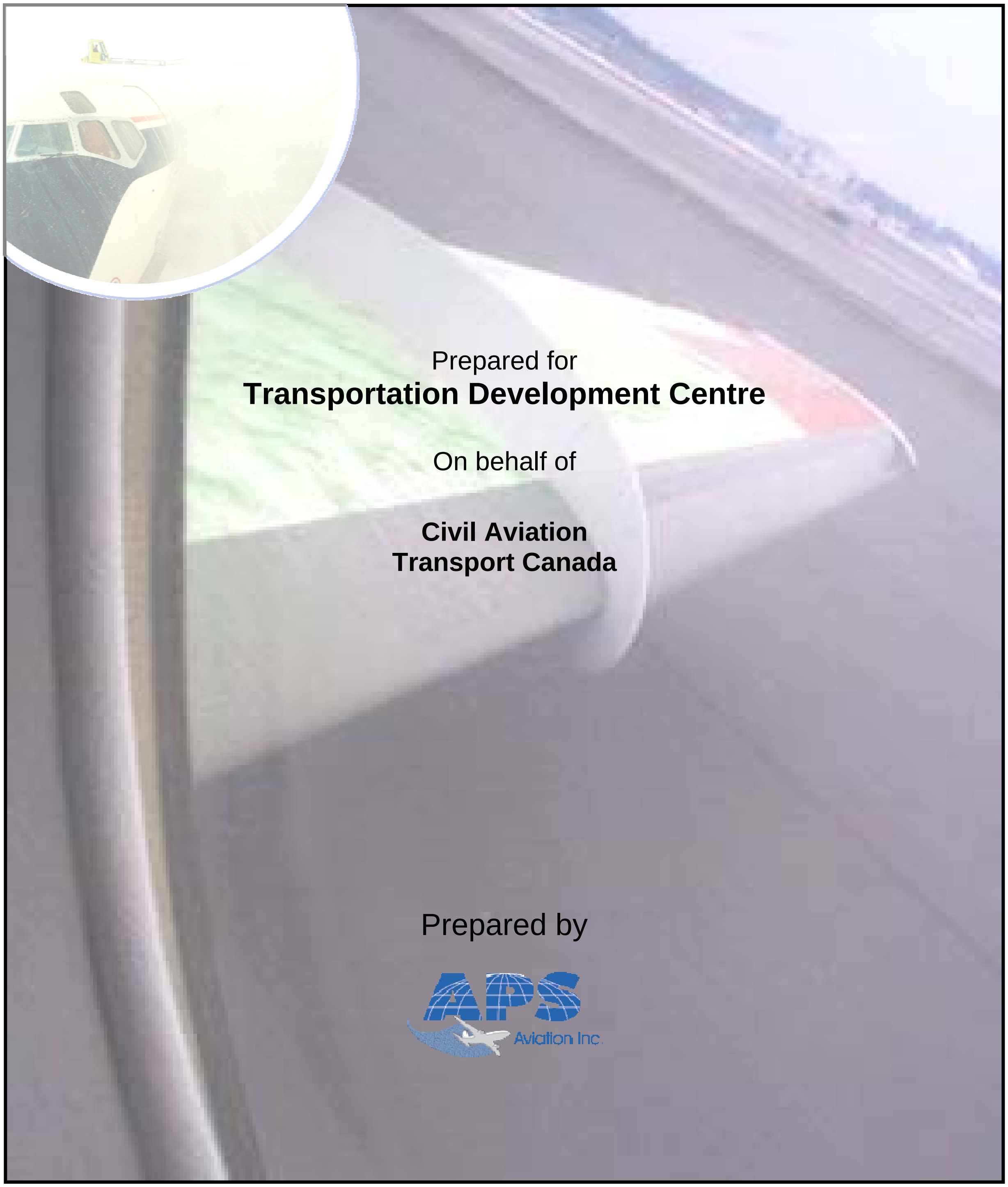
TP 14147E

Aircraft Takeoff Test Program for Winter 2002-03: Testing to Evaluate the Aerodynamic Penalties of Clean or Partially Expended De/Anti-Icing Fluid



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Transportation Development Centre

On behalf of

Civil Aviation
Transport Canada

Prepared by

APS Aviation Inc.

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Final Version 1.0

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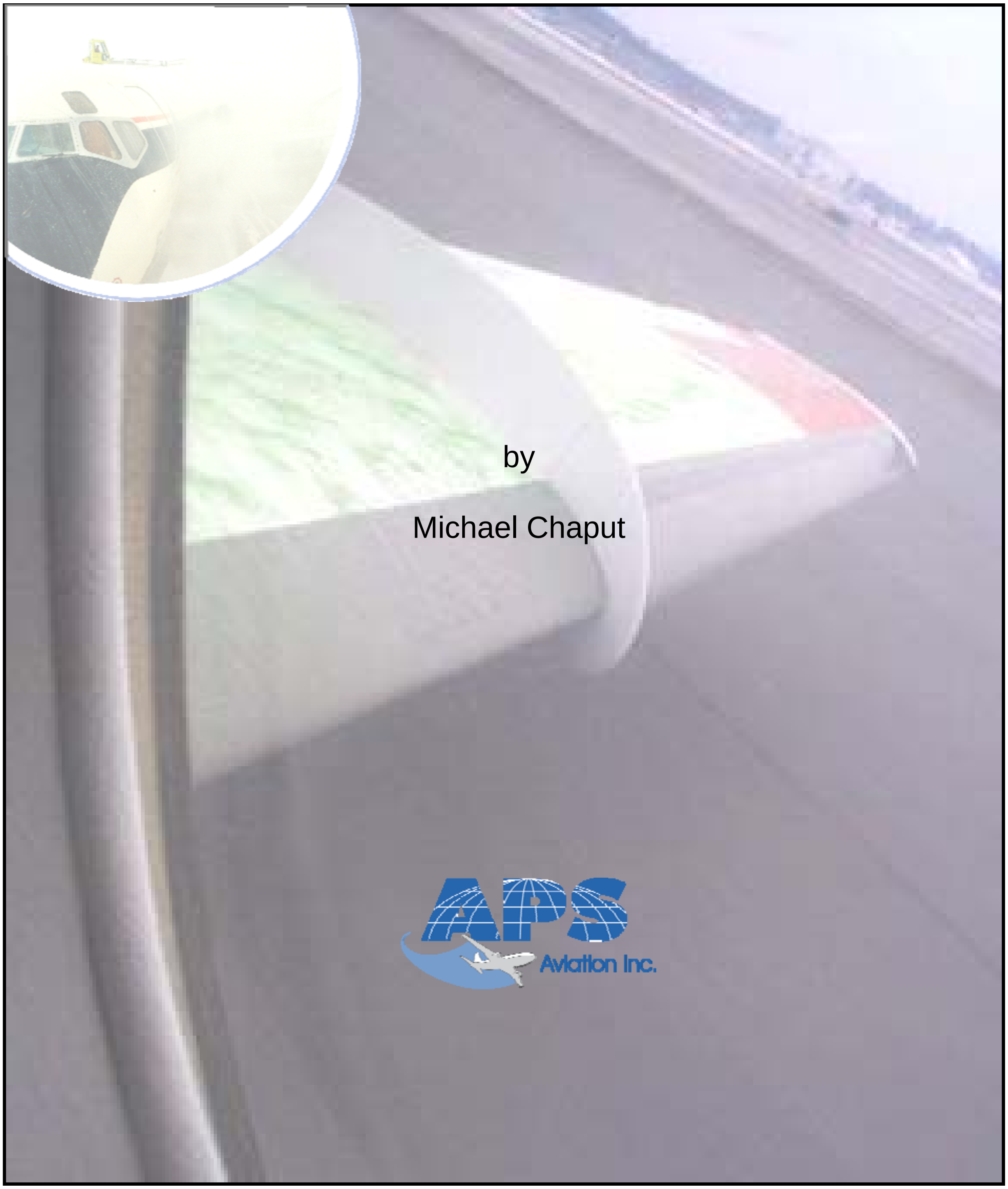

by

Michael Chaput

APS Aviation Inc.

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DOCUMENT ORIGIN AND APPROVAL RECORD

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Un sommaire français se trouve avant la table des matières.

PREFACE

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

- To develop holdover time data for all newly-qualified de/anti-icing fluids;
- To evaluate the parameters that are specified in the proposed Aerospace Standard 5485 for frost endurance time tests in a laboratory;
- To evaluate weather data from previous winters to establish a range of conditions suitable for the evaluation of holdover time limits;
- To further evaluate the flow of contaminated fluid from the wing of an aircraft during simulated takeoff runs;
- To compare endurance times from natural snow with those generated from simulations of laboratory snow;
- To compare fluid endurance time, holdover time and protection time;
- To compare snowfall rates obtained by the National Center for Atmospheric Research hotplate with rates obtained using rate pans;
- To further analyze the relationship between snowfall rate and visibility;
- To stimulate the development of Type III fluids;
- To measure endurance times of fluids applied using forced air-assist systems;
- To conduct exploratory research including measuring temperatures of applied Type IV fluids, measuring the effect of lag time on holdover time, evaluating the effectiveness of fluid coverage and assessing the impact of taxi time on deicing holdover time; and
- To provide support services to Transport Canada.

The research activities of the program conducted on behalf of Transport Canada during the winter of 2002-03 are documented in thirteen reports. The titles of the reports are as follows:

- TP 14144E Aircraft Ground De/Anti-Icing Fluid Holdover Time Development Program for the 2002-03 Winter;
- TP 14145E Laboratory Test Parameters for Frost Endurance Time Tests;
- TP 14146E Winter Weather Impact on Holdover Time Table Format (1995-2003);
- 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;
- TP 14148E Endurance Time Testing in Snow: Comparison of Indoor and Outdoor Data for 2002-03;
- TP 14149E Adhesion of Aircraft Anti-Icing Fluids on Aluminum Surfaces;
- TP 14150E Evaluation of a Real-Time Snow Precipitation Gauge for Aircraft Deicing Operations;
- TP 14151E Relationship between Visibility and Snowfall Intensity;
- TP 14152E A Potential Solution for De/Anti-Icing of Commuter Aircraft;

- TP 14153E Endurance Times of Fluids Applied with Forced Air Systems;
- TP 14154E Aircraft Ground Icing Exploratory Research for the 2002-03 Winter;
- TP 14155E Aircraft Ground Icing Research Support Activities for the 2002-03 Winter; and
- TP 14156E Variance in Endurance Times of De/Anti-Icing Fluids.

This report, TP 14147E, has the following objective:

- To further evaluate the flow of contaminated fluid from the wing of an aircraft during simulated takeoff runs.

This objective was met by performing a series of takeoff tests using the NRC Falcon 20 aircraft in February 2003.

ACKNOWLEDGEMENTS

This research has been funded by Transport Canada with support from the U.S. Federal Aviation Administration, William J. Hughes Technical Center. This program could not have been accomplished without the participation of many organizations. APS would therefore like to thank the Civil Aviation Directorate and the Transportation Development Centre of Transport Canada, the U.S. Federal Aviation Administration, National Research Council Canada, the Meteorological Service of Canada, and several fluid manufacturers. Special thanks are extended to US Airways Inc., Federal Express, American Eagle Airlines Inc., the National Center for Atmospheric Research, AéroMag 2000, Aéroports de Montreal, Ottawa International Airport Authority, GlobeGround North America, and Dow Chemical Company for provision of personnel and facilities and for their co-operation with the test program. APS 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: Alia Alwaid, Stephanie Bendickson, Nicolas Blais, Richard Campbell, Mike Chaput, Sami Chebil, John D'Avirro, Peter Dawson, Caroline Duclos, Miljana Horvat, Luis Lopez, Bob MacCallum, Mark Mayodon, Chris McCormack, Nicoara Moc, Marco Ruggi, Sherry Silliker, Ben Slater, and Kim Vepsa.

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Research reports produced on behalf of Transport Canada for testing during previous winters are available from the Transportation Development Centre (TDC). Thirteen reports (including this one) were produced as part of this winter's research program. Their subject matter is outlined in the preface.

16. Abstract

The objective of this study was to ascertain whether there is an aerodynamic penalty on an aircraft due to the presence of neat and partially expended anti-icing fluid on the wings. To satisfy this objective, takeoff tests were performed with a National Research Council Falcon 20 research aircraft at the Ottawa Airport. Six different types of tests were performed in 2002-03: tests with clean, uncontaminated anti-icing fluid; tests with clean, uncontaminated anti-icing fluid on the wing areas inboard of the boundary layer fence only; tests with clean, uncontaminated anti-icing fluid on the wing areas outboard of the boundary layer fence only; tests with diluted and partially contaminated anti-icing fluid; tests with pre-mixed diluted anti-icing fluid; and tests with wings containing a residual fluid from a previous test.

APS coordinated and provided support for the Falcon 20 tests. The aircraft was flown by NRC flight crews. All non-flight related test data were recorded by APS personnel. Analysis of the Falcon 20 flight data was performed by the NRC project management team. The test wings were treated with ethylene and propylene glycol-based Type IV fluids in a one-step anti-icing operation. Simulated light freezing rain was then sprayed over the test fluid until specified levels of contamination were achieved. Data such as fluid thickness, wing temperatures, and fluid freeze points were recorded. The aircraft was then operated through a takeoff run, including aircraft rotation and climb-out. The behaviour of the fluid during the takeoff run was documented with hand-held video cameras from the cabin.

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

Les rapports de recherche produits au nom de Transports Canada sur les essais réalisés au cours des hivers antérieurs peuvent être obtenus auprès du Centre de développement des transports (CDT). Le programme de la saison hivernale a donné lieu à treize rapports (dont celui-ci). On trouvera dans la préface l'objet de ces rapports.

16. Résumé

Cette étude avait pour objectif de déterminer si la présence sur les ailes de liquides antigivrage intacts ou partiellement contaminés entraîne une dégradation de l'aérodynamisme de l'aéronef. À cette fin, des essais de décollage ont été réalisés à l'aide d'un avion de recherche Falcon 20 du Conseil national de recherches du Canada à l'aéroport d'Ottawa. Six types d'essais ont eu lieu en 2002-2003 : des essais avec du liquide antigivrage intact, non contaminé; des essais avec du liquide antigivrage intact, non contaminé, appliqué uniquement sur les zones des ailes à l'intérieur de la cloison de décrochage; des essais avec du liquide antigivrage intact, non contaminé, appliqué uniquement sur les zones des ailes à l'extérieur de la cloison de décrochage; des essais avec du liquide antigivrage dilué, partiellement contaminé; des essais avec du liquide antigivrage dilué, prémélangé; des essais avec des ailes recouvertes d'un liquide résiduel, vestige d'un essai antérieur.

APS a coordonné les essais et en assuré le soutien. Le Falcon 20 était piloté par des équipages du CNRC. Le personnel d'APS enregistrait toutes les données d'essai autres que les données de vol. L'analyse des données de vol du Falcon 20 a été effectuée par l'équipe de gestion du projet du CNRC. Les ailes d'essai étaient traitées à l'aide de liquides de type IV à base d'éthylèneglycol et de propylèneglycol, en une opération antigivrage à une seule étape. De l'eau était alors pulvérisée sur le liquide, à la manière d'une pluie verglaçante légère, jusqu'à ce que les degrés de contamination voulus soient atteints. Différents paramètres étaient notés, comme l'épaisseur du liquide, la température des ailes et le point de congélation du liquide. L'avion effectuait alors un décollage, y compris la rotation et la montée. Le comportement du liquide pendant le décollage était filmé à l'aide de caméras vidéo, depuis la cabine.

17. Mots clés Aéronef, contamination glacée, essais de décollage, éthylèneglycol, Falcon 20, élimination, épaisseur, viscosité	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires imprimés. Disponible également en ligne à www.tc.gc.ca/cdt/menu.htm

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EXECUTIVE SUMMARY

Under contract to the Transportation Development Centre (TDC) of Transport Canada (TC), APS Aviation Inc. (APS) has undertaken a research program to examine the potential aerodynamic penalties resulting from the presence of clean, diluted, and partially contaminated anti-icing fluid on aircraft wings.

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 identification of contamination on an aircraft surface generally relies on a visual inspection by personnel located on the ground or by pilots from flight deck and/or aircraft cabin windows. When the fluid's failure to absorb ice crystals is identified, it can only be assumed that this contamination is adhering.

Previous Testing

During the 1997-98 and 1998-99 winter test seasons, several simulated takeoff runs were conducted using a National Research Council Canada (NRC) Falcon 20 aircraft to examine the issue of removal of contaminated fluid from aircraft wings during a simulated takeoff run. These tests were intended to fill an information gap thus far not resolved by either theoretical analysis or wind tunnel laboratory research. These tests were reported in TC reports, TP 13316E, *Contaminated Aircraft Takeoff Tests for the 1997-98 Winter* and TP 13479E, *Contaminated Aircraft Takeoff Tests for the 1998-99 Winter*.

The 1997-98 and 1998-99 series of simulated takeoff runs provided an initial level of understanding of the issue and did prove to be useful in gaining a more complete understanding of elimination of contaminated anti-icing fluid. Tests were performed with contaminated ethylene glycol (EG) and propylene glycol (PG) fluids. The Falcon 20 aircraft was accelerated to rotation speed but did not actually fly in these tests.

2001-02 Testing

In 2001-02, TDC began a new three-year study to examine the aerodynamic penalties resulting from the presence of neat, diluted, and partially contaminated fluid on aircraft wings. The long-term goal of this research program is to determine the effects of a limited level of unabsorbed winter precipitation present in or on an anti-icing fluid while maintaining a safe takeoff condition below the protection time limit for the fluid. In other words, the wing is to be maintained aerodynamically 'clean' even though it may not be visually clean.

The role of APS in the test program was to coordinate and provide support for the Falcon 20 tests. The aircraft is owned and operated by the National Research Council, and was flown by NRC flight crews. Analysis of the Falcon 20 flight data was performed by the NRC project team.

The test program undertaken during the winter of 2001-02 using the NRC Falcon 20 aircraft addressed the effects of unshed anti-icing fluid on aircraft takeoff performance. Testing was conducted to ascertain whether there is an aerodynamic penalty on the aircraft due to the presence of neat or partially expended anti-icing fluid on the wings. One ethylene glycol-based Type IV fluid was examined for this purpose.

To satisfy the objective of the test program, takeoff tests were performed with the NRC Falcon 20 research aircraft. Three different types of tests were performed:

a) Baseline tests with clean, bare wings;

b) Tests using clean, undiluted ethylene glycol Type IV fluid; and

c) Tests using partially diluted ethylene glycol Type IV fluid (with precipitation).

The test wings were treated with the Type IV fluid either in a one-step or a two-step de/anti-icing operation. In the tests involving two-step operations, the wings were first cleaned with an ethylene glycol-based Type I fluid prior to the application of the Type IV fluid. Artificial freezing rain was then sprayed over the test fluid until specified levels of contamination were achieved. Data such as fluid thickness, wing temperatures, and fluid freezing points were recorded.

The aircraft was subsequently operated through a takeoff run, including aircraft rotation and climb-out. The aircraft then performed a circuit of the airport and returned.

These tests were reported in 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*.

2002-03 Testing

In 2002-03, TDC continued its three-year study to examine the aerodynamic penalties resulting from the presence of neat, diluted, and partially contaminated anti-icing fluid on aircraft wings.

The test program undertaken during the winter of 2002-03 using the NRC Falcon 20 aircraft addressed the effects of unshed anti-icing fluid on aircraft takeoff performance. Testing was again conducted to ascertain whether there is an aerodynamic penalty on the aircraft due to the presence of neat, diluted, or partially contaminated anti-icing fluid on the wings. Both ethylene and propylene glycol-based Type IV fluids were examined in 2002-03.

To satisfy the objective of the test program, takeoff tests were performed with the NRC Falcon 20 research aircraft. Six different types of tests were performed in 2002-03:

a) Tests with clean, uncontaminated anti-icing fluid(s) on the wings;

b) Tests with clean, uncontaminated anti-icing fluid(s) on the wing areas inboard of the boundary layer fences only;

c) Tests with clean, uncontaminated anti-icing fluid(s) on the wing areas outboard of the boundary layer fences only;

d) Tests with diluted and partially contaminated fluid (simulating a fluid just prior to the loss of ability to absorb further freezing precipitation) on the wings;

e) Tests with pre-mixed diluted Type IV fluid on the wings; and

f) Tests with wings containing residual fluid from a previous test.

APS coordinated and provided support for testing with the Falcon 20 to evaluate the aerodynamic penalties of clean or partially expended de/anti-icing fluid. All non-flight related test data were recorded by APS personnel.

The test wings were treated with the Type IV fluid in a one-step operation. Artificial freezing rain was then sprayed over the test fluid until specified levels of dilution were achieved, including small areas of partially contaminated fluid. Data such as fluid thickness, wing temperatures, and fluid freezing points were recorded at the threshold of the runway, prior to the takeoff of the aircraft.

The aircraft was subsequently operated through a takeoff run, including aircraft rotation and climb-out. The aircraft then performed a circuit of the airport and returned. The behaviour of the fluid during the takeoff run was recorded with hand-held video cameras from the cabin.

The results of the tests show that the anti-icing fluids on the wings were almost entirely eliminated from the wing surface during takeoff, regardless of the quantity and thickness of the fluid on the leading edge of the aircraft prior to the takeoff roll. Both fluids underwent near complete elimination, leaving only a very thin film of residual fluid at landing. The remaining fluid film was much less than 0.1 mm when present on leading edge surfaces, but ranged from 0.1 mm to 0.3 mm in areas of localized pooling on the trailing edge.

In the two tests with partially contaminated EG-based fluid, the small areas of ice present on the leading edge of the Falcon 20 prior to takeoff were adhering to the wing surface. While most of the ice had been eliminated by the shear forces exerted by the aircraft acceleration, rotation, climb-out and circuit of the airport, in one test, a small area of ice remained on the wing at the time of landing.

In the two tests with partially contaminated PG-based fluid, the areas of contamination were located primarily around the trailing edge, and the ice embedded within the fluid was not adhering to the wing surface. All of the ice contamination was eliminated by the shear forces exerted by the aircraft acceleration, rotation, climb-out and circuit of the airport.

The tests conducted during the 2002-03 winter were part of a three-year test program. It is recommended that this testing continue in 2003-04.

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SOMMAIRE

À la demande du Centre de développement des transports (CDT) de Transports Canada (TC), APS Aviation Inc. (APS) a entrepris un programme de recherche qui visait à mesurer la perte d'aérodynamisme susceptible de résulter de la présence de liquides antigivrage intacts, dilués et partiellement contaminés sur les ailes d'un avion.

Les règles sur le décollage dans des conditions givrantes interdisent aux pilotes de décoller lorsqu'une forme ou une autre de contamination (glace, givre, neige ou neige fondante) adhère aux surfaces critiques pour la portance aérodynamique de l'avion. La façon de déterminer la présence de contamination sur les surfaces de l'avion est l'observation visuelle, par le personnel au sol ou par l'équipage de conduite, depuis les fenêtres du poste de pilotage et/ou de la cabine. Lorsque l'on constate que le liquide n'absorbe plus les cristaux de glace, on ne peut que conclure que cette contamination adhère aux surfaces.

Essais antérieurs

Au cours des saisons d'essai hivernales 1997-1998 et 1998-1999, plusieurs simulations de décollage d'un avion Falcon 20 du Conseil national de recherches du Canada (CNRC) ont eu lieu, afin d'examiner si le liquide contaminé était chassé des ailes pendant un décollage simulé. Ces essais visaient à combler une lacune à laquelle n'avaient pas encore réussi à remédier ni les analyses théoriques ni les expériences en soufflerie. Ils sont documentés par les rapports TP13316E, Contaminated Aircraft Takeoff Tests for the 1997-98 Winter et TP13479E, Contaminated Aircraft Takeoff Tests for the 1998-99 Winter, de TC.

Les séries de décollages simulés réalisées en 1997-1998 et en 1998-1999 ont permis de défricher le terrain et de mieux comprendre le phénomène d'élimination du liquide antigivrage contaminé. Les essais étaient réalisés avec des liquides à base d'éthylèneglycol (EG) et de propylèneglycol (PG) contaminés. Au cours de ces essais, le Falcon 20 était amené jusqu'à la vitesse de rotation mais ne décollait pas.

Essais de 2001-2002

En 2001-2002, le CDT lançait un nouveau programme d'essais triennal dont l'objectif était d'examiner la perte d'aérodynamisme attribuable à la présence, sur les ailes d'un avion, de liquide intact, dilué, et partiellement contaminé. L'objectif à long terme de ce programme était de déterminer si la présence, dans ou sur un liquide antigivrage, d'une petite quantité de précipitation hivernale non absorbée, influe sur la sûreté d'un décollage fait dans les limites de la durée d'efficacité établie pour le liquide. Autrement dit, il faut que l'aile soit «propre» du point de vue aérodynamique, même si elle n'est pas nécessairement propre visuellement.

Le rôle d'APS a été de coordonner les essais menés à l'aide du Falcon 20 et d'en assurer le soutien. Des équipages du Conseil national de recherches du Canada,

qui est le propriétaire et l'exploitant du Falcon 20, pilotaient l'avion. L'équipe de projet du CNRC a analysé les données de vol du Falcon 20.

Le programme d'essais de 2001-2002 mettant en jeu l'avion Falcon 20 portait sur les effets de la présence de liquide antigivrage résiduel sur le comportement au décollage d'un avion. Des essais ont eu lieu, pour déterminer si la présence, sur les ailes d'un avion, d'un fluide antigivrage intact ou partiellement contaminé conduit à une perte d'aérodynamisme. Un seul liquide de type IV à base d'éthylèneglycol a été examiné à cette fin.

Pour atteindre l'objectif assigné au programme d'essais, des décollages ont été effectués avec l'avion de recherche Falcon 20 du CNRC. Trois types d'essais ont été réalisés :

a) des essais de référence, avec des ailes propres et nues;

b) des essais avec un liquide de type IV à base d'éthylèneglycol intact, non dilué;

c) des essais avec un liquide de type IV à base d'éthylèneglycol partiellement dilué (par des précipitations).

Les ailes d'essai étaient revêtues du liquide de type IV au cours d'une opération de dégivrage/antigivrage à une seule étape ou à deux étapes. Les opérations à deux étapes consistaient à d'abord nettoyer les ailes à l'aide d'un liquide de type I à base d'éthylèneglycol, pour ensuite appliquer le liquide de type IV. C'est alors que les ailes étaient exposées à des précipitations artificielles de pluie verglaçante, jusqu'à ce que les degrés de contamination voulus soient atteints. Différents paramètres étaient enregistrés, comme l'épaisseur du liquide, la température des ailes et le point de congélation du liquide.

L'avion effectuait alors un décollage, y compris les phases de rotation et de montée. Après avoir décrit un circuit autour de l'aéroport, il revenait se poser.

Ces essais ont été documentés dans le rapport 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, de TC.

Essais de 2002-2003

En 2002-2003, le CDT a poursuivi son programme triennal qui avait pour but d'examiner la perte d'aérodynamisme attribuable à la présence, sur les ailes d'un avion, de liquide antigivrage intact, dilué, et partiellement contaminé.

Le programme d'essais réalisé au cours de l'hiver 2002-2003 à l'aide de l'avion Falcon 20 du CNRC s'intéressait aux effets de la présence de liquide antigivrage non chassé pendant la course au décollage sur le comportement au décollage de l'avion. Les essais ont encore une fois cherché à déterminer si la présence sur les ailes de liquide antigivrage intact, dilué ou partiellement contaminé nuisait aux propriétés aérodynamiques de l'avion. Des liquides de type IV à base d'éthylèneglycol et de propylèneglycol ont été examinés.

Conformément aux objectifs du programme d'essai, des décollages ont été effectués avec l'avion de recherche Falcon 20 du CNRC. Six types d'essais ont eu lieu :

a) des essais avec du (des) liquide(s) antigivrage intact(s), non contaminé(s) sur les ailes;

b) des essais avec du (des) liquide(s) antigivrage intact(s), non contaminé(s), appliqué(s) uniquement sur les zones des ailes à l'intérieur de la cloison de décrochage;

c) des essais avec du (des) liquide(s) antigivrage intact(s), non contaminé(s), appliqué(s) uniquement sur les zones des ailes à l'extérieur de la cloison de décrochage;

d) des essais avec du liquide dilué et partiellement contaminé (simulant un liquide juste avant sa perte de capacité d'absorber davantage de précipitation givrante) sur les ailes;

e) des essais avec du liquide antigivrage de type IV prémélangé et dilué sur les ailes;

f) des essais avec des ailes recouvertes d'un liquide résiduel, vestige d'un essai antérieur.

APS a coordonné et soutenu les essais menés à l'aide du Falcon 20 afin d'évaluer la perte d'aérodynamisme causée par du liquide de dégivrage/antigivrage intact ou partiellement contaminé. Le personnel d'APS a enregistré toutes les données d'essai autres que les données de vol.

Les ailes d'essai étaient traitées à l'aide du liquide de type IV en une opération à une seule étape. De l'eau était alors pulvérisée sur le liquide d'essai, à la manière d'une pluie verglaçante, jusqu'à ce que les degrés de dilution voulus soient atteints; cela comprenait des petites zones où le liquide était partiellement contaminé. Différents paramètres, comme l'épaisseur du liquide, la température des ailes et le point de congélation du liquide, étaient enregistrés au seuil de la piste, avant le décollage.

L'avion effectuait alors un décollage, y compris la rotation et la montée. Après avoir décrit un circuit autour de l'aéroport, il revenait se poser. Des caméras vidéo portables placées dans la cabine filmaient le comportement du liquide pendant le décollage.

Les résultats des essais montrent que les liquides antigivrage présents sur les ailes étaient presque complètement chassés pendant le décollage, peu importe la quantité et l'épaisseur du liquide sur le bord d'attaque avant la course au décollage. Les deux liquides ont été éliminés presque complètement : il ne restait, à l'atterrissage, qu'une pellicule très mince de liquide résiduel. Sur les surfaces du bord d'attaque, la pellicule résiduelle, le cas échéant, avait une épaisseur de beaucoup inférieure à 0,1 mm, mais l'épaisseur des flaques localisées formées dans la région du bord de fuite variait de 0,1 mm à 0,3 mm.

Aux deux essais mettant en jeu des liquides à base d'EG partiellement contaminés, les petites plaques de glace présentes sur le bord d'attaque des ailes du Falcon 20 avant le décollage adhéraient à la surface de l'aile. La plupart de la glace avait été éliminée par les forces de cisaillement engendrées par la course au décollage de l'avion, sa rotation, sa montée et son circuit autour de l'aéroport. Mais à un des deux essais, une petite plaque de glace était encore présente sur l'aile au moment de l'atterrissage.

Aux deux essais mettant en jeu des liquides à base de PG partiellement contaminés, les zones de contamination étaient surtout situées sur le bord de fuite, et la glace présente dans le liquide n'adhérait pas à la surface de l'aile. Toute la contamination glacée a été éliminée par les forces de cisaillement engendrées par la course au décollage de l'avion, sa rotation, sa montée et son circuit autour de l'aéroport.

Les essais menés au cours de l'hiver 2002-2003 faisaient partie d'un programme d'essais triennal. Il est recommandé de poursuivre ces essais en 2003-2004.

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GLOSSARY

ADMS	Airport De-Icer Management System
APS	APS Aviation Inc.
CDU	Cockpit Display Unit
cP	Centipoises
CSA	Canadian Space Agency
DND	Department of National Defence
EG	Ethylene Glycol
GPS	Global Positioning System
ILS	Instrument Landing System
NASA	National Aeronautics and Space Administration
NRC	National Research Council Canada
PG	Propylene Glycol
SAE	Society of Automotive Engineers
TC	Transport Canada
TDC	Transportation Development Centre
VOR	VHF Omnidirectional Range
YOW	MacDonald Cartier International Airport

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1 INTRODUCTION

Under contract to the Transportation Development Centre (TDC) of Transport Canada (TC), APS Aviation Inc. (APS) has undertaken a research program to examine the potential aerodynamic penalties resulting from the presence of neat, diluted, and partially contaminated anti-icing fluid on aircraft wings.

1.1 Background

The risk of a catastrophic aircraft accident at takeoff caused by on-going winter precipitation may be regarded as the product of the probabilities of:

a) Anti-icing fluid failing to prevent contamination adhering to the aircraft;
b) Fluid failure being undetected and a decision made to takeoff; and
c) Contamination of the aerodynamic surfaces being sufficient to cause significant loss of lift and/or loss of control.

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 the bare hand over an area of the wing surface such as the leading edge, or scraping the surface with the fingernails to detect the presence of a very thin ice film.

1.1.1 1997-98 Testing

During the winter of 1997-98, several simulated takeoff runs were conducted using a National Research Council Canada (NRC) Falcon 20 aircraft to examine the issue of removal of contaminated fluid from aircraft wings during takeoff. These tests were intended to fill an information gap thus far not resolved by either theoretical analysis or wind tunnel laboratory research. These tests were reported in TC report, TP 13316E, *Contaminated Aircraft Takeoff Tests for the 1997-98 Winter* (1).

The series of simulated takeoff runs conducted in 1997-98 provided an initial level of understanding of the issue and did prove to be useful in gaining a more complete understanding of elimination of contaminated fluid. Several observations were drawn from those tests:

a) The first documented evidence related to the nature of the process of contaminated aircraft anti-icing fluid elimination from aircraft wings during takeoff was obtained;

b) In some cases, the contaminated fluid failed to adhere to the wing surface and showed freedom of movement while staying on the wing;

c) In general, the contamination was not completely eliminated from the wing surface during acceleration of the aircraft to rotation speed in the simulated takeoff run; and

d) These tests identified the need to conduct a further series of tests at takeoff speeds up to and including rotation to verify the results.

1.1.2 1998-99 Testing

As other avenues of research had yet to provide resolution of the issue, it was decided to conduct additional simulated takeoff runs during the winter of 1998-99. A perceived shortcoming of the series of runs conducted in 1997-98 was that, although aircraft speed was increased to normal takeoff speed, the aircraft was not rotated at takeoff speed and therefore offered an incomplete representation of the true takeoff condition. It was proposed that this series of tests examine ways to include rotation at takeoff speed as part of the simulation, and that both ethylene and propylene glycol-based Society of Automotive Engineers (SAE) Type IV fluids be tested. These tests were reported in the TC report, TP 13479E, *Contaminated Aircraft Takeoff Tests for the 1998-99 Winter* (2).

The observations and conclusions from the 1998-99 tests were as follows:

a) Uncontaminated fluid, both ethylene glycol-based (EG) and propylene glycol-based (PG), was almost completely eliminated from the wing surface during the takeoff run;

b) In tests with EG Type IV fluid, ice formations that had existed prior to the takeoff run continued to exist following takeoff regardless of the extent of contamination and independent of adhesion or lack of adhesion to the wing skin prior to the takeoff run;

c) PG Type IV fluid was completely eliminated when a reasonable level of contaminated fluid was tested;

d) For similar exposure times, the PG Type IV fluid gave the appearance of being contaminated to a greater extent than the EG fluid. Conversely, the contamination developed on the PG Type IV was completely eliminated from the wing during the takeoff run, whereas the contamination on the EG fluids remained; and

e) Rotation of the aircraft at normal rotation speed during the takeoff run failed to eliminate contaminated fluid remaining on the wing.

1.1.3 Planned Testing in 1999-2000 and 2000-01

Tests were again planned for the 1999-2000 and 2000-01 winter test seasons. Due to a lack of suitable weather in the period allotted for testing in each year, no tests were conducted. The procedures for the 1999-2000 tests with the Falcon 20 were included in the TC report, TP 13666E, *Contaminated Aircraft Simulated Takeoff Tests for the 1999-2000 Winter: Preparation and Procedures* (3).

1.1.4 2001-02 Testing

In 2001-02, TDC began a new three-year study to examine the aerodynamic penalties resulting from the presence of diluted and undiluted fluid on aircraft wings. The long-term goal of this research program is to determine the effects of a limited level of unabsorbed winter precipitation present in or on an anti-icing fluid while maintaining a safe takeoff condition below the protection time limit for the fluid. In other words, the wing is to be maintained aerodynamically 'clean' even though it may not be visually clean.

The test program undertaken during the winter of 2001-02 using the NRC Falcon 20 aircraft addressed the effects of unshed anti-icing fluid on aircraft takeoff performance. The aerodynamic penalty on the aircraft due to presence of clean anti-icing fluid and also partially expended anti-icing fluid on the wings were examined for one EG-based Type IV fluid.

Three different tests were performed:

a) Baseline tests with clean, bare wings;
b) Tests with clean, undiluted EG-based Type IV fluid; and
c) Tests with semi-diluted EG glycol-based Type IV fluid.

APS coordinated and provided support for the Falcon 20 tests. The aircraft was flown by NRC flight crews. Analysis of the Falcon 20 flight data was performed by the NRC project team.

The test wings were treated with the Type IV fluid either in a one-step or a two-step de/anti-icing operation. In the tests involving two-step operations, the wings were first cleaned with an ethylene glycol-based Type I fluid prior to the application of the Type IV fluid. Artificial freezing rain was then sprayed over the test fluid until specified levels of contamination were achieved. Data such as fluid thickness, wing temperatures, and fluid freezing points were recorded.

The aircraft was subsequently operated through a takeoff run, including aircraft rotation and climb-out. The aircraft then performed a circuit of the airport and returned. The behaviour of the fluid during the takeoff run was recorded with hand-held video cameras. Upon the aircraft's return to the inspection pad, the wing condition was again examined and documented.

The results of the tests show that uncontaminated fluid was nearly completely eliminated from the wing surface during takeoff. In general, a small film of fluid, usually in the range of less than 0.1 mm to 0.3 mm, remained on certain wing surfaces, most notably on the trailing edge of the aircraft, after the aircraft had returned to the deicing pad. The leading edge surfaces occasionally had residual fluid after takeoff. The thickness of the fluid film never measured more than 0.1 mm.

The results of these tests have been included in 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* (4).

1.2 Program Objectives

The tests conducted during the 2002-03 winter were part of a three-year test program.

The three-year test program will address the following objectives:

a) To ascertain whether there is an aerodynamic penalty on the aircraft due to presence of clean or partially expended anti-icing fluid on the wings;

b) To determine the effects of a limited level of unabsorbed frozen contamination present in or on an anti-icing fluid while maintaining a safe takeoff condition below the endurance time limit for the fluid; and

c) To determine the level of contamination of anti-icing fluid (caused by winter precipitation) at which the airflow at takeoff fails to remove the resultant slush.

In 2002-03, testing was conducted to address objectives a) and b). To satisfy these objectives, a series of takeoff runs were performed with the NRC Falcon 20 research aircraft.

1.3 Work Statement

The work statement for the Falcon 20 tests is provided in Appendix A. Item 5.15 on Page A-1, *The Dispersion of Fluids on Airport Surfaces*, was a supplementary activity conducted in conjunction with the Falcon 20 testing. Data was collected during one run with the Falcon 20 in 2002-03 to address the data requirements listed in 5.15. Limited funding resources were used to gather this data.

1.4 Report Format

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

a) Section 2 describes the methodology used in testing, as well as equipment and personnel requirements necessary to carry out testing;

b) Section 3 describes the data collected and the different conditions in which data were collected;

c) Section 4 presents the data analysis and the overall results of the testing;

d) Section 5 presents conclusions derived from testing; and

e) Section 6 lists recommendations for future testing.

2 METHODOLOGY

This section describes the test conditions and experimental methodologies followed in the 2002-03 testing with the Falcon 20 aircraft, as well as the equipment and the personnel requirements.

2.1 Test Site

The 2002-03 series of takeoff tests was performed at MacDonald Cartier International Airport (YOW) in Ottawa using a NRC Falcon 20 aircraft (see Photo 2.1). Figure 2.1 provides a schematic of the airport showing the runways and the location of the NRC hangar and apron.

Flight tests were carried out over a four day period at YOW in February 2003.

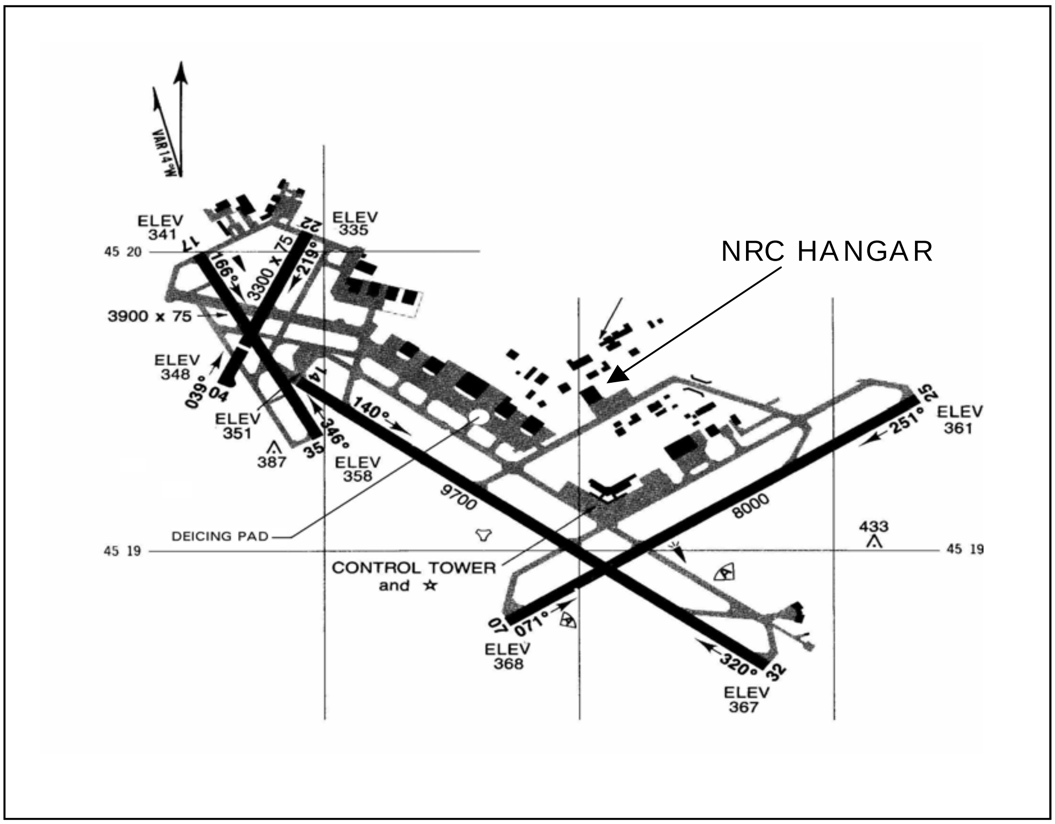

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Figure 2.1: Schematic of Ottawa Airport

2.2 Description of Test Procedures

2.2.1 Test Schedule

Tests with the Falcon 20 aircraft were scheduled for three periods during the 2002-03 winter test season:

a) November 2002;
b) December 2002; and
c) February 2003.

In November 2002, the question was raised whether the presence of water on the wings of the Falcon 20 would have a similar effect on the lift capacity as neat or diluted anti-icing fluid. APS prepared a procedure for a test with the Falcon 20 in heavy rain conditions. The objective of this test was to provide a "rain on wing" baseline for comparison with the "fluid on wing" tests. Unfortunately, the desired meteorological conditions did not occur during the assigned test window and the rain test was not conducted. The procedure for the November 2002 rain test is shown in Appendix B.

Additional testing with the Falcon 20 was planned for December 2002. Five tests were scheduled for this period, including:

a) A clean wing baseline test (no fluid);
b) A clean fluid test with ethylene glycol Type IV;
c) Two clean fluid tests with propylene glycol Type IV; and
d) Weather permitting, the "rain on wing" test that remained from November 2002.

Unfortunately, the NRC Falcon 20 experienced engine troubles prior to the December 2002 test session and the aircraft was rendered unserviceable for a prolonged period. The December 2002 tests were therefore never completed. The procedure for these tests is provided in Appendix C.

The extensive engine repair work on the NRC Falcon 20 was completed just prior to the February 2003 test period and testing went forward as outlined in the procedure, provided in Appendix D.

2.2.2 Preparations and Procedures

Prior to the February testing, NRC personnel used markers to draw a grid with dimensions of 0.61 m x 0.61 m (2 ft. x 2 ft.) grid just inside the fence on each wing of the Falcon 20 (see Photo 2.2). Smaller boxes with dimensions of 5.1 cm x 5.1 cm (2 in. x 2 in.) were then drawn inside the larger grid, perpendicular to the fence and not parallel to the leading edge of the aircraft (see Photo 2.3). This grid was used to facilitate visual observations of the fluid shearing off the wing during takeoff tests.

In 1997-98 and 1998-99 testing with the Falcon 20 aircraft, a single area on the port wing just inboard of the fence was selected to serve as the test surface on the Falcon 20 research aircraft. Because the 2002-03 tests aimed to determine the effects of anti-icing fluid on the overall lift generated by the aircraft, the test area was increased to include the entire surface area of both wings. Attempts were made to reduce the effects of aerodynamic asymmetry by applying similar quantities of fluid on each wing and diluting fluids to similar freezing points on each wing using the artificial freezing rain sprayer.

In addition to the full-wing tests, a limited number of tests were conducted with fluid sprayed only on the wings sections inside or outside of the boundary layer fence. In these tests, the wing sections that were not intended for fluid application were protected with a tarp (see Photo 2.4).

In 2001-02 tests in Ottawa, GlobeGround personnel conducted the fluid application at the central deicing pad at the airport. GlobeGround had only one ethylene glycol Type IV fluid (Dow Ultra+) available for use, and therefore this was the only fluid tested.

To prevent the cross-contamination of glycol-based products at the Ottawa Airport central deicing pad during the glycol recovery phase, the Ottawa Airport Authority has restricted the use of all deicing agents other than ethylene glycol. It is forbidden to dispense propylene-glycol fluids within the confines of the deicing pad.

Because the dispensing of propylene glycol-based products was required in 2002-03 tests, APS examined other potential areas for the conduct of tests at the Ottawa Airport. To facilitate the testing, APS inquired about the use of the NRC apron in front of the NRC hangar at YOW. This test site would greatly facilitate the tests due to its proximity to the NRC installations. Furthermore, all unnecessary taxiing of the aircraft to the central deicing pad would be eliminated, allowing for increased productivity. Although reluctant at first, the Ottawa Airport Authority allowed the use of the NRC apron for the deicing tests, provided a glycol mitigation plan was prepared by APS and approved by the airport. The glycol mitigation plan covered items such as the proposed fluid application procedures, proposed locations for fluid application, anticipated fluid spray quantities as well as the proposed fluid recovery plan. The Ottawa Airport Authority approved the mitigation plan in early February 2003. The glycol mitigation plan appears in Appendix E.

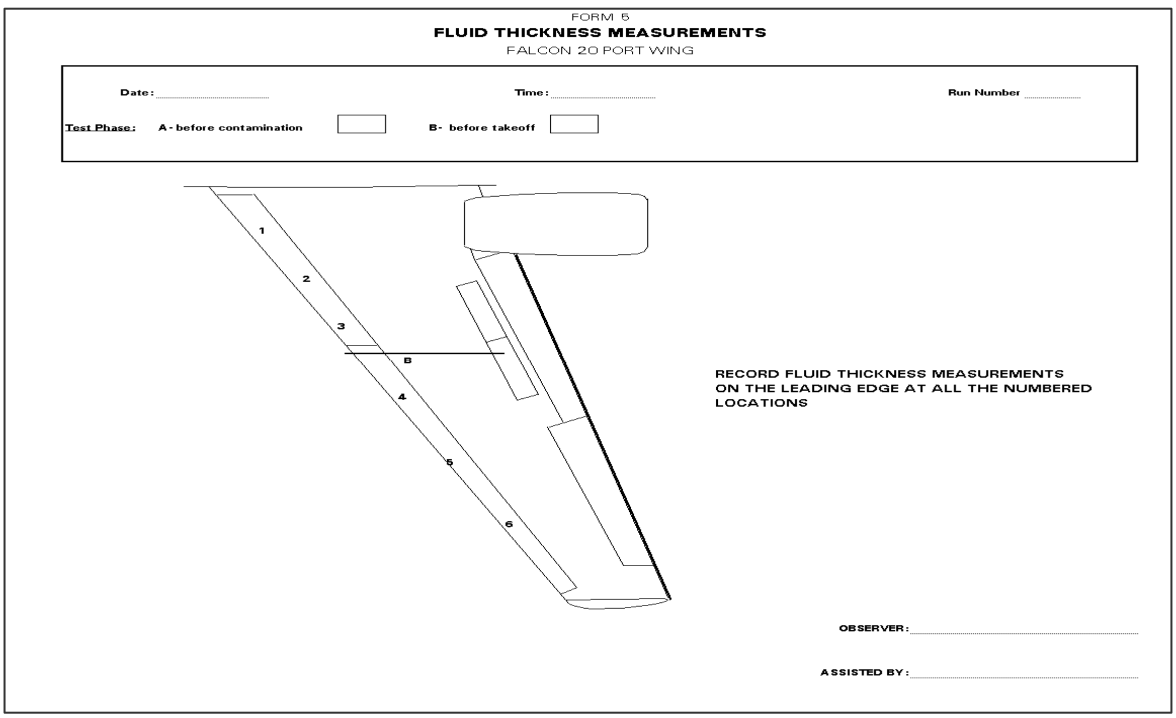
All fluid spraying, for both ethylene and propylene glycol applications, was performed by APS personnel at the NRC pad using the Type IV mobile sprayer. Photo 2.5 shows an APS personnel applying Type IV fluid to the Falcon 20 using the mobile sprayer. Spray applications at the NRC pad were conducted in close proximity to the NRC hangar. Two separate areas were assigned, one for ethylene glycol applications, the other for propylene glycol applications. For environmental concerns, the aircraft was not positioned near the stormwater catch basins located on the southern edge of the NRC apron.

Inland Technologies at YOW was contracted to provide fluid recovery services at the NRC pad. Inland provided sweeper vehicles at the end of each day of testing to collect both the propylene and ethylene glycol waste solutions. The waste solutions were recovered in separate sweeper vehicles and stored apart to prevent cross-contamination of the EG and PG-based products.

Prior to fluid application process for each test, Type IV samples were collected from each fluid container. Fluids samples were again gathered from the wing following fluid application, light freezing rain application (if applicable), and upon return of the aircraft to the NRC pad following the takeoff and flight. Fluid samples were collected using spatulas (see Photo 2.6). These samples were transported to the APS laboratory and subjected to viscosity testing.

The thickness of the Type IV fluid film was measured using octagonal thickness gauges at six locations along the leading edge of each wing for each test. Figure 2.2 provides the fluid thickness data form that was used in Falcon 20 tests. The locations designated for thickness measurement on the leading edge of each wing are identified with the numbers 1 through 6 in Figure 2.2. For all tests, fluid thickness was measured only at the threshold of the departure runway, just prior to the takeoff of the aircraft.

Hand-held temperature probes were used to measure wing temperatures at the button of the departure runway, just prior to the takeoff of the aircraft. Wing temperatures were measured at the same leading edge positions used for fluid thickness measurements (see Figure 2.2).



FORM 5

FLUID THICKNESS MEASUREMENTS

FALCON 20 PORT WING

Date: ______ Time: ______ Run Number ______

Test Phase: A - before contamination ☐ B- before takeoff ☐

RECORD FLUID THICKNESS MEASUREMENTS ON THE LEADING EDGE AT ALL THE NUMBERED LOCATIONS

OBSERVER: ______

ASSISTED BY: ______

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Figure 2.2: Thickness Measurement Data Form

For tests involving dilution of the fluid on the wings, precipitation in the form of light freezing rain was applied with the use of custom-designed hand-held sprayers by operators located on rolling stairs over each wing (see Photo 2.7). Artificial freezing rain was applied until a predetermined level of dilution had been achieved, based on measurements of the refractive index of the fluid at several points on the wing. Fluid freezing point measurements were recorded by observers at 5-minute intervals at the 6 numbered locations and baseline location (designated by “B” in Figure 2.2) on the port wing, and at the baseline location only on the starboard wing. Fluid freezing points were recorded for both wings at the 6 leading edge positions at the threshold of the departure runway, just prior to the takeoff of the aircraft.

Hand-held digital video cameras filmed the appearance of the fluid contaminant mixture throughout the taxi phase (see Photo 2.8), the takeoff run (see Photo 2.9), climb-out of the aircraft (see Photo 2.10), and the subsequent return to the inspection pad at the central deicing facility. During the takeoff run, the First Officer read off the ground speed from aircraft instrumentation for the audio track on the videotape.

The original test plan for 2002-03 testing with the Falcon 20 aircraft is shown in Table 2.1. Modifications were made to the original test plan based on discussions with TDC. Further modifications were made during conduct of the February 2003 tests, and the table containing the actual tests performed is given in Section 3 (Table 3.1).

Table 2.1: Test Plan for Falcon 20 Tests in 2002-03

Test #	OAT°C	Fluid	Precipitation	Wing Condition
1	<-3	Type IV EG Neat	No	Clean Fluid
2	<-3	Type IV EG Neat	No	Clean Fluid
3	<-3	Type IV PG Neat	No	Clean Fluid
4	<-3	Type IV PG Neat	No	Clean Fluid
5	<-3	Type IV EG Neat	No	Clean Fluid/Inboard Wing Sections
6	<-3	Type IV EG Neat	No	Clean Fluid/Inboard Wing Sections
7	<-3	Type IV EG Neat	No	Clean Fluid/Outboard Wing Sections
8	<-3	Type IV EG Neat	No	Clean Fluid/Outboard Wing Sections
9	<-3	Type IV EG Neat	Yes	Diluted Fluid
10	<-3	Type IV EG Neat	Yes	Diluted Fluid
11	-3	Type IV PG Neat	Yes	Diluted Fluid
12	-3	Type IV PG Neat	Yes	Diluted Fluid

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2.3 Data Forms

Several different forms were used to facilitate the documentation of the various data collected in the Falcon 20 tests. These forms include:

a) Form 1: General Form (Every Test);

b) Form 2: Fluid Freezing Point Measurement Locations During Precipitation – Port Wing;

c) Form 2A: Fluid Freezing Point Measurement Locations During Precipitation – Starboard Wing;

d) Form 2B: Fluid Freezing Point Measurements on Aircraft;

e) Form 3: Fluid Freezing Point Distribution Prior to Takeoff – Port Wing;

f) Form 3A: Fluid Freezing Point Distribution Prior to Takeoff – Starboard Wing;

g) Form 4: Wing Temperature Form – Port Wing;

h) Form 4A: Wing Temperature Form – Starboard Wing;

i) Form 5: Fluid Thickness on Aircraft Prior to Takeoff – Port Wing;

j) Form 5A: Fluid Thickness on Aircraft Prior to Takeoff – Starboard Wing;

k) Form 6: Thickness Measurements to Support Development of the Airport De-Icer Management Systems (ADMS) Model; and

l) Form 7: Freezing Rain/Snow Quantity Form.

Copies of these forms are provided in the test procedure for the February 2003 tests shown in Appendix D.

2.4 Equipment

A considerable array of test equipment was required to perform these tests, some of which are worthy of comment.

2.4.1 Falcon 20 Research Aircraft

The aircraft used for testing was a Dassault Falcon 20 twin-engine, mid-size business jet, operated by the NRC (see Photo 2.1). The aircraft is a multi-purpose 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.

The NRC acquired the Falcon 20 from the Department of National Defence (DND) in 1991. In partnership with the Canadian Space Agency (CSA) and TC, the 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 still in place to allow the aircraft to fly "zero" G parabolic maneuvers, and 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 determining aircraft landing and takeoff performance changes as a result of runway contaminant.

2.4.1.1 Falcon 20 design characteristics

A three-view diagram of the Falcon 20 aircraft has been included in Figure 2.3. Some of the pertinent dimensions of the Falcon 20 are noteworthy:

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.).

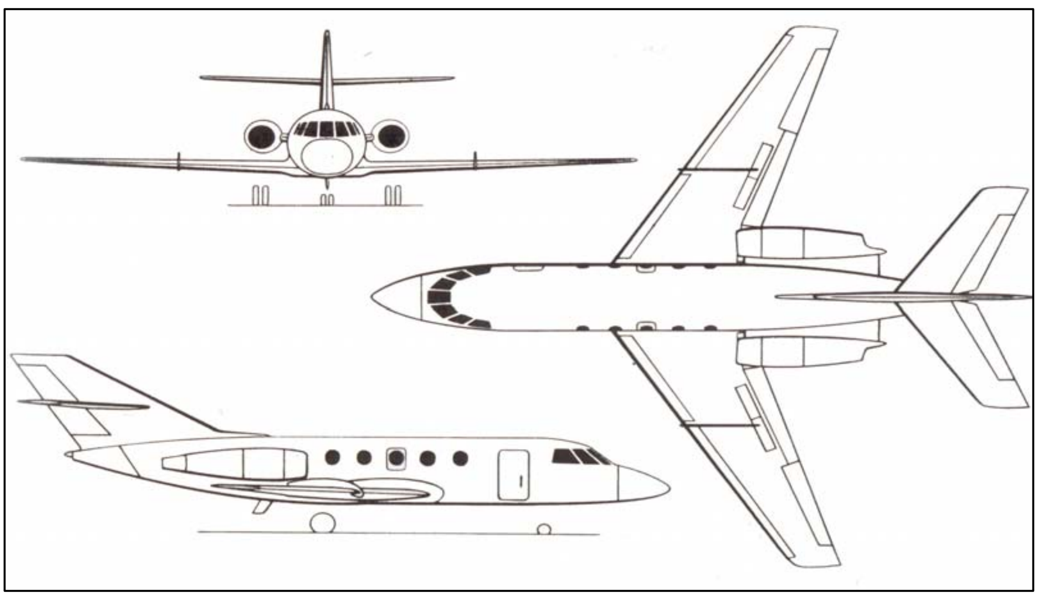

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Figure 2.3: Schematic View of Dassault Falcon 20

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

2.4.1.2 Falcon 20 on-board installations

The NRC Falcon 20 research aircraft is equipped with the following on-board installations:

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

b) Data acquisition system is an MVME167 computer with removable hard disk;

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

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

e) A Litton 92 Inertial Navigation System was added to the aircraft for the wing contamination tests.

2.4.1.3 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) Outside air temperature; and
f) Flight director system signals.

2.4.2 Fluid Application Equipment

Most deicing operators only carry and spray fluid of one glycol base. Due to APS test requirements that often require that fluid other than that available at any given site be used, a mobile fluid sprayer was developed by APS personnel (see Photo 2.11). The mobile sprayer was designed to enable outdoor and indoor testing in all conditions using different Type IV fluids as required. It comprises three interrelated components: a fluid reservoir, a fluid pump, and a fluid application nozzle. The components of the mobile sprayer are described below:

a) A non-shearing fluid pump, identical to those installed in deicing vehicles, forces the fluid from the reservoir. The fluid reservoir is a 200-L drum adapted with the appropriate fittings and hoses to supply the pump and receive fluid when the application nozzle is closed;

b) A pressure gauge monitors the pump system fluid pressure. An adjustable relief valve controls the system pressure. A check valve mounted at the root of the fluid supply hose prevents any fluid from draining back to the reservoir when the pump is turned off;

c) The pump is driven by an electric motor, which requires a generator capable of producing a minimum of 550 V, 30 kW, and three-phase current; and

d) A Task Force Tips nozzle is connected to the pump with a pressure-resistant rubber hose fitted with locking couplings.

The sprayer system weighs approximately 315 kg (not including the generator) and can be easily transported with a pickup truck, although a winch is required for loading. The generator required for tests with the mobile sprayer was a large portable unit mounted on its own trailer as shown in Photo 2.12.

2.4.3 Fluid Dilution Equipment

The objective of the three-year test program with the Falcon 20 research aircraft is to ascertain the aerodynamic penalty on the aircraft due to the presence of partially expended anti-icing fluid on the wings of the aircraft. Fluid diluted by snow and freezing rain will be examined as part of this research program. For 2002-03 testing, only fluid dilution by simulated light freezing rain was examined.

2.4.3.1 Freezing rain sprayer unit

A water sprayer to produce artificial freezing rain was designed by APS for the 1997-98 and 1998-99 Falcon 20 tests. Because only a small section of one wing was contaminated in those tests, only a single spray bar was required.

One of the requirements of the tests conducted in 2001-02 and 2002-03 was to dilute the fluid on the entire wing surface area. A new sprayer, based largely on the original sprayer, was designed to accomplish this task.

The sprayer system included several principal elements:

a) A liquid pumping unit;
b) An air compressor;
c) A portable generator;
d) A water reservoir; and
e) Two hand-held spray bars.

The freezing rain sprayer system controls are shown in Photo 2.13. The freezing rain sprayer equipped with the spray hoses is shown in Photo 2.14. This photo was taken in 2001-02 when the system was mounted in the back of a rented van. In 2002-03 tests, the freezing rain sprayer was mounted in the pick-up used to transport the mobile sprayer and the fluid containers.

Each spray bar unit was equipped with three spray heads that accepted hypodermic needles of various gauges as used at the NRC's Climatic Engineering Facility to produce different droplet sizes. In this application, 20 gauge hypodermic needles were installed to produce droplet sizes appropriate to light freezing rain.

In tests with the freezing rain sprayer, operators were positioned on rolling stair units. Depending on the intensity of the wind, the spray bar was positioned anywhere from approximately 1.2 m to 2.4 m (4 ft. to 8 ft.) above the wing surface.

The water temperature in the fluid reservoir was approximately 5°C and the droplet size of the light freezing rain was approximately 1 mm. Rates of precipitation were measured using plate pans positioned on the wings of the Falcon 20 prior to the start of testing. The rate pans were identical to those used in fluid holdover time tests by APS. After the fluid dilution process, the rate pans were weighed and the ice catch determined.

The operation manual for the freezing rain sprayer has been included in Appendix E of TP 13995E (4).

2.4.4 Fluid Viscometer

Fluid samples for viscosity tests were gathered from various points within the wing test area and were stored in small wide-mouth glass bottles with screw caps. Viscosity measurements of these samples were carried out using a Brookfield viscometer (Model DV-1+, Photo 2.15) fitted with a thermostatted re-circulating fluid bath and small sample adapter.

2.4.5 Hand-Held Video Camera

In 1997-98 and 1998-99 tests, a video camera was installed on the Falcon 20. This camera was mounted in a temporary structure, which replaced the normal aircraft emergency exit hatch. The camera was fixed in position, and was focused on the forward portion of the test area, including the leading edge. Because the takeoff and climb of the aircraft were not examined in these tests, it was possible to remove the window and replacing it with a temporary structure.

For tests conducted in 2001-02 and 2002-03 with the Falcon 20, the aircraft was rotated and flown for a circuit of the airport prior to its return. The temporary door used for mounting the video camera in previous tests was not airworthy and an alternate solution was needed to enable the recording of video documentation of the condition of the wing during takeoff. After much debate, it was decided that APS personnel would be positioned in the cabin over the wings of the Falcon 20 with hand-held digital video cameras.

2.4.6 Other Equipment

Octagonal wet film thickness gauges, shown in Figure 2.4, were used to measure fluid film thickness. These gauges were selected because they provide an adequate range of thickness (0.1 mm to 10.2 mm) for Type IV fluids. The rectangular gauge shown in the figure has a finer scale and was used in some cases when the fluid film was less thick (toward the end of a test). Uncorrected thickness values, as read directly from the thickness gauge, were recorded by the observer in the field. These values were then converted to a corrected thickness in millimeters using the Film Thickness Conversion Table, shown in Section 3 of this report.

Fluid freezing points on the wing were measured using a hand-held Misco refractometer with a Brix scale.

Wing temperatures were measured using hand-held Wahl surface temperature probes.

A full list of equipment is provided in Appendix D.

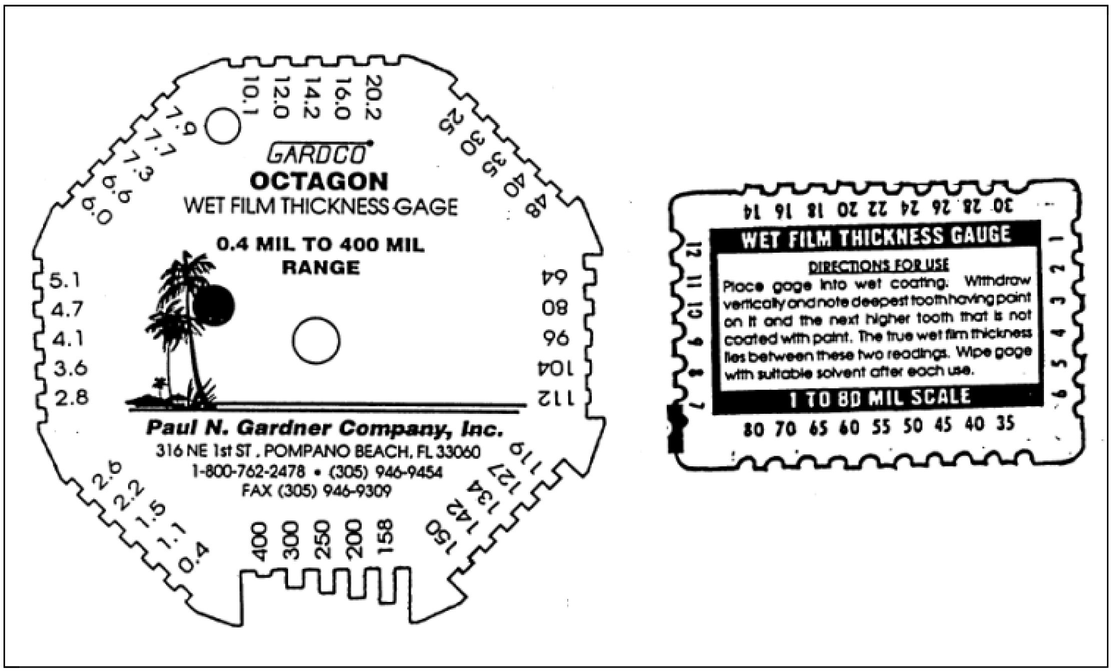

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Figure 2.4: Thickness Gauges

2.5 Fluids

Two fluids were used in the Falcon 20 tests:

a) Dow Chemical UCAR Ultra+ Type IV ethylene glycol fluid; and
b) Kilfrost ABC-S propylene glycol Type IV fluid (manufactured by Cryotech).

Both fluids were dispensed by APS personnel at the NRC apron in Ottawa.

The Brix of the neat Dow Ultra+ fluid was 40°. The viscosity of the virgin Dow Ultra+ sample was 33,000 centipoises (cP) using the standard AIR 9968 viscosity measurement method.

The Brix of the neat Kilfrost ABC-S fluid was 36°. The viscosity of the virgin Kilfrost ABC-S sample was 22,500 cP using the standard AIR 9968 viscosity measurement method.

The fluids used in Falcon 20 tests were received from the manufacturers in 200-litre drums and 1000-litre totes (see Photo 2.16).

2.6 Personnel

The NRC Falcon 20 research aircraft was operated by NRC crew out of Ottawa, Ontario.
Representatives from the TDC provided direction in testing and participated as observers.

Seven APS staff members were required for the aircraft tests at Ottawa airport. One additional person was hired to record digital video of the testing.

Ethylene and propylene glycol applications were performed by APS personnel at the NRC hangar using the Type IV mobile sprayer.

Waste fluid clean-up and recovery was performed by Inland Technologies at the NRC hangar.

Photo 2.1: NRC Canada Falcon 20

Photo 2.2: Drawing of Grid on Falcon 20 Wing

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Photo 2.3: Finished Grid on the Starboard Wing

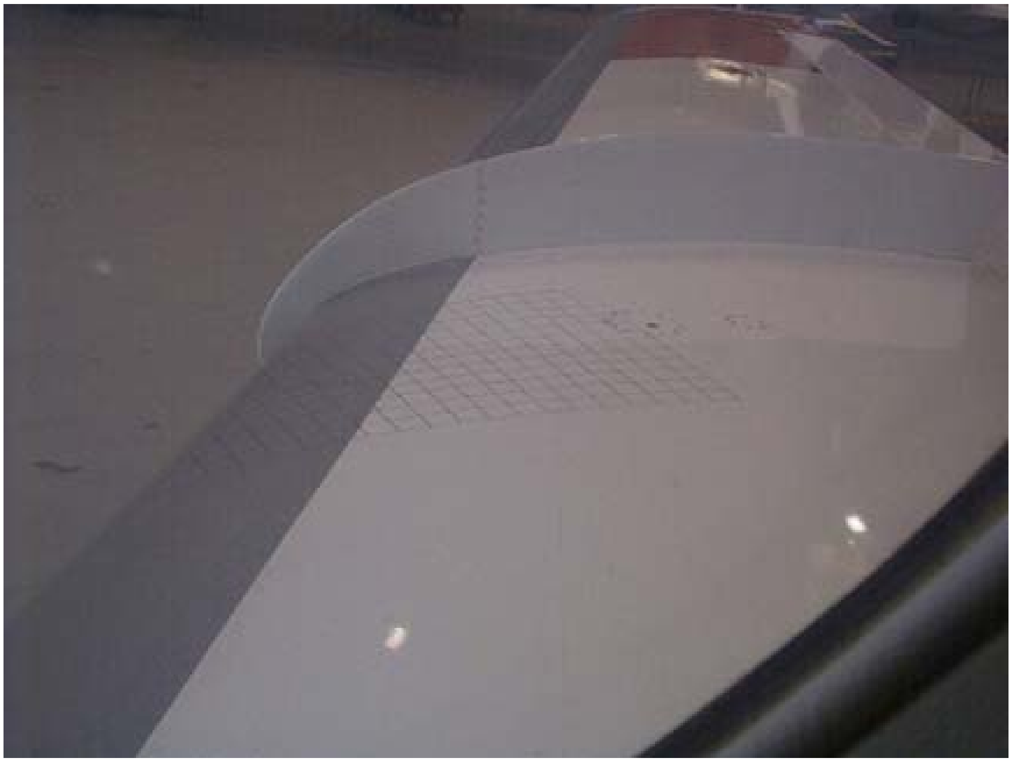

Photo 2.4: Tarp Used to Protect Wing Sections From Fluid Application

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Photo 2.5: APS Personnel Applying Type IV Fluid Using the Mobile Sprayer

Photo 2.6: Sample Collection for Viscosity Analysis

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Photo 2.7: Light Freezing Rain Sprayed on Falcon 20

Photo 2.8: Appearance of Type IV Fluid During Taxi

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Photo 2.9: Appearance of Type IV Fluid During Takeoff

Photo 2.10: Appearance of Wing During Climb-Out

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Photo 2.11: Mobile Type IV Fluid Sprayer Unit

Photo 2.12: Generator Used to Power Mobile Sprayer Unit

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Photo 2.13: Freezing Rain Sprayer

Photo 2.14: Freezing Rain Sprayer with Hoses

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Photo 2.15: Brookfield Digital Viscometer Model DV-1+ and Temperature Bath

Photo 2.16: Fluid Containers Received From Manufacturers

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3 DESCRIPTION AND PROCESSING OF DATA

3.1 Overview of Tests

The February 2003 Falcon 20 tests were conducted over a four-day period at MacDonald Cartier International Airport in Ottawa, Ontario.

A summary of the actual tests conducted in February 2003 is shown in Table 3.1. A more detailed summary of the pertinent information for each test is presented in Subsections 3.1.1 to 3.1.14.

Table 3.1: Summary of 2002-03 Testing with Falcon 20

Date	Run	Fluid Applied	Zr- Applied	Wing Condition
24-Feb-03	1	Type IV EG Neat	No	Clean Fluid on Inboard Wing Sections Only
24-Feb-03	2	Type IV EG Neat	No	Clean Fluid
24-Feb-03	3	Type IV EG Neat	No	Clean Fluid
24-Feb-03	4	Type IV EG Neat	No	Clean Fluid on Outboard Wing Sections Only
25-Feb-03	5	Type IV PG Neat	No	Clean Fluid
25-Feb-03	6	Type IV PG Neat	No	Clean Fluid
25-Feb-03	7	Type IV PG Neat	No	Clean Fluid
25-Feb-03	8	Residual PG Fluid from Test # 7	No	Residual PG Fluid from Test # 7
26-Feb-03	9	Type IV PG Neat	Yes	Contaminated Fluid
26-Feb-03	10	Type IV PG Neat	Yes	Contaminated Fluid
26-Feb-03	11	Type IV EG Neat	Yes	Contaminated Fluid
26-Feb-03	12	Residual EG Fluid from Test # 11	No	Residual EG Fluid from Test # 11
26-Feb-03	13	Type IV EG Neat	Yes	Contaminated Fluid
27-Feb-03	14	Type IV EG Diluted	No	Pre-Diluted Type IV, No Additional Dilution

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Runs 8 and 12 were performed with residual fluid on the wings of the aircraft following Runs 7 and 11, respectively. In each of the runs with residual fluid, the aircraft exited the arrival runway from its preceding flight and taxied back to the departure runway. The EG and PG anti-icing fluids present on the wings at the beginning of the takeoff rolls in Runs 7 and 11 were largely removed due to shear forces exerted on the fluid. A very thin film of fluid remained on the wing after the aircraft landed. The objective of the residual fluids tests was to examine the effect of the residual anti-icing fluid on the lift generated by the aircraft.

3.1.1 Run 1, February 24, 2003

- Ambient temperature: -13°C
- Wind direction / speed: 260°/ 3 knots
- Sky condition: Partly cloudy
- Runway used: 25
- Fluid spray start time (port wing): 13:50:30
- Fluid spray end time (port wing): 13:52:00
- Fluid spray start time (starboard wing): 13:47:00
- Fluid spray end time (starboard wing): 13:48:30
- Fluid spray quantities (port wing): 26 L Type IV EG
- Fluid spray quantities (starboard wing): 22 L Type IV EG
- Departure time from deicing pad: 14:23:00
- Start of takeoff roll: 14:28:50
- Time of landing: 14:33:50
- Return time to deicing pad: 14:41:00

3.1.2 Run 2, February 24, 2003

- Ambient temperature: -13°C
- Wind direction / speed: 280°/ 4 knots
- Sky condition: Partly cloudy
- Runway used: 25
- Fluid spray start time (port wing): 14:58:00
- Fluid spray end time (port wing): 14:59:40
- Fluid spray start time (starboard wing): 14:55:00
- Fluid spray end time (starboard wing): 14:56:30
- Fluid spray quantities (port wing): 50 L Type IV EG
- Fluid spray quantities (starboard wing): 66 L Type IV EG
- Departure time from deicing pad: 15:24:30
- Start of takeoff roll: 15:34:50
- Time of landing: 15:39:20
- Return time to deicing pad: 15:44:20

3.1.3 Run 3, February 24, 2003

- Ambient temperature: -13°C
- Wind direction / speed: 240°/ 4 knots
- Sky condition: Overcast
- Runway used: 25
- Fluid spray start time (port wing): 15:59:20
- Fluid spray end time (port wing): 16:00:20
- Fluid spray start time (starboard wing): 15:56:30
- Fluid spray end time (starboard wing): 15:57:20
- Fluid spray quantities (port wing): 52 L Type IV EG
- Fluid spray quantities (starboard wing): 61 L Type IV EG
- Departure time from deicing pad: 16:18:00
- Start of takeoff roll: 16:27:50
- Time of landing: 16:34:50
- Return time to deicing pad: 16:39:30

3.1.4 Run 4, February 24, 2003

- Ambient temperature: -13°C
- Wind direction / speed: 280°/ 4 knots
- Sky condition: Overcast
- Runway used: 25
- Fluid spray start time (port wing): 16:54:30
- Fluid spray end time (port wing): 16:55:00
- Fluid spray start time (starboard wing): 16:51:30
- Fluid spray end time (starboard wing): 16:52:00
- Fluid spray quantities (port wing): 27 L Type IV EG
- Fluid spray quantities (starboard wing): 24 L Type IV EG
- Departure time from deicing pad: 17:17:30
- Start of takeoff roll: 17:25:00
- Time of landing: 17:32:00
- Return time to deicing pad: 17:36:50

3.1.5 Run 5, February 25, 2003

- Ambient temperature: -20°C
- Wind direction / speed: 295°/ 12 knots, gusting 18
- Sky condition: Sky clear
- Runway used: 25
- Fluid spray start time (port wing): 9:28:00
- Fluid spray end time (port wing): 9:29:05
- Fluid spray start time (starboard wing): 9:25:40
- Fluid spray end time (starboard wing): 9:27:00

- Fluid spray quantities (port wing): 60 L Type IV PG
- Fluid spray quantities (starboard wing): 53 L Type IV PG
- Departure time from deicing pad: 9:48:30
- Start of takeoff roll: 9:57:50
- Time of landing: 10:05:20
- Return time to deicing pad: 10:11:00

3.1.6 Run 6, February 25, 2003

- Ambient temperature: -20°C
- Wind direction / speed: 300°/ 10 knots, gusting 15
- Sky condition: Sky clear
- Runway used: 32
- Fluid spray start time (port wing): 10:20:00
- Fluid spray end time (port wing): 10:21:00
- Fluid spray start time (starboard wing): 10:17:00
- Fluid spray end time (starboard wing): 10:18:00
- Fluid spray quantities (port wing): 50 L Type IV PG
- Fluid spray quantities (starboard wing): 50 L Type IV PG
- Departure time from deicing pad: 10:41:50
- Start of takeoff roll: 11:01:15
- Time of landing: 11:07:00
- Return time to deicing pad: 11:11:00

3.1.7 Run 7, February 25, 2003

- Ambient temperature: -18°C
- Wind direction / speed: 300°/ 10 knots
- Sky condition: Sky clear
- Runway used: 32
- Fluid spray start time (port wing): 11:25:40
- Fluid spray end time (port wing): 11:26:30
- Fluid spray start time (starboard wing): 11:23:00
- Fluid spray end time (starboard wing): 11:24:00
- Fluid spray quantities (port wing): 53 L Type IV PG
- Fluid spray quantities (starboard wing): 50 L Type IV PG
- Departure time from deicing pad: 11:47:00
- Start of takeoff roll: 11:59:15
- Time of landing: 12:08:00
- Return time to deicing pad: N/A

3.1.8 Run 8, February 25, 2003

• Ambient temperature:	-18°C
• Wind direction / speed:	300°/ 10 knots
• Sky condition:	Sky clear
• Runway used:	25
• Fluid spray start time (port wing):	N/A (residual fluid – test # 7)
• Fluid spray end time (port wing):	N/A (residual fluid – test # 7)
• Fluid spray start time (starboard wing):	N/A (residual fluid – test # 7)
• Fluid spray end time (starboard wing):	N/A (residual fluid – test # 7)
• Fluid spray quantities (port wing):	N/A (residual fluid – test # 7)
• Fluid spray quantities (starboard wing):	N/A (residual fluid – test # 7)
• Departure time from deicing pad:	N/A
• Start of takeoff roll:	12:12:50
• Time of landing:	12:19:00
• Return time to deicing pad:	12:24:00

3.1.9 Run 9, February 26, 2003

• Ambient temperature:	-23°C
• Wind direction / speed:	115°/ 2 knots
• Sky condition:	Sky clear
• Runway used:	25
• Fluid spray start time (port wing):	7:36:40
• Fluid spray end time (port wing):	7:37:40
• Fluid spray start time (starboard wing):	7:39:20
• Fluid spray end time (starboard wing):	7:40:15
• Fluid spray quantities (port wing):	55 L Type IV PG
• Fluid spray quantities (starboard wing):	60 L Type IV PG
• Rate of precipitation (port wing):	14 $g/dm^2/h$
• Rate of precipitation (starboard wing):	23 $g/dm^2/h$
• Zr-spray start time (port wing):	7:48:20
• Zr-spray end time (port wing):	7:56:40
• Zr-spray start time (starboard wing):	7:47:20
• Zr-spray end time (starboard wing):	7:56:40
• Departure time from deicing pad:	8:25:50
• Start of takeoff roll:	8:40:20
• Time of landing:	8:45:30
• Return time to deicing pad:	8:49:50

3.1.10 Run 10, February 26, 2003

- Ambient temperature: -23°C
- Wind direction / speed: 115°/ 2 knots
- Sky condition: Sky clear
- Runway used: 25
- Fluid spray start time (port wing): 9:02:00
- Fluid spray end time (port wing): 9:03:00
- Fluid spray start time (starboard wing): 8:59:30
- Fluid spray end time (starboard wing): 9:00:20
- Fluid spray quantities (port wing): 50 L Type IV PG
- Fluid spray quantities (starboard wing): 56 L Type IV PG
- Rate of precipitation (port wing): 12 $g/dm^2/h$
- Rate of precipitation (starboard wing): 14 $g/dm^2/h$
- Zr-spray start time (port wing): 9:10:50
- Zr-spray end time (port wing): 9:33:45
- Zr-spray start time (starboard wing): 9:11:20
- Zr-spray end time (starboard wing): 9:39:30
- Departure time from deicing pad: 9:56:30
- Start of takeoff roll: 10:08:10
- Time of landing: 10:15:00
- Return time to deicing pad: 10:19:00

3.1.11 Run 11, February 26, 2003

- Ambient temperature: -19°C
- Wind direction / speed: Calm
- Sky condition: Sky clear
- Runway used: 25
- Fluid spray start time (port wing): 10:41:50
- Fluid spray end time (port wing): 10:42:30
- Fluid spray start time (starboard wing): 10:38:50
- Fluid spray end time (starboard wing): 10:39:15
- Fluid spray quantities (port wing): 51 L Type IV EG
- Fluid spray quantities (starboard wing): 54 L Type IV EG
- Rate of precipitation (port wing): 13 $g/dm^2/h$
- Rate of precipitation (starboard wing): 11 $g/dm^2/h$
- Zr-spray start time (port wing): 10:46:15
- Zr-spray end time (port wing): 11:13:30
- Zr-spray start time (starboard wing): 10:46:15
- Zr-spray end time (starboard wing): 11:16:15
- Departure time from deicing pad: 11:40:30
- Start of takeoff roll: 11:52:00
- Time of landing: 11:59:15

- Return time to deicing pad: N/A

3.1.12 Run 12, February 26, 2003

- Ambient temperature: -15°C
- Wind direction / speed: Calm
- Sky condition: Sky clear
- Runway used: 32
- Fluid spray start time (port wing): N/A (residual fluid – test 11)
- Fluid spray end time (port wing): N/A (residual fluid – test 11)
- Fluid spray start time (starboard wing): N/A (residual fluid – test 11)
- Fluid spray end time (starboard wing): N/A (residual fluid – test 11)
- Fluid spray quantities (port wing): N/A (residual fluid – test 11)
- Fluid spray quantities (starboard wing): N/A (residual fluid – test 11)
- Departure time from deicing pad: N/A
- Start of takeoff roll: 12:04:00
- Time of landing: 12:11:00
- Return time to deicing pad: N/A

3.1.13 Run 13, February 26, 2003

- Ambient temperature: -12°C
- Wind direction / speed: 120°/ 5 knots
- Sky condition: Sky clear
- Runway used: 32
- Fluid spray start time (port wing): 17:01:15
- Fluid spray end time (port wing): 17:01:50
- Fluid spray start time (starboard wing): 16:59:30
- Fluid spray end time (starboard wing): 17:00:00
- Fluid spray quantities (port wing): 52 L Type IV EG
- Fluid spray quantities (starboard wing): 50 L Type IV EG
- Rate of precipitation (port wing): 15 $g/dm^2/h$
- Rate of precipitation (starboard wing): 13 $g/dm^2/h$
- Zr-spray start time (port wing): 17:06:15
- Zr-spray end time (port wing): 17:28:50
- Zr-spray start time (starboard wing): 17:05:30
- Zr-spray end time (starboard wing): 17:28:50
- Departure time from deicing pad: 17:49:00
- Start of takeoff roll: 18:02:15
- Time of landing: 18:09:20
- Return time to deicing pad: 18:15:00

3.1.14 Run 14, February 27, 2003

- Ambient temperature: -16°C
- Wind direction / speed: 105°/ 4 knots
- Sky condition: Sky clear
- Runway used: 32
- Fluid spray start time (port wing): 9:08:20
- Fluid spray end time (port wing): 9:09:00
- Fluid spray start time (starboard wing): 9:10:20
- Fluid spray end time (starboard wing): 9:11:00
- Fluid spray quantities (port wing): 67 L Type IV EG Diluted
- Fluid spray quantities (starboard wing): 50 L Type IV EG Diluted
- Departure time from deicing pad: 9:40:00
- Start of takeoff roll: 10:00:45
- Time of landing: 10:07:35
- Return time to deicing pad: 10:10:50

3.2 Description of Data Collected and Analysis Methodology

For every run, the following data were collected:

a) Fluid thickness;

b) Fluid freezing point (for tests with light freezing rain only);

c) Fluid viscosity; and

d) Wing skin temperature.

The procedures for the collection of data for each run were previously described in Section 2. This section discusses the various methods used to process the fluid thickness, fluid freezing point, wing skin temperature and fluid viscosity data.

3.2.1 Fluid Thickness

For each test, the fluid film thickness of anti-icing fluid remaining at six leading edge locations on each wing was recorded prior to the takeoff of the aircraft at the runway threshold. Octagonal wet film thickness gauges, shown previously in Figure 2.3, were used to measure fluid film thickness. For each location, the observer in the field recorded an uncorrected thickness value (in mils, 1 mil=25.4 microns=0.001 inch), as read off directly from the thickness gauge. These values were then converted to a corrected thickness in millimeters using the Film Thickness Conversion Table, shown in Table 3.2.

Table 3.2: Film Thickness Conversion Table

RECTANGULAR GAUGE			OCTAGON GAUGE		
Reading*	Calculated Thickness		Reading*	Calculated Thickness	
(mil)	(mil)	(mm)	(mil)	(mil)	(mm)
			0.4	0.8	0.0
1.0	1.5	0.0	1.1	1.3	0.0
			1.5	1.9	0.0
2.0	2.5	0.1	2.2	2.4	0.1
			2.6	2.7	0.1
3.0	3.5	0.1	2.8	3.2	0.1
			3.6	3.9	0.1
4.0	4.5	0.1	4.1	4.4	0.1
			4.7	4.9	0.1
5.0	5.5	0.1	5.1	5.6	0.1
6.0	6.4	0.2	6.0	6.4	0.2
			6.6	7.0	0.2
7.0	7.5	0.2	7.3	7.5	0.2
8.0	8.5	0.2	7.7	7.8	0.2
9.0	9.5	0.2	7.9	9.0	0.2
10	11	0.3	10	11	0.3
11	12	0.3			
12	13	0.3	12	13	0.3
14	15	0.4	14	15	0.4
16	18	0.4	16	18	0.4
18	19	0.5			
20	21	0.5	20	23	0.6
22	23	0.6			
24	25	0.6	25	28	0.7
26	27	0.7			
28	29	0.7			
30	33	0.8	30	33	0.8
35	38	1.0	35	38	1.0
40	43	1.1	40	43	1.1
45	48	1.2			
50	53	1.3	48	56	1.4
55	58	1.5			
60	63	1.6			
65	68	1.7	64	72	1.8
70	73	1.8			
75	78	2.0			
80	88	2.2	80	88	2.2
			96	100	2.5
			104	108	2.7
			112	116	2.9
			119	123	3.1
			127	131	3.3
			134	138	3.5
			142	146	3.7
			150	154	3.9
			158	179	4.5
			200	225	5.7
			250	275	7.0
			300	350	8.9
			400	400	10.2

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* Reading of last wetted tooth.

3.2.2 Fluid Freezing Points

Two fluids were used in 2002-03 tests with the Falcon 20, Dow Ultra+ and Kilfrost ABC-S (manufactured by Cryotech). Fluid freezing points were collected at various points on the wing during the application of light freezing rain and just prior to the takeoff of the aircraft.

3.2.2.1 Dow Ultra+

Brix values of the Dow Ultra+ Type IV fluid were obtained using hand-held refractometers. The freezing points (in °C) of the various fluid samples were then determined using the conversion curve shown in Figure 3.1. Dow Chemical produced the curve for use with Ultra+.

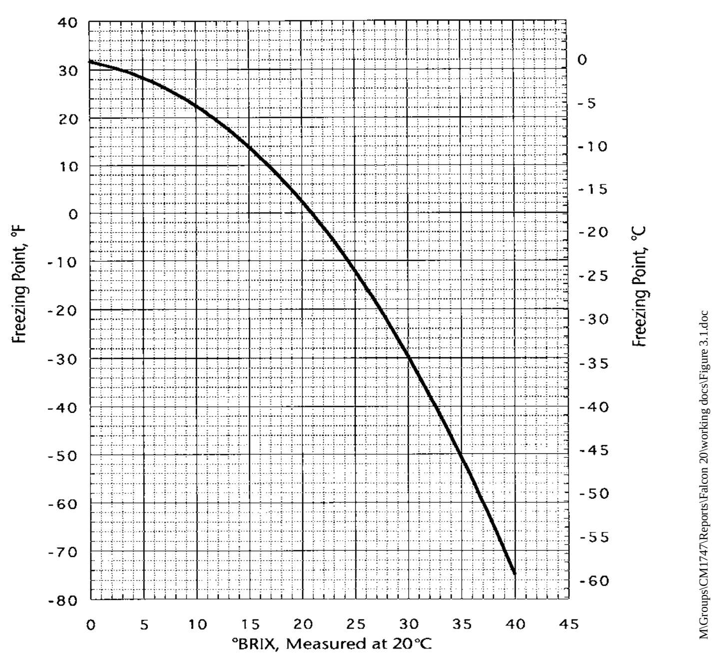

Figure 3.1: Freezing Point vs. Brix of Aqueous Solutions of Dow UCAR Ultra+

3.2.2.2 Kilfrost ABC-S

Brix values of the Kilfrost ABC-S Type IV fluid were also obtained using hand-held refractometers. The freezing points (in °C) of the various fluid samples were then determined using the conversion table shown in Table 3.3. Cryotech made the table available for use.

Table 3.3: Freezing Point vs. Brix of Aqueous Solutions of Kilfrost ABC-S

Conc. (% vol)	BRIX (20°C)	RI (20°C)	Freezing Point (°C)	Conc. (% vol)	BRIX (20°C)	RI (20°C)	Freezing Point (°C)	Conc. (% vol)	BRIX (20°C)	RI (20°C)	Freezing Point (°C)
20%	8.20	1.345	-3.4	**50%**	**18.90**	**1.362**	**-10.6**	80%	29.40	1.380	-23.1
21%	8.59	1.345	-3.6	51%	19.26	1.363	-11.1	81%	29.73	1.380	-23.7
22%	8.98	1.346	-3.8	52%	19.62	1.364	-11.6	82%	30.06	1.381	-24.2
23%	9.37	1.346	-4.0	53%	19.98	1.364	-12.0	83%	30.36	1.382	-24.8
24%	9.76	1.347	-4.2	54%	20.34	1.365	-12.4	84%	30.72	1.382	-25.4
25%	10.15	1.348	-4.4	55%	20.70	1.365	-12.8	85%	31.05	1.383	-26.0
26%	10.54	1.348	-4.6	56%	21.06	1.366	-13.1	86%	31.38	1.383	-26.7
27%	10.93	1.349	-4.9	57%	21.42	1.366	-13.4	87%	31.71	1.384	-27.3
28%	11.32	1.349	-5.1	58%	21.78	1.367	-13.8	88%	32.04	1.384	-28.0
29%	11.71	1.350	-5.3	59%	22.14	1.368	-14.1	89%	32.37	1.385	-28.6
30%	12.10	1.351	-5.5	60%	22.50	1.368	-14.5	90%	32.70	1.386	-29.3
31%	12.43	1.351	-5.8	61%	22.85	1.369	-14.9	91%	33.02	1.386	-30.1
32%	12.76	1.352	-6.0	62%	23.20	1.369	-15.2	92%	33.34	1.387	-30.8
33%	13.09	1.352	-6.3	63%	23.55	1.370	-15.7	93%	33.66	1.387	-31.5
34%	13.42	1.353	-6.5	64%	23.90	1.371	-16.0	94%	33.98	1.388	-32.2
35%	13.75	1.354	-6.8	65%	24.25	1.371	-16.4	95%	34.30	1.389	-33.0
36%	14.08	1.354	-7.0	66%	24.60	1.372	-16.8	96%	34.62	1.389	-33.8
37%	14.41	1.355	-7.3	67%	24.95	1.372	-17.2	97%	34.94	1.390	-34.6
38%	14.74	1.355	-7.6	68%	25.30	1.373	-17.6	98%	35.26	1.391	-35.4
39%	15.07	1.356	-7.9	69%	25.65	1.373	-18.0	99%	35.58	1.391	-36.2
40%	15.40	1.356	-8.1	70%	26.00	1.374	-18.4	**100%**	**35.90**	**1.392**	**-37.0**
41%	15.75	1.357	-8.4	71%	26.34	1.375	-18.9				
42%	16.10	1.358	-8.7	72%	26.68	1.375	-19.3				
43%	16.45	1.358	-9.0	73%	27.02	1.376	-20.0				
44%	16.80	1.359	-9.3	74%	27.36	1.376	-20.7				
45%	17.15	1.359	-9.5	**75%**	**27.70**	**1.377**	**-21.4**				
46%	17.50	1.360	-9.8	76%	28.04	1.378	-21.7				
47%	17.85	1.361	-10.0	77%	28.38	1.379	-22.0				
48%	18.20	1.361	-10.2	78%	28.72	1.379	-22.3				
49%	18.55	1.362	-10.4	79%	29.06	1.379	-22.6				

3.2.3 Fluid Viscosity

Prior to the fluid application process for each test, Type IV samples were collected from each fluid container. Fluids samples were again gathered from the wing following fluid application, after the application of light freezing rain (if applicable) and upon return of the aircraft to the NRC pad following the takeoff. The fluid samples were transported to the APS laboratory and subjected to viscosity testing.

The measurement method used to determine the viscosities for both fluids was the standard AIR 9968 viscosity measurement method:

a) Spindle SC4-31;
b) 10 mL of fluid;
c) 10 minute duration;

d) 0.3 r/min; and
e) 20°C.

3.2.4 Viscosity Profiles of Dow Ultra+ and Kilfrost ABC-S

The 2001-02 Falcon 20 report to TC contained a recommendation that a preliminary measurement of the relationship between viscosity and refractive index should be performed for all test fluids at different levels of dilution and at different temperatures. APS completed this preliminary study as part of the 2002-03 Falcon 20 test program.

3.2.4.1 Viscosity profiles of Dow Ultra+

The viscosity profile for Dow Ultra+ fluid at different temperatures and dilutions is shown in Figure 3.2. Viscosity curves have been plotted at -20°C, 0°C, and 20°C as a function of the concentration of the fluid.

In general, the viscosity of Ultra+ appears to increase with reduced temperature.

The fluid viscosity of Ultra+ reduces dramatically with dilution. This result was expected as Ultra+ fluid films have been observed to erode quickly with the addition of water in all laboratory and field tests previously conducted by APS.

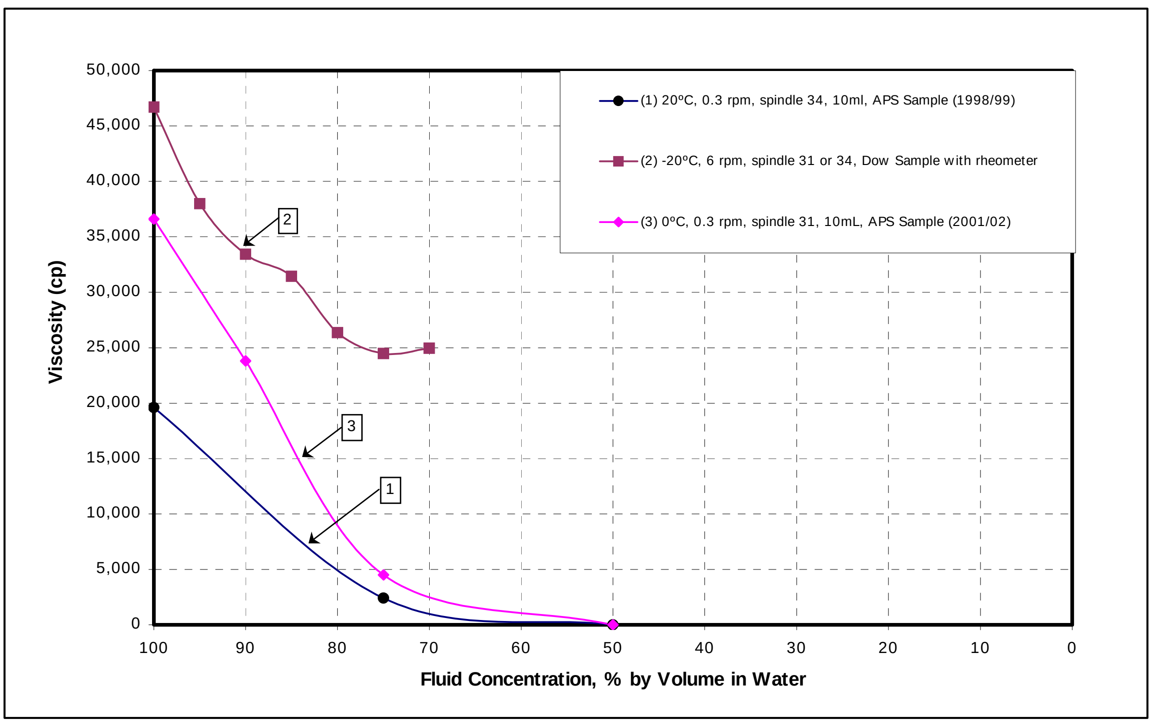

Figure 3.2: Viscosity Profiles of Dow Ultra+

The relationship of viscosity and refractive index was deemed irrelevant and was not examined as part of this study. The refractive index of any given fluid is only a function of the glycol content in the fluid, and would not fluctuate due to differences in fluid viscosity.

3.2.4.2 Viscosity profiles of Kilfrost ABC-S

The viscosity profile for Kilfrost ABC-S fluid at different temperatures and dilutions is shown in Figure 3.3. Viscosity curves have been plotted at 0°C and 20°C as a function of the concentration of the fluid.

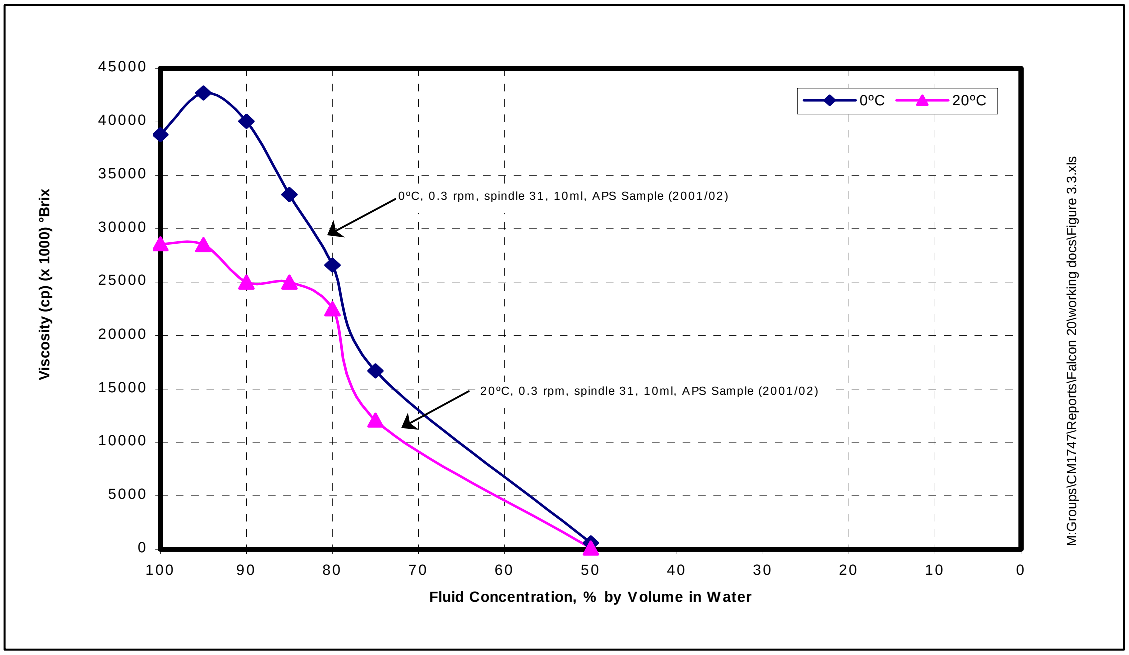

Figure 3.3: Viscosity Profiles of Kilfrost ABC-S

In general, the viscosity of Kilfrost ABC-S appears to increase with reduced temperature. No measurements were conducted below 0°C, however.

In previous laboratory and field tests with Kilfrost ABC-S, the fluid films were observed to initially swell in thickness with the addition of water, and then shrink once a certain dilution had been achieved. This was the case with the 0°C viscosity curve in Figure 3.3, as the viscosity of the fluid initially increased with dilution, peaked and then began to decrease. The 20°C curve, however, decreased gradually from the start, without an initial increase. This appears to be an anomaly.

Additional research conducted by APS was performed to study the effect of fluid dilution on the viscosity of Kilfrost ABC-S fluid (see Table 3.4). Viscosity tests were previously performed with a different fluid sample of ABC-S at several dilutions. Tests were performed at 6 and 60 r/min at a temperature of -20°C. In both cases, the ABC-S fluid viscosity increased with the addition of water until the fluid reached an 85/15 fluid/water mixture, and then decreased gradually.

Table 3.4: Dilution Effect on Viscosity for Kilfrost ABC-S

Water % by volume	Fluid concentration, % by volume in water	Viscosity (cP)	
		Kilfrost ABC-S (6 r/min,-20 ºC)	Kilfrost ABC-S (60 r/min, -20 ºC)
0	100	37436	7243
5	95	45452	8510
10	90	40038	8144
15	85	48262	9121
20	80	45936	8718
25	75	47201	8528
30	70	42397	7351

3.2.5 Wing Skin Temperature

Hand-held temperature probes were used to measure wing temperatures at six leading edge locations on each wing at the button of the departure runway, just prior to the takeoff of the aircraft. Wing temperatures were directly read off the temperature probe and recorded on the appropriate data from.

3.2.6 Aerodynamic Penalties

There is a complete report prepared by NRC on the aerodynamic penalties of the Falcon 20 aircraft, please see TC report, TP 14184E, *Lift-loss Due to the Presence of Ethylene and Propylene Glycol Anti-Icing Fluids on a Falcon 20 Aircraft* (5).

4 ANALYSIS AND OBSERVATIONS

In this section, data collected and observations are discussed for each test. Remarks on the fluid viscosity are based on measurements of the fluid samples recovered during the tests. The viscosity measurements were completed after the conclusion of the tests, and the results of the viscometric analysis will be presented separately in Section 4.15.

4.1 February 24, 2003 – Run 1: Type IV Ethylene Glycol; No Dilution; Clean Fluid on Inboard Wing Sections Only

Run 1 was conducted with clean EG Type IV fluid sprayed only on the wing sections inboard of the boundary layer fence. The fluid was applied in neat concentration and was not further diluted. The objective of this test was to determine the effect on lift of the fluid coverage on the inboard wing only.

4.1.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at three positions on each wing at the runway threshold and were read off the octagonal fluid thickness gauge in mils and then were converted to millimeters using Table 3.2. Measurements for Run 1, recorded in millimeters, are shown in Figure 4.1. Fluid thickness on the inboard wing sections ranged from 0.7 mm to 1.1 mm, and were higher on the port wing.

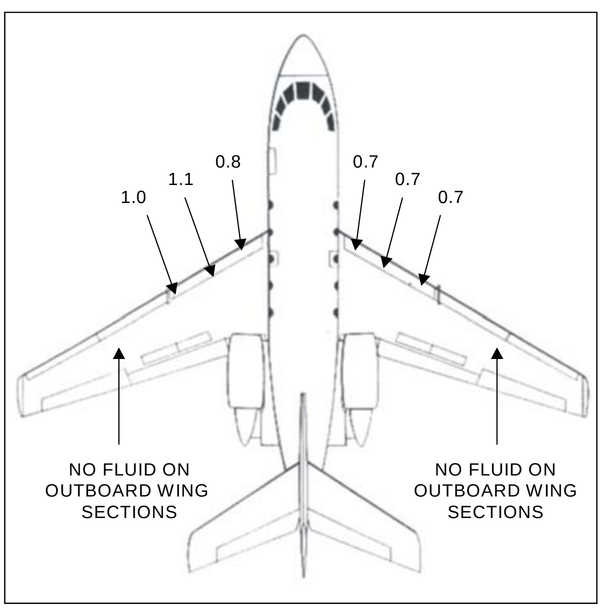

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Figure 4.1: Fluid Thickness Measurements for Run 1 (mm)

After the takeoff and circuit of the Ottawa Airport had been completed, the fluid had been largely removed from the wings of the NRC Falcon 20. A very thin film of fluid remained on most wing surfaces, but in most cases the thickness was immeasurable (less than 0.1 mm). Some pooling of remaining fluid was observed on the trailing edge control surfaces. This fluid generally measured between 0.1 and 0.2 mm, with localized areas of pooled fluid reaching a maximum of 0.3 mm. Samples of the residual fluid were collected for viscometric analysis. This residual fluid was observed in all 14 tests with the Falcon 20 in 2002-03. An example of the residual fluid that remained on the wings of the Falcon 20 at the end of each test is shown in Photo 4.1.

4.1.2 Wing Skin Temperatures

Wing skin temperatures were recorded on the leading edge at six positions on each wing at the runway threshold, with a hand-held temperature probe. Temperatures for Run 1, presented in degrees Celsius, are shown in Figure 4.2.

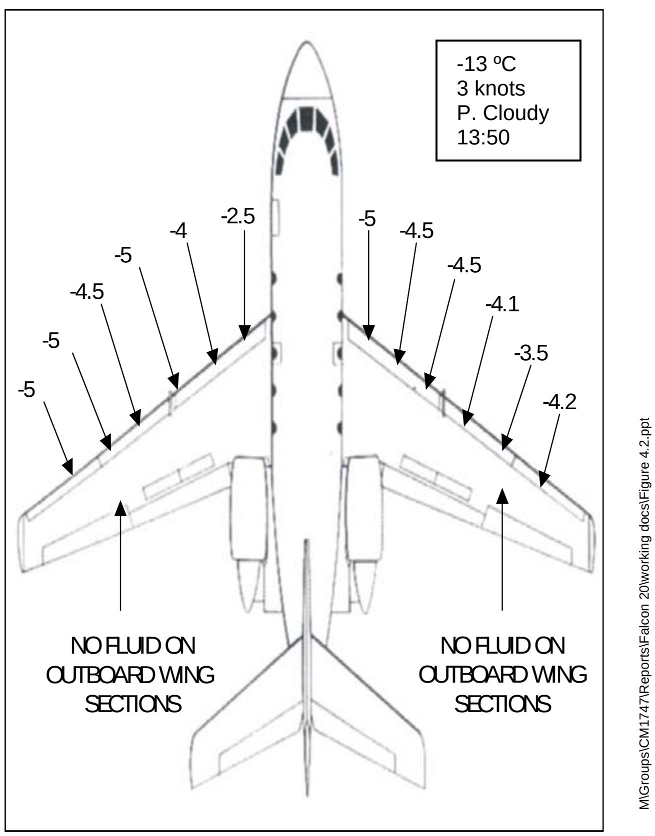

Figure 4.2: Wing Skin Temperatures for Run 1 (°C)

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -3.5°C to -5°C (see Figure 4.2). Temperatures at each of the outboard leading edge positions were taken directly on the wing surface, as no fluid was present at these locations. The ambient air temperature at the start of testing was -13°C, however the sky was partially cloudy and the wing temperatures warmed significantly due to solar radiation.

4.2 February 24, 2003 – Run 2: Type IV Ethylene Glycol; No Dilution

Run 2 was conducted with EG Type IV fluid sprayed entirely over both wing surfaces. The fluid was applied in neat concentration and was not further diluted. The objective of this test was to provide a clean EG fluid baseline for comparison with clean wing and diluted and contaminated fluid tests.

4.2.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at six positions on each wing at the runway threshold. Measurements for Run 2, recorded in millimeters, are shown in Figure 4.3. Fluid thickness ranged from 0.7 mm to 1.0 mm, and the coverage was similar on each wing.

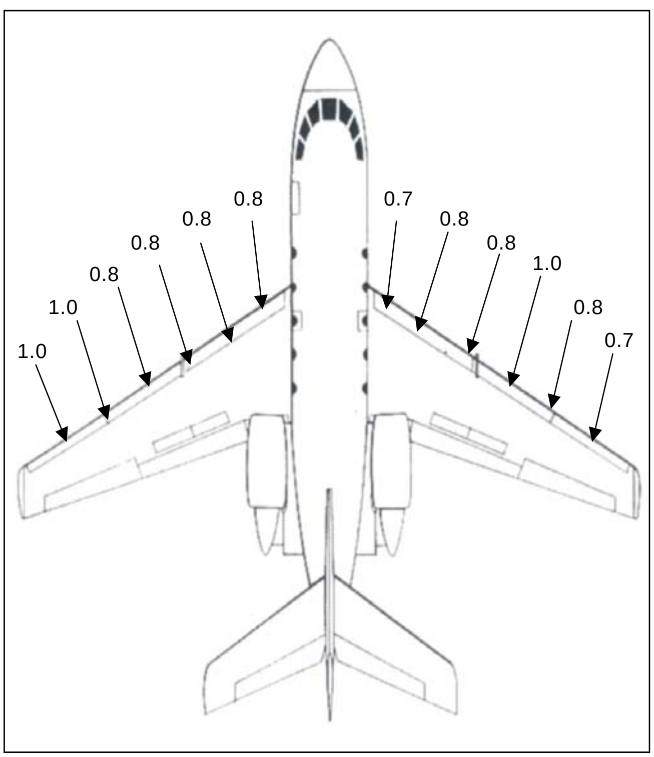

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Figure 4.3: Fluid Thickness Measurements for Run 2 (mm)

4.2.2 Wing Skin Temperatures

Wing skin temperatures were recorded on the leading edge at six positions on each wing at the threshold of Runway 25, just prior to takeoff. Temperatures for Run 2, presented in degrees Celsius, are shown in Figure 4.4.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -5.5°C to -7.5°C (see Figure 4.4). The ambient air temperature at the start of testing was again -13°C, however the sky was only partially cloudy and the wing temperatures warmed due to solar radiation.

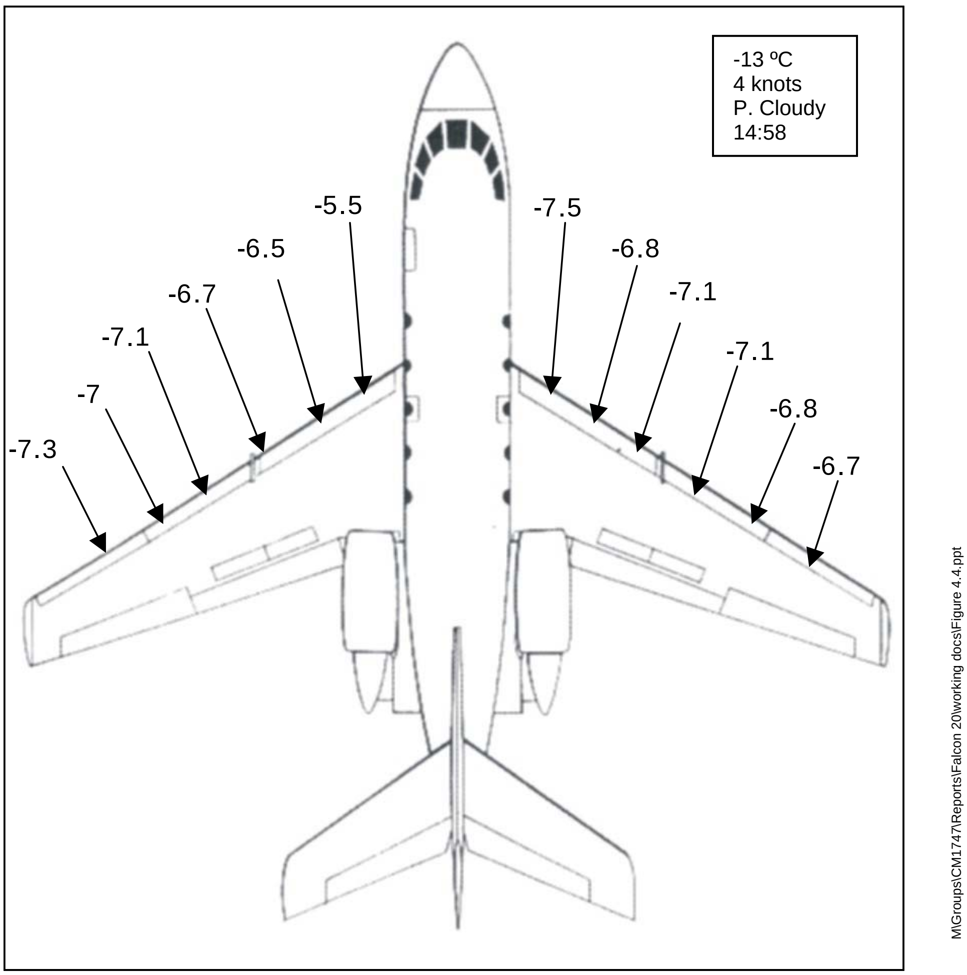

Figure 4.4: Wing Skin Temperatures for Run 2 (°C)

4.3 February 24, 2003 – Run 3: Type IV Ethylene Glycol; No Dilution

Run 3 was conducted with clean EG Type IV fluid sprayed entirely over both wing surfaces. The fluid was applied in neat concentration and was not further diluted. The objective of this test was to provide a clean EG fluid baseline for comparison with clean wing and diluted and contaminated fluid tests. Run 3 was a duplicate test of Run 2.

4.3.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded at the six pre-determined locations on each wing at the runway threshold. Measurements for Run 3, recorded in millimeters, are shown in Figure 4.5. Fluid thickness ranged from 0.7 mm to 1.0 mm, and the coverage was similar on each wing. Values recorded in Run 3 were very similar to those of Run 2.

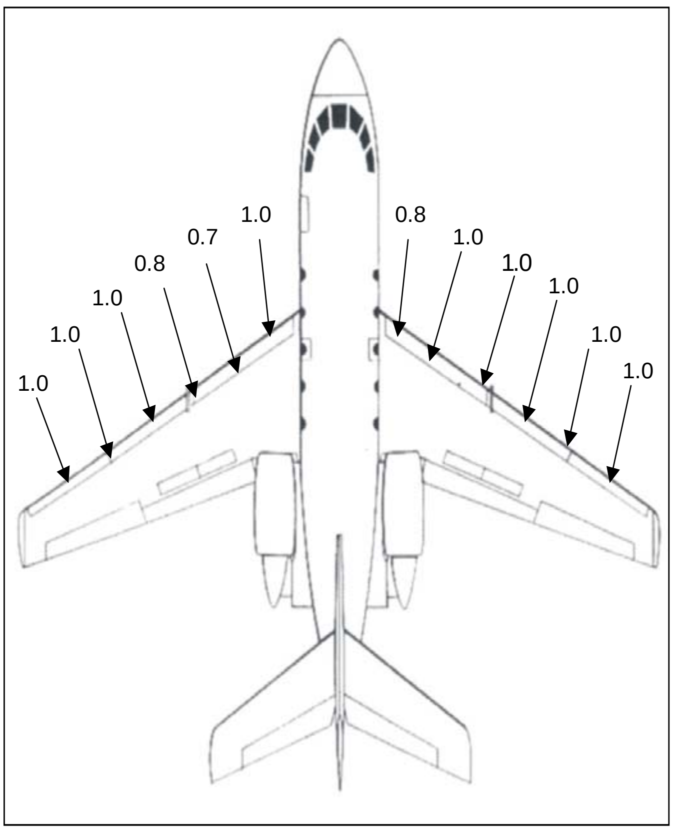

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Figure 4.5: Fluid Thickness Measurements for Run 3 (mm)

4.3.2 Wing Skin Temperatures

Wing skin temperatures were recorded at the six leading edge positions on each wing at the threshold of runway 25, just prior to takeoff, with a hand-held temperature probe. Temperatures for Run 3 are shown in Figure 4.6.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -8.3°C to -9.6°C (see Figure 4.6). The ambient air temperature at the start of Run 3 was again -13°C. The sky condition for Run 3 was reported as overcast, which contributed to lowering the wing skin temperatures closer to the ambient temperature. Despite having the same ambient test temperature (-13°C) as the two previous runs, the wing skin temperatures in Runs 1 and 2 were warmer due to the partially cloudy sky in those tests.

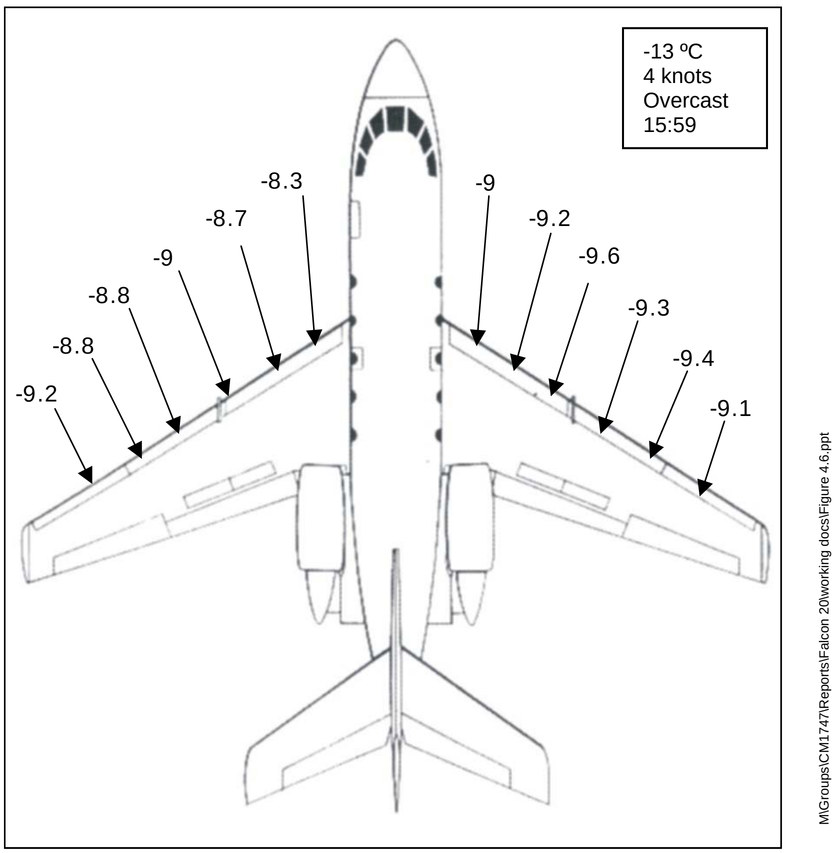

Figure 4.6: Wing Skin Temperatures for Run 3 (°C)

4.4 February 24, 2003 – Run 4: Type IV Ethylene Glycol; No Dilution; Clean Fluid on Outboard Wing Sections Only

Run 4 was conducted with clean EG Type IV fluid sprayed only on the wing sections outboard of the boundary layer fence. The fluid was applied in neat concentration and was not further diluted. The objective of this test was to determine the effect on lift of the localized fluid coverage.

4.4.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded at three positions on the outboard leading edge of each wing. Measurements for Run 4, presented in millimeters, are shown in Figure 4.7. Fluid thickness ranged from 0.8 mm to 1.0 mm and were of similar distribution on each wing.

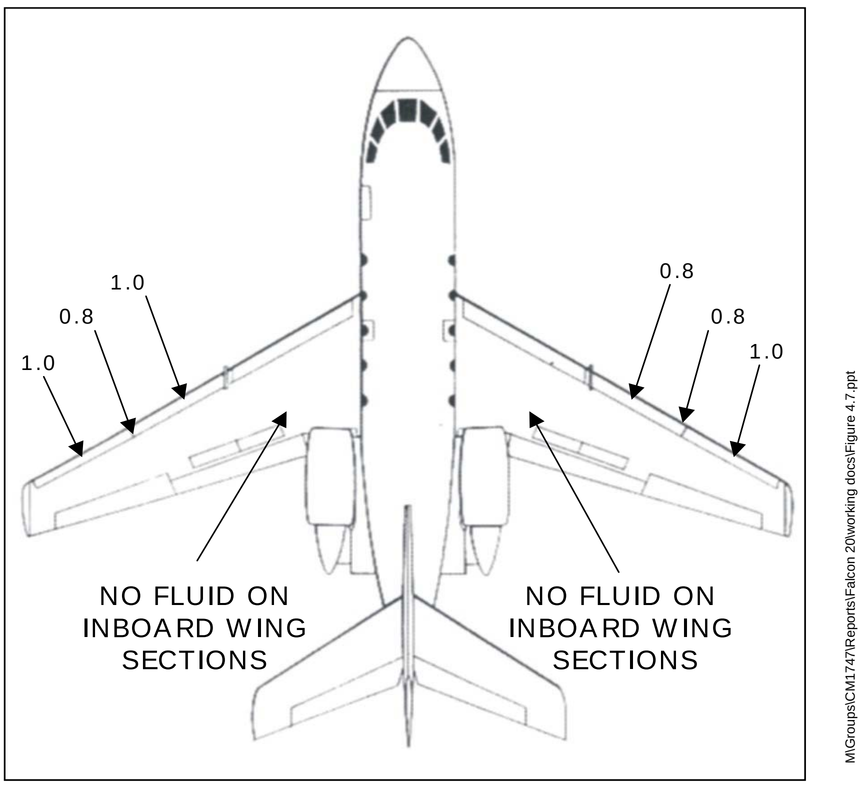

Figure 4.7: Fluid Thickness Measurements for Run 4 (mm)

4.4.2 Wing Skin Temperatures

Wing skin temperatures were recorded on the leading edge at the six pre-determined positions on each wing at the threshold of Runway 25, just prior to takeoff. Temperatures at each of the inboard leading edge positions were taken directly on the wing surface, as no fluid was present at these locations and were recorded with a hand-held temperature probe in degrees Celsius. Temperatures for Run 4 are shown in Figure 4.8.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -9.5°C to -11.5°C (see Figure 4.8). The ambient air temperature at the start of Run 4 was again -13°C. For this run, the sky was overcast and daylight was receding, which contributed to lowering the wing skin temperatures near the ambient temperature.

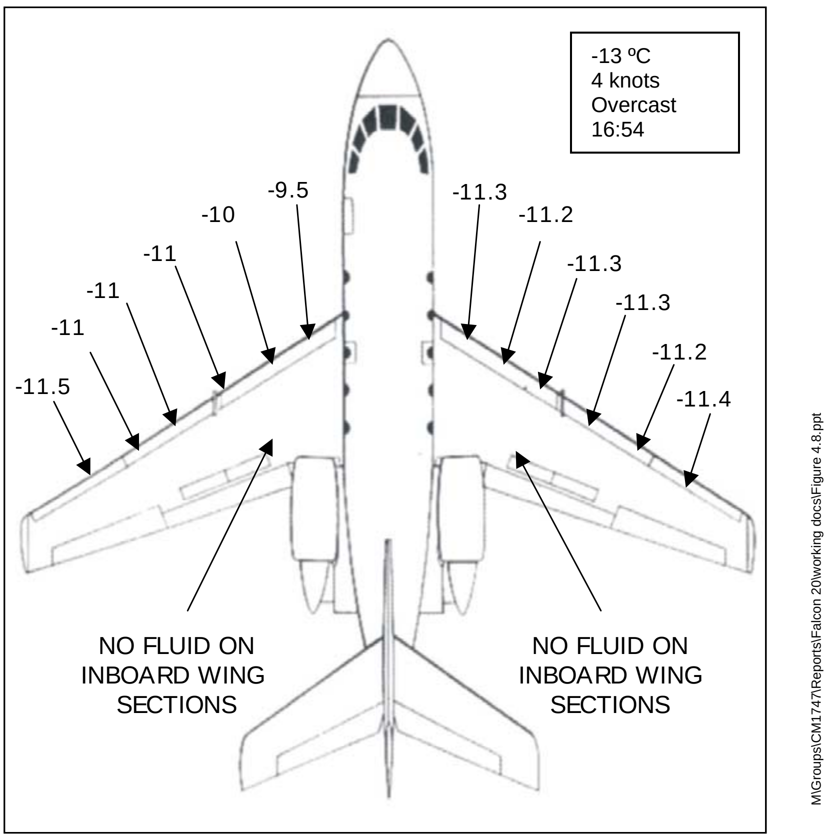

Figure 4.8: Wing Skin Temperatures for Run 4 (°C)

4.5 February 25, 2003 – Run 5: Type IV Propylene Glycol; No Dilution

Run 5 was conducted with clean PG Type IV fluid sprayed entirely over both wing surfaces. The fluid was applied in neat concentration and was not further diluted. The objective of this test was to provide a clean PG fluid baseline for comparison with clean wing and diluted and contaminated fluid tests.

4.5.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at the pre-determined positions on each wing at the runway threshold. Measurements for Run 5 are shown in Figure 4.9. Fluid thicknesses ranged from 0.4 mm to 0.7 mm, and were of similar distribution on each wing. The average thickness of the PG fluid on the leading edge just prior to takeoff was considerably lower than that observed in the tests with EG fluid.

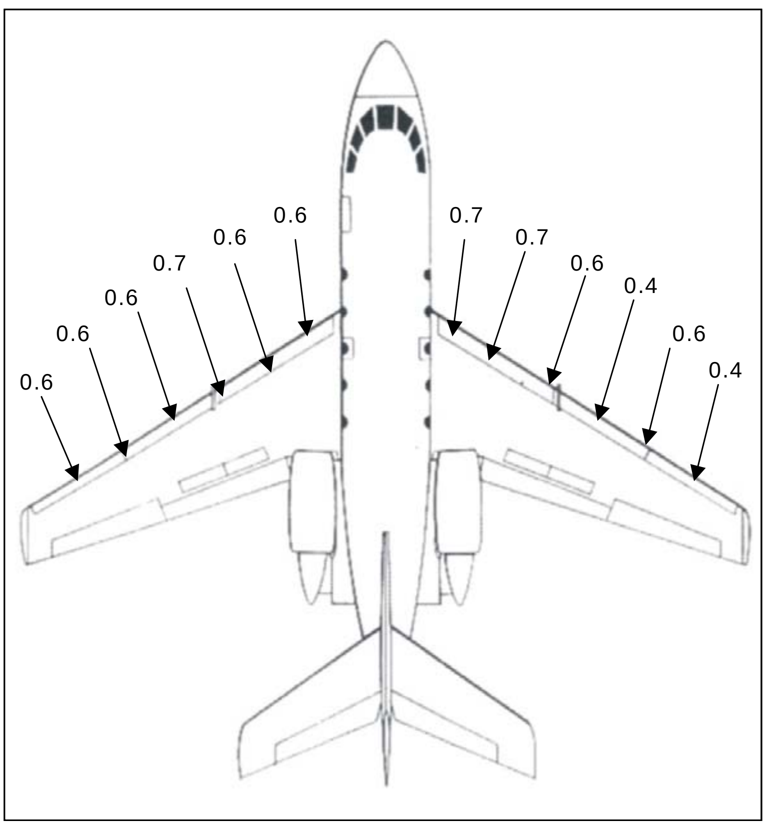

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Figure 4.9: Fluid Thickness Measurements for Run 5 (mm)

4.5.2 Wing Skin Temperatures

Wing skin temperatures were recorded at the six pre-determined leading edge positions on each wing at the threshold of Runway 25, just prior to takeoff, with a hand-held temperature probe. Temperatures for Run 5 are shown in Figure 4.10.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -6°C to -11.4°C on the port wing and -2.7°C to -4.2°C on the starboard wing (see Figure 4.10). The ambient air temperature at the start of testing was -20°C. For Run 5, the sky was clear and sun was shining brightly, which contributed to raising the skin temperatures of the aircraft well above ambient temperature. The port wing of the Falcon 20 was shaded from the sun during the fluid application and taxi phase of the test, which attributed for the colder skin temperatures on this wing, especially the wing section near the fuselage which was almost completely obscured from the sun.

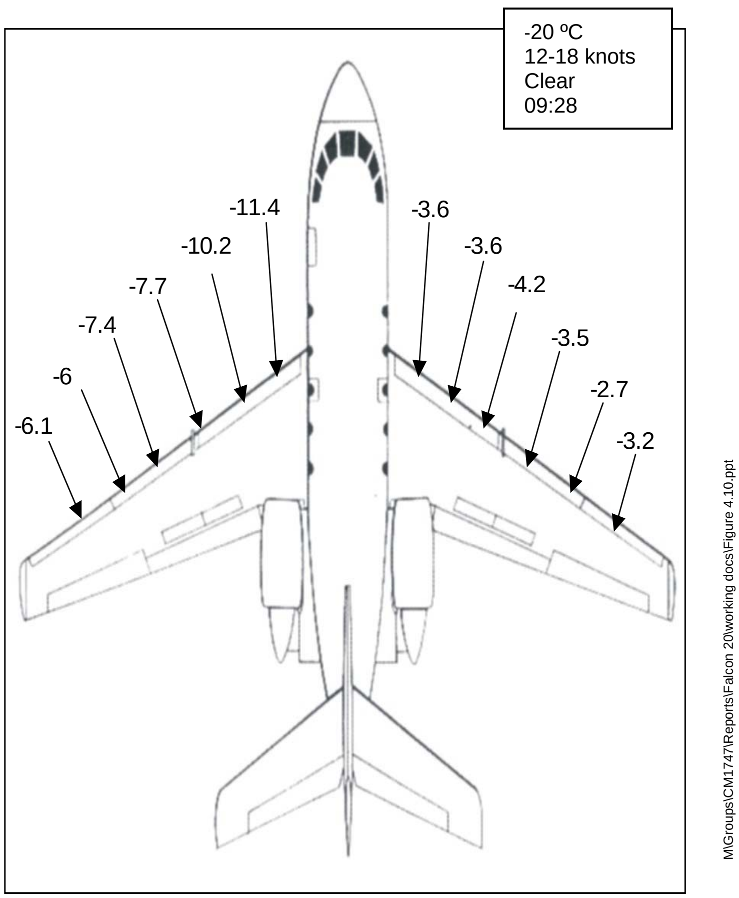

Figure 4.10: Wing Skin Temperatures for Run 5 (°C)

4.6 February 25, 2003 – Run 6: Type IV Propylene Glycol; No Dilution

Run 6 was conducted with clean PG Type IV fluid sprayed entirely over both wing surfaces. The fluid was applied in neat concentration and was not further diluted. The objective of this test was to provide a clean PG fluid baseline for comparison with clean wing and diluted and contaminated fluid tests. Run 6 was a duplicate test of Run 5.

4.6.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded at the six leading edge positions on each wing at the runway threshold. Measurements for Run 5 are shown in Figure 4.11. Fluid thicknesses ranged from 0.4 mm to 0.7 mm, and were of similar distribution on each wing.

Additional fluid thickness measurements were recorded at 18 locations on two chords of each wing during Run 6 and were performed to generate data for a separate project, the development of an ADMS model. Tests with EG fluid had been conducted in 2001-02 to support this project, and similar test data were required for PG fluid. The results of this test appear in Appendix F.

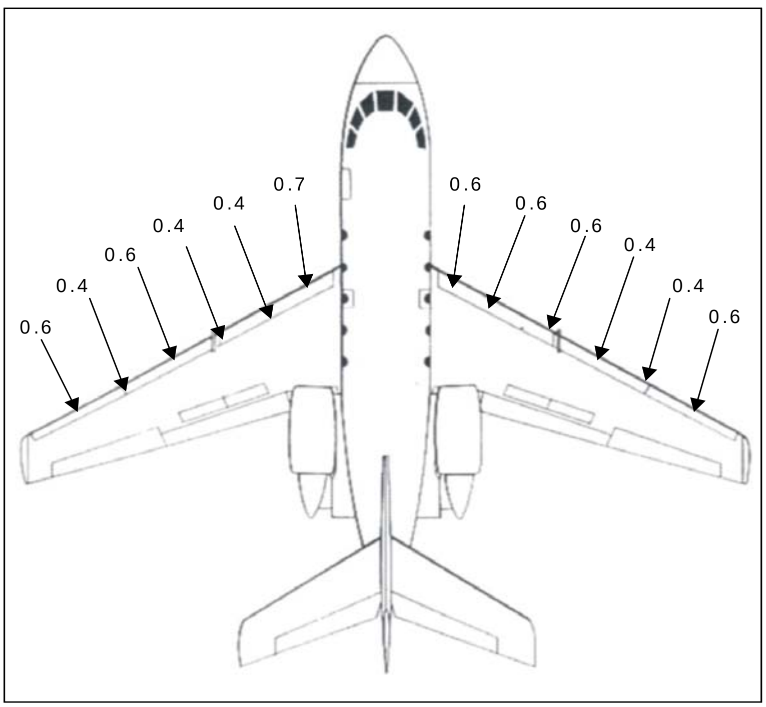

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Figure 4.11: Fluid Thickness Measurements for Run 6 (mm)

4.6.2 Wing Skin Temperatures

Wing skin temperatures were recorded at the six pre-determined leading edge positions on each wing at the threshold of Runway 32, just prior to the takeoff of the aircraft, with a hand-held temperature probe. Temperatures for Run 6 are shown in Figure 4.12.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -8.5°C to -10.3°C on the port wing and -14°C to -15.3°C on the starboard wing (see Figure 4.12). The ambient air temperature at the start of testing was again -20°C. For this run, the sky was clear and sun was shining brightly, which contributed to raising the skin temperatures of the aircraft well above ambient temperature. For this test, the aircraft was positioned into the wind at the NRC pad, shading the starboard wing from the sun during the fluid application process.

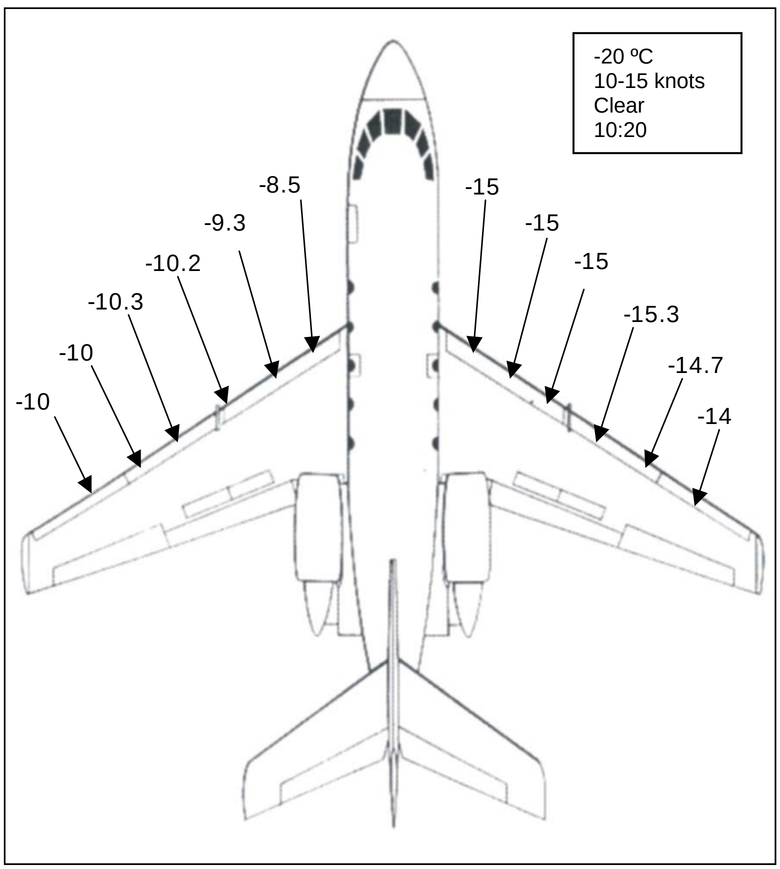

Figure 4.12: Wing Skin Temperatures for Run 6 (°C)

4.7 February 25, 2003 – Run 7: Type IV Propylene Glycol; No Dilution

Run 7 was conducted with clean PG Type IV fluid sprayed entirely over both wing surfaces. The fluid was applied in neat concentration and was not further diluted. The objective of this test was to provide a clean PG fluid baseline for comparison with clean wing and diluted and contaminated fluid tests. Run 7 was a duplicate test of Runs 5 and 6.

4.7.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at six positions on each wing prior to takeoff. Measurements for Run 7 are shown in Figure 4.13. Fluid thickness ranged from 0.3 mm to 0.6 mm on each wing. The six fluid thickness measurements on the starboard wing were all identical at 0.4 mm.

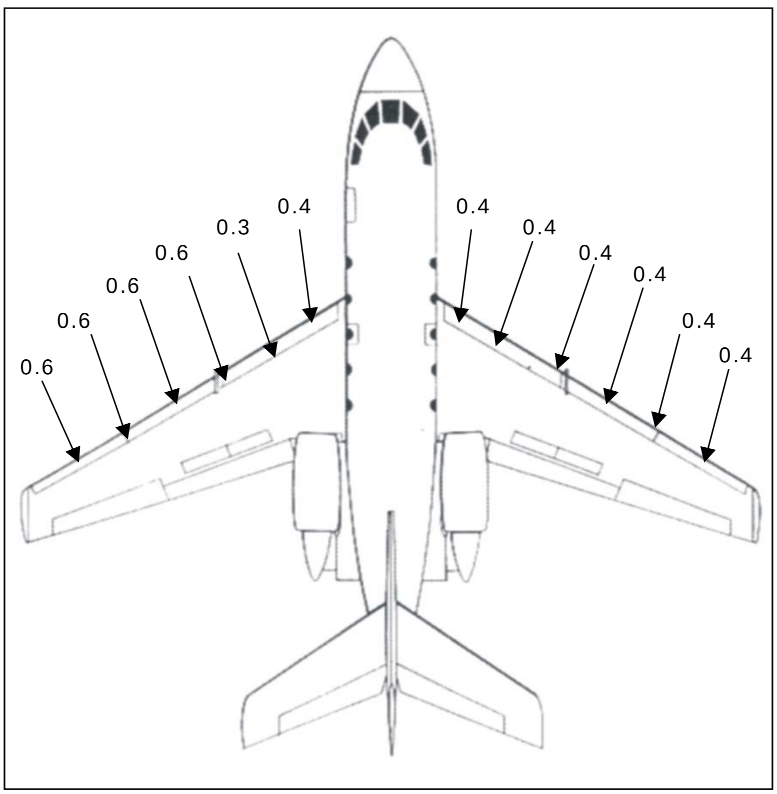

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Figure 4.13: Fluid Thickness Measurements for Run 7 (mm)

4.7.2 Wing Skin Temperatures

Wing skin temperatures were recorded at the threshold of Runway 32, just prior to takeoff, with a hand-held temperature probe. Temperatures for Run 7 are shown in Figure 4.14.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -6.2°C to -7.8°C on the port wing and -11.7°C to -13.7°C on the starboard wing (see Figure 4.14). The ambient air temperature at the start of testing was -18°C. For this run, the sky was clear and sun was shining brightly, which contributed to raising the skin temperatures of the aircraft well above ambient temperature. For this test, the aircraft was positioned into the wind at the NRC pad, shading the starboard wing from the sun during the fluid application process.

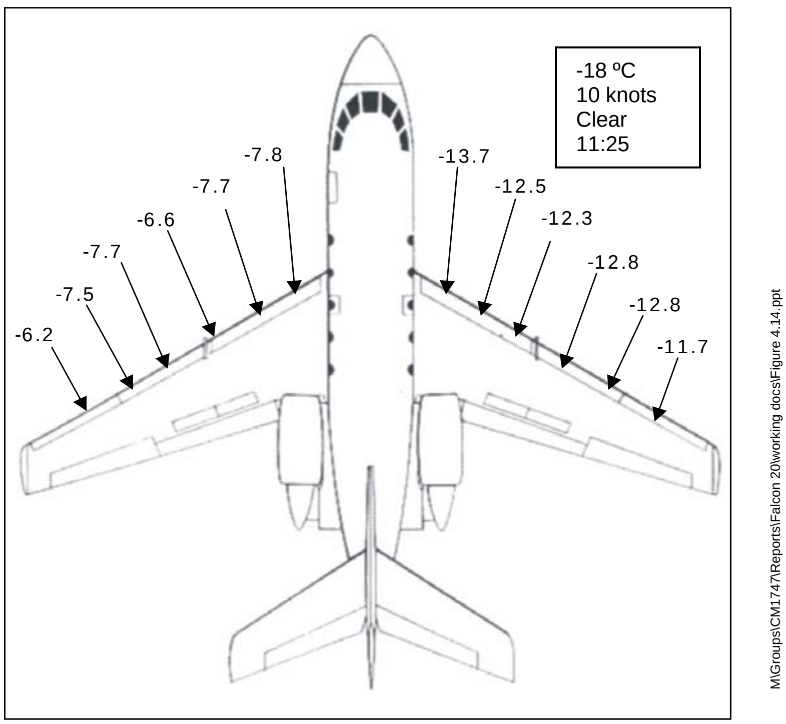

Figure 4.14: Wing Skin Temperatures for Run 7 (°C)

4.8 February 25, 2003 – Run 8: Residual Type IV Propylene Glycol from Run 7; No Dilution

After the Falcon 20 had landed from Run 7, the aircraft exited the arrival runway and taxied back to the departure runway. The PG anti-icing fluid present on the wings at the beginning of the takeoff roll in Run 7 was largely removed due to shear forces exerted on the fluid. A very thin film of fluid remained on the wing after the aircraft landed. The objective of this test was to examine the effect of the residual PG fluid on the lift generated by the aircraft.

4.8.1 Fluid Thickness Measurements

Fluid thickness measurements were not recorded for Run 8, as the aircraft merely taxied into position on the departure runway following Run 7 (see Figure 4.15). Residual fluid could be seen on the wings of the aircraft following Run 7. A very thin film of fluid remained. Tests were previously conducted to measure the thickness of the residual fluid. In most cases, the residual fluid thickness was immeasurable (less than 0.1 mm). Some pooling of fluid was observed on and around the trailing edge control surfaces. This fluid generally measures between 0.1 and 0.3 mm.

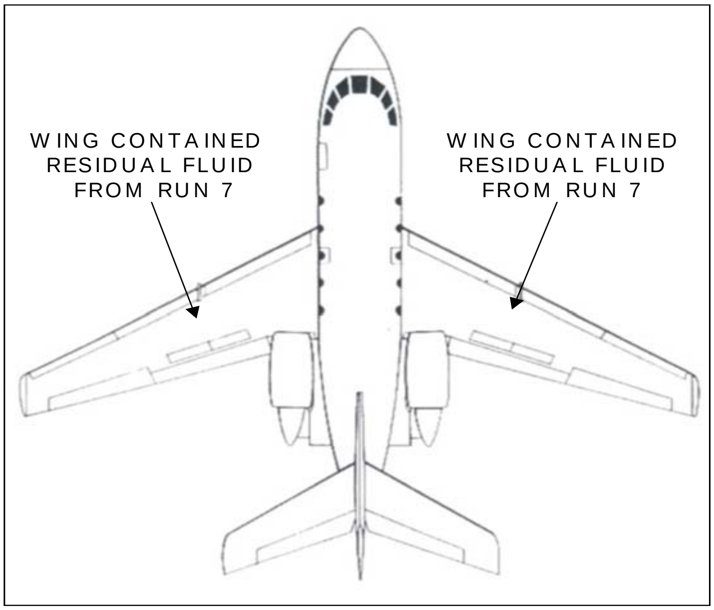

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Figure 4.15: Fluid Thickness Measurements for Run 8 (mm)

4.8.2 Wing Skin Temperatures

Wing skin temperatures were not recorded prior to the departure of the aircraft for Run 8.

4.9 February 26, 2003 – Run 9: Type IV Propylene Glycol; Light Freezing Rain Applied

Run 9 was conducted with PG Type IV fluid. The fluid was applied to both wings of the aircraft in neat concentration and was diluted with light freezing rain until the fluid had reached the onset of failure. The objective of this test was to examine the effects of the diluted PG Type IV on the lift generated by the Falcon 20.

4.9.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at six positions on each wing at the runway threshold. Measurements for Run 9 are shown in Figure 4.16. Fluid thicknesses on each wing ranged from 0.6 mm to 1.1 mm and were of similar distribution on both wings. These thickness values were higher than those observed in previous tests with the undiluted propylene glycol Type IV. This can be explained by the formulation of the Kilfrost ABC-S fluid, which readily accepts water, increasing in thickness and viscosity until a certain dilution has been attained, at which point it begins to decrease in thickness and viscosity.

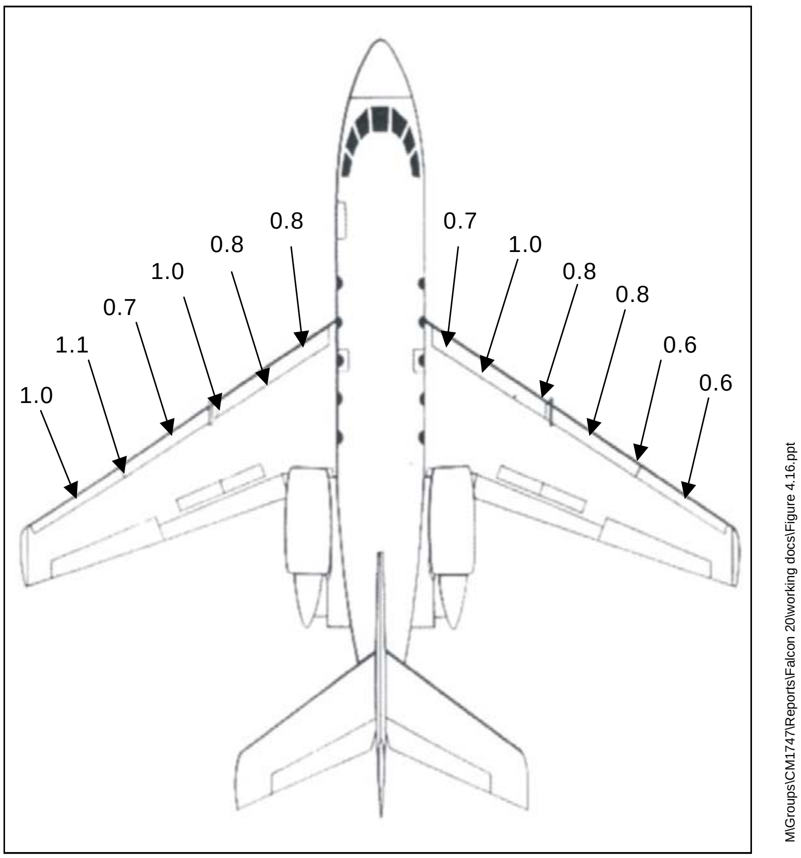

Figure 4.16: Fluid Thickness Measurements for Run 9 (mm)

4.9.2 Wing Skin Temperatures

Wing skin temperatures were recorded on the leading edge at six positions on each wing just prior to takeoff, with a hand-held temperature probe. Temperatures for Run 9 are shown in Figure 4.17.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -12°C to -14.8°C on the port wing and -9.5°C to -10.9°C on the starboard wing (see Figure 4.17). The ambient air temperature at the start of testing was -23°C. For this run, the sky was clear and sun was shining brightly, which contributed to raising the skin temperatures of the aircraft well above ambient temperature. For this test, the starboard wing obtained more exposure to sunlight and thus had warmer skin temperatures.

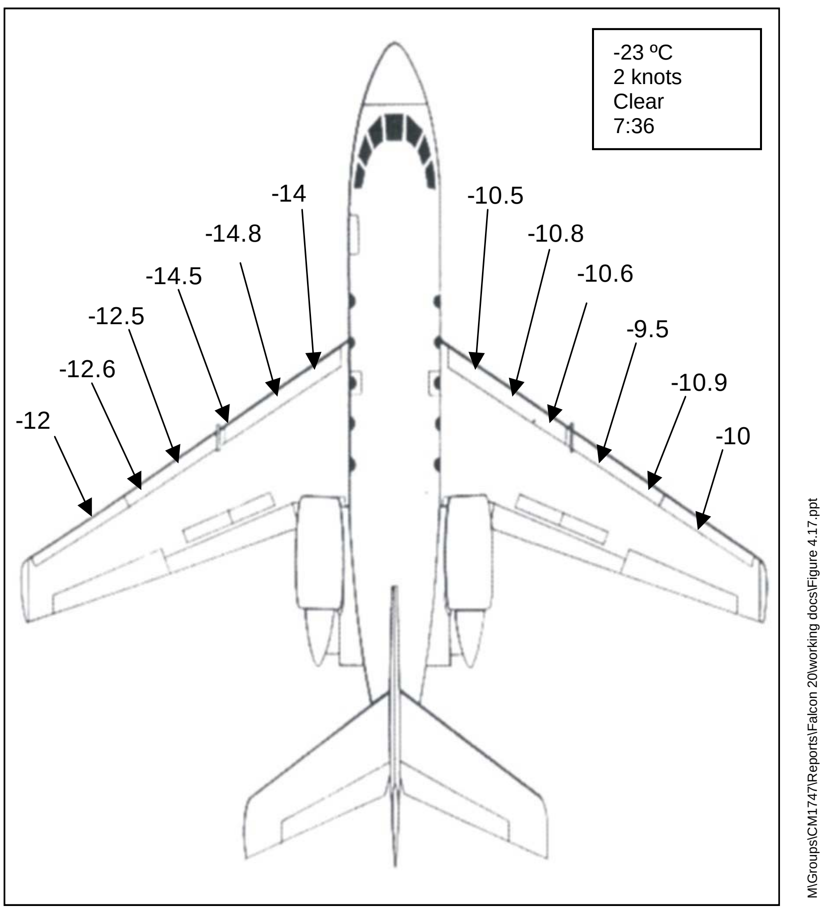

Figure 4.17: Wing Skin Temperatures for Run 9 (°C)

4.9.3 Fluid Freezing Points

Light freezing rain was applied to the fluid covering the wings of the Falcon 20 during Run 9. Fluid freezing points were measured with hand-held refractometers during the application of the light freezing rain to ensure that the ideal condition of the fluid was obtained for each test. The desired condition of the fluid was on the onset of fluid failure. Fluid freezing points were measured at 5-minute intervals at various wing locations during the application of the light freezing rain, and then again at the six leading edge locations on each wing at the threshold of the departure runway, prior to the takeoff of the aircraft. The fluid freezing points were read directly of the refractometer (in °Brix) and the converted to a freezing point in degrees Celsius using the conversion chart included in Table 3.2 for Kilfrost ABC-S fluid. The freezing points of the Kilfrost ABC-S fluid on the wings of the Falcon 20 at the departure runway are shown in Figure 4.18.

At the threshold of the departure runway, ice embedded within the fluid was observed at several locations on the trailing edges of both wings. As the ambient temperature was -23°C at the runway threshold, the freezing point buffer of the fluid on the leading edge ranged from 3° to 12°C. In all cases, the ice was not adhering to the wing surfaces. This is a typical failure mechanism of Kilfrost ABC-S fluid at this temperature.

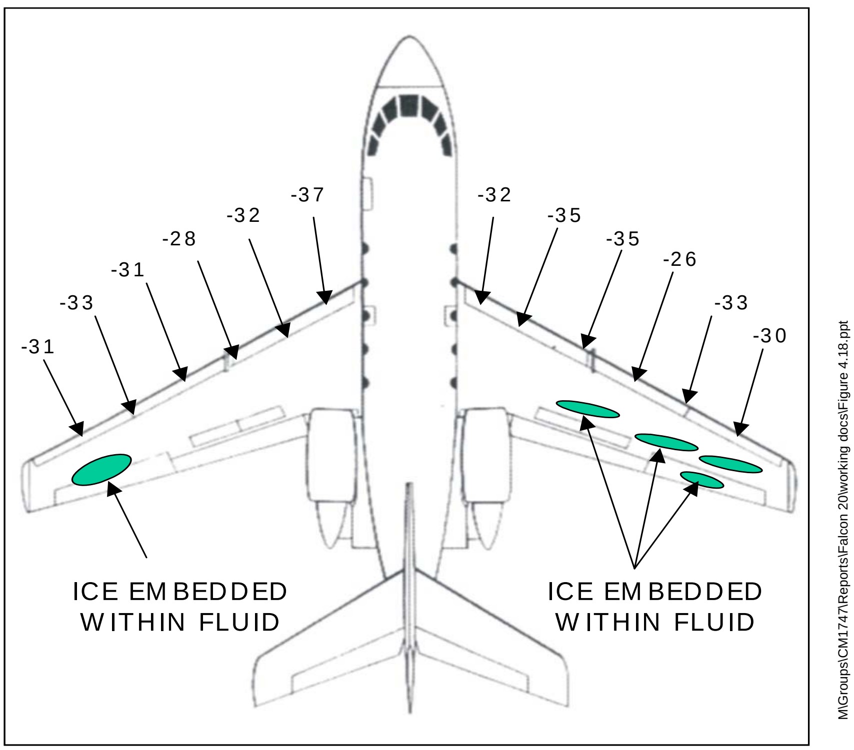

Figure 4.18: Fluid Freezing Points for Run 9 (°C)

4.10 February 26, 2003 – Run 10: Type IV Propylene Glycol; Light Freezing Rain Applied

Run 10 was conducted with PG Type IV fluid. The fluid was applied to both wings of the aircraft in neat concentration and was diluted with light freezing rain until the fluid had reached the onset of failure. The objective of this test was to examine the effects of the diluted PG Type IV on the lift generated by the Falcon 20. Run 10 was a duplicate of Run 9.

4.10.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at six positions on each wing at the runway threshold. Measurements for Run 10 are shown in Figure 4.19. Fluid thicknesses on each wing ranged from 0.4 mm to 1.0 mm, and were of similar distribution on both wings.

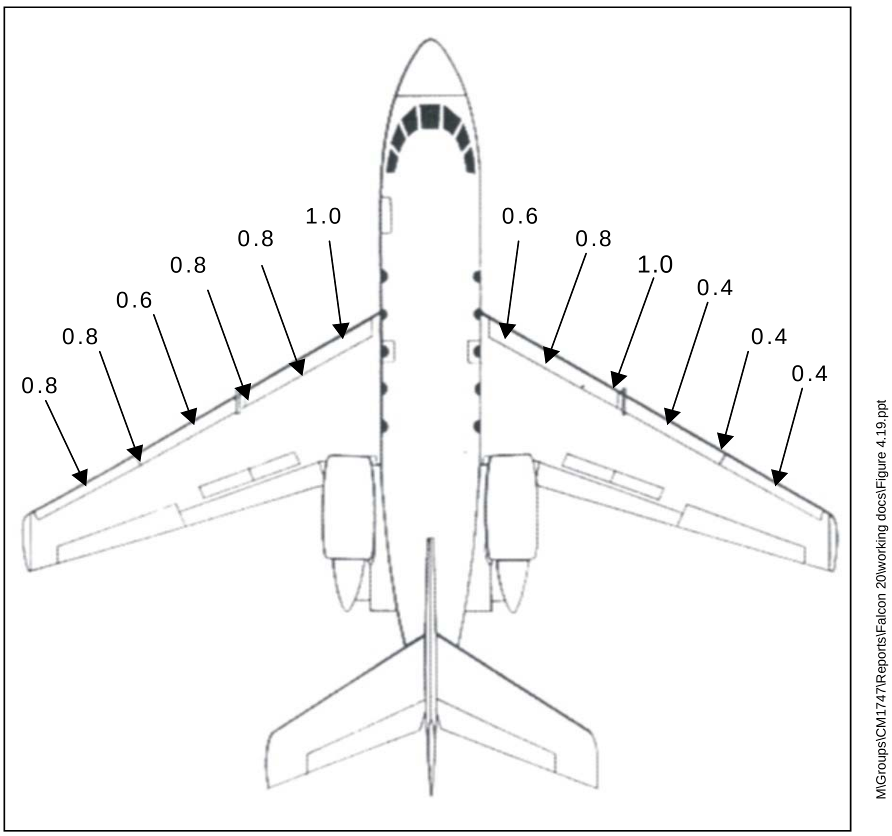

Figure 4.19: Fluid Thickness Measurements for Run 10 (mm)

4.10.2 Wing Skin Temperatures

Wing skin temperatures were recorded on the leading edge at six positions on each wing at the threshold of Runway 25, just prior to takeoff. Temperatures for Run 10 are shown in Figure 4.20.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -8.5°C to -12.3°C on the port wing and 0.3°C to -3°C on the starboard wing (see Figure 4.20). The ambient air temperature at the start of testing was -23°C. For this run, the sky was clear and sun was shining brightly, which contributed to raising the skin temperatures of the aircraft well above ambient temperature. For this test, the port wing was shaded during the application of the light freezing rain.

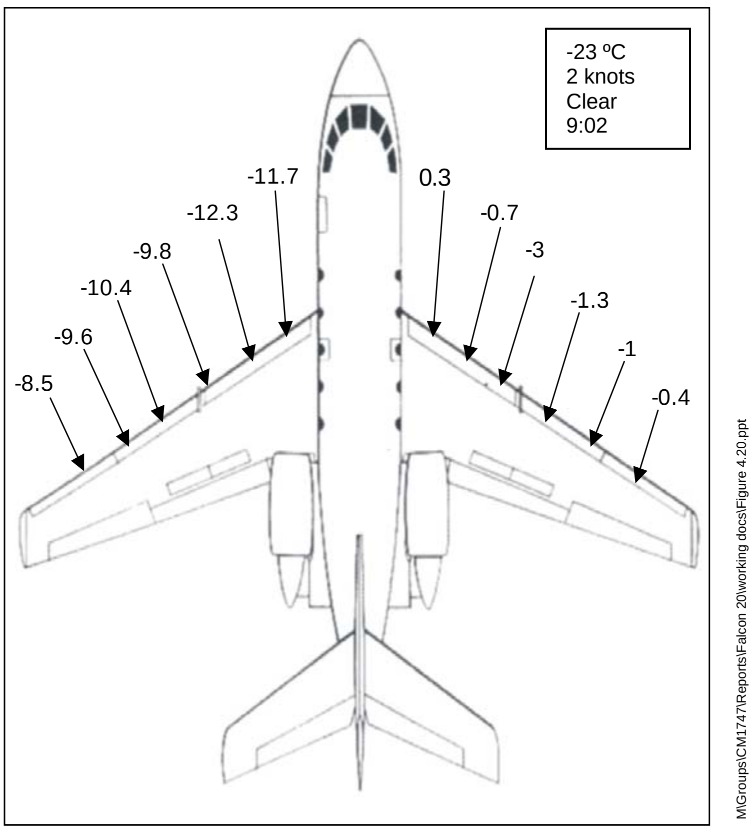

Figure 4.20: Wing Skin Temperatures for Run 10 (°C)

4.10.3 Fluid Freezing Points

Light freezing rain was applied to the fluid covering the wings of the Falcon 20 during Run 10. Fluid freezing points were measured with hand-held refractometers during the application of the light freezing rain to ensure that the ideal condition of the fluid was obtained for each test. The desired condition of the fluid was on the onset of fluid failure. Fluid freezing points were recorded at the six leading edge locations on each wing at the threshold of the departure runway, prior to the takeoff of the aircraft. The fluid freezing points were read directly off the refractometer (in °Brix) and converted to a freezing point in degrees Celsius using the conversion chart included in Table 3.2 for Kilfrost ABC-S fluid. The freezing points of the Kilfrost ABC-S fluid on the wings of the Falcon 20 at the departure runway are shown in Figure 4.21.

In Run 10, the PG anti-icing fluid was exposed to light freezing rain for 23 to 28 minutes. At the runway threshold, the freezing points of the fluid on the leading edge ranged from -20°C to -33°C. As the ambient temperature was -23°C, it would have been expected that leading edge ice would have been present on the aircraft. This was not the case, however, as the wing surface temperatures were much warmer than the ambient temperature. Ice was embedded within the fluid at several trailing edge and mid-chord locations. No ice was adhering to the wing surface.

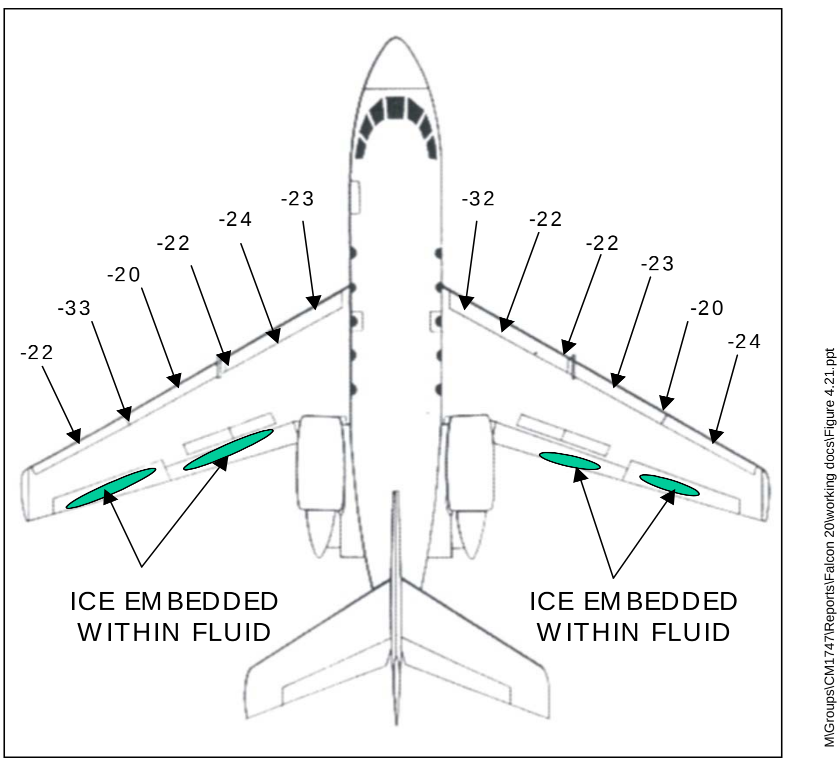

Figure 4.21: Fluid Freezing Points for Run 10 (°C)

4.11 February 26, 2003 – Run 11: Type IV Ethylene Glycol; Light Freezing Rain Applied

Run 11 was conducted with EG Type IV fluid. The fluid was applied to both wings of the aircraft in Neat concentration and was diluted with light freezing rain until the fluid had reached the onset of failure. The objective of this test was to examine the effects of the diluted EG Type IV on the lift generated by the Falcon 20.

4.11.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at six positions on each wing at the runway threshold. Measurements for Run 11 are shown in Figure 4.22. Fluid thicknesses at the six leading edge positions on each wing ranged from 0.4 mm to 0.6 mm, and were of similar distribution on both wings. These values were lower than those seen in previous tests with undiluted ethylene glycol Type IV. This can be explained by the formulation of the Dow Ultra+ fluid, which readily dilutes under precipitation, eroding the thickness of the fluid layer until ice begins to form on the surface of the wing.

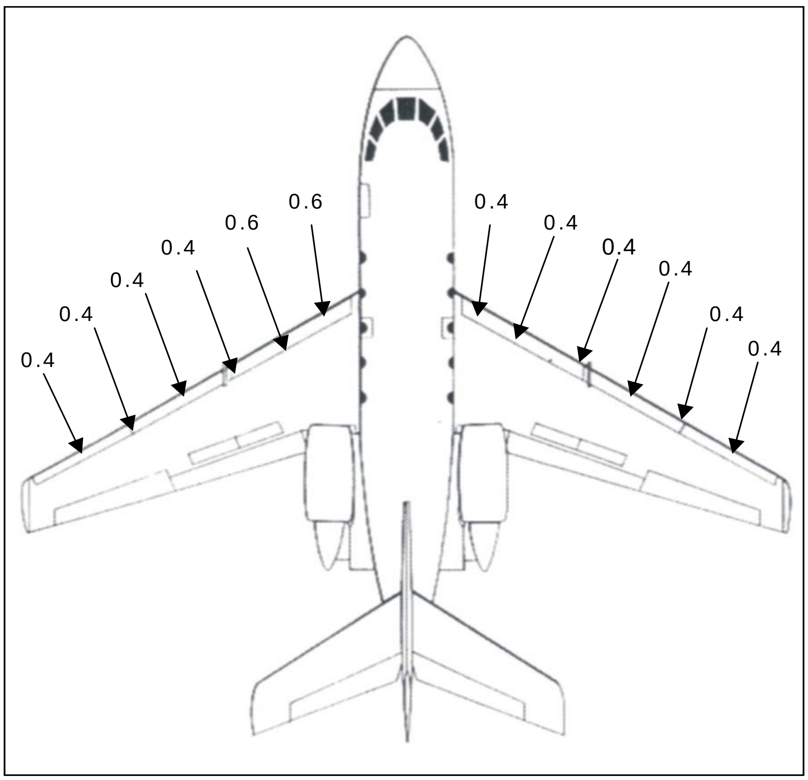

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Figure 4.22: Fluid Thickness Measurements for Run 11 (mm)

4.11.2 Wing Skin Temperatures

Wing skin temperatures were recorded on the leading edge at six positions on each wing at the threshold of Runway 25, just prior to takeoff. Temperatures for Run 11 are shown in Figure 4.23.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -3.9°C to -11.2°C on the port wing and 3.3°C to 6.9°C on the starboard wing (see Figure 4.23). The ambient air temperature, recorded just prior to the departure of the aircraft was -15°C. For this run, the sky was clear and sun was shining brightly, which contributed to increasing the skin temperatures of the aircraft well above ambient temperature. For this test, the port wing was shaded during the application of the light freezing rain, while the starboard wing was exposed to the bright sun.

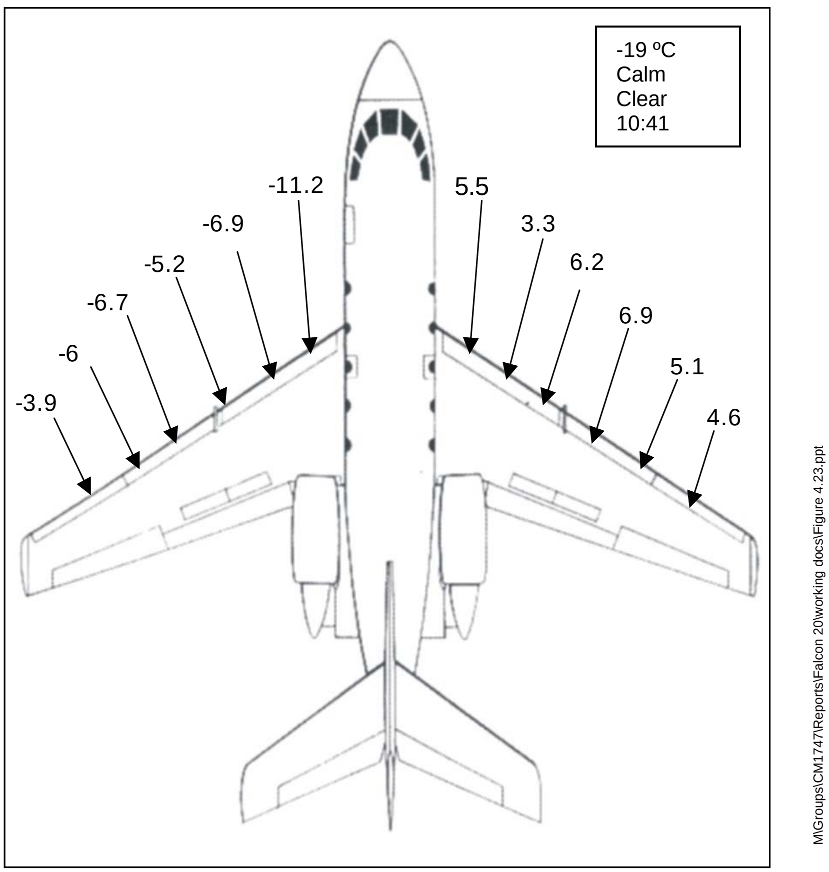

Figure 4.23: Wing Skin Temperatures for Run 11 (°C)

4.11.3 Fluid Freezing Points

Light freezing rain was applied to the fluid covering the wings of the Falcon 20 during Run 11. Fluid freezing points were measured with hand-held refractometers during the application of the light freezing rain to ensure that the ideal condition of the fluid was obtained for each test. The desired condition of the fluid was determined to be the onset of failure. Once the desired fluid freezing point was attained, the light freezing rain was halted and the aircraft was taxied to the departure runway. At the threshold of the departure runway, fluid freezing points were recorded at the 6 leading edge locations on each wing, prior to the takeoff of the aircraft. The fluid freezing points were read directly off the refractometer (in °Brix) and converted to a freezing point in degrees Celsius using the conversion chart included in Figure 3.1 for Dow Ultra+ fluid. The freezing points of the Dow Ultra+ fluid on the wings of the Falcon 20 at the departure runway are shown in Figure 4.24.

The only locations that had ice adhering to the wing were located on the leading edge of the port wing. Fluid at this location also had the highest freezing point at -9°C. The ambient temperature for this test was -15°C. All other leading edge locations contained fluid with freezing points well below the ambient temperature.

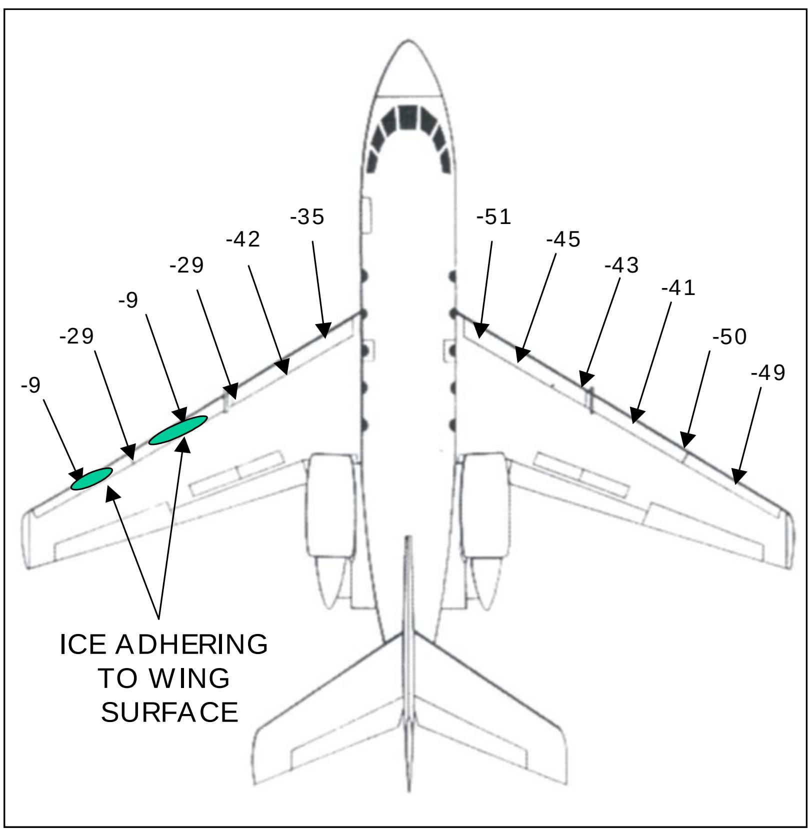

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Figure 4.24: Fluid Freezing Points for Run 11 (°C)

4.12 February 26, 2003 – Run 12: Residual Type IV Ethylene Glycol from Run 11; No Dilution

After the Falcon 20 landed from Run 11, the aircraft exited the arrival runway and taxied back to the departure runway. The EG anti-icing fluid present on the wings at the beginning of the takeoff roll in Run 11 was largely removed due to shear forces exerted on the fluid. A very thin film of fluid remained on the wing after the aircraft landed. The objective of this test was to examine the effect of residual EG fluid on the lift generated by the aircraft.

4.12.1 Fluid Thickness Measurements

Fluid thickness measurements were not recorded for Run 12, as the aircraft merely taxied into position on the departure runway following Run 11 (see Figure 4.25). Residual fluid could be observed on the wings of the aircraft from inside the cabin.

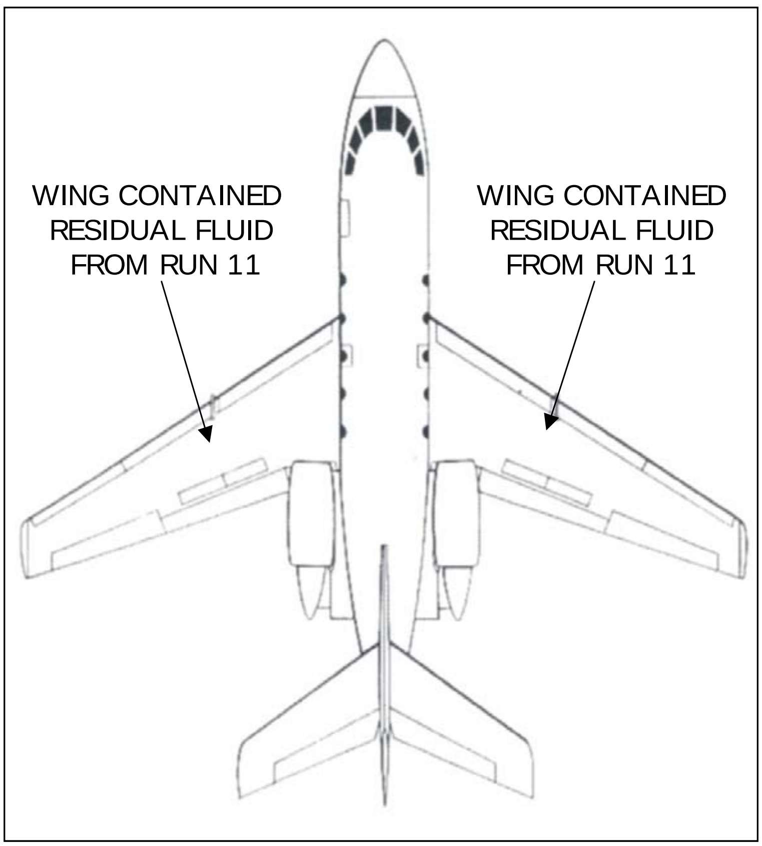

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Figure 4.25: Fluid Thickness Measurements for Run 12 (mm)

4.12.2 Wing Skin Temperatures

Wing skin temperatures were not recorded prior to the departure of the aircraft for Run 12.

4.12.3 Fluid Freezing Points

Run 12 was flown with residual fluid from Run 11 on the wings of the Falcon 20. As only residual fluid remained on the aircraft, no fluid freezing point measurements were recorded prior to the takeoff in Run 12. A quick external examination of the wings was performed prior to the takeoff at the runway threshold. A very small quantity of ice from Run 11, located on the leading edge of the aircraft outside of the boundary layer fence, was still adhering to the leading edge surface. The location of the ice is shown in Figure 4.26. The ice was not present when the aircraft returned to the NRC apron after Run 12, removed entirely by the second takeoff and flight.

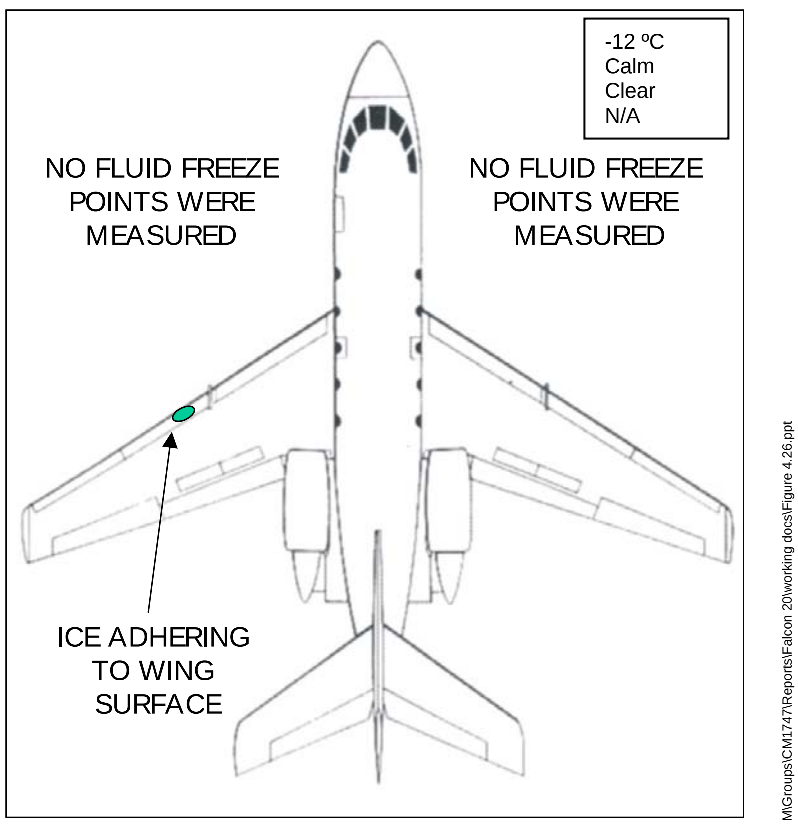

Figure 4.26: Location of Adhering Ice for Run 12 (°C)

4.13 February 26, 2003 – Run 13: Type IV Ethylene Glycol; Light Freezing Rain Applied

Run 13 was conducted with EG Type IV fluid. The fluid was applied to both wings of the aircraft in neat concentration and was diluted with light freezing rain until the fluid had reached the onset of failure. The objective of this test was to examine the effects of the diluted EG Type IV on the lift generated by the Falcon 20. Run 13 was a duplicate test of Run 11.

4.13.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at six positions on each wing at the runway threshold. Measurements for Run 13 are shown in Figure 4.27. Fluid thicknesses at the six leading edge positions on each wing ranged from 0.3 mm to 0.6 mm, and were of similar distribution on both wings. These values are lower than those seen in previous tests with undiluted ethylene glycol Type IV. This can be explained by the formulation of the Dow Ultra+ fluid, which readily dilutes under precipitation, eroding the thickness of the fluid layer until ice begins to form on the surface of the wing.

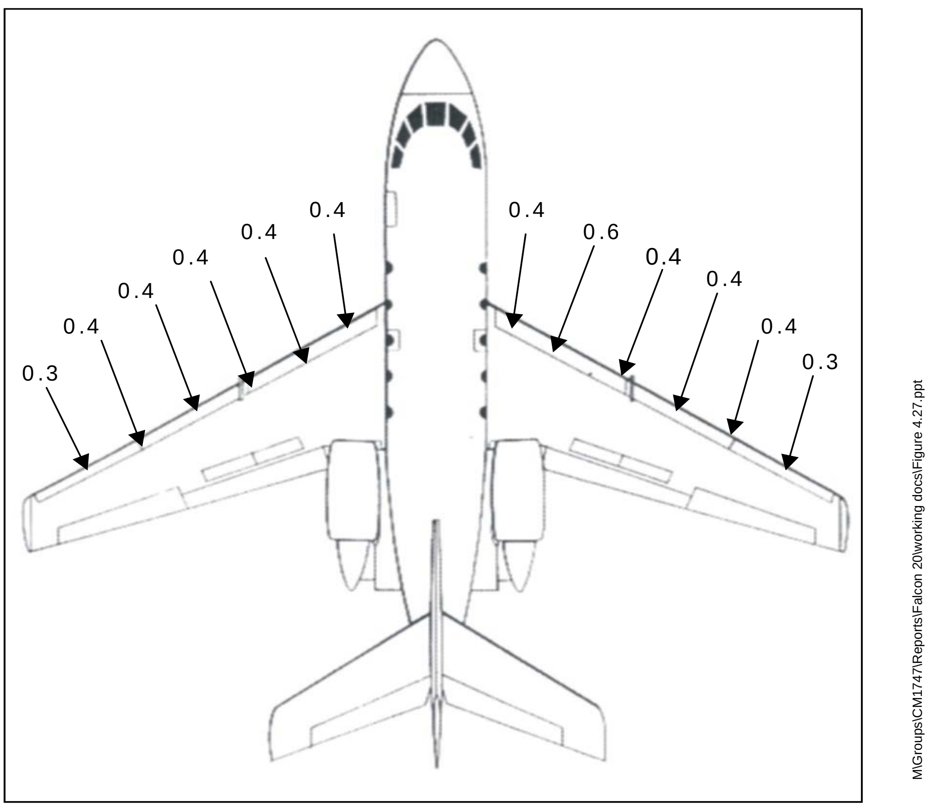

Figure 4.27: Fluid Thickness Measurements for Run 13 (mm)

4.13.2 Wing Skin Temperatures

Wing skin temperatures were recorded on the leading edge at six positions on each wing at the threshold of Runway 32, just prior to takeoff, with a hand-held temperature probe. Temperatures for Run 13 are shown in Figure 4.28.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged from -11.6 to -12.6°C on both wings of the falcon 20 (see Figure 4.28). The ambient air temperature, recorded just prior to the departure of the aircraft from the NRC apron was -12°C. For this run, the sky was clear but due to the late hour of the afternoon, the sun had almost completely set, which contributed to lowering the skin temperatures of the aircraft to the ambient temperature.

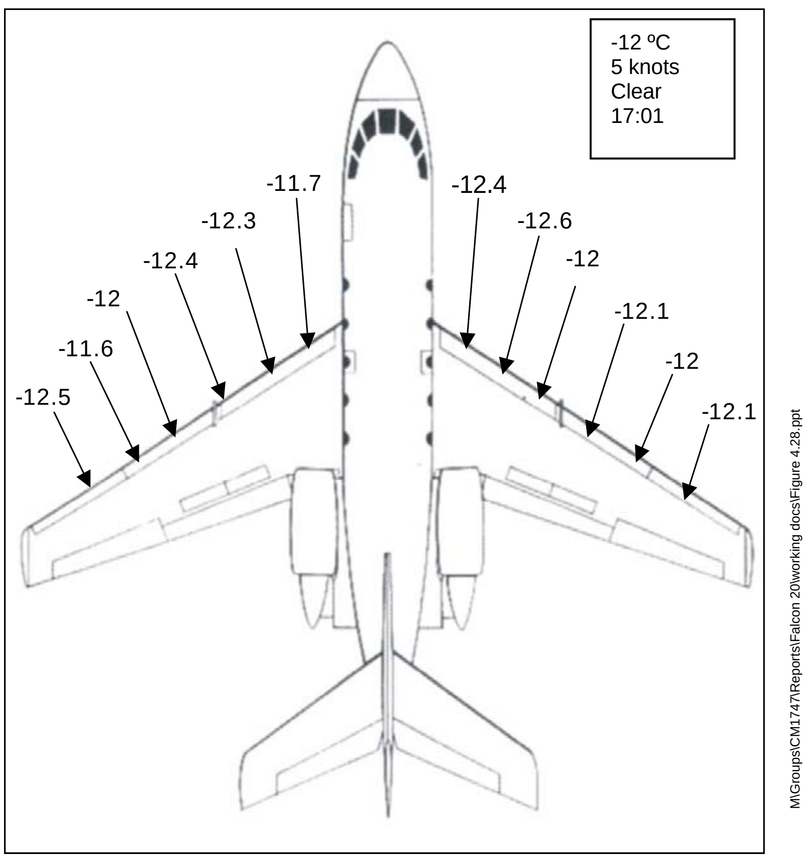

Figure 4.28: Wing Skin Temperatures for Run 13 (°C)

4.13.3 Fluid Freezing Points

Fluid freezing points were measured with hand-held refractometers during the application of the light freezing rain to ensure that the ideal condition of the fluid was obtained for each test. The desired condition of the fluid was determined to be the onset of failure.

Once the desired fluid freezing point was attained, the light freezing rain was halted and the aircraft was taxied to the departure runway. At the threshold of the departure runway, fluid freezing points were recorded at the 6 leading edge locations on each wing, prior to the takeoff of the aircraft. The fluid freezing points were read directly off the refractometer (in °Brix) and converted to a freezing point in degrees Celsius using the conversion chart included in Figure 3.1 for Dow Ultra+ fluid. The freezing points (in °C) of the Dow Ultra+ fluid on the wings of the Falcon 20 at the departure runway are shown in Figure 4.29.

The only location that had ice adhering to the wing was located on the leading edge of the port wing. Fluid at this location also had the warmest freezing point at -10°C. The ambient temperature for this test was -12°C.

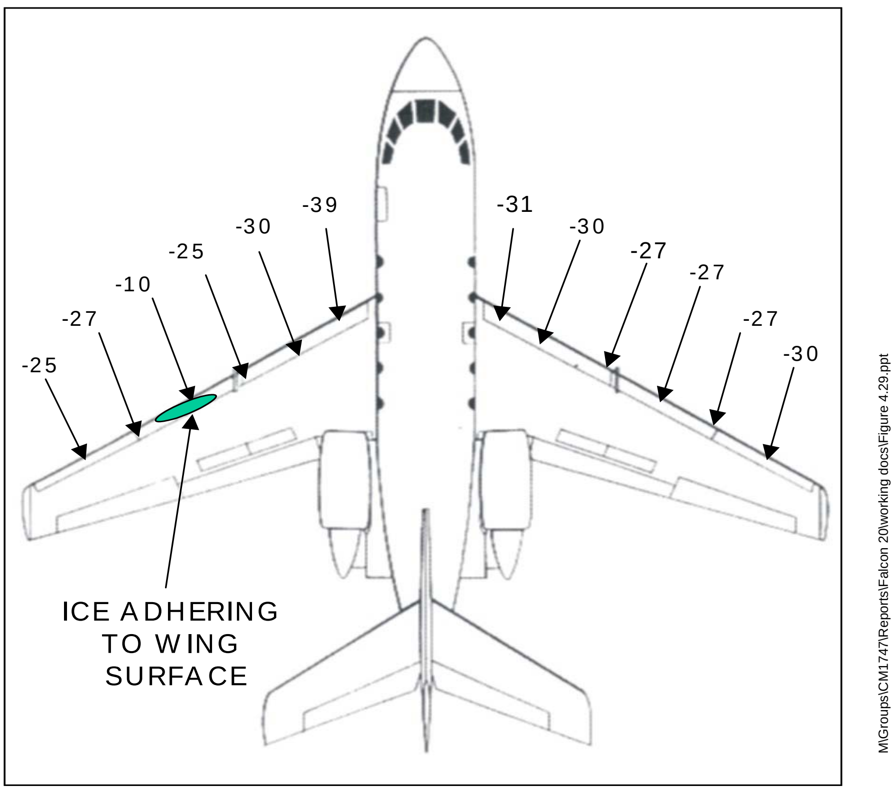

Figure 4.29: Fluid Freezing Points for Run 13 (°C)

4.14 February 27, 2003 – Run 14: Type IV Ethylene Glycol; Pre-Diluted Fluid (-23°C Freezing Point)

Run 14 was conducted with EG Type IV fluid. The fluid was applied to both wings of the aircraft pre-diluted to a freezing point of -23°C. The objective of this test was to examine the effects of the pre-diluted EG Type IV on the lift generated by the Falcon 20, and compare the results of pre-diluted fluid with tests with fluid diluted using simulated light freezing rain.

4.14.1 Fluid Thickness Measurements

Fluid thickness measurements were recorded on the leading edge at six positions on each wing at the runway threshold. Measurements for Run 14 are shown in Figure 4.30. Fluid thicknesses at the six leading edge positions on each wing ranged from 0.1 mm to 0.3 mm, and were of similar distribution on both wings. The pre-diluted fluid thickness values are significantly lower than the undiluted thickness values for this fluid. This can be explained by the formulation of the Dow Ultra+ fluid, which dilutes readily with water, eroding the thickness of the fluid layer.

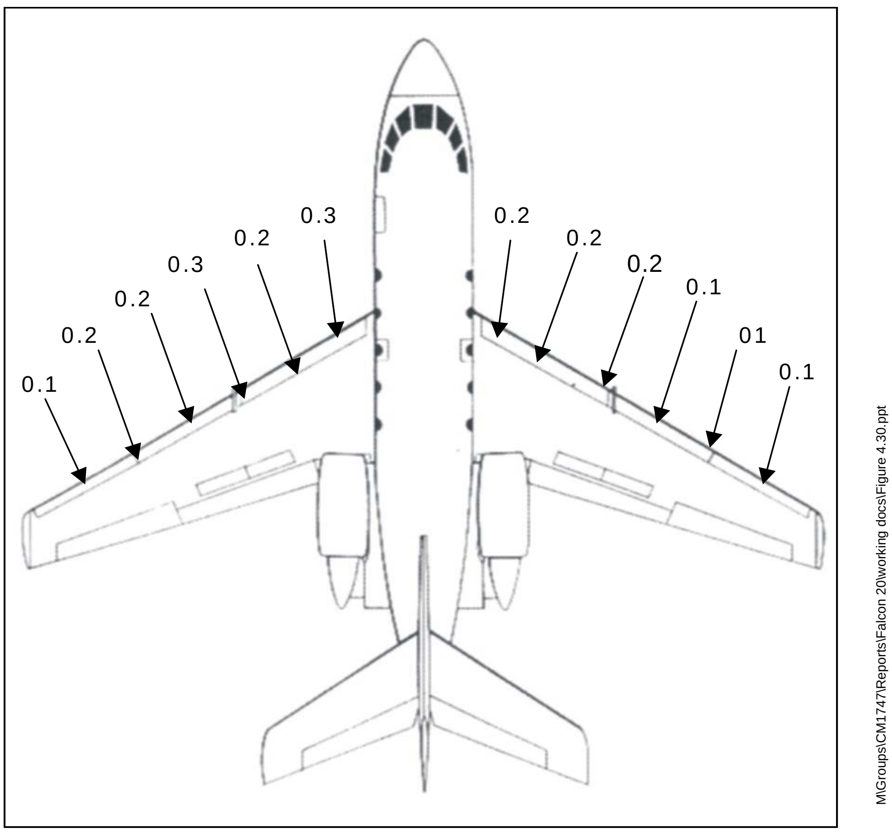

Figure 4.30: Fluid Thickness Measurements for Run 14 (mm)

4.14.2 Wing Skin Temperatures

Wing skin temperatures were recorded on the leading edge at six positions on each wing at the threshold of Runway 32, just prior to takeoff, with a hand-held temperature probe. Temperatures for Run 14 are shown in Figure 4.31.

Prior to the takeoff of the Falcon 20, the wing temperatures ranged primarily from -3.6 to -5.7°C on both wings of the Falcon 20 (see Figure 4.31). One leading edge location on the starboard wing had a temperature of -9.1°C, however this location was shaded from the sun while the aircraft was outdoors at the NRC apron. The ambient air temperature for this test was -16°C.

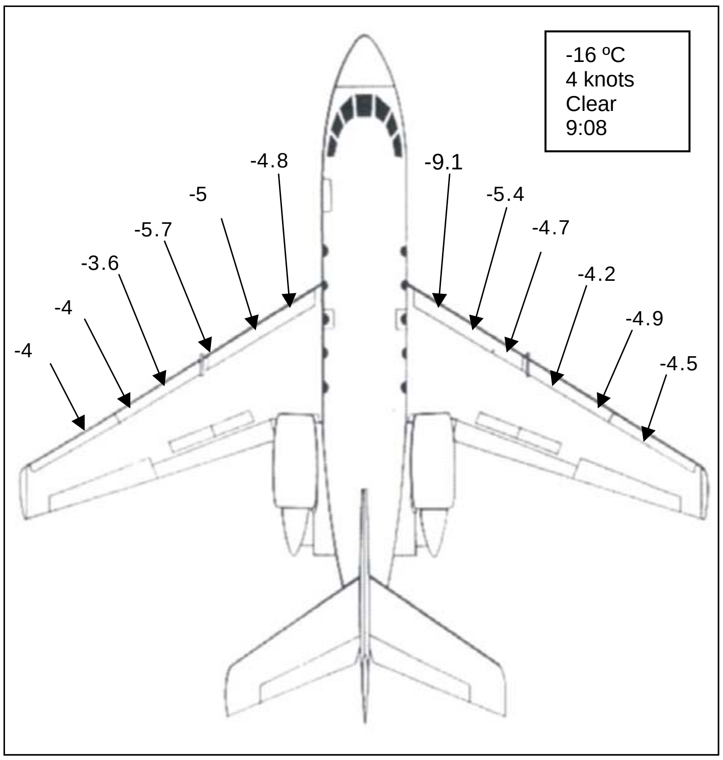

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Figure 4.31: Wing Skin Temperatures for Run 14 (ºC)

4.14.3 Fluid Freezing Points

Since the fluid was pre-diluted to a freezing point of -23°C, freezing point measurement of the fluid on the wings of the Falcon 20 was not required for this run.

4.15 Fluid Viscosity

Prior to fluid application process for each test, Type IV samples were collected from each fluid container. Fluids samples were again gathered from the wing following fluid application, following light freezing rain application (if applicable), and upon return of the aircraft to the NRC pad following the takeoff. The fluid samples were transported to the APS laboratory and subjected to viscosity testing.

The measurement method used to determine the viscosities for both fluids was the standard AIR 9968 viscosity measurement method:

a) Spindle SC4-31;
b) 10 mL of fluid;
c) 10 minute duration;
d) 0.3 r/min; and
e) 20°C.

The above-mentioned method, which requires only a 10 mL sample of fluid, was used for all viscosity tests in Falcon 20 tests. The manufacturer's recommended viscosity measurement method for Kilfrost ABC-S normally requires a 150 mL sample of fluid, but as it is often difficult to collect a 150 mL sample from the wing after a flight, the simplified, standardized AIR method was selected. The viscosity log from Falcon 20 tests in February 2003 is shown in Table 4.1. All viscosity values in Table 4.1 are presented in centipoises (cP).

Table 4.1: Viscosity Log from February 2003 Falcon 20 Tests

Run #	Fluid	Virgin Fluid	Test #	Port wing			Starboard wing		
				After fluid spray	After rain spray	After flight	After fluid spray	After rain spray	After flight
1	UCAR Ultra+	33000	1	26600	N/A	9700	26800	N/A	2600
2	UCAR Ultra+	33000	1	31600	N/A	8400	30900	N/A	15900
3	UCAR Ultra+	33000	1	22500	N/A	12500	25300	N/A	1900
4	UCAR Ultra+	33000	1	25200	N/A	24800	15700	N/A	1900
5	Kilfrost ABC-S	22500	1	19400	N/A	600	17100	N/A	2400
6	Kilfrost ABC-S	22500	1	26100	N/A	16600	19900	N/A	12800
9	Kilfrost ABC-S	22500	1	14100	18800	14300	19400	18100	54000
			2	13000	17800	12600	18800	-	38900
			3	12700	-	-	16800	-	37700
10	Kilfrost ABC-S	22500	1	12500	21200	18700	11300	21000	24500
11	UCAR Ultra+	33000	1	23800	23400	700	24600	6900	200
13	UCAR Ultra+	33000	1	29400	27000	23000	29200	15400	26600
14	UCAR Ultra+	33000	1	300	N/A	300	200	N/A	200

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4.16 Summary of Tests

4.16.1 Fluid Thickness

A summary of the thickness measurements recorded at the threshold of the runway, just prior to the takeoff of the Falcon 20, is shown in Table 4.2.

The neat, undiluted ethylene glycol Type IV fluid (Dow Ultra+) had thickness measurements on the leading edge that ranged from 0.7 mm to 1.1 mm just prior to the departure of the aircraft.

The neat, undiluted propylene glycol Type IV fluid (Kilfrost ABC-S) had thickness measurements on the leading edge that ranged from 0.3 mm to 0.7 mm just prior to the departure of the aircraft.

When the two Type IV fluids were diluted with simulated light freezing rain, the thickness trends reversed. The thickness of the diluted ethylene glycol Type IV fluid (Dow Ultra+) was inferior (0.3 mm to 0.6 mm) to the neat, undiluted Type IV EG thickness values. The thickness of the diluted propylene glycol Type IV fluid (Kilfrost ABC-S) was superior (0.4 mm to 1.1 mm) to the neat, undiluted Type IV PG thickness values.

The thickness results with the diluted Type IV fluids highlight two distinctly different fluid failure mechanisms:

a) Dilution failure: The fluid film erodes due to dilution and contamination begins to accumulate on the surface of the aircraft. This mechanism of failure is common with Ultra+ fluid; and

b) Bridging failure: The fluid film swells with dilution, and contamination begins to bridge on top of the fluid layer or begins to embed within the fluid. This mechanism of failure is common with propylene glycol formulations, in particular the Kilfrost ABC-S fluid.

The Ultra+ fluid pre-diluted to a -23°C freezing point had very low thickness measurements on the leading edge, 0.1 mm to 0.3 mm.

4.16.2 Wing Temperatures

A summary of the wing temperatures measured prior to takeoff from the Falcon 20 tests is shown in Table 4.3.

Table 4.2: Summary of Falcon 20 Thickness Tests

Run	Fluid	Fluid Condition	Wing	Min. Thickness (mm)	Max. Thickness (mm)	Avg. Thickness (mm)
1	Ultra+ (EG)	Neat, Undiluted	Port	0.8	1.1	1.0
1	Ultra+ (EG)	Neat, Undiluted	Starboard	0.7	0.7	0.7
2	Ultra+ (EG)	Neat, Undiluted	Port	0.8	1.0	0.9
2	Ultra+ (EG)	Neat, Undiluted	Starboard	0.7	1.0	0.8
3	Ultra+ (EG)	Neat, Undiluted	Port	0.7	1.0	0.9
3	Ultra+ (EG)	Neat, Undiluted	Starboard	0.8	1.0	1.0
4	Ultra+ (EG)	Neat, Undiluted	Port	0.8	1.0	0.9
4	Ultra+ (EG)	Neat, Undiluted	Starboard	0.8	1.0	0.9
5	ABC-S (PG)	Neat, Undiluted	Port	0.6	0.7	0.6
5	ABC-S (PG)	Neat, Undiluted	Starboard	0.4	0.7	0.6
6	ABC-S (PG)	Neat, Undiluted	Port	0.4	0.7	0.5
6	ABC-S (PG)	Neat, Undiluted	Starboard	0.4	0.6	0.5
7	ABC-S (PG)	Neat, Undiluted	Port	0.3	0.6	0.5
7	ABC-S (PG)	Neat, Undiluted	Starboard	0.4	0.4	0.4
8	ABC-S (PG)	Residual	Port	N/A	N/A	N/A
8	ABC-S (PG)	Residual	Starboard	N/A	N/A	N/A
9	ABC-S (PG)	Neat, Diluted with Zr-	Port	0.7	1.1	0.9
9	ABC-S (PG)	Neat, Diluted with Zr-	Starboard	0.6	1.0	0.8
10	ABC-S (PG)	Neat, Diluted with Zr-	Port	0.6	1.0	0.8
10	ABC-S (PG)	Neat, Diluted with Zr-	Starboard	0.4	1.0	0.6
11	Ultra+ (EG)	Neat, Diluted with Zr-	Port	0.4	0.6	0.5
11	Ultra+ (EG)	Neat, Diluted with Zr-	Starboard	0.4	0.4	0.4
12	Ultra+ (EG)	Residual	Port	N/A	N/A	N/A
12	Ultra+ (EG)	Residual	Starboard	N/A	N/A	N/A
13	Ultra+ (EG)	Neat, Diluted with Zr-	Port	0.3	0.4	0.4
13	Ultra+ (EG)	Neat, Diluted with Zr-	Starboard	0.3	0.6	0.4
14	Ultra+ (EG)	Pre-Diluted	Port	0.1	0.3	0.2
14	Ultra+ (EG)	Pre-Diluted	Starboard	0.1	0.2	0.2

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Table 4.3: Summary of Falcon 20 Wing Temperatures

Date	Run	OAT (° C)	Wing	Max. Temperature (° C)	Min. Temperautre (° C)	Avg. Temperature (° C)
24-Feb-03	1	-13	Port	-2.5	-5.0	-4.3
24-Feb-03	1	-13	Starboard	-3.5	-5.0	-4.3
24-Feb-03	2	-13	Port	-5.5	-7.3	-6.9
24-Feb-03	2	-13	Starboard	-6.7	-7.5	-7
24-Feb-03	3	-13	Port	-8.3	-9.2	-8.8
24-Feb-03	3	-13	Starboard	-9.0	-9.6	-9.3
24-Feb-03	4	-13	Port	-9.5	-11.5	-10.7
24-Feb-03	4	-13	Starboard	-11.2	-11.4	-11.3
25-Feb-03	5	-20	Port	-6.0	-11.4	-8.1
25-Feb-03	5	-20	Starboard	-2.7	-4.2	-3.5
25-Feb-03	6	-20	Port	-8.5	-10.3	-9.7
25-Feb-03	6	-20	Starboard	-14.0	-15.3	-14.8
25-Feb-03	7	-18	Port	-6.2	-7.8	-7.3
25-Feb-03	7	-18	Starboard	-11.7	-13.7	-12.6
25-Feb-03	8	-18	Port	N/A	N/A	N/A
25-Feb-03	8	-18	Starboard	N/A	N/A	N/A
26-Feb-03	9	-23	Port	-12.0	-14.8	-13.4
26-Feb-03	9	-23	Starboard	-9.5	-10.8	-10.4
26-Feb-03	10	-23	Port	-8.5	-12.3	-10.4
26-Feb-03	10	-23	Starboard	0.3	-3.0	-1
26-Feb-03	11	-19	Port	-3.9	-11.2	-6.7
26-Feb-03	11	-19	Starboard	3.3	6.9	5.3
26-Feb-03	12	-15	Port	N/A	N/A	N/A
26-Feb-03	12	-15	Starboard	N/A	N/A	N/A
26-Feb-03	13	-12	Port	-11.6	-12.5	-12.1
26-Feb-03	13	-12	Starboard	-12.0	-12.6	-12.2
27-Feb-03	14	-16	Port	-3.6	-5.7	-4.5
27-Feb-03	14	-16	Starboard	-4.2	-9.1	-5.5

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4.16.3 Fluid Viscosity

A summary of the viscosity results from the Falcon 20 tests was previously shown in Table 4.1.

In general, the viscosity values from the Falcon 20 tests followed an expected trend.

4.16.3.1 Dow Ultra+

The virgin Dow Ultra+ samples had viscosity values of 33,000 cP, determined using the AIR 9968 standard viscosity measurement method. The average viscosity of the Ultra+ fluid when sprayed through the Type IV sprayer decreased by approximately 20 percent.

After simulated light freezing rain spray on the Ultra+ fluid, the viscosities diminished to varying degrees, based largely on exposure to the light freezing rain. This was expected, as the fluid film of Ultra+ erodes rapidly with dilution.

Following the takeoff and flight of the Falcon 20, samples of the residual fluid on the trailing edge of the aircraft were collected. Although the results have been deemed largely inconclusive, the residual Ultra+ samples that were collected at the conclusion of each test run had viscosity values inferior to the pre-takeoff viscosities. In some cases, the differences were significant.

4.16.3.2 Kilfrost ABC-S (manufactured by Cryotech)

The virgin Kilfrost ABC-S samples had viscosity values of 22,500 cP, determined using the AIR 9968 standard viscosity measurement method. The average viscosity of the Ultra+ fluid when sprayed through the Type IV sprayer decreased by approximately 30 percent.

After simulated light freezing rain spray on the Kilfrost ABC-S fluid, the viscosities increased by approximately 15 percent. This result can be explained by the formulation of the Kilfrost ABC-S fluid, which readily accepts water, increasing in thickness and viscosity as it dilutes.

Following the takeoff and flight of the Falcon 20, samples of the residual fluid on the trailing edge of the aircraft were collected. In most cases, the viscosities of the residual fluid collected on the wing were inferior to the pre-takeoff fluid viscosities, although in some cases the viscosities were actually higher. The results of viscosity tests with the residual fluid are largely inconclusive.

4.16.4 Fluid Freezing Points

Four tests were conducted with Type IV fluid diluted with simulated light freezing rain in 2002-03. Another test was conducted with fluid pre-diluted to selected freezing point. A summary of the fluid freeze data from the Falcon 20 tests appears in Table 4.4.

In Run 9 on February 26, 2003, the PG anti-icing fluid was exposed to light freezing rain for approximately 9 minutes. At the runway threshold, the freezing point buffer of the fluid on the leading edge ranged from 5°C to 14°C on the port wing, 3°C to 12°C on the starboard wing. Ice was embedded within the fluid at several trailing edge and mid-chord locations. No ice was adhering to the wing surface.

Table 4.4: Summary of Falcon 20 Fluid Freezing Points

Date	Run	Fluid	Fluid Condition	Wing	Amb. Temp. (° C)	Lowest Freeze Point (° C)	Highest Freeze Point (° C)	Avg. Freeze Point (° C)
26-Feb-03	9	ABC-S (PG)	Neat, Diluted with Zr-	Port	-23	-37	-28	-32
26-Feb-03	9	ABC-S (PG)	Neat, Diluted with Zr-	Starboard	-23	-35	-26	-32
26-Feb-03	10	ABC-S (PG)	Neat, Diluted with Zr-	Port	-23	-33	-20	-24
26-Feb-03	10	ABC-S (PG)	Neat, Diluted with Zr-	Starboard	-23	-32	-20	-24
26-Feb-03	11	Ultra+ (EG)	Neat, Diluted with Zr-	Port	-15	-42	-9	-26
26-Feb-03	11	Ultra+ (EG)	Neat, Diluted with Zr-	Starboard	-15	-51	-41	-47
26-Feb-03	13	Ultra+ (EG)	Neat, Diluted with Zr-	Port	-12	-39	-10	-26
26-Feb-03	13	Ultra+ (EG)	Neat, Diluted with Zr-	Starboard	-12	-31	-27	-29
27-Feb-03	14	Ultra+ (EG)	Pre-Diluted	Port	-16	-23	-23	-23
27-Feb-03	14	Ultra+ (EG)	Pre-Diluted	Starboard	-16	-23	-23	-23

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In Run 10 on February 26, 2003, the PG anti-icing fluid was exposed to light freezing rain for 23 to 28 minutes. At the runway threshold, the freezing point buffer of the fluid on the leading edge ranged from -3°C to 10°C on the port wing, -3°C to 9°C on the starboard wing. Ice was embedded however within the fluid at several trailing edge and mid-chord locations. No ice was adhering to the wing surface.

In Run 11 on February 26, 2003, the EG anti-icing fluid was exposed to light freezing rain for on average 28 minutes. The ambient temperature for the test was -15°C. The fluid freezing point buffer on the leading edge of the aircraft ranged from -6°C to 27°C on the port wing, 26°C to 36°C on the starboard wing. At two locations on the port wing, the freezing point of the fluid was inferior to the ambient temperature and ice had accumulated on the wing structure at these points.

In Run 13 on February 26, 2003, the EG anti-icing fluid was exposed to light freezing rain for on average 13 minutes. The ambient temperature for the test was -12°C. The fluid freezing point buffer on the leading edge of the aircraft ranged from -2°C to 27°C on the port wing, 15°C to 19°C on the starboard wing. At one location on the port wing, the freezing point of the fluid was inferior to the ambient temperature, and ice had accumulated on the wing structure at this location.
In Run 14, the EG anti-icing fluid was pre-diluted to a freezing point of -23°C. The ambient air temperature was -16°C.

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Photo 4.1: Residual Fluid on Trailing Edge

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5 CONCLUSIONS

Tests performed in 2002-03 with the Falcon 20 were conducted during the second year of a three-year test program. The following sections describe the conclusions reached from field tests conducted in the 2002-03 winter season.

5.1 Test Coordination and Provision of Support

APS coordinated and provided support for tests aimed to quantify the aerodynamic penalties associated with the presence of neat, diluted, or partially contaminated anti-icing fluids on the wings of the NRC Falcon 20. The test methodologies employed for the application of light freezing rain and the collection of fluid thickness, fluid viscosity, wing temperature, and fluid freezing point data were satisfactory.

5.2 Fluid Thickness Measurements

5.2.1 Fluid Thickness Data Prior to Takeoff

The neat, undiluted Ultra+ Type IV fluid (EG) had thickness measurements on the leading edge that ranged from 0.7 mm to 1.1 mm just prior to the departure of the aircraft. The neat, undiluted ABC-S Type IV fluid (PG) had thickness measurements on the leading edge that ranged from 0.3 mm to 0.7 mm.

When diluted with simulated light freezing rain, the Ultra+ Type IV fluid (EG) had thickness measurements in the 0.3 mm to 0.6 mm range on the leading edge, considerably less than the undiluted measurements for this fluid. The thickness measurements of the diluted ABC-S Type IV fluid (PG) were increased (0.4 mm to 1.1 mm) when compared to the undiluted fluid thickness measurements for this fluid.

The thickness results with the diluted Type IV fluids highlight the differences in fluid formulation that ultimately produce two distinctly different fluid failure mechanisms:

a) Dilution failure: The fluid film erodes due to dilution and contamination begins to accumulate on the surface of the aircraft. This mechanism of failure is common with Ultra+ fluid; and
b) Bridging failure: The fluid film swells with dilution, and contamination begins to bridge on top of the fluid layer or begins to embed within the fluid. This mechanism of failure is common with propylene glycol formulations, in particular the Kilfrost ABC-S fluid.

The Ultra+ fluid pre-diluted to a -23°C freezing point had very low thickness measurements on the leading edge, 0.1 mm to 0.3 mm.

5.2.2 Elimination of Neat, Diluted, and Partially Contaminated Fluids

One EG-based Type IV fluid (Ultra+) and one PG-based Type IV fluid were tested in neat, diluted, and partially contaminated state to observe the process of fluid elimination from the wing surface during takeoff.
For tests with neat and diluted fluids, the videotape of the fluid surface during the takeoff run showed that the majority of the EG and PG-based fluids had been eliminated from the wing surface by the time the aircraft speed had reached 80 knots. A thin film of Type IV fluid can be observed, receding toward the trailing edge of the aircraft, at the time of rotation.

Both fluids underwent near complete elimination, leaving only a very thin film of residual fluid. The remaining fluid film was much less than 0.1 mm when present on leading edge surfaces, but ranged from 0.1 mm to 0.3 mm in areas of localized pooling on the trailing edge.

In the two tests with partially contaminated EG-based fluid, the small areas of ice present on the leading edge of the Falcon 20 prior to takeoff were deemed to be adhering to the wing surface. Most of the ice had been eliminated by the shear forces exerted by the aircraft acceleration, rotation, climb-out and circuit of the airport. In one test, however, a small area of ice remained on the wing at the time of landing.

In the two tests with partially contaminated PG-based fluid, the areas of contamination were located primarily around the trailing edge. Ice embedded within the fluid was deemed not to be adhering to the wing surface. All of the ice contamination was eliminated by the shear forces exerted by the aircraft acceleration, rotation, climb-out and circuit of the airport.

5.3 Fluid Viscosity

In general, the viscosity values from the Falcon 20 tests followed an expected trend.

The Ultra+ fluid viscosities diminished by approximately 20 percent when sprayed through the mobile sprayer. After dilution of the fluid by simulated light freezing rain, the viscosities of the Ultra+ fluid diminished to varying degrees, based largely on exposure to the light freezing rain. This was expected, as the fluid film of Ultra+ erodes rapidly with dilution.

The ABC-S fluid viscosities diminished by approximately 30 percent when sprayed through the mobile sprayer. After dilution of the fluid by simulated light freezing rain, the viscosities of the ABC-S fluid increased by approximately 15 percent. This result can be explained by the formulation of the Kilfrost ABC-S fluid, which readily accepts water, increasing in thickness and viscosity as it dilutes.

Following the takeoff and flight of the Falcon 20, samples of the residual fluid on the trailing edge of the aircraft were collected. Although the results of viscosity tests with the residual fluid have been deemed largely inconclusive, the samples that were collected at the conclusion of each test run had viscosity values that were generally inferior to the pre-takeoff viscosities.

6 RECOMMENDATIONS

Tests conducted to examine the lift penalties associated with the presence of neat, diluted, or partially contaminated anti-icing fluid on the wings of the NRC Falcon 20 aircraft were conducted in 2002-03 as the second year of a three-year test program.

Several recommendations can be put forth from the results of this testing:

a) Further takeoff tests should be conducted using natural snow precipitation. The objective of these tests would be to evaluate whether snow provides results similar to freezing rain with respect to the elimination of diluted fluid from aircraft wings;

b) Further takeoff tests should be conducted using different fluid formulations, including non-glycol fluid formulations;

c) Further takeoff tests should be conducted using higher levels of dilution, including contamination; and

d) Clean wing takeoff tests should be performed during a natural rain occurrence to use as a baseline for comparison with anti-icing fluid tests.

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REFERENCES

1. Dawson, P., Hanna, M., Chaput, M., *Contaminated Aircraft Takeoff Test 1997-98 Winter*, APS Aviation Inc., Transportation Development Centre, Montreal, December 1998, TP 13316E, 52.

2. 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.

3. 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.

4. Chaput, M., Campbell, R., *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.

5. Bastian, B., Hui K., *Lift-loss Due to the Presence of Ethylene and Propylene Glycol Anti-Icing Fluids on a Falcon 20 Aircraft*, National Research Centre Canada, Transportation Development Centre, Ottawa, April 2004, TP 14184E.

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APPENDIX A

TRANSPORTATION DEVELOPMENT CENTRE
WORK STATEMENT EXCERPT
AIRCRAFT & ANTI-ICING FLUID WINTER TESTING
2002-03

TRANSPORTATION DEVELOPMENT CENTRE
WORK STATEMENT EXCERPT
AIRCRAFT & ANTI-ICING FLUID WINTER TESTING
2002-03

5.14 Flow of Contaminated Fluid from Aircraft Wings During Takeoff

5.14.1 Develop a test plan jointly with NRC staff who operate the aircraft;

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

5.14.3 Plan for and co-ordinate the application of controlled amounts of snow and /or freezing rain contamination on the applied fluids;

5.14.4 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;

5.14.5 Collect the following data during the trials:

a) Type and amount of fluid applied;
b) Record of type and rate of contamination applied;
c) Extent of fluid contamination prior to the takeoff run; and
d) Measurements of thickness, concentration, viscosity, and adherence of clean and contaminated fluid prior to departure for the flight test;

5.14.6 Co-ordinate the ground aspect of test activities and initiate tests in conjunction with NRC staff based on forecast weather and aircraft availability; and

5.14.7 Document collected data from the ground aspect of testing for inclusion in the analysis and report.

5.15 Dispersion of Fluids on Airport Surfaces

5.15.1 Perform tests on the NRC Falcon 20 to ascertain the aerodynamic penalties of clean and partially diluted anti-icing fluid on the wings of the aircraft at the time of takeoff;

5.15.2 Conduct tests with propylene and ethylene Type IV fluids in periods without precipitation;

5.15.3 Perform fluid thickness measurements prior to departure of the aircraft from the spray application area and at the runway threshold to determine the amount of fluid that fell to the ground on the taxiways;

5.15.4 Data will be analyzed; and

5.15.5 Report data as an appendix to the Falcon report.

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APPENDIX B

PROCEDURE FOR THE CONDUCT OF TESTS TO EXAMINE THE EFFECTS OF NATURAL RAIN ON THE LIFT GENERATED BY THE FALCON 20 FOR WINTER 2002-03

CM1747.001

PROCEDURE FOR THE CONDUCT OF TESTS TO EXAMINE THE EFFECTS OF NATURAL RAIN ON THE LIFT GENERATED BY THE FALCON 20

Winter 2002-03

Prepared by: Michael Chaput

Reviewed by: John D'Avirro

November 8, 2002
Version 1.0

1. BACKGROUND

A preliminary analysis of the flight data recorded by the NRC for tests conducted in 2001-02 winter with the Falcon 20 revealed that a 10% degradation in lift occurs as a result of the presence of neat (undiluted) anti-icing fluid on the wings of the Falcon 20. No differences were noted in tests conducted with diluted anti-icing fluid. Consequently, the question was raised whether the presence of water on the wings of the Falcon 20 would have a similar effect on the lift capacity.

This document provides the procedures and equipment required to support the Falcon 20 tests in a natural rain event at MacDonald Cartier International in Ottawa.

2. OBJECTIVE

The main objective of this test is to provide a “rain on wing” baseline for comparison with “de/anti-icing fluid on wing” tests.

3. PERSONNEL

Two APS staff members are required for tests on aircraft at Ottawa airport.

National Research Council flight crews will operate the National Research Council aircraft.

4. DATA FORMS

The following data forms are required for the natural rain tests. These forms were first published in the procedure in TDC 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.*

Figure 1 General Form (Every Test)
Figure 2 General Form (Once per Session)
Figure 3 Adherence and Wing Temperature Form – Port Wing
Figure 4 Adherence and Wing Temperature Form – Starboard Wing
Figure 5 Fluid Thickness on Aircraft
Figure 6 Rain/Snow Quantity Form

5. PROCEDURES

APS personnel will:

- Place two rate pans outdoors near the NRC hangar prior to the departure of the aircraft. The pans will be weighed prior to and following each takeoff test to determine the rate of precipitation;

- Take thickness measurements of the water on the wings prior to the departure of the aircraft. Measurements will be conducted at the runway threshold;
- Record wing temperature profiles prior to and following each takeoff test using a hand-held temperature gauge; and
- Record the elimination of the water on the wings of the Falcon 20 using a hand-held video camera.

6. EQUIPMENT

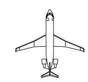
- Test procedures and data forms
- Hand-held temperature probe
- Thickness gauges (both kinds)
- Clipboards
- Rate pans x 2
- Type IV fluid (2 litres) to line rate pans
- Digital video camera and cassettes
- Satorius weigh scale

GENERAL FORM (EVERY TEST)
(TO BE FILLED IN BY OVERALL COORDINATOR)

DATE: ____________________ **AIRCRAFT TYPE:** FALCON 20

RUN #: ____________________

DIRECTION OF AIRCRAFT: ________ DEGREES **DRAW DIRECTION OF WIND AT DEICING CENTRE WRT AIRCRAFT:**



DEPARTURE TIME FROM DE-ICING BAY: ____________

START OF TAKE-OFF ROLL: ____________

TIME OF LANDING: ____________

RETURN TO DEICING BAY: ____________

FLUID APPLICATION - PORT WING

Actual Start Time: ____________ **am / pm** **Actual End Time:** ____________ **am / pm**

Amount of Type I: ____________ **L / gal** **Amount of Type IV:** ____________ **L / gal**

Fluid Sample Collected from Truck or Barrel: **Y / N**

FLUID APPLICATION - STARBOARD WING

Actual Start Time: ____________ **am / pm** **Actual End Time:** ____________ **am / pm**

Amount of Type I: ____________ **L / gal** **Amount of Type IV:** ____________ **L / gal**

Fluid Sample Collected from Truck or Barrel: **Y / N**

CONTAMINANT SPRAY APPLICATION

Actual Start Time (port wing): ____________ **am / pm** **Actual End Time:** ____________ **am / pm**

Actual Start Time (starboard wing): ____________ **am / pm** **Actual End Time:** ____________ **am / pm**

End of Test Time: ____________ (hr:min:ss) am/pm

COMMENTS: ____________________

MEASUREMENTS BY: ____________

HANDWRITTEN BY: ____________

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Form 2

Figure 1: General Form (Every Test)

GENERAL FORM (ONCE PER SESSION)
(TO BE FILLED IN BY OVERALL COORDINATOR)

AIRPORT: YMX YOW

AIRCRAFT TYPE: FALCON 20

EXACT PAD LOCATION OF TEST: ______________________

AIRLINE: ______________

DATE: ______________

FIN #: ______________

APPROX. AIR TEMPERATURE: _____ ºC

FUEL LOAD: ______________ **LB / KG**

TYPE I FLUID APPLICATION	***TYPE IV FLUID APPLICATION***
TYPE I FLUID TEMP: _____ ºC	**TYPE IV FLUID TEMP:** _____ ºC
Type I Truck #: _____	**Type IV Truck #:** _____
Type I Fluid Nozzle Type: _____	**Type IV Fluid Nozzle Type:** _____

COMMENTS: ______________________

MEASUREMENTS BY: ______________

HANDWRITTEN BY: ______________

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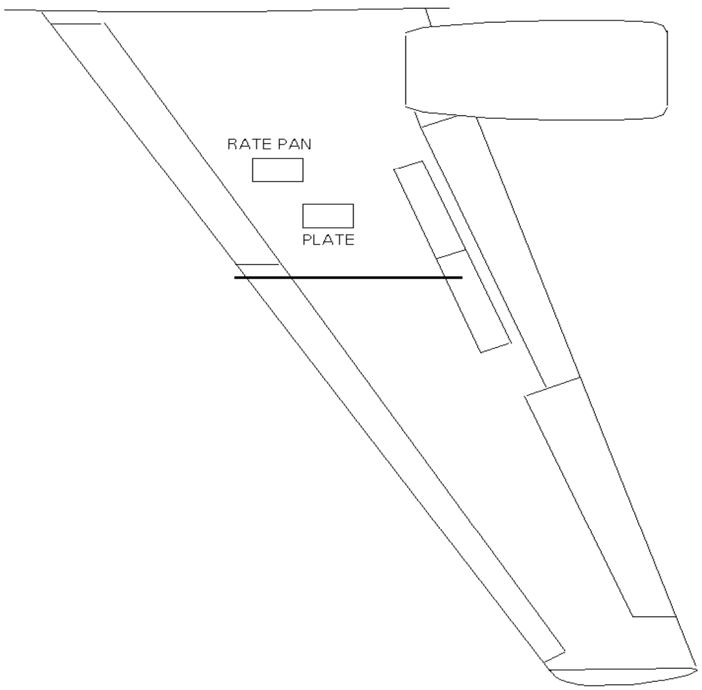
Form 2a

Figure 2: General Form (Once per session)

Date: ______________ Time: ______________ Run Number ________

Test Phase: A- before contamination ☐ B- before taxi ☐ C- after takeoff ☐



Skin Temperature
Record Temperature and Time at several points in test area, include shaded and sun areas.
Show location on wing form

Rate Pan

Precipitation = ________g

During Takeoff Run:

OAT = ______ °C

Wind = ______ kph

RH = ______ %

Sky Condition: ______________

OBSERVER: ______________

ASSISTED BY: ______________

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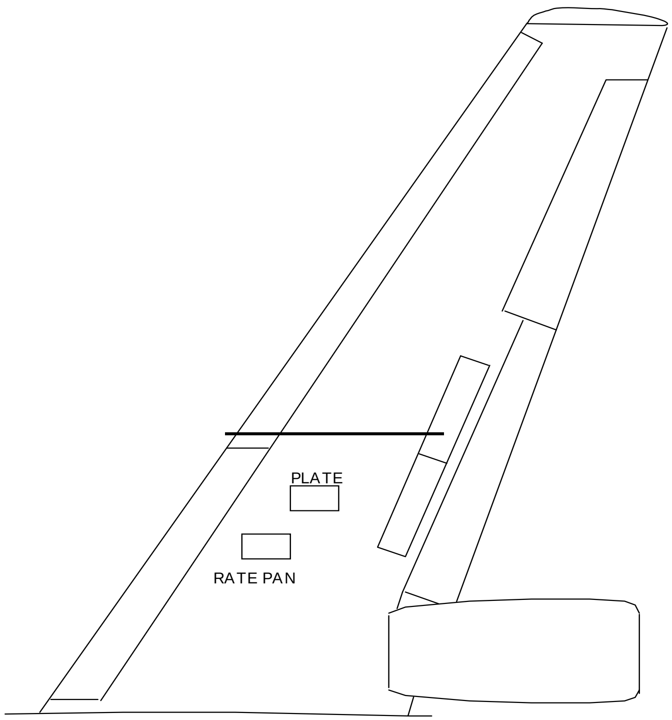
Form 5

Figure 3: Adherence and Wing Temperature Form – Port Wing

Date: ______________ **Time:** ______________ **Run Number** ________

Test Phase: **A- before contamination** ☐ **B- before taxi** ☐ **C- after takeoff** ☐



Skin Temperature
Record Temperature and Time at several points in test area, include shaded and sun areas.
Show location on wing form

Rate Pan

Precipitation = ________g

During Takeoff Run:

OAT = ______ ° C

Wind = ______ kph

RH = ______ %

Sky Condition: __________________

OBSERVER: ____________________________

ASSISTED BY: ____________________________

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Form 5a

Figure 4: Adherence and Wing Temperature Form – Starboard Wing

		PORT				STARBOARD			
	Wing Position	BEFORE RAIN SPRAY	AFTER RAIN SPRAY	BEFORE TAKEOFF	AFTER TAKEOFF	BEFORE RAIN SPRAY	AFTER RAIN SPRAY	BEFORE TAKEOFF	AFTER TAKEOFF
OUTBOARD	1								
	2								
	3								
	4								
	5								
	6								
	7								
	8								
	9								
INBOARD	1								
	2								
	3								
	4								
	5								
	6								
	7								
	8								
	9								

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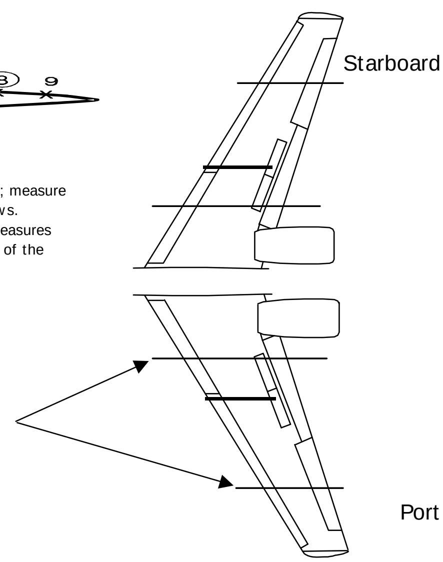
Location
1 - LE Nose
2, 8 – Halfway
3,4,6,7 – 1” From joint
5 – As far as can reach
9 – 6” From TE

Note:
Give priority to circled locations; measure other locations only if time allows. Lateral locations of thickness measures are 1 to 2 metres on both sides of the fence.



Location of inboard and outbourd test denoted by lines.

Figure 5: Fluid Thickness on Aircraft

Date: ___________

Time Before	Time After	Run	ZR- or Snow	Container Weight (kg)	
				Before	After

Measured by: ____________________

Handwritten by: ____________________

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Form 7

Figure 6: Rain-Snow Quantity Form

APPENDIX C

EXPERIMENTAL PROGRAM
FIELD TRIALS TO EXAMINE REMOVAL OF NEAT AND DILUTED FLUID FROM AIRCARFT WINGS DURING THE TAKEOFF RUN
DECEMBER 2002 TESTS

CM1747.001

EXPERIMENTAL PROGRAM
FIELD TRIALS TO EXAMINE REMOVAL OF NEAT AND DILUTED FLUID FROM AIRCRAFT WINGS DURING THE TAKEOFF RUN
DECEMBER 2002 TESTS

Winter 2002-03

Prepared for

Transportation Development Centre
Transport Canada

Prepared by: Michael Chaput

Reviewed by: John D'Avirro

December 6, 2002
Version 1.0

EXPERIMENTAL PROGRAM
FIELD TRIALS TO EXAMINE REMOVAL OF NEAT AND DILUTED FLUID FROM AIRCRAFT WINGS DURING THE TAKEOFF RUN
DECEMBER 2002 TESTS

Winter 2002-03

Previous trials to examine the elimination of failed SAE Type IV fluid from aircraft wings during takeoff were conducted during the 1997-98 and 1998-99 winter seasons. Those trials, based on simulated takeoff runs using a National Research Council Falcon 20 aircraft, provided an improved understanding of the subject and showed that the selected test approach was a viable one. Additional trials were planned for the 1999-2000 and 2000-01 winter test seasons, however these trials were not conducted due to lack of suitable weather conditions in the limited time that the aircraft and crew were available for testing.

The test program conducted during winter 2001-2002 using the NRC Falcon 20 addressed the effects of unshed anti-icing fluid on aircraft take-off performance. Tests were performed with one ethylene glycol-based Type IV fluid, Dow/UCAR Ultra+, in neat and diluted form. Diluted anti-icing fluid tests used artificial precipitation and a simulated distribution of precipitate over the surface that approximated ‘real world’ conditions.

A preliminary analysis of the flight data recorded by the NRC for tests conducted in 2001-02 winter revealed that a 10% degradation in lift occurs as a result of the presence of neat (undiluted) anti-icing fluid on the wings of the Falcon 20. No differences were noted in tests conducted with diluted anti-icing fluid.

Because only ethylene glycol-based were tested in 2001-02 trials with the Falcon 20, additional tests with propylene fluid are planned for 2002-03. This document provides the procedures and equipment required to support the Falcon 20 tests scheduled for December 2002.

These trials will be co-ordinated and reported by APS. They will be conducted at Ottawa International Airport (YOW) on a Falcon 20 research aircraft owned and piloted by the National Research Council Canada.

This document provides the detailed procedures and equipment required to support these trials.

No tests with artificial precipitation will be performed during the December 2002 trials. These tests will be conducted at a later date, most likely in February or March 2003.

1. OBJECTIVE

This project addresses the following objective:

- To ascertain whether there is an aerodynamic penalty on the aircraft due to presence of partially expended anti-icing fluid on the wings.

2. TEST REQUIREMENTS

APS will co-ordinate and plan test activities and prepare a final report as well as present results at industry deicing meetings.

APS will provide support to these tests for instrumentation, fluid application, and artificial precipitation application. A high-quality digital videotape record of fluid behaviour on aircraft wings during the takeoff run is required and will be recorded by observers in the Falcon 20 cabin.

Desired weather conditions are dry, with subfreezing outside air temperature. Tests will be limited to a maximum of 10kts crosswind. Overcast skies are very important to avoid overheating of aircraft wings from exposure to the sun. Runway conditions are to be clean and dry.

Attachment I provides a description of test procedures. Table 2.1 provides a plan overview of the different tests.

Table 2.1: Test Plan
Removal of Neat Fluid from Aircraft Wings During Takeoff Run

TEST #	OAT °C	Fluid	Precipitation	Wing Condition
1	-3	No fluid	No	Clean Fluid
2	> 0	No fluid	Rain	Rain on Wing
3	-3	Type IV EG Neat	No	Clean Fluid
4	-3	Type IV PG Neat	No	Clean Fluid
5	-3	Type IV PG Neat	No	Clean Fluid

3. EQUIPMENT AND FLUIDS

3.1 Equipment

Equipment to be employed is shown in Attachment II.

3.2 Fluids

Ethylene glycol-based UCAR Ultra+ Type IV and propylene glycol-based Kilfrost ABC-S Type IV will be used in December 2002 trials.

4. PERSONNEL

Three APS staff members are required for tests on aircraft at Ottawa airport.

Ethylene glycol applications will be conducted by Globe Ground personnel at the central deicing facility in Ottawa. Propylene glycol applications will be performed by APS personnel at the NRC hangar using the Type IV mobile sprayer.

National Research Council flight crews will operate the National Research Council aircraft.

Attachment III provides task assignments.

5. DATA FORMS

The following data forms are required for the December 2002 Falcon 20 tests. These forms were first published in the procedure in TDC 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.*

Form 1 General Form (Every Test)
Form 2 General Form (Once per Session)
Form 3 Adherence and Wing Temperature Form – Port Wing
Form 4 Adherence and Wing Temperature Form – Starboard Wing
Form 5 Fluid Thickness on Aircraft
Form 6 Rain/Snow Quantity Form

GENERAL FORM (EVERY TEST)
(TO BE FILLED IN BY OVERALL COORDINATOR)

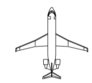
DATE: ______________________

AIRCRAFT TYPE: FALCON 20

RUN #: ______________________

DIRECTION OF AIRCRAFT: ________ DEGREES

DRAW DIRECTION OF WIND AT DEICING CENTRE WRT AIRCRAFT:



DEPARTURE TIME FROM DE-ICING BAY: ____________

START OF TAKE-OFF ROLL: ____________

TIME OF LANDING: ____________

RETURN TO DEICING BAY: ____________

FLUID APPLICATION - PORT WING

Actual Start Time: ____________ **am / pm** **Actual End Time:** ____________ **am / pm**

Amount of Type I: ____________ **L / gal** **Amount of Type IV:** ____________ **L / gal**

Fluid Sample Collected from Truck or Barrel: Y / N

FLUID APPLICATION - STARBOARD WING

Actual Start Time: ____________ **am / pm** **Actual End Time:** ____________ **am / pm**

Amount of Type I: ____________ **L / gal** **Amount of Type IV:** ____________ **L / gal**

Fluid Sample Collected from Truck or Barrel: Y / N

CONTAMINANT SPRAY APPLICATION

Actual Start Time (port wing): ____________ **am / pm** **Actual End Time:** ____________ **am / pm**

Actual Start Time (starboard wing): ____________ **am / pm** **Actual End Time:** ____________ **am / pm**

End of Test Time: ____________ (hr:min:ss) am/pm

COMMENTS: ______________________

MEASUREMENTS BY: ______________________

HANDWRITTEN BY: ______________________

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Form 2

Form 1: General Form (Every Test)

GENERAL FORM (ONCE PER SESSION)
(TO BE FILLED IN BY OVERALL COORDINATOR)

AIRPORT: YMX YOW

AIRCRAFT TYPE: FALCON 20

EXACT PAD LOCATION OF TEST: ______________________

AIRLINE: ______________

DATE: ______________

FIN #: ______________

APPROX. AIR TEMPERATURE: _____ ºC

FUEL LOAD: ______________ **LB / KG**

TYPE I FLUID APPLICATION	***TYPE IV FLUID APPLICATION***
TYPE I FLUID TEMP: _____ ºC	**TYPE IV FLUID TEMP:** _____ ºC
Type I Truck #: _____	**Type IV Truck #:** _____
Type I Fluid Nozzle Type: _____	**Type IV Fluid Nozzle Type:** _____

COMMENTS: ______________________

MEASUREMENTS BY: ______________

HANDWRITTEN BY: ______________

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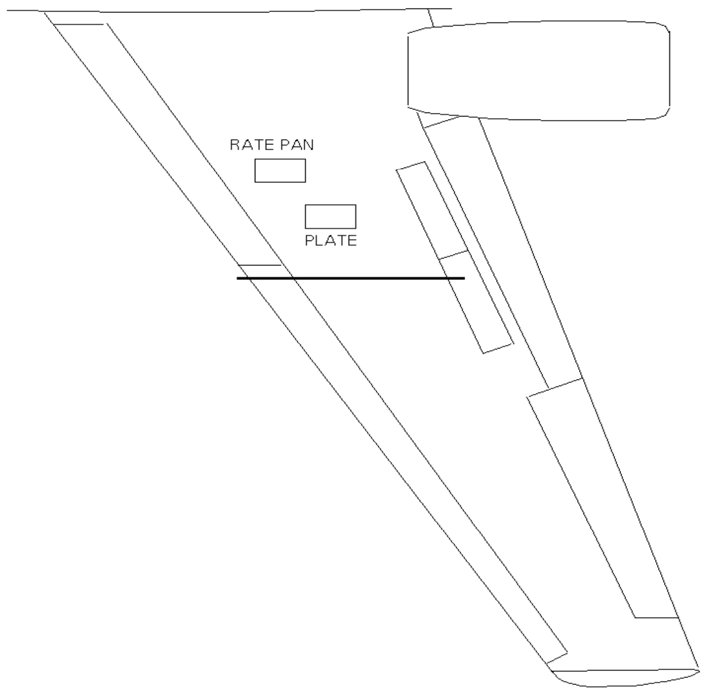
Form 2a

Form 2: General Form (Once per Session)

Date: ______	Time: ______	Run Number ______

Test Phase: A- before contamination [ ] B- before taxi [ ] C- after takeoff [ ]



Skin Temperature
Record Temperature and Time at several points in test area, include shaded and sun areas.
Show location on wing form

Rate Pan

Precipitation = ______g

During Takeoff Run:

OAT = ______ °C

Wind = ______ kph

RH = ______ %

Sky Condition: ______

OBSERVER: ______

ASSISTED BY: ______

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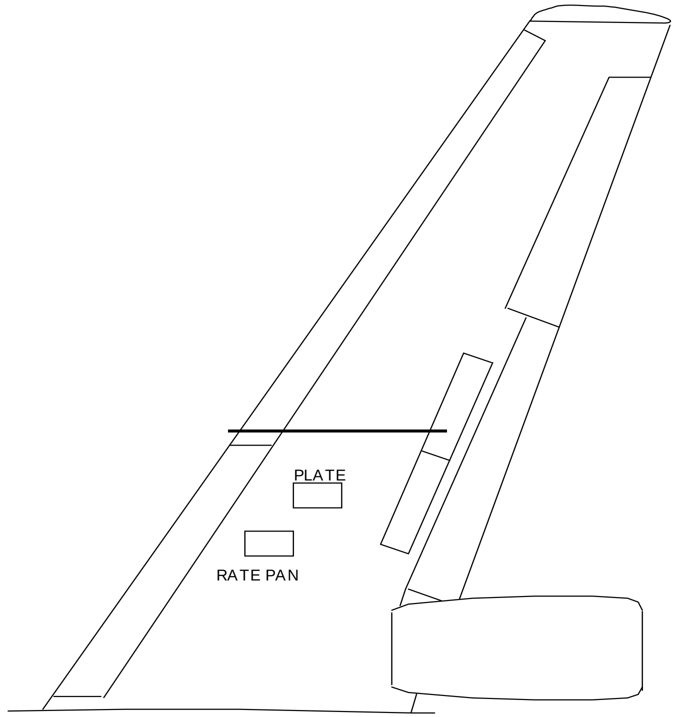
Form 5

Form 3: Adherence and Wing Temperature Form – Port Wing

Date: ______________ **Time:** ______________ **Run Number** ________

Test Phase: **A- before contamination** ☐ **B- before taxi** ☐ **C- after takeoff** ☐



Skin Temperature
Record Temperature and Time at several points in test area, include shaded and sun areas.
Show location on wing form

Rate Pan

Precipitation = ________g

During Takeoff Run:

OAT = ______ ° C

Wind = ______ kph

RH = ______ %

Sky Condition: ________________

OBSERVER: ____________________________

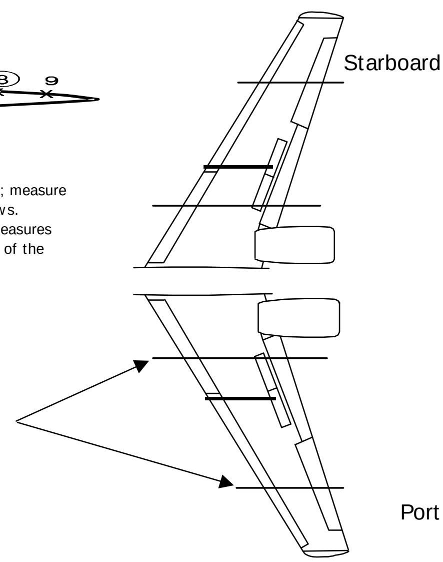
ASSISTED BY: ____________________________

I:\Groups\Cm1680 (01-02)\Procedures\Falcon 20\Data Forms
Form 5a

Form 4: Adherence and Wing Temperature Form – Starboard Wing

		PORT				STARBOARD			
	Wing Position	BEFORE RAIN SPRAY	AFTER RAIN SPRAY	BEFORE TAKEOFF	AFTER TAKEOFF	BEFORE RAIN SPRAY	AFTER RAIN SPRAY	BEFORE TAKEOFF	AFTER TAKEOFF
OUTBOARD	1								
	2								
	3								
	4								
	5								
	6								
	7								
	8								
	9								
INBOARD	1								
	2								
	3								
	4								
	5								
	6								
	7								
	8								
	9								

M:\Groups\Cm1680 (01-02)\Reports\Falcon 20\Working Documents\Table 2.1



Location
1 - LE Nose
2, 8 – Halfway
3,4,6,7 – 1" From joint
5 – As far as can reach
9 – 6" From TE

Note:
Give priority to circled locations; measure other locations only if time allows.
Lateral locations of thickness measures are 1 to 2 metres on both sides of the fence.

Location of inboard and outbourd test denoted by lines.

Form 5: Fluid Thickness on Aircraft

Date: ____________

Time Before	Time After	Run	ZR- or Snow	Container Weight (kg)	
				Before	After

Measured by: ____________________

Handwritten by: ____________________

I:\Groups\Cm1680 (01-02)\Procedures\Falcon 20\Data Forms

Form 7

Form 6: Rain/Snow Quantity Form

Attachment I
Test Procedures

1. PRE-TEST SETUP

- Co-ordinate with Globe Ground for anti-icing fluid, and access to deicing pad (MC).
- Co-ordinate with Ottawa Airport Authority and NavCan (MC).
- Arrange for security escorts and passes, if required.
- Find video specialists and photographers in Ottawa to record behaviour of fluid on the aircraft during the precipitation phase, taxi and takeoff of the Falcon 20 (MC).
- Hotels and advances for APS personnel (CD).
- Arrange personnel travel arrangements.
- Ensure mobile sprayer functions properly (NB).
- Transport equipment to Ottawa.

2. CONDUCT TESTS

Prior to Spray Application:

- Record OAT, wind speed and direction, RH and sky condition.

After Spray Application (One-step Type IV application):

- Record fluid application quantities;
- Measure fluid thickness at the 18 pre-determined locations on each wing;
- Collect Type IV fluid samples for viscosity tests;
- Record wing temperatures;
- Photograph and videotape the appearance of the fluid on the wing.

Prior to Takeoff:

- Measure fluid thickness at the 18 pre-determined locations on each wing.

During Takeoff:

- Videotape the behaviour of the fluid on the wing during the takeoff run and climb, capturing any movement of fluid;
- With a second video camera, record readings from the air speed indicator.

Upon Return to the De-icing Pad:

- Document fluid condition on the wing;
- Measure thickness of any fluid remaining;
- Record wing skin temperatures;
- Collect Type IV fluid samples for later viscosity measurement.

Attachment II
Test Equipment Checklist

TASK Logistics for Every Test	STATUS
Monitor Forecast	
Coordinate test initiation with NRC, TDC	
Rent generator for mobile sprayer	
Rent pick-up truck for mobile sprayer	
Advise Globe Ground; arrange for Deicing Truck with Type IV	
Advise YOW Airport Operations	
Arrange for fluid recovery vehicle at NRC hangar	
Advise Security agency	
TEST EQUIPMENT	
Aircraft Support	
Generator to support aircraft heating	
220 volt extension cable for Falcon heater with correct plug	
Aluminum rate pan	
Camera Equipment	
Digital video camera for over-wing position	
Digital still camera	
General Support Equipment	
Fuel for generators	
Large tape measure	
Step Ladders – Short + Tall	
Test Equipment	
Test Procedures, data forms	
Rate pan with Type IV fluid	
Clipboards, pencils	
Sartorius weigh scale	
Wing markers for sample locations and solvent	
Thickness Gauges	
Temperature Probe x 2 and spare batteries	
Devices to lift fluid samples for viscosity	
Sample bottles for viscosity measurement	
Personnel Equipment	
Hearing Protectors (yellow foam)	
Security passes	

Attachment III
APS Staff Task Description

Co-ordinator (MC)

- Initiate test with NRC, TDC, Globe Ground;
- Advise all other agencies, including airport security;
- Advise APS test team;
- Ensure that all required equipment is available and functional;
- Provide direction as required during the tests;
- Maintain General Form for every test (Form 1);
- Maintain General Form for every session (Form 2);
- Ensure all data are collected and recorded, and that all test records submitted;
- Record amount of fluid applied (get from spray team);
- Collect viscosity samples;
- Record thickness measurements; and
- Record natural rain rates.

Video/Photographer – Port Wing and Starboard Wing (YOW)

- Ensure time stamp operating and accurately set.
- Photograph all test set-up, outside and onboard the aircraft.
- Videotape fluid on wings "before and after" each run and during climb, ensuring constant viewing angles are used, to facilitate comparisons.

Fluid Thickness, Spray Application, and Fluid Samples (NB)

  - Spray propylene Type IV fluid using mobile sprayer;
  - Collect samples of Type IV fluid for subsequent viscosity tests;
  - Record specifics for each sample.
- Take one fluid sample of each fluid used in tests
  - Type IV ethylene from deicing vehicle
  - Type IV propylene from mobile sprayer

    Sampling Protocol during Test

    a) Before Take-off

    Take one sample on each wing; note locations.

    b) After Take-Off

    Take one sample of any fluid remaining on each wing; note locations.

  - Measure thickness at selected chord-wise locations. Record fluid thickness on Fluid Thickness on Aircraft form (Form 5).

APPENDIX D

EXPERIMENTAL PROGRAM
FIELD TRIALS TO EXAMINE REMOVAL OF NEAT AND DILUTED FLUID FROM AIRCRAFT WINGS DURING THE TAKEOFF RUN
FEBRUARY 2003 TESTS

CM1747.001

EXPERIMENTAL PROGRAM
FIELD TRIALS TO EXAMINE REMOVAL OF NEAT AND DILUTED FLUID FROM AIRCRAFT WINGS DURING THE TAKEOFF RUN
FEBRUARY 2003 TESTS

Winter 2002-03

Prepared for

Transportation Development Centre
Transport Canada

Prepared by: Michael Chaput

Reviewed by: John D'Avirro

February 13, 2003
Version 1.0

EXPERIMENTAL PROGRAM
FIELD TRIALS TO EXAMINE REMOVAL OF NEAT AND DILUTED FLUID FROM AIRCRAFT WINGS DURING THE TAKEOFF RUN
FEBRUARY 2003 TESTS

Winter 2002-03

Previous trials to examine the elimination of failed SAE Type IV fluid from aircraft wings during takeoff were conducted during the 1997-98 and 1998-99 winter seasons. Those trials, based on simulated takeoff runs using a National Research Council Falcon 20 aircraft, provided an improved understanding of the subject and showed that the selected test approach was a viable one. Additional trials were planned for the 1999-2000 and 2000-01 winter test seasons, however these trials were not conducted due to lack of suitable weather conditions in the limited time that the aircraft and crew were available for testing.

The test program conducted during winter 2001-2002 using the NRC Falcon 20 addressed the effects of unshed anti-icing fluid on aircraft take-off performance. Tests were performed with one ethylene glycol-based Type IV fluid, Dow/UCAR Ultra+, in neat and diluted form. Diluted anti-icing fluid tests used artificial precipitation and a simulated distribution of precipitate over the surface that approximated ‘real world’ conditions.

A preliminary analysis of the flight data recorded by the NRC for tests conducted in 2001-02 winter revealed that a 10% degradation in lift occurs as a result of the presence of neat (undiluted) anti-icing fluid on the wings of the Falcon 20. No differences were noted in tests conducted with diluted anti-icing fluid.

Because only ethylene glycol-based were tested in 2001-02 trials with the Falcon 20, additional tests with propylene fluid are planned for 2002-03. This document provides the procedures and equipment required to support the Falcon 20 tests scheduled for February 2003.

These trials will be co-ordinated and reported by APS. They will be conducted at Ottawa International Airport (YOW) on a Falcon 20 research aircraft owned and piloted by the National Research Council Canada.

This document provides the detailed procedures and equipment required to support these trials.

1. OBJECTIVE

This project addresses the following objective:

- To ascertain whether there is an aerodynamic penalty on the aircraft due to presence of partially expended anti-icing fluid on the wings.

2. TEST REQUIREMENTS

APS will co-ordinate and plan test activities and prepare a final report as well as present results at industry deicing meetings.

APS will provide support to these tests for instrumentation, fluid application, and artificial precipitation application. A digital videotape record of fluid behaviour on aircraft wings during the takeoff run is required and will be recorded by an observer located in the Falcon 20 cabin.

Desired weather conditions are dry, with subfreezing outside air temperature. Tests will be limited to a maximum of 10kts crosswind. Overcast skies are very important to avoid overheating of aircraft wings from exposure to the sun. Runway conditions are to be clean and dry.

Attachment I provides a description of test procedures. Table 2.1 provides a plan overview of the different tests.

Four different sets of tests will be run in February 2003:

1. Tests with clean, uncontaminated anti-icing fluid(s) on the wings (Tests #1-4 in Table 2.1);

2. Tests with clean, uncontaminated anti-icing fluid(s) on the wing areas inboard of the boundary layer fences only (Tests #5-6 in Table 2.1);

3. Tests with clean, uncontaminated anti-icing fluid(s) on the wing areas outboard of the boundary layer fences only (Tests #7-8 in Table 2.1); and

4. Tests with diluted fluid (simulating a fluid just prior to the loss of ability to absorb further freezing precipitation) on the wings (Tests #9-12 in Table 2.1).

Baseline calibration tests with clean, dry wings will be conducted by NRC personnel prior to the designated test period in February 2003 to compare with reference case tests from 2001-02 winter trials.

In the event of a moderate natural rain event during the specified test period in February 2003, tests described in a previous procedure, *Procedure for the Conduct of Tests to Examine the Effects of Natural Rain on the Lift Generated by the Falcon 20, will be conducted.*

A glycol mitigation plan was required by the Ottawa Airport Authority prior to according approval for the conduct of tests at YOW. The glycol mitigation plan has been included in Attachment IV.

Table 2.1: Test Plan
Removal of Neat Fluid from Aircraft Wings During Takeoff Run

TEST #	OAT °C	Fluid	Precipitation	Wing Condition
1	<-3	Type IV EG Neat	No	Clean Fluid
2	<-3	Type IV EG Neat	No	Clean Fluid
3	<-3	Type IV PG Neat	No	Clean Fluid
4	<-3	Type IV PG Neat	No	Clean Fluid
5	<-3	Type IV EG Neat	No	Clean Fluid/Inboard Wing Sections
6	<-3	Type IV EG Neat	No	Clean Fluid/Inboard Wing Sections
7	<-3	Type IV EG Neat	No	Clean Fluid/Outboard Wing Sections
8	<-3	Type IV EG Neat	No	Clean Fluid/Outboard Wing Sections
9	<-3	Type IV EG Neat	Yes	Diluted Fluid
10	<-3	Type IV EG Neat	Yes	Diluted Fluid
11	-3	Type IV PG Neat	Yes	Diluted Fluid
12	-3	Type IV PG Neat	Yes	Diluted Fluid

Six different tests are listed in Table 2.1. All of these tests will be conducted in duplicate to ensure reproducibility.

3. EQUIPMENT AND FLUIDS

3.1 Equipment

Equipment to be employed is shown in Attachment II.

3.2 Fluids

Ethylene glycol-based UCAR Ultra+ Type IV and propylene glycol-based Kilfrost ABC-S Type IV will be used in February 2003 trials.

4. PERSONNEL

Seven APS staff members are required for tests on aircraft at Ottawa airport.

One additional person will be required from Ottawa to record digital video of the testing.

Ethylene and propylene glycol applications will be performed by APS personnel at the NRC hangar using the Type IV mobile sprayer.

Waste fluid clean-up and recovery will be performed by Inland Technologies at the NRC hangar.

National Research Council flight crews will operate the National Research Council aircraft.

Attachment III provides task assignments.

5. DATA FORMS

The following data forms are required for the February 2003 Falcon 20 tests.

Form 1	General Form (Every Test);
Form 2	Fluid Freeze Point Measurement Locations During Precipitation – Port Wing;
Form 2A	Fluid Freeze Point Measurement Locations During Precipitation – Starboard Wing;
Form 2B	Fluid Freeze Point Measurements on Aircraft;
Form 3	Fluid Freeze Point Distribution Prior to Takeoff – Port Wing;
Form 3A	Fluid Freeze Point Distribution Prior to Takeoff – Starboard Wing;
Form 4	Wing Temperature Form – Port Wing;
Form 4A	Wing Temperature Form – Starboard Wing;
Form 5	Fluid Thickness on Aircraft Prior to Takeoff – Port Wing;
Form 5A	Fluid Thickness on Aircraft Prior to Takeoff – Starboard Wing;
Form 6	Thickness Measurements to Support Development of the ADMS Model; and
Form 7	Freezing Rain/Snow Quantity Form.

FORM 1

GENERAL FORM (EVERY TEST)

(TO BE FILLED IN BY OVERALL COORDINATOR)

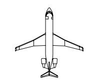
AIRCRAFT TYPE: FALCON 20

DATE: ____________________

RUN #: ____________________

DIRECTION OF AIRCRAFT: ________ DEGREES

DRAW DIRECTION OF WIND AT DEICING CENTRE WRT AIRCRAFT:



DEPARTURE TIME FROM DE-ICING BAY: ____________

START TIME OF TAKE-OFF ROLL: ____________

TIME OF LANDING: ____________

RETURN TO DEICING BAY: ____________

OAT (° C) BEFORE TEST: ____________

OAT (° C) AFTER TEST: ____________

WIND SPEED / DIRECTION: ____________

DEPARTURE RUNWAY: ____________

FLUID APPLIED: ____________

FLUID APPLICATION - PORT WING			
Actual Start Time:	____________ **am / pm**	**Actual End Time:**	____________ **am / pm**
Amount of Type I:	____________ **L / gal**	**Amount of Type IV:**	____________ **L / gal**
Fluid Sample Collected from Truck or Barrel:	**Y / N**		
FLUID APPLICATION - STARBOARD WING			
Actual Start Time:	____________ **am / pm**	**Actual End Time:**	____________ **am / pm**
Amount of Type I:	____________ **L / gal**	**Amount of Type IV:**	____________ **L / gal**
Fluid Sample Collected from Truck or Barrel:	**Y / N**		
CONTAMINANT SPRAY APPLICATION			
Actual Start Time (port wing):	____________ **am / pm**	**Actual End Time:**	____________ **am / pm**
Actual Start Time (starboard wing):	____________ **am / pm**	**Actual End Time:**	____________ **am / pm**

End of Test Time: ____________ (hr:min:ss) am/pm

COMMENTS: ____________________

SKY CONDITIONS: ____________________

MEASUREMENTS BY: ____________________

HANDWRITTEN BY: ____________________

I:\Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms

FORM 2

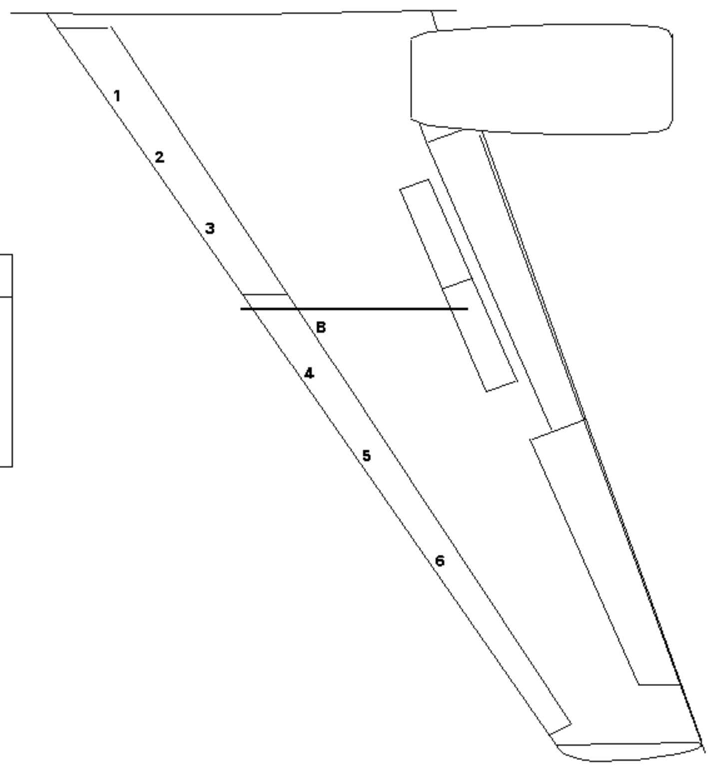
FLUID FREEZE POINT MEASUREMENT LOCATIONS DURING PRECIPITATION (FOR USE WITH FORM 2B)

FALCON 20 PORT WING

Date: .... **Time:** .... **Run Number** ....

Monitor Brix at 6 locations and at baseline location "B"

UCAR ULTRA+		KILFROST ABC-S	
FFP (°C)	Brix	FFP (°C)	Brix
-2	5.6	-2	5
-4	8.8	-4	8
-6	11.2	-6	12.5
-8	13.3	-8	17
-10	15.1	-10	19.3
-12	16.8	-12	22
-14	18.3	-14	23.5
-16	19.7	-16	25.5



COMMENTS: ....

OBSERVER: ....

ASSISTED BY: ....

Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms
Form 2

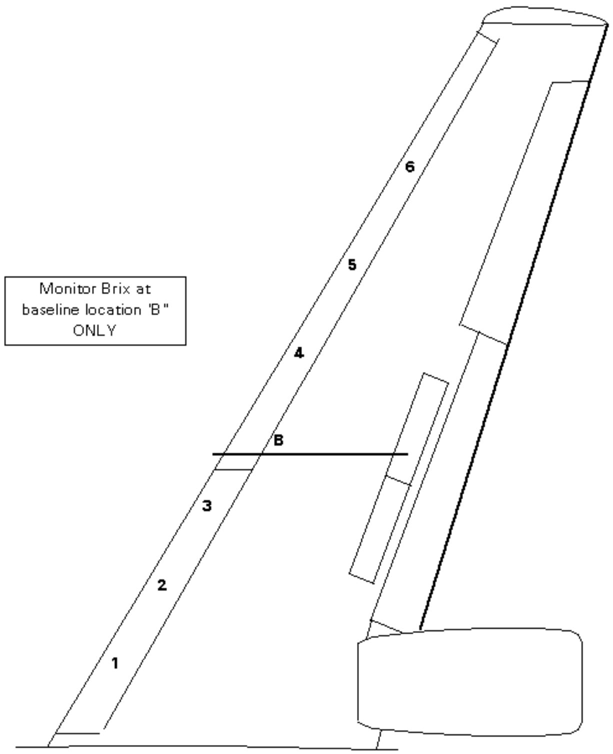
FORM 2A

FLUID FREEZE POINT MEASUREMENT LOCATIONS DURING PRECIPITATION (FOR USE WITH FORM 2B)

FALCON 20 STARBOARD WING

Date: .... **Time:** .... **Run Number** ....

Monitor Brix at baseline location 'B' ONLY



UCAR ULTRA+		KILFROST ABC-S	
FFP (°C)	Brix	FFP (°C)	Brix
-2	5.6	-2	5
-4	8.8	-4	8
-6	11.2	-6	12.5
-8	13.3	-8	17
-10	15.1	-10	19.3
-12	16.8	-12	22
-14	18.3	-14	23.5
-16	19.7	-16	25.5

COMMENTS: ....

OBSERVER: ....

ASSISTED BY: ....

I:\Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms
Form 2a

FORM 2B

FLUID FREEZE POINT MEASUREMENTS ON AIRCRAFT

AIRPORT: YOW

AIRCRAFT TYPE: FALCON 20

DATE: ____________

WING: PORT STARBOARD

DRAW DIRECTION OF WIND WRT WING:

RUN #: ____________

DIRECTION OF AIRCRAFT: ________ DEGREES

PRIOR TO TAKEOFF

Location	Time	Brix	Time	Brix	Time	Brix	Time	Brix	Time	Brix	Time	Brix	Time	Brix	Time	Brix
1																
2																
3																
4																
5																
6																
B																

COMMENTS:

MEASUREMENTS BY: ________

HAND WRITTEN BY: ________

I:\Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms
Form 2B

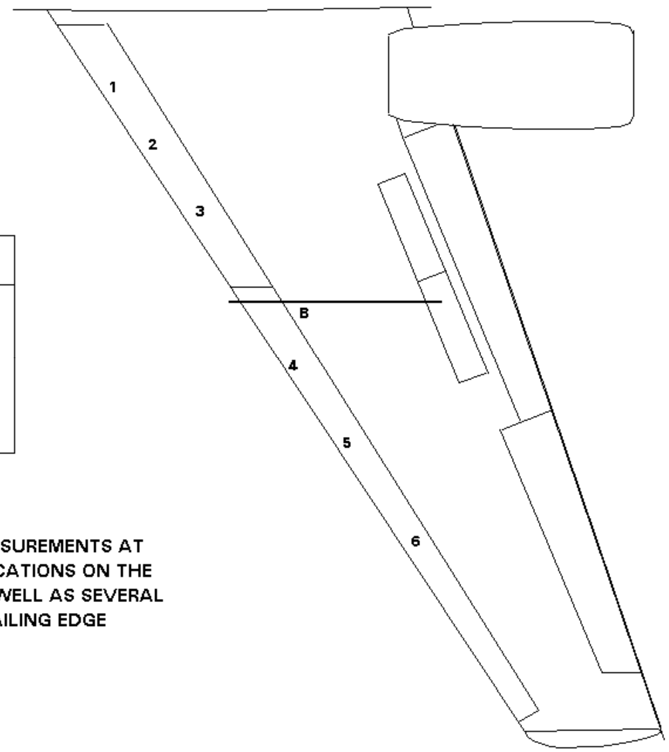
FORM 3

FLUID FREEZE POINT DISTRIBUTION PRIOR TO TAKEOFF

FALCON 20 PORT WING

Date: ____________ **Time:** ____________ **Run Number** ________

UCAR ULTRA+		KILFROST ABC-S	
FFP (°C)	Brix	FFP (°C)	Brix
-2	5.6	-2	5
-4	8.8	-4	8
-6	11.2	-6	12.5
-8	13.3	-8	17
-10	15.1	-10	19.3
-12	16.8	-12	22
-14	18.3	-14	23.5
-16	19.7	-16	25.5



MAP OUT BRIX MEASUREMENTS AT ALL NUMBERED LOCATIONS ON THE LEADING EDGE AS WELL AS SEVERAL LOCATIONS ON TRAILING EDGE

COMMENTS: ____________________

OBSERVER: ____________________

ASSISTED BY: ____________________

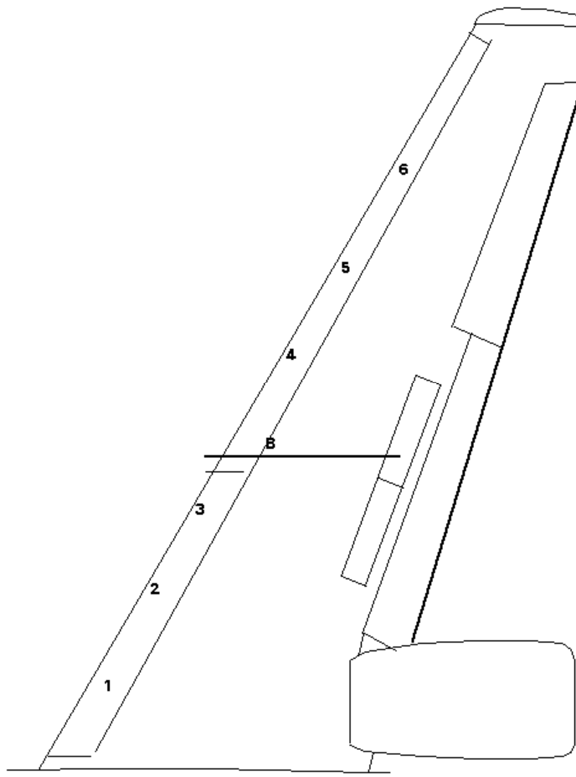
Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms
Form 3

FORM 3A

FLUID FREEZE POINT DISTRIBUTION PRIOR TO TAKEOFF

FALCON 20 STARBOARD WING

Date: ____________ Time: ____________ Run Number ________



UCAR ULTRA+		KILFROST ABC-S	
FFP (°C)	Brix	FFP (°C)	Brix
-2	5.6	-2	5
-4	8.8	-4	8
-6	11.2	-6	12.5
-8	13.3	-8	17
-10	15.1	-10	19.3
-12	16.8	-12	22
-14	18.3	-14	23.5
-16	19.7	-16	25.5

MAP OUT BRIX MEASUREMENTS AT ALL NUMBERED LOCATIONS ON THE LEADING EDGE AS WELL AS SEVERAL LOCATIONS ON TRAILING EDGE

COMMENTS: ____________________

OBSERVER: ____________________

ASSISTED BY: ____________________

I:\Groups\Cm1747\Procedures\Falcon 20\FEB 2003\Data Forms
Form 3a

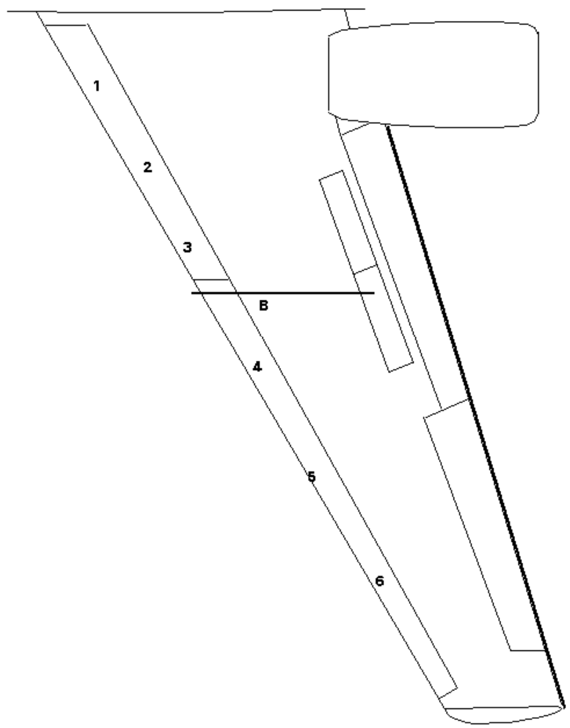
FORM 4

WING TEMPERATURE FORM

FALCON 20 PORT WING

Date:.................... **Time:**.................... **Run Number** ....

Test Phase: **A - before contamination** ☐ **B- before takeoff** ☐



RECORD WING TEMPERATURES ON THE LEADING EDGE AT ALL THE NUMBERED LOCATIONS

OBSERVER:....................................

ASSISTED BY:....................................

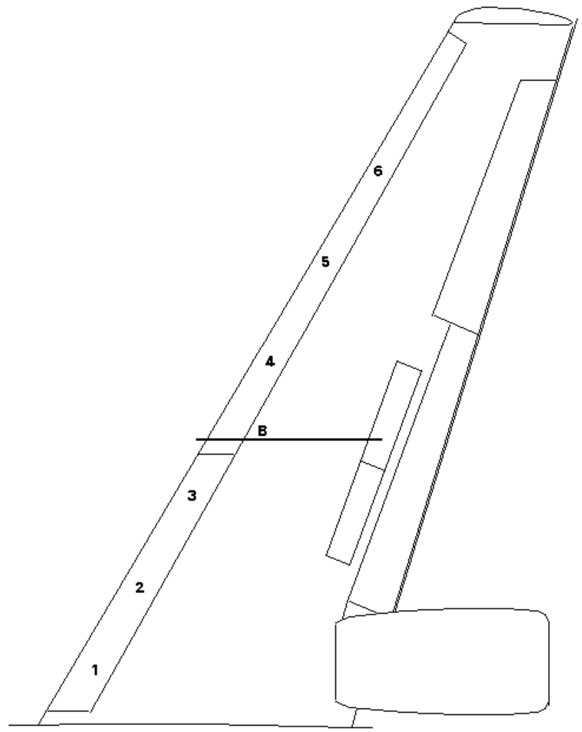
I:\Groups\Cm1747\Procedures\Falcon 20\feb 2003\Data Forms
Form 4

FORM 4A

WING TEMPERATURE FORM

FALCON 20 STARBOARD WING

Date: ______	**Time:** ______	**Run Number** ______
Test Phase: **A - before contamination** ☐	**B - before takeoff** ☐	



RECORD WING TEMPERATURES ON THE LEADING EDGE AT ALL THE NUMBERED LOCATIONS

OBSERVER: ______

ASSISTED BY: ______

I:\Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms
Form 4a

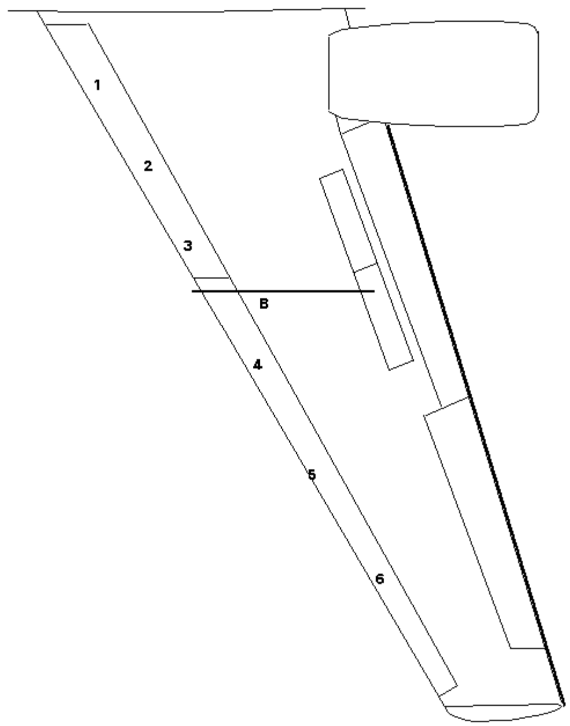
FORM 5

FLUID THICKNESS MEASUREMENTS

FALCON 20 PORT WING

Date: ________ **Time:** ________ **Run Number** ________

Test Phase: **A - before contamination** [ ] **B - before takeoff** [ ]



RECORD FLUID THICKNESS MEASUREMENTS ON THE LEADING EDGE AT ALL THE NUMBERED LOCATIONS

OBSERVER: ________

ASSISTED BY: ________

I:\Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms
Form 5

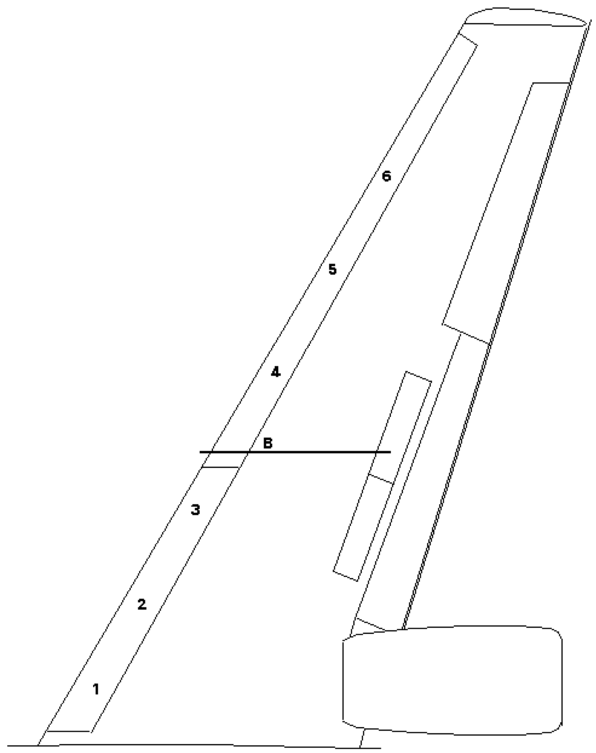
FORM 5A

FLUID THICKNESS MEASUREMENTS

FALCON 20 STARBOARD WING

Date: .... **Time:** .... **Run Number** ....

Test Phase: **A - before contamination** ☐ **B - before takeoff** ☐



RECORD FLUID THICKNESS MEASUREMENTS ON THE LEADING EDGE AT ALL THE NUMBERED LOCATIONS

OBSERVER: ....

ASSISTED BY: ....

I:\Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms
Form 5a

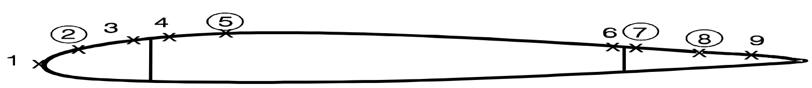
FORM 6
THICKNESS MEASUREMENTS TO SUPPORT DEVELOPMENT OF THE ADMS MODEL

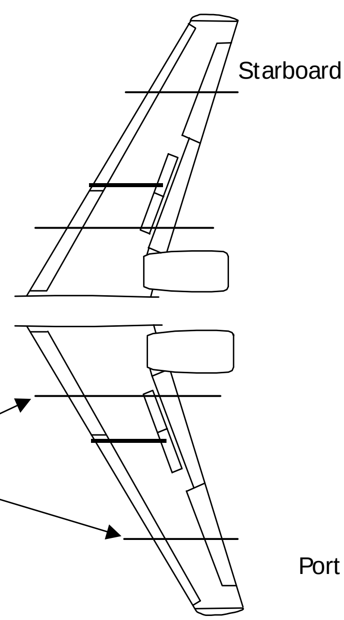
Run: ________________

Date: ________________

		PORT				STARBOARD			
	Wing Position	BEFORE RAIN SPRAY	AFTER RAIN SPRAY	BEFORE TAKEOFF	AFTER TAKEOFF	BEFORE RAIN SPRAY	AFTER RAIN SPRAY	BEFORE TAKEOFF	AFTER TAKEOFF
OUTBOARD	1								
	2								
	3								
	4								
	5								
	6								
	7								
	8								
	9								
INBOARD	1								
	2								
	3								
	4								
	5								
	6								
	7								
	8								
	9								

M:\Groups\Cm1680 (01-02)\Reports\Falcon 20\Working Documents\Table 2.1





Location
1 - LE Nose
2, 8 – Halfway
3,4,6,7 – 1” From joint
5 – As far as can reach
9 – 6” From TE

Note:
Give priority to circled locations; measure other locations only if time allows.
Lateral locations of thickness measures are 1 to 2 metres on both sides of the fence.

Location of inboard and outbourd test denoted by lines.

M:\Groups\CM1747\Procedures\Falcon 20\February 2003\Form 6.doc

FORM 7

FREEZING RAIN/SNOW QUANTITY FORM

Date: ___________

Time Before	Time After	Run	ZR- or Snow	Container Weight (kg)	
				Before	After

Measured by: ____________________

Handwritten by: ____________________

I:\Groups\Cm1747\Procedures\Falcon 20\Feb 2003\Data Forms

Form 7

Attachment I
Test Procedures

1. PRE-TEST SETUP

- Co-ordinate with Ottawa Airport Authority (MC);
- Arrange for security escorts and passes, if required (MC);
- Find video specialist in Ottawa to record behaviour of fluid on the aircraft during the precipitation phase, taxi and takeoff of the Falcon 20 (MC);
- Hotels and advances for APS personnel (CD);
- Arrange for vehicles to transport fluid and freezing rain sprayers (NB);
- Arrange personnel travel to Ottawa (MC);
- Ensure proper functioning of mobile sprayer (NB);
- Ensure proper functioning of freezing rain sprayer (NB);
- Mark aircraft data collection locations (see Forms 2, 2A and 6) (NB/RC);
- Ensure NRC personnel draw grid on aircraft wings (MC); and
- Prepare and arrange for transport of equipment to Ottawa (NB/RC).

2. CONTACT LIST

- NRC Flight Research Laboratory: Matthew Bastian (613) 998-3337;
- GlobeGround: Gary Martin (613) 521-4730;
- Inland Technologies: Don Larabie (613) 736-7524 ;
- Harvey Airfield: Doug Harvey (613) 794-6884; and
- Ottawa Airport Authority: Yvon Larochelle (613) 248-2000 ext. 1157.

3. CONDUCT TESTS

Tests # 1 - 4

Prior to Fluid Spray Application:

- Record OAT, wind speed and direction, RH and sky condition; and
- Collect virgin samples of Type IV fluid for viscosity tests.

Fluid Spray Application (One-step Type IV application):

- Conduct spray application at the NRC hangar and prepare fluid sprayer for next application;
- Record fluid application times;
- Record fluid application quantities (if applicable);
- Measure fluid thickness at the 18 pre-determined locations on each wing for two PG Type IV tests (see Form 6);
- Collect Type IV fluid samples for viscosity tests; and
- Photograph and videotape the appearance of the fluid on the wing.

Prior to Takeoff (at runway button):

- Measure fluid thickness at the 18 pre-determined locations on each wing for PG Type IV tests;
- Record wing temperatures on the leading edge (see Forms 4 and 4a);
- Measure fluid thickness on the leading edge (see Forms 5 and 5a);
- Record departure runway, wind speed and direction; and
- Record time of departure.

During Takeoff:

- Videotape the behaviour of the fluid on the wing during the takeoff run and climb, capturing any movement of fluid; and
- With a second video camera, record readings from the air speed indicator (NRC to perform).

Upon Return to the De-icing Pad:

- Collect Type IV fluid samples on wings (if any) for later viscosity measurement.

Tests # 5 - 8

Prior to Fluid Spray Application:

- Record OAT, wind speed and direction, RH and sky condition; and
- Collect virgin samples of Type IV fluid for viscosity tests.

Fluid Spray Application (One-step Type IV application):

- Protect wing surfaces not intended for fluid spraying with tarps; in Tests # 5-6, the wing sections outboard of the fence will be covered and protected from fluid spray; in Tests # 7-8, the wing sections inboard of the fence will be covered and protected from fluid spray;
- Conduct spray application at the NRC hangar and prepare fluid sprayer for next application;
- Record fluid application times;
- Record fluid application quantities (if applicable);
- Remove tarps from the wing surfaces;
- Collect Type IV fluid samples for viscosity tests; and
- Photograph and videotape the appearance of the fluid on the wing.

Prior to Takeoff (at runway button):

- Record wing temperatures on the leading edge (see Forms 4 and 4a);
- Measure fluid thickness on the leading edge (see Forms 5 and 5a);
- Record departure runway, wind speed and direction; and
- Record time of departure.

During Takeoff:

- Videotape the behaviour of the fluid on the wing during the takeoff run and climb, capturing any movement of fluid; and
- With a second video camera, record readings from the air speed indicator (NRC to perform).

Upon Return to the De-icing Pad:

- Collect Type IV fluid samples from wings (if any) for later viscosity measurement.

Tests # 9 - 12

Prior to Fluid Spray Application:

- Record OAT, wind speed and direction, RH and sky condition; and
- Collect virgin samples of Type IV fluid for viscosity tests.

Fluid Spray Application (One-step Type IV application):

- Conduct spray application at the NRC hangar and prepare fluid sprayer for next application;
- Record fluid application times;
- Record fluid application quantities (if applicable);
- Collect Type IV fluid samples for viscosity tests;
- Prepare and place rate pans on wings; and
- Photograph and videotape the appearance of the fluid on the wing.

Freezing Rain Application

- Start the rate collection period;
- Apply the freezing rain over the two wings. Record the start of the precipitation application process;
- Measure fluid freeze points on the wings at 6 numbered locations and the baseline location on the port wing (Forms 2 and 2B) and at the baseline location on the starboard wing (Forms 2A and 2B) at 5-minute intervals;
- When the desired level of precipitation (onset of failure on the trailing edge) has been applied to the wings, the wing observer will call for the end of the precipitation application process;
- Remove rate pans from wing surfaces; and
- Photograph and videotape the appearance of the fluid on the wing.

Prior to Takeoff (at runway button):

- Map the fluid freeze point distribution on each wing (see Forms 3 and 3A)
- Record wing temperatures on the leading edge (see Forms 4 and 4a);
- Measure fluid thickness on the leading edge (see Forms 5 and 5a);
- Record departure runway, wind speed and direction; and

- Record time of departure.

During Takeoff:

- Videotape the behaviour of the fluid on the wing during the takeoff run and climb, capturing any movement of fluid; and
- With a second video camera, record readings from the air speed indicator (NRC to perform).

Upon Return to the Deicing Pad:

- Collect Type IV fluid samples from wings (if any) for later viscosity measurement.

After Each Test Session

- Inland will be contacted to collect the waste solution from the NRC apron. APS will apply EG and PG-based Type IV fluids at different locations on the NRC apron to ensure the waste solutions are properly separated.

Attachment II
Test Equipment Checklist

TASK **Logistics for Every Test**	STATUS
Monitor Forecast	
Coordinate test initiation with NRC, TDC	
Alert APS test Personnel	
Rent Cube Truck for rain sprayer	
Rent portable generators (10 KW, 220V 30 AMPS twist lock 4 prongs)	
Rent Cube van for equipment delivery	
Advise YOW Airport Operations	
Advise Security agency, confirm number of passes and escorts	
Advise Inland	
TEST EQUIPMENT	
Freezing Rain Sprayer with needles for freezing rain	
Water for rain sprayer	
APS Generator	
Dish heater for cube van	
Type IV fluid sprayer and hoses	
2 large tarps for wing coverage	
Pylons	
Aluminum rate pan on legs, to mount on wing x 2	
Digital video camera	
Cassettes for video camera	
Digital still camera	
Fuel for generators	
Large tape measure	
Step Ladders – Short + Tall	
Electrical extension cables (heavy gauge extension 25 ft – compressor)	
Radios X 2 (walkie-talkies)	
Test Procedures	
Data Forms	
Clipboards	
Pencils	
Sartorius Weigh scale and insulation	
Devices for lifting fluid samples for Brix tests	
Hearing Protectors (yellow foam)	
Wing markers for sample locations and solvent	
Tape measures	
Thickness Gauges x 8	
Hand held temperature probe x 2 and spare batteries	
Surface and liquid extensions for temperature probe	
Brixometer X 3 Devices for lifting fluid samples for Brix tests	
Plastic spatulas x 5 (lift fluid samples for viscosity)	
Glass sample bottles for viscosity measurement (small bottles x 30)	
Sample bottles for viscosity measurement (1 litre x 15)	
Anemometer	

Attachment III
APS Staff Task Description

Co-ordinator (MC)

- Apply markings to aircraft prior to testing;
- Co-ordinate tests with NRC, TDC, Globe Ground, Inland;
- Advise all other agencies, including security;
- Advise APS test team;
- Ensure that all required equipment is available and functional;
- Provide direction as required during the tests;
- Maintain General Form for every test (Form 1);
- Ensure all data are collected and recorded, and that all test records submitted;
- Record start and end of precipitation on each wing;
- Announce end-of-precipitation according to test plan for each wing;
- Record amount of precipitation applied (get from spray team); and
- Record thickness, brix, and temperature information prior to takeoff.

Videographer/Photographer (YOW)

- Ensure time stamps are operating and accurately set;
- Videotape fluid on wing "before and after" each run and during climb, ensuring constant viewing angles are used, to facilitate comparisons; and
- Photograph all test set-up, outside and onboard the aircraft.

Fluid Thickness, Brix, Temperature (RC)

  - Assist fluid spray manager in fluid spray applications;
  - Measure thickness, brix and temperature at the appropriate locations prior to takeoff (at the runway button) for tests without precipitation;
- For tests with artificial precipitation, measure fluid freeze points on the wings at 6 numbered locations and the baseline location on the port wing (Forms 2 and 2B) and at the baseline location on the starboard wing (Forms 2A and 2B) at 5-minute intervals during the application of freezing precipitation; and
- For Tests # 3-4, measure fluid thickness at the 18 pre-determined locations on each wing (see Form 6) after fluid application, following the taxi of the aircraft to the button, and following the return of the aircraft to the de-icing pad;

Samples, Rates, Fluid Thickness (MM)

  - For all tests, collect samples of Type IV fluid for subsequent viscosity tests:
    - Virgin Type IV prior to spraying;
    - Type IV fluid on wing applied through sprayer; and
    - Type IV fluid remaining on trailing edge following takeoff.

- Record the specifics for each sample on the bottle in permanent marker;
- For tests with precipitation, set-up scale in cube van for weighing precipitation;
- Install rate pans on wings prior to each test;
- Weigh and record the amount of precipitation collected during the test in the rate pan mounted on the wings (Form 7);
- Remove rate pans from wings following each test, prior to starting the engines; and
- For Tests # 3-4, assist in measurement of fluid thickness at the 18 pre-determined locations on each wing (see Form 6) after fluid application, following the taxi of the aircraft to the button, and following the return of the aircraft to the de-icing pad;

Type IV Fluid / Freezing Rain Sprayer Manager (NB)

- Apply markings to aircraft prior to testing;
- Responsible to ensure proper functioning of the Type IV fluid sprayer;
- Conduct spray application at the NRC hangar and prepare fluid sprayer for next application;
- Responsible to ensure proper functioning of the rain sprayer equipment, giving attention to preventing lines from freezing between tests;
- Responsible for overall equipment operation including re-fuelling portable generators; and
- Manage and guide two spray assistants;

Freezing Rain Sprayer Assistants 1 (YOW1) and 2 (YOW2)

- Responsible for spraying freezing rain over the wings until advised by the *wing observer* that the desired amount of precipitation has been dispensed.

ATTACHMENT IV

GLYCOL MITIGATION PLAN

APS AVIATION INC.

AIRCRAFT ANTI-ICING FLUID ELIMINATION TESTS WITH THE NATIONAL RESEARCH COUNCIL FALCON 20 AIRCRAFT OTTAWA, ONTARIO (YOW) FEBRUARY 18-28, 2003

1. CORPORATE PROFILE

APS Aviation Inc. (APS), member of the ADGA Group of companies, is a worldwide leader in aircraft de-icing research and development. Since 1990, APS has been contracted by the Transportation Development Centre (TDC) of Transport Canada to further advance aircraft pre-flight de/anti-icing technology. During the past twelve years, APS has produced 61 technical reports for the TDC-funded research projects.

2. BACKGROUND

At the request of the Transportation Development Centre (TDC) of Transport Canada, APS has undertaken a research program to examine the potential aerodynamic penalties resulting from the presence of clean and diluted anti-icing fluid on aircraft wings.

Previous trials to examine the aerodynamic elimination of failed Type IV fluid from aircraft wings during takeoff were conducted on behalf of Transport Canada during the 1997-98 and 1998-99 winter seasons at Mirabel Airport (YMX). Those trials, based on simulated takeoff runs using a National Research Council Falcon 20 aircraft, provided an improved understanding of the subject matter and demonstrated that the selected test approach was a viable one.

During the winter of 2001-2002, flight tests were performed at Ottawa International Airport (YOW). Tests were performed with one ethylene glycol-based Type IV fluid, Dow Ultra+, in neat and diluted form. Fluid was applied at the central de-icing pad at YOW by GlobeGround personnel.

A preliminary analysis of the flight data recorded by the NRC for tests conducted in 2001-02 winter revealed that a 10% degradation in lift occurs as a result of the presence of neat (undiluted) ethylene glycol anti-icing fluid on the wings of the Falcon 20. No differences were noted in tests conducted with diluted anti-icing fluid. Because only ethylene glycol-based fluid was tested in 2001-02 trials with the Falcon 20, additional tests with propylene fluid are planned for 2002-03 at YOW.

This document describes the glycol mitigation plan for the planned tests as follows:

1. The fluid application procedures;
2. The locations designated for fluid application;

3. The anticipated fluid quantities to be sprayed; and
4. The fluid recovery plan.

3. FLUID APPLICATION PROCEDURES

In previous tests conducted at YOW with ethylene fluid, GlobeGround personnel applied the Dow Ultra+ Type IV fluid to the wings of the Falcon 20 at the central deicing pad. The GlobeGround deicing vehicles were manufactured by Superior, model 1045, and were equipped with Task Force Tips spray nozzles, model # BH-Type 2. All deicing fluid that fell to the ground within the application area was properly recovered.

In February 2003, tests will be conducted at YOW with ethylene and propylene glycol-based Type IV fluids.

Because only one Type IV fluid of ethylene glycol formulation is used by operators at YOW, APS personnel developed a mobile sprayer to enable application of a propylene fluid. The mobile sprayer comprises three interrelated components: a fluid reservoir, a fluid pump, and a fluid application nozzle. The components of the mobile sprayer are described below:

a) A non-shearing fluid pump, identical to those installed in deicing vehicles, forces the fluid from the reservoir. The fluid reservoir is a 200-L drum adapted with the appropriate fittings and hoses to supply the pump and receive fluid when the application nozzle is closed;
b) A pressure gauge monitors the pump system fluid pressure. An adjustable relief valve controls the system pressure. A check valve mounted at the root of the fluid supply hose prevents any fluid from draining back to the reservoir when the pump is turned off;
c) The pump is driven by an electric motor, which requires a generator capable of producing a minimum of 550 V, 30 kW, and three-phase current; and
d) A Task Force Tips nozzle is connected to the pump with a pressure-resistant rubber hose fitted with locking couplings.

The sprayer system will be transported on the bed of a pickup truck and will be operated by APS personnel. APS personnel are highly experienced in aircraft deicing matters, and attempts will be made to limit the quantities of fluid applied to the aircraft.

At this time, APS is unsure whether the ethylene fluid applications will be performed by APS personnel using the mobile sprayer at the NRC pad or by GlobeGround personnel at the central deicing pad. All propylene glycol applications will be performed by APS personnel using the mobile sprayer at the NRC pad.

All Type IV fluids will be applied unheated to the wings of the Falcon 20 using industry-accepted spray procedures. No Type I fluid will be applied prior to the Type IV.

4. LOCATIONS DESIGNATED FOR FLUID APPLICATION

Two locations have been identified as potential sites for fluid application activities:

- The central deicing pad; and
- NRC pad

Should the services of GlobeGround be required, the central deicing pad will be the designated location for the ethylene glycol spray applications.

Spray applications at the NRC pad will be conducted in close proximity to the NRC hangar. Two separate areas will be assigned, one for ethylene applications (if necessary), the other for propylene applications. NRC personnel will determine the precise locations prior to testing. The aircraft will not be positioned near the stormwater catch basins located on the southern edge of the NRC apron.

5. ANTICIPATED FLUID QUANTITIES TO BE SPRAYED

Twelve tests are anticipated for February 2003 at YOW. Of this total, six will be performed with Dow Ultra+ (ethylene) and six will be performed with Kilfrost ABC-S (propylene).

Based on typical spray quantities for this aircraft, the estimated maximum amount of fluid required for the conduct of these tests will be 1400 litres (700 of each glycol base). Of this quantity, roughly 50% falls to the ground immediately following application.

6. FLUID RECOVERY PLAN

Inland Technologies at YOW was contacted to provide fluid recovery services at the NRC pad. Inland will provide sweeper vehicles to collect both the propylene and ethylene waste solutions. The waste solutions will be recovered and stored separately to prevent cross-contamination of the products. APS will incur the costs of these fluid recovery services.

If tests are conducted at the central deicing pad, APS will use the services of GlobeGround and standard fluid recovery procedures will apply.

7. ADDITIONAL REPORTS

A subsequent report will be provided by APS to the airport authority following the conduct of tests at YOW to provide the quantities of fluid used in testing.

APPENDIX E

GLYCOL MITIGATION PLAN

GLYCOL MITIGATION PLAN

APS AVIATION INC.

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If tests are conducted at the central deicing pad, APS will use the services of GlobeGround and standard fluid recovery procedures will apply.

7. ADDITIONAL REPORTS

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APPENDIX F

VOLUME OF PROPYLENE GLYCOL FLUID THAT FELL TO THE GROUND AT VARIOUS STAGES DURING THE FALCON 20 TESTS AIRPORT DE-ICER MANAGEMENT SYSTEM (ADMS) DATA FOR RUN 6

VOLUME OF PROPYLENE GLYCOL FLUID THAT FELL TO THE GROUND AT VARIOUS STAGES DURING THE FALCON 20 TESTS

Propylene Glycol Test, February 25, 2003
Ottawa, Ontario

Volume of Type IV Fluid that Fell to the Ground Within the Application Area

The volume of fluid that fell to the ground within the application area during the Falcon 20 test with propylene glycol Type IV (Run 6) can be approximated for each wing at any time during the thickness decay period using the following formula:

V = Q – (t x a)
Where

V= Volume of fluid that falls to the ground in the application area (litres)
Q= Fluid application quantity (litres)
t= Average fluid thickness on wing (mm)
a= surface area of the wing = 20.5 m^2

For the port wing, the average fluid thickness on the wing prior to the departure of the aircraft from the deicing bay was 1.7 mm. As such, the approximate volume of fluid remaining on this wing would be 34.9 litres. Since 50 litres of Type IV fluid were applied to the wing, it can be deduced that about 15.1 litres fell to the ground in the deicing bay as a result of overspray and dripping.

For the starboard wing, the average fluid thickness on the wing prior to the departure of the aircraft from the deicing bay was 1.5 mm, which is incredibly low. The approximate volume of fluid remaining on this wing was 30.8 litres. Since 50 litres of Type IV fluid was applied to the wing, it can be assumed that 19.2 litres fell to the ground at the deicing bay.

Volume of Type IV Fluid that Fell to the Ground on the Taxiways

The volume of fluid that had fallen to the ground on the taxiways during the Falcon 20 tests could be approximated for each wing using the following formula:

V = Q – (t x a)
Where

V= Volume of fluid that falls to the ground on the taxiways (litres)
Q= Quantity of fluid on wing prior to leaving the deicing bay (litres)
t= Average fluid thickness on wing (mm)
a= surface area of the wing = 20.5 m^2

For the port wing, the average fluid thickness on the wing before take-off was 1 mm. As such, the approximate volume of fluid remaining on the port wing was 20.5 litres. Since 34.9 litres of Type IV fluid were present on the wing when it departed from the deicing pad, it can be deduced that 14.4 litres fell to the ground on the taxiways.

For the starboard wing, the average fluid thickness on the wing before takeoff was 1 mm. As such, the approximate volume of fluid remaining on the port wing was 20.5 litres. Since 30.8 litres of Type IV fluid were present on the wing when it departed from the deicing pad, it can be deduced that 10.3 litres fell to the ground on the taxiways.