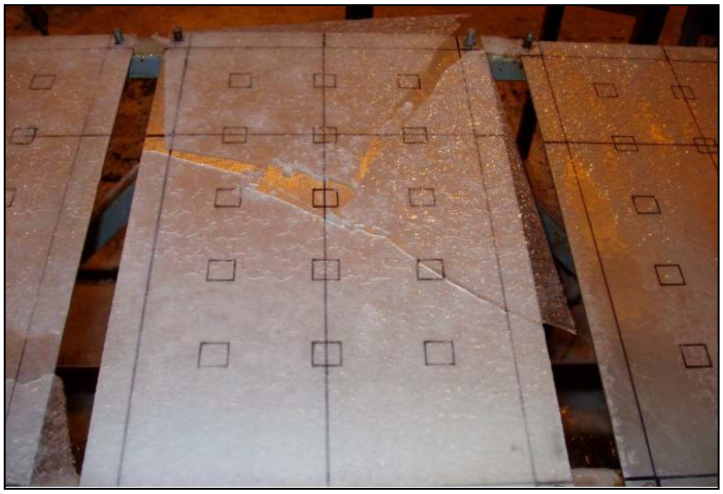
TP 14377E

Adhesion of Aircraft Anti-Icing Fluids on Aluminum Surfaces



Prepared by

APS Aviation Inc.

Prepared for
Transportation Development Centre

In cooperation with

Civil Aviation
Transport Canada

And

The Federal Aviation Administration
William J. Hughes Technical Center

December 2004
Final Version 1.0

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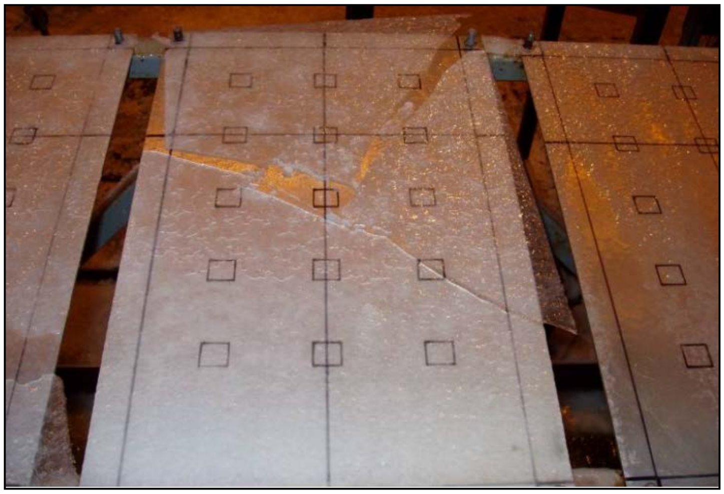

By:

Nicoara Moc

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

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

DOCUMENT ORIGIN AND APPROVAL RECORD

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Un sommaire français se trouve avant la table des matières.

This report was first provided to Transport Canada as Final Draft 1.0 in December 2004.
It has been published as Final Version 1.0 in August 2018.

***Final Draft 1.0 of this report was signed and provided to Transport Canada in December 2004. A Transport Canada technical and editorial review was subsequently completed and the report was finalized in August 2018; Nicoara Moc and Jean Valiquette were not available to participate in the final review or to sign the current version of the report.*

PREFACE

Under contract to the Transportation Development Centre of Transport Canada, APS Aviation Inc. (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 weather data from previous winters to establish a range of conditions suitable for the evaluation of holdover time limits;
- 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 with a real-time snow precipitation gauge with rates obtained using rate pans;
- To further develop and to assist with the commercialization of Type III fluids;
- To develop a test procedure for evaluating forced-air assist systems; and
- To conduct general and exploratory de/anti-icing research.
- To evaluate the possibility of using a fluid failure sensor in holdover time testing.

The research activities of the program conducted on behalf of Transport Canada during the winter of 2003-04 are documented in nine reports. The titles of the reports are as follows:

• TP 14374E	Aircraft Ground De/Anti-Icing Fluid Holdover Time Development Program for the 2003-04 Winter;
• TP 14375E	Winter Weather Impact on Holdover Time Table Format (1995-2004);
• TP 14376E	Endurance Time Testing in Snow: Comparison of Indoor and Outdoor Data for 2003-04;
• TP 14377E	Adhesion of Aircraft Anti-Icing Fluids on Aluminum Surfaces;
• TP 14378E	Evaluation of a Real-Time Snow Precipitation Gauge for Aircraft Deicing Operations (2003-04);
• TP 14379E	Development of Holdover Time Guidelines for Type III Fluids;
• TP 14380E	A Protocol for Testing Fluids Applied with Forced Air Systems;
• TP 14381E	Aircraft Ground Icing General and Exploratory Research Activities for the 2003-04 Winter; and
• TP 14382E	A Sensor for Detecting Anti-Icing Fluid Failure: Phase I.

In addition, the following interim report is being prepared:

- *Substantiation of Aircraft Ground Deicing Holdover Times in Frost Conditions.*

This report, TP 14377E, has the following objective:

- To document the adhesion of aircraft anti-icing fluids on aluminum surfaces.

This objective was met by conducting fluid adhesion tests under natural snow, artificial snow and simulated freezing precipitation conditions. The information collected from these tests was analysed to document the instances in which fluid adhesion occurs, and in these cases, to determine the extent of the safety buffer between endurance time and adhesion time.

PROGRAM ACKNOWLEDGEMENTS

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

APS 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: Stephanie Bendickson, Nicolas Blais, Richard Campbell, Michael Chaput, Sami Chebil, John D’Avirro, Peter Dawson, Marco Di Zazzo, Miljana Horvat, Mark Mayodon, Chris McCormack, Nicoara Moc, Catalin Palamaru, Filomeno Pepe, Marco Ruggi, Joey Tiano, Kim Vepsa, and David Youssef.

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

Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 14377E	2. Project No. B14W	3. Recipient's Catalogue No.

4. Title and Subtitle

Adhesion of Aircraft Anti-Icing Fluids on Aluminum Surfaces

5. Publication Date

December 2004

6. Performing Organization Document No.

CM1892.001

7. Author(s)

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8. Transport Canada File No.

2450-BP-14

9. Performing Organization Name and Address

APS Aviation Inc.
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10. PWGSC File No.

TOR-4-37170

11. PWGSC or Transport Canada Contract No.

T8156-140243/001/TOR

12. Sponsoring Agency Name and Address

Transportation Development Centre (TDC)
Transport Canada
330 Sparks St., 25th Floor
Ottawa, Ontario, K1A 0N5

13. Type of Publication and Period Covered

Final

14. Project Officer

Antoine Lacroix for Barry Myers

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

Research reports produced on behalf of Transport Canada for testing during previous winters are available from the Transportation Development Centre (TDC). Nine reports (including this one) were produced as part of this winter's research program. Their subject matter is outlined in the preface. This project was co-sponsored by the Federal Aviation Administration.

16. Abstract

A research program to study and document the adhesion of aircraft anti-icing fluids subjected to winter precipitation on aluminum surfaces was undertaken by APS Aviation Inc. (APS) in the winters of 2002-03 and 2003-04.

During conduct of Type I snow endurance time testing in the winter of 2001-02, it was observed that at milder temperatures (typically above -3ºC), fluids often completely dilute to water sometime before freezing. When freezing finally occurs, the resulting ice adheres to the surface. Since fluid adhesion is the critical aspect of the clean-wing policy, it would be useful to have a better understanding of the relationship between fluid holdover time and the time that adherence occurs. The difference in these times can be considered a safety buffer, and varies considerably for different conditions.

The objectives of this study were to document the instances in which fluid adhesion occurs and determine the extent of the safety buffer after fluid failure. To satisfy these objectives, laboratory tests under freezing precipitation conditions were conducted at the National Research Council Canada in Ottawa, and natural snow tests were conducted at the APS test site at Trudeau Airport. Tests were also performed under artificial snowmaking system in a cold chamber operated by PMG Technologies Inc. These tests were conducted under a wide range of ambient temperature, precipitation rate, precipitation type, and wind conditions using samples of Type I, Type II, and Type IV fluids supplied by fluid manufacturers for endurance time testing. These tests were conducted over a period of two years, between 2002-03 and 2003-04.

It was concluded that, in terms of adhesion, Type I and Type II/IV fluids exhibit similar behaviour under freezing precipitation conditions, while they exhibit different patterns in snow conditions. In snow, Type I fluids were found to adhere to the test surface at moderate and high precipitation rates (typically, above 10 g/dm²/h). It was also observed that the extent of the safety buffer as the concentration of the glycol in the solution increases. Type II/IV fluids were not observed to adhere to the underlying surface under snow conditions, irrespective to the precipitation rate and outside temperature. These fluids appear to continue to provide a level of protection far beyond the point when failure calls (endurance time) would normally be made. Type II/IV fluid testing using heated rather than the standard ambient temperature fluids showed that the fluid might eventually adhere to the surface, providing its freezing point approached 0°C. Contrary to snow conditions, adhesion was detected under freezing precipitation conditions for both Type I and Type II/IV fluids. Independent of the precipitation rate and ambient temperature, fluid adhesion was observed under freezing drizzle, light freezing rain and rain on cold-soaked wing conditions. Under freezing precipitation conditions, the Type IV propylene-based fluids formed a crust of solidified contamination at the air-fluid interface, while still preserving a very thin film of fluid underneath. Testing on bare surfaces showed that adhesion could occur if the snowflakes land on a slightly heated surface. Partial melting occurs, and as the surface cools down toward the ambient temperature, freezing occurs. Testing with Type I fluids under frost conditions showed that frost always adheres to the test surface and is usually rough in texture.

A general conclusion is there is a significant amount of time between the failure call and the onset of adhesion. However, there are notable exceptions, especially under freezing precipitation conditions.

17. Key Words Adhesion, adherence, natural snow, artificial snow, freezing precipitation, Type I fluid, Type II/IV fluids, precipitation rate, fluid dilution, holdover time	18. Distribution Statement Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages xx, 104 apps	23. Price —

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. Nº de la publication de Transports Canada
TP 14377E

2. Nº de l'étude
B14W

3. Nº de catalogue du destinataire

4. Titre et sous-titre
Adhesion of Aircraft Anti-Icing Fluids on Aluminum Surfaces

5. Date de la publication
Décembre 2004

6. Nº de document de l'organisme exécutant
CM1892.001

7. Auteur(s)
Nicoara Moc

8. Nº de dossier - Transports Canada
2450-BP-14

9. Nom et adresse de l'organisme exécutant
APS Aviation Inc.
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10. Nº de dossier - TPSGC
TOR-4-37170

11. Nº de contrat - TPSGC ou Transports Canada
T8156-140243/001/TOR

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
Transport Canada
330 rue Sparks, 25e étage
Ottawa (Ontario) K1A 0N5

13. Genre de publication et période visée
Final

14. Agent de projet
Antoine Lacroix pour Barry Myers

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

Les rapports de recherches effectuées pour le compte de Transports Canada sur les essais des hivers antérieurs sont disponibles au Centre de développement des transports (CDT). Neuf rapports (y compris celui-ci) ont été produits dans le cadre du programme de recherche de cet hiver. Leur objet est présenté à l'avant-propos. Le projet était coparrainé par la Federal Aviation Administration.

16. Résumé

Un programme de recherche, entrepris par APS Aviation Inc. (APS) au cours des hivers 2002-2003 et 2003-2004, visait à étudier et documenter l'adhérence des liquides d'antigivrage aux surfaces d'aluminium d'aéronefs soumises aux précipitations hivernales.

Au cours des essais sur les durées d'efficacité dans la neige des liquides de Type I au cours de l'hiver 2001-2002, on a constaté qu'aux températures plus douces (généralement supérieures à -3ºC), les liquides se diluent souvent complètement en eau avant de geler. Lorsque le gel se produit, la glace adhère à la surface. Puisque l'aspect critique du concept d'aile propre réside dans l'adhérence du liquide, il serait utile de mieux comprendre le rapport entre la durée d'efficacité du liquide et le moment d'adhérence. La différence entre ces deux instants peut représenter un tampon de sécurité, qui varie considérablement sous différentes conditions.

La présente étude avait pour objectifs de documenter les moments d'adhérence du liquide et d'identifier l'ampleur du tampon de sécurité, après la perte d'efficacité du liquide. Afin de rencontrer ces objectifs, des essais en laboratoire dans des conditions de précipitations verglaçantes ont été menés au Conseil national de recherches du Canada à Ottawa, ainsi que des essais dans la neige naturelle au site d'essai d'APS de l'Aéroport Trudeau. Des essais ont également été effectués dans la neige artificielle à l'aide d'un système de fabrication de neige artificielle, dans une chambre froide exploitée par PMG Technologies Inc. Ces essais de durées d'efficacité ont été effectués sur une vaste plage de températures ambiantes, de taux de précipitation, de types de précipitation et de conditions de vent, avec des échantillons de liquides de Types I, II et IV, fournis par des fabricants de liquides. Ils ont été effectués sur une période de deux ans, entre 2002-2003 et 2003-2004.

Il a été conclu qu'en termes d'adhérence, les liquides de Types I, II et IV affichent un comportement semblable dans des conditions de précipitations verglaçantes, mais qu'ils affichent des comportements différents dans la neige. Dans la neige, les liquides de Type I ont démontré qu'ils adhèrent à la surface d'essai à des taux de précipitation modérés et élevés (généralement supérieurs à 10 g/dm^2/h). On a également observé que l'ampleur du tampon de sécurité croît avec la concentration de glycol de la solution. Les liquides de Types II et IV n'ont pas démontré d'adhérence à la surface sous-jacente dans des conditions de neige, peu importe le taux de précipitation et la température extérieure. Ces liquides semblent continuer à fournir un niveau de protection bien au-delà du point normal de défaillance (durée d'efficacité). Les essais avec des liquides de Types II et IV chauffés, plutôt qu'avec des liquides à la température ambiante normale, ont démontré que le liquide pourrait éventuellement adhérer à la surface, à la condition que son point de congélation approche de 0°C. Contrairement aux conditions dans la neige, nous avons décelé de l'adhérence dans des conditions de précipitation verglaçante, autant pour les liquides de Type I que pour les liquides de Types II et IV. Indépendamment du taux de précipitation et de la température ambiante, l'adhérence des liquides a été observée dans des conditions de bruine verglaçante, de pluie verglaçante légère et de pluie sur une aile imprégnée de froid. Dans des conditions de précipitation verglaçante, les liquides de Type IV à base de propylène formaient une croûte de contamination solidifiée au point de contact du liquide et de l'air, tout en maintenant un très mince film de liquide au-dessous. Des essais sur surfaces propres ont démontré que de l'adhérence pouvait se produire si les flocons de neige se posent sur une surface légèrement chauffée. Une fonte partielle se produit et, à mesure que la surface se refroidit vers la température ambiante, le givre se produit. Des essais avec des liquides de Type I dans des conditions de givre ont démontré que le givre adhère toujours à la surface d'essai et qu'il présente normalement une texture rugueuse.

En conclusion, il existe généralement une période de temps importante entre le point de défaillance et le début de l'adhérence. Cependant, des exceptions importantes existent, surtout dans des conditions de précipitation verglaçante.

17. Mots clés
Adhésion, adhérence, neige naturelle, neige artificielle, précipitation verglaçante, liquide de Type I, liquides de Types II et IV, taux de précipitation, dilution du liquide, durée d'efficacité

18. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires

19. Classification de sécurité (de cette publication)
Non classifiée

20. Classification de sécurité (de cette page)
Non classifiée

21. Déclassification (date)
—

22. Nombre de pages
xx, 104 ann.

23. Prix
—

CDT/TDC 79-005
Rev. 96

EXECUTIVE SUMMARY

Under contract to the Transportation Development Centre (TDC) of Transport Canada (TC), APS Aviation Inc. (APS) undertook a research program to study and document the adhesion of aircraft anti-icing fluids subjected to winter precipitation on aluminum surfaces.

Background

In the winter of 2001-02, a series of natural snow tests was conducted at Montréal-Trudeau Airport using the newly developed Type I protocol.

During conduct of snow endurance time testing using the new outdoor Type I test protocol, it was observed that:

a) Fluid enrichment was experienced on the test surface just after application of the heated fluid, even during snow precipitation;

b) When the test surface was exposed far beyond the time when failure was detected (in snow at colder temperatures), the final fluid concentration did not dilute beyond a Brix value of 4 or 5 (-2 to -2.5°C). In these cases, the failed fluid did not adhere to the surface; and

c) At milder temperatures (-3°C and above), the fluid often diluted to water sometime before freezing. Surface protection was provided solely by heat in these cases. When freezing finally occurred, the resulting ice adhered to the surface.

A full account of these tests can be found in TC report TP 13994E *Generation of Holdover Times Using the New Type I Fluid Test Protocol* (1).

Since fluid adhesion is the critical aspect of the clean-wing policy, it would be useful to have a better understanding of the relationship between fluid holdover time (HOT) and adherence time. The difference in these times can be considered to be a safety buffer, and may vary considerably for different conditions.

The objectives of this study were to document the instances in which fluid adhesion occurs and determine the extent of the safety buffer between endurance time and adhesion time. A graphical display was developed to illustrate the extent of the safety buffer for various weather conditions and fluid types. Types of documentation include: photography, narrative description, and measurements of physical properties such as adhesion, fluid concentration and film thickness.

Description and Processing of Data

To satisfy these objectives, laboratory tests under freezing precipitation conditions were conducted at the National Research Council Canada (NRC) Climatic Engineering Facility in Ottawa, and natural snow tests were conducted at the APS test site at Montréal-Trudeau Airport. The climatic chamber provided a controlled environment satisfying test variables of ambient temperature and artificial precipitation. During natural snow tests, precipitation rates and ambient air temperature were monitored. Tests were also performed in artificial snow using the National Center Atmospheric Research (NCAR) snowmaking system in a cold chamber operated by PMG Technologies Inc. (PMG) in Blainville, Quebec. These tests were conducted over a period of two years, between 2002 and 2004. For all of the aforementioned sessions, various fluids were applied to test surfaces and examined at specific stages from the time of application until after complete plate failure. The physical properties of the fluid were documented as the fluids progressed toward and beyond a standard failure.

Sixteen runs, including forty-four individual tests, were conducted in natural snow and freezing drizzle on several occasions from January 7, 2003 to February 4, 2004. In the PMG laboratory, over a two-day period, eleven artificial snow tests were performed at different temperatures and precipitation rates. Forty-nine indoor tests were conducted in April 2003 and April 2004 at the NRC climatic chamber in Ottawa.

These tests were conducted using samples of Type I, Type II, and Type IV fluids under a wide range of temperature, precipitation rate, precipitation type, and wind conditions.

In all tests, documentation stating whether the fluid did or did not adhere to the test surface was developed.

Results and Conclusions

The characteristics of contamination under different weather conditions were recorded using several monitoring techniques and instruments. Following the standard failure, the tests were run for a minimum of one hour (whenever possible) in an attempt to document the onset of adherence. All endurance testing was performed using the methodology developed in the conduct of similar tests for Transport Canada (TC) in previous years.

Data from the various tests enabled comparisons of various characteristics of different fluids in different conditions. It was noted that, in terms of fluid adhesion, Type I and Type II/IV fluids have similar behaviours under freezing precipitation conditions, while they exhibit different patterns in snow conditions.

Using a tool specially designed to provide a relative measure of adhesion in the various test conditions, it was noted that under snow conditions, Type I fluids adhere to the test surface only at moderate and high precipitation rates (typically, above 10 g/dm²/h). It was also observed that the extent of the safety buffer increases as the concentration of glycol in the solution increases.

Type II/IV fluids were not observed to adhere to the underlying surface under snow conditions, irrespective of the precipitation rate and outside temperature. These fluids appear to provide a level of protection far beyond the point when failure calls would normally be made. Testing using heated Type II/IV fluids showed that the fluid might eventually adhere to the surface, providing its freezing point reached 0°C.

Contrary to snow conditions, under freezing precipitation conditions adhesion was detected for both Type I and Type II/IV fluids. Independent of the precipitation rate and the ambient temperature, fluid adhesion was observed under freezing drizzle, light freezing rain and rain on cold-soaked wing conditions. None of the low temperature (-25°C) freezing fog tests using Type I or Type II/IV fluids presented adhesion. Previous findings presented in TC report TP 13484E, *Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation: 1998-99* (7), showed that Type IV propylene-based fluid experienced no adhesion at ambient temperatures of -10ºC, even when complete plate failure was identified. Testing conducted at NRC in April 2004 showed that, under freezing precipitation conditions, Type IV propylene-based fluids form a crust of solidified contamination at the air-fluid interface, while still preserving a very thin film of fluid underneath.

Testing on bare surfaces in snow confirmed that adhesion can be attained if snowflakes land on a slightly heated surface. This is a result of the "warm-soaked wing" effect. Partial melting occurs, and as the surface cools down toward the ambient temperature, freezing occurs. Under freezing precipitation, the adhesion of contamination to the test surface occurs almost instantaneously.

Adhesion testing conducted with Type I fluids under frost conditions showed that frost always adheres to the test surface and it is usually rough in texture.

A tabular display of adherence times versus endurance times was developed to illustrate the extent of the safety buffer for various weather conditions and fluid types. The HOT guideline tables, for both Type I and Type II/IV fluids, are used to portray the results. The HOT values in each cell of the table are replaced by either "no adherence" or a numerical value representing the extent of the safety buffer between the failure time and the onset of adhesion.

Recommendations

Based on the tests conducted, it is recommended that the findings of this report be disseminated to the industry.

If Type II/IV fluid is applied heated more caution should be taken. The operator should be aware of the increased potential for adhesion in such cases.

Under freezing precipitation conditions, the values in the HOT guideline tables should be complied rigorously, as the safety margin between the failure call and onset of adhesion is minimal.

SOMMAIRE

En vertu d’un contrat avec le Centre de développement des transports (CDT) de Transports Canada (TC), APS Aviation Inc. (APS) a entrepris un programme de recherche visant à étudier et documenter l’adhérence des liquides d’antigivrage d’aéronefs soumis à des précipitations hivernales sur des surfaces d’aluminium.

Contexte

Au cours de l’hiver 2001-2002, une suite d’essais dans la neige naturelle a été effectuée à l‘Aéroport Montréal Trudeau avec le nouveau protocole pour les liquides de type I.

Au cours des essais de durées d’efficacité dans la neige avec le nouveau protocole d’essai à l’extérieur pour les liquides de type I, on a observé que :

a) Une valorisation du liquide a été constatée sur la surface d’essai immédiatement après l’application du liquide chauffé, même durant les chutes de neige ;

b) Lorsque la surface d’essai était exposée bien au-delà du point de défaillance observé (dans la neige à des températures plus froides), la concentration finale du liquide n’était pas diluée au-delà d’une valeur Brix de 4 ou 5 (-2 à -2.5°C). Dans ces situations, le liquide ayant perdu son efficacité n’adhérait pas à la surface ; et

c) À des températures plus douces (-3°C et plus), le liquide se diluait souvent en eau quelque temps avant de congeler. Dans ces situations, la protection de la surface n’était assurée que par de la chaleur. Lorsque le gel se matérialisait finalement, la glace adhérait à la surface.

Un compte rendu complet sur ces essais peut être consulté dans le rapport de TC TP 13994E, *Generation of Holdover Times Using the New Type I Fluid Test Protocol* (1).

Puisque l’aspect critique du concept d’aile propre réside dans l’adhérence du liquide, il serait utile de mieux comprendre le rapport entre la durée d’efficacité du liquide et le moment d’adhérence. La différence entre ces deux instants peut représenter un tampon de sécurité, qui peut considérablement varier sous différentes conditions.

La présente étude avait pour objectifs de documenter les moments d’adhérence du liquide et d’identifier l’ampleur du tampon de sécurité, entre la durée d’efficacité et l’instant d’adhérence. Un affichage graphique a été élaboré pour illustrer l’ampleur du tampon de sécurité dans diverses conditions météorologiques et pour différents

types de liquide. Le genre de documentation comprend : la photographie, une description narrative et la mesure des propriétés physiques comme l'adhérence, la concentration de liquide et l'épaisseur du film.

Description et traitement des données

Afin de rencontrer ces objectifs, des essais en laboratoire dans des conditions de précipitations verglaçantes ont été menés à l'Installation d'ingénierie climatique du Conseil national de recherches du Canada (CNRC) à Ottawa, ainsi que des essais dans la neige naturelle au site d'essai d'APS de l'Aéroport Trudeau. La chambre climatique offrait un environnement contrôlé qui rencontrait les variables d'essai en matière de température ambiante et de précipitation artificielle. Au cours des essais dans la neige naturelle, les taux de précipitation et la température ambiante de l'air étaient contrôlés. Des essais ont également été effectués dans la neige artificielle à l'aide du système de fabrication de neige du National Center for Atmospheric Research (NCAR), dans une chambre froide exploitée par PMG Technologies Inc. (PMG) à Blainville, Québec. Ces essais ont été effectués sur une période de deux ans, entre 2002 et 2004. Pour toutes les séances susmentionnées, plusieurs liquides ont été appliqués aux surfaces d'essai et examinés à différentes étapes, entre l'application et la défaillance complète de la plaque. Les propriétés physiques du liquide étaient documentées à mesure que le liquide évoluait jusqu'au-delà du point de défaillance normale.

Seize séries d'essais, comprenant quarante-quatre essais individuels, ont été menées dans la neige naturelle et la bruine verglaçante en plusieurs séances entre le 7 janvier 2003 et le 4 février 2004. Sur une période de deux jours au laboratoire de PMG, onze essais ont été effectués dans la neige artificielle, à diverses températures et à des taux de précipitation différents. En avril 2003 et avril 2004, quarante-neuf essais ont été complétés à l'intérieur, dans la chambre climatique du CNRC à Ottawa.

Ces essais ont été effectués avec des échantillons de liquides de types I, II et IV, sous une vaste plage de températures, de taux de précipitation, de type de précipitation et de conditions de vent.

Pour tous les essais, la documentation établissant l'adhérence ou la non adhérence du liquide à la surface d'essai a été élaborée.

Résultats et Conclusions

Les caractéristiques de la contamination sous différentes conditions météorologiques ont été enregistrées à l'aide de plusieurs techniques et instruments de contrôle. Après le point de défaillance normale, les essais se poursuivaient pour au moins une heure (si possible) pour tâcher de documenter le début de l'adhérence. Tous les essais d'endurance ont été effectués avec la méthodologie développée pour les essais semblables menés pour Transports Canada (TC) au cours des années antérieures.

Les données provenant des différents essais ont permis de comparer les caractéristiques propres aux différents liquides dans diverses conditions. On a remarqué qu'en termes d'adhérence des liquides, les liquides de type I et ceux de types II et IV se comportent de façon semblable dans des conditions de précipitation verglaçante, mais qu'ils présentent des caractéristiques différentes dans la neige.

À l'aide d'un outil spécialement conçu pour donner une mesure d'adhérence relative sous différentes conditions d'essai, on a remarqué que sous différentes conditions de neige, les liquides de type I n'adhèrent à la surface d'essai qu'à des taux de précipitation modérés et élevés (généralement au-dessus de 10 $g/dm^2/h$). On a également observé que l'ampleur du tampon de sécurité croît avec la concentration de glycol de la solution.

Les liquides de types II et IV n'ont pas démontré d'adhérence à la surface sous-jacente dans la neige, peu importe le taux de précipitation et la température extérieure. Ces liquides semblent offrir un niveau de protection bien au-delà du point normal de défaillance (durée d'efficacité). Les essais avec des liquides de types II et IV chauffés ont démontré que le liquide pourrait éventuellement adhérer à la surface, à la condition que son point de congélation atteigne 0°C.

Contrairement aux conditions dans la neige, nous avons décelé de l'adhérence dans des conditions de précipitation verglaçante, autant pour les liquides de type I que pour les liquides de types II et IV. Indépendamment du taux de précipitation et de la température ambiante, l'adhérence des liquides a été observée dans des conditions de bruine verglaçante, de pluie verglaçante légère et de pluie sur une aile imprégnée de froid. Aucun des essais avec les liquides de type I et les liquides de types II et IV dans le brouillard verglaçant à basse température (-25°C) n'a démontré d'adhérence. Les résultats antérieurs exposés dans le rapport de TC TP 13484E, *Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation: 1998-99* (7), ont démontré que le liquide de type IV à base de propylène n'avait pas d'adhérence aux températures ambiantes de -10°C, même lorsque la défaillance complète de la plaque était constatée. Des essais effectués au CNRC en avril 2004 ont démontré que, dans des conditions de précipitation verglaçante, les liquides de type IV à base de propylène forment une croûte de contamination solidifiée au point de contact du liquide et de l'air, tout en maintenant un très mince film de liquide au-dessous.

Des essais sur surfaces propres dans la neige ont démontré que de l'adhérence peut se produire si les flocons de neige se posent sur une surface légèrement chauffée. Cela est dû à l'effet « d'aile imprégnée de chaleur ». Une fonte partielle se produit et, à mesure que la surface se refroidit vers la température ambiante, le givre se produit. Dans la précipitation verglaçante, l'adhérence de contamination à la surface d'essai se produit presque instantanément.

Des essais d'adhérence menés avec des liquides de type I dans des conditions de givres ont démontré que le givre adhère toujours à la surface d'essai et qu'il présente normalement une texture rude.

Un tableau comparatif des temps d'adhérence et des temps d'endurance a été élaboré pour illustrer l'ampleur du tampon de sécurité pour différentes conditions météorologiques et différents types de liquides. Les tableaux de durées d'efficacité, autant pour les liquides de type I que pour les liquides de types II et IV, servent à illustrer les résultats. Les valeurs de durée d'efficacité de chaque cellule du tableau sont remplacées par « aucune adhérence » ou par une valeur numérique qui représente l'ampleur du tampon de sécurité entre le moment de défaillance et le début de l'adhérence.

Recommandations

Conformément aux essais effectués, il est recommandé de diffuser les conclusions du présent rapport à l'industrie.

Si le liquide de type II et IV est chauffé pour son application on devrait être plus vigilant. Dans de tels cas, l'exploitant devrait réaliser la possibilité accrue d'adhérence.

Dans des conditions de précipitation verglaçante, les valeurs des tableaux de durées d'efficacité devraient être respectées rigoureusement, car la marge de sécurité est minime entre le point de défaillance et le début de l'adhérence.

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GLOSSARY

AMS	Aerospace Material Specification
APS	APS Aviation Inc.
CARs	Canadian Air Regulations
HOT	Holdover Time
MSC	Meteorological Service of Canada
NCAR	National Center for Atmospheric Research
NRC	National Research Council Canada
OAT	Outside Air Temperature
PMG	PMG Technologies Inc.
SAE	SAE International
TC	Transport Canada
TDC	Transportation Development Centre

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1. INTRODUCTION

Under contract to the Transportation Development Centre (TDC) of Transport Canada (TC), APS Aviation Inc. (APS) undertook a research program to study and document the adhesion time of aircraft anti-icing fluids on aluminum surfaces.

1.1 Background

In the winter of 2001-02, a series of natural snow tests was conducted at Montréal-Trudeau Airport using the newly developed Type I protocol.

During conduct of snow endurance time testing using the new outdoor Type I test procedure, it was observed that:

a) Fluid enrichment was experienced on the test surface just after application of the heated fluid, even during snow precipitation;

b) When the test surface was exposed far beyond the time when failure was detected (in snow at colder temperatures), the final fluid concentration did not dilute beyond a Brix value of 4 or 5 (-2 to -2.5°C). In these cases, the failed fluid did adhere to the surface; and

c) At milder temperatures (-3°C and above), the fluid often completely diluted to water sometime before freezing. Surface protection was provided solely by heat in these cases. When freezing finally occurred, the resulting ice adhered to the surface.

A full account of these tests can be found in TC report TP 13994E, *Generation of Holdover Times Using the New Type I Fluid Test Protocol* (1).

The Canadian Air Regulation (CAR) 602.11 specifies that “No person shall conduct or attempt to conduct a takeoff in an aircraft that has frost, ice or snow adhering to any of its critical surfaces”. Since fluid adhesion is the critical aspect of the clean-wing policy, it is useful to have a better understanding of the relationship between fluid endurance time and adherence time. The difference in these times can be considered a safety buffer, and may vary considerably for different conditions.

In addition, discussions within the aviation industry about adhesion of contamination to wing surfaces led to the recommendation of a research project to examine and document the properties of anti-icing fluids as they are exposed to precipitation conditions following standard plate failure.

APS was subsequently asked to develop a procedure for the conduct of adhesion tests under simulated freezing precipitation, natural snow and artificial snow conditions. The artificial snow tests would be conducted using the National Center Atmospheric Research (NCAR) snowmaking system. These tests were carried out over two seasons, 2002-03 and 2003-04.

Based on the 2002-03 testing, it was concluded that under snow conditions, Type I fluids adhere to the test surface only at moderate and high precipitation rates (typically, above 10 g/dm²/h). Type II/IV fluids were not observed to adhere to the underlying surface under snow conditions, irrespective of the precipitation rate and outside temperature. Contrary to snow conditions, adhesion was detected under freezing precipitation conditions for both Type I and Type II/IV fluids.

At the end of the 2002-03 testing season, several key recommendations were made for completion of this research: Type II/IV fluid adhesion testing using heated fluids, adhesion testing in frost, bare surface adhesion testing and testing under freezing precipitation using Type IV propylene-based fluids. All these additional objectives were addressed in the 2003-04 testing season.

1.2 Objective

The objectives of this study were to document the instances in which fluid adhesion occurs and determine the extent of the safety buffer between the failure time and the onset of adhesion. A graphical display of endurance times versus adherence times for fluid types in different conditions was developed to illustrate the size of the safety buffer for various weather conditions and fluid types.

Each fluid test was monitored as it approached, reached, and surpassed its operational limit. Discrete measurements of the fluid's physical properties were recorded at pre-selected stages of visual failure. The physical properties measured included fluid concentration, wet film thickness, and adhesion. These tests were conducted using samples of Type I, Type II, and Type IV fluids supplied by fluid manufacturers for endurance time testing, under a wide range of temperature, precipitation rate, precipitation type, and wind conditions.

The applicable sections of the work statement for this project are provided in Appendix A.

2. METHODOLOGY

This section describes the test sites, procedure, equipment, fluids, and personnel requirements that were necessary to perform and record a series of fluid tests under both natural precipitation conditions and in a controlled environment during the 2002-03 and 2003-04 test sessions.

The issue of clarity when discussing fluid failure and fluid adhesion is significant. In order for all parties to arrive at a common point, icing definitions have been included in Section 2.1. These definitions are taken directly from the TC report TP 13832E, *Aircraft Anti-Icing Fluid Endurance, Holdover, and Failure Times Under Winter Precipitation Conditions: A Glossary of Terms* (2).

2.1 Icing Definitions

2.1.1 Failed Fluid

Fluid that has reached and is well past the fluid failure condition.

2.1.2 Fluid Failure

Two major forms of failure are currently in use: visual failure and adhesion failure.

2.1.3 Visual Failure

A layer of ice crystals is plainly visible at the surface and the layer is building up thickness as precipitation continues. Generally, in the case of Type II, III, and IV fluids, uncontaminated fluid is in contact with the supporting surface at this time and therefore the ice crystal layer is not in contact with that surface and is not adhering to it. The growth of crystals in the fluid is compounded by incoming precipitation, resulting in an increased accumulation of crystals on the surface and thus in a visibly contaminated surface. When this area is large enough to be seen by an observer, a visual failure is adjudged. Obviously, the distance of the observer from the surface will influence what can be seen. For a test technician observing a plate from inches away, visual failure is characterized as a loss of gloss or obscuration of the surface by ice or slush affecting one third of a standard test plate surface. For an aircrew member viewing a wing through a window at night at a distance of several feet, only slush or bridging snow covering about one third of a critical area such as an aileron *or a leading edge will be visible. Visual failure on test plates is the mode used to establish endurance times and thus holdover times.*

The method used to determine the visual failure of the fluid for all the tests described in this report is according to the proposed Aerospace Standard AS5485. This standard specifies that failure is called when 30 percent of the plate is covered with frozen contamination.

2.1.4 Adhesion/Adherence Failure

The failure of the fluid to perform as an anti-icing fluid. A layer of ice crystals builds up, the crystals come in contact with the surface below, and they are bonded to it.

2.1.5 Standard Plate Failure

Failure is established as a visual failure of one third of the test surface based on the observation of conditions on full-scale aircraft. This usually occurs when the failure front on the plate crosses the 15 cm (6 in.) line. However, in outside snow tests, because there is usually wind, the start point may be anywhere on the plate and the progression in any direction. Under these conditions, visual failure may be estimated. Alternatively, when contamination is visible on 5 of the 15 cross hairs, the plate is determined to be one-third covered and therefore visually failed.

The method used to determine the standard plate failure is as described in the proposed Aerospace Standard AS5485. This standard specifies that a fluid is considered failed when the accumulating snow (not slush, but white snow), when viewed from a shallow angle, is no longer being absorbed at any five of the crosshair marks on the plates or when 30 percent of the test plate is covered with accumulating precipitation.

2.1.6 Plate Failure

Usually the same as standard plate failure.

2.1.7 Contamination

With regards to de-icing and anti-icing operations, contamination refers to any sort of precipitation in solid or liquid state. Liquid contamination includes rain, drizzle, freezing rain, and freezing drizzle. Fog and freezing fog are considered special cases of liquid precipitation. Examples of solid contamination include snow, hail, and ice *pellets. Mixtures of solid and liquid contamination are occasionally observed in nature.*

2.1.8 Visible Contamination

When anti-icing fluid has been applied to the wing, the fluid has a freezing point substantially below the ambient air temperature. Furthermore, there is a temperature gradient through the fluid from the hot wing skin to the cold ambient air. In a snowstorm, flakes hit the fluid surface and melt immediately, absorbing heat from the fluid. The fluid is thereby cooled at the air-surface interface, approaching the ambient temperature rapidly and being simultaneously diluted by the precipitation. The decreasing fluid temperature causes the snowflakes to melt and be absorbed more slowly and, as a result, the incoming snow lands on partially melted flakes and a mat of slush develops. This mat of slush is the visible contamination. It has partially melted snow on top, which acts as an insulator and further slows the melting process.

2.1.9 Slush

Snow or ice that has been reduced to a soft, watery mixture by rain, heat, or chemical treatment. Slush is an accumulation of ice crystals in a fluid forming a non-rigid agglomeration.

2.1.10 Failure Adhesion

The initial bonding of ice crystals in a fluid to the surface, resulting from the diluted fluid freezing point rising above the surface temperature at a nucleation site on the surface.

2.1.11 Nucleation Site

The site at which an ice crystal is stimulated to form from supercooled water.

2.1.12 Fluid Adhesion

Viscosity and surface tension forces, along with a possible matrix of ice crystals in the fluid layer, impede the fluid's movement under shear and represent the effective adhesion of the fluid to the surface, resisting its removal.

2.1.13 Protection Time

The period that an anti-icing treatment protects aerodynamically critical surfaces from the adhesion of contamination and the resulting roughness that could cause a premature stall or result in loss of control and prevent the crew from safely operating the aircraft.

The protection time has recently been given a more comprehensive meaning. It is not defined solely with respect to the adhesion of contamination, but also with respect to the aerodynamic performance of the fluid. An explanation of the relationship between the protection time, endurance time and adhesion time can be found in Section 4.4.

2.1.14 Endurance Time

The time from initial application of anti-icing fluid to a standard test plate to the moment of the standard plate failure for a specific test condition simulating a weather condition.

2.1.15 Holdover Time

The time from initial application of anti-icing fluid onto an aircraft to the moment the fluid can no longer be guaranteed to provide protection at the anticipated takeoff time. These times must be at least five minutes less than the protection time, and may be substantially less.

2.1.16 Artificial vs. Simulated

In July 2003, two more definitions were developed:

An artificial product is one that represents the product in its physical form, i.e. "look and feel" (but does not necessarily simulate the effect of the real thing).

A simulation should simulate the way the product interacts with a particular environment having the same effect (but does not need to have the look and feel of the real thing).

2.2 Test Sites

Natural snow tests were conducted by APS at a test site located at Montréal-Trudeau Airport. The location of the site is shown on the plan view of the airport in Figure 2.1. Photo 2.1 and Photo 2.2 were taken at the test site and show the trailer and the associated equipment. This same trailer was used in past winters. The APS test site is located near the Meteorological Service of Canada (MSC) automated weather observation station (Photo 2.3).

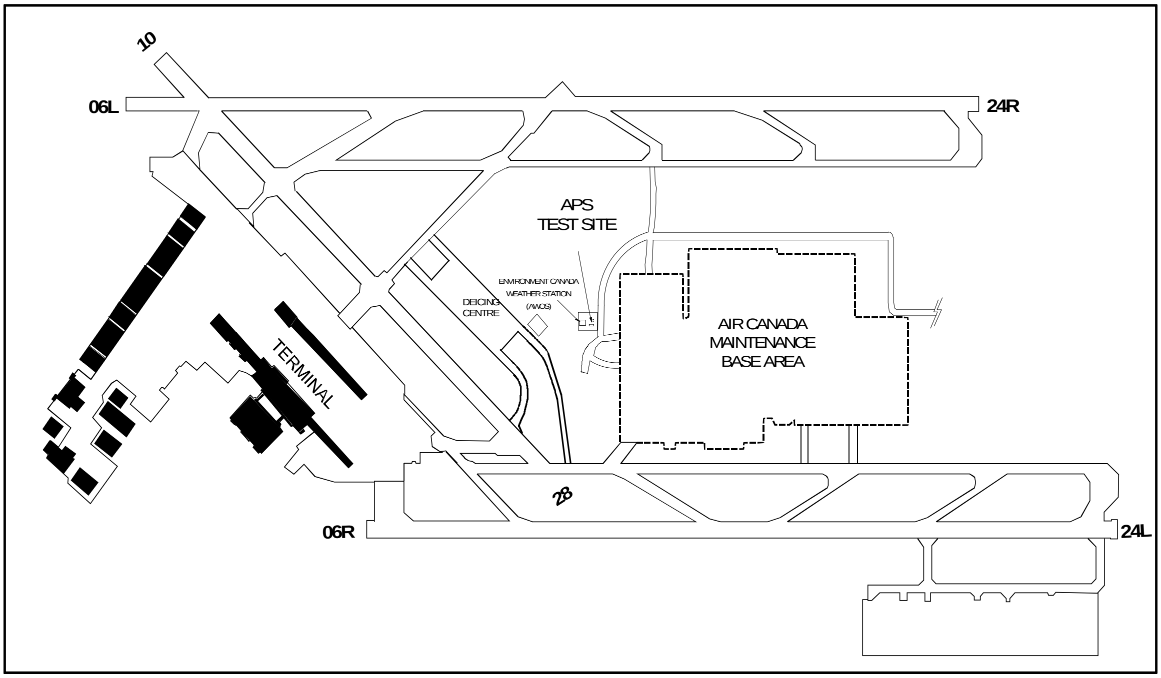


Figure 2.1: Location of APS Test Site at Montréal–Trudeau Airport

Tests under conditions of freezing fog, rain on a cold-soaked surface, freezing drizzle, and light freezing rain were conducted indoors at the National Research Council Canada (NRC) Climatic Engineering Facility, where simulated precipitation was produced. The NRC test facility is partitioned into two sections separated by an insulated door. Conditions in each section can be controlled independently, permitting different tests to be conducted simultaneously. Photo 2.4 provides an exterior view of the building. Photo 2.5 and Photo 2.6 provide interior images of the small and large ends of the facility.

Tests in simulated snow conditions were conducted at PMG Technologies Inc. (PMG) in Blainville, Quebec using the NCAR artificial snowmaking system. The climatic chamber in combination with the NCAR snowmaking system provided a controlled environment satisfying test variables of ambient temperature and artificial precipitation. Photo 2.7 provides a view of the PMG building from the outside. Photo 2.8 provides an interior image of the chamber used for testing under artificial snow at PMG.

2.3 Description of Test Procedures

An experimental procedure was developed in the winter of 2002-03 to document the extent of the buffer time between the endurance time and the adherence time for SAE International (SAE) Type I, II and IV fluids under various weather conditions. The procedure is presented in Appendix B (Comparison of Adherence Time versus Endurance Times of De/Anti-Icing Fluids, Winter 2002-03). The procedure contains generic sections describing the parameters to be measured, and also specific sections pertaining to each precipitation condition. This procedure addresses fluid adhesion testing conducted under natural snow, artificial snow and simulated freezing precipitation conditions.

The purpose of this study was to document the size of the buffer time in each cell of the Type I and Type II/IV holdover time (HOT) guideline tables. However, due to time limitations and budgetary constraints, only selected conditions considered to be representative were tested. A proposed matrix of these selected tests was developed and is presented in Table 2.1. This matrix served as starting point and was modified as testing progressed.

As shown in Table 2.1, the tests were performed at different temperatures and precipitation rates, both indoors and outdoors. Along with the presence of fluid adhesion, the following parameters were recorded: endurance time, fluid type, fluid dilution (Brix), fluid temperature, fluid thickness, weather condition, rate of precipitation and test surface temperature. Adhesion was documented for at least one hour after fluid failure.

At the end of the 2002-03 testing season, several recommendations were made for completion of this research. The objective of the 2003-04 testing was to complete the documentation for all cases and also to elaborate on results from completed tests. Key recommendations of the research program included: Type II/IV fluid adhesion testing using heated fluids, adhesion testing in frost, bare surface adhesion testing and testing under freezing precipitation using Type IV propylene-based fluids.

To address these recommendations, an experimental procedure was developed for the winter of 2003-04. This procedure is also presented in Appendix B (Adhesion of Aircraft De/Anti-Icing Fluids on Aluminum Surfaces, Winter 2003-04). The procedure is very similar to the procedure developed in the previous year and addresses Type I, II, III and IV fluid adhesion testing conducted under natural snow, frost and simulated freezing precipitation conditions.

A proposed matrix of these tests is presented in Table 2.2.

Table 2.1: Test Matrix for 2002-03

Location	NRC	NRC	NRC	NRC	NRC	NRC	NRC	NRC	NRC	Dorval	Dorval	Dorval	Dorval	PMG	PMG	PMG	PMG
Precipitation Type	CSW	ZF	ZF	ZD	ZD	ZD	ZD	ZR	ZR	Nat. Snow	Nat. Snow	Nat. Snow	Nat. Snow	Indoor Snow	Indoor Snow	Indoor Snow	Indoor Snow
Rate (g/dm²/h)	5	5	5	5	13	5	13	25	25	1*	10*	15*	30*	10	25	*** 75	25
OAT (°C)	1	-25	-3	-3	-3	-10	-10	-10	-3	-20*	-10*	-5*	-1*	-3	-3	-3	-10
Type I EG (10°C buffer)	Box	Box	Box	Box	Box	Box	Box	Box	Box	Box	Box	Box	Box	Pl.	Pl.	Pl.	Pl.
Type I PG (10°C buffer)	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl								
Clariant Safewing MPIV 2030 ECO - Neat	** Box/Pl	** Box/Pl		** Box/Pl			** Box/Pl	** Box/Pl		Box	Box	Box	Box			Pl.	Pl.
Clariant Safewing MPIV 2030 ECO – 75/25			** Box/Pl		** Box/Pl				** Box/Pl					Pl.	Pl.		
Clariant Safewing MPII 2025 ECO - Neat						** Box/Pl											
Clariant Safewing MPII 2025 ECO – 75/25		** Box/Pl					** Box/Pl	** Box/Pl		Box	Box	Box	Box			Pl.	Pl.
Clariant Safewing MPIV 2030 ECO – 50/50				** Box/Pl					** Box/Pl								
Clariant Safewing MPII 2025 ECO – 50/50	** Box/Pl		** Box/Pl		** Box/Pl	** Box/Pl	** Box/Pl	** Box/Pl	** Box/Pl	Box	Box	Box	Box	Pl.	Pl.		
UCAR Ultra+	** Box/Pl	** Box/Pl	** Box/Pl	** Box/Pl		** Box/Pl		** Box/Pl	** Box/Pl	Box	Box	Box	Box	Pl.	Pl.	Pl.	Pl.

* An attempt will be made to get a range of conditions.
** Only one test surface will be used for testing depending on the previous findings.
*** A high precipitation rate (between 50 and 100 g/dm²/h) will be chosen.

Table 2.2: Test Matrix for 2003-04

Location / Equipment	NRC	NRC	NRC	NRC	Dorval	Dorval	Dorval	Dorval	Dorval
Precipitation Type	ZD	ZD	ZR	ZR	Nat. Snow	Nat. Snow	Nat. Snow	Nat. Snow	Natural Frost
Rate (g/dm^2/h)	13	13	25	25	1	10	15	30	Any
OAT (°C)	-3	-10	-10	-3	-20	-10	-5	-1	Any
Type I EG (10°C buffer)	-	-	-	-	-	-	-	-	Plate(4)
Type I PG (10°C buffer)	-	-	-	-	-	-	-	-	Plate(4)
Type IV EG	-	-	-	-	Box(1)	Box(1)	Box(1)	Box(1)(2)	-
Type IV PG	Plate(6)	Plate(6)	Plate(6)	Plate(6)	Box(1)	Box(1)	Box(1)	Box(1)(2)	-
Type II PG	Plate(6)	Plate(6)	Plate(6)	Plate(6)	Box(1)	Box(1)	Box(1)	Box(1)(2)	-
Type III	Plate(5)	Plate(5)	Plate(5)	Plate(5)	Box(1)(5)	Box(1)(5)	Box(1)(5)	Box(1)(2)(5)	-
Bare Surface	-	-	-	-	Box(3)	Box(3)	Box(3)	Box(3)	Plate(4)

(1) Tests conducted with heated fluids.
(2) An attempt will be made to test at very mild temperatures (around 0°C) to investigate the effect of wet snow.
(3) Tests conducted on bare surfaces (heated and cold aluminum boxes simultaneously).
(4) Frost Tests (conducted using the white-painted aluminum with insulated backing test surface).
(5) Tests conducted with Type III fluids applied at ambient test temperature.
(6) Tests conducted with propylene fluids applied at ambient test temperature.

Below is a short description of the procedures.

2.3.1 Surface Temperature

For both outdoor and indoor testing at NRC, test surface temperature was measured using a thermistor probe mounted at the 15 cm (6″) line. The connection was designed to not impede fluid flow. A SmartReader Eight-Channel temperature logger was used to measure and record temperature. The sampling rate (how often the logger takes readings) was set to eight seconds, the smallest possible increment.

For artificial snow adhesion testing, the software running the NCAR snowmaking system provided a measure of the surface temperature at six-second intervals. Temperature was measured via temperature probe mounted on the underside of the plate.

2.3.2 Fluid Dilution

Fluid dilution was measured at the 15 cm (6″) line, using a Misco 10431VP brixometer. The measurements were conducted to determine the concentration of the fluid on the test surface before and after fluid failure. The original Brix value was measured on fluid in the container before pouring and the second measurement was taken from fluid on the test surface immediately after pouring. Additional measurements were typically taken a few more times following fluid failure.

2.3.3 Fluid Thickness

For Type I tests, fluid thickness measurements were taken at the start of the test (right after pouring) and every two minutes thereafter. For Type II/IV tests, measurements were taken at the start of the test and every five minutes thereafter. Fluid thickness was measured with wet film thickness gauges at the 15 cm (6″) line.

Under artificial snow conditions, fluid thickness measurements were not conducted due to accessibility constraints.

2.3.4 Precipitation Rate

Precipitation rates were measured throughout the adherence test. The methodology of collecting precipitation rates was dependent on whether the tests were conducted outdoors or indoors.

The procedure for outdoor tests can be found in Appendix C of TC report TP 14144E*, Aircraft Ground De/Anti-Icing Fluid Holdover Time and Endurance Time Testing Program for the 2002-03 Winter* (3). The precipitation rate was measured at the start of the test and every ten minutes thereafter.

The procedure for indoor tests can be found in Appendix E of TC report TP 14144E, *Aircraft Ground De/Anti-Icing Fluid Holdover Time and Endurance Time Testing Program for the 2002-03 Winter* (3). Rate pans were placed on the test plate support at each test location. The precipitation rate for any location on the stand was calculated by averaging the two rates collected prior to the test and the two rates collected following the test.

Under freezing precipitation conditions, fluid adhesion testing was conducted in conjunction with endurance time testing. In this case, the precipitation rate measurements and preparation of fluids were provided by the endurance time testing personnel.

Under artificial snow, the software running the NCAR machine provided an instantaneous output of the precipitation rate. Among other parameters, the software calculated two precipitation rates; one instantaneous value every six seconds, and a forty-second average precipitation rate. The forty-second precipitation rate was disregarded for this analysis. Because the machine interprets fluid application as precipitation rate, several precipitation rate values at the beginning of each electronic file were ignored.

Under frost conditions, two white-painted aluminum test plates mounted at a 10° slope on a test stand were used as frost collecting surfaces. The precipitation rate was calculated by weighing the test plates at 30-minute intervals. The two test surfaces collecting frost were weighed at staggered time intervals.

2.3.5 Fluid Application

For outdoor testing in snow, fluid was applied to empty aluminum boxes according to the following procedure:

a) Type I fluids: the fluid was diluted to a freezing point 10ºC below ambient temperature, heated to 60°C, with a quantity of 0.5 L applied through a spreader; and

b) Type II/IV fluids: the fluid was applied at ambient temperature and also heated to various temperatures, with a quantity of 1.0 L, poured.

For outdoor testing in frost, the Type I fluid was diluted to a freezing point 10ºC below ambient temperature and was applied at 20°C to white painted aluminum surfaces through a 12-hole spreader.

For indoor testing, the fluid was applied to empty aluminum boxes and standard endurance time plates according to the following procedure:

a) Type I fluids: the fluid was diluted to a freezing point 10ºC below test temperature, heated to 20ºC and a quantity of 1.0 L was applied to the surface by pouring; and

b) Type II, III and IV fluids: the fluid was applied at the ambient test temperature and a quantity of 1.0 L was poured.

For artificial snow testing, the fluid was applied to the NCAR plate according to the following procedure:

a) Type I fluids: the fluid was diluted to a freezing point 10ºC below test temperature. The fluid application temperature varied from -7.5°C to 65°C and a quantity of 1.0 L was applied to the surface by pouring; and

b) Type II/IV fluids: the fluid was applied at ambient test temperature and a quantity of 1.0 L was poured.

2.3.6 Fluid Adhesion

Adhesion was originally measured at the time of standard plate failure call (5th crosshair) at various locations on the surface of the plate. An attempt was made to document and record the first occurrence of fluid adhesion at any location on the surface of the plate. Between standard plate failure and complete plate failure calls, adhesion was measured at various locations periodically. When the entire plate had failed (complete plate failure), adhesion was measured again at several points. Typically, a few more measurements were conducted thereafter at various locations on the test surface.

In the absence of a recognized standard method or apparatus for measuring failure adhesion, the degree of bonding was determined using an electrically driven dental flossing device. Several other methods for measuring adhesion were considered and evaluated during previous testing seasons. These methods included checking the adhesion of fluid by using a device that scraped the plate from top to bottom, and also checking the adhesion using air jets. Out of all testing methodologies analysed, the dental flossing device was found to produce the best results for two main reasons: the instrument exerted a constant shearing force upon the fluid, and the method of checking adhesion with this device is nondestructive. The nondestructive nature of this method is very useful as it allows taking multiple measurements over the course of a test run.

During operation, the device spins a thread of floss. The floss segment extends about 3 to 4 mm from the tip of the unit. When the device is brought into contact with the fluid covered plate, the spinning floss segment may carve out a circle (or not, depending upon whether adhesion had occurred) 3 to 4 mm in radius on a failed surface element. In a layer of non-adhered fluid failure, the force of the spinning floss is sufficient to expose the surface of the test plate. As the rotation speed of the unit is fixed, the applied force was constant for all tests, providing a basis of comparison among various test conditions, and between different stages of contamination for individual tests. This device proved to be the most satisfactory of the various approaches to establish whether an area had undergone surface bonding to the substrate and to give a measure of the strength of the bond formed.

An analysis of the shearing force exerted by this instrument (presented as Appendix C) determined it to be in the range of $1.3 \text{ x}10^{-4}$ to $2.0 \text{ x } 10^{-4}$ mPa. With respect to the shearing force exerted by this instrument, a few comments are needed to provide substantiation of validity of the device. Between taking adhesion measurements, the instrument was placed at all times on the charger. As a result, all adhesion measurements were conducted with a fully charged battery. To ensure the consistency of the readings, multiple instruments were employed simultaneously in checking the adhesion on the same plate, and they always produced identical results.

To further provide validation of the testing results, it is worth mentioning that all fluid adhesion measurements were conducted by the same person. As a result, the subjectivity in results due to interpretation was minimal.

2.3.7 Layout of Test Surfaces on Stand

The positioning of test surfaces on the test stand for testing under natural precipitation was as shown in Figure 2.2. The test surfaces were the 7.5 cm empty aluminum box (in snow) and the white-painted aluminum test plate (in frost). The thermistors were placed at the 15 cm (6″) line.

For testing under simulated freezing precipitation at NRC, the test surfaces were positioned on two test stands adjacent to the endurance time testing stands. In this case, fluid adhesion testing was conducted on standard endurance time plates and a 7.5 cm empty aluminum box. As testing progressed, the arrangement of test surfaces on the two stands changed. However, most of the time the testing was conducted according to the layout presented in Figure 2.3. A few adhesion tests were conducted on test surfaces undergoing fluid endurance time tests by documenting the occurrence of adherence after the fluid had failed. The thermistors were placed at the 15 cm (6″) line.

Testing under artificial snow conditions was conducted using the NCAR snow machine by testing one fluid at a time on the bucket assembly.

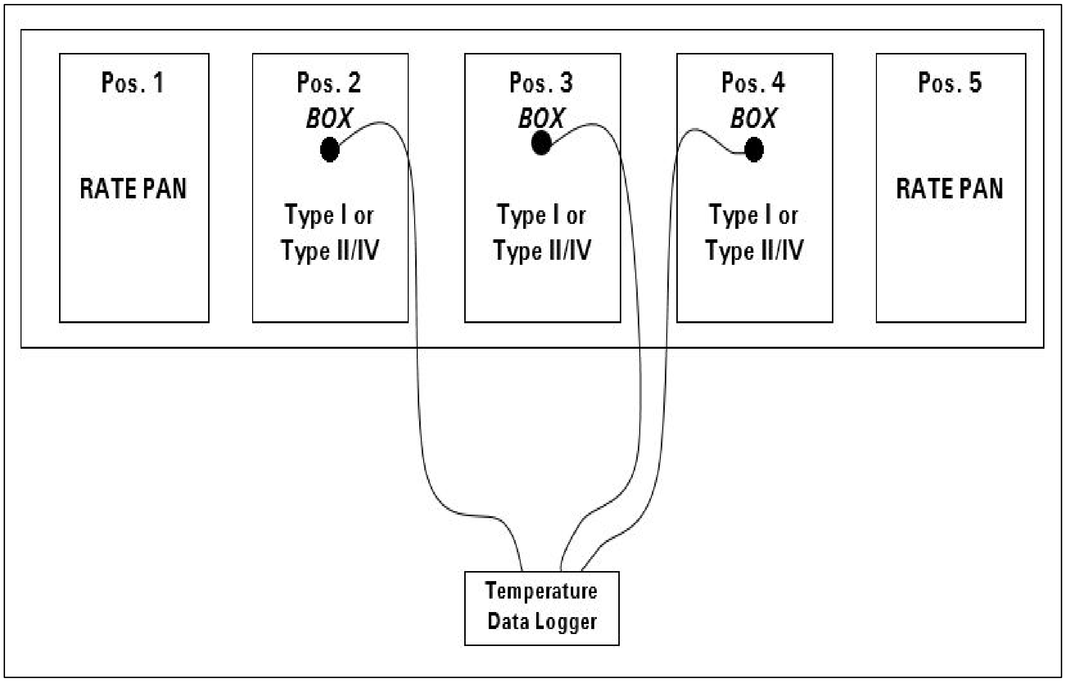


Figure 2.2: Test Stand Positions for Outdoor Testing

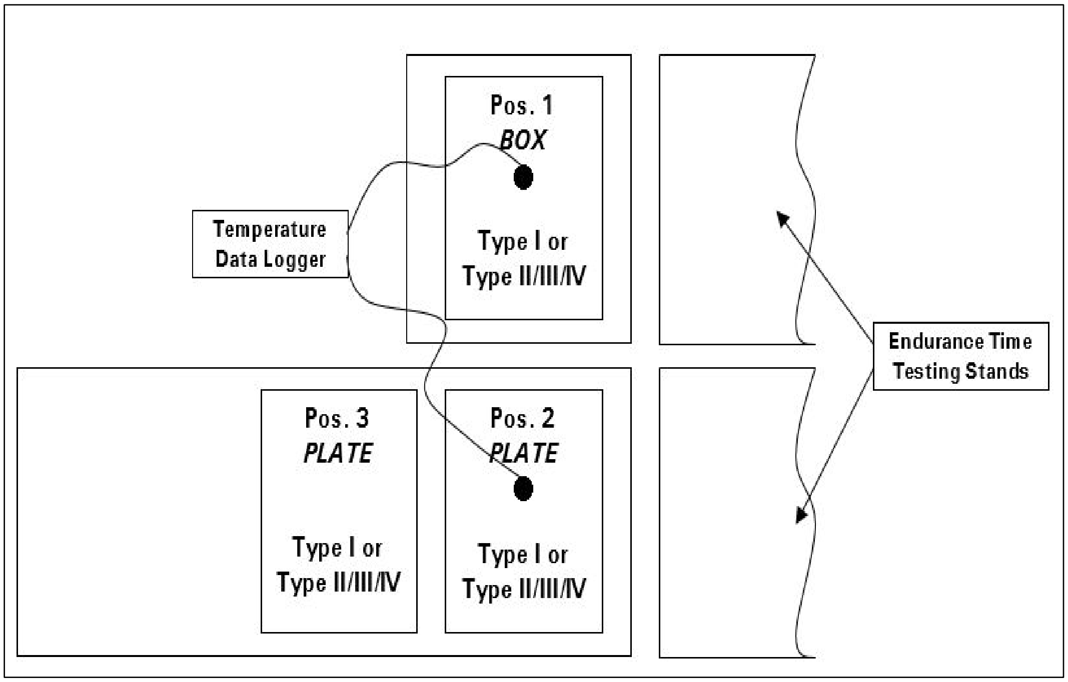


Figure 2.3: Test Stand Positions at NRC

2.4 Equipment and Fluids

2.4.1 Equipment

APS measurement instruments and test equipment were calibrated/verified at the start of the testing program. This calibration is carried out according to a calibration plan based upon approved ISO 9001:2000 standards and developed internally by APS.

The equipment used was, in general, the same as for the fluid HOT tests. A comprehensive description of the equipment can be found in TC report TP 13991E, *Aircraft Ground De/Anti-Icing Fluid Holdover Time and Endurance Time Testing Program for the 2001-02 Winter* (4). Candidate test surfaces used for these tests were:

a) Standard endurance time plates;

b) 7.5 cm deep empty aluminum boxes;

c) White-painted aluminum test plates with insulated backing; and

d) NCAR plate.

The NCAR plate consists of a standard endurance time plate placed inside the collection bucket in the snow machine enclosure. This test surface is referred to as "NCAR plate" throughout the report.

In addition to the test surfaces, several other pieces of equipment were required, including:

a) Fluid spreader device with twelve holes used for applying Type I fluids outdoors;

b) SmartReader Eight-Channel temperature logger and thermistor probes for logging test surface temperatures;

c) Misco 10431VP brixometer utilised for fluid dilution rate measurements;

d) Wet film thickness gauges; and

e) Braun electrically driven dental flossing device (OralB Interclean 2000 KD).

The electrically driven dental flossing device was used in this study to determine fluid adhesion and the degree of bonding. For a description of the methodology used to document the adherence, see Section 2.3.6. This device is shown in Photo 2.9.

2.4.2 Fluids

As per Table 2.1 and Table 2.2, test fluids were selected to provide a representation of SAE Type I and SAE Type II/IV fluids. Both ethylene glycol and propylene glycol-based fluids are represented in the data collected.

Table 2.3 shows a full list of the fluids used for adhesion testing during the 2002-03 and 2003-04 winter seasons.

Table 2.3: Fluids Tested by APS in 2002-03 and 2003-04

Fluid Manufacturer	Fluid Trade Name	Fluid Type	Glycol Type
Clariant GmbH	Safewing MP I 1938 ECO	I	Propylene
HOC Industries	SafeTemp I ES	I	Propylene
Metss Corporation	ADF-2	I	Non-glycol
Dow Chemical Company	UCAR™ PG ADF	I	Propylene
Dow Chemical Company	UCAR™ EG ADF	I	Ethylene
Clariant GmbH	Safewing MP II 2025 ECO	II	Propylene
Kilfrost Limited	Kilfrost ABC-2000	II	Propylene
Octagon Process Inc.	E Max II	II	Propylene
Clariant GmbH	Safewing MP III 2031	III	Propylene
Clariant GmbH	Safewing MP IV 2001	IV	Propylene
Clariant GmbH	Safewing MP IV 2030 ECO	IV	Propylene
Dow Chemical Company	UCAR™ ADF/AAF ULTRA+	IV	Ethylene
Octagon Process Inc.	MaxFlight	IV	Propylene

Type I fluids are usually obtained from manufacturers in concentrated form. Each manufacturer sets its own concentration based on performance requirements and cost. Type I fluid adhesion testing used 10°C buffer solutions and standard mix solutions. The term ″10°C buffer″ signifies that for any test, the test solution must possess a freezing point 10°C below that of the ambient test temperature. Whenever fluid dilution was required, the concentrations were adjusted by mixing with hard water and verified by measuring the Brix of the resulting solution. The fluids were mixed using fluid mixture tables produced from data provided by fluid manufacturers. The hard water was produced according to Aerospace Material Specification (AMS) 1424.

Type II/IV fluids were tested "as ready", at 50/50, 75/25 and full-strength concentrations. Type III fluids were tested "as ready", at full-strength concentrations. The fluids were poured onto the test surfaces at the ambient test temperature, unless otherwise noted.

2.5 Personnel

The nature of the fluid adhesion tests resulted in a number of simultaneous documentation activities during the progression and beyond fluid failure. This testing required precipitation rate, adhesion, wet film thickness, and fluid dilution measurements. The test surface temperature was also recorded. Normally, tests were run simultaneously on several test surfaces. As all of these activities required close access, special safety measures were taken to prevent crowding around the test stand and to minimize the risk of raising local air temperatures from body heat and exhaled air. This was more critical in tests carried out at higher temperatures and lower precipitation rates. The test personnel were mainly technicians and university students supervised by APS project staff.

In 2002-03, the completion of documentation and collection activities under natural snow conditions required the involvement of four technicians:

a) Technician one called failures and documented adherence;
b) Technician two prepared and helped pour fluids;
c) Technician three measured precipitation rates; and
d) Technician four measured Brix and thickness.

The experience acquired during the 2002-03 season enabled the use of only two technicians for the 2003-04 test season:

a) Technician one called failures and documented adherence; and
b) Technician two prepared fluids, measured precipitation rates and measured Brix and thickness.

Under freezing precipitation conditions, fluid adhesion testing was conducted in conjunction with endurance time testing. In this case, the precipitation rate measurements and preparation of fluids were provided by the endurance time testing personnel. Based on these procedural changes, the personnel required for the conduct of adhesion testing dropped to two.

Because only one test can be run at a time under artificial snow conditions, the test team comprised of only two testers:

a) Technician one ran the NCAR machine and conducted Brix measurements; and
b) Technician two prepared and poured fluids, called failures and documented adherence.

2.6 Analysis Methodology

The information collected from the adhesion tests was analysed to document the time at which fluid adhesion occurs, and for these cases, to determine the extent of the safety buffer between endurance time and adhesion time. The time at which adhesion occurs will be referred to as “adhesion time” throughout this document.

The size of the safety buffer, *SB*, was calculated by dividing the adhesion time, T_{ADH}, by the endurance time, T_{ET}, as shown in the equation below:

$$SB = \frac{T_{ADH}}{T_{ET}}$$

The resulting number represents the interval following standard failure until fluid adhesion was first documented and is expressed as a percentage of endurance time. For instance, a safety buffer of 1.33 for a test reporting fluid failure at ten minutes signifies that the onset of adherence was recorded at about 3.3 minutes after fluid failure.

To comply with the test procedure (Appendix B), an attempt was made to document the first occurrence of fluid adhesion at any location on the surface of the plate. Although the procedure outlined strict guidelines to be followed with respect to checking plates, in practice, parts of the procedure were difficult to follow and therefore several minor changes had to be made. The main difficulty was that the tests were “piggybacked” onto other tests in an attempt to minimize the cost of testing. The first occurrence of fluid adhesion was not always recorded. In some cases, the fluid adhesion was recorded for the first time when the frozen contamination presented bonding to the 30 cm line. If the first occurrence of adhesion had been documented in these cases, the resulting safety buffer would have been lower. Regardless of the progression of adherence on the surface, the time of its first documentation was used to determine the size of the safety buffer.

Photo 2.1: Outdoor View of APS Test Site

Photo 2.2: APS Test Site – Test Stand Used for Natural Snow Adhesion Tests

Photo 2.3: MSC's Weather Observation Station at Montréal–Trudeau Airport

Photo 2.4: Outdoor View of NRC Facility

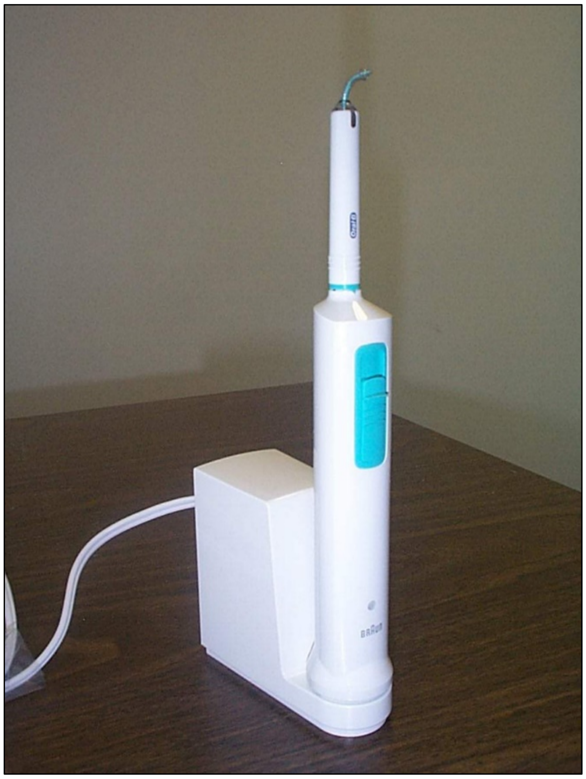
Photo 2.5: Inside View of Small End of NRC Facility

Photo 2.6: Inside View of Large End of NRC Facility

Photo 2.7: PMG Facility in Blainville, Quebec

Photo 2.8: Inside View of the PMG Facility Chamber

Photo 2.9: Braun Electrically Driven Dental Flossing Device



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3. DESCRIPTION AND PROCESSING OF DATA

This section provides a description of the data collected for the adhesion tests conducted in natural snow, artificial snow and freezing precipitation during the winter of 2002-03 and 2003-04.

The data collected during this study were focused on providing documentation of the physical nature of deicing and anti-icing fluids prior to and past failure. The test parameters documented included test surface temperature and measurements of physical characteristics including fluid concentration, fluid film thickness and fluid adhesion.

Sixteen runs, including forty-four individual tests, were conducted in natural snow and freezing drizzle on several occasions between January 7, 2003 and February 4, 2004. In the PMG laboratory, eleven artificial snow tests were performed at different temperatures and precipitation rates over a two-day period. Forty-nine indoor tests were conducted in April 2003 and April 2004 at the NRC test facility in Ottawa.

3.1 Log of Tests – Natural Snow, Artificial Snow and Frost

During the winters of 2002-03 and 2003-04, a series of fluid adhesion tests were conducted under natural and artificial snow conditions. As well, one test was conducted under natural freezing drizzle and four tests were conducted under frost conditions. Thirteen fluids provided by six manufacturers were tested. These tests included different concentrations and test surfaces.

A summary of conditions for the outdoor tests conducted by APS over the two-year period is presented below:

a) Seven snow events;
b) Thirty-nine natural snow tests;
c) One natural freezing drizzle test;
d) Four frost tests;
e) Snow precipitation rates between 5.7 and 76.9 g/dm²/h;
f) Outside air temperatures between -0.3 and -8.1°C; and
g) Wind speeds between 0.7 and 47 km/h.

A summary of conditions for the artificial snow tests conducted by APS during a two-day test session at PMG is presented below:

a) Eleven artificial snow tests;
b) Precipitation rate between 1.3 and 82 g/dm²/h; and
c) Ambient test temperature: -3.0 and -10.0°C.

A complete log of the natural and artificial snow tests is presented in Table 3.1. The log gives the pertinent information needed to understand the tests run by APS. Following is a brief explanation of the column headings in Table 3.1:

Test no.:	Exclusive number identifying each test;
Date:	The date on which each test was run;
Fluid Name:	The fluid trade name, given by the manufacturer;
Fluid Dilution:	The concentration of the fluid tested (10°C buffer or Standard mix for Type I fluids, and 50/50, 75/25 or Neat for Type II/IV fluids);
Surface:	The surface on which the test was run (empty aluminum box for snow testing, white aluminum plate for frost testing, and NCAR plate for indoor testing);
Fluid Type:	The type of fluid tested (I, II or IV);
Fluid Temperature:	The temperature of the test fluid, measured in °C;
Fail Time:	The endurance time of the fluid (in minutes), defined as per Section 2.1;
Average Rate:	Average precipitation rate for the duration of each test, measured in $g/dm^2/h$;
Outside Air Temperature:	The average outside ambient temperature (OAT) for the duration of each test, measured in °C;
Wind Speed:	Average wind speed for the duration of each test, measured at a height of 10 m, in km/h. Wind speed, wind direction and visibility data were sourced from Environment Canada records;
Wind Direction:	The average direction in which the wind was blowing for the test duration, measured in degrees. Zero degrees represent Magnetic North;
Visibility:	The average visibility for the duration of each test (in miles), measured using the Belfort Forward Scattermeter, which provides an estimate of visibility. Visibility is a measure of the opacity of the atmosphere and is expressed in terms of the horizontal distance at which a person can see and identify specified objects;
Precipitation Type:	The type of precipitation under which the test was run. The log contains natural and artificial snow tests, one natural freezing drizzle test and four frost tests;
Chart:	Identifies whether the parameters recorded over the entire duration of test were charted or not; and
Adherence, No Adh.:	Indicates whether the failed test fluid adhered to the underlying test surface.

Table 3.1: Log of Fluid Adhesion Tests Under Snow Conditions

Test No.	Date	Fluid Name	Fluid Dilution	Surface	Fluid Type	Fluid Temp (°C)	Fail Time (min.)	AVG RATE (g/dm²/h)	OAT (°C)	Environment Canada Data			Precip. Type	Chart	ADH	NO ADH
										Wind Speed (km/h)	Wind Dir. (degrees)	Visibility (miles)				
2	8-Jan-03	Clariant MP I 1938 ECO	10° Buffer	Box	I	60	7.5	9.2	-5.7	15.4	148	0.7	Snow	X		X
3	8-Jan-03	HOC Safe Templ ES	10° Buffer	Box	I	60	9.2	9.0	-5.7	15.7	147	0.7	Snow	X		X
4	8-Jan-03	METSS ADF-2	Std. mix	Box	I	60	10.5	8.9	-5.7	15.6	147	0.7	Snow	X		X
5	22-Feb-03	Clariant Safewing MP II 2025 ECO	75%	Box	II	OAT	77.0	13.0	-5.5	43.2	39	0.7	Snow	X		X
6	22-Feb-03	Clariant Safewing MP IV 2030 ECO	100%	Box	IV	OAT	88.7	13.7	-5.6	43.6	39	0.7	Snow	X		X
7	22-Feb-03	Clariant Safewing MP II 2025 ECO	50%	Box	II	OAT	25.0	13.8	-5.5	43.9	41	0.7	Snow	X		X
8	22-Feb-03	UCAR PG ADF	10° Buffer	Box	I	60	13.2	18.9	-6.4	47.4	37	0.5	Snow	X		X
10	22-Feb-03	Clariant Safewing MP II 2025 ECO	75%	Box	II	OAT	48.8	21.4	-6.3	47.3	37	0.4	Snow	X		X
11	4-Mar-03	UCAR EG ADF	10° Buffer	Box	I	60	9.2	7.4	-7.4	0.7	54	0.7	Snow	X		X
12	4-Mar-03	Clariant Safewing MP IV 2001	100%	Box	IV	OAT	97.0	5.7	-6.6	1.4	108	0.7	Snow	X		X
13	4-Mar-03	Kilfrost ABC-2000	75%	Box	II	OAT	55.0	6.1	-6.9	0.9	64	0.7	Snow	X		X
14	4-Mar-03	UCAR EG ADF	10° Buffer	Box	I	60	9.0	7.2	-8.1	14.1	50	0.8	Snow	X	X	
15	4-Mar-03	UCAR ULTRA+	100%	Box	IV	OAT	136.0	7.0	-8.0	15.1	30	1.0	Snow	X		X
16	4-Mar-03	Kilfrost ABC-2000	75%	Box	II	OAT	73.3	5.8	-8.0	13.1	29	0.9	Snow	X		X
30	8-Mar-03	UCAR EG ADF	10° Buffer	Box	I	60	8.2	29.8	-1.5	8.5	68	0.3	Snow	X	X	
31	8-Mar-03	Clariant Safewing MP IV 2001	100%	Box	IV	OAT	59.0	16.8	-1.5	11.0	35	0.4	Snow	X		X
32	8-Mar-03	E Max II	50%	Box	II	OAT	11.8	20.6	-1.5	7.4	43	0.3	Snow		X	
33	9-Mar-03	UCAR EG ADF	10° Buffer	Box	I	60	7.8	24.1	-2.3	17.5	12	0.3	Snow	X	X	
34	9-Mar-03	Kilfrost ABC-2000	75%	Box	II	OAT	23.5	16.5	-2.4	17.1	23	0.4	Snow	X		X
35	9-Mar-03	E Max II	50%	Box	II	OAT	18.5	16.5	-2.4	17.1	24	0.4	Snow	X		X
36	5-Apr-03	UCAR ULTRA+	100%	Box	IV	OAT	127.0	6.9	-4.4	N/A	N/A	N/A	Snow	X		X
37	5-Apr-03	Clariant Safewing MP IV 2030 ECO	100%	Box	IV	OAT	145.5	7.2	-4.4	N/A	N/A	N/A	Snow	X		X
38	5-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Box	I	60	16.0	7.7	-3.7	N/A	N/A	N/A	Snow	X		X
39	5-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Box	I	60	16.5	9.1	-3.6	N/A	N/A	N/A	Snow	X		X
50	14-Dec-03	Kilfrost ABC-2000	100%	Box	II	1.6	12.2	47.9	-7.7	24.0	40	0.7	Snow			X
51	14-Dec-03	Kilfrost ABC-2000	100%	Box	II	7.9	11.7	47.9	-7.7	24.0	40	0.7	Snow			X
52	14-Dec-03	E Max II	75%	Box	II	3.4	17.2	47.7	-7.7	24.0	40	0.7	Snow			X
53	14-Dec-03	E Max II	75%	Box	II	7	16.8	47.7	-7.7	24.0	40	0.7	Snow			X

Table 3.1: Log of Fluid Adhesion Tests Under Snow Conditions (cont'd)

Test No.	Date	Fluid Name	Fluid Dilution	Surface	Fluid Type	Fluid Temp (°C)	Fail Time (min.)	AVG RATE (g/dm^2/h)	OAT (°C)	Environment Canada Data			Precip. Type	Chart	ADH	NO ADH
										Wind Speed (km/h)	Wind Dir. (degrees)	Visibility (miles)				
54	3-Feb-04	Octagon Maxflight	50%	Box	IV	-0.5	20.7	16.2	-0.3	25.0	135	2.2	Snow			X
55	3-Feb-04	Octagon Maxflight	50%	Box	IV	55	21.2	16.4	-0.3	25.0	135	2.2	Snow		X	
56	3-Feb-04	Kilfrost ABC-2000	100%	Box	II	60	17.8	16.7	-0.3	25.0	135	2.2	Snow		X	
57	3-Feb-04	Kilfrost ABC-2000	100%	Box	II	-0.5	14.8	16.2	-0.3	25.0	135	2.2	Snow			X
58	3-Feb-04	Octagon Maxflight	100%	Box	IV	-11.4	11.3	76.9	-1.3	9.0	90	0.2	Snow			X
59	3-Feb-04	Octagon Maxflight	100%	Box	IV	60	12.5	76	-1.3	9.0	90	0.2	Snow			X
60	3-Feb-04	Kilfrost ABC-2000	50%	Box	II	-1.4	2.0	75.7	-1.3	9.0	90	0.2	Snow			X
61	3-Feb-04	Kilfrost ABC-2000	50%	Box	II	60	4.5	75.7	-1.3	9.0	90	0.2	Snow		X	
62	4-Feb-04	Kilfrost ABC-2000	75%	Box	II	-1.4	23.3	8.1	-1.2	13.0	130	1.7	Snow			X
63	14-Dec-03	BARE SURFACE HOT	-	Box	-	-	-	30.2	-7.6	26.0	45	0.6	Snow		X	
64	14-Dec-03	BARE SURFACE COLD	-	Box	-	-	-	36.0	-7.5	30.0	50	0.4	Snow			X
P1	6-Mar-03	UCAR EG ADF	10° Buffer	NCAR Plate	I	20	9.0	10.5	-3.0	-	-	-	Artificial Snow	X	X	
P2	6-Mar-03	Clariant Safewing MP IV 2001	100%	NCAR Plate	IV		48.0	10.1	-3.0	-	-	-	Artificial Snow	X		X
P3	6-Mar-03	E Max II	50%	NCAR Plate	II	3	23.5	9.9	-3.0	-	-	-	Artificial Snow	X		X
P4	6-Mar-03	UCAR EG ADF	10° Buffer	NCAR Plate	I	25	4.0	23.4	-3.0	-	-	-	Artificial Snow	X	X	
P5	6-Mar-03	UCAR EG ADF	10° Buffer	NCAR Plate	I	20	5.5	24.6	-3.0	-	-	-	Artificial Snow	X	X	
P8	7-Mar-03	UCAR ULTRA+	100%	NCAR Plate	IV	1.5	36.8	24.8	-10.0	-	-	-	Artificial Snow	X		X
P9	7-Mar-03	UCAR EG ADF	10° Buffer	NCAR Plate	I	25	3.0	25.9	-10.0	-	-	-	Artificial Snow	X	X	
P10	7-Mar-03	UCAR EG ADF	10° Buffer	NCAR Plate	I	65	3.0	57.9	-10.0	-	-	-	Artificial Snow	X	X	
P11	7-Mar-03	UCAR EG ADF	10° Buffer	NCAR Plate	I	50	2.3	81.6	-10.0	-	-	-	Artificial Snow	X	X	
P12	7-Mar-03	UCAR EG ADF	10° Buffer	NCAR Plate	I	-7.5	29.0	1.3	-10.0	-	-	-	Artificial Snow	X		X
P13	7-Mar-03	Pure Water	-	NCAR Plate	-	-	2.5	30.0	-10.0	-	-	-	Artificial Snow	X	X	
1	7-Jan-03	METSS ADF-2	Std. Mix	Box	I	60	30.2	2.3	-5.7	14.6	157	4.0	Freezing Drizzle	X	X	
65	8-Dec-03	UCAR EG ADF	10° Buffer	White Al. Plate	I	20	46.0	0.129	-8.7	7.0	120	15.5	Frost		X	
66	8-Dec-03	UCAR PG ADF	10° Buffer	White Al. Plate	I	20	65.0	0.154	-8.7	7.0	120	15.5	Frost		X	
67	8-Dec-03	UCAR EG ADF	10° Buffer	White Al. Plate	I	20	79.5	0.129	-11.0	4.0	85	4.5	Frost		X	
68	8-Dec-03	UCAR PG ADF	10° Buffer	White Al. Plate	I	20	84.5	0.129	-11.0	4.0	85	4.5	Frost		X	

N/A – Data not available.

Ten tests conducted under natural and artificial snow precipitation conditions did not experience fluid failure. These tests were not included in this analysis.

3.2 Log of Tests – Simulated Freezing Precipitation Conditions

In 2003 and 2004, APS conducted a series of fluid adhesion tests under simulated precipitation conditions. These tests were conducted under freezing fog, freezing drizzle, light freezing rain and cold-soak conditions, using eight fluids provided by four manufacturers. The tests included different fluid concentrations and test surfaces.

A summary of conditions for the indoor tests conducted by APS in April 2003 and April 2004 is presented below:

a) Forty-nine fluid adhesion tests;
b) Eleven separate weather conditions;
c) Precipitation rate between 2.2 and 28.8 g/dm²/h; and
d) Air temperature between 0.4 and -25.1°C.

A complete log of adhesion tests conducted under simulated freezing precipitation conditions is presented in Table 3.2. The log gives the pertinent information needed to understand the test results. A brief explanation of the column headings can be found in Section 3.1. The chamber temperature presented in Table 3.2 is the average of all temperature probes in the testing area.

3.3 Illustration of Data Collected

Using data collected for plate temperature, fluid dilution expressed as fluid freeze point, and fluid thickness, a graphic representation was created for most tests. The time of occurrence of fluid adhesion was also indicated on the charts. to give a complete picture of the phenomena that took place during testing. The charts are discussed in Section 3.3.5.

3.3.1 Surface Temperature

For all fluid adhesion tests conducted under natural and artificial snow, the surface temperature was recorded throughout the test. Under natural precipitation, measurements were recorded with a thermistor probe and data logger as described in Section 2.3.1 and shown in Photo 2.2. Under artificial snow, the software running the NCAR system recorded the test surface temperature using a temperature probe installed on the underside of the plate. The test stands used under simulated freezing precipitation in 2003 are presented in Photo 3.1. The majority of freezing precipitation adhesion tests were run on the far right position on the lower stand (adjacent to the endurance time stand) and on the one-position stand. Only these two adhesion test positions were instrumented to record test surface temperature. For 2004, all test positions were instrumented for surface temperature.

3.3.2 Fluid Dilution

Fluid dilution was measured at the 15 cm (6") line, using a Misco 10431VP brixometer as described in Section 2.3.2.

For type I fluids the recorded Brix value was converted to fluid freeze point temperature for comparison to the recorded test surface temperature.

For Type II and IV fluids, the dilution of the fluid is indicated on the charts using "negative Brix" values as conversion charts of Brix values to freeze point temperatures were not available for many of the fluids tested. Generic conversion values for both ethylene and propylene glycol are given in Table 3.3. The values in Table 3.3 are for information purposes only.

3.3.3 Fluid Thickness

Fluid thickness was measured progressively at the 15 cm line as described in Section 2.3.3, until the contamination turned into slush or ice on the plate surface. Photo 3.2 shows the gauge used for measuring fluid thickness.

3.3.4 Fluid Adhesion

Fluid adhesion was documented at different stages and different locations on the test surface as described in Section 2.3.6. Photo 3.3 to Photo 3.6, taken at the NRC climatic chamber, illustrate the fluid adhesion at various degrees of bonding, from the onset of adhesion at the top of the plate to complete fluid adhesion over the entire area of the test surface. Photo 3.7 shows a typical case of fluid adhesion under artificial snow conditions. Photo 3.8 illustrates the presence of adhered frost on the white aluminum plate.

Table 3.2: Log of Fluid Adhesion Tests Under Simulated Freezing Precipitation

Test No.	Date	Fluid Name	Fluid Dilution	Surface	Fluid Type	Fluid Temp (°C)	Fail Time (min.)	Actual Rate of Precip. (g/dm^2/h)	Actual Chamber Temp. (°C)	Precip. Type	Chart	ADH	NO ADH
E7	7-Apr-03	UCAR EG ADF	10° Buffer	Plate	I	20	7.3	2.2	-25.1	ZF	X		X
4	7-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Plate	I	20	5.5	4.9	-24.2	ZF	X		X
5	7-Apr-03	Clariant Safewing MP IV 2030 ECO	100%	Box	IV	OAT	39.5	5.2	-24.2	ZF	X		X
6	7-Apr-03	UCAR ULTRA +	100%	Plate	IV	OAT	48.0	4.9	-24.2	ZF	X		X
7	2-Apr-03	UCAR EG ADF	10° Buffer	Plate	I	20	13.3	3.9	-3.1	ZF	X	X	
8	2-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Box	I	20	20.3	4.0	-3.1	ZF	X	X	
9	2-Apr-03	Clariant Safewing MP IV 2030 ECO	75%	Plate	IV	OAT	89.0	4.5	-3.1	ZF	X	X	
10	2-Apr-03	Clariant Safewing MP II 2025 ECO	50%	Box	II	OAT	28.5	4.0	-3.2	ZF	X	X	
11	2-Apr-03	UCAR ULTRA +	100%	Box	IV	OAT	249.0	4.6	-4.8	ZF	X	X	
A2	20-Apr-04	Kilfrost ABC-2000	100%	Plate	II	OAT	64.5	5.6	-3.0	ZD		X	
A3	20-Apr-04	Clariant Safewing MP III 2031	100%	Plate	III	OAT	22.7	5.9	-2.9	ZD		X	
17	9-Apr-03	UCAR EG ADF	10° Buffer	Plate	I	20	10.2	15.3	-3.2	ZD	X	X	
18	9-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Plate	I	20	11.4	15.3	-3.2	ZD	X	X	
19	9-Apr-03	Clariant Safewing MP IV 2030 ECO	75%	Plate	IV	OAT	31.5	12.9	-3.2	ZD	X	X	
20	9-Apr-03	Clariant Safewing MP II 2025 ECO	50%	Plate	II	OAT	9.8	12.9	-3.2	ZD	X	X	
A5	21-Apr-04	Kilfrost ABC-2000	100%	Plate	II	OAT	47.8	5.2	-10.4	ZD		X	
A6	21-Apr-04	Clariant Safewing MP III 2031	100%	Plate	III	OAT	21.2	5.4	-10.4	ZD		X	
21	8-Apr-03	UCAR EG ADF	10° Buffer	Box	I	20	9.4	5.2	-10.3	ZD	X	X	
22	8-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Box	I	20	10.0	5.2	-10.3	ZD	X	X	
23	8-Apr-03	Clariant Safewing MP II 2025 ECO	100%	Plate	II	OAT	59.5	3.8	-10.3	ZD	X	X	
25	8-Apr-03	UCAR ULTRA +	100%	Plate	IV	OAT	130.5	3.8	-10.2	ZD	X	X	
E1	8-Apr-03	Clariant Safewing MP IV 2030 ECO	75%	Box	IV	OAT	49.2	5.2	-10	ZD	X	X	
A8	21-Apr-04	Kilfrost ABC-2000	100%	Plate	II	OAT	29.0	14.5	-10.3	ZD		X	
A9	21-Apr-04	Clariant Safewing MP III 2031	100%	Plate	III	OAT	12.5	12.7	-10.3	ZD		X	
26	8-Apr-03	UCAR EG ADF	10° Buffer	Box	I	20	5.6	13.4	-10.2	ZD	X	X	
27	8-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Box	I	20	4.6	13.2	-10	ZD	X	X	
28	8-Apr-03	Clariant Safewing MP IV 2030 ECO	100%	Plate	IV	OAT	46.2	11.7	-10.1	ZD	X	X	
29	8-Apr-03	Clariant Safewing MP II 2025 ECO	75%	Plate	II	OAT	24.8	11.7	-10.2	ZD	X	X	

Table 3.2: Log of Fluid Adhesion Tests Under Simulated Freezing Precipitation (cont'd)

Test no.	Date	Fluid Name	Fluid Dilution	Surface	Fluid Type	Fluid Temp. (°C)	Fail Time (min.)	Actual Rate of Precip. (g/dm²/h)	Actual Chamber Temp. (°C)	Precip. Type	Chart	ADH	NO ADH
A10	21-Apr-04	Octagon Maxflight	100%	Plate	IV	OAT	21.3	24.9	-10.2	ZR		X	
A11	21-Apr-04	Kilfrost ABC-2000	100%	Plate	II	OAT	19.9	25.4	-10.2	ZR		X	
A12	21-Apr-04	Clariant Safewing MP III 2031	100%	Plate	III	OAT	9.8	25.3	-10.1	ZR		X	
31	8-Apr-03	UCAR EG ADF	10° Buffer	Box	I	20	5.0	25.8	-9.8	ZR	X	X	
32	8-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Plate	I	20	5.5	26.4	-10.1	ZR	X	X	
33	8-Apr-03	Clariant Safewing MP IV 2030 ECO	100%	Plate	IV	OAT	23.3	26.1	-9.8	ZR	X	X	
34	8-Apr-03	Clariant Safewing MP II 2025 ECO	75%	Plate	II	OAT	12.3	26.1	-9.7	ZR	X	X	
36	8-Apr-03	UCAR ULTRA +	100%	Plate	IV	OAT	39.7	26.1	-9.9	ZR	X	X	
39	9-Apr-03	Clariant Safewing MP IV 2030 ECO	75%	Plate	IV	OAT	38.4	12.4	-3.1	ZR	X	X	
40	9-Apr-03	Clariant Safewing MP IV 2030 ECO	50%	Plate	IV	OAT	16.7	12.4	-3	ZR	X	X	
41	9-Apr-03	Clariant Safewing MP II 2025 ECO	50%	Plate	II	OAT	10.3	12.4	-3	ZR	X	X	
42	9-Apr-03	UCAR ULTRA +	100%	Plate	IV	OAT	52.0	12.4	-3.1	ZR	X	X	
A13	19-Apr-04	Octagon Maxflight	100%	Plate	IV	OAT	74.1	24.9	-3.3	ZR		X	
A14	19-Apr-04	Kilfrost ABC-2000	100%	Plate	II	OAT	29.3	27.0	-3.2	ZR		X	
A15	19-Apr-04	Clariant Safewing MP III 2031	100%	Plate	III	OAT	10.9	28.8	-2.9	ZR		X	
E2	9-Apr-03	Clariant MP I 1938 ECO	10° Buffer	Plate	I	20	13.2	23.6	-2.9	ZR	X	X	
E3	9-Apr-03	UCAR EG ADF	10° Buffer	Box	I	20	19.3	24.8	-2.9	ZR	X	X	
E4	9-Apr-03	UCAR ULTRA +	100%	Plate	IV	OAT	38.6	26.1	-3.1	ZR	X	X	
E5	9-Apr-03	Clariant Safewing MP IV 2030 ECO	50%	Plate	IV	OAT	8.6	26.1	-2.8	ZR	X	X	
E6	9-Apr-03	Clariant Safewing MP II 2025 ECO	50%	Plate	II	OAT	5.7	26.1	-2.8	ZR	X	X	
E11	9-Apr-03	Clariant Safewing MP II 2025 ECO	75%	Box	II	OAT	49.8	5.3	0.4	Cold Soak	X	X	

3.3.5 Plotting of Test Data

Figure 3.1 illustrates the mechanism by which the test surface temperature and fluid freeze point temperature lead to fluid failure, followed by fluid adhesion to the test surface. The test surface and ambient air temperature profile curves are shown. The surface temperature curve gradually approaches the ultimate value of ambient temperature. The fluid freeze point temperature curve was derived from fluid concentration (Brix) values measured progressively throughout testing. The curve representing the fluid freeze point temperature gradually rises as the fluid is progressively diluted, increasing from its initial value toward an ultimate value.

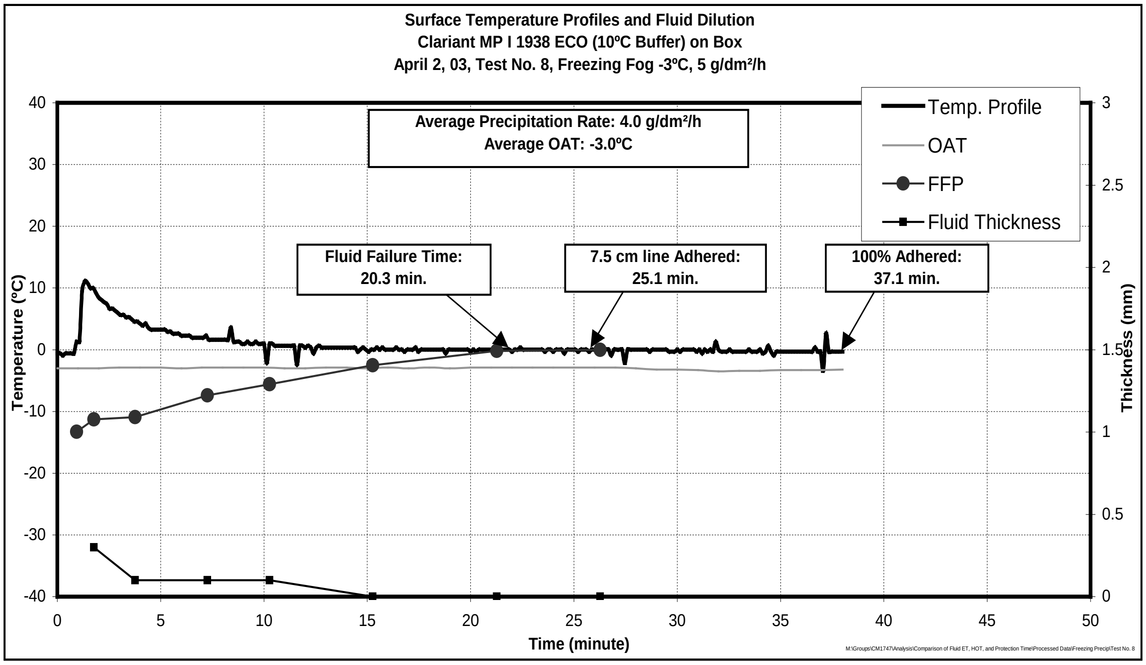


Figure 3.1: Surface Temperature Profiles and Fluid Dilution

In summary, both curves represent temperature profiles. One curve represents the surface temperature decay-rate profile and the other represents the temperature profile of the fluid's freeze point. The point where the two curves intersect is the expected endurance time in actual operations. In other words, freezing is expected to occur when the fluid freeze point and the surface temperature match.

The data displayed in Figure 3.1 shows the surface temperature decay profile on the aluminum box for a test run on April 2, 2003 under freezing fog conditions at NRC. The surface temperature peaked when the 20°C fluid was first applied and then gradually cooled toward ambient test temperature of -3°C. The empty aluminum box holds its temperature longer than a standard endurance time plate due to its geometry and insulation. The outcome is a more gradual and extended temperature profile curve and subsequently a longer endurance time.

In Figure 3.1, the Type I fluid freeze point temperature was charted over time as the fluid progressively diluted under precipitation. About 20 minutes after pouring, the fluid freeze point temperature curve reached its final value, corresponding to pure water. Shortly after, fluid failure was recorded. When freezing finally occurred, the resulting ice adhered to the surface, as presented in Figure 3.1.

At about 5 minutes after failure, fluid adhesion at the 7.5 cm line was recorded. At about 17 minutes after fluid failure, the entire test surface was covered with adhered contamination.
Fluid thickness is also plotted on the chart in Figure 3.1.

A full set of test results, grouped by weather conditions, is provided in Appendix D. If adhesion did not occur, the time of the last adhesion check is indicated on the charts. At failure time, the fluid did not show adhesion, unless otherwise specified on the chart.

The results from the 2002-03 and 2003-04 testing seasons under natural snow, artificial snow, frost and simulated freezing precipitation conditions were analysed in a similar manner and are discussed in Section 4.

As noted in Section 3.3.2, Type II and IV fluids dilution is indicated on the charts using “negative Brix” values as conversion charts of Brix values to freezing point temperatures were not available for many of the fluids tested. Generic conversion values for both ethylene and propylene glycol given in Table 3.3 are for information purposes only.

Table 3.3: Generic Conversion of Brix to Freeze Point

BRIX	Approximate Freezing Point for Ethylene (°C)	Approximate Freezing Point for Propylene (°C)
0	0	0
2	-1	-
5	-2	-
8	-4	-3
10	-5	-4
15	-9	-8
20	-16	-12
25	-24	-17
30	-34	-24
35	-45	-35

3.4 Summary of Results

As presented in Section 2.3, the purpose of this study was to document the buffer time in each cell of the Type I and Type II/IV HOT guidelines. However, due to time limitations and budgetary constraints, only selected conditions considered to be representative were tested. A planned matrix of the selected tests was developed for each of the two testing seasons, as presented in Table 2.1 and Table 2.2. Table 3.4 shows a matrix of the actual tests performed between 2002 and 2004.

Table 3.4 specifies the test surface, the type of test surface used, and also the number of tests whenever more than one test was conducted for a specific cell of the table. Due to the high number of fluids tested and to enable a global analysis, the fluid names are not indicated in the table. The fluids are grouped by fluid type, glycol type and glycol concentration.

The 2002-03 testing session started with fluid adhesion tests conducted on the empty aluminum box under natural snow precipitation conditions at the APS test site. Subsequently, the artificial snow testing session at PMG, conducted under controlled temperatures and precipitation rate conditions, provided more information and consolidated the findings from outdoor testing. The NCAR snowmaking system allowed very high snow precipitation rates to be tested. Adherence testing under simulated freezing precipitation was conducted at NRC in April 2003, and addressed a variety of weather conditions.

The 2003-04 test session started with fluid adhesion tests conducted under natural snow precipitation conditions and under natural frost conditions at the APS test site. Subsequently, adherence testing under simulated freezing precipitation was conducted at NRC in April 2004. The 2003-04 testing addressed the recommendations made in the previous testing season, including Type II/IV fluid adhesion testing using heated fluids, adhesion testing in frost, bare surface adhesion testing and testing under freezing precipitation using Type IV propylene-based fluids.

Table 3.4: Matrix of Actual Tests Conducted Between 2002 and 2004

Location	NRC	NRC	NRC	NRC	NRC	NRC	NRC	NRC	NRC	NRC	NRC	Dorval	Dorval	Dorval	Dorval	Dorval	PMG	PMG	PMG	PMG	PMG
Precipitation Type	CSW	ZF	ZF	ZF	ZD	ZD	ZD	ZD	ZR	ZR	ZR	Natural ZD	Natural Frost	Light Snow	Moderate Snow	Heavy Snow	Indoor Snow	Indoor Snow	Indoor Snow	Indoor Snow	Indoor Snow
Rate ($g/dm^2/h$)	5	2	5	5	5	13	5	13	13	25	25	2.3	0.129 to 0.154	5.7 to 9.2	13 to 24.1	29.8 to 76.9	10	25	57.9 and 81.6	25	1.3
OAT (°C)	1	-25	-25	-3	-3	-3	-10	-10	-3	-3	-10	-5.7	-8.7 to -11.0	-1.2 to -8.1	-0.3 to -6.4	-1.3 to -7.7	-3	-3	-10	-10	-10
Type I EG (10° Buffer)		Pl		Pl		Pl	Box	Box		Box	Box		White Pl (2)	Box (2)	Box	Box	Pl	Pl (2)	Pl (2)	Pl	Pl
Type I PG (10° Buffer)			Pl	Box		Pl	Box	Box		Pl	Pl	Box	White Pl (2)	Box (5)	Box						
Type IV PG (Neat)			Box					Pl		Pl	Pl (2)			Box (2)	Box (2)	Box (2)	Pl				
Type IV PG (75/25)				Pl		Pl	Box		Pl												
Type IV PG (50/50)									Pl	Pl					Box (2)						
Type IV EG (Neat)			Pl	Box			Pl		Pl	Pl	Pl			Box (2)						Pl	
Type III PG (Neat)					Pl		Pl	Pl		Pl	Pl										
Type II PG (Neat)					Pl		Pl (2)	Pl		Pl	Pl				Box (2)	Box (2)					
Type II PG (75/25)	Box							Pl			Pl			Box (3)	Box (3)	Box (2)					
Type II PG (50/50)				Box		Pl			Pl	Pl					Box (3)	Box (2)	Pl				
Bare Surface																Box (2)					

Pl – Plate
White Pl – White aluminum plate
(x) – Number of tests

Photo 3.1: Test Stands Used for Freezing Precipitation Adhesion Tests

Photo 3.2: Thickness Gauge

Photo 3.3: Onset of Adhesion Under Freezing Precipitation at NRC

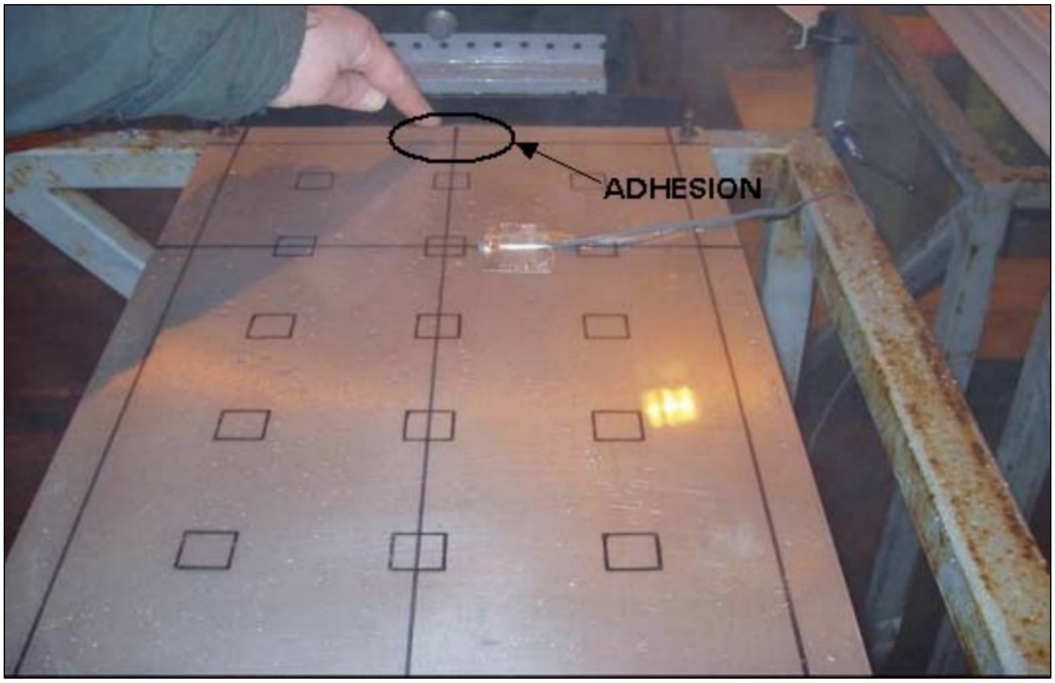


Photo 3.4: Close-Up of Onset of Adhesion Under Freezing Precipitation at NRC

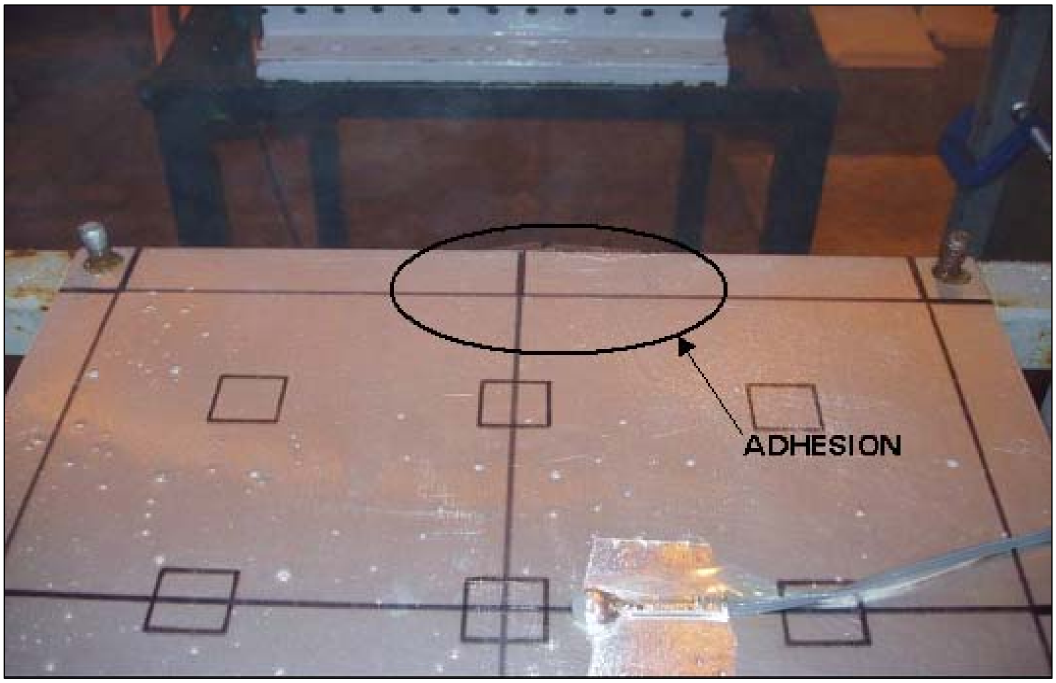


Photo 3.5: Presence of Fluid Adhesion on Test Surface Under Freezing Precipitation at NRC

Photo 3.6: Presence of Adhesion of Completely Solidified Contamination on Test Surface

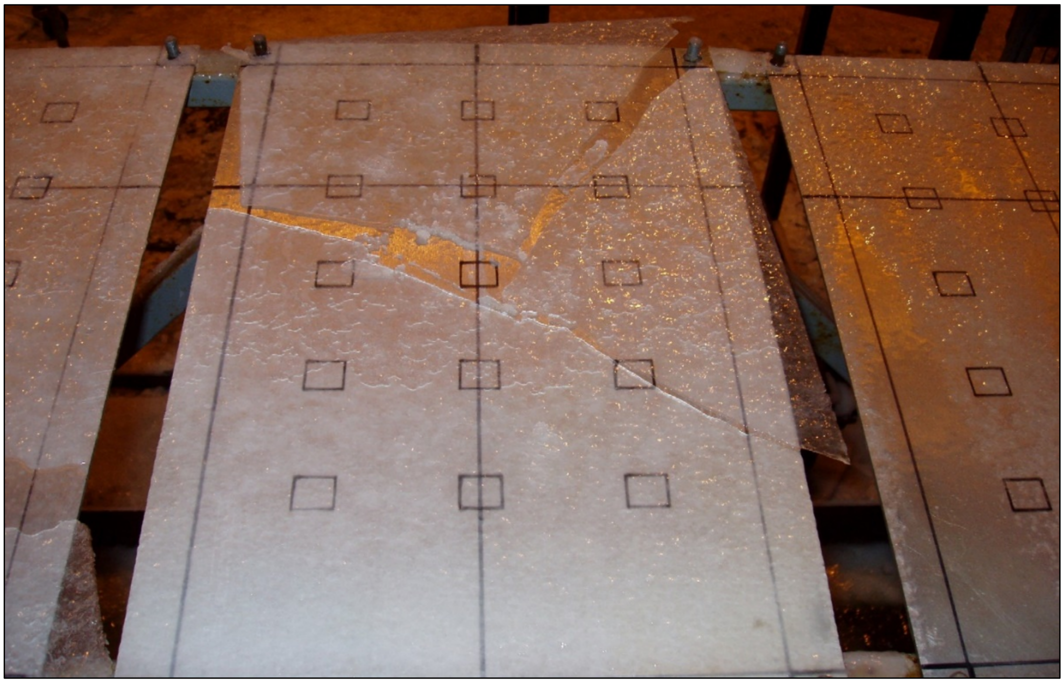


Photo 3.7: Presence of Fluid Adhesion Under Artificial Snow at PMG

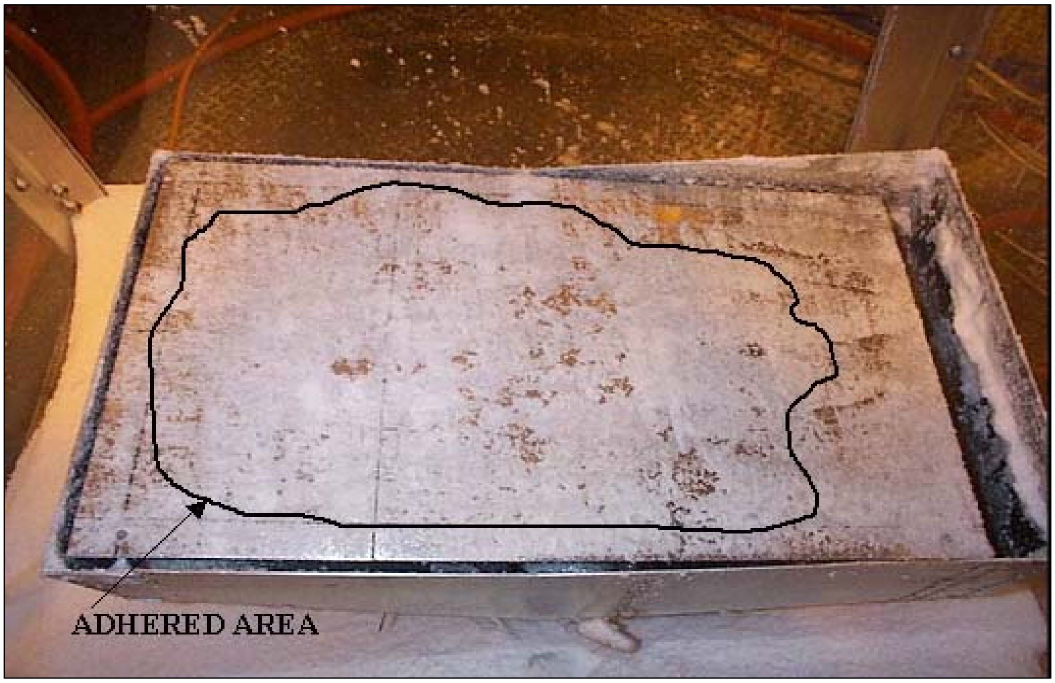
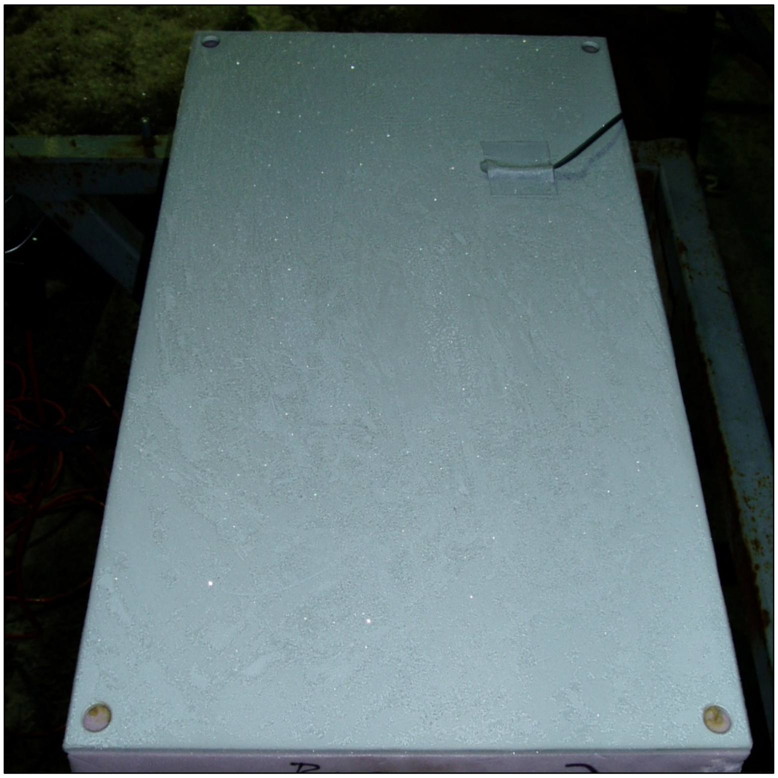


Photo 3.8: Presence of Frost on the White Aluminum Plate



4. ANALYSIS AND DISCUSSION

This section presents discussions and analysis of the experimental data collected, with specific consideration given to the nature and occurrence of fluid adhesion. The discussion and analysis are intended to address each weather condition and fluid type according to the matrix presented in Table 3.4. The test results for Type I and Type II, III and IV fluids are analysed in separate subsections, with each subsection being further divided by weather condition. Results from specific tests are discussed within each subsection.

4.1 Type I Fluid Adhesion

The application of the Type I fluid left a thin, transparent orange layer of liquid on the plate. The fluid film thickness quickly stabilized as excess fluid flowed off the test plate. Immediately after the fluid was poured, snow particles began accumulating on the fluid surface and quickly penetrated through the thin fluid film. The Type I fluid layer was generally too thin to absorb the snowflakes before they came into contact with the underlying plate surface, as shown in Photo 4.1. The quantity of snow on the plate increased rapidly and the fluid surface became completely covered by the precipitation.

Under freezing precipitation conditions, failures tended to occur from the top edge to the bottom edge of the test plate. The resulting failures consisted of small particles of ice embedded in the fluid. The particles rapidly fused together and proceeded to adhere to the plate surface, creating a layer of ice on the test plate.

During the first few minutes after application, the thickness of the applied fluid film diminished rapidly, leaving a thin film of about 0.1 mm in depth. Typically, the film reached a stabilized thickness before the time of plate failure. Due to the thinness of the fluid layer, the fluid temperature gradient and fluid concentration gradient throughout the fluid layer were neglected for this analysis.

4.1.1 Natural and Artificial Snow: Type I Fluid

In some cases, during the 2002-03 testing session, it was observed that after a short while following fluid failure, the contamination adhered to the surface. Regarding this phenomenon, two significant observations were made:

a) Fluid failure when the fluid has diluted to water prior to the plate temperature dropping below 0°C can result in adherence. At milder temperatures (-3°C and above), heated fluid is more likely to dilute to water before the surface temperature drops below 0ºC. This is particularly true in the application of heated fluid onto the empty aluminum box, where additional surface protection is provided by the box cavity heat. When freezing finally occurred, the resulting ice adhered to the surface; and

b) At colder temperatures and lower snow precipitation rates when the test surface was exposed far beyond the time when failure was called, the final fluid concentration did not dilute beyond a Brix value of 4 or 5 (above a fluid freeze point of -2 to -2.5ºC. The failed fluid had the aspect and consistency of slush. In these cases, the visually failed fluid did not adhere.

4.1.1.1 Moderate and high precipitation rates

According to the Type I HOT guideline table, moderate snow is defined as precipitation rates within the range of 10 to 25 g/dm²/h and heavy snow as precipitation rates greater than 25 g/dm²/h.

Test No. 33, Precipitation Rate 24.1 g/dm²/h, OAT -2.3°C, Natural Snow

Figure 4.1 illustrates a typical case of a Type I fluid test that exhibited adherence under natural snow precipitation. The fluid used was UCAR EG ADF.

The adhesion test was conducted under a rate of precipitation of 24.1 g/dm²/h on the empty aluminum box surface. The average OAT over the duration of the test was -2.3°C and the fluid was applied at 60°C. When exposed to natural snow at this precipitation rate, the fluid experienced rapid dilution, with the freezing point rising to 0°C in about 6 minutes. At this point, the fluid was completely diluted, the concentration of the solution on the test surface being that of pure water. The test surface temperature dropped below 0°C in 5.2 minutes, exposing the contamination to freezing conditions. Shortly after, at 7.8 minutes after pouring, the visual failure of the fluid was recorded on the data form. As mentioned in Section 2.1, visual failure is called when 30 percent of the plate is covered with frozen contamination.

At the time of failure, surface protection was not provided by either glycol or heat, and as the cold-box surface continued to cool down towards ambient temperature, the contamination started to freeze. At about 10.4 minutes after pouring, the failed fluid layer showed bonding to the substrate test surface at the 7.5 cm line. After about 40 minutes, failed fluid was adhered over the entire surface of the empty aluminum box.

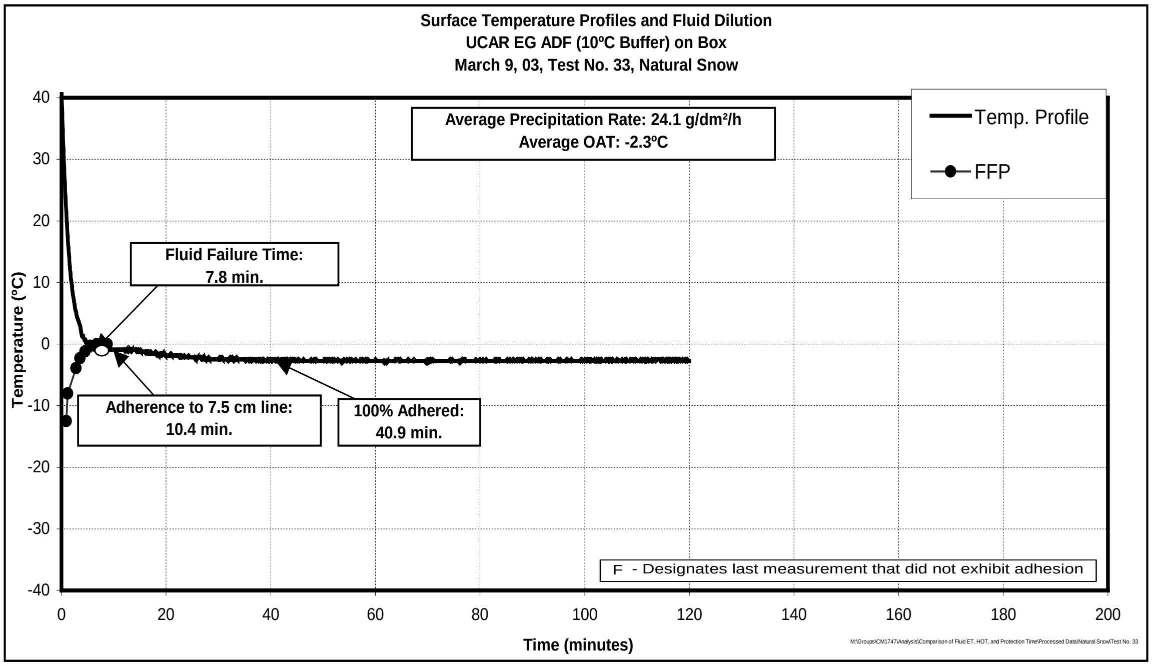


Figure 4.1: Test No. 33, Natural Snow

For this test, the first occurrence of fluid adhesion was documented at 10.4 minutes, while fluid failure was recorded after 7.8 minutes. By dividing the adhesion time by the endurance time according to the methodology presented in Section 2.6, the size of the safety buffer was calculated to be 1.33. This indicates that the onset of adherence will occur after fluid failure at an interval equal to about 33 percent of the endurance time.

Test No. P4, Precipitation Rate 23.4 g/dm²/h, OAT -3°C, Artificial Snow

Similar tests were performed under artificial snow conditions at PMG. Figure 4.2 illustrates an adhesion test conducted at a test temperature of -3°C and a precipitation rate of 23.4 g/dm²/h using the same ethylene glycol-based fluid, UCAR EG ADF.

Even though the fluid was applied at 25°C, the test surface temperature dropped below 0°C after about 2 minutes, much faster than in the previous case. At this time, the concentration of the fluid corresponded to a freeze point of around -6°C. At this instant, surface protection was being provided by the existing glycol, its concentration preventing the contamination from freezing. At 4 minutes after pouring, standard plate failure was recorded. When the visual failure was called, the freeze point of the fluid was close to the ambient test temperature. After further exposure to precipitation, the fluid diluted to a freeze point of -1°C in about

7 minutes. At this instant, the freeze point of the fluid had been higher than the test surface temperature for about 1 minute, as the surface continued to cool down towards the ambient temperature. The contamination started to freeze and, at about 7 minutes after pouring, the frozen contamination presented bonding at the 15 cm line. The size of the safety buffer was calculated to be 1.75.

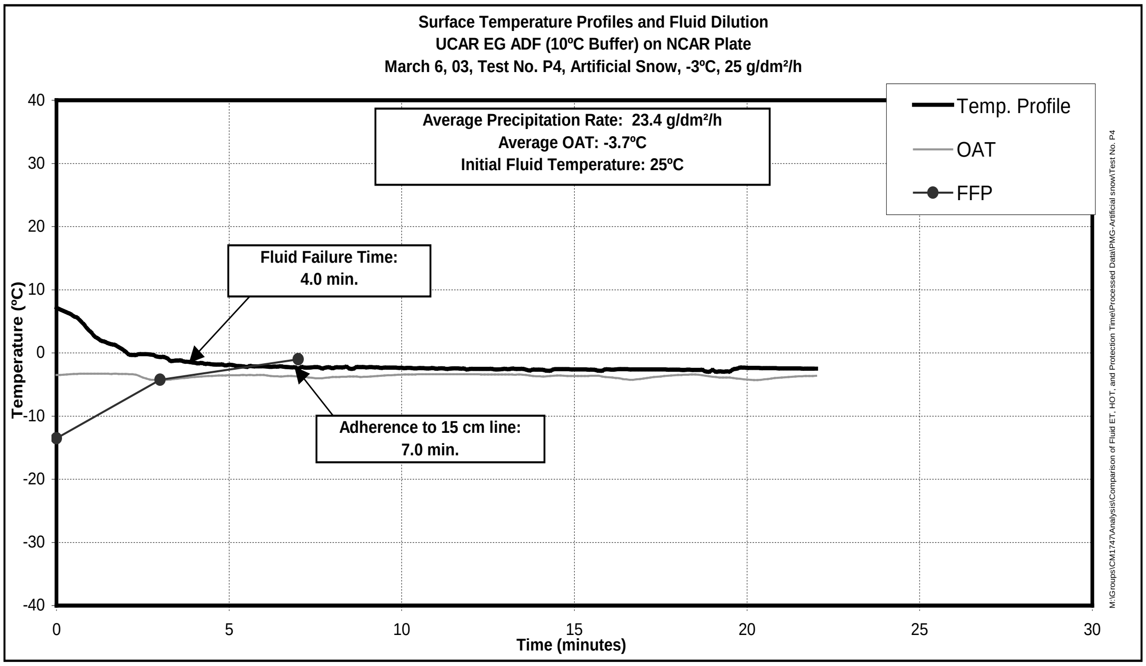


Figure 4.2: Test No. P4, Artificial Snow

The occurrence and aspect of adherence in this case were similar to those presented in Figure 4.1. That leads to the conclusion that under these specific test parameters, mild temperatures and high precipitation rates, regardless of the test surface used, fluid adhesion is likely to occur.

In Figure 4.2, the peak of the surface temperature profile is not shown. That is because the machine interprets fluid application as precipitation rate, and consequently several precipitation rate values at the beginning of each electronic file were ignored. As a result, the beginning of the test was offset by around 45 seconds. This is the case for all tests conducted under artificial snow conditions.

In the foregoing examples, the fluid had a 10°C buffer concentration of glycol, based on an OAT of -3°C. In conjunction with a high precipitation rate, this led to an early dilution of the fluid, and consequently to fluid adhesion to the test surface.

Test No. P9, Precipitation Rate 25.9 g/dm²/h, OAT -10°C, Artificial Snow

Figure 4.3 presents an artificial snow adhesion test conducted at an ambient temperature of -10°C. The precipitation rates in Figure 4.2 and Figure 4.3 were close but slightly higher in this case. The fluid was applied at 25°C. Exposure to a temperature of -10°C caused the plate temperature to drop below 0°C in less than 2 minutes. Due to the lower test temperature and somewhat higher precipitation rate, the visual fluid failure was recorded earlier than in the previous example (Figure 4.2), at only 3 minutes after pouring. At failure, the concentration of the fluid corresponded to a freeze point of around -7°C, while the surface temperature was -3.9°C. At this time, surface protection was provided solely by the existing glycol in the solution. Further exposure to precipitation resulted in complete dilution of the fluid 9 minutes after pouring.

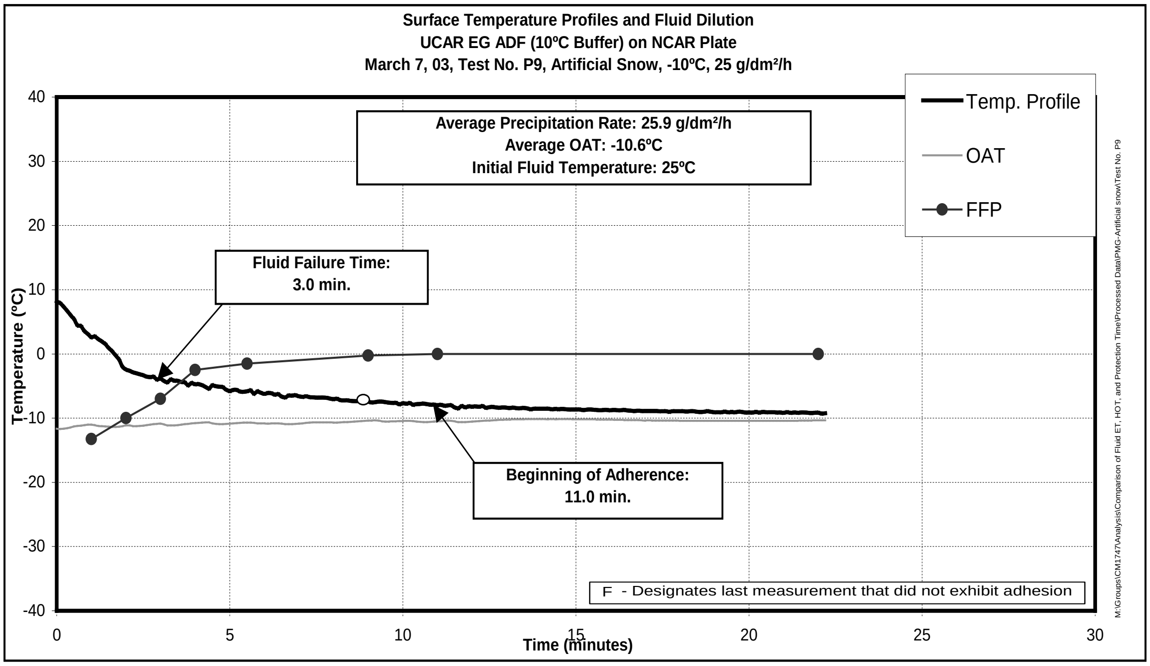


Figure 4.3: Test No. P9, Artificial Snow

The surface continued to cool down towards ambient temperature, and at the 9-minute mark reached -7.5°C. At this time, given that the concentration of the solution on the test surface was that of pure water, the contamination started to freeze, and 11 minutes after pouring, the onset of adherence was documented.

For this test, fluid adhesion was 3.7 times longer than the failure time, after standard plate failure was called. The explanation for the larger safety buffer is that, under similar precipitation rates, the higher concentration fluid needed more time to dilute to water.

Test No. 8, Precipitation Rate 18.9 g/dm²/h, OAT -6.4°C, Natural Snow

Figure 4.4 illustrates a natural snow adhesion test performed in comparable conditions to the test presented in Figure 4.3. In this case, the propylene glycol-based fluid was applied to the empty aluminum box at 60°C.The empty aluminum box holds its temperature longer than a standard endurance time plate, primarily due to its geometry and insulation. As a result, it generated a longer endurance time. At about 13 minutes after pouring, the standard plate failure was recorded. At 19 minutes after pouring, the entire test surface area was covered with failed fluid.

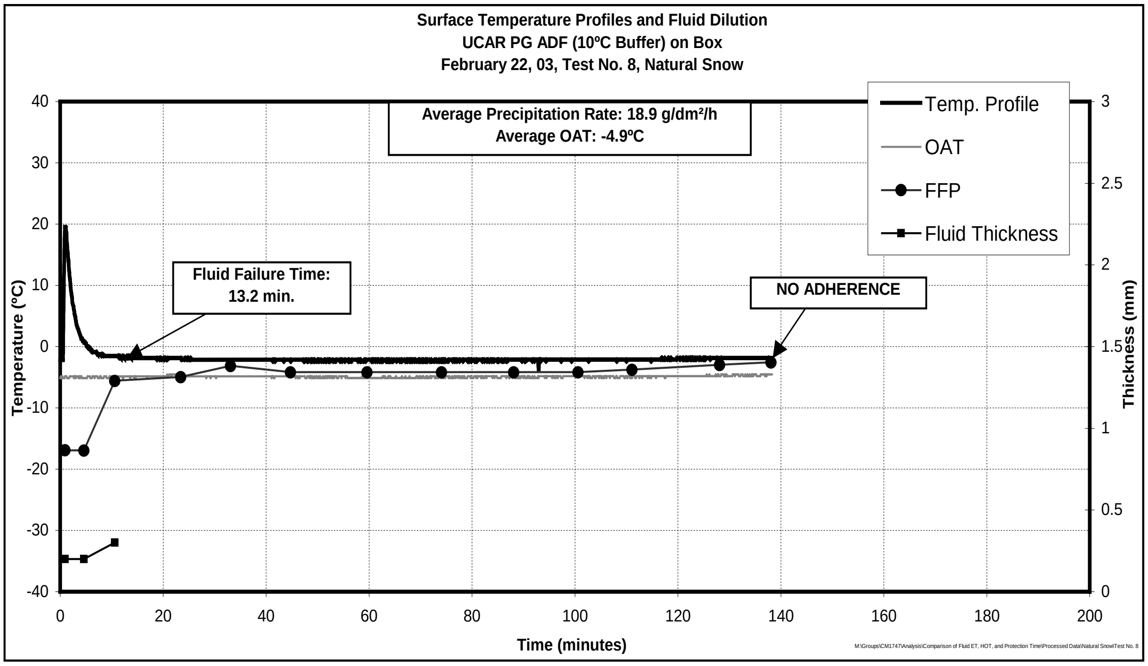


Figure 4.4: Test No. 8, Natural Snow

This test presented a peculiarity in the sense that the fluid did not dilute to water. Flakes hit the fluid surface and melted, absorbing heat from the fluid. The fluid was thereby cooled, approaching the ambient temperature and being simultaneously diluted by the precipitation. The decreasing fluid temperature caused the snowflakes to be melted more slowly and, as a result, the incoming snow landed on partially melted flakes, and a mat of slush developed as visible contamination. The partially melted snow on the fluid surface acted as an insulator and further slowed the melting process. Ongoing exposure to precipitation led to further accumulation of snow on the failed fluid surface, while the layer of fluid under the snow did not dilute beyond a Brix value of 8 (-4.0°C) even though the test ran far beyond the time when failure was called.

Since the freeze point of the contaminated fluid was lower than the box surface temperature throughout the test, no adhesion was detected at any point over the duration of the test.

Out of the entire set of Type I fluid natural and artificial snow tests conducted at a precipitation rate greater than 10 g/dm²/h, this is the only test that did not experience adherence. It is also the only adhesion test performed under moderate snow using a propylene glycol-based Type I fluid. However, an adhesion test conducted with a 50/50 propylene glycol-based Type II fluid (see test No. 61 in Appendix D) did exhibit adhesion. In that case, the fluid was applied at 60°C, in common with the test presented in Figure 4.4. Since the 50/50 Type II fluid produces endurance times comparable to the Type I fluid, it can be inferred that propylene-based Type I fluids will also experience adherence.

The exception in the case of test No. 8 may also be due to the physics of the snow on that particular day. Snow is characterized by its texture and density. According to its liquid water content, snow can be classified as dry or wet. Dry snow has lower density than wet snow and its grains have little tendency to adhere to each other when pressed together. If test No. 8 was run under dry snow, the high wind speed during this test (47 km/h) was probably sufficient to blow away the snowflakes from the surface of the plate. As a result, melting of snowflakes was prevented and fluid dilution was repressed. This can be explained due to the gentler impact of dry grains on the fluid surface as opposed to impact from heavier wet grains. The impact can be thought of as a means of mechanical mixing. The mixing efficiency is greater for the more massive grains characteristic of wet snow.

Fluid adhesion tests were also conducted under high precipitation rates. Due to the lack of suitable conditions outdoors, these tests were generally run under artificial snow. All heavy precipitation rate tests exhibited adherence.

Test No. P11, Precipitation Rate 81.6 g/dm²/h, OAT -10°C, Artificial Snow

Figure 4.5 illustrates a typical case of a test conducted under heavy precipitation in snow conditions. The ambient test temperature was -10°C and the test was run under a precipitation rate of 82 g/dm²/h. In an attempt to dilute the fluid prior to the surface temperature dropping below 0°C, the fluid was applied at 50°C. The test surface temperature dropped below 0°C in about 2 minutes. At the same time, around 2 minutes after pouring, the concentration of the fluid exposed to precipitation had diluted to pure water. At this point in time, surface protection was not being provided by either heat or glycol, and the contamination started to freeze as surface temperature continued to cool down.

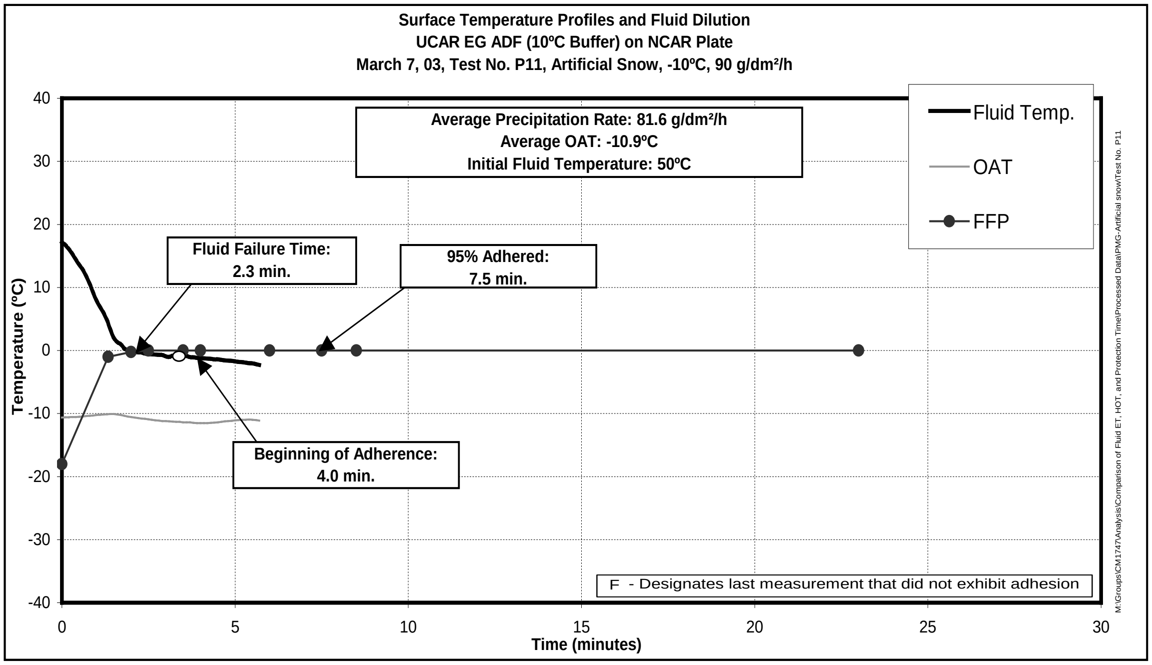


Figure 4.5: Test No. P11, Artificial Snow

The fluid failure was recorded at 2.3 minutes after pouring. Shortly after, the contamination started to freeze and, at about 4 minutes after pouring the frozen contamination presented bonding to the substrate surface. At 7.5 minute after failure 95 percent of the plate was covered with adhered contamination. For this test, the safety buffer was calculated to be 1.74.

The mechanisms driving the adhesion of the fluid to the test surface under heavy and moderate precipitation rates are identical. Under heavy precipitation the process is accelerated as the fluid dilutes faster. In the case of complete fluid dilution before surface temperature dropping to zero, the surface protection is provided only by heat, and as the surface cools down the resulting ice adheres to the test surface. Since Type I fluid adhesion tests did not provide sufficient data regarding this phenomenon, an adhesion test was conducted using water instead of fluid.

Test No. P13, Precipitation Rate 30 g/dm²/h, OAT -10°C, Artificial Snow

Figure 4.6 shows an artificial snow test conducted at an ambient temperature of -10°C, using 20°C water and under a precipitation rate of 30 g/dm²/h. Because of better conductivity, a water-treated surface will cool faster. The temperature of the fluid dropped below 0°C about 1 minute after pouring. As surface protection was nonexistent, the contamination started to freeze and at about 2.5 minutes after pouring, the failure was recorded. When freezing occurred, the resulting ice adhered to the entire area of the test surface, as presented in Photo 4.2.

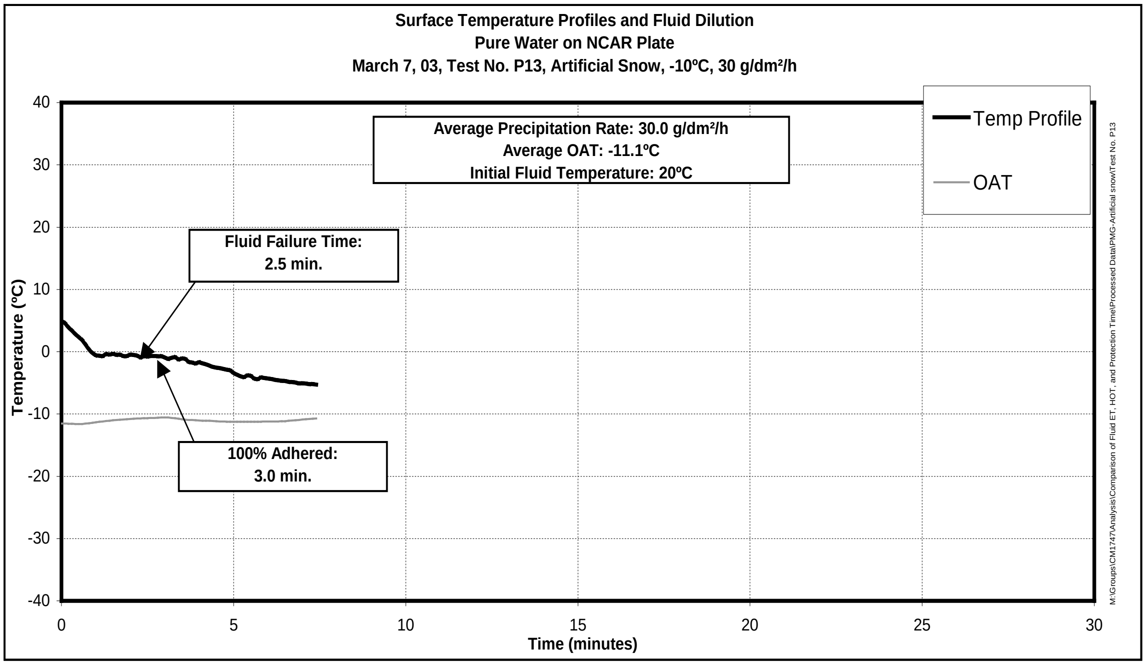


Figure 4.6: Test No. P13, Artificial Snow

4.1.1.2 Light and very light precipitation rates

According to the classification in the TC Type I HOT table, light and very light precipitation occurs at less than 10 g/dm²/h and 4 g/dm²/h, respectively. Seven tests were run under light snow outdoors, and one test was conducted under very light snow precipitation using the NCAR machine.

Figure 4.7 shows a typical case of a fluid adhesion test conducted under light snow conditions at the APS test site. The propylene-based fluid was applied at 60°C to the empty aluminum box, and the ambient outside temperature was -3.6°C. The surface temperature dropped below 0°C in 7.5 minutes. At this time the fluid had a freeze point of -7.5°C. Subjected to precipitation, the fluid continued to dilute, and at 16.5 minutes reached a freezing point of -1.7°C and visual fluid failure was recorded. Surface protection was provided by the existing glycol, its concentration preventing the contamination from freezing. Exposure to precipitation past standard failure resulted in snow build-up on the test surface, while the layer of fluid under the snow did not dilute beyond a Brix value of 2 (-1.0°C) even after 60 minutes. The layer of snow acted as an insulator and limited melting of snowflakes, as shown in Photo 4.3. The existing glycol concentration in the contamination prevented it from freezing throughout the test. The failed fluid had the aspect and consistency of slush. Adhesion was not detected at any point throughout the duration of the test.

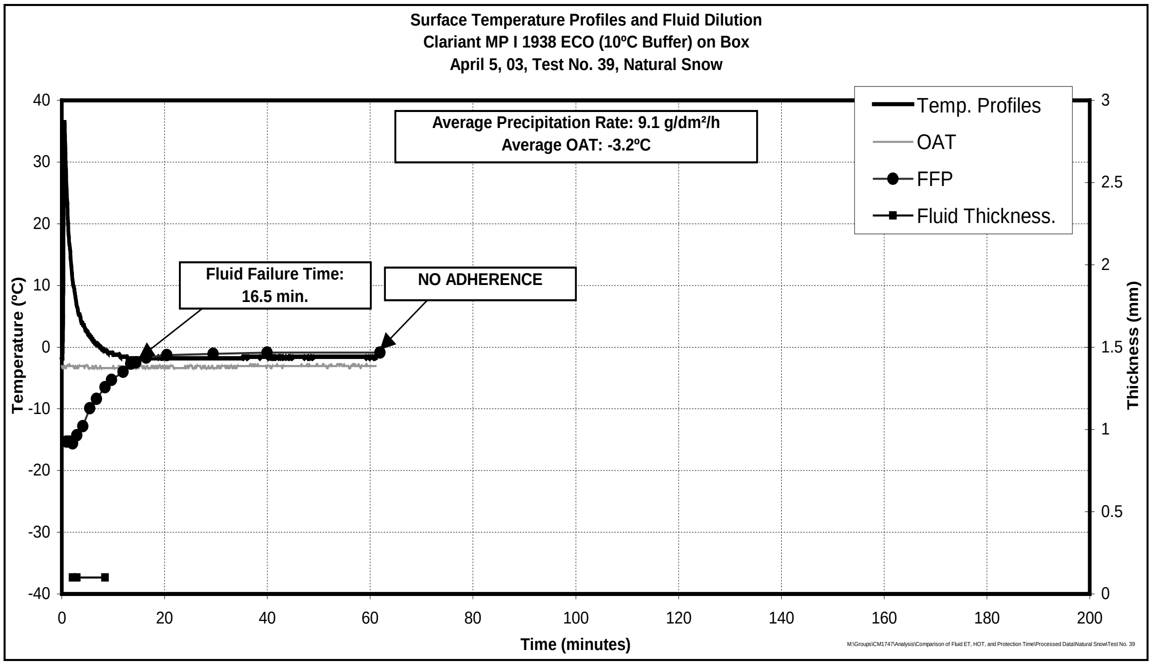


Figure 4.7: Test No. 39, Natural Snow

As recorded in Figure 4.7, the precipitation rate was close to the upper limit of the light snow classification, the fluid was applied at 60°C and the test surface used was the empty aluminum box. These, in conjunction with a relatively high precipitation rate, are factors that facilitate the occurrence of adherence. However, under light and very light snow conditions, and regardless of the surface type and initial fluid temperature, the precipitation rate typically did not prove to be sufficient to produce enough dilution of the fluid to generate adherence. As the fluid temperature decreased, the snowflakes were absorbed more slowly and, as a result, the incoming snow landed on partially melted flakes and a mat of slush developed. This mat of slush acted as an insulator and considerably slowed the melting process. Thereafter, the slushy solution preserved its glycol concentration preventing the fluid from freezing.

Out of the seven tests performed under light snow, only one presented fluid adhesion. In that case (test No. 14), the fluid failed after 9 minutes and the beginning of fluid adhesion was recorded on the data form after 137.3 minutes. This produced a safety buffer of 15.3 between adhesion time and endurance time. A safety buffer of this size has no significance in real field deicing operations, which leads to the conclusion that, under light snow conditions, the occurrence of fluid adhesion is highly improbable.

Also, under even lighter precipitation rates corresponding to very light snow conditions, the fluid did not dilute to a level that would stimulate bonding to the test surface.

Figure 4.8 demonstrates this by presenting an artificial snow adhesion test conducted at a precipitation rate of 1.3 g/dm²/h. In this case the fluid was applied at -7.5°C.

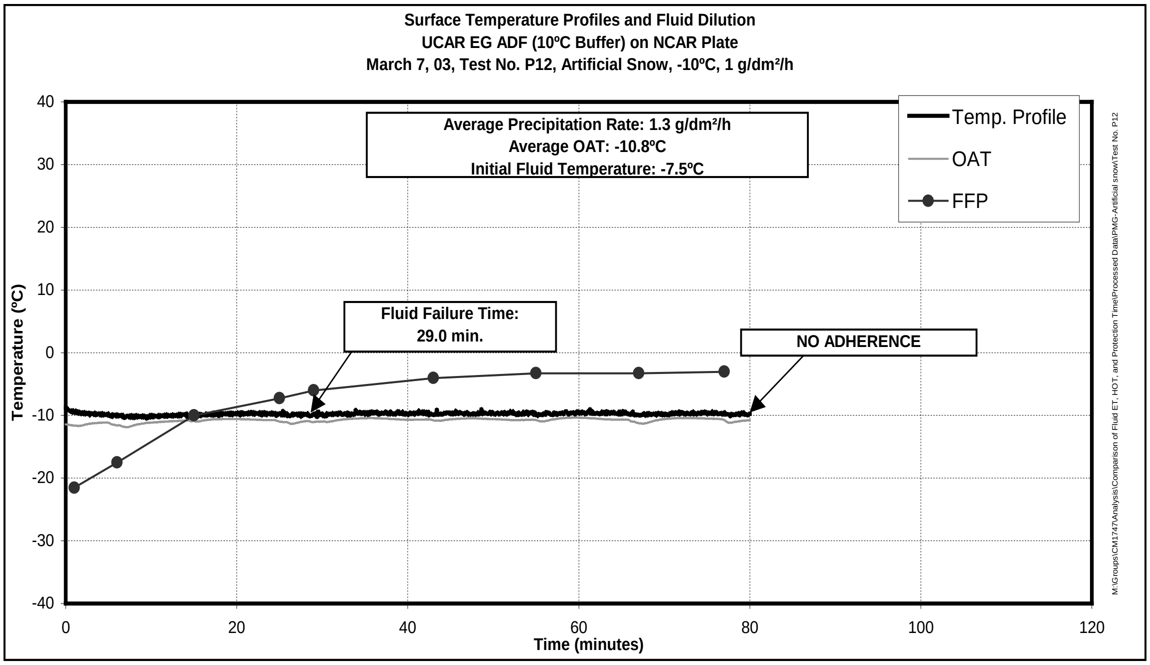


Figure 4.8: Test No. P12, Artificial Snow

As observed on the chart, the plate temperature was very close to the ambient temperature throughout the test. Under this precipitation rate, the fluid diluted gradually and the visual failure was called after 29 minutes. At failure time, the fluid freezing point was -6°C. Exposed to further precipitation, the fluid diluted to a Brix of 5.25 (-3.3°C) after 55 minutes.

Subsequent Brix measurements were taken, but the glycol concentration in the solution did not change further, so at about 80 minutes after pouring, the test was stopped. Again, the failed fluid had the aspect and consistency of slush. Throughout the test, the fluid had sufficient strength to prevent freezing and bonding to the substrate surface.

The findings from the tests, presented in Figure 4.7 and Figure 4.8, were also confirmed by several tests run under similar precipitation conditions using ethylene glycol, propylene glycol and non-glycol based fluids.

A full set of test results grouped by weather conditions is provided in Appendix D.

Figure 4.9 shows a graphical representation of the failure mechanism during natural snow precipitation. The chart presents two snow adhesion tests conducted using the same ethylene-based Type I fluid under light and heavy snow. The phenomena that take place on the test surface as the fluid dilutes towards and beyond standard plate failure are indicated using measurements of precipitation rate, Brix, surface temperature and fluid thickness.

Under light snow conditions, the fluid did not dilute past a Brix of 1, corresponding to a freezing point of -0.7°C, and it did not exhibit adherence.

Under heavy precipitation, the process is accelerated as the fluid dilutes faster. The test fluid diluted to water prior to the surface temperature falling below 0°C. When freezing finally occurred, the contamination bonded to the underlying surface.

Based on the Type I testing under natural and artificial snow conditions, the following conclusions can be drawn:

a) There are two circumstances in which the occurrence of adherence was documented: fluid dilution to water prior to the surface temperature dropping below 0°C, and fluid dilution to water after the surface temperature reached subzero temperatures. If the fluid does not dilute to very low concentrations of glycol close to a freezing point of 0°C, the contamination will not freeze solid, preventing the occurrence of adhesion;

b) Fluid failures where the fluid has diluted to water prior to the plate temperature dropping below 0ºC result in adhesion. At mild temperatures and high precipitation rates, the fluid is more likely to dilute to water prior to the surface temperature dropping below 0ºC due to its low glycol concentration. When freezing occurs, the resulting ice adheres to the underlying surface;

c) Typically, the Type I adhesion tests conducted under moderate or heavy snow precipitation conditions exhibit adhesion regardless of ambient temperature, initial fluid temperature and test surface type;

d) Higher glycol concentrations (at colder temperatures) applied heated on empty aluminum box surfaces generate longer endurance times and extended safety buffers;

e) Under light and very light snow conditions, the fluid does not usually dilute to a level that would stimulate bonding to the test surface, irrespective of the surface type and initial fluid temperature. However, if the fluid is exposed to precipitation far beyond complete plate failure, the failed fluid might eventually adhere to the supporting surface, providing its freezing point reaches 0°C;

f) When the test surface was exposed far beyond the time when failure was called, sometimes the final fluid concentration did not dilute beyond a certain Brix value. The failed fluid had the aspect and consistency of slush. In these cases, the visually failed fluid did not adhere to the surface; and

g) The effect of the glycol type seemed insignificant, since adhesion tests yielded the same results for ethylene and propylene glycol-based Type I fluids.

4.1.2 Freezing Fog: Type I Fluid

As shown in Table 3.4, tests were performed under freezing fog, freezing drizzle and light freezing rain conditions using both the standard endurance time plate and the empty aluminum box test surfaces.

Four adhesion tests were run under simulated freezing fog conditions, at -3 and -25°C. Figure 4.10 illustrates a freezing fog adhesion test conducted at an ambient test temperature of -3°C and a precipitation rate of 5 g/dm^2/h. The ethylene glycol-based Type I fluid was applied at 20°C on the standard endurance time plate. The surface temperature rose to around 6°C following the application of the fluid and, as a result of ambient test temperature and incoming precipitation, dropped below 0°C in about 4.7 minutes. At about 10 minutes after pouring, the surface temperature reached -2.1°C and the curve flattened. Following application, the freezing point of the fluid started to rise and, after 10 minutes, matched the surface temperature. At this point in time, surface protection was being provided by the existing glycol, its concentration preventing the contamination from freezing. Further exposed to precipitation, the fluid diluted to a freezing point of 0°C in about 13.3 minutes. At this instant, the failure call was made. As a result of the diluted fluid freezing point rising above surface temperature for 3.5 minutes, the contamination started to freeze. Shortly after, at about 14.1 minutes after pouring, the frozen contamination presented bonding at the 7.5 cm line. At 24.5 minutes, the contamination exhibited adhesion over the entire surface of the plate. For this test the size of the safety buffer was 1.1.

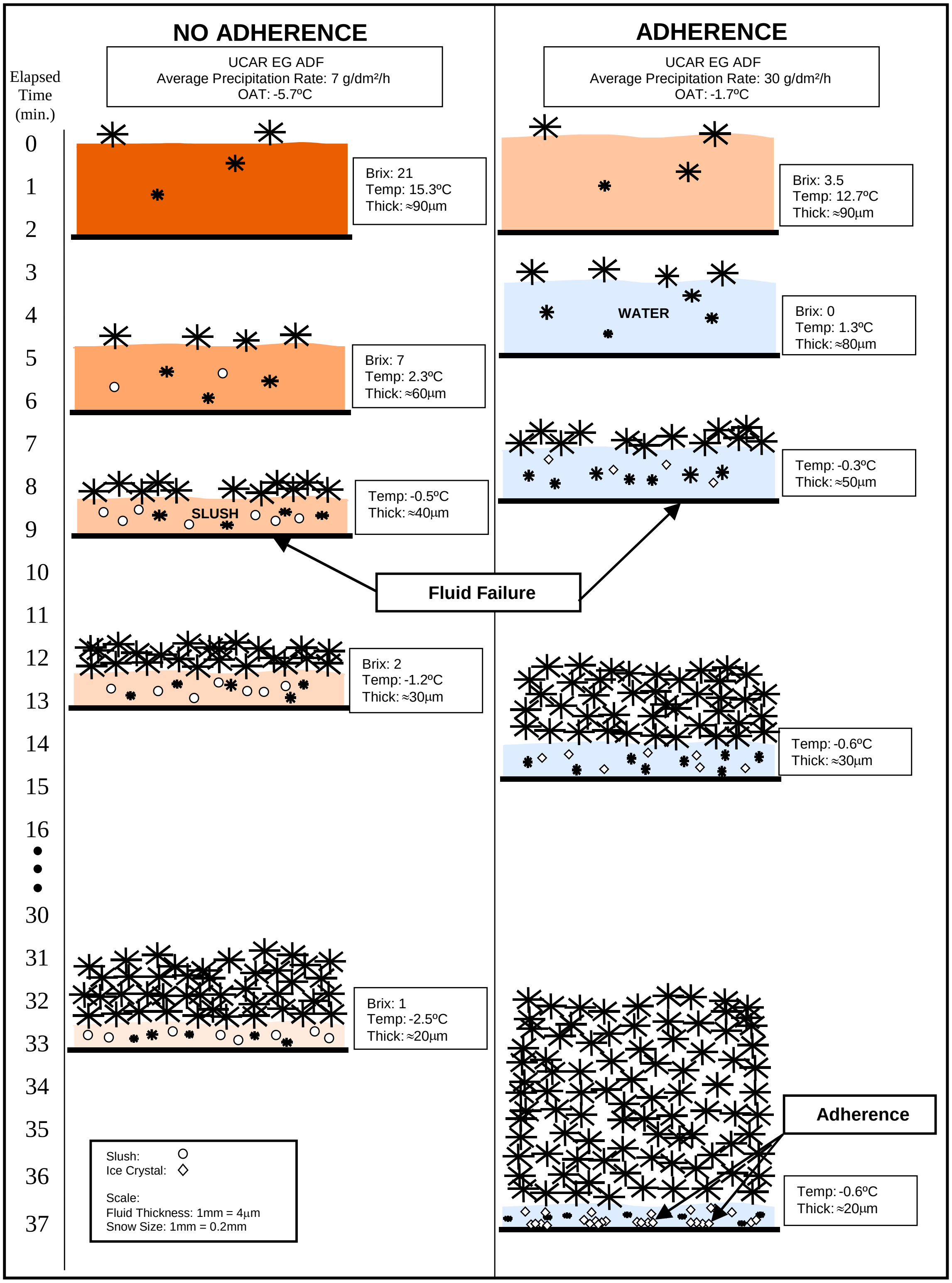


Figure 4.9: Failure Mechanism During Natural Snow Precipitation

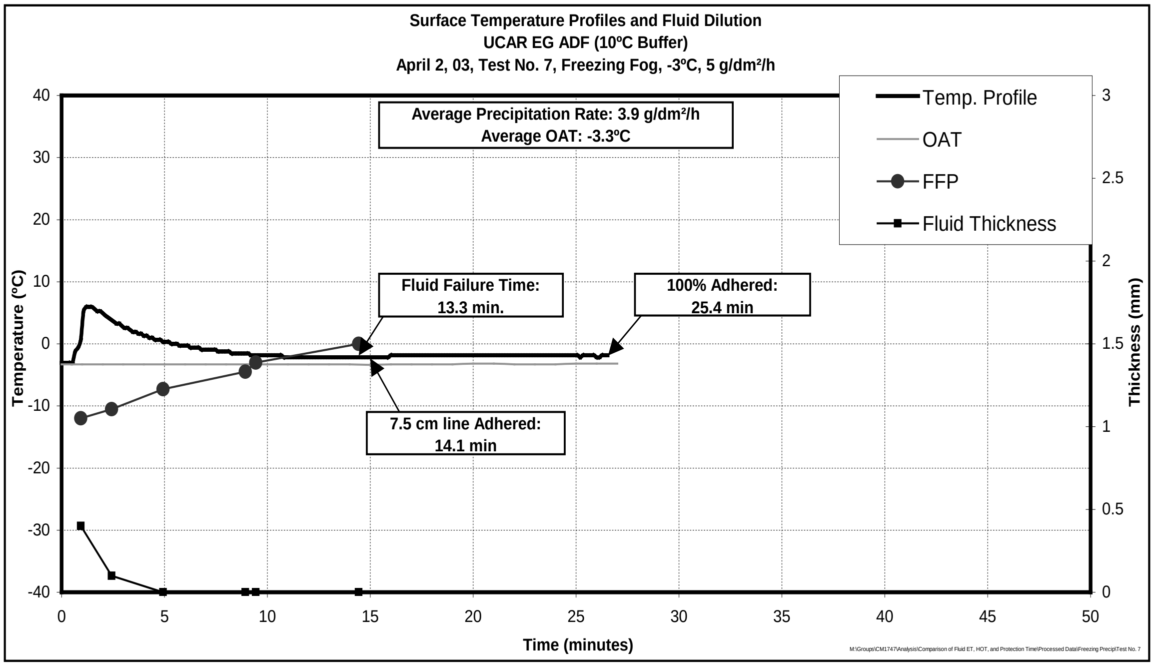


Figure 4.10: Test No. 7, Freezing Fog

It was observed that the fluid thickness reached its ultimate value (a very thin film) by four minutes after application.

A test under similar precipitation conditions was conducted on the empty aluminum box (test No. 8, Table 3.2) using a propylene-based fluid. As this test surface provides longer endurance times, fluid failure occurred at about 20 minutes after pouring. The size of the safety buffer was 1.2.

Figure 4.11 shows a fluid adhesion test performed under freezing fog conditions at a temperature of -25°C using a propylene glycol-based fluid. Subjected to these test conditions, the fluid approached the ambient temperature rapidly, being simultaneously diluted by the precipitation. At 5.5 minutes after pouring, standard plate failure was recorded. When fluid failure occurred, the freeze point of the fluid was lower than the surface temperature, preventing the fluid from freezing. Exposed to precipitation the fluid diluted further, but not beyond a Brix value of 8, corresponding to a freeze point of about -4°C. At a fluid freeze point of -4°C, the fluid had sufficient strength to avoid freezing. Adhesion was not detected at any point over the duration of the test.

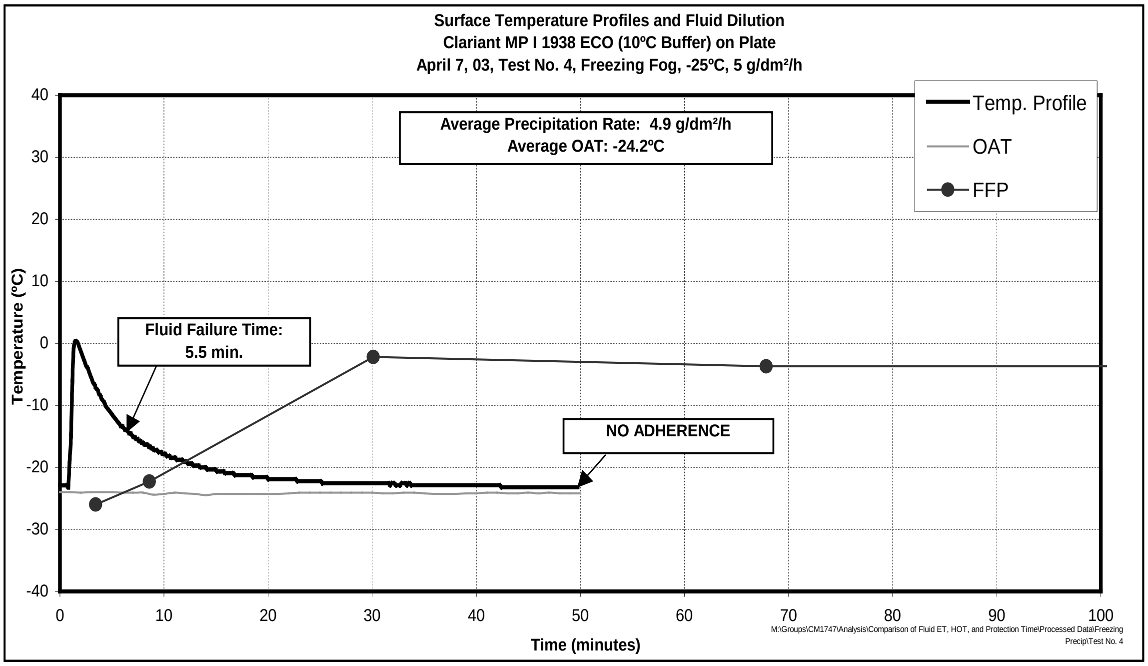


Figure 4.11: Test No. 4, Freezing Fog

A different test (test No. E7) conducted under comparable weather conditions yielded similar results. The test was run under a precipitation rate of 2 g/dm²/h using an ethylene glycol-based Type I fluid. The fluid did not dilute beyond a freeze point of -2°C, preventing the contamination from freezing.

4.1.3 Freezing Drizzle: Type I Fluid

Seven fluid adhesion tests were run under simulated freezing drizzle conditions at -3 and -10°C. Also, a natural freezing drizzle adhesion test was conducted at APS test site on January 7, 2003.

Figure 4.12 illustrates a freezing drizzle adhesion test conducted at an ambient test temperature of -3°C and a precipitation rate of 13 g/dm²/h.

The ethylene-based Type I fluid was applied at 20°C on the standard endurance time plate. The surface temperature profile curve is not available, as temperature was not logged for this test. Following application, the freeze point of the fluid started to rise and, after 10 minutes, it reached -0.5°C. At this point in time, the failure call was made. Shortly after, at about 11 minutes after pouring, the fluid was diluted to pure water. As surface protection was not being provided by the glycol, the contamination started to freeze, and at about 11.7 minutes after pouring, the frozen contamination presented bonding on about 80 percent of the surface of the plate. At 17.7 minutes, the contamination exhibited adhesion over the entire surface of the plate. For this test the size of the safety buffer was calculated to be 1.1.

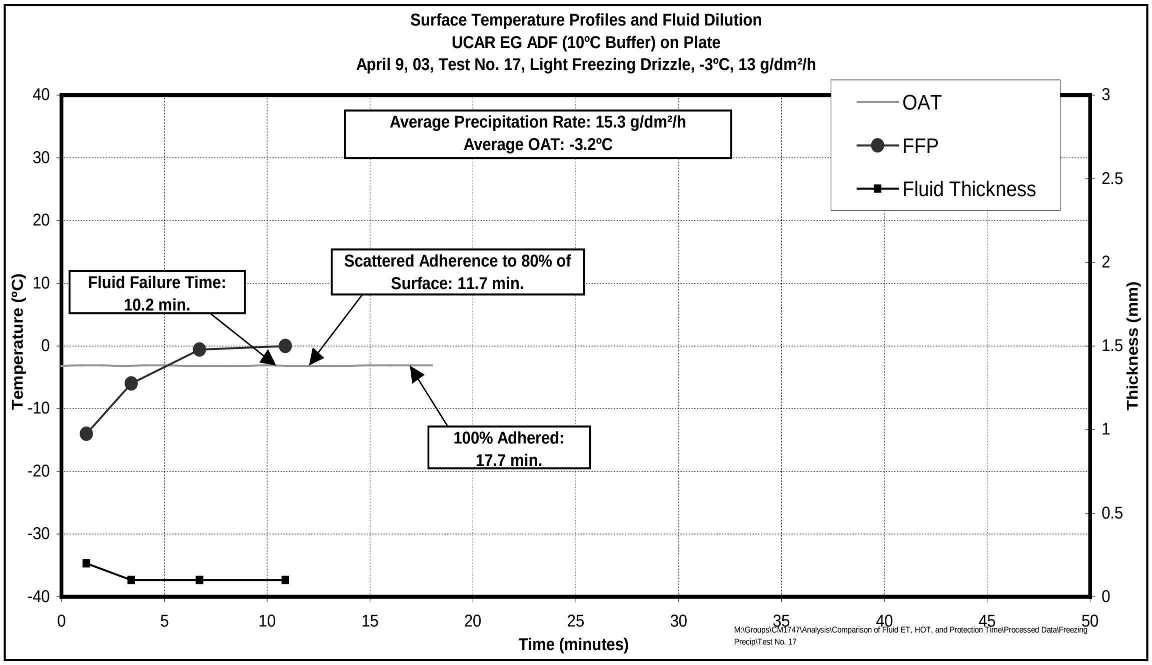


Figure 4.12: Test No. 17, Freezing Drizzle

The fluid thickness reached a stabilized thickness of 0.1 mm within 4 minutes following application.

A fluid adhesion test was conducted under similar precipitation conditions outdoors. This test was run on the empty aluminum box, and the fluid was poured at 60°C. The fluid failure occurred 9 minutes after pouring and the size of the safety buffer was determined to be 1.8.

Figure 4.13 shows an empty aluminum box adhesion test performed under simulated freezing drizzle using a propylene-based fluid mixed for an ambient test temperature of -10°C. Similar to the case presented in Figure 4.12, the fluid diluted under precipitation and reached a freeze point of -4°C at the time of fluid failure, 4.6 minutes after pouring. At this time, since the surface temperature was -1 °C, surface protection was being provided only by glycol. Subjected to an ongoing precipitation rate of 13 g/dm²/h, the fluid diluted further and at about 7.6 minutes after pouring, adhesion was documented at the 30 cm line. At 10.9 minutes, the full surface was adhered.

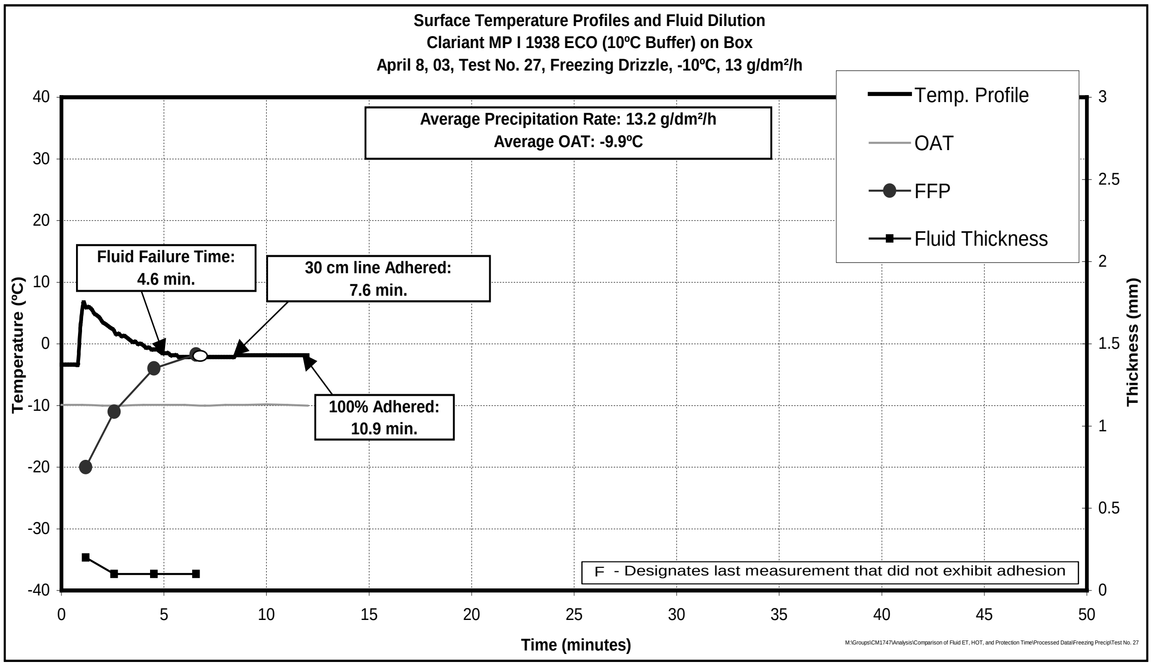


Figure 4.13: Test No. 27, Freezing Drizzle

All Type I fluid adhesion tests conducted under natural and simulated freezing drizzle precipitation presented adherence shortly after fluid failure.

4.1.4 Light Freezing Rain: Type I Fluid

Four fluid adhesion tests were run under simulated light freezing rain conditions at -3 and -10°C. All tests were run under a precipitation rate of 25 g/dm²/h.

Figure 4.14 illustrates a light freezing rain adhesion test conducted at an ambient test temperature of -3°C on the empty aluminum box. The ethylene-based Type I fluid was applied at 20°C. Following application, the freeze point of the fluid started to rise and reached 0°C after 7.5 minutes. The test surface temperature, in the process of cooling after fluid application, reached 0.3°C in about 10 minutes and settled at this temperature. It did not cool to the ambient temperature of -3ºC. At this point, surface protection was being provided only by heat, the test surface temperature preventing the contamination from freezing. As the test surface attempted to cool below 0°C some freezing occurred, and the surface temperature was supported by the release of latent heat of freezing. As a result of this state of equilibrium between the cooling force of ambient temperature and the warming force of released latent heat of freezing, the surface temperature fluctuated between 0.1 and 0.9°C. At 19.3 minutes after pouring, the fluid failure was called. During the interval between 10 minutes after pouring until failure call was made, the surface was covered with a mixture of ice and water similar to that of an ice bath. At about 25.6 minutes after pouring, ice patches of frozen contamination presented bonding over the entire surface of the plate.

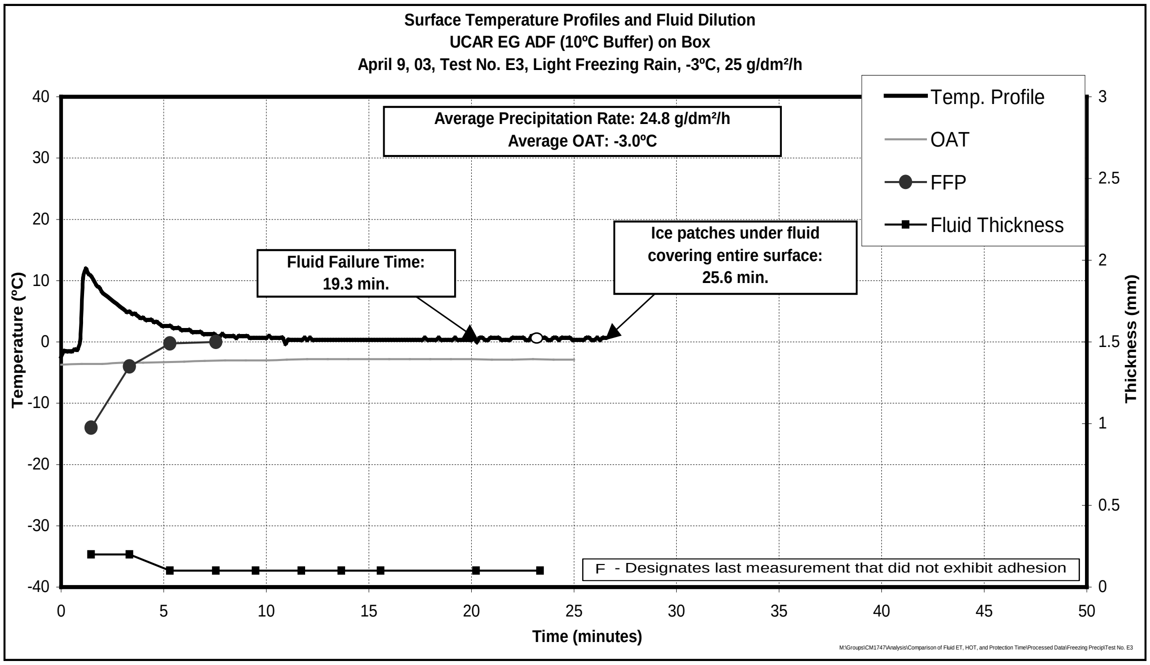


Figure 4.14: Test No. E3, Light Freezing Rain

This phenomenon of the latent heat of freezing being released into the ice/water mix and sustaining its temperature under light freezing rain conditions at -3°C is discussed in Section 7 of TC report TP 14144E, *Aircraft Ground De/Anti-Icing Fluid Holdover Time and Endurance Time Testing Program for the 2002-03 Winter* (3).

The fluid thickness reached a stabilized thickness of 0.1 mm within 5 minutes following application.

A similar test conducted using a propylene glycol-based Type I fluid applied to a standard endurance time plate (test No. E2) confirmed the results presented in Figure 4.14.

Figure 4.15 shows a light freezing rain adhesion test performed at an ambient test temperature of -10°C on the standard endurance time plate.

Following application, the freezing point of the fluid started to rise, and reached -1.7°C 4.5 minutes after pouring. Shortly after, at about 5.5 minutes after pouring, standard plate failure was recorded. Exposed to precipitation, the fluid diluted further, and since plate temperature had previously dropped below 0°C, surface protection was not being provided by either heat or glycol. Subsequently, at an elapsed time of 6 minutes, the frozen contamination presented bonding to about 50 percent of the surface of the plate. At 8 minutes after pouring, the contamination exhibited adhesion over the entire surface of the plate. In this case, the release of latent heat of freezing was not sufficient to raise and sustain the surface temperature above 0°C. For this test the size of the safety buffer was calculated to be 1.1.

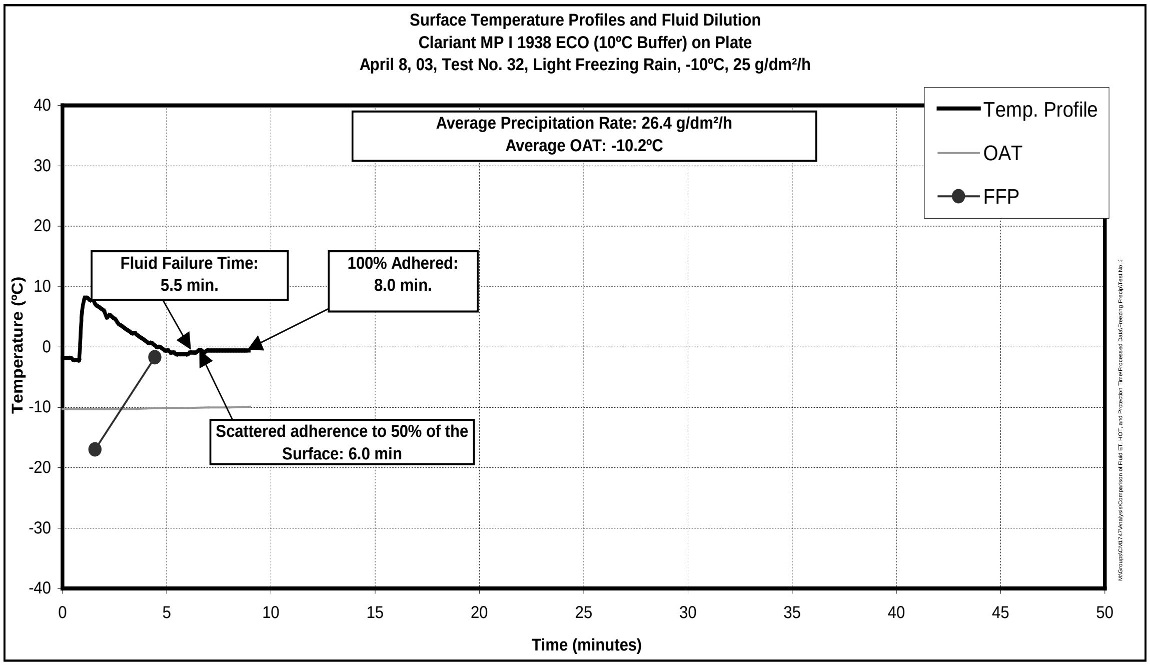


Figure 4.15: Test No. 32, Light Freezing Rain

Based on the Type I adhesion testing under simulated freezing precipitation conditions, the following conclusions can be drawn:

a) Except for freezing fog at -25°C, adherence occurred under all freezing precipitation conditions tested regardless of the test surface, precipitation rate or test temperature. Typically, adhesion occurred shortly after failure during the freezing precipitation tests; and

b) The glycol type does not seem to have an influence, since adhesion tests yielded the same results for both ethylene and propylene glycol-based Type I fluids.

4.1.5 Frost: Type I Fluid

As presented in TC report TP 14145E, *Laboratory Test Parameters for Frost Endurance Time Tests* (5), frost can be an insidious type of threat to the safety of aircraft operations. Because it often has the appearance of having a minor degree of contamination, it does not offer the same obvious signal of danger as do other types of contamination such as snow or ice. The factors that generate frost in natural conditions are a combination of ambient air temperature, the level of humidity in the air, the surface temperature of any exposed body, and calm or low winds.

A deicing survey conducted at a number of airports worldwide over a three-year period yielded the distribution of deicing operations shown in Figure 4.16, and reported in TC report TP 14375E, *Winter Weather Impact on Holdover Time Table Format (1995-2004)* (6).

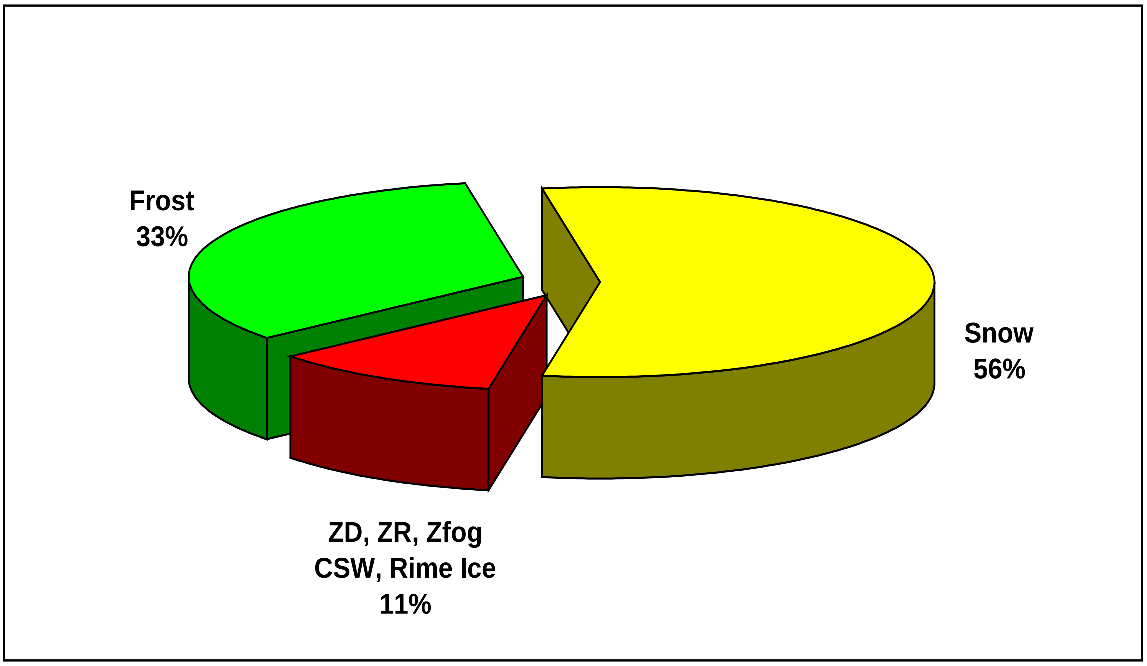


Figure 4.16: Frequency of Deicing Operations Airport Survey 2000-03

Frost accounted for 33 percent of the deicing operations worldwide. The survey reported that frost removal operations were more prevalent at airport locations having relatively mild winter climates such as London and Paris.

The major threat to the safety of aircraft posed by this type of contamination, in conjunction with its high rate of occurrence worldwide, led to the recommendation that fluid adhesion testing under frost conditions be conducted. This objective was addressed in the 2003-04 testing season. A total of four Type I tests were conducted under natural frost conditions at Montréal-Trudeau Airport. These tests were run in conjunction with HOT testing by exposing the endurance time test surfaces to frost conditions beyond the time of fluid failure. All frost adhesion tests were run on white-painted aluminum test plates with insulated backing surfaces.

Figure 4.17 shows an adhesion test performed with an ethylene-based Type I fluid under natural frost at an ambient test temperature of -8.7°C. In an attempt to minimize the contact with the test plate during testing, fluid Brix measurements were conducted only at the beginning of the test and when the fluid failed.

The freezing point of the fluid at the beginning of the test was -18°C. The fluid was applied to the plate at 20°C and, as a result, the test surface temperature rose to approximately 2°C. Exposed to frost conditions, the plate temperature dropped below ambient temperature in approximately 11 minutes, and reached a stable value of around -14°C in about 50 minutes following application. As observed on the chart, except for the first few minutes at the beginning of the experiment, the temperature of the plate was fairly constant and lower than ambient temperature throughout the test. During the first part of the test, surface protection was provided by the existing glycol, its concentration preventing the contamination from freezing. At an elapsed time of 46 minutes, fluid failure was recorded. The freeze point of the fluid at the failure time was -12°C, no longer providing surface protection. Subjected further to frost conditions, the contamination presented bonding to the 15 cm line 140 minutes into the test, and bonding to the entire area of the plate in about 239 minutes following the application. For this test the size of the buffer time was calculated to be 3.0.

Figure 4.18 shows a similar adhesion test performed under natural frost at an ambient test temperature of -11°C. In this case, the freeze point of the fluid at the beginning of the test was -20°C. The failure time of the fluid was recorded at 79.5 minutes following the application. For this test the size of the buffer time was calculated to be 1.8.

Adhesion testing in frost conditions with a propylene-based Type I fluid yielded similar results (see tests No. 66, 68 in Appendix D).

Certain characteristics of frost cause it to be of genuine concern: it always adheres to the test surface, and it is always rough in surface texture.

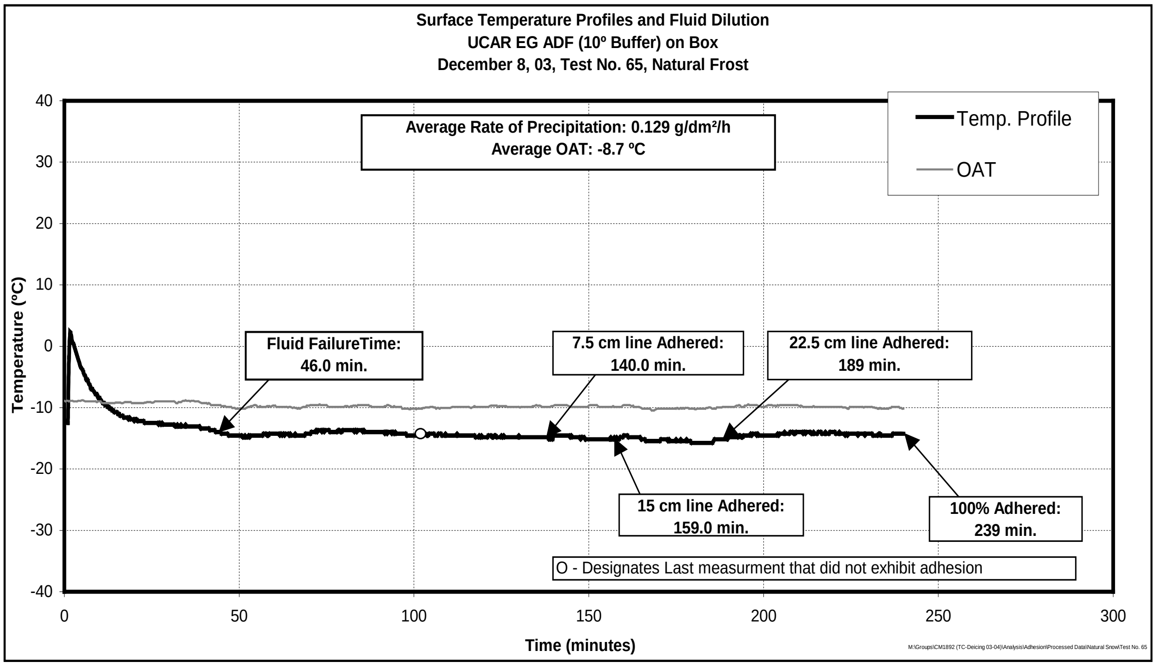


Figure 4.17: Test No. 65, Active Frost

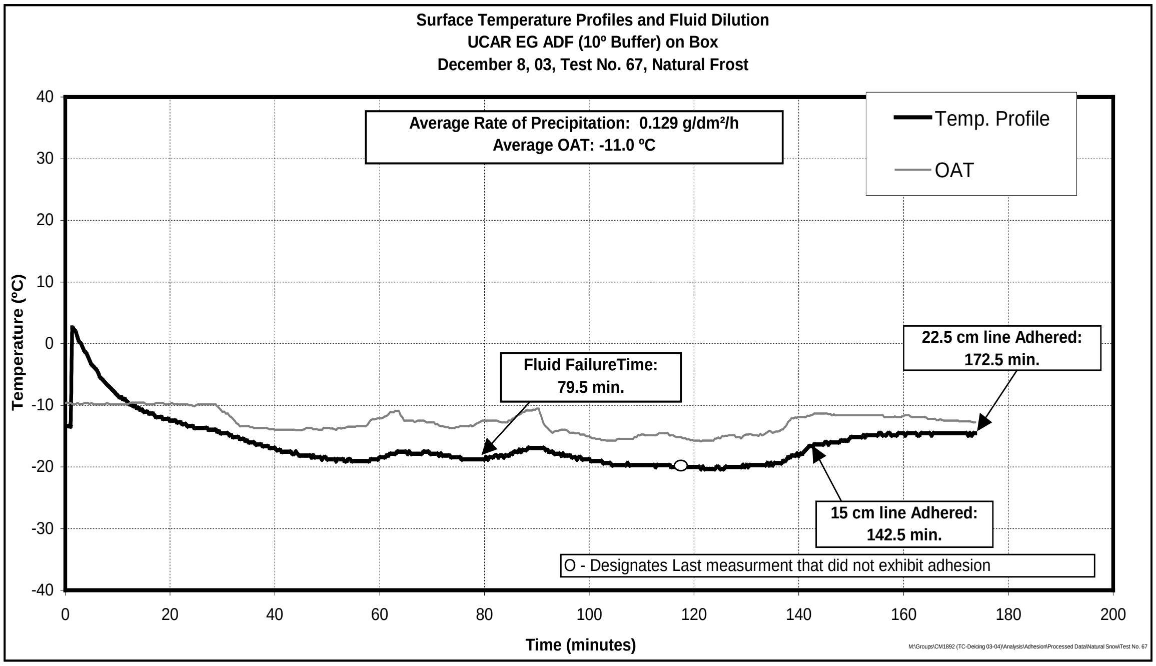


Figure 4.18: Test No. 67, Active Frost

4.2 Type II, III and IV Fluid Adhesion

During the 2002-03 and 2003-04 testing seasons, sixty-eight Type II, III and IV fluid adhesion tests were conducted under natural snow, artificial snow and simulated freezing precipitation conditions. These tests were run on standard endurance time plates, NCAR plate and empty aluminum box test surfaces, using 50/50, 75/25 and full strength concentrations. The fluids were always at the ambient test temperature when poured.

As presented in TC report TP 13484E, *Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation: 1998-99* (7), for these fluids, there is a fluid concentration gradient between the top and bottom layers of the fluid. Fluid freeze point temperature differences as large as 25°C were observed in low rate (5 g/dm^2/h) freezing drizzle tests. This can be explained by the low precipitation rate as well as the gentler impact of freezing drizzle droplets reaching the surface of the fluid layer as opposed to impacts from larger rain droplets. Droplet impact can be thought of as a means of mechanical mixing. The mixing efficiency will be greater for the larger (more massive) droplets characteristic of rain. The freeze point of the bottom layer of fluid gradually rose to meet the freeze point of the top layer near the time of standard plate failure. During snow contamination tests, the top and bottom fluid layer freeze points did not diverge as much as observed in the freezing precipitation tests. Since the fluid doesn’t absorb snow contamination as quickly as liquid contamination, the dilution of the concentration during snow precipitation tests is relatively diminished.

During the conduct of these tests, fluid dilution was not measured at various locations across the thickness (depth) of the fluid, and therefore the concentration gradient through the fluid film was unavailable for analysis.

4.2.1 Natural and Artificial Snow: Type II/IV Fluid

Typically, failure adhesion was not detected during tests performed under either natural or artificial snow conditions, independent of fluid type, glycol concentration, ambient test temperature or precipitation rate. The combination of fluid and snow resulted in a slush that could not absorb further precipitation and that did not bond to the underlying plate surface. As presented in TC report TP 13484E, *Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation: 1998-99* (7), one possible explanation for this behaviour is the capillarity of snowflakes.

Capillarity is a property that a fluid exhibits toward a porous solid medium as a result of the attractive forces between the fluid and the porous medium. The operative forces in this type of system are adhesive and cohesive, and are related to the wetting process and the fluid’s surface tension, respectively. Adhesional forces occur between the fluid and the medium, whereas cohesional forces act among the components of the fluid. When the adhesive forces are much greater than the cohesive forces, the medium is said to be easily wetted, as is the case for a glycol/water-ice mixture. Here, the porous medium is ice in the form of snow crystals.

This capillary action is the phenomenon responsible for the non-adhesion of failed regions in the precipitation conditions where dilution from contamination is minimal. The fluid concentration gradient can be said to maintain the highest fluid concentration directly on the plate surface, eliminating the possibility of adherence.

Unless there is a drastic temperature increase during the snow event, minimal melting will occur on the surface of anti-icing fluid. Without this component, relatively small quantities of liquid water are available for fluid dilution. The accumulation of relatively dry snow on the fluid surface forms slush (the snow accumulating on the surface is wetted and forms slush, but does not melt appreciably). Due to the capillarity of the snow (as a porous medium), the fluid/water solution is wicked up into the snow failure accumulating on top of the fluid layer. At a certain point, the capillary action due to adhesion forces between the medium and the solution will equal the gravitational force opposing the fluid rise in the medium. A quasi-equilibrium will be established and keep the fluid from rising further into the failure layer, thereby limiting melting. The underlying fluid layer will attain a concentration gradient that decreases with height above the test surface. This gradient is like a glycol reservoir, and any small dilutions come from very slow melting of the contaminant snow.

However, if the fluid is exposed to precipitation far beyond complete plate failure, the failed fluid might eventually adhere to the surface, providing its freezing point reaches 0°C. Or, if the Type II/IV fluid is heated, the melting of snowflakes will be facilitated, generating larger quantities of water which can lead to earlier dilution of the fluid and subsequently, to fluid adhesion.

Test No. 6, Precipitation Rate 13.7 g/dm²/h, OAT -5.6°C, Natural Snow

Figure 4.19 illustrates a natural snow adhesion test performed with a neat propylene-based Type IV fluid. As mentioned in Section 3.3.5, for Type II and IV fluids the dilution of the fluid is indicated on the charts using “negative Brix” values as conversion charts of Brix values to fluid freeze point temperatures were not available for many of the fluids tested. Generic conversion values for both ethylene and propylene glycol are given in Table 3.3 for information purposes only.

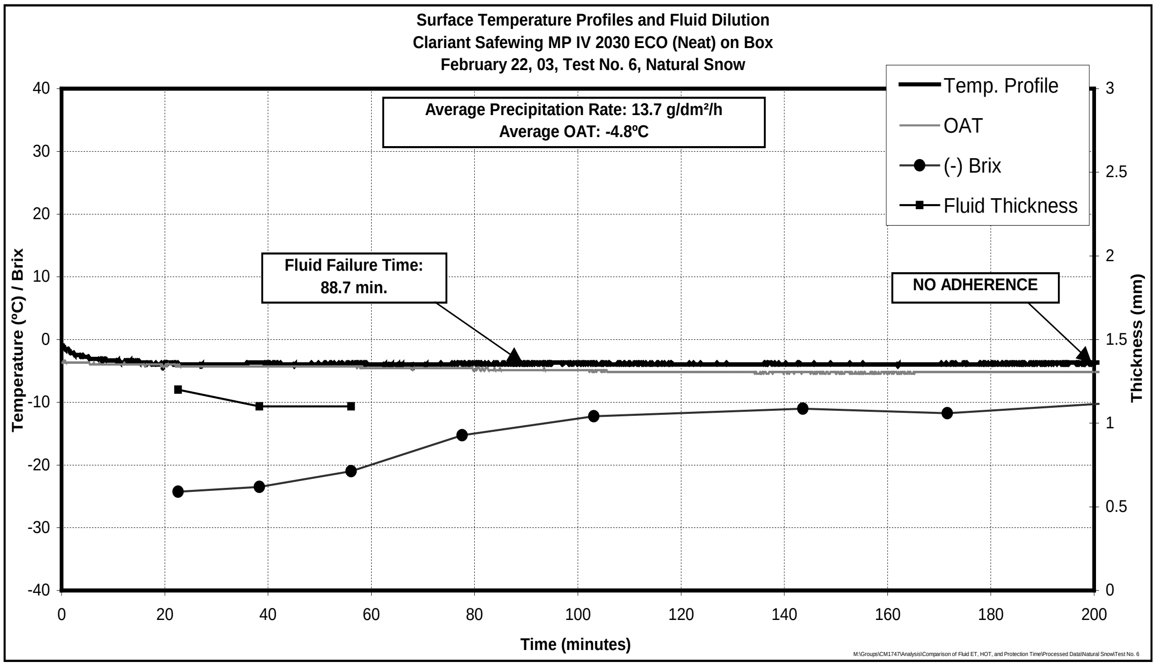


Figure 4.19: Test No. 6, Natural Snow

As the fluid was applied at ambient temperature to the empty aluminum box, the surface temperature trace closely followed the ambient temperature throughout the test. Following application, the fluid layer started to dilute and reached a stable value at about 2 hours after pouring. About 89 minutes into the test, the visual failure was recorded. At the time of failure, a layer of almost uncontaminated fluid was still in contact with the supporting surface, impeding the ice crystal layer from reaching the surface and adhering to it. The measurements were continued for over 200 minutes and, as the fluid did not seem to dilute beyond a Brix of 10, the test was stopped. Similar results were obtained using an ethylene-based Type IV fluid (see test No. 36 in Appendix D).

Test No. 58, Precipitation Rate 76.9 g/dm²/h, OAT -1.3°C, Natural Snow

Similar results were observed with a different propylene-based Type IV fluid. As an exception, in this test the fluid temperature was about -10°C below ambient. As shown in Figure 4.20, even when testing was conducted under extreme precipitation conditions (a precipitation rate of 76.9 g/dm²/h), the fluid did not present bonding long after the failure call. At approximately two hours following failure, the test was stopped, and no adhesion was documented on the test surface.

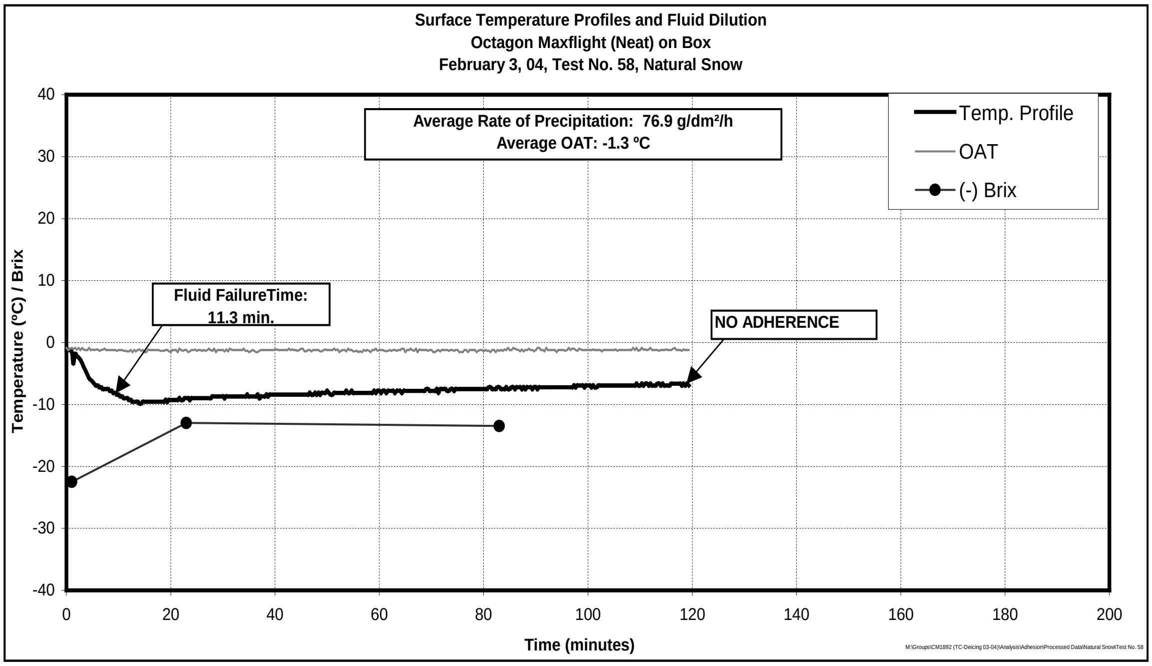


Figure 4.20: Test No. 58, Natural Snow

As seen in the chart, the dilution of the fluid reached a stable value at about 25 minutes into the test, providing surface protection far beyond fluid failure.

Test No. 5, Precipitation Rate 13.0 g/dm²/h, OAT -5.5°C, Natural Snow

A test conducted under identical weather conditions and on the same date as test No. 6 is illustrated in Figure 4.21. In this case, a propylene-based Type II fluid at a concentration of 75/25 was applied. As the fluid had a lower glycol concentration, the failure call was made earlier, at about 77 minutes after pouring. As can be seen on the chart, the fluid film thickness diminished faster than in Test No. 6. Still, the combination of fluid and snow resulted in a slush that provided sufficient strength to prevent bonding to the surface. The fluid did not dilute beyond a Brix value of 9.5 for over 100 minutes after standard plate failure. As failure adhesion was not detected at any point over the duration of this test, the test was stopped at around 200 minutes after pouring.

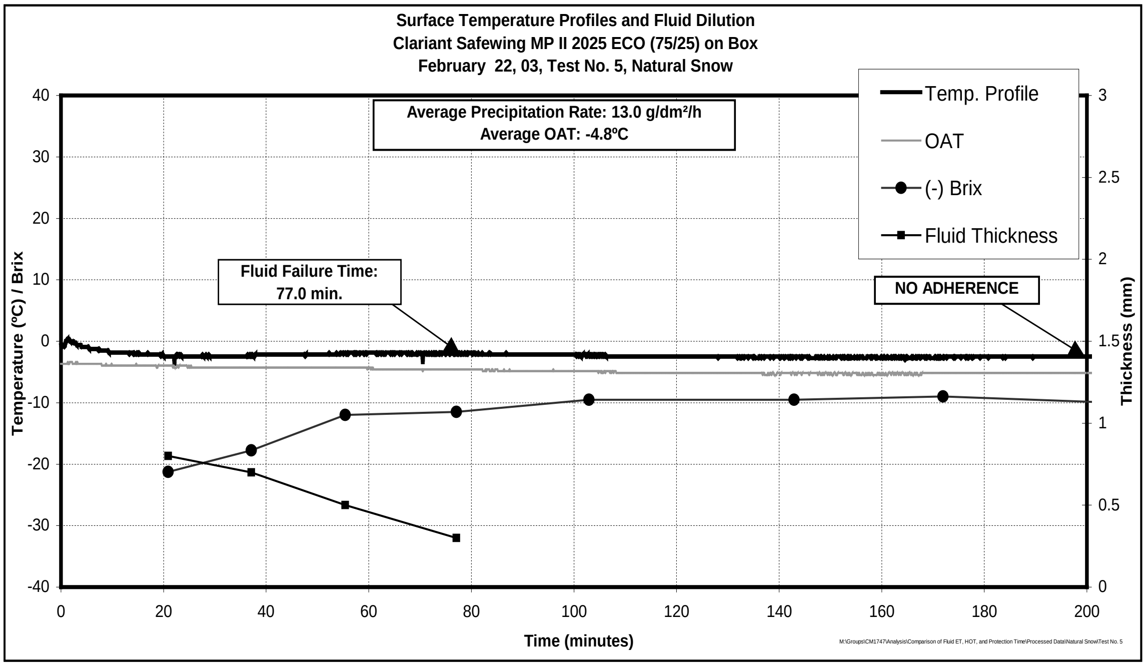


Figure 4.21: Test No. 5, Natural Snow

Test No. 53, Precipitation Rate 47.7 g/dm²/h, OAT -7.7°C, Natural Snow

The findings from test No. 5 were confirmed, even when the test was run under significantly higher precipitation rates with a different propylene-based Type II fluid. The average precipitation rate was almost four times higher than that of test No. 5. As presented in Figure 4.22, the test was run under heavy snow conditions, at an ambient temperature of -7.7°C and the fluid was applied at about 14°C above ambient temperature. Several dilution and adhesion measurements were conducted over two hours following standard failure and no adhesion was documented. The surface protection was provided throughout the test by the glycol concentration of the fluid.

The last fluid Brix value recorded was 7. After taking the last Brix measurement, the test plate was left on the stand under precipitation. The snowstorm on this particular event was long lasting. The next day, approximately fourteen hours after failure, one more dilution measurement was taken. At this time the surface had been under continuous snow for over 15 hours. Still, the fluid did not present bonding to the surface, its dilution having diminished at an extremely slow rate. The fluid Brix documented by this last measurement was 6.

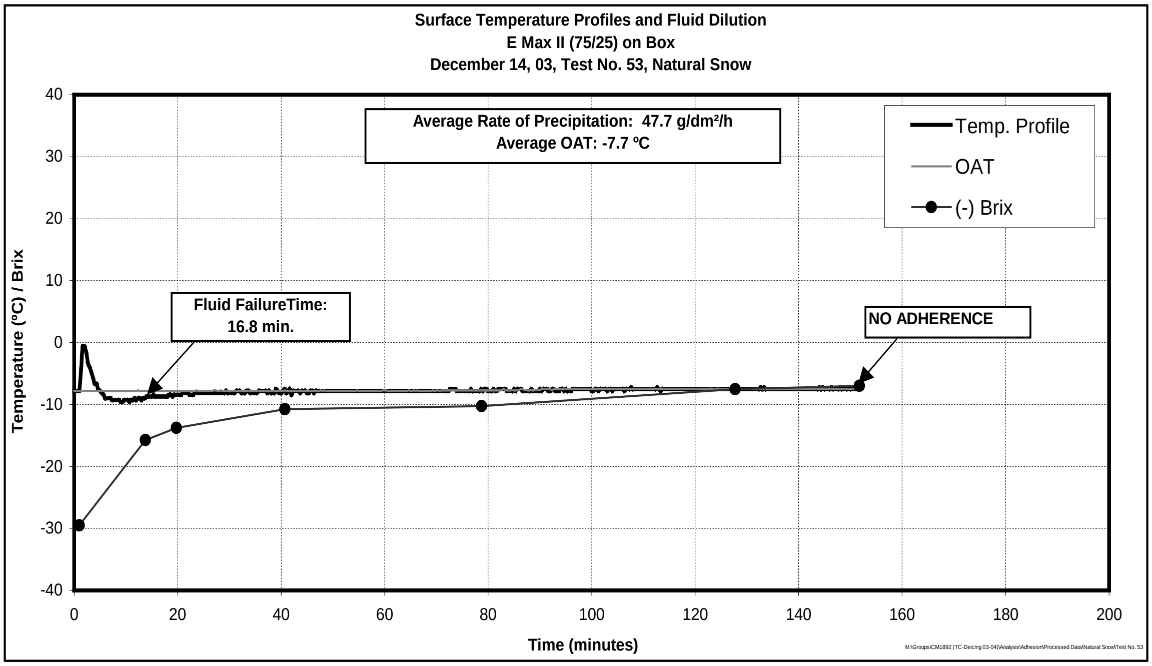


Figure 4.22: Test No. 53, Natural Snow

Test No. P3, Precipitation Rate 9.9 g/dm²/h, OAT -3°C, Artificial Snow

Similar results were obtained using 50/50 fluids, as presented in Figure 4.23.

In this case, the test surface was the NCAR plate and the ambient temperature was -3°C. Following the same pattern, the Type II fluid diluted to slush under precipitation. The slushy solution at the fluid-air interface acted as an insulator, and the rate at which the fluid was being absorbed diminished significantly.

Again, failure adhesion was not detected at any point over the duration of this test, even though the fluid was exposed to precipitation beyond the time when failure was called. Test No. 7, conducted with a different 50/50 propylene-based Type II fluid, confirmed these findings. Subjected to an even higher precipitation rate (see test No. 35), the 50/50 fluid still did not dilute past a Brix value of 2.5, preventing fluid adhesion.

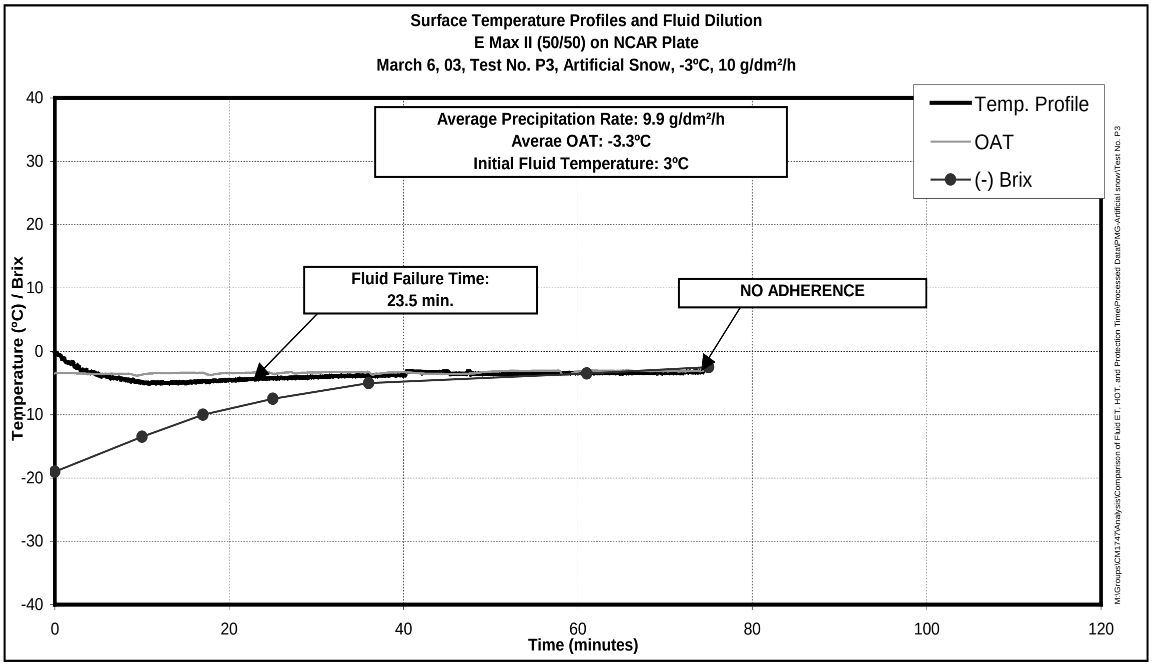


Figure 4.23: Test No. P3, Artificial Snow

Test No. 60, Precipitation Rate 75.7 g/dm²/h, OAT -1.3°C, Natural Snow

Similar results were observed with a different propylene-based Type II fluid (Figure 4.24). Even though in this case testing was conducted under extreme precipitation conditions (a precipitation rate of 75.7 g/dm²/h), the fluid did not present bonding long after the failure call. At approximately two hours following failure, the test was stopped, and no adhesion was documented on the test surface.

Test No. 32, Precipitation Rate 20.6 g/dm²/h, OAT -1.5°C, Natural Snow

If the fluid is exposed to precipitation far beyond complete plate failure, the failed fluid might eventually adhere to the surface, provided its freezing point reaches 0°C. The test presented in Figure 4.25, conducted using a 50/50 Type II fluid at an ambient test temperature of -1.5°C and a precipitation rate of 20.6 g/dm²/h, exhibited some bonding of the fluid to the supporting surface. For this test, the surface temperature profile curve and fluid thickness measurements are not available. The visual failure of the fluid was recorded approximately 12 minutes after pouring.

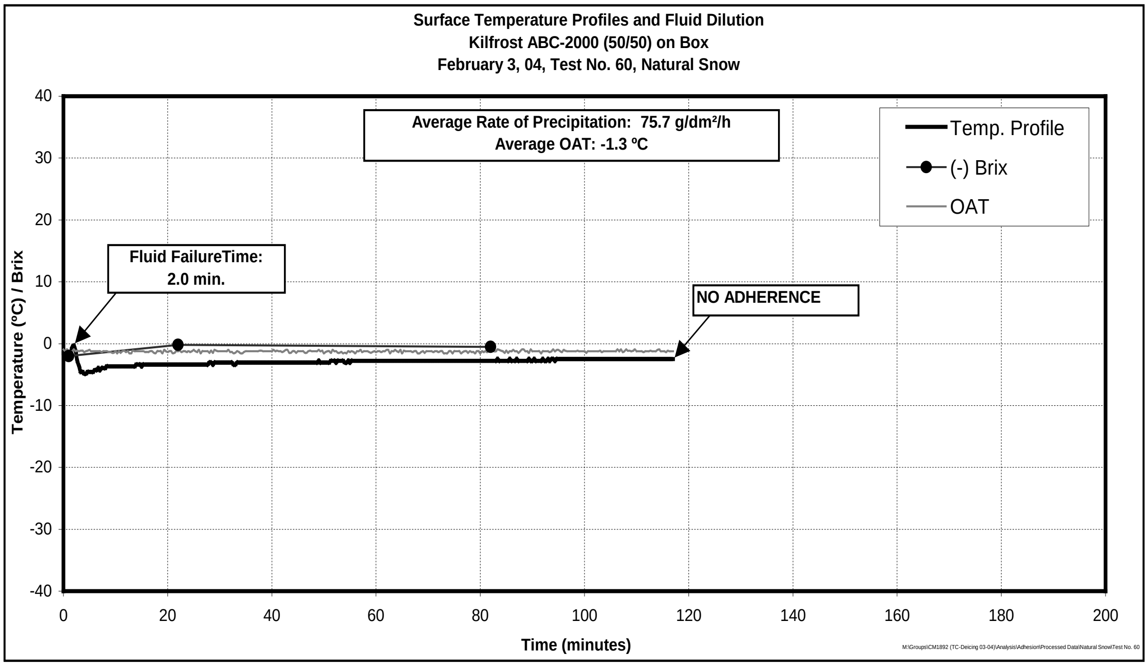


Figure 4.24: Test No. 60, Natural Snow

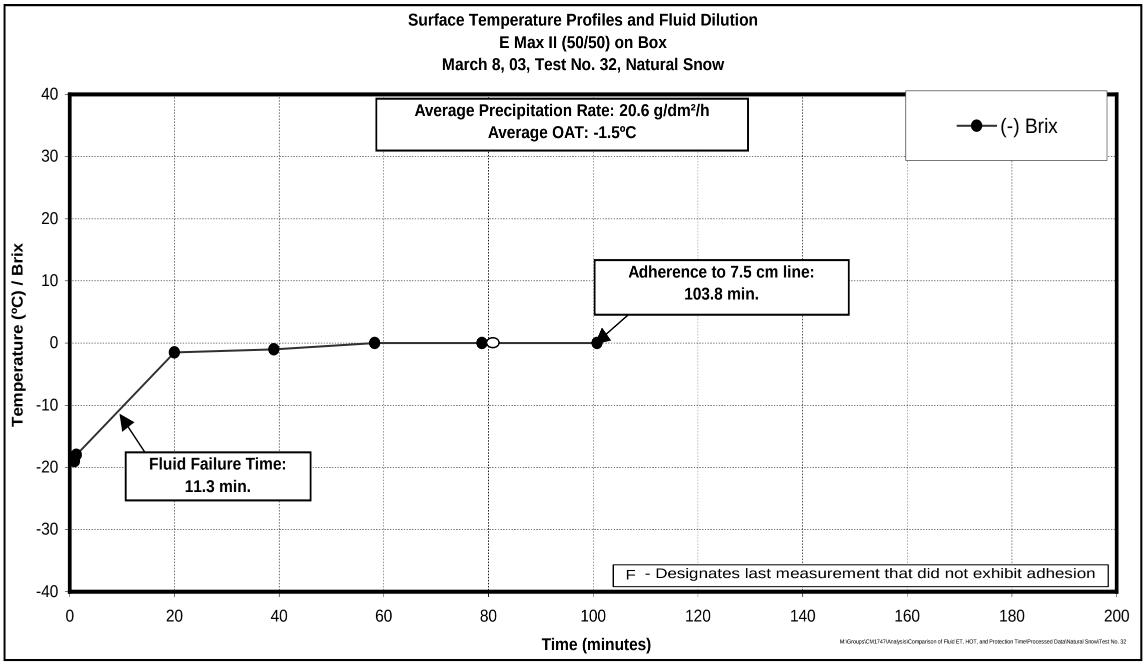


Figure 4.25: Test No. 32, Natural Snow

At failure time, surface protection was provided by glycol. Exposed further to precipitation, the fluid slowly diluted to water in about 45 minutes, and the onset of adherence was documented. The adherence had the aspect of an ice patch (approximately 2 by 2 cm) situated at the 15 cm line on the surface. Adherence had grown to the 7.5 cm line after 104 minutes, at which time the test was stopped.

As mentioned earlier in this section, unless there is a significant temperature increase during the snow event, minimal melting will occur on the surface of the anti-icing fluid. In this test, both the OAT and applied fluid temperatures were warm, at -1.5°C. As a result, melting of snowflakes was facilitated, generating fairly large quantities of liquid water for fluid dilution.

Test No. 53 is important in conjunction with the results from a field survey conducted at a number of airports to gauge and document the typical temperature of Type IV fluids sprayed from trucks during actual deicing operations. As shown in TC report TP 14154E, *Aircraft Ground Icing Exploratory Research for the 2002-03 Winter* (8), based on the sixty-two tests carried out during this survey, the anti-icing fluids were applied at an average temperature 14°C higher than the OAT. Tests from two stations showed considerably higher values of mean deviation between Type IV fluids and OAT. Separate analysis, where tests from these two stations were excluded, showed more uniform results, with the average differential of the measured Type IV fluid and OAT as 7.2°C. The analysis showed that there are influences on Type IV fluids, including the type of trucks that they are transported in, the heating duration of Type I fluid in adjacent tanks and OAT. They also showed that it is rarely the case that one of these factors is dominant in influencing the temperature of a Type IV fluid. In most cases it is the combination of factors, with the most significant impact being the OAT.

At the end of the 2002-03 testing season, several recommendations were made for completion of this research and specifically included Type II/IV fluid adhesion testing using heated fluids. In 2003-04 eight more tests were conducted with Type II/IV fluids heated at various temperatures, from 9°C to 61°C above ambient temperature.

As previously shown in test No. 53 (Figure 4.22), the Type II fluid was heated at about 14°C above ambient temperature in an attempt to replicate the results from the field survey. The fluid in that case had a dilution of 75/25, and the test was run under very heavy snow precipitation rates. The surface was checked for adhesion fourteen hours following standard failure and no adhesion was documented. Three more adhesion tests were conducted at the same time (see tests No. 50, 51 and 52 in Appendix D) and all yielded the same results.

Since heating the fluid to a temperature of 14°C above ambient did not result in adhesion, the research was taken a step further and four tests were conducted with Type II/IV fluids heated to approximately 60°C.

Test No. 56, Precipitation Rate 16.7 g/dm²/h, OAT -0.3°C, Natural Snow

Test No. 56 (Figure 4.26) was run with a neat propylene-based Type II fluid applied at 60°C, under moderate snow conditions. The high fluid temperature, combined with a relatively high ambient test temperature, slowed the cooling process of the fluid. Melting of snowflakes was facilitated and, as a result, the fluid weakened at an accelerated rate. At the failure time, 17.8 minutes into the test, the fluid was almost completely diluted, the concentration of the solution on the test surface being very close to that of pure water. One hour later, the first occurrence of adhesion was documented at the 7.5 cm line. For this test the safety buffer time was calculated to be 4.5.

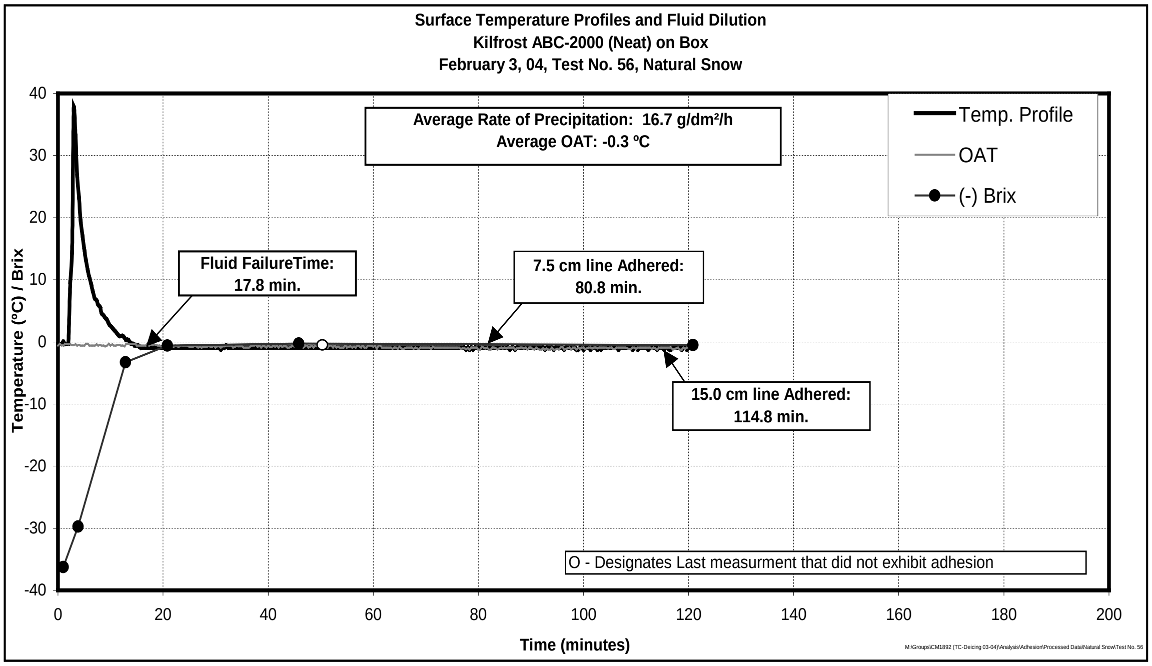


Figure 4.26: Test No. 56, Natural Snow

The findings from the adhesion tests presented above were also confirmed by two additional tests run using 50/50 Type IV and Type II propylene glycol-based fluids at different precipitation rates (see tests No. 55 and 61 in Appendix D).

However, a neat propylene-based Type IV fluid tested at a very high precipitation rate (matching test No. 61 rate which was run at a 50/50 strength) did not present adhesion two hours after standard failure was called. This test is presented below.

Test No. 59, Precipitation Rate 76 g/dm²/h, OAT -1.3°C, Natural Snow

Test No. 59 (Figure 4.27) was run with a neat propylene-based Type IV fluid applied at 60°C, under heavy snow conditions. Even subjected to a precipitation rate of 76 g/dm²/h, the fluid did not dilute beyond a certain Brix value. The failed fluid had the aspect and consistency of slush. In this case, the visually failed fluid did not adhere to the surface. Adhesion was not documented even though the fluid was exposed to precipitation far beyond failure time.

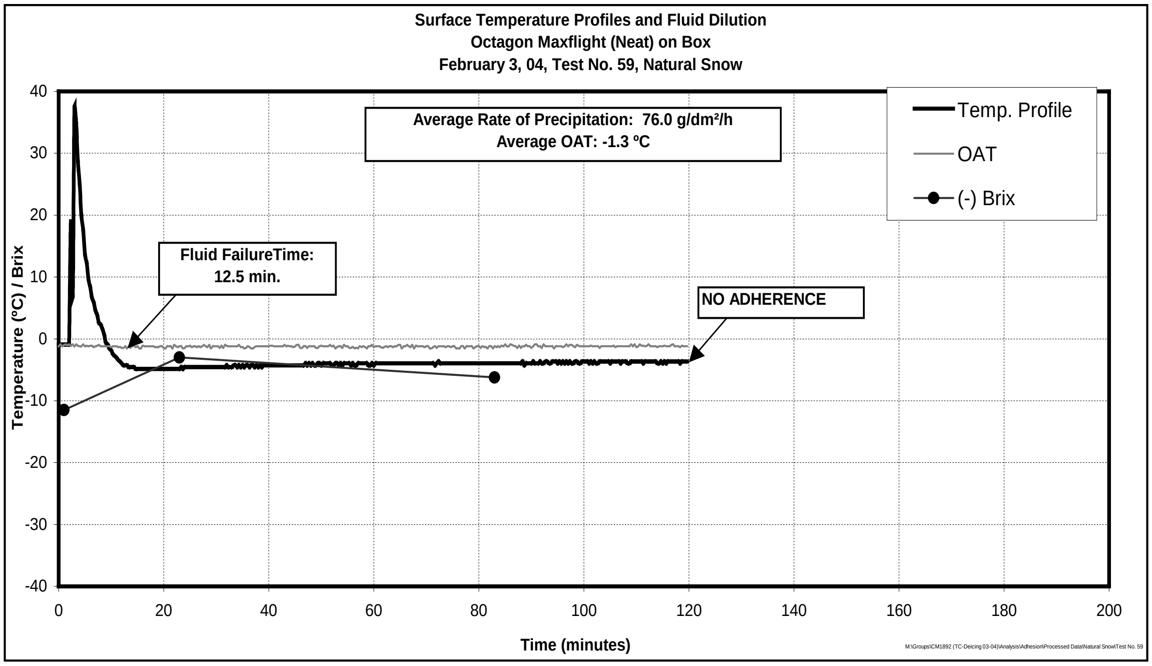


Figure 4.27: Test No. 59, Natural Snow

Thus, in the case of a neat Type IV fluid, a fluid application temperature of 60°C may not be sufficient to generate adhesion of contamination to the surface.

As per Table 3.1, a full set of test results grouped by weather conditions is provided in Appendix D.

The Type II/IV adhesion testing conducted under natural and artificial snow conditions leads to the conclusion that, typically, failure adhesion does not occur with these unheated fluids. This finding is independent of fluid type, glycol concentration, ambient test temperature and rate of precipitation. Also, the type of glycol does not seem to have any influence on the occurrence of adherence. If the Type II/IV fluid is heated, melting of snowflakes is facilitated, generating fairly large quantities of water for fluid dilution. This can lead to early dilution of the fluid and, particularly in the case of lower concentration fluids, to adhesion.

4.2.2 Freezing Fog: Type II/IV Fluid

As shown in Table 3.4, tests were performed under freezing fog, freezing drizzle and light freezing rain conditions using both the standard endurance time plate and the empty aluminum box test surfaces.

Five adhesion tests were run under simulated freezing fog conditions at -3 and-25°C.

Figure 4.28 illustrates a freezing fog adhesion test conducted at an ambient test temperature of -3°C and a precipitation rate of 5 g/dm²/h.

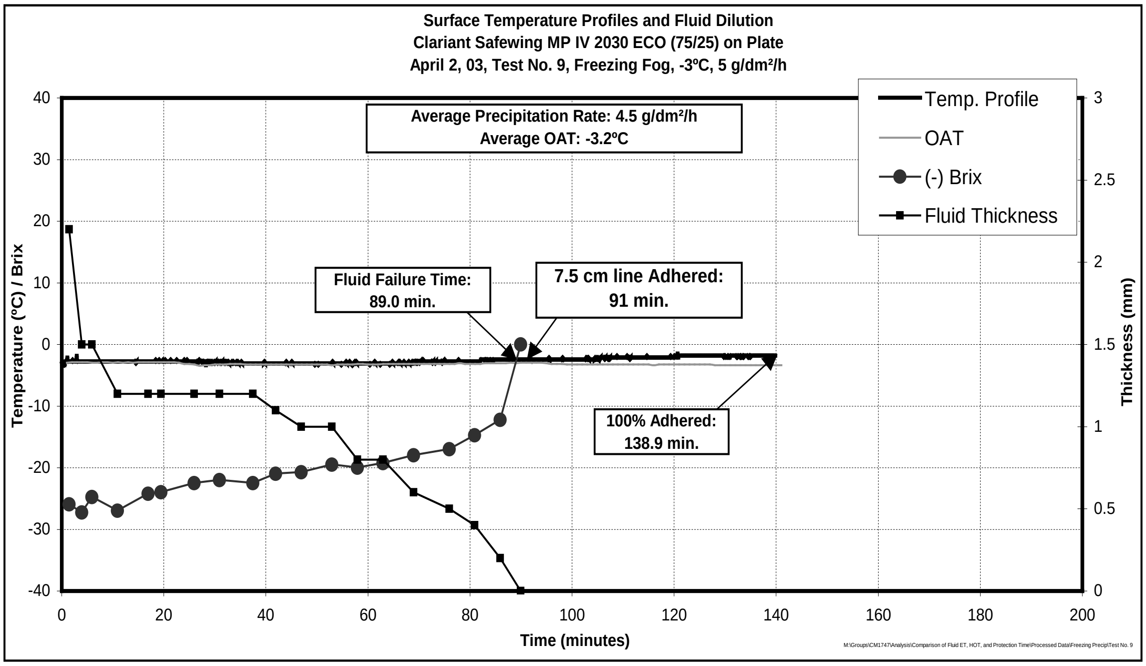


Figure 4.28: Test No. 9, Freezing Fog

The propylene glycol-based Type IV fluid was applied at ambient test temperature on the standard endurance time plate (Photo 4.4). Following application, the freezing point of the fluid started to rise and, after 89 minutes, reached ambient temperature. As surface protection was not being provided by glycol, the contamination started to freeze and shortly after the failure call, the fluid presented adherence to the 7.5 cm line. As observed on the chart, the release of latent heat of freezing on the surface generated sufficient heat to gradually raise the surface temperature by 1°C. Further exposure to precipitation led to fluid adhesion over the entire surface of the plate. It was also noted that the thickness of the fluid layer diminished continuously over the duration of the test, to reach its ultimate value at the time of failure. Two more tests were conducted under similar weather conditions (tests No. 10 and 11), and both exhibited fluid adhesion. The earliest adhesion was observed to occur at the top edge of the test surface.

Figure 4.29 shows a fluid adhesion test performed under freezing fog conditions at a temperature of -25°C using a neat propylene glycol-based Type IV fluid applied to the empty aluminum box surface. Subjected to test conditions, the fluid diluted, but not beyond a Brix value of 9, providing sufficient strength to avoid freezing and bonding.

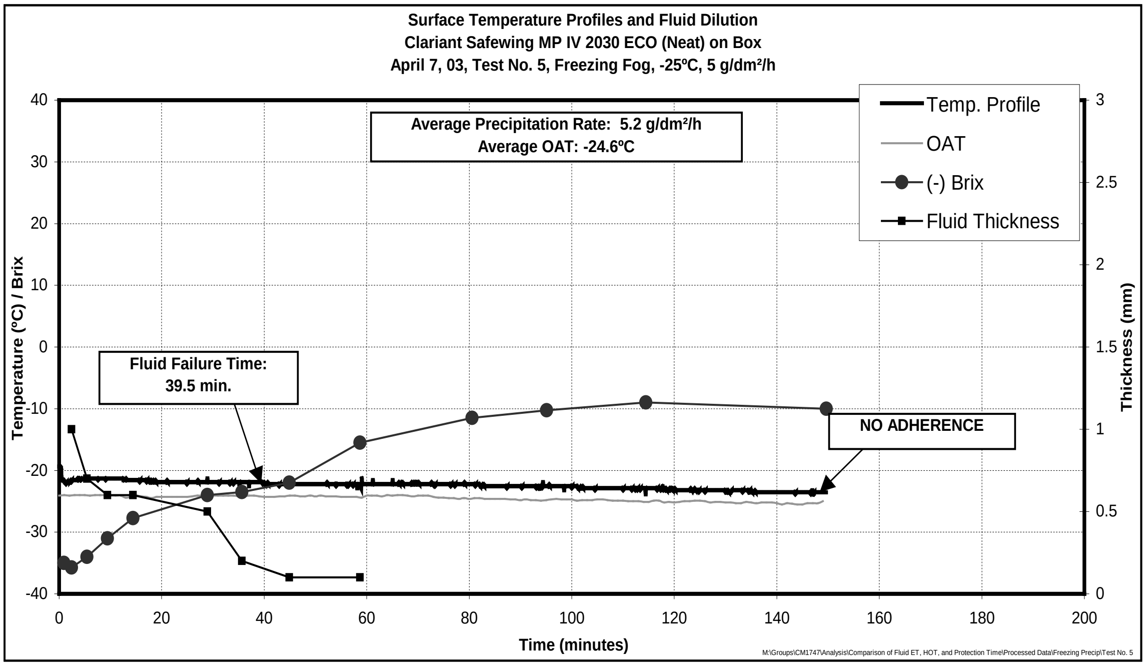


Figure 4.29: Test No. 5, Freezing Fog

A different test (test No. 6) conducted under comparable weather conditions yielded similar results. During the simulated freezing fog tests at -25°C, no adhesion was detected at any point during the tests.

Freezing fog adhesion tests using Type II/IV fluids were not conducted at a precipitation rate of 2 g/dm²/h. Even though insufficient data is available to enable a strong conclusion, the appearance and severity of fluid adhesion to the underlying surface under simulated fog precipitation conditions seemed to be related primarily to the ambient test temperature, and secondly to the rate of precipitation.

4.2.3 Freezing Drizzle: Type II, III and IV Fluid

Sixteen fluid adhesion tests were run under simulated freezing drizzle conditions at -3 and -10°C, under precipitation rates of 5 and 13 g/dm²/h. All experienced adhesion. Figure 4.30 illustrates a freezing drizzle adhesion test conducted at an ambient test temperature of -3°C and a precipitation rate of 13 g/dm²/h.

The 50/50 Type II fluid was applied at ambient temperature on the standard endurance time plate. Following application, the freezing point of the fluid started to rise and after about 10 minutes, reached a Brix value of 7. At this time, the failure call was made and the contamination started to freeze. Subjected to ongoing precipitation, the fluid diluted further, and 15.7 minutes after pouring, the frozen contamination presented bonding to the 30 cm line. At 20.8 minutes, the contamination was adhered over the entire surface of the plate. For this test the buffer time was calculated to be 1.6. The release of latent heat of freezing was more significant in this case, raising the surface temperature by almost 2°C as the contamination completely solidified.

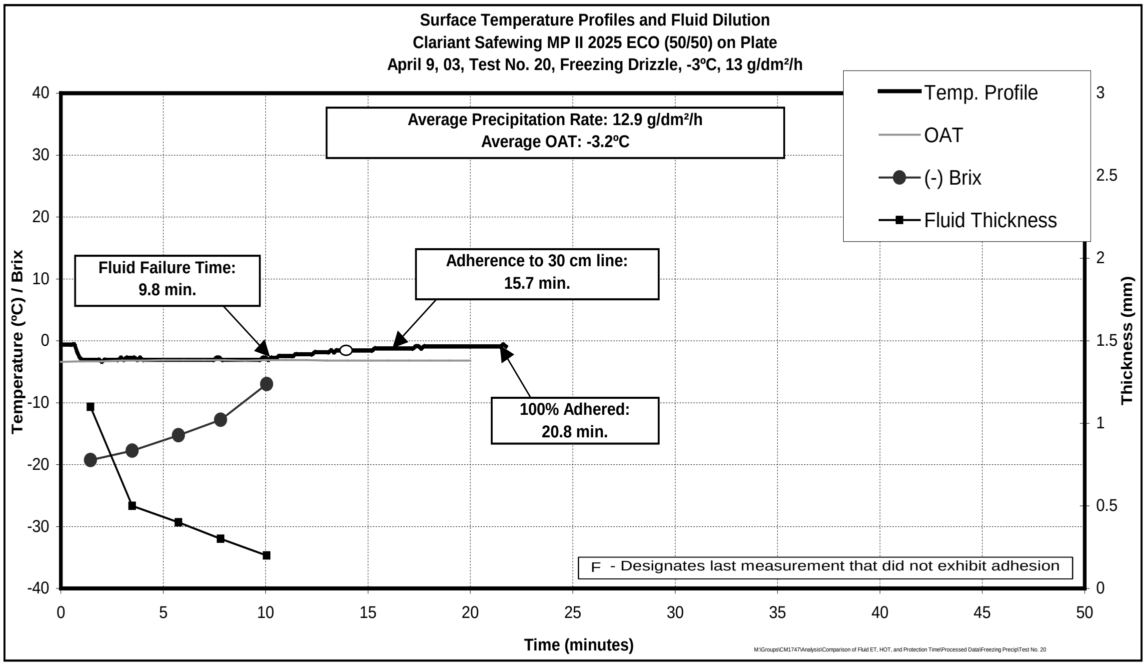


Figure 4.30: Test No. 20, Freezing Drizzle

Figure 4.31 shows a standard endurance time plate adhesion test performed under simulated freezing drizzle at -3°C using a neat Type III fluid. In this case, the fluid dilution under a precipitation rate of 5 g/dm²/h produced a safety buffer of 1.1 between endurance time and adhesion time. The release of the latent heat of freezing can be observed on the chart as the contamination started to freeze over the entire surface of the test plate.

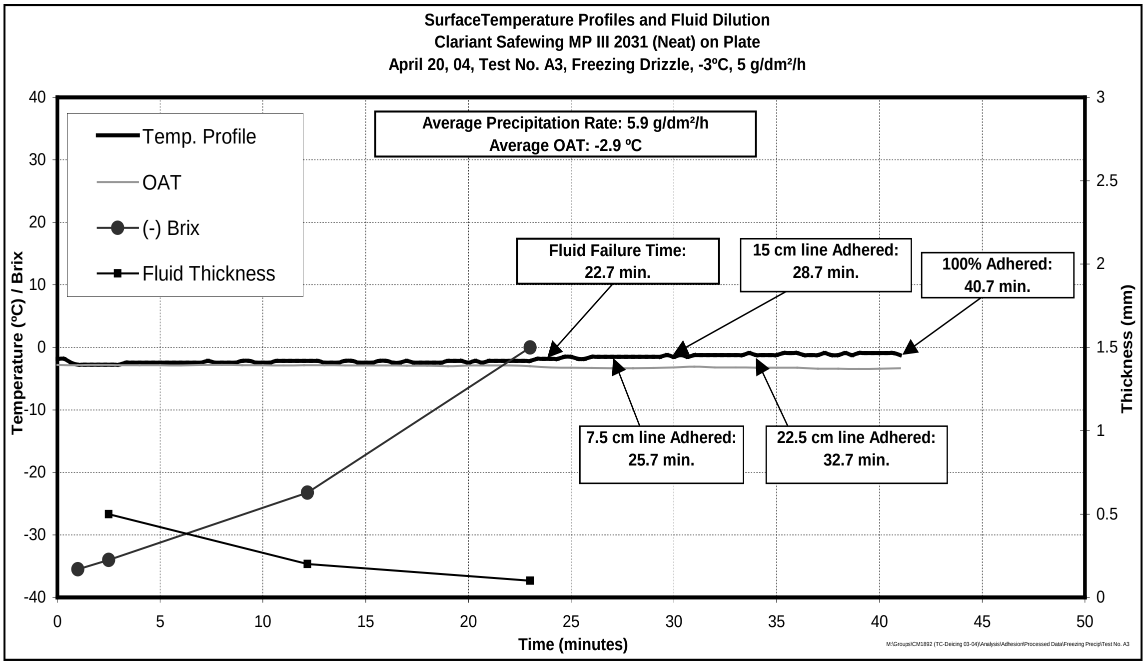


Figure 4.31: Test No. A3, Freezing Drizzle

Figure 4.32 shows an adhesion test performed on the standard endurance time plate, under simulated freezing drizzle at a rate of 13 g/dm²/h, OAT at -10°C, using a neat Type IV fluid at OAT. The surface temperature profile curve is not available, as temperature logging was not implemented for this test. In this case, the fluid dilution resulted in a safety buffer of 1.2.

Figure 4.33 shows a standard endurance time plate adhesion test performed under simulated freezing drizzle at -10°C using a neat Type III fluid. In this case, the safety buffer was determined to be 1.8.

In conclusion, all Type II, III and IV fluid adhesion tests conducted under simulated freezing drizzle precipitation presented adherence shortly after fluid failure, independent of the glycol concentration, the precipitation rate and ambient temperature.

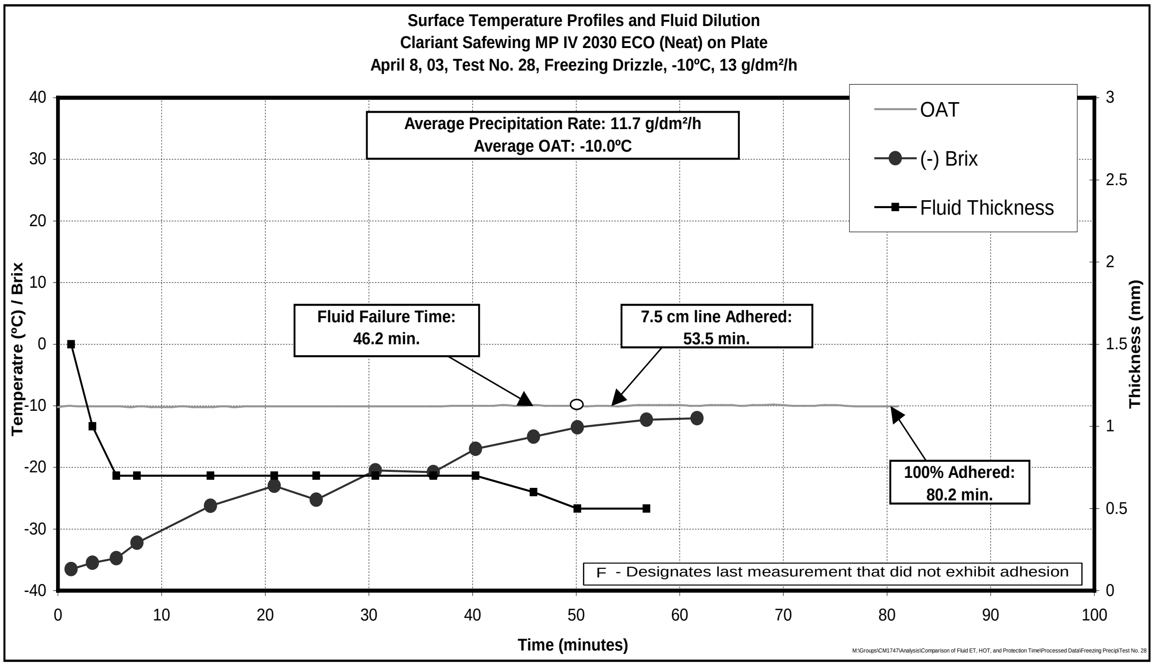


Figure 4.32: Test No. 28, Freezing Drizzle

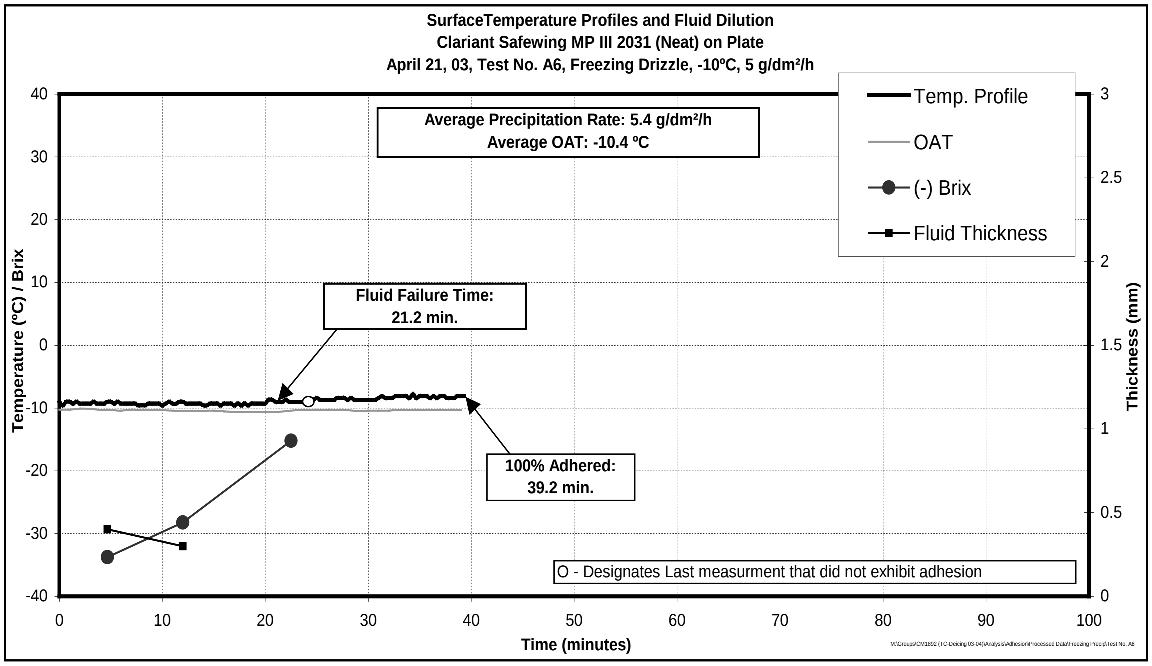


Figure 4.33: Test No. A6, Freezing Drizzle

4.2.4 Light Freezing Rain: Type II, III and IV Fluid

Sixteen Type II, III and IV fluid adhesion tests were run under simulated light freezing rain conditions at ambient temperatures of -3 and -10°C and precipitation rates of 13 and 25 g/dm²/h.

Figure 4.34 illustrates a light freezing rain adhesion test No. E6 conducted at an ambient test temperature of -3°C on the standard endurance time plate. As observed on the chart, for about 2.5 minutes prior to fluid application, the surface temperature was above ambient test temperature. The 50/50 propylene-based Type II fluid was applied at a temperature slightly below ambient test temperature. The test surface temperature, in the process of warming after fluid application, reached room temperature after about 5.7 minutes where the fluid failure call was made. As the test surface attempted to stagnate at room temperature, some freezing occurred and the release of latent heat of freezing increased the surface temperature by almost 3°C. Under precipitation, the fluid freeze point of the fluid started to rise and 15.6 minutes after pouring, the bonding of frozen contamination to the 22.5 cm line was documented. At 27.6 minutes, the fluid presented adhesion over the entire surface of the plate. The fluid thickness diminished continuously over the duration of the test and reached 0.1 mm about 11.5 minutes following application.

Five more tests run under similar temperature and precipitation conditions confirmed the results from test No. E6 (see tests No. E4, E5, A13, A14 and A15 in Appendix D).

A total of four adhesion tests were run at -3°C under low precipitation rates (around 13 g/dm²/h) with Type II and IV fluids at different concentrations. They all adhered to the test surface shortly after the standard failure was documented (see tests No. 39, 40, 41 and 42 in Appendix D).

Figure 4.35 shows a light freezing rain adhesion test No. 36 performed at an ambient test temperature of -10°C on the standard ET plate using a neat ethylene-based Type IV fluid. Following application, the test surface reached a temperature of -8.5°C and flattened. Exposed to precipitation, the fluid started to dilute, its freezing point typically following an ascending slope throughout the test. At about 35 minutes after pouring, it reached a diluted concentration level that could not prevent freezing. The contamination started to freeze and, shortly after, the standard plate failure was recorded. At almost the same time, the contamination presented adhesion to the 7.5 cm line, producing a safety buffer of 1.0. As freezing progressed over the entire surface of the plate, the release of latent heat increased the plate temperature by almost 6°C. Subsequently, at the elapsed time of 60 minutes, the frozen contamination exhibited adhesion over the entire surface of the plate.

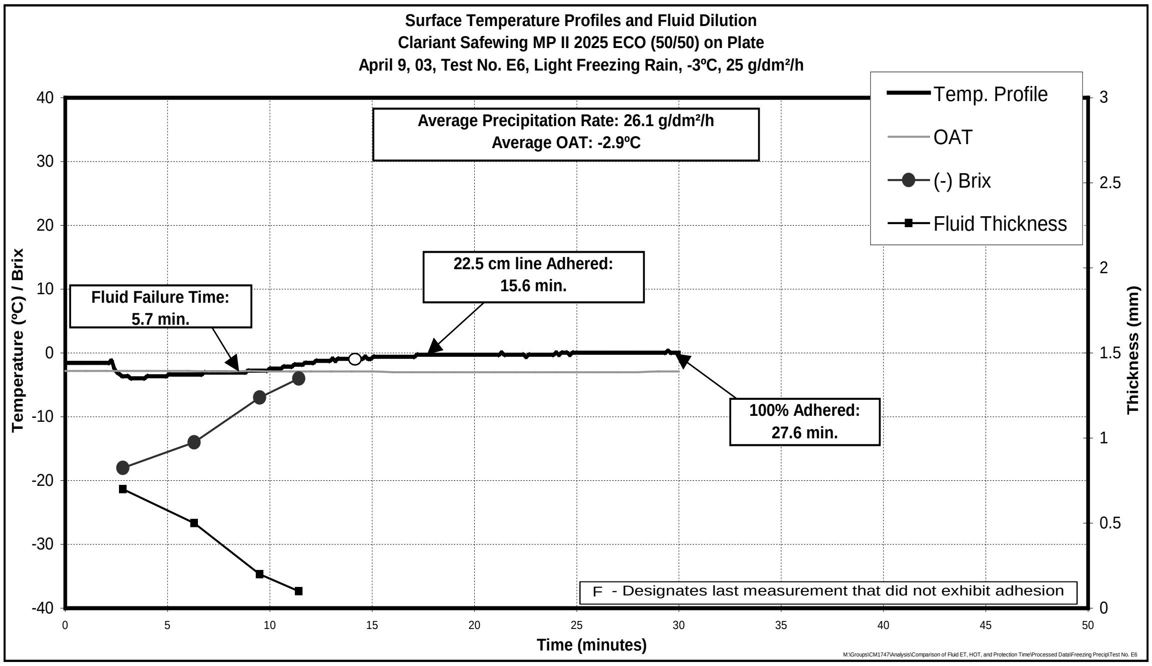


Figure 4.34: Test No. E6, Light Freezing Rain

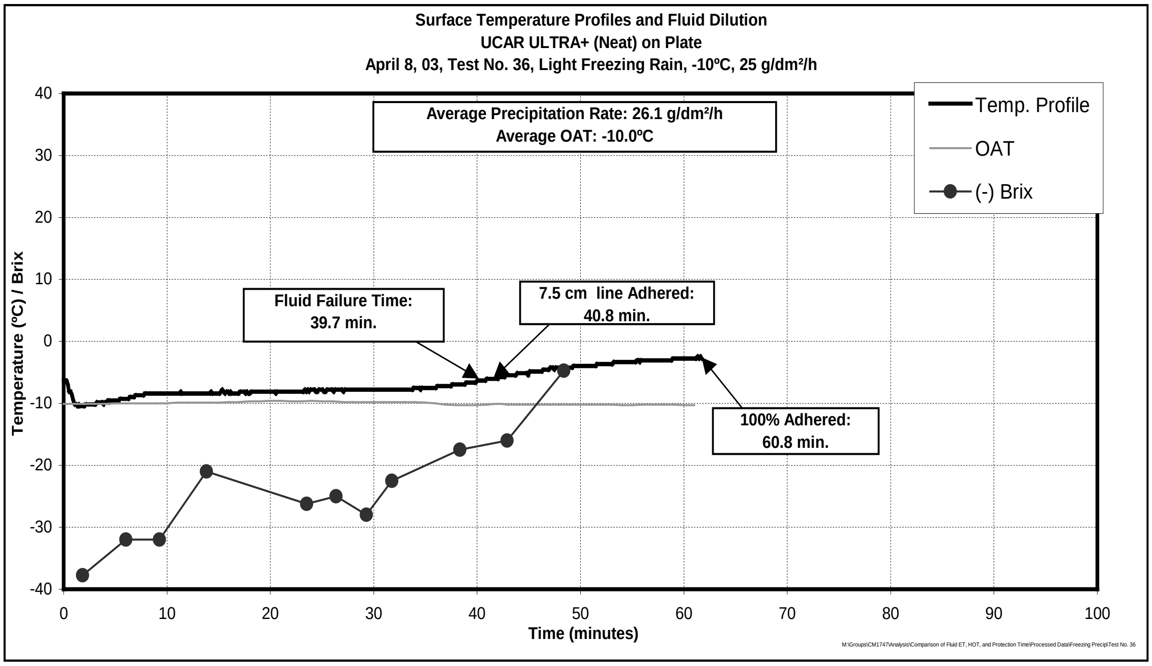


Figure 4.35: Test No. 36, Light Freezing Rain

Figure 4.36 shows a light freezing rain adhesion test performed under similar conditions with test No. 36, but with a neat propylene-based Type IV fluid. Exposed to precipitation, the fluid started to dilute, its freezing point typically following an ascending slope throughout the test. The standard plate failure was recorded at 21.3 minutes into the test. The first documentation of adhesion was recorded at the top edge of the plate, 23 minutes following standard plate failure. At 38 minutes after the failure call was made, adhesion covered the entire surface of the test plate.

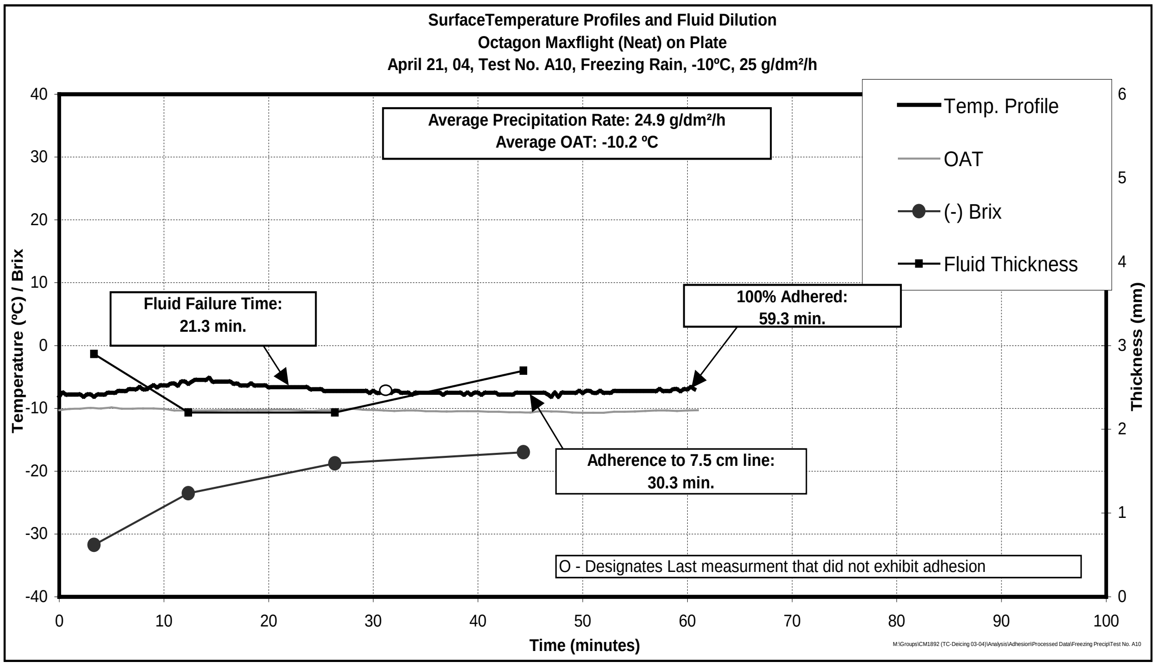


Figure 4.36: Test No. A10, Light Freezing Rain

It was observed that the Type IV propylene-based fluid formed a crust of solidified contamination at the air-fluid interface, while still preserving a very thin film of fluid underneath. This crust was solid and could not be removed with the instrument used to check for fluid adhesion. So, in accordance with the standard method of documenting adhesion described in Section 2.3.6, the test presented adhesion. However, when the solid crust was subjected to shear forces (i.e. by using a scraper), the contamination came off relatively easy and all at once.

In conclusion, Type II, III and IV fluid adhesion tests conducted under simulated freezing rain precipitation presented adherence after fluid failure, independent of the glycol concentration, the precipitation rate and ambient temperature.

4.2.5 Rain on a Cold-Soaked Wing: Type II/IV Fluid

One adhesion test was conducted under this condition using a 75/25 Type II fluid. Since this test surface that was undergoing endurance time testing, fluid dilution and fluid thickness measurements were not recorded. Following standard failure, fluid adhesion measurements were conducted on the surface.

Figure 4.37 illustrates the evolution of fluid adhesion to the supporting surface over time. The standard failure was recorded about 58 minutes after pouring. Shortly after, the entire surface of the cold-soak box was covered with failed fluid. The presence of adherence to the 7.5 cm line was documented at about 71 minutes after fluid application, and 6 minutes later, the adhered contamination spanned the entire surface of the box. This indicates that fluid dilution was a continuous process throughout the test and eventually led to a glycol concentration insufficient to prevent freezing.

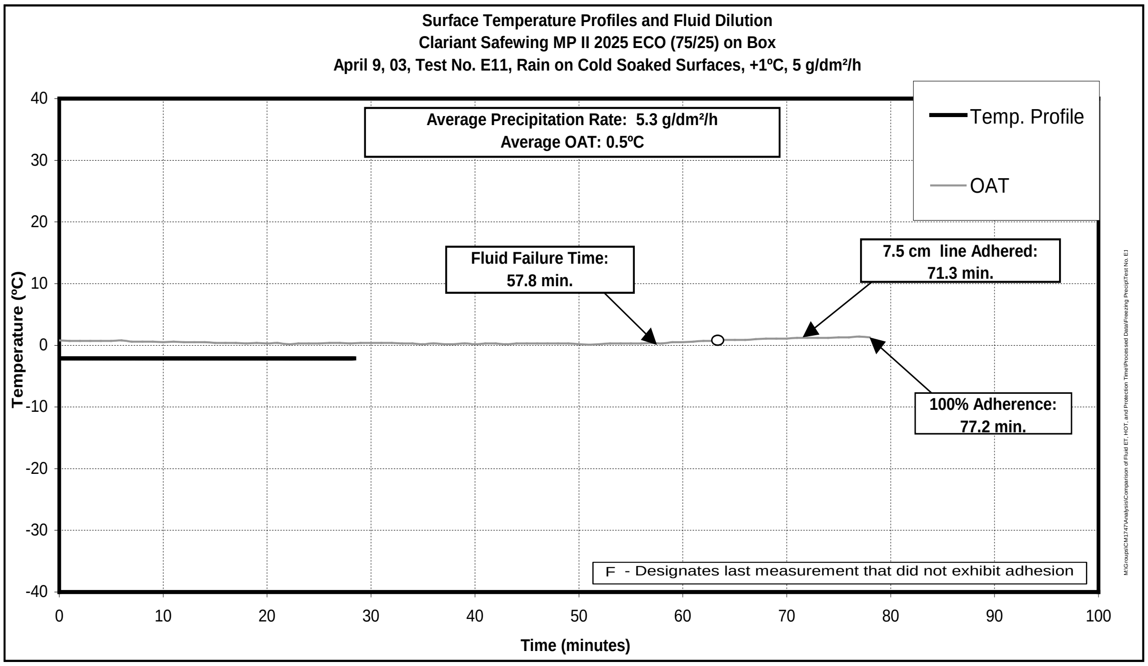


Figure 4.37: Test No. E11, Rain on Cold-Soak Wing

4.2.6 Summary of Results

Based on the Type II, III and IV adhesion testing under simulated freezing precipitation conditions, the following conclusions can be drawn:

a) Except for freezing fog at -25°C, adherence was documented under all freezing precipitation conditions tested, regardless of the test surface type, fluid type, ambient test temperature and rate of precipitation. Typically, adhesion occurred shortly after failure during the freezing precipitation tests.

b) Using exclusively the data provided by the 2002-03 testing season, the effect of the glycol type seemed insignificant, since adhesion tests yielded the same results for ethylene and propylene glycol-based anti-icing fluids.

Testing conducted during the 1998-99 winter season exhibited different results. As presented in TC report TP 13484E, *Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation: 1998-99* (7), only Type IV ethylene glycol-based fluids demonstrated failure adhesion. The Type IV propylene-based fluid experienced no adhesion at ambient temperatures of -10°C, even when complete plate failure was identified. A possible explanation for this different behaviour could reside in the nature of the fluids tested in 2002-03. The entire set of propylene-based Type II/IV adhesion tests was conducted using only two fluids, Safewing MP II 2025 ECO and Safewing MP IV 2030 ECO. Subsequently, it was acknowledged that the latter fluid is not temperature dependent, and is not representative for Type IV propylene-based fluids.

All the tests conducted in 2003-04 with various Type II/III and IV propylene fluids showed adhesion. It was also observed that the Type IV propylene-based fluid formed a crust of solidified contamination at the air-fluid interface, while still preserving a very thin film of fluid underneath. So, in accordance with the standard method of documenting adhesion, the test presented adhesion. However, when the solid crust was subjected to shear forces (i.e. by using a scraper), the contamination came off relatively easy and all at once.

c) Droplet impact can be thought of as a means of mechanical mixing. The mixing efficiency will be greater for the larger (more massive) droplets, which are characteristic of rain. The most severe instances of adhesion occurred at -10°C under light freezing rain, followed by freezing drizzle at the same temperature, which afforded a slightly less severe level of adhesion.

The results from testing under natural snow, artificial snow and simulated precipitation conditions were analysed to document the extent of the safety buffer for each weather condition and fluid type. The findings are presented in Section 4.3.

4.3 Safety Buffer Analysis

The information collected from the adhesion tests was analysed to document the instances in which fluid adhesion occurred, and for these cases, to determine the extent of the safety buffer between endurance time and adhesion time.

As mentioned in Section 2.6, the size of the safety buffer was calculated by dividing the adhesion time by the endurance time. The resulting number signifies the interval between the time of standard failure and the time when fluid adhesion was first documented. This number is expressed as a percentage of endurance time. For instance, a safety buffer of 1.33 for a ten-minute fluid failure test signifies that the onset of adherence was recorded about 3.3 minutes after fluid failure.

As seen on the charts presented in this section, the first documentation of fluid adhesion was not always recorded at the 7.5 cm line. In some cases, fluid adhesion was recorded for the first time when the frozen contamination presented bonding to the 30 cm line. If the later time of adhesion at the 7.5 cm line had been documented in these cases, the resulting safety buffer would have been greater. Regardless of the location of adherence on the surface, the time of its first documentation was used to determine the safety buffer.

A tabular display of adherence times versus endurance times was developed to illustrate the size of the safety buffer for various weather conditions and fluid types. The HOT table guidelines for both Type I and Type II/IV tables are used to portray the results.

The HOT values in each cell of the table are replaced by either a “no adherence” decision or a numerical value representing the extent of the safety buffer between adhesion time and endurance time. The number of tests in each cell of the table is shown in parenthesis beside the number indicating the safety buffer. Whenever more than one test was conducted in a specific cell of the table, the size of the safety buffer was determined by taking the average of their safety buffers.

Table 4.1 presents the adhesion testing results obtained using Type I fluids under various weather conditions, temperature ranges and rates of precipitation.

As observed in the table, with the exception of cold-soaked wing, all precipitation conditions were addressed by the current testing session. Each cell of the table that contains values was documented and explained in Section 4.

Table 4.1: Safety Buffer for Tests Conducted with Type I Fluids

OAT	**Approximate Safety Buffers Under Various Weather Conditions**								
°C	**Frost**	**Freezing Fog**	**Very Light Snow**	**Light Snow**	**Moderate Snow**	**Freezing Drizzle**	**Light Freezing Rain**	**Rain on Cold Soaked Wing**	**Other**
-3 and above		**1.1 (2)**			**1.3 (1)** ***4.5 (1)**	**1.2 (2)**	**1.4 (2)**		
below -3 to -6				**No Adh. (5)**	**1.9 (3)**	**1.0 (1)**			
below -6 to -10	**2.7 (2)**		**No Adh. (1)**	**No Adh. (1)** **15.3 (1)**	**3.7 (1)** **No Adh. (1)** ***1.5 (2)**	**1.7 (4)**	**1.0 (2)**		
below -10	**1.8 (2)**	**No Adh. (2)**							

* Type I adhesion tests conducted at high precipitation rates (> 25g/dm²/h) under snow conditions. All presented adhesion.
(X) Value in bracket designates number of tests.

It was noted that, with the exception of freezing fog at -25°C, adherence was documented under all freezing precipitation conditions, regardless of the test surface, precipitation rate or test temperature.

The Type I adhesion tests conducted under moderate or heavy snow precipitation conditions typically exhibit adherence. Higher glycol concentrations (at colder temperatures) applied heated to empty aluminum box surfaces generated longer endurance times and extended safety buffers.

Under light and very light snow conditions, the precipitation rate was insufficient to dilute the fluid to a level that would stimulate bonding to the test surface, irrespective of the surface type and initial fluid temperature. However, if the fluid is exposed to precipitation far beyond complete plate failure, the failed fluid might eventually adhere to the supporting surface, provided its freeze point reaches 0°C.

Table 4.2 shows the adhesion test results obtained using Type II, III and IV fluids under various weather conditions and temperature ranges.

Type II/IV adhesion testing was conducted under all precipitation conditions in the HOT table, except for frost. Type III fluids were tested only under simulated freezing precipitation conditions. The phenomena that take place prior to and beyond fluid failure for each cell of the table that was addressed by testing were discussed and explained earlier in Section 4.

Table 4.2: Safety Buffer for Tests Conducted with Type II, III and IV Fluids

OAT	Approximate Safety Buffers Under Various Weather Conditions					
°C	Frost	Freezing Fog	Snow	Freezing Drizzle	Light Freezing Rain	Rain on Cold Soaked Wing	Other
above 0						1.2 (1)	
0 to -3		1.3 (2)	No Adh. (11)* 6.1 (4)**	1.3 (4)	1.4 (10)		
below -3 to -14		1.1 (1)	No Adh. (15)***	1.3 (9)	1.3 (6)		
below -14 to -25		No Adh. (2)					
below -25							

* Includes one Type IV neat adhesion test conducted with fluid heated at 60°C.

* * Includes three adhesion tests conducted with fluid heated at around 60°C.

* * * Includes four adhesion tests conducted with fluid heated at a maximum temperature of 15°C above OAT.

(X) Value in bracket designates number of tests.

It was noted that, with the exception of freezing fog at -25°C, adherence was documented under all freezing precipitation conditions tested regardless of the test surface, precipitation rate or test temperature. Typically, the Type II, III and IV adhesion tests conducted under snow precipitation conditions did not exhibit adherence.

The results presented in Table 4.2 analyse the ethylene and propylene-based fluids combined. A separate analysis was conducted to determine whether the results vary depending upon the glycol type used in the fluid formulation. For this purpose, separate tables were created for the propylene-based and ethylene-based fluids, and are presented in Table 4.3 and Table 4.4. It is worth mentioning that, while various propylene-based fluids were tested, only one ethylene-based fluid was available for this study, namely UCAR Ultra+. In this analysis, an assumption was made that this fluid is representative of all ethylene-based anti-icing fluids.

As a result of the limited data collected with UCAR Ultra+, many cells of Table 4.4 are empty or present a safety buffer based on only one test. As can be observed in the two tables, there are no significant differences between the two fluid types. However, the ethylene-based fluid seems to produce a somewhat smaller safety buffer, indicating that this fluid may be more prone to earlier adhesion.

Table 4.3: Safety Buffer for Tests Conducted with Propylene-Based Type II, III and IV Fluids

OAT	Approximate Safety Buffers Under Various Weather Conditions						
°C	**Frost**	**Freezing Fog**	**Snow**	**Freezing Drizzle**	**Light Freezing Rain**	**Rain on Cold Soaked Wing**	**Other**
above 0						**1.2 (1)**	
0 to -3		**1.3 (2)**	**No Adh. (11)*** **6.1 (4)****	**1.3 (4)**	**1.4 (8)**		
below -3 to -14			**No Adh. (12)*****	**1.3 (8)**	**1.4 (5)**		
below -14 to -25		**No Adh. (1)**					
below -25							

* Includes one Type IV neat adhesion test conducted with fluid heated at 60°C.

** Includes three adhesion tests conducted with fluid heated at around 60°C.

*** Includes four adhesion tests conducted with fluid heated at a maximum temperature of 15°C above OAT.

(X) Value in bracket designates number of tests.

Table 4.4: Safety Buffer for Tests Conducted with Ethylene-Based Type IV Fluids

OAT	Approximate Safety Buffers Under Various Weather Conditions						
°C	Frost	Freezing Fog	Snow	Freezing Drizzle	Light Freezing Rain	Rain on Cold Soaked Wing	Other
above 0							
0 to -3					1.2 (2)		
below -3 to -14		1.1 (1)	No Adh. (3)*	1.1 (1)	1.0 (1)		
below -14 to -25		No Adh. (1)					
below -25							

* Includes one adhesion test conducted with fluid heated at approximately 12°C above OAT.
(X) Value in bracket designates number of tests.

In conclusion, it was noted that, with the exception of freezing fog at -25°C, adherence was documented under all freezing precipitation conditions tested regardless of the test surface, precipitation rate or test temperature. Typically, the Type II, III and IV adhesion tests conducted under snow precipitation conditions did not exhibit adherence.

4.4 Evaluation of Protection Time with Respect to Endurance Time and Adhesion Time

As mentioned in Section 2.1, the TC report TP 13832, *Aircraft Anti-Icing Fluid Endurance, Holdover, and Failure Times Under Winter Precipitation Conditions: A Glossary of Terms* (2), defines the protection time as the period that an anti-icing treatment protects aerodynamically critical surfaces from the adhesion of contamination and the resulting roughness that could cause a premature stall or result in loss of control and prevent the crew from safely operating the aircraft.

The protection time has recently been given a more comprehensive meaning. It is not defined solely with respect to the adhesion of contamination, but also with respect to the aerodynamic performance of the fluid.

Figure 4.38 shows a graphical display of protection time with respect to endurance time and adhesion time.

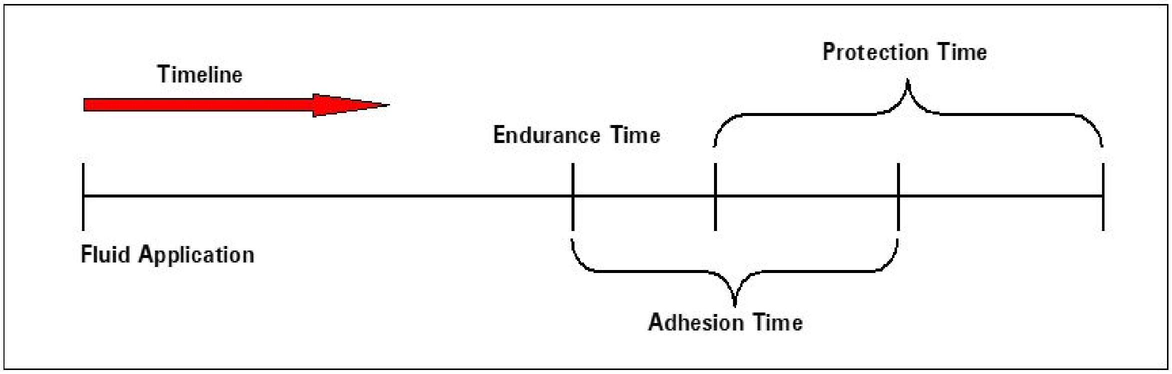


Figure 4.38: Graphical Representation of Protection Time with Respect to Endurance Time and Adhesion Time

The first indication on the timeline represents the time of application of the fluid. Following the application, the fluid starts to dilute under precipitation and, after a certain period of time, the failure call is made. The time elapsed between the time of fluid application and the failure call corresponds to the endurance time of the fluid. Fluid endurance times documented in testing are subsequently converted to holdover times for the HOT tables.

As shown earlier in this section, exposure to precipitation beyond the endurance time generates more water for fluid dilution and can lead to adhesion of contaminated fluid to the supporting surface. This occurs mostly under freezing precipitation conditions, irrespective of fluid type. Under snow conditions, the behaviour of Type I and Type II/IV fluids is different, the latter presenting adhesion only when applied at a temperature above the OAT. The mechanisms driving the contaminated fluid adhesion to the test surface under precipitation were explained earlier in this section. The severity of adherence is in strong correlation with the dilution of the fluid, weather condition and rate of precipitation. As a result, the time at which the adhesion was documented covered a wide range of values, as shown in Figure 4.38.

As illustrated in Figure 4.38, the protection time is also represented by a range of values partially superimposed over the adhesion time range. This identifies two scenarios: protection time occurring before adhesion time, and protection time following adhesion.

4.4.1 Protection Time Before Adhesion Time

The Canadian Air Regulations (CARs) 602.11 specifies:

> *(1) In this section, "critical surfaces" means the wings, control surfaces, rotors, propellers, horizontal stabilizers, vertical stabilizers or any other stabilizing*

> *surface of an aircraft and, in the case of an aircraft that has rear-mounted engines, includes the upper surface of its fuselage.*
>
> *(2) No person shall conduct or attempt to conduct a take-off in an aircraft that has frost, ice or snow adhering to any of its critical surfaces.*

As per the TC definition, the protection time is defined as the period that an anti-icing treatment protects aerodynamically critical surfaces from the adhesion of contamination. In conjunction with the CAR 602.11 requirements, this definition places the protection time prior to adhesion time on the timescale.

In some cases, especially when using Type II/IV fluids under snow precipitation, adhesion did not occur even though the fluid was exposed to precipitation far beyond failure time. The protection time of the fluid is ended if the fluid does not comply with the aerodynamic acceptance requirements outlined in AMS1428 at any time following fluid failure. In these cases, protection time could be exhausted before adhesion occurs.

4.4.2 Protection Time Following Adhesion Time

At industry meetings, test data presented by the NRC has suggested that a limited level of adhesion of freezing rain/freezing drizzle contamination to the leading edge of the wing may improve its aerodynamic performance. This theory applies only if the layer of ice is smooth and minimal, just enough to cover the small indentations and nicks present on the leading edge.

A different illustration of protection time following adhesion time was documented in TC report TP 14147E, *Aircraft Takeoff Test Program for Winter 2002-03: Testing to Evaluate the Aerodynamic Penalties of Clean or Partially Expended De/Anti-Icing Fluid* (9).

The long-term goal of the research program is to determine the effect of a limited level of unabsorbed winter precipitation present in or on an anti-icing fluid on the maintenance of a safe takeoff condition. In other words, the wing is to be maintained aerodynamically “clean” even though it may not be visually clean. To satisfy the program objective, takeoff tests were performed with an NRC Falcon 20 research aircraft at the Ottawa Airport. The test wings were treated with ethylene and propylene glycol-based Type IV fluids. Simulated light freezing rain was then sprayed over the test fluid until specified levels of contamination were achieved.

It was found that the fluid present on the wings was nearly completely eliminated during the takeoff. In general, a small film of fluid remained on certain wing surfaces, most notably on the trailing edge of the aircraft.

In two tests with a partially contaminated ethylene glycol-based fluid, the small areas of ice present on the leading edge prior to takeoff were adhering to the wing surface. In one test at the time of landing, 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, a small area of ice remained on the wing.

4.5 Adhesion Testing on Bare Surface

As presented earlier in this section, heating the fluid seems to increase the likelihood of fluid adhesion. At high temperatures, melting of snowflakes is facilitated, generating liquid water leading to fluid dilution. In the examples shown in Section 4, heat was introduced to the system through the fluid. It is believed that the same effect could be obtained if heat is provided by the supporting surface, simulating a “warm-soaked wing”. This condition can take place in real field operations if the fuel is supplied warm from underground tanks to the aircraft. In this case, the fuel will transfer some heat to the wing, raising its temperature. This condition can be a concern when a preventative anti-icing treatment of the surface is not carried out (bare wing).

At very mild ambient air temperatures (typically above -2°C) the snow could have an increased liquid water content (wet snow), stimulating adhesion to the surface. Dry snow usually occurs at temperatures below -2°C, and has a lower density than wet snow. Its grains have little tendency to adhere to each other or to the supporting surface when pressed together. In this condition, the dry snow can be seen to blow off a bare wing or test surface. Still, adhesion to the surface could occur in the case of dry snow if the snowflakes land on a slightly heated surface. Partial melting of snowflakes takes place, and as the surface cools down toward the ambient temperature, freezing occurs.

Under freezing precipitation conditions, adhesion of contamination to the bare test surface occurs almost instantaneously. The contamination might have a rough aspect, impairing the aerodynamic performance of the aircraft.

To address these concerns, at the end of the 2002-03 testing season, several recommendations were made for completion of this research and specifically included adhesion testing using heated and unheated standard endurance time plates. In 2003-04 two bare surface tests were conducted.

Test No. 63, Precipitation Rate 30.2 g/dm²/h, OAT -7.6°C, Natural Snow

To simulate the “warm-soaked wing” effect, the test was conducted with a box heated above ambient temperature (Figure 4.39). At the beginning of the test the surface temperature was just above 10°C. The snow landed on a slightly heated surface, and, as a result, partial melting of snowflakes occurred. Subjected to an ambient temperature of -7.5°C, the box started to cool down rapidly and reached 0°C in about four minutes. As the surface cooled down toward ambient temperature, freezing occurred. The release of latent heat of freezing caused the surface to warm and thus extended the interval to freezing. At about 7 minutes into the test the surface temperature reached -2.4°C, at which time the adhesion of precipitation to the surface was documented. The adhesion had the aspect of ice patches evenly distributed across the surface, with an increased roughness in the upper section of the plate.

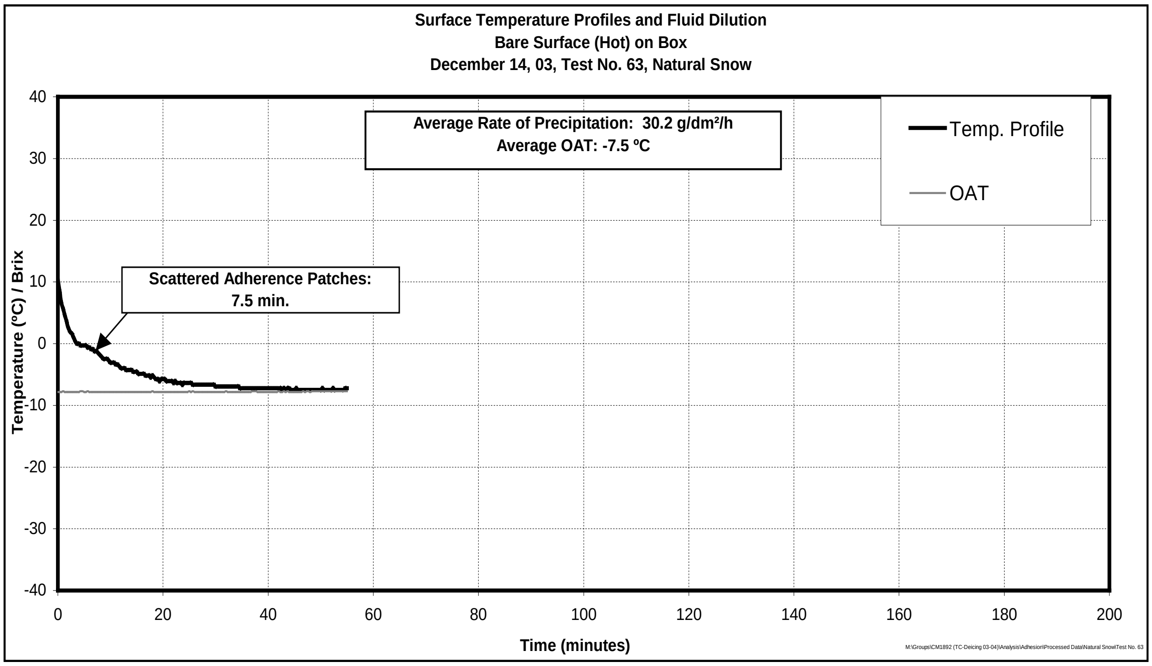


Figure 4.39: Test No. 63, Natural Snow

Test No. 64, Precipitation Rate 36 g/dm²/h, OAT -7.5°C, Natural Snow

The test illustrated in Figure 4.40 is similar to test No. 63, with the only difference being that the test surface was at ambient temperature at the beginning of the test. The test was conducted under identical weather conditions the same day. The snow landed on the test surface and bounced off the plate without changing its temperature. As presented in Figure 4.40, the surface temperature was constant throughout the test, as the snow grains had no tendency to adhere to the plate. The test was stopped after one hour and no accumulation of snow was documented.

4.6 Roughness of Adhesion Areas

The adhesion of contamination to the wing's leading edge represents a concern, particularly when it has a coarse aspect (increased roughness). The wing's leading edge is highly sensitive to surface roughness because roughness increases the coefficient of surface friction (drag) and could cause a premature stall or result in loss of control and prevent the crew from safely operating the aircraft.

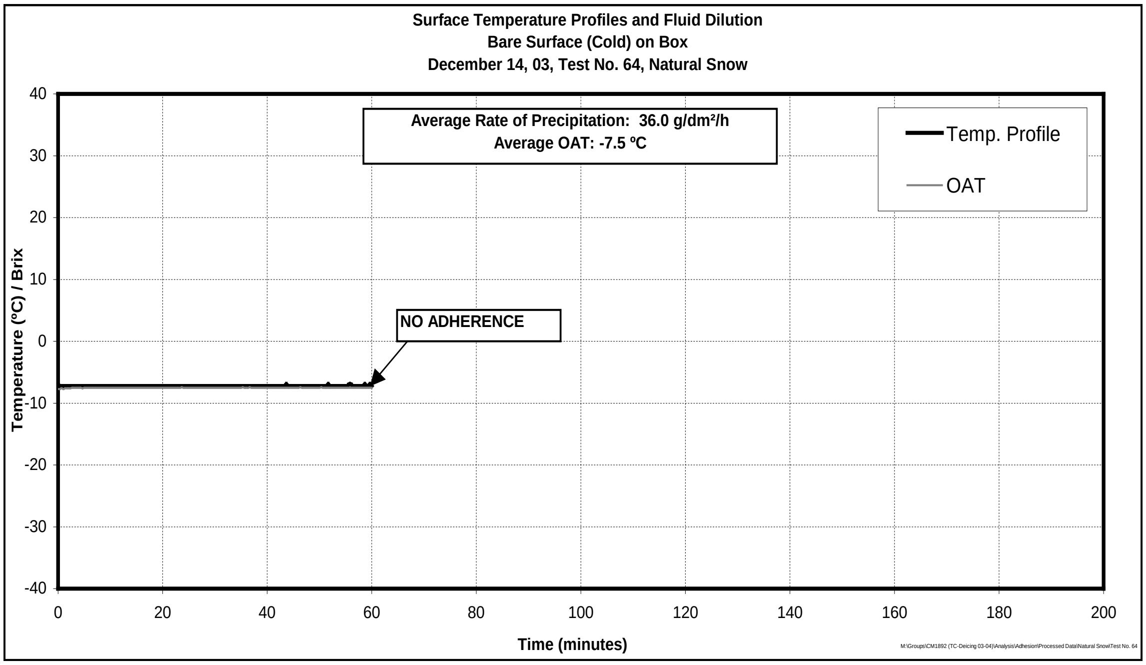


Figure 4.40: Test No. 64, Natural Snow

Although roughness was not assessed during the conduct of the fluid adhesion tests, a few observations can be made for each weather condition. As stated in Section 4.1.5, certain characteristics of frost cause it to be of genuine concern: it is always adhered to the aircraft surface, and it is always rough. Natural snow tests were also characterized by a coarse aspect of the adhered area. The tests conducted under freezing precipitation conditions produced a smoother and even surface.

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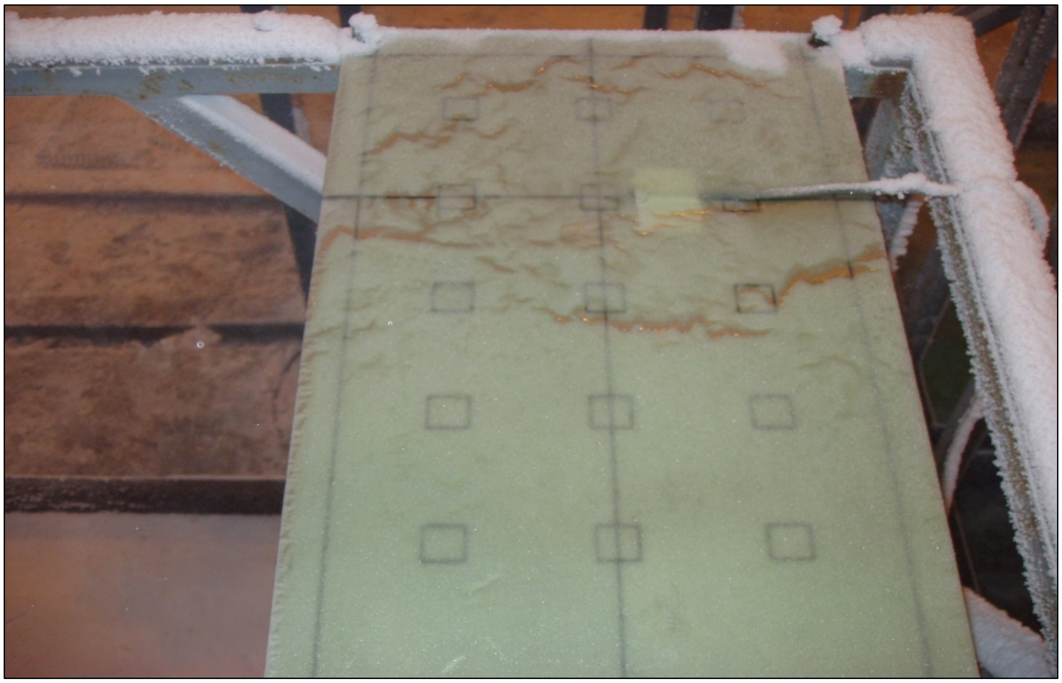
Photo 4.1: Artificial Snow Testing – Appearance of Type I Fluid After Application

Photo 4.2: Artificial Snow Testing – Adhesion Failure

Photo 4.3: Artificial Snow Testing – Snow Build-Up on the Surface of the Plate

Photo 4.4: Type IV Fluid Application Under Freezing Precipitation at NRC



5. CONCLUSIONS

The purpose of these tests was to answer questions commonly posed during discussions on the nature of fluid adhesion, and to document the occurrence of contaminated fluid bonding to test surfaces under each winter weather condition. The study has documented the circumstances in which fluid adhesion occurs and has determined the extent of the safety buffer between the failure time and the onset of adhesion. Data from the various tests have enabled the examination of fluid adhesion for Type I, II, III and IV fluids under each winter weather condition.

5.1 Documentation of the Degree of Adherence

To satisfy the objectives, laboratory tests under freezing precipitation conditions were conducted at the NRC climatic chamber in Ottawa, and natural snow and frost tests were conducted at the APS test site at Montréal–Trudeau Airport. Tests were also performed under artificial snow using the NCAR snowmaking system in a cold chamber operated by PMG in Blainville, Quebec. For all the aforementioned test sessions, various fluids were applied to test surfaces and examined at specific stages from time of application until after complete plate failure. The physical properties of the fluids were documented as they progressed toward and beyond standard failure.

Sixteen runs including forty-four tests were conducted in natural snow, frost and freezing drizzle on several occasions from January 7, 2003 to February 4, 2004. In the PMG laboratory, eleven artificial snow tests were performed at different temperatures and precipitation rates over a two-day period. Forty-nine indoor plate and box fluid adhesion tests were conducted in April 2003 and April 2004 at the NRC.

These tests were conducted using samples of Type I, Type II, Type III and Type IV fluids under a wide range of temperatures, precipitation rates, precipitation type, and wind conditions. Each test documented whether the fluid adhered to the test surface.

5.2 Type I Fluids

5.2.1 Natural and Artificial Snow

Based on the Type I testing session under natural and artificial snow conditions, the following conclusions can be drawn:

a) There are two circumstances in which the occurrence of adherence was documented: fluid dilution to water prior to surface temperature dropping below 0°C, and fluid dilution to water after surface temperature reached subzero temperatures. If the fluid does not dilute to very low concentrations of glycol – close to a freeze point of 0°C – the contamination will not freeze solid;

b) Fluid failures where the fluid has diluted to water prior to the plate temperature dropping below 0ºC result in adherence. At mild temperatures and high precipitation rates, the fluid is more likely to dilute to water prior to the surface temperature dropping below 0ºC due to its low glycol concentration. When freezing occurs, the resulting ice adheres to the underlying surface;

c) Typically, Type I adhesion tests conducted under moderate or heavy snow precipitation conditions exhibited adherence regardless of ambient temperature initial fluid temperature or test surface type;

d) Higher glycol concentrations (at colder temperatures) applied heated on empty aluminum box surfaces generate longer endurance times and extended safety buffers;

e) Under light and very light snow conditions, the precipitation rate did not substantially dilute the fluid even after a large amount of time. Under these conditions, the fluid does not usually dilute to a level that would stimulate bonding to the test surface, irrespective of the surface type or initial fluid temperature. However, if the fluid is exposed to precipitation far beyond complete plate failure, the failed fluid might eventually adhere to the supporting surface, providing its freezing point reaches 0°C;

f) When the test surface was exposed far beyond the time when failure was called, at times the final fluid concentration did not dilute beyond a certain Brix value. The failed fluid had the aspect and consistency of slush. In these cases, the visually failed fluid did not adhere to the surface; and

g) The effect of glycol type seemed insignificant under light and very light snow precipitation conditions as adhesion tests yielded the same results for ethylene and propylene glycol-based Type I fluids.

5.2.2 Simulated Freezing Precipitation

Based on the Type I adhesion testing under simulated freezing precipitation conditions, the following conclusions can be drawn:

a) Except for freezing fog at -25°C, adherence occurred under all freezing precipitation conditions tested regardless of the test surface, precipitation rate or test temperature. It was generally noted that Type I fluids adhere shortly after failure, resulting in a very thin film strongly bonded to the surface. It was also observed that the release of latent heat of freezing under simulated freezing rain at an ambient temperature of -3°C caused the surface to warm and thus extended the interval to adherence; and

b) Under freezing precipitation, the glycol type does not seem to have an influence, as adhesion tests yielded the same results for ethylene and propylene glycol-based Type I fluids.

5.2.3 Active Frost

The testing using Type I fluids showed that frost always adheres to the test surface, and it is always rough in surface texture.

5.3 Type II/IV Fluids

5.3.1 Natural and Artificial Snow

The Type II/IV adhesion testing conducted under natural and artificial snow conditions over two years shows that, typically, adhesion failure does not occur. This finding is independent of fluid type, glycol concentration, ambient test temperature and rate of precipitation. The combination of fluid and snow resulted in a slush that could not absorb more precipitation, although it was sufficiently liquid to not adhere to the underlying plate surface. Also, the type of glycol does not seem to have any influence on the occurrence of adherence.

However, if the fluid is exposed to precipitation far beyond complete plate failure, the failed fluid might eventually adhere to the surface providing its freezing point reached 0°C.

If the Type II/IV fluid is applied heated, melting of snowflakes is facilitated, generating more water for fluid dilution. This can lead to early dilution of the fluid and, subsequently, to fluid adhesion.

5.3.2 Simulated Freezing Precipitation

Based on the Type II, III and IV adhesion testing under simulated freezing precipitation conditions, the following conclusions can be drawn:

a) Except for freezing fog at -25°C, the occurrence of adherence was documented under all freezing precipitation conditions tested, regardless of the test surface type, fluid type, ambient test temperature or rate of precipitation. Typically, adhesion occurred shortly after standard plate failure.

b) Using the data provided by the 2002-03 testing season only, the effect of glycol type seems insignificant, since adhesion tests yielded the same results for ethylene and propylene glycol-based anti-icing fluids.

Testing conducted during the 1998-99 winter season exhibited different results. As presented in TC report TP 13484E, *Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation: 1998-99* (7), only Type IV ethylene glycol-based fluids demonstrated failure adhesion. The Type IV propylene-based fluid experienced no adhesion at ambient temperatures of -10ºC, even when complete plate failure was identified. A possible explanation for this different behaviour could reside in the nature of the fluids tested in 2002-03. All of the propylene-based Type II/IV adhesion tests were conducted using only two fluids, Safewing MP II 2025 ECO and Safewing MP IV 2030 ECO. Subsequently, it was acknowledged that this fluid is not temperature dependent, and is not representative of Type IV propylene-based fluids.

All tests conducted in 2003-04 with Type II, III and IV propylene fluids other than Safewing MP II 2025 ECO and Safewing MP IV 2030 ECO, showed adhesion. It was also observed that the Type IV propylene-based fluid formed a crust of solidified contamination at the air-fluid interface, while still preserving a very thin film of fluid underneath. So, in accordance with the standard method of documenting adhesion, the test presented adhesion. However, when the solid crust was subjected to shear forces (i.e. by using a scraper), the contamination came off relatively easy and all at once.

c) Droplet impact can be thought of as a means of mechanical mixing. The mixing efficiency will be greater for the larger (more massive) droplets characteristic of rain. The most severe instances of adhesion occurred at -10°C under light freezing rain and freezing fog, followed by freezing drizzle at the same temperature, which afforded a slightly less severe level of adhesion.

5.4 Adhesion Testing on Bare Surface

Heating the fluid seems to increase the likelihood of fluid adhesion. At high temperatures, melting of snowflakes is facilitated, generating an accelerated fluid dilution. The same effect can be obtained if heat is introduced by the supporting surface, simulating a “warm-soaked wing”. Testing has shown that adhesion to the surface can be obtained if the snowflakes land on a slightly heated surface. Melting of the snowflakes may take place, and as the surface cools down toward ambient temperature, freezing occurs. The contamination might have a rough aspect.

Under freezing precipitation conditions, the adhesion of contamination to the bare test surface occurs almost instantaneously. The contamination might have a rough aspect, impairing the proper aerodynamic performance of the aircraft.

6. RECOMMENDATIONS

Based on the tests conducted, it is recommended that the findings of this report be disseminated to the industry.

Under freezing precipitation conditions, it is recommended that the values in the HOT guideline tables should be complied with rigorously, as the safety margin between the failure call and onset of adhesion is minimal.

It is also recommended that the following precautions be taken during operations:

a) Avoid, if possible, the use of Type I fluid for anti-icing during moderate and heavy snow conditions; and

b) If Type II/IV fluid is applied heated more caution should be taken. The operator should be aware of the increased potential for adhesion in such cases.

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APPENDIX A

TRANSPORTATION DEVELOPMENT CENTRE WORK STATEMENT EXCERPT – AIRCRAFT & ANTI-ICING FLUID WINTER TESTING 2003-05

TRANSPORTATION DEVELOPMENT CENTRE
WORK STATEMENT EXCERPT –
AIRCRAFT & ANTI-ICING FLUID WINTER TESTING
2003-05

5.8 Adhesion of Contaminated Fluids to Surfaces

a) Prepare an action plan and test procedures for conduct of adhesion testing needed to elaborate on results documented in previous tests;

b) Conduct adhesion tests;

- Type II/IV fluid adhesion testing using heated fluids;
- Tests on bare surfaces, using heated and unheated standard ET plates in attempt to simulate a "warm soaked wing";
- Adhesion testing under freezing drizzle precipitation using different Type IV propylene-based fluids (i.e. Kilfrost ABC-S, Octagon Max-Flight);
- Type II/IV fluid adhesion testing at very mild temperatures (around 0°C) to investigate the effect of wet snow; and
- Fluid adhesion testing under frost conditions.

c) Analyse the data collected; and

d) Report the findings and prepare a report and presentation.

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APPENDIX B

PROCEDURES:

- **EXPERIMENTAL PROGRAM – COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS – WINTER 2002-03**
- **EXPERIMENTAL PROGRAM – ADHESION OF AIRCRAFT DE/ANTI-ICING FLUIDS ON ALUMINUM SURFACES – WINTER 2003-04**

EXPERIMENTAL PROGRAM:
COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS – WINTER 2002-03

CM1747.001

EXPERIMENTAL PROGRAM
COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS

Winter 2002 - 2003

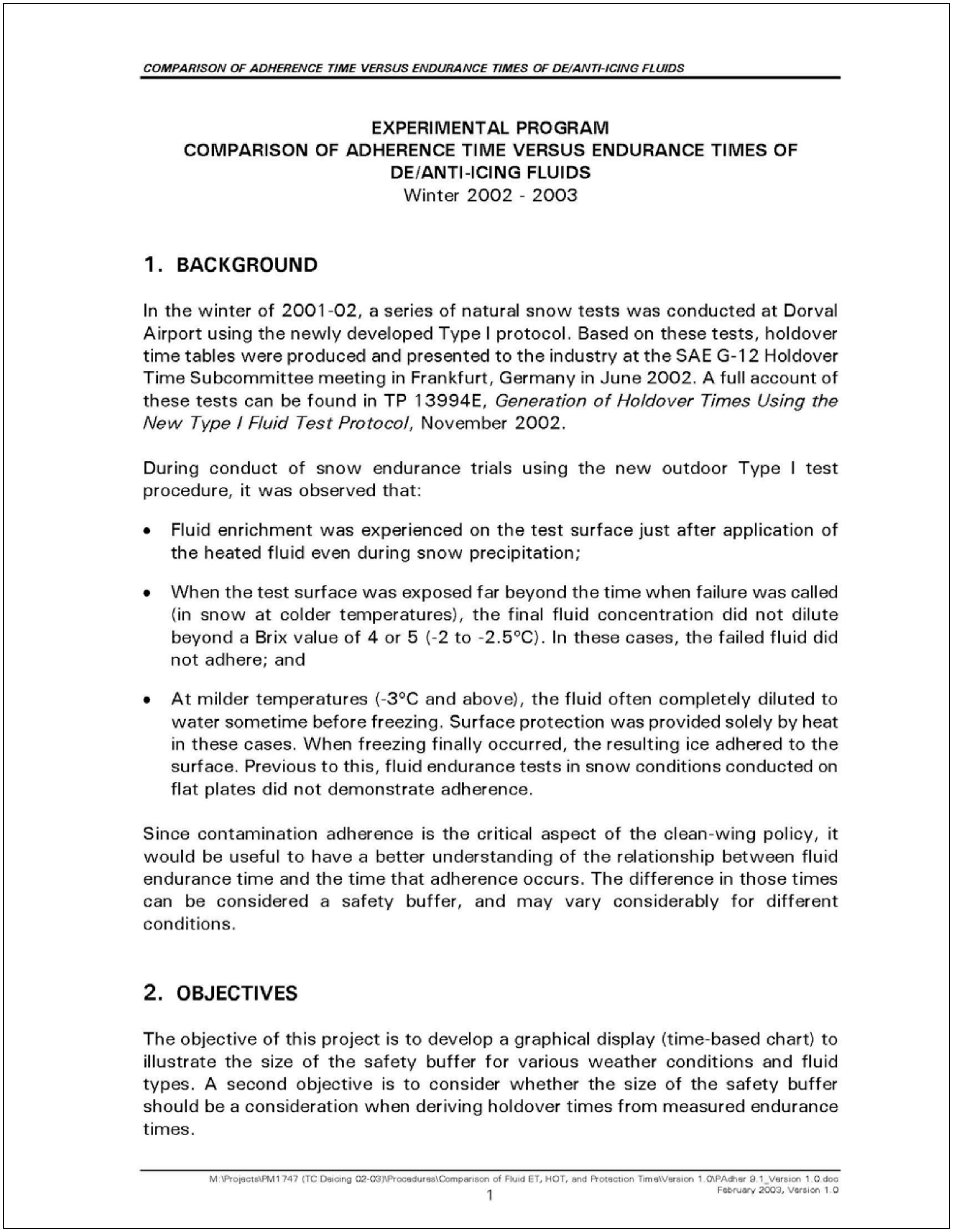
Prepared for

Transportation Development Centre
Transport Canada

Prepared by: Nicoara Moc

Reviewed by: John D'Avirro

February 10, 2003
Version 1.0



EXPERIMENTAL PROGRAM
COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS
Winter 2002 - 2003

1. BACKGROUND

In the winter of 2001-02, a series of natural snow tests was conducted at Dorval Airport using the newly developed Type I protocol. Based on these tests, holdover time tables were produced and presented to the industry at the SAE G-12 Holdover Time Subcommittee meeting in Frankfurt, Germany in June 2002. A full account of these tests can be found in TP 13994E, *Generation of Holdover Times Using the New Type I Fluid Test Protocol*, November 2002.

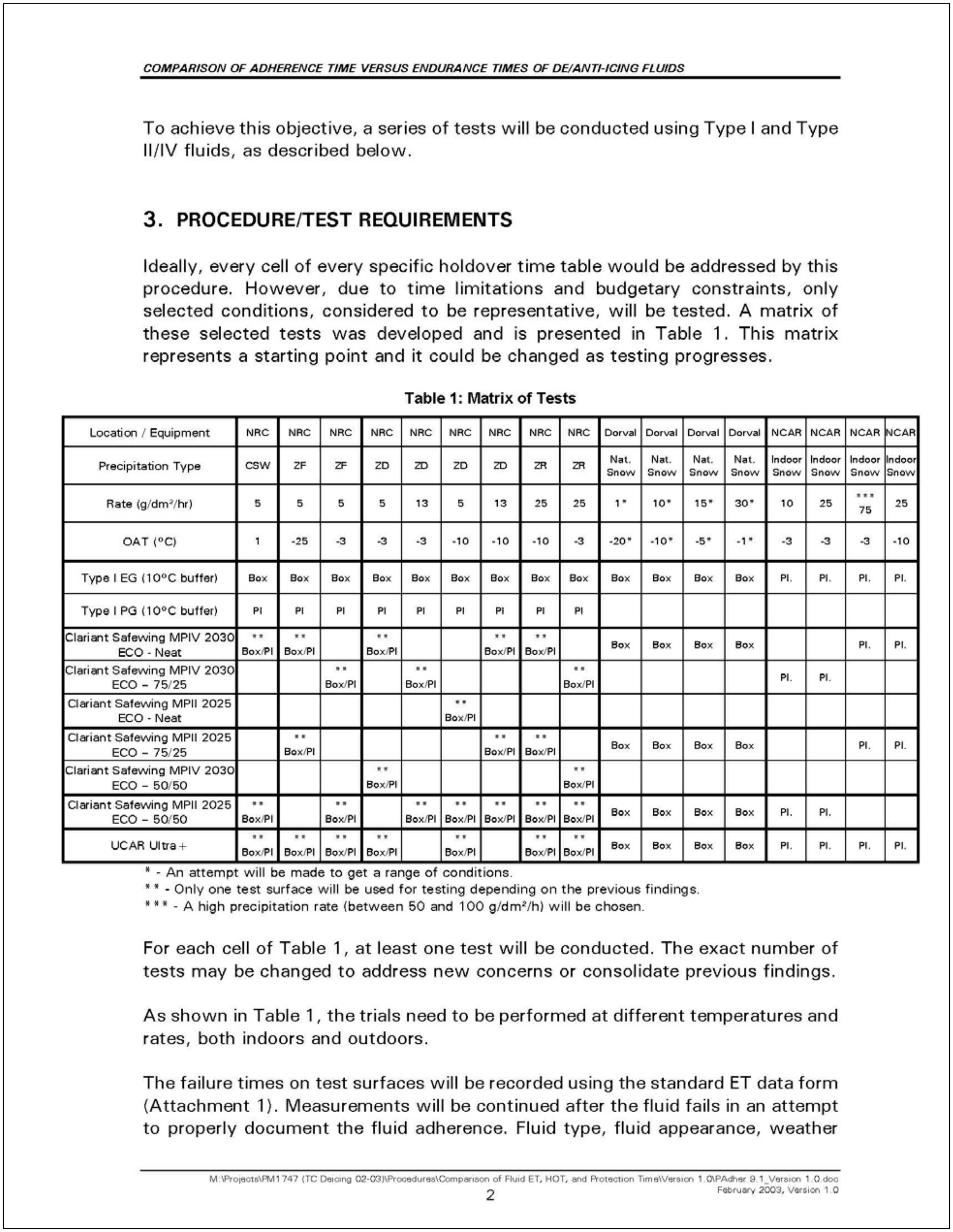
During conduct of snow endurance trials using the new outdoor Type I test procedure, it was observed that:

- Fluid enrichment was experienced on the test surface just after application of the heated fluid even during snow precipitation;
- When the test surface was exposed far beyond the time when failure was called (in snow at colder temperatures), the final fluid concentration did not dilute beyond a Brix value of 4 or 5 (-2 to -2.5°C). In these cases, the failed fluid did not adhere; and
- At milder temperatures (-3°C and above), the fluid often completely diluted to water sometime before freezing. Surface protection was provided solely by heat in these cases. When freezing finally occurred, the resulting ice adhered to the surface. Previous to this, fluid endurance tests in snow conditions conducted on flat plates did not demonstrate adherence.

Since contamination adherence is the critical aspect of the clean-wing policy, it would be useful to have a better understanding of the relationship between fluid endurance time and the time that adherence occurs. The difference in those times can be considered a safety buffer, and may vary considerably for different conditions.

2. OBJECTIVES

The objective of this project is to develop a graphical display (time-based chart) to illustrate the size of the safety buffer for various weather conditions and fluid types. A second objective is to consider whether the size of the safety buffer should be a consideration when deriving holdover times from measured endurance times.



To achieve this objective, a series of tests will be conducted using Type I and Type II/IV fluids, as described below.

3. PROCEDURE/TEST REQUIREMENTS

Ideally, every cell of every specific holdover time table would be addressed by this procedure. However, due to time limitations and budgetary constraints, only selected conditions, considered to be representative, will be tested. A matrix of these selected tests was developed and is presented in Table 1. This matrix represents a starting point and it could be changed as testing progresses.

Table 1: Matrix of Tests

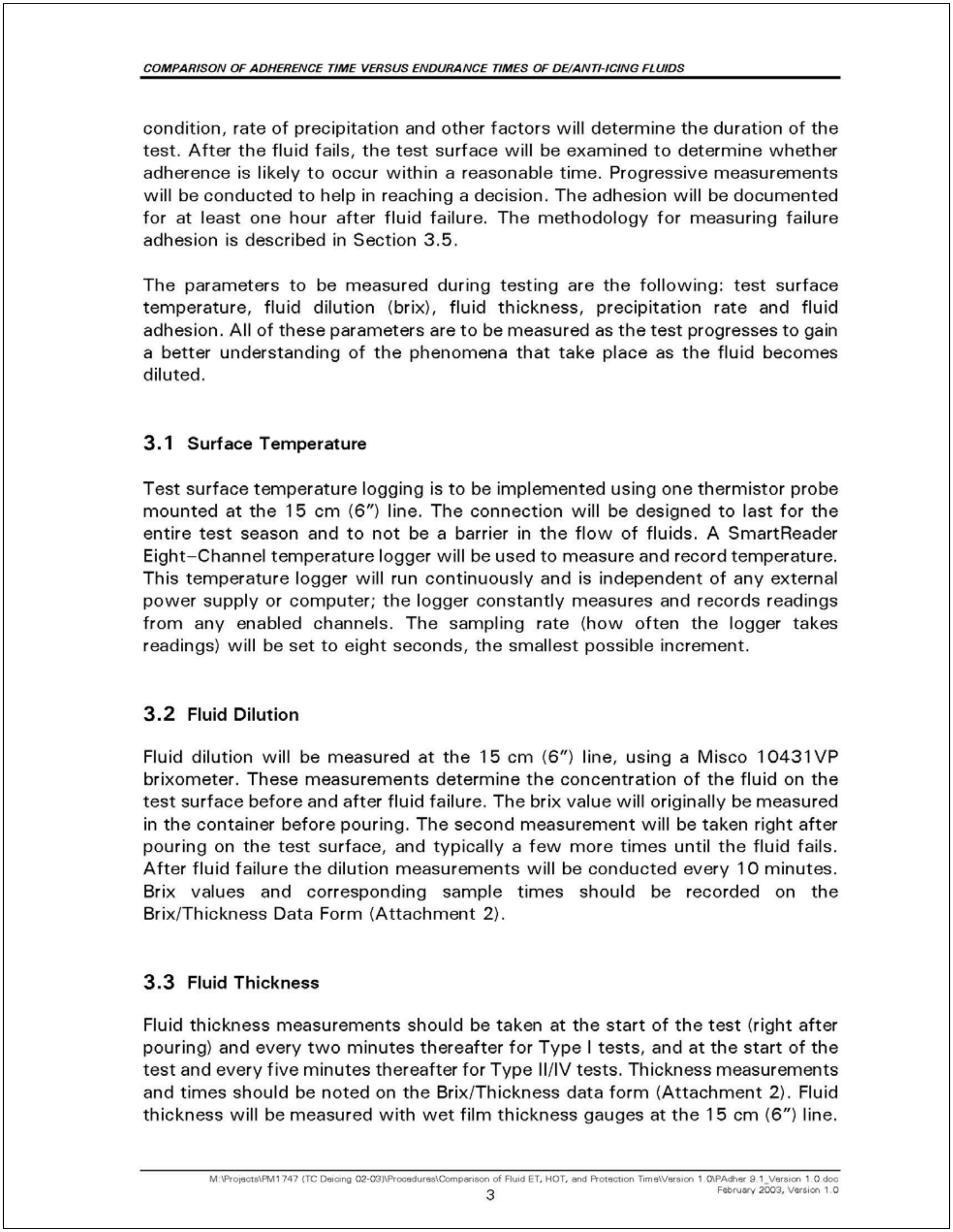
Location / Equipment	NRC	NRC	NRC	NRC	NRC	NRC	NRC	NRC	NRC	Dorval	Dorval	Dorval	Dorval	NCAR	NCAR	NCAR	NCAR
Precipitation Type	CSW	ZF	ZF	ZD	ZD	ZD	ZD	ZR	ZR	Nat. Snow	Nat. Snow	Nat. Snow	Nat. Snow	Indoor Snow	Indoor Snow	Indoor Snow	Indoor Snow
Rate (g/dm²/hr)	5	5	5	5	13	5	13	25	25	1*	10*	15*	30*	10	25	*** 75	25
OAT (°C)	1	-25	-3	-3	-3	-10	-10	-10	-3	-20*	-10*	-5*	-1*	-3	-3	-3	-10
Type I EG (10°C buffer)	Box	Box	Box	Box	Box	Box	Box	Box	Box	Box	Box	Box	Box	Pl.	Pl.	Pl.	Pl.
Type I PG (10°C buffer)	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl								
Clariant Safewing MPIV 2030 ECO - Neat	** Box/Pl	** Box/Pl		** Box/Pl			** Box/Pl	** Box/Pl		Box	Box	Box	Box			Pl.	Pl.
Clariant Safewing MPIV 2030 ECO – 75/25			** Box/Pl		** Box/Pl				** Box/Pl					Pl.	Pl.		
Clariant Safewing MPII 2025 ECO - Neat						** Box/Pl											
Clariant Safewing MPII 2025 ECO – 75/25		** Box/Pl					** Box/Pl	** Box/Pl		Box	Box	Box	Box			Pl.	Pl.
Clariant Safewing MPIV 2030 ECO – 50/50				** Box/Pl					** Box/Pl								
Clariant Safewing MPII 2025 ECO – 50/50	** Box/Pl		** Box/Pl		** Box/Pl	** Box/Pl	** Box/Pl	** Box/Pl	** Box/Pl	Box	Box	Box	Box	Pl.	Pl.		
UCAR Ultra+	** Box/Pl	** Box/Pl	** Box/Pl	** Box/Pl		** Box/Pl		** Box/Pl	** Box/Pl	Box	Box	Box	Box	Pl.	Pl.	Pl.	Pl.

* - An attempt will be made to get a range of conditions.
** - Only one test surface will be used for testing depending on the previous findings.
*** - A high precipitation rate (between 50 and 100 g/dm²/h) will be chosen.

For each cell of Table 1, at least one test will be conducted. The exact number of tests may be changed to address new concerns or consolidate previous findings.

As shown in Table 1, the trials need to be performed at different temperatures and rates, both indoors and outdoors.

The failure times on test surfaces will be recorded using the standard ET data form (Attachment 1). Measurements will be continued after the fluid fails in an attempt to properly document the fluid adherence. Fluid type, fluid appearance, weather



condition, rate of precipitation and other factors will determine the duration of the test. After the fluid fails, the test surface will be examined to determine whether adherence is likely to occur within a reasonable time. Progressive measurements will be conducted to help in reaching a decision. The adhesion will be documented for at least one hour after fluid failure. The methodology for measuring failure adhesion is described in Section 3.5.

The parameters to be measured during testing are the following: test surface temperature, fluid dilution (brix), fluid thickness, precipitation rate and fluid adhesion. All of these parameters are to be measured as the test progresses to gain a better understanding of the phenomena that take place as the fluid becomes diluted.

3.1 Surface Temperature

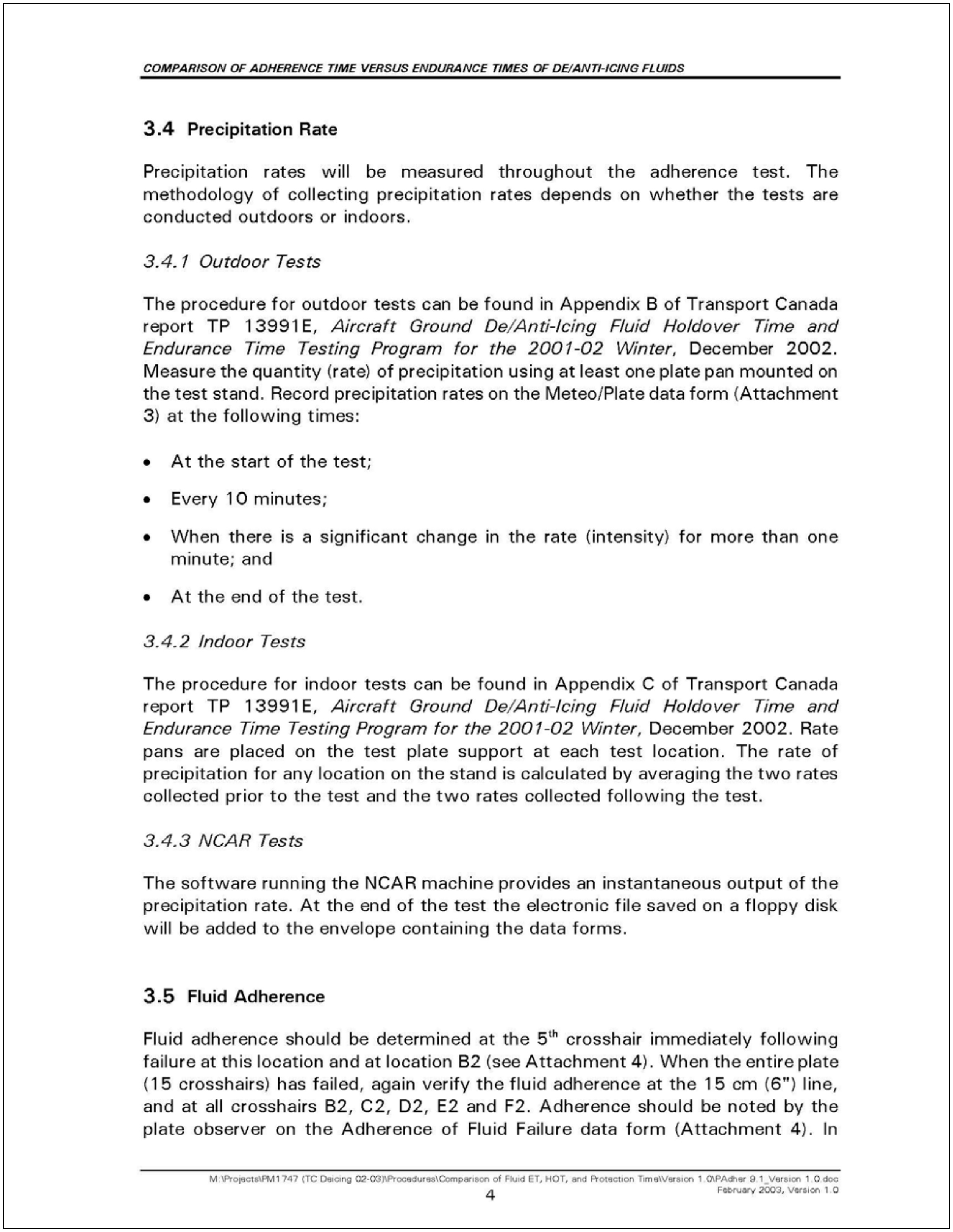
Test surface temperature logging is to be implemented using one thermistor probe mounted at the 15 cm (6″) line. The connection will be designed to last for the entire test season and to not be a barrier in the flow of fluids. A SmartReader Eight–Channel temperature logger will be used to measure and record temperature. This temperature logger will run continuously and is independent of any external power supply or computer; the logger constantly measures and records readings from any enabled channels. The sampling rate (how often the logger takes readings) will be set to eight seconds, the smallest possible increment.

3.2 Fluid Dilution

Fluid dilution will be measured at the 15 cm (6″) line, using a Misco 10431VP brixometer. These measurements determine the concentration of the fluid on the test surface before and after fluid failure. The brix value will originally be measured in the container before pouring. The second measurement will be taken right after pouring on the test surface, and typically a few more times until the fluid fails. After fluid failure the dilution measurements will be conducted every 10 minutes. Brix values and corresponding sample times should be recorded on the Brix/Thickness Data Form (Attachment 2).

3.3 Fluid Thickness

Fluid thickness measurements should be taken at the start of the test (right after pouring) and every two minutes thereafter for Type I tests, and at the start of the test and every five minutes thereafter for Type II/IV tests. Thickness measurements and times should be noted on the Brix/Thickness data form (Attachment 2). Fluid thickness will be measured with wet film thickness gauges at the 15 cm (6″) line.



3.4 Precipitation Rate

Precipitation rates will be measured throughout the adherence test. The methodology of collecting precipitation rates depends on whether the tests are conducted outdoors or indoors.

3.4.1 Outdoor Tests

The procedure for outdoor tests can be found in Appendix B of Transport Canada report TP 13991E, *Aircraft Ground De/Anti-Icing Fluid Holdover Time and Endurance Time Testing Program for the 2001-02 Winter*, December 2002. Measure the quantity (rate) of precipitation using at least one plate pan mounted on the test stand. Record precipitation rates on the Meteo/Plate data form (Attachment 3) at the following times:

- At the start of the test;
- Every 10 minutes;
- When there is a significant change in the rate (intensity) for more than one minute; and
- At the end of the test.

3.4.2 Indoor Tests

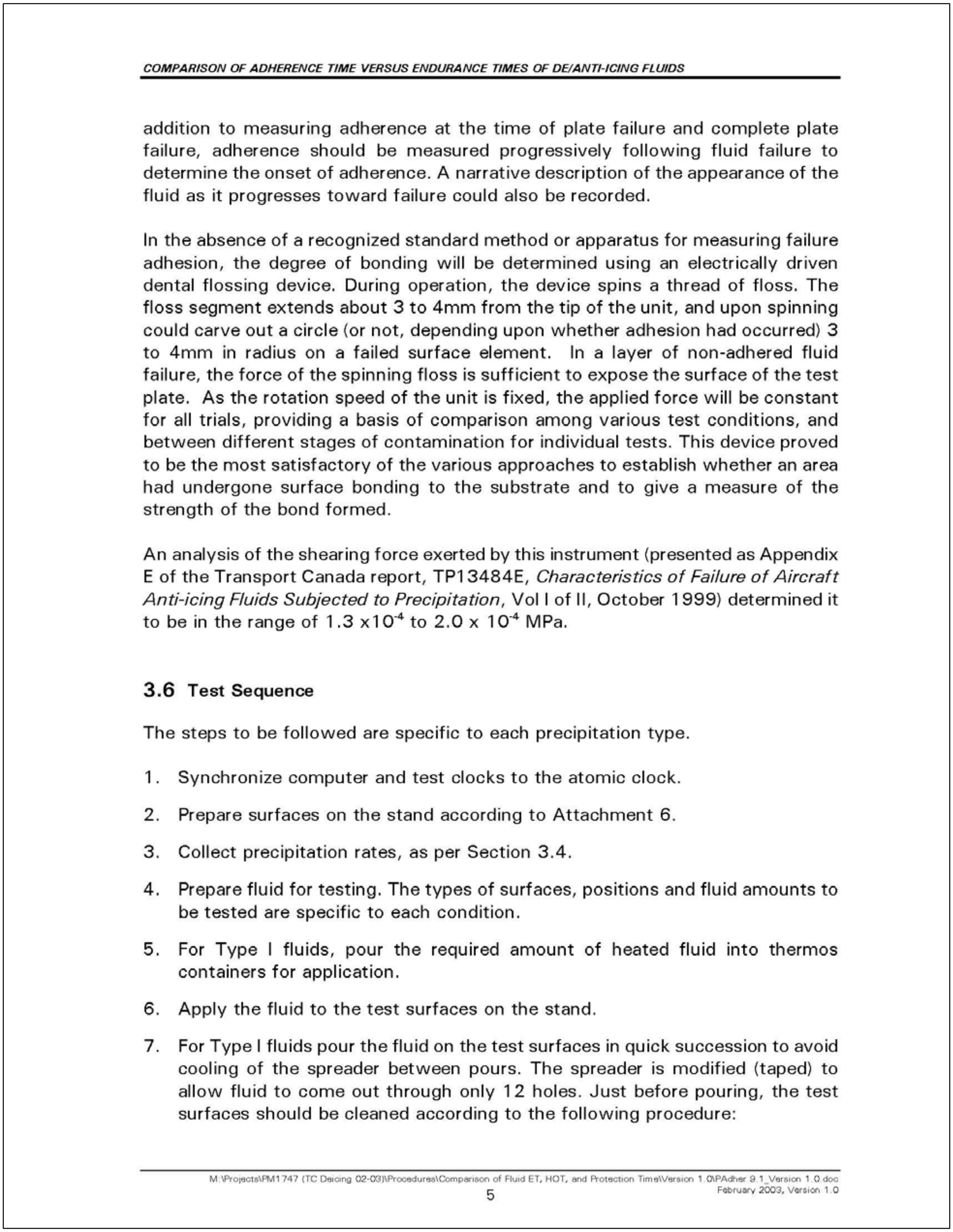
The procedure for indoor tests can be found in Appendix C of Transport Canada report TP 13991E, *Aircraft Ground De/Anti-Icing Fluid Holdover Time and Endurance Time Testing Program for the 2001-02 Winter*, December 2002. Rate pans are placed on the test plate support at each test location. The rate of precipitation for any location on the stand is calculated by averaging the two rates collected prior to the test and the two rates collected following the test.

3.4.3 NCAR Tests

The software running the NCAR machine provides an instantaneous output of the precipitation rate. At the end of the test the electronic file saved on a floppy disk will be added to the envelope containing the data forms.

3.5 Fluid Adherence

Fluid adherence should be determined at the 5th crosshair immediately following failure at this location and at location B2 (see Attachment 4). When the entire plate (15 crosshairs) has failed, again verify the fluid adherence at the 15 cm (6") line, and at all crosshairs B2, C2, D2, E2 and F2. Adherence should be noted by the plate observer on the Adherence of Fluid Failure data form (Attachment 4). In



addition to measuring adherence at the time of plate failure and complete plate failure, adherence should be measured progressively following fluid failure to determine the onset of adherence. A narrative description of the appearance of the fluid as it progresses toward failure could also be recorded.

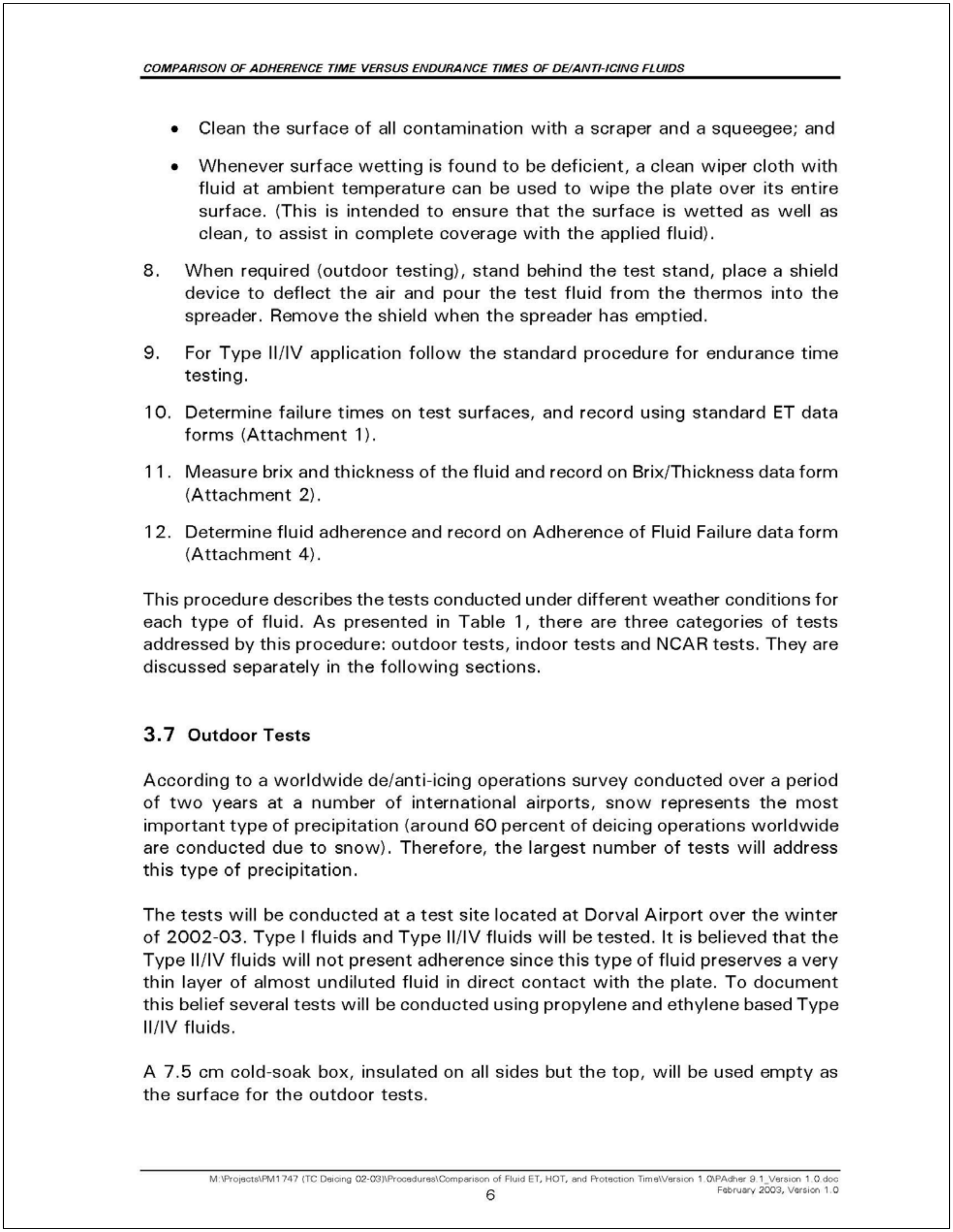
In the absence of a recognized standard method or apparatus for measuring failure adhesion, the degree of bonding will be determined using an electrically driven dental flossing device. During operation, the device spins a thread of floss. The floss segment extends about 3 to 4mm from the tip of the unit, and upon spinning could carve out a circle (or not, depending upon whether adhesion had occurred) 3 to 4mm in radius on a failed surface element. In a layer of non-adhered fluid failure, the force of the spinning floss is sufficient to expose the surface of the test plate. As the rotation speed of the unit is fixed, the applied force will be constant for all trials, providing a basis of comparison among various test conditions, and between different stages of contamination for individual tests. This device proved to be the most satisfactory of the various approaches to establish whether an area had undergone surface bonding to the substrate and to give a measure of the strength of the bond formed.

An analysis of the shearing force exerted by this instrument (presented as Appendix E of the Transport Canada report, TP13484E, *Characteristics of Failure of Aircraft Anti-icing Fluids Subjected to Precipitation*, Vol I of II, October 1999) determined it to be in the range of 1.3 x10^{-4} to 2.0 x 10^{-4} MPa.

3.6 Test Sequence

The steps to be followed are specific to each precipitation type.

1. Synchronize computer and test clocks to the atomic clock.
2. Prepare surfaces on the stand according to Attachment 6.
3. Collect precipitation rates, as per Section 3.4.
4. Prepare fluid for testing. The types of surfaces, positions and fluid amounts to be tested are specific to each condition.
5. For Type I fluids, pour the required amount of heated fluid into thermos containers for application.
6. Apply the fluid to the test surfaces on the stand.
7. For Type I fluids pour the fluid on the test surfaces in quick succession to avoid cooling of the spreader between pours. The spreader is modified (taped) to allow fluid to come out through only 12 holes. Just before pouring, the test surfaces should be cleaned according to the following procedure:



- Clean the surface of all contamination with a scraper and a squeegee; and
- Whenever surface wetting is found to be deficient, a clean wiper cloth with fluid at ambient temperature can be used to wipe the plate over its entire surface. (This is intended to ensure that the surface is wetted as well as clean, to assist in complete coverage with the applied fluid).

8. When required (outdoor testing), stand behind the test stand, place a shield device to deflect the air and pour the test fluid from the thermos into the spreader. Remove the shield when the spreader has emptied.
9. For Type II/IV application follow the standard procedure for endurance time testing.
10. Determine failure times on test surfaces, and record using standard ET data forms (Attachment 1).
11. Measure brix and thickness of the fluid and record on Brix/Thickness data form (Attachment 2).
12. Determine fluid adherence and record on Adherence of Fluid Failure data form (Attachment 4).

This procedure describes the tests conducted under different weather conditions for each type of fluid. As presented in Table 1, there are three categories of tests addressed by this procedure: outdoor tests, indoor tests and NCAR tests. They are discussed separately in the following sections.

3.7 Outdoor Tests

According to a worldwide de/anti-icing operations survey conducted over a period of two years at a number of international airports, snow represents the most important type of precipitation (around 60 percent of deicing operations worldwide are conducted due to snow). Therefore, the largest number of tests will address this type of precipitation.

The tests will be conducted at a test site located at Dorval Airport over the winter of 2002-03. Type I fluids and Type II/IV fluids will be tested. It is believed that the Type II/IV fluids will not present adherence since this type of fluid preserves a very thin layer of almost undiluted fluid in direct contact with the plate. To document this belief several tests will be conducted using propylene and ethylene based Type II/IV fluids.

A 7.5 cm cold-soak box, insulated on all sides but the top, will be used empty as the surface for the outdoor tests.

For the Type I fluids, the recommended fluid temperatures is 60°C with an acceptance range of + 2°C and -0°C. The recommended quantity is 0.5 L, and the fluid will be applied on the surface through a spreader. The fluid will be diluted to a freeze point 10°C below ambient temperature and also (lower priority) to a standard mix (the standard mix used in North America, which is close to a concentration of 50/50). The procedure for the test can be found in Appendix H of Transport Canada report TP 13994E, *Generation of Holdover Times Using the New Type I Fluid Test Protocol*, December 2002.

For the Type II/IV fluid tests, the recommended fluid temperature is the outside air temperature and the quantity is 1.0 L, as per standard procedures for ET tests.

For this experiment three cold-soak boxes will be placed on the stand at the same time.

In order to have a more accurate representation of the holdover time obtained in real field deicing operations, an attempt will be made to cover a wide range of outside air temperatures and precipitation rates, during several snowstorms, as presented in Table 1.

Depending on the availability of the NCAR snow generation system, several endurance/adherence tests will be conducted at high precipitation rates (>50 g/dm²/h) for both Type I and Type II/IV fluids. Tests in simulated snow conditions will be conducted at the National Research Council Canada (NRC) facility using the NCAR artificial snow generation system.

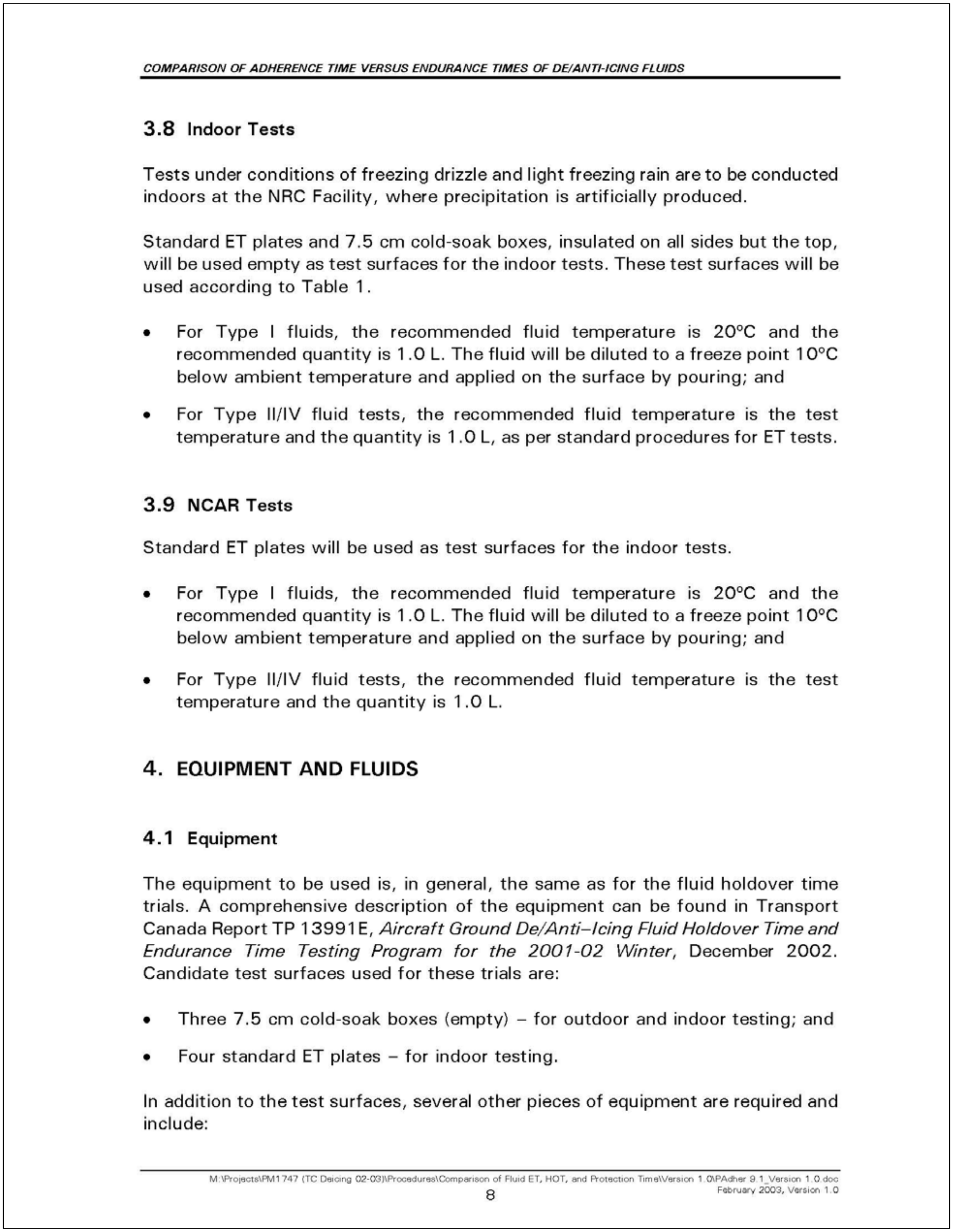
It is recommended several tests be run according to the following procedure:

- Apply the Type I fluid using 10°C buffer fluid, heated at 60°C; and
- Within 3 minutes from the Type I fluid application, treat the test surface with anti-icing fluid (Type II or IV). The Type II/IV fluid will be applied to the surface by pouring.

A test conducted following the above sequence is a closer representation of a real field deicing operation. These tests should be conducted under heavy precipitation (the NCAR system could be used) and at above -3°C temperatures. These tests will try to document whether it is possible to dilute the Type II/IV fluid to water before the surface temperature drops below 0°C generating adherence.

A summary of test parameters for each fluid type is provided below:

- Type I fluids: fluid heated at 60°C, quantity 0.5L, applied through a spreader; and
- Type II/IV fluids: fluid applied at ambient temperature, quantity 1.0L, poured.



3.8 Indoor Tests

Tests under conditions of freezing drizzle and light freezing rain are to be conducted indoors at the NRC Facility, where precipitation is artificially produced.

Standard ET plates and 7.5 cm cold-soak boxes, insulated on all sides but the top, will be used empty as test surfaces for the indoor tests. These test surfaces will be used according to Table 1.

- For Type I fluids, the recommended fluid temperature is 20°C and the recommended quantity is 1.0 L. The fluid will be diluted to a freeze point 10°C below ambient temperature and applied on the surface by pouring; and
- For Type II/IV fluid tests, the recommended fluid temperature is the test temperature and the quantity is 1.0 L, as per standard procedures for ET tests.

3.9 NCAR Tests

Standard ET plates will be used as test surfaces for the indoor tests.

- For Type I fluids, the recommended fluid temperature is 20°C and the recommended quantity is 1.0 L. The fluid will be diluted to a freeze point 10°C below ambient temperature and applied on the surface by pouring; and
- For Type II/IV fluid tests, the recommended fluid temperature is the test temperature and the quantity is 1.0 L.

4. EQUIPMENT AND FLUIDS

4.1 Equipment

The equipment to be used is, in general, the same as for the fluid holdover time trials. A comprehensive description of the equipment can be found in Transport Canada Report TP 13991E, *Aircraft Ground De/Anti–Icing Fluid Holdover Time and Endurance Time Testing Program for the 2001-02 Winter*, December 2002. Candidate test surfaces used for these trials are:

- Three 7.5 cm cold-soak boxes (empty) – for outdoor and indoor testing; and
- Four standard ET plates – for indoor testing.

In addition to the test surfaces, several other pieces of equipment are required and include:

- Fluid spreader device, with 12 holes, will be used for applying Type I fluids outdoors;
- SmartReader Eight–Channel temperature logger and thermistor probes will be used for logging test surface temperatures;
- Misco 10431VP brixometer will be utilized for fluid dilution rate measurements; and
- Wet film thickness gauges.

4.2 Fluids

Tests shall be conducted using Type I and Type II/IV fluids as presented in Table 1.

Type I fluids are to be mixed to a freeze point 10°C below OAT.

Type II/IV fluids will be tested as ready.

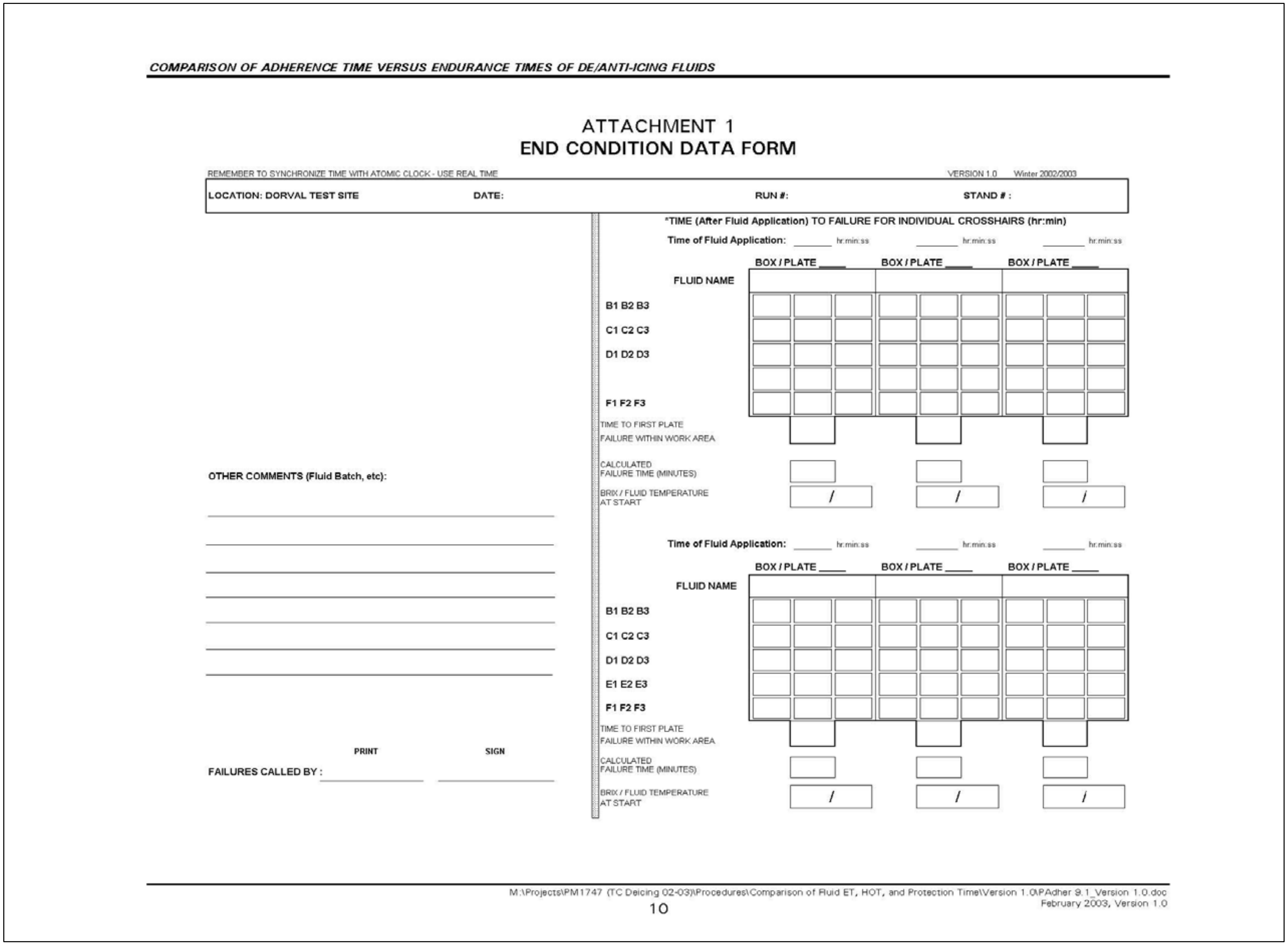
5. PERSONNEL

Four technicians are needed to conduct the tests:

- Technician one calls failures, and documents adherence;
- Technician two prepares and helps pour fluids;
- Technician three measures precipitation rates; and
- Technician four measures brix and thickness.

6. DATA FORMS

- End Condition Data Form (Attachment 1);
- Fluid Brix / Thickness data Form (Attachment 2);
- Meteo / Plate Pan data Form (Attachment 3); and
- Adherence of Fluid Failure Data Form (Attachment 4).



COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS

ATTACHMENT 1
END CONDITION DATA FORM

REMEMBER TO SYNCHRONIZE TIME WITH ATOMIC CLOCK - USE REAL TIME

VERSION 1.0 Winter 2002/2003

LOCATION: DORVAL TEST SITE **DATE:** **RUN #:** **STAND # :**

***TIME (After Fluid Application) TO FAILURE FOR INDIVIDUAL CROSSHAIRS (hr:min)**

Time of Fluid Application: _______ hr:min:ss _______ hr:min:ss _______ hr:min:ss

	BOX / PLATE ____			**BOX / PLATE ____**			**BOX / PLATE ____**		
FLUID NAME									
B1 B2 B3									
C1 C2 C3									
D1 D2 D3									
F1 F2 F3									
TIME TO FIRST PLATE FAILURE WITHIN WORK AREA									
CALCULATED FAILURE TIME (MINUTES)									
BRIX / FLUID TEMPERATURE AT START	/			/			/		

Time of Fluid Application: _______ hr:min:ss _______ hr:min:ss _______ hr:min:ss

	BOX / PLATE ____			**BOX / PLATE ____**			**BOX / PLATE ____**		
FLUID NAME									
B1 B2 B3									
C1 C2 C3									
D1 D2 D3									
E1 E2 E3									
F1 F2 F3									
TIME TO FIRST PLATE FAILURE WITHIN WORK AREA									
CALCULATED FAILURE TIME (MINUTES)									
BRIX / FLUID TEMPERATURE AT START	/			/			/		

OTHER COMMENTS (Fluid Batch, etc):

____

____

____

____

____

____

____

FAILURES CALLED BY : **PRINT** ______________ **SIGN** ______________

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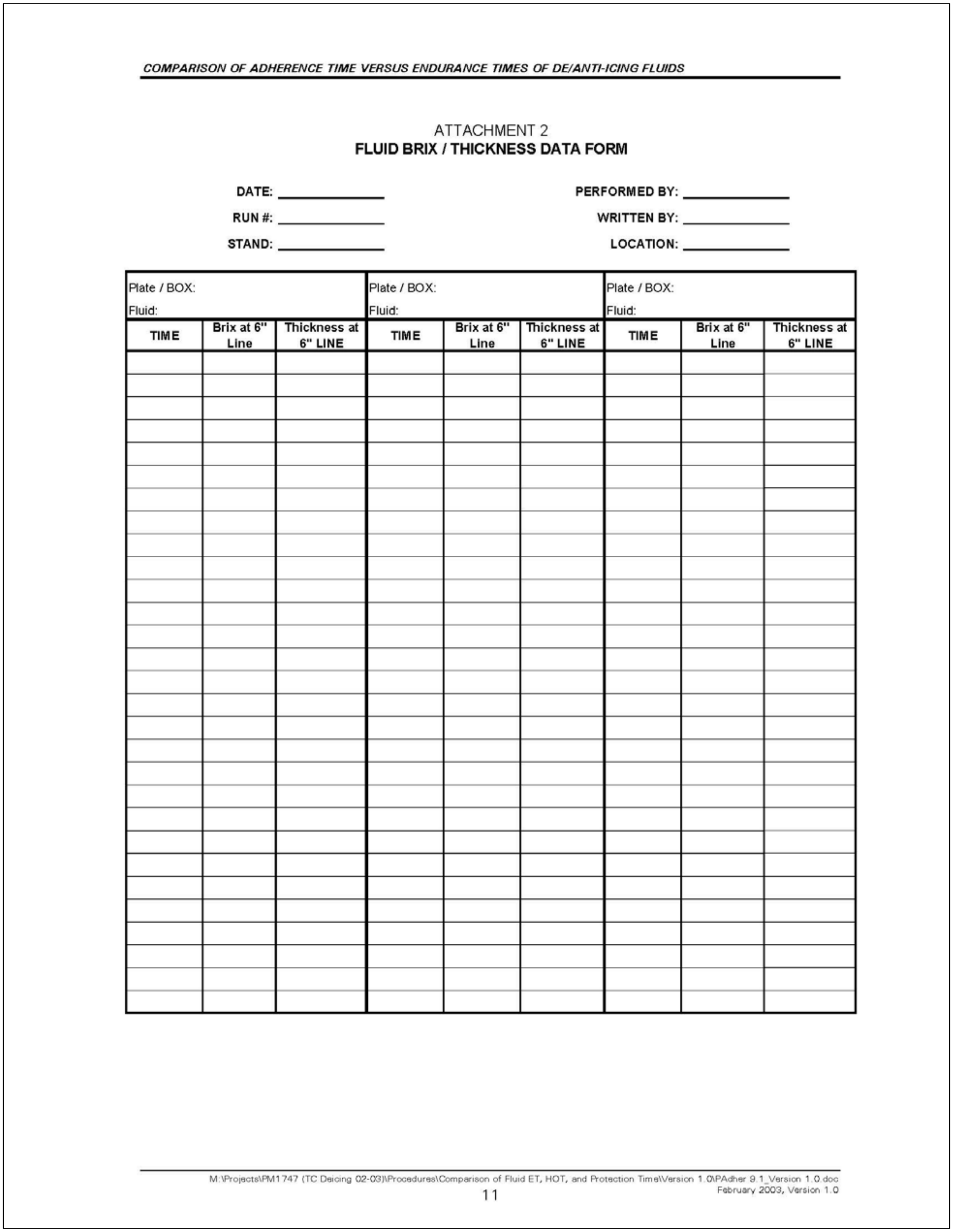

COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS

ATTACHMENT 2
FLUID BRIX / THICKNESS DATA FORM

DATE: ______________ **PERFORMED BY:** ______________

RUN #: ______________ **WRITTEN BY:** ______________

STAND: ______________ **LOCATION:** ______________

Plate / BOX: Fluid:			Plate / BOX: Fluid:			Plate / BOX: Fluid:		
TIME	**Brix at 6" Line**	**Thickness at 6" LINE**	**TIME**	**Brix at 6" Line**	**Thickness at 6" LINE**	**TIME**	**Brix at 6" Line**	**Thickness at 6" LINE**

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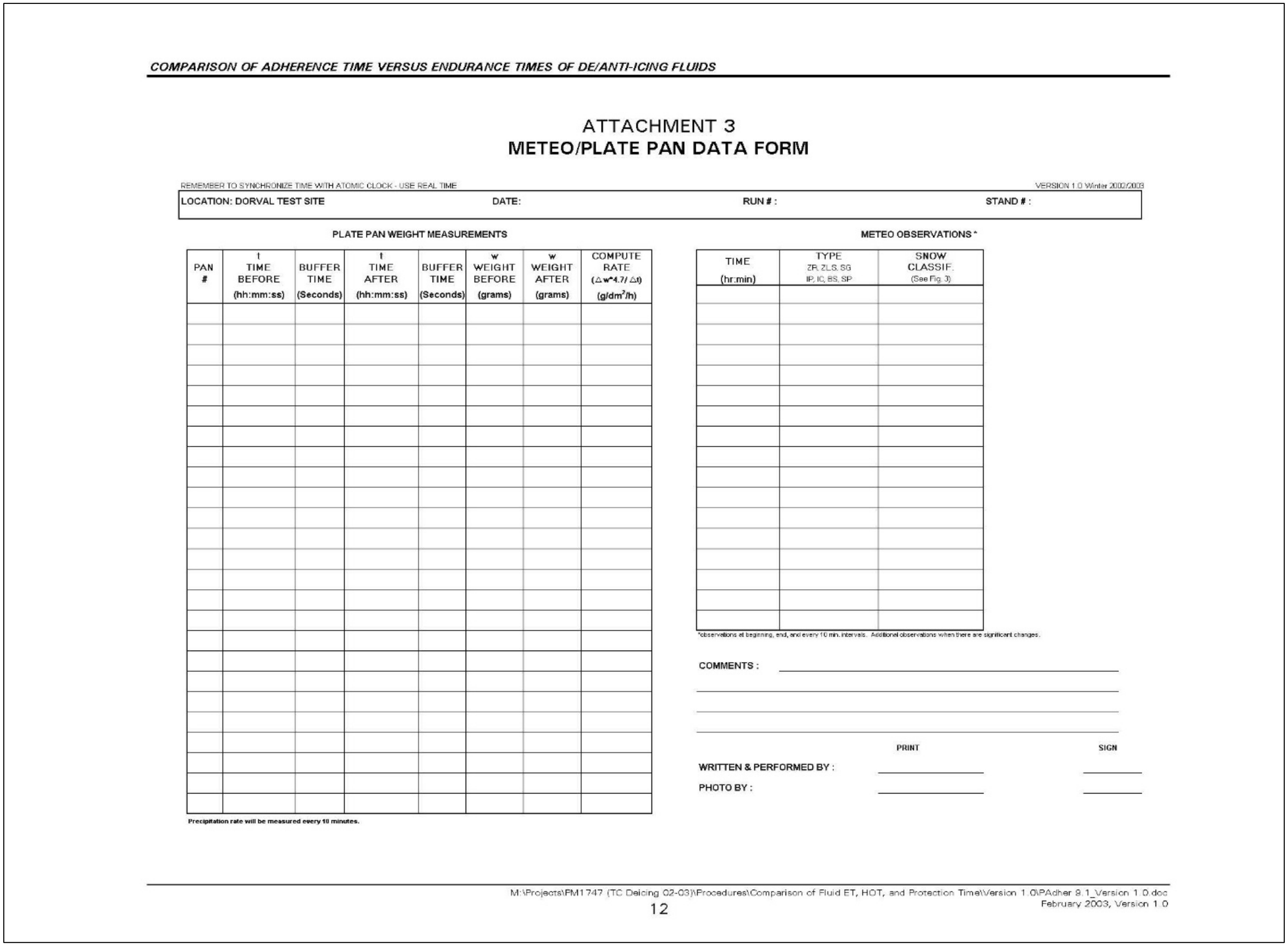

COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS

ATTACHMENT 3
METEO/PLATE PAN DATA FORM

REMEMBER TO SYNCHRONIZE TIME WITH ATOMIC CLOCK - USE REAL TIME

VERSION 1.0 Winter 2002/2003

LOCATION: DORVAL TEST SITE	**DATE:**	**RUN # :**	**STAND # :**

PLATE PAN WEIGHT MEASUREMENTS

PAN #	t TIME BEFORE (hh:mm:ss)	BUFFER TIME (Seconds)	t TIME AFTER (hh:mm:ss)	BUFFER TIME (Seconds)	w WEIGHT BEFORE (grams)	w WEIGHT AFTER (grams)	COMPUTE RATE (Δw*4.7/ Δt) ($g/dm^2/h$)

Precipitation rate will be measured every 10 minutes.

METEO OBSERVATIONS *

TIME (hr:min)	TYPE ZR, ZLS, SG IP, IC, BS, SP	SNOW CLASSIF. (See Fig. 3)

*observations at beginning, end, and every 10 min. intervals. Additional observations when there are significant changes.

COMMENTS : ______________________________

____

____

____

	PRINT	SIGN
WRITTEN & PERFORMED BY :	____________	________
PHOTO BY :	____________	________

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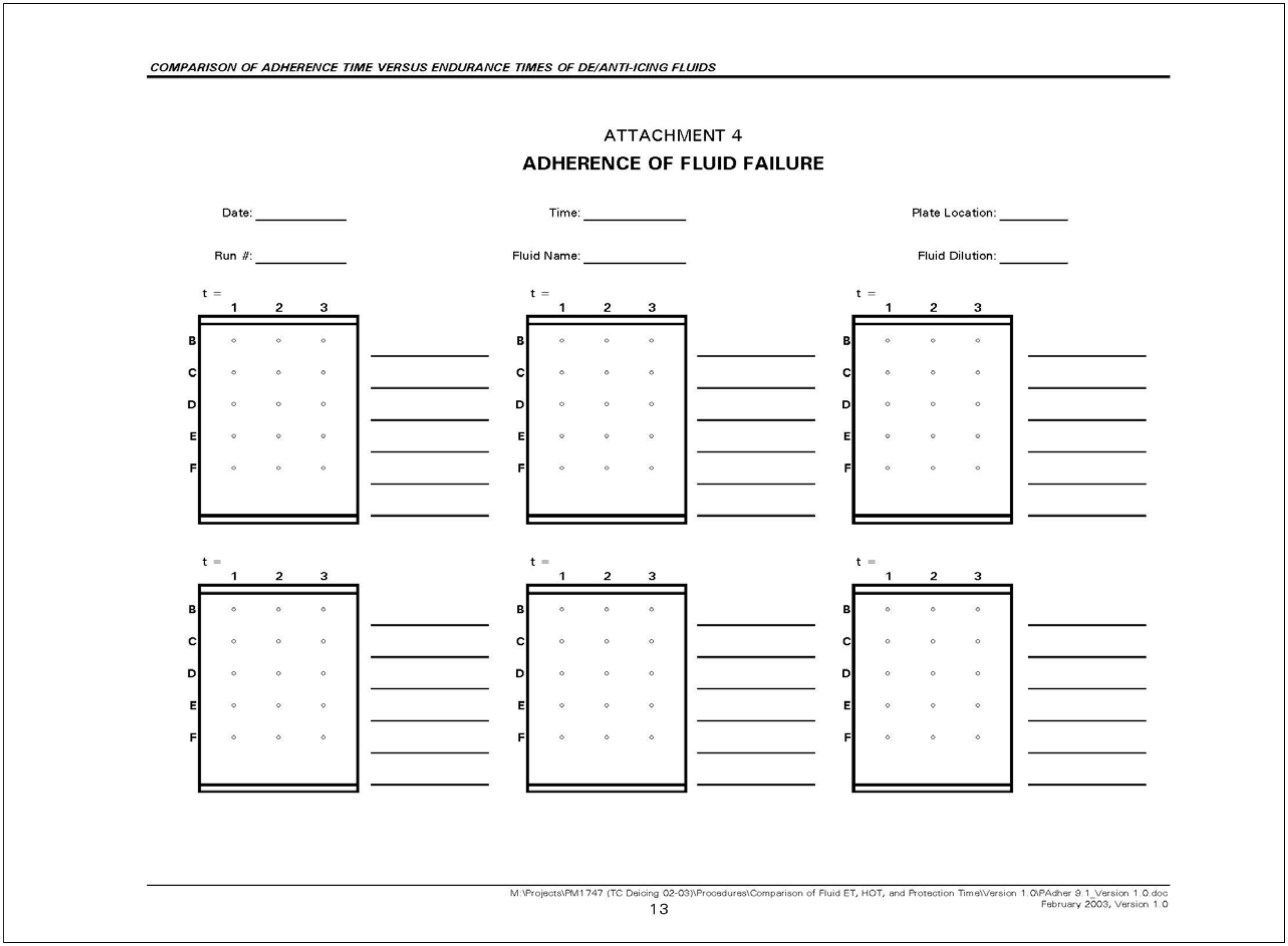

COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS

ATTACHMENT 4

ADHERENCE OF FLUID FAILURE

Date: ____________ Time: ____________ Plate Location: __________

Run #: ____________ Fluid Name: ____________ Fluid Dilution: __________

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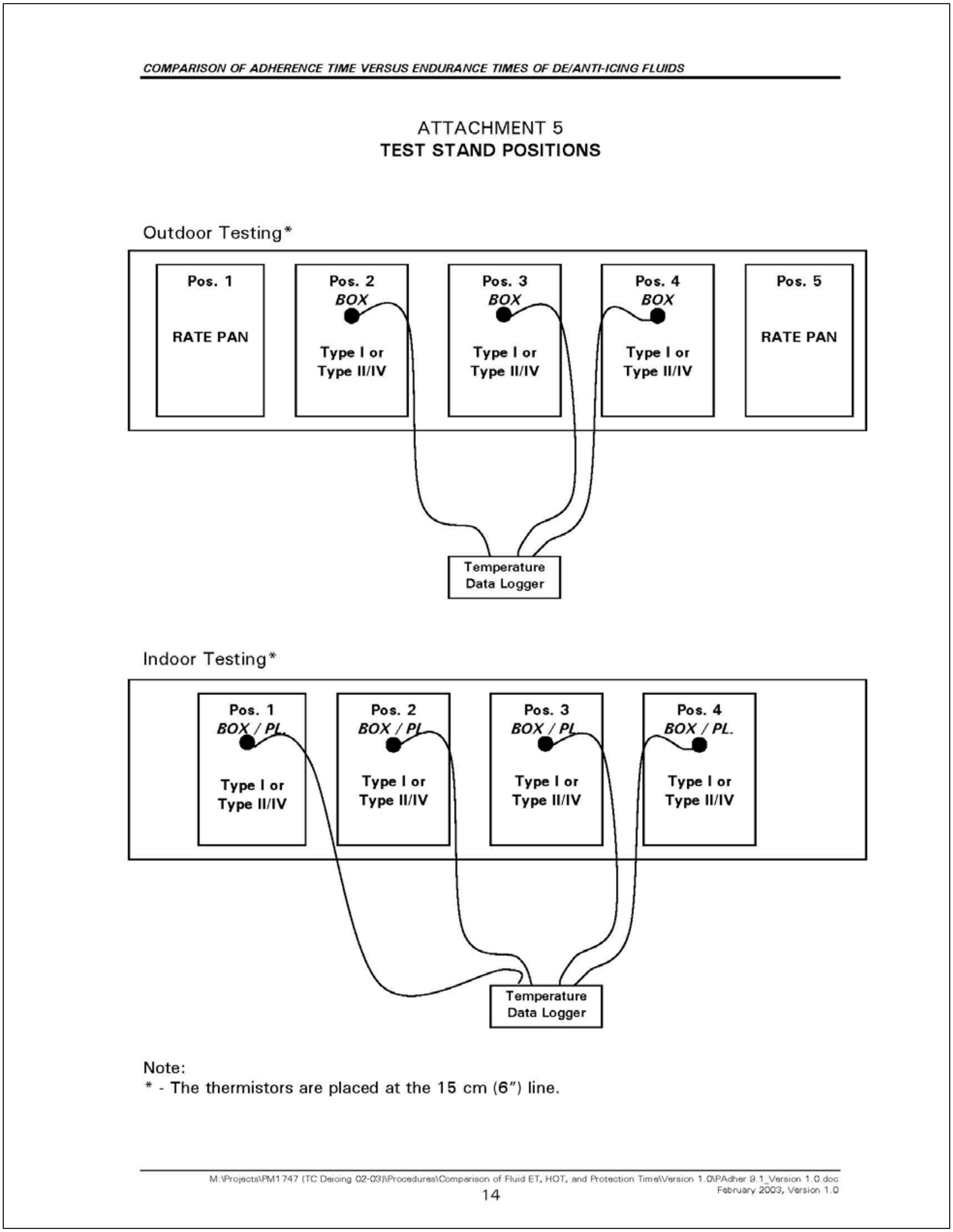

COMPARISON OF ADHERENCE TIME VERSUS ENDURANCE TIMES OF DE/ANTI-ICING FLUIDS

ATTACHMENT 5

TEST STAND POSITIONS

Outdoor Testing*

Indoor Testing*

Note:
* - The thermistors are placed at the 15 cm (6") line.

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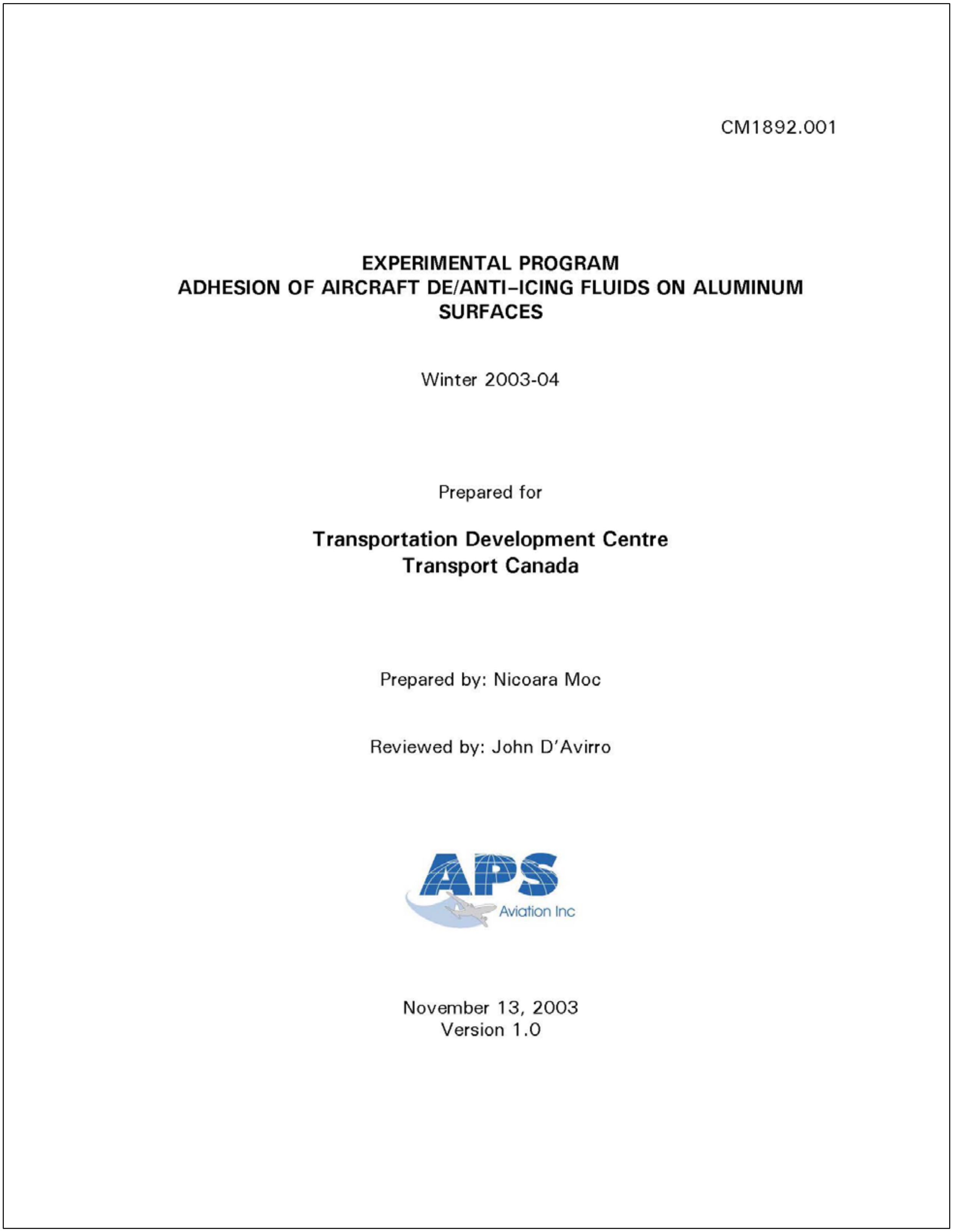
EXPERIMENTAL PROGRAM:
ADHESION OF AIRCRAFT DE/ANTI-ICING FLUIDS ON ALUMINUM SURFACES – WINTER 2003-04



CM1892.001

EXPERIMENTAL PROGRAM
ADHESION OF AIRCRAFT DE/ANTI-ICING FLUIDS ON ALUMINUM SURFACES

Winter 2003-04

Prepared for

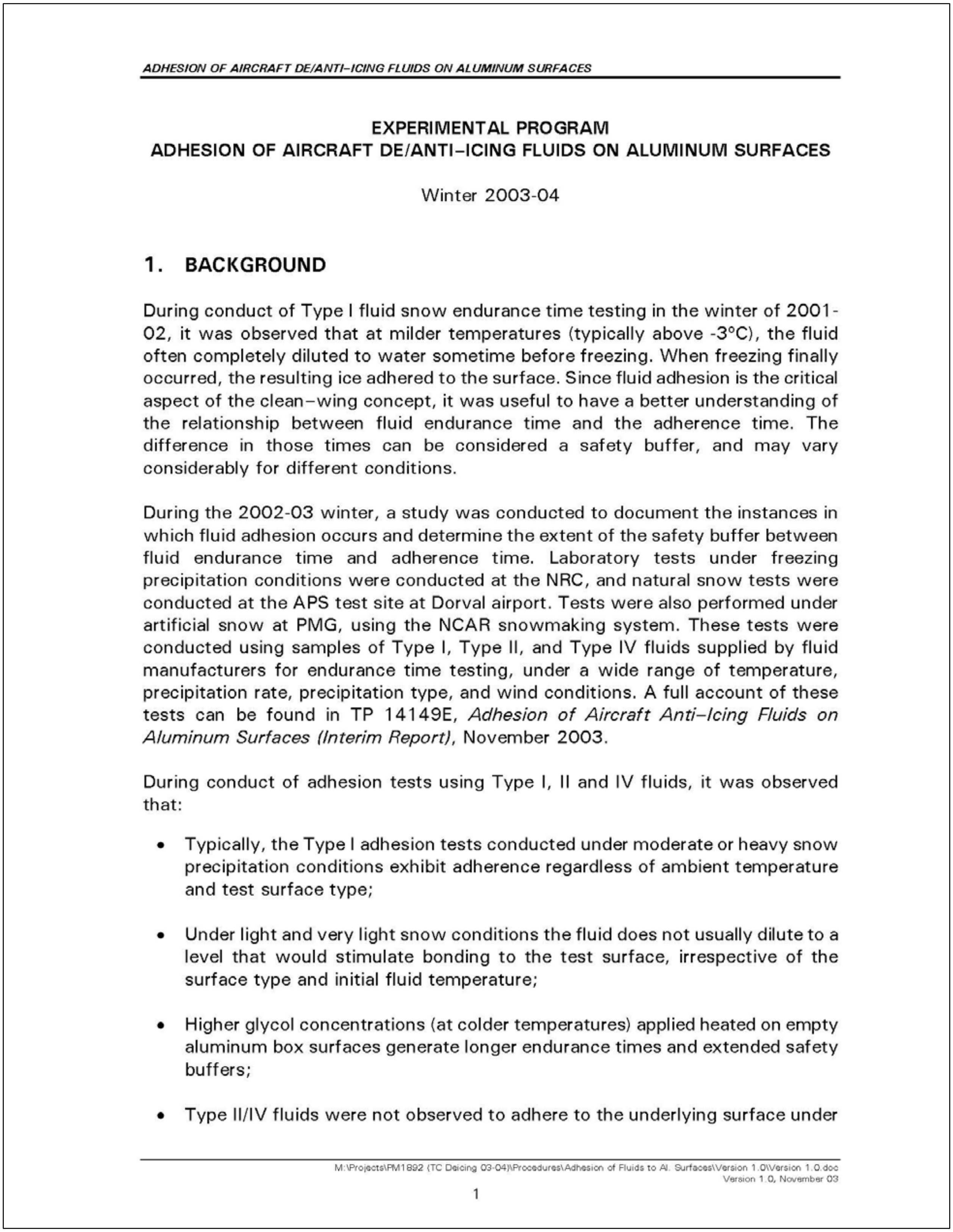
Transportation Development Centre
Transport Canada

Prepared by: Nicoara Moc

Reviewed by: John D'Avirro

APS
Aviation Inc

November 13, 2003
Version 1.0



ADHESION OF AIRCRAFT DE/ANTI–ICING FLUIDS ON ALUMINUM SURFACES

EXPERIMENTAL PROGRAM
ADHESION OF AIRCRAFT DE/ANTI–ICING FLUIDS ON ALUMINUM SURFACES

Winter 2003-04

1. BACKGROUND

During conduct of Type I fluid snow endurance time testing in the winter of 2001-02, it was observed that at milder temperatures (typically above -3°C), the fluid often completely diluted to water sometime before freezing. When freezing finally occurred, the resulting ice adhered to the surface. Since fluid adhesion is the critical aspect of the clean–wing concept, it was useful to have a better understanding of the relationship between fluid endurance time and the adherence time. The difference in those times can be considered a safety buffer, and may vary considerably for different conditions.

During the 2002-03 winter, a study was conducted to document the instances in which fluid adhesion occurs and determine the extent of the safety buffer between fluid endurance time and adherence time. Laboratory tests under freezing precipitation conditions were conducted at the NRC, and natural snow tests were conducted at the APS test site at Dorval airport. Tests were also performed under artificial snow at PMG, using the NCAR snowmaking system. These tests were conducted using samples of Type I, Type II, and Type IV fluids supplied by fluid manufacturers for endurance time testing, under a wide range of temperature, precipitation rate, precipitation type, and wind conditions. A full account of these tests can be found in TP 14149E, *Adhesion of Aircraft Anti–Icing Fluids on Aluminum Surfaces (Interim Report)*, November 2003.

During conduct of adhesion tests using Type I, II and IV fluids, it was observed that:

- Typically, the Type I adhesion tests conducted under moderate or heavy snow precipitation conditions exhibit adherence regardless of ambient temperature and test surface type;

- Under light and very light snow conditions the fluid does not usually dilute to a level that would stimulate bonding to the test surface, irrespective of the surface type and initial fluid temperature;

- Higher glycol concentrations (at colder temperatures) applied heated on empty aluminum box surfaces generate longer endurance times and extended safety buffers;

- Type II/IV fluids were not observed to adhere to the underlying surface under

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snow conditions, irrespective to the precipitation rate and outside temperature. However, if the fluid is exposed to precipitation far beyond complete plate failure, the failed fluid might eventually adhere to the surface providing its freeze point reached 0°C;

- If the Type II/IV fluid is heated, melting of snowflakes is facilitated, generating fairly large quantities of water for fluid dilution. This can lead to early dilution of the fluid and, subsequently, to fluid adhesion; and
- Contrary to snow conditions, adhesion was detected under freezing precipitation conditions for both Type I and Type II/IV fluids. Independent of the fluid type, precipitation rate and the ambient temperature, fluid adhesion was observed under freezing drizzle, light freezing rain and rain on cold–soaked wing conditions. However, Type IV testing conducted during the 1998-99 winter season showed that only Type IV ethylene glycol–based fluids demonstrated failure adhesion under freezing precipitation conditions.

Based on these findings, a tabular display of adherence times versus endurance times was developed to illustrate the size of the safety buffer for various weather conditions and fluid types.

2. OBJECTIVES

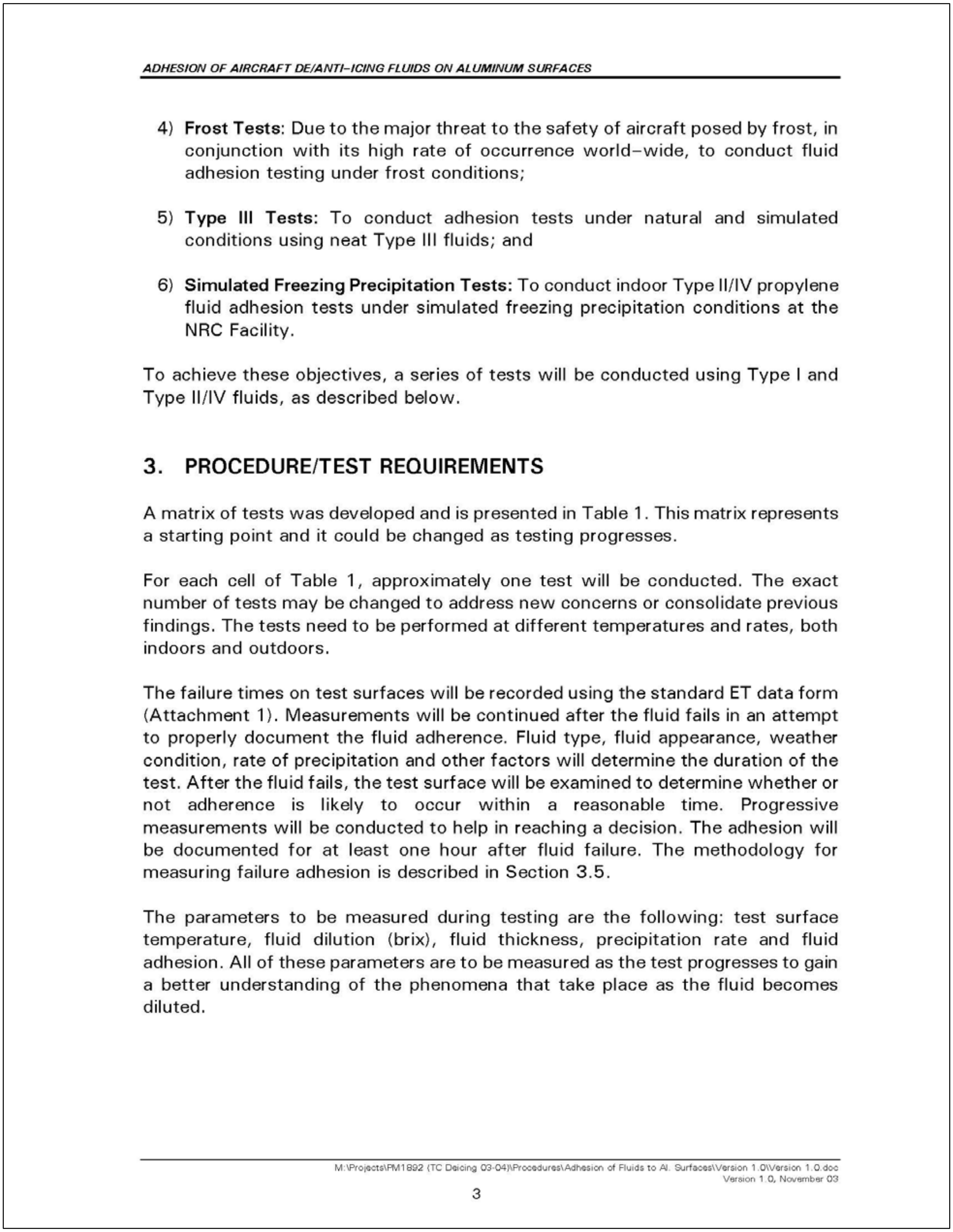
The objective of this project is to complete the documentation for all cases and to elaborate on results from completed tests.

The 2003-04 adhesion testing has six main objectives:

1) **Heated Type II/IV Fluids:** To conduct Type II/IV fluid adhesion tests using heated fluids under natural snow. If the anti–icing fluid is applied at a temperature above 0°C, melting of snowflakes is facilitated, generating fairly large quantities of liquid water for fluid dilution. Also, the results from a field survey conducted at a number of airports to document the typical temperature of Type IV fluids sprayed from trucks during actual deicing operations showed the average temperature differential of the measured Type IV fluid and OAT ranging from 7.2 to 14°C;

2) **Wet Snow:** To conduct Type II/IV fluid adhesion testing at very mild temperatures (around 0°C) to investigate the effect of wet snow;

3) **Bare Surface Tests:** To conduct adhesion tests on bare surfaces using heated and unheated empty aluminum boxes in attempt to simulate a "warm–soaked wing";



4) **Frost Tests**: Due to the major threat to the safety of aircraft posed by frost, in conjunction with its high rate of occurrence world-wide, to conduct fluid adhesion testing under frost conditions;

5) **Type III Tests:** To conduct adhesion tests under natural and simulated conditions using neat Type III fluids; and

6) **Simulated Freezing Precipitation Tests:** To conduct indoor Type II/IV propylene fluid adhesion tests under simulated freezing precipitation conditions at the NRC Facility.

To achieve these objectives, a series of tests will be conducted using Type I and Type II/IV fluids, as described below.

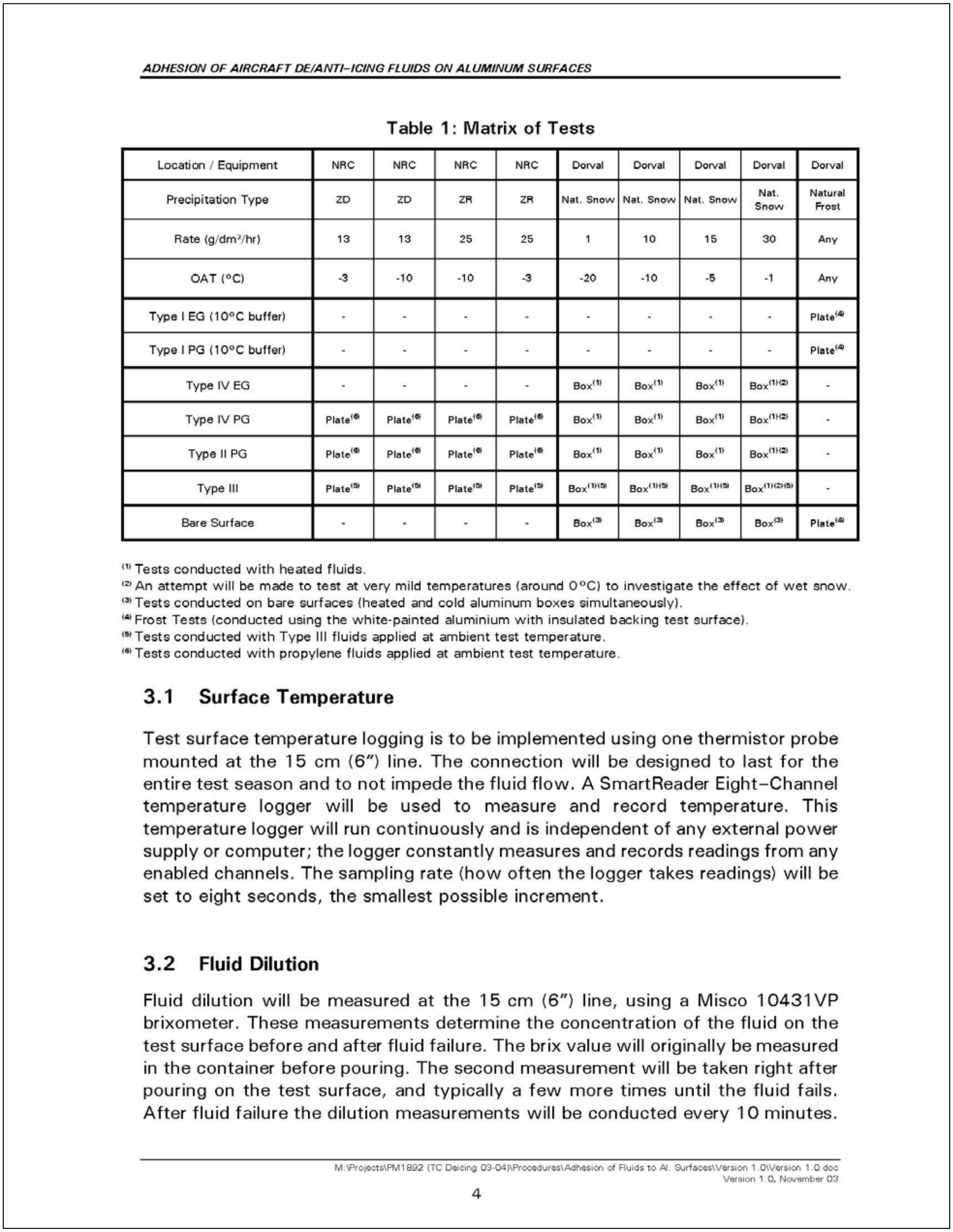
3. PROCEDURE/TEST REQUIREMENTS

A matrix of tests was developed and is presented in Table 1. This matrix represents a starting point and it could be changed as testing progresses.

For each cell of Table 1, approximately one test will be conducted. The exact number of tests may be changed to address new concerns or consolidate previous findings. The tests need to be performed at different temperatures and rates, both indoors and outdoors.

The failure times on test surfaces will be recorded using the standard ET data form (Attachment 1). Measurements will be continued after the fluid fails in an attempt to properly document the fluid adherence. Fluid type, fluid appearance, weather condition, rate of precipitation and other factors will determine the duration of the test. After the fluid fails, the test surface will be examined to determine whether or not adherence is likely to occur within a reasonable time. Progressive measurements will be conducted to help in reaching a decision. The adhesion will be documented for at least one hour after fluid failure. The methodology for measuring failure adhesion is described in Section 3.5.

The parameters to be measured during testing are the following: test surface temperature, fluid dilution (brix), fluid thickness, precipitation rate and fluid adhesion. All of these parameters are to be measured as the test progresses to gain a better understanding of the phenomena that take place as the fluid becomes diluted.



ADHESION OF AIRCRAFT DE/ANTI–ICING FLUIDS ON ALUMINUM SURFACES

Table 1: Matrix of Tests

Location / Equipment	NRC	NRC	NRC	NRC	Dorval	Dorval	Dorval	Dorval	Dorval
Precipitation Type	ZD	ZD	ZR	ZR	Nat. Snow	Nat. Snow	Nat. Snow	Nat. Snow	Natural Frost
Rate (g/dm²/hr)	13	13	25	25	1	10	15	30	Any
OAT (°C)	-3	-10	-10	-3	-20	-10	-5	-1	Any
Type I EG (10°C buffer)	-	-	-	-	-	-	-	-	Plate(4)
Type I PG (10°C buffer)	-	-	-	-	-	-	-	-	Plate(4)
Type IV EG	-	-	-	-	Box(1)	Box(1)	Box(1)	Box(1)(2)	-
Type IV PG	Plate(6)	Plate(6)	Plate(6)	Plate(6)	Box(1)	Box(1)	Box(1)	Box(1)(2)	-
Type II PG	Plate(6)	Plate(6)	Plate(6)	Plate(6)	Box(1)	Box(1)	Box(1)	Box(1)(2)	-
Type III	Plate(5)	Plate(5)	Plate(5)	Plate(5)	Box(1)(5)	Box(1)(5)	Box(1)(5)	Box(1)(2)(5)	-
Bare Surface	-	-	-	-	Box(3)	Box(3)	Box(3)	Box(3)	Plate(4)

(1) Tests conducted with heated fluids.
(2) An attempt will be made to test at very mild temperatures (around 0°C) to investigate the effect of wet snow.
(3) Tests conducted on bare surfaces (heated and cold aluminum boxes simultaneously).
(4) Frost Tests (conducted using the white-painted aluminium with insulated backing test surface).
(5) Tests conducted with Type III fluids applied at ambient test temperature.
(6) Tests conducted with propylene fluids applied at ambient test temperature.

3.1 Surface Temperature

Test surface temperature logging is to be implemented using one thermistor probe mounted at the 15 cm (6") line. The connection will be designed to last for the entire test season and to not impede the fluid flow. A SmartReader Eight–Channel temperature logger will be used to measure and record temperature. This temperature logger will run continuously and is independent of any external power supply or computer; the logger constantly measures and records readings from any enabled channels. The sampling rate (how often the logger takes readings) will be set to eight seconds, the smallest possible increment.

3.2 Fluid Dilution

Fluid dilution will be measured at the 15 cm (6") line, using a Misco 10431VP brixometer. These measurements determine the concentration of the fluid on the test surface before and after fluid failure. The brix value will originally be measured in the container before pouring. The second measurement will be taken right after pouring on the test surface, and typically a few more times until the fluid fails. After fluid failure the dilution measurements will be conducted every 10 minutes.

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Version 1.0, November 03

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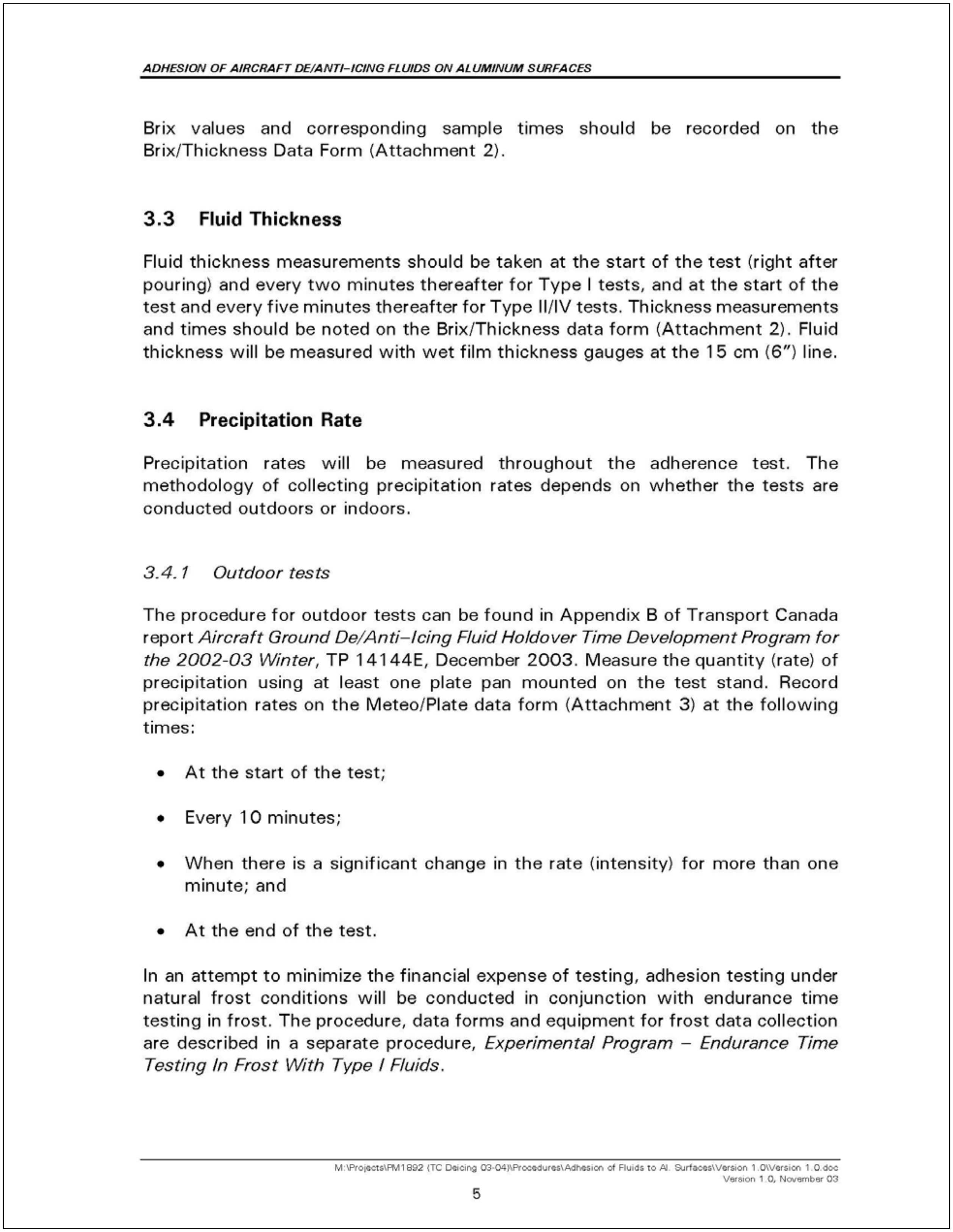


Brix values and corresponding sample times should be recorded on the Brix/Thickness Data Form (Attachment 2).

3.3 Fluid Thickness

Fluid thickness measurements should be taken at the start of the test (right after pouring) and every two minutes thereafter for Type I tests, and at the start of the test and every five minutes thereafter for Type II/IV tests. Thickness measurements and times should be noted on the Brix/Thickness data form (Attachment 2). Fluid thickness will be measured with wet film thickness gauges at the 15 cm (6") line.

3.4 Precipitation Rate

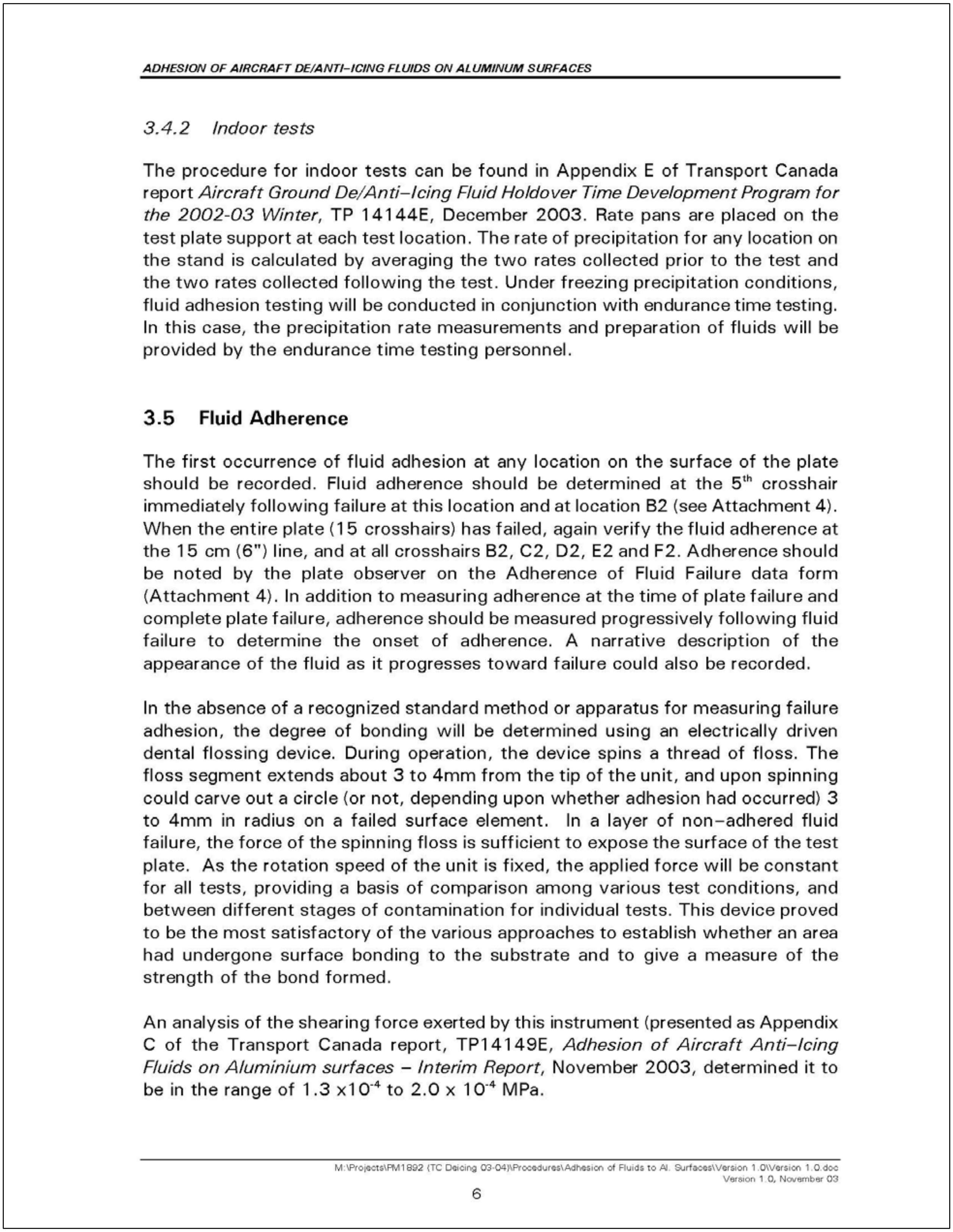
Precipitation rates will be measured throughout the adherence test. The methodology of collecting precipitation rates depends on whether the tests are conducted outdoors or indoors.

3.4.1 Outdoor tests

The procedure for outdoor tests can be found in Appendix B of Transport Canada report *Aircraft Ground De/Anti–Icing Fluid Holdover Time Development Program for the 2002-03 Winter*, TP 14144E, December 2003. Measure the quantity (rate) of precipitation using at least one plate pan mounted on the test stand. Record precipitation rates on the Meteo/Plate data form (Attachment 3) at the following times:

- At the start of the test;
- Every 10 minutes;
- When there is a significant change in the rate (intensity) for more than one minute; and
- At the end of the test.

In an attempt to minimize the financial expense of testing, adhesion testing under natural frost conditions will be conducted in conjunction with endurance time testing in frost. The procedure, data forms and equipment for frost data collection are described in a separate procedure, *Experimental Program – Endurance Time Testing In Frost With Type I Fluids*.



3.4.2 Indoor tests

The procedure for indoor tests can be found in Appendix E of Transport Canada report *Aircraft Ground De/Anti–Icing Fluid Holdover Time Development Program for the 2002-03 Winter*, TP 14144E, December 2003. Rate pans are placed on the test plate support at each test location. The rate of precipitation for any location on the stand is calculated by averaging the two rates collected prior to the test and the two rates collected following the test. Under freezing precipitation conditions, fluid adhesion testing will be conducted in conjunction with endurance time testing. In this case, the precipitation rate measurements and preparation of fluids will be provided by the endurance time testing personnel.

3.5 Fluid Adherence

The first occurrence of fluid adhesion at any location on the surface of the plate should be recorded. Fluid adherence should be determined at the 5th crosshair immediately following failure at this location and at location B2 (see Attachment 4). When the entire plate (15 crosshairs) has failed, again verify the fluid adherence at the 15 cm (6") line, and at all crosshairs B2, C2, D2, E2 and F2. Adherence should be noted by the plate observer on the Adherence of Fluid Failure data form (Attachment 4). In addition to measuring adherence at the time of plate failure and complete plate failure, adherence should be measured progressively following fluid failure to determine the onset of adherence. A narrative description of the appearance of the fluid as it progresses toward failure could also be recorded.

In the absence of a recognized standard method or apparatus for measuring failure adhesion, the degree of bonding will be determined using an electrically driven dental flossing device. During operation, the device spins a thread of floss. The floss segment extends about 3 to 4mm from the tip of the unit, and upon spinning could carve out a circle (or not, depending upon whether adhesion had occurred) 3 to 4mm in radius on a failed surface element. In a layer of non–adhered fluid failure, the force of the spinning floss is sufficient to expose the surface of the test plate. As the rotation speed of the unit is fixed, the applied force will be constant for all tests, providing a basis of comparison among various test conditions, and between different stages of contamination for individual tests. This device proved to be the most satisfactory of the various approaches to establish whether an area had undergone surface bonding to the substrate and to give a measure of the strength of the bond formed.

An analysis of the shearing force exerted by this instrument (presented as Appendix C of the Transport Canada report, TP14149E, *Adhesion of Aircraft Anti–Icing Fluids on Aluminium surfaces – Interim Report*, November 2003, determined it to be in the range of 1.3 x10^{-4} to 2.0 x 10^{-4} MPa.

3.6 Test Sequence

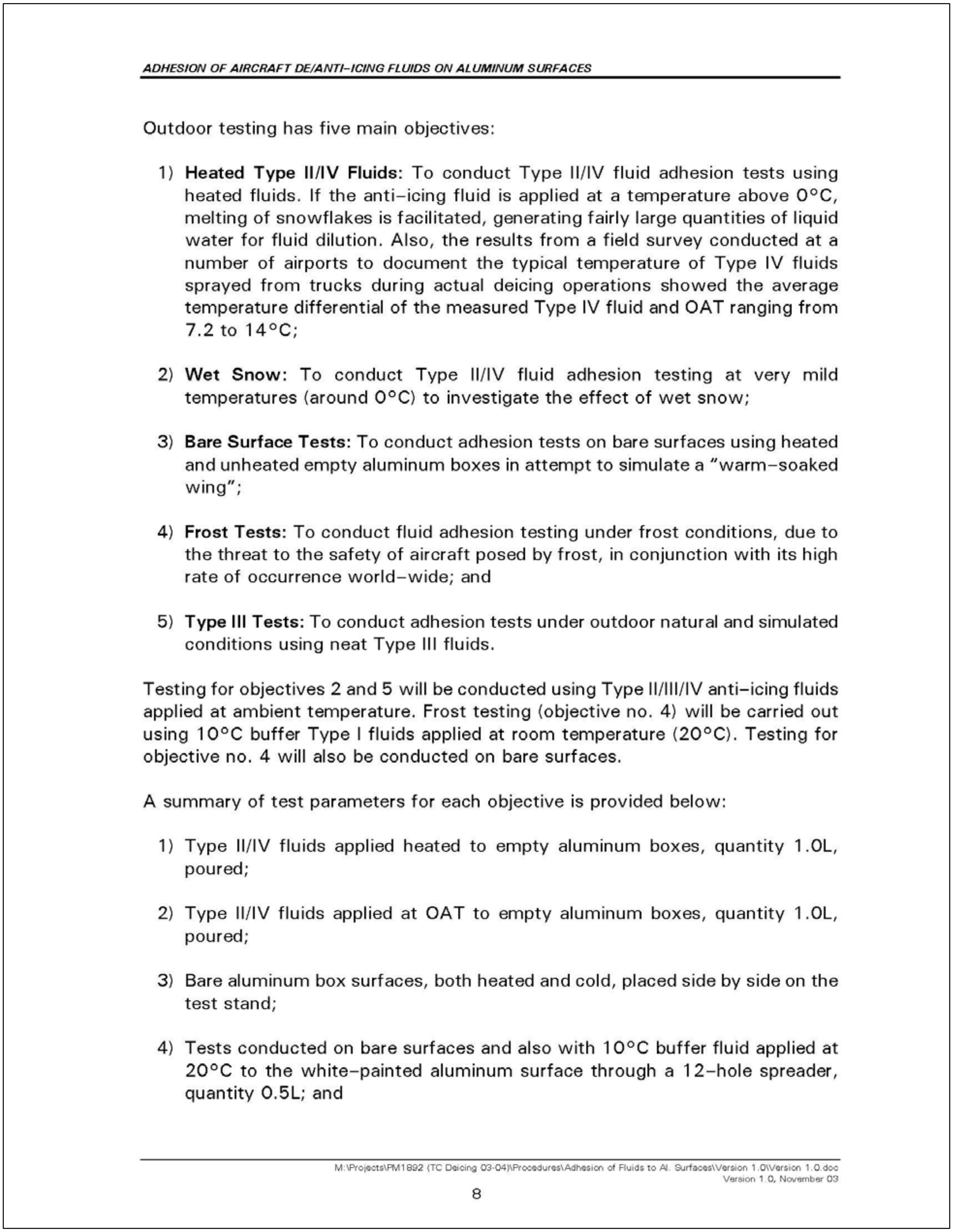
The steps to be followed are specific to each precipitation type.

1) Synchronize computer and test clocks to the atomic clock;
2) Prepare surfaces on the stand according to Attachment 5;
3) Initiate temperature logging, as per Section 1.1;
4) Collect precipitation rates, as per Section 3.4;
5) Prepare fluids for testing. The fluid types, fluid amounts and application temperatures are specific to each condition, as per Sections 3.7 and 3.8;
6) Apply the fluid to the test surfaces according to the pertaining procedure, as per Sections 3.7 and 3.8;
7) Just before pouring, the test surfaces should be cleaned of all contamination with a scraper and a squeegee;
8) When required (outdoor testing in frost), stand behind the test stand, place a shield device to deflect the air and pour the test fluid from the thermos into the spreader. Remove the shield when the spreader has emptied;
9) Determine failure times on test surfaces, and record using standard ET data forms (Attachment 1);
10) Measure brix and thickness of the fluid and record on Brix/Thickness data form (Attachment 2);
11) Determine fluid adherence and record on Adherence of Fluid Failure data form (Attachment 5); and
12) At the end of the testing session save the temperature data on a floppy disk and also e-mail it to the office. Label the diskette and place in the same envelope with the data forms.

This procedure describes the tests conducted under different weather conditions for each type of fluid. As presented in Table 1, there are two categories of tests addressed by this procedure: outdoor tests and indoor tests. They are discussed separately in the following sections.

3.7 Outdoor Tests

The tests will be conducted at a test site located at Dorval Airport over the winter of 2003-04.



Outdoor testing has five main objectives:

1) **Heated Type II/IV Fluids:** To conduct Type II/IV fluid adhesion tests using heated fluids. If the anti-icing fluid is applied at a temperature above 0°C, melting of snowflakes is facilitated, generating fairly large quantities of liquid water for fluid dilution. Also, the results from a field survey conducted at a number of airports to document the typical temperature of Type IV fluids sprayed from trucks during actual deicing operations showed the average temperature differential of the measured Type IV fluid and OAT ranging from 7.2 to 14°C;

2) **Wet Snow:** To conduct Type II/IV fluid adhesion testing at very mild temperatures (around 0°C) to investigate the effect of wet snow;

3) **Bare Surface Tests:** To conduct adhesion tests on bare surfaces using heated and unheated empty aluminum boxes in attempt to simulate a "warm-soaked wing";

4) **Frost Tests:** To conduct fluid adhesion testing under frost conditions, due to the threat to the safety of aircraft posed by frost, in conjunction with its high rate of occurrence world-wide; and

5) **Type III Tests:** To conduct adhesion tests under outdoor natural and simulated conditions using neat Type III fluids.

Testing for objectives 2 and 5 will be conducted using Type II/III/IV anti-icing fluids applied at ambient temperature. Frost testing (objective no. 4) will be carried out using 10°C buffer Type I fluids applied at room temperature (20°C). Testing for objective no. 4 will also be conducted on bare surfaces.

A summary of test parameters for each objective is provided below:

1) Type II/IV fluids applied heated to empty aluminum boxes, quantity 1.0L, poured;

2) Type II/IV fluids applied at OAT to empty aluminum boxes, quantity 1.0L, poured;

3) Bare aluminum box surfaces, both heated and cold, placed side by side on the test stand;

4) Tests conducted on bare surfaces and also with 10°C buffer fluid applied at 20°C to the white-painted aluminum surface through a 12-hole spreader, quantity 0.5L; and

5) Type III fluids applied at OAT to empty aluminum boxes, quantity 1.0L, poured;

In order to have a more accurate representation of the holdover time obtained in real field deicing operations, an attempt will be made to cover a wide range of outside air temperatures and precipitation rates, during several snowstorms, as presented in Table 1.

3.8 Indoor Tests

The objective of indoor testing is to conduct Type II/III/IV propylene fluid adhesion tests under simulated freezing precipitation conditions at the NRC Facility. These tests will be conducted in conjunction with endurance time testing. The fluid will be applied at ambient test temperature. Depending on the findings or to address new concerns, tests may be conducted using fluids heated at various temperatures. The quantity is 1.0 L, as per standard procedures for ET tests.

Standard ET plates will be used as test surfaces for the indoor tests. These test surfaces will be used according to Table 1 and Attachment 5.

4. EQUIPMENT AND FLUIDS

4.1 Equipment

The equipment to be used is, in general, the same as for the fluid holdover time tests. A comprehensive description of the equipment can be found in Transport Canada Report *Aircraft Ground De/Anti–Icing Fluid Holdover Time Development Program for the 2002-03 Winter*, TP 14144E, December 2003. Candidate test surfaces used for these tests are:

- Standard ET plates – for indoor testing;
- 7.5 cm aluminum boxes – for outdoor testing;
- White–painted aluminum test plates with insulated backing – frost testing.

In addition to the test surfaces, several other pieces of equipment are required and include:

- Fluid spreader device, with 12 holes, will be used for applying Type I fluids under natural frost conditions;

- SmartReader Eight-Channel temperature logger and thermistor probes will be used for logging test surface temperatures;

- Misco 10431VP brixometer will be utilized for fluid dilution rate measurements; and

- Wet film thickness gauges.

4.2 Fluids

Tests shall be conducted using Type I and Type II/III/IV fluids as presented in Table 1.

Type I fluids are to be mixed to a freeze point 10°C below OAT. Any SAE Type I fluid, EG or PG-based, can be used.

Type II/III/IV fluids will be tested as ready. The following Type II/IV fluids will be used: Kilfrost ABC 2000, Octagon Max-Flight and Kilfrost ABC-S.

5. PERSONNEL

Two technicians are needed to conduct the tests:

- Technician one calls failures, and documents adherence; and

- Technician two prepares fluids, measures precipitation rates and measures brix and thickness.

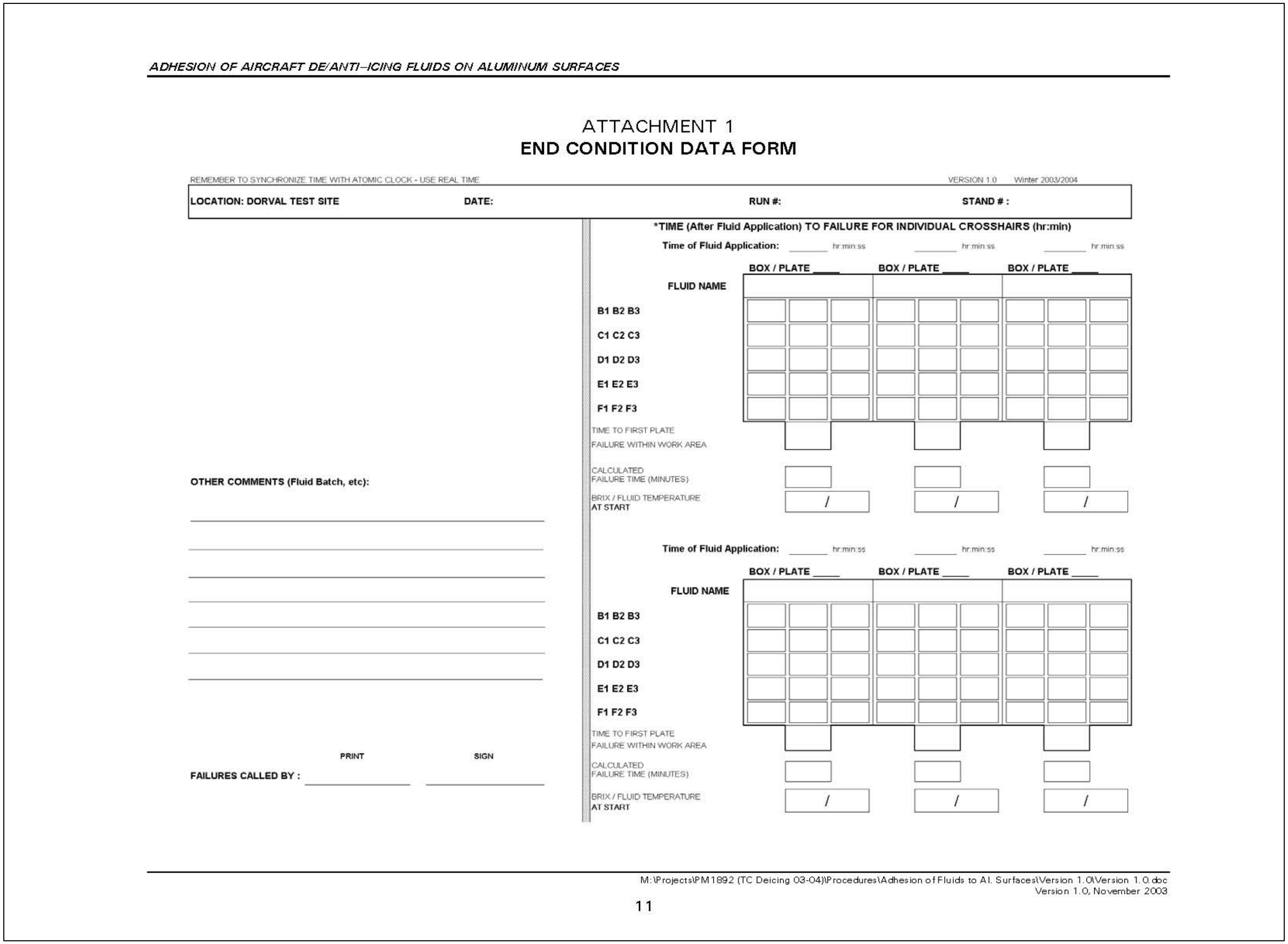
6. DATA FORMS

- End Condition Data Form (Attachment 1);

- Fluid Brix/Thickness data Form (Attachment 2);

- Meteo/Plate Pan data Form (Attachment 3); and

- Adherence of Fluid Failure Data Form (Attachment 4).



ADHESION OF AIRCRAFT DE/ANTI–ICING FLUIDS ON ALUMINUM SURFACES

ATTACHMENT 1

END CONDITION DATA FORM

REMEMBER TO SYNCHRONIZE TIME WITH ATOMIC CLOCK - USE REAL TIME

VERSION 1.0 Winter 2003/2004

LOCATION: DORVAL TEST SITE	**DATE:**	**RUN #:**	**STAND # :**

***TIME (After Fluid Application) TO FAILURE FOR INDIVIDUAL CROSSHAIRS (hr:min)**

Time of Fluid Application: _______ hr:min:ss _______ hr:min:ss _______ hr:min:ss

	BOX / PLATE ____	**BOX / PLATE ____**	**BOX / PLATE ____**
FLUID NAME			
B1 B2 B3			
C1 C2 C3			
D1 D2 D3			
E1 E2 E3			
F1 F2 F3			
TIME TO FIRST PLATE FAILURE WITHIN WORK AREA			
CALCULATED FAILURE TIME (MINUTES)			
BRIX / FLUID TEMPERATURE AT START	/	/	/

Time of Fluid Application: _______ hr:min:ss _______ hr:min:ss _______ hr:min:ss

	BOX / PLATE ____	**BOX / PLATE ____**	**BOX / PLATE ____**
FLUID NAME			
B1 B2 B3			
C1 C2 C3			
D1 D2 D3			
E1 E2 E3			
F1 F2 F3			
TIME TO FIRST PLATE FAILURE WITHIN WORK AREA			
CALCULATED FAILURE TIME (MINUTES)			
BRIX / FLUID TEMPERATURE AT START	/	/	/

OTHER COMMENTS (Fluid Batch, etc):

FAILURES CALLED BY : PRINT ______________ SIGN ______________

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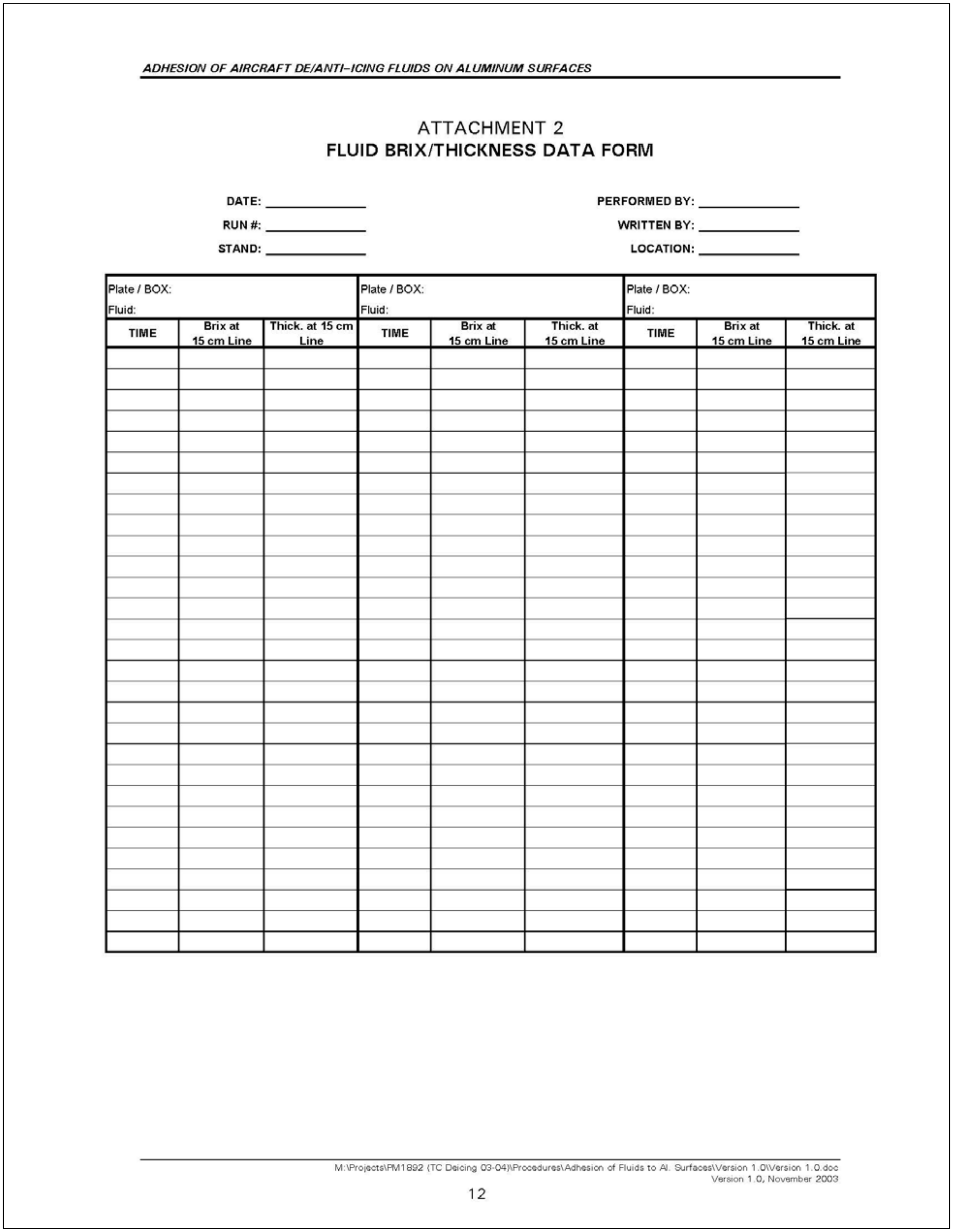

ADHESION OF AIRCRAFT DE/ANTI–ICING FLUIDS ON ALUMINUM SURFACES

ATTACHMENT 2
FLUID BRIX/THICKNESS DATA FORM

DATE: ______________

RUN #: ______________

STAND: ______________

PERFORMED BY: ______________

WRITTEN BY: ______________

LOCATION: ______________

Plate / BOX: Fluid:			Plate / BOX: Fluid:			Plate / BOX: Fluid:		
TIME	**Brix at 15 cm Line**	**Thick. at 15 cm Line**	**TIME**	**Brix at 15 cm Line**	**Thick. at 15 cm Line**	**TIME**	**Brix at 15 cm Line**	**Thick. at 15 cm Line**

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Version 1.0, November 2003

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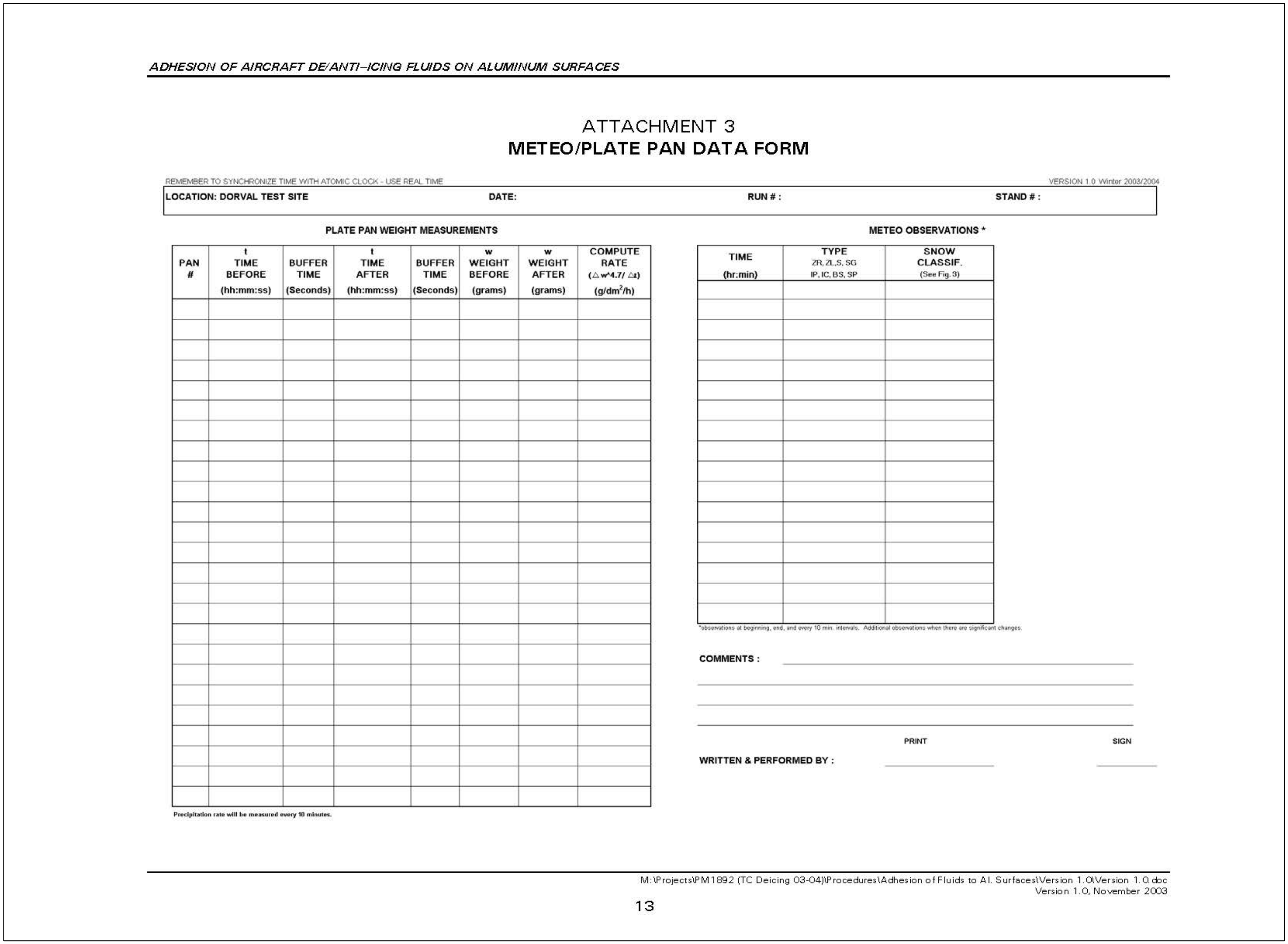

ADHESION OF AIRCRAFT DE/ANTI–ICING FLUIDS ON ALUMINUM SURFACES

ATTACHMENT 3
METEO/PLATE PAN DATA FORM

REMEMBER TO SYNCHRONIZE TIME WITH ATOMIC CLOCK - USE REAL TIME

VERSION 1.0 Winter 2003/2004

LOCATION: DORVAL TEST SITE **DATE:** **RUN # :** **STAND # :**

PLATE PAN WEIGHT MEASUREMENTS

PAN #	t TIME BEFORE (hh:mm:ss)	BUFFER TIME (Seconds)	t TIME AFTER (hh:mm:ss)	BUFFER TIME (Seconds)	w WEIGHT BEFORE (grams)	w WEIGHT AFTER (grams)	COMPUTE RATE (△w^4.7/ △t) ($g/dm^2/h$)

Precipitation rate will be measured every 10 minutes.

METEO OBSERVATIONS *

TIME (hr:min)	TYPE ZR, ZL,S, SG IP, IC, BS, SP	SNOW CLASSIF. (See Fig. 3)

*observations at beginning, end, and every 10 min. intervals. Additional observations when there are significant changes.

COMMENTS : ____________________

____

____

____

PRINT SIGN

WRITTEN & PERFORMED BY : ____________ ____________

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Version 1.0, November 2003

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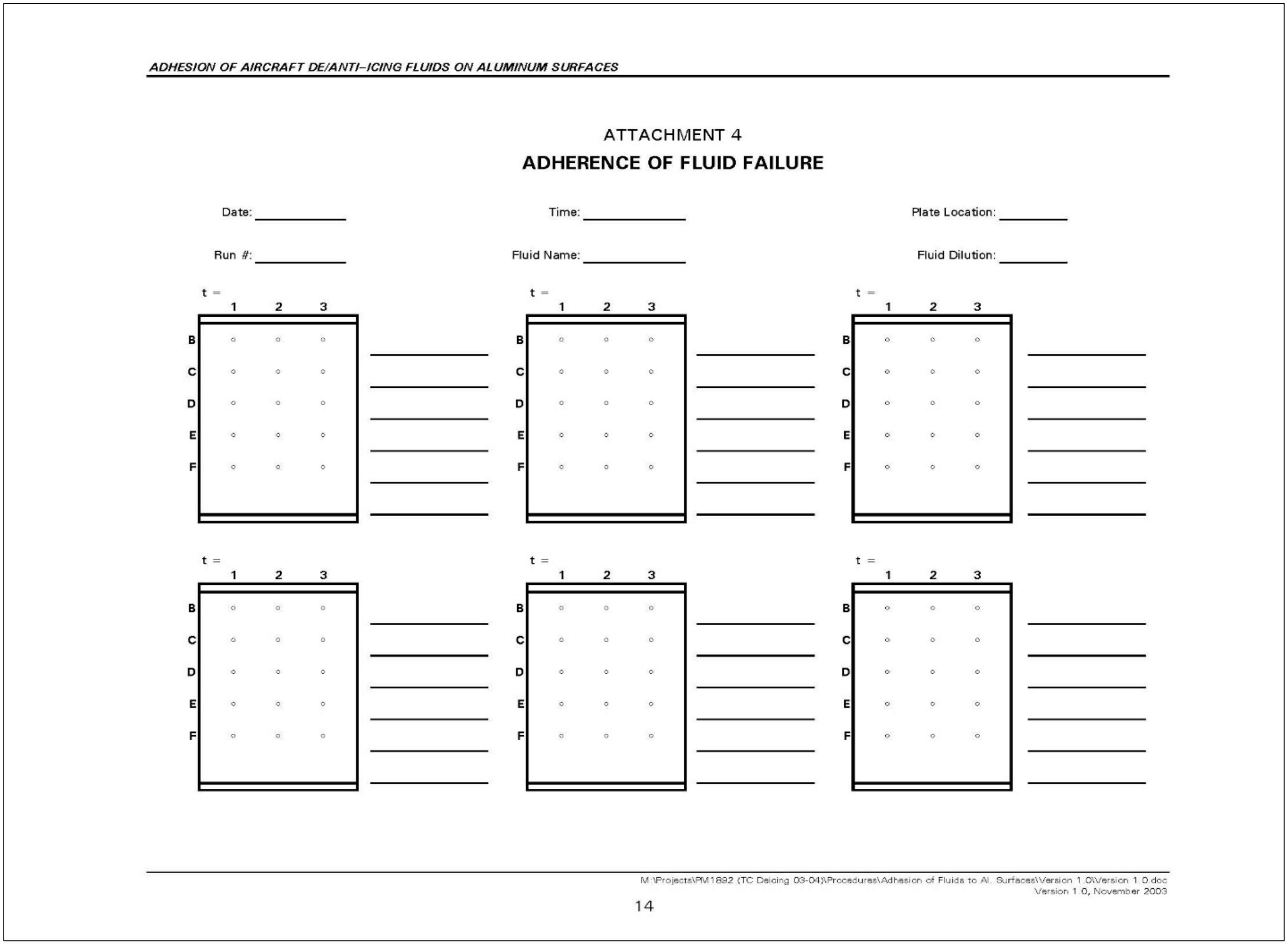


ATTACHMENT 4

ADHERENCE OF FLUID FAILURE

Date: ____________ Time: ______________ Plate Location: _________

Run #: ____________ Fluid Name: ______________ Fluid Dilution: _________

t =
1 2 3
B ○ ○ ○ ____________
C ○ ○ ○ ____________
D ○ ○ ○ ____________
E ○ ○ ○ ____________
F ○ ○ ○ ____________
____

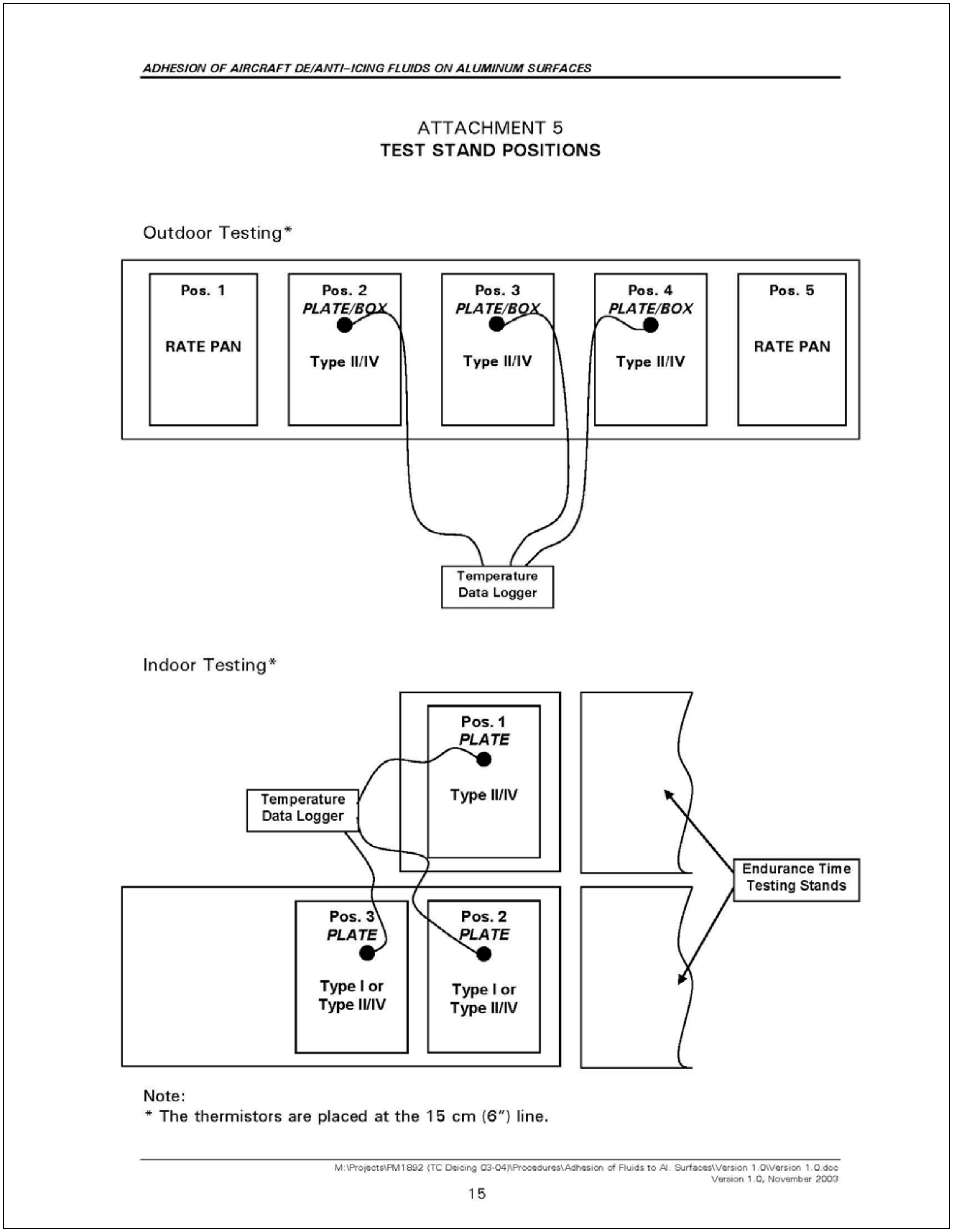
t =
1 2 3
B ○ ○ ○ ____________
C ○ ○ ○ ____________
D ○ ○ ○ ____________
E ○ ○ ○ ____________
F ○ ○ ○ ____________
____

t =
1 2 3
B ○ ○ ○ ____________
C ○ ○ ○ ____________
D ○ ○ ○ ____________
E ○ ○ ○ ____________
F ○ ○ ○ ____________
____

t =
1 2 3
B ○ ○ ○ ____________
C ○ ○ ○ ____________
D ○ ○ ○ ____________
E ○ ○ ○ ____________
F ○ ○ ○ ____________
____

t =
1 2 3
B ○ ○ ○ ____________
C ○ ○ ○ ____________
D ○ ○ ○ ____________
E ○ ○ ○ ____________
F ○ ○ ○ ____________
____

t =
1 2 3
B ○ ○ ○ ____________
C ○ ○ ○ ____________
D ○ ○ ○ ____________
E ○ ○ ○ ____________
F ○ ○ ○ ____________
____



ATTACHMENT 5
TEST STAND POSITIONS

Outdoor Testing*

Indoor Testing*

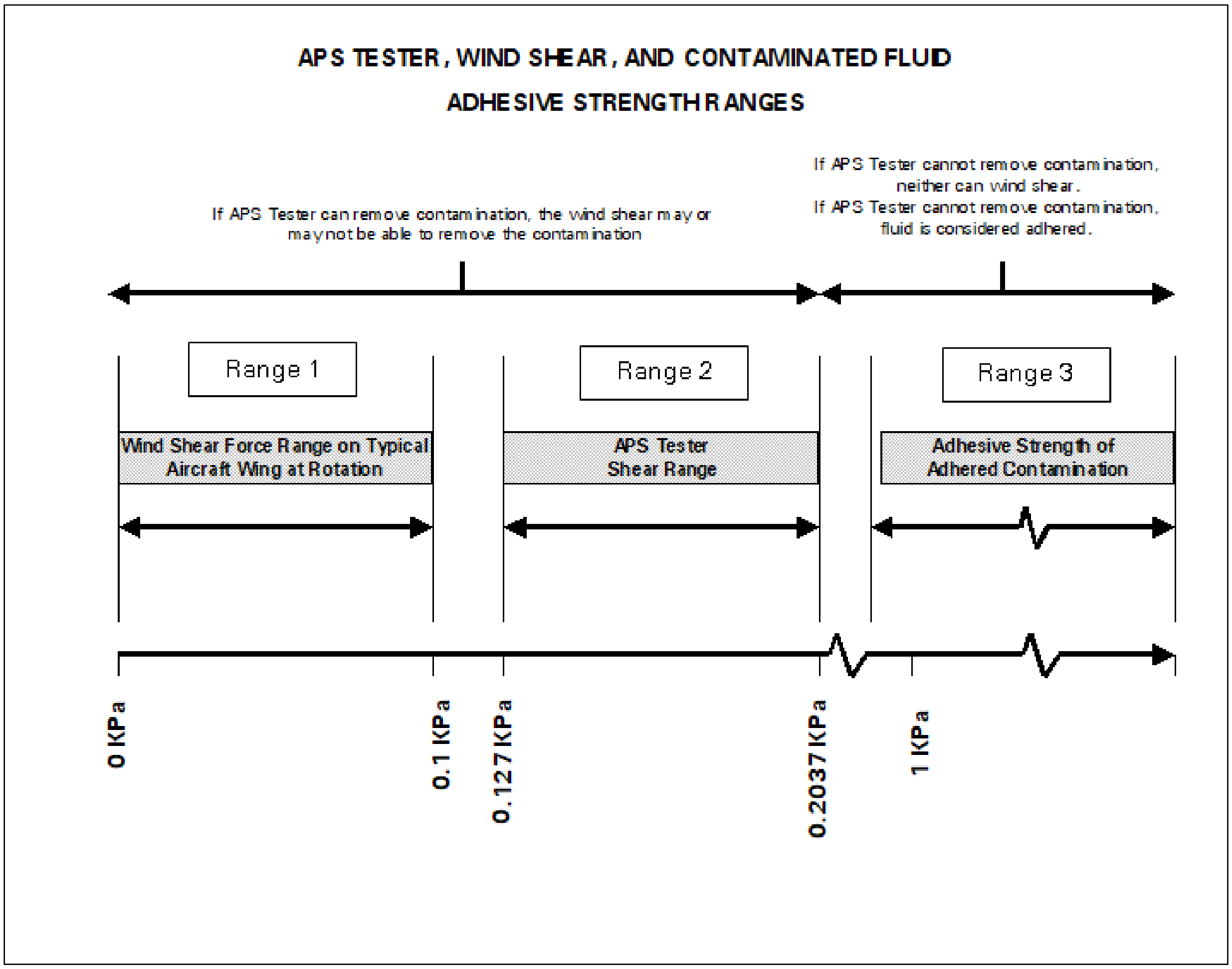
Note:
* The thermistors are placed at the 15 cm (6") line.

APPENDIX C

ANALYSIS OF INSTRUMENT THAT MEASURES ADHESION

ANALYSIS OF ADHERENCE TESTER

The adherence tester exerts a shearing force in the range 1.274×10^{-4} to 2.037×10^{-4} MPa. Under contract to the Transportation Development Centre of Transport Canada, Optima Specialty Chemicals and Technology Inc. undertook in 1995-96 a study to investigate the adhesion of freezing precipitates to de/anti-iced and non-deiced aircraft surfaces. According to this study, the maximum wind shearing force acting on the wing is equal to 1×10^{-4} MPa, and the adhesive strength of ice and failed de/anti-icing fluids is of the order 10^{-3} to 10^{-1} MPa. Therefore, the tester shearing force is almost equal to the wind shearing force when compared to the failed fluid adhesive strength. In the Figure below, APS tester agrees with Optima results in the first range because both the tester and the wind will shear off the failed de/anti-icing fluid. Also in range 3, the tester and the wind cannot shear off the failed fluid. Range number 2 is an indeterminate region where the tester may shear off the failed fluid but the wind will not.



Adherence Tester Force Analysis

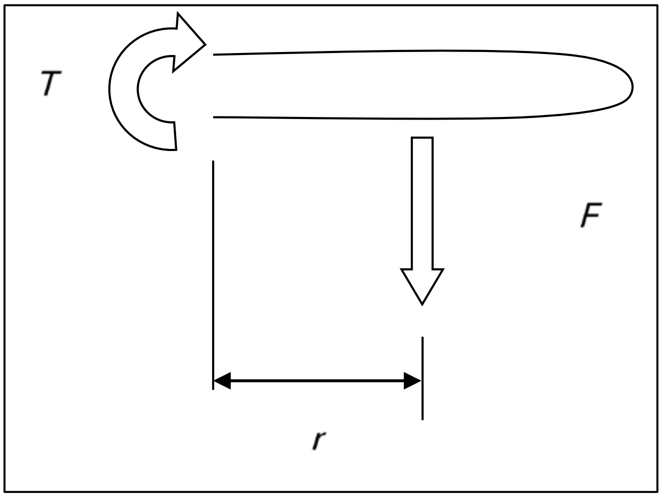
The Adherence Tester exerts a force on the ice particle through the filament. This force can be calculated from the tester motor ratings; namely, the output power, P_{out}, and the shaft rotational speed, ω,

$$P_{out} = T.\omega$$

The above equation gives the shaft torque, *T*, which can be used to find the adherence force, *F*, used to shear off the ice particle,

$$F = \frac{T}{r}$$

where *r* is the torque arm. The figure below illustrates the torque and force on the filament.



The shearing stress is equal to the force divided by the area over which the filament operates

$$\tau = \frac{F}{A} = \frac{F}{\pi(2r)^2}$$

The output power and rotational speed provided by the tester manufacturer are:

P_{out} = 1 Watt and ω = 6500 Hz

Therefore, the torque is

$$T = \frac{1\ W}{6500\ \ Hz * \dfrac{2\pi\ \ rad}{1\ \ revolution}} = 2.45 * 10^{-5}\, N.m$$

The load on the filament is a uniform load. This load can be considered as a concentrated force acting at the average filament radius, $r = 2.5$ mm. Therefore, the shearing force is

$$F = \frac{2.45 * 10^{-5}\, N.m}{2.5 * 10^{-3}\, m} = 0.0098\ \ N$$

and the shearing stress is

$$\tau = \frac{0.0098\ \ N}{\pi * (2 * 2.5 * 10^{-3})^2\, m^2} = 124.8\ \ Pa = 1.248\ \ MPa$$

The above is the theoretical value. If the same analysis was done using the forces obtained from the electric balance, the shearing stress would be in the range 1.274×10^{-4} to 2.037×10^{-4} MPa.

Notes:

(1) It should be noted that the elasticity of the filament is a source of error in the force measurement using the electric balance.

(2) An electric balance of 0.2 g accuracy was used to verify the calculations.

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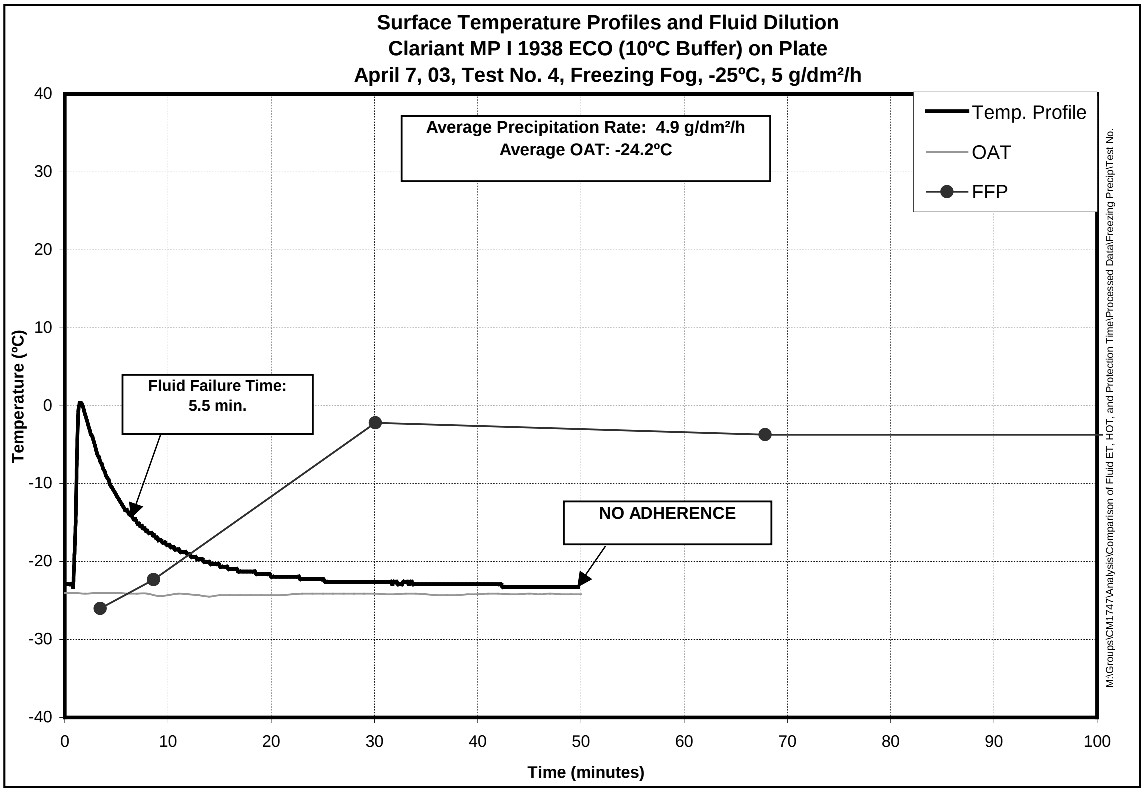
APPENDIX D

GRAPHS OF TEST RESULTS

- Simulated Freezing Precipitation
- Natural Snow, Artificial Snow, Natural Freezing Drizzle

SIMULATED FREEZING PRECIPITATION


Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Plate
April 7, 03, Test No. 4, Freezing Fog, -25ºC, 5 g/dm²/h
Average Precipitation Rate: 4.9 g/dm²/h
Average OAT: -24.2ºC
Temp. Profile
OAT
FFP
Fluid Failure Time:
5.5 min.
NO ADHERENCE
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70
80
90
100
Time (minutes)
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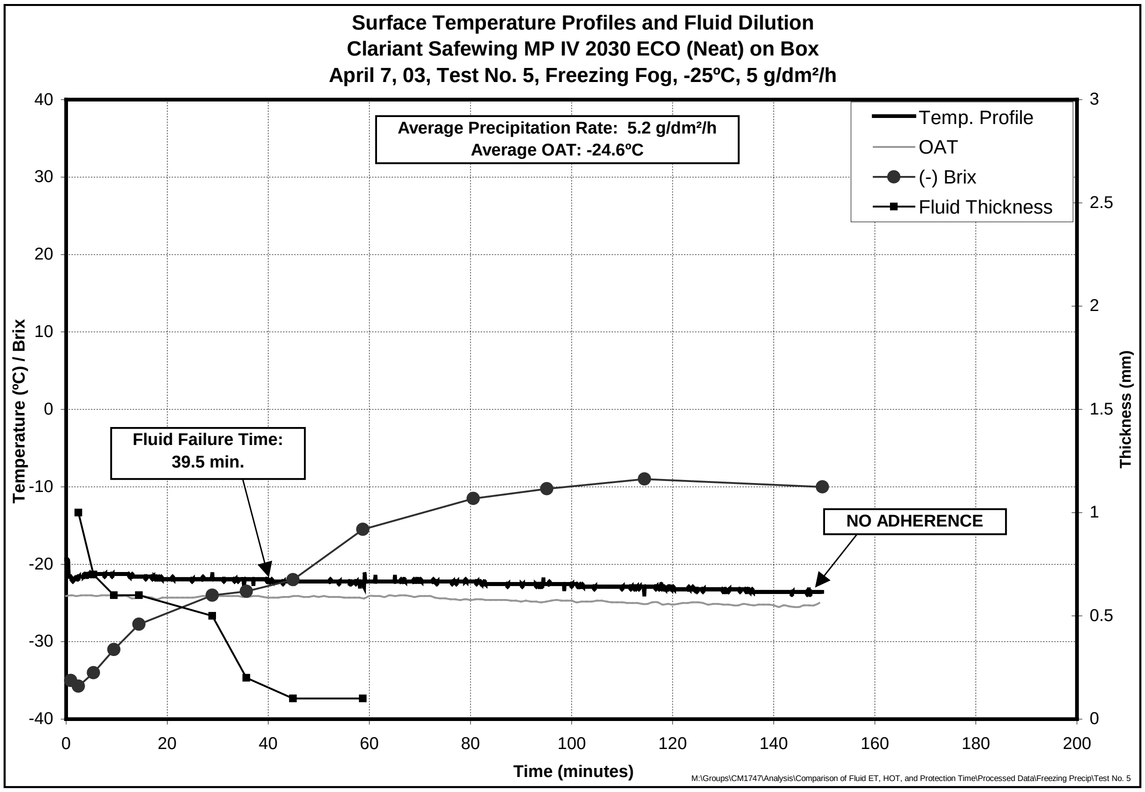
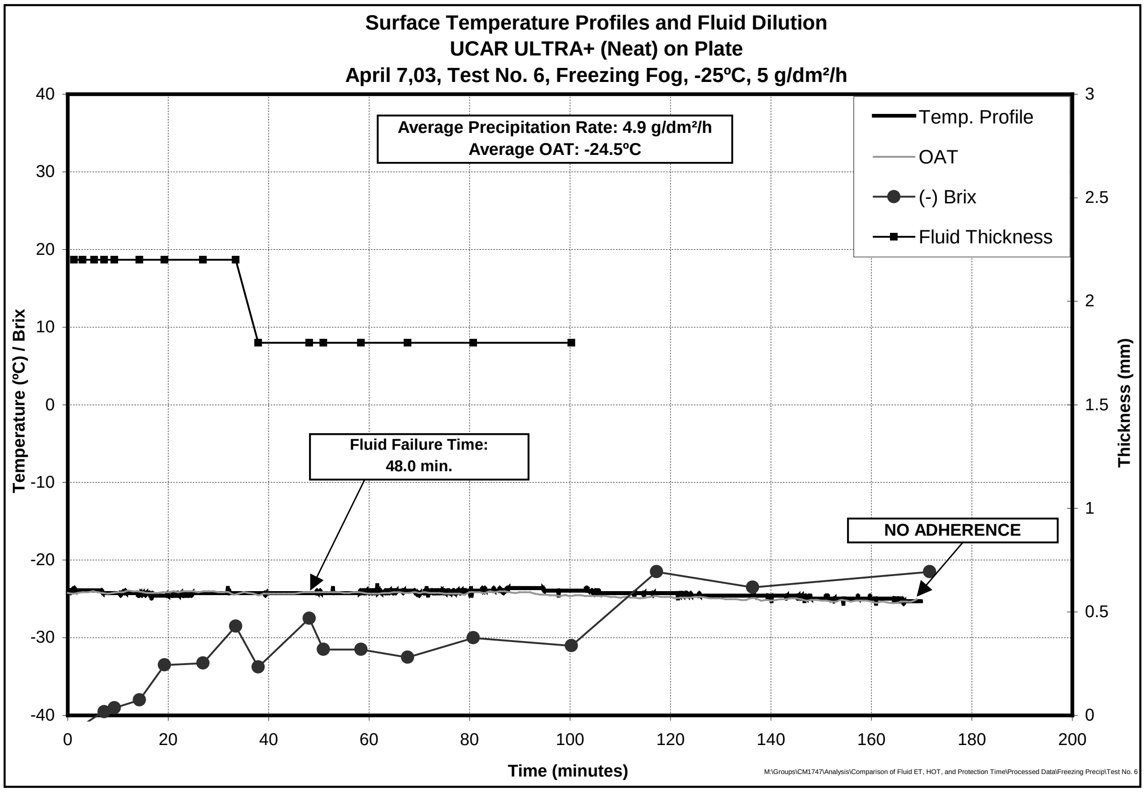

Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (Neat) on Box
April 7, 03, Test No. 5, Freezing Fog, -25ºC, 5 g/dm²/h
Average Precipitation Rate: 5.2 g/dm²/h
Average OAT: -24.6ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time:
39.5 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 5



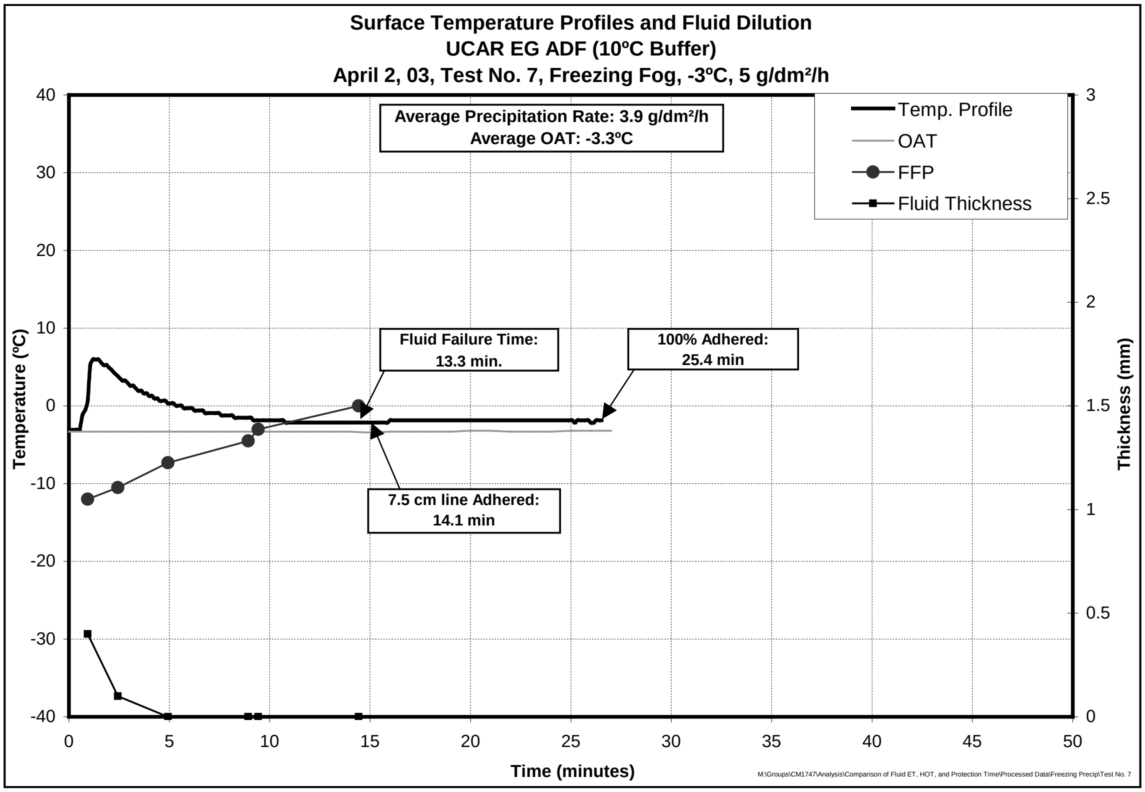
Surface Temperature Profiles and Fluid Dilution
UCAR ULTRA+ (Neat) on Plate
April 7,03, Test No. 6, Freezing Fog, -25ºC, 5 g/dm²/h

Average Precipitation Rate: 4.9 g/dm²/h
Average OAT: -24.5ºC

Fluid Failure Time:
48.0 min.

NO ADHERENCE

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 6



Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer)
April 2, 03, Test No. 7, Freezing Fog, -3ºC, 5 g/dm²/h

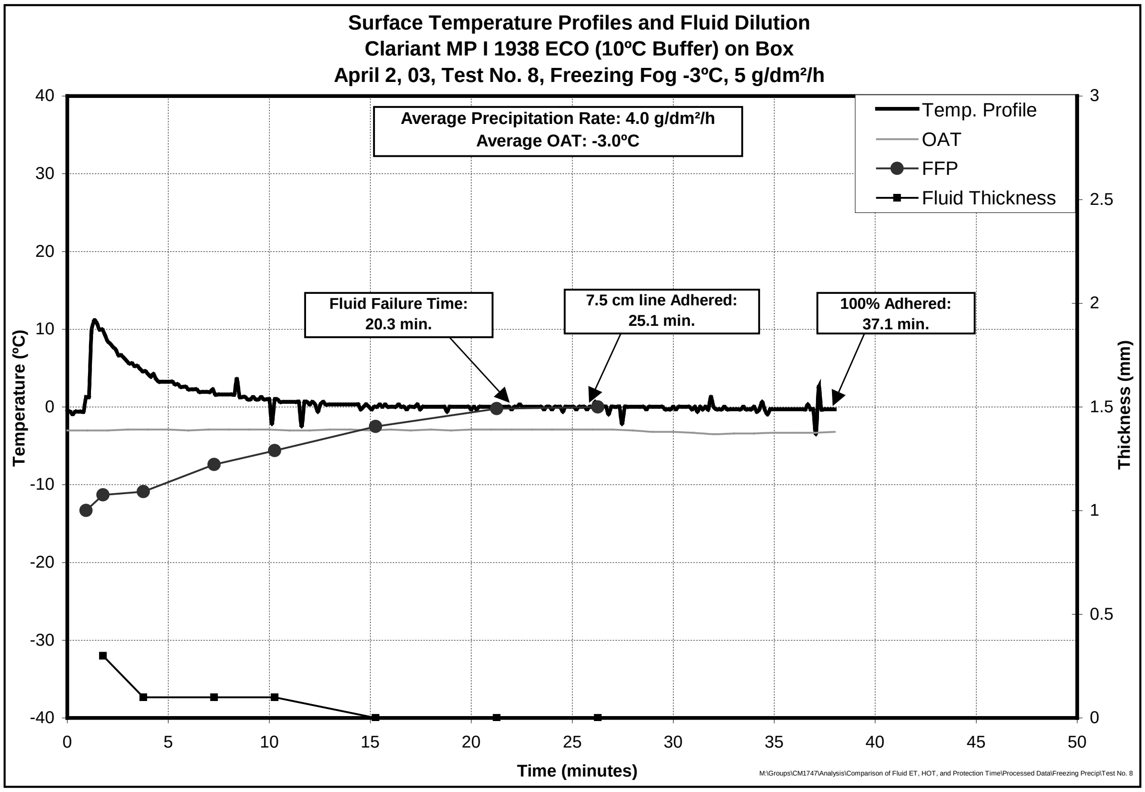
Average Precipitation Rate: 3.9 g/dm²/h
Average OAT: -3.3ºC

Fluid Failure Time:
13.3 min.

100% Adhered:
25.4 min

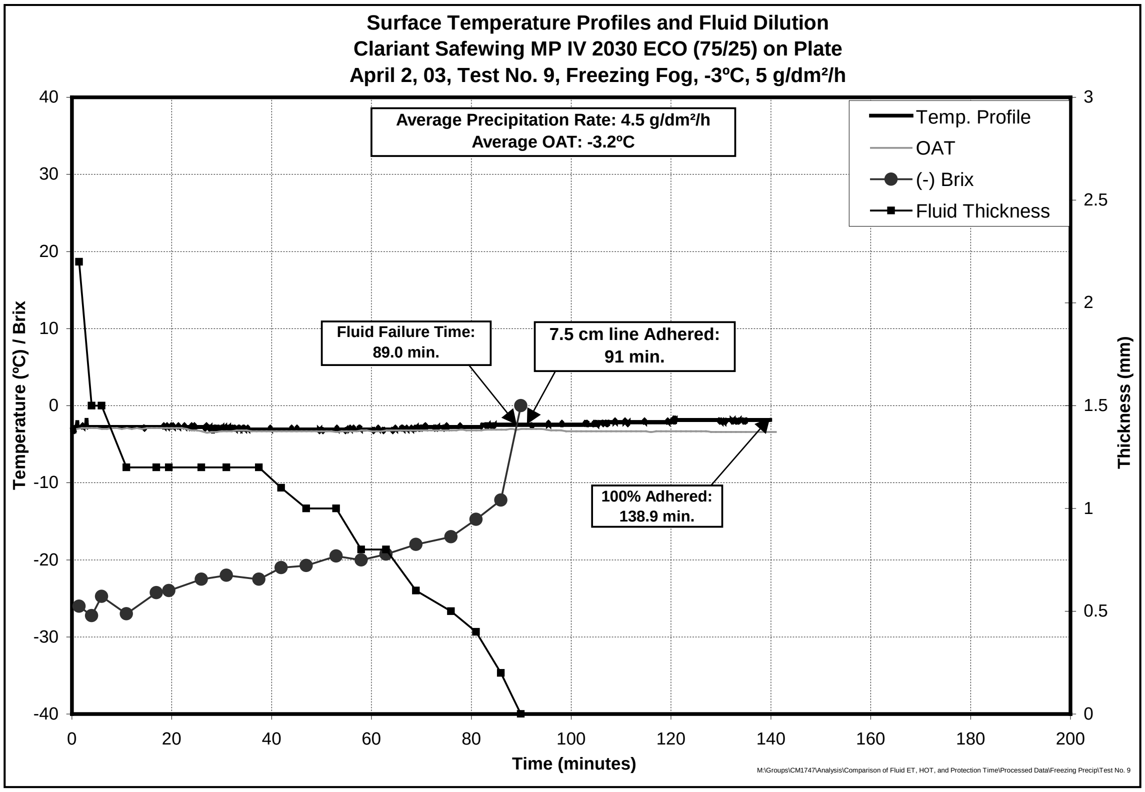
7.5 cm line Adhered:
14.1 min

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 7



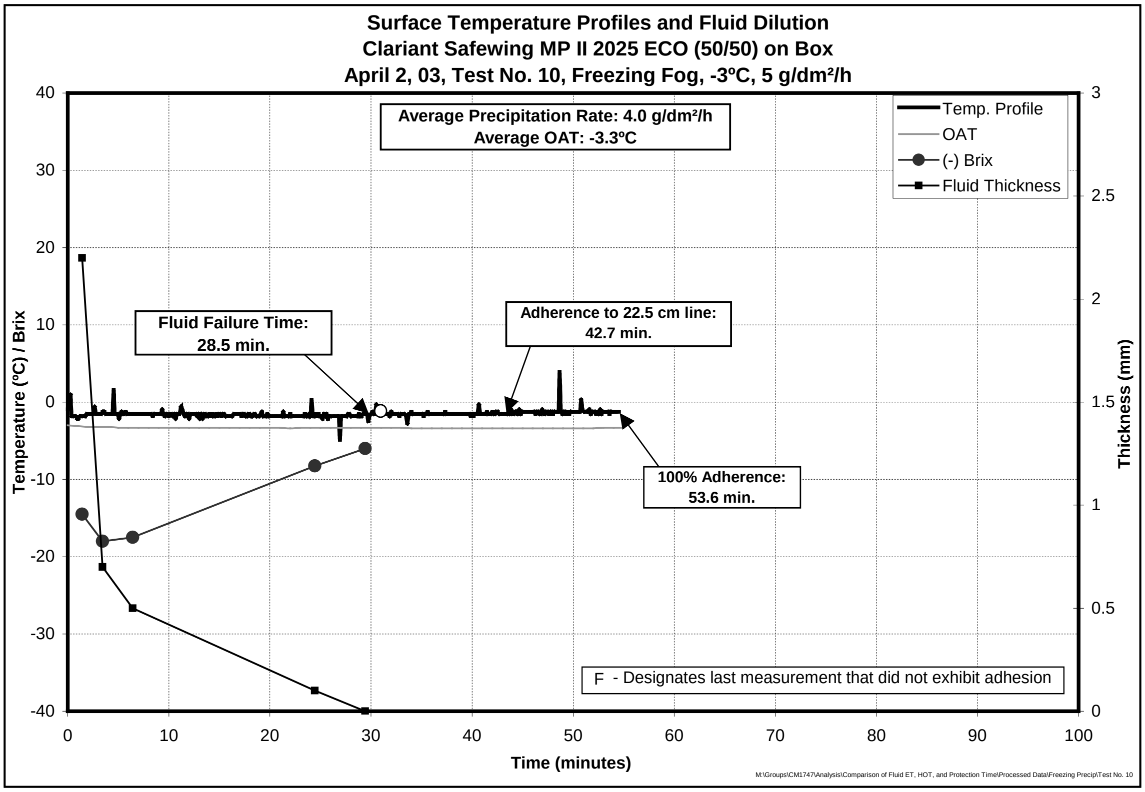
Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Box
April 2, 03, Test No. 8, Freezing Fog -3ºC, 5 g/dm²/h

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 8



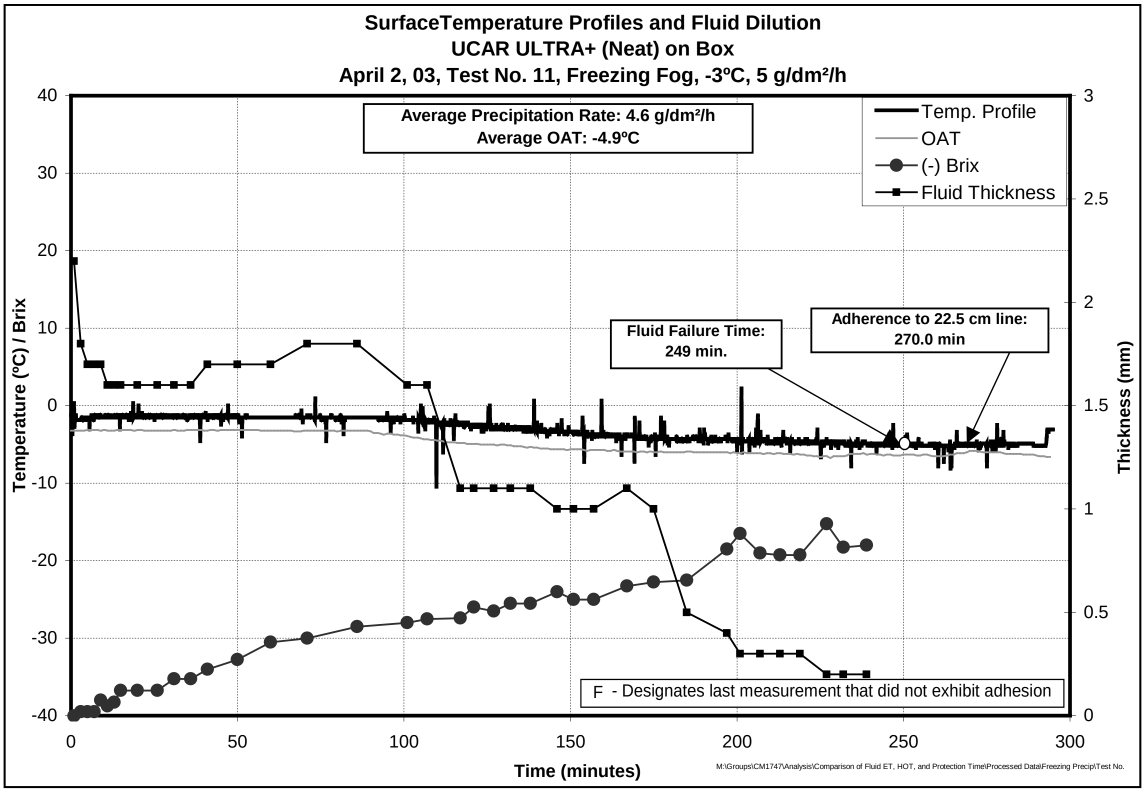
Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (75/25) on Plate
April 2, 03, Test No. 9, Freezing Fog, -3ºC, 5 g/dm²/h

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 9



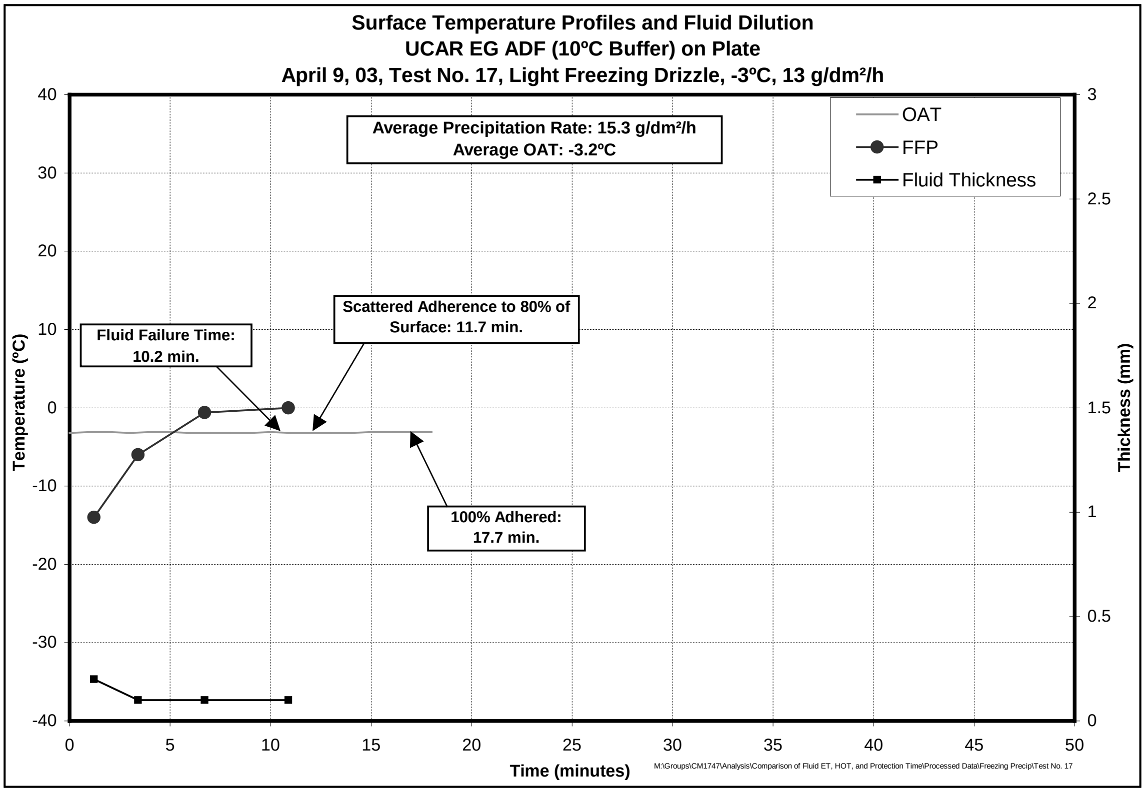
Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (50/50) on Box
April 2, 03, Test No. 10, Freezing Fog, -3ºC, 5 g/dm²/h

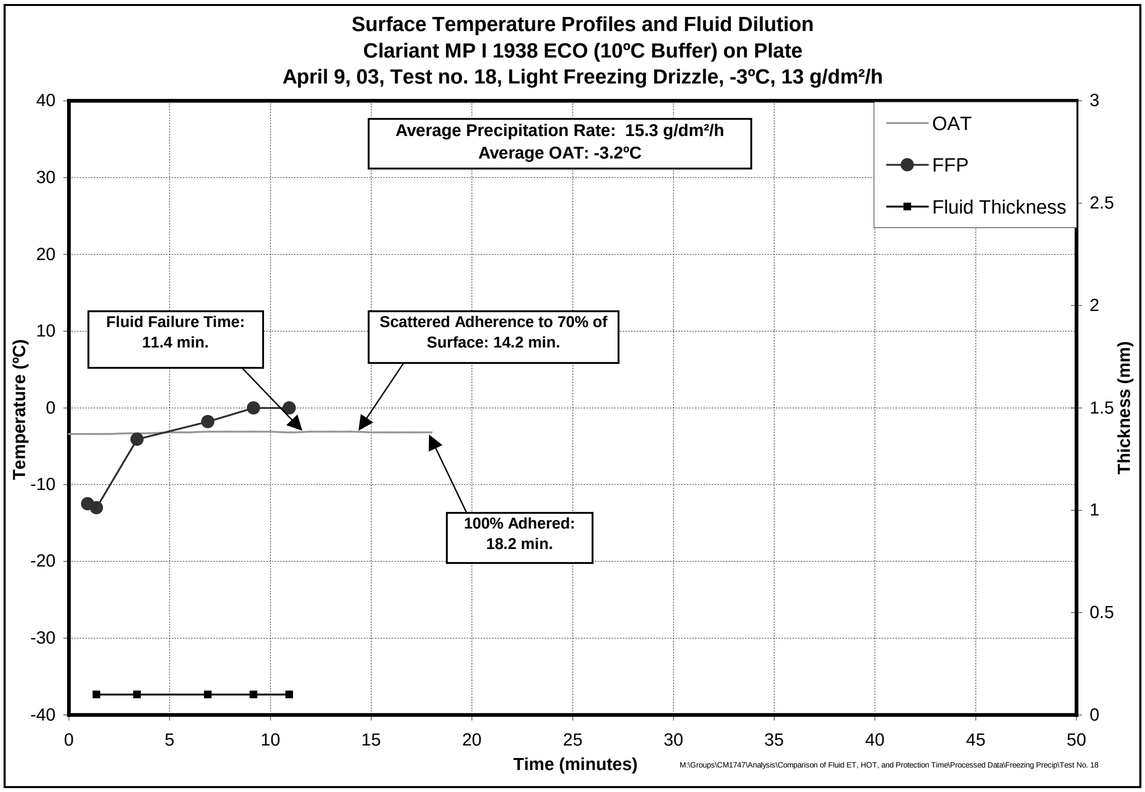
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 10

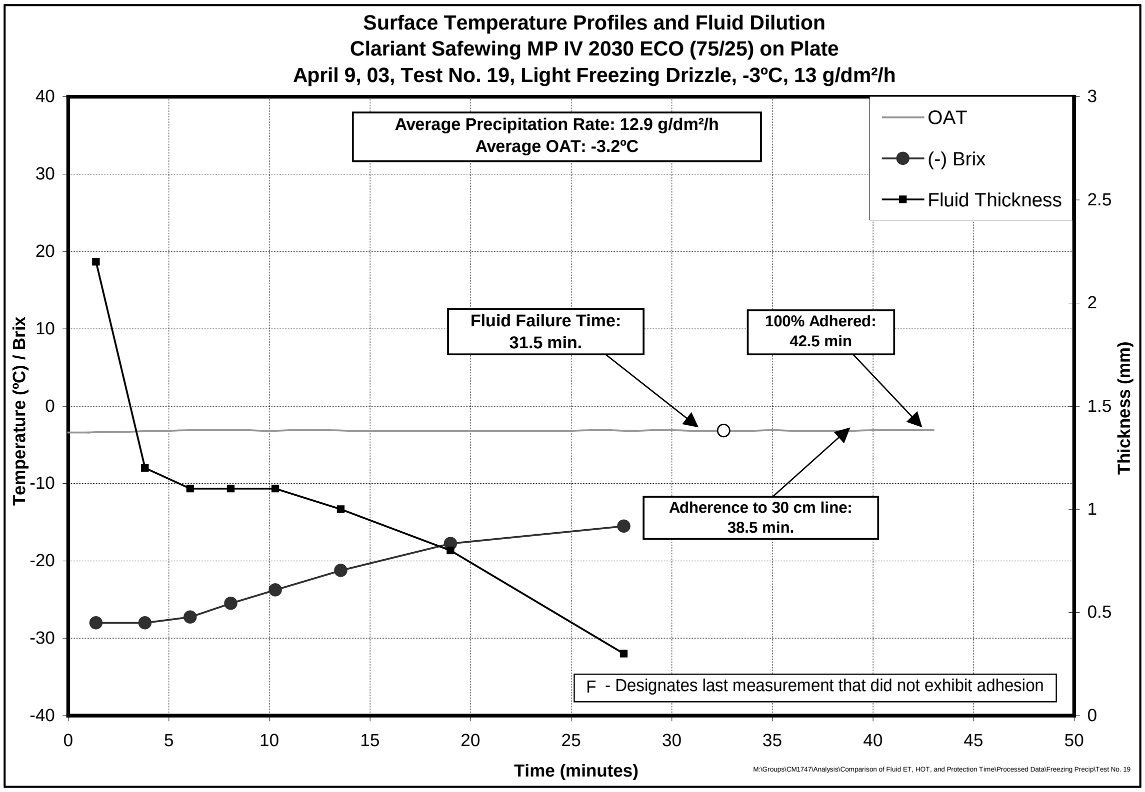


SurfaceTemperature Profiles and Fluid Dilution
UCAR ULTRA+ (Neat) on Box
April 2, 03, Test No. 11, Freezing Fog, -3ºC, 5 g/dm²/h

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No.


Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Plate
April 9, 03, Test No. 17, Light Freezing Drizzle, -3ºC, 13 g/dm²/h
Average Precipitation Rate: 15.3 g/dm²/h
Average OAT: -3.2ºC
OAT
FFP
Fluid Thickness
Fluid Failure Time: 10.2 min.
Scattered Adherence to 80% of Surface: 11.7 min.
100% Adhered: 17.7 min.
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
Time (minutes)
0
5
10
15
20
25
30
35
40
45
50
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 17


Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Plate
April 9, 03, Test no. 18, Light Freezing Drizzle, -3ºC, 13 g/dm²/h
Average Precipitation Rate: 15.3 g/dm²/h
Average OAT: -3.2ºC
OAT
FFP
Fluid Thickness
Fluid Failure Time: 11.4 min.
Scattered Adherence to 70% of Surface: 14.2 min.
100% Adhered: 18.2 min.
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
Time (minutes)
0
5
10
15
20
25
30
35
40
45
50
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 18



Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (75/25) on Plate
April 9, 03, Test No. 19, Light Freezing Drizzle, -3ºC, 13 g/dm²/h

Average Precipitation Rate: 12.9 g/dm²/h
Average OAT: -3.2ºC

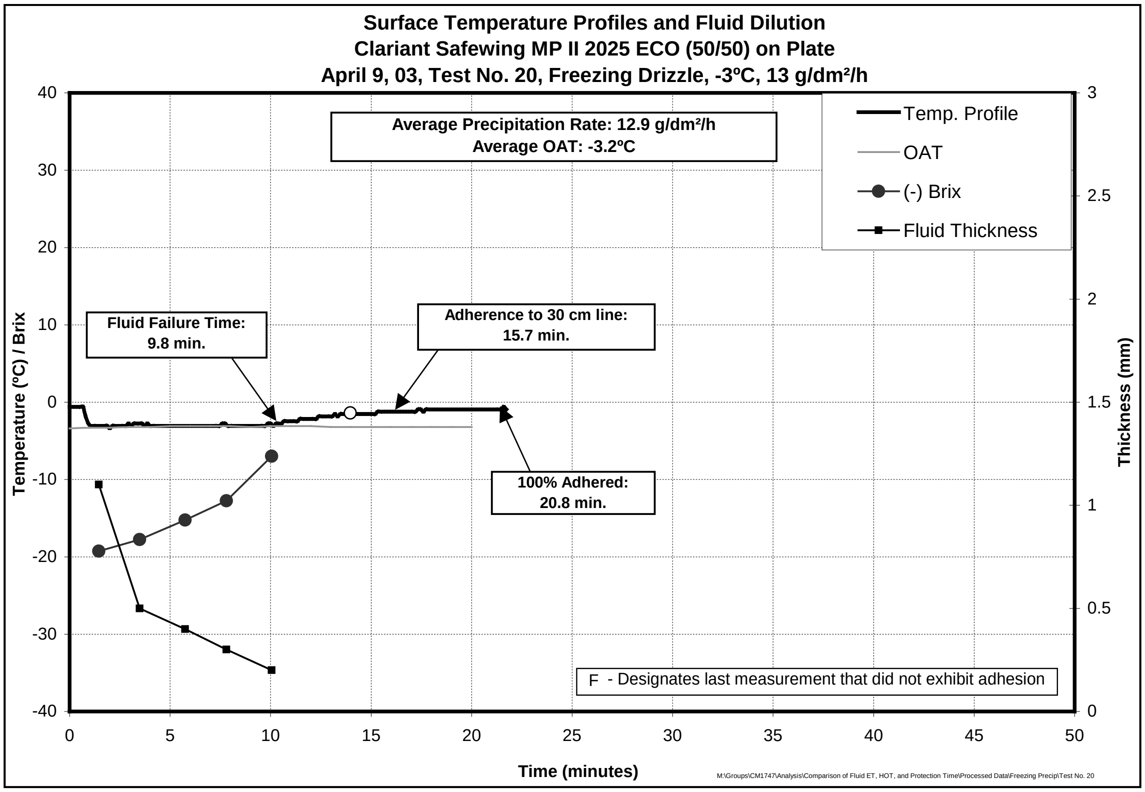
Fluid Failure Time: 31.5 min.

100% Adhered: 42.5 min

Adherence to 30 cm line: 38.5 min.

F - Designates last measurement that did not exhibit adhesion

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 19



Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (50/50) on Plate
April 9, 03, Test No. 20, Freezing Drizzle, -3ºC, 13 g/dm²/h

Average Precipitation Rate: 12.9 g/dm²/h
Average OAT: -3.2ºC

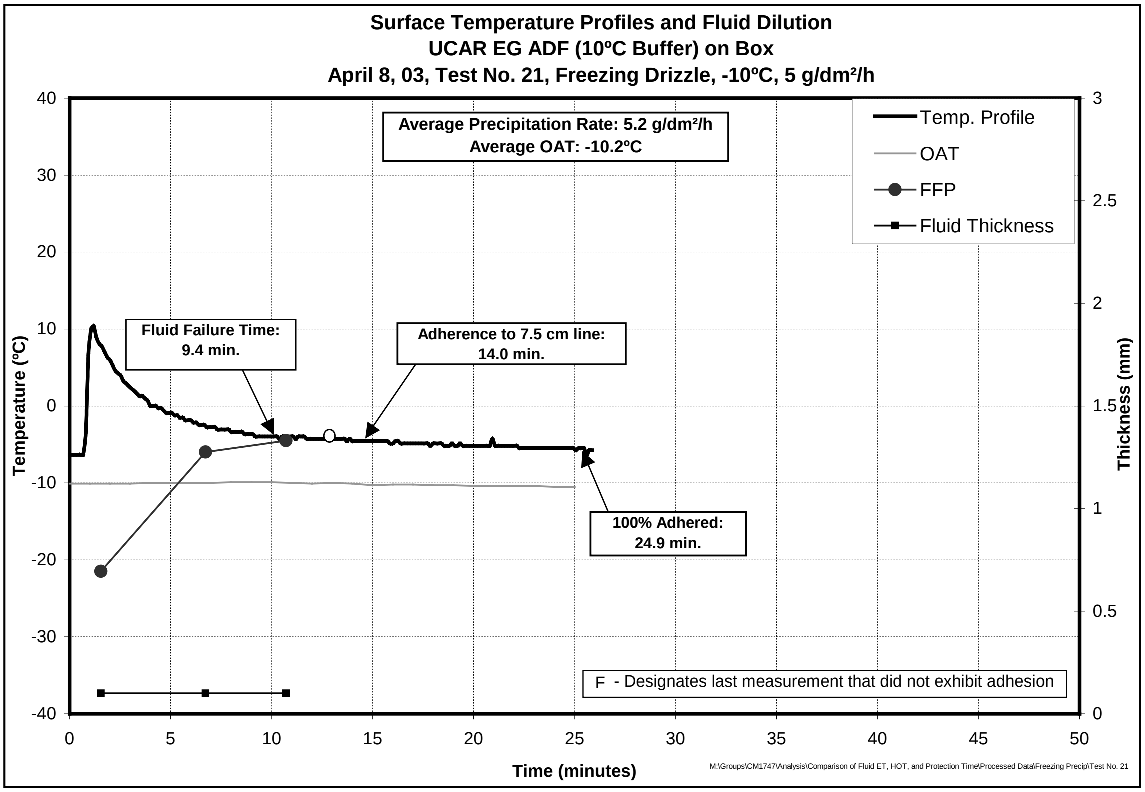
Fluid Failure Time: 9.8 min.

Adherence to 30 cm line: 15.7 min.

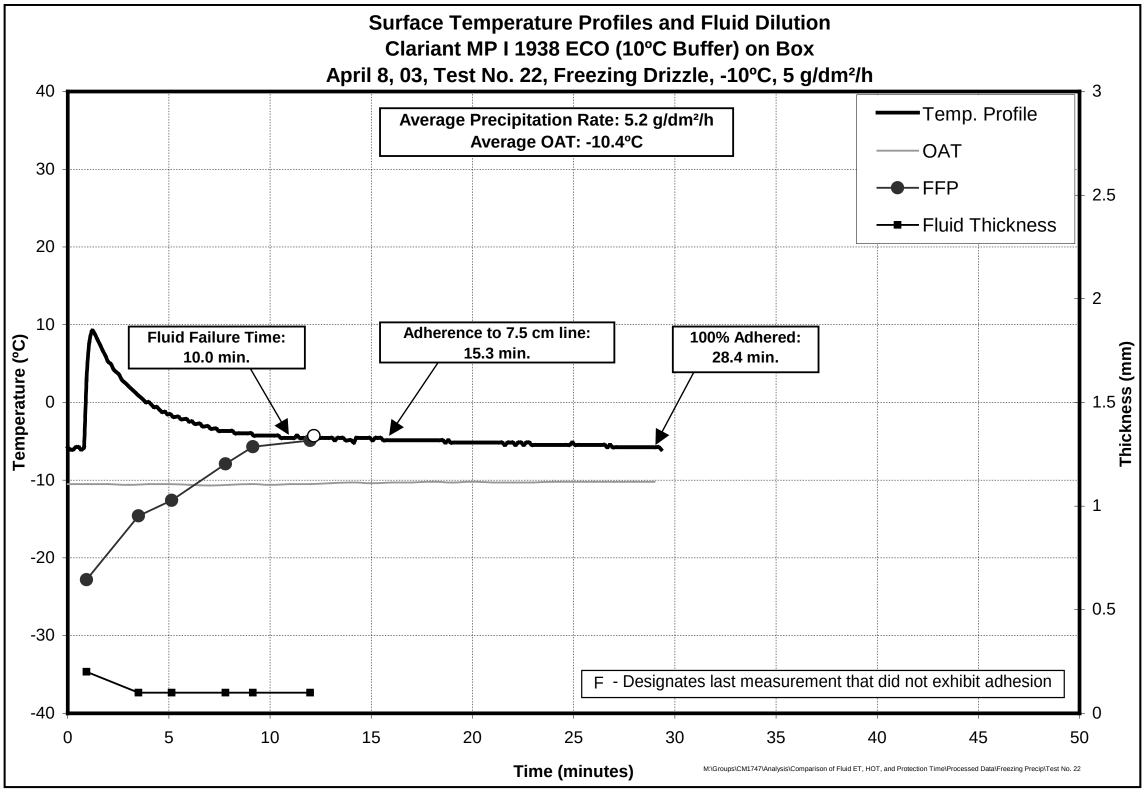
100% Adhered: 20.8 min.

F - Designates last measurement that did not exhibit adhesion

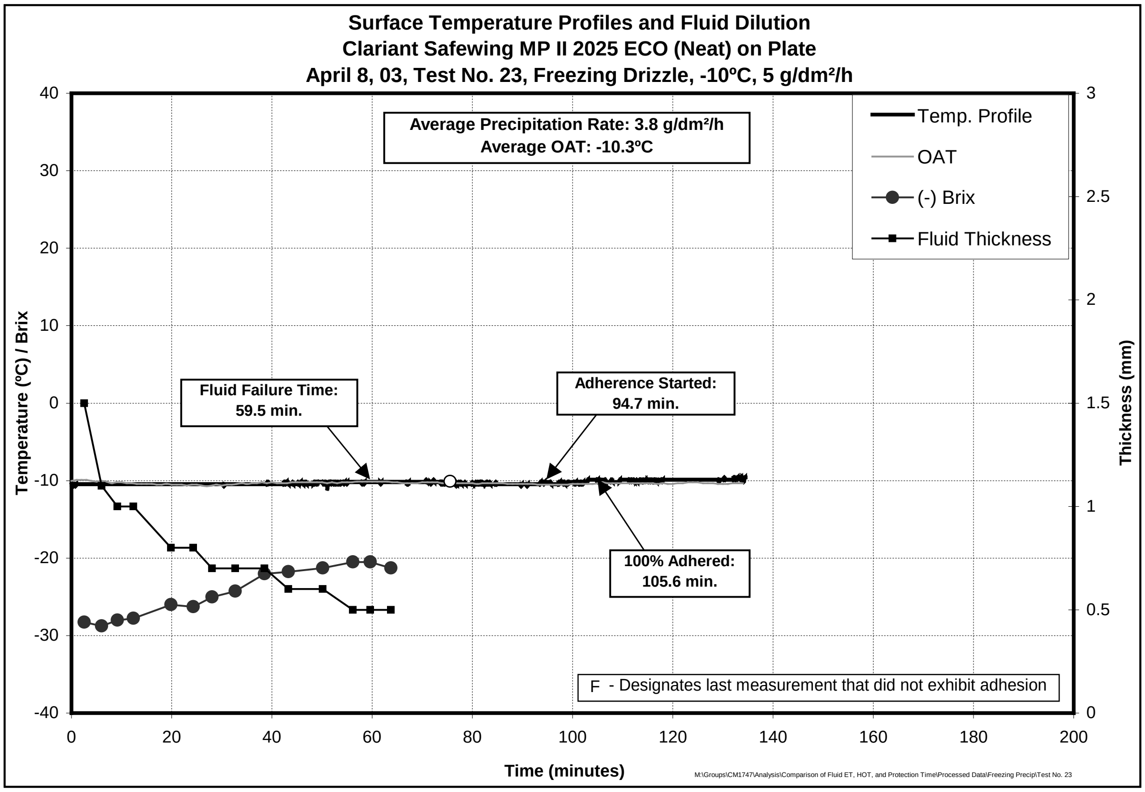
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 20

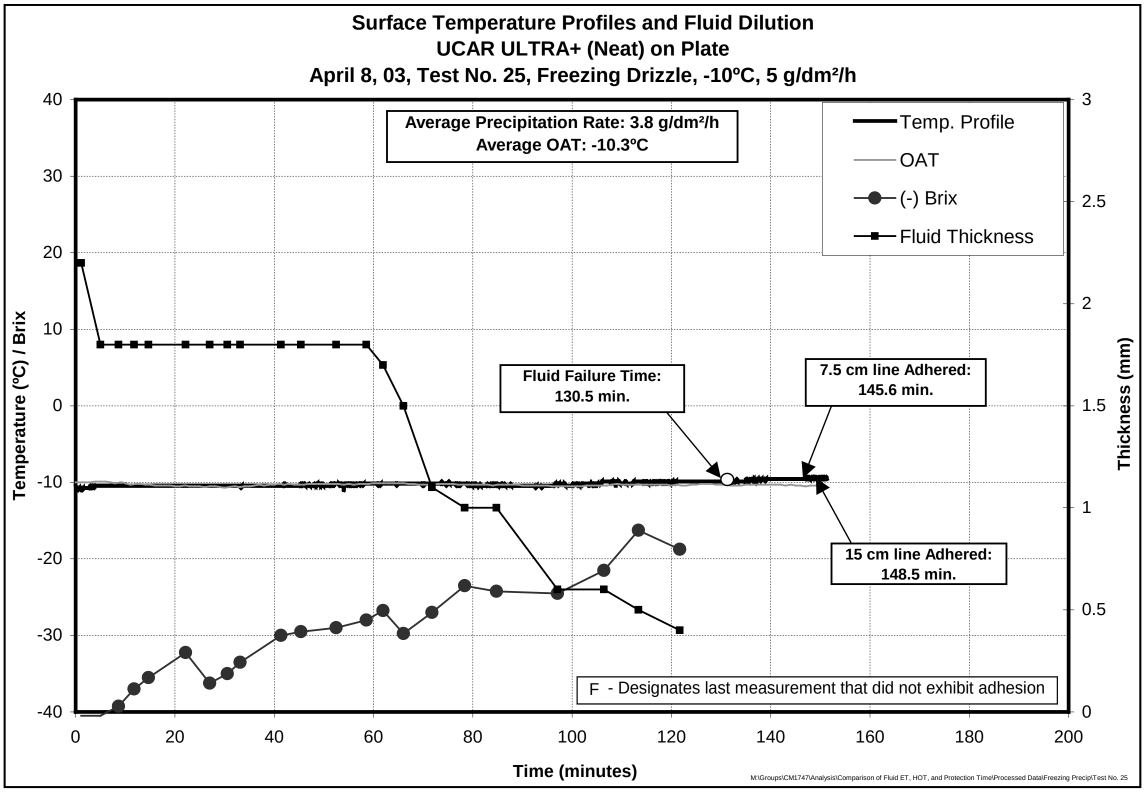


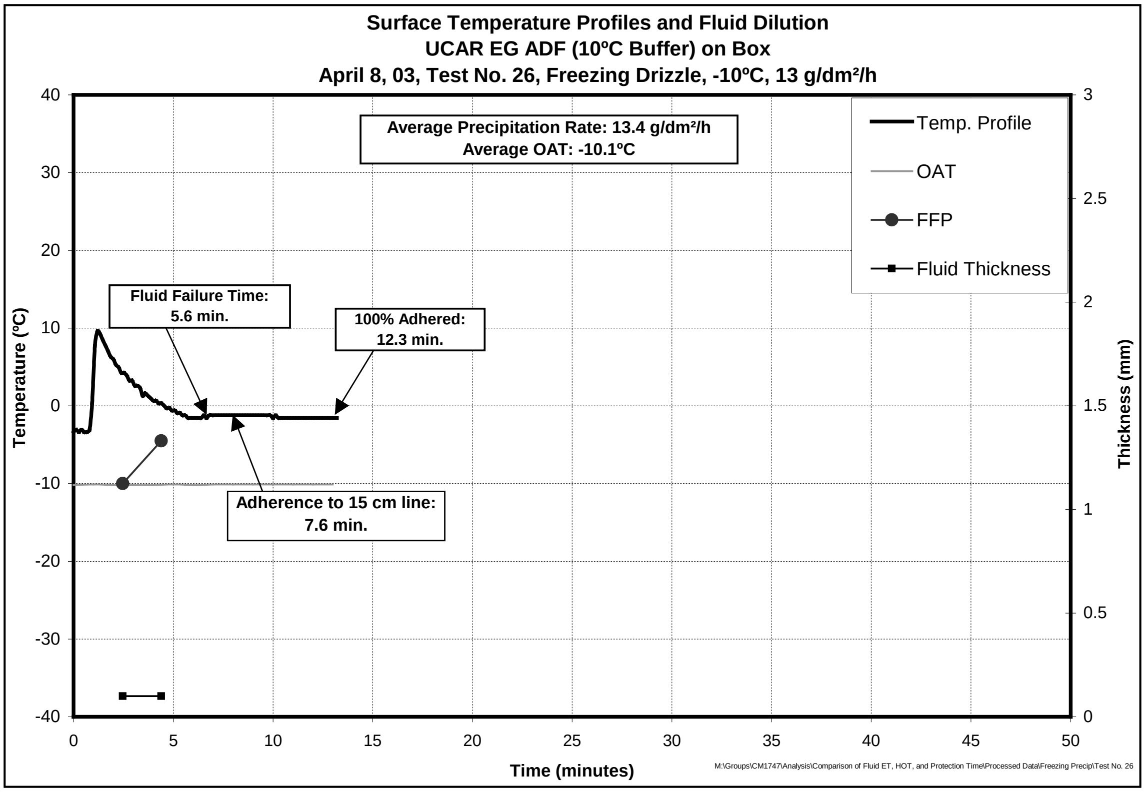
Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Box
April 8, 03, Test No. 21, Freezing Drizzle, -10ºC, 5 g/dm²/h



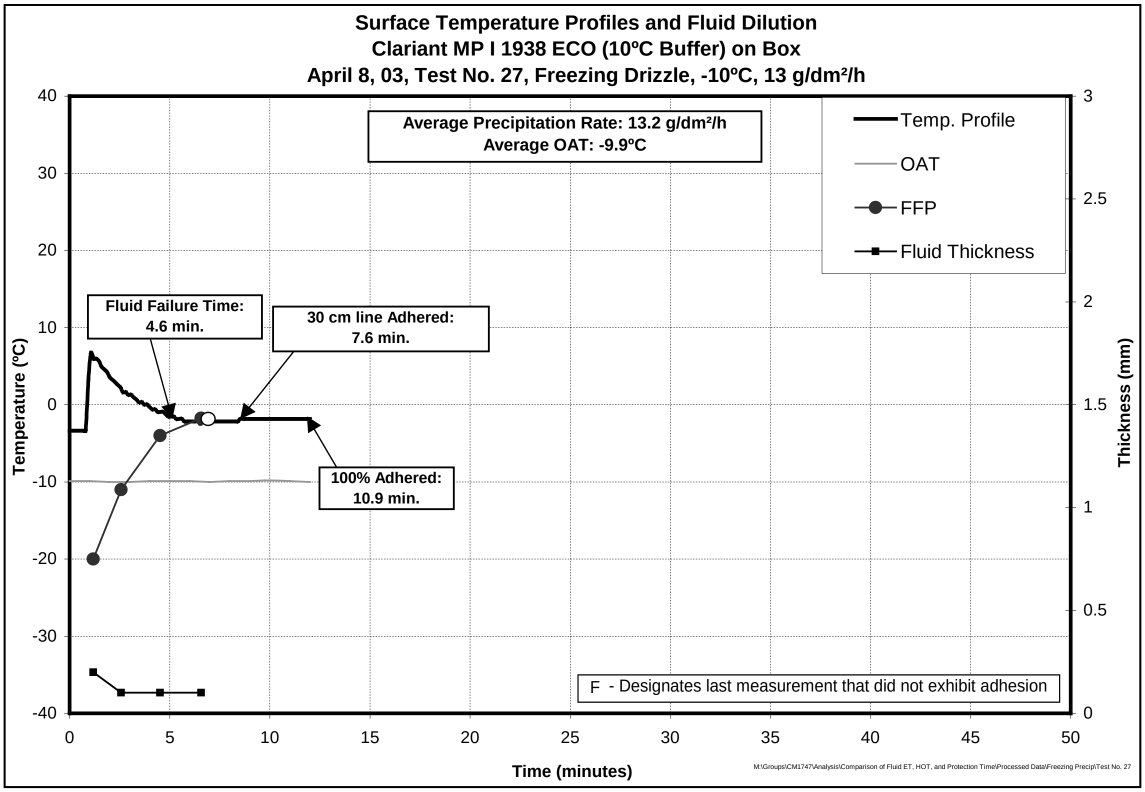
Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Box
April 8, 03, Test No. 22, Freezing Drizzle, -10ºC, 5 g/dm²/h


Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (Neat) on Plate
April 8, 03, Test No. 23, Freezing Drizzle, -10ºC, 5 g/dm²/h
Average Precipitation Rate: 3.8 g/dm²/h
Average OAT: -10.3ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 59.5 min.
Adherence Started: 94.7 min.
100% Adhered: 105.6 min.
F - Designates last measurement that did not exhibit adhesion
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 23

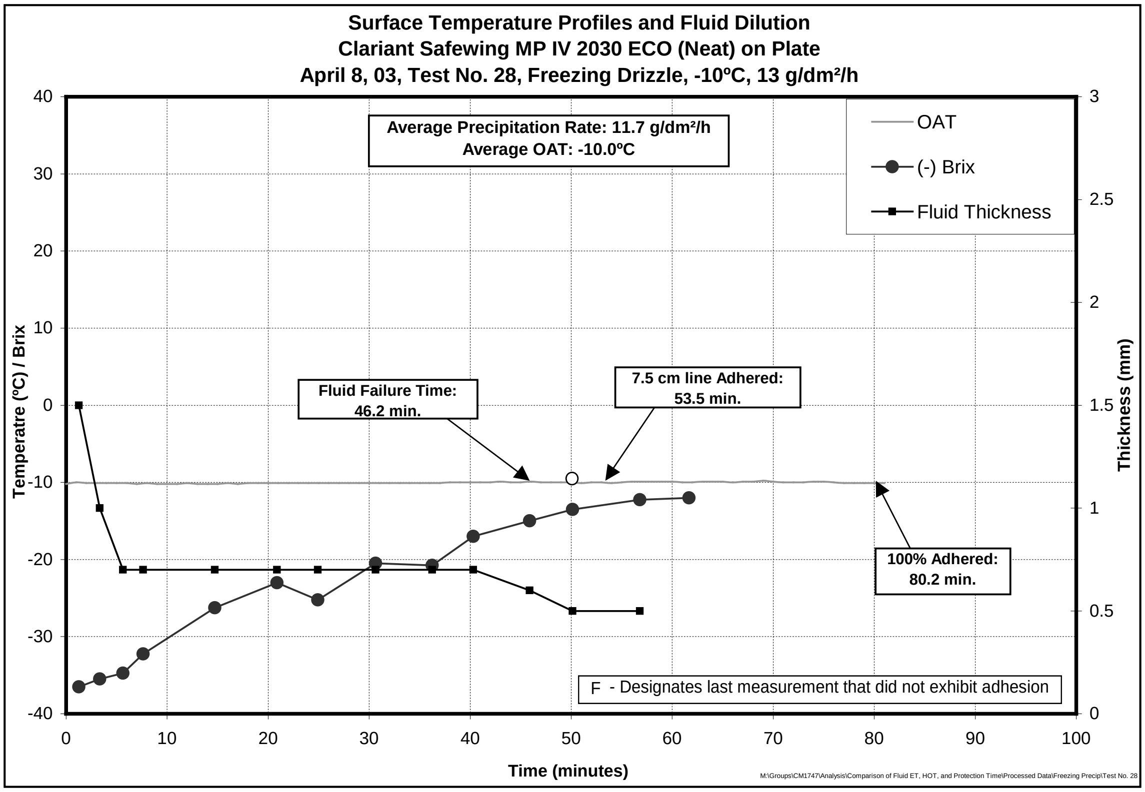

Surface Temperature Profiles and Fluid Dilution
UCAR ULTRA+ (Neat) on Plate
April 8, 03, Test No. 25, Freezing Drizzle, -10ºC, 5 g/dm²/h
Average Precipitation Rate: 3.8 g/dm²/h
Average OAT: -10.3ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 130.5 min.
7.5 cm line Adhered: 145.6 min.
15 cm line Adhered: 148.5 min.
F - Designates last measurement that did not exhibit adhesion
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 25



Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Box
April 8, 03, Test No. 26, Freezing Drizzle, -10ºC, 13 g/dm²/h



Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Box
April 8, 03, Test No. 27, Freezing Drizzle, -10ºC, 13 g/dm²/h



Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (Neat) on Plate
April 8, 03, Test No. 28, Freezing Drizzle, -10ºC, 13 g/dm²/h

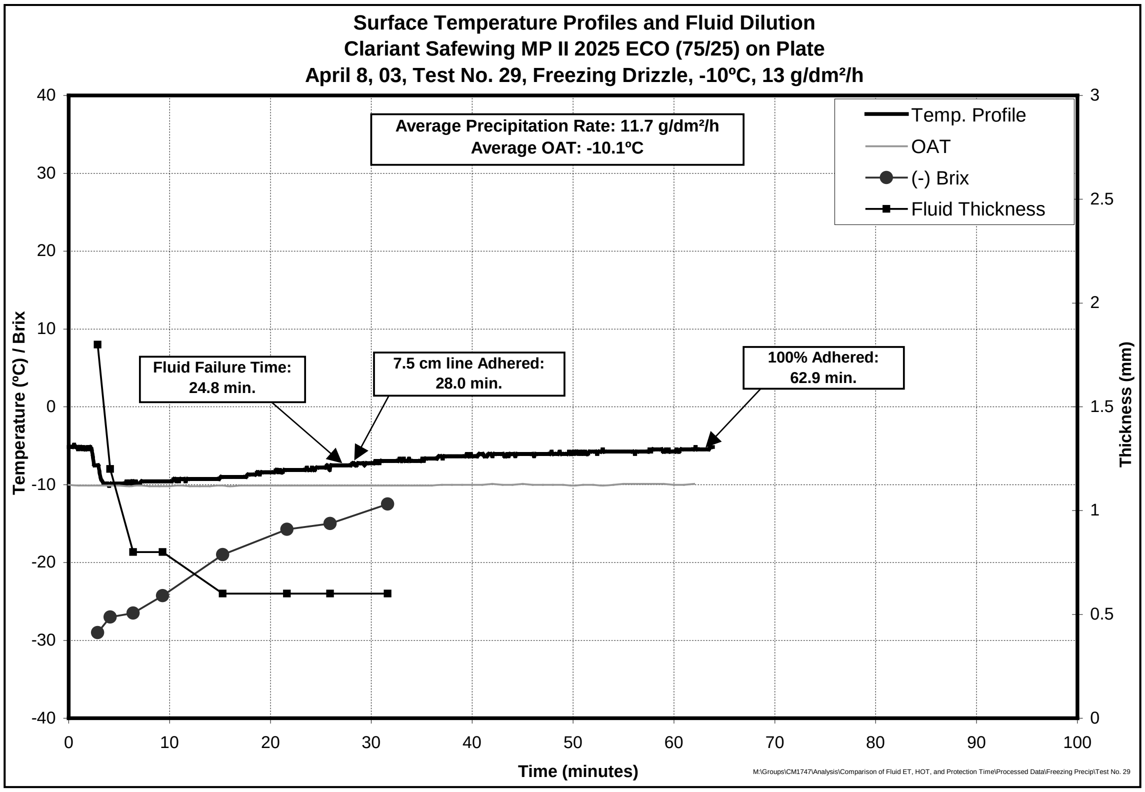
Average Precipitation Rate: 11.7 g/dm²/h
Average OAT: -10.0ºC

Fluid Failure Time:
46.2 min.

7.5 cm line Adhered:
53.5 min.

100% Adhered:
80.2 min.

F - Designates last measurement that did not exhibit adhesion



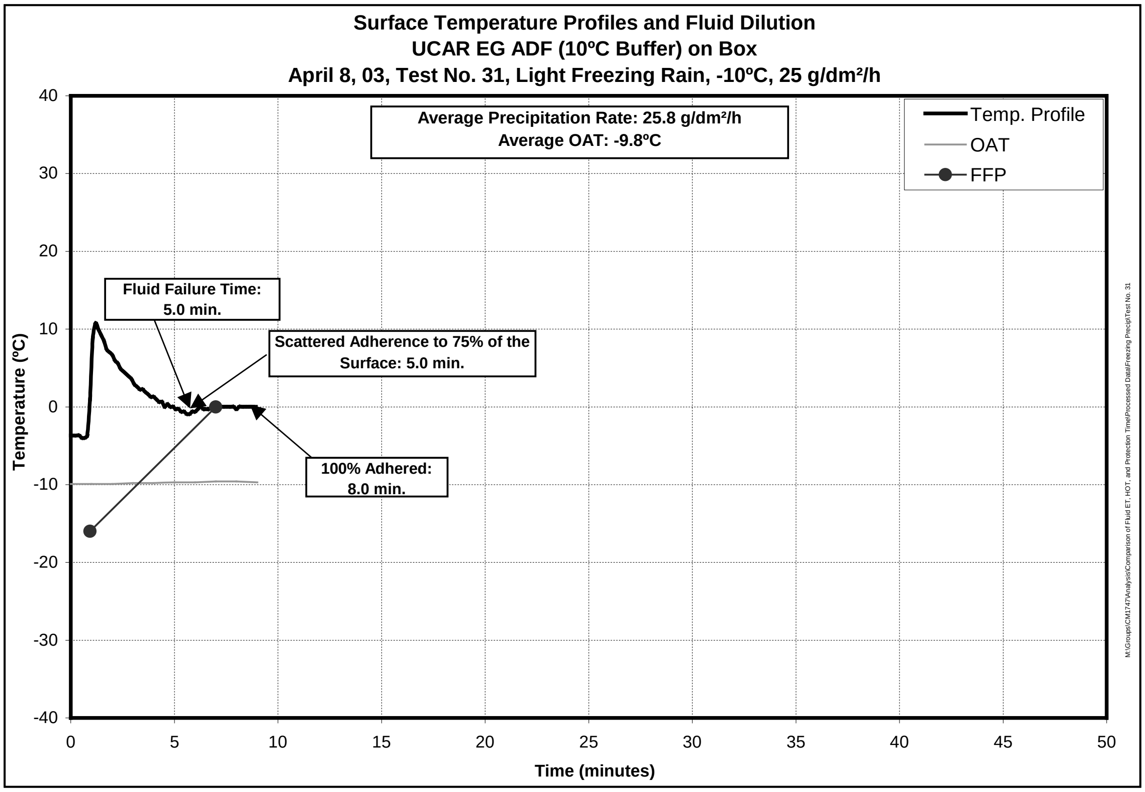
Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (75/25) on Plate
April 8, 03, Test No. 29, Freezing Drizzle, -10ºC, 13 g/dm²/h

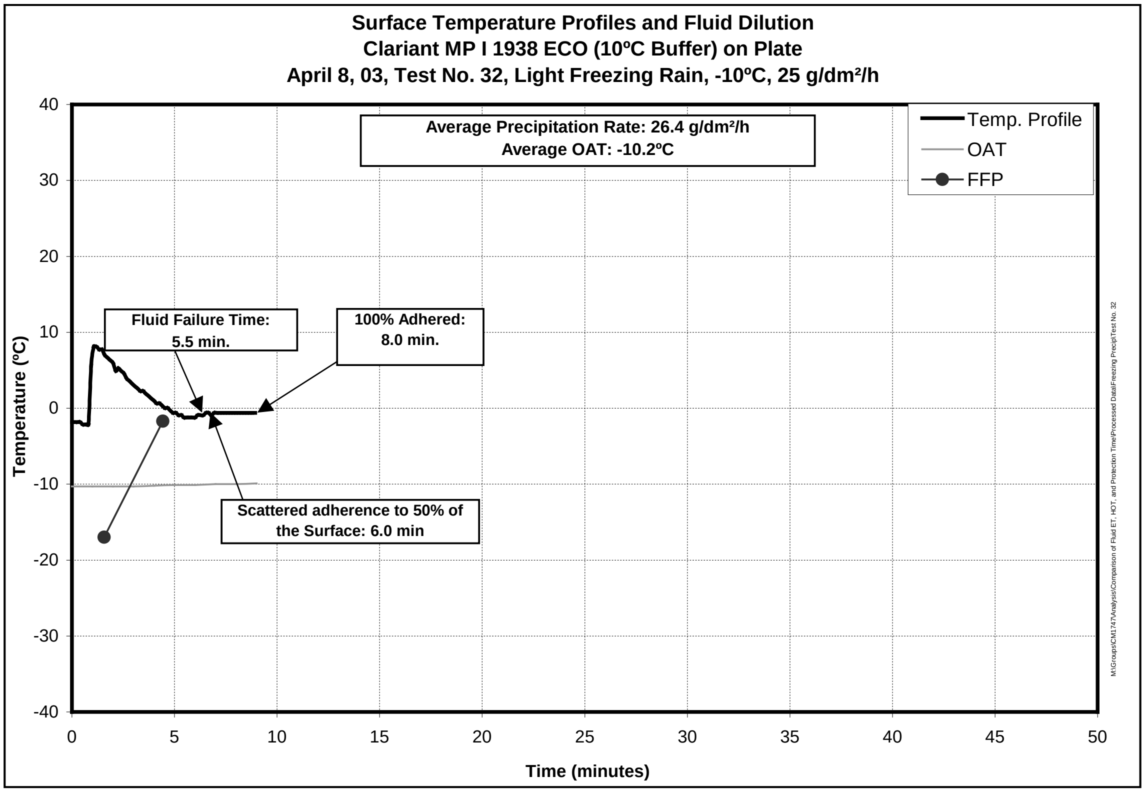
Average Precipitation Rate: 11.7 g/dm²/h
Average OAT: -10.1ºC

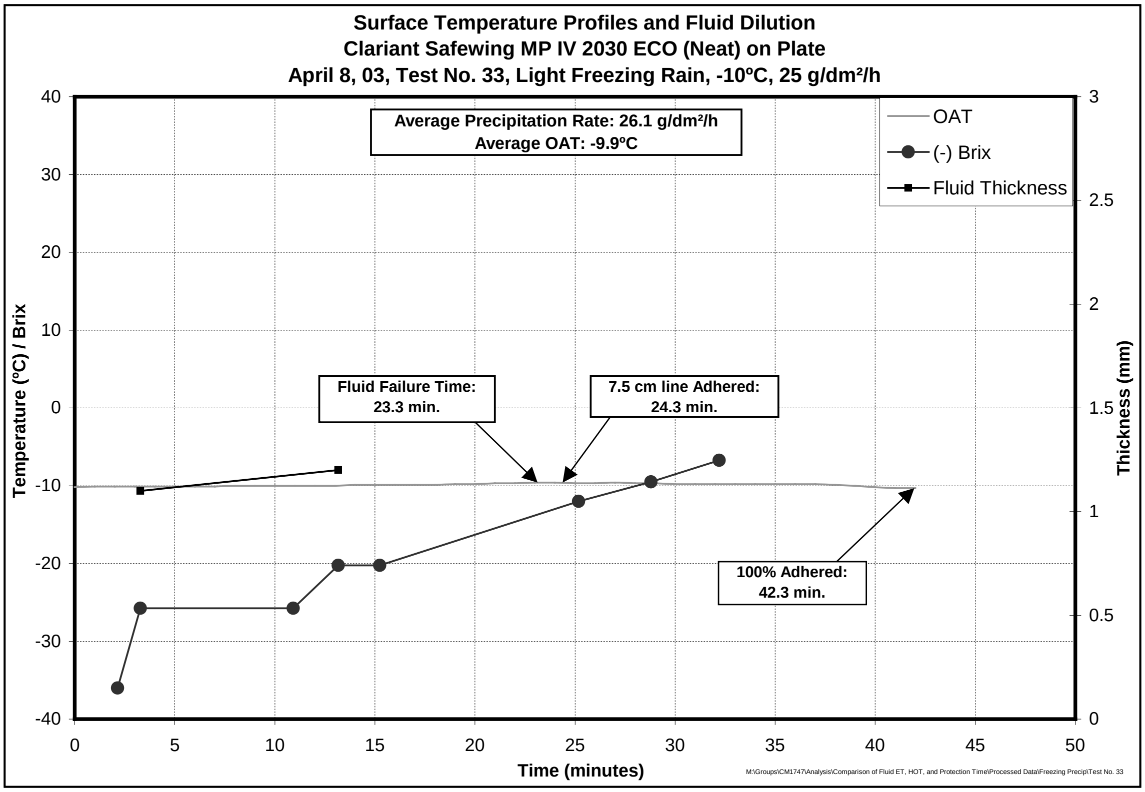
Fluid Failure Time:
24.8 min.

7.5 cm line Adhered:
28.0 min.

100% Adhered:
62.9 min.

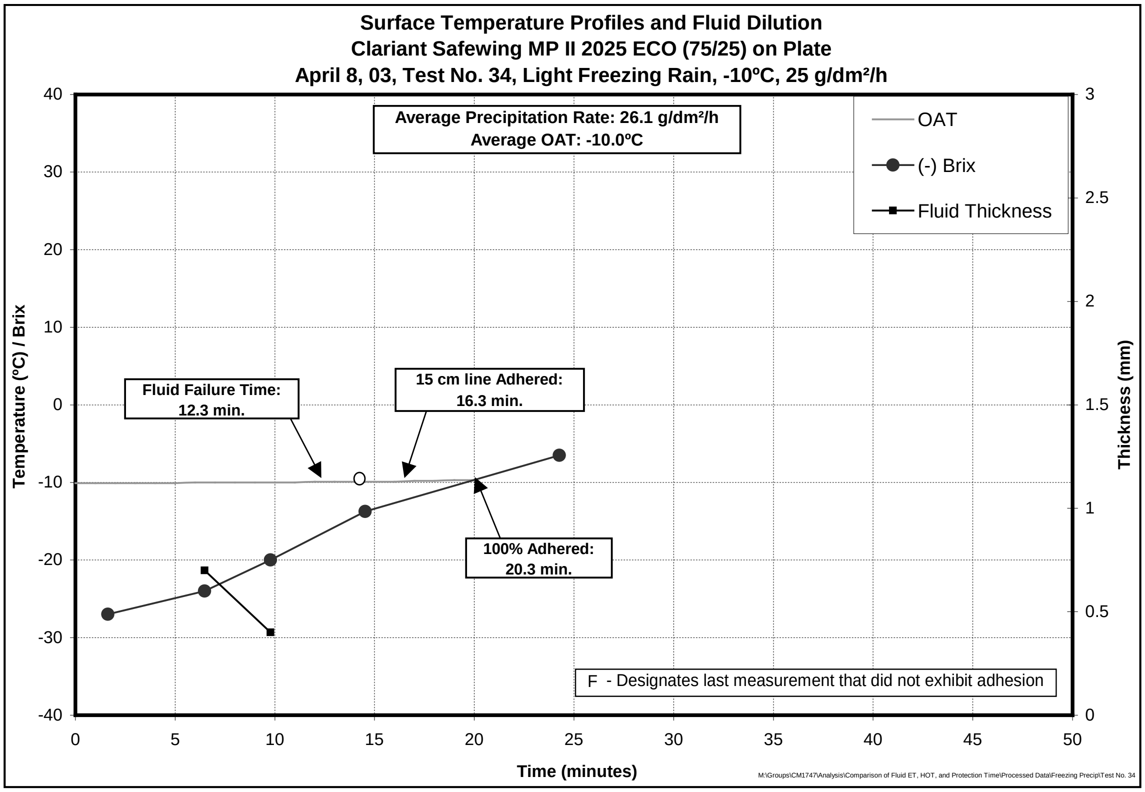

Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Box
April 8, 03, Test No. 31, Light Freezing Rain, -10ºC, 25 g/dm²/h
Average Precipitation Rate: 25.8 g/dm²/h
Average OAT: -9.8ºC
Temp. Profile
OAT
FFP
Fluid Failure Time: 5.0 min.
Scattered Adherence to 75% of the Surface: 5.0 min.
100% Adhered: 8.0 min.
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 31


Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Plate
April 8, 03, Test No. 32, Light Freezing Rain, -10ºC, 25 g/dm²/h
Average Precipitation Rate: 26.4 g/dm²/h
Average OAT: -10.2ºC
Temp. Profile
OAT
FFP
Fluid Failure Time: 5.5 min.
100% Adhered: 8.0 min.
Scattered adherence to 50% of the Surface: 6.0 min
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 32



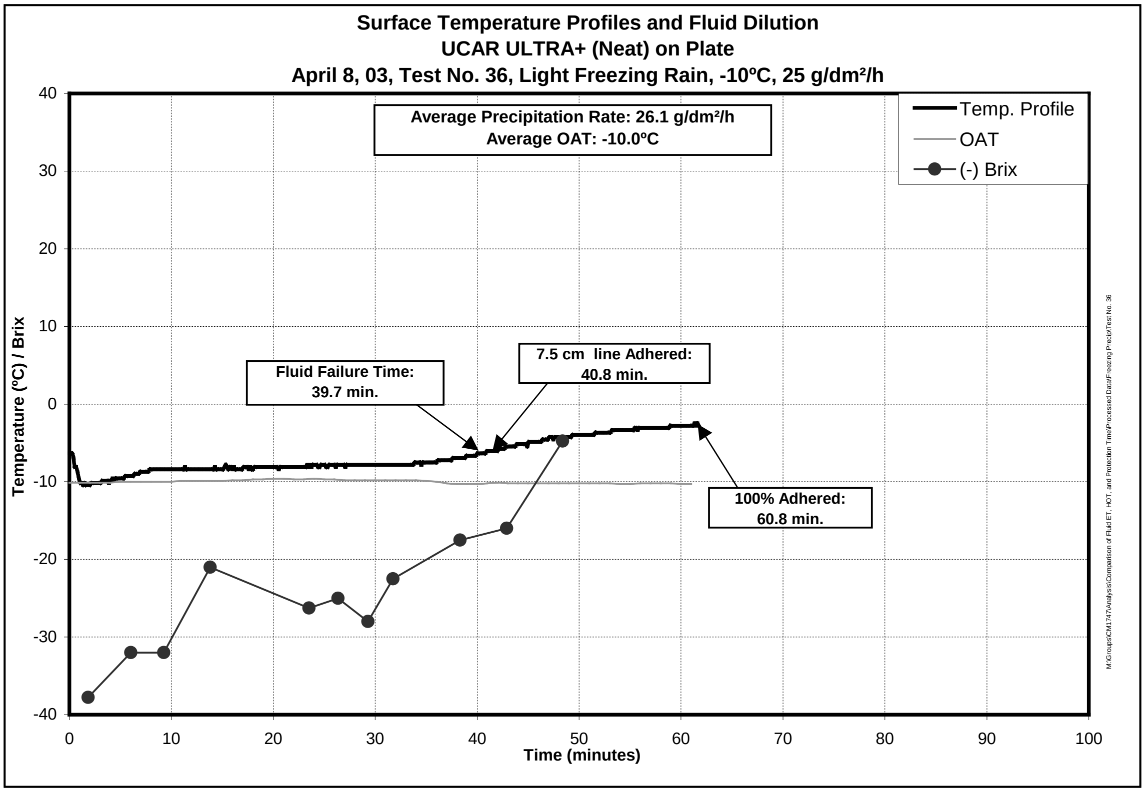
Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (Neat) on Plate
April 8, 03, Test No. 33, Light Freezing Rain, -10ºC, 25 g/dm²/h

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 33

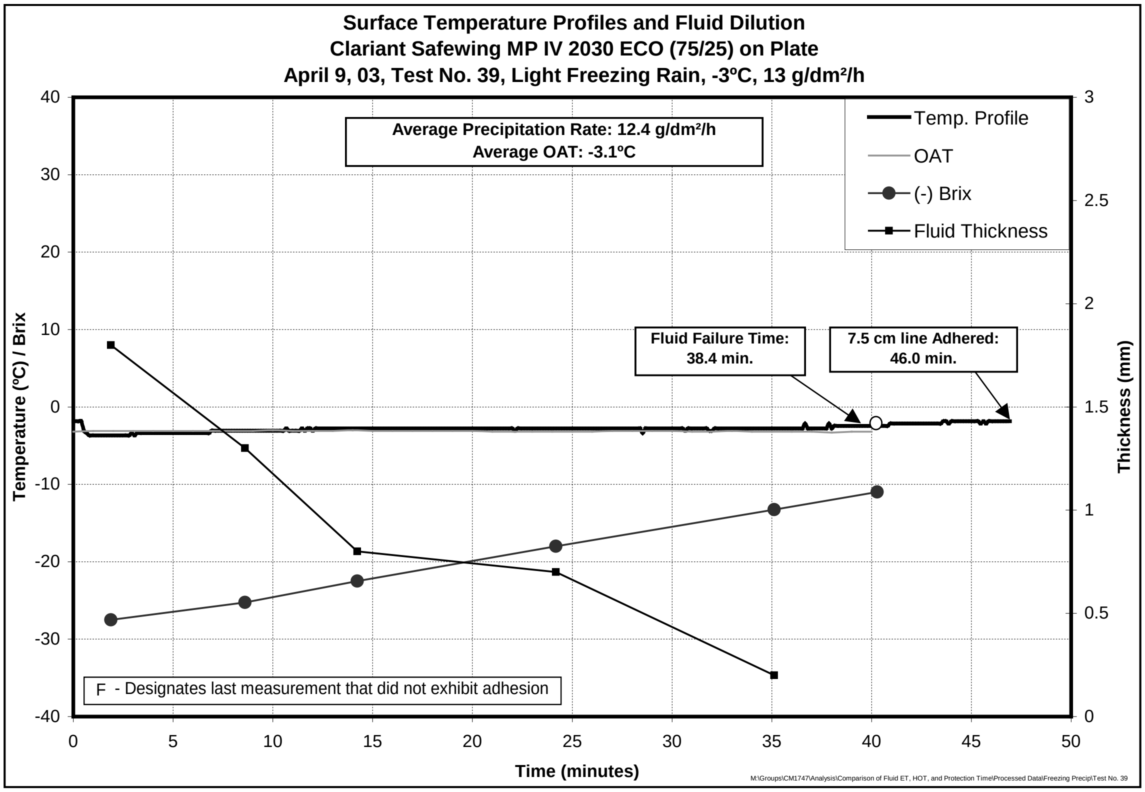


Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (75/25) on Plate
April 8, 03, Test No. 34, Light Freezing Rain, -10ºC, 25 g/dm²/h

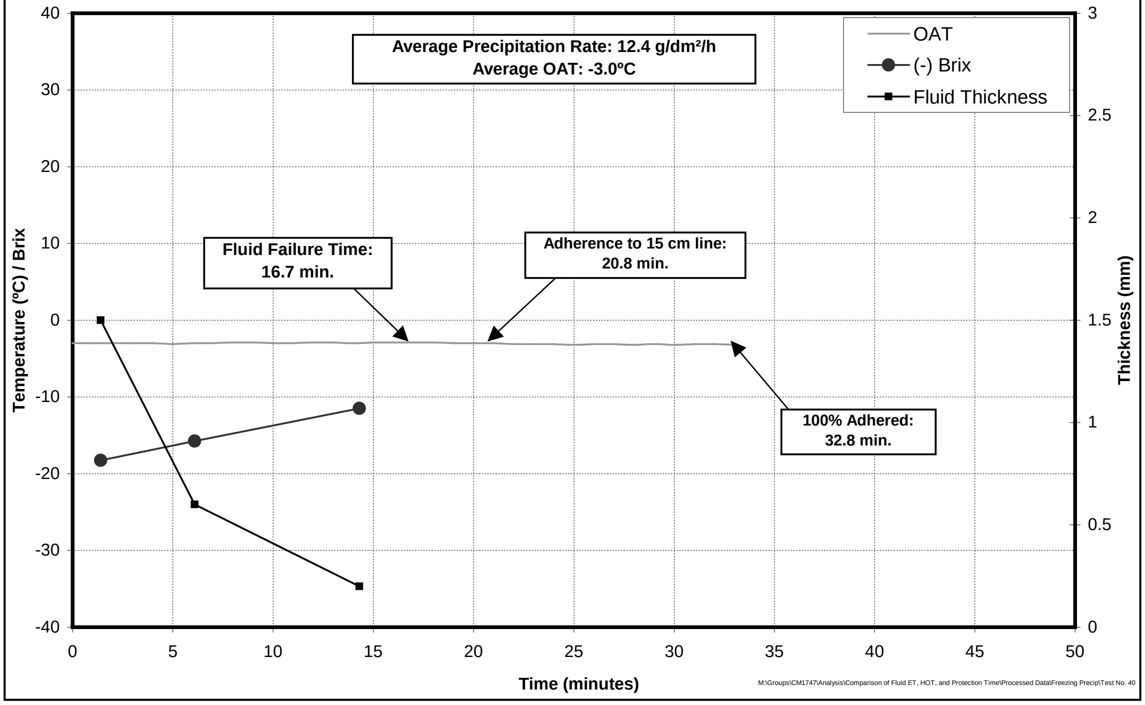
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 34



Surface Temperature Profiles and Fluid Dilution
UCAR ULTRA+ (Neat) on Plate
April 8, 03, Test No. 36, Light Freezing Rain, -10ºC, 25 g/dm²/h



Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (75/25) on Plate
April 9, 03, Test No. 39, Light Freezing Rain, -3ºC, 13 g/dm²/h



Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (50/50) on Plate
April 9, 03, Test No. 40, Light Freezing Rain, -3ºC, 13 g/dm²/h

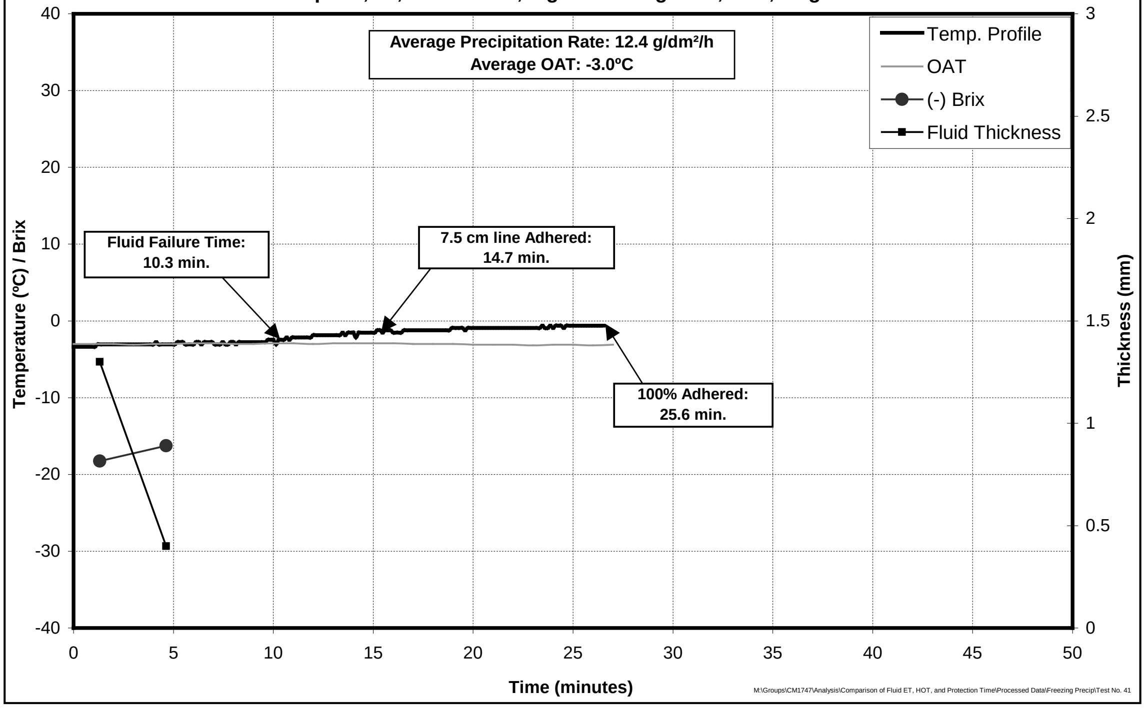
Average Precipitation Rate: 12.4 g/dm²/h
Average OAT: -3.0ºC

Fluid Failure Time:
16.7 min.

Adherence to 15 cm line:
20.8 min.

100% Adhered:
32.8 min.

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 40



Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (50/50) on Plate
April 9, 03, Test No. 41, Light Freezing Rain, -3ºC, 13 g/dm²/h

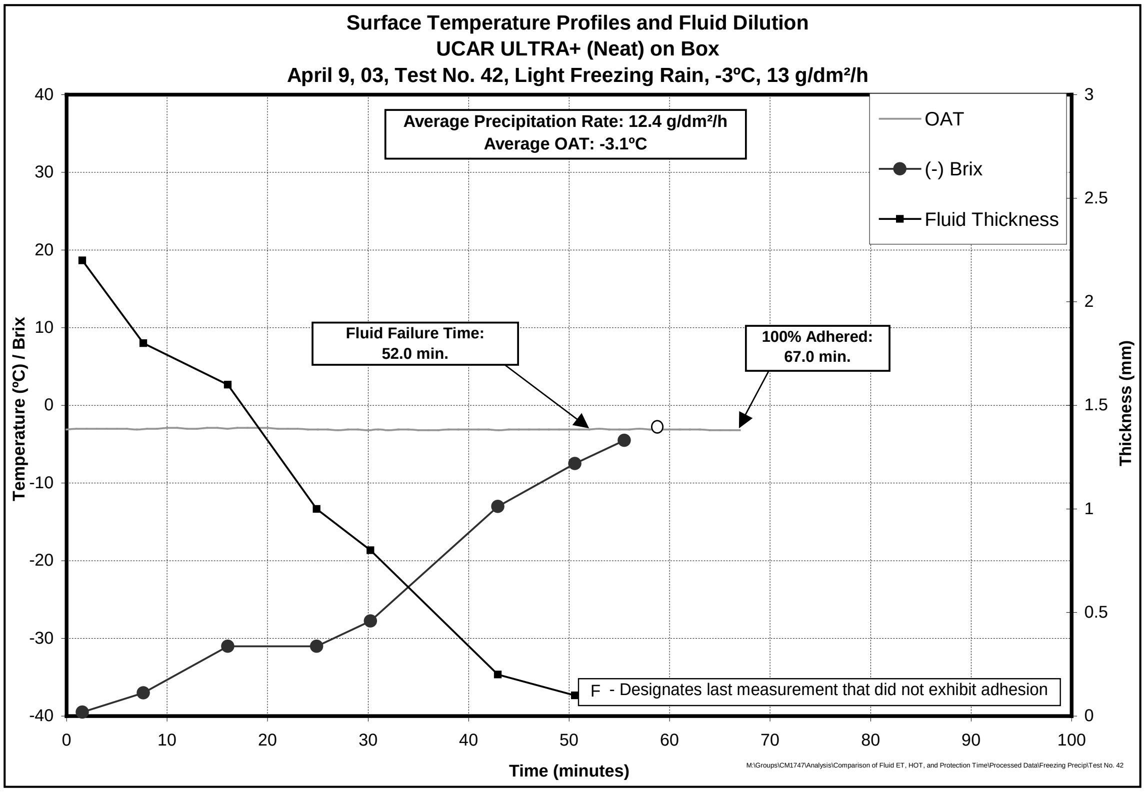
Average Precipitation Rate: 12.4 g/dm²/h
Average OAT: -3.0ºC

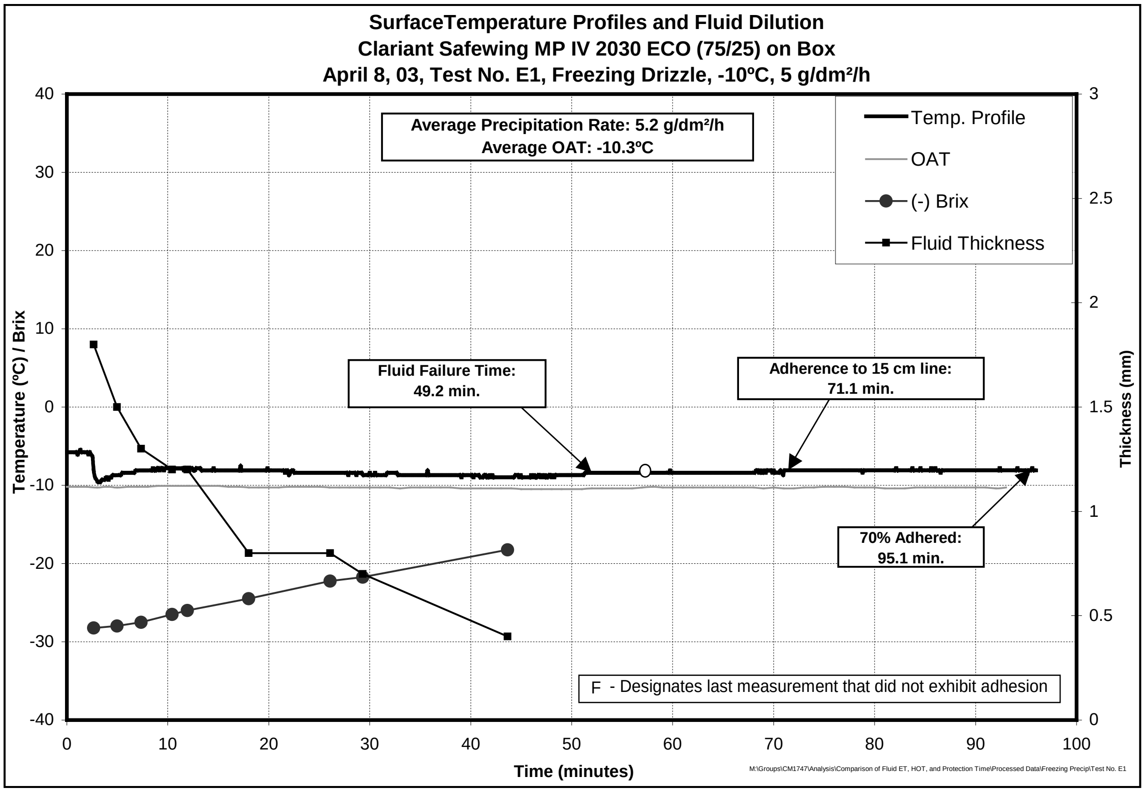
Fluid Failure Time:
10.3 min.

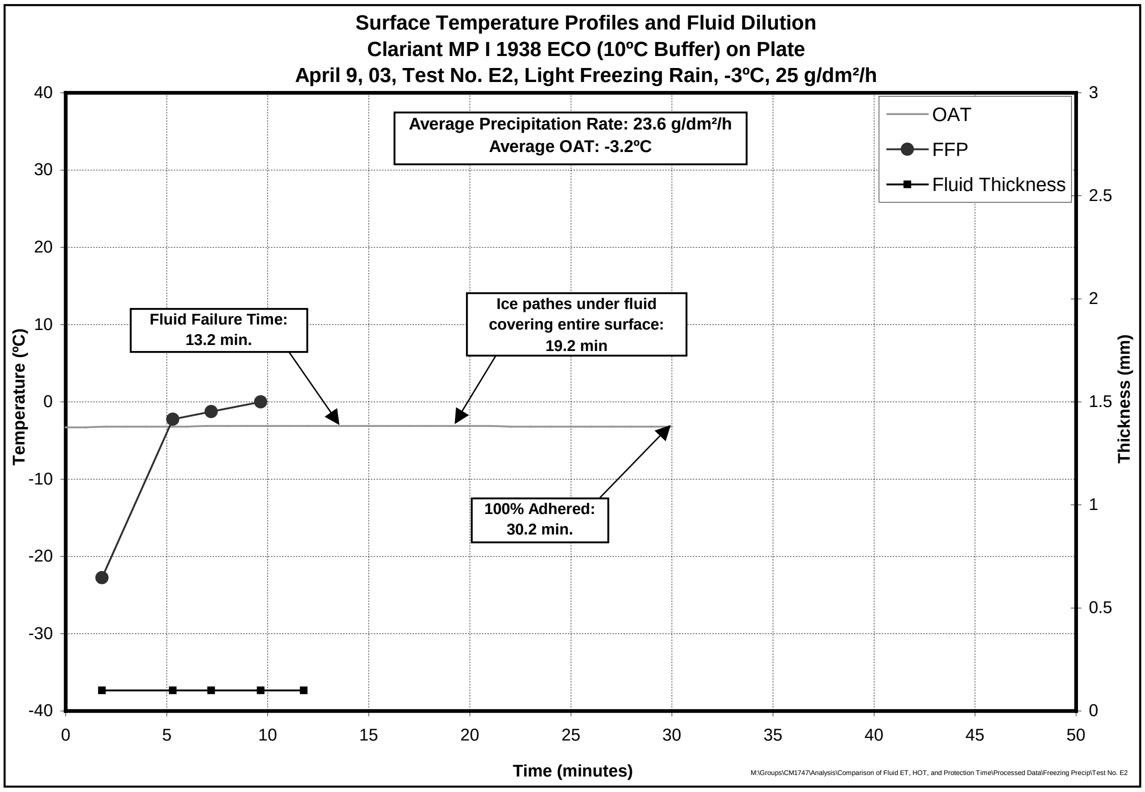
7.5 cm line Adhered:
14.7 min.

100% Adhered:
25.6 min.

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 41

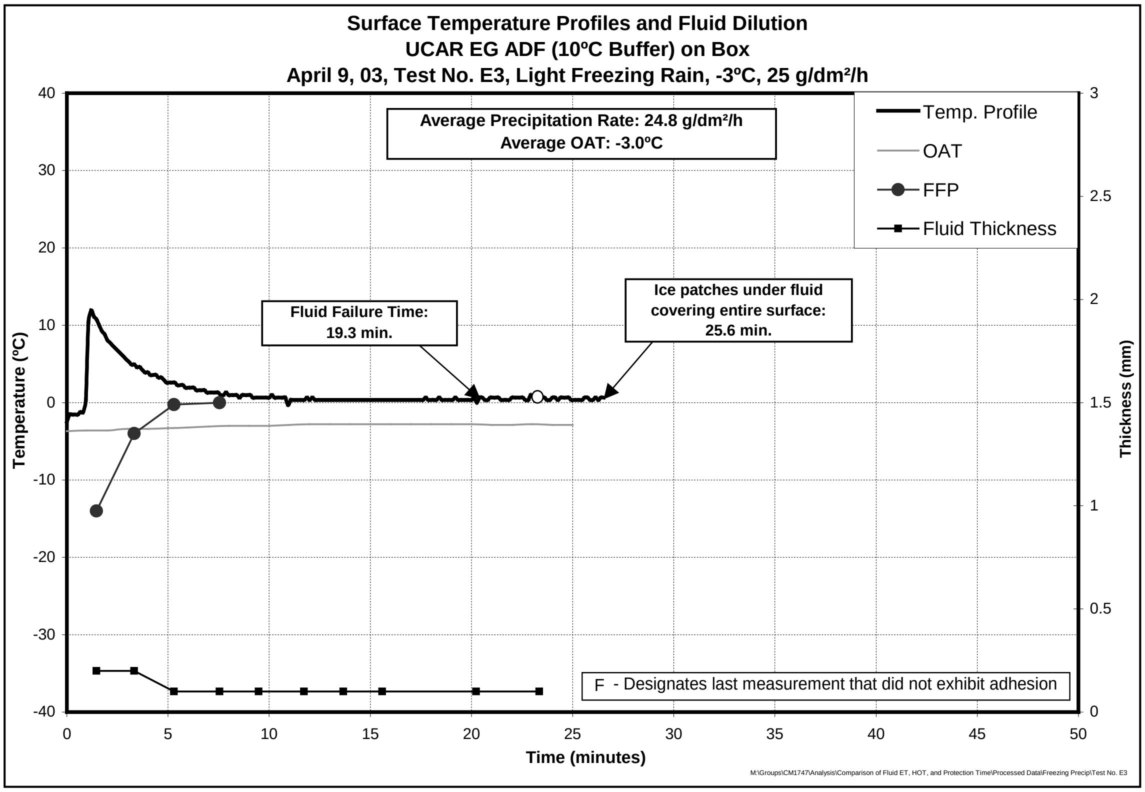

Surface Temperature Profiles and Fluid Dilution
UCAR ULTRA+ (Neat) on Box
April 9, 03, Test No. 42, Light Freezing Rain, -3ºC, 13 g/dm²/h
Average Precipitation Rate: 12.4 g/dm²/h
Average OAT: -3.1ºC
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time:
52.0 min.
100% Adhered:
67.0 min.
F - Designates last measurement that did not exhibit adhesion
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. 42


SurfaceTemperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (75/25) on Box
April 8, 03, Test No. E1, Freezing Drizzle, -10ºC, 5 g/dm²/h
Average Precipitation Rate: 5.2 g/dm²/h
Average OAT: -10.3ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time:
49.2 min.
Adherence to 15 cm line:
71.1 min.
70% Adhered:
95.1 min.
F - Designates last measurement that did not exhibit adhesion
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. E1



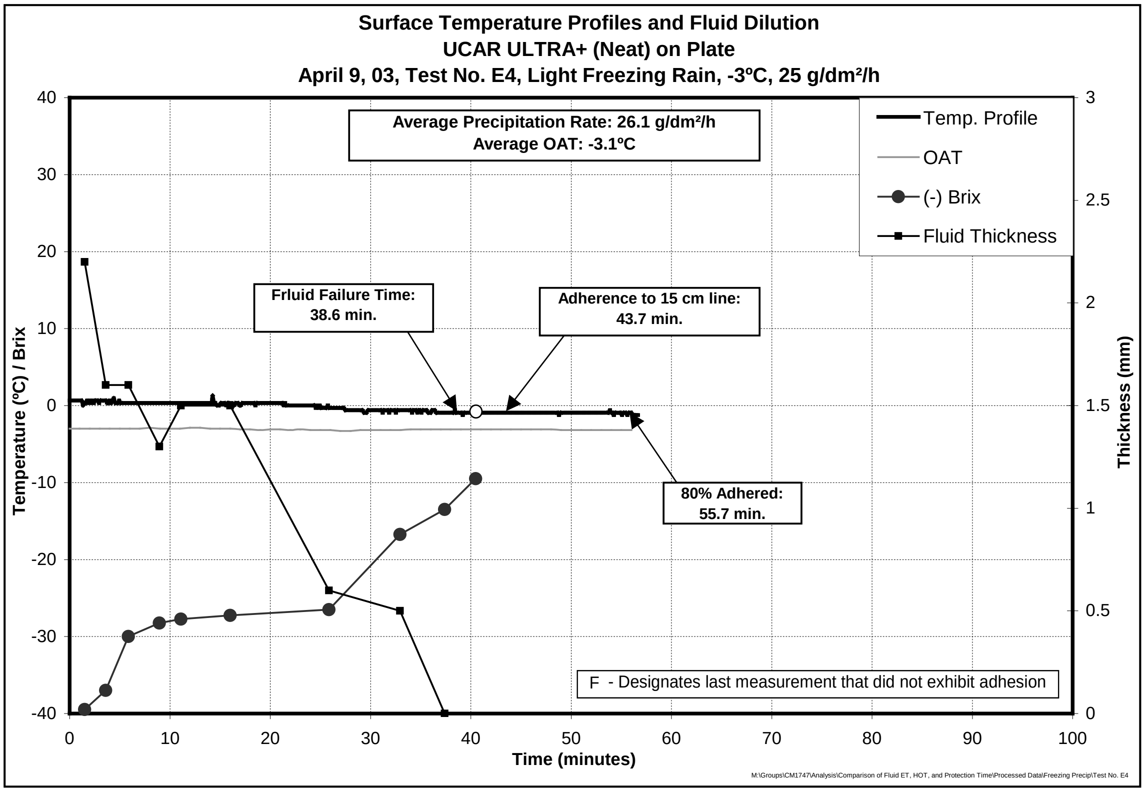
Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Plate
April 9, 03, Test No. E2, Light Freezing Rain, -3ºC, 25 g/dm²/h

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. E2



Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Box
April 9, 03, Test No. E3, Light Freezing Rain, -3ºC, 25 g/dm²/h

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. E3



Surface Temperature Profiles and Fluid Dilution
UCAR ULTRA+ (Neat) on Plate
April 9, 03, Test No. E4, Light Freezing Rain, -3ºC, 25 g/dm²/h

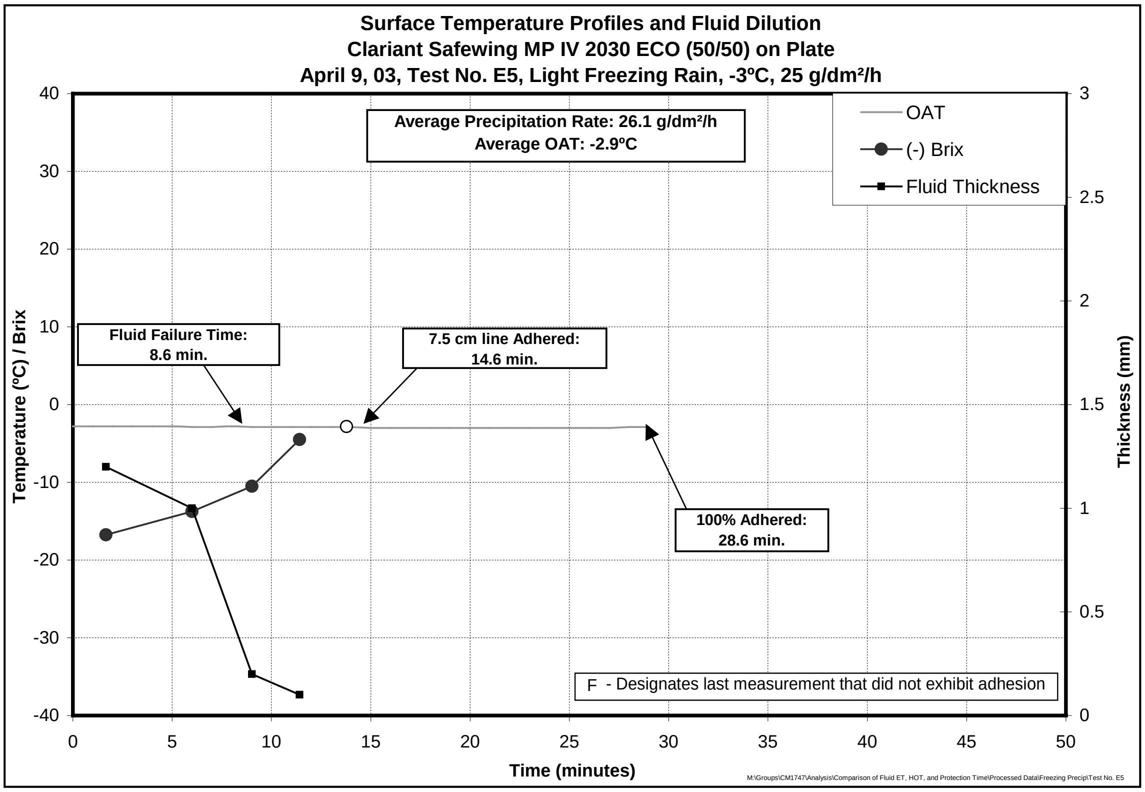
Average Precipitation Rate: 26.1 g/dm²/h
Average OAT: -3.1ºC

Frluid Failure Time: 38.6 min.

Adherence to 15 cm line: 43.7 min.

80% Adhered: 55.7 min.

F - Designates last measurement that did not exhibit adhesion



Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (50/50) on Plate
April 9, 03, Test No. E5, Light Freezing Rain, -3ºC, 25 g/dm²/h

Average Precipitation Rate: 26.1 g/dm²/h
Average OAT: -2.9ºC

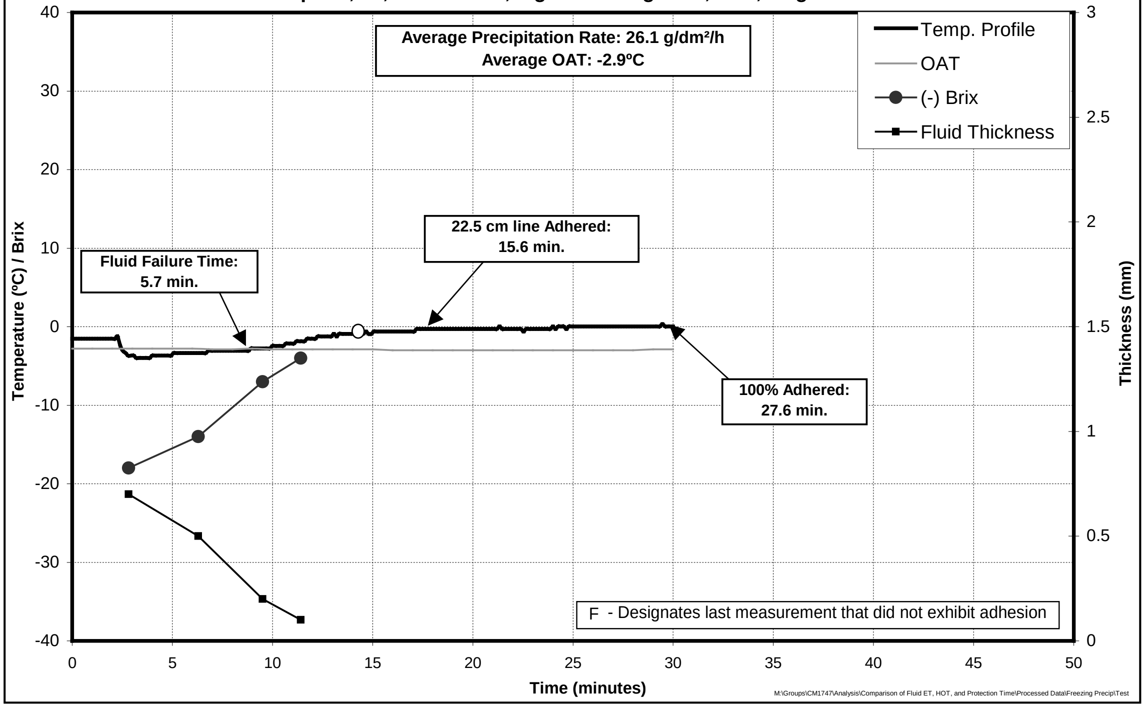
Fluid Failure Time: 8.6 min.

7.5 cm line Adhered: 14.6 min.

100% Adhered: 28.6 min.

F - Designates last measurement that did not exhibit adhesion

Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (50/50) on Plate
April 9, 03, Test No. E6, Light Freezing Rain, -3ºC, 25 g/dm²/h


Average Precipitation Rate: 26.1 g/dm²/h
Average OAT: -2.9ºC

Fluid Failure Time: 5.7 min.

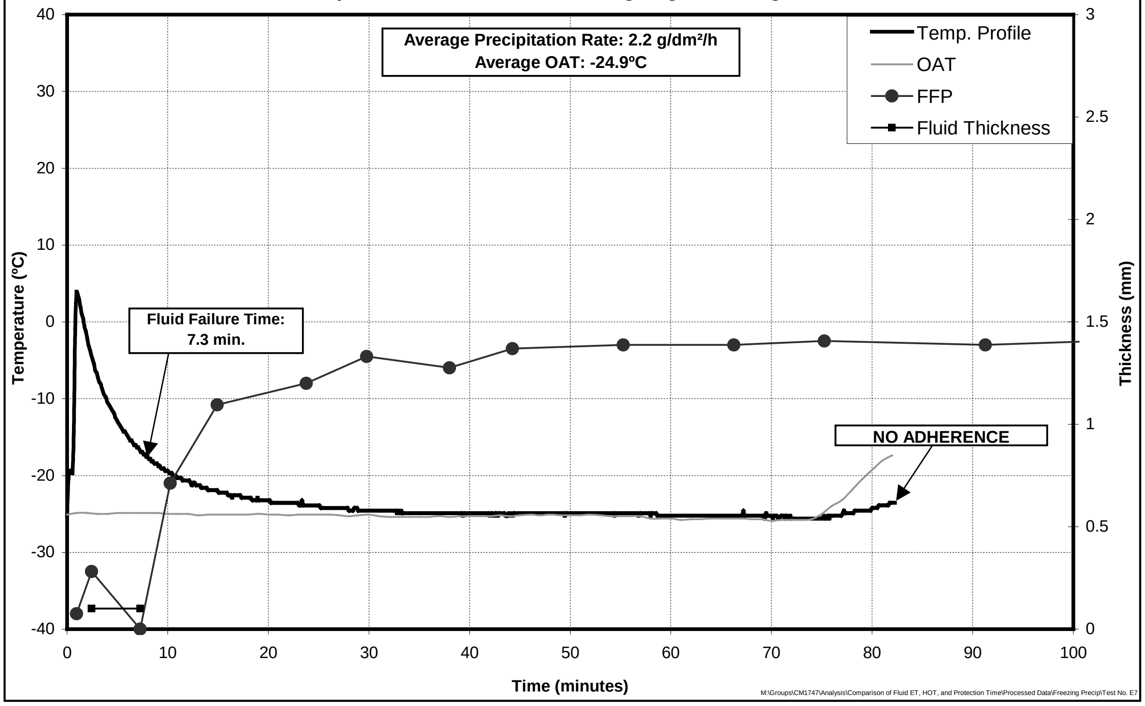
22.5 cm line Adhered: 15.6 min.

100% Adhered: 27.6 min.

F - Designates last measurement that did not exhibit adhesion

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test

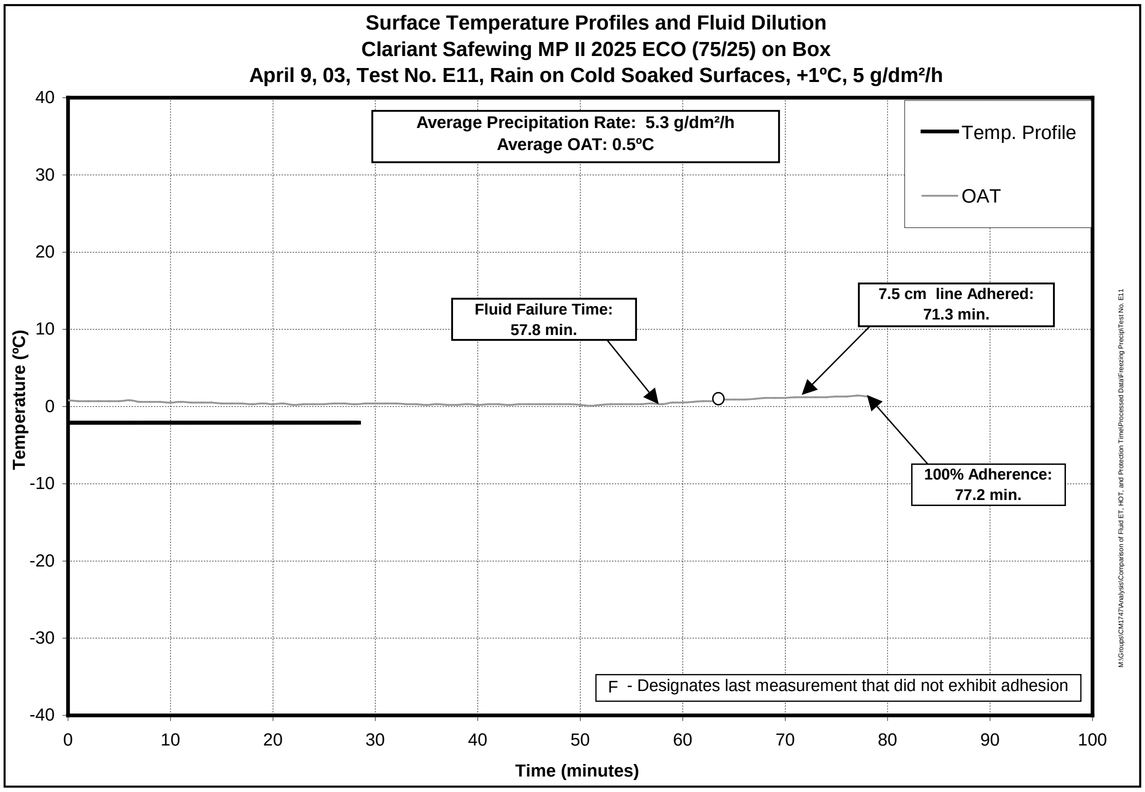
Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Plate
April 7, 03, Test No. E7, Freezing Fog, -25ºC, 2 g/dm²/h

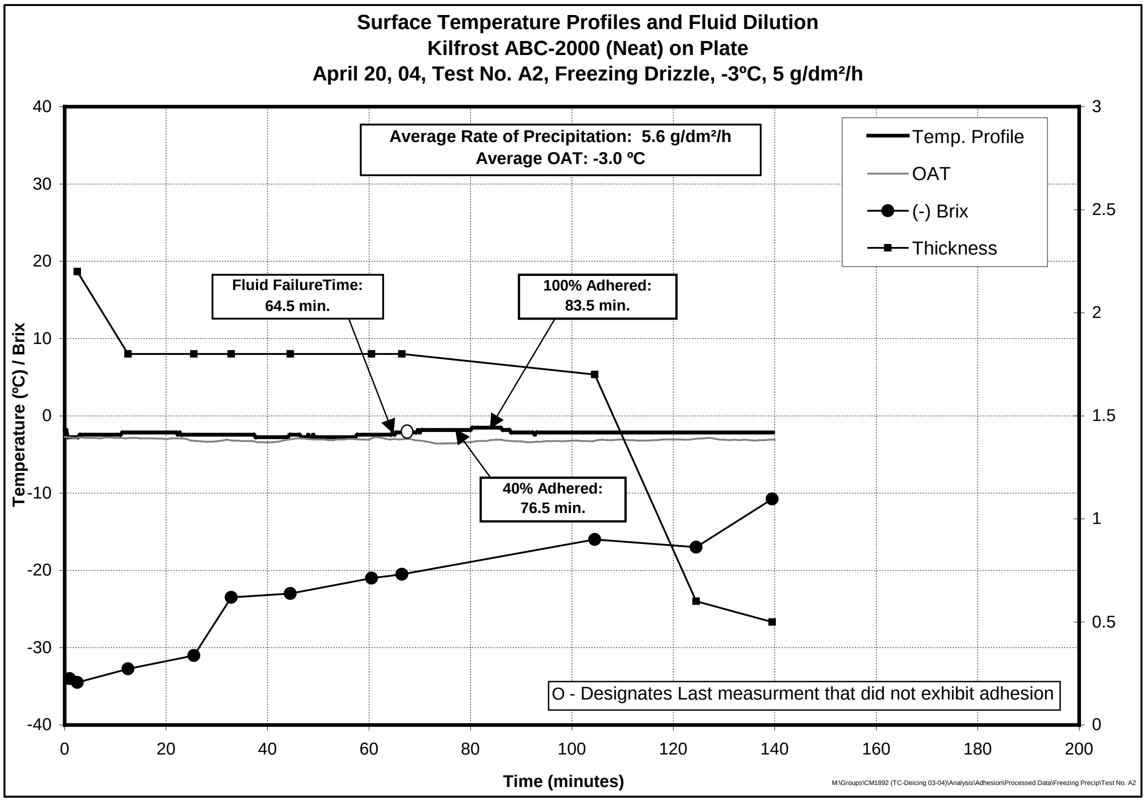

Average Precipitation Rate: 2.2 g/dm²/h
Average OAT: -24.9ºC

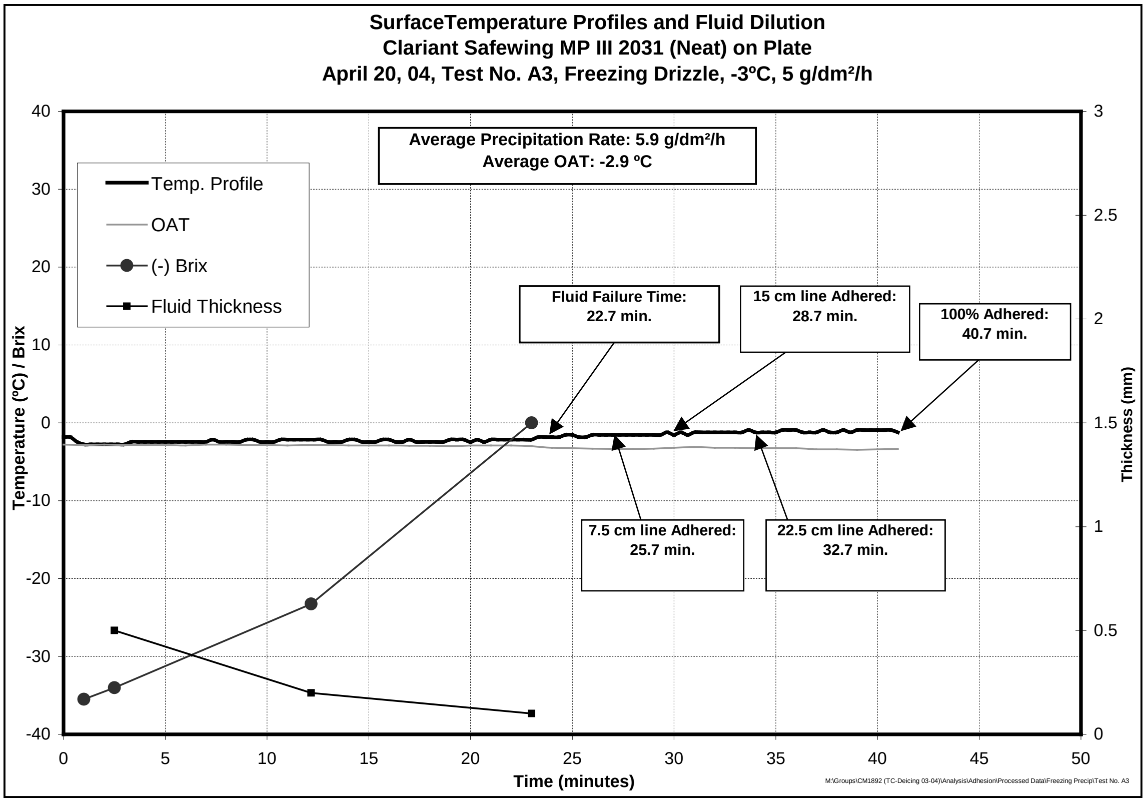
Fluid Failure Time: 7.3 min.

NO ADHERENCE

M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. E7


Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (75/25) on Box
April 9, 03, Test No. E11, Rain on Cold Soaked Surfaces, +1ºC, 5 g/dm²/h
Average Precipitation Rate: 5.3 g/dm²/h
Average OAT: 0.5ºC
Temp. Profile
OAT
Fluid Failure Time: 57.8 min.
7.5 cm line Adhered: 71.3 min.
100% Adherence: 77.2 min.
F - Designates last measurement that did not exhibit adhesion
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
Time (minutes)
0
10
20
30
40
50
60
70
80
90
100
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Freezing Precip\Test No. E11


Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Plate
April 20, 04, Test No. A2, Freezing Drizzle, -3ºC, 5 g/dm²/h
Average Rate of Precipitation: 5.6 g/dm²/h
Average OAT: -3.0 ºC
Temp. Profile
OAT
(-) Brix
Thickness
Fluid FailureTime: 64.5 min.
100% Adhered: 83.5 min.
40% Adhered: 76.5 min.
O - Designates Last measurment that did not exhibit adhesion
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
Time (minutes)
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Freezing Precip\Test No. A2



SurfaceTemperature Profiles and Fluid Dilution
Clariant Safewing MP III 2031 (Neat) on Plate
April 20, 04, Test No. A3, Freezing Drizzle, -3ºC, 5 g/dm²/h

Average Precipitation Rate: 5.9 g/dm²/h
Average OAT: -2.9 ºC

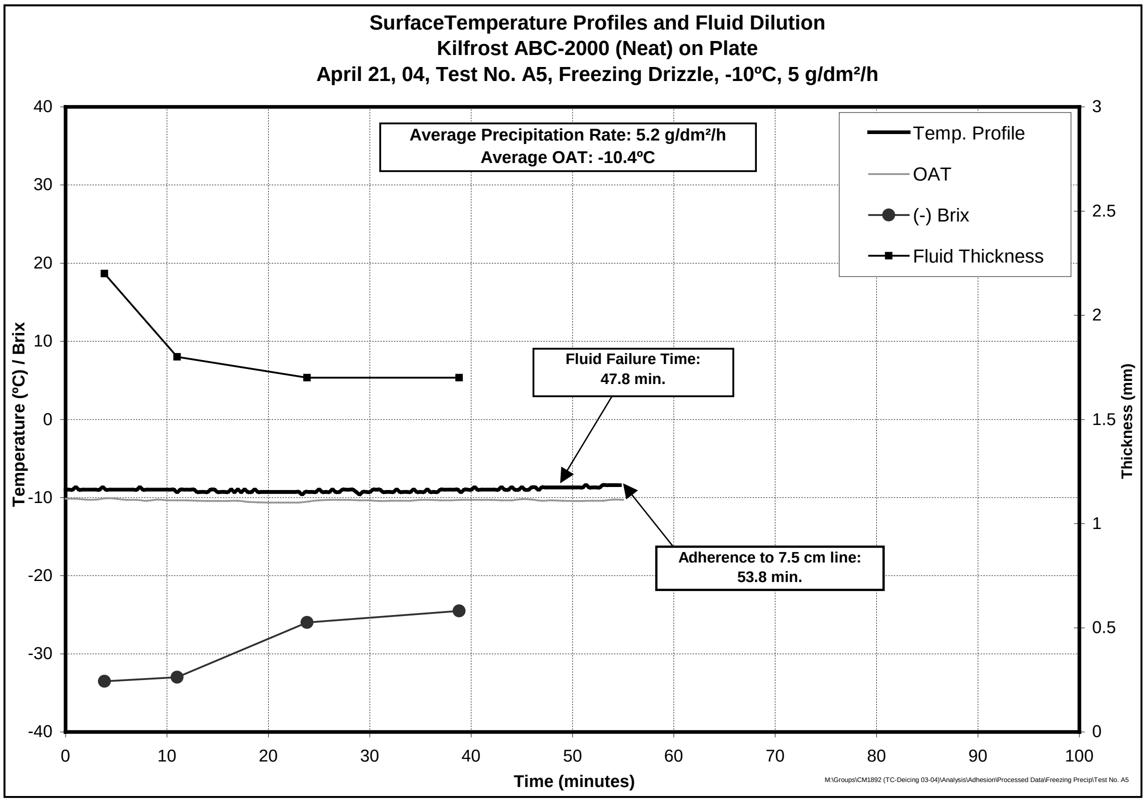
Fluid Failure Time: 22.7 min.

15 cm line Adhered: 28.7 min.

100% Adhered: 40.7 min.

7.5 cm line Adhered: 25.7 min.

22.5 cm line Adhered: 32.7 min.

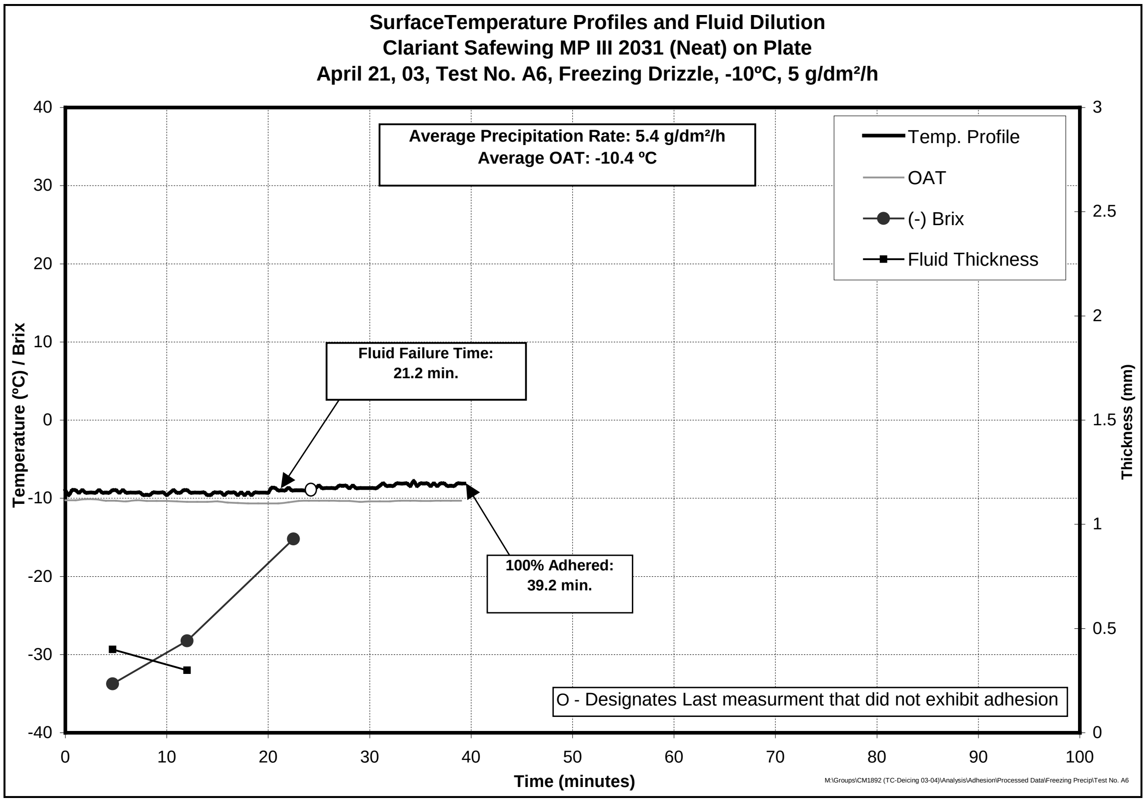


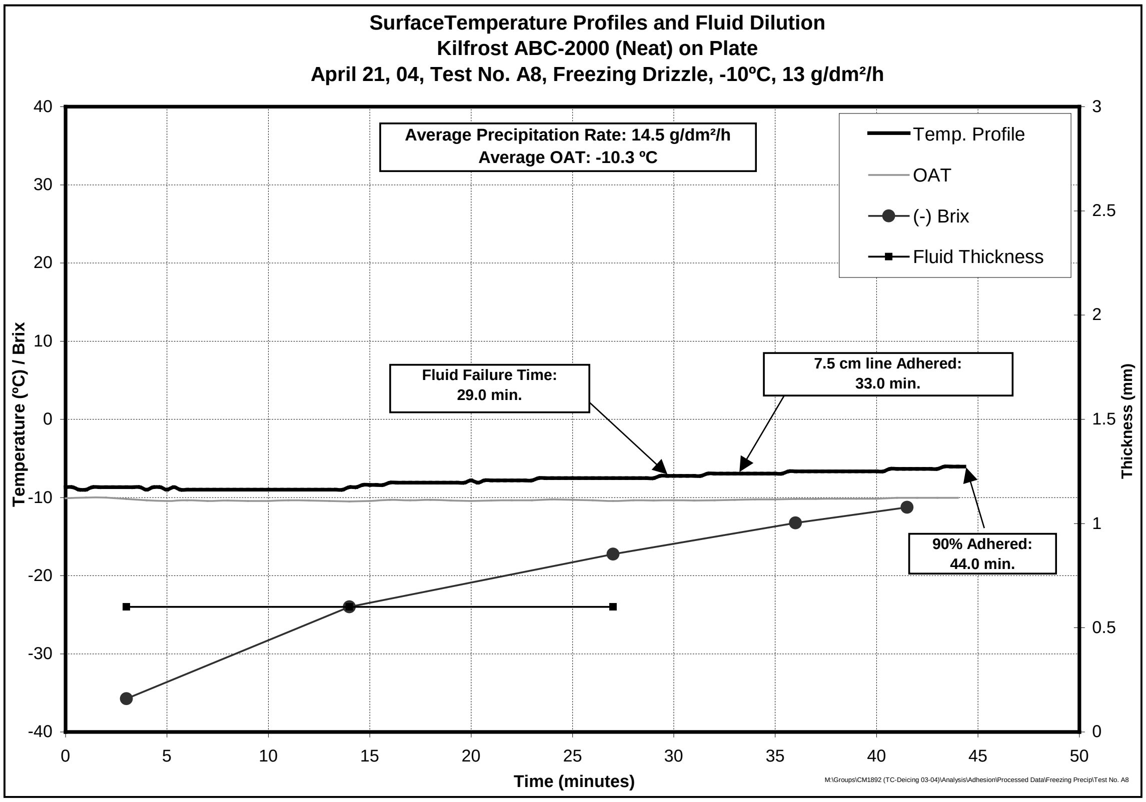
SurfaceTemperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Plate
April 21, 04, Test No. A5, Freezing Drizzle, -10ºC, 5 g/dm²/h

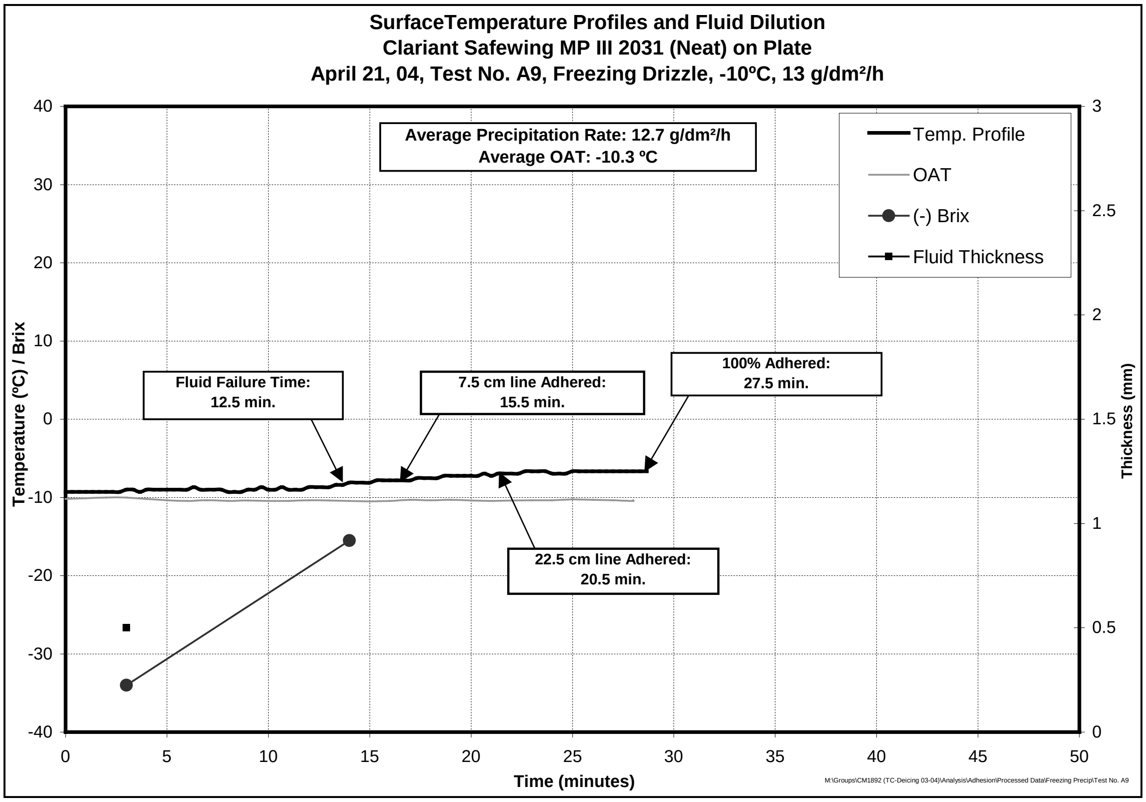
Average Precipitation Rate: 5.2 g/dm²/h
Average OAT: -10.4ºC

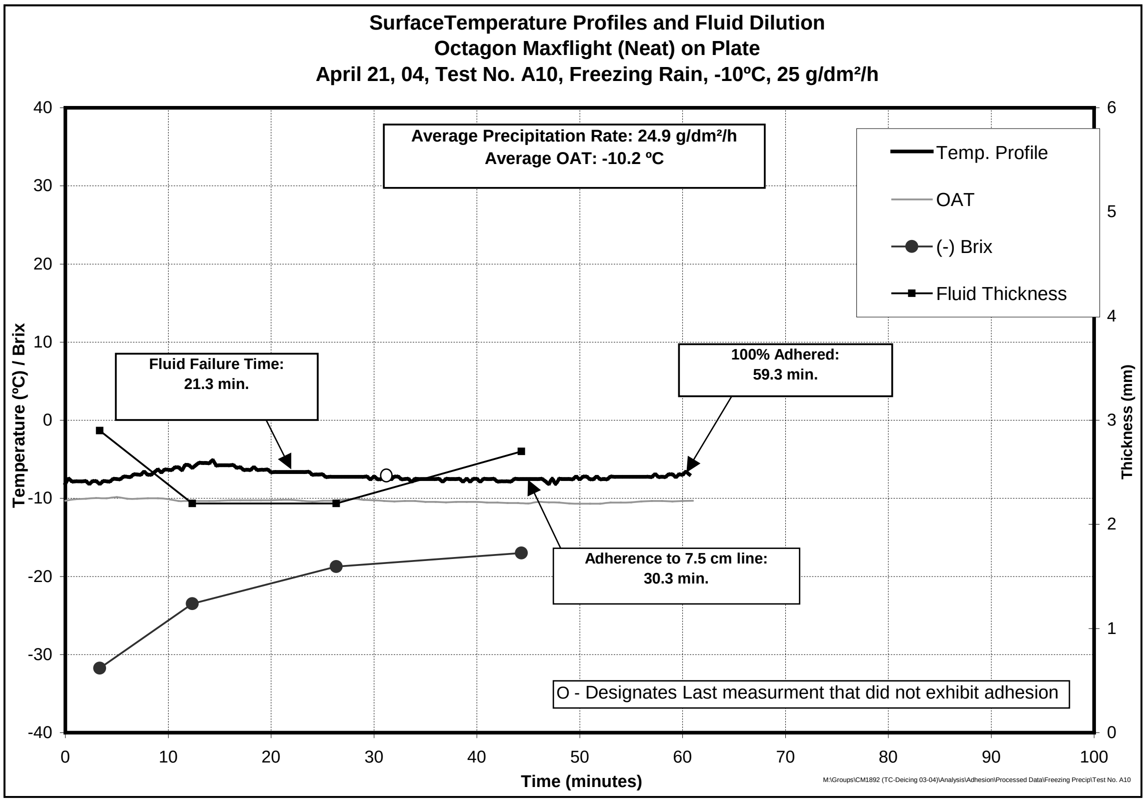
Fluid Failure Time: 47.8 min.

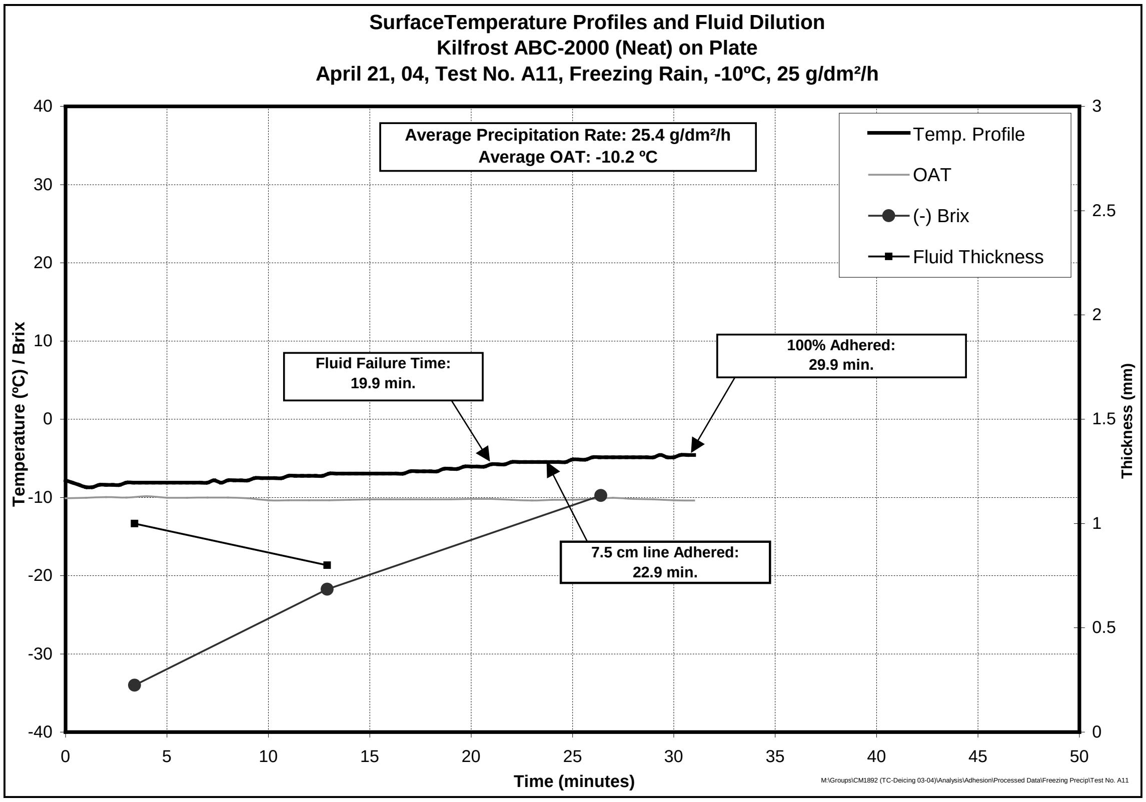
Adherence to 7.5 cm line: 53.8 min.

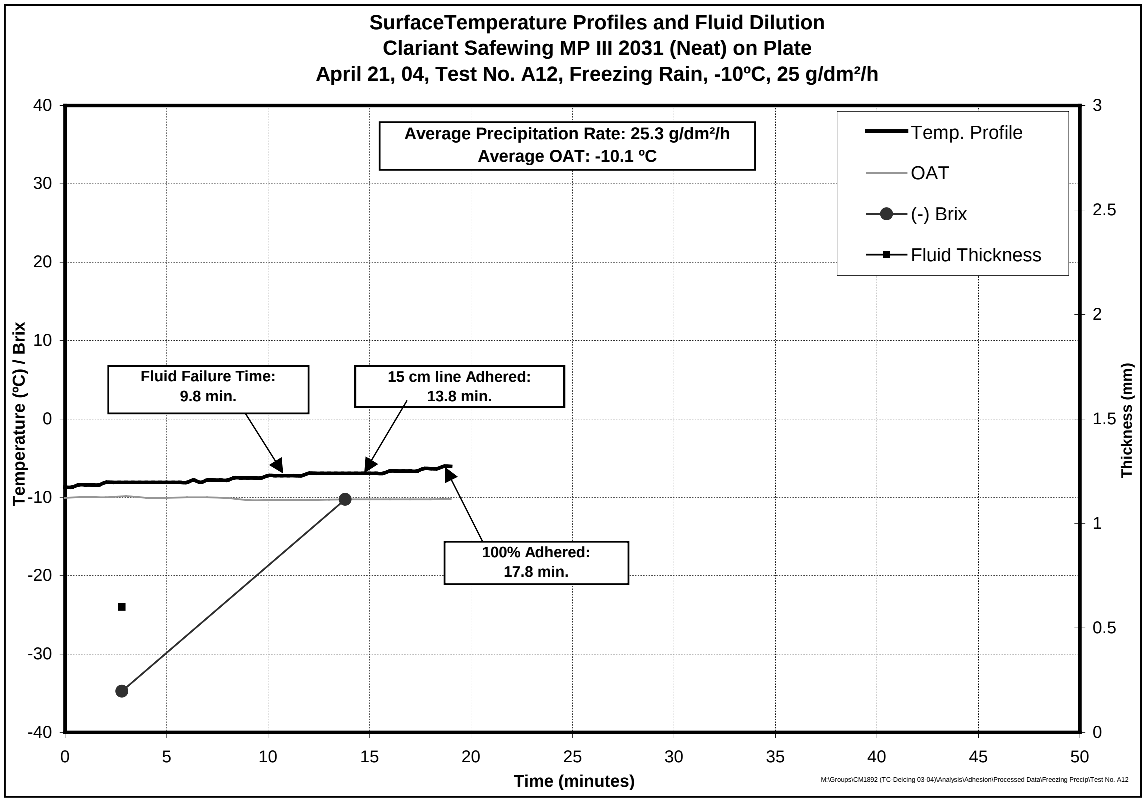

SurfaceTemperature Profiles and Fluid Dilution
Clariant Safewing MP III 2031 (Neat) on Plate
April 21, 03, Test No. A6, Freezing Drizzle, -10ºC, 5 g/dm²/h
Average Precipitation Rate: 5.4 g/dm²/h
Average OAT: -10.4 ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 21.2 min.
100% Adhered: 39.2 min.
O - Designates Last measurment that did not exhibit adhesion
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Freezing Precip\Test No. A6

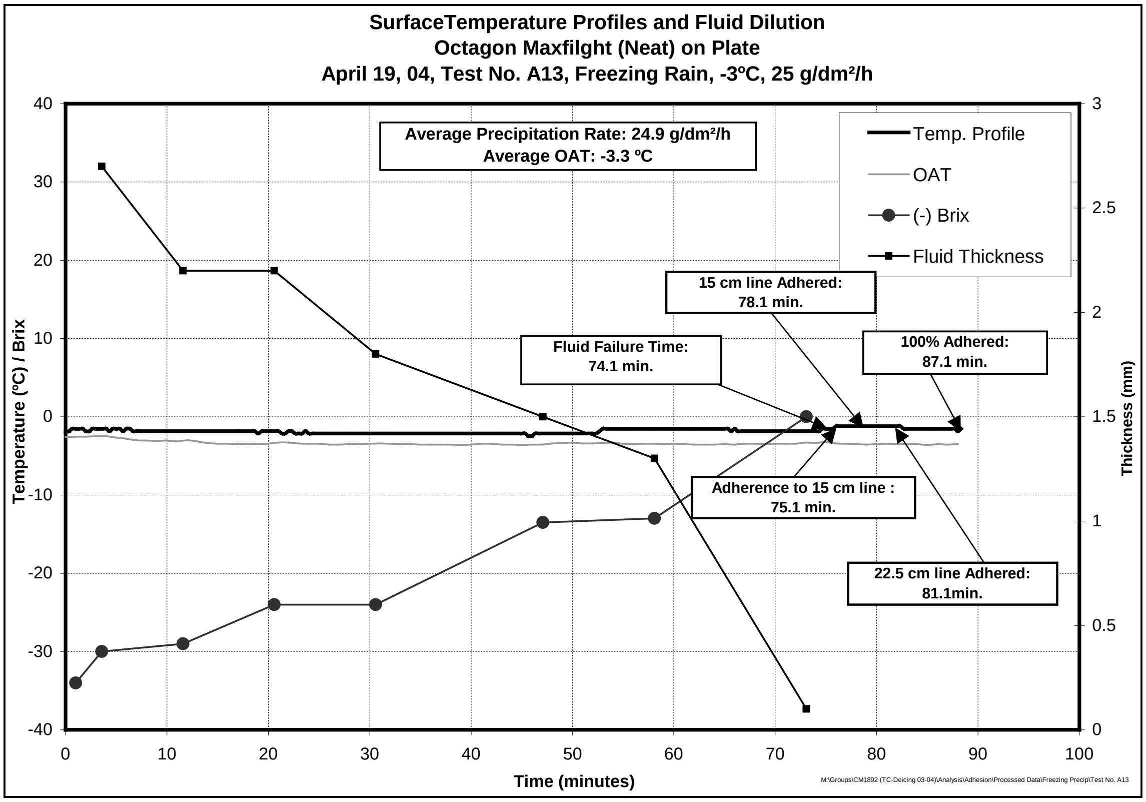

SurfaceTemperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Plate
April 21, 04, Test No. A8, Freezing Drizzle, -10ºC, 13 g/dm²/h
Average Precipitation Rate: 14.5 g/dm²/h
Average OAT: -10.3 ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 29.0 min.
7.5 cm line Adhered: 33.0 min.
90% Adhered: 44.0 min.
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Freezing Precip\Test No. A8


SurfaceTemperature Profiles and Fluid Dilution
Clariant Safewing MP III 2031 (Neat) on Plate
April 21, 04, Test No. A9, Freezing Drizzle, -10ºC, 13 g/dm²/h

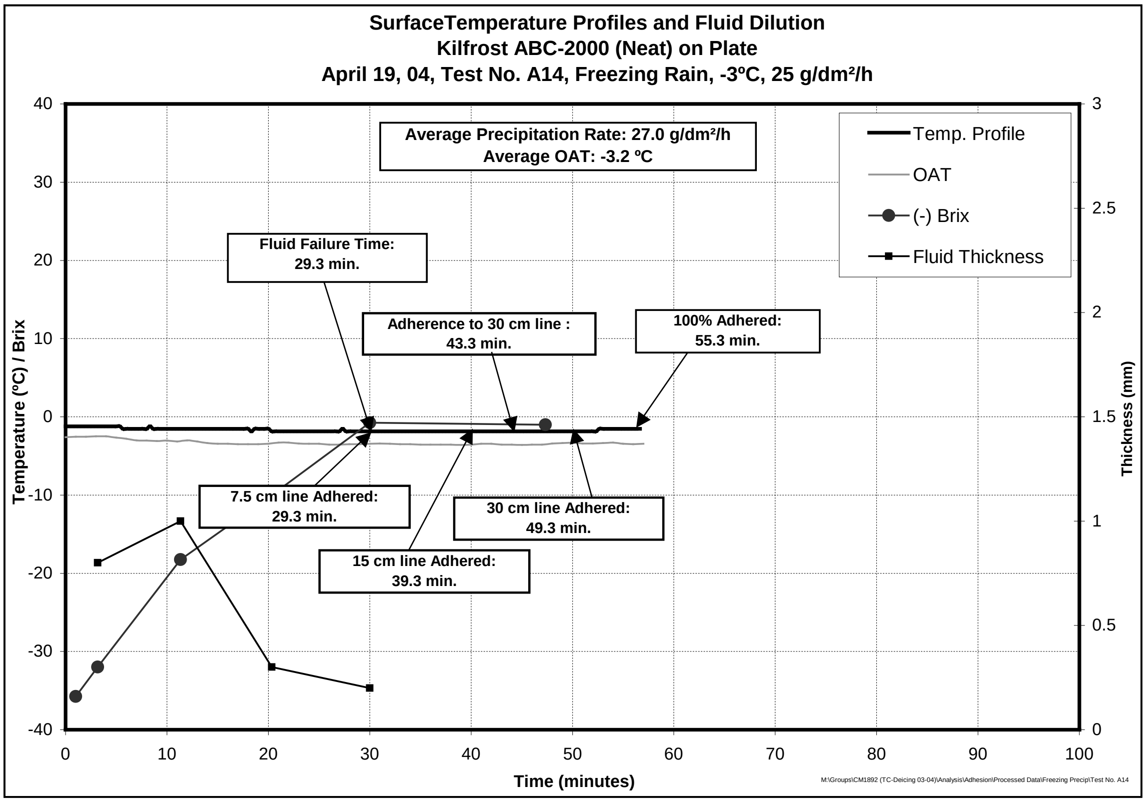

SurfaceTemperature Profiles and Fluid Dilution
Octagon Maxflight (Neat) on Plate
April 21, 04, Test No. A10, Freezing Rain, -10ºC, 25 g/dm²/h


SurfaceTemperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Plate
April 21, 04, Test No. A11, Freezing Rain, -10ºC, 25 g/dm²/h
Average Precipitation Rate: 25.4 g/dm²/h
Average OAT: -10.2 ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 19.9 min.
100% Adhered: 29.9 min.
7.5 cm line Adhered: 22.9 min.
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Freezing Precip\Test No. A11

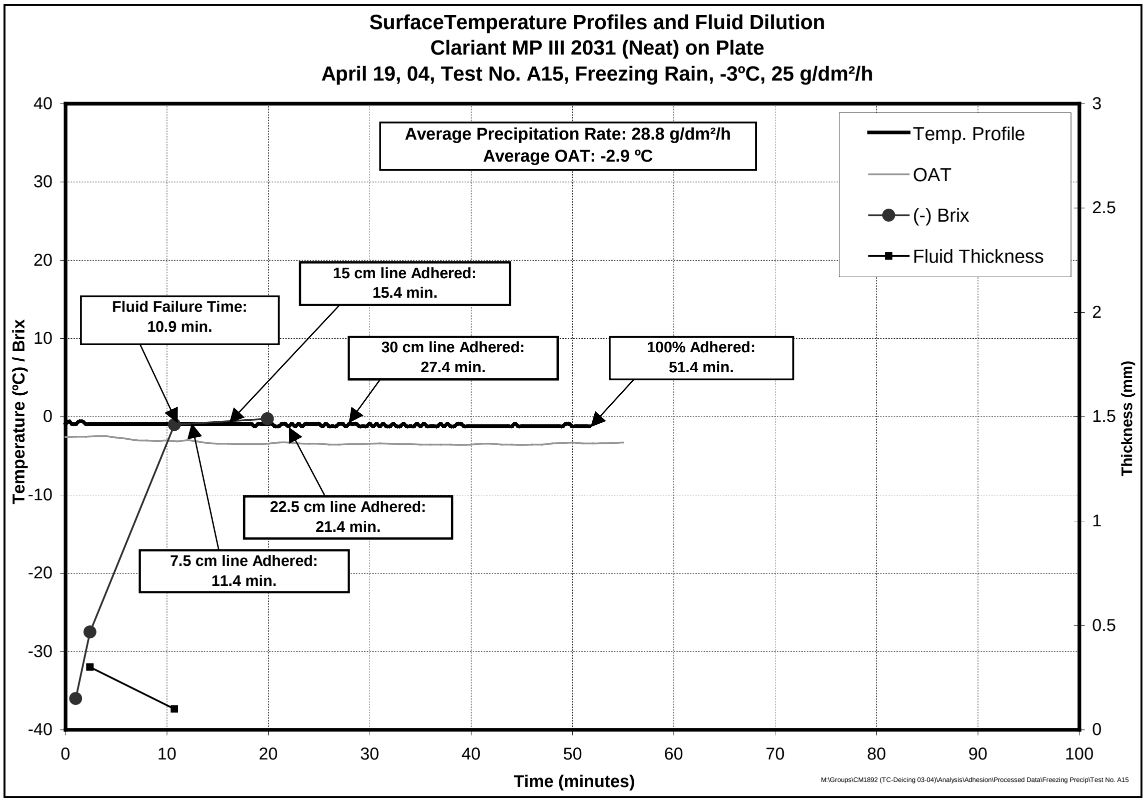

SurfaceTemperature Profiles and Fluid Dilution
Clariant Safewing MP III 2031 (Neat) on Plate
April 21, 04, Test No. A12, Freezing Rain, -10ºC, 25 g/dm²/h
Average Precipitation Rate: 25.3 g/dm²/h
Average OAT: -10.1 ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 9.8 min.
15 cm line Adhered: 13.8 min.
100% Adhered: 17.8 min.
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Freezing Precip\Test No. A12



SurfaceTemperature Profiles and Fluid Dilution
Octagon Maxfilght (Neat) on Plate
April 19, 04, Test No. A13, Freezing Rain, -3ºC, 25 g/dm²/h



SurfaceTemperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Plate
April 19, 04, Test No. A14, Freezing Rain, -3ºC, 25 g/dm²/h


SurfaceTemperature Profiles and Fluid Dilution
Clariant MP III 2031 (Neat) on Plate
April 19, 04, Test No. A15, Freezing Rain, -3ºC, 25 g/dm²/h
Average Precipitation Rate: 28.8 g/dm²/h
Average OAT: -2.9 ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 10.9 min.
15 cm line Adhered: 15.4 min.
30 cm line Adhered: 27.4 min.
100% Adhered: 51.4 min.
22.5 cm line Adhered: 21.4 min.
7.5 cm line Adhered: 11.4 min.
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Freezing Precip\Test No. A15

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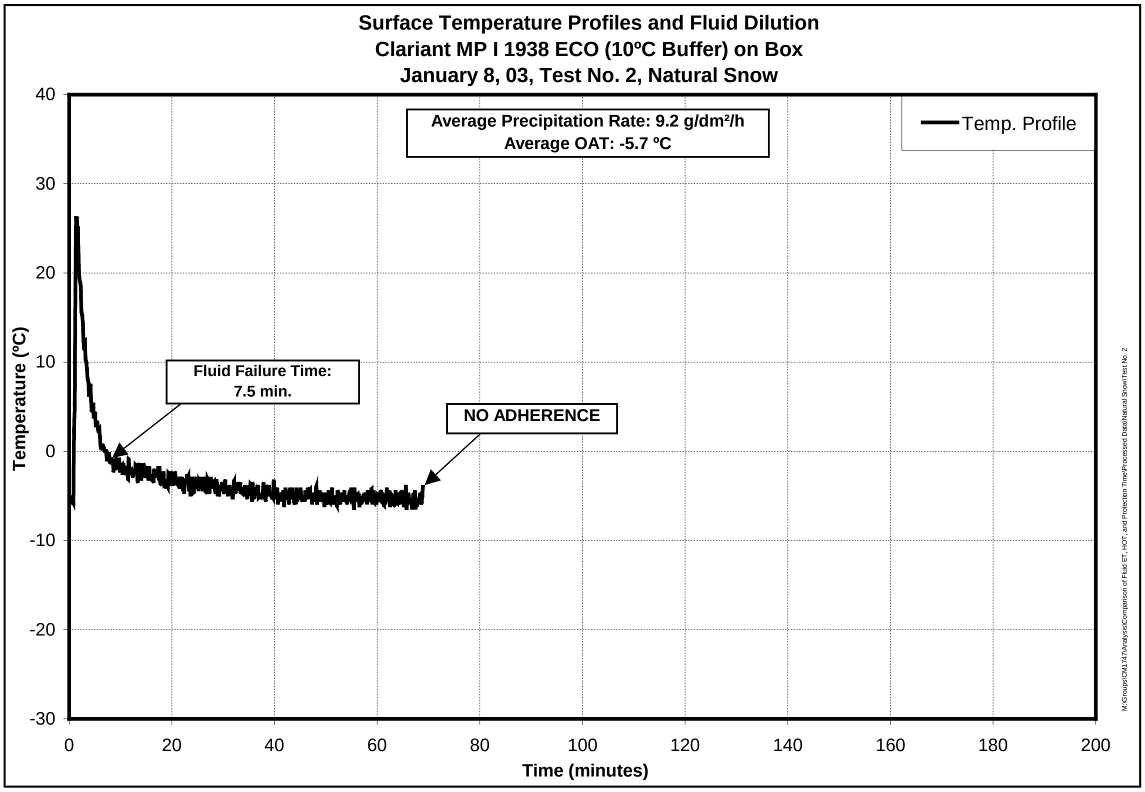
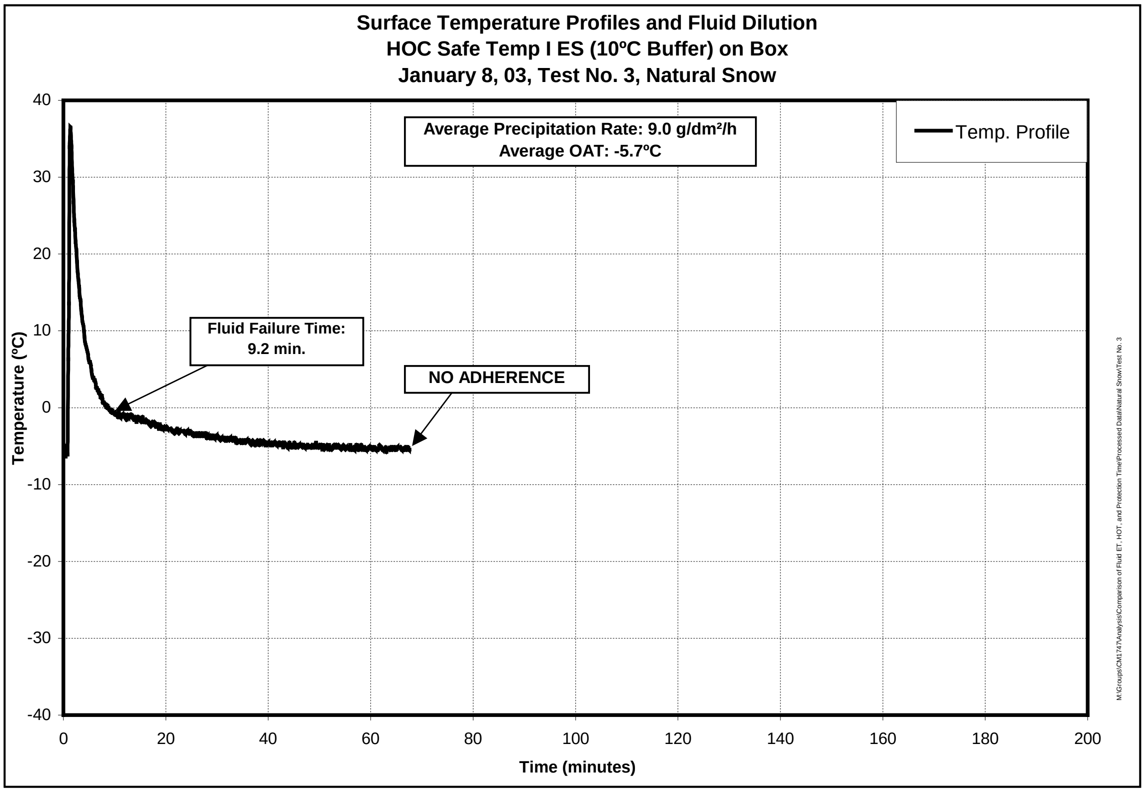
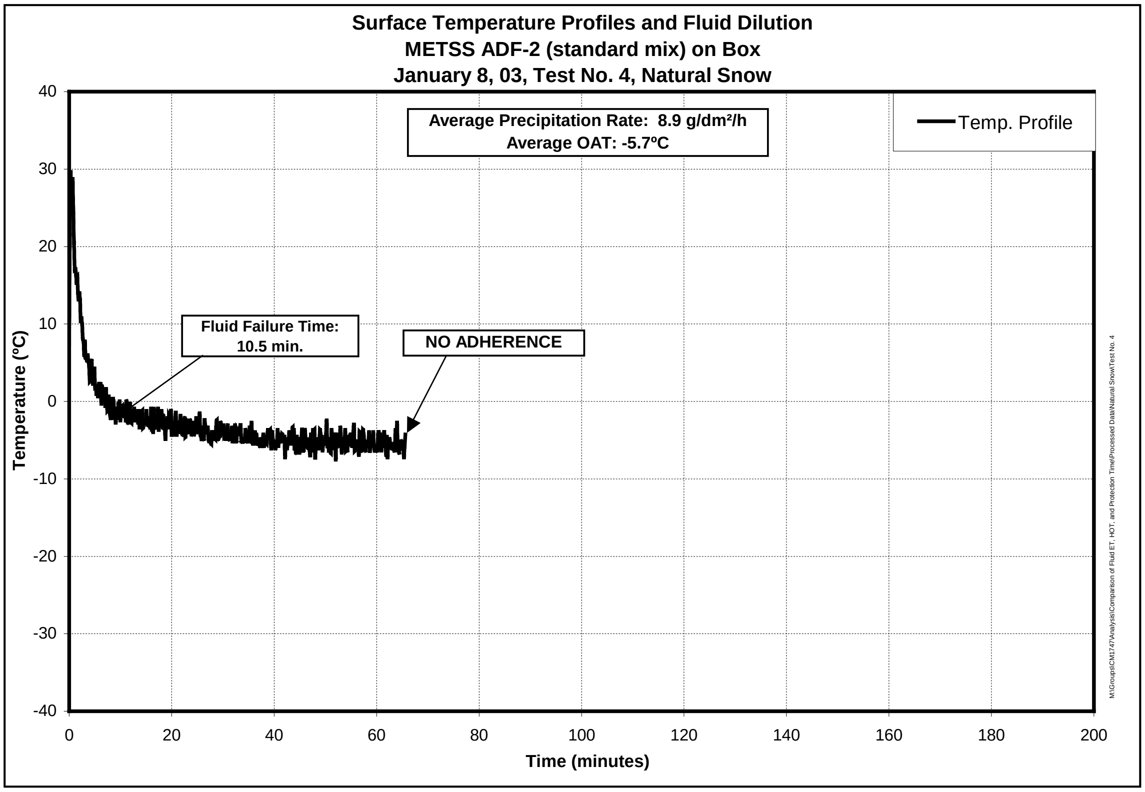
NATURAL SNOW, ARTIFICIAL SNOW, NATURAL FREEZING DRIZZLE



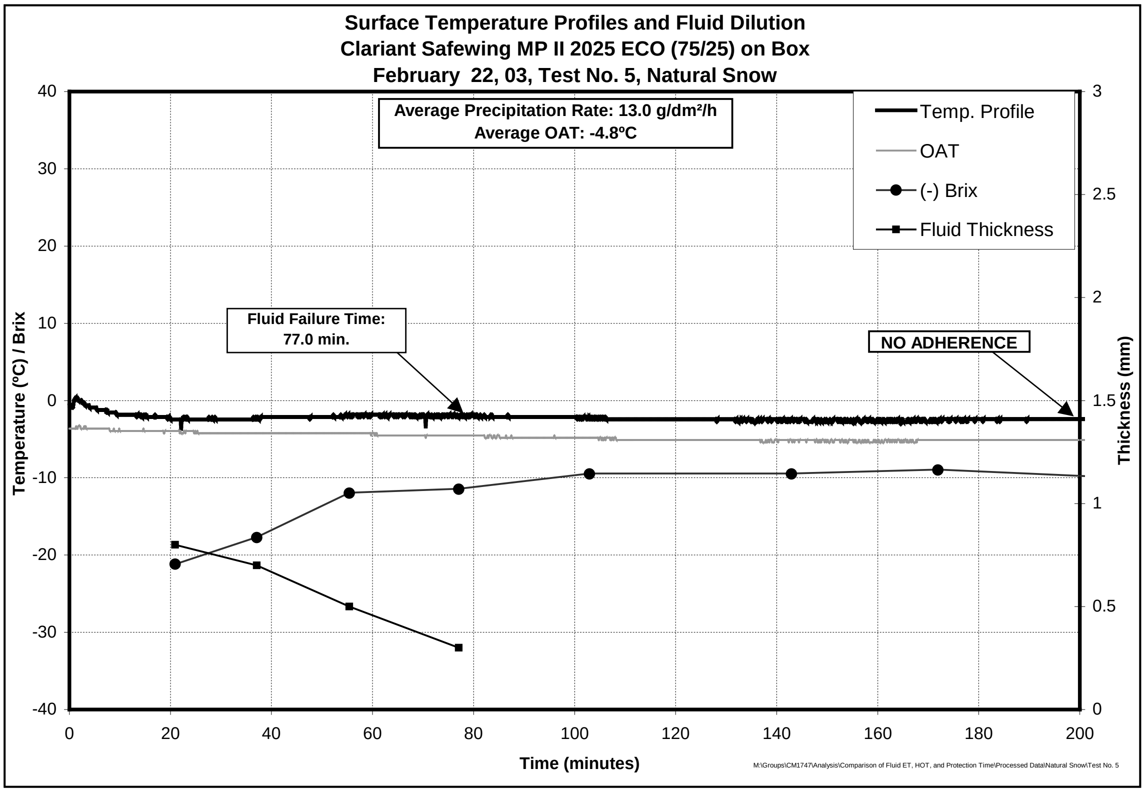
Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Box
January 8, 03, Test No. 2, Natural Snow



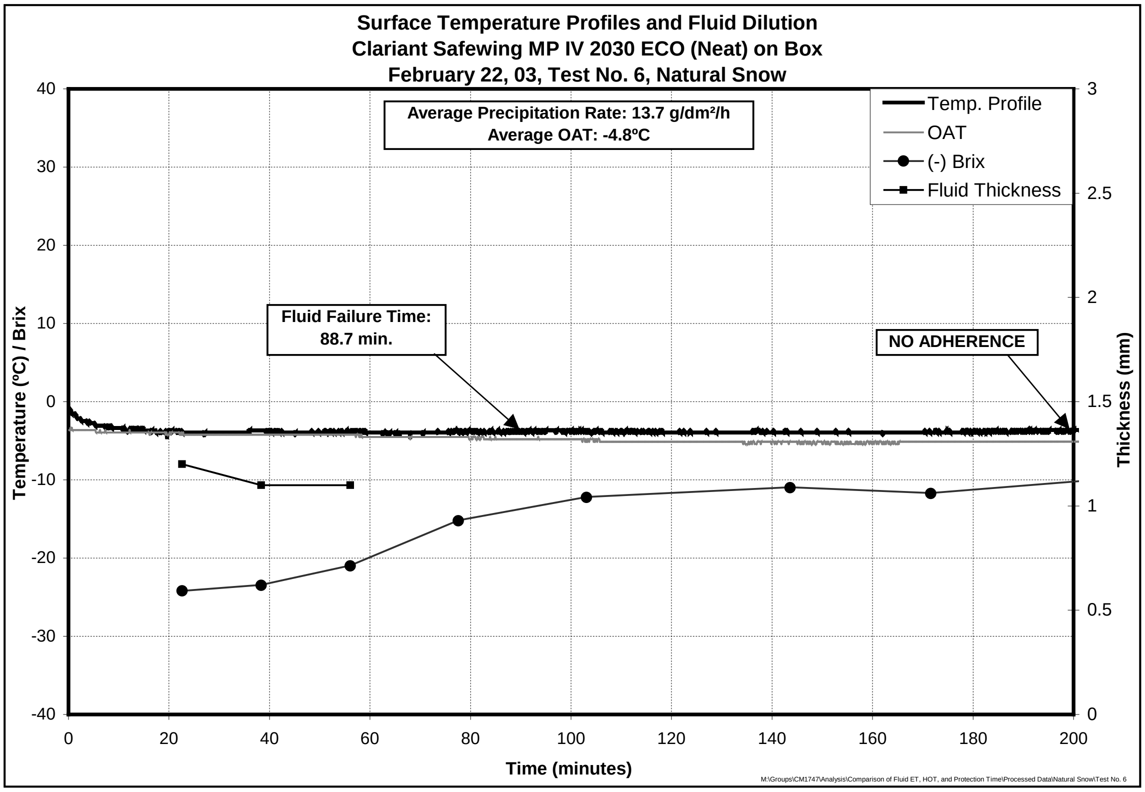
Surface Temperature Profiles and Fluid Dilution
HOC Safe Temp I ES (10ºC Buffer) on Box
January 8, 03, Test No. 3, Natural Snow



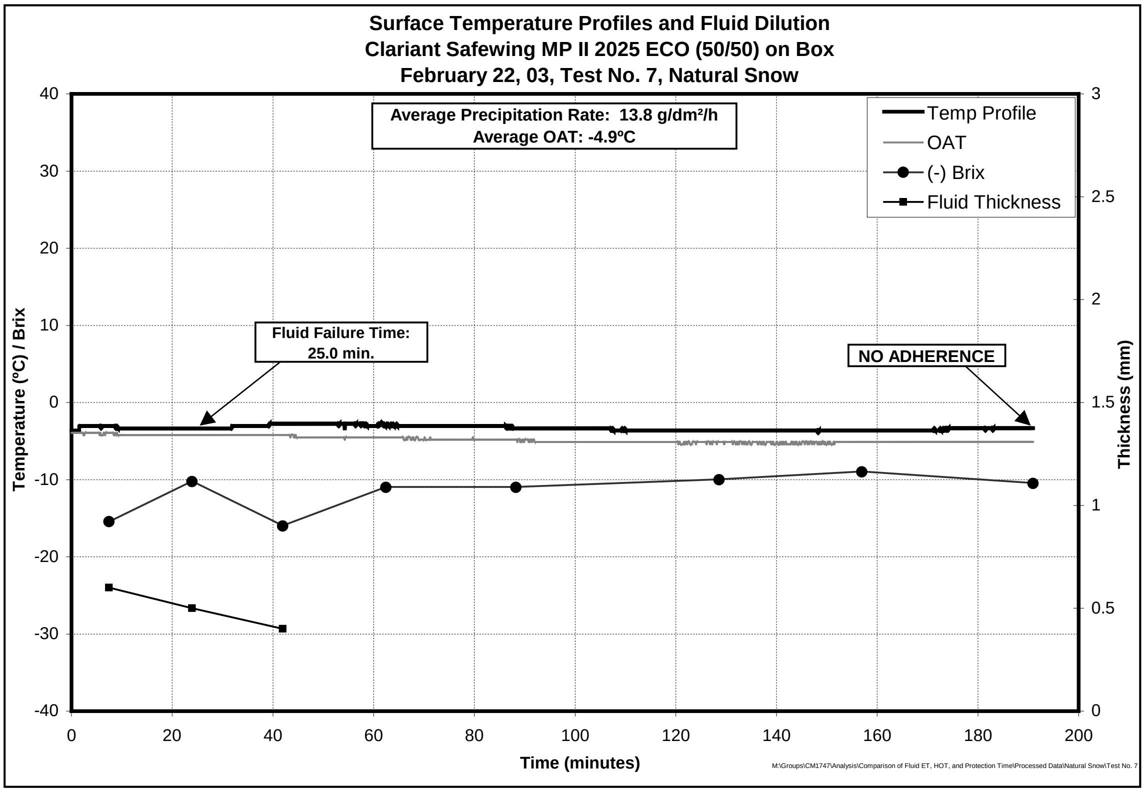
Surface Temperature Profiles and Fluid Dilution
METSS ADF-2 (standard mix) on Box
January 8, 03, Test No. 4, Natural Snow



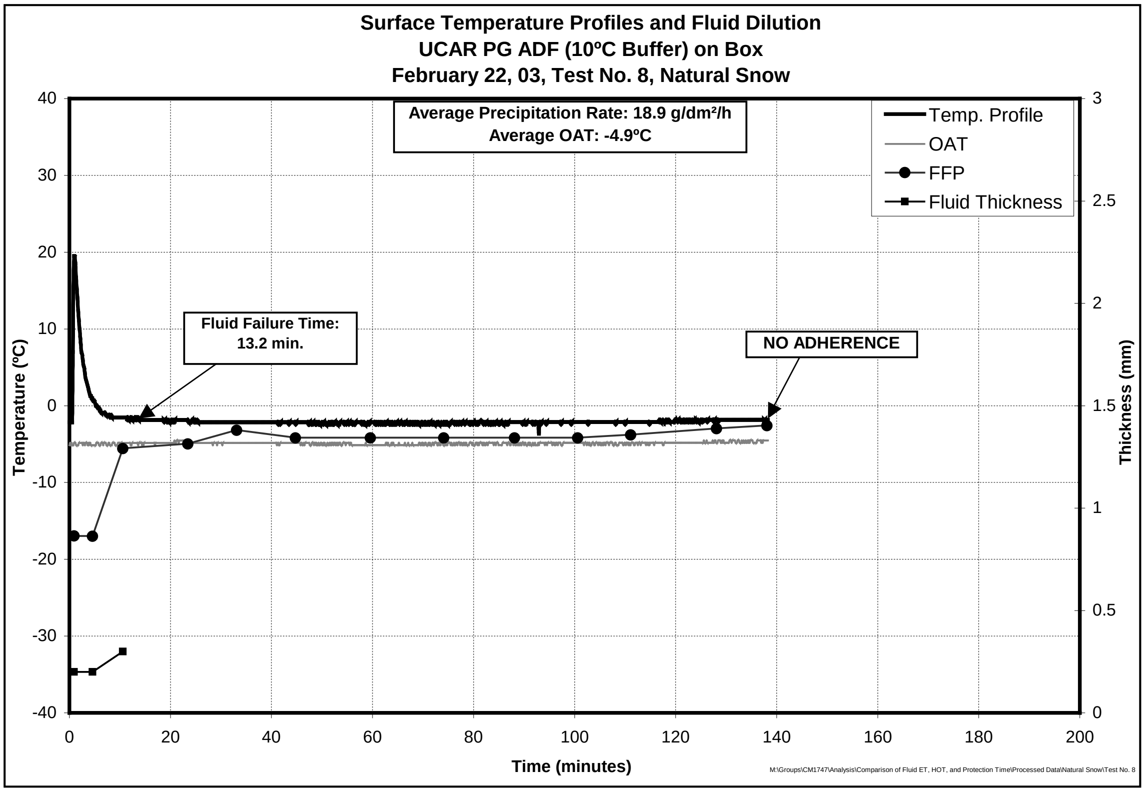
Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (75/25) on Box
February 22, 03, Test No. 5, Natural Snow

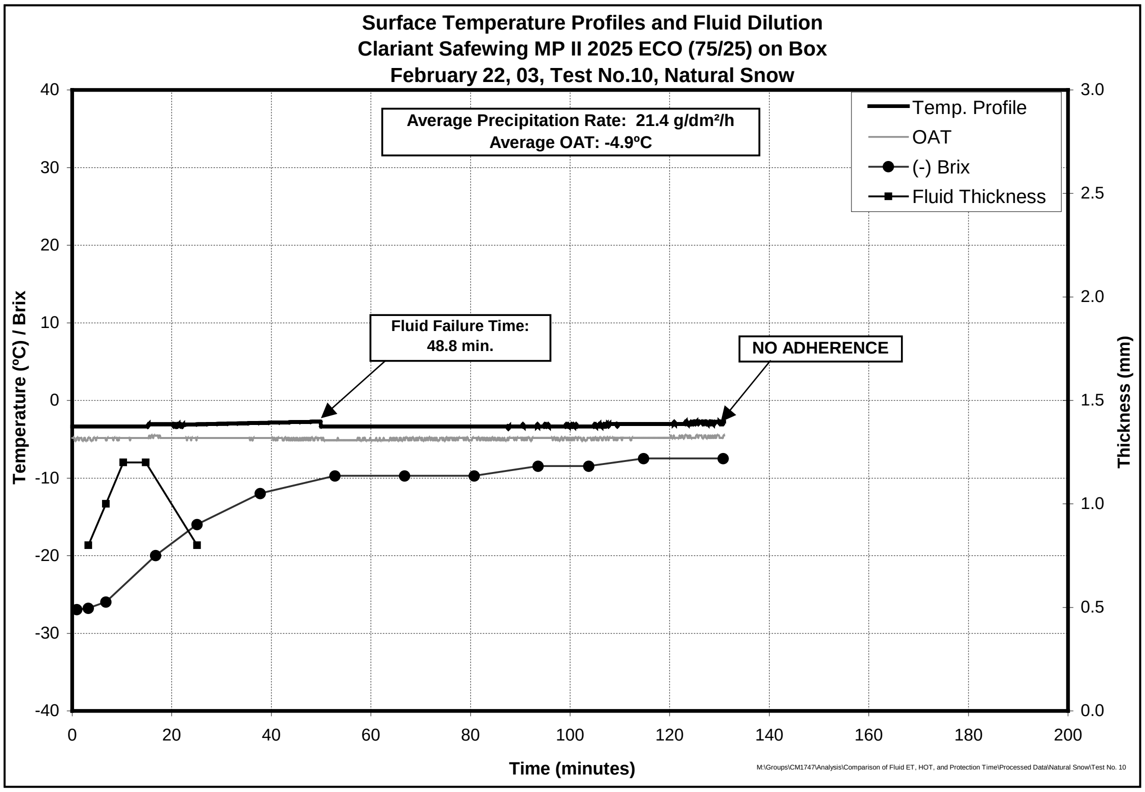


Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (Neat) on Box
February 22, 03, Test No. 6, Natural Snow



Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (50/50) on Box
February 22, 03, Test No. 7, Natural Snow


Surface Temperature Profiles and Fluid Dilution
UCAR PG ADF (10ºC Buffer) on Box
February 22, 03, Test No. 8, Natural Snow
Average Precipitation Rate: 18.9 g/dm²/h
Average OAT: -4.9ºC
Temp. Profile
OAT
FFP
Fluid Thickness
Fluid Failure Time:
13.2 min.
NO ADHERENCE
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 8


Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP II 2025 ECO (75/25) on Box
February 22, 03, Test No.10, Natural Snow
Average Precipitation Rate: 21.4 g/dm²/h
Average OAT: -4.9ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time:
48.8 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
Thickness (mm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
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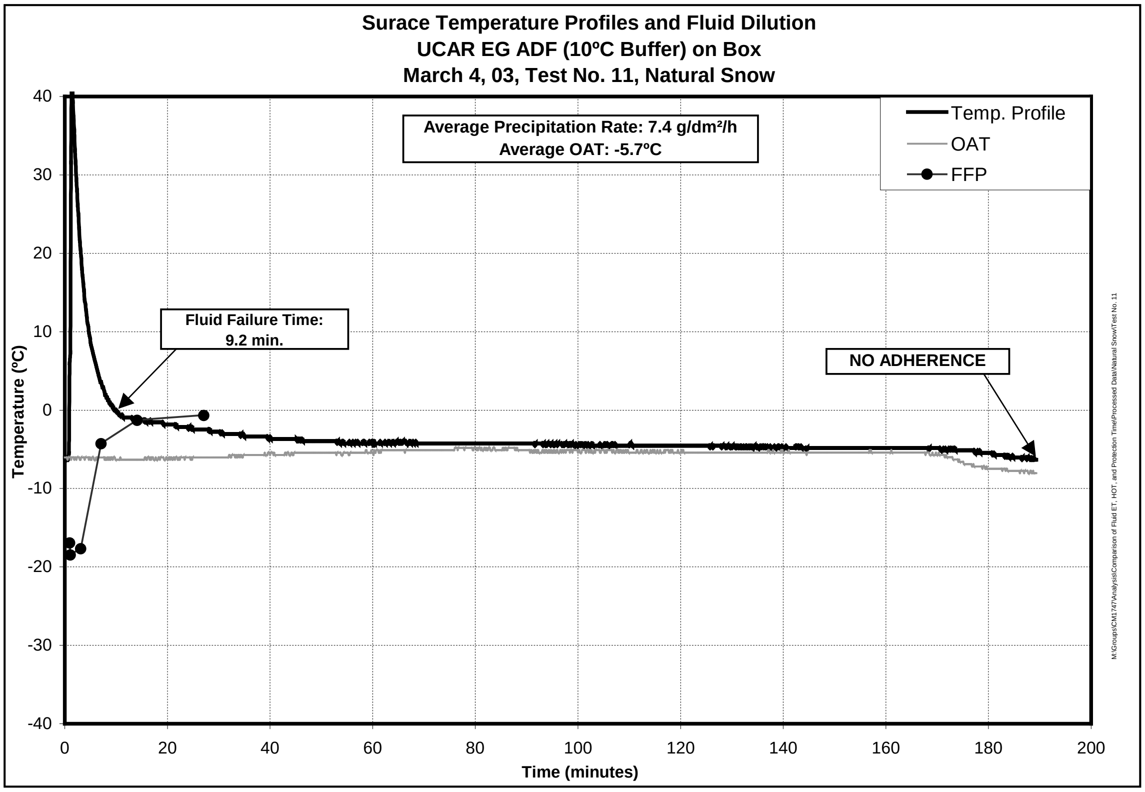
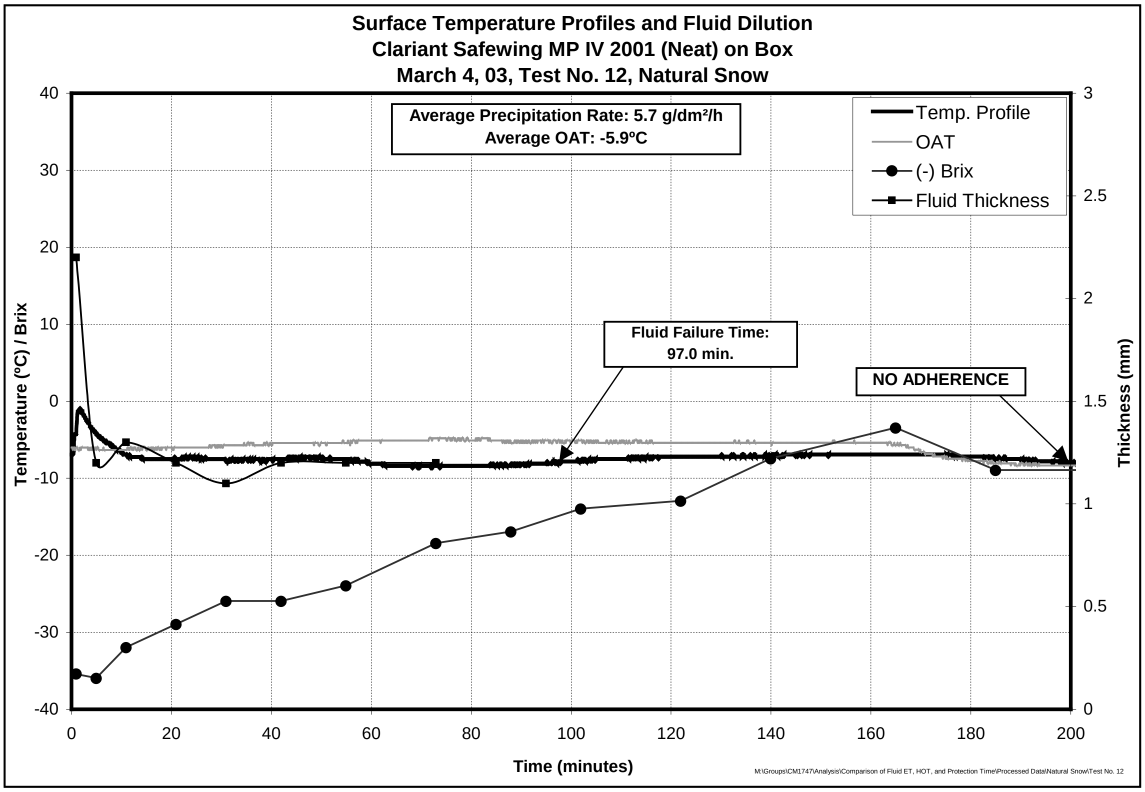
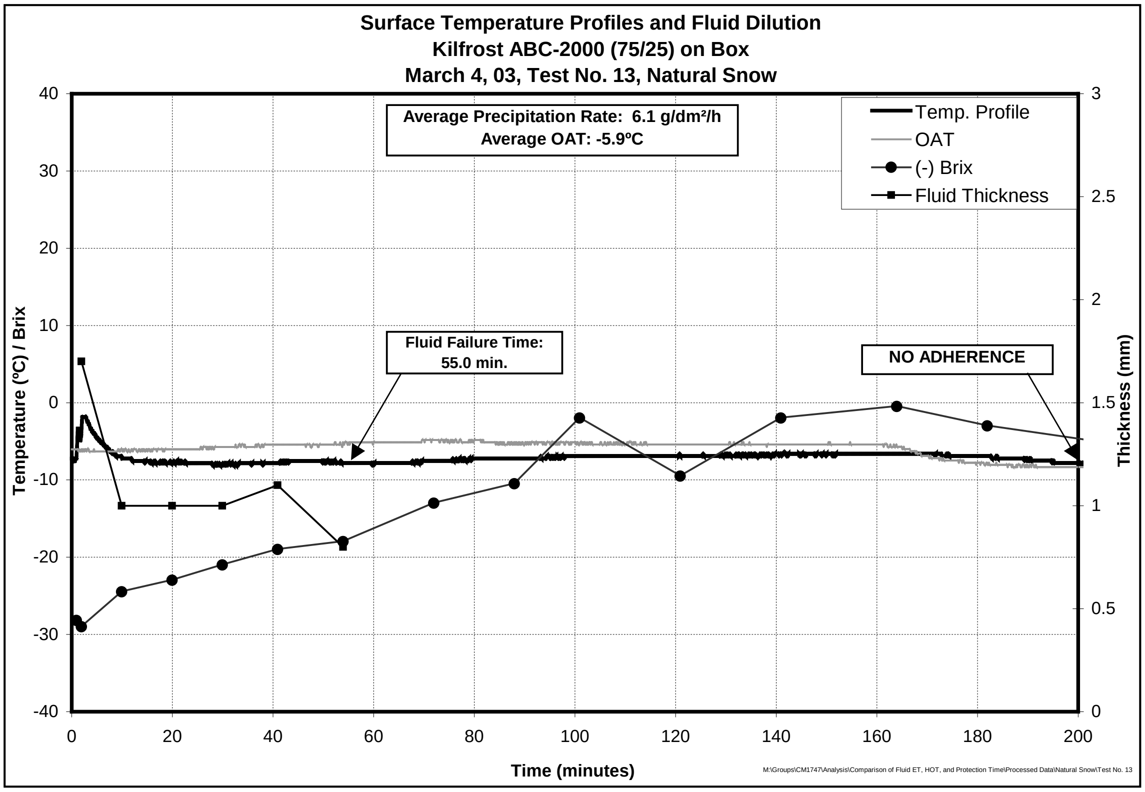
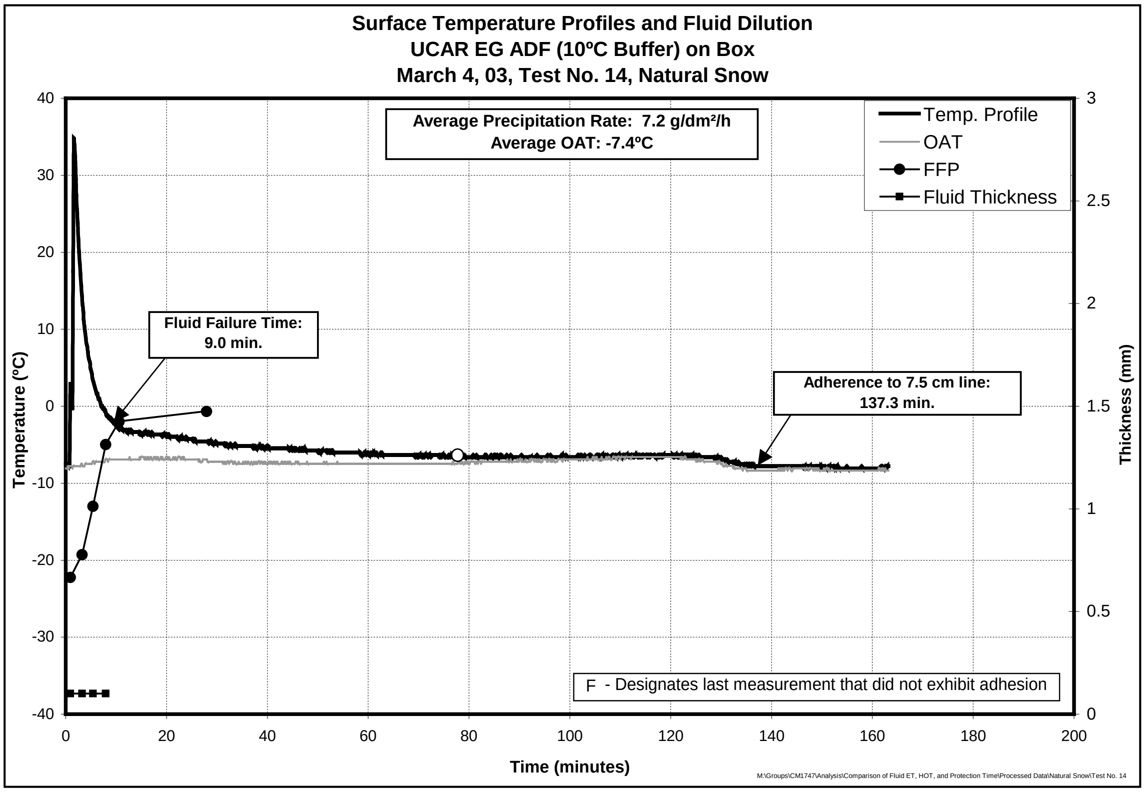

Surace Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Box
March 4, 03, Test No. 11, Natural Snow
Average Precipitation Rate: 7.4 g/dm²/h
Average OAT: -5.7ºC
Temp. Profile
OAT
FFP
Fluid Failure Time:
9.2 min.
NO ADHERENCE
Temperature (ºC)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 11

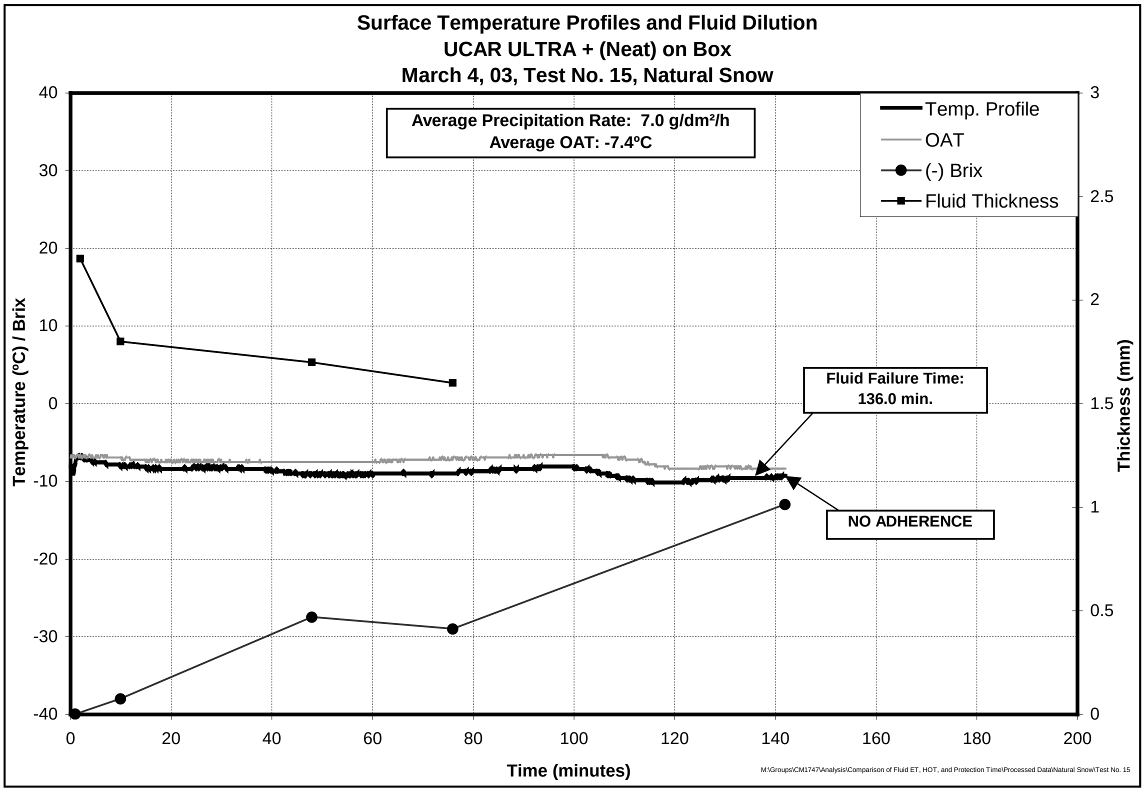

Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2001 (Neat) on Box
March 4, 03, Test No. 12, Natural Snow
Average Precipitation Rate: 5.7 g/dm²/h
Average OAT: -5.9ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time:
97.0 min.
NO ADHERENCE
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 12



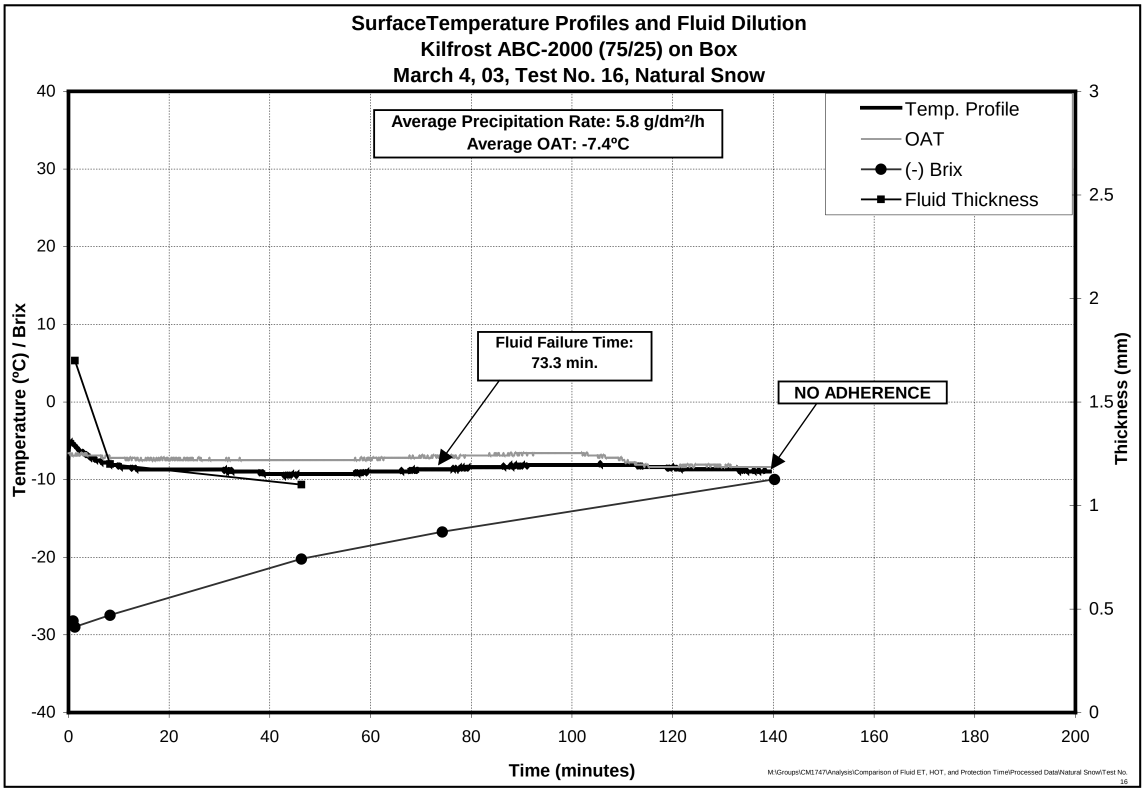
Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (75/25) on Box
March 4, 03, Test No. 13, Natural Snow



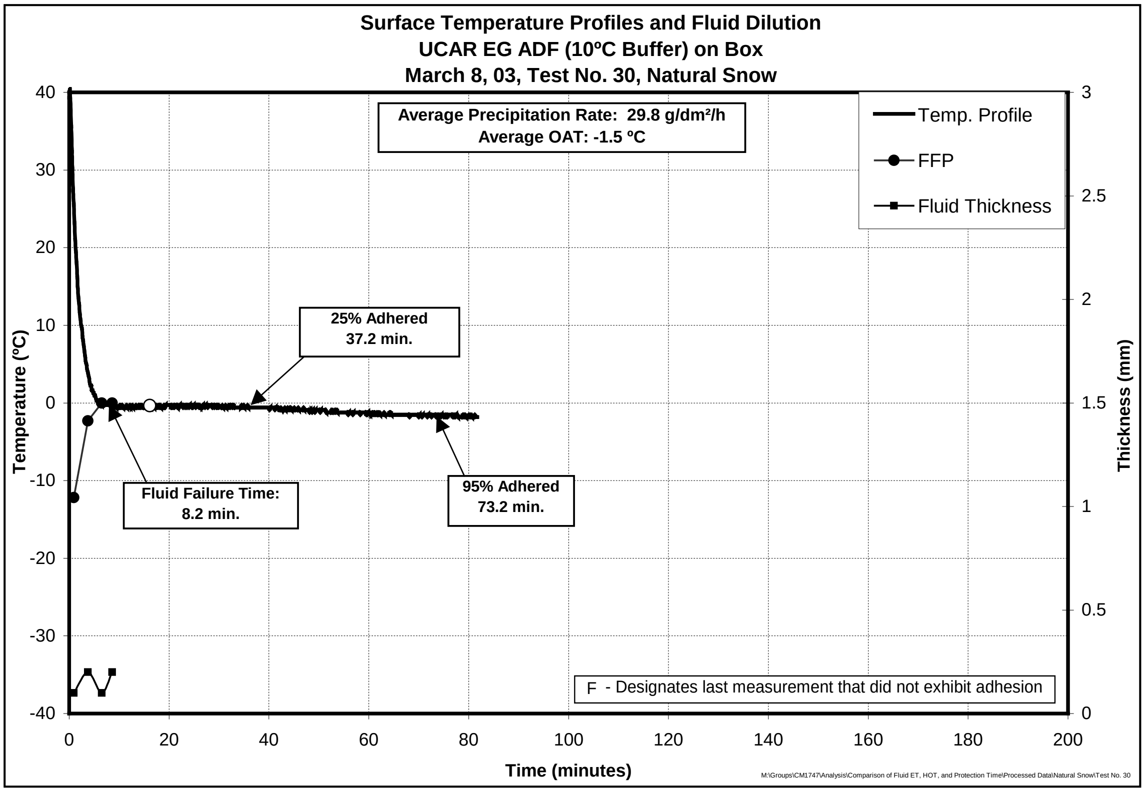
Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Box
March 4, 03, Test No. 14, Natural Snow



Surface Temperature Profiles and Fluid Dilution
UCAR ULTRA + (Neat) on Box
March 4, 03, Test No. 15, Natural Snow

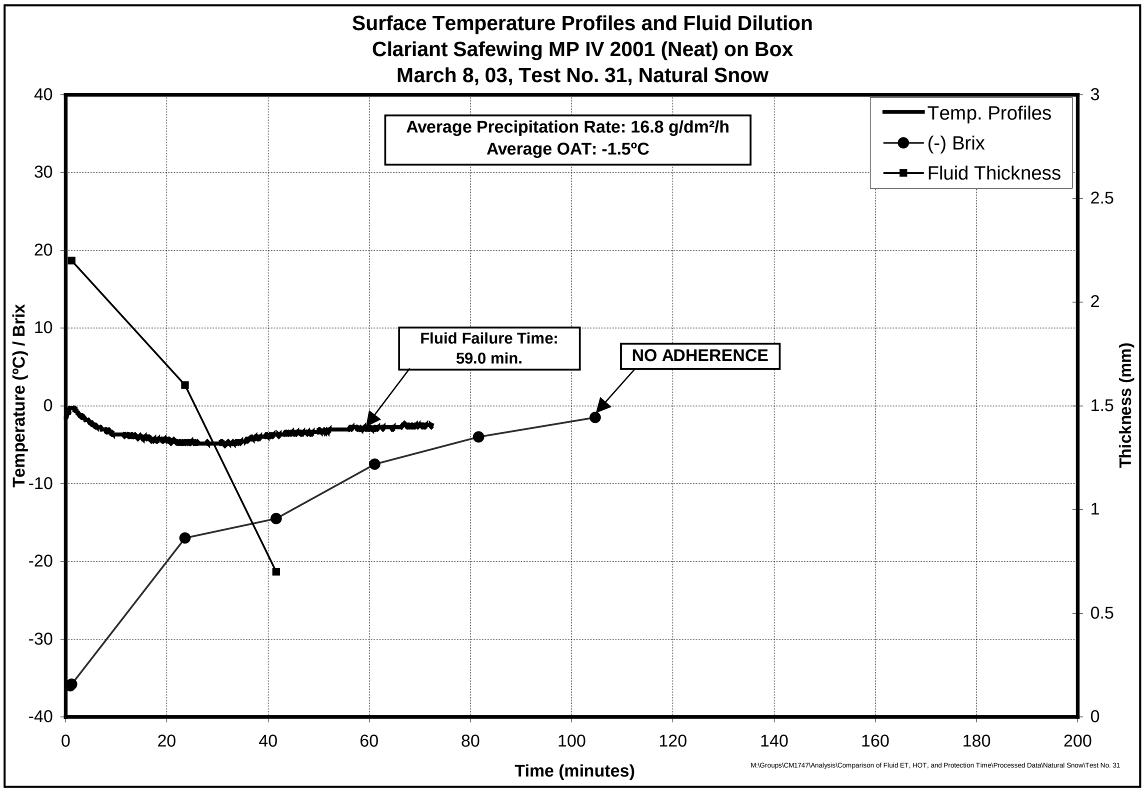


SurfaceTemperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (75/25) on Box
March 4, 03, Test No. 16, Natural Snow



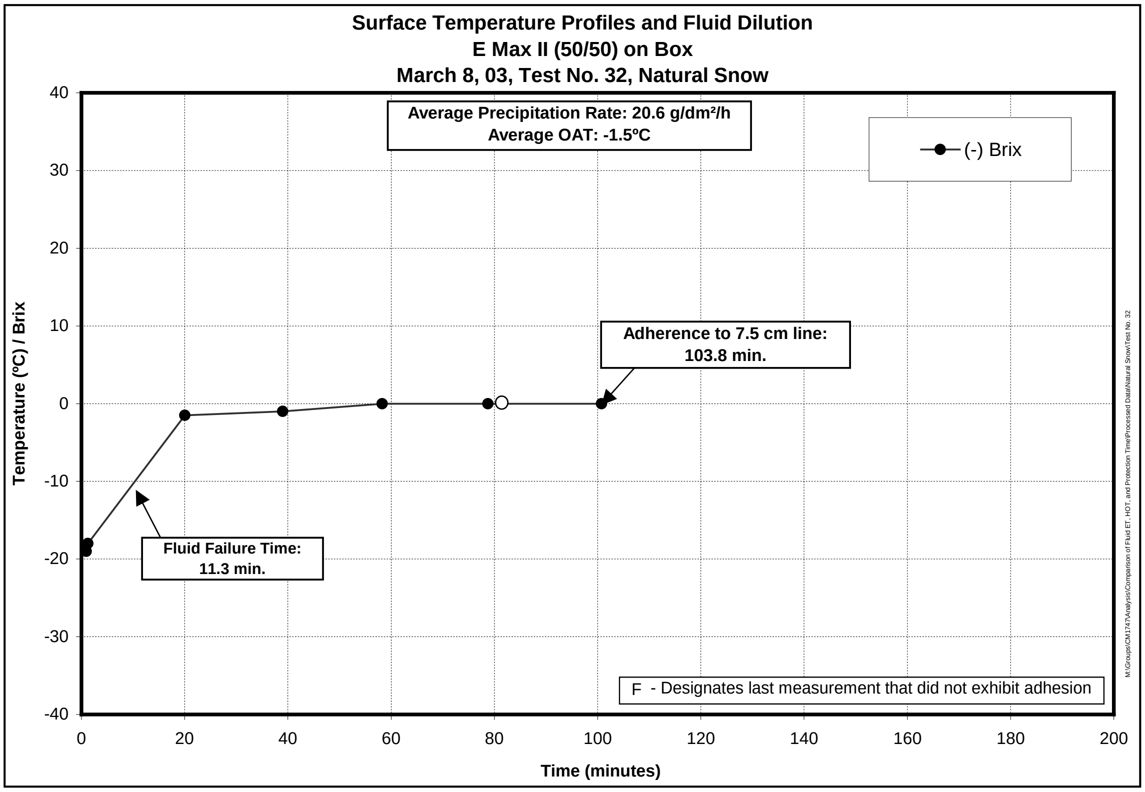
Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Box
March 8, 03, Test No. 30, Natural Snow

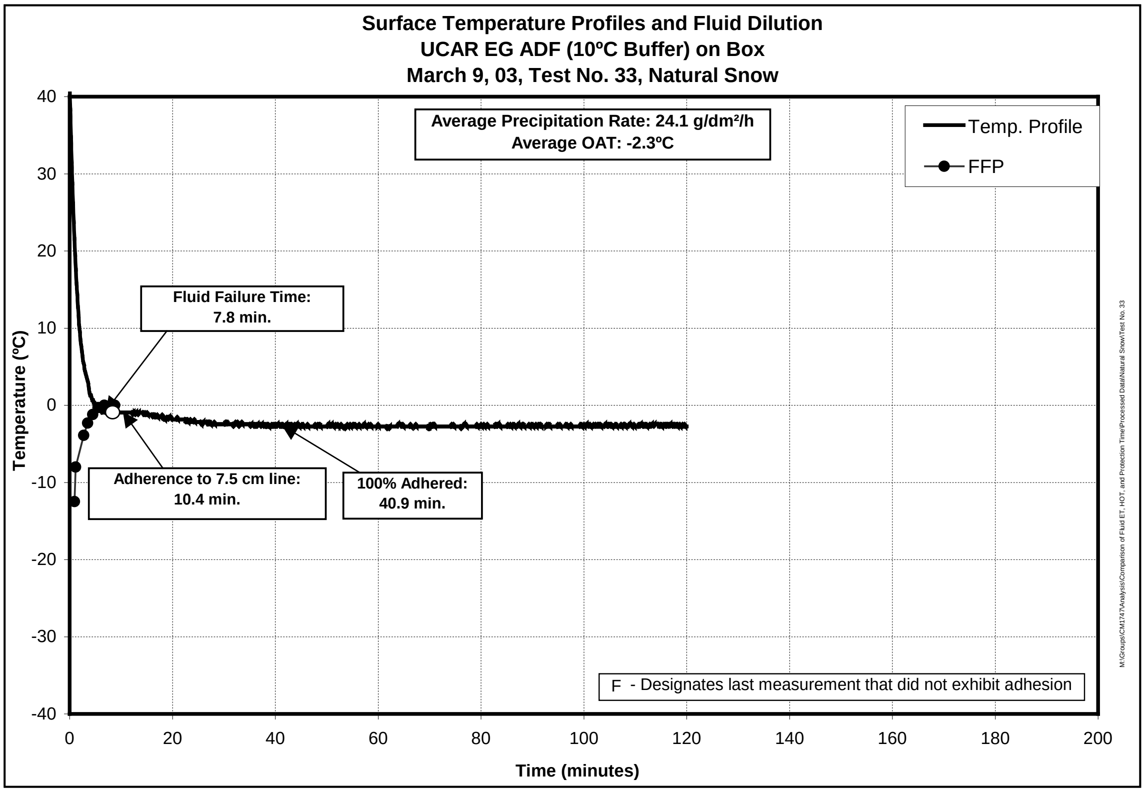
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 30

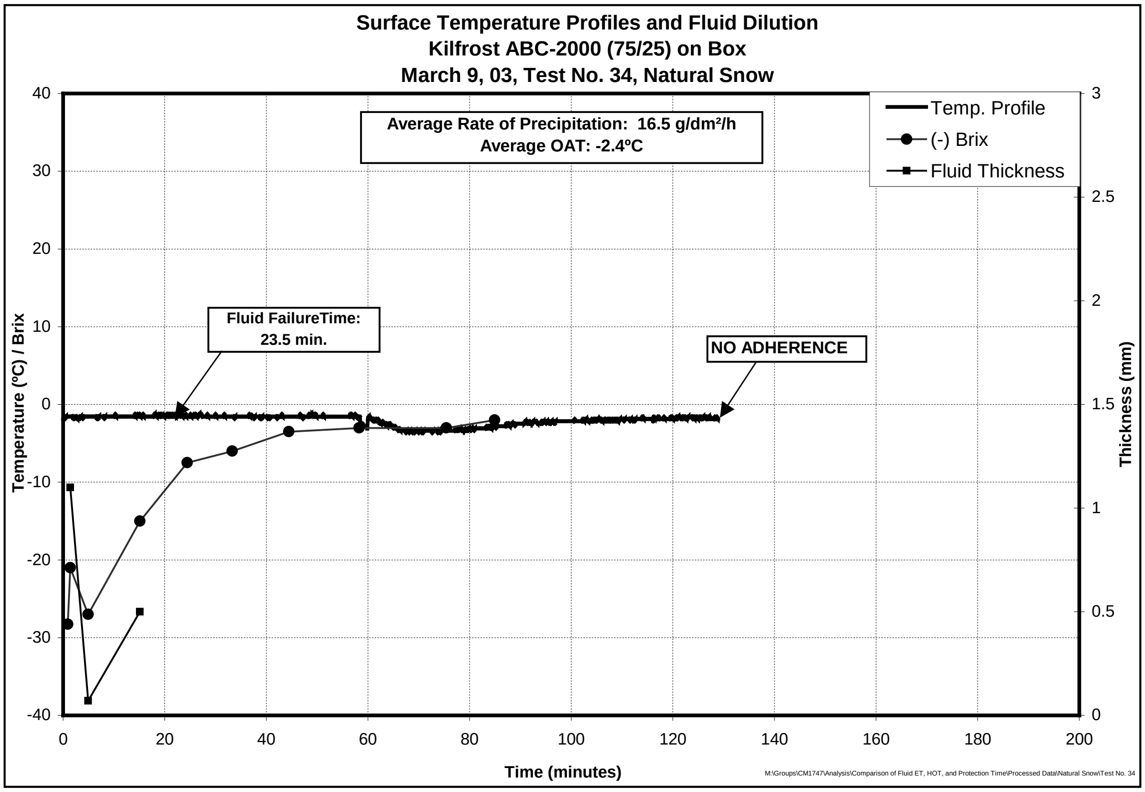


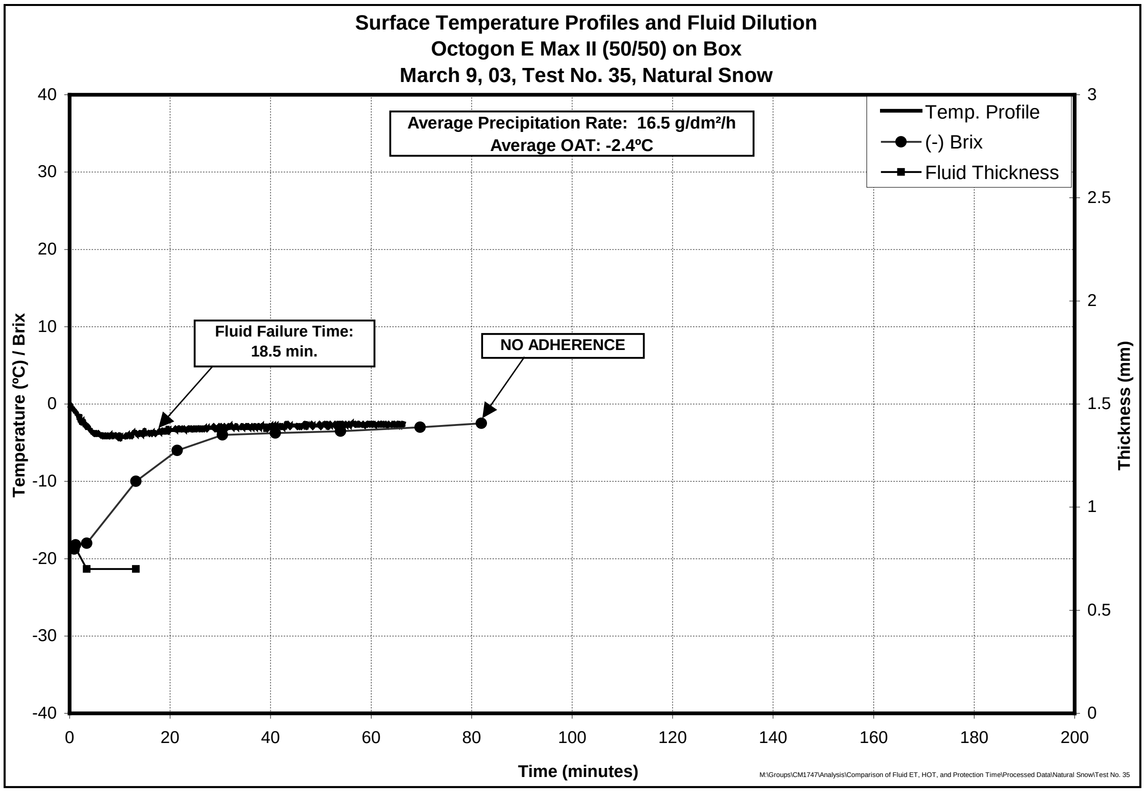
Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2001 (Neat) on Box
March 8, 03, Test No. 31, Natural Snow

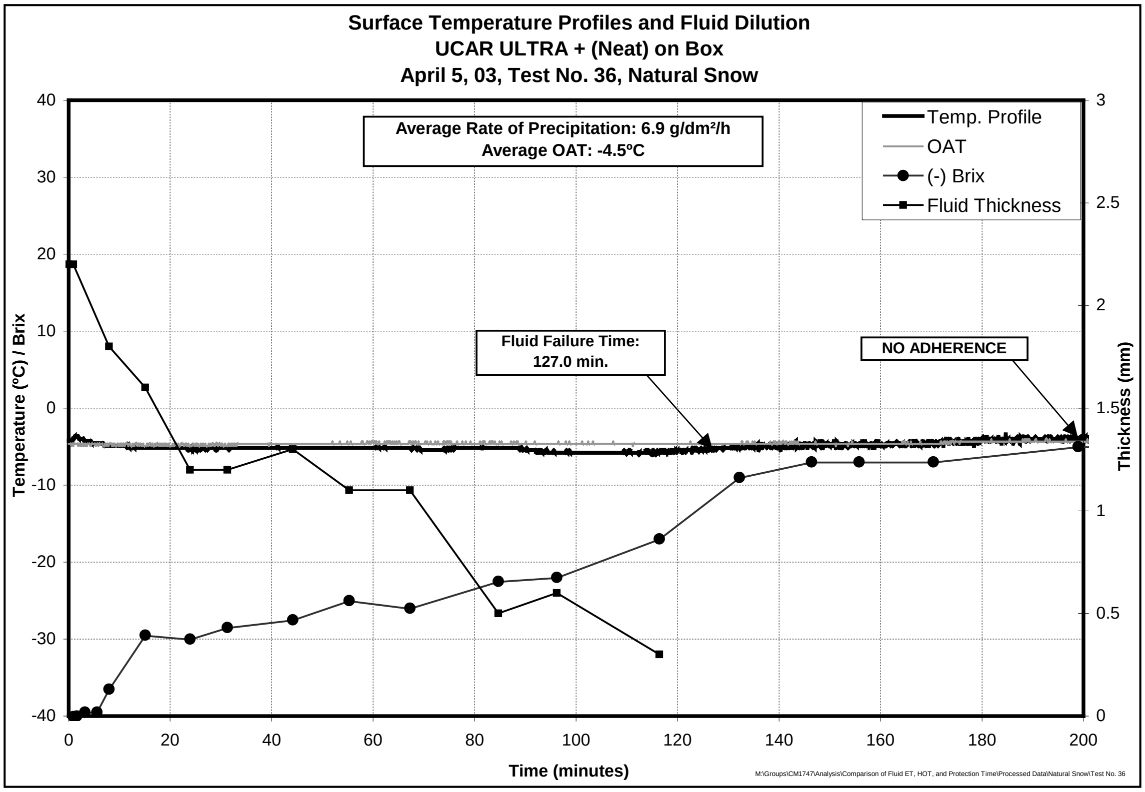
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 31

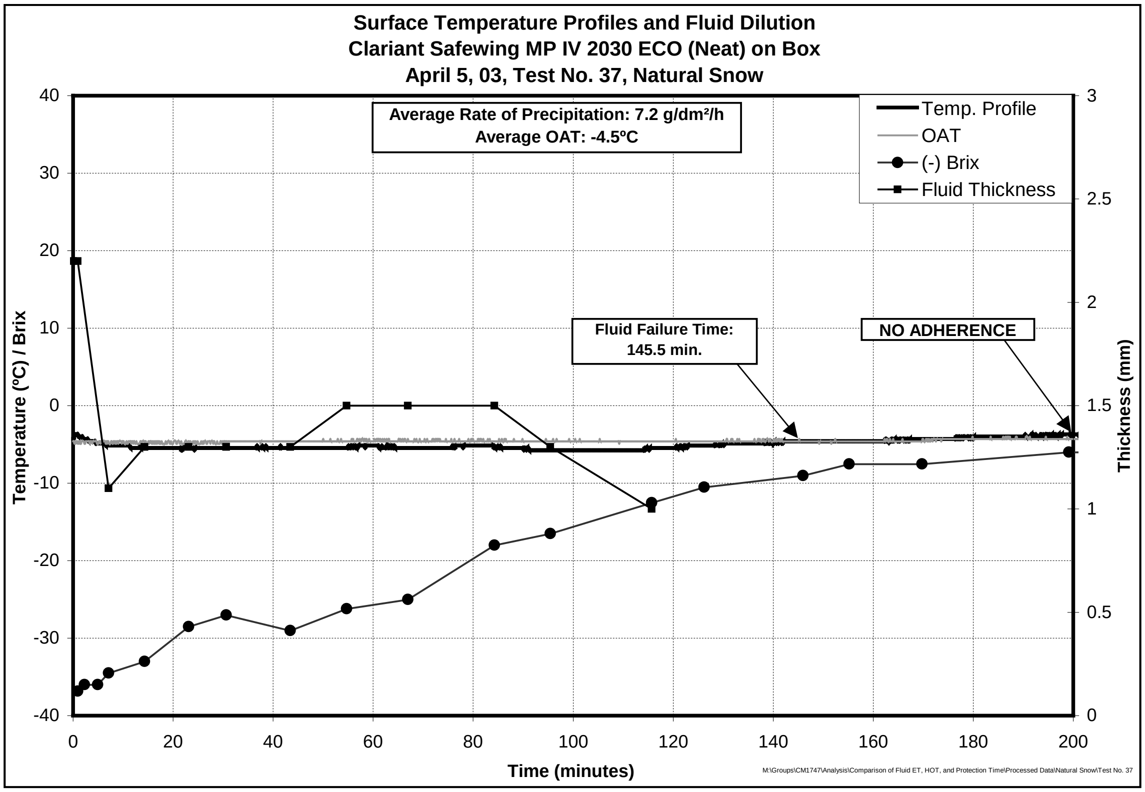

Surface Temperature Profiles and Fluid Dilution
E Max II (50/50) on Box
March 8, 03, Test No. 32, Natural Snow
Average Precipitation Rate: 20.6 g/dm²/h
Average OAT: -1.5ºC
(-) Brix
Adherence to 7.5 cm line:
103.8 min.
Fluid Failure Time:
11.3 min.
F - Designates last measurement that did not exhibit adhesion
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 32

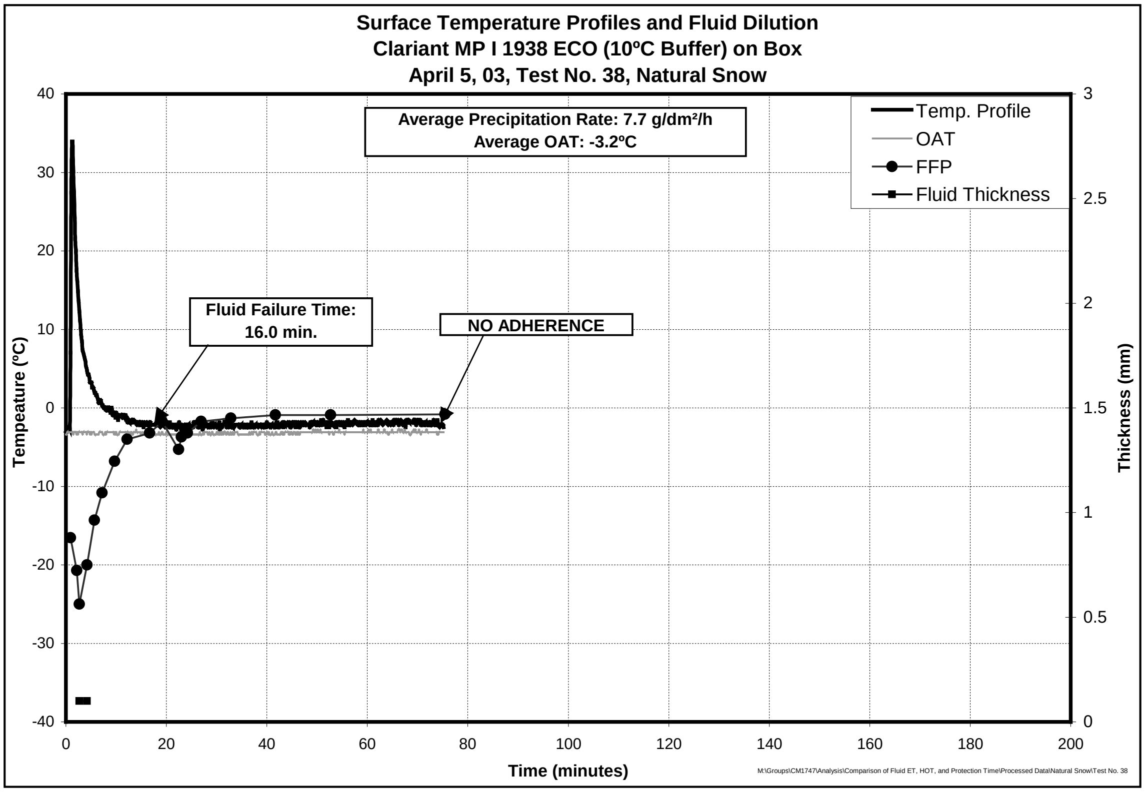

Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on Box
March 9, 03, Test No. 33, Natural Snow
Average Precipitation Rate: 24.1 g/dm²/h
Average OAT: -2.3ºC
Temp. Profile
FFP
Fluid Failure Time:
7.8 min.
Adherence to 7.5 cm line:
10.4 min.
100% Adhered:
40.9 min.
F - Designates last measurement that did not exhibit adhesion
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 33

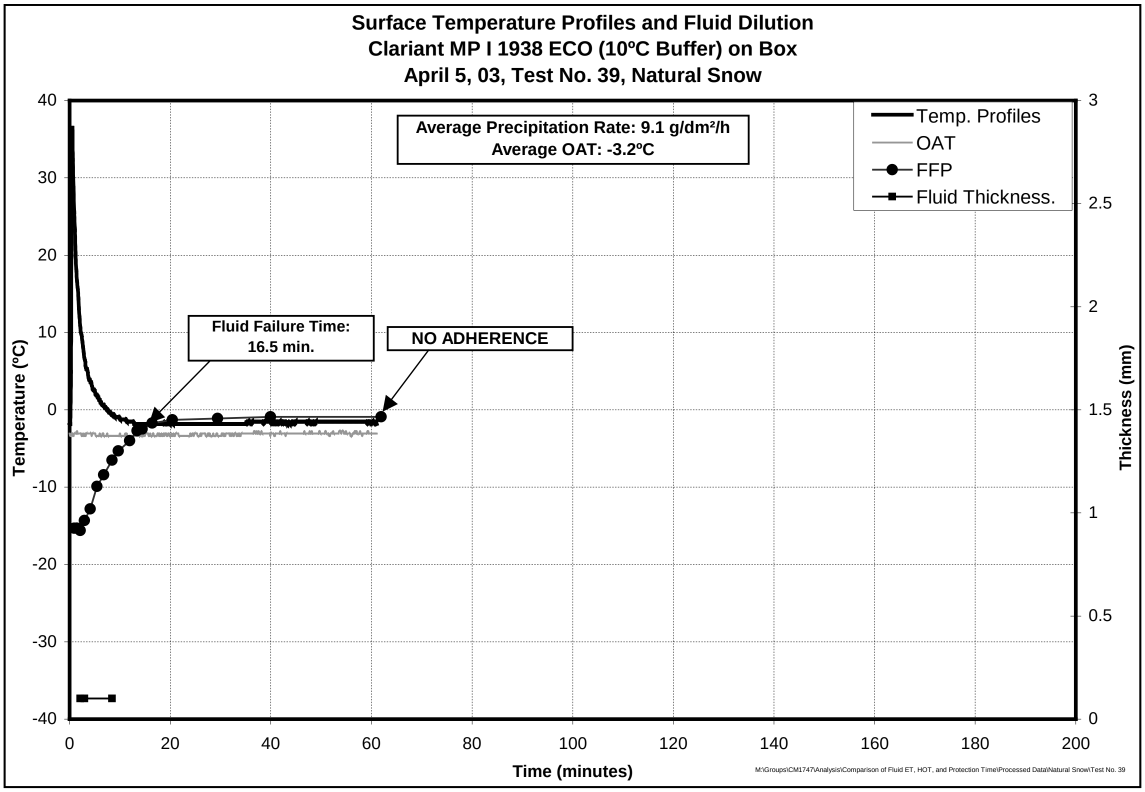

Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (75/25) on Box
March 9, 03, Test No. 34, Natural Snow
Average Rate of Precipitation: 16.5 g/dm²/h
Average OAT: -2.4ºC
Temp. Profile
(-) Brix
Fluid Thickness
Fluid FailureTime:
23.5 min.
NO ADHERENCE
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 34

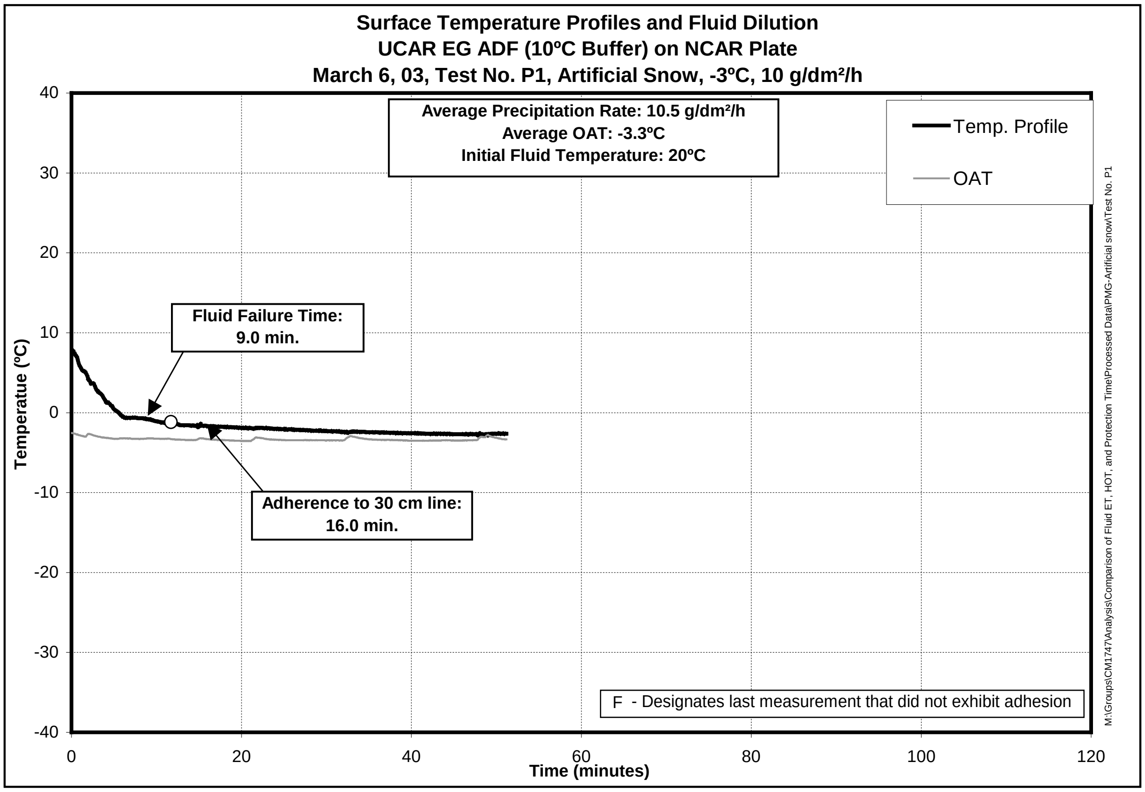

Surface Temperature Profiles and Fluid Dilution
Octogon E Max II (50/50) on Box
March 9, 03, Test No. 35, Natural Snow
Average Precipitation Rate: 16.5 g/dm²/h
Average OAT: -2.4ºC
Temp. Profile
(-) Brix
Fluid Thickness
Fluid Failure Time:
18.5 min.
NO ADHERENCE
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 35

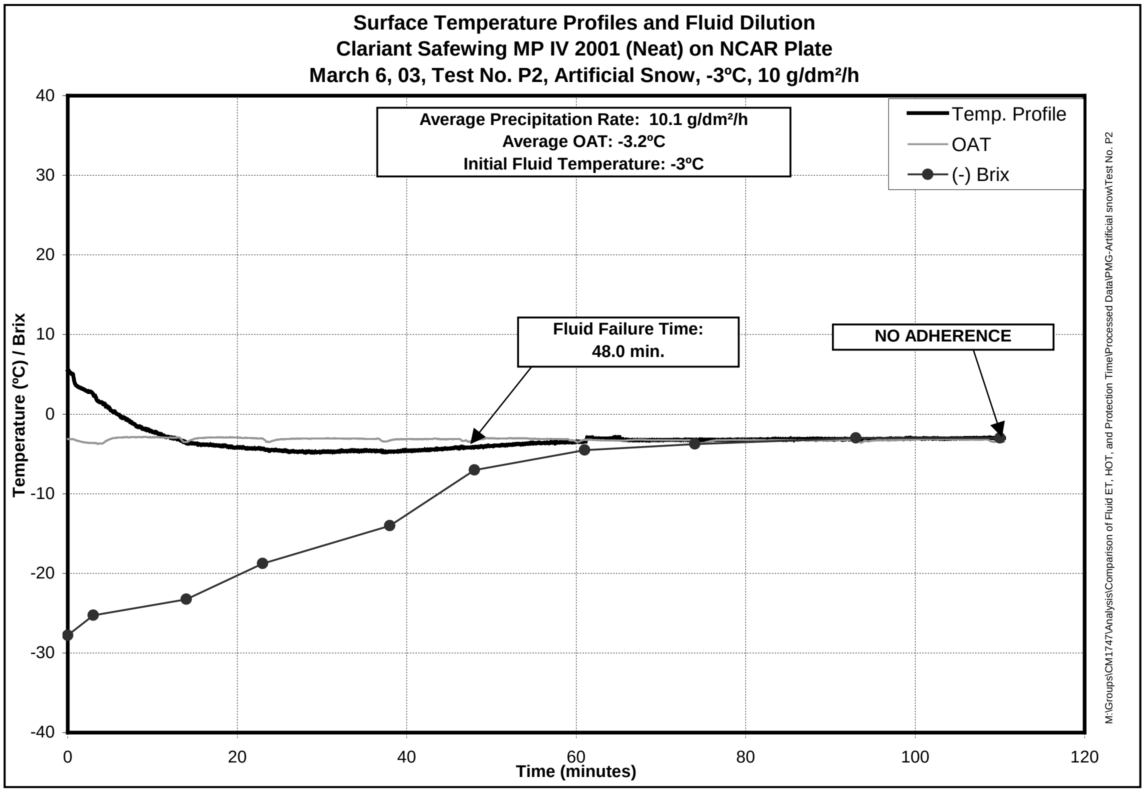

Surface Temperature Profiles and Fluid Dilution
UCAR ULTRA + (Neat) on Box
April 5, 03, Test No. 36, Natural Snow
Average Rate of Precipitation: 6.9 g/dm²/h
Average OAT: -4.5ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 127.0 min.
NO ADHERENCE
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 36

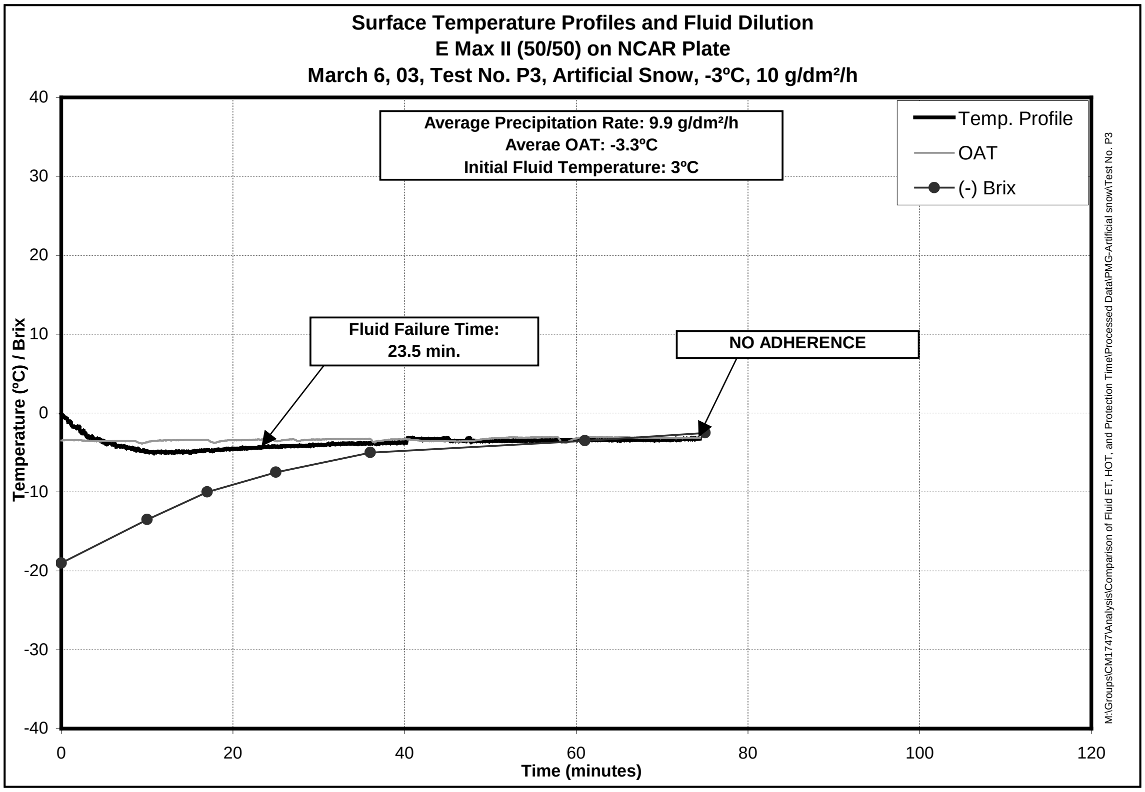

Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2030 ECO (Neat) on Box
April 5, 03, Test No. 37, Natural Snow
Average Rate of Precipitation: 7.2 g/dm²/h
Average OAT: -4.5ºC
Temp. Profile
OAT
(-) Brix
Fluid Thickness
Fluid Failure Time: 145.5 min.
NO ADHERENCE
Temperature (ºC) / Brix
Thickness (mm)
Time (minutes)
40
30
20
10
0
-10
-20
-30
-40
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 37


Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Box
April 5, 03, Test No. 38, Natural Snow


Surface Temperature Profiles and Fluid Dilution
Clariant MP I 1938 ECO (10ºC Buffer) on Box
April 5, 03, Test No. 39, Natural Snow


Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on NCAR Plate
March 6, 03, Test No. P1, Artificial Snow, -3ºC, 10 g/dm²/h
Average Precipitation Rate: 10.5 g/dm²/h
Average OAT: -3.3ºC
Initial Fluid Temperature: 20ºC
Temp. Profile
OAT
Fluid Failure Time:
9.0 min.
Adherence to 30 cm line:
16.0 min.
F - Designates last measurement that did not exhibit adhesion
Temperatue (ºC)
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\PMG-Artificial snow\Test No. P1


Surface Temperature Profiles and Fluid Dilution
Clariant Safewing MP IV 2001 (Neat) on NCAR Plate
March 6, 03, Test No. P2, Artificial Snow, -3ºC, 10 g/dm²/h
Average Precipitation Rate: 10.1 g/dm²/h
Average OAT: -3.2ºC
Initial Fluid Temperature: -3ºC
Temp. Profile
OAT
(-) Brix
Fluid Failure Time:
48.0 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\PMG-Artificial snow\Test No. P2

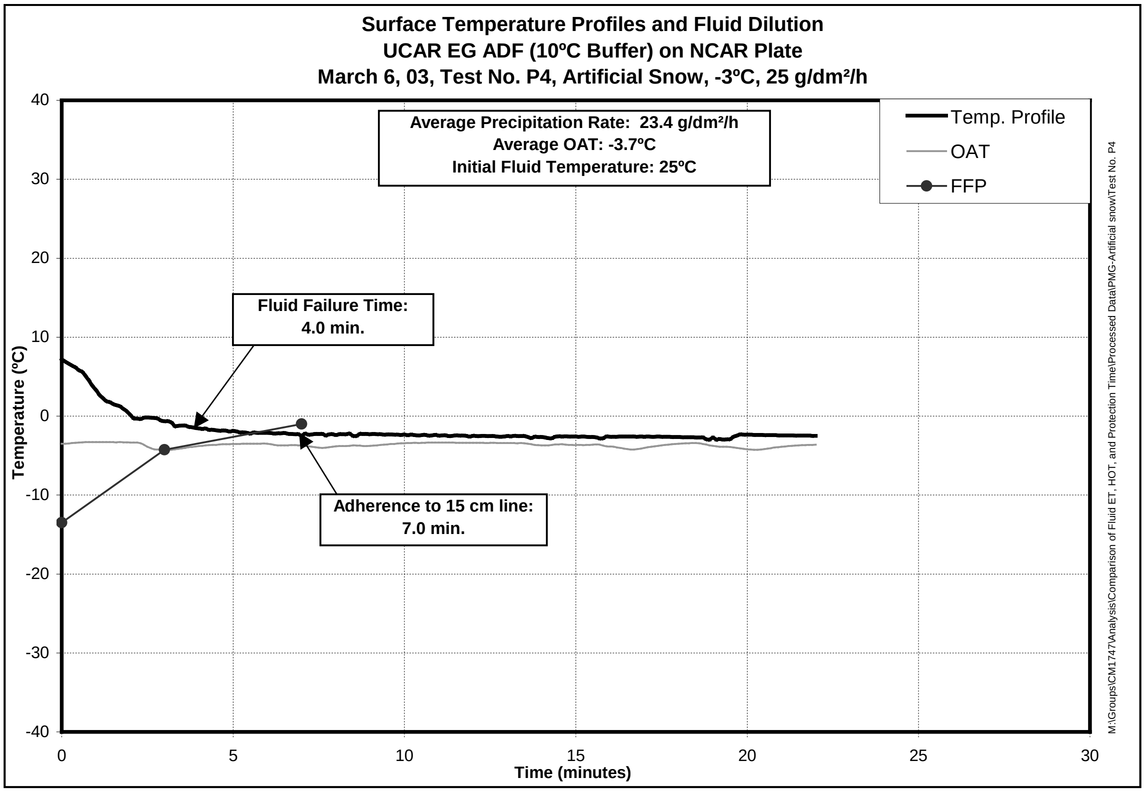


Surface Temperature Profiles and Fluid Dilution
E Max II (50/50) on NCAR Plate
March 6, 03, Test No. P3, Artificial Snow, -3ºC, 10 g/dm²/h

Average Precipitation Rate: 9.9 g/dm²/h
Averae OAT: -3.3ºC
Initial Fluid Temperature: 3ºC

Fluid Failure Time: 23.5 min.

NO ADHERENCE

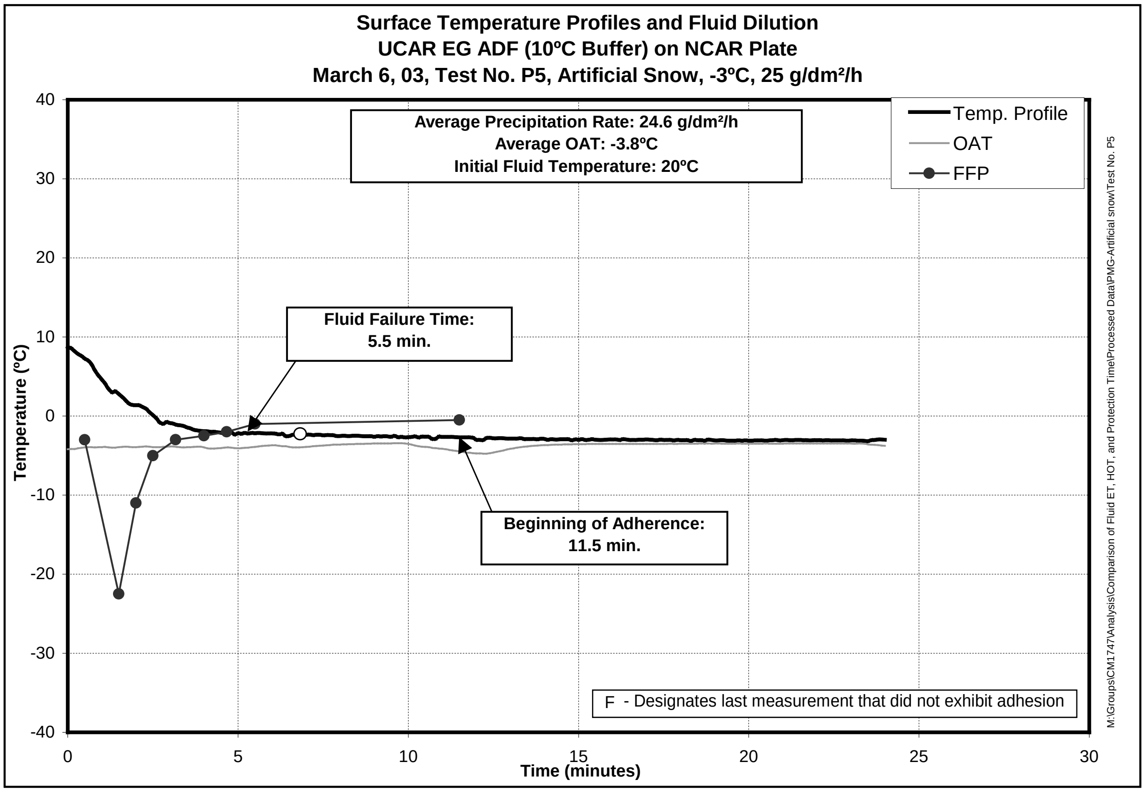


Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on NCAR Plate
March 6, 03, Test No. P4, Artificial Snow, -3ºC, 25 g/dm²/h

Average Precipitation Rate: 23.4 g/dm²/h
Average OAT: -3.7ºC
Initial Fluid Temperature: 25ºC

Fluid Failure Time: 4.0 min.

Adherence to 15 cm line: 7.0 min.

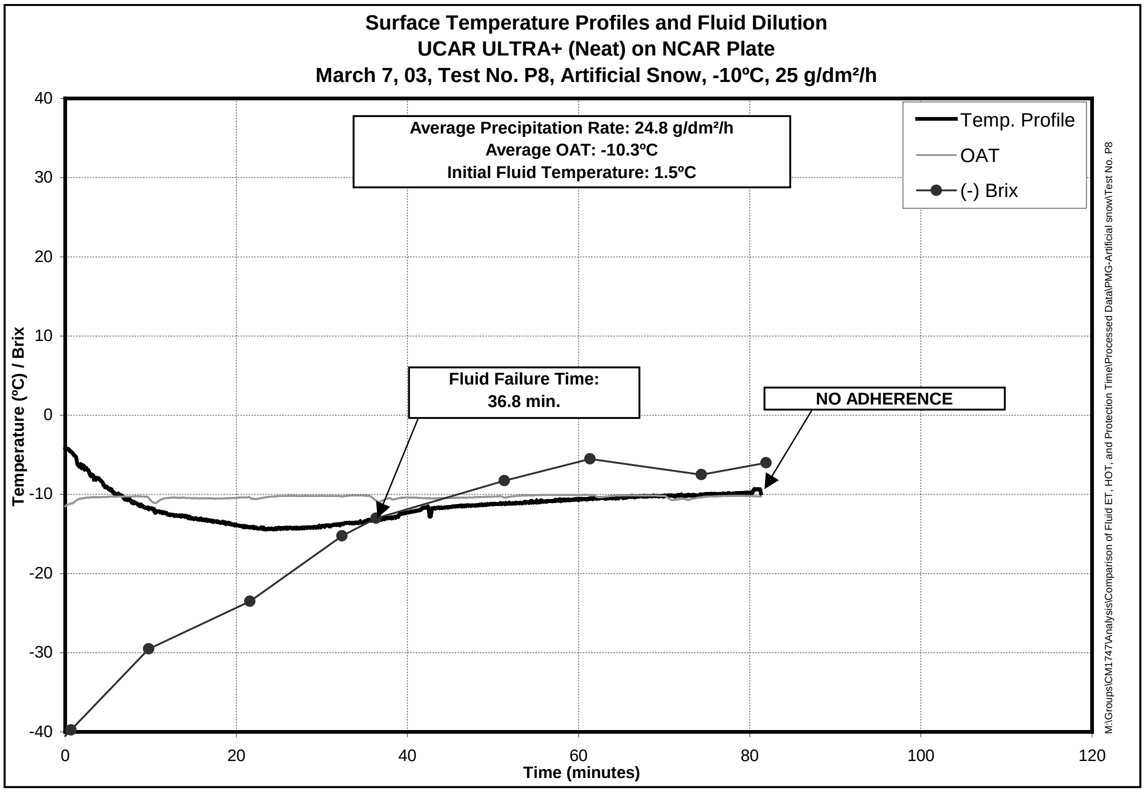

Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on NCAR Plate
March 6, 03, Test No. P5, Artificial Snow, -3ºC, 25 g/dm²/h

Average Precipitation Rate: 24.6 g/dm²/h
Average OAT: -3.8ºC
Initial Fluid Temperature: 20ºC

Fluid Failure Time:
5.5 min.

Beginning of Adherence:
11.5 min.

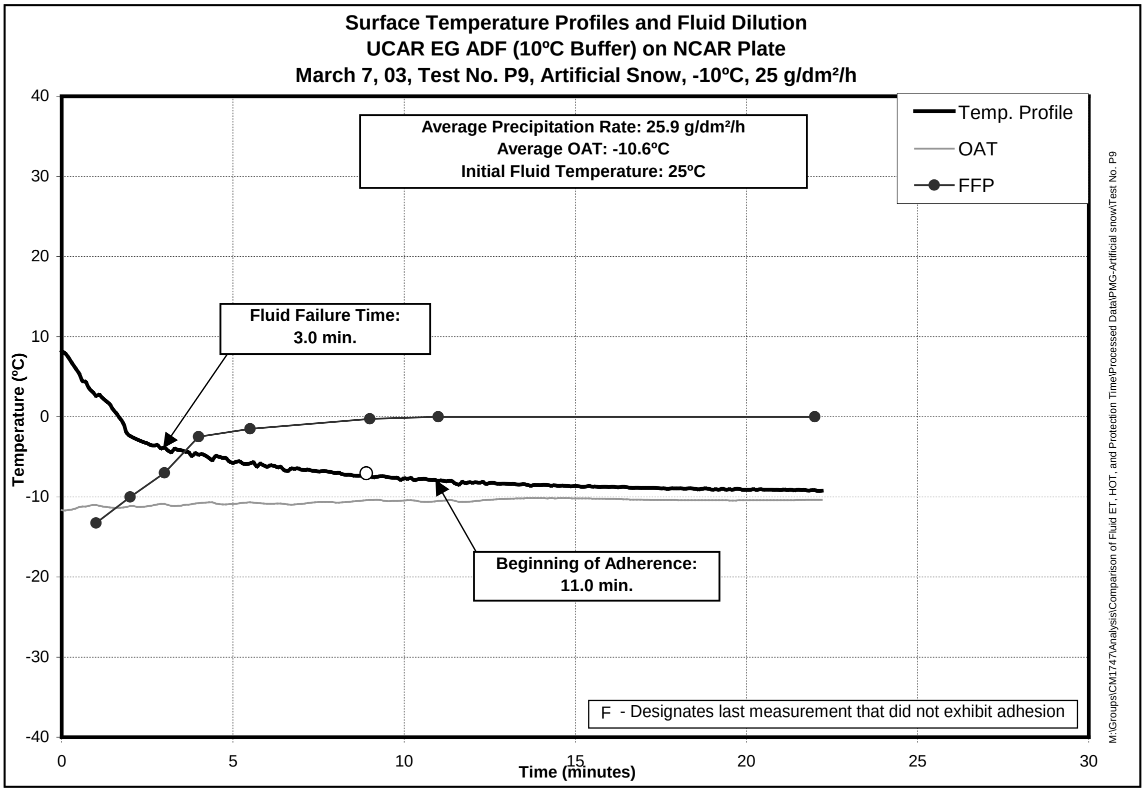
F - Designates last measurement that did not exhibit adhesion


Surface Temperature Profiles and Fluid Dilution
UCAR ULTRA+ (Neat) on NCAR Plate
March 7, 03, Test No. P8, Artificial Snow, -10ºC, 25 g/dm²/h

Average Precipitation Rate: 24.8 g/dm²/h
Average OAT: -10.3ºC
Initial Fluid Temperature: 1.5ºC

Fluid Failure Time:
36.8 min.

NO ADHERENCE



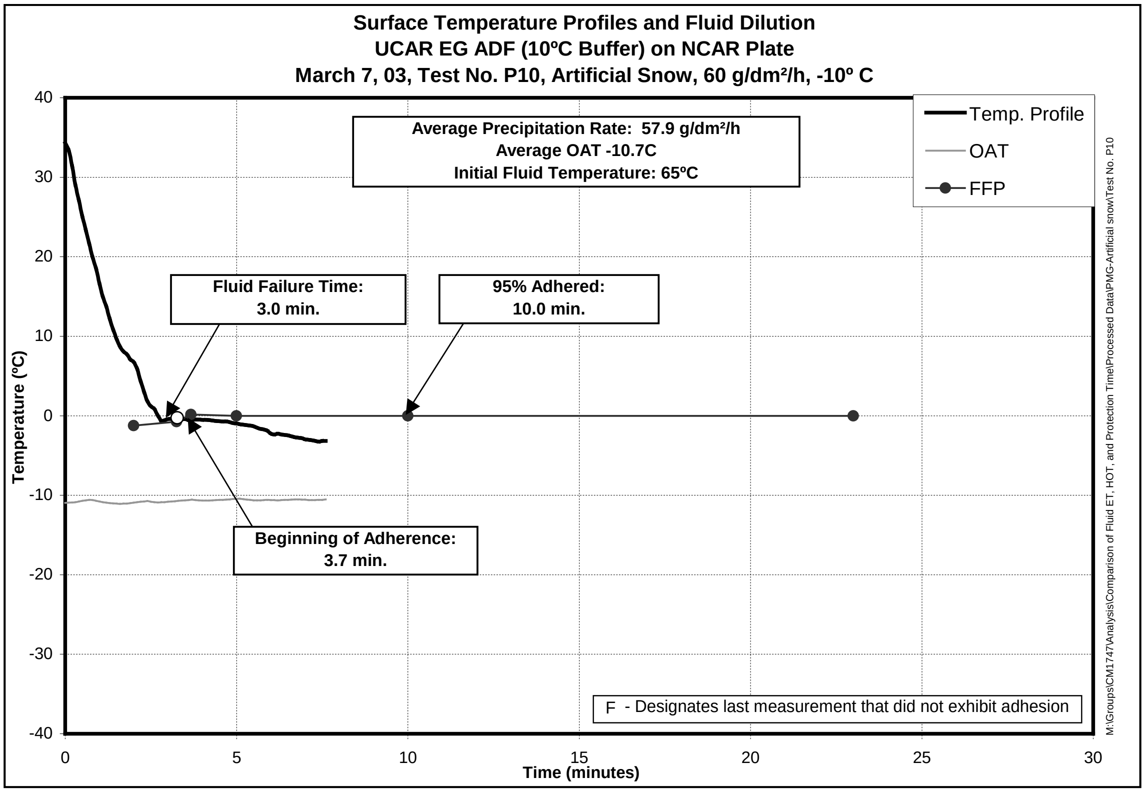
Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on NCAR Plate
March 7, 03, Test No. P9, Artificial Snow, -10ºC, 25 g/dm²/h

Average Precipitation Rate: 25.9 g/dm²/h
Average OAT: -10.6ºC
Initial Fluid Temperature: 25ºC

Fluid Failure Time:
3.0 min.

Beginning of Adherence:
11.0 min.

F - Designates last measurement that did not exhibit adhesion



Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on NCAR Plate
March 7, 03, Test No. P10, Artificial Snow, 60 g/dm²/h, -10º C

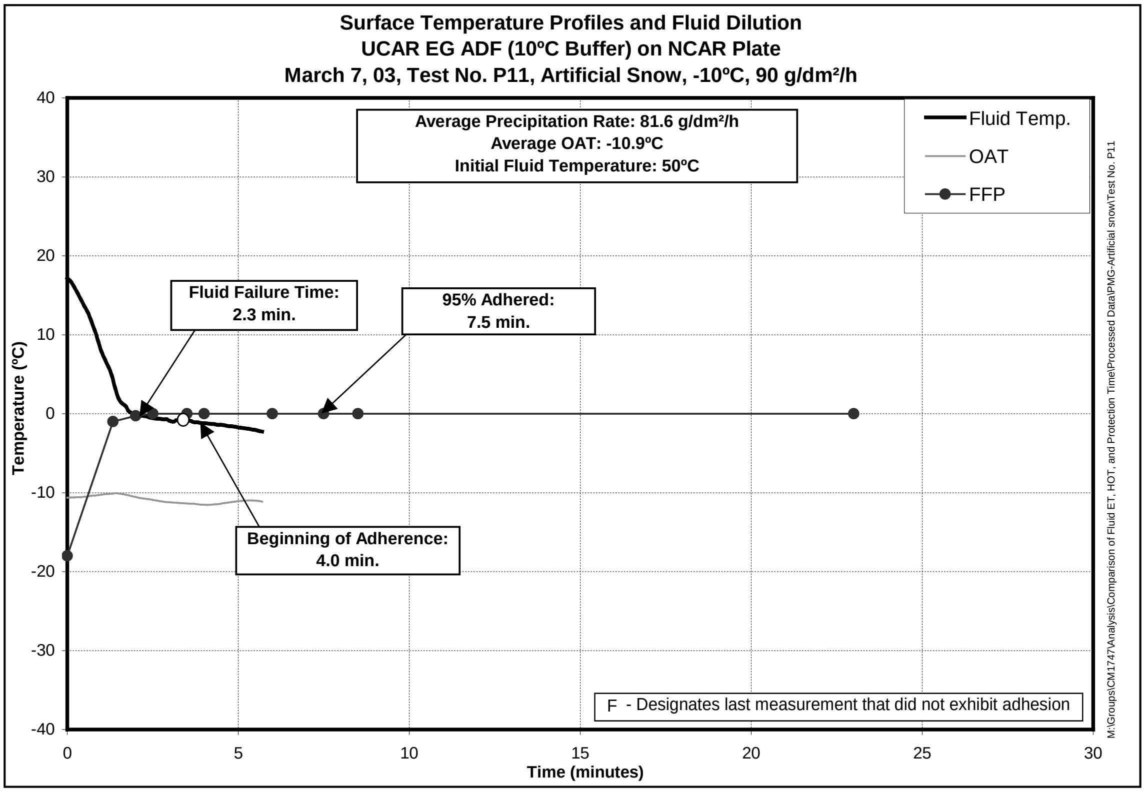
Average Precipitation Rate: 57.9 g/dm²/h
Average OAT -10.7C
Initial Fluid Temperature: 65ºC

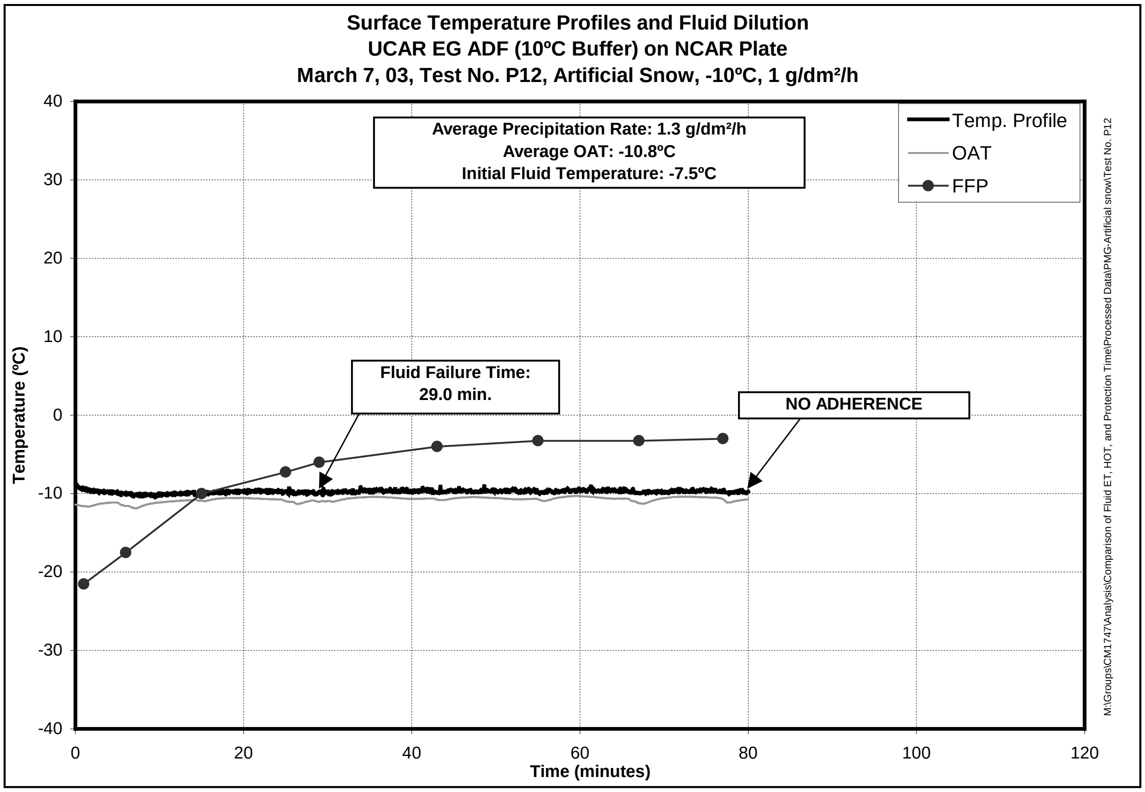
Fluid Failure Time:
3.0 min.

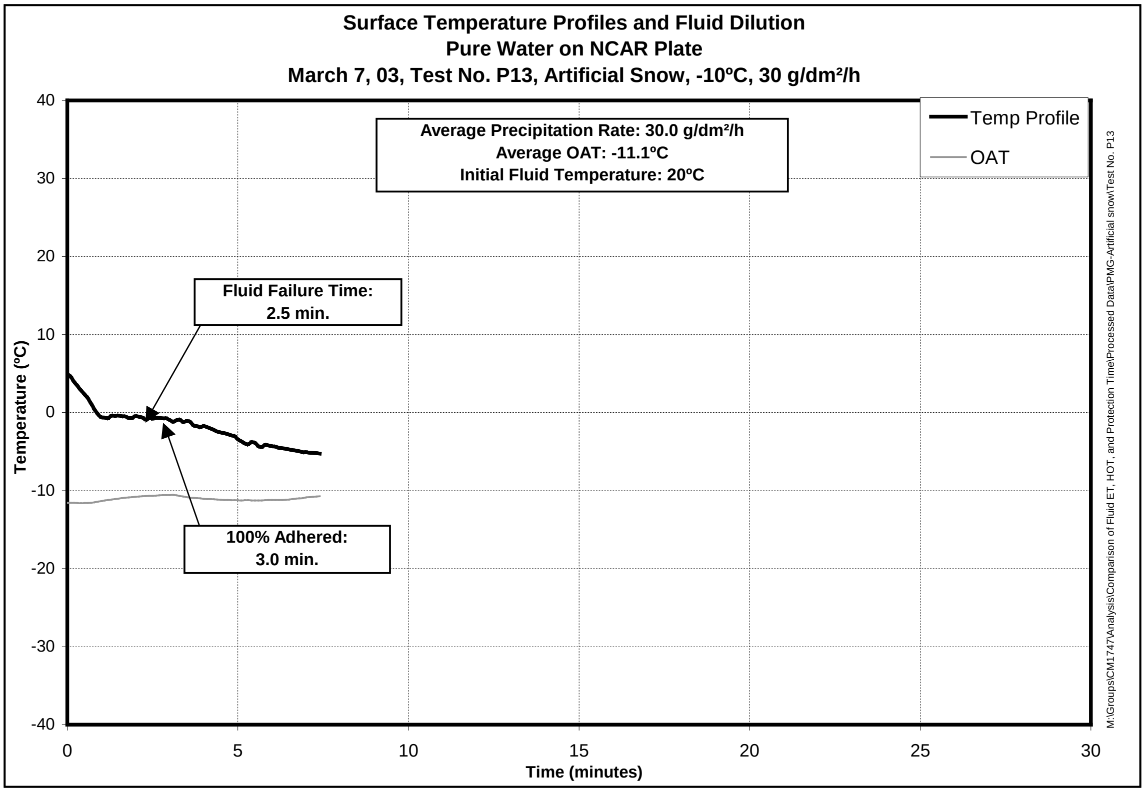
95% Adhered:
10.0 min.

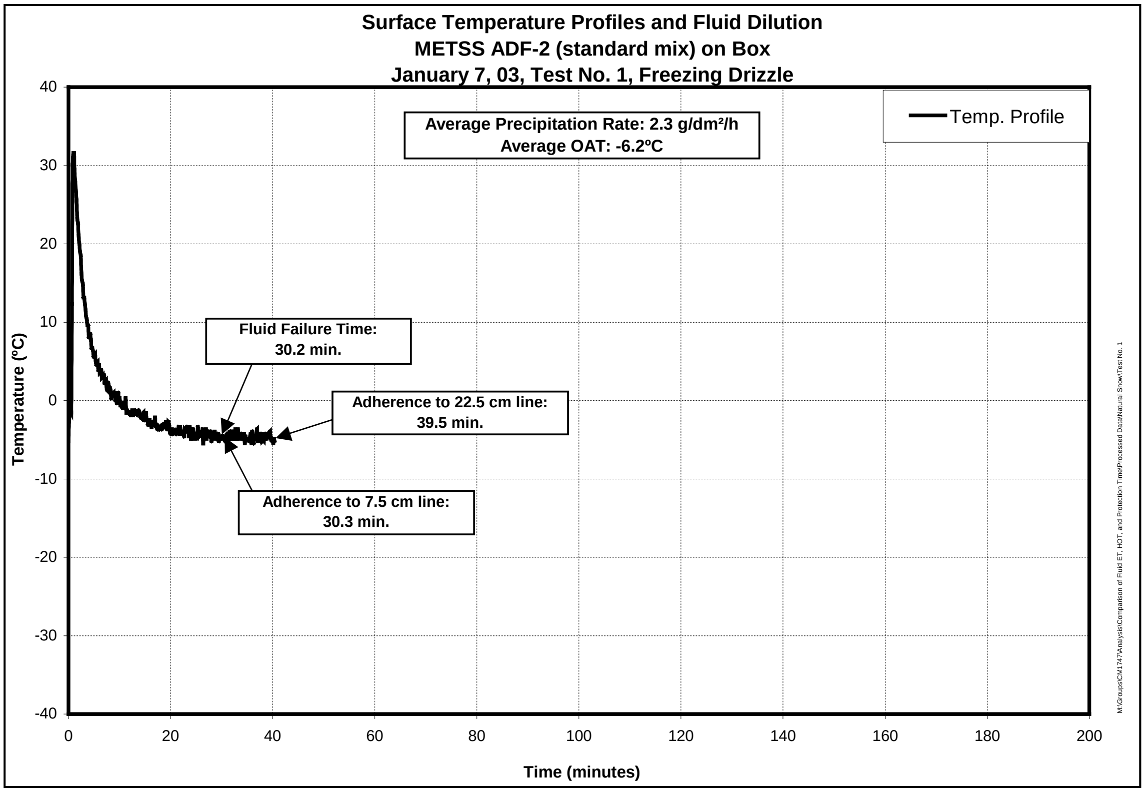
Beginning of Adherence:
3.7 min.

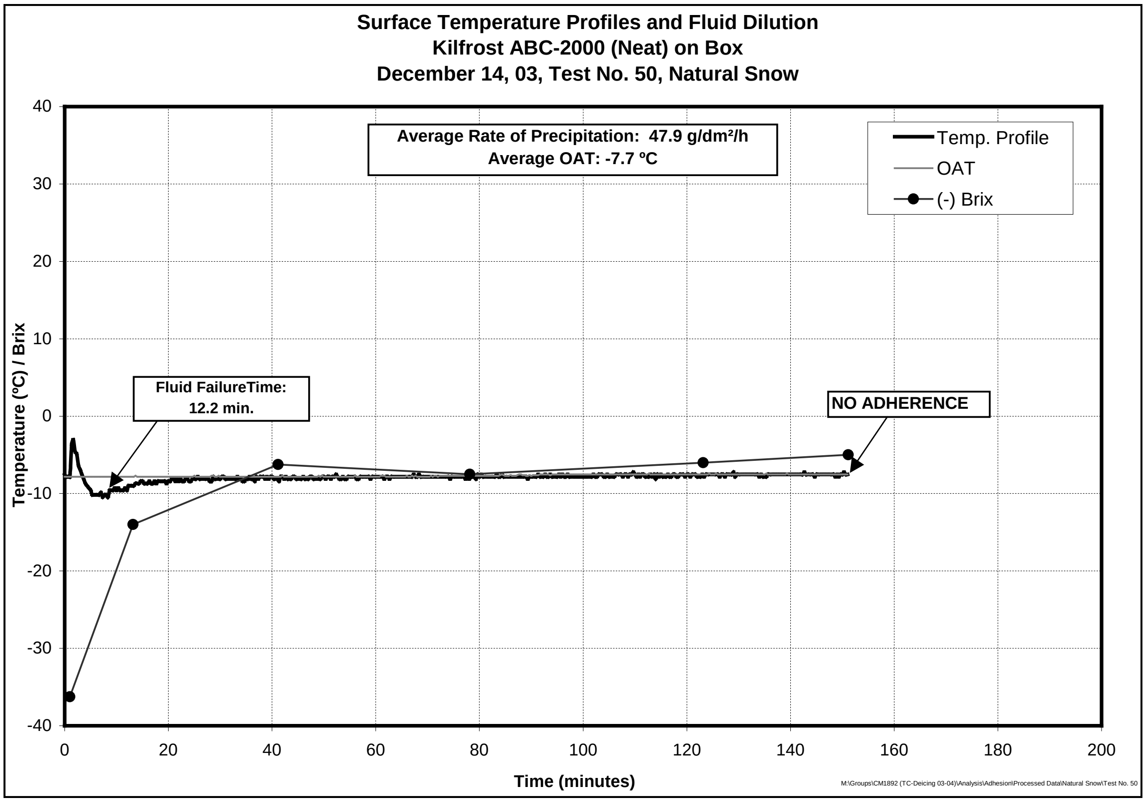
F - Designates last measurement that did not exhibit adhesion

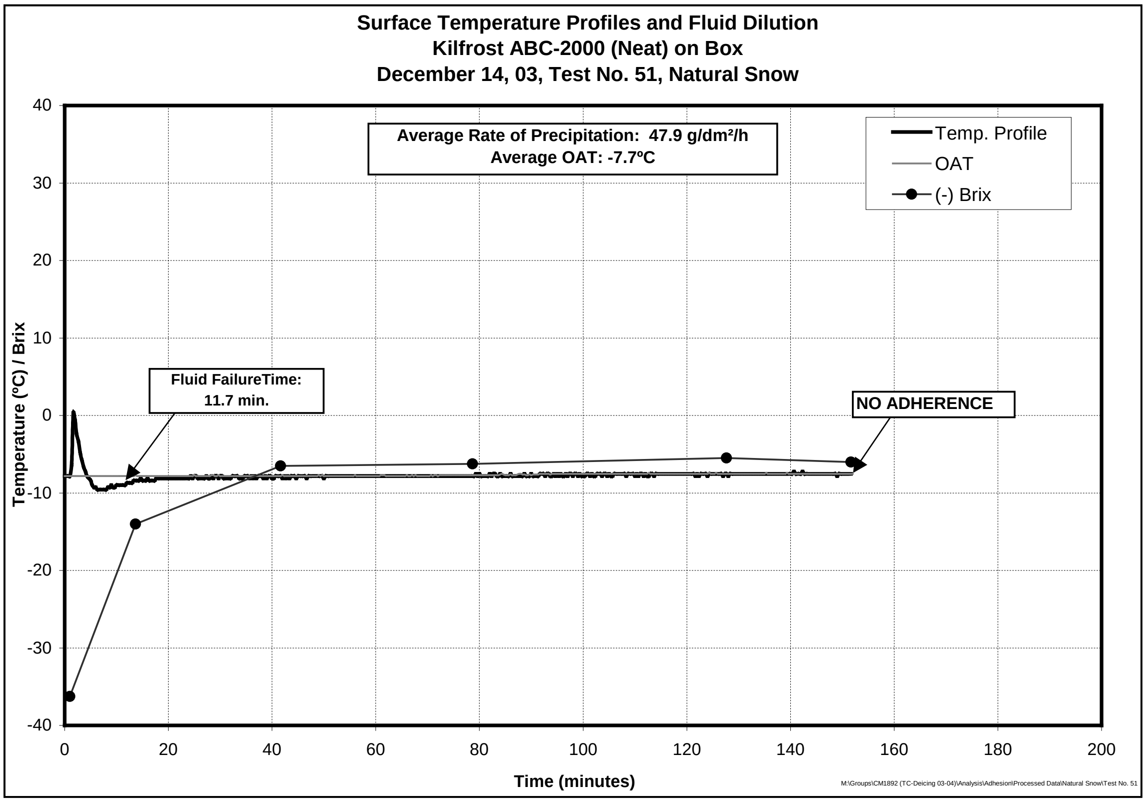

Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on NCAR Plate
March 7, 03, Test No. P11, Artificial Snow, -10ºC, 90 g/dm²/h
Average Precipitation Rate: 81.6 g/dm²/h
Average OAT: -10.9ºC
Initial Fluid Temperature: 50ºC
Fluid Temp.
OAT
FFP
Fluid Failure Time: 2.3 min.
95% Adhered: 7.5 min.
Beginning of Adherence: 4.0 min.
F - Designates last measurement that did not exhibit adhesion
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
0
5
10
15
20
25
30
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\PMG-Artificial snow\Test No. P11

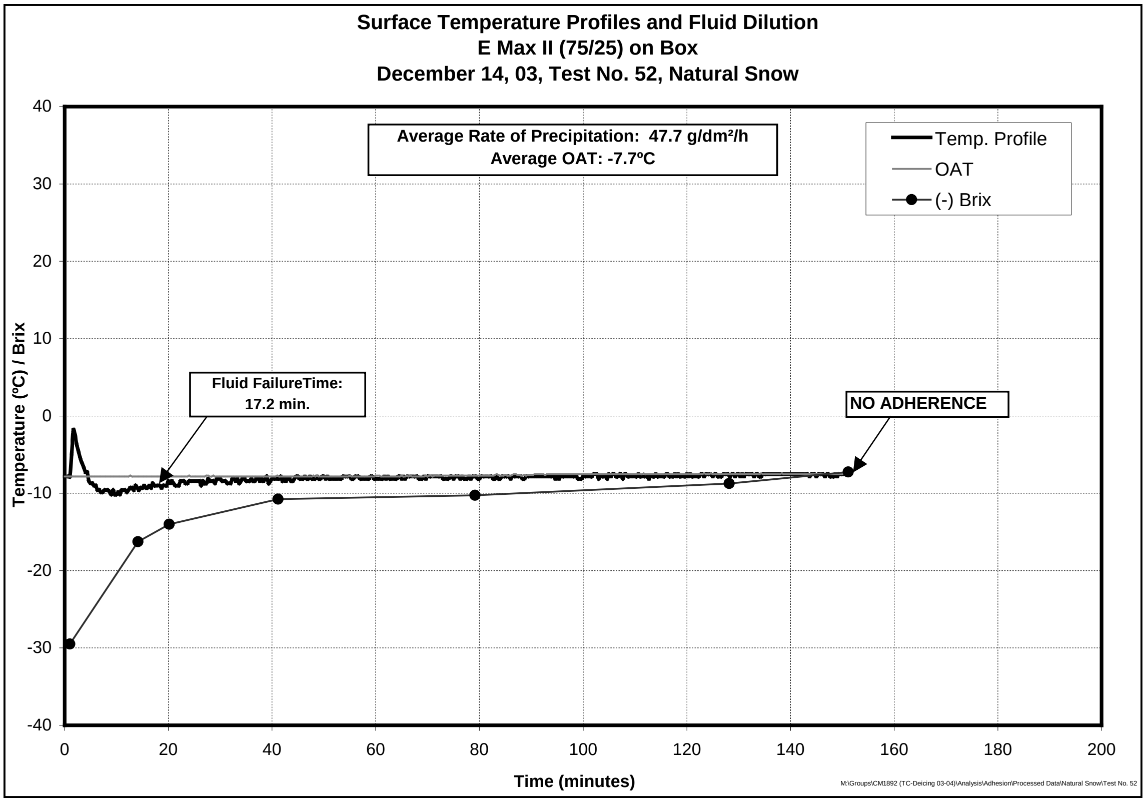

Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10ºC Buffer) on NCAR Plate
March 7, 03, Test No. P12, Artificial Snow, -10ºC, 1 g/dm²/h
Average Precipitation Rate: 1.3 g/dm²/h
Average OAT: -10.8ºC
Initial Fluid Temperature: -7.5ºC
Temp. Profile
OAT
FFP
Fluid Failure Time: 29.0 min.
NO ADHERENCE
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
Time (minutes)
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\PMG-Artificial snow\Test No. P12


Surface Temperature Profiles and Fluid Dilution
Pure Water on NCAR Plate
March 7, 03, Test No. P13, Artificial Snow, -10ºC, 30 g/dm²/h
Average Precipitation Rate: 30.0 g/dm²/h
Average OAT: -11.1ºC
Initial Fluid Temperature: 20ºC
Temp Profile
OAT
Fluid Failure Time:
2.5 min.
100% Adhered:
3.0 min.
Temperature (°C)
40
30
20
10
0
-10
-20
-30
-40
Time (minutes)
0
5
10
15
20
25
30
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\PMG-Artificial snow\Test No. P13

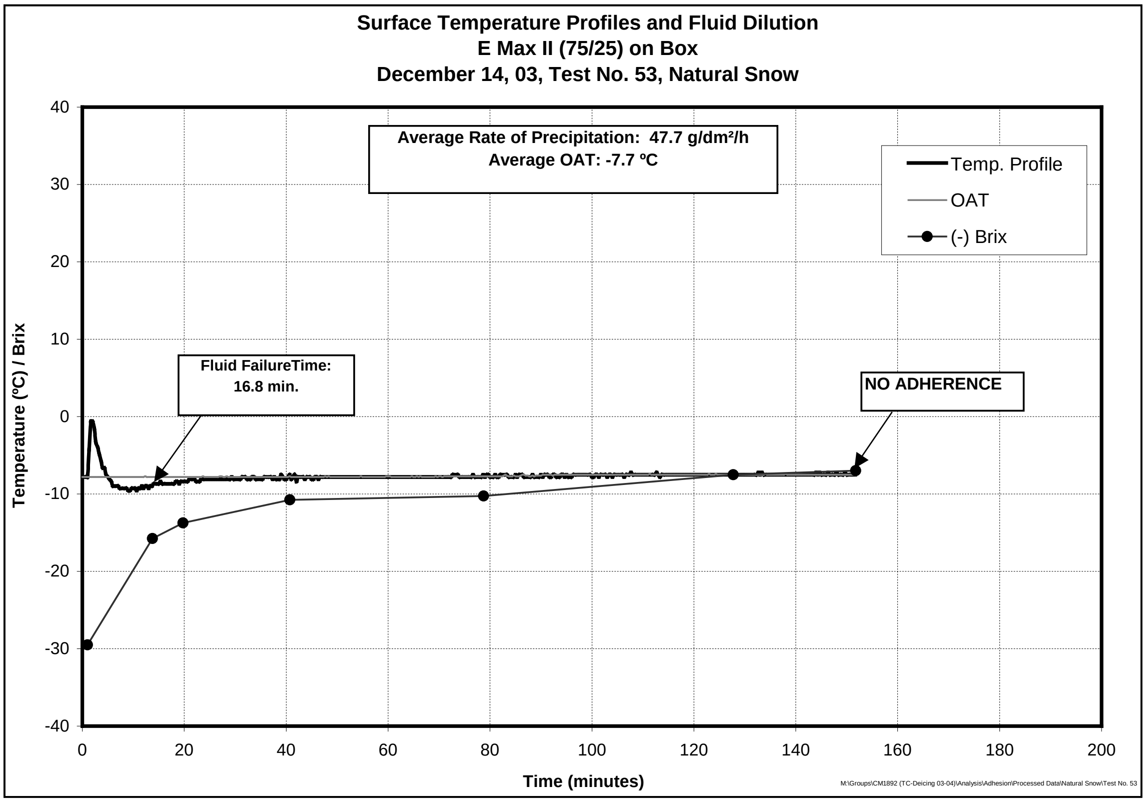

Surface Temperature Profiles and Fluid Dilution
METSS ADF-2 (standard mix) on Box
January 7, 03, Test No. 1, Freezing Drizzle
Average Precipitation Rate: 2.3 g/dm²/h
Average OAT: -6.2ºC
Temp. Profile
Fluid Failure Time:
30.2 min.
Adherence to 22.5 cm line:
39.5 min.
Adherence to 7.5 cm line:
30.3 min.
Temperature (°C)
40
30
20
10
0
-10
-20
-30
-40
Time (minutes)
0
20
40
60
80
100
120
140
160
180
200
M:\Groups\CM1747\Analysis\Comparison of Fluid ET, HOT, and Protection Time\Processed Data\Natural Snow\Test No. 1


Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Box
December 14, 03, Test No. 50, Natural Snow
Average Rate of Precipitation: 47.9 g/dm²/h
Average OAT: -7.7 ºC
Temp. Profile
OAT
(-) Brix
Fluid FailureTime:
12.2 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 50

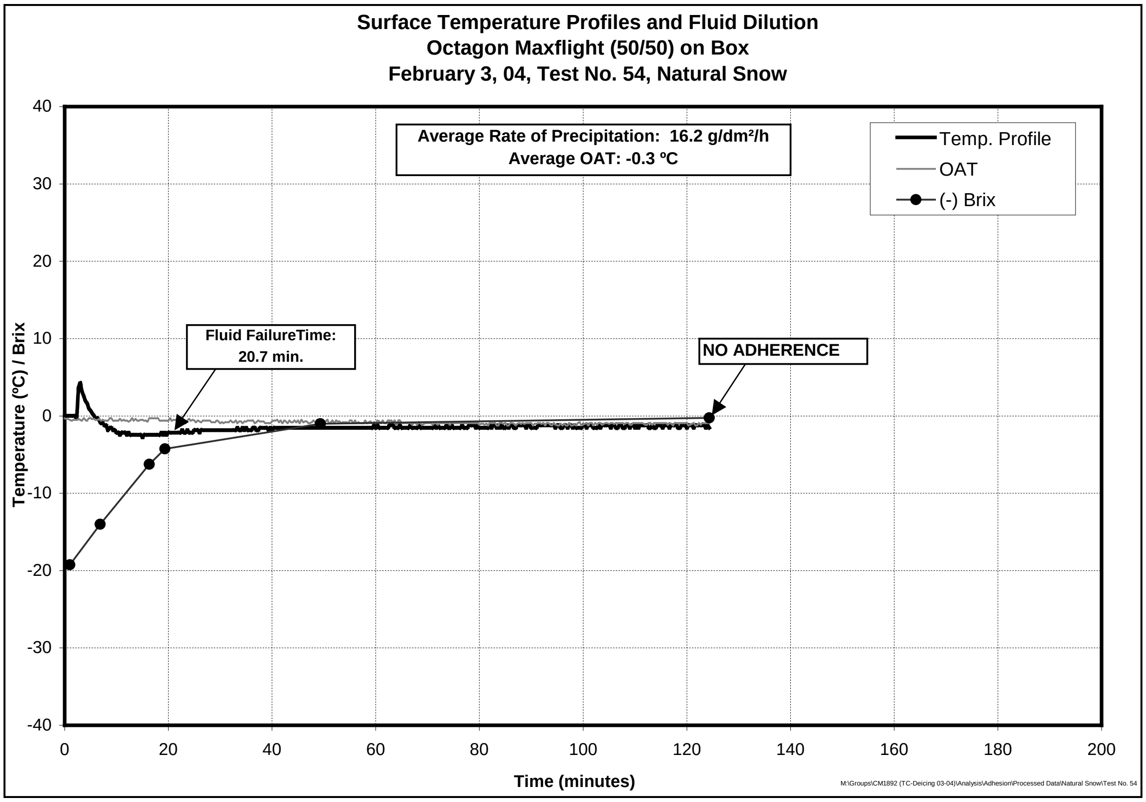

Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Box
December 14, 03, Test No. 51, Natural Snow
Average Rate of Precipitation: 47.9 g/dm²/h
Average OAT: -7.7ºC
Temp. Profile
OAT
(-) Brix
Fluid FailureTime:
11.7 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 51

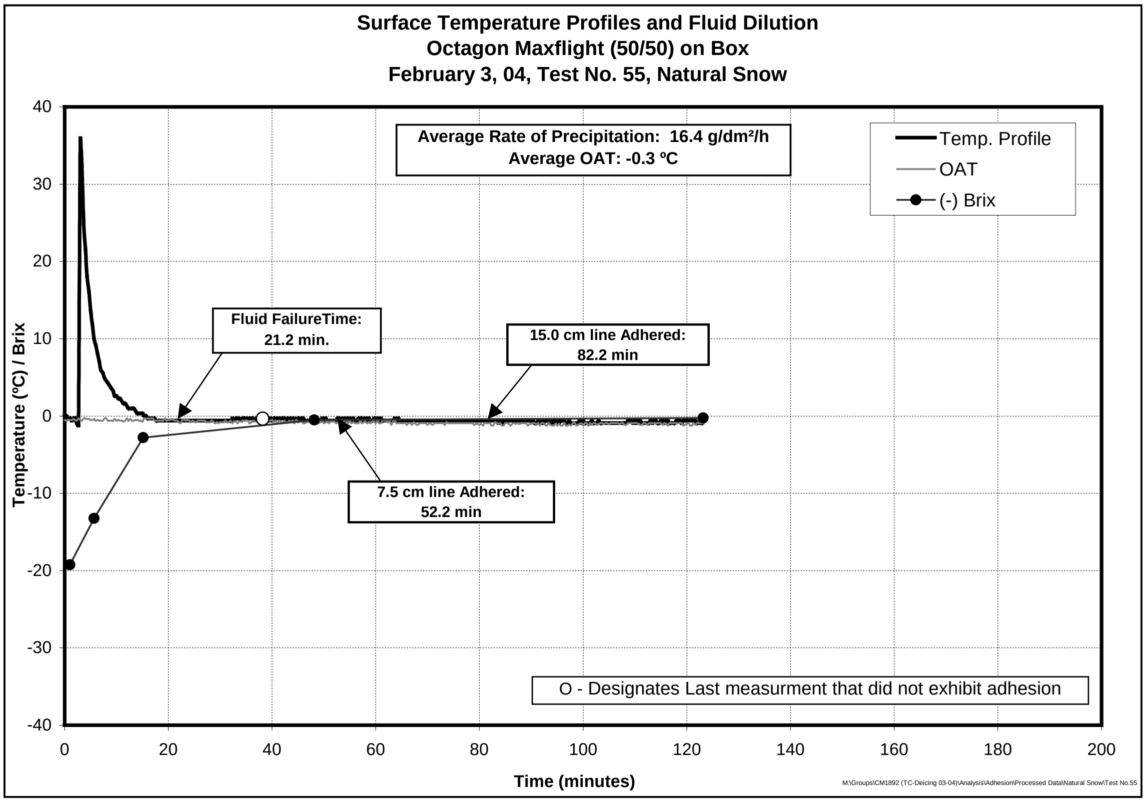


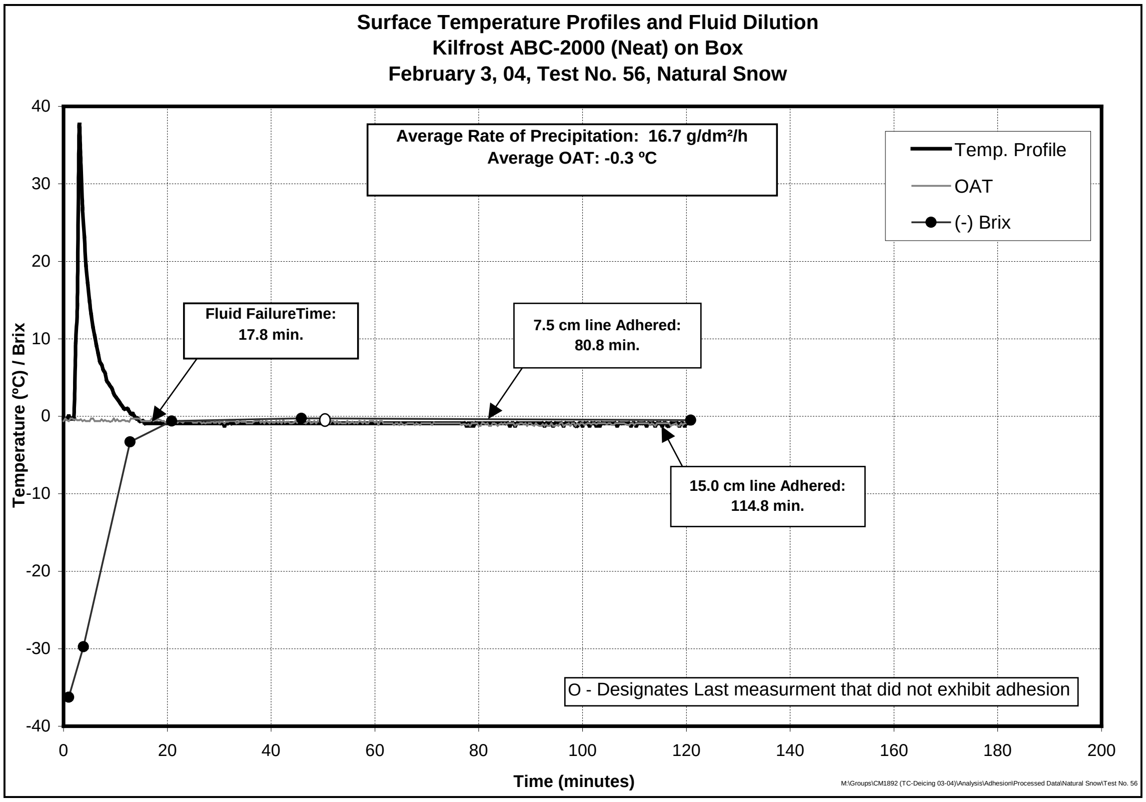
Surface Temperature Profiles and Fluid Dilution
E Max II (75/25) on Box
December 14, 03, Test No. 52, Natural Snow



Surface Temperature Profiles and Fluid Dilution
E Max II (75/25) on Box
December 14, 03, Test No. 53, Natural Snow

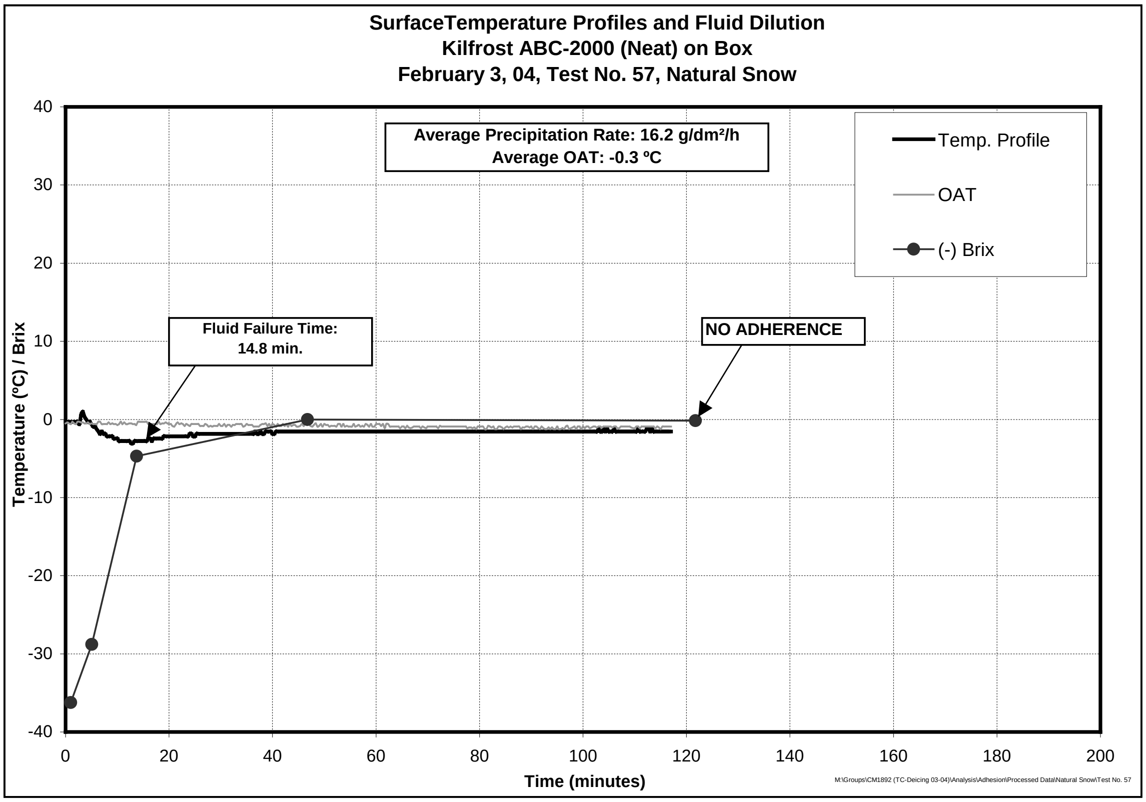

Surface Temperature Profiles and Fluid Dilution
Octagon Maxflight (50/50) on Box
February 3, 04, Test No. 54, Natural Snow
Average Rate of Precipitation: 16.2 g/dm²/h
Average OAT: -0.3 ºC
Temp. Profile
OAT
(-) Brix
Fluid FailureTime:
20.7 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 54


Surface Temperature Profiles and Fluid Dilution
Octagon Maxflight (50/50) on Box
February 3, 04, Test No. 55, Natural Snow
Average Rate of Precipitation: 16.4 g/dm²/h
Average OAT: -0.3 ºC
Temp. Profile
OAT
(-) Brix
Fluid FailureTime:
21.2 min.
15.0 cm line Adhered:
82.2 min
7.5 cm line Adhered:
52.2 min
O - Designates Last measurment that did not exhibit adhesion
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No.55



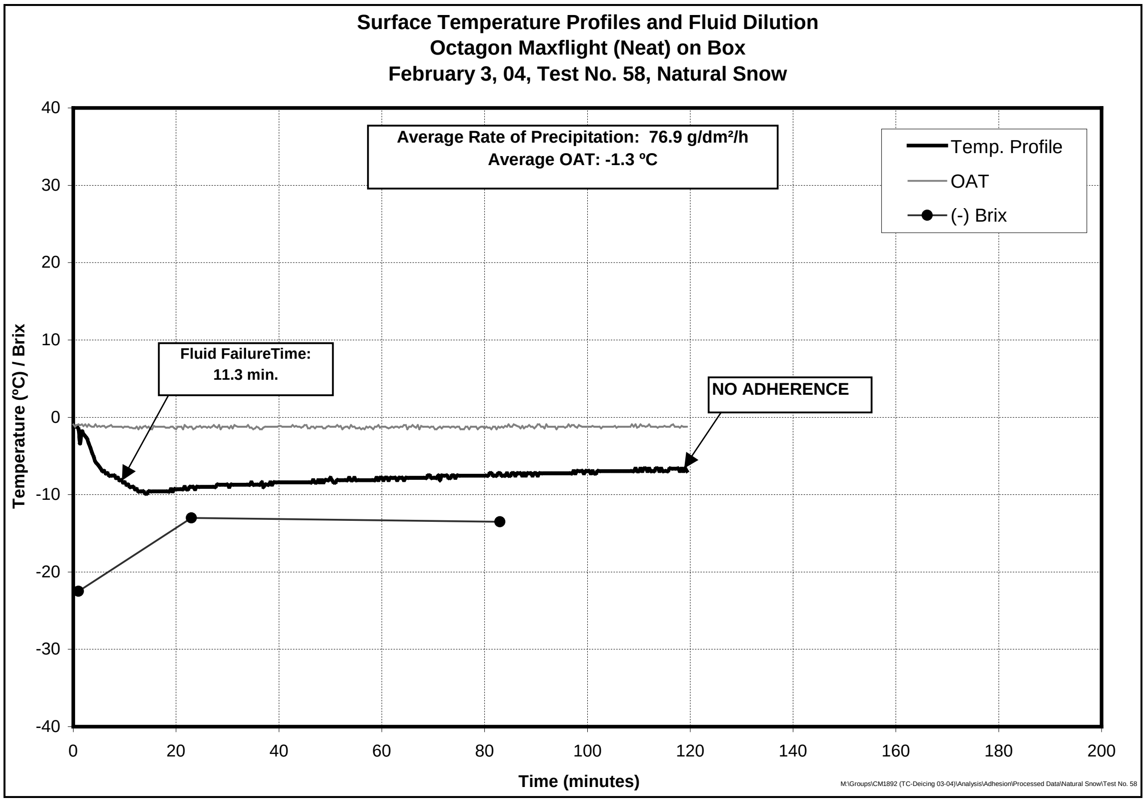
Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Box
February 3, 04, Test No. 56, Natural Snow

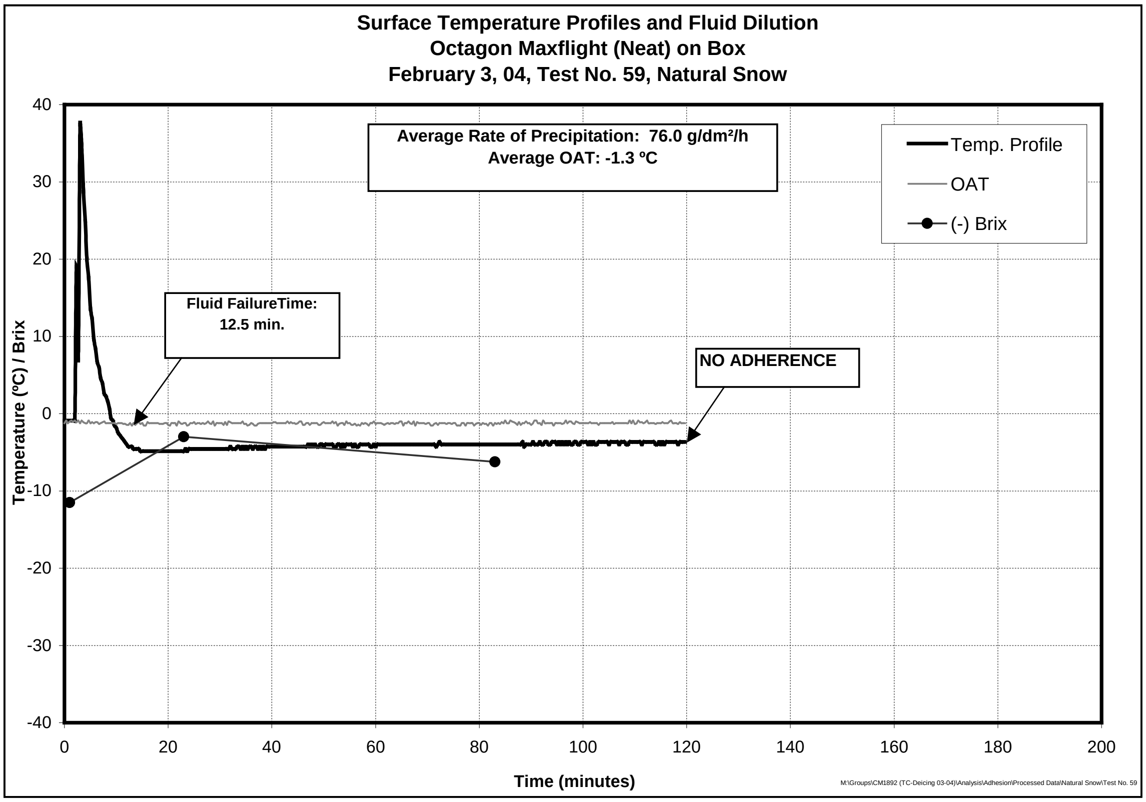
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 56

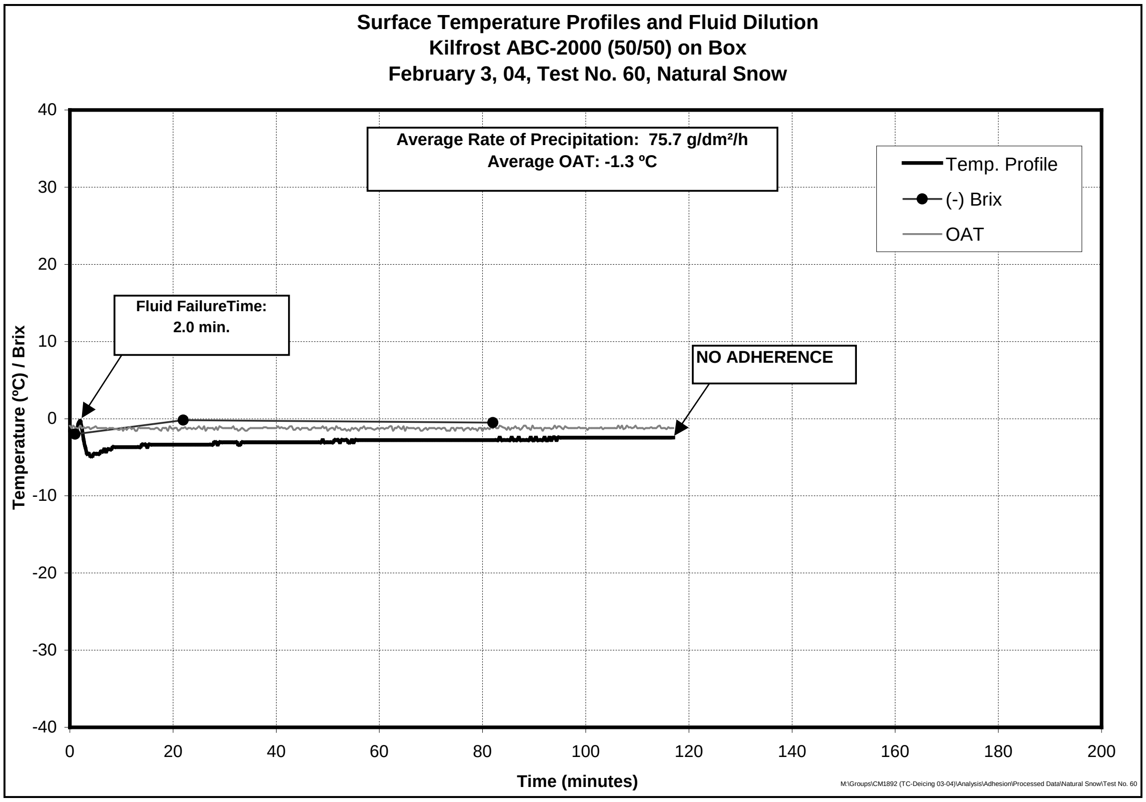


SurfaceTemperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (Neat) on Box
February 3, 04, Test No. 57, Natural Snow

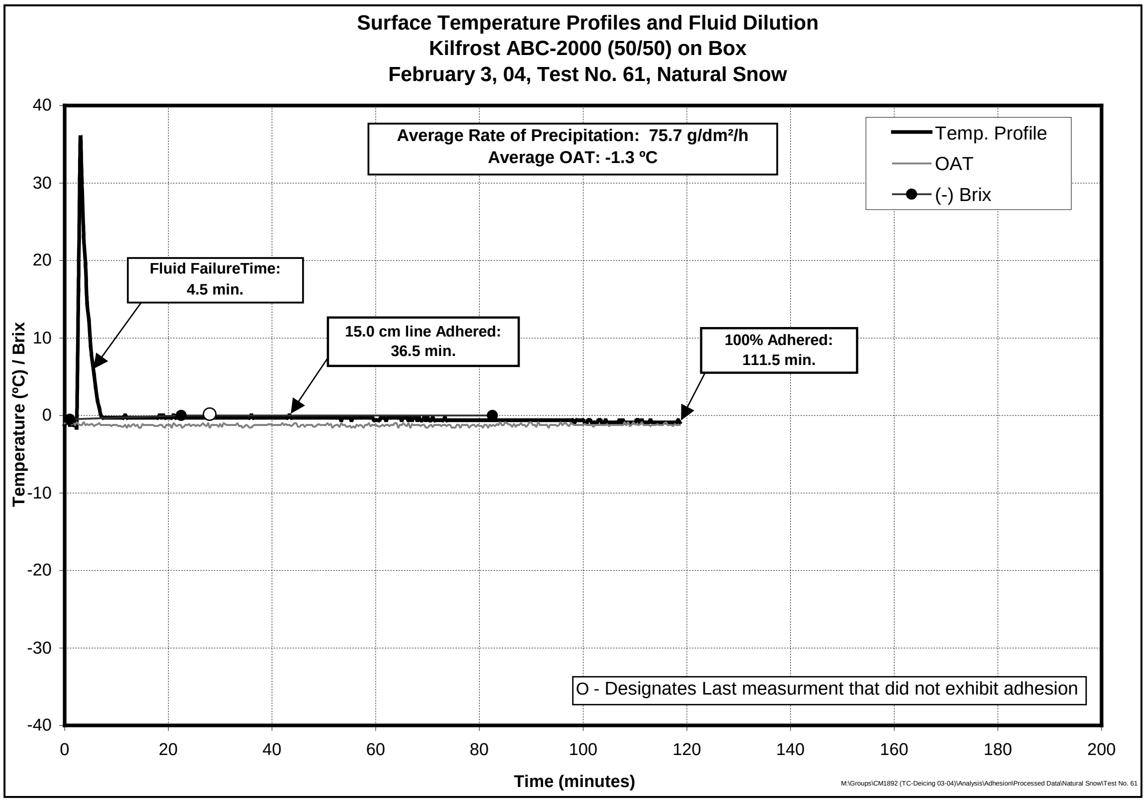
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 57


Surface Temperature Profiles and Fluid Dilution
Octagon Maxflight (Neat) on Box
February 3, 04, Test No. 58, Natural Snow
Average Rate of Precipitation: 76.9 g/dm²/h
Average OAT: -1.3 ºC
Temp. Profile
OAT
(-) Brix
Fluid FailureTime:
11.3 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 58

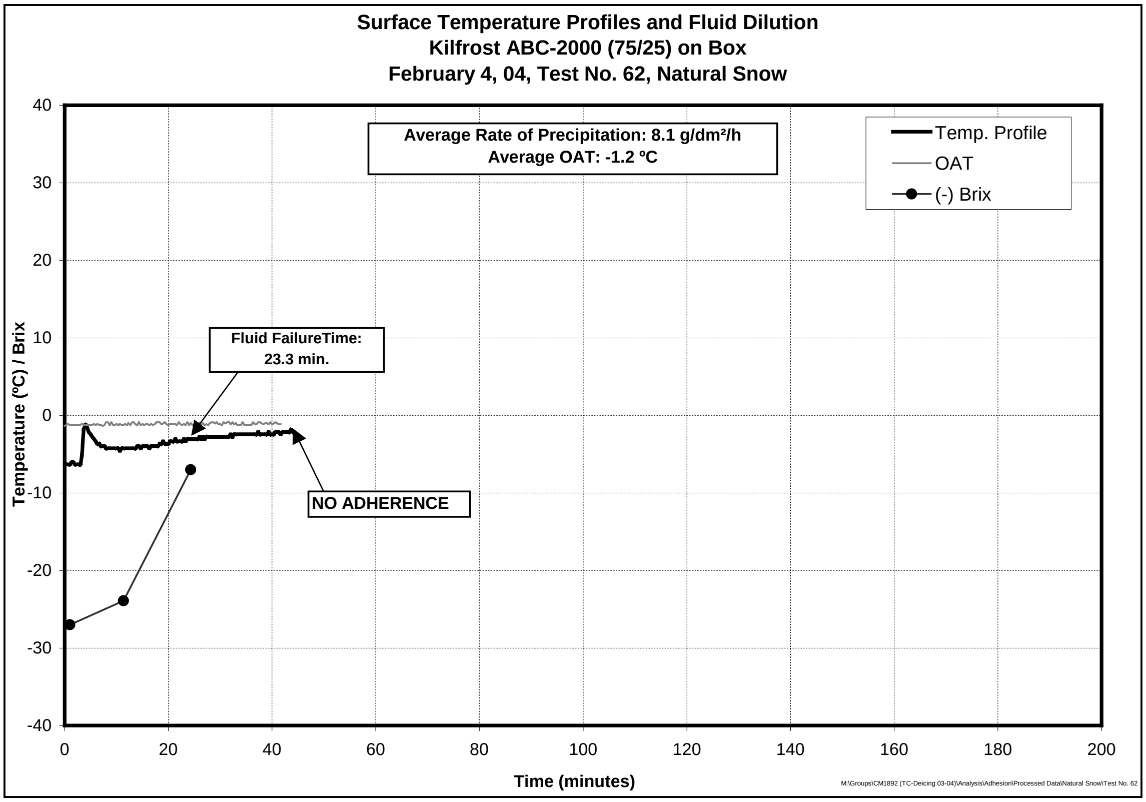

Surface Temperature Profiles and Fluid Dilution
Octagon Maxflight (Neat) on Box
February 3, 04, Test No. 59, Natural Snow
Average Rate of Precipitation: 76.0 g/dm²/h
Average OAT: -1.3 ºC
Temp. Profile
OAT
(-) Brix
Fluid FailureTime:
12.5 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 59

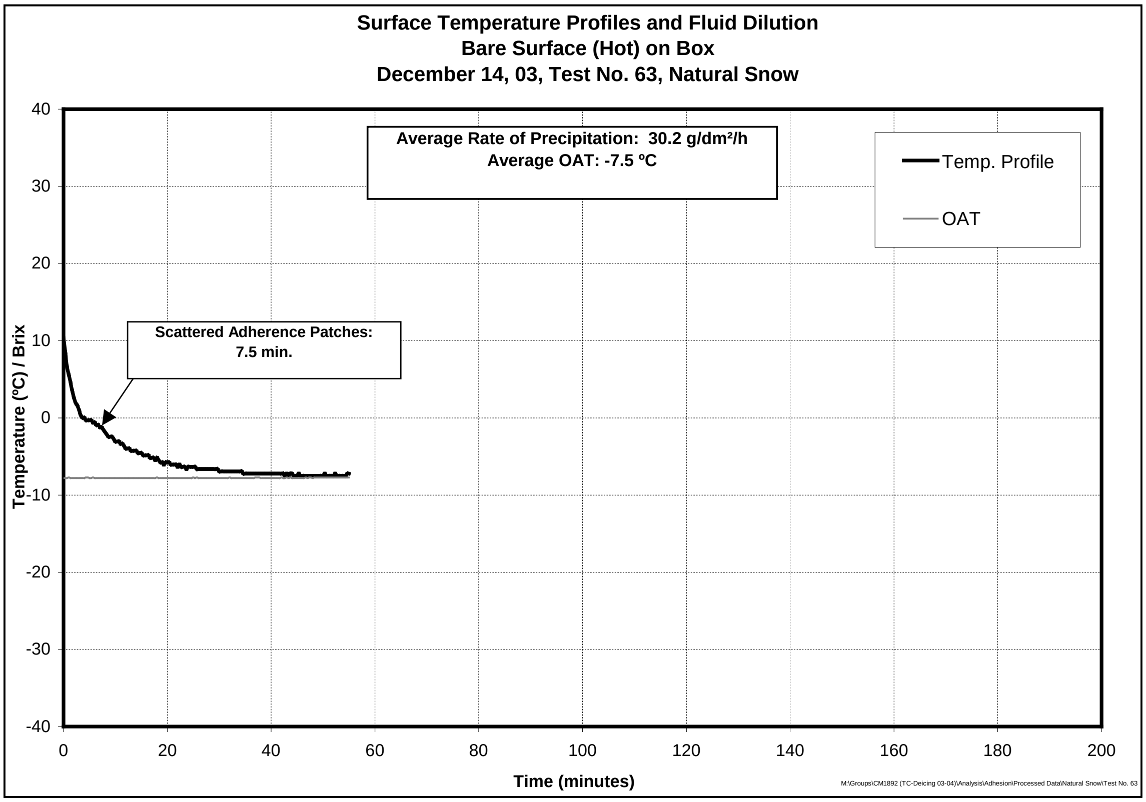


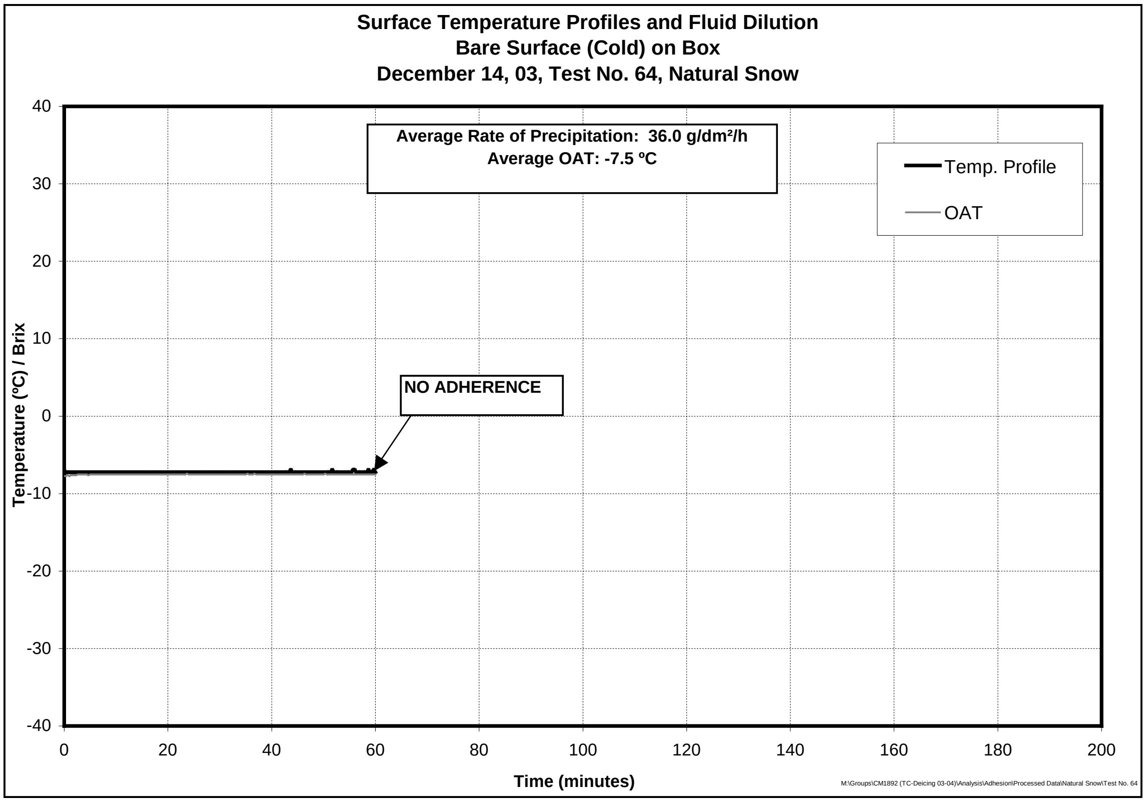
Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (50/50) on Box
February 3, 04, Test No. 60, Natural Snow



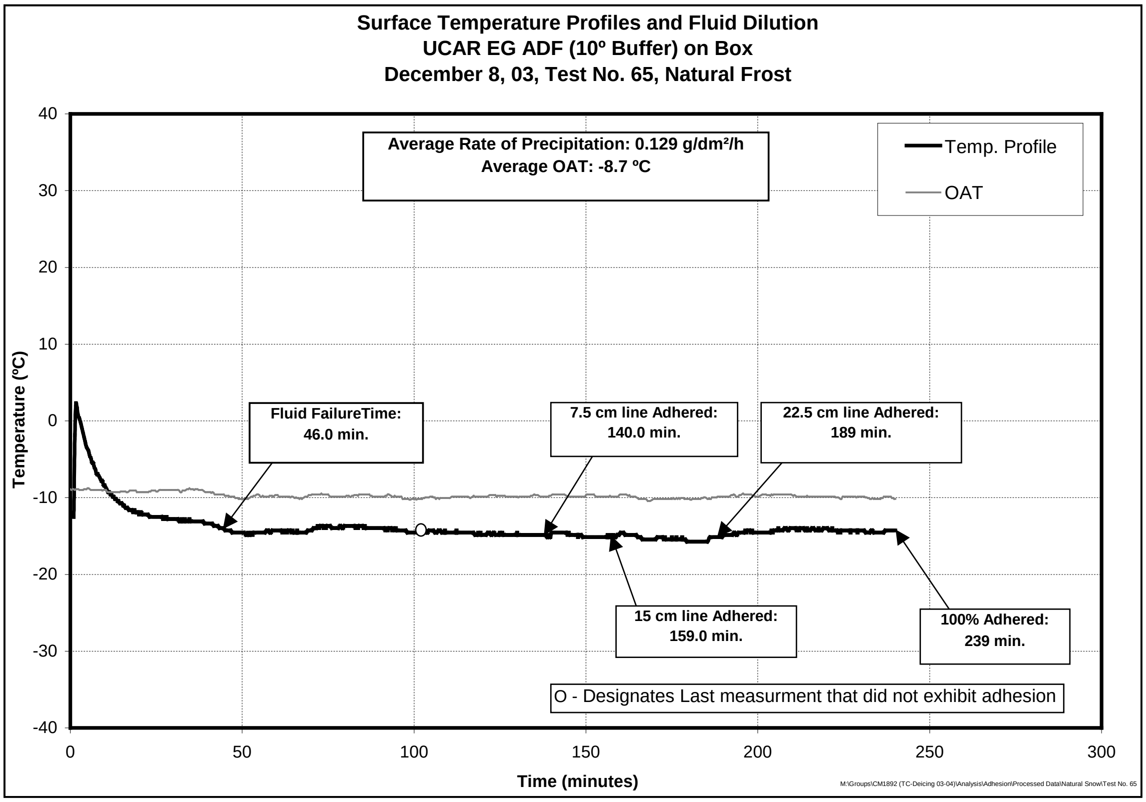
Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (50/50) on Box
February 3, 04, Test No. 61, Natural Snow


Surface Temperature Profiles and Fluid Dilution
Kilfrost ABC-2000 (75/25) on Box
February 4, 04, Test No. 62, Natural Snow
Average Rate of Precipitation: 8.1 g/dm²/h
Average OAT: -1.2 ºC
Temp. Profile
OAT
(-) Brix
Fluid FailureTime:
23.3 min.
NO ADHERENCE
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 62

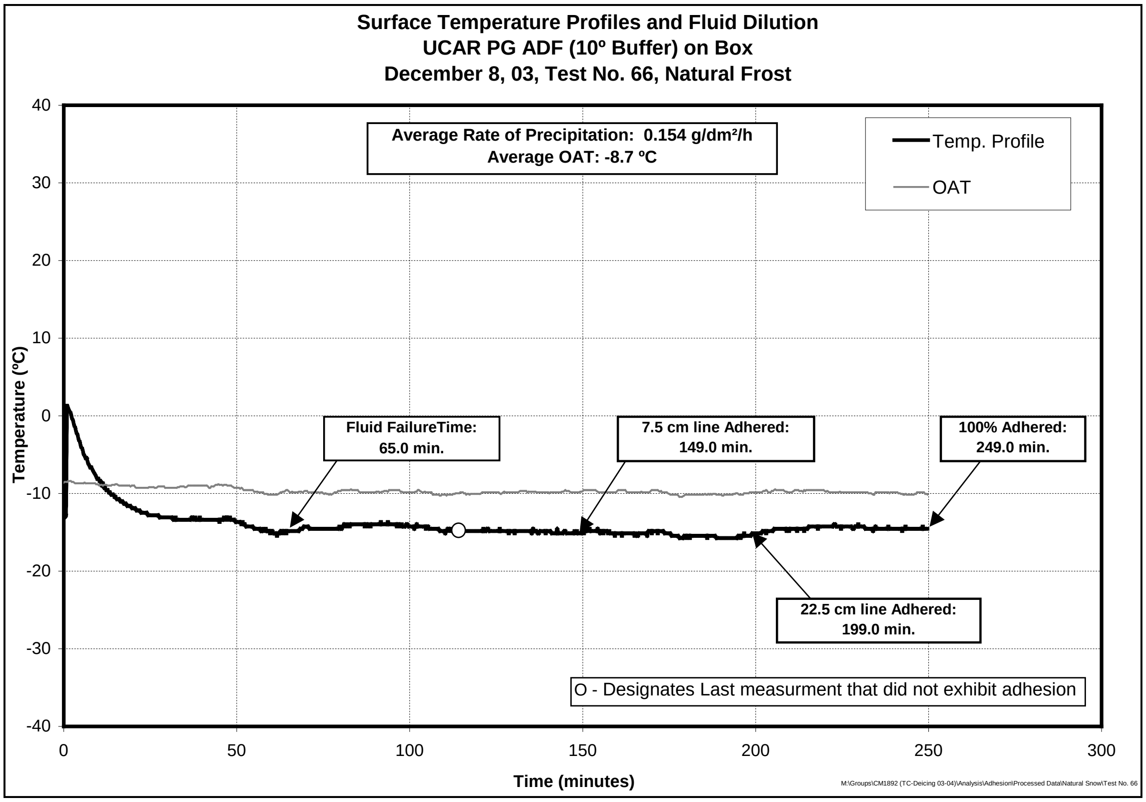

Surface Temperature Profiles and Fluid Dilution
Bare Surface (Hot) on Box
December 14, 03, Test No. 63, Natural Snow
Average Rate of Precipitation: 30.2 g/dm²/h
Average OAT: -7.5 ºC
Temp. Profile
OAT
Scattered Adherence Patches:
7.5 min.
Temperature (ºC) / Brix
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 63

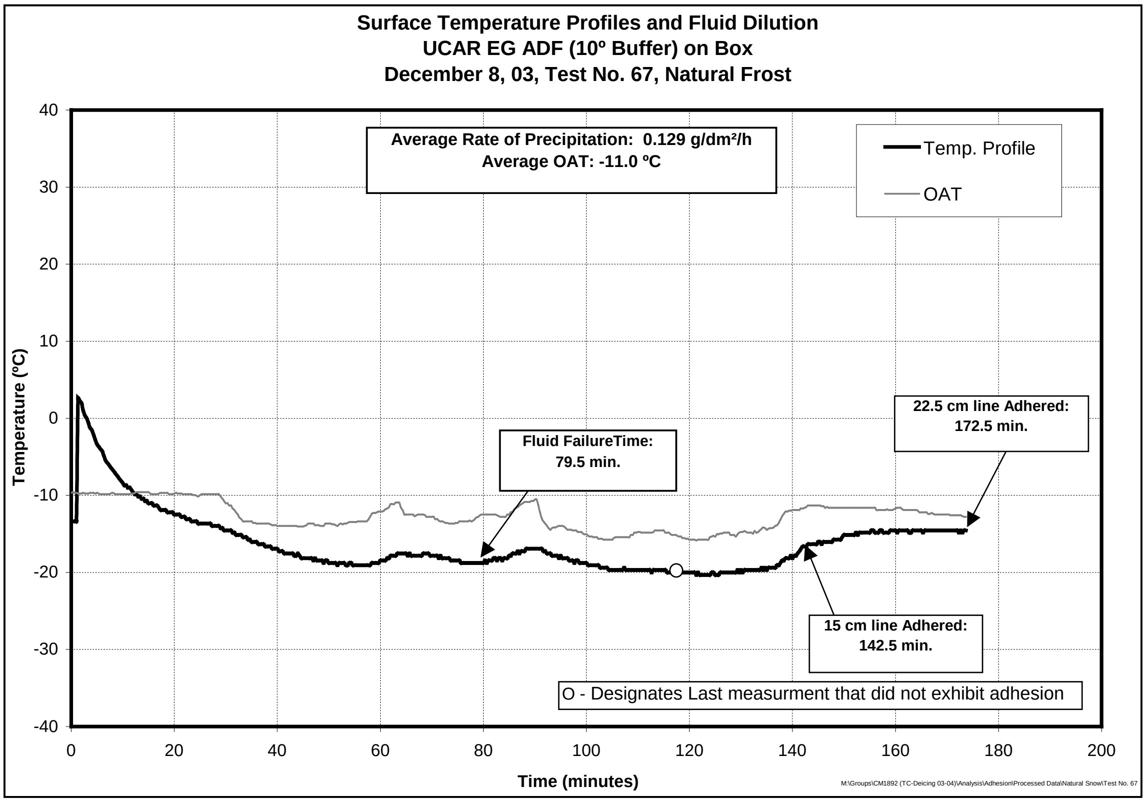


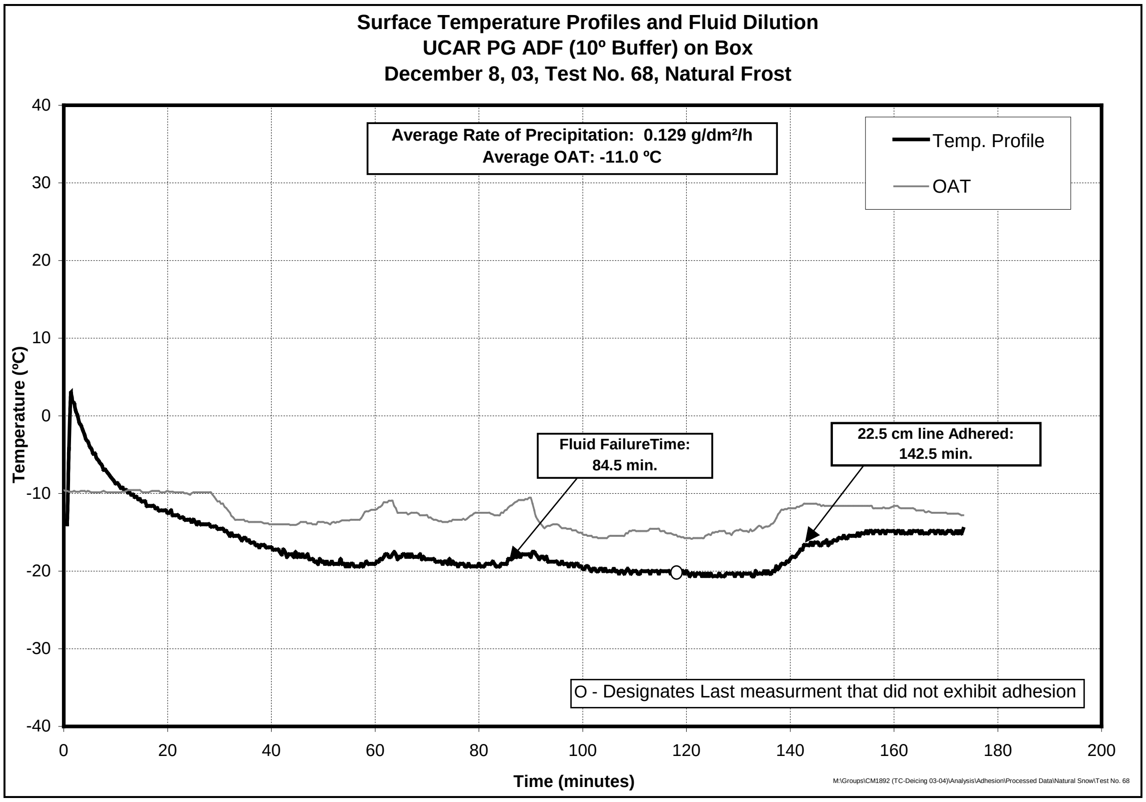
Surface Temperature Profiles and Fluid Dilution
Bare Surface (Cold) on Box
December 14, 03, Test No. 64, Natural Snow



Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10º Buffer) on Box
December 8, 03, Test No. 65, Natural Frost


Surface Temperature Profiles and Fluid Dilution
UCAR PG ADF (10º Buffer) on Box
December 8, 03, Test No. 66, Natural Frost
Average Rate of Precipitation: 0.154 g/dm²/h
Average OAT: -8.7 ºC
Temp. Profile
OAT
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
Fluid FailureTime: 65.0 min.
7.5 cm line Adhered: 149.0 min.
100% Adhered: 249.0 min.
22.5 cm line Adhered: 199.0 min.
O - Designates Last measurment that did not exhibit adhesion
0
50
100
150
200
250
300
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 66


Surface Temperature Profiles and Fluid Dilution
UCAR EG ADF (10º Buffer) on Box
December 8, 03, Test No. 67, Natural Frost
Average Rate of Precipitation: 0.129 g/dm²/h
Average OAT: -11.0 ºC
Temp. Profile
OAT
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
22.5 cm line Adhered: 172.5 min.
Fluid FailureTime: 79.5 min.
15 cm line Adhered: 142.5 min.
O - Designates Last measurment that did not exhibit adhesion
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 67


Surface Temperature Profiles and Fluid Dilution
UCAR PG ADF (10º Buffer) on Box
December 8, 03, Test No. 68, Natural Frost
Average Rate of Precipitation: 0.129 g/dm²/h
Average OAT: -11.0 ºC
Temp. Profile
OAT
Fluid FailureTime:
84.5 min.
22.5 cm line Adhered:
142.5 min.
O - Designates Last measurment that did not exhibit adhesion
Temperature (ºC)
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Time (minutes)
M:\Groups\CM1892 (TC-Deicing 03-04)\Analysis\Adhesion\Processed Data\Natural Snow\Test No. 68