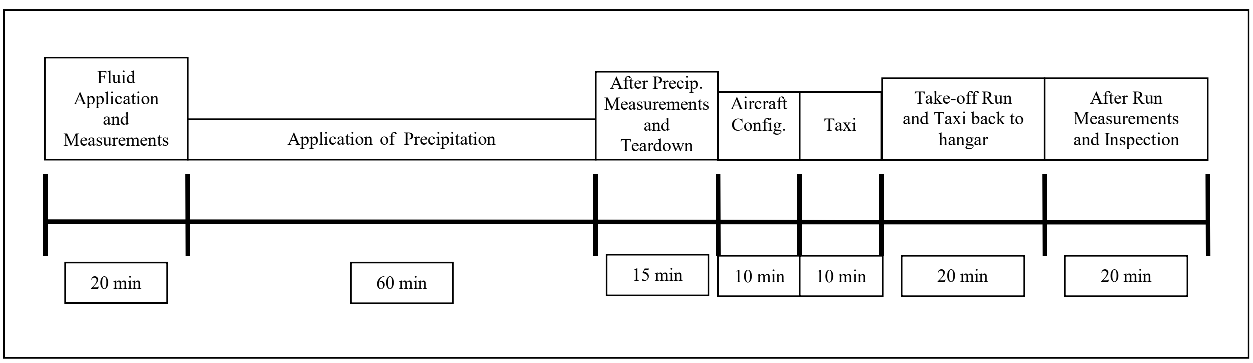


Figure 3.3: Typical Falcon 20 Run Timeline

3.1.7 Safety

Falcon 20 tests have been conducted at the Ottawa International Airport in recent years. The test setup is executed airside, outside the NRC hangar. Security escorts must be present at all times. Working in the environment (around the aircraft) involves several safety issues that need to be addressed:

- All personnel must be familiar with MSDS for fluids;
- When in controlled airport areas, ensure correct procedures are followed and make sure escorts are available;
- When engines are operating, no loose objects should be used around the engines;
- When engines are operating, ensure ear plugs are worn and safe distances are kept;
- When working on ladders, ensure equipment is stable;
- Appropriate footwear and clothing for frigid temperatures are to be worn by all personnel;
- The test area must be cleared of snow and ice before testing;
- If fluid comes into contact with skin, rinse hands under running water; and
- If fluid comes into contact with eyes, flush with the portable eyewash station.

3.2 Simulated Precipitation

The three types of simulated precipitation used during the Winter 2006-07 Falcon 20 tests were:

- Freezing rain;
- Ice pellets; and
- Snow.

3.2.1 Freezing Rain

Simulated freezing rain was generated by an APS in-house constructed freezing rain sprayer system. The sprayer system uses compressed air and water to produce freezing rain. The air compressor, water pump, and water tank are stored in a panel van (Photo 3.3). The sprayer is operated from a platform positioned high enough to provide even coverage across the test area (Photo 3.4). Hypodermic needles are mounted onto a sprayer head whose movement is controlled by an operator (Photo 3.5).

The water temperature is a critical setup parameter. It was found that water temperature should be approximately 15°C to 20°C to prevent freeze-ups, especially when the sprayer is operated at cold temperatures.

During the 2006-07 test session, a freezing rain rate of 20 g/dm^2/h was simulated. It was noted that the effectiveness of the sprayer is inversely proportional to the wind speed present during the test. Two rate pans were used during the 2006-07 tests to estimate the effective freezing precipitation application rate. One rate pan was placed on the leading edge (Photo 3.6) and one on the trailing edge.

3.2.2 Ice Pellets

Ice pellets were manufactured from ice cubes inside a rented refrigerated truck. The procedure used for the wind tunnel tests was applied to fabricate and dispense the ice pellets. The ice pellets were applied from the leading edge and trailing edge using one dispenser on each side.

Ice pellet rates ranging from 5 to 167 g/dm^2/h were replicated during the previous two Falcon 20 test sessions.

3.2.3 Snow

Snow was manufactured using a similar process as that used for ice pellets. The snow was fabricated and applied using the same techniques employed during the wind tunnel testing. The snow was applied using two dispensers, one on the leading edge and one on the trailing edge. Precipitation rates ranging from 4 to 77 g/dm^2/h were reproduced in the wind tunnel.

3.3 Ambient Test Temperature and Sky Conditions

The test temperature is one of the critical parameters of the Falcon 20 testing. The test temperature is not a controlled variable because it depends on the OAT, sky conditions, and solar radiation. The desired test weather conditions are dry, with subfreezing OATs. Tests should be limited to crosswinds of a maximum 10 knots. Overcast skies are very important to avoid aircraft wings overheating from exposure to the sun. If the test window is limited and clear sky conditions are forecasted, testing in the early morning hours is recommended. Runway conditions are to be clean and dry.

During the 2005-06 and 2006-07 seasons, the clear sky conditions present during most of the test windows required early morning test sessions.

3.4 Fluid Application

The Type IV fluids were stored outside and kept at ambient temperature. The fluids were poured rather than sprayed so that application would not to change the fluid viscosity. This methodology was appropriate given the relatively small test area and the goal of minimizing the amount of fluid flowing off the wing.

Type IV fluids were applied to the wing section using APS-made fluid pouring devices. Each device has a capacity of approximately 3 L. A total of 20 L of fluid were applied to the test area. Fluid was typically applied at the NRC hangar by two people, one applying fluid to the leading edge and the other applying fluid to the trailing edge. A third person is required to refill and prepare the fluid dispensers.

3.5 Photo and Video Recording

Two Canon Digital Rebel XT SLR (single lens reflex) digital still cameras were used to obtain high-speed, high-resolution photographs of the testing. The cameras are described in Subsection 2.5.

Digital still cameras were used to record visual observations of the testing. To create a consistent and stable setup for the cameras, NRC personnel replaced the emergency doors overlooking the wing and the test area with removable hatches. Each hatch had two standard tripod mounts and a removable Plexiglas window. NRC personnel used one mount for a digital high-definition video camera, and APS personnel used the second mount for a digital still camera (Photo 3.7).

It must be noted that the camera mounting space is limited and does not allow the mounting of two SLR still cameras (Photo 3.8). In addition, the two hatches are not airworthy and cannot be used in testing involving actual aircraft takeoff.

A professional photographer used a digital still camera to take pictures of the test setup and all phases of the test runs.

Photo 3.1: Falcon 20 Aircraft

Photo 3.2: Falcon 20 Test Area and Grid

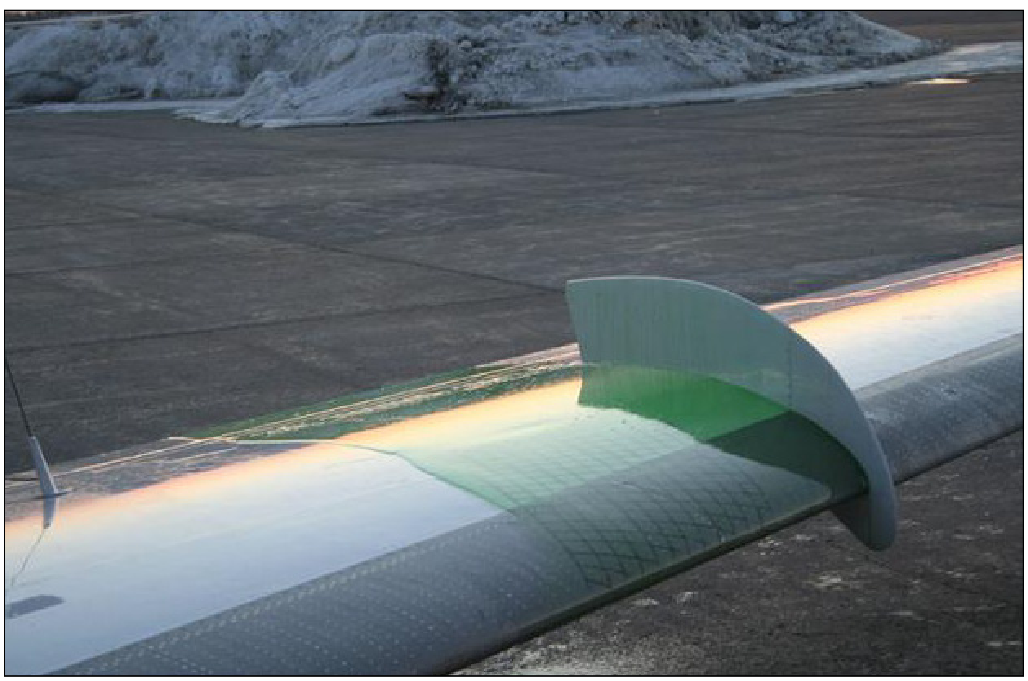


Photo 3.3: Panel Van Used for Freezing Rain Sprayer Setup

Photo 3.4: Freezing Rain Sprayer Setup

Photo 3.5: Freezing Rain Sprayer Operator

Photo 3.6: Leading Edge Rate Pan Used for Falcon 20 2006-07 Tests

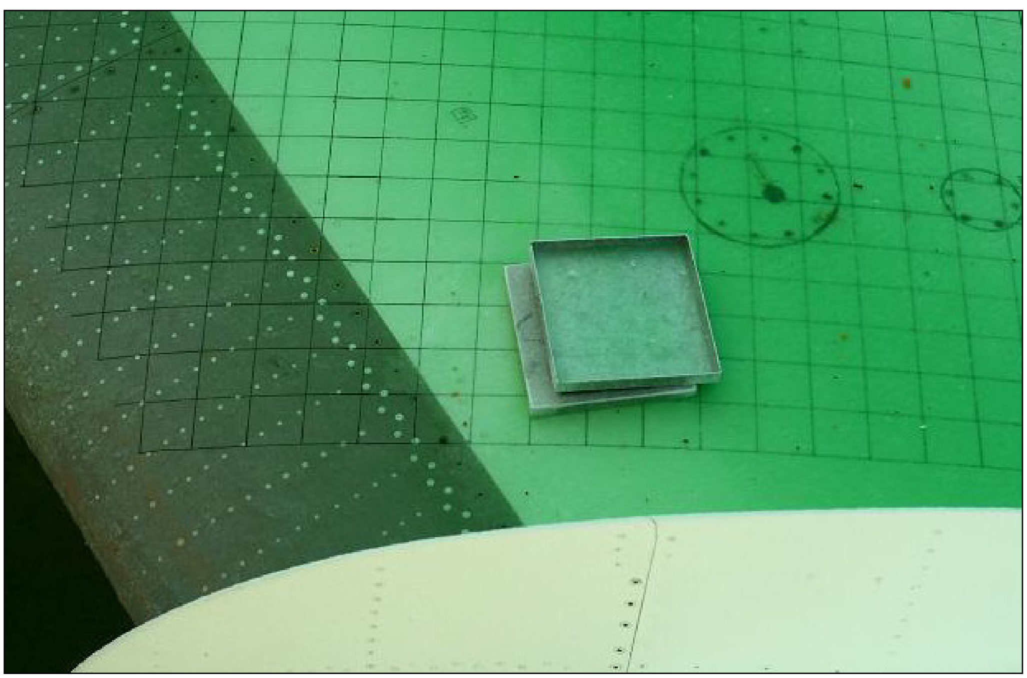


Photo 3.7: Still and Video Camera Overlooking Test Area

Photo 3.8: Camera Mounts Inside Falcon 20 Aircraft

4. CONCLUSIONS

The conclusions from the feasibility analysis of the wind tunnel and Falcon 20 testing are provided below.

4.1 Wind Tunnel Tests

The wind tunnel tests that were run for the first time during the 2006-07 winter season were successful. The wind tunnel tests showed that it is possible to simulate takeoff runs with freezing rain, ice pellet, and snow contamination. It can be concluded that the wind tunnel controlled test environment can be used to evaluate the level of safety of the current HOTs.

See below the several conclusions that were drawn from these tests.

a) The NRC freezing rain sprayer provides good distribution as well as proper droplet size.

b) Ice pellet size and quantity are controllable; however, ice pellet distribution throughout the test area requires further refinement. Dispensing from both the leading and trailing edge should provide a better distribution.

c) The snow distribution is very dependent on the airflow inside the tunnel. Further work is required to refine the snow distribution. The distribution can be improved by increasing the number of dispensers and shielding the test area from any airflow.

d) A typical wind tunnel test takes two hours. The length of the test may be shortened by reducing the number of measurements and improving personnel management.

e) The low-light conditions were challenging for the photographic documentation of the wind tunnel tests. Even though the results obtained with the available equipment were satisfactory, better lenses (with a larger aperture) and more reliable flashes could optimize the results.

f) Other conditions such as freezing drizzle and frost can likely be tested in the wind tunnel.

4.2 Falcon 20 Tests

The Falcon 20 tests were successful. It can be concluded that full-scale aircraft tests can be used to support the wind tunnel tests that determine HOTs.

See below the several conclusions that were drawn from these tests.

a) The Falcon 20 tests conducted over several winter seasons showed that it is possible to simulate takeoff runs with freezing rain, ice pellet, and snow contamination.

b) The freezing rain sprayer effectiveness is highly susceptible to wind speed. Tests should be conducted in calm wind conditions.

c) The APS freezing rain sprayer requires attention to prevent freeze-ups and to control the precipitation rate. Additional work is required to improve freezing rain sprayer control if extensive testing is necessary.

d) Ice pellet size and quantity are controllable. The distribution is dependent on wind conditions.

e) Snow distribution is very dependent on wind conditions. Testing in calm winds and application with more dispensers should optimize the snow distribution.

f) A typical Falcon 20 test takes two hours. The length of the test is highly dependent on the time required by NRC personnel to prepare the aircraft for the takeoff run. A major time improvement was achieved in the past when the test procedure allowed preparation for consecutive tests with the engines on.

g) The photo documentation of Falcon 20 tests obtained with the available equipment was satisfactory; better lenses (with a larger aperture) may improve the results. A redesign of the over-wing hatches to provide additional space for the cameras would be beneficial.

5. RECOMMENDATIONS

5.1 Wind Tunnel Tests

Based on the 2006-07 wind tunnel testing, it is recommended that:

a) Testing be conducted with other wing sections and types;

b) Ice pellet and snow distributions across the test area be refined;

c) If solar radiation overheats the test area during the day, testing be conducted overnight with the doors of the wind tunnel closed;

d) Personnel be increased and the number of measurements be decreased to shorten test duration;

e) Larger aperture lenses and more reliable flashes be purchased to optimize photo documentation of tests; and

f) The wind tunnel be tested to determine if it can replicate low rotation speed (80 knots) aircraft. (The 2006-07 tests successfully replicated rotation speeds in the order of 100 knots.) It is recommended that the electrical drive of the wind tunnel be used for this purpose.

5.2 Falcon 20 Tests

Based on the Falcon 20 testing that has been conducted in recent years, it is recommended that:

a) Testing be conducted with other available aircraft to study other wing configurations, rotation speeds, et cetera;

b) Additional testing be conducted to improve control of the freezing rain sprayer;

c) Wind speed limitations be instituted for testing and a shield to protect the test area from wind be developed;

d) Snow dispersion devices be improved;

e) Larger aperture lenses and more reliable flashes be purchased to optimize photo documentation of tests; and

f) The over-wing hatches be redesigned to provide additional space for cameras.

This page intentionally left blank.

REFERENCES

1) Ruggi, M., *Development of Allowance Times for Aircraft Deicing Operations During Conditions with Ice Pellets*, APS Aviation Inc., Transportation Development Centre, Montreal, January 2008, TP 14779E, 184.

2) Chaput, M., Dawson, P., Hanna, M., *Contaminated Aircraft Takeoff Test for the 1997/98 Winter*, APS Aviation Inc., Transportation Development Centre, Montreal, December 1998, TP 13316E, 54.

3) Dawson, P., Hanna, M., *Contaminated Aircraft Takeoff Tests for the 1998-99 Winter*, APS Aviation Inc., Transportation Development Centre, Montreal, October 1999, TP 13479E, 157.

4) Dawson, P., *Contaminated Aircraft Simulated Takeoff Tests for the 1999-2000 Winter: Preparation and Procedures*, APS Aviation Inc., Transportation Development Centre, Montreal, August 2000, TP 13666E, 18.

5) Campbell, R., Chaput, M., *Aircraft Takeoff Test Program for Winter 2001-02: Testing to Evaluate the Aerodynamic Penalties of Clean or Partially Expended De/Anti-Icing Fluid,* APS Aviation Inc., Transportation Development Centre, Montreal, November 2002, TP 13995E, 92.

6) Chaput, M., *Aircraft Takeoff Test Program for Winter 2002-03: Testing to Evaluate the Aerodynamic Penalties of Clean or Partially Expended De/Anti-Icing Fluid,* APS Aviation Inc., Transportation Development Centre, Montreal, November 2003, TP 14147E, 92.

7) Balaban, G., *Falcon 20 Trials to Examine Fluid Removed from Aircraft During Takeoff with Ice Pellets,* APS Aviation Inc., Transportation Development Centre, Montreal, December 2006, TP 14716E, 92.

This page intentionally left blank.

APPENDIX A

TRANSPORTATION DEVELOPMENT CENTRE
WORK STATEMENT EXCERPT –
AIRCRAFT & ANTI-ICING FLUID WINTER TESTING 2006-07

TRANSPORTATION DEVELOPMENT CENTRE
WORK STATEMENT EXCERPT –
AIRCRAFT & ANTI-ICING FLUID WINTER TESTING 2006-07

6.3 AIRCRAFT PERFORMANCE RESEARCH

6.3.1 Flow of Contaminated Fluid from Aircraft Wings During Takeoff (Falcon 20 Tests)

a) Develop a test plan jointly with the NRC staff who operate the aircraft. Consideration will be given to using both slatted and non-slatted wing aircraft i.e. Bombardier Global Express and Dassault Falcon 20;

b) Plan and co-ordinate the application of SAE Type IV fluid (ethylene and propylene-based) at Ottawa airport over a period of four days;

c) Plan and co-ordinate the application of controlled amounts of ice pellets, snow and/or freezing rain contamination on the applied fluids;

d) Document the appearance of fluids on the wing and adherence of fluid to the wing prior to departure of the aircraft for the test flight;

e) Collect the following data during the tests:

   i) Type and amount of fluid applied;

   ii) Type and rate of contamination applied;

   iii) Extent of fluid contamination prior to the takeoff run;

   iv) Document the appearance of fluid on the wings during the takeoff run and climb of the aircraft by analyzing the video records; and

   v) Measurements of thickness, concentration, viscosity, and adherence of clean and contaminated fluid prior to and following the takeoff run.

f) Co-ordinate the ground aspects of test activities and initiate tests in conjunction with NRC staff based on forecast weather and aircraft availability.

6.3.2 Flow of Contaminated Fluid from Simulated Aircraft Wings During Takeoff (Wind Tunnel Tests)

a) Develop a test plan jointly with the NRC staff who operate the wind tunnel;

b) Plan and co-ordinate the application of SAE Type IV fluid (ethylene and propylene-based) at the Ottawa NRC open circuit Propulsion Wind Tunnel over a period of five days to establish feasibility;

c) Plan and co-ordinate the application of controlled amounts of ice pellets, snow and/or freezing rain contamination on the applied fluids;

d) Document the appearance of fluids on the wing and adherence of fluid to the wing prior to, during and following the wind tunnel run;

e) Collect the following data during the tests:

   i) Type and amount of fluid applied;

   ii) Type and rate of contamination applied;

   iii) Extent of fluid contamination prior to the wind tunnel run;

   iv) Document the appearance of fluid on the wing during the simulated take off by analyzing the video records; and

   v) Measurements of thickness, concentration, viscosity, and adherence of clean and contaminated fluid prior to and following the tunnel test.

f) Co-ordinate the fluid contamination of test activities and initiate tests in conjunction with NRC staff based on forecast weather, testing over a period of ten days.

APPENDIX B

TEMPERATURE PROFILE LOGGED INSIDE THE WING SECTION FOR WIND TUNNEL RUN #11

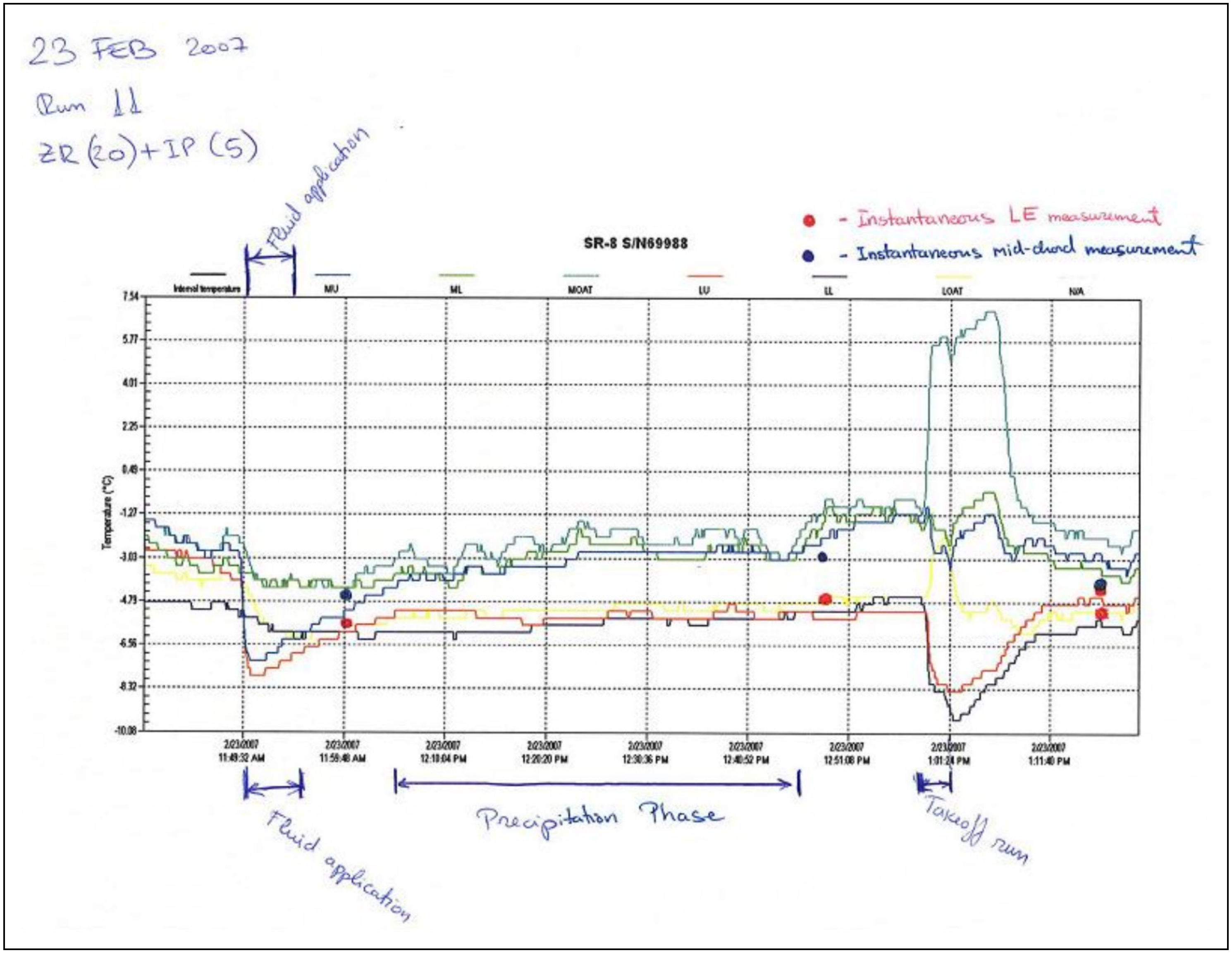


Figure B-1: Temperature Profile Logged Inside the Wing Section for Wind Tunnel Run #11

This page intentionally left blank.