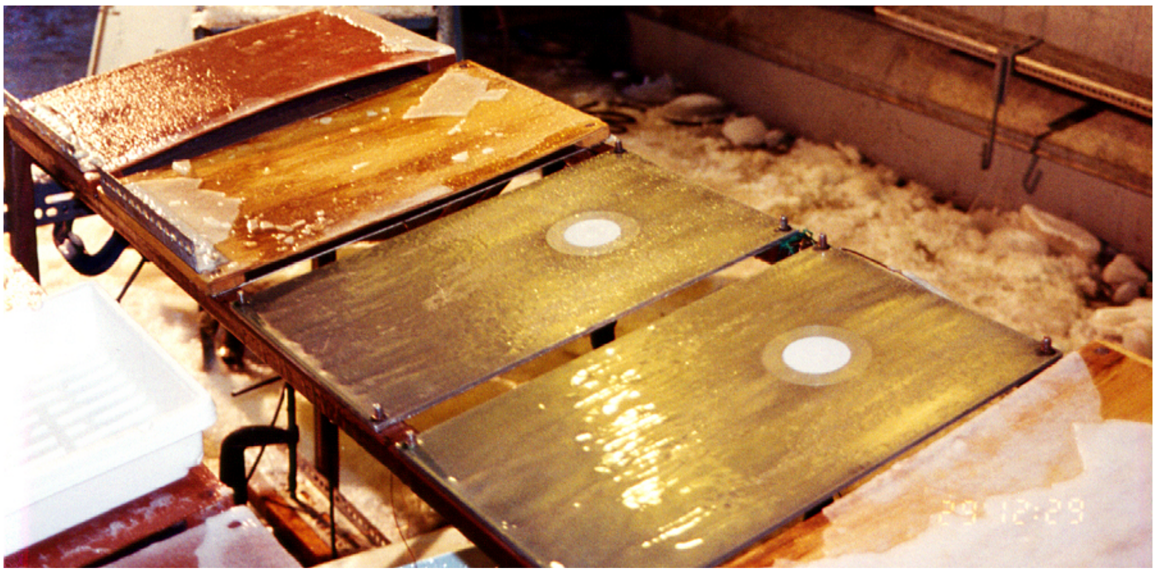
TP 13484E

Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation: 1998-99



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Safety and Security
Transport Canada

APS AVIATION INC.

November 2001

Final Version 1.0

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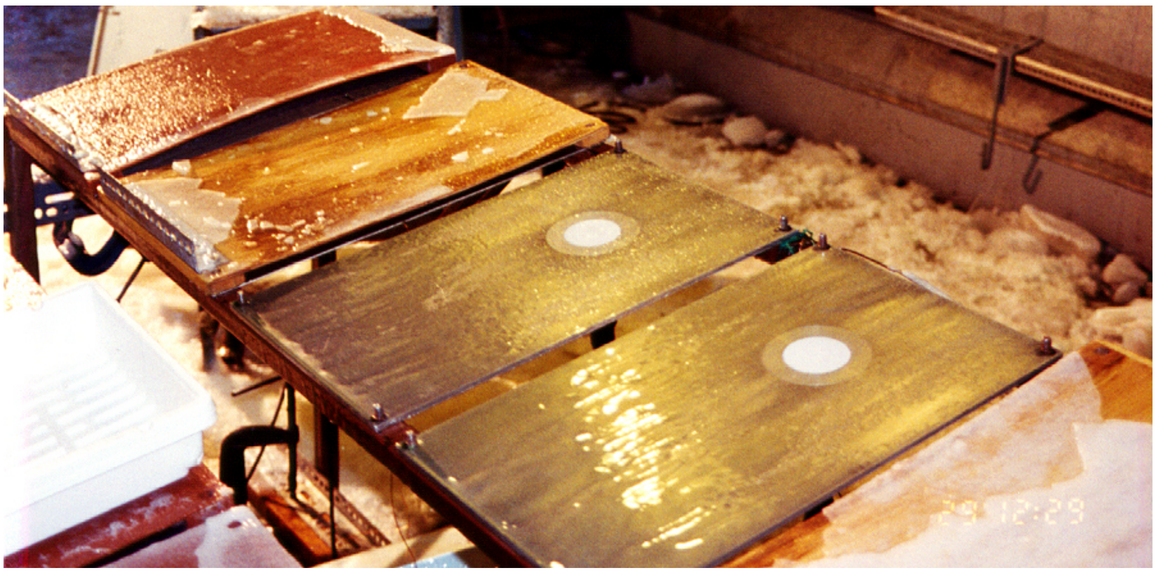

by

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Un sommaire français se trouve avant la table des matières.

PREFACE

At the request of the Transportation Development Centre of Transport Canada, APS Aviation Inc. has undertaken a research program to further advance aircraft ground deicing/anti-icing technology. The specific objectives of the APS test program were:

- To develop holdover time tables for new anti-icing fluids, and to validate fluid-specific and SAE holdover time tables;
- To gather enough supplemental experimental data to support development of a deicing-only table;
- To examine conditions for which contamination due to anti-icing fluid failure in freezing precipitation fails to flow from the wing of a jet transport aircraft when subjected to speeds up to and including rotation;
- To measure the jet-blast wind speeds developed by commercial airliners in order to generate air-velocity distribution profiles (to predict the forces that could be experienced by deicing vehicles), and to develop a method of evaluating the stability of deicing vehicles during live deicing operations;
- To determine the feasibility of examining the surface conditions on wings before takeoff through the use of ice-contamination sensor systems, and to evaluate the sensitivity of one ice-detection sensor system;
- To evaluate the use of warm fuel as an alternative approach to ground deicing of aircraft;
- To evaluate hot water deicing to determine safe and practicable limits for wind and outside ambient temperature;
- To document the appearance of fluid failure, to measure its characteristics at the point of failure, and to compare the failures of various fluids in freezing precipitation;
- To determine the influence of fluid type, precipitation (type and rate), and wind (speed and relative direction) on both the locations and times to fluid failure initiation, with special attention to failure progression on the Bombardier Canadair Regional Jet and on high-wing turboprop commuter aircraft;
- To evaluate snow weather data from previous winters to identify a range of snow-precipitation suitable for the evaluation of holdover time limits;
- To compare the holdover times from natural and artificial snow tests and to evaluate the functionality of the NCAR simulated snowmaking system; and
- To develop a plan for implementing a full-scale wing test facility that would enable the current testing of deicing and anti-icing fluids in natural and artificial freezing precipitation on a real aircraft wing.

The research activities of the program conducted on behalf of Transport Canada during the 1998-99 winter season are documented in twelve separate reports. The titles of these reports are as follows:

- TP 13477E Aircraft Ground De/Anti-Icing Fluid Holdover Time Field Testing Program for the 1998-99 Winter;

- TP 13478E Aircraft Deicing Fluid Freeze Point Buffer Requirements for Deicing Only Conditions;
- TP 13479E Contaminated Aircraft Takeoff Tests for the 1998-99 Winter;
- TP 13480E Air Velocity Distribution Behind Wing-Mounted Aircraft Engines;
- TP 13481E Feasibility of Use of Ice Detection Sensors for End-of-Runway Wing Checks;
- TP 13482E Evaluation of Warm Fuel as an Alternative Approach to Deicing;
- TP 13483E Hot Water Deicing of Aircraft;
- TP 13484E Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation: 1998-99;
- TP 13485E Aircraft Full-Scale Test Program for the 1998-99 Winter;
- TP 13486E Evaluation of Snow Weather Data for Aircraft Anti-Icing Holdover Times;
- TP 13487E Development of a Plan to Implement a Full-Scale Test Site; and
- TP 13488E A Snow Generation System – Prototype Testing.

This report, TP 13484E addresses the following objectives:

- To document the appearance of fluid failure, to measure its characteristics at the point of failure, and to compare the failures of various fluids in freezing precipitation.

This objective was met by conducting and documenting a series of tests on flat plates in a cold chamber laboratory and under natural snow conditions. Test parameters included type of fluid, temperature, precipitation rate and type of precipitation. Various fluid properties were recorded by human observers as well as ice detection sensors as the fluid failure progressed. Visual and narrative observations were recorded at pre-determined stages in the failure progression.

ACKNOWLEDGEMENTS

This research has been funded by the Civil Aviation Group, Transport Canada, and with support from the Federal Aviation Administration. This research program could not have been accomplished without the participation of many organizations. APS would therefore like to thank the Transportation Development Centre, the Federal Aviation Administration, the National Research Council of Canada, Atmospheric Environment Services Canada, Transport Canada, and several fluid manufacturers, for their contributions to and assistance with the program. Special thanks are extended to US Airways Inc., Delta Airlines, Air Canada, the National Research Council of Canada, Canadian Airlines International, AéroMag 2000, Aéroport de Montreal, The Greater Toronto Airport Authority, Hudson General, Union Carbide, RVSI, Cox and Company Inc., The Department of National Defence, and Shell Aviation, for provision of personnel and facilities, and for their co-operation on the test program. APS would also like to acknowledge the dedication of the research team, whose performance was crucial to the acquisition of hard data leading to the preparation of this document.

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16. Abstract

The objective of this study was to document the appearance and properties of anti-icing fluids subjected to precipitation, both in the laboratory and in natural conditions.

Laboratory trials were conducted under controlled conditions of ambient temperature and artificial precipitation. During natural snow trials, precipitation rates and ambient air temperature were monitored. Various fluids were applied to flat plates and examined at specific stages from time of application until complete contamination was reached. The appearance and properties of the fluid were documented as the fluid progressed toward failure. Documentation included photographic and videotape records, visual description, readings from various ice detection sensors, and measurements of physical characteristics such as adhesion, viscosity, fluid concentration and film thickness.

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16. Résumé

L'étude avait pour objectif de documenter l'apparence et les propriétés des fluides antigivre soumis à des précipitations naturelles et artificielles.

Des essais en laboratoire ont été réalisés à des températures ambiantes et sous des précipitations artificielles commandées. Des essais sous neige naturelle ont aussi eu lieu, où les taux de précipitation et la température de l'air ambiant étaient surveillés. Divers fluides étaient appliqués sur des plaques planes, puis ils étaient examinés à différentes étapes entre le moment de l'application et la contamination complète de la plaque. Ainsi, l'apparence et les propriétés du fluide étaient documentées tout au long de la progression de celui-ci vers la perte d'efficacité. La documentation comprenait des photos, des bandes vidéo, une description visuelle, les lectures de divers capteurs de givre ainsi que des mesures de paramètres physiques, comme l'adhérence, la viscosité, le degré de concentration du fluide et l'épaisseur de la pellicule.

17. Mots clés	Dégivrage, antigivre, signes de perte d'efficacité, adhérence après perte d'efficacité, viscosité
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EXECUTIVE SUMMARY

At the request of the Transportation Development Centre (TDC) of Transport Canada, APS Aviation Inc. undertook a research program to examine anti-icing fluids at the time that the fluid reaches its operational limit.

The objective of this study was to document the appearance of fluid failure and the characteristics of the fluid up to and at the time that it reached this operational limit. Types of documentation included: photography and videotape; narrative description; readings from various ice detection sensors; and measurements of physical properties such as adhesion, viscosity, fluid concentration and film thickness.

To satisfy this objective, laboratory tests were conducted at National Research Council Canada's Climatic Engineering Facility in Ottawa, and natural snow tests were conducted at the APS test site at Dorval airport. The climatic chamber, in combination with the National Center for Atmospheric Research snowmaking system, 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. Various fluids were applied to flat plates and examined at specific stages from time of application until complete plate failure was reached. The appearance and physical properties of the fluid were documented as the fluid progressed toward and beyond a pre-defined standard plate failure.

Fourteen runs, including 28 individual plate tests, were conducted in the laboratory over a two-day period during the 1997-98 test season. Twelve individual plate tests were conducted in natural snow in January 1999 and 17 indoor plate tests were conducted in April 1999, including 11 artificial snow tests.

Test conditions were established to allow examination of specific fluids under different conditions, as well as to enable the following comparisons:

- Appearance of Type I versus Type IV – light freezing rain;
- Appearance of Type I versus Type IV – snow;
- Appearance of Type IV – light freezing rain versus freezing drizzle;
- Appearance of Type IV – freezing drizzle versus snow;
- Appearance of Type IV – effect of temperature (-4ºC and -10ºC);
- Ethylene glycol-based Type IV fluid versus propylene glycol-based Type IV fluid – freezing drizzle;
- Time to adhere – Type I versus Type IV; and
- Appearance of Type I versus Type IV 50/50 – light freezing rain.

Results and Conclusions

The appearance and characteristics of various fluids up to and at the time that each fluid reached its operational limit were recorded using a variety of monitoring techniques and instruments.

Data from the various tests enabled comparisons of the appearance and nature of fluids under different conditions. Photographs and video documentation were recorded to portray the appearance of fluid at specific stages from time of application until complete plate failure. These images could potentially be made available to users in the field (pilots and ground staff) to assist in the visual identification of fluid at its operational limit.

Comparisons of various characteristics of different fluids in different conditions were made based on the test data. It was noted that ethylene and propylene glycol-based fluids exhibit different failure progressions in freezing precipitation conditions, and all fluids had similar failure appearances in snow conditions.

Using a tool specially designed to provide a relative measure of adhesion in the various test conditions, it was noted that Type I fluid in light freezing rain (24.5 $g/dm^2/h$) adhered to the surface within 30 to 60 seconds after failure: a very thin film of highly diluted fluid froze to the surface.

Identification of the operational limits of propylene glycol-based Type IV fluids at -10ºC in freezing drizzle was found to be a challenge. This fluid appears to continue to provide a level of protection far beyond the point when failure calls would normally be made, with no adhesion even at time of complete plate failure.

Ethylene glycol-based Type IV fluids adhered within three to six minutes following failure in light freezing rain (25 $g/dm^2/h$) and an ambient temperature of -10ºC. Contrary to freezing precipitation conditions, adhesion was not detected in snow conditions. Independent of the fluid, precipitation rate and the ambient temperature, fluid failures in snow conditions were not observed to adhere to the underlying surface.

Viscosity of fluids at the time when they have reached their operational limit was found to be a difficult property to measure. The test samples collected after complete plate failure and measured with a Brookfield Viscometer generally provided viscosity values equivalent to water for ethylene glycol-based fluids and for most propylene glycol-based fluids tested at warmer temperatures. The majority of snow test samples collected also provided viscosity values equivalent to water. The results from the propylene glycol-based samples were temperature dependent in freezing drizzle conditions. At colder temperatures the propylene glycol-based fluid demonstrated a significant residual viscosity due to the layer of pristine fluid remaining under the surface failures.

This study did not include natural or artificial snow conditions with ambient air temperatures near -3°C.

SOMMAIRE

À la demande du Centre de développement des transports (CDT) de Transports Canada, APS Aviation Inc. a effectué une étude qui consistait à examiner les fluides antigivre au moment où ils atteignent leur limite d'efficacité.

L'étude visait à documenter l'apparence que présente la perte d'efficacité d'un fluide et ses caractéristiques pendant sa progression vers ce point, et lorsqu'il y est parvenu. Divers moyens ont été pris pour documenter le phénomène : photos, bandes vidéo, description narrative, lectures de divers capteurs de givre et mesures de paramètres physiques, comme l'adhérence, la viscosité, le degré de concentration du fluide et l'épaisseur de la pellicule.

Les essais en laboratoire ont été menés à l'Installation de génie climatique du Conseil national de recherches du Canada (CNRC), à Ottawa et les essais sous neige naturelle, au site d'essai d'APS, à l'aéroport de Dorval. L'utilisation combinée de la chambre climatique du CNRC et de la machine à fabriquer de la neige du National Center for Atmospheric Research permettait de faire varier à volonté la température ambiante et les précipitations artificielles. Au cours des essais sous neige naturelle, les taux de précipitation et la température de l'air ambiant étaient surveillés. Divers fluides étaient appliqués sur des plaques planes, puis ils étaient examinés à des étapes précises entre le moment de l'application et la contamination complète de la plaque. Ainsi, l'apparence et les propriétés physiques du fluide étaient documentées tout au long de la progression de celui-ci vers des critères prédéfinis de perte d'efficacité sur plaque standard, et après cette perte d'efficacité.

Au cours de la saison 1997-1998, 14 séances d'essai réparties sur deux jours, soit des essais sur 28 plaques, ont eu lieu en laboratoire. En janvier 1999, douze essais sur plaques ont eu lieu sous des précipitations de neige naturelle, suivis, en avril 1999, de 17 essais sur plaques menés à l'intérieur, dont 11 sous des précipitations de neige artificielle.

Les conditions d'essai étaient établies de façon à permettre l'examen de certains types de fluides dans différentes conditions, et à autoriser les comparaisons suivantes :

- apparence d'un fluide de type I comparé à un fluide de type IV – pluie verglaçante légère;
- apparence d'un fluide de type I comparé à un fluide de type IV – neige;
- apparence d'un fluide de type IV – pluie verglaçante légère comparée à de la bruine verglaçante;
- apparence d'un fluide de type IV – bruine verglaçante comparée à de la neige;
- apparence d'un fluide de type IV – effet de la température (-4 ºC et -10 ºC);

- fluide de type IV à base d'éthylène comparé à un fluide de type IV à base de propylène – bruine verglaçante;
- délai jusqu'à l'adhérence – fluide de type I comparé à un fluide de type IV;
- apparence d'un fluide de type I comparé à un fluide de type IV 50/5 –; pluie verglaçante légère.

Résultats et conclusions

L'apparence et les caractéristiques des divers fluides jusqu'à leur limite d'efficacité ont été enregistrées à l'aide de diverses techniques de surveillance et instruments de mesure.

Les données recueillies au cours des divers essais ont permis de comparer l'apparence et les caractéristiques des fluides dans différentes conditions. Des photos et des bandes vidéo ont permis de définir l'apparence du fluide à certaines étapes entre le moment de l'application et la perte d'efficacité du fluide sur toute la plaque. Ces images pourraient être mises à la disposition des utilisateurs sur le terrain (pilotes et personnel au sol) et aider ceux-ci à reconnaître les signes visuels d'un fluide parvenu à sa limite d'efficacité.

Les données d'essai ont servi à comparer diverses caractéristiques de différents fluides, dans différentes conditions. Ainsi, il a été noté que, sous des précipitations givrantes, la progression du fluide vers la perte d'efficacité n'est pas la même selon qu'il est à base d'éthylène ou à base de propylène, et que, sous la neige, tous les fluides présentent une apparence semblable lorsqu'ils atteignent leur limite d'efficacité.

Grâce à un outil spécialement conçu pour donner une mesure relative de l'adhérence dans les diverses conditions d'essai, il a été observé que le fluide de type I soumis à une pluie verglaçante légère (24,5 g/dm^2/h) adhérait à la surface dans les 30 à 60 secondes après être devenu inefficace : une mince pellicule du fluide très dilué gelait sur la surface.

Sous bruine verglaçante, à -10 ºC, la perte d'efficacité des fluides de type IV à base de propylèneglycol était difficile à discerner. Ce fluide semble continuer à assurer un certain degré de protection bien au-delà du moment où la perte d'efficacité serait normalement décrétée; en effet, aucune adhérence n'a été observée, même lorsque toute la plaque était contaminée.

Sous pluie verglaçante légère (25 g/dm^2/h), à -10 ºC de température ambiante, les fluides de type IV à base d'éthylèneglycol adhéraient dans les trois à six minutes suivant leur perte d'efficacité. Mais sous la neige, aucune adhérence n'était observée. De même, aucun des fluides essayés sous la neige n'adhérait à la surface sous-jacente, une fois devenu inefficace, peu importe le type de fluide, le taux de précipitation et la température ambiante.

La viscosité des fluides au moment où ils atteignent leur limite d'efficacité s'est avérée difficile à mesurer. Les échantillons étaient prélevés après contamination de toute la plaque et soumis au viscosimètre Brookfield. Les valeurs de viscosité ainsi obtenues étaient généralement équivalentes à celles de l'eau dans le cas des fluides à base d'éthylèneglycol et de la plupart des fluides à base de propylèneglycol essayés aux températures élevées. La majorité des échantillons issus des essais sous neige ont également mené à des valeurs de viscosité équivalentes à celle de l'eau. Sous bruine verglaçante, la viscosité des échantillons à base de propylèneglycol était tributaire de la température. À basse température, le fluide à base de propylèneglycol présentait une viscosité résiduelle importante, en raison de la couche de fluide intact qui subsistait sous la contamination de surface.

La présente étude n'a pas examiné les fluides antigivre dans des conditions de neige naturelle ou artificielle à des températures de l'air ambiant voisines de -3 ºC.

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GLOSSARY

APS	APS Aviation Inc.
C/FIMS	Contamination/Fluid Integrity Monitoring System
CEF	Climatic Engineering Facility
FAA	Federal Aviation Administration (U.S.)
FP	Freeze Point
NCAR	National Center for Atmospheric Research
NRC	National Research Council Canada
RVSI	Robotic Vision System Inc.
SAE	Society of Automotive Engineers
TDC	Transportation Development Centre
UCAR	Union Carbide

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1. INTRODUCTION

This study formed part of the winter 1997-98 and the winter 1998-99 research programs on deicing, as described in the detailed work statement, Appendix A. This report encompasses all the data and analysis included in the 1997-98 Transport Canada report, *Characteristics of Failure of Aircraft Anti-icing Fluids Subjected to Precipitation,* TP 13317E (1).

Discussions within the aviation industry on the subject of wing contamination and related testing of anti-icing fluids invariably question the nature of fluid failures.

Here are some examples of commonly asked questions:

- What does a fluid failure look like?
- How does a fluid failure progress?
- How visible is the failure? Was the failure obvious or difficult to discern?
- Did it have a distinctive appearance at different temperatures, under specific precipitation conditions and according to different fluid types?
- Did it adhere to the underlying surface?

At the request of the Transportation Development Centre (TDC) of Transport Canada, APS Aviation undertook a research project to examine and document the appearances and properties of deicing and anti-icing fluids when exposed to precipitation conditions. The appearance and the physical properties of each fluid examined were monitored on standard flat plate test surfaces from the instant of fluid application to the point at which visual fluid failure completely covered the test surface.

Each fluid test was observed as it approached, reached, and surpassed its operational limit. Discrete measurements of each fluid's physical properties were recorded at pre-selected stages of visual failure. The physical properties measured included fluid concentration, wet film thickness, viscosity, and adhesion. Variations in the appearance of applied fluids were documented and recorded using still photography, videos (analog and digital), ice detection sensors and ice detection cameras.

When this report was written, the lexicon of terminology describing fluid failures within the deicing community had not yet evolved to support the clear and precise communication of the appearance of fluid that has reached or surpassed its operational limit. Consequently, a strong common visual image of the appearance of fluid at the time of failure did not exist. A shared common image of the nature of the various types of fluid failures will contribute to better communication within the community involved in deicing research, and will promote better recognition of fluid failures in field operations.

A glossary of de/anti-icing terms was compiled by the Transportation Development Centre. Please refer to the Transport Canada report *Aircraft Anti-Icing Fluid Endurance, Holdover, and Failure Times Under Winter Precipitation Conditions,* TP 13832 (2).

To promote clearer communication in the field, narrative descriptions of the progress of fluid failures, recorded by seasoned observers, have also been prepared.

Throughout this report, the term *fluid failure* is frequently used to indicate *fluid at its operational limit*. In this context, fluid that is considered to have failed need not to have reached its ultimate limit, but demonstrates characteristics accepted by the industry as indicators of failure.

To satisfy the goals of this study, tests were conducted in two distinct environments. Laboratory tests were conducted at several temperatures, with controlled precipitation types and rates. Outdoor tests were conducted during natural snow precipitation. The precipitation rate and ambient temperature changed as the tests progressed. Test conditions were established to allow observation of specific fluids under various conditions to enable the following comparisons to be made:

- Appearance of Type I versus Type IV – light freezing rain;
- Appearance of Type I versus Type IV – snow;
- Appearance of Type IV – light freezing rain versus freezing drizzle;
- Appearance of Type IV – freezing drizzle versus snow;
- Appearance of Type IV – effect of temperature (-4°C and -10°C);
- Ethylene glycol-based Type IV fluid versus propylene glycol-based Type IV fluid – freezing drizzle;
- Time to adhere – Type I versus Type IV; and
- Appearance of Type I versus Type IV 50/50 – light freezing rain.

2. METHODOLOGY

This section describes the test sites, procedures and equipment, data forms, fluids, and personnel requirements that are necessary to perform and record a series of fluid tests under natural precipitation conditions and in a controlled environment during the 1998-99 test session.

As mentioned in Section 1, the issue of clarity when discussing fluid failure is significant. In order for all parties to arrive at a common point, Section 2.1 Icing Definitions has been included. These definitions are taken directly from the Transport Canada report TP 13832 (2), except for those in italics, which have been included to provide a better understanding of this report.

For the terminology specifically used to describe the development of a progression of failure, please refer to Section 3.6.

2.1 Icing Definitions

i) Acceptable Fluid

Anti-icing fluid that may be sporadically covered with frozen precipitation but is capable of absorbing more contamination because its overall surface has not met failure conditions.

ii) Pristine Fluid

Fluid that is entirely uncontaminated by frozen or liquid precipitation.

iii) Fluid failure

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

iv) 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.

v) 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.

vi) Test surface; substrate

Any surface onto which deicing and/or anti-icing fluid is applied. Usually used to refer to aircraft surfaces, flat plates, or airfoil sections.

vii) Contamination; contaminant(s)

With regard to deicing and anti-icing operations, 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. Solid contamination includes snow, hail, and ice pellets. Mixtures of solid and liquid contamination are occasionally observed in nature.

viii) 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.

ix) Failed fluid

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

x) First failure/First icing event/Initial Plate Failure

At surface discontinuities, such as gaps, and at the edges of surfaces, the fluid is at its thinnest. The first ice crystals form at such locations, known as nucleation sites. Generally the areas of ice crystal coverage grow from these locations. Depending on the thoroughness of the de/anti-icing process, first failure may occur very quickly; it is not a significant event in the history leading to fluid failure.

xi) 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 five of the 15 cross hairs, the plate is determined to be one-third covered and therefore visually failed.

xii) Complete/Total/Full/Entire plate failure

100 percent of the plate has reached a visual failure condition.

xiii) Fifth Cross Hair Failure

When the ice crystals that indicate visual failure obliterate only four cross hairs on a standard test plate, the fluid is considered to be good. When the fifth cross hair is obscured, the fluid is considered to be visually failed. This represents a standard plate failure mode.

xiv) Standard test plate

The standard test plate, for the purpose of this document, is restricted to the plate used in endurance time testing. It is an aluminum alloy plate 50 cm (20 in.) long and 30 cm (12 in.) wide adopted by SAE for the evaluation and certification of de/anti-icing fluid performance. For testing, it is mounted at 10° to the horizontal. Along the top and two sides, a line is marked 2.5 cm (1 in.) from the edge; ice crystals commencing in these zones are ignored as these are outside the test area. The bottom edge is a special case because the fluid is held back and is excessively thick there. The test area of the test plate is about 75 percent of the total area. The plate is marked with horizontal lines parallel to the top edge at 7.5 cm (3 in.), 15 cm (6 in.), 22.5 cm (9 in.), 30 cm (12 in.), and 37.5 cm (15 in.). On each of these lines are marked three cross hairs, one in the middle of the line and the other two evenly spaced 7.5 cm (3 in.) each side of it for a total of 15 cross-hair sites.

xv) Nucleation site

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

xvi) Precipitation rate (as used in holdover time tables)

The total rate of deposition of frozen and liquid water on a surface, including any effects of wind-induced deposition; it is really the "catch rate" for a wet surface and is equivalent to the rate of catch on a wet aircraft surface. This use of catch rate to replace precipitation rate allows the visibility definitions of light, moderate, and heavy snow to be readily used, because visibility is also affected by wind speed.

xvii) 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.

xviii) 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.

xix) 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.

2.2 Test Sites

The laboratory tests were conducted at National Research Council Canada's (NRC) Climatic Engineering Facility (CEF) in Ottawa. This facility provided a test environment that satisfied the need to control the ambient temperature, and both the type and rate of artificial precipitation.

Natural snow tests were conducted at the Dorval test site used by APS for holdover time tests. Precipitation rates and ambient air temperature were monitored throughout the duration of the tests.

Artificial snow tests were conducted at NRC's CEF in Ottawa. This facility provided a test environment to control the ambient temperature. The precipitation was produced by a snowmaking machine developed by the National Center for Atmospheric Research (NCAR). The rate of precipitation was controlled by the NCAR system.

2.3 Description of Test Procedures

The experimental procedures for this study are presented in Appendix B, Appendix C and Appendix D.

The experiments were conducted following the same procedures as employed in the test program to determine fluid holdover times. Flat plates mounted with C/FIMS sensor heads were employed as the test surfaces, when available.

2.3.1 Fluid

Type IV fluids were allowed to equilibrate to the ambient test temperature prior to the tests. However, Type I fluids were kept at room temperature.

2.3.2 Concentration

Fluid refractive index was measured with a hand-held Brix-scale refractometer. Brix measurements were taken prior to fluid application and at predetermined intervals during the course of the tests. The sampling intervals for Type I and for Type IV fluids were two minutes and five minutes, respectively.

For Type IV fluid tests, samples were collected from the top and bottom of the fluid layer. Top samples were obtained by laying a strip of acetate film on the surface of the fluid. Bottom samples were drawn with a syringe. The sampling location for all fluid tests was at a crosshair on the 15 cm (6 in.) line. As well, a Brix sample was taken at the boundary of the failed fluid when a standard plate failure call was made. This sample represented a mixture of top and bottom layers.

For Type I fluid tests, samples were collected from the top of the fluid by laying a strip of acetate film on the surface of the fluid. These samples were assumed to be average fluid samples since the fluid layer was too thin to allow for bottom samples to be collected.

2.3.3 Wet Film Thickness

The wet film thickness gauges were used to perform fluid layer thickness measurements. Fluid thickness was measured at test initiation and thereafter at two minute intervals for Type I fluids, and at five minute intervals for Type IV fluids. Measurements were conducted at the 15 cm (6 in.) line and were collected until the fluid was completely solidified or until the fluid thickness was not measurable.

2.3.4 Viscosity Measurements

Two different sample sets were taken depending on the test period.

For tests 1 to 28 (1997-98), a fluid sample for viscosity measurement was collected at the time and location of the standard plate failure call (fifth crosshair to undergo failure). At complete plate failure, fluid samples were collected at both the B2 and F2 crosshairs (see Figure 2.1), as well as at a point adjacent to the fifth crosshair, for a total of four samples.

For tests 29 and up (1998-99), a fluid sample for viscosity measurement was collected from the clean fluid at the time of pouring. At complete plate failure, fluid samples were collected from each of the top, middle and bottom thirds of the plate. If the amount of fluid remaining after failure was insufficient, one single sample was collected from the plate.

2.3.5 Adhesion

Adhesion was identified at the time and point of standard plate failure call (fifth crosshair) and at various other locations. Between standard plate failure and complete plate failure calls, adhesion was periodically measured at various locations. When the entire plate had failed (complete plate failure), adhesion was measured again at several points.

2.3.6 Photo and Video Record

Fluid application, initial failure, standard plate failure and complete plate failure were photographed with a 35 mm still camera, a digital still camera and a digital video camera. Two analog video cameras were focused on the test plates and allowed to run continuously during tests to record the fluid contamination process.

2.3.7 Ice Detection Sensors and Cameras

The C/FIMS, RVSI BF Goodrich, and Spar/Cox ice detection systems were run continuously during selected tests. It should be noted that the Intertechnique ice detection unit was not available at the time of these tests.

During the 1997-98 test season a *no-touch* zone (3 cm x 5 cm rectangle) was marked on each plate near the C/FIMS sensor head to serve as a reference area for ice detection cameras. This area was to remain undisturbed when lifting fluid samples or measuring thickness.

During the 1998-99 test season, the RVSI BF Goodrich system was not available. The Spar/Cox ice detection camera was focused on the entire plate surface.

2.4 Equipment

Complete equipment lists are provided in Appendix B, C and D for each test.

2.4.1 Plates

Standard flat plate test equipment was used in tests to determine fluid holdover times. The test bed consists of an array of flat plates with installed C/FIMS ice detection sensors mounted on a flat plate stand for both the laboratory tests and the natural snow tests.

During laboratory tests the stand was positioned under a spray device designed to provide controlled precipitation rates and produce a satisfactory range of droplet sizes, to be representative of natural conditions. For the natural snow tests the stand was positioned perpendicular to the wind, with the inclined plates facing into the wind. The NCAR snowmaker, evaluated in Transport Canada report TP 13488E (3), contains one plate mounted to a collection bucket.

All plates were marked to show crosshair positions that are identified in the procedure, on data sheets and throughout this report by the reference of row number and the position from left to right (example B1 = row B, left crosshair). A schematic of crosshair positions on a flat plate with installed C/FIMS sensor is provided in Figure 2.1.

2.4.2 Cameras

A 35 mm still camera, a digital still camera and a digital video camera were used to photograph fluid appearance at several pre-selected stages of the fluid failure progression. Two analog video cameras were focused on the test plates and ran continuously. The video recording procedure included a photograph of the test status board at the start of each new test run to assist in relating images to test runs (Photo 2.2). Test summary sheets in the 1998-99 procedure replaced the test status board. The video recording procedure was modified to include a photograph of the general form (Photo 2.3).

2.4.3 Ice Sensors

In addition to the C/FIMS sensor, the RVSI BF Goodrich and the Spar/Cox ice detection sensor were employed when available. The two latter systems provided ongoing still images at 30-second intervals of ice formation on the subject plates. All sensors provided a data reference profile over the test duration that gives an indication of the time related extent of fluid failure. A complete test set-up with the RVSI BF Goodrich and Spar/Cox video cameras mounted at each end of the test stand provided ongoing video records of the failure progression. The C/FIMS sensor recorded the plate temperatures during tests (Photo 2.1).

2.4.4 Fluid Thickness

Fluid thickness was measured with wet film thickness gauges shown in Figure 2.2.

FIGURE 2.1

TYPICAL FLAT PLATE

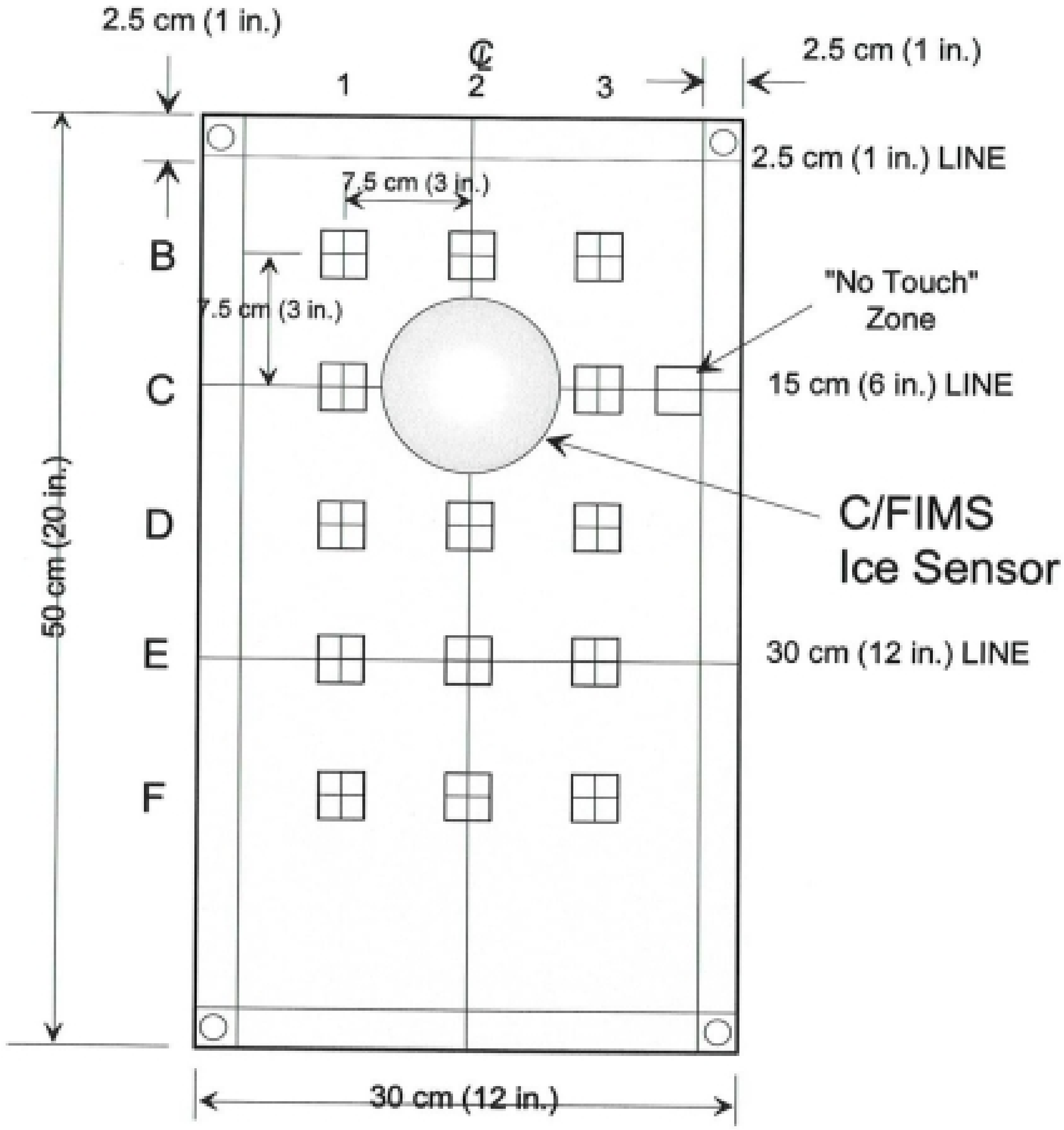
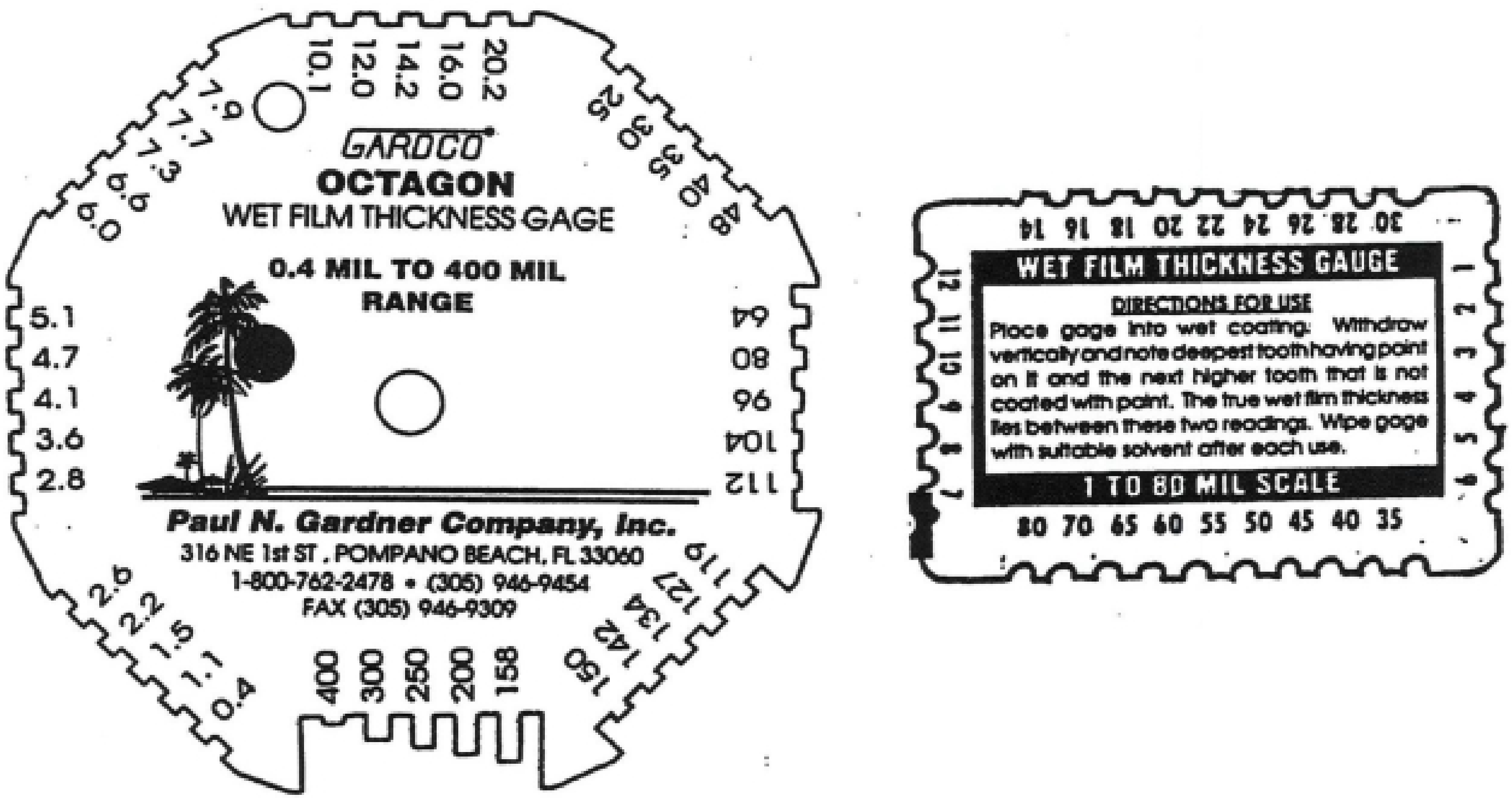


FIGURE 2.2

WET FILM THICKNESS GAUGES



cm1380/report/fluiddoc/THK_GAUG

2.4.5 Fluid Concentration

Fluid concentration was measured with a hand-held Brix-scale refractometer. Fluid samples were collected from the plate with small acetate strips and with syringes (Photos 2.4 and 2.5). The plates shown in Photo 2.5 illustrate the plate markings, including the no-touch zone to the right of the sensor installation. The no-touch zone was only used during the 1997-98 test season.

2.4.6 Fluid Adhesion

In the absence of a recognized standard method or apparatus for measuring adhesion, attempts had been made during earlier tests to quantify this characteristic through use of prototype devices or ad-hoc procedures. These attempts were generally based on an evaluation of the resistance to movement of the layer of failed fluid. One approach was based on the stiffness of the bristles of a brush mounted in a device to be drawn through the fluid. This device proved awkward and invasive, disturbing too much of the subject fluid. Another approach used pliable plastic strips of various degrees of stiffness. When drawn through the fluid the strips provided a sense of fluid resistance, sliding over areas where adhesion had set in, but dislodging failures where no adhesion to the plate had developed. Another approach involved directing a jet of air at the subject fluid and observing whether the fluid would be dislodged or moved. None of these approaches were fully satisfactory. In this study, adhesion and the degree of bonding were determined using an electric dental flossing device (Photo 2.6).

During operation (Photo 2.7), a thread of floss was spun by the device. The floss segment extended about 3 to 4 mm from the tip of the unit, and upon spinning could 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 was sufficient to expose the surface of the test plate. As the rotation speed of the unit was 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 (see Appendix E) determined it to be in the range of 1.3×10^{-4} to 2.0×10^{4} MPa. This shearing force is higher than the wind shear on a wing during takeoff. If the fluid failure cannot be dislodged by the dental floss device, it will not shear off an aircraft wing during rotation. If, however, it is removed by the adherence tester, it may not remain on the aircraft wing during rotation.

2.4.7 Fluid Viscosity

Fluid samples for viscosity tests were gathered during the tests and preserved in small wide-mouth glass bottles with screw caps. Viscosity levels of these samples were subsequently measured by use of a Brookfield viscometer (Model DV-1+; Photo 2.8) fitted with a thermostatted recirculating fluid bath and micro sampling option.

The 1997-98 viscosity samples were tested with the SCR-16/8R spindle/chamber assembly due to the small fluid samples collected. In 1998-99, larger samples were collected and the SCH-31/13R assembly was used.

2.5 Data Forms

Standard data forms used for fluid holdover time tests were used for recording failure times, precipitation rates and fluid thickness measurements. Special data forms were designed to record Brix readings, viscosity sampling, fluid failure adhesion, and the subjective appearance of fluid failure. The complete set of forms used during the 1997-98 tests are included in Appendix B. The forms used during the 1998-99 season are included in full for outdoor and indoor tests in Appendix C and D, respectively.

2.6 Fluids

Test fluids were selected to provide a representation of SAE Type I and SAE Type IV fluids. Both ethylene glycol- and propylene glycol-based fluids are represented in the data collected. Fluids were tested at full strength except for one particular Type IV fluid that was diluted to a 50/50 concentration in order to provide comparisons to Type I fluid. Table 2.1 shows a full list of the fluids used.

TABLE 2.1

SUMMARY OF FLUIDS TESTED

Fluid Name	Fluid Type	Nature	Concentration
Clariant Safewing Four	IV	Propylene	Neat
Fluid X	IV	Ethylene	Neat
Kilfrost ABC-S	IV	Propylene	Neat
Octagon Max-Flight	IV	Propylene	Neat
SPCA AD-480	IV	Propylene	Neat & 50/50
UCAR Ultra+	IV	Ethylene	Neat
UCAR XL54	I	Ethylene	Standard

Fluids tested during the two test seasons were from different batches. Some variations in fluid properties were detected for some of the fluids. The fluids included UCAR XL54, SPCA AD-480 (50 percent), UCAR Ultra+, Octagon Max-Flight, Kilfrost ABC-S, SPCA AD-480, Clariant Safewing Four and an ethylene glycol-based reference fluid (Fluid X). The Octagon Max-Flight used in 1998 was highly sheared. The Max-Flight fluid from the 1998-99 test season was a typical mid-specification range viscosity fluid.

2.7 Personnel

The nature of the tests resulted in a number of simultaneous documentation activities triggered by events of significance that occurred during the progression of fluid failure. Completion of documentation and collection activities within a short time period required the involvement of an unusually large number of test personnel.

The most critical event in any given test was the standard plate failure call. This event required samples to be collected for concentration, wet film thickness, and viscosity measurements. Narrative descriptions of the appearance of the failed fluid were recorded. Both still photography and video capture of the event were also carried out at this point, as was adhesion testing. Normally, tests were run simultaneously on two or three plates. On two occasions, up to four flat plate tests were simultaneously in progress. As all of these activities required close access to the test plate, a sequence of activities was developed wherein test members took turns approaching the plate, performing their function, and then stepping back. This discipline prevented crowding around the test stand and minimised 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.

Ten APS personnel were involved in the test process during the 1998 tests. Based on the experience gained during the previous test season and due to procedural changes, the personnel required dropped to eight during the 1999 tests. One person recorded both the video and still photography documentation. Additionally, personnel from both RVSI and Cox were present to provide support in operating their equipment (when used) and to ensure ongoing recording of fluid condition in tests underway.

Photo 2.1
General Test Setup

Photo 2.2
Test Status Board

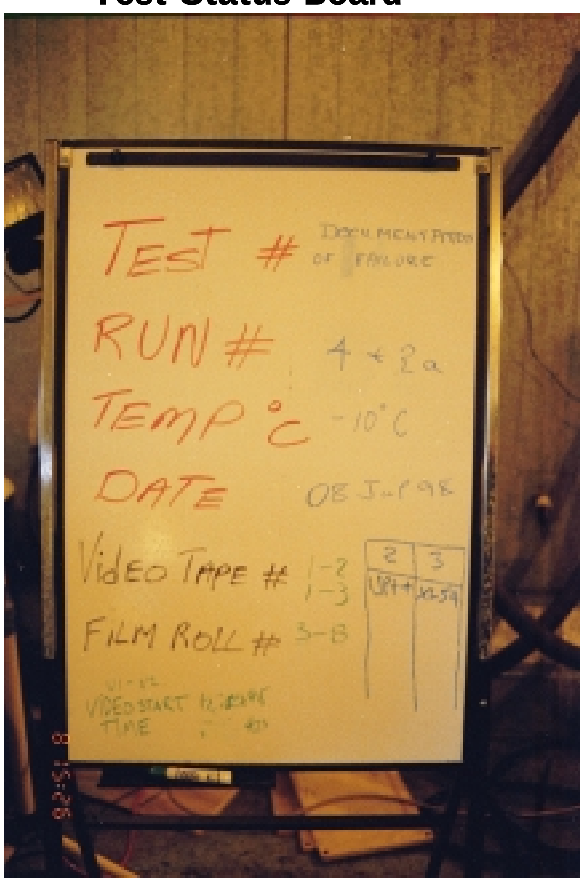


Photo 2.3
General Form

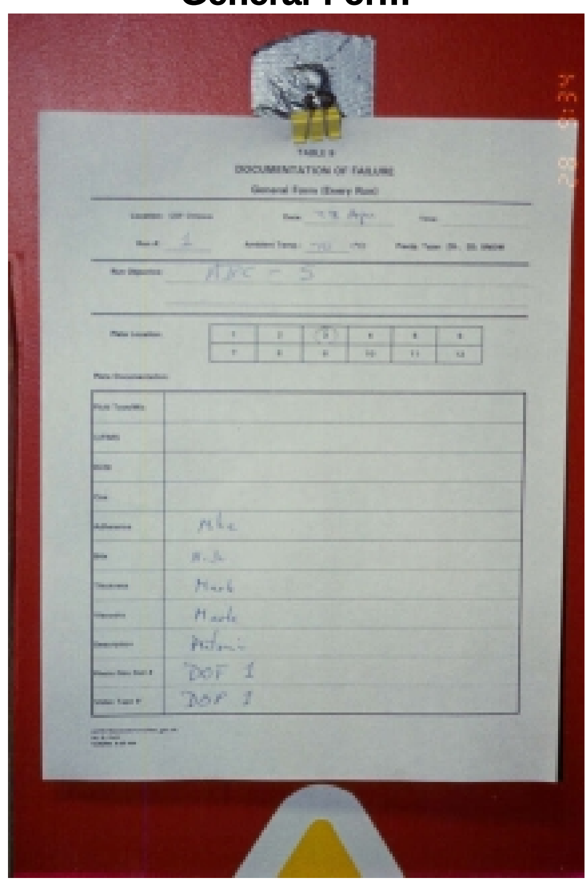


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Photo 2.4
Syringe for Collecting Fluid Samples from Bottom Layer

Photo 2.5
Collecting Fluid Samples with Syringe

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Photo 2.6
Dental Flossing Device Used to Test Adhesion

Photo 2.7
Adhesion Tests Performed with Flossing Device

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Photo 2.8
Brookfield Digital Viscometer Model DV-I+ and Temperature Bath

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3. DESCRIPTION AND PROCESSING OF DATA

3.1 Overview of Test Sessions

Fourteen runs, including 28 individual plate tests, were conducted over a two-day period during the 1997-98 test season. Twelve individual plate tests were conducted in natural snow in January 1999 and seventeen indoor plate tests were conducted in April 1999, including 11 artificial snow tests. A summary of test parameters is presented in Table 3.1.

Table 3.2 provides a log of all tests with associated test conditions and failure times. The table indicates duplicate tests conducted to ensure reproducibility.

3.2 Discussion of Test Variables

Test conditions were established to address the following considerations:

- Appearance of Type I versus Type IV – light freezing rain;
- Appearance of Type I versus Type IV – snow;
- Appearance of Type IV – light freezing rain versus freezing drizzle;
- Appearance of Type IV – freezing drizzle versus snow;
- Appearance of Type IV – effect of temperature (-4ºC and -10ºC);
- Ethylene glycol-based Type IV fluid versus propylene glycol-based Type IV fluid – freezing drizzle;
- Time to adhesion – Type I versus Type IV; and
- Appearance of Type I versus Type IV 50/50 – light freezing rain.

During the afternoon of the first day of testing in the 1997-98 test season, under ambient temperature conditions of -10°C, it was noted that the test plate temperature was not as cold as expected. Following some experimentation, it was found that the photographers' lights were a problem source of heat on the test plates. All light sources, including those associated with the ice detection sensors, were turned off or positioned farther back from the test stand for subsequent tests. The light sources required for photography were turned off between pictures. Personnel concentration close to a test stand was minimized to reduce the effects of body heat, particularly during runs performed at higher temperatures.

TABLE 3.1

DOCUMENTATION OF FLUID FAILURE

SUMMARY OF TESTS CONDUCTED

Location	NRC	NRC	NRC	NRC	NRC	NRC	Dorval	Dorval	Dorval	Dorval	NCAR	NCAR	NCAR	NCAR
Precipitation Type	ZD	ZD	ZD	ZD	ZR	ZR	Snow	Snow	Snow	Snow	Snow	Snow	Snow	Snow
Rate (g/dm²/hr)	5	13	5	10	25	25	1	10	15	30	10	25	10	25
OAT (°C)	-3	-3	-10	-10	-10	-4	-22	-16	-16	-14	-4	-4	-12	-12
UCAR XL54					5,7	14,18		34		39	56	57		46
UCAR Ultra+		20,22	24,27	1,4	6,9	13,19	29		32	37	48	53	44	43
Octagon Maxflight		21,23	25,26	2,3	8,11	16	30		31,36		51	52	47	45
Kilfrost ABC-S	49,50	54,55	41,42		10,12									
SPCA AD-480			28											
Clariant Safewing Four									35	40				
FLUID X									33	38				
SPCA AD-480 (50%)						15,17								

Notes:
- Values in cells represent test numbers.
- Tests 1 to 28 were performed during the 1997-98 season
- Tests 29 to 57 were performed during the 1998-99 season

cm1514/report/doc_fail/SUMMARY
AT: Summ

TABLE 3.2

DOCUMENTATION OF FAILURE - TEST LOG

Test No.	Test Season	Form No.	Date	Start Time (Local)	First Time (Local)	End Time (6 in.) (Local)	Stop Time (All) (Local)	Fluid Name	Fluid Dilution	Fluid Type	Plate Location	C/FIMS #	SPAR/ Cox	RVSI	Final Brix	Fail Time (min.)	First Failure Time (min)	Rate of Precipitation (g/dm*2/hr)	Ambient Temp (C)	Precipitation Type	Duplicate Tests	Comments
1	1998	1	Jul-08-98	11:13:10	11:50	12:03	12:19	UCAR ULTRA +	Neat	4	2	15		√	13	50	36	10.4	-10.3	frz_drizzle	1,4	
2	1998	1	Jul-08-98	11:23:05	11:36	11:56	12:07	OCTAGON	Neat	4	3	17	√	√	20	33	12	9.8	-10.3	frz_drizzle	2,3	
3	1998	2	Jul-08-98	12:53:45	13:04	13:33	13:46	OCTAGON	Neat	4	2	15		√	18	39	10	11.0	-10.1	frz_drizzle	2,3	
4	1998	2	Jul-08-98	12:57:05	13:52	14:01	14:18	UCAR ULTRA +	Neat	4	3	17		√		64	54	10.1	-10.1	frz_drizzle	1,4	
5	1998	3	Jul-08-98	15:38:45	15:42	15:43	15:44	UCAR XL54	Std	1	3	17		√	6	5	3	24.5	-10.5	frz_rain	5,7	
6	1998	4	Jul-08-98	15:25:50	15:30	15:57	16:05	UCAR ULTRA +	Neat	4	2	15		√		31	4	25.2	-10.3	frz_rain	6,9	
7	1998	4	Jul-08-98	15:27:10	15:29	15:31	15:32	UCAR XL54	Std	1	3	17	√	√	5	4	1	24.5	-10.3	frz_rain	5,7	
8	1998	5	Jul-08-98	16:11:00	16:18	16:33	16:41	OCTAGON	Neat	4	2	15		√		22	7	25.2	-10.5	frz_rain	8,11	
9	1998	5	Jul-08-98	15:54:30	16:10	16:23	16:30	UCAR ULTRA +	Neat	4	3	17		√		29	15	24.5	-10.2	frz_rain	6,9	
10	1998	6	Jul-08-98	17:01:50	17:07			KILFROST ABC-S	Neat	4	2	15		√		N/F	5	25.2	-10.5	frz_rain	10,12	Test stopped - chamber temp. problem
11	1998	6	Jul-08-98	16:37:20	16:50	16:57	17:02	OCTAGON	Neat	4	3	17		√	7.5	20	12	24.5	-10.5	frz_rain	8,11	
12	1998	7	Jul-08-98	17:40:50	17:48			KILFROST ABC-S	Neat	4	3	17	√	√		N/F	7	24.5	-10.5	frz_rain	10,12	Test stopped - chamber temp. problem
13	1998	8	Jul-09-98	9:13:45	9:42	9:49	9:54	UCAR ULTRA +	Neat	4	2	15		√		35	28	24.1	-3.5	frz_rain	13,19	
14	1998	8	Jul-09-98	9:16:00	9:25	9:27	9:35	UCAR XL54	Std	1	3	17		√		12	9	24.8	-3.6	frz_rain	14,18	Intial brix = 24.5 (Possibly wrong fluid)
15	1998	9	Jul-09-98	9:41:15	9:55	9:57	9:59	SPCA AD-480	50%	4a	3	N/A	√	√		16	13	24.8	-3.3	frz_rain	15,17	
16	1998	10	Jul-09-98	10:02:40	10:17	10:25	10:27	OCTAGON	Neat	4	2	15		√	3	22	14	24.1	-3.7	frz_rain	16	
17	1998	10	Jul-09-98	10:10:00	10:23	10:26	10:27	SPCA AD-480	50%	4a	3	17		√	6	16	13	24.8	-3.7	frz_rain	15,17	
18	1998	11	Jul-09-98	10:33:45	10:40	10:42	10:47	UCAR XL54	Std	1	2	15		√	3	8	6	24.1	-4.0	frz_rain	14,18	
19	1998	11	Jul-09-98	10:37:30	11:01	11:10	11:17	UCAR ULTRA +	Neat	4	3	17		√	6	33	23	24.8	-3.7	frz_rain	13,19	
20	1998	12	Jul-09-98	12:47:30	13:34	13:44	13:51	UCAR ULTRA +	Neat	4	2	15	√	√	11	57	46	12.4	-3.5	frz_drizzle	20,22	
21	1998	12	Jul-09-98	12:50:05	13:12	13:28	13:35	OCTAGON	Neat	4	3	17		√	9	38	21	12.4	-3.4	frz_drizzle	21,23	
22	1998	12	Jul-09-98	12:54:45	13:34	13:52	13:57	UCAR ULTRA +	Neat	4	4	23		√	9	57	39	13.0	-3.5	frz_drizzle	20,22	
23	1998	12	Jul-09-98	12:56:15	13:13	13:20	13:37	OCTAGON	Neat	4	5	N/A		√	10	24	16	13.5	-3.1	frz_drizzle	21,23	
24	1998	13	Jul-09-98	15:29:30	16:36	16:51	16:54	UCAR ULTRA +	Neat	4	2	15		√	16	82	66	4.7	-10.6	frz_drizzle	24,27	
25	1998	13	Jul-09-98	15:31:15	15:54	16:36	16:49	OCTAGON	Neat	4	3	17		√	15	65	22	5.0	-10.6	frz_drizzle	25,26	
26	1998	13	Jul-09-98	15:33:20	15:55	16:34	16:50	OCTAGON	Neat	4	5	N/A		√		61	21	4.9	-10.6	frz_drizzle	25,26	
27	1998	13	Jul-09-98	15:32:20				UCAR ULTRA +	Neat	4	4	23		√	14	N/F	N/A	4.8	-10.6	frz_drizzle	24,27	Test stopped at 16:26
28	1998	14	Jul-09-98	16:27:30	16:47	17:26	17:46	SPCA AD-480	Neat	4	4	23	√	√	24	59	19	4.8	-10.9	frz_drizzle	28	
29	1999	D1	Jan-12-99	7:19:30				OCTAGON	Neat	4	U	17			33	N/F	N/A	0.9	-22.0	natural_snow	29	Test stopped due to lack of precipitation
30	1999	D1	Jan-12-99	7:29:30				UCAR ULTRA +	Neat	4	V	N/A			34	N/F	N/A	0.9	-22.0	natural_snow	30	Test stopped due to lack of precipitation
31	1999	D1	Jan-14-99	23:23:00	23:32	23:45	0:00	OCTAGON	Neat	4	U	17			22	22	9	15.8	-16.7	natural_snow	31,36	
32	1999	D1	Jan-14-99	23:16:00	23:39	23:55	0:04	UCAR ULTRA +	Neat	4	V	N/A			27	39	23	15.5	-16.6	natural_snow	32	
33	1999	D2	Jan-15-99	0:30:00	0:43	1:26	1:31	FLUID X	Std	N/A	U	17			21	56	13	17.5	-15.9	natural_snow	33	
34	1999	D2	Jan-15-99	0:38:00	0:40	0:44	0:48	UCAR XL54	Std	1	V	N/A			N/A	7	2	9.4	-16.0	natural_snow	34	
35	1999	D3	Jan-15-99	1:51:00	2:02	2:23	2:29	SAFEWING FOUR	Neat	4	U	17			24	32	11	16.4	-15.1	natural_snow	35	
36	1999	D3	Jan-15-99	1:59:00	2:20	2:41	2:48	OCTAGON	Neat	4	V	N/A			26	42	21	16.6	-15.0	natural_snow	31,36	

TABLE 3.2

DOCUMENTATION OF FAILURE - TEST LOG (cont.)

Test No.	Test Season	Form No.	Date	Start Time (Local)	First Time (Local)	End Time (6 in.) (Local)	Stop Time (All) (Local)	Fluid Name	Fluid Dilution	Fluid Type	Plate Location	C/FIMS #	SPAR/ Cox	RVSI	Final Brix	Fail Time (min.)	First Failure Time (min)	Rate of Precipitation (g/dm^2/hr)	Ambient Temp (C)	Precipitation Type	Duplicate Tests	Comments
37	1999	D4	Jan-15-99	3:14:00	3:27	3:39	3:43	UCAR ULTRA +	Neat	4	U	17			21	25	13	26.8	-14.3	natural_snow	37	
38	1999	D4	Jan-15-99	3:23:00	3:36	3:56	4:01	FLUID X	Std	N/A	V	N/A			21	33	13	27.3	-14.3	natural_snow	38	
39	1999	D5	Jan-15-99	4:11:15	4:13	4:14	4:15	UCAR XL54	Std	1	U	17			N/A	3	1	30.2	-14.1	natural_snow	39	
40	1999	D5	Jan-15-99	4:19:00	4:33	4:42	4:49	SAFEWING FOUR	Neat	4	V	N/A			24	23	14	32.3	-14.0	natural_snow	40	
41	1999	N1	Apr-28-99	9:41:30	10:04	11:00	11:33	KILFROST ABC-S	Neat	4	3	17			20	79	22	5.1	-10.0	frz_drizzle	41,42	
42	1999	N2	Apr-28-99	10:06:50	10:31	11:20	11:51	KILFROST ABC-S	Neat	4	4	23			27	73	24	5.3	-10.0	frz_drizzle	41,42	
43	1999	N3	Apr-28-99	12:07:00	12:26	12:27	12:37	UCAR ULTRA +	Neat	4	NCAR	N/A	√		13	20	19	28.4	-12.6	snow	43	
44	1999	N4	Apr-28-99	13:04:00	13:30	13:57	14:20	UCAR ULTRA +	Neat	4	NCAR	N/A			8.8	53	28	10.2	-12.7	snow	44	
45	1999	N5	Apr-28-99	14:40:20	14:50	14:57	15:04	OCTAGON	Neat	4	NCAR	N/A	√		17	17	9	23.0	-11.9	snow	45	
46	1999	N6	Apr-28-99	15:30:50	15:32	15:35	15:38	UCAR XL54	Std	1	NCAR	N/A	√		4.5	5	1	17.9	-11.9	snow	46	
47	1999	N7	Apr-28-99	15:58:00	16:36			OCTAGON	Neat	4	NCAR	N/A			18	N/F	38	8.3	-12.0	snow	47	Ice core broke at 1" failure progression
48	1999	N8	Apr-29-99	8:29:00	9:24	10:00	10:12	UCAR ULTRA +	Neat	4	NCAR	N/A			7	91	55	9.4	-4.2	snow	48	
49	1999	N9	Apr-29-99	9:32:20	12:01	12:23	12:48	KILFROST ABC-S	Neat	4	3	17	√		3	171	148	4.7	-2.9	frz_drizzle	49,50	
50	1999	N10	Apr-29-99	9:48:20	12:00	12:27	13:00	KILFROST ABC-S	Neat	4	4	23	√		2	159	131	5.0	-2.9	frz_drizzle	49,50	
51	1999	N11	Apr-29-99	10:38:00	11:18	11:58	12:09	OCTAGON	Neat	4	NCAR	N/A			13	80	40	9.8	-4.1	snow	51	
52	1999	N12	Apr-29-99	13:02:20	13:17	13:29	13:37	OCTAGON	Neat	4	NCAR	N/A			16	27	14	26.7	-4.2	snow	52	
53	1999	N13	Apr-29-99	13:56:00	14:15	14:35	14:44	UCAR ULTRA +	Neat	4	NCAR	N/A			8.5	39	19	29.0	-4.2	snow	53	
54	1999	N14	Apr-29-99	14:15:00	15:54	16:24	16:41	KILFROST ABC-S	Neat	4	3	17			3.3	129	99	12.4	-2.9	frz_drizzle	54,55	
55	1999	N15	Apr-29-99	14:25:00	15:59	16:35	16:45	KILFROST ABC-S	Neat	4	4	23			3.5	130	94	12.8	-2.9	frz_drizzle	54,55	
56	1999	N16	Apr-29-99	15:01:30	15:07	15:09	15:12	UCAR XL54	Std	1	NCAR	N/A			1.5	8	6	5.9	-4.5	snow	56	
57	1999	N17	Apr-29-99	15:22:50	15:26	15:27	15:29	UCAR XL54	Std	1	NCAR	N/A			2	5	3	24.4	-4.6	snow	57	

Number of Tests:

T1	Standard	T4	Neat	50/50
UCAR XL54=	9	OCTAGON Maxflight=	16	
		KILFROST ABC-S=	8	
		UCAR ULTRA+=	17	
		Clariant FOUR=	2	
		FLUID X=	2	
		SPCA AD-480=	1	2
Total	9		46	2
TOTAL # OF TESTS =			57	

3.3 Description of Collected Data and Analysis

The data collected during this study were focused to provide documentation of the appearances and physical nature of deicing and anti-icing fluid failures. The various media required to provide this documentation included still photography and videotape, narrative descriptions, response profiles from various ice detection sensors, and measurements of physical characteristics including fluid concentration, fluid film thickness, adhesion and viscosity.

Data from the various means used to document fluid failures were sorted by test and arranged in a fixed order of presentation. A full set of test results, arranged in a set order and sorted by individual tests, is presented in the CD Attachment. A sample of the documentation for a single test (ID #1) follows.

3.3.1 Photographic Documentation

Figure 3.1 provides general test information including test conditions, test start and failure times, and some quantitative results.

A set of four photos (Photos 3.1 to 3.4) show the appearance of fluid at four specific stages during the test:

- at time of pouring;
- at time of initial (first) failure;
- at time of standard plate failure call; and
- at complete plate failure.

The photos were taken as soon as possible after the time of each specified failure progression stage. The average delay between a failure time and the picture time is approximately two minutes for anti-icing fluids, and shorter for Type I fluids. This delay occurred due to the time required to measure the physical properties of the fluid after failure was called. If the elapsed time before the photo is taken is longer or if the failure has progressed beyond the specified stage, a comment is included in the photo caption.

The C/FIMS sensor head, the markings (squares) denoting crosshair locations and the *no-touch* zone are visible in the photos. In Photo 3.2 the area of initial fluid failure appears as surface roughness along the near top of the plate. In Photo 3.3, failure appears in the plate area above the sensor and as fingers of failed fluid extending toward the middle of the plate. In Photo 3.4 complete plate failure has occurred. The fingers of failure are extending to the bottom of the plate.

FIGURE 3.1

GENERAL TEST INFORMATION

ID # 1

July 8, 1998

Ambient Air Temperature:	-10.3°C
Precipitation Type:	Freezing Drizzle
Rate of Precipitation:	10.4 g/dm²/hr
Fluid:	UCAR ULTRA +
Dilution:	Neat
Start of Test:	11:13:10
Failure Mode:	Fifth Crosshair
Failure Location:	D2
Failure Time (Standard):	12:03:00
Failure Time (Complete Plate):	12:19:00

3.3.2 Video Documentation

In addition to the photos described in the preceding section, each stage of the fluid failure progression was recorded on videotape. During the 1997-98 test session, two video cameras were focussed on the no-touch zone of the two most frequently used plates and ran continuously. During the 1998-99 test session, a video camera ran continuously, taking a wide angle view of the test area. In addition, the RVSI and Spar/Cox systems maintained an ongoing video record of the events that occurred at the test stand.

3.3.3 Observer Description

Figure 3.2 is an experienced observer's narrative description of the appearance of the fluid as it progresses toward failure. Sketches illustrating points of interest support the narrative.

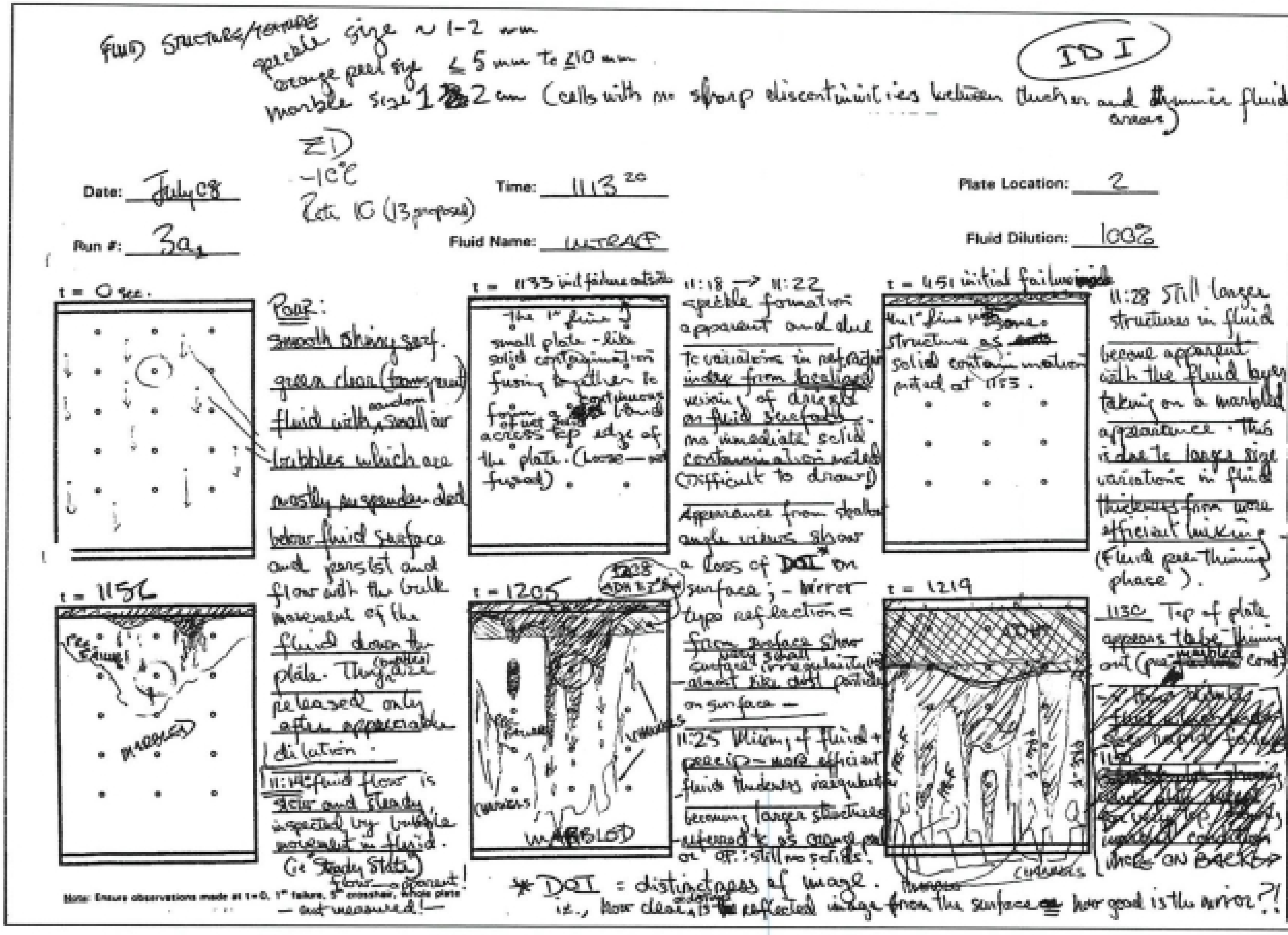
3.3.4 Fluid Thickness

Figure 3.3 is a record of fluid thickness over the duration of the test. The fluid thickness graphs include vertical time lines indicating initial (first) failure, standard plate failure and complete plate failure.

3.3.5 Fluid Freeze Point

Figure 3.4 is a profile of the fluid freeze point temperature as the deicing fluid concentration is progressively diluted from its initial strength. When testing Type IV fluids, the fluid concentration was sampled from both the top and bottom of the fluid layer, and the respective freeze points are shown as indicated by the legend. Since the fluid layer is very thin for Type I fluids, fluid concentration was only measured on top of the fluid and the value was taken as an average fluid concentration. When available, profiles of ambient temperature or plate temperature are presented to serve as a base line for fluid freeze point values. The comparison of fluid freeze point temperature to plate temperature at the time of standard plate failure is of interest. In this case, the fluid freeze point matched ambient temperature near the time of standard plate failure. In some cases, fluid freeze points may climb above ambient temperature due to samples being collected from the top layer of the fluid or due to uneven failure patterns.

FIGURE 3.2
SUBJECTIVE APPEARANCE OF FLUID FAILURE

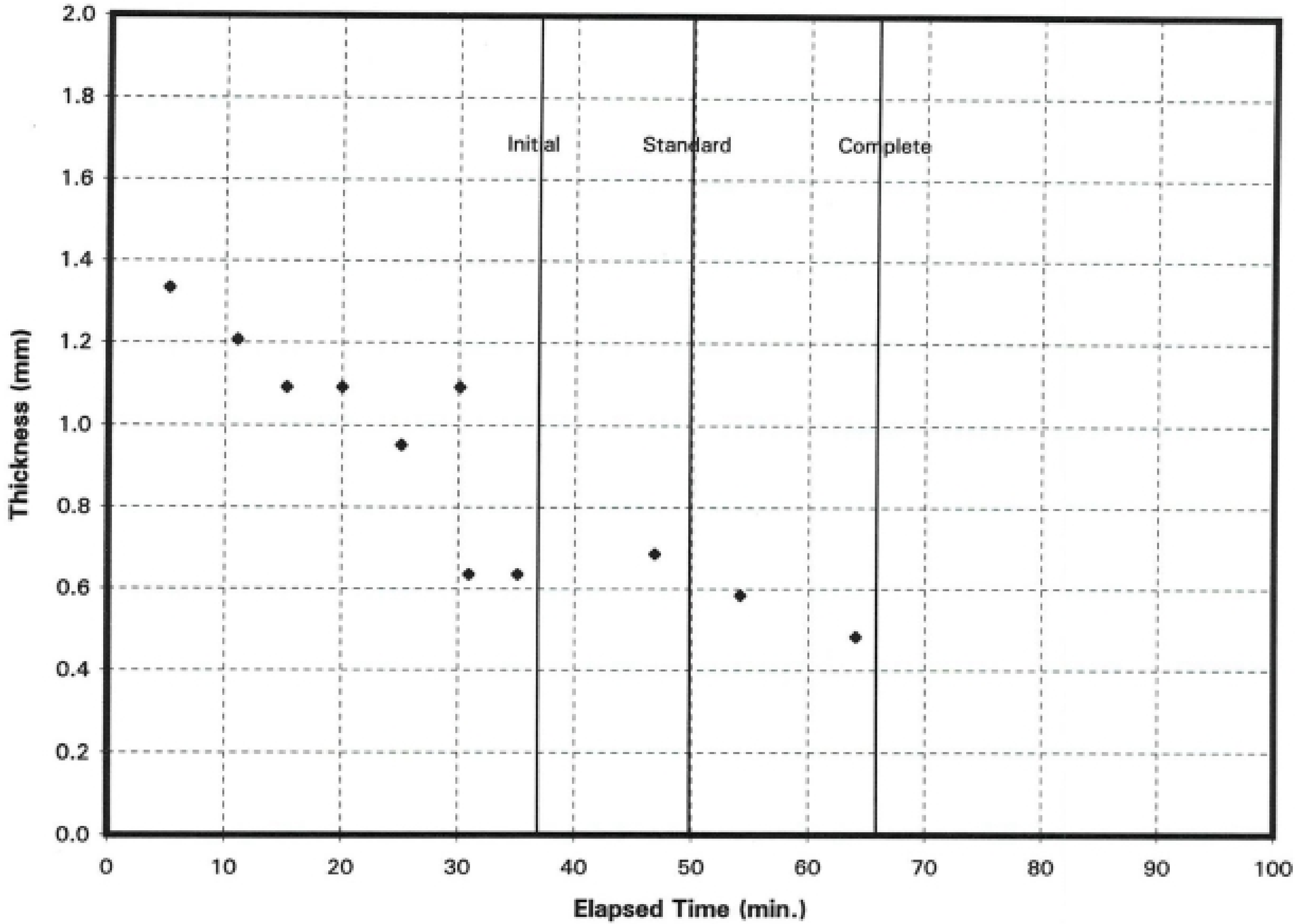


cm1514/report/doc_fail/SUBJ_ID1

FIGURE 3.3
DOCUMENTATION OF FLUID FAILURE

FLUID THICKNESS TESTS

ID # 1



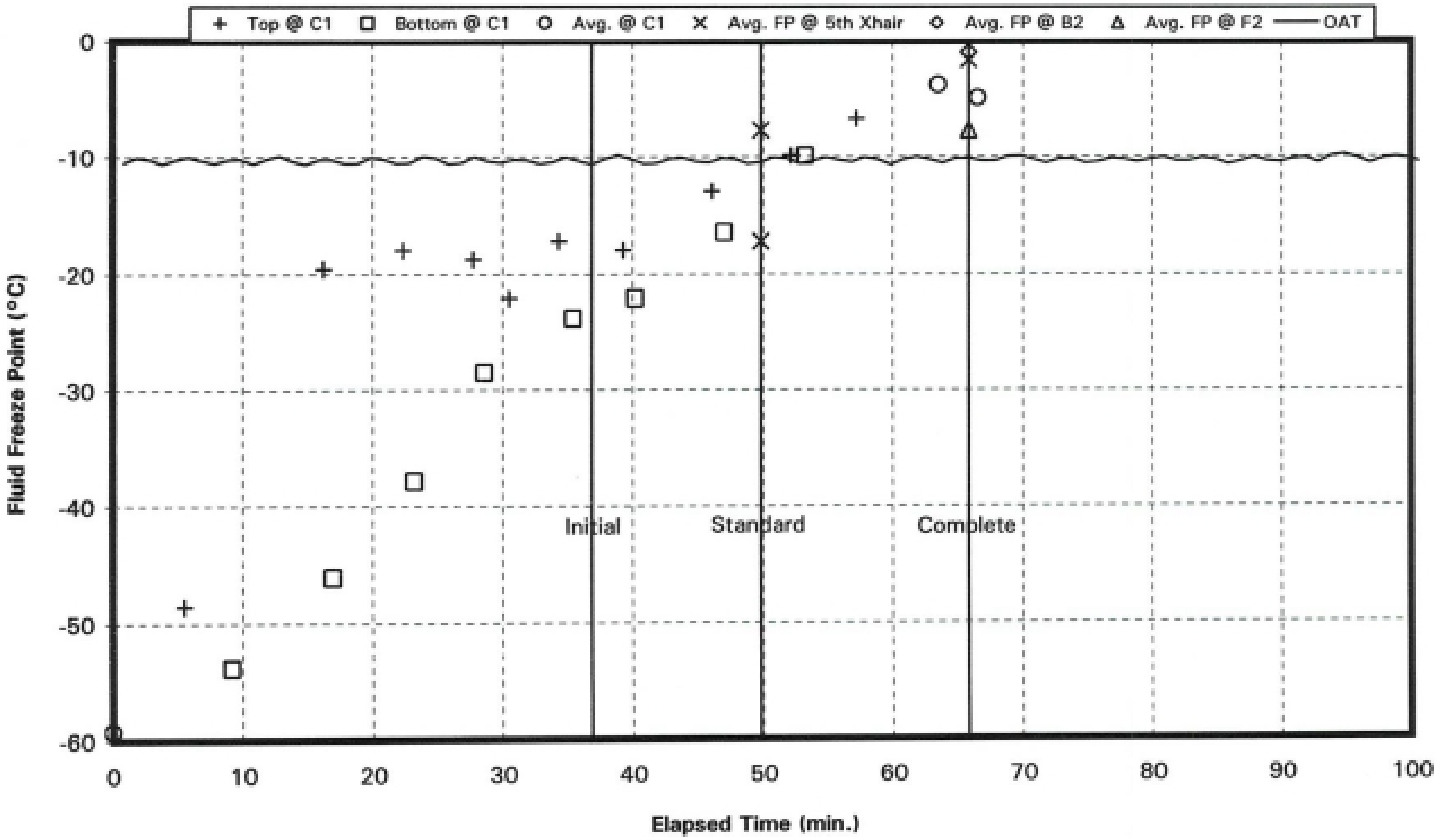
CM1514/Report/Doc_Fail/THK_ID1

FIGURE 3.4

DOCUMENTATION OF FLUID FAILURE

FLUID FREEZE POINT

ID # 1



CM1514/Report/Doc_Fail/BRX_ID1

3.3.6 C/FIMS Sensor Trace

Figure 3.5 records three contamination sensing traces from the C/FIMS sensor as well as a profile of plate temperature. The sensor manufacturer has not provided a method of interpreting the sensor traces to identify the point of standard plate failure. In an operational installation, the C/FIMS system would normally be supplemented with decision-making software to provide the operator with a go/no-go indication. However, such functionality was not incorporated into the system used for these tests. In view of this deficiency, interpretation of the sensor traces is based on a 1992-93 study by APS Aviation of the C/FIMS sensor in operation, Transport Canada report TP 11836E (4), that describes the nature of the C/FIMS sensor traces as fluids progressively absorb precipitation and reach the point of standard plate failure. The sensor records the admittance (inverse of electrical impedance) of the fluid overlaying the sensor head to three different levels within the fluid layer. Immediately following the application of fluid, the curves show a notable downturn caused by the rapid thinning of the initial fluid layer during that time. Subsequently, as the fluid absorbs precipitation, the curves slowly climb and then eventually reach a limit and start to decline as the ultimate capacity of the fluid to absorb water is reached. At the bottom of the decline, when the slope of the curve changes from negative to positive, the point of fluid failure has been reached. In this case, the C/FIMS sensor indicated that failure occurred at 42 minutes, as compared to the visual identification of standard plate failure which was called at 50 minutes (and which may have occurred elsewhere on the plate).

3.3.7 RVSI BF Goodrich Sensor Trace

The RVSI BF Goodrich ice contamination sensor detects ice based on the optical properties of the target surface. The system illuminates the surface with a polarized light source and measures the polarization of the reflected light.

The surface observed by the sensor was the *no-touch* zone, a small plate surface at the six inch line of the test plate. The traces shown are based on the output of the sensor for that small area.

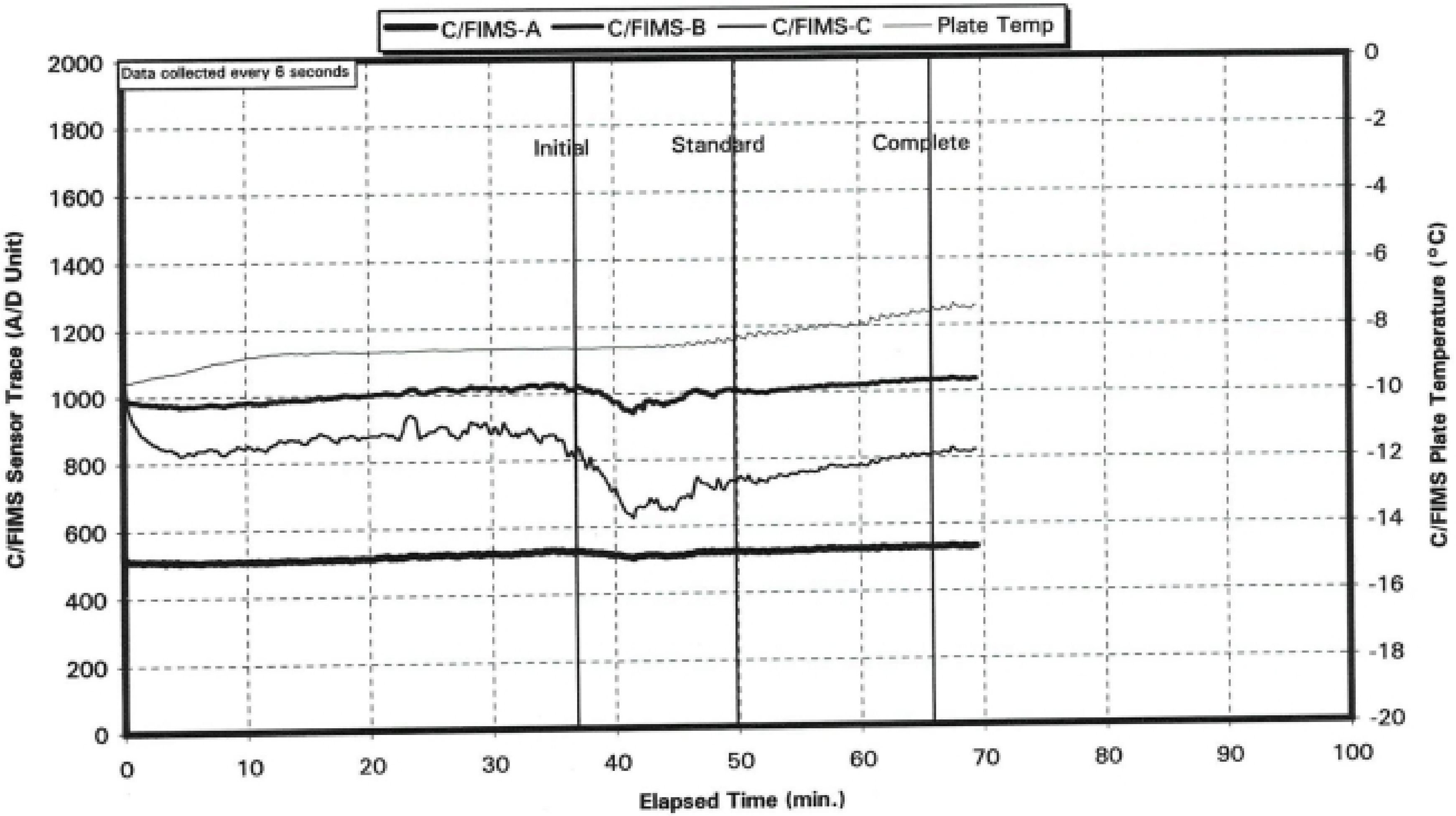
Figure 3.6 shows the trace from the RVSI BF Goodrich ice contamination sensor. The RVSI BF Goodrich sensor interprets fluid failure as the point where the trace changes direction and begins a rapid downturn. In this case, the RVSI BF Goodrich sensor identified fluid failure at about the same time (50 minutes) as the visual failure identification.

FIGURE 3.5

DOCUMENTATION OF FLUID FAILURE

C/FIMS SENSOR TRACE

ID # 1



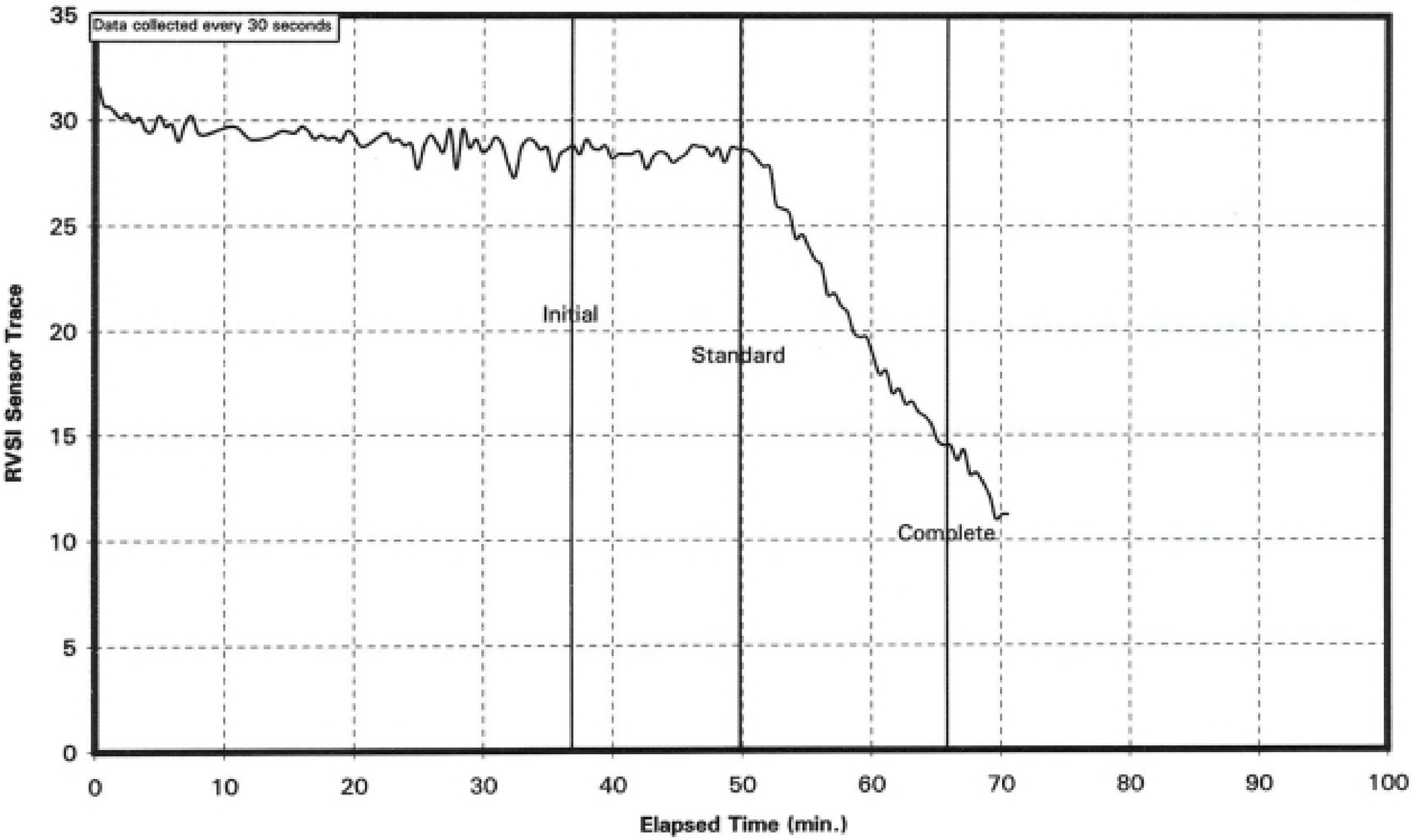
CM1514/Report/Doc_Fail/CFM_ID1

FIGURE 3.6

DOCUMENTATION OF FLUID FAILURE

RVSI SENSOR TRACE

ID # 1



CM1514/Report/Doc_Fail/RVS_ID1

3.3.8 Spar/Cox Sensor Trace

Figure 3.7 shows a trace from the Spar/Cox ice contamination detection system. Sensor traces were made and supplied by the manufacturer. Only a limited number of sample traces were made available for this report.

The surface observed by the sensor was the *no-touch* zone, a small plate surface at the six inch line of the test plate. The traces shown are based on the output of the sensor for that small area.

The trace shown in Figure 3.7 was generated using data from Test ID #20, which examined Ultra+ fluid in conditions of freezing drizzle at an outside air temperature of -4°C. This test illustrates how the trace pattern for the Spar/Cox sensor gradually ascends with time as the fluid undergoes progressive contamination. The Spar/Cox sensor measures the intensity of infra-red (IR) light reflected off target surfaces at specific narrow bandwidths. The contrast between the ambient IR intensity and the IR intensity from the plate image is used to detect ice on the plate surface. The numerical values on the vertical scale represent the *average contrast ratio*. Positive values indicate the existence of ice, and values of 0.003 (or in some tests, 0.005 or greater) delimit failure in the observed area.

3.3.9 Adhesion Tests

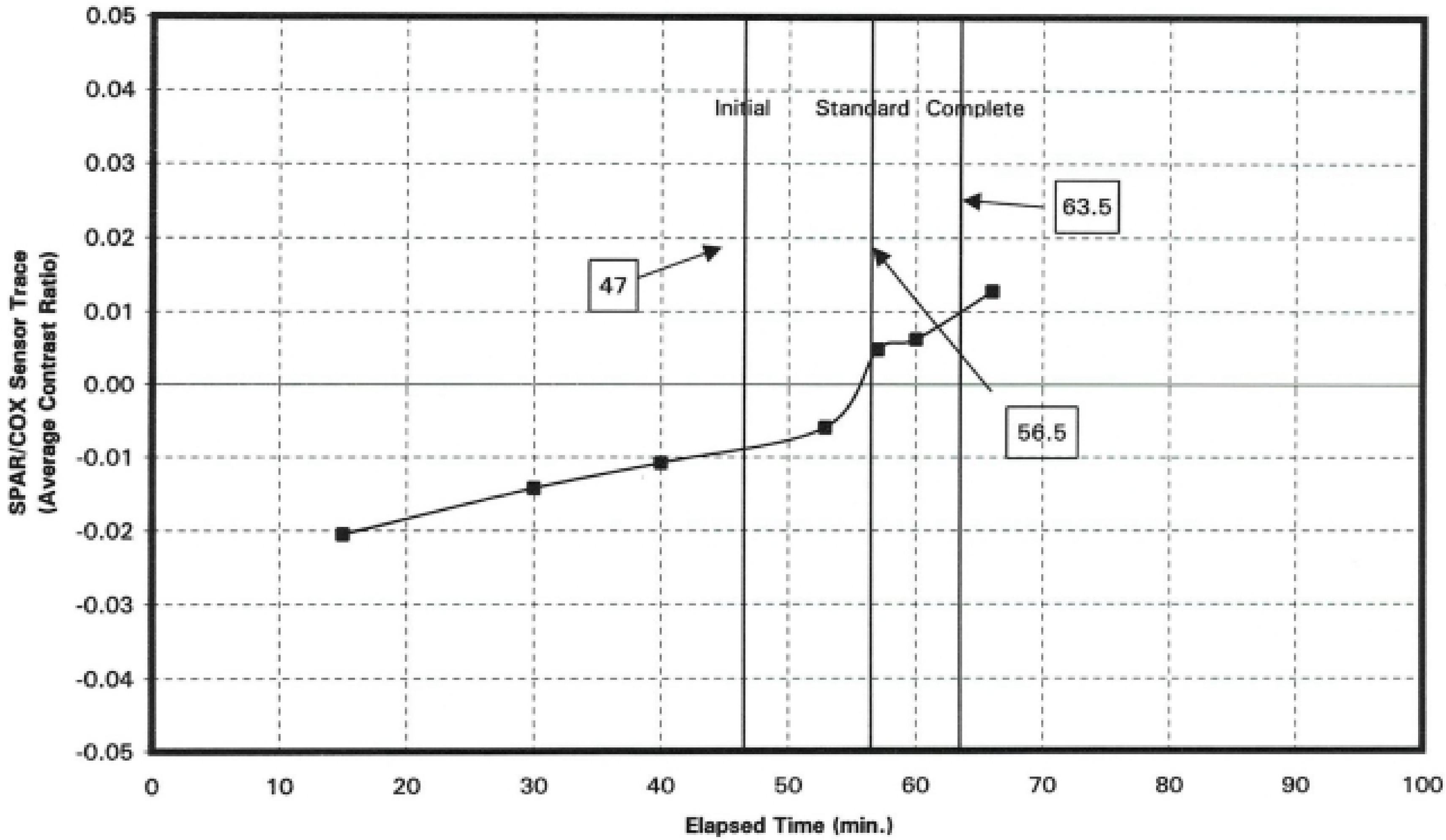
Figure 3.8 shows the record of adhesion to the plate surface at certain times during the test. Because of the numerous measurements taken, in some instances the figures in The CD Attachment (of this report), were depicted out somewhat differently. The crosshair location on the plate where adherence was measured is indicated on the left-hand margin, with a legend in the upper right corner denoting crosshair references. In this case, at 50 minutes into the test (standard plate failure), fluid failures at locations B2 and D2 had not adhered to the plate surface. At 74 minutes into the test (following complete plate failure), adhesion was not noted at locations D2, E2, or F2. As the pattern of freezing initiated at the top edge of the plate and progressed downwards, locations B2 and C3 had experienced longer exposure to freezing, sufficient to cause adhesion.

FIGURE 3.7

DOCUMENTATION OF FLUID FAILURE

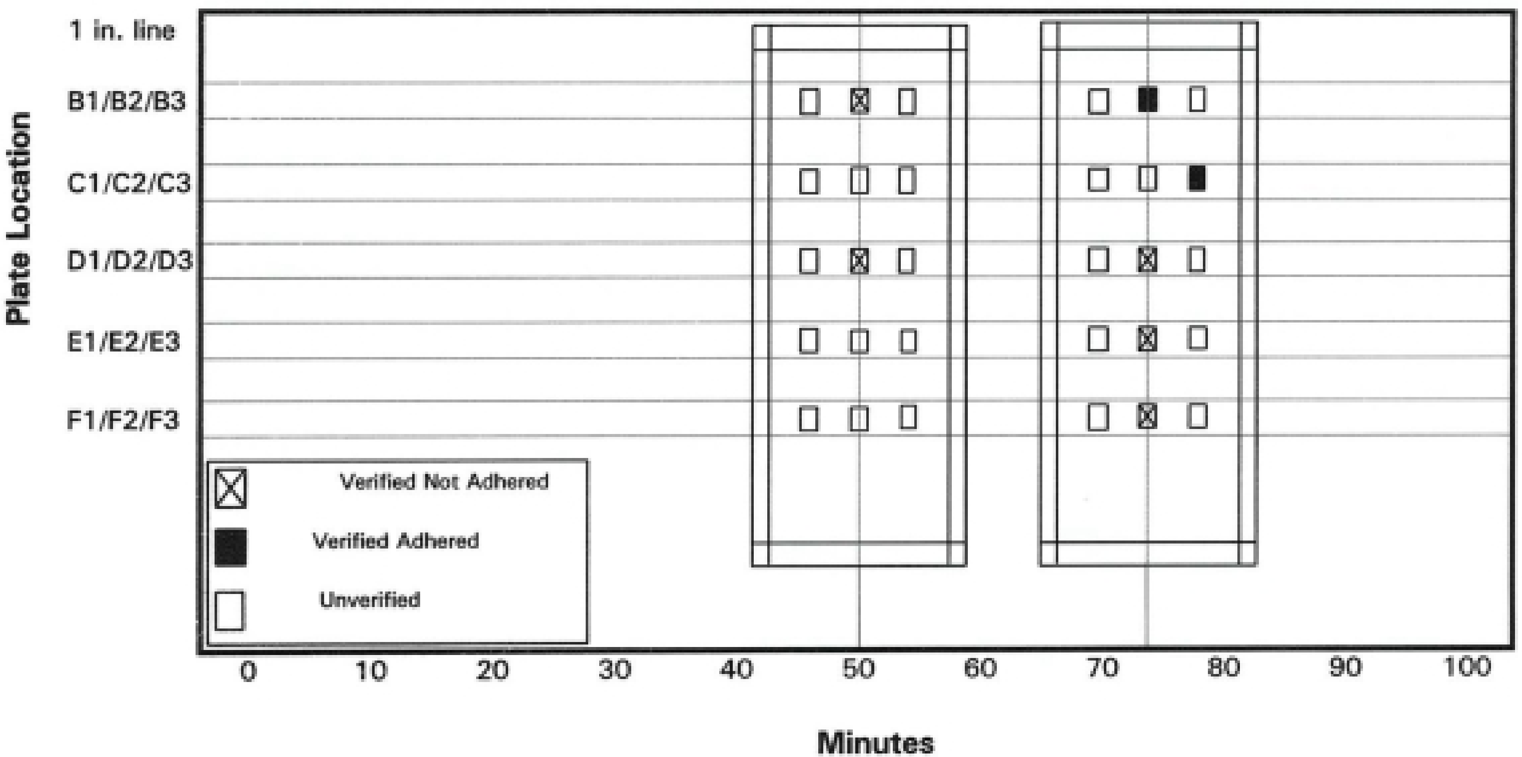
SPAR/COX SENSOR TRACE

ID # 20



CM1514/Report/Doc_Fail/COX_ID20

FIGURE 3.8
DOCUMENTATION OF FLUID FAILURE
ADHERANCE TESTS
ID#1



M:\Groups\CM1514\REPORT\DOC_FAIL\fig3.8
A:Sheet1 (2)

3.4 Viscosity Measurements

An attempt was made to examine the viscosity of each test fluid at time of failure. For the tests performed during the 1997-98 test season, fluid samples were collected at the time and location of the standard (fifth) crosshair failure and at time of complete plate failure at locations B2, F2 and adjacent to the location of fifth crosshair failure with the intent to measure fluid viscosity with a Brookfield Viscometer. It was subsequently determined that individual samples had insufficient volume for accurate testing and consequently, samples were consolidated within each test to enable measurement.

For the tests performed during the 1998-99 test season, four fluid samples were lifted for each individual plate test. Once complete plate failure had occurred, samples were collected from the fluid before it was poured on the plate from the top, middle and bottom thirds of the plate. To ensure that a sufficient amount of fluid was collected for each sample to be measured separately, only one sample bottle was collected for Type I fluid tests, due to the thin fluid layer associated with these fluids. For ease of discussion, and because the results apply to various fluids and conditions tested, the results are discussed separately in Section 4.

3.5 Terminology and Definitions

Section 1 mentions deficiencies in the clear and precise communication on the appearance of aqueous solutions of deicing and anti-icing fluids during the various stages of the fluid from application to failure.

A glossary of terminology has been assembled that should prove helpful in facilitating the interpretation of the material presented in Section 4 (see also Section 2.1, and the Transportation Development Centre report, *Aircraft Anti-Icing Fluid Endurance, Holdover, and Failure Times Under Winter Precipitation Conditions: A Glossary of Terms,* TP 13832, (2)). The terms contained are presented in the order of failure development rather than being arranged alphabetically. Alternative terms are also provided when available.

i) Test surface; substrate

Please refer to Section 2.1.

ii) Distinctness of image; DOI

A measure of the quality of a reflected image off a surface that has been treated with a coating. Usually used to describe painted finishes, especially on automobiles. In this context it refers to a fluid-treated surface once the fluid has stabilized (Photo 3.5).

iii) Contamination; contaminant(s)

Please refer to Section 2.1.

iv) Speck-covered stage (a pre-failure fluid condition)

This refers to the first visible signs of contamination on an Ultra+ fluid surface in certain conditions of freezing rain and freezing drizzle. In this stage, the fluid appears to contain specks similar to dust particles on an otherwise mirror-smooth surface. These are caused by contaminant droplets penetrating the fluid surface. No solids are actually present at this stage, but very localized refractive index variations change the appearance of the fluid surface layer. The distances between specks in this stage are greater than the specks' dimensions (Photo 3.6).

v) Streaks and dots (a pre-failure fluid condition)

Frozen precipitation in the form of short streaks or dots embedded in the fluid surface and most commonly observed in propylene glycol-based anti-icing fluids at temperatures of -10ºC or below. These are not stationary or fused, but seem to form on contaminant droplet contact with the fluid surface and are more readily observed once the fluid thickness stabilizes following application (Photo 3.7).

vi) Orange-peel; orange-peel texture (a pre-failure fluid condition)

A later stage in the appearance of fluid, prior to initial fluid failure, in which the density of specks (defined above) is such that the distance between specks is of the order of the specks' dimensions. This produces a surface that resembles the surface of an orange peel. It is a common term used to describe extended surface defects in paint finishes. It can be observed in Ultra+ (Photo 3.8).

vii) Gelatinous stage (a pre-failure fluid condition)

The final stage in the evolution of fluid appearance prior to initial fluid failure. It is seen in Ultra+ and sheared Octagon fluids and is observed when the orange-peel stage coalesces to form thicker and thinner fluid regions on the surface with no abrupt boundaries. Its appearance can be described as being similar to a warm sample of colourless or pale-green, well-sheared gelatine. It is still transparent and the test plate surface below takes on the appearance of polished marble (Photo 3.9).

viii) Visual fluid failure;

Also please see Section 2.1.

Visual fluid failure has occurred when any of the following are true:

- There is a visible accumulation of snow bridging on top of the fluid at the crosshair when viewed from the front. There should be an indication that the fluid can no longer absorb the precipitation at this point;

- Ice has formed or accumulated on top of the fluid or on the test surface, or ice remains suspended within the fluid; or

- Precipitation or frosting produces a dulling of the surface reflectivity, a change in colour (dye) to grey or greyish appearance, or ice (or crusty snow) has formed on the crosshair. This condition is only applicable during light freezing rain, freezing drizzle, ice pellets, freezing fog, rain on a cold-soaked surface or during a mixture of snow and light freezing rain, freezing drizzle and ice pellets.

ix) Standard plate failure; end condition definitions

The procedure and the determination of the end condition evolved from the experience derived from various test programs of previous winter seasons. Plate failure time is the interval from test start until end condition is reached. Standard plate failure occurs when the accumulating precipitation causes failures to be detected at any five of the fifteen crosshair marks on the panel, or on more than 1/3 of the entire plate surface.

a) Slush

Also please see Section 2.1.

An initial stage of fluid failure observed under certain conditions of freezing drizzle, freezing rain and natural snow that can be described as a liquid mixture of ice and fluid. Although the ice solids are soluble in the fluid, they are not being absorbed due to the fluid dilution caused by the contaminants. In some cases the solid particles are too large to be suspended in the fluid for any significant time interval and settle on the substrate surface. In many cases the solid particles will remain suspended and will continue to accumulate (Photo 3.10).

b) Fusion

In this context, fusion refers to the process whereby the individual ice particles in a failed region fuse to one another, resulting in a contiguous solid mass.

c) Drainage channels;

Channels carved into the fluid layer due to the flow of draining unfrozen precipitation and diluted fluid mixtures. Fingers of frozen contamination eventually extend and progress from these drainage channels. Photo 3.11 shows examples of both fingers and drainage channels.

d) Fingers of failure; fingers

Pattern of failure propagation in the form of fingers proceeding on a downward angle on a substrate. This condition precedes fusion.

e) Adhesion

The condition reached in advanced stages of fluid failure when the failures actually bond to a substrate.

f) Colloidal suspension; colloid

A colloid is a long-lived suspension of very fine particles in a fluid. The particle size distribution is far smaller than in slush and is usually not in a high enough concentration to agglomerate into larger particles. Colloids may appear clear or turbid. Clear colloids will still scatter light far more efficiently than true single-phase solutions. Some neat Type IV fluids can be considered colloidal suspensions in which the particles are polymer strands or coils.

g) Flash freezing; bloom ice

Ice formations initiated at random points on a substrate or test surface that propagate outward from the origin to form the characteristic *ice flower* or *snow fern* patterns seen on cold window panes exposed to humid air. It is usually observed after application of hot water or warm diluted deicing fluids onto cold-soaked surfaces and is an example of a super-cooled liquid that rapidly undergoes a phase transition to the solid state (Photo 3.12).

Photo 3.1
Fluid Application - ID # 1
After Pouring, t = 0 min. (Est.)

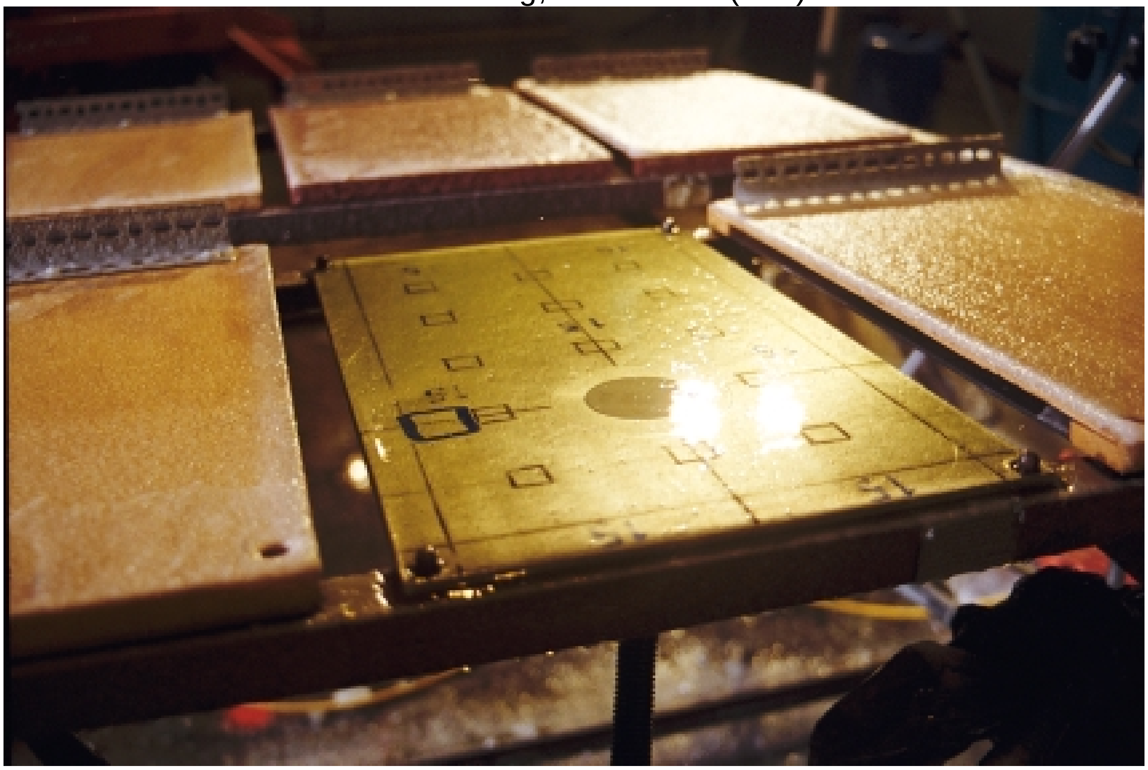


Photo 3.2
First Failure - ID # 1
First Failure, t = 37 min. (Est.)

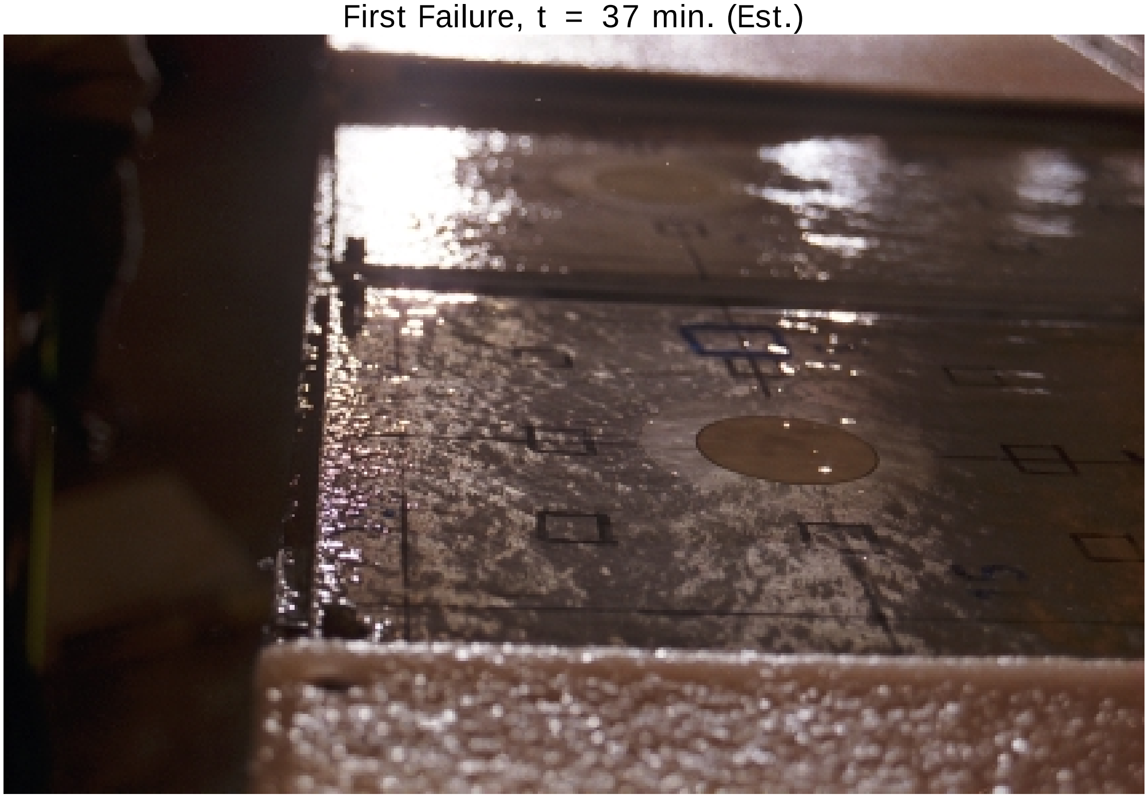


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Photo 3.3
Standard Failure - ID # 1
Standard Failure (1/3 or 5th Crosshair), t = 50 min. (Est.)

Photo 3.4
Complete Failure - ID # 1
Complete Fluid Failure, t = 66 min. (Est.)

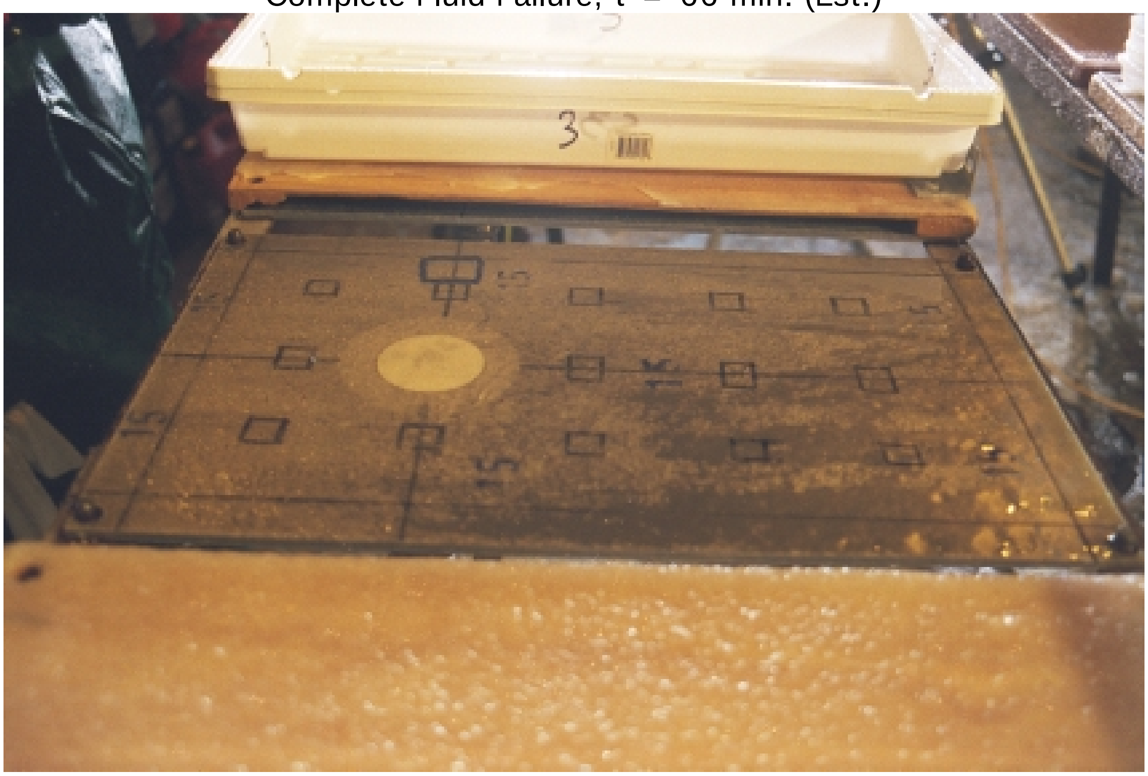

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Photo 3.5
Distinctness of Image

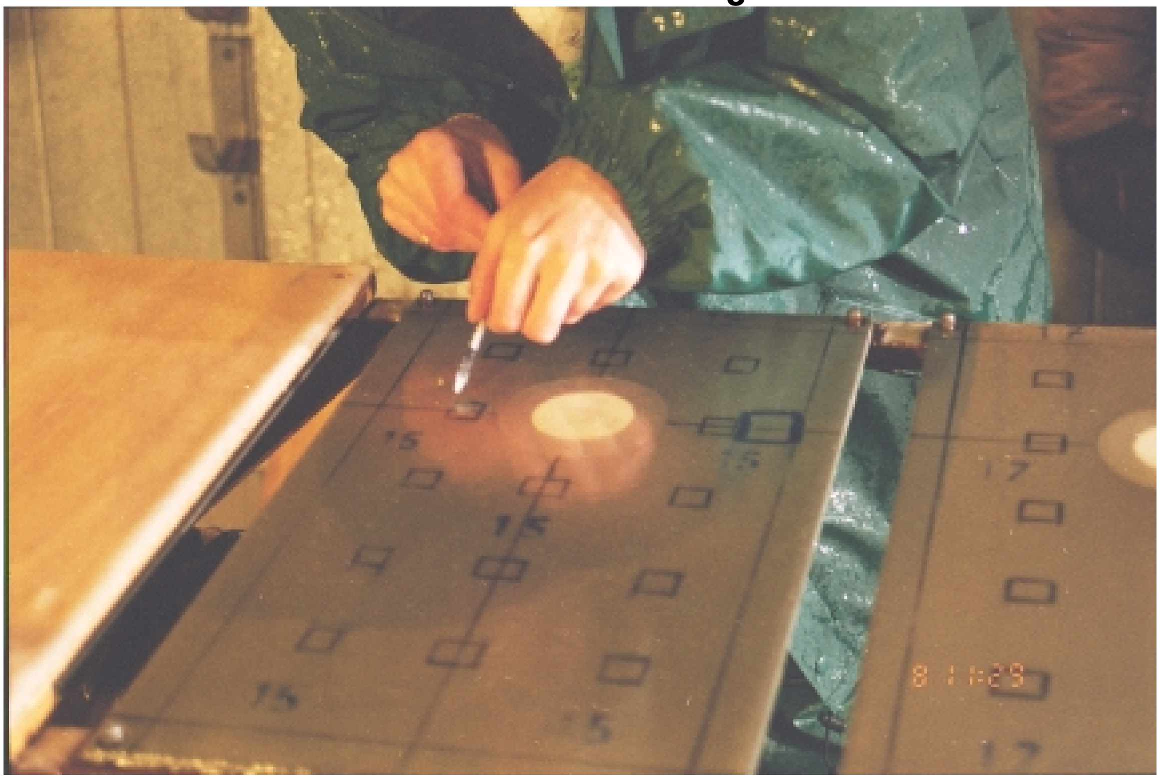

Photo 3.6
Speck Covered Stage

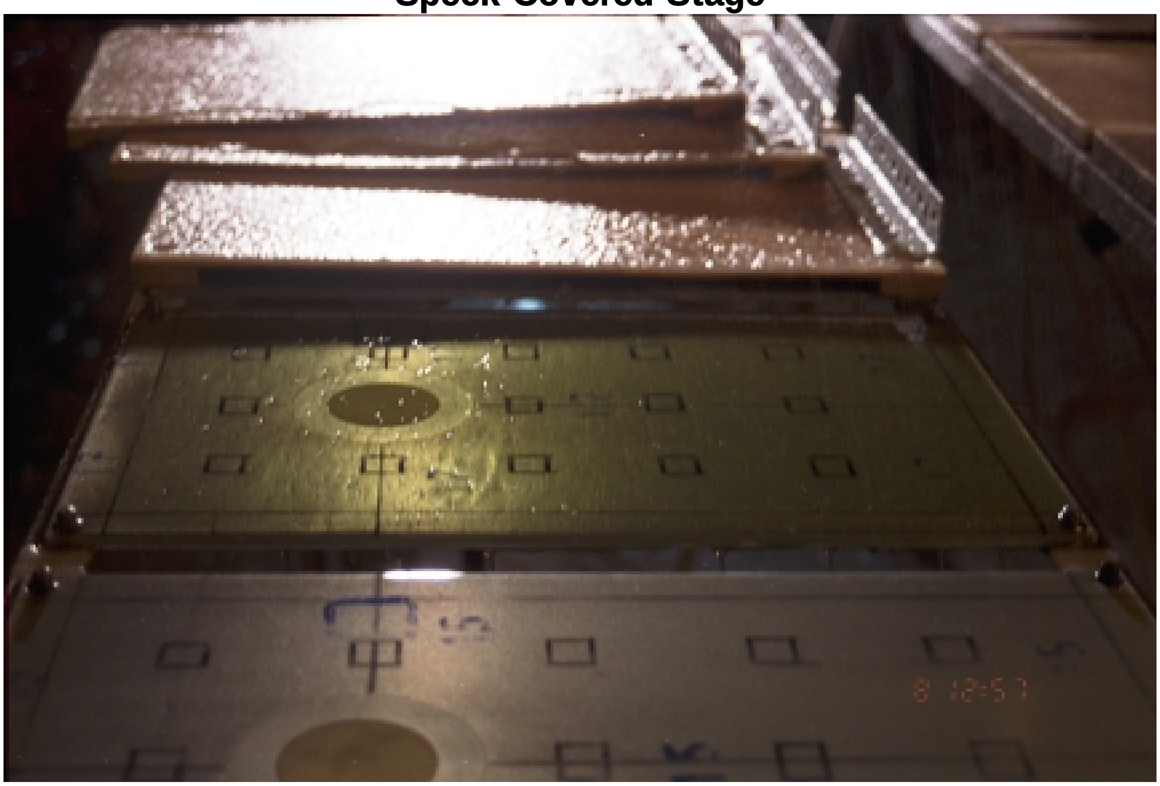

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Photo 3.7
Streaks and Dots

Photo 3.8
Orange-Peel Texture

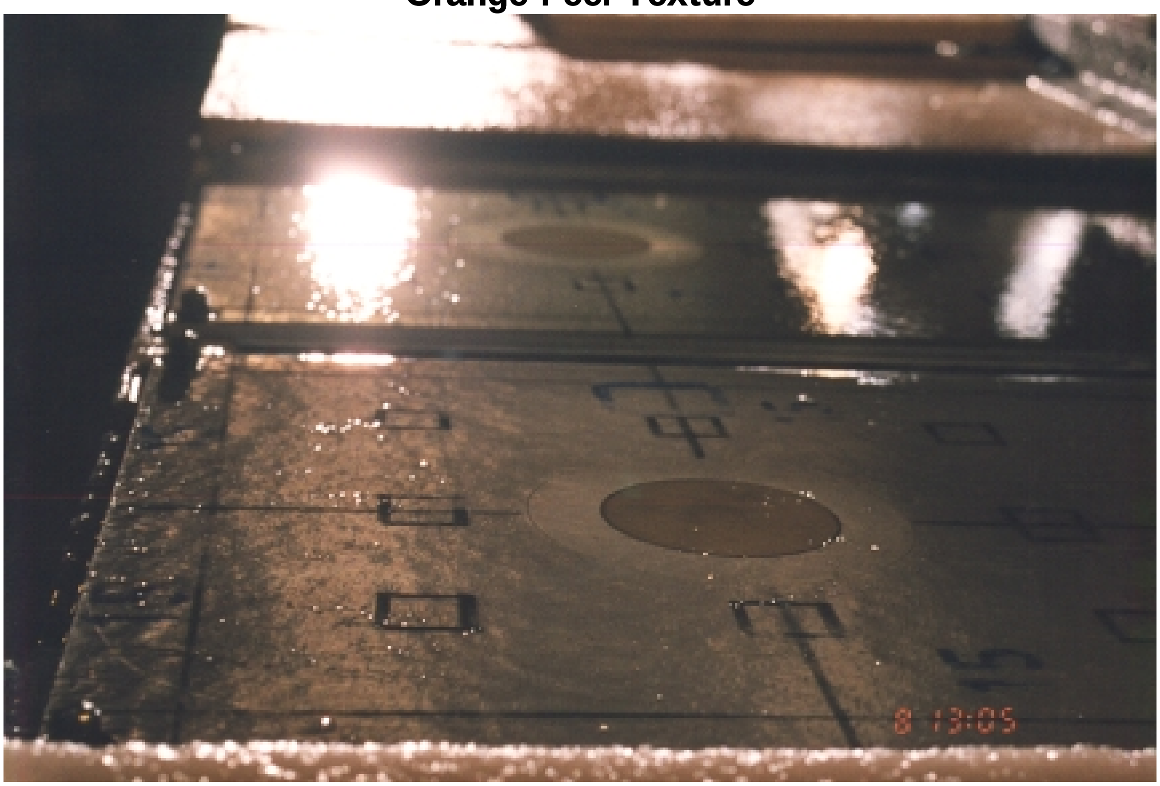

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Photo 3.9
Gelatinous

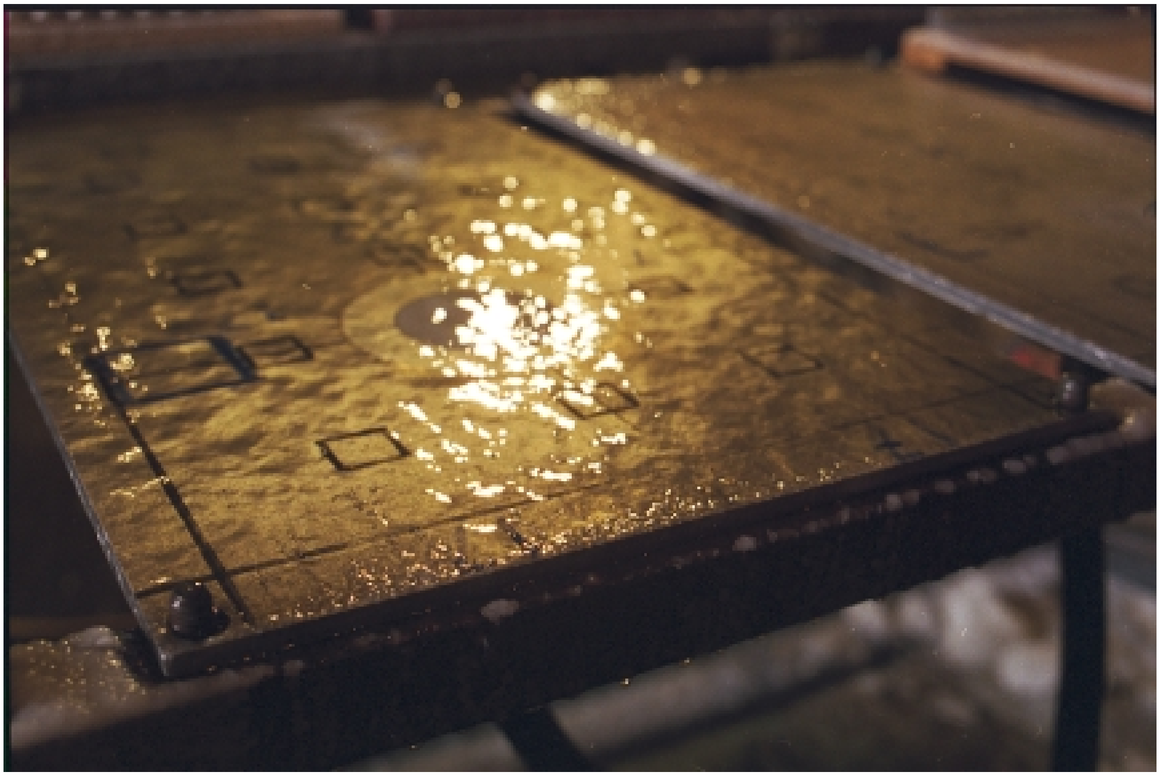

Photo 3.10
Slush

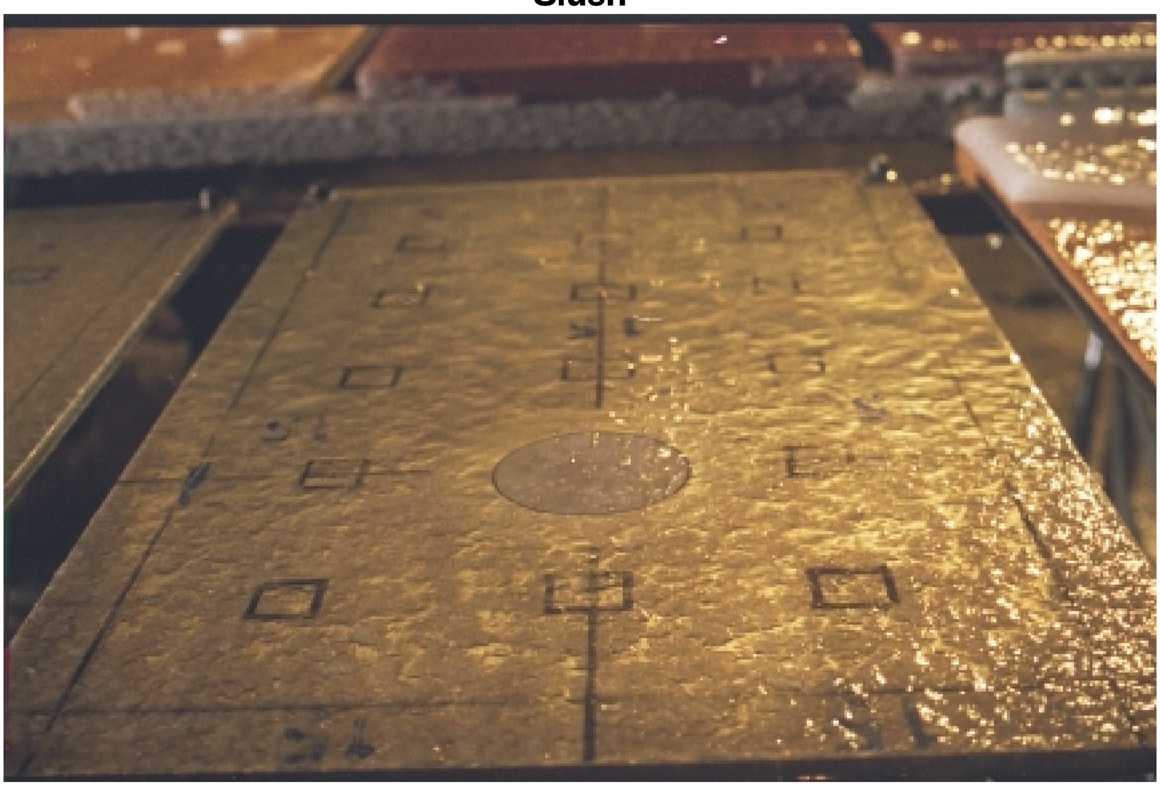

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Photo 3.11
Drainage Channels and Fingers

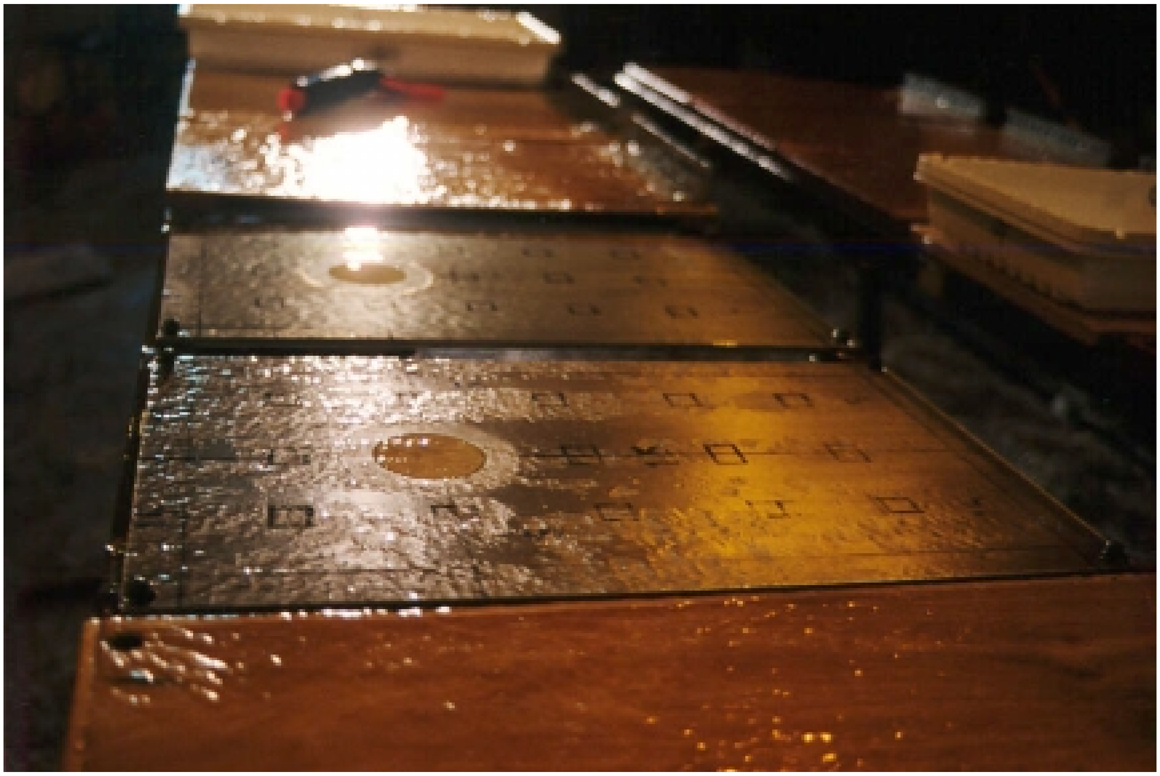

Photo 3.12
Flash Freezing

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4. ANALYSIS AND DISCUSSION

This section presents discussions of the observations made during tests and also presents discussions of the experimental data collected and presented in the CD Attachment, with specific consideration given to the nature of failure of the fluids used in these tests. The discussions are intended to address (where appropriate) each of the main objectives. Results of specific tests used in each discussion are indicated following the subsection title.

4.1 Type I Fluid (XL54 Standard Concentration)

(CD Attachment – Test ID #s 5, 7, 14, 18, 34, 39, 46, 56, 57) (see Table 3.1)

4.1.1 Appearance

The application of this unthickened fluid left a thin transparent orange layer of liquid on the plate. The fluid film thickness quickly stabilized and excess fluid flowed off the test plate. This film almost immediately began to show specks of solid precipitation resting on the fluid surface profile when viewed at a shallow angle. During some of the Type I tests the pour was accompanied by a small quantity of loose foam that quickly ran off the plate with the excess fluid (see Photo 5.1 [CD] and Photo 7.1 [CD]). [Note: photo references that include [CD] are found in the CD Attachment.]

Flash freezing has been observed in previous tests using Type I fluids and also in tests using 50/50 Type IV fluids. However, this mode of failure was not observed in this series of tests.

For the freezing precipitation tests, significant differences in failure appearances were noted when the results of the tests conducted with Type I fluids at higher temperatures (≥ -4°C) were compared to the results of Type I fluid tests conducted at lower temperatures (≤ -10°C).

At lower temperatures, failures tended to occur from the top to the bottom 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.

At higher temperatures, the overall plate failures resembled extended islands of thin, shiny, wet ice that displayed well-developed snow fern patterns. The failures extended from single point failures; however, they did not always originate at the top of the plate.

Fluid failures observed during the tests conducted in natural and artificial snow conditions varied greatly from the failures observed in the freezing precipitation tests. The variations in temperature and rate of precipitation did not have a strong effect on the appearance of the failures observed.

After the fluid was poured, snow particles immediately began accumulating on the fluid surface and quickly penetrated through the thin fluid film. The Type I fluid layer was too thin to absorb the snowflakes before they came into contact with the underlying plate surface. The quantity of snow on the plate increased rapidly and the fluid surface becomes completely covered by the precipitation. However, the precipitation did not adhere to the plate surface during snow tests.

4.1.2 Film Thickness

During the first two minutes after application, the thickness of the applied fluid film diminished rapidly to leave a thin film of about 0.1 mm in depth. The film had reached a stabilized thickness before the time of plate failure.

4.1.3 Fluid Freeze Point

When exposed to the test precipitation conditions of light freezing rain at the rate of 25 g/dm²/h, the fluid experienced rapid dilution with the freeze point rising to 0°C in about six minutes. This corresponds to findings regarding dilution of full strength fluid during the 1997-98 study (1). The fluid freeze point rose rapidly for all test conditions.

4.1.4 Adhesion

Adhesion occurred shortly after failure during the freezing precipitation tests. During the snow tests, no adhesion was detected at any point during the tests.

4.1.5 C/FIMS Ice Detection Sensor

The sensor traces displayed large variations and were difficult to interpret. Generally, the minimum in the curve of the sensor trace, where the slope of the curve changes from negative to positive (indicating fluid failure), occurred prior to the visual identification of plate failure. The C/FIMS trace for the snow precipitation test was not possible to interpret.

4.1.6 RVSI BF Goodrich Ice Detection Sensor

The RVSI BF Goodrich sensor trace showed a clearly defined downturn, indicating failure of fluid within the *no-touch* zone. The time of occurrence of the downturn coincided with the time of the visual identification of standard plate failure.

4.1.7 Spar/Cox Ice Detection Sensor

The single sensor trace provided for Type I fluid was for Test ID #7 (light freezing rain, rate = 25 g/dm²/h, outside air temperature = -10°C). The sensor trace reached the point where the sensor system would indicate fluid failure (average contrast ratio of selected pixels equals 0.003) at about the time of visual identification of standard plate failure.

4.2 Dilute Type IV Fluid (SPCA AD-480 50/50 Mix)

(CD Attachment – Test ID #s 15, 17)

Tests for the fluid in 50/50 concentration were conducted in freezing rain with an ambient air temperature of -4ºC and a precipitation rate of 25 g/dm^2/h.

4.2.1 Appearance

Application of this 50/50 Type IV fluid resulted in a thick layer of transparent fluid (Photo 17.1 [CD]) on the test plate. Some bubbles were observed to be present in the fluid (Photo 17.2 [CD]) as it flowed down the plate.

Early failures appeared to resemble an accumulation of small plate-like ice formations on the upper edge of the plate. The slush then grew into finger-like projections toward the bottom of the plate. The projections widened laterally to eventually fuse and cover the entire plate. Adhesion was noted above the 7.5 cm (3 in.) line when complete plate failure was called.

Failures occurred earlier than for the neat Type IV fluids and followed a failure progression similar to those observed for neat, sheared propylene glycol based Type IV fluid. The time interval to complete plate failure was reduced to the order of that observed for Type I fluids.

4.2.2 Film Thickness

This fluid was tested in freezing rain under precipitation rates of 25 g/dm^2/h, in common with Type I fluid tests. Initial film thickness was considerably greater than for Type I fluid (up to 1.5 mm compared to 0.5 mm), and the rate of thinning was much slower. At the time of standard plate failure, the film thickness at the failure front was about 0.2 mm, in contrast with the Type I fluid thickness of 0.1 mm.

4.2.3 Fluid Freeze Point

The rate of dilution was much slower than that observed with Type I fluids. Concentration values measured on the top and bottom layers of the fluid did not show the large gradients displayed by neat Type IV fluids. From an initial freeze point of -9°C, the fluid freeze point rose to outside air temperature (-4°C) in about 10 minutes and appeared to be somewhat higher than the plate temperature of -3°C at the time of standard plate failure.

4.2.4 Adhesion

The fluid failures did not adhere at the time of standard plate failure. By the time complete plate failure was achieved, some adhesion was observed at a point near the top of the plate that had been in a failed condition for about four minutes. The remainder of the plate was covered with a non-adhering layer of failed fluid.

4.2.5 C/FIMS Ice Detection Sensor

Visual identification of plate failure occurred close to the point at which the C/FIMS curve indicated failure.

4.2.6 RVSI BF Goodrich Ice Detection Sensor

The RVSI BF Goodrich sensor trace showed a clearly defined downturn that indicated fluid failure within the *no-touch* zone. The time of the downturn coincided with the visual failure call.

4.2.7 Spar/Cox Ice Detection Sensor

The sensor trace provided for this fluid was generated for Test ID #15 (light freezing rain, rate = 25 g/dm²/h, outside air temperature = -4°C). The sensor trace reached the point where the sensor system would indicate fluid failure (0.003) following visual identification of initial (first) failure and just prior to visual identification of standard plate failure.

4.3 Base Case Type IV Fluid (Union Carbide Ultra + Neat)

(CD Attachment – Test ID #s 1, 4, 6, 9, 13, 19, 20, 22, 24, 27, 30, 32, 37, 43, 44, 48, 53)

Failure of this fluid was observed under various combinations of conditions; precipitation rates of 25, 13, 10 and 5 g/dm²/h, light freezing rain, freezing drizzle, natural snow and artificial snow, and ambient air temperature -4, -10 and -16°C.

4.3.1 Appearance

This section describes the fluid appearance before failure occurs and the actual failure progression.

4.3.1.1 Appearance Before Failure

Prior to actual failure, the fluid takes on certain appearances as a result of variations in refractive index due to very localized concentration gradients caused by the absorbed precipitation. Depending on the ambient test temperature, and the intensity and type of precipitation, solid contamination may become apparent during this time. In Ultra + fluid, there is a gradual progression in appearance from the time of application to the point at which failures begin to occur. The freshly applied fluid takes on the appearance of a smooth, shiny, transparent green layer containing a sparse, random distribution of small air bubbles embedded in the fluid matrix (Photo 6.1 [CD]). The failures always progressed from the top edge of the plate to the bottom edge under the conditions imposed in these tests.

The earliest stage of this fluid's failure progression appearance can be described as one in which tiny irregularities or specks in the fluid surface, caused by the absorption of precipitation, reduce the clarity of the reflected image. The specks appear to be in the size range of 1 mm or smaller and look similar to dust particles on a liquid surface (Photo 4.1 and Photo 37.1 [CD]).

Depending on the type of precipitation, the failure progression will then take on one of the two following appearances. The first progression is observed for all types of freezing precipitation, such as freezing rain or freezing drizzle. The second progression describes the appearance of a snow failure progression.

1) In freezing precipitation, the following stage in the contamination process occurs when the speck density on the fluid surface increases until the specks are either separated only by distances of the order of the specks themselves, or the specks overlap. At this point, the surface takes on a more coarse orange-peel appearance. The surface roughness ranges between 1 and 3 mm. In Photo 4.2, the surface of the fluid below the initial point of failure provides an illustration of this texture.

   As the fluid surface absorbs more contamination, the orange-peel-like surface coalesces into thicker and thinner regions, giving the substrate surface a marble-like appearance when viewed through the still transparent fluid layer. The size range of the thicker areas of fluid is from 5 mm to 2 cm with no abrupt boundaries. The fluid itself resembles well-sheared gelatine (Photo 4.3).

   At lower precipitation rates, especially in freezing drizzle, this final pre-failure gelatinous stage can persist for a considerable time before failures begin to set in. It can also be overlapped by failure initiation.

2) In snow precipitation, the following stage in the fluid's appearance progression is observed when the snow speck density on the fluid surface increases until the specks are either separated only by distances of the order of the specks themselves or the specks overlap (Photo 37.2 [CD]). Once the snow specks cover the fluid layer, snow will begin accumulating on the top layer of the fluid (Photo 37.3 [CD]). The operational limit of the fluid is not yet reached since the fluid layer is still absorbing the contaminant. The gelatinous fluid progression is not observed in this type of precipitation.

   As the fluid film absorbs the precipitation, the surface becomes dull and the fluid matrix becomes a slushy combination of fluid and partially absorbed snow. Failure occurs once the fluid cannot absorb and dilute the contaminant.

4.3.1.2 Failure Progression

The onset of failure generally overlaps with some pre-failure fluid states. Small areas of failed fluid are present in a pre-failure fluid matrix. The extent or duration of the overlap depends on the rate of failure propagation, which in turn is dependent on the rate and type of precipitation, and the ambient test temperature.

Solid Contamination

Dots and streaks of solidified precipitation were visible in the top surface layer and moved with the fluid as it flowed down the plate. This behaviour occurred more frequently for freezing precipitation tests at lower ambient air temperatures and with lower precipitation rates where fluid mixing from mechanical and diffusional influences was less efficient. This type of failure was observed in all snow contamination trails.

Top Edge Failure

For all precipitation types, the onset of failure invariably took place as a bar of solid contamination across the top edge of the test plate where the fluid was thinned rapidly. The initial failure was in the form of dried slush accumulations. Failure first occurred at one location on the top edge of the plate and spreads across the top edge before progressing down the plate (Photos 4.2 and 4.6).

Once the progression reached the 2.5 cm (1 in.) line, most of the top edge of the plate showed failure as a continuous network of small ice accumulations, which rapidly saturated the surrounding free fluid and caused the failure to propagate down the plate.

Initial (First) Failure to Standard Plate (Fifth Crosshair) Failure

During this time interval, failure progression continued down the plate as the failed areas grew in size. The earliest failed surface area began to accumulate a thicker layer of contamination (Photo 9.3 [CD]).

In freezing precipitation conditions, the wet slush reduced in moisture content and began to fuse into a solid bumpy layer with a wet surface, which at first showed signs of adhesion above the 2.5 cm line. As failures progressed, adhesion to the plate became stronger and more extended over the surface of the plate.

Adhesion was only observed in freezing precipitation tests; no adhesion was detected in any of the natural or artificial snow tests. During the freezing precipitation tests the following behaviour was observed. By the time of standard plate (fifth crosshair) failure, the failure propagation (slush of diluted fluid and ice) began to work its way into the now gelatinous fluid, and drainage channels carved the thicker fluid layer into smaller and smaller regions until only scattered areas of thick fluid persisted. As the test proceeded, fingers of failure progressed down the plate, soaking up the surrounding fluid and fusing together (Photo 4.7).

During the snow tests the slush and fluid mixture progressively became less liquid and the fluid layer was not able to absorb the contaminant. As the failures progressed down the plate, the dry slush region grew from the top of the plate toward the bottom. The contaminant layer thickened as the test continued. Failures were called when cracks in the contaminant layer revealed no free fluid.

During freezing precipitation tests, adhesion of the solid contaminant followed failure. The interval between plate failure and observed adhesion is discussed in Section 4.20.

Standard Plate (Fifth Crosshair) Failure to Complete (Full) Plate Failure

For freezing precipitation tests, the failure progression continued down the plate as previously described. The remaining scattered areas of thicker fluid were diluted and washed away, leaving a thin, dilute, fluid layer that quickly underwent failure except where drainage from the upper portion of the plate surface maintained some clear channels and regions that were not completely failed.

During the snow tests, the failure progression previously mentioned for this type of precipitation continued to propagate down the plate surface. Adhesion was not present at the complete (full) plate failures for snow tests.

In the case of freezing precipitation tests, the degree of adhesion varied and was found to depend on the duration of the last two stages of the failure progression described. Adhesion can be anywhere between the 7.5 cm (3 in.) line and the 22.5 cm (9 in.) line, (and sometimes even beyond the 22.5 cm line). The adhering contaminant layer generally grew in thickness with time once a failure was established on any given surface element.

4.3.2 Film Thickness

The fluid film thickness, measured five minutes following its application, was near 1.4 mm as noted in Table 4.1. Under all test conditions, fluid films had thinned considerably by the time of the standard plate failure call. At that stage of failure, film thicknesses measured at the 15 cm (6 in.) line were in the range of 0.1 to 0.6 mm, with some pattern related to conditions, as can be seen in Table 4.1. During the snow tests the fluid thickness was more difficult to measure due to the snow buildup on the fluid layer.

TABLE 4.1
Fluid Thickness – Ultra +

ID #	OAT (°C)	Precipitation Type	Precipitation Rate (g/dm²/h)	Thickness at 15 cm (6 in.) Line at 5 min. (mm)	Thickness at 15 cm (6 in.) Line at Plate Failure (mm)	Time to Plate Failure (min.)
1,4	-10	ZD	10	1.4	0.6	57
6,9	-10	ZR	25	1.4	0.4	30
20,22	-4	ZD	13	1.4	0.2	57
13,19	-4	ZR	25	1.4	0.1	34
24	-10	ZD	5	1.4	0.5	82
30	-22	NATURAL SNOW	1	1.6	N/A	N/A
32	-17	NATURAL SNOW	15	1.4	N/A	39
37	-14	NATURAL SNOW	27	1.7	N/A	25
43	-12	ARTIFICIAL SNOW	29	1.3	1.0	20
44	-12	ARTIFICIAL SNOW	10	1.4	0.5	53
48	-4	ARTIFICIAL SNOW	10	1.4	0.5	91
53	-4	ARTIFICIAL SNOW	29	1.3	0.5	39

4.3.3 Fluid Freeze Point

The freeze points of the top and bottom fluid layers showed the largest gradients when the fluid is first exposed to ongoing contamination. Freeze point temperature differences as large as 25°C were observed in low rate (5 g/dm^2/h) freezing drizzle tests. The fluid top layer quickly rose to a stabilized freeze point near -20°C, as shown in Table 4.2, for all the freezing precipitation tests. The bottom layer freeze point of the fluid gradually rose to meet the top layer freeze point near the time of standard plate failure. After this time the freeze point temperature of both layers began to increase uniformly. During low rate freezing drizzle, the difference between the top and bottom of layer freeze points was much more significant. This can be explained due to the lower rate of precipitation impacting on the fluid layer as well as the gentler impacts of freezing drizzle droplets on the fluid surface 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 fluid concentration and, in turn, the freeze point did not behave in the same manner during snow contamination tests. The top and bottom fluid freeze points did not diverge as much as observed in the freezing precipitation tests. Since the fluid is not capable of absorbing snow contamination as quickly as liquid contamination, the dilution in concentration during snow precipitation tests is diminished in comparison to the freezing precipitation tests.

4.3.4 Adhesion

Adhesion only occurred during freezing precipitation tests and it did not occur immediately upon fluid failure, but only after some period of ongoing exposure to precipitation. The earliest adhesion was observed to occur in the area where first failure occurred. The early appearance and severity of adhesion seemed to be related primarily to the ambient test temperature, and secondarily to the rate of precipitation. 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. A still lower degree of adhesion was noted at -4°C.

TABLE 4.2

SUMMARY OF PARAMETERS
UCAR ULTRA+ TYPE IV FLUID FREEZING PRECIPITATION TESTS

ID #	Rate (g/dm²/hr)	Precip. Type		OAT		Thickness (mm)		Time to Plate Failure (min.)	Σ Precipitation (g/dm²)	Freeze Point at 15 cm (6 in.) Line at Plate Failure	Plate Brix		Stabilized Freeze Point Top Layer (°C)	Adherence Location	
		ZD	ZR-	-10°C	-4°C	5 Minutes After Pour	15 cm (6 in.) Line at Plate Failure				Brix at Fifth Crosshair	Percent Concent.		At Standard Plate Failure	At Complete Plate Failure
1	10	√		√		1.4	0.6	50	8.3	-8	13	19	-20		B,C
4	10	√		√		1.4	0.5	64	10.7	-7	10.5	16	-20		B,C
6	25		√	√		1.5	0.3	31	12.9	-2	5.5	8	-18	B	B,C,D
9	25		√	√		1.4	0.4	29	12.1	-1	3.5	5	-20	B	B,C,D
13	25		√		√	1.5	0.1	35	14.6	0	0	0	-14		B
19	25		√		√	1.3	0.1	33	13.8	-2	6	9	-15	B	B,C,D
20	13	√			√	1.4	0.2	57	12.4	-6	11	16	-20		B
22	13	√			√	1.5	0.1	57	12.4	-4	9	13	-20	B	B
24	5	√		√		1.4	0.4	82	6.8	-11	16	24	-30		B
27	5	√		√		1.4		N/F		-9	14	21			

4.3.5 C/FIMS Ice Detection Sensor

The C/FIMS sensor trace for freezing precipitation tests generally showed a well-defined pattern that clearly indicated the onset of fluid failure. This pattern frequently occurred during the interval between visual identification of initial failure and standard plate failure. This observation also holds true for the single snow test where the C/FIMS sensor trace was available.

The temperature trace provided by the instrument is worthy of comment. In nearly every test, the temperature trace started to climb at the time of failure. This may be a result of elimination of the insulating layer of fluid that had previously isolated the sensor from the rain spray and from radiant heat from light sources. Heat of fusion may have had some influence on temperature.

4.3.6 RVSI Ice Detection Sensor

At an outside air temperature of -10°C, the RVSI sensor trace showed a marked downward trend, with the slope becoming strongly negative coincident with the onset of failure. The sensor indication during warmer conditions was not as marked, but was still recognizable. In almost all cases, indications of failure from the RVSI sensor were coincident with visual calls of plate failure. The RVSI sensor was not made available for any of the snow tests.

4.3.7 Spar/Cox Ice Detection Sensor

The sensor trace that provides the baseline for Type IV fluid (Union Carbide Ultra IV) failure behaviour was generated for Test ID #20 (freezing drizzle, rate = 13 g/dm^2/h, outside air temperature = -4°C). The sensor trace reached the point where the sensor system would indicate fluid failure (0.003) at a time simultaneous with visual identification of standard plate failure. At that point in the progression of fluid failure, the trace appeared to stray from a steadily ascending line with a brief excursion to a higher level, and then resumed its previous climb.

4.4 Type IV Fluid (Octagon Max-Flight Neat)

(CD Attachment – ID #s 2, 3, 8, 11, 16, 21, 23, 25, 26, 29, 31, 36, 45, 47, 51, 52)

This fluid was examined to enable a comparison of failure characteristics of a propylene glycol-based fluid to those of an ethylene glycol-based fluid (Union Carbide Ultra+). Failure was observed under combinations of conditions similar to tests on Ultra+.

Test conditions included precipitation rates of 25, 13, 10 and 5 g/dm²/h, light freezing rain, freezing drizzle, natural snow and artificial snow, and outside air temperatures of -4, -10, and -16°C.

It should be noted that the samples of this fluid used during the 1997-98 test season had been inadvertently sheared prior to testing. As noted later in the discussion of other Type IV propylene glycol-based fluids (Sections 4.5 and 4.6), it was initially expected that this fluid would demonstrate a tendency to resist mixing, resulting in a mode of failure quite different from that seen with Ultra+. The fact that this did not occur is attributed to its pre-sheared treatment and, consequently, this documentation on Octagon Max-Flight in freezing precipitation conditions should be viewed only as representative of a highly sheared fluid.

The fluid samples used for snow tests during the 1998-99 test season were within the manufacturer's specified viscosity range and can be considered representative of the Octagon Max-Flight fluid shipped for operational use.

4.4.1 Appearance

This section describes the fluid appearance before failure and throughout the progression of failure. Under the test conditions employed, the neat Octagon fluid used for these tests generally failed as described in the following subsections.

4.4.1.1 Appearance Before Failure

Before actual failures were detected, neat Octagon fluid took on an appearance similar to, but not identical to Ultra+ fluid. The pour resulted in a very smooth, shiny fluid layer on the surface free of any small bubbles like those observed in the Ultra+ fluid. The fluid was a paler shade of green in comparison with the Ultra+ fluid and was also slightly turbid but still transparent (Photo 8.1 [CD], 11.1 [CD]).

During the freezing precipitation tests, this fluid did not go through the speck-covered stage, but did enter a short-lived stage leading up to the appearance of failure in which the surface texture was not unlike that of an orange-peel. This orange-peel pre-failure fluid stage was superseded by a gelatinous stage. (Photo 8.2 [CD], 11.2 [CD]). The sizes of the structures formed in this final pre-failure stage of Octagon fluid were on average 3 mm to 1.5 cm across, with no abrupt boundaries between the structures.

The fluid behaved similarly for the snow tests. Contaminant particles were initially melted as they came into contact with the fluid layer. Variations in the refractive index of the fluid film were observed and the contaminant particles were absorbed less rapidly as the fluid began to dilute. At a time near the onset of initial failure, slush began to form with the layer of fluid, although the fluid was absorbing snow at a slower rate than the precipitation rate.

In tests conducted with both the pre-sheared fluid and the regular fluid, the general mode of failure progression was from plate top to plate bottom.

4.4.1.2 Failure Progression

Dots, streaks and flakes of solidified precipitation on the fluid surface prior to fluid failure detection (Photo 8.3 [CD], 11.3 [CD] and 51.2 [CD]) were numerous and easily visible during freezing precipitation tests.

The following describes the progression of the fluid failures of the sheared fluid tested in freezing precipitation.

- Top Edge Failure, generally preceded by the initial appearance of small plate-like ice formations. The interval before which accumulation of solid contaminant became apparent seemed to be shorter than for the Ultra+ fluid;

- The progression of failure into the work area of the test plate preceded first by the formation of a slush composed of the fine plate-like ice particles that grew down the plate (Photo 11.2 [CD], 4.9). As the slush soaked up the available fluid, it became saturated, giving rise to drainage channels in which only a thin fluid layer remained. These thinned-out fluid channels formed fingers of failure within minutes. The fingers (Photo 11.3 [CD]) similar to those shown in Photo 4.7, proceeded down the plate between drainage channels extending from the top portion of the plate. This was accompanied by fusion of the early failed regions and finally by adhesion of the earliest failed surface elements; and

- The gelatinous pre-failure stage of the fluid did not break up into scattered lumps to be gradually washed away. The fluid tended to maintain a thinning slurry that gradually underwent fusion as the test proceeded to the complete (full) plate failure interval. Run-off from the top portion of the plate maintained some open drainage channels to the bottom edge of the plate.

The failure progression for the snow test was similar to the progression described for the Ultra+ fluid; however, the Octagon fluid did not absorb precipitation as quickly. The fluid matrix slowly absorbed the snow until the diluted fluid was unable to melt the contaminant. The slush within the fluid matrix became denser as the test continued and snow bridging took place on top of the fluid slush. The failures progressed from the top of the plate toward the bottom of the plate, leaving a dry layer of contaminant on top of the slush below.

4.4.2 Film Thickness

Film thickness measured at five minutes following fluid application (Table 4.3) was considerably thinner than the Ultra+ fluid (≈0.8 mm versus ≈1.4 mm) for the pre-sheared fluid. The film thickness of the 1998-99 test was significantly higher. At this stage, the fluid showed a much greater variability in thickness than did the Ultra+. This fluid demonstrated an increase in thickness as it absorbed fluid during the initial interval after application, then thinned out prior to standard plate failure.

In common with Ultra+ fluid, film thickness at time of standard plate failure appears greater under lower precipitation rates (at constant temperature) and also at colder temperatures (at constant precipitation rates).

4.4.3 Fluid Freeze Point

While fluid concentration values measured on the top and bottom layers of this fluid showed a gradient, the pattern was somewhat different than that of Ultra+, as shown in Figure 4.1. The top layer freeze point of the Octagon fluid quickly took on a value several degrees (three to eight degrees) above that of the bottom layer, as shown in Table 4.4, and then rose in concert with the bottom layer while the two values gradually converged.

TABLE 4.3
Fluid Thickness – Octagon Max-Flight

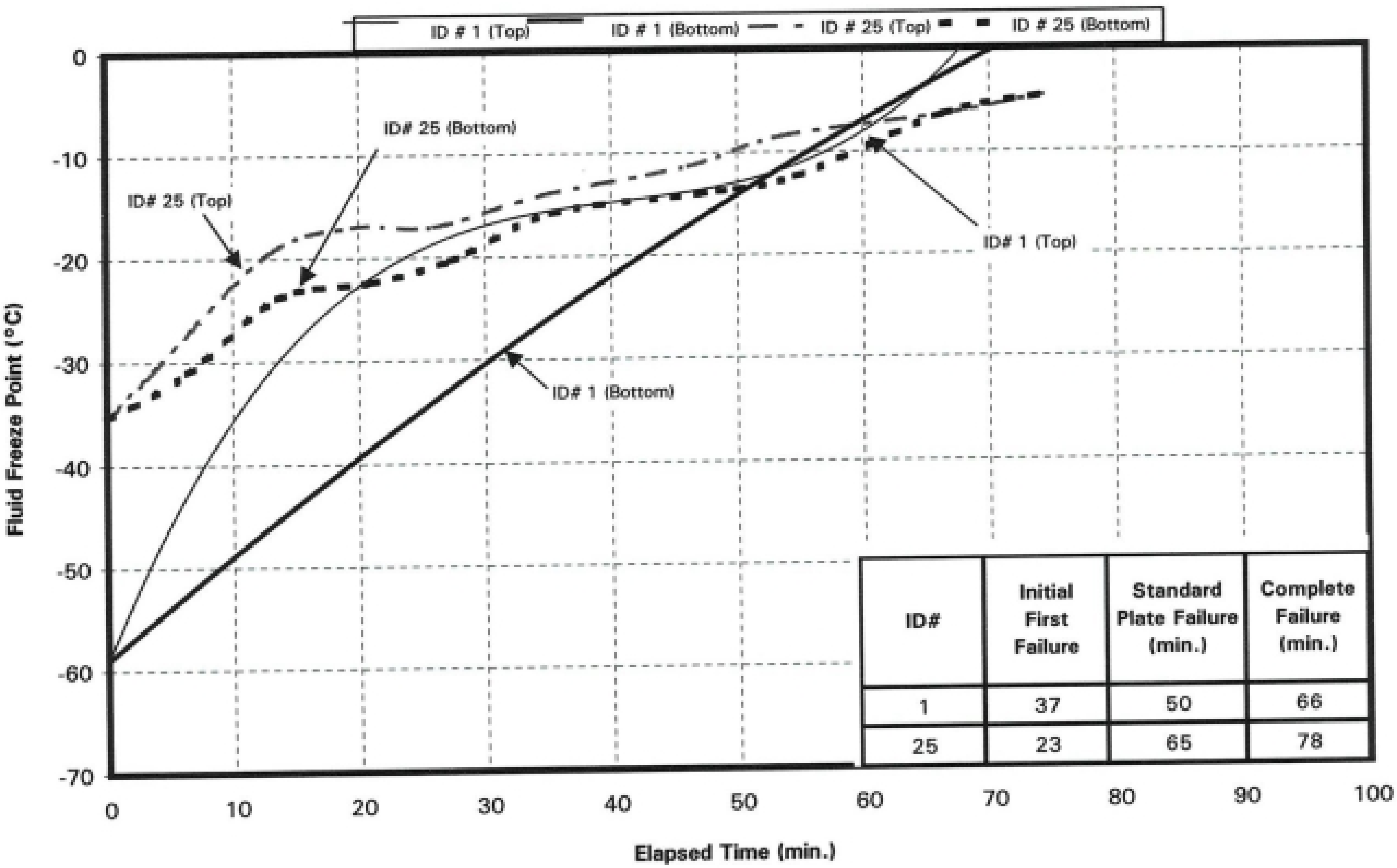
ID #	OAT (°C)	Precipitation Type	Precipitation Rate g/dm²/h	Thickness at 15 cm (6 in.) Line at Five min. (mm)	Thickness at 15 cm (6 in.) Line at Maximum (mm)	Thickness at 15 cm (6 in.) Line at Standard Plate Failure (mm)	Time to Standard Plate Failure (min.)
2,3	-10	ZD / 10	10	0.8	1.2	0.6	36
8,11	-10	ZR / 25	25	0.7	0.8	0.3	21
21,23	-4	ZD / 13	13	0.6	0.8	0.2	31
16	-4	ZR / 25	25	0.5	0.7	0.3	22
25,26	-10	ZD / 5	5	0.8	0.8	0.6	63
29	-22	NATURAL SNOW	1	1.5	1.5	N/A	N/F
31	-17	NATURAL SNOW	16	1.5	1.5	1.2	22
36	-15	NATURAL SNOW	17	1.7	1.8	N/A	42
45	-12	ARTIFICIAL SNOW	23	0.8	0.8	0.7	17
47	-12	ARTIFICIAL SNOW	8	0.8	1.1	N/A	N/F
51	-4	ARTIFICIAL SNOW	10	1.2	1.5	N/A	80
52	-4	ARTIFICIAL SNOW	27	1.2	2.2	2.0	27

N/A = Not Available
N/F = Not Failed

FIGURE 4.1

COMPARISON OF FLUID FREEZE POINTS

ID # 1 (Ultra+) and ID # 25 (Octagon Max-Flight)



ID#	Initial First Failure	Standard Plate Failure (min.)	Complete Failure (min.)
1	37	50	66
25	23	65	78

CM1514/Report/Doc_Fail/BRX_ID01&25

TABLE 4.4

OCTAGON MAX-FLIGHT TYPE IV FLUID FREEZING PRECIPITATION TESTS

ID #	Rate (g/dm²/hr)	Precipitation Type		OAT		Thickness (mm)			Time to Plate Failure (min)	Σ Precipitation (g/dm²)	Freeze Point at 15 cm (6 in.) Line at Plate Failure	Plate Brix		Stabilized Freeze Point Top Layer (°C)	Adherence Location	
		ZD	ZR-	-10°C	-4°C	5 Minutes After Pour	Maximum	15 cm (6 in.) Line at Plate Failure				Fifth Brix	Percent Concentration		At Standard Fail	At Complete Plate
2	10	√		√		0.7	1.1	0.6	33	5.5	-11.9	21	68%	Did Not Stabilize		B
3	10	√		√		0.8	1.2	0.7	39	6.5		N/A				B,C
8	25		√	√		0.7	0.8	0.3	22	9.2	-2.6	9	29%			B,C,D
11	25		√	√		0.6	0.8	0.4	20	8.2	-1.9	7.5	24%		B	B,C
16	25		√		√	0.5	0.7	0.3	22	9.3	-0.5	3.0	10%			B,C
21	13	√			√	0.6	0.8	0.1	38	8.2	-2.6	9.0	29%		B	B,C
23	13	√			√	0.6	0.7	0.2	24	5.1	-3.1	10.0	32%		B	B,C,D
25	5	√		√		0.7	0.7	0.6	65	5.4	-6.4	15.0	48%			1"
26	5	√		√		0.8	0.8	0.5	61	5.1	-5.3	13.5	44%			1"

The Ultra+ top and bottom layer values tended to converge prior to time of standard plate failure. For the Octagon fluid, the values were still time of failure at ambient temperatures below -10ºC and the freeze points converge near the time of initial failure for tests at -3ºC.

For drizzle and snow conditions, the average freeze point values of top and bottom layers matched outside air temperature at the time of plate failure. However, for rain conditions, the average freeze point value was considerably higher than the outside air temperature at the time of standard plate failure.

4.4.4 Adhesion

Adhesion for the low viscosity Octagon Max-Flight fluid was observed during conditions of liquid contamination. Adhesion on a given test surface element occurred some time following the actual occurrence of failure. As initial failure occurred at the top of the plate, adhesion was first observed in this area. Among the various cases tested, severity of adhesion did not follow any particular pattern related to temperature or to precipitation. No adhesion was detected during the snow tests conducted with the higher viscosity fluid.

4.4.5 C/FIMS Ice Detection Sensor

With this fluid, the C/FIMS sensor traces showed the strongest patterns with the widest swings during freezing rain conditions. The traces ***did*** indicate failures that were concurrent with visual failure calls. During freezing drizzle conditions, the sensor trace gave a weak indication of failure at an outside air temperature of -10°C, but a slightly better indication at warmer temperatures (-4ºC). During the snow test, the sensor trace gave no indication of failure.

4.4.6 RVSI BF Goodrich Ice Detection Sensor

For freezing rain conditions, the sensor traces gave strong fluid failure signals that were registered just prior to the visual call of standard plate failure. In these cases, the trace proceeded on a fairly flat, horizontal line, but abruptly changed to a steeply descending slope at the point of failure detection.

For freezing drizzle conditions, the sensor traces tended to proceed on a gradually descending curve without any apparent indications of plate failure (for example, a marked variation in slope at a given time).

The RVSI BF Goodrich sensor system was not available for any of the natural or artificial snow tests.

4.4.7 Spar/Cox Ice Detection Sensor

The sensor trace provided for this fluid was generated in Test ID #2 (freezing drizzle, rate = 10 g/dm²/h, outside air temperature = -10°C). The sensor trace reached the point where the system indicated failure had occurred (average contrast ratio = 0.005) at a time coincident with visual plate failure identification. The sensor trace showed a steady rate of increase throughout.

4.5 Type IV Fluid (Kilfrost ABC-S Neat, SPCA AD-480 Neat)

(CD Attachment – Test ID #s 10, 12, 28, 41, 42, 49, 50, 54, 55)

4.5.1 Appearance

These fluids are treated in the same subsection since they demonstrated a similar type of failure progression under the conditions tested. Both fluids are propylene glycol-based (in common with the Octagon Max-Flight fluid). No snow precipitation tests were performed with these fluids.

The neat SPCA AD-480 fluid was a more vivid green (Photo 28.1 [CD]) than the Ultra+ fluid, and completely transparent. This fluid was tested in freezing drizzle at -10ºC ambient air temperature with a precipitation rate of 5 g/dm^2/hr.

The fluid formed a smooth shiny surface with tiny embedded air bubbles. Once applied to the test surface, the fluid immediately began to accumulate small dots of frozen contamination on the fluid-air interface. These appeared denser and more numerous from angles less than normal to the surface. Viewing from an angle near to the surface clearly showed these to be the same type of solid dots as previously described for Ultra+ and Octagon fluids, except that these were less readily accepted by the upper layer of the anti-icing fluid film and froze in isolation as a consequence.

The neat Kilfrost fluid formed a thick, light green, transparent layer upon application, and also showed immediate signs of supporting solid dots of frozen contamination.

The tendency to resist mixing shared by the neat Kilfrost and SPCA AD-480 fluids was also expected from the Octagon fluid. It is suspected that the pre-shearing treatment of the Octagon fluid was responsible for its unexpected mode of failure during freezing precipitation tests.

Two distinct patterns of failure were observed for the Kilfrost ABC-S fluid. The first pattern of failure was observed for both Kilfrost and SPCA fluids. The fluids exhibited this failure pattern in freezing precipitation at air temperatures of -10°C. Solid dots of precipitation ran down the plate on the fluid surface and accumulated at the bottom of the plate, where they eventually dammed up and caused a bottom-to-top overall failure progression. The second pattern was a standard top-to-bottom dilution failure. This type of failure was observed during Kilfrost tests at ambient temperatures above -10°C. This failure progression is similar in appearance to Ultra+.

The point of standard plate failure for this fluid was based on observer judgement that the aggregate area of all dots of frozen precipitation would be equivalent to 1/3 of the plate surface area.

4.5.2 Film Thickness

Progressive thickness measurements were made for the SPCA AD-480 and some Kilfrost tests. Unlike the Octagon fluid, these fluids did not demonstrate a large increase in thickness during the first period of exposure to precipitation, but progressively thinned from their first measured thickness (1.7 mm for SPCA AD-480 and 2.2 mm for Kilfrost at five minutes following application) and reached a stable thickness at about 20 minutes following application. This thickness persisted until time of initial failure.

Photo 28.4 [CD], taken at the end of the SPCA AD-480 test, shows a bare area as a result of lifting a fluid sample. This image gives a good illustration of the thickness of fluid remaining at that time.

4.5.3 Fluid Freeze Point

Upon exposure to precipitation, the fluid freeze points of the top and bottom layers quickly diverged from their initial values of approximately -34°C. For the freezing drizzle tests, after application, the top fluid freeze point rapidly climbed to produce a large variation between the freeze points of the two layers. A notable spread was observed between top and bottom layer freeze points until standard plate failure was called, with value differences of -5 to -15°C between the top and bottom layers.

The thickness of the fluid at the test end indicates that there was still a reasonable quantity of acceptable fluid (capable of offering further anti-icing protection) available at that time.

The samples collected for this fluid at the time that complete plate failure was called were the only samples to demonstrate a measurable level of viscosity.

4.5.4 Adhesion

There was no evidence of adhesion during the course of tests for these two fluids at temperatures of -10ºC. At -3ºC, Kilfrost ABC-S adhered to the plate surface.

4.5.5 C/FIMS Ice Detection Sensor

The sensor traces for SPCA AD-480 provided no indication of fluid failure. The trace was very flat, showing a slight increase from the horizontal with time.

The traces recorded for the Kilfrost ABC-S during the 1998-99 test season showed a noticeable indication of failure at ambient temperatures of -3ºC very near the time where the visual failure calls were made. Traces recorded at -10ºC showed very little indication of failure.

4.5.6 RVSI Ice Detection Sensor

The RVSI sensor trace progressed at a steady rate of descent during the course of the test, and did not give a clear indication of the point of fluid failure. Subsequently, RVSI plate condition images were retrieved for the test and are shown in Photos 4.10 and 4.11. These images show formation of ice within the fluid, and would normally be interpreted as an indication of standard plate failure. The assessment of *10 percent failure* was based on judgement of experienced RVSI staff.

4.5.7 Spar/Cox Ice Detection Sensor

The sensor trace provided was for a propylene glycol-based fluid (Kilfrost ABC-S) and was generated for Test ID #12 (light freezing rain, rate = 25 g/dm²/h, outside air temperature = -10°C). The sensor trace reached the point where the system indicated fluid failure (average contrast ratio =0.003) at about five minutes prior to visual identification of standard plate failure (74 minutes versus 79 minutes). The sensor trace for this fluid did not show the same steady rate of climb seen with some other fluids, but showed significant excursions throughout, until the final reading at 76 minutes into the test.

4.6 Type IV Fluid (Clariant Safewing Four Neat)

(CD Attachment – Test ID #s 35 and 40)

4.6.1 Appearance

This fluid is described separately since it does not respond similarly to the previously mentioned fluids and also because the test conditions were very different. This propylene glycol-based fluid was tested in natural snow conditions with an ambient temperature of -15ºC.

The thick green, transparent fluid formed a smooth shiny surface with fine air bubbles once applied to the test surface. The fluid slowly began to accumulate small dots of frozen contamination on the fluid surface and within the fluid matrix. Specks of contamination continued to be absorbed during the test, but the speck density increased as time increased. The top of the plate surface exhibited the first signs of failure. The specks began to overlap and the slushy fluid separated to expose the dried plate surface below.

After the initial failure was detected, the surface finish dulled as a thicker layer of slush formed on top of the fluid layer. The slush was not fully saturated, and the fluid layer continued to absorb the contaminant.

The failures progressed, non-uniformly, from the top to the bottom of the test surface. Short fingers of failure developed down the plate as the fluid film below the slush began to dry. Spatial dendrites and snow flakes collected on the test surface as complete plate failure was called.

4.6.2 Film Thickness

Due to the nature of the natural snow tests, the film thickness was very difficult to measure for the Clariant Safewing Four fluid. The slush created by the mixing of the fluid and the precipitation hindered the measuring of the underlying fluid layer. Initial thickness measurements were available for the beginning of the tests. For both the tests, the stabilized thickness of the fluid film remained between 1.6 and 1.7 mm. Throughout the duration of the test, the top layer of fluid was covered with slush, while relatively clean fluid remained below.

4.6.3 Fluid Freeze Point

Upon exposure to precipitation, the fluid freeze points of the top and bottom layers rapidly rose from their initial values of approximately -34°C. After application, the top fluid freeze point and the bottom fluid freeze point diverged slightly to produce a 3 to 5°C variation between the freeze points of the two layers. The spread between top and bottom layer freeze points remained until the failure was called, with freeze points of -13°C and -18°C for the top and bottom layers, respectively.

4.6.4 Adhesion

There was no evidence of adhesion during the course of the tests for this fluid.

4.6.5 C/FIMS Ice Detection Sensor

The sensor trace (ID # 35) for this fluid gave no indication of fluid failure. The traces were very flat, showing a very slight increase with time.

4.6.6 RVSI BF Goodrich Ice Detection Sensor

The RVSI BF Goodrich sensor was not available for the test involving this fluid.

4.6.7 Spar/Cox Ice Detection Sensor

The Spar/Cox ice detection sensor was not available for the test involving this fluid.

4.7 Type IV Reference Fluid (Fluid X)

(CD Attachment – Test ID #s 33 and 38)

Fluid X is an experimental fluid formulation prepared according to specifications indicated by Union Carbide. The formulation consists of ethylene glycol and water, with Xantham gum as a rheological additive. Two Fluid X batches were prepared and the resulting Brix and viscosity profiles were measured to be within experimental error limits. These fluids were tested in natural snow conditions with an ambient temperature near -15ºC.

4.7.1 Fluid Appearance

The appearance of the bulk fluid can be described as a very runny gel. High-speed mixing does not improve the homogeneity of the fluid rheology and causes air to be incorporated into the fluid. Air release is exceedingly slow and the various-sized bubbles impart a grey tinge to the fluid.

The resulting fluid samples were poured onto test plates according to standard holdover time procedures. The fluid pours in a manner that indicates cohesive forces to be much stronger than adhesive forces (fluid affinity for itself is greater than for the plate). The fluid tends to slip off the side of the plate in clumps while the plate surface is hardly wetted. This occurs during application when the fluid flow onto the plate is interrupted or not poured at a sufficiently high rate. This behaviour is more pronounced at colder temperatures.

Once successfully poured, the fluid was subject to holdover time testing in a reasonably heavy snowfall. The fluid was observed to pull away from the plate edges and contracted toward the middle of the plate. Runoff at the bottom edge of the plate was maintained during ongoing precipitation. The top and side edges of the plate became bare as the fluid tended to coagulate toward the plate centre and away from these three edges.

4.7.2 Holdover Time Performance and Failure Appearance

Failures on the bared surfaces (essentially outside the work area of the plate) were observed first. The majority of the work surface of the plate remained fluid-covered and exhibited holdover time performance superior to that of commercially available Type IV fluids. This is likely due to the coagulating action of the fluid, which resulted in a thicker fluid layer over the surface that remained fluid-covered. The failure progresses more slowly than for Type IV fluids, but finally achieves an appearance similar to that of Type IV fluid failures. Some streak-like failure propagation was also observed prior to complete plate failure. Failures were easily observed for this fluid. No adhesion was observed with Fluid X in the snow tests.

4.7.3 Comments

The Fluid X holdover time is abnormally high; however, this is not the objective of the formulation. The desired potential reference fluid formulation is a standard worst-case fluid that is easy to prepare, gives holdover time performance near the lower limit of currently available Type IV fluids, and behaves in a rheologically similar fashion to Type IV fluids.

4.8 Rheology, Mixing Processes, and Mechanisms of Fluid Failure for the Fluids Tested

This section discusses some of the processes and mechanisms that operate in the degradation of the fluids as caused by freezing rain and freezing drizzle.

The rheology, or flow characteristics, of a fluid can be adjusted by the addition of suitable modifying agents. In the case of anti-icing fluids, the fluid rheology influences the way a fluid behaves when subject to different forms of precipitation. For example, fluid rheology influences its ability to accept contamination and has important consequences on the rate and degree of mixing of fluid and contaminant. The rheological differences among the different fluid brands are manifested by the different patterns of failure initiation and propagation observed among the fluids tested.

The Ultra+ fluid was the only ethylene glycol-based fluid among the Type IV fluids tested. It appears that this Type IV fluid will return to its previous viscosity after turbulent shearing. The other propylene glycol-based fluids exhibited permanent shear-induced reductions to their viscosity. This suggests that the thixotropy of the propylene glycol-based fluids relies on a different mechanism than the Ultra+ fluid. The Octagon, Kilfrost, Clariant and SPCA fluids are all propylene glycol-based.

4.8.1 Influence of Droplet Impact on the Mechanical Component of Mixing

Contaminant absorption rate (mixing) is enhanced by mechanical considerations such as droplet impact on fluid surface, which varies proportionally with droplet size and mass. Another important mechanical parameter is the rate of precipitation. The mechanical component of mixing is likely an important factor in fluid failure rate differences between freezing drizzle and light freezing rain holdover times determined at the same temperatures and precipitation rates for a given fluid.

There may also be differences in contaminant absorption rate as a function of temperature due to surface tension effects on the fluid surface and on the droplets themselves.

The possibility of partial droplet solidification before impact on the fluid surface also exists and presents another parameter that should be considered as a possible contributor to mechanical mixing.

It is also possible that droplet size has an influence on the fraction of precipitation, impinging on a fluid-covered surface that actually remains in the fluid layer after droplet impact. This aspect of fluid and contaminant behaviour is considered in Subsection 4.8.3.

The diffusional component of mixing is operative in the dilution of fluid by liquid or melted contamination. While this process always occurs to a greater or lesser extent depending on the physical state of the contaminant, it can be considered to be a secondary effect.

4.8.2 Comments on the Rheology and Failure Mode Generally Exhibited by the Propylene Glycol-Based Anti-Icing Fluids

The propylene glycol-based anti-icing fluids generally exhibit a reduced tendency to mix with contamination.

From previous test experience, it had been expected that, due to the reduced mixing tendency, failures exhibited by these fluids would occur in a manner that results in a layer of relatively undiluted fluid between the plate and the failed fluid surface.

The point at which this uppermost surface layer fuses and becomes too solidified to be sheared completely off the wings upon rotation of the aircraft was investigated during tests documented in Transport Canada report TP 13479E (5).

The fact that mechanical shearing can permanently reduce the viscosity of some propylene glycol-based fluids suggests that a thixotrope composed of long delicate polymer strands is present in this fluid. Mechanical shearing of the fluid from turbulent flow is probably sufficient to break the length of these polymer chains and permanently alter the fluid's rheological properties.

4.8.3 Surface Tension Effects

The surface tension effects on a fluid surface and on the falling droplets themselves influence the ability of the fluid to accept contamination into its surface layer. The significantly lower surface tension of the fluid, in comparison to the surface tension of water, enhances the acceptance of contamination into the surface layer of the fluid.

On the other hand, the surface tension on a droplet of liquid is inversely proportional to the radius of the droplet. Therefore, the surface tension of a droplet of liquid approaches infinity as the droplet radius approaches zero. It is expected that smaller droplets should display a reduced tendency to be absorbed by the fluid surface and an enhanced tendency to bead or bounce and roll off the test surface. Along this line of thinking, larger droplets are expected to penetrate the fluid surface, and subsequently mix more efficiently with the surrounding fluid.

As a droplet of rain penetrates the fluid surface, a percentage of it is instantly solidified. As a result, the dilution effect of the each individual droplet is reduced. The solidified rain drops remain suspended in the fluid and are not active in reducing the overall fluid concentration.

4.8.4 Mixing Tendency/Dilution

Highly viscous fluids tend to remain in a thicker layer on a surface and exhibit a reduced tendency to flow-off. Some propylene glycol-based fluids tend to resist mixing to a greater extent than ethylene glycol-based fluids, and are thus diluted at a much slower rate. This resistance to mixing may be due to surface tension effects or possibly to the presence of an additive that has a coagulating effect. A coagulant might tend to attract fluid around the contaminant without allowing complete mixing. The mixing seems to be most efficient in the Ultra+ fluid and least efficient for the propylene glycol-based Type IV fluids.

4.8.5 Flow-Off

The rheology of the fluid is responsible for maintaining a thick fluid layer on test surfaces. One rheological property is the viscosity of the fluid. The higher the viscosity, the greater the resistance to flow. Flow is influenced by dilution, which reduces the fluid viscosity especially on the top of the fluid layer and to various depths depending on the mixing tendency of the fluid. The more easily the fluid is diluted, the more easily the fluid will flow off the plate, with subsequent reduction in effective fluid thickness. This is often referred to as erosion of the fluid. A fluid that resists mixing will accumulate a solid surface above the good fluid layer, leading to an encapsulating type of adhesion due to fusion of fluid surface contamination in a layer parallel to the substrate surface.

4.8.6 Bounce and Roll-Off

It was observed that in flat plate experiments, a considerable portion of contamination consisting of water droplets actually bounced upon impact and rolled off the plate. This was noted for all fluids and has important consequences as to the difference between a larger surface, like an aircraft wing, and a relatively small surface element such as a standard test plate.

If much of the contamination is able to escape the surface in a bounce and roll-off fashion, this means that not all the impinging precipitation at a given precipitation rate ends up being absorbed into the fluid surface. While this is true for the first bounce on an extended surface, the roll-off counterpart of this phenomenon is only significant close to the edge of an extended surface (like an aircraft wing). There is a significant difference between the flat plate and the aircraft wing for the categories of precipitation including freezing rain, freezing drizzle, and ice pellet conditions.

It would be worthwhile to investigate what fraction of the precipitation impacting on a given surface element actually remains on, or is accepted by, the fluid layer at known rates of precipitation. This might be accomplished using a hooded trap at the bottom of the plate positioned to allow for flow-off and to also allow the fluid to continue to fall to the floor, but the bouncing droplets could be caught in the trap and weighed. It might also be interesting to monitor the refractive index of the recovered droplet mix to determine how much, if any, fluid is picked up by the bouncing droplets escaping the plate.

4.9 Comparison of Type I and Type IV Failures in Light Freezing Rain (25 g/dm²/h)

Type I Union Carbide XL54
Test ID Numbers 5, 7 and 14, 18

Appearance
- Unthickened fluid;
- Left a very thin, transparent orange layer when applied;
- Almost immediate accumulation of solid contaminant;
- Failure propagated from top of plate and from points of failure; and
- Rapid failures with complete adhesion.

Film Thickness
- Rapid reduction to 0.1 mm thickness or less.

Fluid Freeze Point
- Dilution to 0ºC in six minutes; and
- Uniform freeze point in fluid layer due to thin unthickened film.

Adhesion
- Rapid and complete adhesion following freezing.

C/FIMS Sensor Trace
- Weak indication of failure, slightly ahead of visual call.

RVSI Sensor Trace
- Clearly definable downturn indicated standard plate failure, concurrent with visual call of plate failure.

Type IV Union Carbide Ultra +
Test ID Numbers 6, 9 and 13, 19

Appearance
- Thickened fluid;
- Left a thick, smooth, shiny, transparent green layer with suspended bubbles when applied;
- Fluid progressed through several phases prior to failure;
- Failure propagated from the top of plate and carved drain channels in fluid below; and
- Contamination fused into solid, bumpy layer appearing as fingers of failed fluid.

Film Thickness
- Thickness at five minutes of ≅ 1.4 mm;
- Initially stabilized at about 1.0 to 1.3 mm then progressively decreased until failure; and
- Reduced thickness just prior to failure was function of temperature and precipitation.

Fluid Freeze Point
- Rate of dilution much slower than Type I;
- Different freeze points of top and bottom layers; and
- Freeze point reached air temperature at failure.

Adhesion
- Adhesion trailed failures by some time; and
- Severity a function of temperature and time.

C/FIMS Sensor Trace
- Well defined indicator of failure, generally between time of visual call of initial and standard plate failures.

RVSI Sensor Trace
- At -10°C, trace provided strong indicator of failure, concurrent with visual failure call; and
- Trace indicator less reliable at warmer temperatures.

4.9.1 Discussion

Ambient temperature appears to have a direct effect on the appearance of Ethylene Type I and Type IV failures in light freezing rain conditions.

- At -10°C, the Type I and Type IV failures were fairly similar in appearance, and both consisted of solid, rough contamination that progressed in a top-to-bottom manner on the plate (Photos 4.12 and 4.13).

- At -3°C, Type IV failures, observed in flat plate tests, were similar to those of tests conducted at -10°C, and consisted primarily of hardened, rough contamination (Photo 4.14). This same appearance of failure was documented in a Type IV fluid failure test conducted on a McDonnell Douglas DC-9 wing in 1995-96 (Photo 4.15). The ambient temperature for this test was -1°C.

- At -3°C, Type I fluid failures consisted primarily of a clear, glossy ice surface. This mode of failure is apparent in photo documentation from a flat plate test and a full-scale fluid failure test conducted on a Boeing 737 wing in 1996-97 (Photos 4.16 and 4.17).

Another noticeable difference between Type I and Type IV failures in light freezing rain was the adhesion of the failure to the test plate.

A comparison of the degree of adhesion was made for two tests. The first test, ID #7, used Type I fluid and the second test, ID #9, used Type IV Neat fluid. The two tests were conducted under light freezing rain at 25 g/dm²/h and the ambient air temperature was -10°C. Data from these tests are plotted in Figure 4.2 to illustrate, for particular locations on the plate, the observed extent of adhesion in relation to the time of fluid failure. Adhesion was measured only twice during the process of failure: at the time of standard plate failure (1/3 or fifth crosshair), and again when the plate was completely failed. The precise onset of adhesion is not known. The line representing fluid failure, based on four data points (start of test application, initial failure, standard plate failure, and complete plate failure), provides an estimate of time of failure at any plate position.

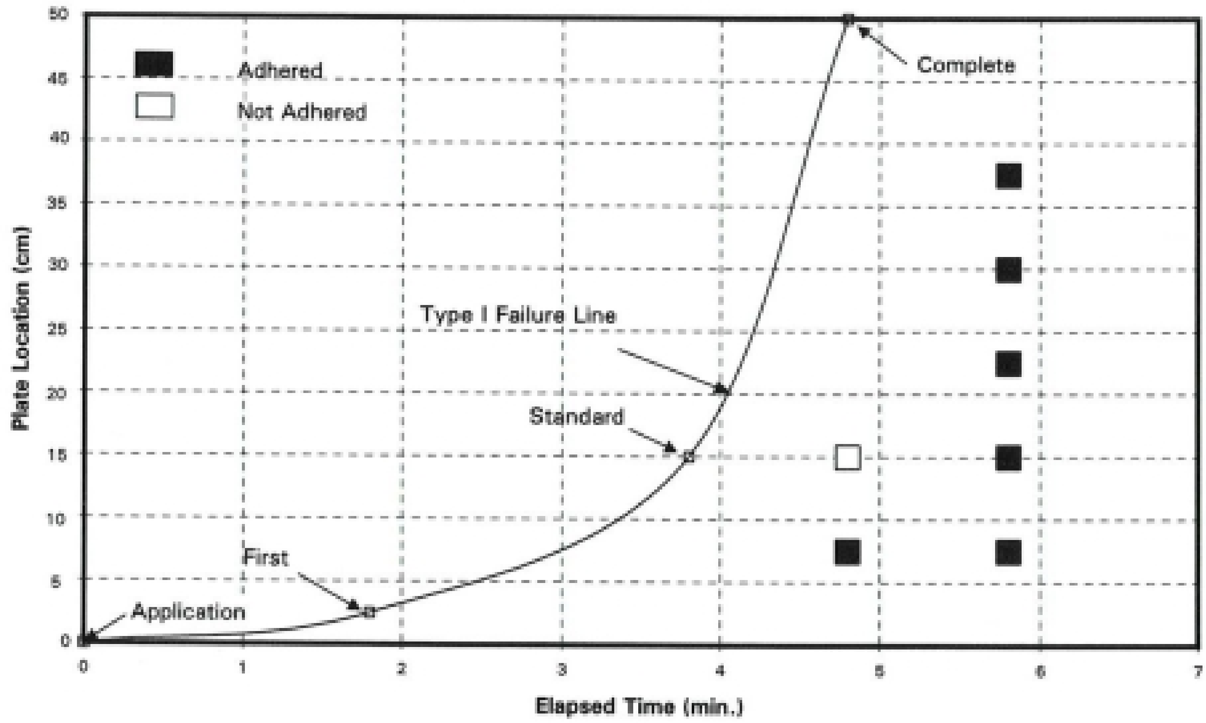
Data plotted for the Type I fluid test demonstrate that adhesion at any position measured occurred either simultaneously with fluid failure or very shortly thereafter. In contrast, data on the Type IV fluid test demonstrate a longer delay from the time of fluid failure to adhesion, in the range of three to six minutes.

FIGURE 4.2

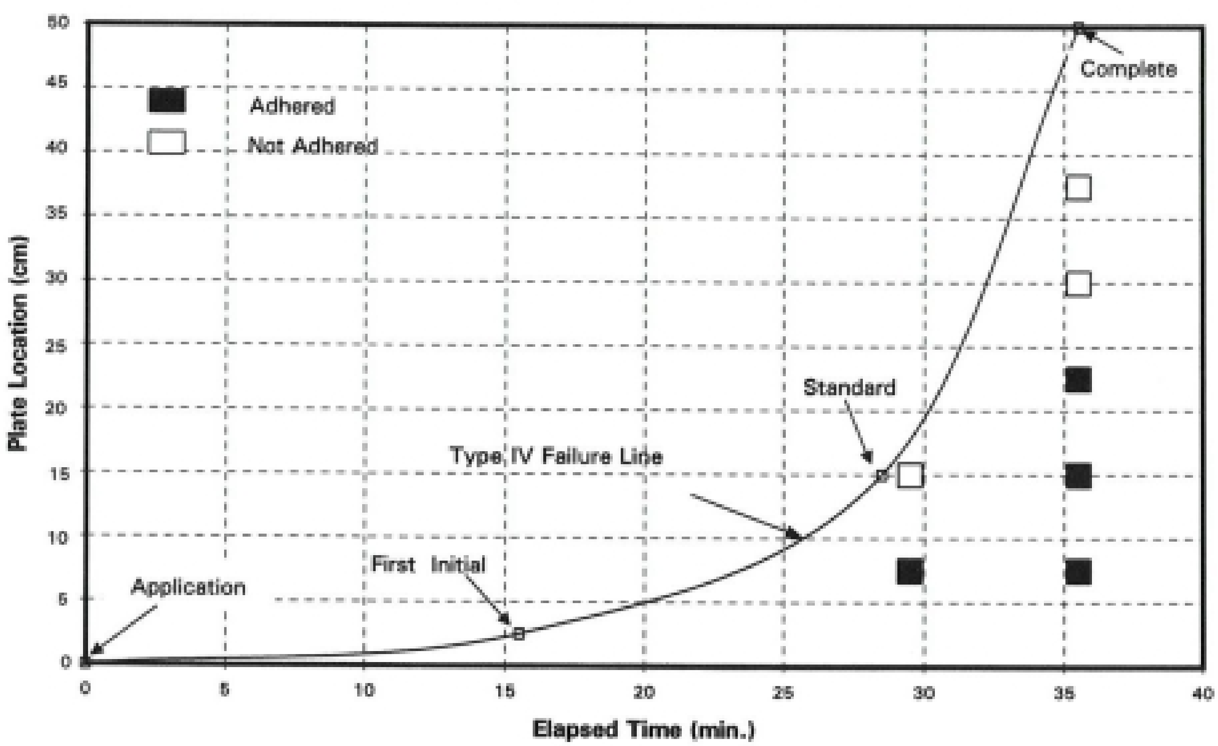
ADHESION COMPARISON - TYPE I VERSUS TYPE IV FLUID

Light Freezing Rain (25 g/dm²/h) at -10°C

ID # 7 (UCAR XL54)



ID # 9 (UCAR ULTRA+ Neat)



CM1514/Report/Doc_Fail/ADHERENC

Two other similar tests (Test ID numbers 5 and 6) provide almost the same results.

The steepness of the Type I curve demonstrates the danger of freezing rain at cold temperatures when using Type I for protection. A pilot could potentially view the aircraft wing just prior to initial failure and determine that it is uncontaminated. Within four minutes the fluid on the wing could be completely failed and, more importantly, would probably be bonded over the entire wing surface. With an application of neat Type IV fluid under these conditions, the time required for bonding to reach significant levels following initial failure is probably greater than 15 minutes.

4.10 Comparison of Type I and Type IV Failures in Snow

Type I Union Carbide XL54
Test ID Numbers 34, 39, 46, 56, 57

Appearance
- Unthickened fluid;
- Left a very thin, transparent orange layer when applied;
- Immediate accumulation of solid contaminant;
- Clumps of snow rapidly accumulated on plate surface;
- Plate area between snow accumulation was dry; and
- Rapid failures without adhesion.

Film Thickness
- Rapid reduction of thickness to 0.1 mm; and
- Difficult to measure thickness due to snow accumulation.

Fluid Freeze Point
- Fluid dilution to freeze point above air temperature before standard plate failure; and
- Uniform freeze point in fluid layer due to thin unthickened film.

Adhesion
- No adhesion detected for any of the tests with these conditions.

C/FIMS Sensor Trace
- Uninterpretable results.

RVSI Sensor Trace
- N/A

Type IV Union Carbide Ultra +
Test ID Numbers 30, 32, 37, 43, 44, 48, 53

Appearance
- Thickened fluid;
- Left a thick, smooth, shiny, transparent green layer with suspended bubbles when applied;
- Fluid surface became dull;
- Precipitation resting in fluid matrix;
- Failures propagated from the top of plate and fluid layer absorbed snow to become slush; and
- Contamination accumulated faster than fluid is capable of absorbing snow.

Film Thickness
- Thickness at five minutes of ≈1.4 mm;
- Stabilized at about 1.0 to 1.3 mm then progressively decreases until failure; and
- Reduced thickness just prior to failure was function of temperature and precipitation rate.

Fluid Freeze Point
- Rate of dilution much slower than Type I;
- Freeze point generally remained below air temperature at standard plate failure; and
- Different freeze points of top and bottom layers.

Adhesion
- No adhesion detected for any of the tests with these conditions.

C/FIMS Sensor Trace
- Noticeable indicator of failure coincided with visual call of standard plate failures.

RVSI Sensor Trace
- N/A

4.10.1 Discussion

The following is a comparison of ethylene glycol-based Type I and Type IV fluids in snow precipitation. Ambient temperature and rate of precipitation did not have much effect on the appearance of failure in snow conditions, with the exception of reducing the time to failure. Natural and artificial snow test results are combined for the purposes of the report. The differences between the two conditions are discussed in Transport Canada report TP 13488E (3). The Type I fluid immediately showed signs of snow building on its thin film. In contrast, the Type IV fluid could absorb a large quantity of precipitation before failures began to appear on the fluid surface.

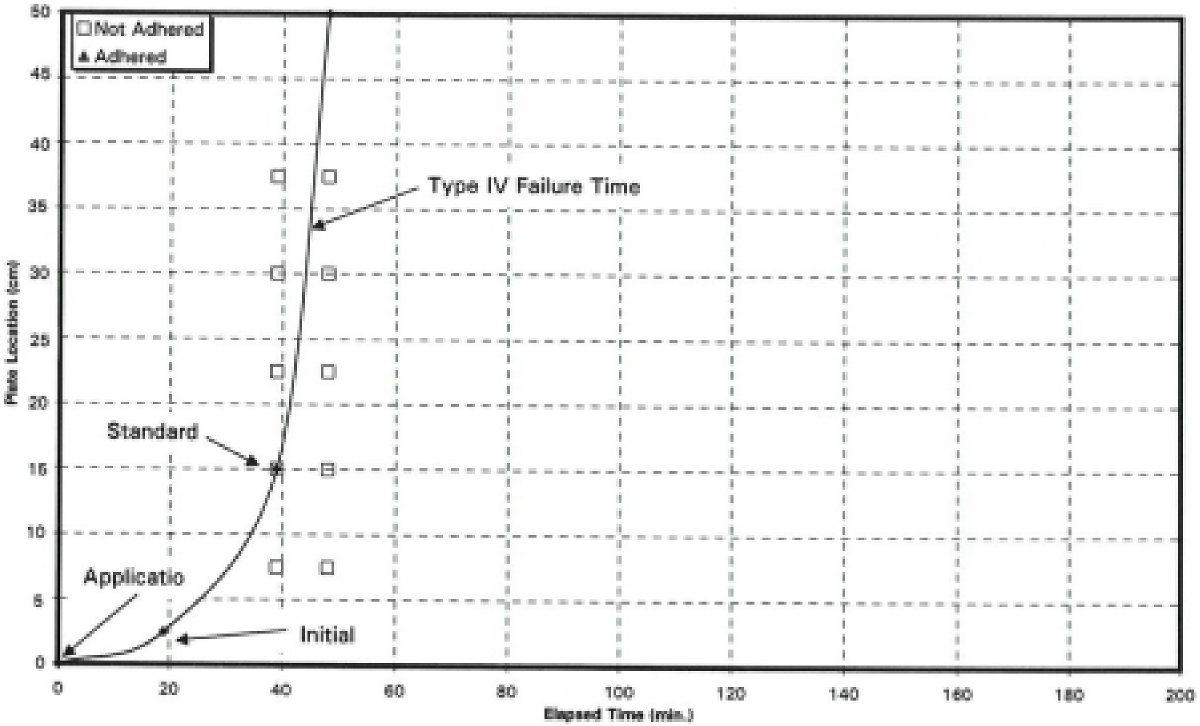
In all snow tests performed, adhesion never occurred between the precipitation and the plate surface, as shown in Figure 4.3. In most tests a layer of slushy fluid resulted from the fluid and precipitation mixture.

FIGURE 4.3

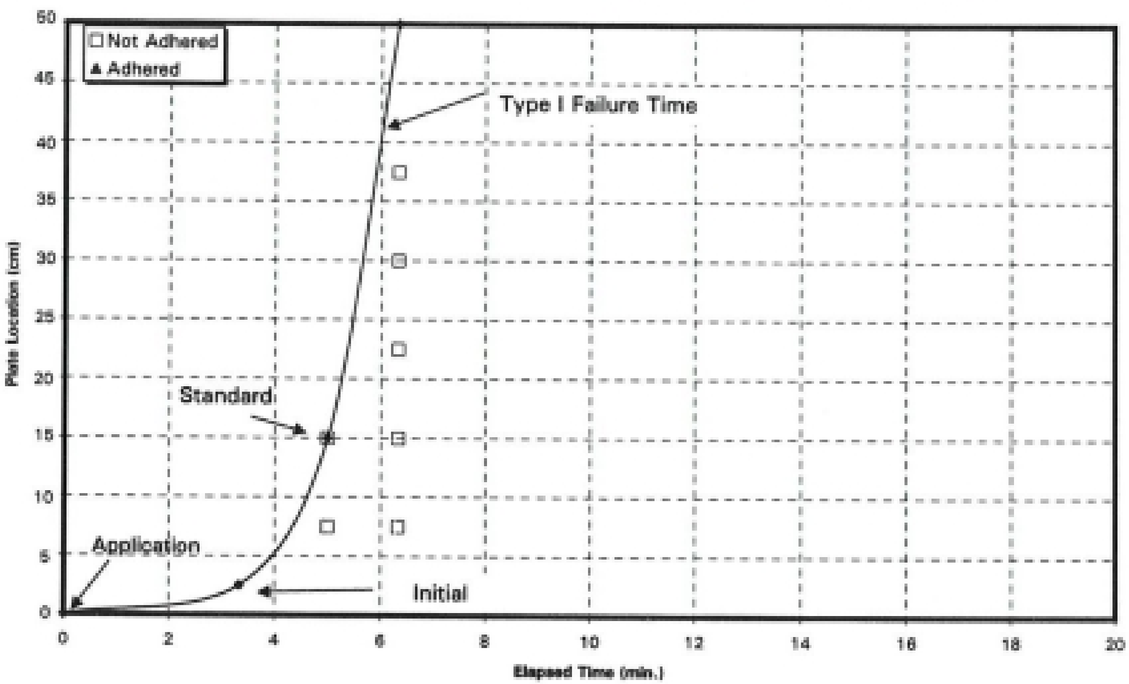
ADHESION COMPARISON - TYPE I VERSUS TYPE IV FLUID FOR SNOW

ID # 53 (UCAR ULTRA+)

Artificial Snow, OAT = -4.2°C, Precipitation Rate = 29 g/dm²/h



Artificial Snow, OAT = -4.6°C, Precipitation Rate = 24.4 g/dm²/h



4.11 Comparison of Type IV Ethylene Glycol-Based Fluid – Freezing Rain versus Freezing Drizzle

Union Carbide Ultra +
Freezing Drizzle, Test ID Numbers 1, 4

Appearance
- Thickened fluid;
- Left a thick, smooth, shiny transparent green layer with suspended bubbles when applied;
- Fluid progressed through several distinct stages prior to failure;
- Failures propagated from the top of plate and carved drain channels into the thick fluid below to form fingers of failure;
- Thick fluid below drainage channels broke up into scattered lumps that were washed away to give rise to rapid failure; and
- Contamination fused into a mottled bumpy layer from the fingers of failed fluid.

Film Thickness
- Common thickness at five minutes of 1.4 mm;
- Initially stabilized at about 1.0 to 1.3 mm then progressively decreased until failure; and
- Film thickness at time of plate failure was 0.5 mm.

Fluid Freeze Point
- At 15 cm line at time of plate failure:

OAT (°C)	*FP (°C)*
-10	-7
-4	-4

Adhesion
- Occurred later than with freezing rain.

C/FIMS Sensor Trace
- Weaker indicator of failure than in freezing rain.

RVSI Sensor Trace
- Strong indication of failure.

Union Carbide Ultra +
Freezing Rain, Test ID Numbers 6, 9, 8, 11

Appearance
- Thickened fluid;
- Left a thick, smooth, shiny transparent green layer with suspended bubbles when applied;
- Fluid progressed through several distinct stages prior to failure;
- Failures propagated from the top of plate and carved drain channels in the fluid below to form fingers of failure;
- Thick fluid below channels broke up into scattered lumps and was superseded by more rapid failure; and
- Contamination fused into a mottled bumpy layer from the fingers of failed fluid.

Film Thickness
- Common thickness at five minutes of 1.4 mm;
- Initially stabilized at about 1.0 to 1.3 mm then progressively decreased until failure; and
- Film thickness at time of plate failure was 0.3 mm.

Fluid Freeze Point
- At 15 cm line at time of plate failure:

OAT (°C)	*FP (°C)*
-10	-1
-4	-1

Adhesion
- Occurred earlier and was more severe than with freezing drizzle.

C/FIMS Sensor Trace
- Stronger indicator of failure than in freezing drizzle.

RVSI Sensor Trace
- Strong indication of failure.

4.11.1 Discussion

The differences in ethylene glycol-based fluid appearances at the time of failure between tests conducted in light freezing rain and freezing drizzle conditions were not significant. At failure, the contamination fused into a mottled, bumpy layer in both conditions (Photos 4.18 and 4.19). The time required for the Type IV fluid to exhibit this failure in freezing drizzle tests was significantly longer than in light freezing rain tests. Scattered lumps of fluid endured longer in freezing drizzle than in freezing rain.

Tests conducted in freezing drizzle exhibited greater film thickness at failure than tests conducted in light freezing rain (0.5 mm compared to 0.3 mm). The adhesion of failures to test surfaces was observed to initiate sooner and to bond more strongly in light freezing rain tests.

The C/FIMS produced a much more noticeable change when failure was detected in freezing rain than in freezing drizzle. The indications of failure for freezing rain were strong and near the time of standard plate failure, whereas the freezing drizzle indicators were weak and between initial failure and standard plate failure. The RVSI BF Goodrich ice detection system produced strong indications of failure for both conditions.

4.12 Comparison of Type IV Propylene Glycol-Based Fluid – Freezing Rain versus Freezing Drizzle

Octagon Max-Flight
Freezing Drizzle, Test ID Numbers 2, 3

Appearance

- Thickened fluid;
- Left a thick, smooth, turbid, shiny transparent green layer with no bubbles when applied;
- Fluid progressed through several distinct stages prior to failure; however, the speck-covered stage was not observed;
- A marbled appearance was observed as a pre-failure stage;
- Failures propagated from the top of plate were streaks, and dots of solid contamination began to fuse together;
- Thick fluid began to uniformly thin below the failed region; and
- Ice particles began to dam at the bottom of the plate and continued to collect until complete plate failure.

Film Thickness

- Common thickness at five minutes of ≈0.8 mm;
- Fluid thickness increased during test and finally decreased as failure approached; and
- Film thickness at time of standard plate failure was dependent on temperature.

Fluid Freeze Point

- At 15 cm line at time of plate failure:

OAT (°C)	*FP (°C)*
-10	-10
-4	-4

Adhesion

- Occurred later than with freezing rain.

C/FIMS Sensor Trace

- Weaker indicator of failure than in freezing rain.

RVSI Sensor Trace

- Relatively weak indication of failure.

Octagon Max-Flight
Freezing Rain, Test ID Numbers 8, 11

Appearance

- Thickened fluid;
- Left a thick, smooth, turbid, shiny transparent green layer with no bubbles when applied;
- Fluid progressed through several distinct stages prior to failure, including large ice pellet accumulation;
- A marbled appearance was observed as a pre-failure stage;
- Failures propagated from the top of plate were streaks, and dots of solid contamination began to fuse together;
- Drainage formed;
- Fingers of solid contamination reached down the plate and islands of contamination began to form; and
- Contamination fused into a mottled bumpy layer from the fingers and islands of failed fluid.

Film Thickness

- Common thickness at five minutes of ≅0.8 mm;
- Fluid thickness increased during test and finally decreased as failure approached; and
- Film thickness at time of standard plate failure was dependent on temperature.

Fluid Freeze Point

- At 15 cm line at time of plate failure:

OAT (°C)	*FP (°C)*
-10	-2
-4	0

Adhesion

- Occured earlier and was more severe than with freezing drizzle.

C/FIMS Sensor Trace

- Strong signal, not temperature related.

RVSI Sensor Trace

Strong indication of failure coincident with visual call.

4.12.1 Discussion

The differences in propylene glycol-based fluid appearances during the progression of failure between tests conducted in light freezing rain at -10°C and tests conducted in freezing drizzle at -10°C conditions were significant. At visual failure, the contamination fused into a mottled, bumpy layer in both conditions, but the marble condition endured longer in the freezing drizzle precipitation and a damming effect was observed. During the freezing rain tests fingers of failure and islands of failure were noted during the failure progression, whereas more uniform top-to-bottom failure was more frequently observed in freezing drizzle tests.

The differences in the appearance of failure for tests conducted at -3°C were not significantly noticeable. The contamination fused into a mottled, bumpy layer in both conditions and fingers of failure and islands of failure were noted during the failure progression.

The decrease in fluid viscosity due to the higher temperatures can affect the fluid's ability to flow down the plate and will help inhibit the damming effect.

Tests conducted in freezing drizzle at colder temperatures exhibited greater film thickness at failure, than light freezing rain tests. The adhesion of failures to the test surface was observed to initiate sooner and be more severe in light freezing rain tests.

The C/FIMS produced a much more noticeable change when failure was detected in freezing rain than in freezing drizzle. The RVSI ice detection system produced strong indications of failure for both conditions.

4.13 Comparison of Type IV Fluid – Freezing Drizzle versus Snow

Union Carbide Ultra +
Freezing Drizzle, Test ID Numbers 1, 4

Appearance
- Thickened fluid;
- Left a thick, smooth, shiny transparent green layer with suspended bubbles when applied;
- Fluid progressed through several distinct stages prior to failure;
- Failures propagated from the top of plate and carved drain channels into the thick fluid below to form fingers of failure;
- Thick fluid below drainage channels broke up into scattered lumps which were washed away to give rise to rapid failure; and
- Contamination fused into a mottled bumpy layer from the fingers of failed fluid.

Film Thickness
- Common thickness at five minutes of 1.4 mm;
- Initially stabilized at about 1.0 to 1.3 mm then progressively decreased until failure; and
- Film thickness at time of plate failure was 0.5 mm.

Fluid Freeze Point
- At 15 cm line at time of plate failure:

OAT (°C)	*FP (°C)*
-10	-10
-4	-4

Adhesion
- Occurred later after the onset of failure.

C/FIMS Sensor Trace
- Weaker indicator of failure than in freezing rain.

RVSI Sensor Trace
- Strong indication of failure.

Union Carbide Ultra +
Snow, Test ID Numbers 30, 32, 37, 43, 44, 48, 53

Appearance
- Thickened fluid;
- Left a thick, smooth, shiny, transparent green layer with suspended bubbles when applied;
- Fluid surface became dull;
- Precipitation resting on surface;
- Failures propagated from the top of plate and fluid layer absorbed snow to become slush; and
- Contamination accumulated faster than fluid is capable of absorbing snow.

Film Thickness
- Thickness at five minutes of 1.4 mm;
- Initially stabilized at about 1.0 to 1.3 mm then progressively decreased until failure; and
- Reduced thickness just prior to failure was function of temperature and precipitation rate.

Fluid Freeze Point
- Different freeze points of top and bottom layers; and
- Freeze point generally remained below air temperature at standard plate failure.

Adhesion
- No adhesion detected for any of the tests with these conditions.

C/FIMS Sensor Trace
- Noticeable indicator of failure coincides with visual call of standard plate failures.

RVSI Sensor Trace
- N/A

4.13.1 Discussion

The difference in fluid appearance during the progression of failure between tests conducted in light freezing drizzle and snow conditions was significant. A progression of several different pre-failure modes was observed during freezing drizzle, contrary to that of snow contamination. In freezing drizzle conditions, the failures carved drainage channels from the top to the bottom of the plate to form fingers of failure. A top-to-bottom failure mode was observed during both freezing drizzle and snow tests. In snow tests the precipitation accumulated in the fluid layer until the fluid was too diluted to absorb the falling precipitation.

Tests conducted in freezing drizzle at the colder condition exhibited greater film thickness at failure than snow tests. The film thickness was very difficult to measure during snow tests due to the accumulation of slush within the fluid matrix. The adhesion of failures to test surfaces was observed in all freezing drizzle tests with Ultra+, whereas adhesion was never noted during snow precipitation tests.

The fluid freeze point for snow tests generally did not converge by standard plate failure. A graph comparing the fluid freeze point progression for both precipitation conditions is shown in Figure 4.4.

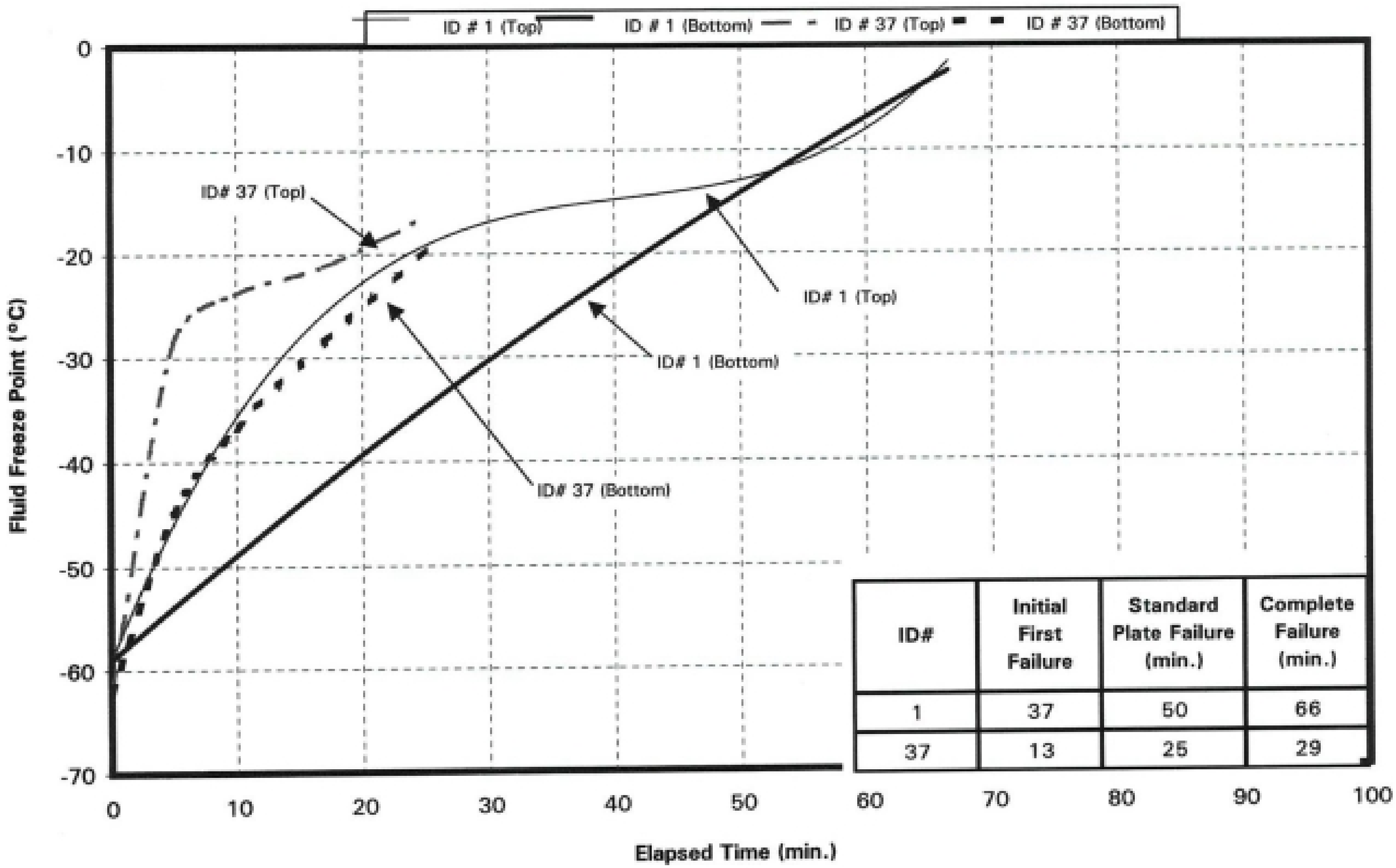
The C/FIMS produced a much more noticeable change when failure was detected in snow than in freezing drizzle. The RVSI ice detection system was not available during snow tests.

The preceding comparison was based on the ethylene glycol-based fluid Ultra+. In snow precipitation, the appearances of failure of all the Type IV fluids tested were similar. Every fluid accumulated precipitation in the fluid layer and on the top surface of the fluid. As the test progressed, the quantity of snow in the fluid matrix increased to create a layer of slushy fluid. Failures were called when the fluid layer was not capable of absorbing further precipitation.

FIGURE 4.4

COMPARISON OF FLUID FREEZE POINTS

ID # 1 (Freezing Drizzle) and ID # 37 (Artificial Snow)



ID#	Initial First Failure	Standard Plate Failure (min.)	Complete Failure (min.)
1	37	50	66
37	13	25	29

CM1514/Report/Doc_Fail/BRX_ID01&37

4.14 Comparison of Type IV Ethylene Glycol-Based Fluid – Effect of Temperature in Light Freezing Rain (-4 versus -10°C)

Union Carbide Ultra+
OAT = -4°C, Test ID Numbers 13, 19

Appearance
- Thickened fluid;
- Left a thick, smooth, shiny transparent green layer with suspended bubbles when applied;
- Fluid progressed through several stages prior to failure: specked, orange-peel, and gelatinous;
- Failures propagated from the top of plate and carved drain channels in the fluid below to form fingers of failure down the plate;
- Fluid below drainage channels broke up into scattered lumps of thick fluid that were washed away to give rise to rapid failure; and
- Contamination fused into a mottled bumpy layer from the fingers of failed fluid.

Film Thickness
- Avg thickness at 15 cm line at time of standard plate failure = 0.1 mm.

Fluid Freeze Point
- At 15 cm line at time of standard plate failure; freeze point = -1°C;
- Top layer temporarily stabilized at -15°C; and
- Top and bottom layer freeze point converged prior to time of standard plate failure and rapidly diluted thereafter.

Adhesion
- Adhered over smaller area at complete failure.

C/FIMS Sensor Trace
- Strong signal, not temperature related.

RVSI Sensor Trace
- Relatively weak indication of failure.

Union Carbide Ultra+
OAT = -10°C, Test ID Numbers 6, 9

Appearance
- Thickened fluid;
- Left a thick, smooth, shiny transparent green layer with suspended bubbles when applied;
- Fluid progressed through several stages prior to failure: specked, orange-peel, gelatinous;
- Failures propagated from the top of plate and carved drain channels in the fluid below to form fingers of failure down the plate;
- Fluid below drainage channels broke up into scattered lumps of thick fluid that were washed away to give rise to rapid failure; and
- Contamination fused into a mottled bumpy layer from the fingers of failed fluid.

Film Thickness
- Avg thickness at 15 cm line at time of standard plate failure = 0.4 mm.

Fluid Freeze Point
- At 15 cm line at time of standard plate failure; freeze point = -1°C;
- Top layer temporarily stabilized at -19°C; and
- Top and bottom layer freeze point converged at time of standard plate failure and rapidly diluted thereafter.

Adhesion
- Adhered over larger area at complete failure.

C/FIMS Sensor Trace
- Strong signal, not temperature related.

RVSI Sensor Trace
- Strong indication of failure coincident with visual call.

4.14.1 Discussion

The appearance of fluid failure was not temperature dependent for this ethylene glycol-based fluid during the test performed. In holdover time tests, it was observed that certain propylene glycol-based Type IV fluids exhibited different failure mechanisms at colder temperatures. This property is described in Section 4.15.

The ethylene glycol-based Ultra+ fluid mixed more easily with contaminants than all the other anti-icing fluids tested. It accepted contaminant, mixed and diluted more readily than other fluids. The mode of failure of the Ultra+ fluid was more consistent than the propylene glycol-based Type IV fluids tested, and showed little or no temperature dependent behaviour over the temperature range of -3ºC to -10ºC.

4.15 Comparison of Type IV Propylene Glycol-Based Fluid – Effect of Temperature in Freezing Drizzle (-4 versus -10°C)

Kilfrost ABC-S
OAT = -4°C, Test ID Numbers 49, 50

Appearance
- Very thick, pale green, transparent fluid layer when applied;
- Fine air bubbles within fluid matrix;
- Surface studded with fine solid particles;
- Orange peel texture formed;
- Surface began to smooth as precipitation was absorbed into fluid layer;
- Progressive thinning of fluid at top edge of test plate;
- Drainage channels began extending from top of plate toward bottom; and
- Thin fluid film adhered to plate surface.

Film Thickness
- At five minutes = 2.2 mm;
- Fluid thickness stabilized slowly after pouring at 20-30 minutes = 1.8;
- Dropped dramatically near the time of initial failure; and
- Tended toward 0 mm thickness as failure propagated.

Fluid Freeze Point
- Top and bottom layer freeze point converged by time of initial failure; and
- At standard plate failure, the fluid freeze point had reached outside air temperature.

Adhesion
- Adhesion begins at top of plate 25 minutes after initial failure; and
- After complete plate failure 80 percent of surface covered by adhered fluid.

C/FIMS Sensor Trace
- Gave strong indication of failure at time of standard plate failure call.

RVSI Sensor Trace
- N/A

Kilfrost ABC-S
OAT = -10°C, Test ID Numbers 41, 42

Appearance
- Very thick, pale green, transparent fluid layer when applied;
- Fine air bubbles within fluid matrix;
- Dots of contamination accumulated without mixing on the fluid surface;
- Islands of contamination formed together to create continuous network of solids on fluid surface;
- Contamination continued to accumulate and solids fused to plate from bottom toward top; and
- Lateral cracking shows underlying fluid.

Film Thickness
- At five minutes = 1.8 mm;
- Fluid thickness stabilized slowly after pouring; and
- 1.5 mm at time of plate failure.

Fluid Freeze Point
- At 15 cm line at time of initial plate failure; freeze point was between -15 and -20º C;
- Top and bottom layer freeze point had not converged by time of standard plate failure; and
- At complete plate failure, freeze point of bottom layer was lower than that of the top layer.

Adhesion
- No adhesion was noted at the time of complete plate failure.

C C/FIMS Sensor Trace
- Gave no indication of failure.

RVSI Sensor Trace
- N/A

4.15.1 Discussion

The appearance of fluid failure was highly temperature dependent for this propylene glycol-based fluid during the test performed. Certain propylene glycol-based Type IV fluids follow different failure progressions at colder temperatures. At temperatures of -4°C Kilfrost ABC-S accepted the contaminants within the fluid layer and the eventual failure was due to fluid dilution. At colder temperatures, such as -10°C, the precipitation does not penetrate the fluid layer. It is suspended on top of the fluid and accumulates above a relatively undiluted fluid layer.

The failure progression exhibited by Kilfrost ABC-S at higher temperatures is similar to Ultra+ at -10ºC. Section 4.16 describes in more detail the differences between ethylene glycol- and propylene glycol-based fluids.

The operative failure mechanism in freezing drizzle, at colder temperatures, prevents failure adhesion from securing on the plate surface. The failure call may be premature for this type of failure since a layer of undiluted fluid is trapped between the overlaying sheet of ice and the test surface. The failure call may be appropriate since the frozen contaminant may not shear off a wing during rotation.

The C/FIMS showed a strong indication of failure for the higher temperature tests since the fluid directly above the sensor was thinning and diluted. The trace produced during the lower temperature test gave virtually no indication of failure. The layer of fluid in contact with the C/FIMS sensor for these tests was the layer of uncontaminated fluid trapped under the ice bridging failures.

The exact temperature at which each different propylene glycol-based fluid began to fail due to ice bridging is not clear. The tests performed for this study are insufficient to determine these temperatures. It can be noted that the transition temperature for Kilfrost ABC-S is between -3ºC and -10ºC.

4.16 Type IV Propylene Glycol-Based Fluid versus Ethylene Glycol-Based Fluid – Freezing Drizzle, Outside Air Temperature = -10°C

Ethylene Glycol
Union Carbide Ultra+
Test ID Numbers 1, 4

Appearance

- Left a thick, smooth, shiny transparent green layer with suspended bubbles when applied;
- Fluid progressed through several stages prior to failure: specked, orange-peel, and gelatinous;
- Failures propagated from the top of plate and carved drain channels in the fluid below; and
- Contamination fused into a mottled, bumpy layer from the fingers of failed fluid.

Film Thickness

- At five minutes = 1.3 mm
- Fluid thinned progressively. No increase as in Octagon; and
- 0.6 mm at time of standard plate failure.

Fluid Freeze Point

- At 15 cm line at time of standard plate failure; freeze point = -8°C;
- Top layer temporarily stabilized at -20°C; and
- Top and bottom layer freeze points converged at time of standard plate failure and rapidly diluted thereafter.

Adhesion

- Adhesion occurred some time after failure.

C/FIMS Sensor Trace

- Strong indication of failure.

RVSI Sensor Trace

- Strong indication of failure.

Propylene Glycol
Octagon Max-Flight
Test ID Numbers 2, 3

Appearance

- Similar to Ultra+ but without bubbles, slightly paler and slightly turbid;
- Progression to failure had short-lived orange-peel stage followed by a gelatinous stage. Size of features observed in the gelatinous phase were 2/3 that observed with Ultra+ fluid; and
- Fluid maintained thinning slurry that gradually underwent fusion. Run-off maintained open channels to bottom edge.

Film Thickness

- At five minutes = 0.8 mm;
- Fluid increased notably during initial interval to 1.2 mm; and
- Similar thickness to Ultra at time of standard plate failure (0.6 mm).

Fluid Freeze Point

- At 15 cm line at time of standard plate failure; freeze point = -10°C;
- Top layer quickly rose such that the freeze point was 5°C above the bottom layer, and then rose in concert with bottom layer; and
- Top and bottom layer freeze point had not converged by time of standard plate failure.

Adhesion

- Adhesion occurred some time after failure.

C/FIMS Sensor Trace

- Not as strong an indication of failure as with Ultra+.

RVSI Sensor Trace

- Progressively decreasing lines without strong indication of failure.

4.16b Type IV; Propylene Glycol-Based Fluid versus Ethylene Glycol-Based Fluid – Freezing Drizzle, Outside Air Temperature = -10°C

Propylene Glycol
SPCA AD-480
Test ID Number 28

Appearance
- Very thick and intense green transparent fluid layer when applied; and
- Dots of contamination accumulated without mixing on the fluid surface. Test was not continued to the point of fusion but was beginning to form a slushy layer on the surface as the density of dots approached a continuum.

Film Thickness
- At five minutes = 1.7 mm;
- Fluid thickness stabilized shortly after pouring; and
- 1.2 mm at time of standard plate failure.

Fluid Freeze Point
- At 15 cm line at time of standard plate failure; freeze point = -16º C;
- Top and bottom layer freeze point had not converged by time of standard plate failure; and
- Following complete plate failure, freeze point of top layer was still 7ºC higher than that of the bottom layer.

Adhesion
- No adhesion was noted at the time of complete plate failure.

C/FIMS Sensor Trace
- Not a strong indicator of failure.

RVSI Sensor Trace
- Progressively decreasing lines without a strong indication of failure.

Propylene Glycol
Kilfrost ABC-S
Test ID Numbers 41, 42

Appearance
- Very thick pale green transparent fluid layer when applied;
- Fine air bubbles within fluid matrix;
- Dots of contamination accumulated without mixing on the fluid surface;
- Islands of contamination formed together to create continuous network of solids on fluid surface;
- Contamination continued to accumulate and solids fused to plate from bottom toward top; and
- Lateral cracking showed underlying fluid.

Film Thickness
- At five minutes = 1.8 mm;
- Fluid thickness stabilized slowly after pouring; and
- 1.5 mm at time of standard plate failure.

Fluid Freeze Point
- At 15 cm line at time of standard plate failure; freeze point is between -15 and -20ºC;
- Top and bottom layer freeze point had not converged by time of standard plate failure; and
- Following complete plate failure, freeze point of top layer was lower than that of the bottom layer.

Adhesion
- No adhesion was noted at the time of complete plate failure.

C/FIMS Sensor Trace
- Gave no indication of failure.

RVSI Sensor Trace
- N/A

4.16.1 Discussion

The characteristics of failure of an ethylene glycol-based fluid were compared to the characteristics of three propylene glycol-based fluids in freezing drizzle at -10ºC. It has been recognized during the process of previous holdover time testing (see Transport Canada report TP 13131E (6)) that two behaviour extremes occurred in the failure mechanisms of propylene and ethylene glycol-based Type IV fluids at colder temperatures. One extreme was exhibited by the ethylene Type IV fluid, Ultra+; this fluid tended to be diluted in a more homogeneous fashion through the fluid depth. The propylene glycol-based Type IV, Octagon, SPCA, and Kilfrost, which tend to resist dilution by maintaining the precipitation at the top of the fluid profile, thereby exhibited the other extreme.

The diagram in Figure 4.5 helps to visualize the difference in behaviour during a freezing drizzle test at -10°C. The Ultra+ fluid failure mechanism is described as follows:

- Initial exposure caused the fluid to absorb precipitation into its upper layers, promoting the fluid to swell;
- Continued dilution enhanced the fluid's ability to flow; and
- The diluted fluid eroded off the surface, and its thickness was diminished until failure occurred.

The typical failure was characterized by a thin layer of solidified precipitation. The Kilfrost and SPCA fluids failed by accumulating precipitation in the upper fluid layers. These fluids resisted dilution (especially at these lower temperatures). The upper layers did flow, but damming of the failed surface layer occurred at the bottom edge of the plate, trapping the failures in place. This situation was interpreted as a failure by an observer because the fluid had developed suspended ice, which eventually formed a layer of solid ice. Considerable unfailed fluid lay below the failed upper surface layer.

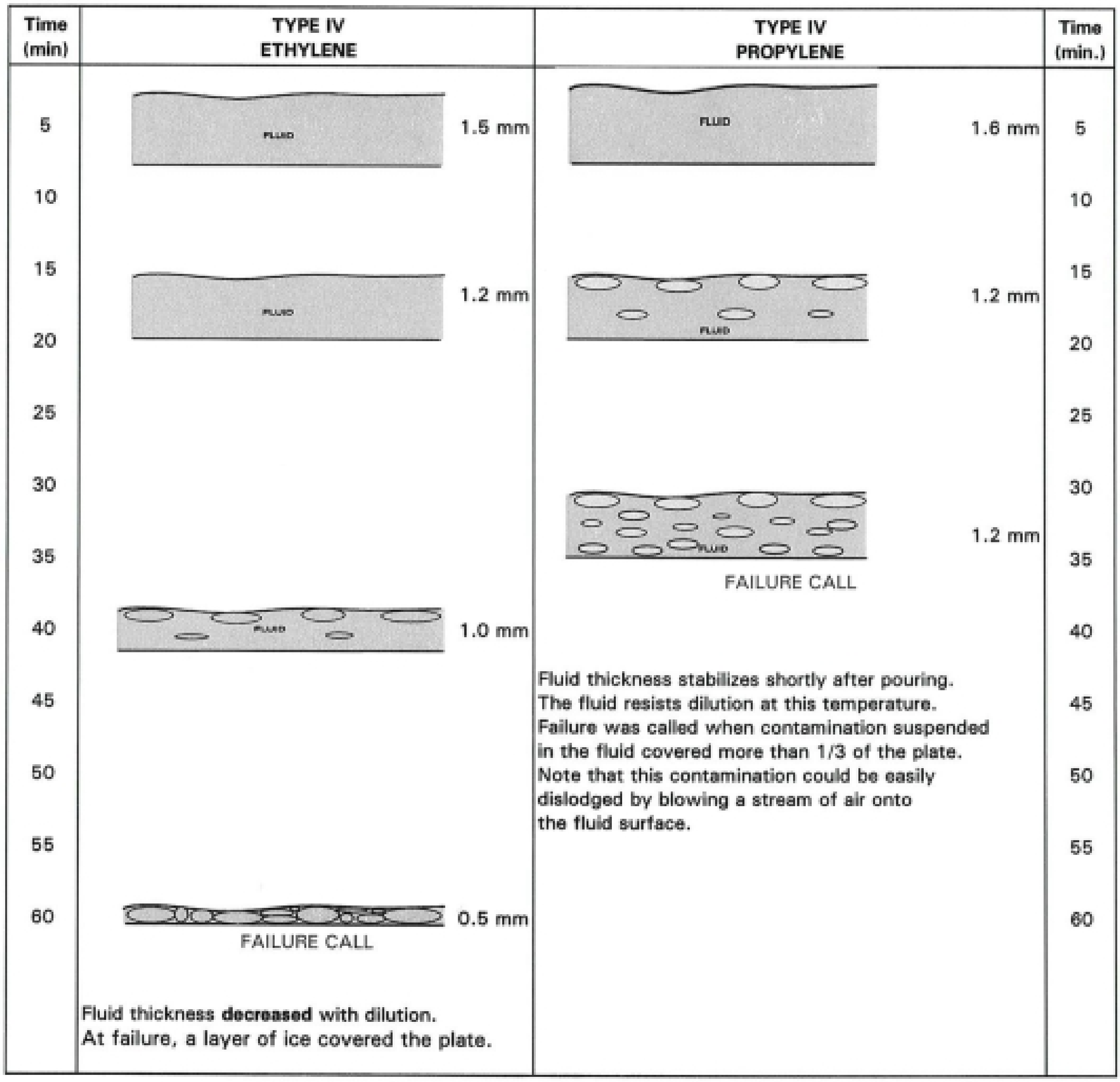
The mechanism of failure described above for propylene glycol-based Type IV fluid was not observed for Octagon in documentation of fluid failure tests. The Octagon fluid used in these tests was inadvertently sheared prior to testing and its viscosity spray was substantially reduced. As a result, the fluid failure appearance was similar to that of the Ultra+ fluid. However, it should be noted that the Octagon Type IV fluid documented in this report may be an adequate representation of an operational fluid, since shearing does occur during fluid application on a wing surface.

FIGURE 4.5

TYPE IV ETHYLENE VERSUS TYPE IV PROPYLENE

SCHEMATIC OF FAILURE MECHANISM

FREEZING DRIZZLE; T = -10°C, Rate = 5g/dm²/h



The appearance of failure of the SPCA fluid was similar to that observed in previous tests using other propylene glycol-based fluids. Prior to the failure, the surface was covered with a thin layer of fine slush. At standard plate failure, the surface of the fluid was covered with fine, solid contamination that had started to fuse. Below this top layer of solid contamination, a layer of uncontaminated fluid remained. Absolutely no adhesion of ice to the plate surface had occurred at or soon after standard plate failure. The film thickness of the SPCA AD-480 fluid at the time of standard plate failure was 1.2 mm, equivalent to twice that of the Ultra + and the sheared Octagon fluid at the same stage of failure.

4.17 Appearance of Flash Freezing – Type I versus Type IV 50/50 in Freezing Rain

Union Carbide XL54
Test ID Numbers 14, 18

Appearance
- Unthickened fluid;
- Left a thin, transparent orange layer when applied;
- Almost immediate accumulation of solid contaminant;
- Fluid layer thinned rapidly, with drying along the top edge;
- Islands of frozen fluid formed after ten minutes, with rapid adhesion to plate; and
- No flash freezing occurred.

Film Thickness
- Rapid reduction to 0.1 mm thickness.

Fluid Freeze Point
- Dilution to 0°C in six minutes.

Adhesion
- Rapid and complete adhesion following freezing.

C/FIMS Sensor Trace
- Weak, undefined indication of failure, slightly ahead of visual call.

RVSI Sensor Trace
- Clearly definable downturn indicated plate failure, concurrent with visual call.

SPCA AD-480 50/50
Test ID Numbers 15, 17

Appearance
- Thickened fluid;
- Left a thick, transparent green layer when applied;
- Failures were similar to other Type IV fluids with accumulation of solid contaminant;
- Time to failure about two times that of Type I (16 minutes versus eight);
- No adherence at time of standard failure; at complete plate failure, some adherence noted at top of plate (four minute lag); and
- No flash freezing occurred.

Film Thickness
- Initial fluid layer much thicker than Type I (1.5 mm versus 0.5 mm);
- Rate of thinning much slower; and
- Thickness at failure was 0.2mm.

Fluid Freeze Point
- Rate of dilution much slower than Type I fluids; and
- Dilution to -4°C in ten minutes.

Adhesion
- No adhesion at time of standard failure; at complete plate failure, some adherence noted at top of plate (four minute lag).

C/FIMS Sensor Trace
- Visual identification of failure slightly ahead of visual call.

RVSI Sensor Trace
- Clearly definable downturn indicated plate failure, concurrent with visual call.

4.17.1 Discussion

No flash freezing occurred in the documentation of fluid failure tests using Type I or Type IV 50/50 fluids. The appearance of failure for both fluid types in this comparison was consistent with previous descriptions of Type I and Type IV failures.

4.18 Appearance of Type IV Neat Fluids in Ice Pellet Precipitation

The following observations were recorded while waiting for snow precipitation. No definition of failure or holdover time is available for ice pellet precipitation.

Light snow began to fall between 01:30 and 04:00 on January 3, 1999. Temperatures were in the process of rising from -18°C to -14°C over this timeframe. At about 04:00 a thick snowfall began, consisting of large snow grains that ranged in diameter from 2 mm to 5 mm. During this session, two runs per stand were executed, the second of which passed the 04:00 time mark, at which point the snow grains underwent a transformation to ice pellets. Rates were on average from 35 to 39 g/dm^2/h.

Clariant Safewing Four is a propylene glycol-based fluid and bridging failures were initially expected. However, Clariant fluids exhibited failure progression similar to that of Ultra+ Type IV fluid, which tends not to support failures on the top of the fluid surface. The large and dense snow particles caused the contaminant to penetrate the surface layer of the fluid and rest on the substrate surface. It is doubtful that snow-bridging failures would have occurred in these conditions with other propylene glycol-based Type IV fluids.

Under snow grain precipitation, the contaminant quickly established itself on the work surface and first signs of contamination were observed within five or six minutes. Prior to this, contamination embedded itself in the fluid layer and the larger particles persisted indefinitely in the fluid layer to begin the failure process. Viewed at shallow angles, the fluid surface could be observed to contain larger grains, which protruded above the fluid surface while resting on the substrate. As the contamination accumulated, this view showed a completely wet surface, but with the contaminant protrusions becoming more and more dense over the entire plate. It was necessary to prod the plate surface to check the underlying fluid supply and to check for adhesion, as these conditions are somewhat rare.

Once the fluid reservoir had been absorbed under each crosshair, failures were called, even though the contaminant top layer was not completely dry and no adhesion was observed. Although the fluid reservoir was not absorbed very quickly, the quantity of precipitation caused plate contamination to be observed in less than 15 minutes.

Once the transformation to ice pellets was complete (before 04:30), rates remained the same well past the completion of the tests. The ice pellets were crystal clear (no occluded air) and could almost be said to be a very fine hail, with particle sizes ranging from 0.5 to 2.5 mm in diameter.

The ice pellets also quickly established themselves in the fluid and began to accumulate rapidly. Ice pellet failures were not as rapid as those observed in snow grain conditions. The ice pellets were denser and the surface area of these particles was relatively small, which reduced the tendency for the fluid to be absorbed. A significant portion of the contamination impinging on the fluid-coated plate bounced off the test surfaces, but most was captured. The precipitation was not so readily observed to protrude out from the fluid surface, and plate contamination was called well past the times recorded earlier for the snow grains.

From initial contamination to just prior to standard plate failure, the fluid-contaminant mixture resembled a thick slush with large particle sizes. Shallow viewing angles gave the best overall views of the plate and allowed the observers to perceive the state of the fluid-contaminant mixture. Although the fluid reservoir at the top of the plate was depleted more rapidly, it did not give rise to a completely dry condition on the plate surface. At standard plate failure call, a large quantity of solid contaminant was observed to be present on the surface, with slightly more fluid on the lower portion of the plate. The plates were left out and were occasionally inspected for fluid content and adhesion. Fluid content decreased, but never to the point of dryness. Some melting was inevitable due to the continued temperature rise. After complete (full) plate contamination, the fluid surface was ridged laterally and contaminant caked together and cracked between the ridges to expose very small lines of the bare, slightly wet test surface. Blowing on the failed surface easily dislodged the slush.

At 06:00 no adhesion was detected and the top layer appeared dry, although a good centimetre of ice pellets was observed to blanket each plate. Gentle prodding of the fluid surface with a pencil tip exhibited no resistance. No crust formed, and a considerable amount of diluted fluid still persisted underneath the top layer.

The ice pellets were considerably more dense than the snow grains and did not reduce visibility nearly as much. To the observer it appeared that the rates were reduced; however, they were not. In these conditions temperatures rose to -11°C and precipitation dwindled to insignificance. The tests were monitored well past complete (full) plate failure.

Once morning airport operations resumed, the ice pellet precipitation did not seem to influence airline operations as aircraft were deiced and took off. Traffic was light. This was most likely due to situations at destinations hit hard by the storm. At 08:00, precipitation rates began to dwindle, and by 11:00, rates were negligible. Temperatures had risen to -8°C.

4.19 Viscosity Measurements and Analysis

The two different procedures used for viscosity sample collection are described below. The first was implemented during the 1997-98 test season. The second procedure was used during the 1998-99 season due to the difficulties encountered in measuring the viscosity of the sample collected the previous year.

4.19.1 Test Samples Collected in 1997-98

An attempt was made to examine the viscosity of the fluid at time of failure. To this end, fluid samples were collected at the time and location of fifth crosshair failure and at time of complete plate failure at positions B2, F2 and adjacent to the location of fifth crosshair failure, with the intent to measure fluid viscosity with a Brookfield Viscometer. It was subsequently determined that individual sample volumes were insufficient for accurate testing and, consequently, individual test samples were consolidated to enable testing.

The results of these consolidated samples are shown in Table 4.5, which presents the test sample concentrations in terms of Brix-scale refractive index values, as well as the measured viscosities. With one exception, the consolidated samples provided a measurement of viscosity equivalent to water. Fluid concentrations were quite low, as indicated by the Brix numbers.

The only fluid sample having a measurable viscosity was from a single test on Type IV (SPCA AD-480) fluid. The measured viscosity value for this fluid was probably lower than its actual viscosity as the sample volume was slightly less than specified (3.8 mL versus 4.1 mL). Standard plate failure for this fluid was called when an observer judged that the extent of the aggregate contaminant plate coverage reached 33 percent. Failure was due to isolated frozen particles suspended in the fluid. During discussion of the test results for this fluid, it was noted that a considerable amount of protective capacity (not yet failed fluid) appeared to exist at the time of the standard plate failure call. Even at test end, when the plate was considered to be fully failed, this appeared to be the case.

4.19.2 Test Samples Collected in 1998-99

The sample collection procedure was modified to ensure a sufficient fluid quantity would be collected. Four samples were collected from each test, when possible. A clean fluid sample was collected before the test

TABLE 4.5

FAILURE SAMPLES COLLECTED AT NRC IN 1997-98
FLUID BRIX AND VISCOSITY

Fluid	Test ID	Exp. Brix	Viscosity (cp) 0.3 rpm	Viscosity (cp) 6 rpm	Viscosity (cp) 30 rpm	Sample Locations
UCAR Ultra+/100	1,4	5.5	0	0	0	All Locations
Octagon 4/100	2,3	12	N/A	N/A	N/A	All Locations
UCAR XL54	5,7,14,18	0	0	0	0	All Locations
UCAR Ultra+/100	6,9	1.5	0	0	0	All Locations
Octagon 4/100	8,11	2.5	0	0	0	Remainder
Octagon 4/100	8,11	5.5	N/A	N/A	N/A	At Failure Boundary
UCAR Ultra+/100	13,19	0	0	0	0	All Locations
SPCA AD-480/100	15,17	0.2	0	0	0	All Locations
Octagon 4/100	16	0	N/A	N/A	N/A	All Locations
UCAR Ultra+/100	20,22	1.5	N/A	N/A	N/A	All Locations
Octagon 4/100	21,23	1	N/A	N/A	N/A	All Locations
UCAR Ultra+/100	24	10.5	N/A	N/A	N/A	All Locations
Octagon 4/100	25,26	10	0	0	0	Remainder
Octagon 4/100	25,26	15	N/A	N/A	N/A	At Failure Boundary
SPCA AD-480/100	28	23	15200	1600	492	All Locations

Note: Viscosity recorded using Brookfield LVII at 20°C, SCR-16/8R
- N/A (not enough fluid available to measure viscosity)

started. This sample served both as a verification of the fluid poured and as a reference of the viscosity of the fluid before contamination.

The other samples represent the top, middle and bottom thirds of the plate once complete plate failure was called and the test was stopped.

The fluid viscosity of the samples was then tested with a Brookfield Viscometer model LVII at 20°C using spindle 31 and the small sample adapter. Most samples collected were of sufficient volume for individual viscosity measurement. The results of the fluid viscosity tests are shown in Table 4.6 and 4.7 along with the Brix value for each sample.

For the majority of the tests, the viscosity of samples collected after complete plate failure was relatively close to the viscosity of water. The Brix values show a distinctive top-to-bottom pattern in most of the tests.

Kilfrost ABC-S was tested in freezing drizzle precipitation with different temperatures and precipitation rates. The samples from the colder temperature tests, 41 and 42, contained a considerable residual viscosity. At colder temperatures the mechanism responsible for the standard plate failure was ice bridging. A film of uncontaminated fluid was still present under the layer of frozen precipitation resting on top of the deicing fluid. When the sample was collected, the uncontaminated fluid and the contaminated fluid were combined into one sample. The residual viscosity is a function of the quantity of uncontaminated fluid underlying the frozen contamination.

The remainder of the Kilfrost tests were performed at a higher ambient temperature. At these temperatures the viscosity of the fluids was lower and the fluid flowed down the plate more readily. Dilution failures resulted from the fluid mixing with the contaminant and thinning out as the tests progressed. At standard plate failure, the fluid layer was very thin, due to fluid draining off the plate. The Brix values measured validate the behaviours described above.

The fluid viscosity of Octagon Max-Flight samples was difficult to measure. The repeatability of the viscosity tests was questionable. After the standard test duration, the viscosity of the fluid was not stable for some of the tests. A second questionable behaviour was the increase in viscosity observed in samples from tests 45 and 47. The clean fluid viscosity at 0.3 rpm was measured at 2000 mPa for the sample from test number 47. The viscosities of the failed samples were 8200, 9800 and 15 600 for the top, middle and bottom respectively. These values represent viscosity increases from four to eight times the uncontaminated fluid viscosity.

TABLE 4.6

NATURAL SNOW FAILURE SAMPLES COLLECTED IN JANUARY 1999
FLUID BRIX AND VISCOSITY

Run	Fluid Name	Concentration	Rate (g/dm²/h)	Condition	Temperature (°C)	Brix	Viscosity (0.3 rpm)	Viscosity (6 rpm)	Viscosity (30 rpm)	Comment
January 12th										
29	Octagon Max-Flight	Neat	0.9	Natural Snow	-22.0	N/A	N/A	N/A	N/A	D1-U Top
29	Octagon Max-Flight	Neat	0.9	Natural Snow	-22.0	31.5	4400	700	321	D1-U Middle
29	Octagon Max-Flight	Neat	0.9	Natural Snow	-22.0	33	5400	840	381	D1-U Bottom
30	UCAR ULTRA +	Neat	0.9	Natural Snow	-22.0	34	11100	1160	385	D1-V Top
30	UCAR ULTRA +	Neat	0.9	Natural Snow	-22.0	35	16700	1445	463	D1-V Middle
30	UCAR ULTRA +	Neat	0.9	Natural Snow	-22.0	36	18200	1490	481	D1-V Bottom
January 15th										
31	Octagon Max-Flight	Neat	15.8	Natural Snow	-16.7	37.5	5800	925	434	D1-U Initial
31	Octagon Max-Flight	Neat	15.8	Natural Snow	-16.7	21.8	3800	640	201	D1-U Top
31	Octagon Max-Flight	Neat	15.8	Natural Snow	-16.7	22.5	3600	595	214	D1-U Middle
31	Octagon Max-Flight	Neat	15.8	Natural Snow	-16.7	24.8	3700	545	248	D1-U Bottom
32	UCAR ULTRA +	Neat	15.5	Natural Snow	-16.6	40.5	24700	2025	649	D1-V Initial
32	UCAR ULTRA +	Neat	15.5	Natural Snow	-16.6	17.3	0	60	38	D1-V Top
32	UCAR ULTRA +	Neat	15.5	Natural Snow	-16.6	N/A	N/A	N/A	N/A	D1-V Middle
32	UCAR ULTRA +	Neat	15.5	Natural Snow	-16.6	N/A	N/A	N/A	N/A	D1-V Bottom
33	Fluid X	Std	17.5	Natural Snow	-15.9	41.0	48900	3280	805	D2-U Initial
33	Fluid X	Std	17.5	Natural Snow	-15.9	17.5	4300	650	205	D2-U Top
33	Fluid X	Std	17.5	Natural Snow	-15.9	17.5	4600	695	217	D2-U Middle
33	Fluid X	Std	17.5	Natural Snow	-15.9	17.5	4800	700	217	D2-U Bottom
34	UCAR XL54	Std	9.4	Natural Snow	-16.0	35.0	0	5	2	D2-V Initial
34	UCAR XL54	Std	9.4	Natural Snow	-16.0	13.0	0	0	0	D2-V Top
34	UCAR XL54	Std	9.4	Natural Snow	-16.0	16.0	0	0	0	D2-V Middle
34	UCAR XL54	Std	9.4	Natural Snow	-16.0	16.0	0	0	2	D2-V Bottom
35	Clariant Safewing Four	Neat	16.4	Natural Snow	-15.1	36.3	13200	1480	586	D3-U Initial
35	Clariant Safewing Four	Neat	16.4	Natural Snow	-15.1	19.8	8700	820	270	D3-U Top
35	Clariant Safewing Four	Neat	16.4	Natural Snow	-15.1	20.5	12106	1050	349	D3-U Middle
35	Clariant Safewing Four	Neat	16.4	Natural Snow	-15.1	21.0	12500	1140	360	D3-U Bottom
36	Octagon Max-Flight	Neat	16.6	Natural Snow	-15.0	37.5	5900	945	442	D3-V Initial
36	Octagon Max-Flight	Neat	16.6	Natural Snow	-15.0	21.0	14300	1740	365	D3-V Top
36	Octagon Max-Flight	Neat	16.6	Natural Snow	-15.0	22.0	17400	1940	386	D3-V Middle
36	Octagon Max-Flight	Neat	16.6	Natural Snow	-15.0	23.3	14400	1415	326	D3-V Bottom
37	UCAR ULTRA +	Neat	26.8	Natural Snow	-14.3	40.5	31300	2220	688	D4-U Initial
37	UCAR ULTRA +	Neat	26.8	Natural Snow	-14.3	16.0	0	65	42	D4-U Top
37	UCAR ULTRA +	Neat	26.8	Natural Snow	-14.3	16.5	0	70	43	D4-U Middle
37	UCAR ULTRA +	Neat	26.8	Natural Snow	-14.3	16.5	0	80	48	D4-U Bottom
38	Fluid X	Std	27.3	Natural Snow	-14.3	41.0	50200	3355	834	D4-V Initial
38	Fluid X	Std	27.3	Natural Snow	-14.3	17.5	4200	650	202	D4-V Top
38	Fluid X	Std	27.3	Natural Snow	-14.3	17.0	4500	685	214	D4-V Middle
38	Fluid X	Std	27.3	Natural Snow	-14.3	18.0	5300	695	210	D4-V Bottle
39	UCAR XL54	Std	30.2	Natural Snow	-14.1	48.5	0	5	5	D5-U Initial
39	UCAR XL54	Std	30.2	Natural Snow	-14.1	15.0	0	0	0	D5-U Top
39	UCAR XL54	Std	30.2	Natural Snow	-14.1	15.0	0	0	0	D5-U Middle
39	UCAR XL54	Std	30.2	Natural Snow	-14.1	16.5	0	0	0	D5-U Bottom
40	Clariant Safewing Four	Neat	32.3	Natural Snow	-14.0	35.5	14800	1575	607	D5-V Initial
40	Clariant Safewing Four	Neat	32.3	Natural Snow	-14.0	18.3	5800	425	148	D5-V Top
40	Clariant Safewing Four	Neat	32.3	Natural Snow	-14.0	20.0	6000	570	192	D5-V Middle
40	Clariant Safewing Four	Neat	32.3	Natural Snow	-14.0	21.0	6900	605	215	D5-V Bottom

- Viscosity recorded using Brookfield LVII at 20°C, SC4-31/13R
- N/A (not enough fluid available to measure viscosity)

TABLE 4.7

FAILURE SAMPLES COLLECTED AT NRC IN APRIL 1999 FLUID BRIX AND VISCOSITY

Run	Fluid Name	Comment	Rate (g/dm²/h)	Condition	Temperature (°C)	Brix	Viscosity (0.3 rpm)	Viscosity (6 rpm)	Viscosity (30 rpm)
41	Kilfrost ABC-S	Initial	5.1	Freezing Drizzle	-10.0	35.8	20100	2225	875
41	Kilfrost ABC-S	Top	5.1	Freezing Drizzle	-10.0	27.5	7000	875	307
41	Kilfrost ABC-S	Middle	5.1	Freezing Drizzle	-10.0	22	8500	985	332
41	Kilfrost ABC-S	Bottom	5.1	Freezing Drizzle	-10.0	21.3	7200	925	306
42	Kilfrost ABC-S	Initial	5.3	Freezing Drizzle	-10.0	35.5	20900	2240	807
42	Kilfrost ABC-S	Top	5.3	Freezing Drizzle	-10.0	21	7000	925	314
42	Kilfrost ABC-S	Middle	5.3	Freezing Drizzle	-10.0	21	8800	1065	369
42	Kilfrost ABC-S	Bottom	5.3	Freezing Drizzle	-10.0	21.5	7700	1030	356
43	UCAR ULTRA +	Initial	28.4	Artificial Snow	-12.6	39	26500	2025	666
43	UCAR ULTRA +	Top	28.4	Artificial Snow	-12.6	11	0	30	18
43	UCAR ULTRA +	Middle	28.4	Artificial Snow	-12.6	12	0	80	34
43	UCAR ULTRA +	Bottom	28.4	Artificial Snow	-12.6	14.5	0	90	50
44	UCAR ULTRA +	Initial	10.2	Artificial Snow	-12.7	39	22500	2035	697
44	UCAR ULTRA +	Top	10.2	Artificial Snow	-12.7	7.75	0	40	10
44	UCAR ULTRA +	Middle	10.2	Artificial Snow	-12.7	8.5	0	10	7
44	UCAR ULTRA +	Bottom	10.2	Artificial Snow	-12.7	10.5	0	15	27
45	Octagon Max-Flight	Initial	23.0	Artificial Snow	-11.9	36	2200	555	309
45	Octagon Max-Flight	Top	23.0	Artificial Snow	-11.9	13.3	400	75	215
45	Octagon Max-Flight	Middle	23.0	Artificial Snow	-11.9	15.3	7100	1050	286
45	Octagon Max-Flight	Bottom	23.0	Artificial Snow	-11.9	17.8	9700	1740	421
46	UCAR XL54	Initial	17.9	Artificial Snow	-11.9	36.5	0	0	0
46	UCAR XL54	Final	17.9	Artificial Snow	-11.9	4	0	30	0
47	Octagon Max-Flight	Initial	8.3	Artificial Snow	-12.0	36	2000	540	315
47	Octagon Max-Flight	Top	8.3	Artificial Snow	-12.0	15.8	8200	1720	450
47	Octagon Max-Flight	Middle	8.3	Artificial Snow	-12.0	17	9800	1930	494
47	Octagon Max-Flight	Bottom	8.3	Artificial Snow	-12.0	19.8	15600	2335	561
48	UCAR ULTRA +	Initial	9.4	Artificial Snow	-11.9	39	24300	2060	655
48	UCAR ULTRA +	Top	9.4	Artificial Snow	-11.9	5	100	0	2
48	UCAR ULTRA +	Middle	9.4	Artificial Snow	-11.9	6	0	20	0
48	UCAR ULTRA +	Bottom	9.4	Artificial Snow	-11.9	8	0	0	0
49	Kilfrost ABC-S	Initial	4.7	Freezing Drizzle	-2.9	35.3	19000	2225	829
49	Kilfrost ABC-S	Final	4.7	Freezing Drizzle	-2.9	1	0	0	0
50	Kilfrost ABC-S	Initial	5.0	Freezing Drizzle	-2.9	35.3	20500	2230	823
50	Kilfrost ABC-S	Final	5.0	Freezing Drizzle	-2.9	1	500	0	0
51	Octagon Max-Flight	Initial	9.8	Artificial Snow	-4.1	36	1600	515	313
51	Octagon Max-Flight	Top	9.8	Artificial Snow	-4.1	10	0	20	114
51	Octagon Max-Flight	Middle	9.8	Artificial Snow	-4.1	11.3	0	35	177
51	Octagon Max-Flight	Bottom	9.8	Artificial Snow	-4.1	12	0	45	168
52	Octagon Max-Flight	Initial	26.7	Artificial Snow	-4.2	35.8	2300	505	311
52	Octagon Max-Flight	Top	26.7	Artificial Snow	-4.2	12.5	0	170	249
52	Octagon Max-Flight	Middle	26.7	Artificial Snow	-4.2	13.3	0	50	153
52	Octagon Max-Flight	Bottom	26.7	Artificial Snow	-4.2	16	2900	1510	398
53	UCAR ULTRA +	Initial	29.0	Artificial Snow	-4.2	39	27900	2160	723
53	UCAR ULTRA +	Top	29.0	Artificial Snow	-4.2	5.75	0	0	1
53	UCAR ULTRA +	Middle	29.0	Artificial Snow	-4.2	7.25	0	0	7
53	UCAR ULTRA +	Bottom	29.0	Artificial Snow	-4.2	8	0	5	10
54	Kilfrost ABC-S	Initial	12.4	Freezing Drizzle	-2.9	35	21700	2360	857
54	Kilfrost ABC-S	Top	12.4	Freezing Drizzle	-2.9	0.5	100	0	4
54	Kilfrost ABC-S	Bottom	12.4	Freezing Drizzle	-2.9	0.5	0	0	0
55	Kilfrost ABC-S	Initial	12.8	Freezing Drizzle	-2.9	35	20900	2305	845
55	Kilfrost ABC-S	Final	12.8	Freezing Drizzle	-2.9	1	0	0	2
56	UCAR XL54	Initial	5.9	Artificial Snow	-4.5	33.5	0	0	3
56	UCAR XL54	Final	5.9	Artificial Snow	-4.5	1	0	0	0
57	UCAR XL54	Initial	24.4	Artificial Snow	-4.6	35	0	0	5
57	UCAR XL54	Final	24.4	Artificial Snow	-4.6	7	0	0	0

- Viscosity recorded using Brookfield LVII at 20°C, SC4-31/13R

The viscosities of the samples collected from the Ultra+ in natural and artificial snow tests were approximately equal to the viscosity of water. The main failure mechanism of this fluid is dilution failure. The fallen precipitation is quickly absorbed into the fluid layer and the diluted fluid flows down the test surface. The snow precipitation created a slushy mass of fluid during the tests. The samples collected were a combination of fluid and partially melted snow. When the samples were melted, the resulting fluid was a highly diluted combination of Ultra+ and water.

4.19.3 Viscosity at Various Concentrations

To understand whether the measured viscosity values were typical of Type IV fluids at low concentration, three Type IV brands (one ethylene glycol-based, two propylene glycol-based) were diluted to various concentrations, and their viscosities measured. The resulting data are displayed graphically in Figures 4.6 and 4.7, which show the viscosities plotted as a function of concentration.

These curves display very different characteristics for the fluids. The ethylene glycol-based fluid (Union Carbide Ultra+) demonstrated a direct relationship between concentration and viscosity, with viscosity values decreasing rapidly as concentration decreased. At a 50/50 concentration, the fluid viscosity had reduced to zero. In contrast, the propylene glycol-based fluid SPCA AD-480 displayed an initial increase in viscosity while concentration was decreased, with the viscosity peaking at about a 60/40 concentration, and returning to initial value at about a 45/55 concentration. Viscosity values then decreased rapidly and reached a value of zero at a 30/70 mix.

Dilution tests were performed at various temperatures for the Kilfrost ABC-S fluid. One of the purposes of this analysis was to obtain further insight into the two different failure progressions demonstrated by this fluid. The results of the viscosity tests, as well as the Brix values for each fluid dilution, are shown in Figure 4.8. The following possible explanation was found for the viscosity behaviour as a function of temperature.

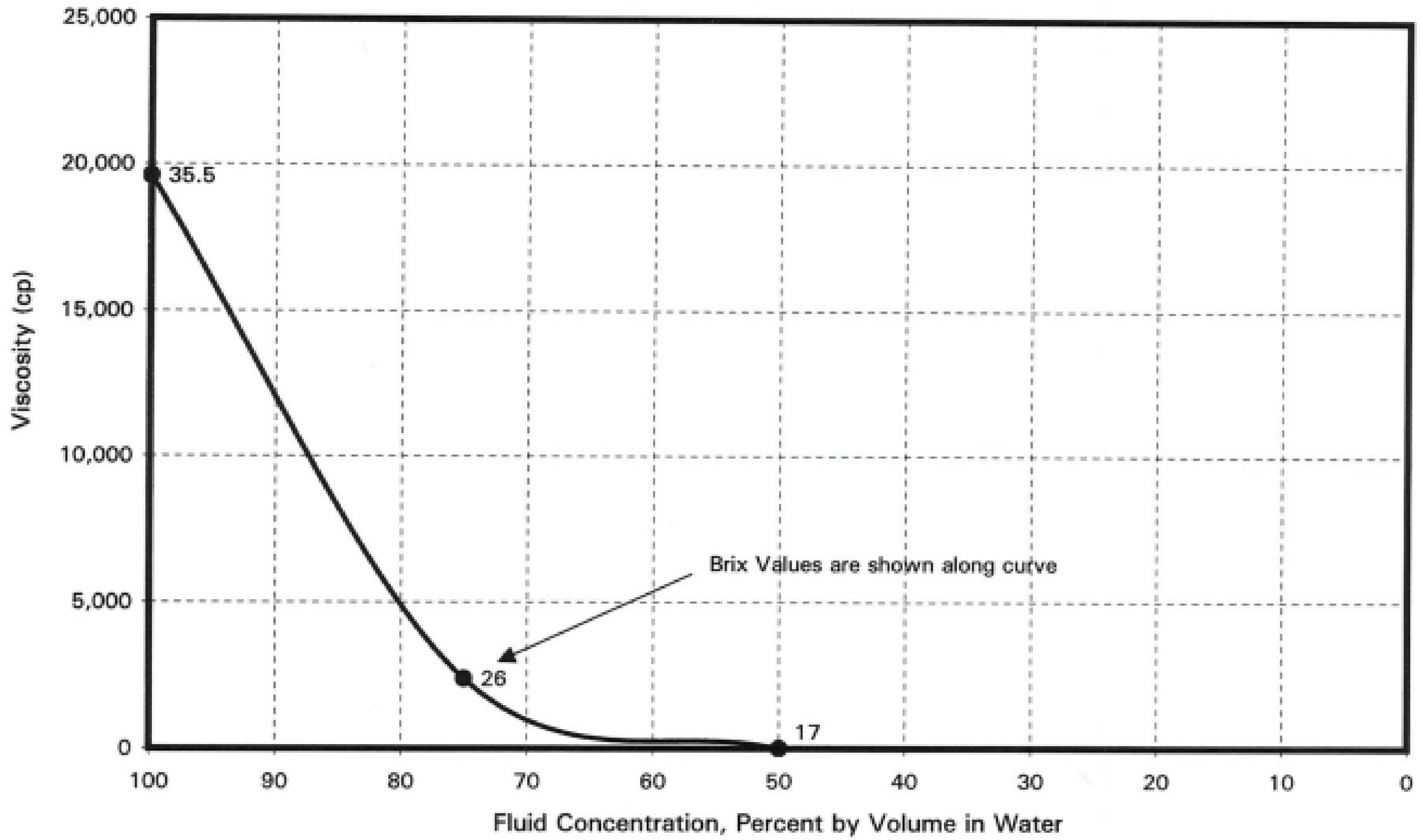
The viscosity of the fluid at -10°C is inferior to the viscosity at -3°C by design. If the fluid viscosity continued to increase as temperature decreased the fluid would not shear off the aircraft wing during rotation at colder temperatures.

The viscosity tests tend to support the observation that an important degree of protective capacity still existed at the time of standard failure call.

FIGURE 4.6

VISCOSITY VERSUS CONCENTRATION FLUID PROFILE

(Ultra +) at 20°C



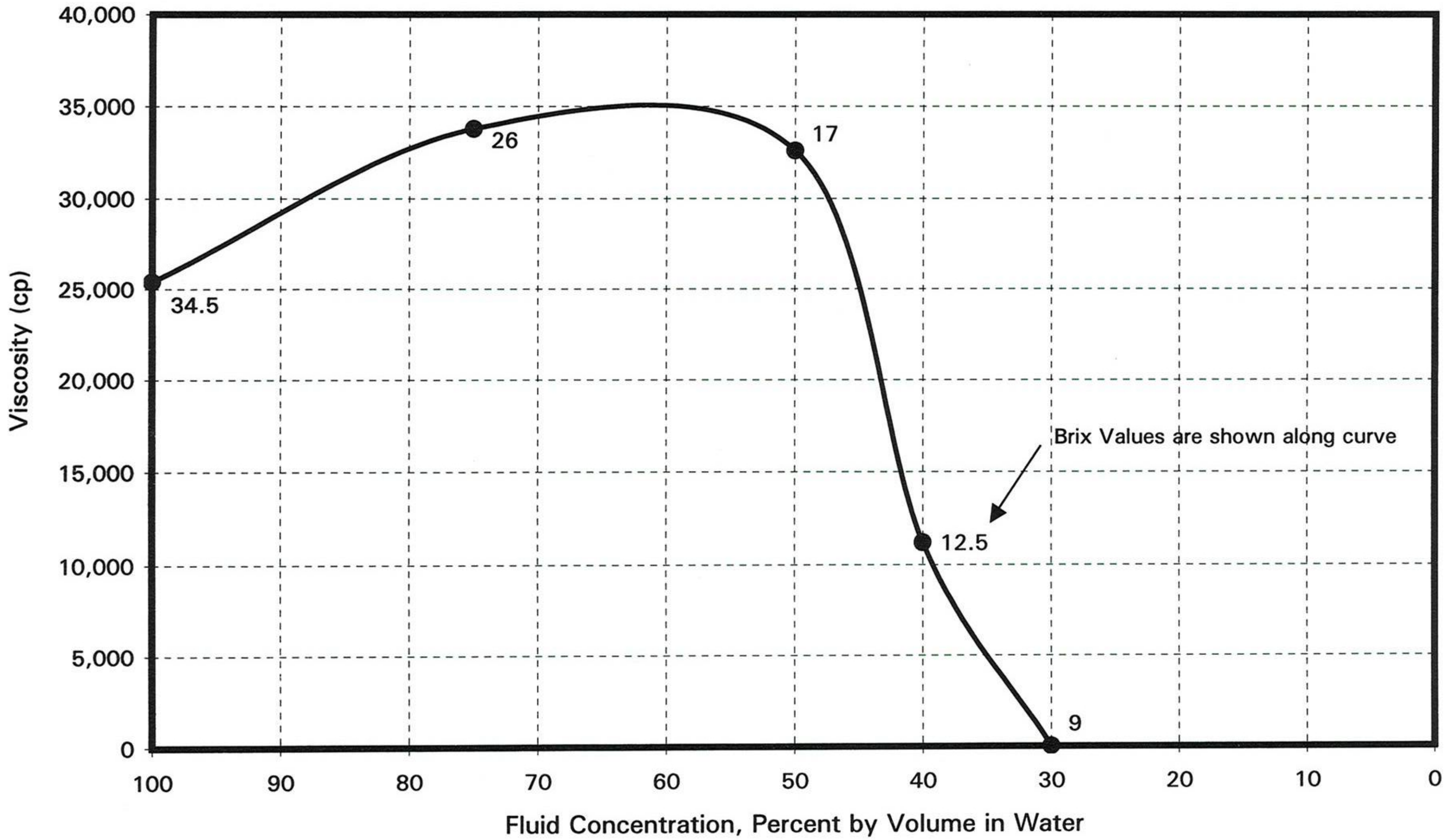
cm1514/report/doc_fail/PETRVISC
At: U+

Viscosity measurements taken at 0.3 Rpm, SCR-34/13R

FIGURE 4.7

VISCOSITY VERSUS CONCENTRATION FLUID PROFILE

(SPCA AD-480) at 20°C

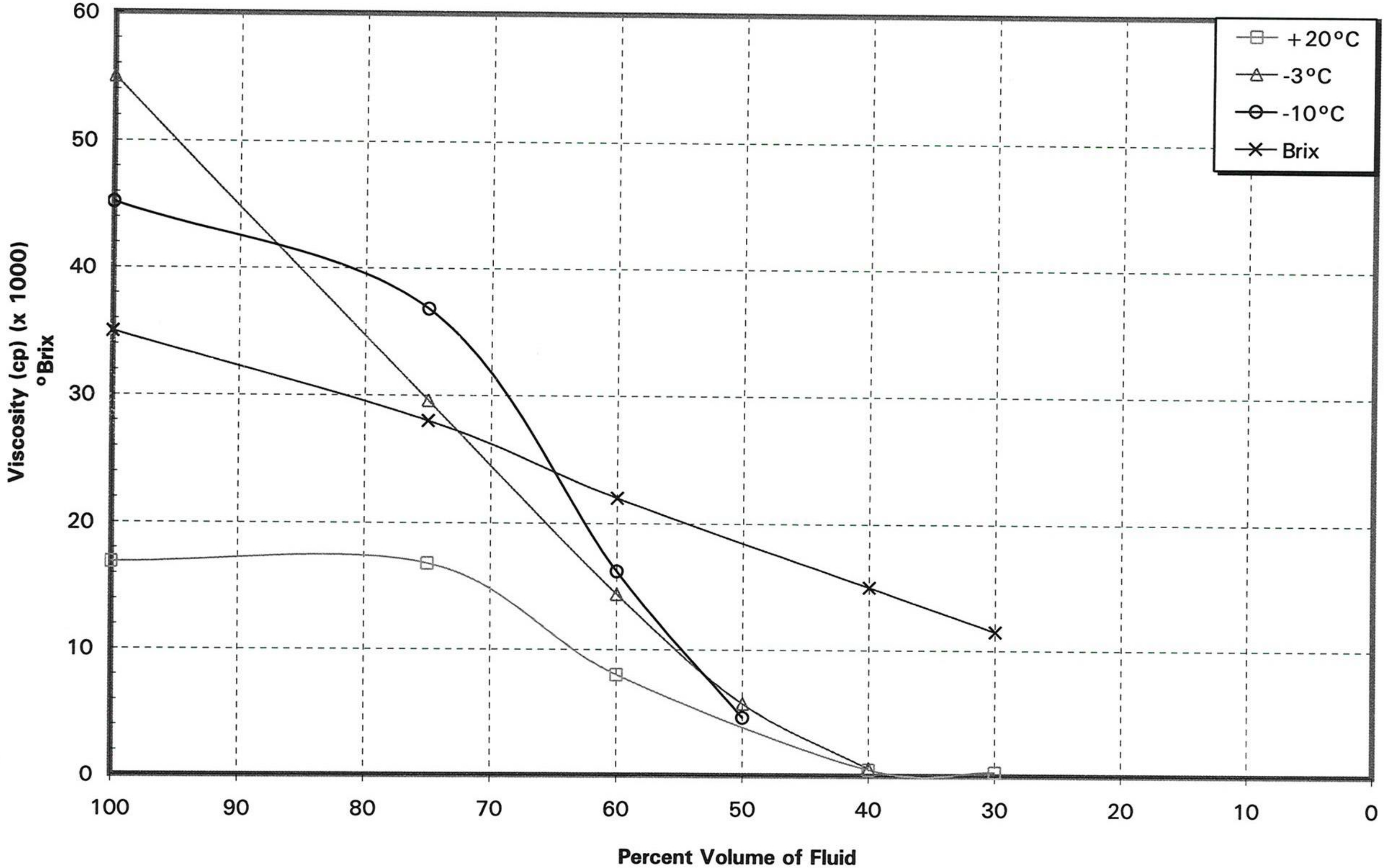


cm1514/report/doc_fail/PETRVISC
At: SPCA

Viscosity measurements taken at 0.3 Rpm, SCR-34/13R

FIGURE 4.8

VISCOSITY OF KILFROST ABC-S AT VARIOUS TEMPERATURES



Viscosity measurements taken at 0.3 Rpm, SC4-31/13R

h:\cm1514\report\doc_fail\kilfrost viscosity

This observation draws attention to the difficulty in making valid visual judgements on fluid failure for fluids exhibiting this failure mode. It also indicates the possibility that the full anti-icing capacity of the fluid is not being used in field operations.

It was noted that neither the C/FIMS nor the RVSI ice detection sensor traces gave a clear indication of the point of fluid failure in these tests. Interpretation of images from the RVSI system (Photos 4.10 and 4.11), however, does lead to the conclusion that the fluid had reached its operational limit.

It is possible that the visual failure calls are correct, if the fluids that accumulate frozen precipitation in the upper strata of the applied fluid film become immobilized. This could occur upon fusion of the contamination layer and may occur in spite of a layer of uncompromised fluid remaining in the lower strata of the applied fluid film.

4.20 Adhesion of Type I and Type IV Fluids

The adhesion of contaminant to the test surface was found to be highly dependent on the fluid properties at test temperature, as well as the type of precipitation. During freezing drizzle and freezing rain, adhesion was detected in a significant number of tests. After the onset of initial failure, given the proper conditions, the precipitation will begin to adhere to the test surface.

4.20.1 Freezing Drizzle and Freezing Rain Adherence

Type I fluids adhere to the substrate surface very quickly after failure. As discussed in section 4.1.4, these fluids can begin to adhere to the plate approximately 1 minute after failure. Figure 4.9 shows approximate time to adhesion points on the same graph as time to failure curves. The short time between the curves and the quick failures does not provide a large safety window for aircraft takeoff.

Type IV fluid failure adherence time curves are shown in Figure 4.10. The ambient temperature and the type of fluid have a significant impact on the mechanism that causes the fluid failure. Ethylene glycol-based fluids (Ultra+) fail due to fluid dilution and fluid layer thinning. As the contaminant falls on the surface, the fluid is diluted and runs off the test plate. The fluid freeze point increases as precipitation falls on the plate surface, and once failure is called, a small margin exists between the air temperature and the fluid freeze point. The additional precipitation absorbed by the fluid after failure causes the fluid to adhere to the plate surface.

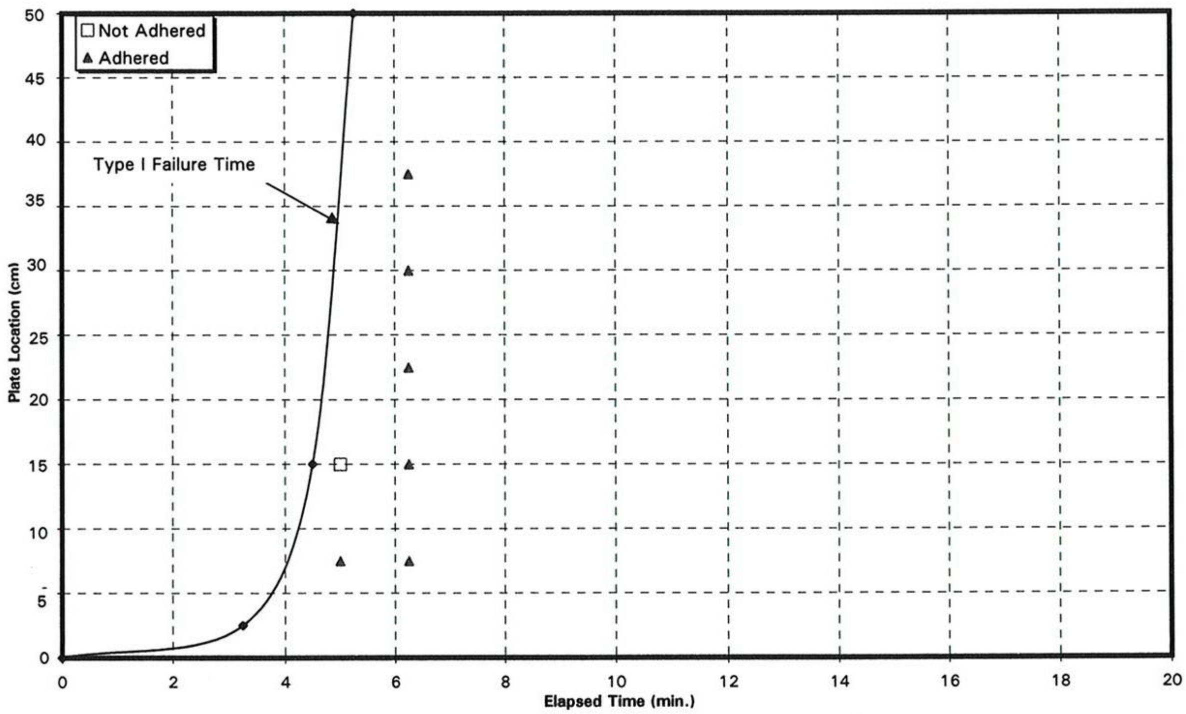
Propylene glycol-based fluids at colder temperatures fail due to surface bridging. According to this mechanism of failure, the precipitation remains on the top surface of the fluid and a layer of uncontaminated fluid remains between the substrate and the contamination. Figure 4.11 indicates that adhesion was detected during Kilfrost ABC-S tests at temperatures of -3°C, and Figure 4.12 shows that adhesion was not detected during Kilfrost ABC-S tests at temperatures of -10°C. At warmer temperatures the viscosity of the fluid is decreased and the failure mechanism is different.

FIGURE 4.9

ADHESION COMPARISON: TYPE I ETHYLENE GLYCOL-BASED FLUID

ID # 5 (UCAR XL54)

Light Freezing Rain, OAT = -10°C, Precipitation Rate = 24.5 g/dm²/h



ID # 18 (UCAR XL54)

Light Freezing Rain, OAT = -4°C, Precipitation Rate = 24.1 g/dm²/h

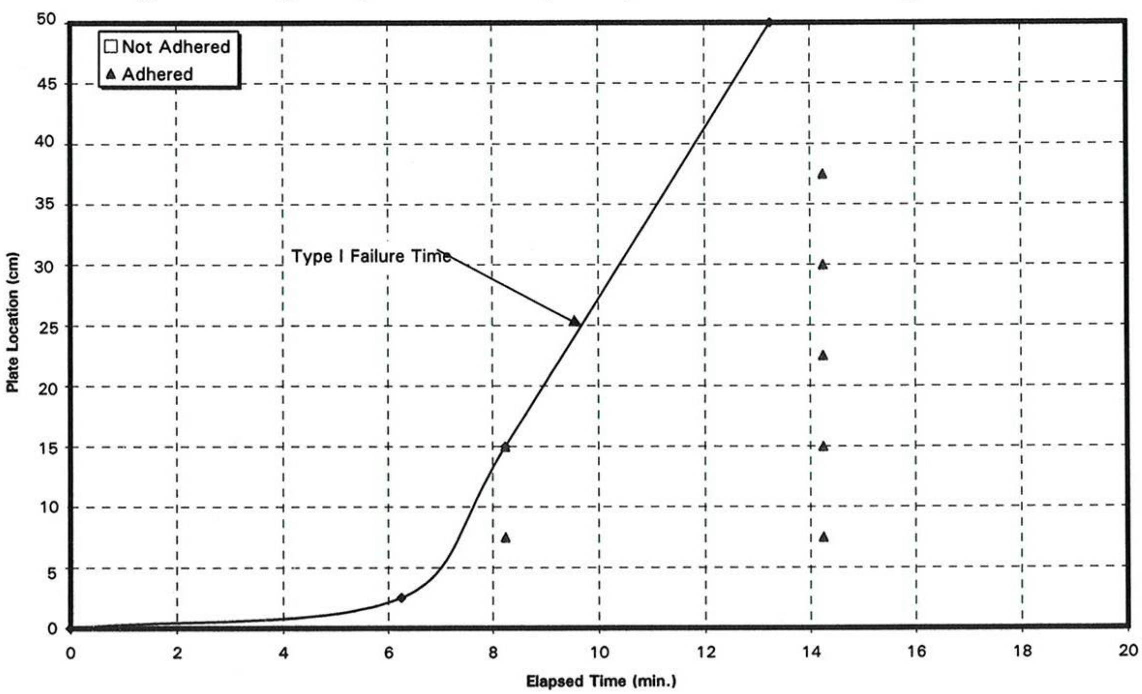
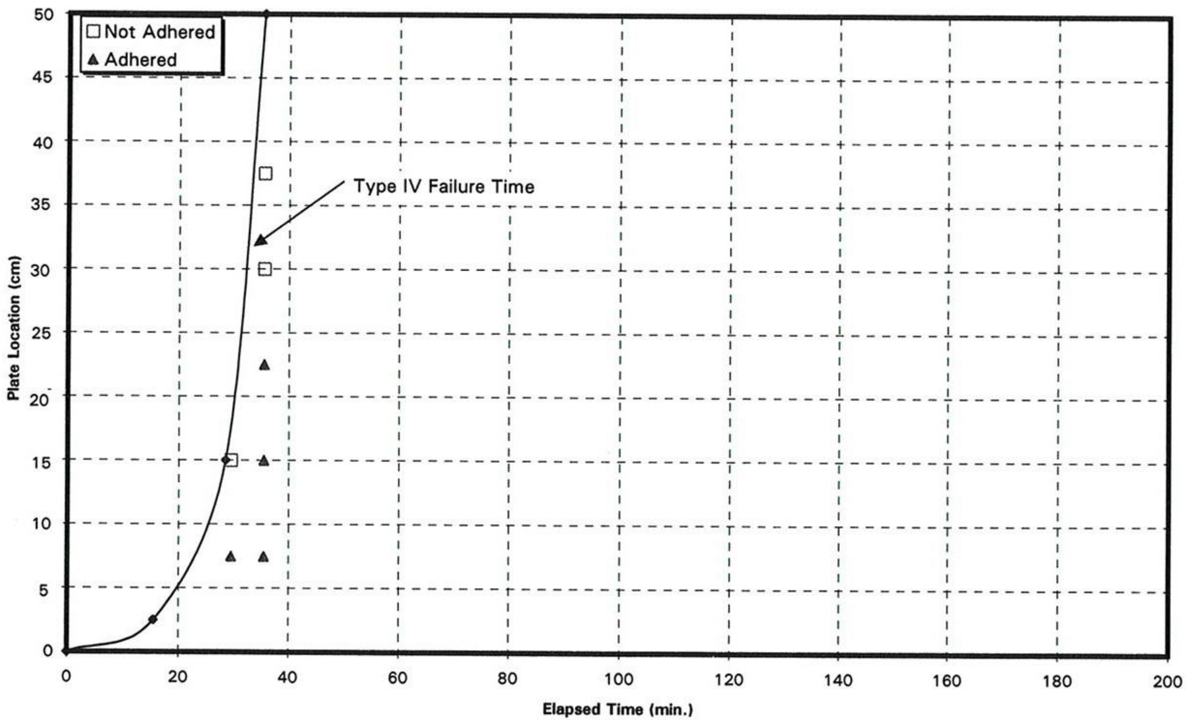


FIGURE 4.10

ADHESION COMPARISON: TYPE IV ETHYLENE GLYCOL-BASED FLUID

ID # 9 (UCAR ULTRA+)
Light Freezing Rain, OAT = -10°C, Precipitation Rate = 24.5 g/dm²/h



ID # 53 (UCAR ULTRA+)
Simulated Snow, OAT = -4°C, Precipitation Rate = 29.0 g/dm²/h

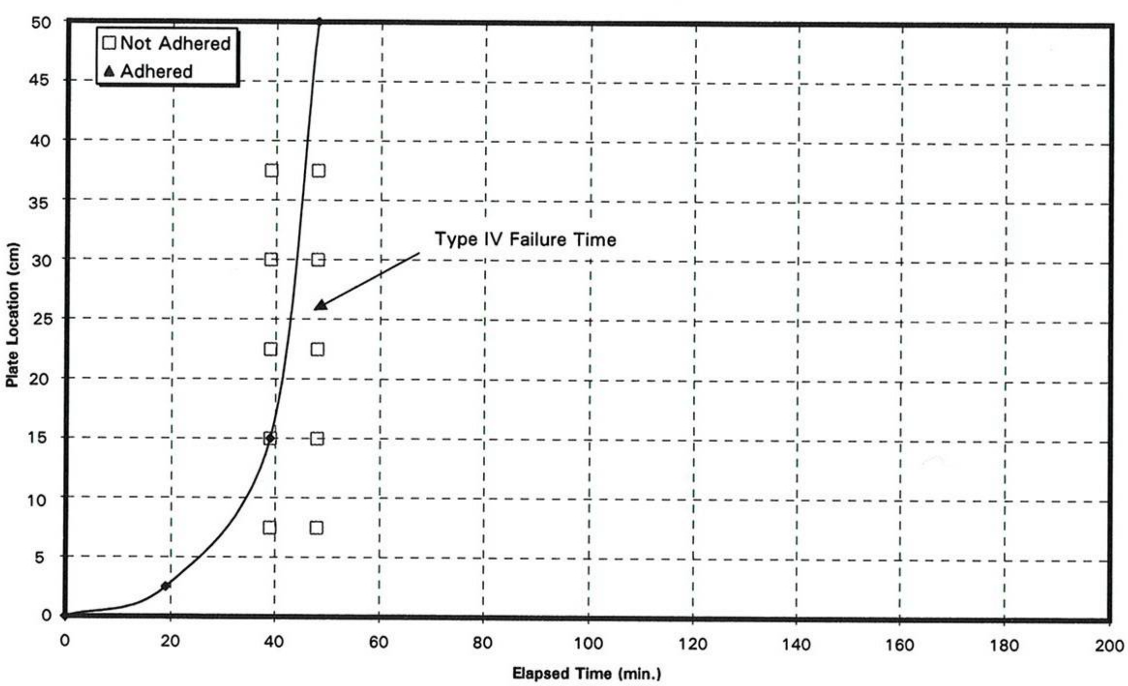
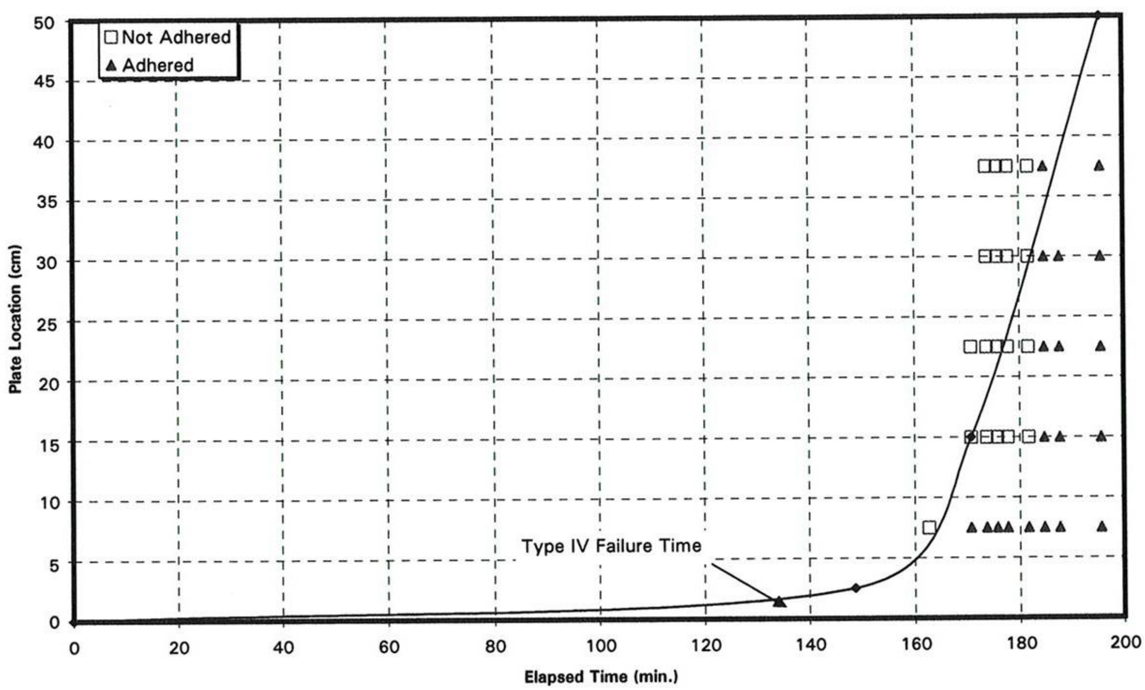


FIGURE 4.11

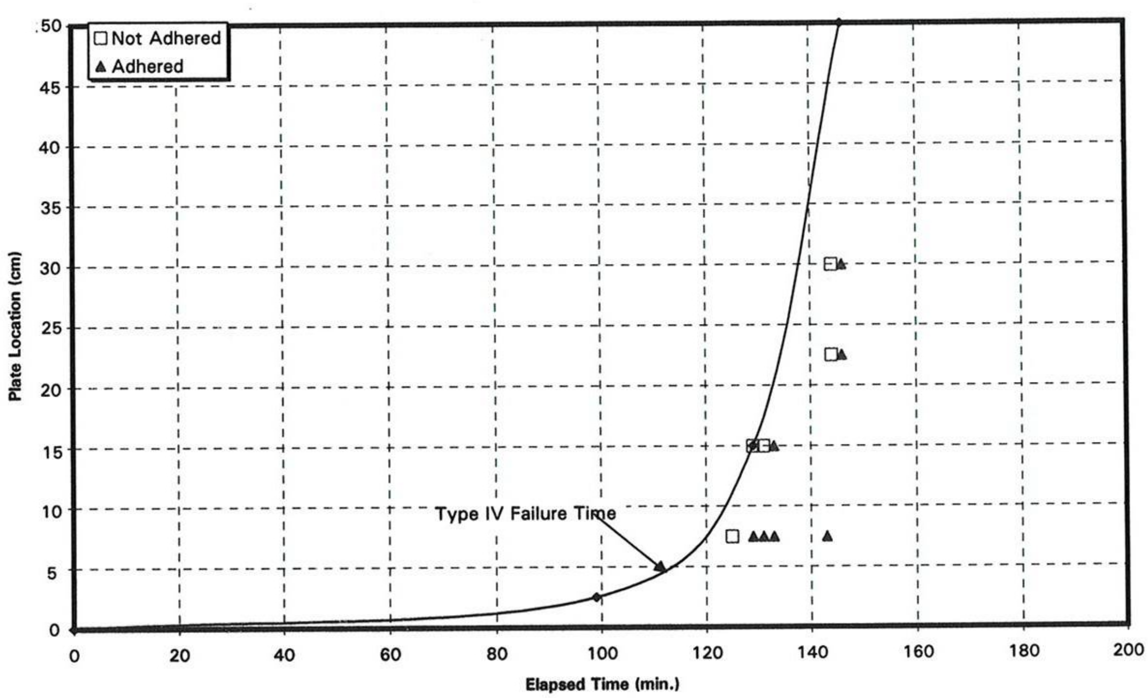
ADHESION COMPARISON: TYPE IV PROPYLENE GLYCOL-BASED FLUID IN HIGH RATE FREEZING DRIZZLE AT -3°C

Freezing Drizzle (13 g/dm²/h)

ID # 49 (KILFROST ABC-S)



ID # 54 (KILFROST ABC-S)



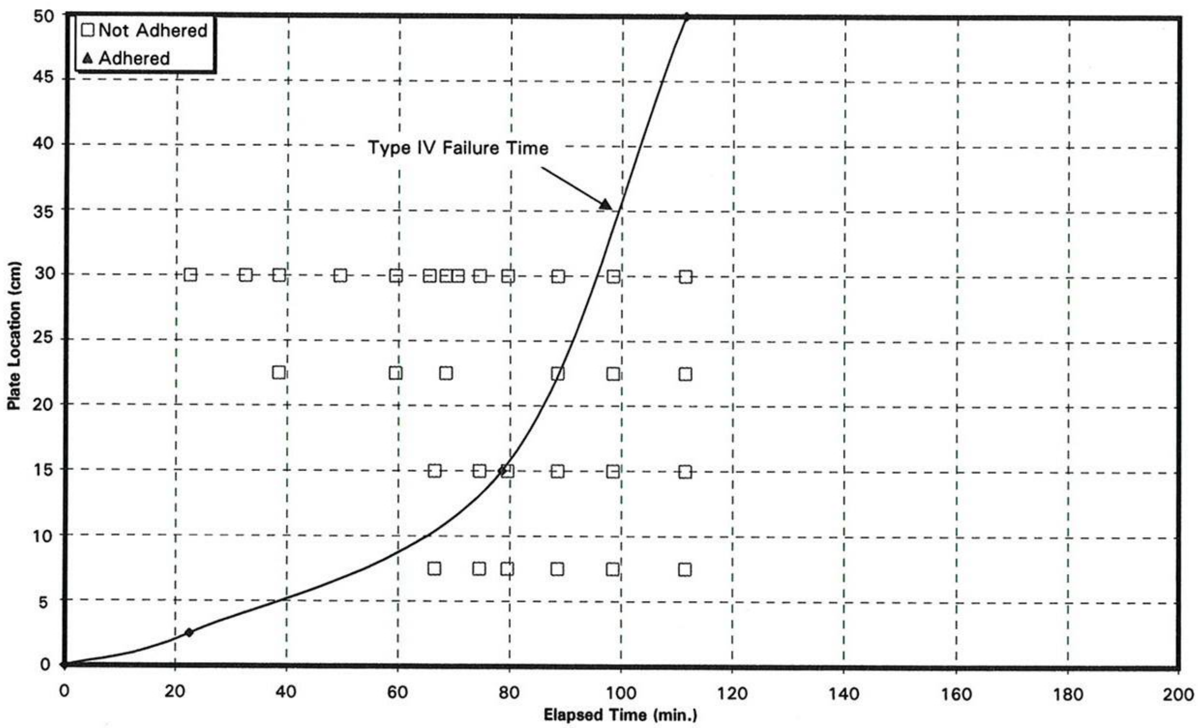
CM1514/Report/Doc_Fail/Adherence Kilfrost

FIGURE 4.12

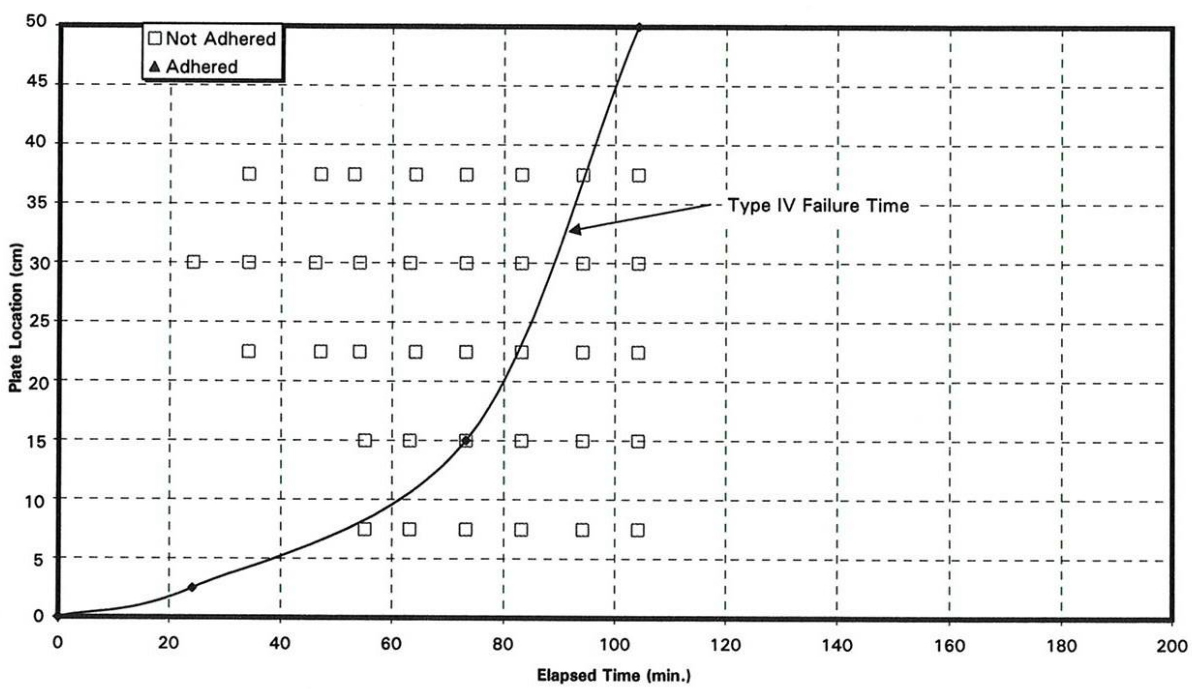
ADHESION COMPARISON: TYPE IV PROPYLENE GLYCOL-BASED FLUID IN LOW RATE FREEZING DRIZZLE AT -10°C

Freezing Drizzle (5 g/dm²/h)

ID # 41 (KILFROST ABC-S)



ID # 42 (KILFROST ABC-S)



4.20.2 Snow Adherence

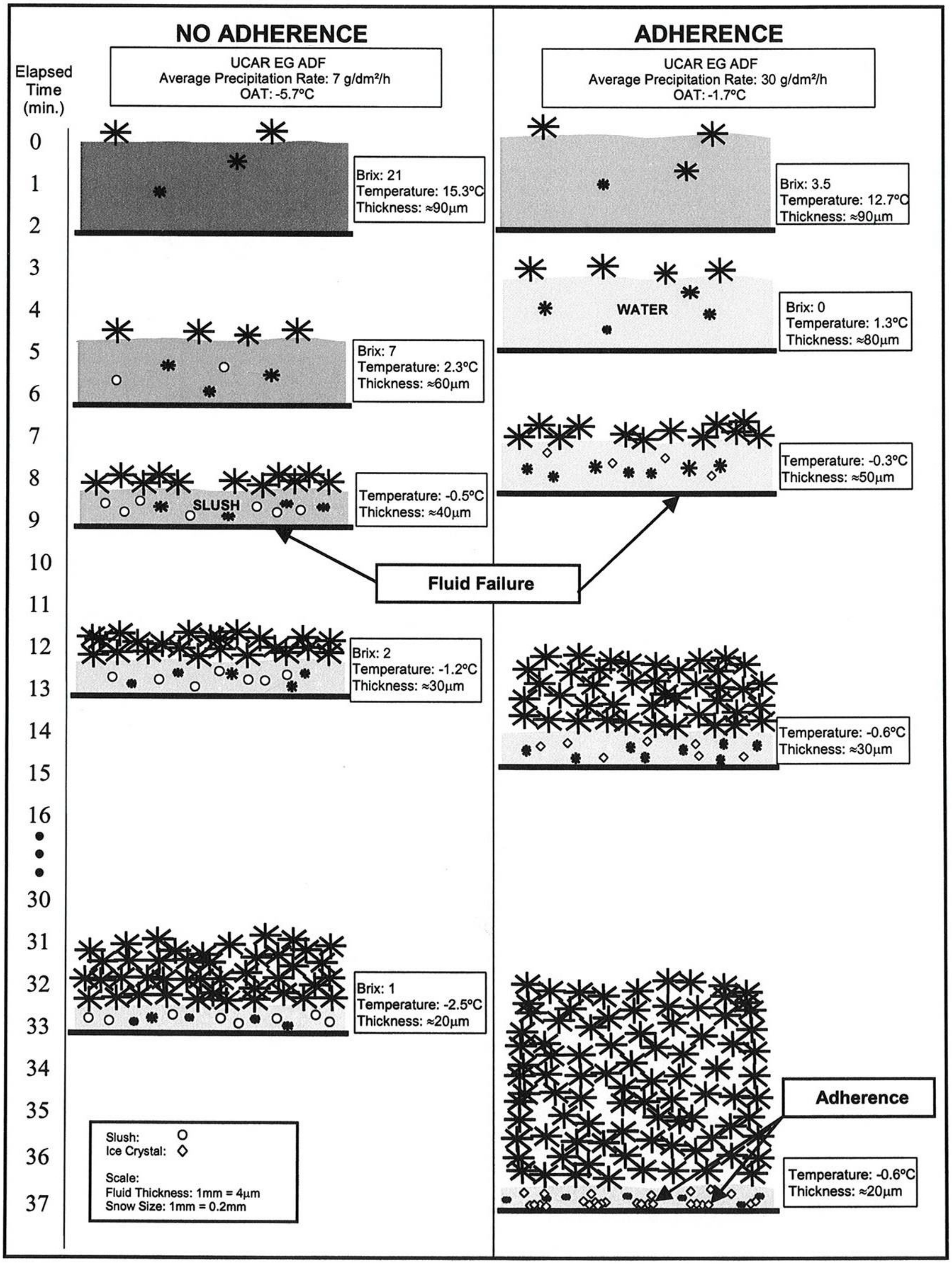
Figure 4.13 shows the difference in failure mechanisms that may be experienced during snow precipitation conditions. The left side of the figure shows an example of a typical test where no adhesion was experienced and the right side shows an example of a test when adhesion was experienced about 29 minutes after failure was visually observed. Adhesion occurred because the solution was fully diluted by the incoming precipitation before the plate temperature fell below 0°C.

Adherence was not detected in any of the natural or artificial snow tests performed during this study. Independent of fluid type, ambient temperature and rate of precipitation, snow did not adhere to the test surface. One possible explanation for this behaviour is the capillarity of snowflakes.

Capillarity is a property that a porous solid medium exhibits with a fluid as a result of attractive forces between the porous medium and the fluid. The forces operative 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, F_a, occur between the fluid and the medium. Cohesional forces, F_c, act among the components of the fluid. When $F_a > F_c$, 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. Insulating effects are likely operative only once a considerable layer of dry snow has accumulated over the already failed region.

FIGURE 4.13
TYPE I FAILURE MECHANISM DURING NATURAL SNOW



4.21 C/FIMS Ice Detection Sensor Analysis

The following comparisons were made based on observation of the C/FIMS traces recorded during the tests performed for this study. The traces varied greatly for each individual fluid, depending on ambient temperature, precipitation rate and precipitation type. Depending on the type of fluid and failure mechanism displayed by that fluid, one of two general behaviours was observed. In most tests the trace either remained constant or climbed (due to contaminant absorption) before initial failure.

4.21.1 Ethylene Glycol-Based Fluids Traces

Figure 4.14 shows that the ethylene glycol-based Type IV fluid (Ultra+) produces a near constant C/FIMS trace from the fluid pour until the start of initial failure. At this time the slope of the trace takes on a negative value. The C/FIMS-B trace displayed more sensitivity to the changing plate condition. For most freezing precipitation tests, the plate failure was easily distinguished from the trace due to the change of the slopes from negative to positive, approximately at the standard plate failure call time.

Ultra+ fluid absorbs the precipitation into the fluid layer, contrary to most propylene glycol-based fluids that suspend the contaminant in the upper fluid surface. This mechanism of precipitation absorption and fluid dilution is more conducive to C/FIMS analysis. Since the sensor is in contact with a less stratified fluid layer, a more accurate measurement of the fluid properties is possible.

The traces recorded for Type I UCAR XL54 are shown in Figure 4.15. These traces are difficult to interpret and do not indicate the time of failure with any confidence. If the time of failure is known, it is possible to observe fluctuations in the C/FIMS trace that may be indicators of failure, but finding the time of failure from the traces is difficult. The results of Type I tests are not very reproducible. The failure times are very short and the fluid layer may be too thin for C/FIMS analysis.

4.21.2 Propylene Glycol-Based Type IV Fluids Traces

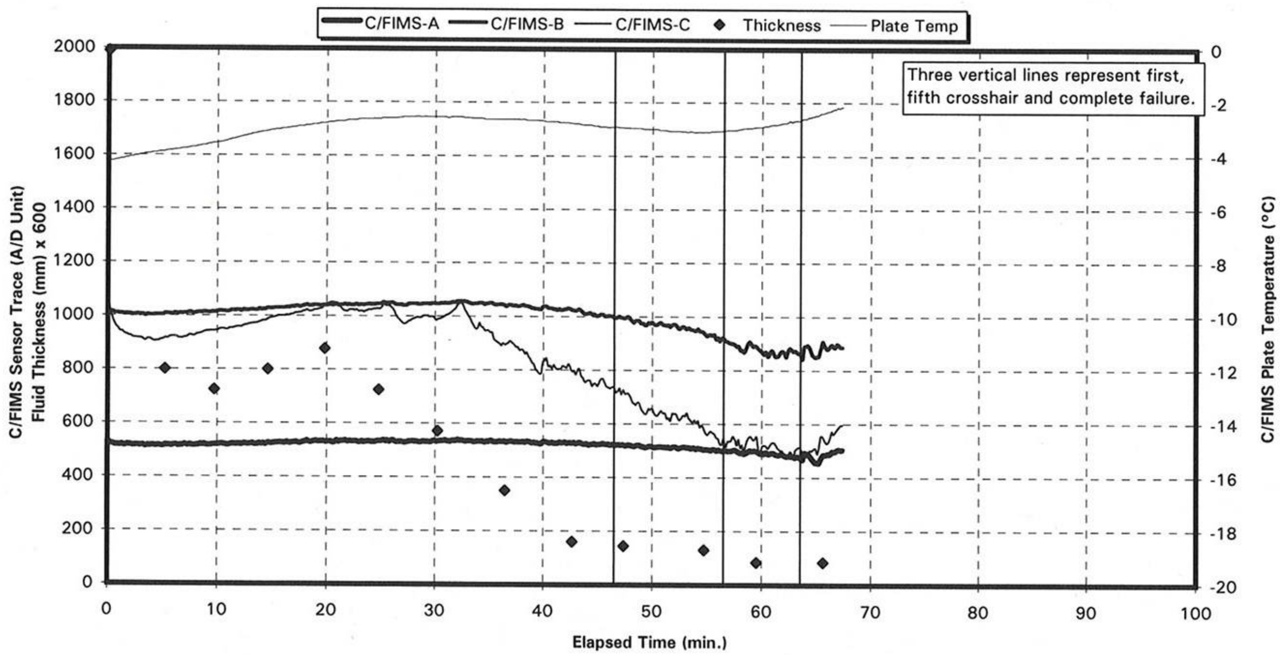
Strong indicators of failure were detected in the traces recorded for the low viscosity propylene Type IV fluid Octagon Max-Flight in freezing precipitation conditions with ambient temperature of -3°C. Figure 4.16 compares the C/FIMS traces recorded for different precipitation rates and conditions. A rapidly changing slope is present on all the freezing

FIGURE 4.14

C/FIMS TRACES FOR UCAR ULTRA+ IN PRECIPITATION CONDITIONS TYPE IV ETHYLENE GLYCOL-BASED FLUID

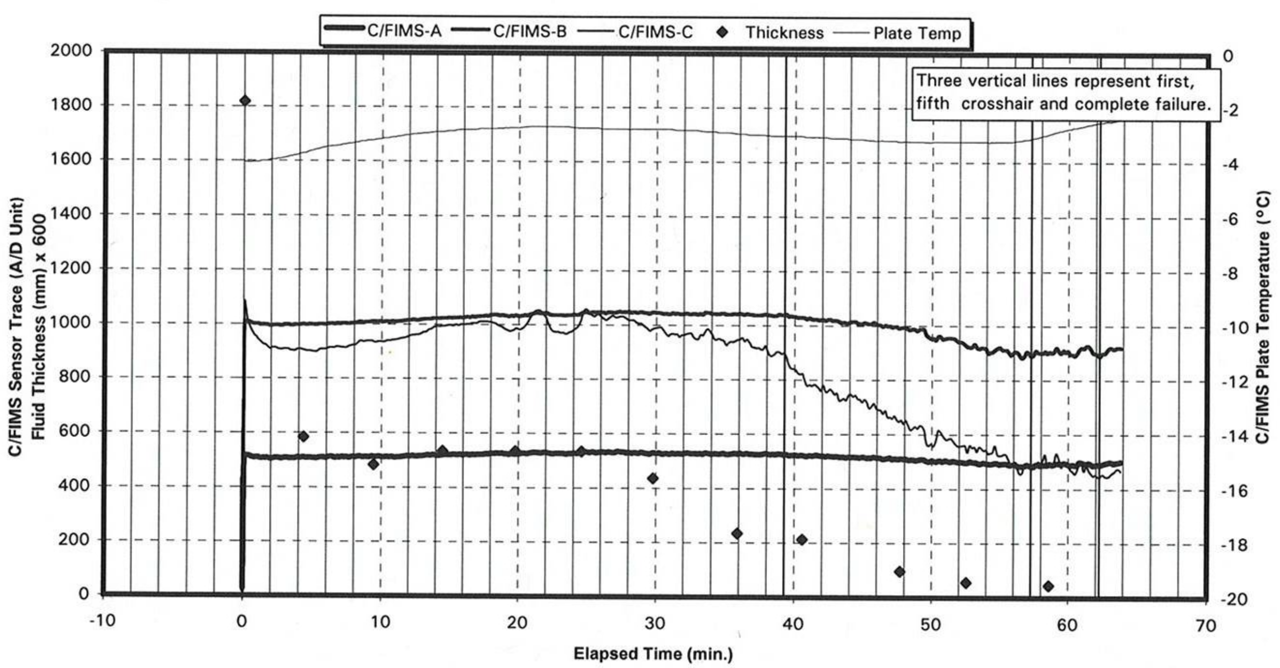
ID # 20

Freezing Drizzle, OAT = -3°C, Precipitation Rate = 12.4 g/dm²/h



ID # 22

Freezing Drizzle, OAT = -3°C, Precipitation Rate = 13.0 g/dm²/h



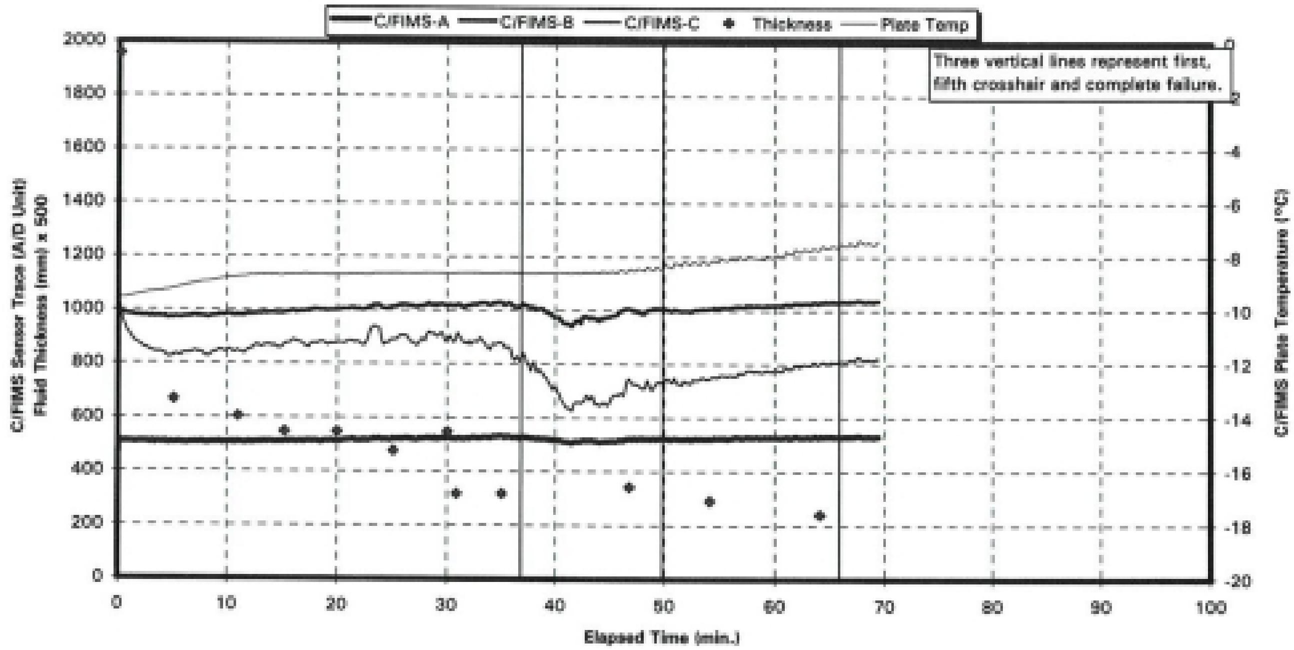
cm1514/report/doc_fail/CF_THK_U AT:ID 20, ID 22

FIGURE 4.14 (cont.)

C/FIMS TRACES FOR UCAR ULTRA+ IN PRECIPITATION CONDITIONS TYPE IV ETHYLENE GLYCOL-BASED FLUID

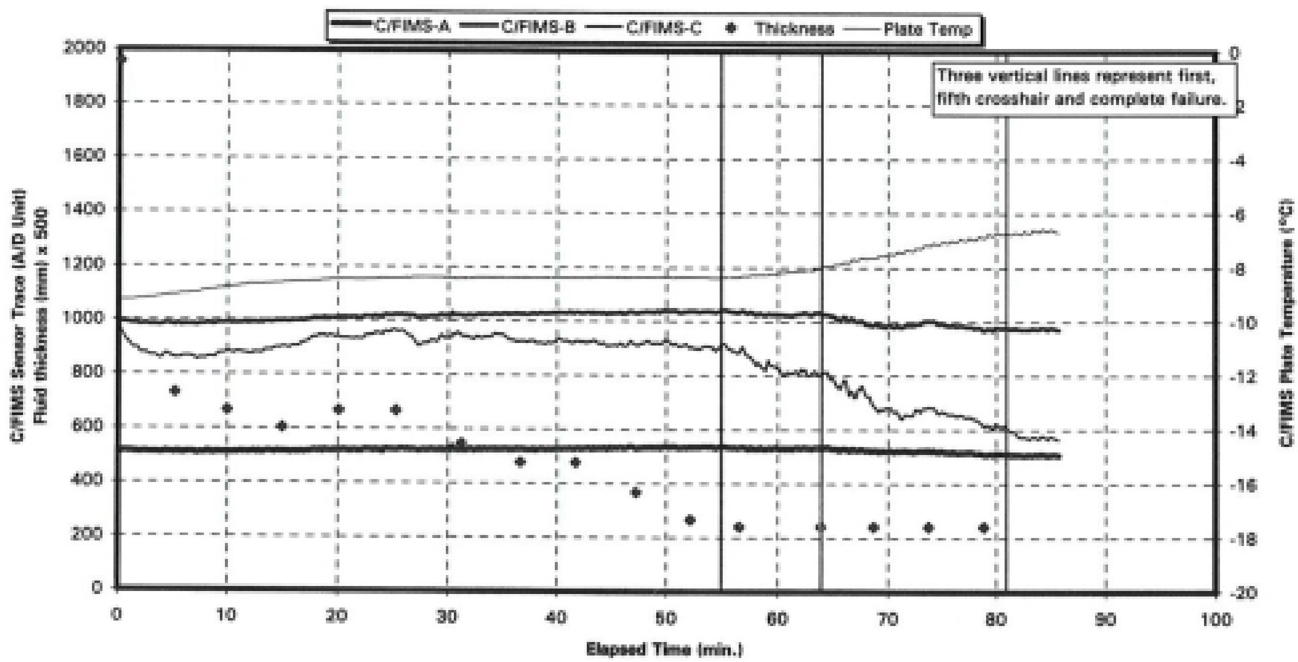
ID # 1

Freezing Drizzle, OAT = -10°C, Precipitation Rate = 10.4 g/dm²/h



ID # 4

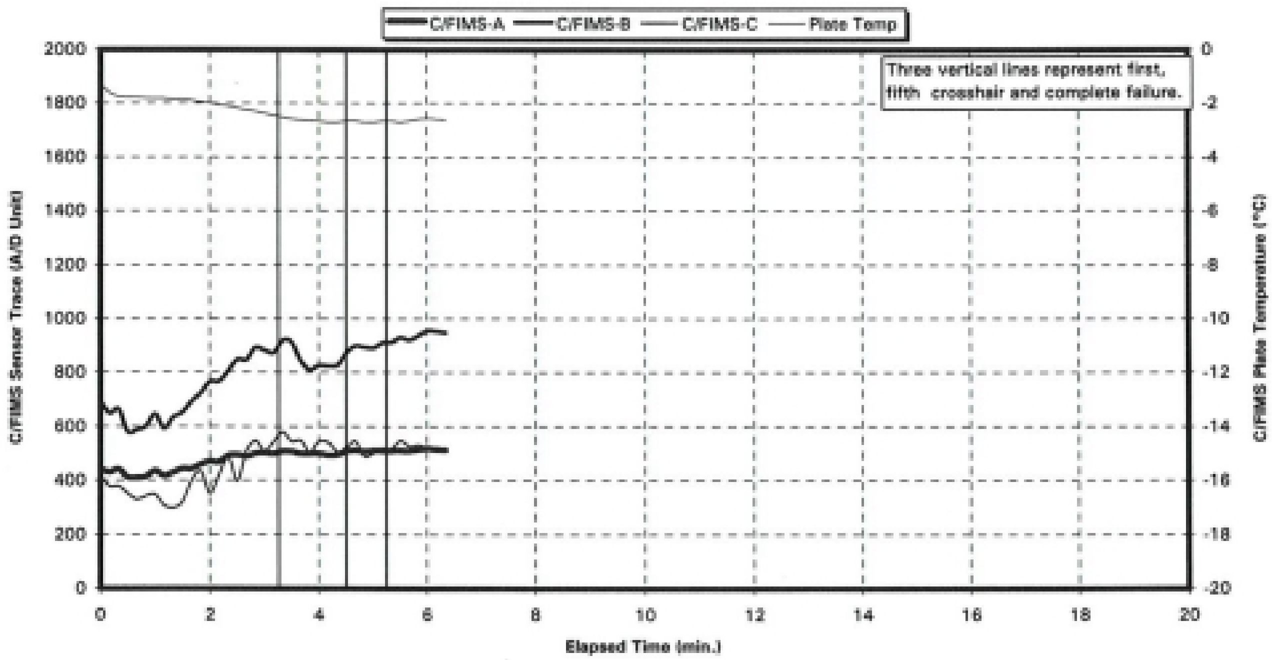
Freezing Drizzle, OAT = -10°C, Precipitation Rate = 10.1 g/dm²/h



cm1514/report/doc_fail/CF_THK_U
AT: ID 1, ID 4

FIGURE 4.15
C/FIMS TRACES FOR UCAR XL54 IN PRECIPITATION CONDITIONS TYPE I ETHYLENE GLYCOL-BASED FLUID

ID # 5
Light Freezing Rain, OAT = -10°C, Precipitation Rate = 24.5 g/dm²/h



ID # 7
Light Freezing Rain, OAT = -10°C, Precipitation Rate = 24.5 g/dm²/h

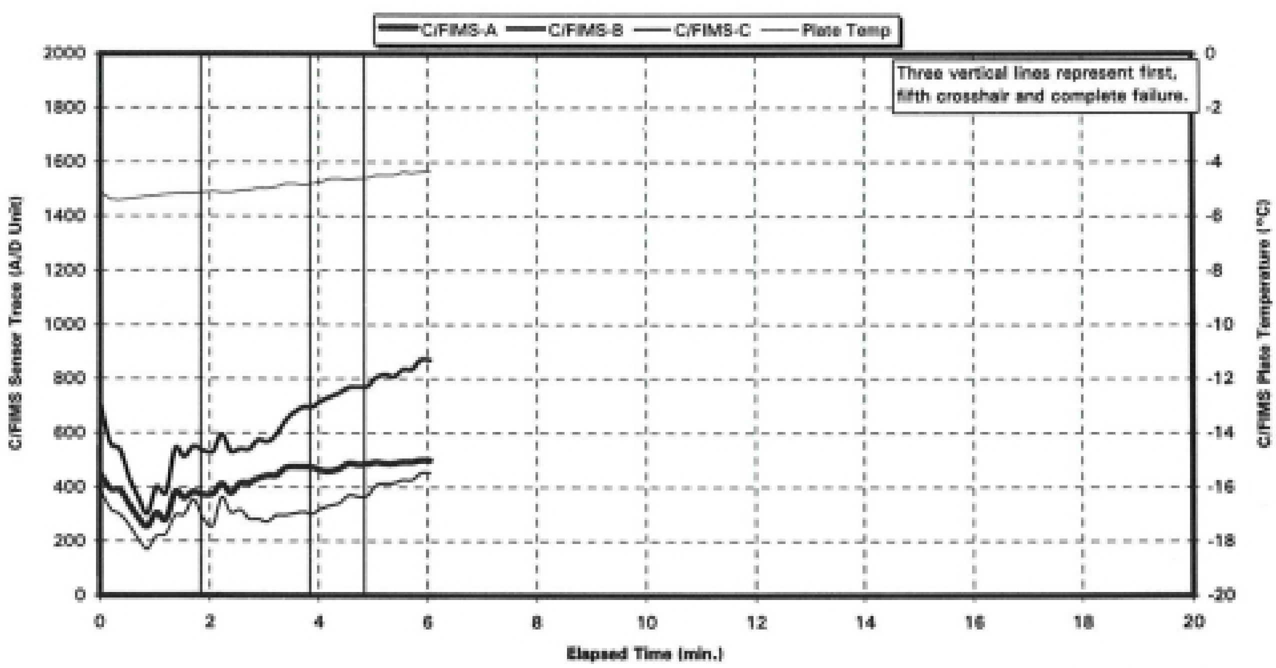
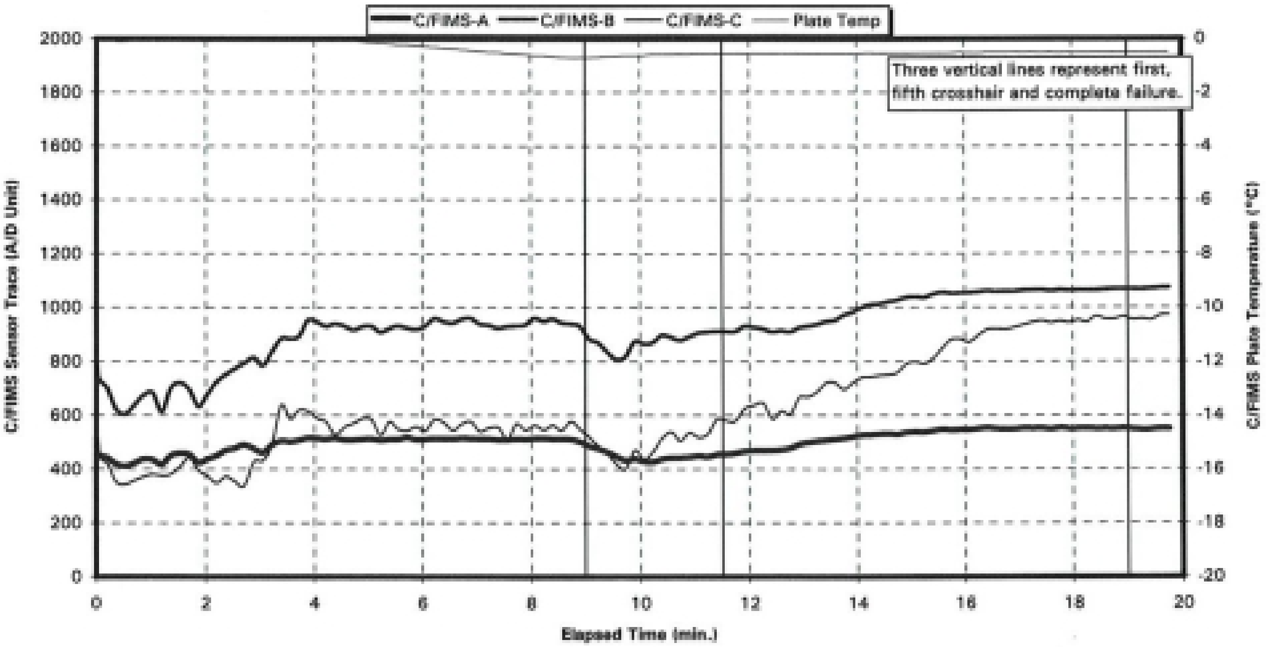


FIGURE 4.15 (cont.)

C/FIMS TRACES FOR UCAR XL54 IN PRECIPITATION CONDITIONS TYPE I ETHYLENE GLYCOL-BASED FLUID

ID # 14

Light Freezing Rain, OAT = -3°C, Precipitation Rate = 24.8 g/dm²/h



ID # 18

Light Freezing Rain, OAT = -3°C, Precipitation Rate = 24.1 g/dm²/h

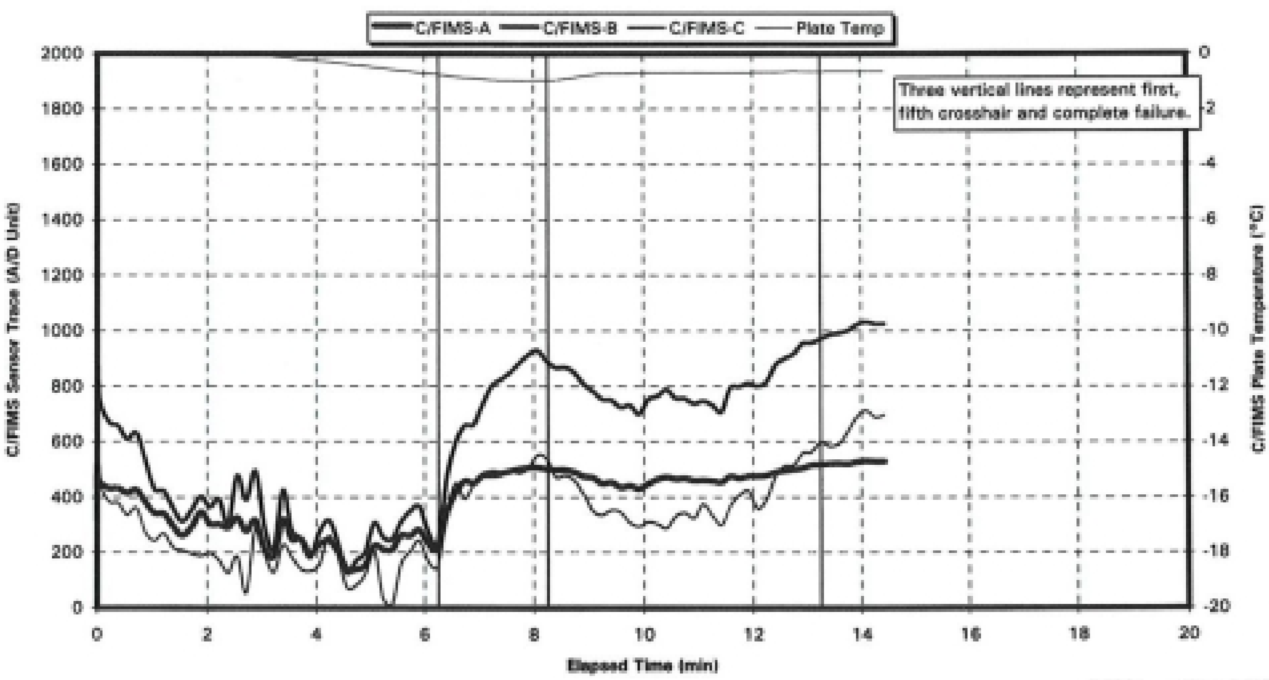
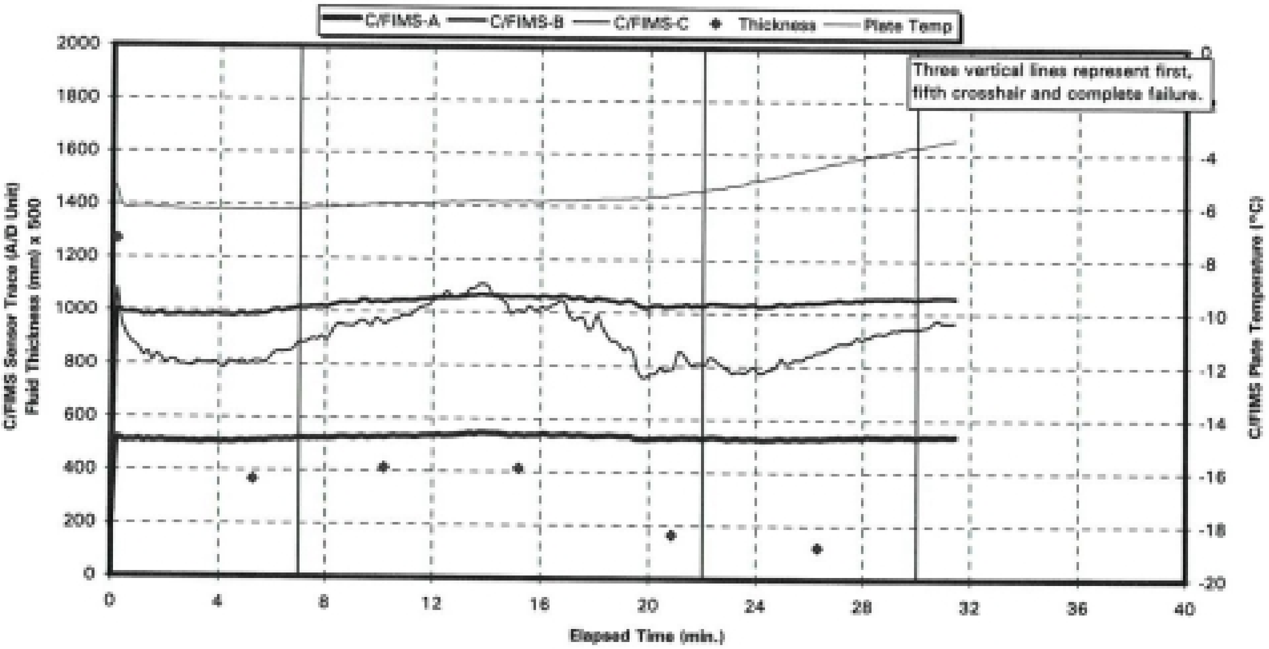


FIGURE 4.16

C/FIMS TRACES FOR THE LOW VISCOSITY OCTAGON MAX-FLIGHT IN PRECIPITATION CONDITIONS TYPE IV PROPYLENE GLYCOL-BASED FLUID

ID # 08

Freezing Rain, OAT = -10°C, Precipitaton Rate = 25.2 g/dm²/h



ID # 11

Freezing Rain, OAT = -10°C, Precipitation Rate = 24.5 g/dm²/h

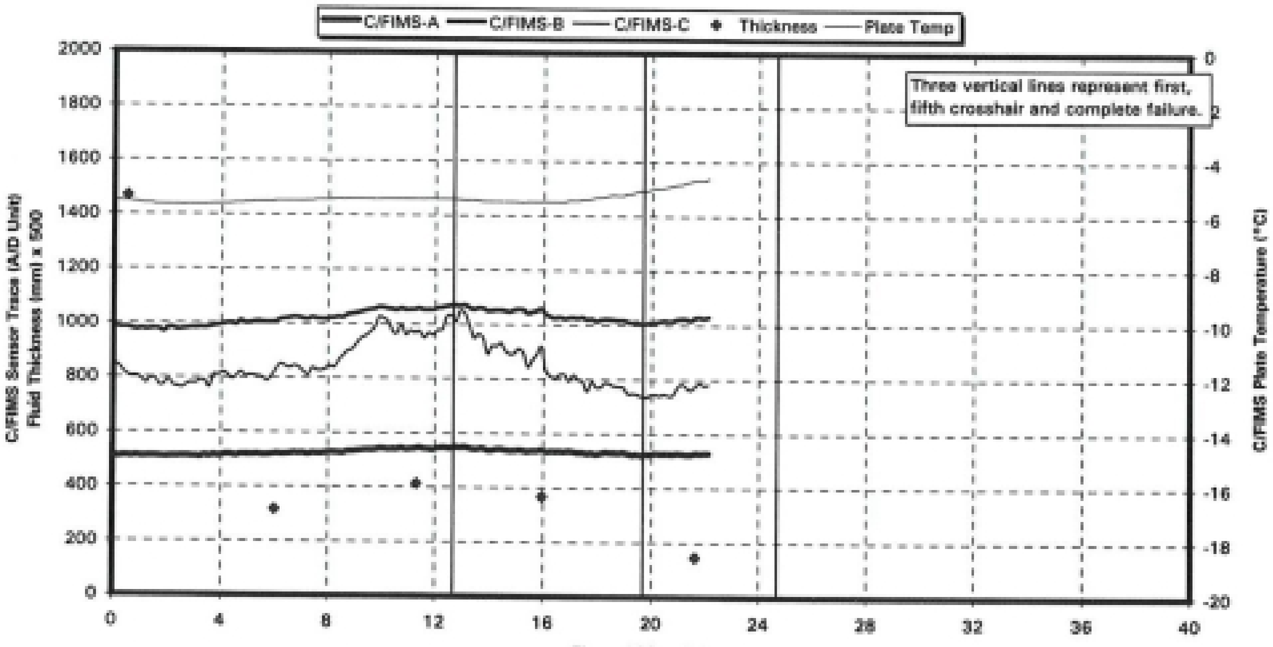
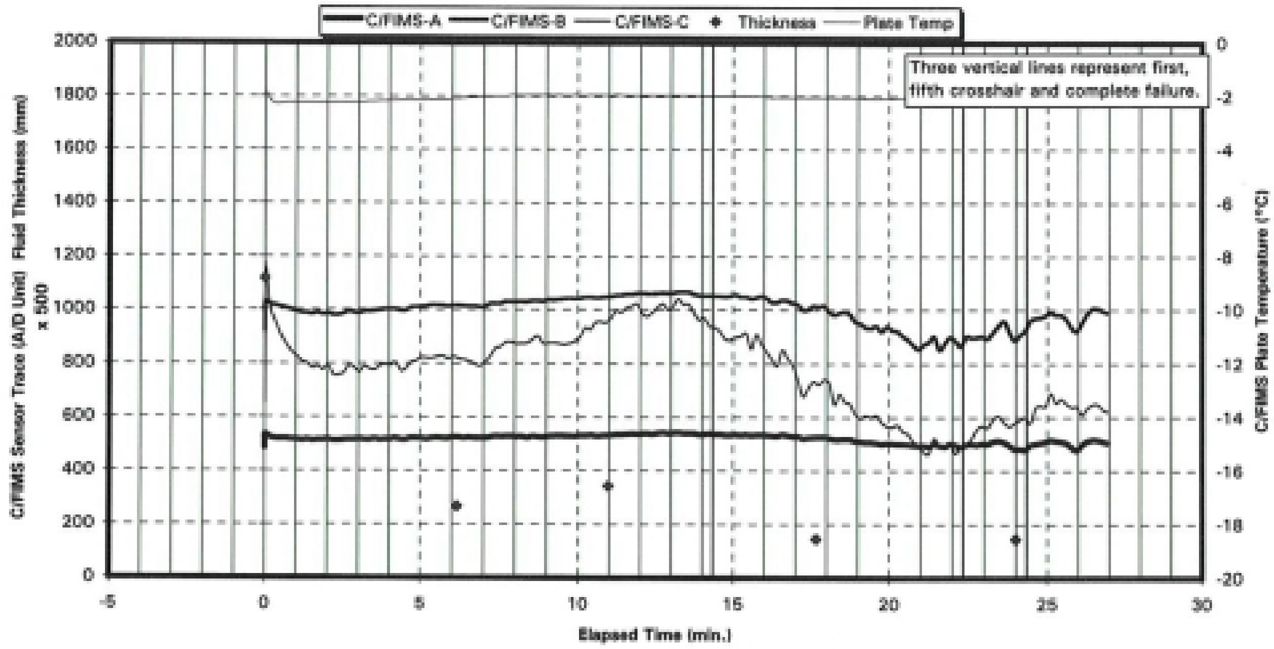


FIGURE 4.16 (cont.)

C/FIMS TRACES FOR THE LOW VISCOSITY OCTAGON MAX-FLIGHT IN PRECIPITATION CONDITIONS TYPE IV PROPYLENE GLYCOL-BASED FLUID

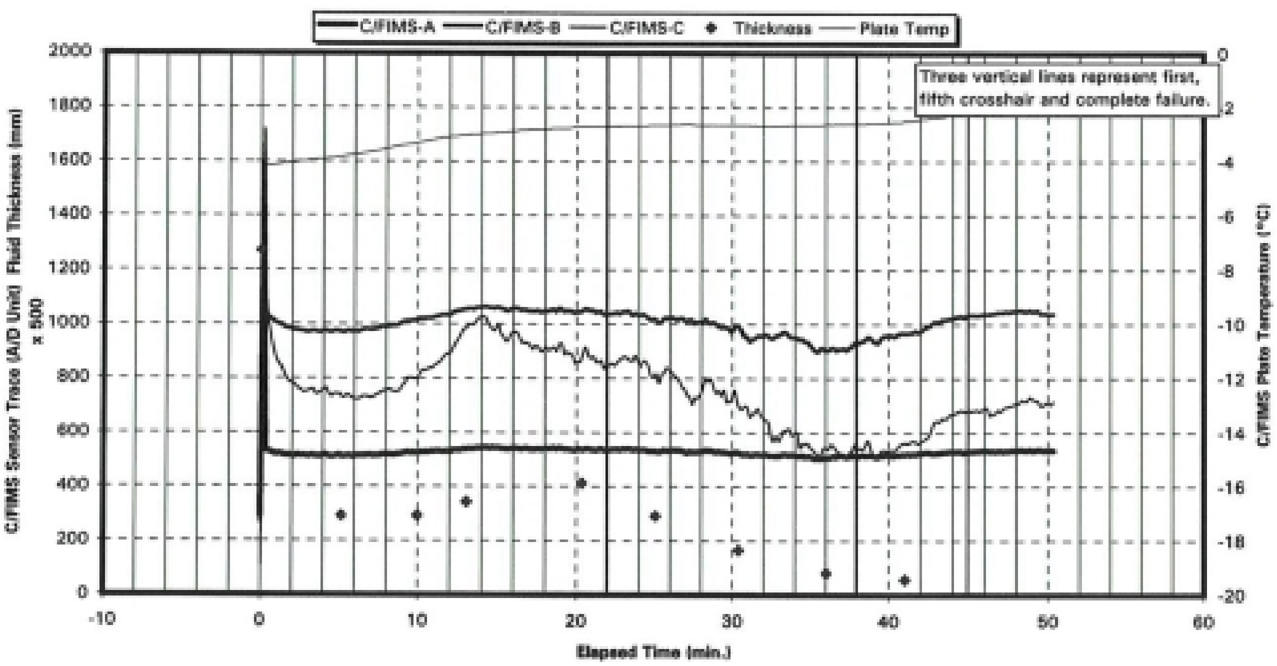
ID # 16

Freezing Rain, OAT = -3°C, Precipitation Rate = 24.1 g/dm²/h



ID # 21

Freezing Drizzle, OAT = -3°C, Precipitation Rate = 12.4 g/dm²/h



precipitation traces in Figure 4.16. The sensor detects the failure condition when the slope of the trace changes from negative to positive. For the conditions previously mentioned, this change occurred around the time at which standard plate failure was called by the observer.

Indicators of failure were not always detected for the Kilfrost propylene glycol-based Type IV fluid in freezing drizzle conditions, as shown in Figure 4.17. At higher temperatures, the failure mechanism for this fluid is mostly a dilution failure, but at lower temperatures (-10°C) the failures were caused by ice bridging above a layer of uncontaminated fluid. During the colder temperature tests, the failures went undetected by the C/FIMS sensor, as shown in Figure 4.17. The layer of uncontaminated fluid prevents the sensor from detecting the ice bridging embedded in the upper fluid layer and above the fluid surface.

4.21.3 C/FIMS Ice Detection Sensor in Snow Precipitation

The C/FIMS traces recorded during snow tests, shown in Figure 4.18, are less indicative of the onset of failure. The natural snow tests included in this report occurred in extremely cold conditions. The plate temperature recorded by the C/FIMS sensors produced a different trace in snow precipitation than other conditions. The plate temperature dropped after the start of the snow test. In all other conditions, the temperature gradually climbed. This behaviour may be attributed to the latent heat absorbed by the snow.

The trace from the sheared standard viscosity Octagon fluid, a Type IV propylene, is very linear and gives no indication of failure at any point during the test. This behaviour can be attributed to the film of clean fluid that remains below the failed fluid. From the refractive index measurements it was observed that a large concentration gradient was present between the top and bottom fluid layers. The snow precipitation tends to accumulate on the top surface of the fluid and the fluid layer in contact with the C/FIMS sensor head may be nearly undiluted at the time of complete plate failure.

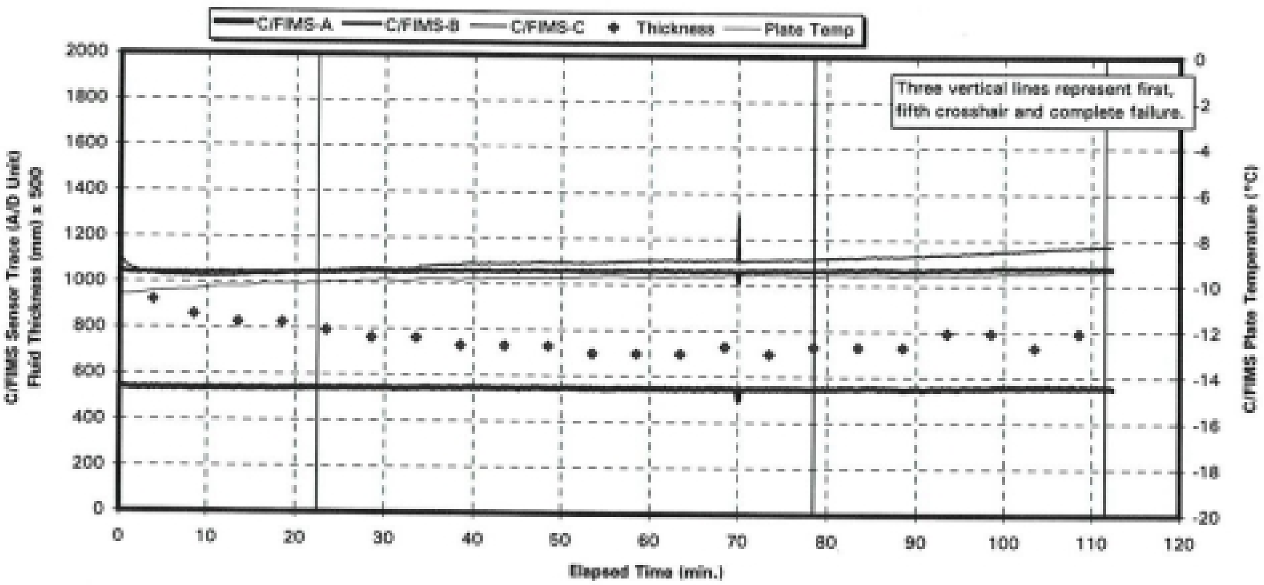
The Ultra+ trace shown in Figure 4.18 does change in slope near the time of standard plate failure. Although the variation in slope is different from the other precipitation conditions for this fluid (negative change in slope as opposed to positive change), the failure does appear in the trace. This could be attributed to the ethylene glycol-based fluid's mixing properties discussed in section 4.21.1 of this report.

FIGURE 4.17

C/FIMS TRACES FOR KILROST ABC-S IN PRECIPITATION CONDITIONS TYPE IV PROPYLENE GLYCOL-BASED FLUID

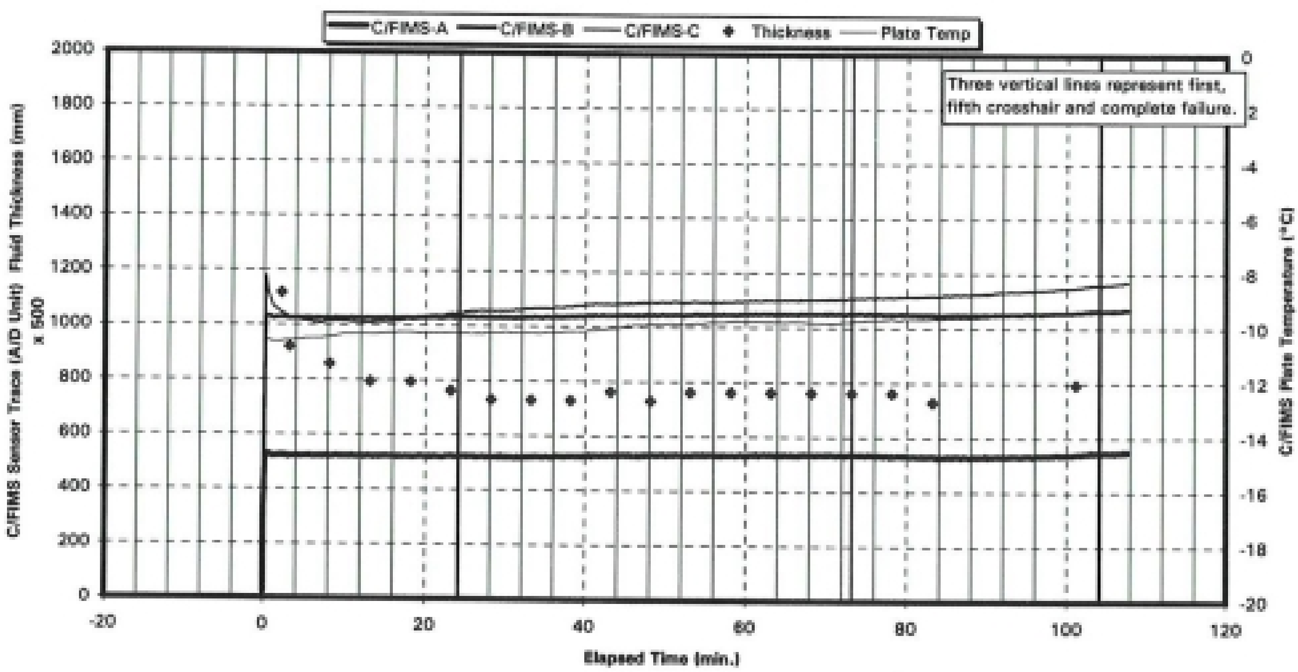
ID # 41

Freezing Drizzle, OAT = -10°C, Precipitation Rate = 5.1 g/dm²/h



ID # 42

Freezing Drizzle, OAT = -10°C, Precipitation Rate = 5.3 g/dm²/h



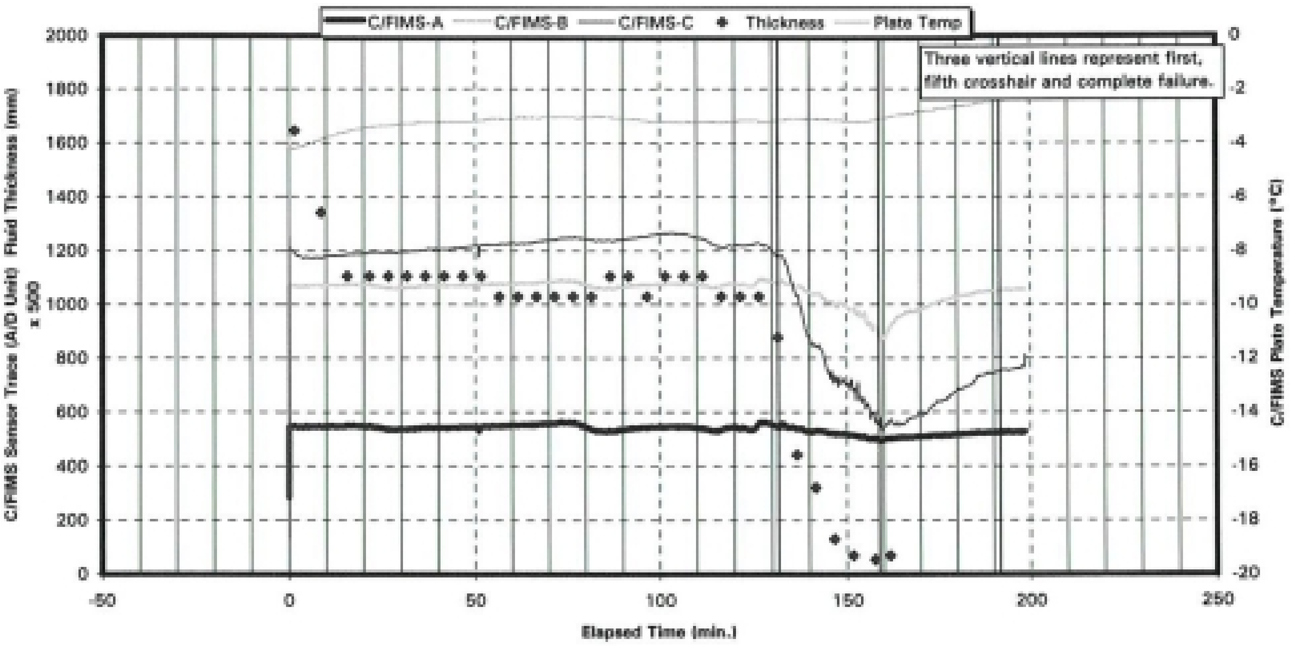
cm1514/report/doc_fail/CF_THK_Kilf
AT: ID 41, ID 42

FIGURE 4.17 (cont.)

C/FIMS TRACES FOR KILROST ABC-S IN PRECIPITATION CONDITIONS TYPE IV PROPYLENE GLYCOL-BASED FLUID

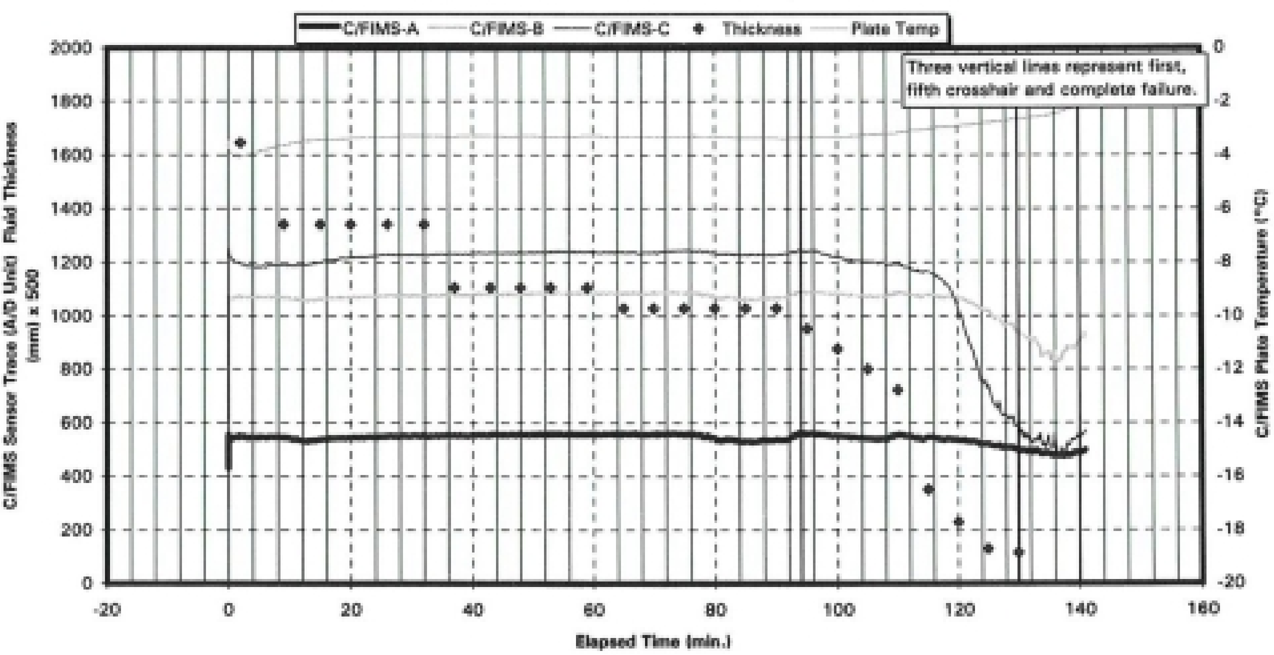
ID # 50

Freezing Drizzle, OAT = -3°C, Precipitation Rate = 5.0 g/dm²/h



ID # 55

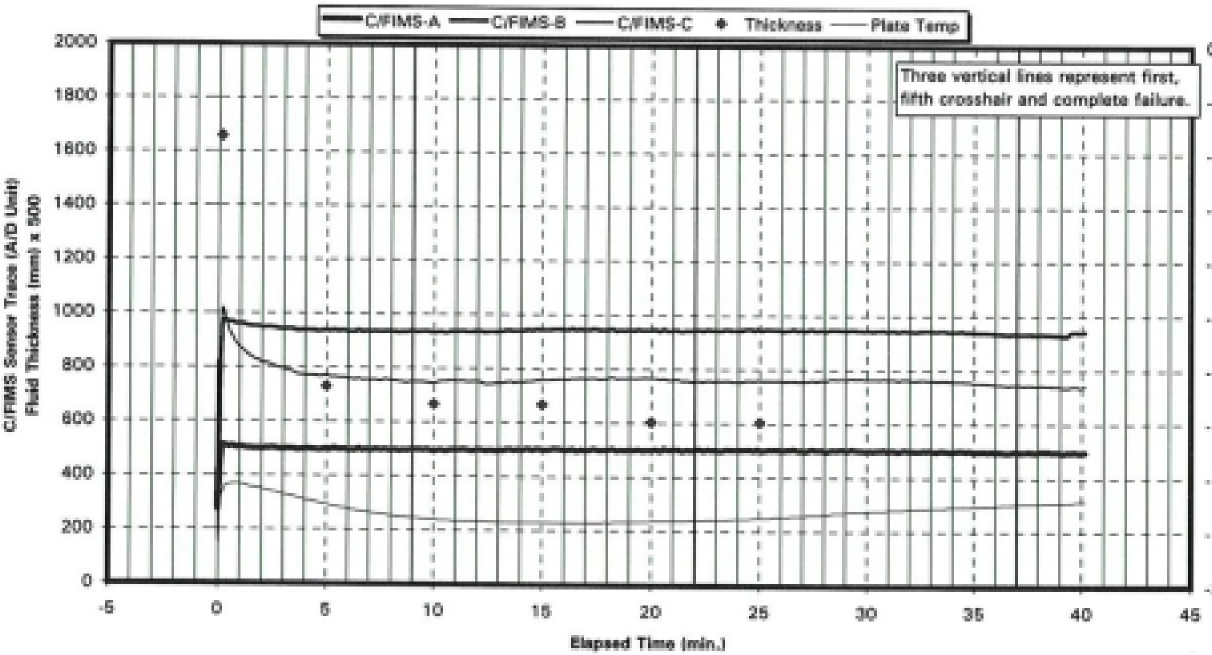
Freezing Drizzle, OAT = -3°C, Precipitation Rate = 12.8 g/dm²/h



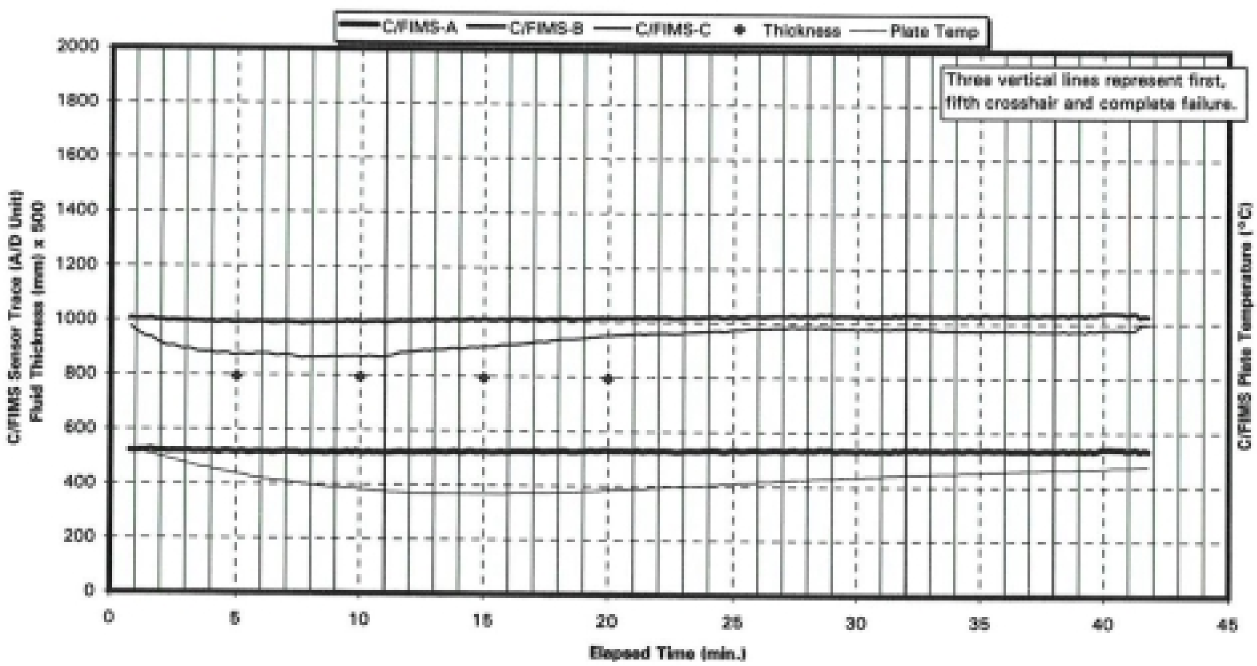
cm1514/report/doc_fall/CF_THK_Kilf
AT: ID 50, ID 55

FIGURE 4.18
C/FIMS TRACES FOR VARIOUS FLUIDS IN NATURAL SNOW PRECIPITATION CONDITIONS

OCTAGON MAX-FLIGHT
Natural Snow, OAT = -17°C, Precipitation Rate = 15.8 g/dm²/h



CLARIANT SAFEWING FOUR
Natural Snow, OAT = -15°C, Precipitation Rate = 16.4 g/dm²/h



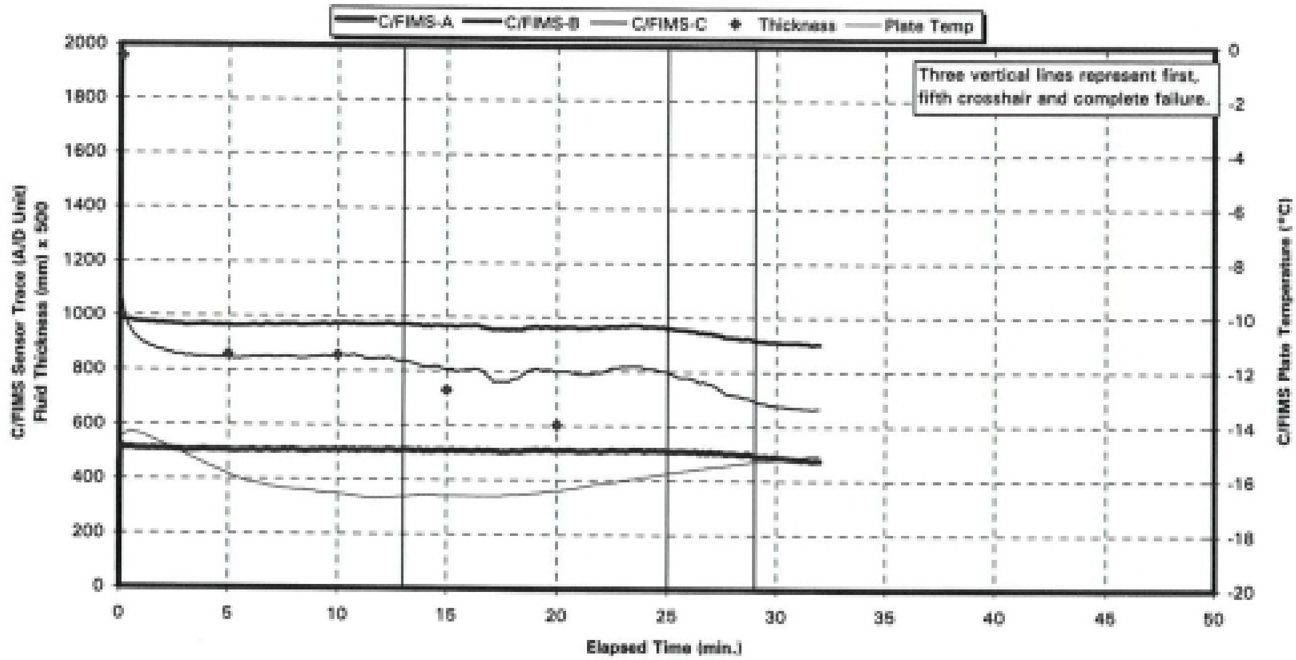
cm1514/report/doc_fail/CF_THK_Snow
AT: OCT, Clariant

FIGURE 4.18 (cont.)

C/FIMS TRACES FOR VARIOUS FLUIDS IN NATURAL SNOW PRECIPITATION CONDITIONS

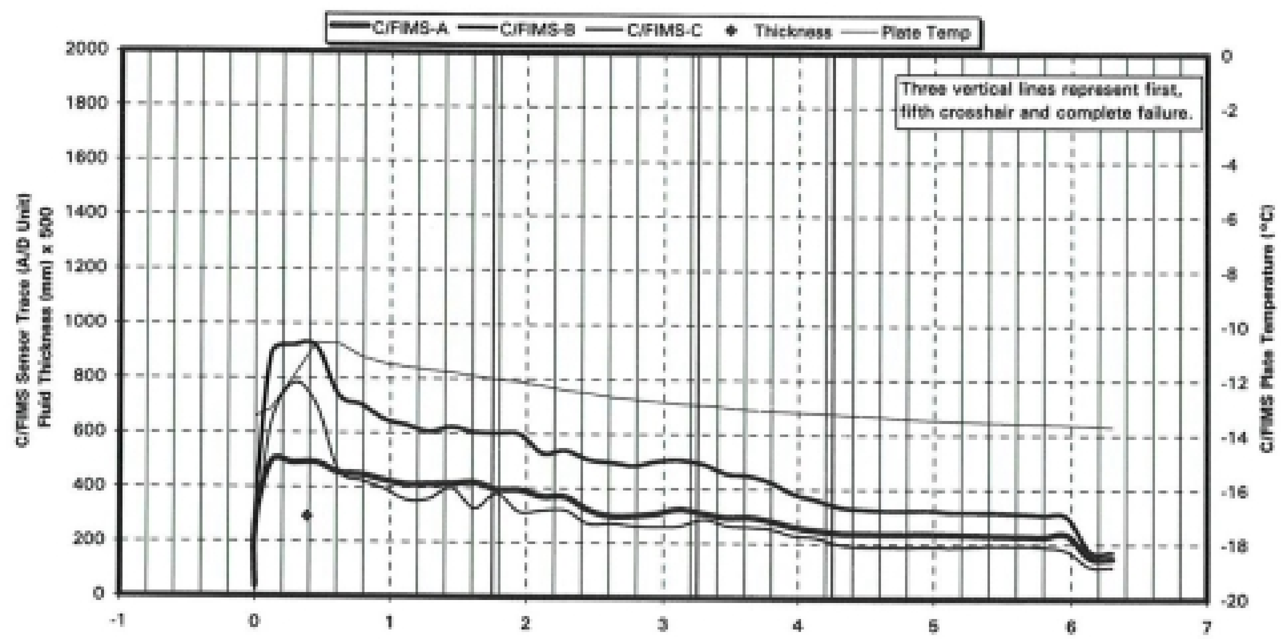
UCAR ULTRA+

Natural Snow, OAT = -14°C, Precipitation Rate = 26.8 g/dm²/h



UCAR XL54

Natural Snow, OAT = -14°C, Precipitation Rate = 30.2 g/dm²/h



cm1514/report/doc_fail/CF_THK_Snow
AT: UCAR Ultra +, UCAR XL54

4.21.4 C/FIMS Traces and Thickness Profiles

The C/FIMS sensor traces shown in Figures 4.14 and 4.16 to 4.17 include the fluid thickness with respect to time. The Type I traces do not include the fluid film thickness since no correlation can be made between the traces and the thin films. In the Type IV tests with freezing precipitation, a similar behaviour can be observed for the progression of both the film thickness and the C/FIMS-B trace.

In ethylene glycol-based fluids, the film thickness decreases from the time of pouring until the time of standard plate failure, due to the dilution failure observed for this fluid. The C/FIMS-B trace gradually decreases from its initial value, following the thickness profile, until failure is observed. At this time the thin fluid film begins to freeze and the C/FIMS traces increase.

The C/FIMS traces do not always provide obvious indications of failure for propylene glycol-based fluids. At higher temperatures, the fluid follows a dilution failure and the traces provide good indications of failure. At lower temperatures, the fluid fails due to ice bridging and a layer of uncontaminated fluid is present below the failure surface. The C/FIMS trace follows the fluid film thickness and shows very little variation as the tests progress

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Photo 4.1
Speck Stage of Failure

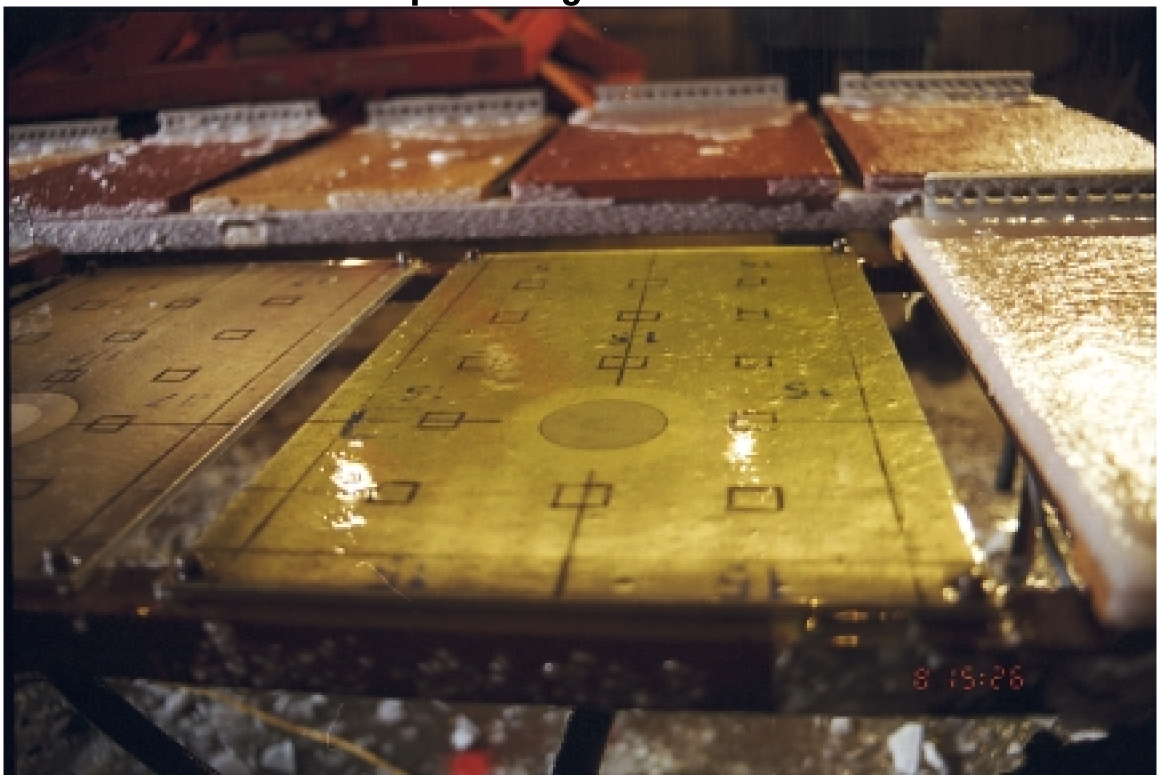

Photo 4.2
Orange-Peel Texture

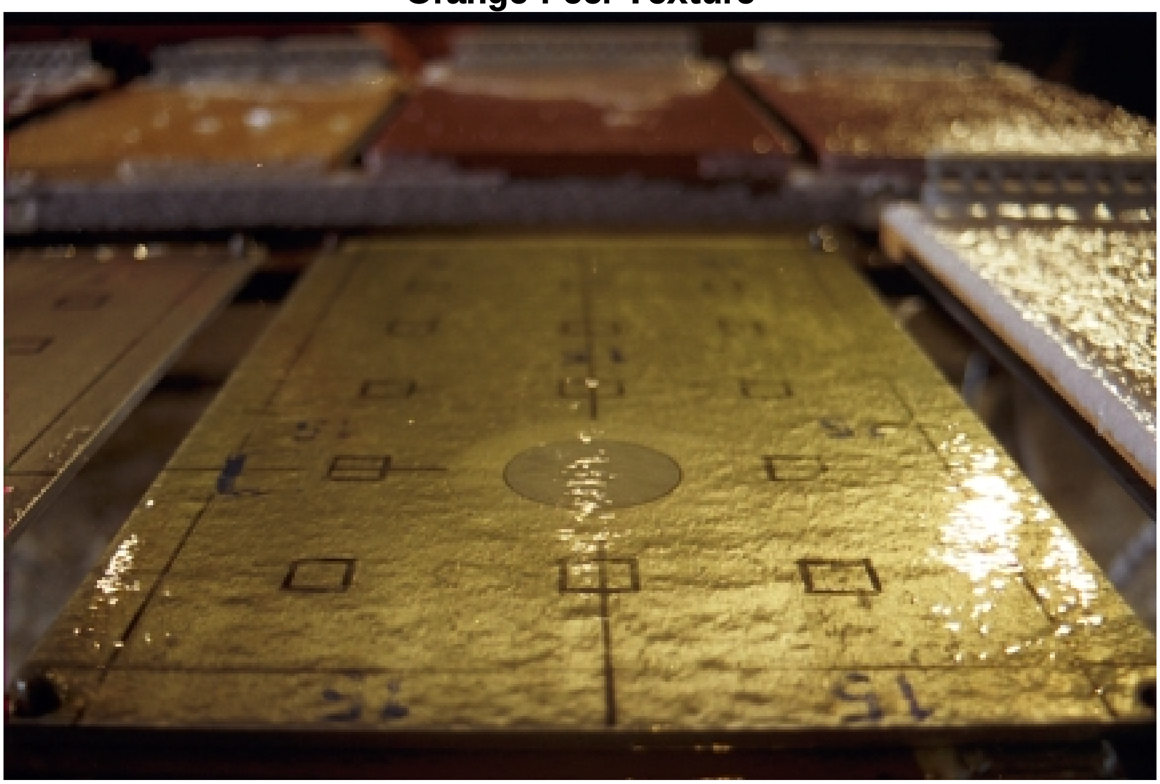

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Photo 4.3
Gelatinous Stage of Failure

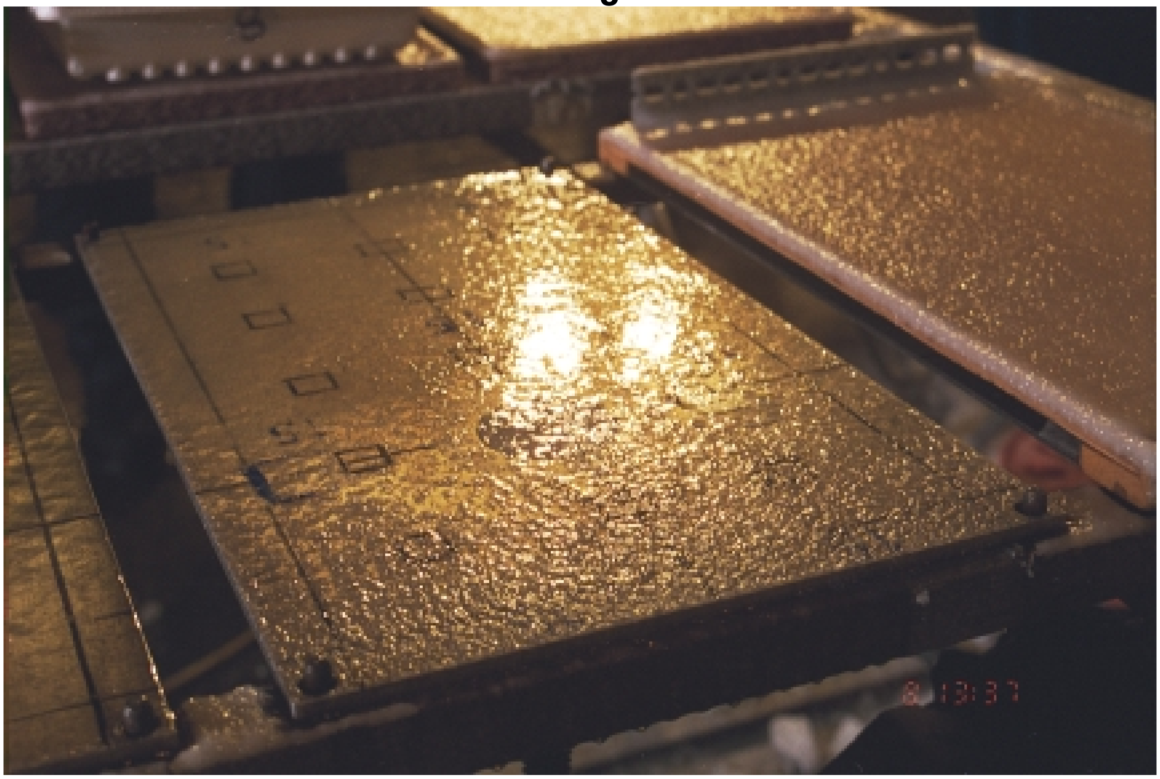

Photo 4.4
Streaks of Solidified Precipitation

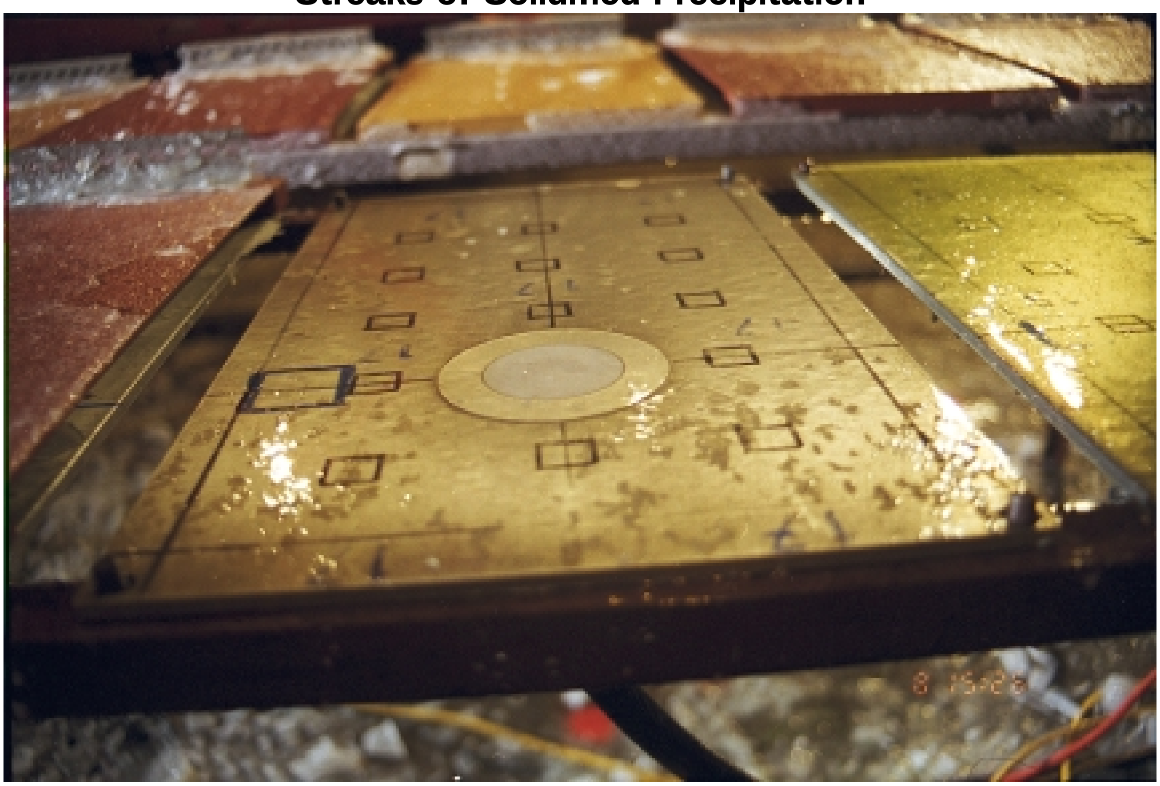

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Photo 4.5
Solidified Precipitation Flowing Down Plate

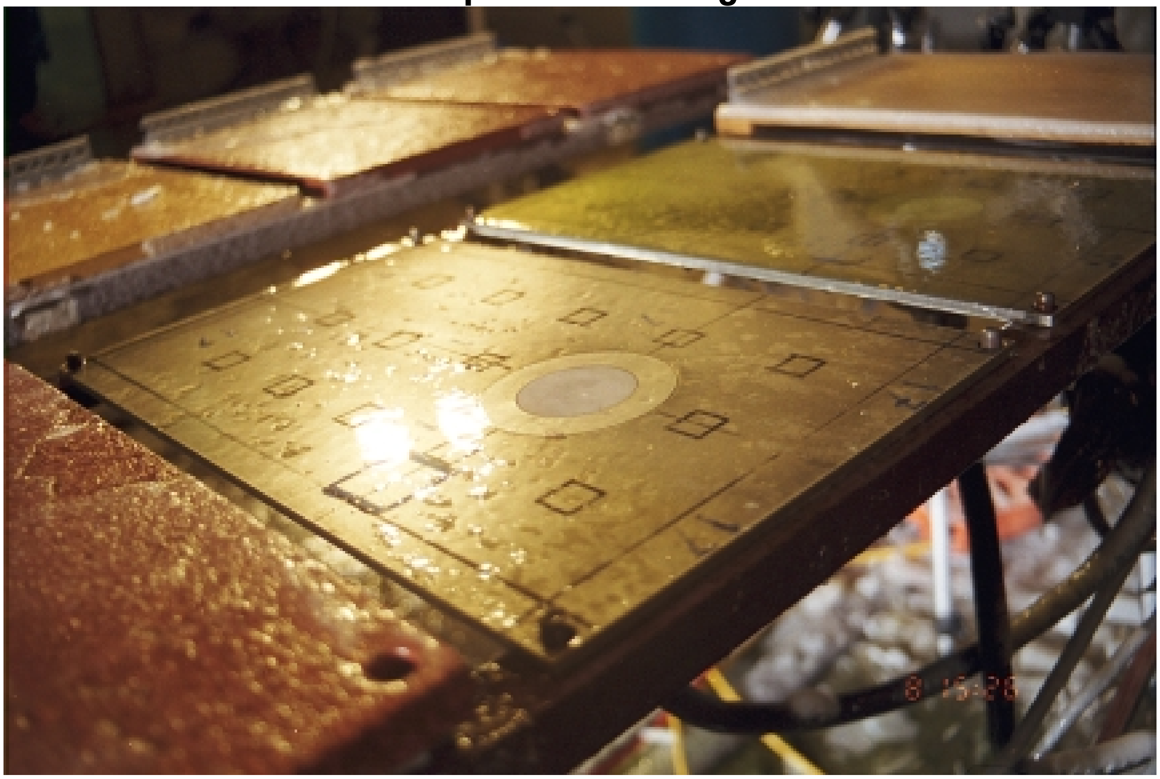

Photo 4.6
Top Edge Failure

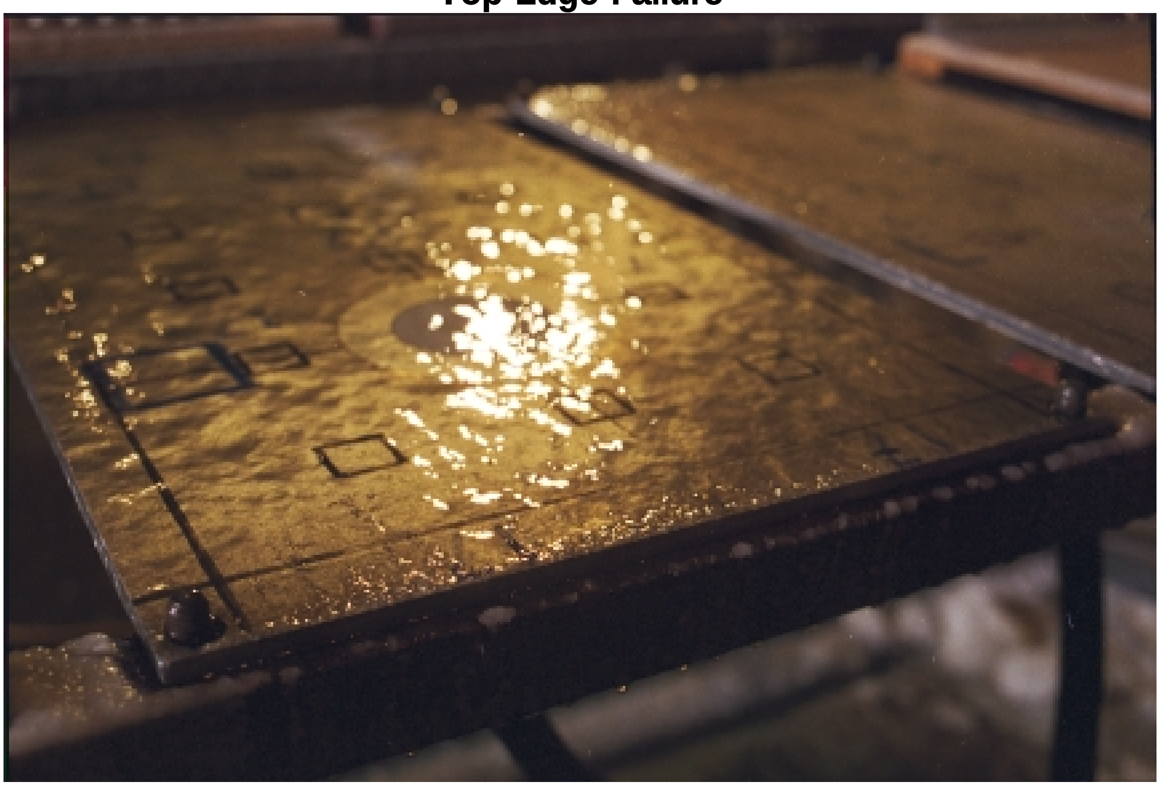

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Photo 4.7
Fingers of Failure

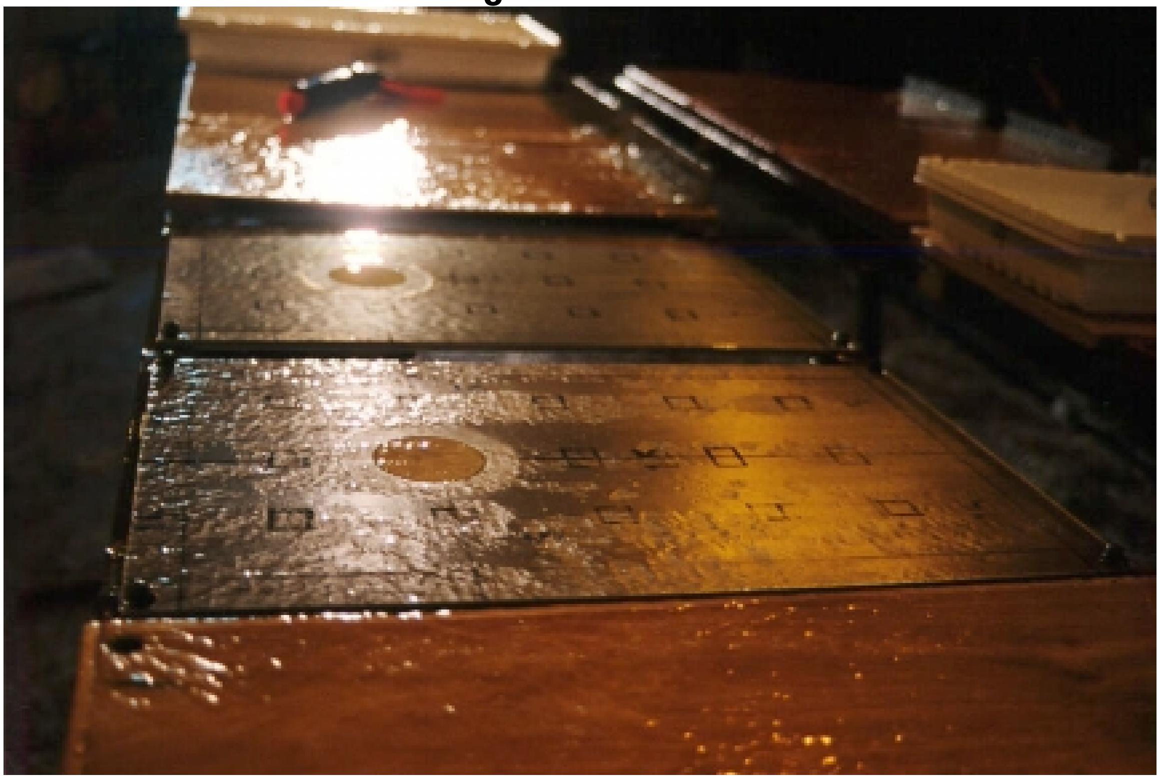

Photo 4.8
Dots and Streaks of Solidified Precipitation

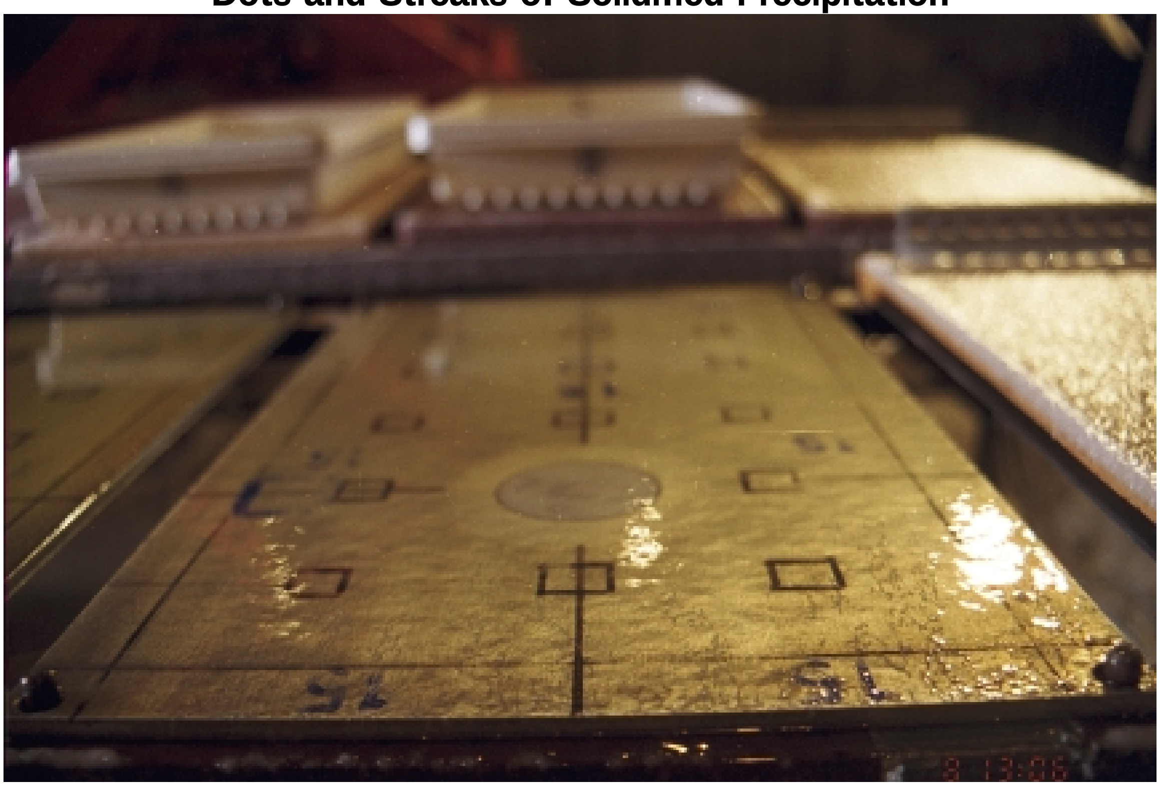

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Photo 4.9
Fingers of Plate-Like Ice Particles

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Photo 4.10
RVSI IMAGES - ID # 28 (3rd Plate from right)
SPCA AD-480 AT 10% FAILURE

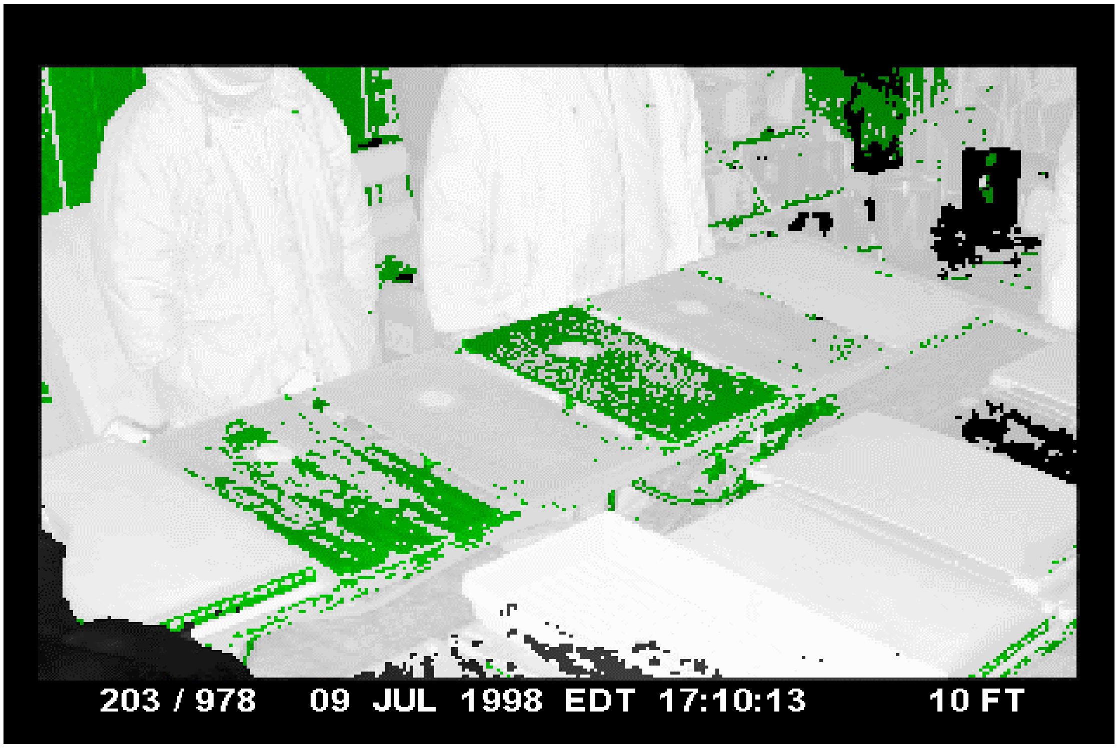

Photo 4.11
RVSI IMAGES - ID # 28 (3rd Plate from right)
SPCA AD-480 AT COMPLETE FAILURE

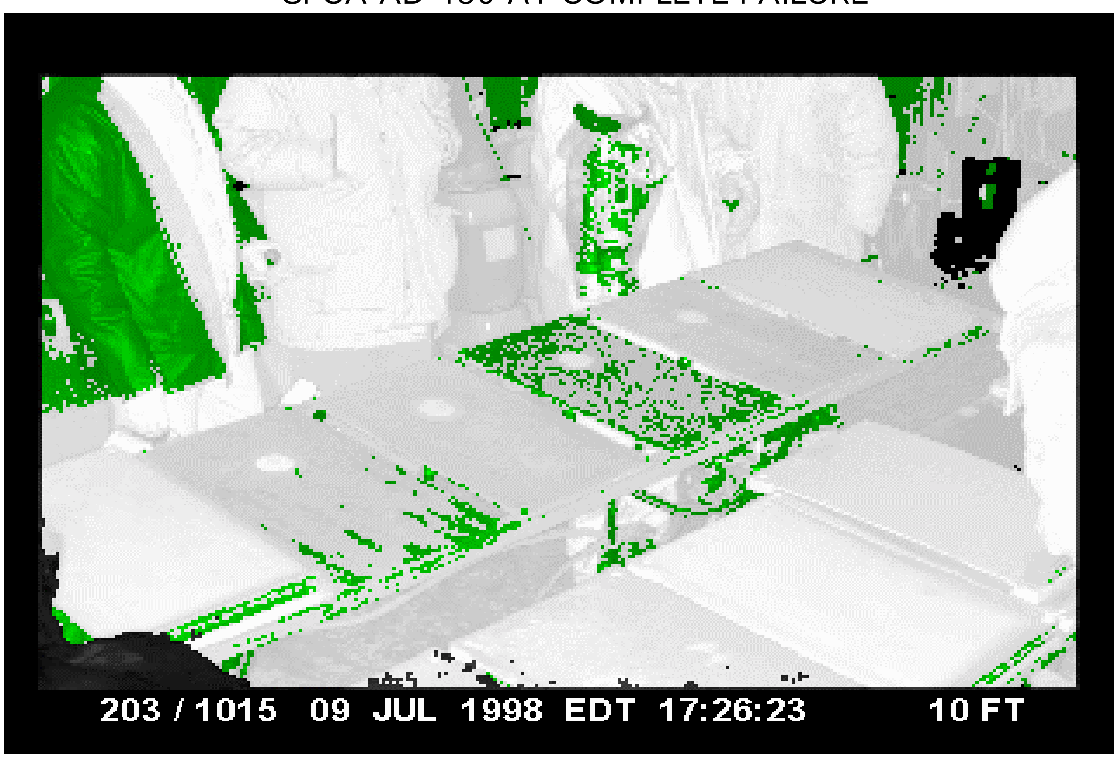

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Photo 4.12
TYPE I FLUID FAILURE
Light Freezing Rain, Temperature = -10°C

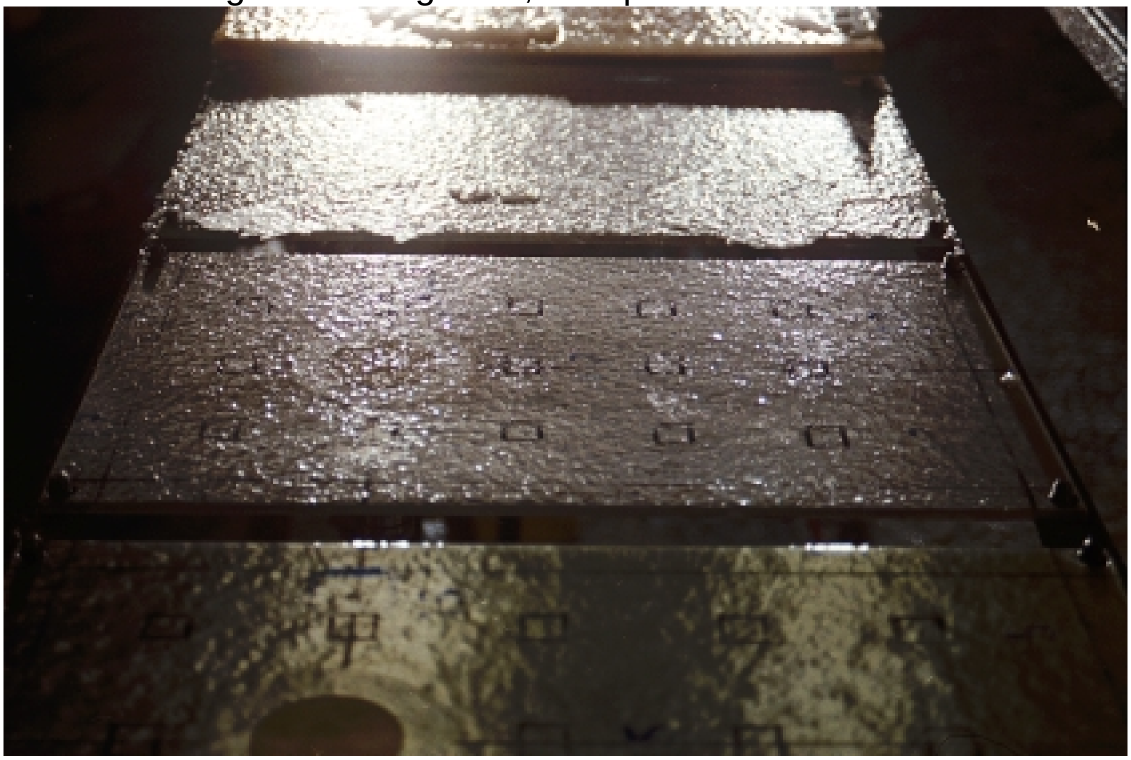

Photo 4.13
TYPE IV FLUID FAILURE
Light Freezing Rain, Temperature = -10°C

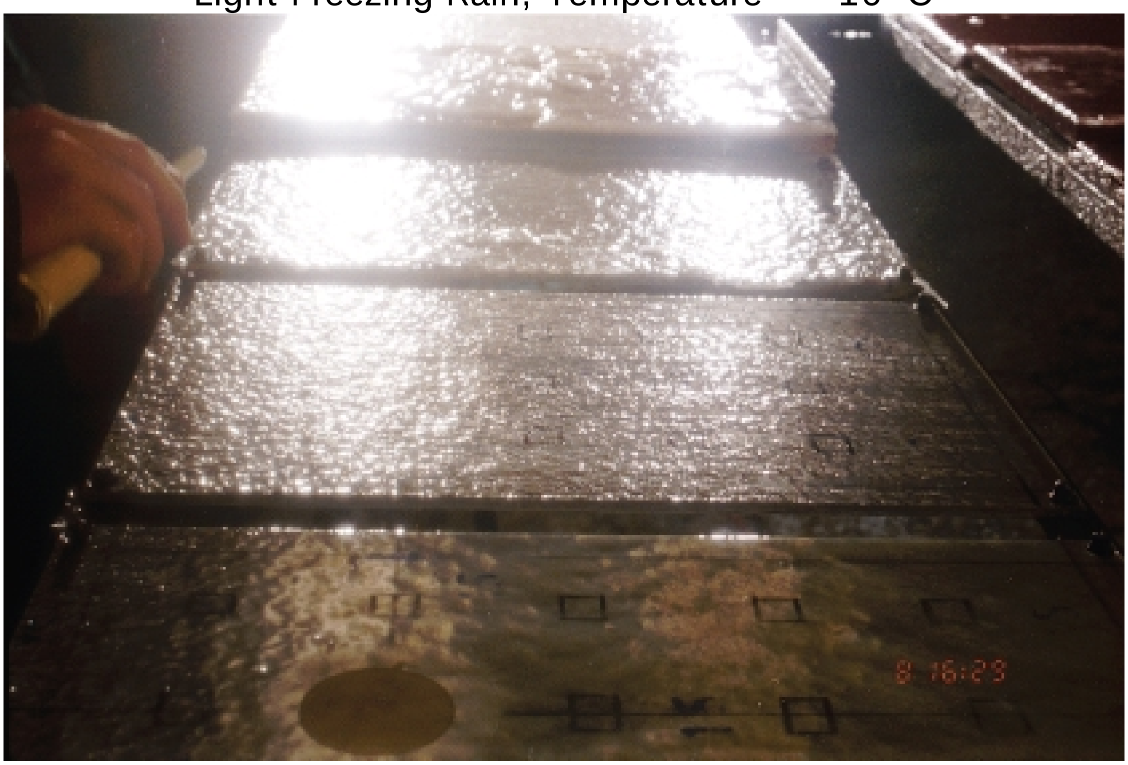

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Photo 4.14
TYPE IV FLUID FAILURE
Light Freezing Rain, Temperature = -3°C

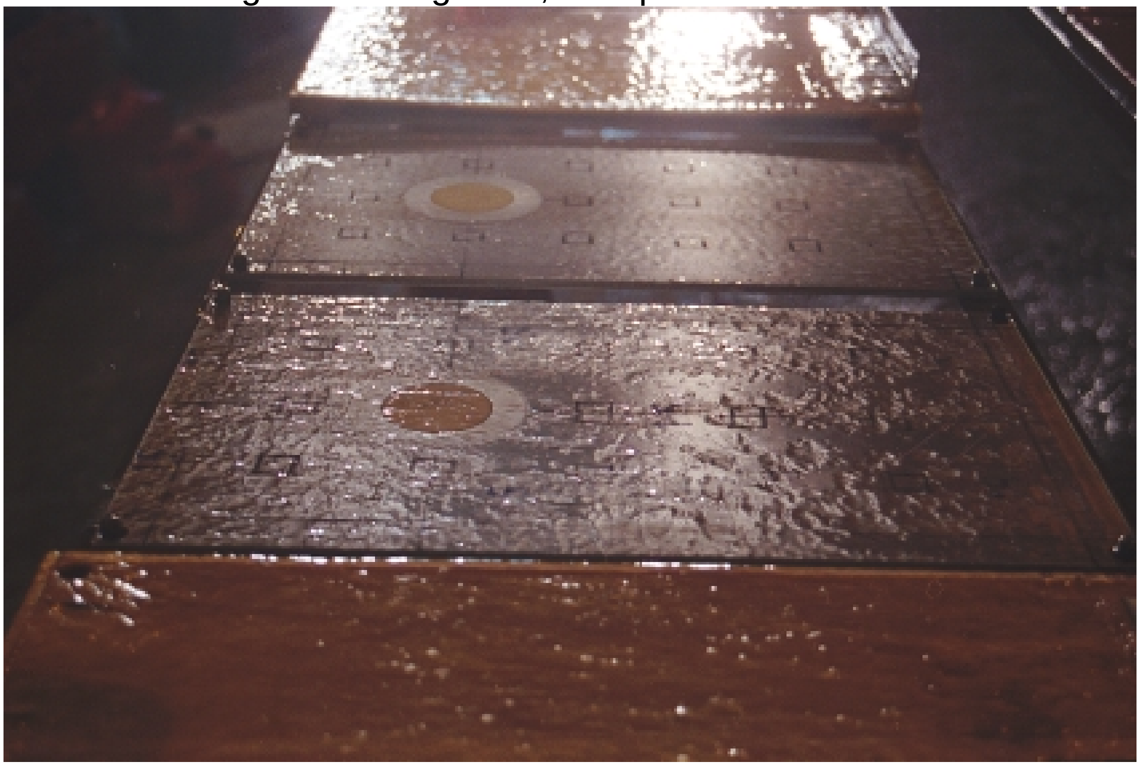

Photo 4.15
TYPE IV FLUID FAILURE ON A DC-9 WING
Light Freezing Rain, Temperature = -1°C

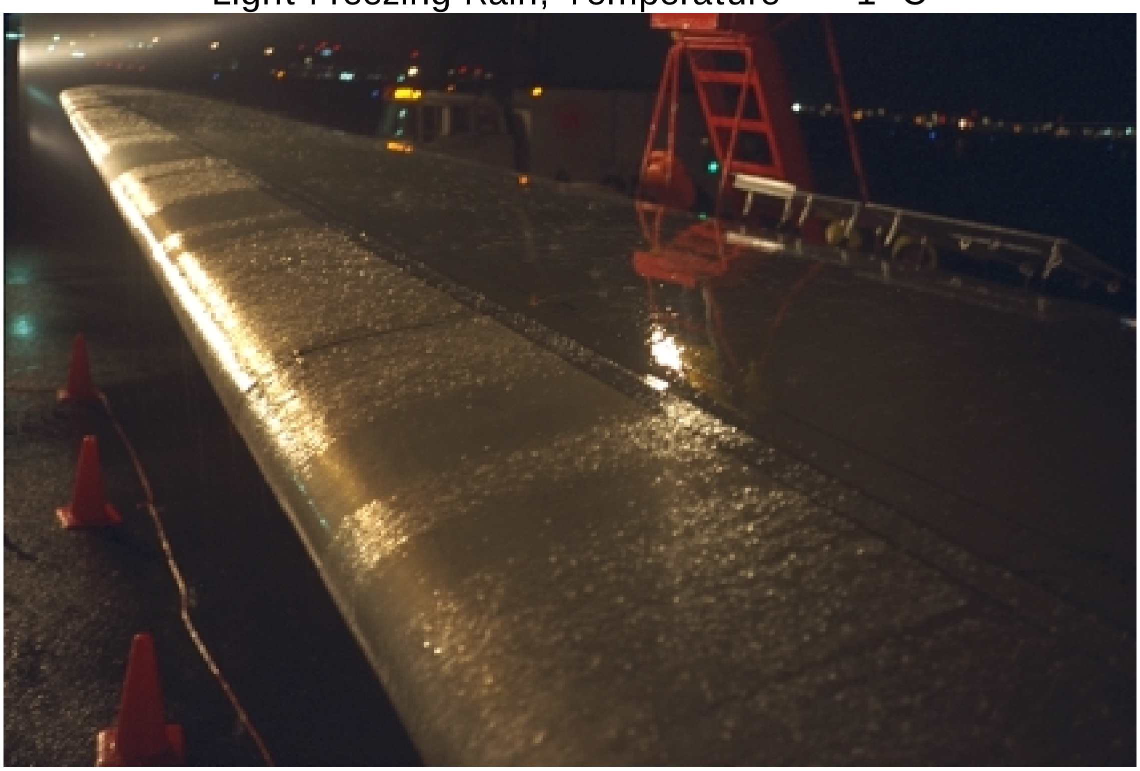

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Photo 4.16
TYPE I FLUID FAILURE
Light Freezing Rain, Temperature = -3°C

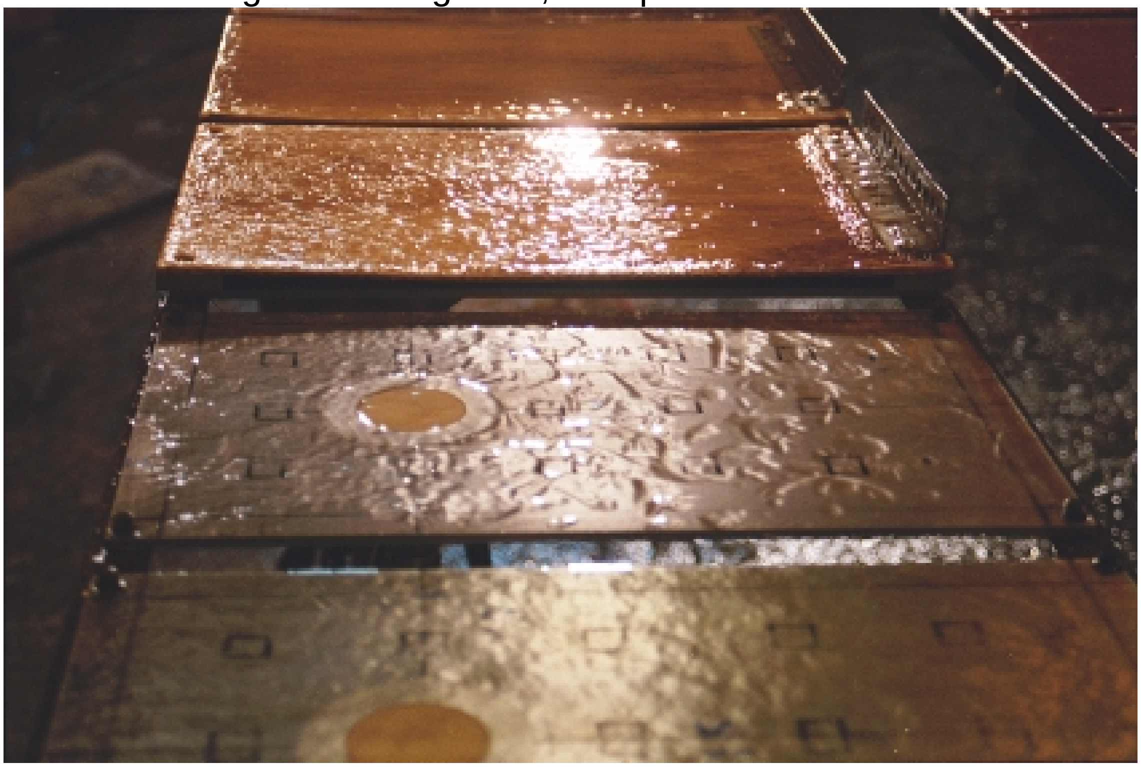

Photo 4.17
TYPE I FLUID FAILURE ON A DC-9 WING
Light Freezing Rain, Temperature = -1.5°C

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Photo 4.18

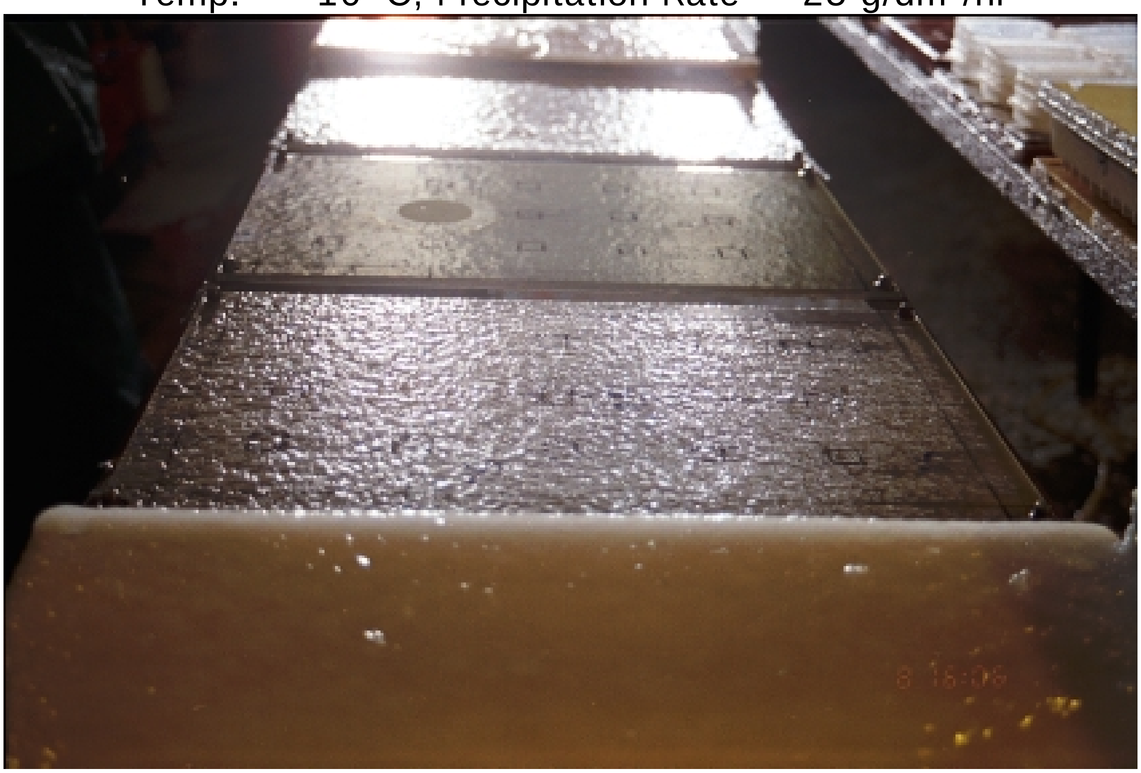
TYPE IV FLUID FAILURE – FREEZING DRIZZLE

Temp. = -10°C, Precipitation Rate = 10 g/dm²/hr

Photo 4.19

TYPE IV FLUID FAILURE – LIGHT FREEZING RAIN

Temp. = -10°C, Precipitation Rate = 25 g/dm²/hr



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5. CONCLUSIONS

This study recorded the appearance and characteristics of various fluids from application up to the time the fluids reached their operational limits, using a variety of recording techniques and instruments.

Data from the various tests have enabled comparisons between the appearances and natures of fluids under different failure producing conditions as detailed in the preceding discussions. Photographs and video records were assembled to portray the appearance of fluid at specific stages from the time of application until complete plate failure. These images could assist users in the field (pilots and ground staff) to visually identify fluid at its operational limit. The descriptions of the characteristics of different fluids tested and various other comparisons attempt to answer questions commonly posed during discussions on the nature of the fluid failure:

- What did the failure look like?
- How did it progress?
- How visible is the failure? Was the failure obvious or difficult to discern?
- Did it appear distinctive for different precipitation conditions and for different fluid types?
- Did it adhere to the underlying surface?

5.1 Failure Appearances

The photographic material included in the CD Attachment shows the appearances of fluid failures in all the conditions tested. The progressions and different stages encountered during the fluid failure tests are documented in detail in Section 4 and in the CD Attachment. A general failure description is insufficient to completely describe all fluid failure, since the failure mechanisms depend on a large number of conditions: ambient temperature, precipitation type, precipitation rate, type of fluid, etc.

An experienced observer can discern a fluid failure consistently, but an inexperienced observer may have difficulty seeing failures in some conditions. Since various fluids fail in diverse ways, it is insufficient to be familiar with only one type of fluid failure. An observer must know all the failure appearances and failure progressions to confidently determine whether a failure is present.

5.2 Fluid Comparisons

Comparisons were made to determine variations in the appearance and physical properties of various fluids in diverse conditions. The following conclusions resulted from these comparisons:

- Type I and Type IV fluids in light freezing rain: similar in appearance but Type I fails more rapidly, adheres more quickly, and does not progress through the same failure stages.

- Type I and Type IV in snow: very similar failure appearances for all precipitation rates and conditions.

- Type IV in freezing rain and freezing drizzle: similar failure progression for ethylene glycol-based fluids, but different failures for propylene glycol-based fluids. In freezing rain, dilution failures were observed. However, ice-bridging failures were observed in freezing drizzle at ambient temperatures of -10ºC.

- Effect of temperature on Type IV in freezing drizzle: appearances of failure were not temperature dependent for ethylene glycol-based fluids. Propylene glycol-based fluids failed due to:
  - ice bridging at lower temperatures, and
  - dilution at higher temperatures.

- Type I versus Type IV 50/50: similar appearances and failure times, although the Type IV fluid was thicker and did not adhere as quickly.

5.3 Viscosity of Failed Fluids

The viscosity of fluids at the time they reach their operational limit was found to be a difficult property to measure. The fluid concentration within the fluid layer could be stratified and could offer varying viscosities at different depths. Indicators of failure may reside only at the top layer.

For example, the nature of frozen contamination present in the fluid, if allowed to warm and melt in the sample container and then be recooled to test temperature for viscosity testing, will not take on the same structure as was present during the test. During these tests, samples collected near the failure front and measured with a Brookfield Viscometer generally provided viscosity values equivalent to water. Some Type IV propylene glycol-based fluids had a significant residual viscosity reading for tests performed at lower temperatures.

5.4 Adhesion of Failures

In freezing precipitation conditions, the adhesion of failures once a fluid has reached its operational limit is an important measure of the fluid's condition. This was not well reported in the past. This study used an innovative approach to provide a relative measure of adhesion relating to the various test conditions, providing an improved understanding of this characteristic. It was generally noted that Type I fluids adhere very quickly (in the order of one minute) after failure, resulting in a very thin film strongly bonded to the surface. Type IV ethylene glycol-based fluids demonstrated a longer delay from time of freezing until failure adhesion, in the order of three to six minutes. The Type IV propylene glycol-based fluid experienced no adhesion at ambient temperatures of -10ºC, even when complete plate failure was identified.

Failure adhesion was not detected during tests performed in natural and artificial snow. The combination of fluid and snow resulted in a slush that could not absorb more precipitation, although it was sufficiently liquid not to stick to the underlying plate surface. If the tests were to continue far beyond complete (full) plate failure, the failed fluid might eventually adhere to the surface.

5.5 Other Conclusions

The Type IV Octagon Max-Flight fluid was initially selected to be representative of propylene glycol-based Type IV fluids. However, the sample tested had been pre-sheared prior to testing and the resultant documentation, while important, can be viewed only as representative of that particular fluid in a sheared state. Furthermore, the Octagon Max-Flight used during the 1999 tests was not the same low viscosity fluid used in previous years.

The Type IV Kilfrost ABC-S fluid was used in subsequent tests as the standard propylene glycol-based fluid. The viscosity of this fluid was within the range specified by the manufacturer test.

Identification of the operational limits for propylene glycol-based Type IV SPCA AD-480 and Kilfrost ABC-S fluids in freezing drizzle was found to be a challenge. These fluids, during the process of absorbing contamination, appear to continue to provide a level of protection far beyond the point when failure calls are normally made. This implies that failure calls should be tailored to specific fluid types. This has similar implications for the calibration of ice detection sensors.

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6. RECOMMENDATIONS

It is recommended that:

i) This study be extended to include documentation of fluid failure outdoors during -3°C snow conditions, and indoors with a laboratory snow-making machine at the same temperature;

ii) Photo documentation of fluids at various stages of contamination be made available to potential users in the aviation industry to assist in identifying when a fluid has reached its operational limit;

iii) Tests be performed to study the possible adhesion of snow precipitation when tests are extended beyond complete plate failure;

iv) An investigation of the impacts of freezing drizzle and light freezing droplets be conducted to document how the contaminant is actually accepted by the fluid (using strobe photography) and also to determine what fraction of contamination impinging on a fluid-covered surface actually remains in the film (gravimetric analysis). A measure of the quantity of deicing or anti-icing fluid picked up by escaping droplets would be afforded from refractive index measurements of the collected fraction;

v) Tests be performed to determine the exact temperature below which each propylene glycol-based Type IV fluid will begin to produce ice bridging failures. The characteristics of failure for these fluids are significantly different below this temperature;

vi) Failure appearance and failure characteristics of new fluids be documented and compared to currently documented fluids if these new fluids differ from fluids documented in this report; and

vii) Calibration of the ice detection sensors be investigated on a specific fluid basis.

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REFERENCES

1. Chaput, M., Dawson, M., Peters, A., D'Avirro, J., *Characteristics of Aircraft Anti-Icing Fluids Subjected to Precipitation,* APS Aviation Inc., Montreal, November 1998, TP 13317E, (to be published).

2. Myers, B., *Aircraft Anti-Icing Fluid Endurance, Holdover, and Failure Times Under Winter Precipitation Conditions: A Glossary of Terms*, Transportation Development Centre, Transport Canada, Montreal, November 2001, TP 13832.

3. Hunt, M., *A Snow Generation System – Prototype Testing,* APS Aviation Inc., Montreal, November 1999, TP 13488E.

4. Bilgen, E., Chan, G., Cleary, C., D'Avirro, J., Foo, H., *Aircraft Ground De-Anti-Icing Fluid Holdover Time Field Testing Program for the 1992-1993 Winter*, APS Aviation Inc., Montreal, October 1993, TP 11836E.

5. Dawson, P. Hanna, M., *Contaminated Aircraft Takeoff Tests for the 1998-99 Winter,* APS Aviation Inc., Montreal, October 1999, TP 13479E.

6. D'Avirro, J., Peters, A., Hanna, M., Dawson, P., Chaput, M., *Aircraft Ground De/Anti-icing Fluid Holdover Time Field Testing Program for the 1996-97 Winter*, APS Aviation Inc., Montreal, November 1997, TP 13131E.

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APPENDIX A

TERMS OF REFERENCE –
TRANSPORTATION DEVELOPMENT CENTRE
WORK STATEMENT

APPENDIX A

TRANSPORTATION DEVELOPMENT CENTRE

WORK STATEMENT

AIRCRAFT AND FLUID HOLDOVER TIME TESTS FOR WINTER 98-99

(December 1998)

1. INTRODUCTION

Following the crash of a F-28 at Dryden in 1989 and the subsequent recommendations of the Commission of Inquiry, the Dryden Commission Implementation Project (DCIP) of Transport Canada (TC) was set up. Together with many other regulatory activities an intensive research program of field testing of deicing and anti-icing fluids was initiated with guidance from the international air transport sector through the Society of Automotive Engineering (SAE) G-12 Committee on Aircraft Ground De/Anti-icing. As a result of the work performed to date Transport Canada and the US Federal Aviation Administration (the FAA) have been introducing holdover time regulations and the FAA has requested that the SAE, continue its work on substantiating the existing ISO/AEA/SAE Holdover Time (HOT) tables (TC research representing the bulk of the testing).

The times given in HOT Tables were originally established by the Association of European Airlines based on assumptions of fluid properties, and anecdotal data. The extensive testing conducted initially by the DCIP R&D Task Group and subsequently by its successor Transport Canada, Transportation Development Centre (TDC) Aviation Winter Operations R&D (AWORD) Group has been to determine the performance of fluids on standard flat plates in order to substantiate the times or, if warranted, to recommend changes.

TDC has undertaken most of the field research and much other allied research to improve understanding of the fluid HoldOver Times. Most of the HOT table cells been substantiated, however low temperatures have not been adequately explored and further tests are needed.

The development of ULTRA by Union Carbide stimulated all the fluid manufacturers to produce new long lasting anti-icing fluids defined as Type IV. All the Type IV fluids were upgraded in early 1996 and therefore all table conditions need to be re-evaluated and the table revised if necessary. Certain special conditions for which advance planning is particularly difficult such as low temperatures with precipitation, rain or other precipitation on cold soaked surfaces, and precipitation rates as high as

25 gm/dm²/hr need to be included in the data set. All lead to the need for further research.

Although the Holdover tables are widely used in the industry as guides to operating aircraft in winter precipitation the significance of the range of time values given in each cell of the table is obscure. There is a clear need to improve the understanding of the limiting weather conditions to which these values relate.

An important effort was made in the 94/95 and 95/96 seasons to verify that the flat plate data were representative of aircraft wings. Airlines cooperated with DCIP by making aircraft and ground support staff available at night to facilitate the correlation testing of flat plates with performance of fluids on aircraft. An extension of this testing was to observe patterns of fluid failure on aircraft in order to provide data to assist pilots with visual determination of fluid failure, and to provide a data to contamination sensor manufacturers. The few aircraft tests made to validate the flat plate tests were inconclusive and more such tests are needed. Additional tests testing with hot water for special deicing conditions were not completed. All these areas are the subjects for the further research that is planned for the 98/99 winter.

The primary objective of 97/98 testing was the performance evaluation of new and previously qualified Type IV fluids over the entire range of conditions encompassed by the holdover time tables. The effect of different variables on the fluid holdover time, in particular the effect of fluid viscosity, was examined and deemed to be significant. As a result, any future Type IV fluid holdover time testing will be conducted using samples representative of the manufacturers lowest recommended on-wing viscosity. Current methods for establishing holdover times in snow involve outdoor testing, which has been the source of industry concern for some time. It is recommended that a snowmaking device in development need to be evaluated for the future conduct of snow holdover time tests in controlled conditions. The study of fluid buffers was also continued in 97/98 and identified several industry concerns which will be addressed in further research. The adherence of contaminated fluid to aircraft wings was also evaluated in a series of simulated takeoff runs without aircraft rotation. Further research in these areas is needed.

2. PROGRAM OBJECTIVE (MCR 16)

Take an active and participatory role to advance aircraft ground de-icing/anti-icing technology. Develop international standards, guidance material for remote and runway-end de-icing facilities, and more reliable methods of predicting de-icing/anti-icing holdover times.

3. PROGRAM SUB-OBJECTIVES

3.1. Develop reliable holdover time (HOT) guideline material based on test information for a wide range of winter weather operating conditions.
3.2. Substantiate the guideline values in the existing holdover time (HOT) tables for fluids that have been qualified as acceptable on the basis of their impact on aircraft take-off performance.
3.3. Perform tests to establish relationships between laboratory testing and real world experience in protecting aircraft surfaces.
3.4. Support development of improved approaches to protecting aircraft surfaces from winter precipitation.

4. PROJECT OBJECTIVES

4.1. Develop holdover time data for all newly qualified de/anti-icing fluids.
4.2. Develop holdover time data for Type IV fluids using lowest qualifying viscosity samples.
4.3. Develop supplementary data for a reduced buffer 'de-icing only' Table.
4.4. Determine whether recycled, recovered fluid can be used as a 'De-icing only' fluid.
4.5. Determine whether the extreme precipitation rates used for laboratory testing of de/anti-icing fluids are in fact encountered in practice.
4.6. Obtain equipment for laboratory production of artificial snow which most closely reproduces natural snow.
4.7. Assess the limiting conditions of wind, precipitation and temperature under which water can be used as the first step of a two-step de-icing procedure.
4.8. Determine the patterns of frost formation and of fluid failure initiation and progression on the wings of high-wing turbo-prop and jet commuter aircraft.
4.9. Assess the practicality of using vehicle-mounted remote contamination detection sensors for pre-flight (end-of-runway) inspection.
4.10. Provide base data on the capabilities of remote sensors.
4.11. Provide pilots with reference data for the identification of fluid failure. Quantify pilot capabilities to identify fluid failure
4.12. Provide support services for the conduct of tests to determine under what conditions contaminated fluid adheres to aircraft lifting surfaces.
4.13. Assess whether pre-warming fuel at time of re-fuelling will help to eliminate the 'cold soaked' wing problem.
4.14. Develop a low-cost test wing which can be used in the laboratory in lieu of field testing full scale aircraft.
4.15. Establish the safe limits for de-icing truck operation when de-icing aircraft with the engines running.
4.16. Provide general support services.
4.17. Disseminate test findings

5. DETAILED STATEMENT OF WORK

5.1. General

5.1.1. Planning and Control

Develop a detailed work plan, activity schedule, cash flow projection, project management control and documentation procedures (as specified in Section 9,"Project Control") within three weeks of effective commencement date, confirming task priorities, suggesting hardware and software suppliers, broadly identifying data needs and defining the roles of subcontractors, and submit to TDC for review and approval.

5.1.2. Safety and Security

Particular consideration will be given to safety in and around aircraft on the airport and deicing sites In the event of conflict between access for data gathering to obtain required test results and safety considerations, safety shall always govern.

5.2. Holdover Time Testing and Evaluation of De/Anti-icing Fluids

5.2.1. Newly Certified Fluids

Conduct flat plate tests under conditions of natural snow and artificial precipitation to record the holdover times, and to develop individual Holdover Time Tables based on samples of newly certified or re-certified fluids supplied by Fluid Manufacturers under as wide a range of temperature, precipitation rate, precipitation type, and wind conditions as can be experienced. Anticipate tests for one new fluid. Snow tests shall be conducted outdoors, and ZD, ZR-, Zfog, and CSW tests will be performed in the laboratory. All testing shall be performed using the methodology developed in the conduct of similar tests for Transport Canada in past years.

5.2.2. Low Viscosity Type IV Anti-icing Fluids

Fluid holdover time testing of Type IV fluids will be conducted using procedures established during past test seasons but using fluid with the lowest operational use viscosity.

5.2.2.1. Flat Plate Tests for New Type IV Fluids

Conduct flat plate tests under conditions of natural snow and artificial precipitation to record the holdover times, and develop individual Holdover Time Tables based on samples of new Type IV fluids supplied by Fluid Manufacturers under as wide a range of temperature, precipitation rate, precipitation type, and wind conditions as can be experienced. Anticipate for four new fluids using samples with one viscosity. Snow tests shall be conducted outdoors, and ZD, ZR-, Zfog, and CSW tests shall be performed in the laboratory using methodology applied in past years.

5.2.2.2.Effect on Holdover Time of Viscosity

Conduct tests aimed at determining the effect of fluid viscosity on holdover time. Tests shall be conducted in light freezing rain and freezing drizzle conditions at various temperatures in the National Research council (NRC) Climatic Environment facility (CEF) using low and high viscosity samples representing production limits of three anti-icing fluids: a propylene, an ethylene and the Fluid X (which will become the benchmark for laboratory based HOT testing).

Anticipate a total of approximately 100 tests to be conducted under ZR- and ZD at -3 and -10 Celsius at low and high rates.

5.2.3. Recycled Fluids as Type I Fluids

5.2.3.1.Holdover Times

A complete set of holdover time tests shall be conducted using two fluid test samples of recovered glycol based freezing point depressant fluid which have been recycled and exhibit nominal conformance to Type I deicing fluid performance characteristics. The objective of this series of tests is to establish a sound base of data sufficient to establish valid holdover time tables for these fluids.

5.2.3.2.Compatibility with Type IV Fluids

Fluid compatibilty trials shall be conducted using various combinations of the recycled fluids and commercial Type IV fluids. Determine how the Inland fluids perform when used in conjunction with a Type IV fluid overspray.

5.3. Supplementary Data for Deicing Only Table

Evaluate the test conditions used in establishing the deicing only table by undertaking the following test series at sub zero temperatures but with no precipitation.

5.3.1. Establish Quantity of Fluid for Field Tests.

Conduct a series of comparative laboratory tests with 0.5, 0.25 and 0.1 litre per plate. Consider the case of spraying for frost with a fan shape to cover a wide area with a small amount of fluid compared with a stream as used to remove snow or ice. Examine typical fluid quantities representing frost removal spray. Conduct some tests on aircraft piggybacking on other testing if feasible.

5.3.2. Establish Temperature of Fluid for Field Tests

Laboratory tests will be performed with fluids initial temperatures at the spray nozzle of 60ºC, 50ºC, and 40ºC initial temperature.

Field tests on aircraft will be designed to measure the loss of fluid temperature and to measure fluid evaporation and enrichment during the air transport phase between spray nozzle and wing surfaces, for various distances and shapes of spray pattern (3 distances; 2 spray patterns).

5.3.2.1.

Examine the effect on the final freeze point of sprayed fluids on the wing, resulting from variations in the temperature of the fluid (60ºC, 50ºC, and 40ºC).

5.3.2.2.

Examine the effect on wing heat and fluid evaporation of removing contaminant from the wing surface. Various degrees of ice depth shall be deposited using a hand-held rainmaker, including a very light coating to simulate frost. The amount of fluid sprayed shall be controlled by the operator, spraying until a clean surface results**.**

5.3.3. Perform tests at current buffer limit as baseline.

Perform a series of comparative tests using buffers at 3ºC and 10ºC to compare to the new data and the data collected last season with buffers at 0ºC .

5.3.4. Simulate High Wind Conditions

Tests shall be performed using NRC fans producing winds up to 30 kph for comparison with the earlier series of tests with speeds up to 20 kph

5.3.5. High Relative Humidity

Perform a series of plate tests at 90% RH to compare results to those already gathered. Review the condition with weather services to determine typical RH values during deicing only conditions.

5.3.6. Cold Soaked Wings

Perform a series of tests on cold soak boxes to establish whether the natural buffer provided by evaporation would be sufficient to provide protection if the wing were in a cold-soaked condition, with wing temperature several degrees below OAT. These tests can be run in conjunction with high humidity tests when deposition of frost on cold soaked surfaces would normally be expected.

5.3.7. Effect of Snow Removal on Fluid Heat Input

Perform tests to establish whether removal of snow results in extensive amounts of heat being carried away and insufficient heat being transferred to the wing during deicing.

Expose flat plates to snowfall (either natural or as simulated by approved equipment) and protect snow catches of various thicknesses. Tests shall be run in an area protected from further snowfall. Fluid shall be applied with a hand sprayer, until the plate is cleaned, measuring the amount of fluid applied.

The final fluid concentration on the plate shall be measured. The heat lost in fluid run off shall be measured. Parallel tests will be conducted on bare surfaces.

A carefully calculated heat balance shall be determined for each experiment based on the temperatures of the applied fluid, the plate and the collected run-off material.

5.3.8. Effect of Composite Surfaces on Evaporation

Evaluate the effects of the use of composite materials in wings on the heat transfer from deicing fluid to the wing. Conduct a series of laboratory comparative tests on a several samples of composite surfaces.

Identify an appropriate aircraft having a wing surface composed of new technology composite material as well as aluminium, determining the thermal pathways connecting the composite surfaces to the main wing structure.

Conduct field tests on a sample aircraft.

5.3.9. Unpowered Flight Control Surfaces

Field trials will be conducted on DC9 aircraft to assess the impact of fluids of various buffers on the freedom of operation of the unpowered elevator control tabs to establish whether the natural buffer provided by evaporation would be sufficient to provide protection if the wing were in a cold-soaked condition, with wing temperature several degrees below OAT

5.3.10. Field Tests on Aircraft

Three overnight test sessions shall be planned for these tests. Tests shall be conducted on aircraft types including the McDonnell Douglas DC-9 and Canadair RJ, with a minimum of one night for each type. Testing on a third aircraft type would be useful to improve confidence and to confirm the universality of the results. Use an ice detector sensor system to provide a separate source of data.

5.3.11. Laboratory Tests

The number of proposed tests shall be controlled by limiting tests to the minimum number of ambient conditions that will support conclusions on the significance of the issues raised while maintaining a good level of confidence. As a minimum, this encompasses about 230 plate tests and would require about 8 days at the NRC CEF Facility or other suitable facility.

5.4. Flow of Contaminated Fluids from Wings during Takeoff

5.4.1. Requirement

Evaluate anti-icing fluids for their influence on adherence, in particular, propylene based Type IV fluids which were observed during fluid failure

A test plan shall be developed jointly with NRC.

Two days of testing at Mirabel Airport shall be planned.
Use an ice contamination sensor to assist in documenting contamination levels to provide valuable assistance in data gathering. A contingency allowance to fund sensor company participation shall be included.
Data collected during these trials shall include:

- type of fluid applied;
- record of contamination level prior to take off runs,;record of level of contamination following takeoff runs;
- observations, photography and video taping, and ice sensor records; and
- specifics on aircraft takeoff runs obtained from NRC personnel.

5.4.2. Conduct of Trials and Assembly of Results

Coordinate all test activities, initiating tests in conjunction with NRC test pilots based on forecast weather. Analyse results and document all findings in a final technical report and in presentation format.

5.5. Aircraft Full-Scale Tests

5.5.1. Purpose of Tests

Conduct full-scale aircraft tests:

- To generate data which can be used to assist pilots with visual identification of fluid failure;
- To generate data to be used to assess a pilot's field of view during adverse conditions of winter precipitation for selected aircraft; (See item 5.11)
- To compare the performance of de/anti-icing fluids on aircraft surfaces with the performance of de/anti-icing fluids on flat plates;
- To examine the pattern of failure using Type IV fluid brands not tested in the past; and
- To further investigate progression of failure on the two wings in crosswind conditions.

5.5.2. Planning and Coordination

Planning and preparation for tests including provision of facilities, personnel selection and training, and test scheduling shall be the same as provided to TDC in previous years

5.5.3. Testing

All tests and dry runs shall be performed using the methodology developed in the conduct of similar tests for Transport Canada in past years.
Test planning will be based on the following aircraft and facilities:

Aircraft	Airline	Test Locn.	Deicing Pad	Deicing Crew
Canadair RJ	Air Canada	Dorval	Central	Aéromag 2000
ATR42	Inter Canadian	Dorval	Central	Aéromag 2000

5.5.4. Test Measurements

Make the following measurements during the conduct of each test:

- Contaminated thickness histories at selected points on the wings. The selection of test points shall be made in cooperation with the Transportation Development Centre,
- Contamination histories at selected points on wings (selected in cooperation with the Transportation Development Centre),
- Location and time of first failure of fluids on the wings,
- Pattern and history of fluid failure progression,
- Time to failure of one third of the wing surface
- Concurrent measurement of time to failure of fluids on flat plates. The plates will be mounted on standard frames and on aircraft wings at agreed locations,
- Wing temperature distributions,
- Amount of fluid applied in each test run and fluid temperature,
- Meteorological conditions, and
- For crosswind tasks, effects of rate of accumulation on each wing.

In the event that there is no precipitation during full-scale tests, the opportunity shall be taken to make measurements of fluid thickness distributions on the wings. These measurements shall be repeated for a number of fluid applications to assess the uniformity of fluid application.

5.5.5. Pilot Observations

Contact airlines and arrange for pilots to be present during the tests to observe fluid failure and failure progression, and to record pilot observations from the cockpit and the cabin for later correlation with aircraft external observations.

5.5.6. Remote Sensor Records

Record the progression of fluid failure on the wing using RVSI and/or Cox remote contamination detection sensors if these sensors are made available.

5.6. Snowmaking Methods and Laboratory Testing for Holdover Times

5.6.1. Evaluation of Winter Weather Data

5.6.1.1. Snow Rates

Collect and evaluate snow weather data (precipitation rate/temperature data) during the winter to ascertain the suitability of the data ranges used to date for evaluation of holdover time limits.

Obtain current data from Environment Canada for three sites in Quebec: Rouyn, Pointe-au-père (Mont-Joli), and Ancienne Lorette (Quebec City), in addition to Dorval (Montreal).

5.6.1.2.Fog Deposition Rates

Devise a procedure and conduct fog deposition measurements outdoors on at least two occasions to determine the range of fog deposition rates which occur in natural conditions.

5.6.1.3. Frost Deposition Rates

Frost deposition rates shall be collected at various temperatures in natural conditions in order to determine a deposition range for this condition. Consideration shall be given to collecting deposition rates in cold temperatures (for example in Thompson, Manitoba). A total of five sessions shall be planned.

5.6.2. Snowmaking Methods

Acquire a version of the new snow generation system recently developed by the National Centre for Atmospheric Research (NCAR).

Evaluate the NCAR system for the future conduct of holdover time testing in simulated snow conditions. Tests shall be conducted in a small climatic chamber at Concordia University, PMG Technologies, or at NRC. Tests shall also be conducted with one Type IV fluid over a range of temperature and snowfall rates to compare the SAE holdover times for this fluid in natural and simulated conditions.

A further series of tests shall be performed with the system in order to assess the holdover time performance of the reference fluid (as described in the proposed SAE test procedures).

A total of 8 days of climatic chamber rental shall be planned for the conduct of the proposed tests.

5.7. Documentation of Appearance of Fluid Failure for Pilots

Current failure documentation deals largely with freezing drizzle and freezing rain conditions

5.7.1. Documentation of Failures

Finalise documentation of failure through limited further research as follows:

5.7.1.1.

provide similar documentation for fluids exposed to snow conditions, taking advantage of the availability of a snow making device for laboratory use;

5.7.1.2.

provide documentation for a propylene based Type IV fluid at typical delivered viscosity, for precipitation conditions tested previously, to determine characteristics at its operational limits and the nature and mechanisms of failure. Conduct selected comparison tests with a second fluid to test commonality of responses. Data from this activity will be cross-analysed with data from proposed research to examine the flow of similar fluids at different levels of contamination from aircraft wings during a simulated takeoff; and

5.7.1.3.

examine and document the appearance and nature of failure of propylene base fluids at cold temperatures (-10 C).

5.7.1.4.

Conduct tests at the National Research Council Climatic Environmental Facility based on last years' procedures, with enhancements as necessary and available. Snow documentation may be conducted in a different laboratory facility. Documentation under outdoor snow conditions will be conducted for comparison purposes to laboratory conditions.

5.7.2. Conduct of trials/assembly of results

Coordinate all test activities, scheduling tests with NRC CEF in conjunction with other test activities. Analyse results and document all findings, recommendations and conclusions in a final technical report and in presentation format. Provide timely updates of schedule revisions to TDC.

5.7.3. Pilot Observations

Contact airlines and arrange for pilots to be present during tests to observe fluid failure and failure progression. Record pilot observations for later correlation with aircraft external observations.

5.8. Feasibility of Performing Wing Inspections at End-of-runway

5.8.1. Requirement

Examine the feasibility of scanning aircraft wings with ice contamination sensors just prior to aircraft entering the departure runway using Dorval airport as an example scenario.

Explore ways of positioning sensors at agreed locations on an airport.

Composition and conduct of tests shall be adapted as information is gained on the practicality of this activity.

5.8.2. Planning

A Project Plan shall be prepared which will include:

a) activities to determine the parameters, operational issues and constraints related to the proposed process, and

b) a test plan for operational trials to examine the capabilities of the contamination sensors to determine the feasibility of their operational use.

The test plan for operational trials (three sessions) shall include:

- establishing test locations with airport authorities,
- establishing operational procedures with airport authorities,

- arranging equipment for scanning; vehicle, sensor installation and radios,
- collecting and coordinating information from the deicing activity at the deicing centre,
- test procedures with detailed responsibilities for all participants,
- control of the confidential data gathered on wing condition, and
- notification to all concerned in the project, including aircraft operators, that scanning activities will take place.

5.8.3. Coordination

Coordination all activites with authorities from Aéroports de Montréal and arrange support from Cox and/or RVSI

5.8.4. Field Trials

Conduct trials to further evaluate the feasibility of integrating such a process within current airport operations management, as well as to gather information on wing condition, just prior to takeoff, during deicing operations. These trials shall be based on the use of mobile equipment currently available. A "truthing" test pannel shall be present at each trial to demonstrate the validity of the wing readings on an ongoing basis

The trials shall be designed to address issues such as:

- equipment positioning versus current runway clearance limitations,
- time delay between inspection and start of take-off
- system capabilityto meet its design objectives in severe weather
- suitability of mobile equipment or fixed facility.
- need for rapid extension and retraction of sensor booms,
- airport support needed, e.g. snow clearance, provision of operating locations,
- accommodating scanner limitations for distance, light, angle of incidence.
- communications needed to support scanning operation,
- recording data from the sensors, and
- communicating results of the scanning to pilots and regulatory authorities.

5.8.5. Test Personnel and Participation

Initiate all tests based on suitable weather conditions. The individual test occasions shall be coordinated with Aéroports de Montréal and Aéromag 2000. Coordinate the provision of a suitable vehicle and the installation of an ice detection sensor. Monitor the test activity, ensuring the collection and protection of all scanning data, as well as the collection of data related to weather conditions and previous aircraft deicing activities. Ensure that the instrument providers deliver data and an objective measure of wing contamination based on scanner information in a timely and reproducible manner.

5.8.6. Study Results

Results from the feasibility study shall be presented in technical report format which shall include comments pertinent to long term implementation.

Results from the scanner tests shall be provided in technical report format and shall include analysis of wing contamination data cross-referred to the deicing history of individual aircraft scanned.

5.9. Ice Detection Sensor Certification Testing

5.9.1. Minimum Ice Thickness Detectable in Tactile Tests

Prepare procedures and conduct tests to establish human limits in identifying ice through tactile senses. These tests shall use the NRC or equivalent test facilities acceptable to TDC and a test setup equivalent to that planned for sensor certification. Several ice thicknesses and textures shall be tested to establish tactile sensing limiting thickness for smooth ice and for roughened ice.

The experiment shall involve sufficient participants and test conditions such as to provide reliable results usable in approving sensors to replace human tactile testing.

TDC shall assist in the experimental design

Tests shall be conducted with both contractor personnel and a selection of pilots as subjects.

A professional human factors scientist shall be used to establish testing parameters such as:

- what proportion of plates should be bare
- whether subjects should be blindfolded to eliminate visual cues.
- whether the same plate should be judged more than once
- how to ensure that subjects do not compare plates
- what should be the minimum time between plate touching

Results of the tests shall be analysed statistically to establish confidence limits for the findings

5.9.2. Field Tests for Sensor Distance and View Angle Limits

Develop a detailed test plan with a matrix of all test parameters, required coordination of equipment detailing the responsibilities of all participants.

Collect test data, including photo and video records of all tests.

The areas of ice contamination used for sensor evaluation shall be quantified by size, location and thickness. Angles of incidence, sensor heights and distances shall be verified independently. In concert with the sesor manufacturer, data from sensor readings and observer data shall be collated and analysed to reach conclusions on sensor limitations for distance and angle of incidence in various weather conditions.

5.10. Planning a Wing Deicing Test Site

Develop a plan for implementing a deicing test site, centred on an aircraft wing and supported by current fluid and rainmaking sprayers.
The plan shall include the acquisition of a surplus complete wing, from either a scrapped or an accidented moderate sized aircraft or an outboard section of a larger aircraft. The wing section should if possible include ailerons and leading edge slats
The design of the test site shall include a test area that could contain and recover sprayed fluids. Installation of the wing should entail a mounting designed to allow the wing to be rotated relative to current winds. The site must be secure yet allow ease of access and ability to install inexpensive solutions to control sprayed fluid.
Costs shall be estimated for the main elements of the development of a wing test bed site including:
wing purchase and delivery,
site lease and development, and
wing mount design and fabrication.

5.11. Evaluation of Hot (and Cold) Water Deicing

Investigate unheated and hot water deicing/defrosting, to determine under what meteorological conditions and temperatures these procedures are safe and practicable.
Unheated water deicing shall be evaluated at air temperatures above 1 degree C(34 degrees F).
Hot water deicing shall be evaluated at air temperatures below 1 degree C and include temperatures below –3 degrees C (27 degrees F).
These experiments shall establish how long it takes for the water to freeze on the surface under these conditions.
This is to be the first step of a two step procedure. From these data, a safe and practical lower limit shall be established considering the three-minute window required for second step anti-icing in the two-step deicing procedure.
Precipitation rates, as utilised in the generation of holdover time tables, shall be considered. Environmental chamber tests shall be correlated with outdoor aircraft tests. All laboratory test procedures and representative test results shall be recorded on videotape, including failure modes where applicable. The video shall depict a recommended full-scale aircraft hot water deicing procedure. A written report shall include the laboratory test results and a recommended aircraft unheated/hot water deicing procedure, including the limitations of precipitation, OAT and wind.

5.12. Evaluation of Warm Refuelling

Conduct a feasibility study of the suitability of refuelling with warm fuel to reduce susceptibility to “cold-soaked wing” icing, and to improve holdover times.

Coordinate activities to support testing the "warm fuel" concept using operational aircraft, including arranging;

- Participation of interested airlines, along with provision of aircraft for test purposes;
- Participation of local refueller;
- Arrangements with the equipment supplier (Polaris) to deliver the equipment to the selected airport along with the required technical support.

Testing will be conducted at Dorval on three occasions, one of which will include snow or freezing precipitation. Test aircraft selected should include a representation of both "wet" and "dry" wings if possible.

Wing surface temperatures of test wings will be monitored at several points over a period of time, to assess the influence thereon of warmed fuel. A reference case based on fuel boarded at the normal local temperature will be conducted.

5.13. Engine Air Velocity Distributions near Deicing Vehicles

Measure air velocity distributions in the vicinity of a de-icing truck when de-icing a large aircraft whose engines are running.

Tests shall be conducted during a period of no precipitation, either frost deicing or following snowfall, on two separate occasions at the Dorval International Airport deicing facility. Aircraft with engines mounted on the wing (e.g. B737) as well as rear engines mounted aircraft (e.g. DC-9 and RJ) will be sampled during live deicing operations, the precise type to be agreed by TDC. The tests shall be coordinated with Aéroport de Montréal and Aéromag 2000.

Wind velocity shall be measured from an Elephant-mu de-icing truck at locations recommended by TDC around the tail of the aircraft at different elevations and distances from the engines depending on the aircraft type, and the de-icing procedure followed by Aéromag 2000.

Photograph and video record the conduct of all tests.

5.14. Provision of Support Services

Provide support services to assist TDC with testing, the reduction of data and presentation of findings in the activites identified below which relate to the content of this work statement, but are not specifically included.

5.14.1. Re-Hydration

Conduct a series of exploratory trials on flat plates at the Dorval site or NRC to observe the behaviour of re-hydrated Type IV fluids and to help determine how re-hydration affects the flow- off characteristics of a Type IV fluid exposed to frost conditions.

5.14.2. Frost Tests on a Regional Jet

Conduct a series of tests to determine the roughness of frost deposition on the wings of a Regional Jet aircraft. Conduct tests on three overnight occasions.

5.14.3. Ice-Phobic Materials Evaluation

Conduct a series of tests on flat plates to determine the effects of ice-phobic materials on the film thickness and on holdover time of de/anti-icing fluids.

5.14.4. Evaluation of Infra-Red Thermometers

Evaluate use of infra-red technology as a method of determining accurate skin and fluid temperatures during operational conditions. Conduct tests in conjunction with full-scale and holdover time testing.

5.14.5. Frost Self-Elimination

Examine the self-elimination of frost on several test surfaces under variable weather conditions. Conduct test in conjunction with frost deposition trials on flat plates.

5.14.6. Environmental Impact Assessment

Assess the environmental issues related to the use of glycol-based products for aircraft de-icing purposes. Examine the waste fluid collection and disposal procedures for several deicing facilities in relation to current and future environmental legislation.

5.14.7. An Approach to Establish Wing Contamination

Document an approach to determining operational limits for levels of contamination on aircraft wings. This approach will include consideration of the location of contamination on the wings and the area contaminated. The levels of contamination on aircraft wings prior to takeoff as determined during the scanning trials prior to takeoff will be factored in.

The approach will discuss how the limits (when defined) could be used in software routines to enable sensor systems to provide Go/No-Go indications to the aircraft pilot and regulatory authorities.

5.14.8. Accident/incident Database Analysis

Provision of database manipulation and support aimed at establishing problem areas and their significance.

5.14.9. Other activities

Other activities, such as the evaluation of forced air technology, the evaluation of alternate (zero glycol) deicing methods, and the evaluation of frost removal equipment at gates, or others may emerge as issues during the course of the winter season.

APPENDIX B

EXPERIMENTAL PROGRAM

PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE

OF FAILED FLUIDS FOR OUTDOOR TESTS

Winter 1997-98

CM1380.001

EXPERIMENTAL PROGRAM
PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE OF FAILED FLUIDS FOR OUTDOOR TESTS

Winter 1997-98

EXTRACTS

APS AVIATION INC.

October 9, 1998
Version 1.1

EXPERIMENTAL PROGRAM
PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE OF FAILED FLUIDS
Winter 1997-98

1. OBJECTIVES

APS will conduct flat plate tests in the National Research Council Climatic Engineering Facility laboratory, and in the field designed to address the following issues:

- What is the appearance of a failed fluid;
- How does the appearance of a Type I fluid failure differ from a Type IV fluid failure;
- How does the appearance of failure under conditions of freezing drizzle differ from failure under conditions of freezing rain, and under conditions of snowfall;
- Under what conditions do de/anti-icing fluids flash freeze;
- Are there differences in failure appearance between ethylene, and propylene glycol fluids when exposed to freezing drizzle; and
- Do strong winds significantly affect failure appearance.

The *July 6 1998 Schedule for HOT Tests* is shown in Figure B-1.

The test plan for *Documentation of Fluid Failure Tests in Natural Conditions* is shown in Table B-1. Table B-2 shows the *Observer Access to Test Plates for Documentation of Failure*. Attachment BIII shows the *CEF Detailed Test Plan* for freezing rain, freezing drizzle, freezing drizzle and light freezing rain, and light freezing rain for documentation of failures

2. TEST PROCEDURES

- Flat plate tests will be conducted at the Dorval test site and at the National Research Council Climatic Engineering Facility in Ottawa for comparison purposes.

- Flat plate tests will be conducted using the same procedures as shown in the *Experimental Program for Dorval Natural Precipitation Flat Plate Testing*.

- For each test, the following additional information should also be recorded:
  - i) Fluid thickness at selected locations;
  - ii) Fluid viscosity at selected locations;
  - iii) Refractive index (Brix) at selected locations;

iv) Video and photos of the plate and crosshairs at the time of fluid failure;
v) RVSI sensor record of fluid failure;
vi) Spar/Cox sensor record of fluid failure;
vii) C/FIMS point sensor record of fluid failure; and
viii) Fluid adherence at selected locations.

- Fluid failures will be recorded by the plate observer using standard flat plate test procedures. Failures will be recorded on the Documentation of Failure form (Table B-3). A narrative description of the appearance of the fluid as it progresses toward failure was also recorded. The data form used to record this description, Subjective Appearance of Fluid Failure, is shown in Table B-4.

- Plate pan rates should be measured every five minutes. Three or four pans should be used.

- Fluid thickness measurements should be taken at the 15 cm (6") line at the start of the test and every two minutes thereafter for Type I tests and at the start of the test and every five minutes thereafter for Type IV tests. Thickness measurements and times should be noted on the data form (Table B-5). Refer to the detailed procedure in Transport Canada report, TP 13130E, Appendix C (Attachment VI).

- Fluid quantity applied to plate should be 1.5 l for outdoor tests and tests conducted at the National Research Council Climatic Engineering Facility.

- A Fluid viscosity sample should be collected at the time and point of fifth crosshair failure, and also at B2, F2 and adjacent to the 5th crosshair after complete plate failure. A 10 ml sample should be collected using a spatula and placed in an air-tight sample container. Sample containers should be labelled with a date, sample collection time, stand and run number, fluid type and plate number. The *Viscosity Sampling Form* is shown in Table B-6. Because of the destructive nature of the sample process, it is recommended that a separate plate be run solely for the purpose of collecting samples.

- The refractive index of each fluid should be taken prior to application using a hand-held refractometer and recorded on the *Brix Sampling and Data Forms* (see Tables B-7 and B-8). For Type I tests, samples should be collected at two-minute intervals thereafter on a crosshair adjacent to the C/FIMS. For Type IV tests, top and bottom fluid samples will be collected at five-minute intervals on a crosshair adjacent to the C/FIMS. Top samples will be obtained by resting a piece of plastic film on the surface of the fluid. Bottom samples will be taken with a syringe by drawing small amounts of fluid at several points near the sample location. Brix values and corresponding sample times should be recorded accurately on the Brix data form (use one form per test plate). Brix of the mixed fluid should also be measured on an adjacent location.

- Fluid application, initial plate failure, 7.5 cm (3") failure, 15 cm (6") failure (15 crosshairs) and entire plate failure should be recorded using a digital video camera and 35 mm still camera. Records should be taken from the front and back of the stand. In addition, a video camera mounted on a tripod should be focused on one crosshair on the 15 cm (6") line to record precipitation absorbency.

- Personnel must ensure that the RVSI and Spar/Cox sensors, and C/FIMS point sensors are operational prior to each test and are left running until complete plate failure. Also, when measuring Brix and thickness etc. on the 15 cm (6") line, do not disrupt the fluid over the C/FIMS sensor head (take measurements on an adjacent crosshair).

- Fluid adherence should be determined at the 5th crosshair immediately following failure at this location (not over the C/FIMS) and at location B2. When the entire plate (15 crosshairs) has failed, again verify the fluid adherence at the 15 cm (6") line on the opposite crosshair, and at all crosshairs B2, C2, D2, E2 and F2. Adherence should be noted by the plate observer on the special data form (Table B-9).

3. PERSONNEL

Personnel requirements for the conduct of documentation of the appearance of failed fluid tests for outdoor tests are:

- One Test Coordinator (NB);
- One End Condition Tester (monitor the progression of failures on the plates) (MC);
- One Meteo Tester (measure plate pan weights, record meteo, ensure sensors are operational);
- Two General Observers (measure and record brix, adherence and thickness, collect samples);
- One Photographer (take photographs of fluid application and failures); and
- One Video Tester (video fluid application and failures, ensure that the fixed video camera for recording precipitation absorbency is operational).

Table B-10 shows the *Personnel CEF Detailed Test Plan*

4. EQUIPMENT

A kit comprising the following equipment should be prepared for the conduct of documentation of failure tests:

- Thickness gauges;
- Sample bottles;
- Spatulas;
- Hand-held refractometer;
- Plastic film;
- Syringe;
- Two video cameras (one digital);
- One video camera tripod;
- 35 mm camera; and
- Adherence tester.

Table B-11 shows the *Supplemental Test Equipment Checklist for the NRC Cold Chamber Tests for July 1998*

FIGURE B-1

HOT TESTS AT CEF - NRC

July 6 - 10, 1998

MONDAY July 6	TUESDAY July 7	WEDNESDAY July 8	THURSDAY July 9	FRIDAY July 10
NRC Wind Capability **HOTs with Wind** Runs W1-W3 3.0 Hours -ZR R=25 -3°C With **WIND** (Attachment V)	**TYPE 0** Runs: R1-R2 3.0 Hours -ZR (x 1) R=25 -10°C (Attachment II)	**DOC. Fail** Runs D 3,4,6,7 6.5 Hours -ZR R=25 -10°C (Attachment III)	**DOC. Fail** Runs D 3,4,6,7 6.5 Hours ZD R=12 -10°C, -3°C (Attachment III)	**Test with AMIL** -ZR R=25 -10°C (Attachment I)
Effect of Slope **Fluid Application** Runs 7-9 3.0 Hours -ZR R=25 -3°C (Attachment IV)	**TYPE 0** **Runs: R5-R6** 2.0 Hours -ZR (x 1) R=25 -3°C **Runs: R3-R4** 2.0 Hours ZD (x 1) R=12 -3°C (Attachment II)			**Effect of Fluid Temperature** **Fluid Application** Runs H1-H4 5.0 Hours -ZR R=25 -3°C (Attachment VI)

THICKNESS TESTS (Attachment VII)

RATE DISTRIBUTION (Attachment VIII)

Personnel

	Monday	Tuesday	Wednesday	Thursday	Friday
Failure	MC	MC	MC	MC	MC
Rate 1	CB	CB	CB	CB	CB
Fluid Prep/Application	ER/ML	ER/ML	ER/ML	ER/ML	ER/ML
Data	MH	MH	MH	MH	MH
Extra people	NB (th, rate)	NB (th, rate)	NB (jd)/PD/JM/DR/AP	NB(jd)/PD/JM/DR/AP	NB (fla, heat)

TABLE B-1

DOCUMENTATION OF FAILURES

#	Activity Description	Location	Temp °C	Wind	Precip. type	Rate g/dm2/hr	Fluid brand	Fluid Type	Concentration
1	Appearance of Type I vs Type IV failures	AES	0 to -5	<10kph	Snow	5 to 20	UCAR ADF UCAR Ultra+	I IV	XL54 Neat
2	Appearance of Type I vs Type IV failures in high wind conditions	AES	0 to -5	>20kph	Snow	5 to 20	UCAR ADF UCAR Ultra+	I IV	XL54 Neat
3	Appearance of Type IV failures in ZD vs Type IV failures in ZR	NRC	-10	N/A	ZD/ZR		Kilfrost ABC-4 Octagon Maxfight	IV IV	Neat Neat
4	Ethylene vs propylene Type IV failures in ZD	NRC	-10	N/A	ZD		UCAR Ultra+ Kilfrost/Octagon	IV IV	Neat Neat
5	Time for Type I and Type IV failures to adhere to the plate following failure	AES	0 to -5	N/A	Snow	5 to20	UCAR ADF UCAR Ultra+	I IV	XL54 Neat
6	Time for Type I and Type IV failures to adhere to the plate following failure	NRC		N/A	ZR		UCAR ADF UCAR Ultra+	I IV	XL54 Neat
7	*Flash freeze* of Type I or Type IV 50/50 in ZD/ZR.	NRC	0 to -3	N/A	ZD/ZR		UCAR ADF Hoechst	I IV	XL54 50/50
8	Appearance of failures in wet vs dry snow	AES	0 to -5	N/A	Snow	5 to 20	UCAR Ultra+	IV	Neat
9	Appearance of high rate vs low rate Type IV fluid failures (snow bridging).	AES	0 to -5	N/A	Snow	5 to 10 >20	UCAR Ultra+	IV	Neat

TABLE B-2

DOCUMENTATION OF FAILURE

OBSERVER ACCESS TO TEST PLATES

Sequence of Activities Triggered by Condition Call

<table>
<tr><th>Activity</th><th>Person</th><th>Preparation</th><th>Application</th><th>Initial Failure</th><th>Plate Failure 5th Crosshair or 1/3 Plate</th><th>Complete Plate Failure</th></tr>
<tr><td>Condition Call</td><td>MC</td><td></td><td></td><td>x1</td><td>x1</td><td>x1</td></tr>
<tr><td>Adherence</td><td>MC</td><td></td><td></td><td></td><td>x5</td><td>x4</td></tr>
<tr><td>Brix (Plate Failure)</td><td>MC</td><td></td><td></td><td></td><td>x4</td><td></td></tr>
<tr><td>Viscosity Sample</td><td>NB</td><td></td><td></td><td></td><td>x6</td><td>x5</td></tr>
<tr><td>Description</td><td>AP</td><td></td><td>x2</td><td>x2</td><td>x2</td><td>x2</td></tr>
<tr><td>Photo</td><td>JM</td><td></td><td>x2</td><td>x2</td><td>x2</td><td>x2</td></tr>
<tr><td>Video</td><td>DR</td><td></td><td>x3</td><td>x3</td><td>x3</td><td>x3</td></tr>
<tr><td>Brix (Continuous)</td><td>ER</td><td>x</td><td></td><td rowspan="2" colspan="4"><u>After Application</u>:
Type I: 2 minute Intervals
Type IV: 5 minute Intervals
Defer to activities triggered by plate condition calls</td></tr>
<tr><td>Thickness (Continuous)</td><td>NB</td><td></td><td>x1</td></tr>
</table>

FIGURE B-2A

DOCUMENTATION OF FAILURES
CEF DETAILED TEST PLAN
FREEZING RAIN

Run # : 1 Rate: 25 g/dm^2/hr
Temperature : -3° ZR

	UCAR XL54 STD	UCAR ULTRA + 100/0	UCAR ULTRA + 100/0	UCAR XL54 STD	

Appearance of Type I vs Type IV failures in Freezing Rain

Video record a circuit around stand with digital video camera

Run # : 2a Rate: 25 g/dm^2/hr
Temperature : -10°C ZR

	UCAR ULTRA + 100/0	OCTAGON MAX. 100/0	OCTAGON MAX. 100/0	UCAR ULTRA + 100/0	

Appearance of Type IV failures in Freezing Rain vs Freezing Drizzle

FIGURE B-2B

DOCUMENTATION OF FAILURES
CEF DETAILED TEST PLAN
FREEZING DRIZZLE

Run # : 2b
Temperature : -10°C

Rate: 5 g/dm^2/hr
ZD

	UCAR ULTRA + 100/0	OCTAGON MAX. 100/0	OCTAGON MAX. 100/0	UCAR ULTRA + 100/0	

Appearance of Type IV failures in Freezing Rain vs Freezing Drizzle

Run # : 3a
Temperature : -10°C

Rate: 13 g/dm^2/hr
ZD

	UCAR ULTRA + 100/0	OCTAGON MAX. 100/0	OCTAGON MAX. 100/0	UCAR ULTRA + 100/0	

Effect of Temperature on the appearance of Type IV failures
Ethylene vs, Propylene Type IV failures in Freezing Drizzle

FIGURE B-2C

DOCUMENTATION OF FAILURES
CEF DETAILED TEST PLAN
FREEZING DRIZZLE AND LIGHT FREEZING RAIN

Run # : 3B   Rate: 13 $g/dm^2/hr$
Temperature : -3°C   ZD

	UCAR ULTRA + 100/0	OCTAGON MAX. 100/0	OCTAGON MAX. 100/0	UCAR ULTRA + 100/0	

Effect of Temperature on the appearance of Type IV failures

Run # : 4   Rate: 25 $g/dm^2/hr$
Temperature : -10°C   ZR

	UCAR XL54 STD	UCAR ULTRA + 100/0	UCAR ULTRA + 100/0	UCAR XL54 STD	

Time for Type I vs Type IV to adhere

* Possibly repeat this trial using propylene Type IV

FIGURE B-2D

DOCUMENTATION OF FAILURES
CEF DETAILED TEST PLAN
LIGHT FREEZING RAIN

Run # : 5
Temperature : -10°C

Rate: 25 g/dm^2/hr
ZR

	UCAR XL54 STD	SPCA AD-480 50/50	SPCA AD-480 50/50	UCAR XL54 STD	

Flash freeze of Type I or Type IV 50/50 in ZR

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3/31/2006

TABLE B-3

DOCUMENTATION OF FAILURE

General Form (Every Run)

Location: CEF Ottawa **Date:** July , 1998 **Time:** ______________

Run #: __________ **Ambient Temperature:** __________ (°C) **Precip. Type: ZR-, ZD**

Run Objective: ____

____

Plate Location:

1	2	3	4	5	6
7	8	9	10	11	12

Plate Documentation:

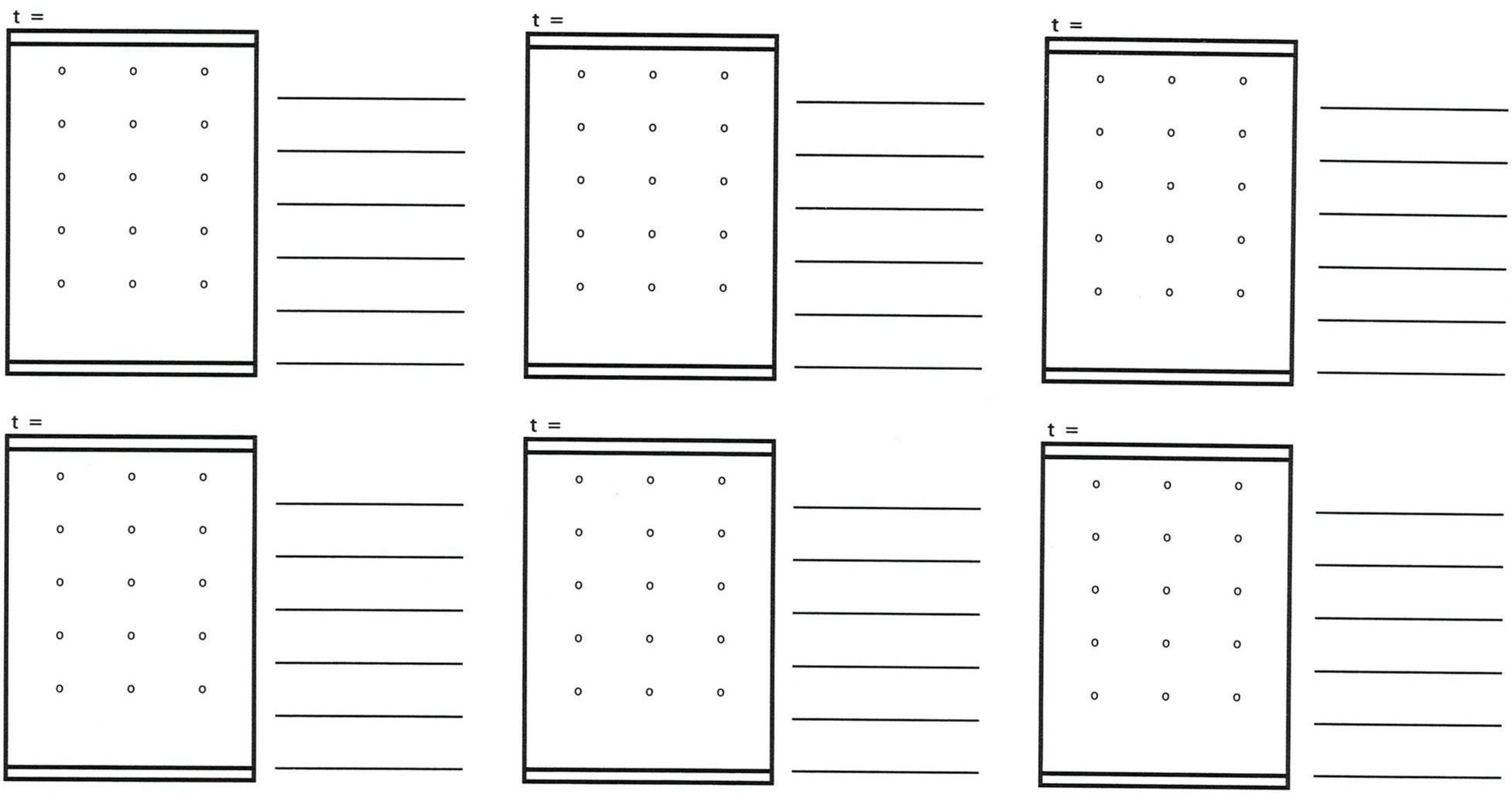
	1	2	3	4
Fluid Type/Mix				
C/FIMS				
RVSI				
Cox				
Adherence				
Brix				
Thickness				
Viscosity				
Description				
Photo				
Video				

TABLE B-4

SUBJECTIVE APPEARANCE OF FLUID FAILURE

Date: ____________ Time: ____________ Plate Location: ________

Run #: ____________ Fluid Name: ____________ Fluid Dilution: ________



Note: Ensure observations made at t=0, 1st failure, 5th crosshair, whole plate
Make observations on C/FIMS

Table B-5

FLUID THICKNESS ON FLAT PLATES

DATE: ____________________ **OAT (°C):** ____________________

RUN NUMBERS: ____________________ **PERFORMED BY:** ____________________

LOCATION: YUL **WRITTEN BY:** ____________________

THICKNESS (mil)							
Plate: Fluid: Fluid Application Time:				Plate: Fluid: Fluid Application Time:			
TIME	**1" LINE**	**6" LINE**	**12" LINE**	**TIME**	**1" LINE**	**6" LINE**	**12" LINE**

TABLE B-6

VISCOSITY SAMPLING FORM

Location: CEF Ottawa

Date: July , 1998

Run #: ____________

Temperature: ____________ (°C)

Precip Type: ZR-, ZD

3" Line	B1	B2	B3
6" Line	C1	C2	C3
9" Line	D1	D2	D3
12" Line	E1	E2	E3
15" Line	F1	F2	F3

Time	Fluid	Plate #	Sample Location	Bottle #	Viscosity

cm1514\report\doc_fail\working documentsVISC_FRM
At: Viscosity

TABLE B-7

BRIX SAMPLING FORM

Location: CEF Ottawa **Date:** July , 1998

Run #: ___________ **C/FIMS #:** ___________

Ambient Temperature: ___________ (°C) **Precip Type: ZR-, ZD**

Plate Location:

1	2	3	4	5	6
7	8	9	10	11	12

Fluid: ___________ **Initial Brix:** ___________

Time	Brix Top	Brix Bottom	Average Brix

TABLE B-8

BRIX DATA FORM

Location: ______________________ C/FIMS #: ______________________

Date: ______________________ Plate: ______________________

Run #: ______________________ Time of fluid application: ____________

Sample location: ______________________

Time	Brix Top	Brix Bottom

Comments: ____

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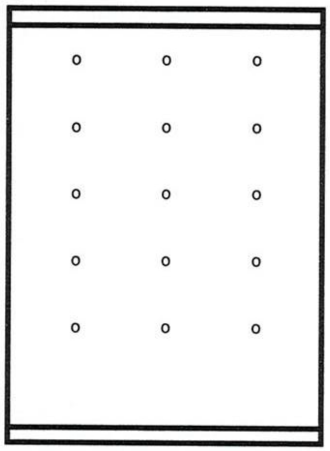
TABLE B-9

ADHERENCE OF FLUID FAILURE

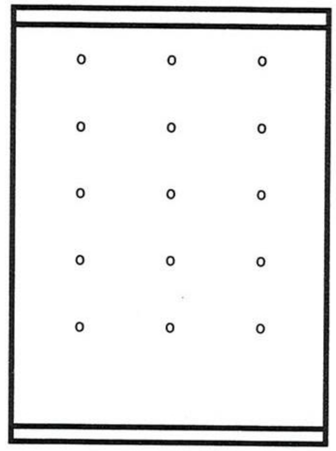
Date: ____________ Time: ____________ Plate Location: ________

Run #: ____________ Fluid Name: ____________ Fluid Dilution: ________

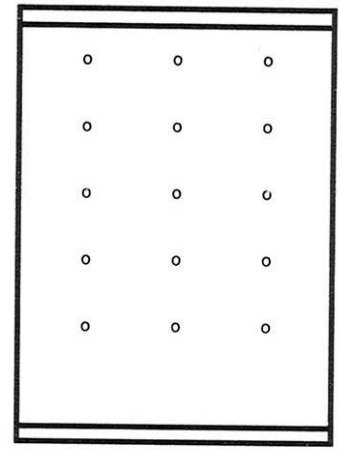
t =



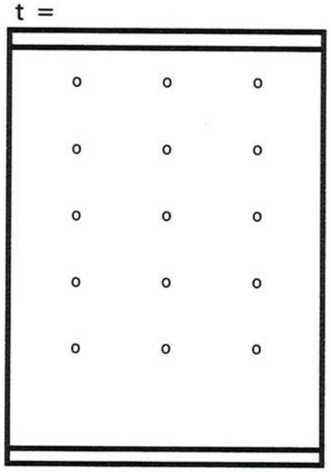
t =



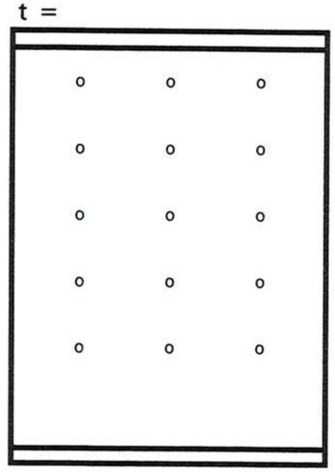
t =



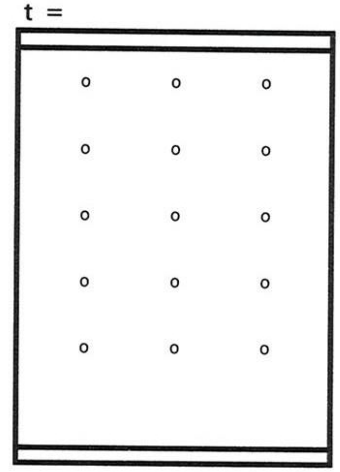
t =



t =



t =



Note: Ensure observations made 5th crosshair, whole plate
Make observations on C/FIMS

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At: Adherence

TABLE B-10

PERSONNEL
CEF DETAILED TEST PLAN
DOCUMENTATION OF FAILURE

MC - Failures on all crosshairs, Adherence

NB - Thickness, Viscosity sampling

ER - Brix (Average, Top, Bottom)

ML - Rates, preparation

MH - Rates, Computers, Sensors

PD - Manager, objective achievement

JM - Photography

DR - Video

JD - Quality control, support for Brix

AP - Subjective evaluation and appearance of failure

CB - Support for Brix

TABLE B-11

NRC COLD CHAMBER TESTS JULY 1998

SUPPLEMENTAL TEST EQUIPMENT CHECKLIST

Test Equipment	Resp.
Nick's brush	ER
Washer for slope test	ER
Inclinometer (old & new) (office & site)	ER
Dental probe (charger)	JD
C/FIMS(computer , cables)	ER
Laptop comp.	MH
Still photo camera (digital + regular)	JD
Call Don Coveney in Ottawa, ask what needs to be put in the chambre on Fri.	MC
Video cameras (surf & snow) from office	ER,JM
Bring extra plates from site	ER
Bring board from the office	ER
Bring a copy of hold over report	ER,JD
procedure & data forms	ER,MH
Give Jeff instructions (dig. Video, reg video, dickie moore)	ER
Fluids for Ottawa	MC
Clipboards	ER
Pencils & pens	ER
Rags & paper towels	ER
Plastic funnels and refills / ext. cords / norm. lighting/squeegees	ER
Brixometer	ER
Tie wraps	ER
Temp Probes	ER
Thickness guages {square +octogonal} (ER)	ER
Fluid sampling bottles	ER
Plastic scraper & transparency for taking fluid sample (ER)	ER
Bring Printer (brother) & paper (office)	ER
Where are the special rate pans (site)	ER
Infrared Thermometer (office)	ER
Viscometer (office)	ER
Syringe (office)	ER
Plexi glass plate	ER
Pallets (return to Rona)	ER,MC

APPENDIX C

EXPERIMENTAL PROGRAM

PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE

OF FAILED FLUIDS FOR OUTDOOR TESTS

Winter 1998-99

CM1514.001

EXPERIMENTAL PROGRAM
PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE OF FAILED FLUIDS FOR OUTDOOR TESTS

Winter 1998-99

APS AVIATION INC.

December 9, 1998
Version 1.0

EXPERIMENTAL PROGRAM
PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE OF FAILED FLUIDS

Winter 1998-99

1. OBJECTIVES

APS will conduct flat plate tests in the field designed to address the following issues:

- What is the appearance of a failed fluid;
- How does the appearance of a Type I fluid failure differ from a Type IV fluid failure;
- How does the appearance of failure under conditions of freezing drizzle differ from failure under conditions of freezing rain, and under conditions of snowfall;
- Under what conditions do de/anti-icing fluids flash freeze;
- Are there differences in failure appearance between ethylene, and propylene glycol fluids when exposed to freezing drizzle; and
- Do strong winds significantly affect failure appearance.

The test plan for documentation of fluid failure tests in natural conditions is shown in Table C-1.

2. TEST PROCEDURES

- Flat plate tests will be conducted in natural precipitation at the Dorval test site.

- Flat plate tests will be conducted using the same procedures as shown in the *Experimental Program for Dorval Natural Precipitation Flat Plate Testing*. The fluid quantity applied to each plate should be 1.5 L.

- For each test, the following additional information should be recorded:
  - i) Fluid thickness at selected locations;
  - ii) Fluid viscosity at selected locations;
  - iii) Refractive index (Brix) at selected locations;
  - iv) Video and photos of the plate and crosshairs at the time of fluid failure;

v) RVSI sensor record of fluid failure;
vi) Spar/Cox sensor record of fluid failure;
vii) C/FIMS point sensor record of fluid failure; and
viii) Fluid adherence at selected locations.

- Fluid failures will be recorded by the plate observer using standard flat plate test procedures. Failures will be recorded on the *End Condition Data Form* (Table C-2). A narrative description of the appearance of the fluid as it progresses toward failure was also recorded. The data form used to record this description, *Subjective Appearance of Fluid Failure*, is shown in Table C-3.

- Plate pan rates should be measured every five minutes. Three or four pans should be used. Precipitation rate and meteo information will be recorded on the *Meteo/Plate Pan Data Form* (Table C-4).

- Fluid thickness measurements should be taken at the 15 cm (6") line at the start of the test and every two minutes thereafter for Type I tests and at the start of the test and every five minutes thereafter for Type IV tests. Thickness measurements and times should be noted on the data form (Table C-5).

- Fluid viscosity samples should be collected at the time of complete plate failure. The failed plate should be divided into three equal sections, the top, middle and bottom, and the failed fluid contained within each section should be placed in an air-tight sample container using a spatula. Sample containers should be labelled with a date, sample collection time, stand and run number, fluid type and plate number. The *Viscosity Sampling Form* is shown in Table C-6.

- The refractive index of each fluid should be taken prior to application using a hand-held refractometer and recorded on the *Brix Sampling Form* (Table C-7). For Type I tests, samples should be collected at two-minute intervals thereafter on a crosshair adjacent to the C/FIMS. For Type IV tests, top and bottom fluid samples will be collected at five-minute intervals on a crosshair adjacent to the C/FIMS. Top samples will be obtained by resting a piece of plastic film on the surface of the fluid. Bottom samples will be taken with a syringe by drawing small amounts of fluid at several points near the sample location. Brix values and corresponding sample times should be recorded accurately on the Brix data form (use one form per test plate). Brix of the mixed fluid should also be measured on an adjacent location.

- Fluid application, initial plate failure, 7.5 cm (3") failure, 15 cm (6") failure (15 crosshairs) and entire plate failure should be recorded using a digital video camera and 35 mm still camera. Records should be taken from the front and back of the stand. In addition, a video camera mounted on a tripod should be focused on one crosshair on the 15 cm (6") line to record precipitation absorbency.

- Personnel must ensure that the RVSI and Spar/Cox sensors, and C/FIMS point sensors are operational prior to each test and are left running until complete plate failure. Also, when measuring brix and thickness etc. on the 15 cm (6") line, do not disrupt the fluid over the C/FIMS sensor head (take measurements on an adjacent crosshair).

- Fluid adherence should be determined at the 5th crosshair immediately following failure at this location (not over the C/FIMS) and at location B2. When the entire plate (15 crosshairs) has failed, again verify the fluid adherence at the 15 cm (6") line on the opposite crosshair, 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 (Table C-8).

  In addition to measuring adherence at the time of plate failure and complete plate failure, adherence should be measured progressively following fluid failure at defined positions to determine the onset of adherence.

3. PERSONNEL

Personnel requirements for the conduct of documentation of the appearance of failed fluid tests for outdoor tests are:

- One Test Coordinator;
- One End Condition Tester (monitor the progression of failures on the plates, verify adherence);
- One Observer recording narrative description of failure;
- One Meteo Tester (measure plate pan weights, record meteo, ensure sensors are operational);
- Two General Observers (measure and record brix, thickness, and collect samples);
- One Photographer (take photographs of fluid application and failures); and
- One Video Tester (video fluid application and failures, ensure that the fixed video camera for recording precipitation absorbency is operational).

4. EQUIPMENT

Standard flat plate test equipment will be used in documentation of fluid failure tests in natural conditions. In addition, a list of supplemental test equipment, specific to documentation of fluid failure tests, is included in Attachment CI.

ATTACHMENT CI

APS SITE DOCUMENTATION OF FAILURE TESTS 1998-99

TEST EQUIPMENT CHECKLIST

Test Equipment
Adherence tester (charger)
Inclinometer
C/FIMS (computer , cables)
Still photo camera (digital + regular) with time stamp
Video cameras
procedure & data forms
Brixometer
Temperature Probes
Thickness guages (square +octogonal)
Fluid sampling bottles
Plastic scraper & transparency for taking fluid samples
Syringe

TABLE C-1
DOCUMENTATION OF FAILURES

#	Activity Description	Location	Temp °C	Wind	Precip. type	Rate g/dm2/hr	Fluid brand	Fluid Type	Concentration
1	Appearance of Type I vs Type IV failures	AES	0 to -5	<10kph	Snow	5 to 20	UCAR ADF Ultra+, Maxflight	I IV	XL54 Neat, Neat
2	Appearance of Type I vs Type IV failures in high wind conditions	AES	0 to -5	>20kph	Snow	5 to 20	UCAR ADF Ultra+, Maxflight	I IV	XL54 Neat
3	Time for Type I and Type IV failures to adhere to the plate following failure	AES	0 to -5	N/A	Snow	5 to20	UCAR ADF Ultra+, Maxflight	I IV	XL54 Neat
4	Effect of temperature on Type IV fluid failures	AES	0 to -3 < -7°C	NA	Snow	5 to 20	UCAR Ultra+ Oct. Maxflight	IV IV	Neat Neat
5	Appearance of failures in wet vs dry snow	AES	0 to -5	N/A	Snow	5 to 20	UCAR Ultra+	IV	Neat
6	Appearance of high rate vs low rate Type IV fluid failures (snow bridging).	AES	0 to -5	N/A	Snow	5 to 10 >20	UCAR Ultra+ Oct. Maxflight	IV IV	Neat Neat

NB: Attempts will be made to capture several of these conditions, however, because these conditions cannot be controlled, some tests may not materialize.

TABLE C-2

END CONDITION DATA FORM

REMEMBER TO SYNCHRONIZE TIME WITH AES - USE REAL TIME

VERSION 5.0 Winter 97/98

LOCATION: **DATE:** **RUN # :** **STAND # :**

RVSI Series # : ____________

CIRCLE SENSOR PLATE: u v w x y z

SENSOR NAME: ___ ___ ___ ___ ___ ___

DIRECTION OF STAND: ______ o

OTHER COMMENTS (Fluid Batch, etc):

____

____

____

____

____

____

____

____

	PRINT	SIGN
FAILURES CALLED BY :		
HAND WRITTTEN BY :		
TEST SITE LEADER :		

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

Time of Fluid Application: ______ hr:min (U & X) ______ hr:min (V & Y) ______ hr:min (W & Z)

	Plate U			Plate V			Plate W		
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 AT FAILURE									

	Plate X			Plate Y			Plate Z		
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 AT FAILURE									

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At: Data Form 11/16/2005

TABLE C-3

SUBJECTIVE APPEARANCE OF FLUID FAILURE

Date: ____________ Time: ____________ Plate Location: ________

Run #: ____________ Fluid Name: ____________ Fluid Dilution: ________

t =

t =

t =

t =

t =

t =

Note: Ensure observations made at t=0, 1st failure, 5th crosshair, whole plate
Make observations on C/FIMS

cm1514\report\doc_fail\SUBJ_EVL
At: Evaluation
11/16/2005

TABLE C-4

METEO/PLATE PAN DATA FORM

REMEMBER TO SYNCHRONIZE TIME WITH AES - USE REAL TIME

VERSION 5.0 Winter 97/98

LOCATION: **DATE:** **RUN # :** **STAND # :**

HAND HELD VIDEO CASSETTE #:

PLATE PAN WEIGHT MEASUREMENTS *

PAN #	t TIME BEFORE (hr:min)	t TIME AFTER (hr:min)	w WEIGHT BEFORE (grams)	w WEIGHT AFTER (grams)	COMPUTE RATE (Δ w*4.7/Δt) ($g/dm^2/h$)

*measurements every 15 min. and at failure time of each test panel.

METEO OBSERVATIONS **

TIME (hr:min)	TYPE (Fig. 4) ZR, ZL,S, SG IP, IC, BS, SP	CLASSIF. (See Fig. 3)	If SNOW, WET or DRY

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

TEMPERATURE AT START OF TEST __________ °C

WIND SPEED AT START OF TEST __________ kph

WIND DIRECTION AT START OF TEST __________ °

COMMENTS : ____________________

	PRINT	SIGN
WRITTEN & PERFORMED BY :	______	______
VIDEO BY :	______	______
TEST SITE LEADER :	______	______

File g:\cm1380\procedur\nat_snow\PFORM5 At:Meteo & Pan

TABLE C-5

FLUID THICKNESS ON FLAT PLATES

DATE: ____________________ **OAT (°C):** ____________________

RUN NUMBERS: ____________________ **PERFORMED BY:** ____________________

LOCATION: ______________ **WRITTEN BY:** ____________________

THICKNESS (mil)							
Plate: Fluid: Fluid Application Time:				Plate: Fluid: Fluid Application Time:			
TIME	**1" LINE**	**6" LINE**	**12" LINE**	**TIME**	**1" LINE**	**6" LINE**	**12" LINE**

TABLE C-6

VISCOSITY SAMPLING FORM

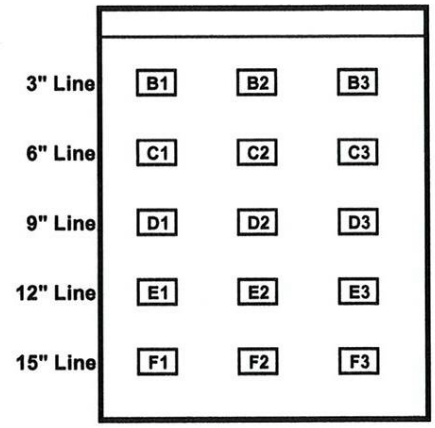
Location: CEF Ottawa

Date: July , 1998

Run #: ____________

Temperature: ____________ (°C)

Precip Type: ZR-, ZD



Time	Fluid	Plate #	Sample Location	Bottle #	Viscosity

TABLE C-7

BRIX SAMPLING FORM

Location: ____________ **Date:** ____________

Run #: ____________ **C/FIMS #:** ____________

Ambient Temperature: ____________ (°C) **Precip Type:** ____________

Plate Location:

1	2	3
4	5	6

Fluid Application Time: ________________________ **Initial Brix:** ____________

Fluid: ________________________ **Diluton:** ____________

Time	Brix Top	Brix Bottom	Average Brix

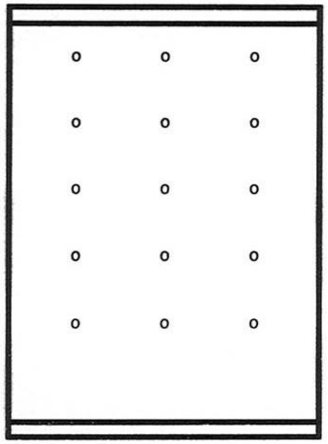
TABLE C-8

ADHERENCE OF FLUID FAILURE

Date: ____________ Time: ____________ Plate Location: ________

Run #: ____________ Fluid Name: ____________ Fluid Dilution: ________

t =



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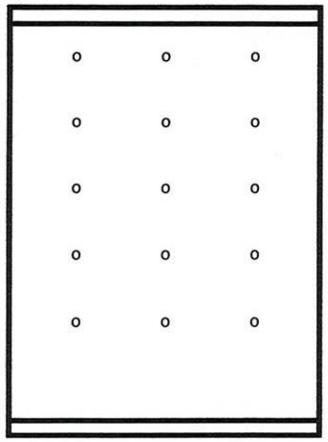
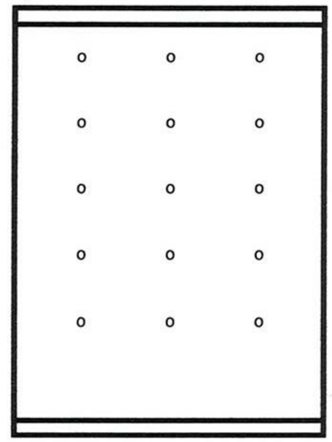
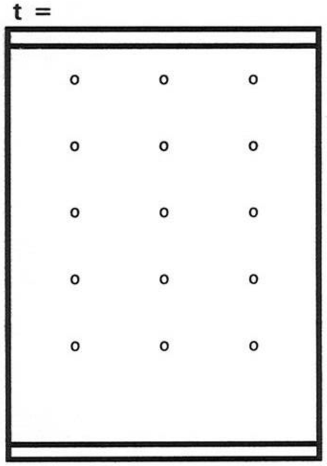


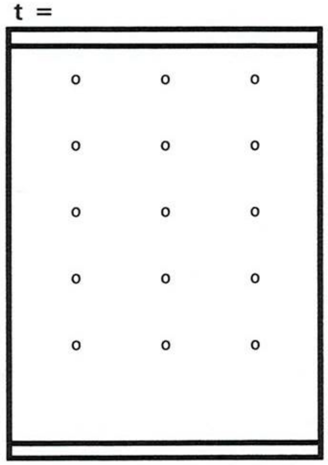
t =



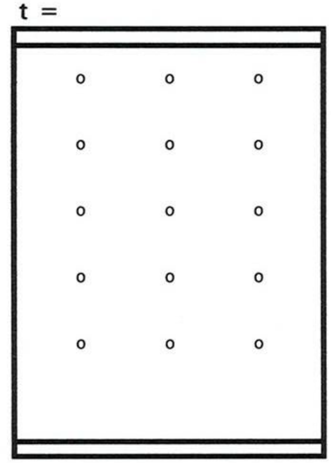
t =



t =



t =



Note: Ensure observations made 5th crosshair, whole plate
Make observations on C/FIMS

cm1514/procedur/dof/ADHER
At: Adherence
11/16/2005

APPENDIX D

EXPERIMENTAL PROGRAM

PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE

OF FAILED FLUIDS FOR INDOOR TESTS

Winter 1998-99

CM1514.001

EXPERIMENTAL PROGRAM
PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE OF FAILED FLUIDS FOR INDOOR TESTS

Winter 1998-99

APS AVIATION INC.

February 10, 1999
Version 1.0

EXPERIMENTAL PROGRAM
PROCEDURE FOR THE DOCUMENTATION OF THE APPEARANCE OF FAILED FLUIDS

Winter 1998-99

1. OBJECTIVES

APS will conduct flat plate tests indoors designed to address the following issues:

- What is the appearance of a failed fluid;
- How does the appearance of a Type I fluid failure differ from a Type IV fluid failure;
- How does the appearance of failure under conditions of freezing drizzle differ from failure under conditions of freezing rain, and under conditions of snowfall;
- Under what conditions do de/anti-icing fluids flash freeze; and
- Are there differences in failure appearance between ethylene, and propylene glycol fluids when exposed to freezing precipitation.

The test plan for documentation of fluid failure tests in simulated conditions is shown in Tables D-1 and D-1A.

2. TEST PROCEDURES

- Flat plate tests will be conducted in simulated precipitation at the National Research Council Climatic Engineering Facility in Ottawa. NCAR snowmaking tests will be conducted at the NRC or at PMG Technologies in Blainville.

- Flat plate tests will be conducted using the same procedures as shown in the *Experimental Program for Flat Plate Testing in Simulated Conditions.* Snow tests using the NCAR snowmaking machine will be conducted using the procedures outlined in the *Evaluation of Snowmaking Apparatus* document. The fluid quantity applied to each plate should be 1.5 L.

- For each test, the following additional information should be recorded:
  - i) Fluid thickness at selected locations;
  - ii) Fluid viscosity at selected locations;
  - iii) Refractive index (Brix) at selected locations;

iv) Video and photos of the plate and crosshairs at the time of fluid failure;
v) RVSI sensor record of fluid failure;
vi) Spar/Cox sensor record of fluid failure;
vii) C/FIMS point sensor record of fluid failure; and
viii) Fluid adherence at selected locations.

- Fluid failures will be recorded by the plate observer using standard flat plate test procedures. Failures will be recorded on the *End Condition Data Form* (Table D-2). Narrative descriptions of the appearance of the fluid as it progresses toward failure and the adherence of the failed fluid over the test period will also be recorded. The data forms used to record these descriptions, *Subjective Appearance of Fluid Failure and Subjective Appearance of Failure Adherence*, are shown in Tables D-3 and D-3A.

- Plate pan rates should be measured every five minutes in light freezing rain and freezing drizzle tests. Three or four pans should be used. Precipitation rate and meteo information will be recorded on the *Meteo/Plate Pan Data Form* (Table D-4).

- Fluid thickness measurements should be taken at the 15 cm (6") line at the start of the test and every two minutes thereafter for Type I tests and at the start of the test and every five minutes thereafter for Type IV tests. Thickness measurements and times should be noted on the data form (Table D-5).

- Fluid viscosity samples should be collected at the time of complete plate failure. The failed plate should be divided into three equal sections, the top, middle and bottom, and the failed fluid contained within each section should be placed in an air-tight sample container using a spatula. Sample containers should be labelled with a date, sample collection time, stand and run number, fluid type and plate number. The *Viscosity Sampling Form* is shown in Table D-6.

- The refractive index of each fluid should be taken prior to application using a hand-held refractometer and recorded on the *Brix Sampling Form* (Table D-7). For Type I tests, samples should be collected at two-minute intervals thereafter on a crosshair adjacent to the C/FIMS. For Type IV tests, top and bottom fluid samples will be collected at five-minute intervals on a crosshair adjacent to the C/FIMS. Top samples will be obtained by resting a piece of plastic film on the surface of the fluid. Bottom samples will be taken with a syringe by drawing small amounts of fluid at several points near the sample location. Brix values and corresponding sample times should be recorded accurately on the Brix data form (use one form per test plate). Brix of the mixed fluid should also be measured on an adjacent location.

- Fluid application, initial plate failure, 7.5 cm (3") failure, 15 cm (6") failure (15 crosshairs) and entire plate failure should be recorded using a digital video camera and 35 mm still camera. Records should be taken from the front and back of the stand. In addition, a video camera mounted on a tripod should be focused on one crosshair on the 15 cm (6") line to record precipitation absorbency.

- Personnel must ensure that the RVSI and Spar/Cox sensors, and C/FIMS point sensors are operational prior to each test and are left running until complete plate failure. Also, when measuring brix and thickness etc. on the 15 cm (6") line, do not disrupt the fluid over the C/FIMS sensor head (take measurements on an adjacent crosshair).

- Fluid adherence should be determined at the 5th crosshair immediately following failure at this location (not over the C/FIMS) and at location B2. When the entire plate (15 crosshairs) has failed, again verify the fluid adherence at the 15 cm (6") line on the opposite crosshair, 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 (Table D-8).

- In addition to measuring adherence at the time of plate failure and complete plate failure, adherence should be measured progressively following fluid failure at defined positions to determine the onset of adherence.

- Prior to each test run, general test information should be recorded by the test coordinator on the *General Form* (Table D-9).

3. PERSONNEL

Personnel requirements for the conduct of documentation of the appearance of failed fluid tests for indoor tests are:

- One Test Coordinator ;
- One End Condition Tester (monitor the progression of failures on the plates, verify adherence);
- One Observer recording narrative description of failure;
- One Meteo Tester (measure plate pan weights, record meteo, ensure sensors are operational) (NRC tests only);

- Two General Observers (measure and record brix, thickness, and collect samples);
- One Photographer (take photographs of fluid application and failures); and
- One Video Tester (video fluid application and failures, ensure that the fixed video camera for recording precipitation absorbency is operational).

4. EQUIPMENT

Standard flat plate test equipment will be used in documentation of fluid failure tests in simulated conditions. In addition, a list of supplemental test equipment, specific to documentation of fluid failure tests, is included in Attachment D-I.

ATTACHMENT D-I

INDOOR DOCUMENTATION OF FAILURE TESTS 1998-99

TEST EQUIPMENT CHECKLIST

Test Equipment
Adherence tester (charger)
Inclinometer
C/FIMS (computer , cables)
Still photo camera (digital + regular) with time stamp
Video cameras
procedure & data forms
Brixometer
Temperature Probes
Thickness guages (square +octogonal)
Fluid sampling bottles
Plastic scraper & transparency for taking fluid samples
Syringe

TABLE D-1
DOCUMENTATION OF FAILURES

#	Activity Description	Location	Temp °C	Wind	Precip. type	Rate g/dm2/hr	Fluid brand	Fluid Type	Concentration
1	Appearance of Type I vs Type IV failures	NRC PMG	-3		Simulated Snow	10 25	UCAR ADF, Fluid X, Ultra+, Maxflight	I, IV, Fluid X	XL54 (I) Neat (IV,X)
2	Ethylene vs Propylene Type IV failures in ZD	NRC	-10 -3		ZD	12 5	Ultra+, Maxflight,	IV	Neat
3	Effect of temperature on Type IV fluid failures	NRC PMG	-10		Simulated Snow	25	Ultra+, Fluid X, Oct. Maxflight	IV, Fluid X	Neat

Table D-1A Indoor Documentation of Failure Test Plan 1998-99

#	FLUID	PRECIP. TYPE	TEMP °C	RATE (g/dm2/hr)
1	X	Simulated snow	-3	10
2	X	Simulated snow	-3	10
3	X	Simulated snow	-3	25
4	X	Simulated snow	-3	25
5	XL54	Simulated snow	-3	25
6	XL54	Simulated snow	-3	25
7	Ultra +	Simulated snow	-3	10
8	Ultra +	Simulated snow	-3	10
9	Ultra +	Simulated snow	-3	25
10	Ultra +	Simulated snow	-3	25
11	Maxflight	Simulated snow	-3	10
12	Maxflight	Simulated snow	-3	10
13	Maxflight	Simulated snow	-3	25
14	Maxflight	Simulated snow	-3	25
15	Ultra +	Simulated snow	-10	25
16	Ultra +	Simulated snow	-10	25
17	Maxflight	Simulated snow	-10	25
18	Maxflight	Simulated snow	-10	25
19	X	Simulated snow	-10	25
20	X	Simulated snow	-10	25
21	Maxflight	ZD	-10	5
22	Maxflight	ZD	-10	5
23	Maxflight	ZD	-3	12
24	Maxflight	ZD	-3	12
25	Maxflight	ZD	-3	5
26	Maxflight	ZD	-3	5

TABLE D-2

END CONDITION DATA FORM

REMEMBER TO SYNCHRONIZE TIME WITH AES - USE REAL TIME

VERSION 5.0 Winter 97/98

LOCATION: **DATE:** **RUN # :** **STAND # :**

RVSI Series # : ____________________

CIRCLE SENSOR PLATE: u v w x y z

SENSOR NAME: ___ ___ ___ ___ ___ ___

DIRECTION OF STAND:_______ °

OTHER COMMENTS (Fluid Batch, etc):

____

____

____

____

____

____

____

____

	PRINT	SIGN
FAILURES CALLED BY :		
HAND WRITTTEN BY :		
TEST SITE LEADER :		

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

Time of Fluid Application: _______ hr:min (U & X) _______ hr:min (V & Y) _______ hr:min (W & Z)

	Plate U			Plate V			Plate W		
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 AT FAILURE									

	Plate X			Plate Y			Plate Z		
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 AT FAILURE									

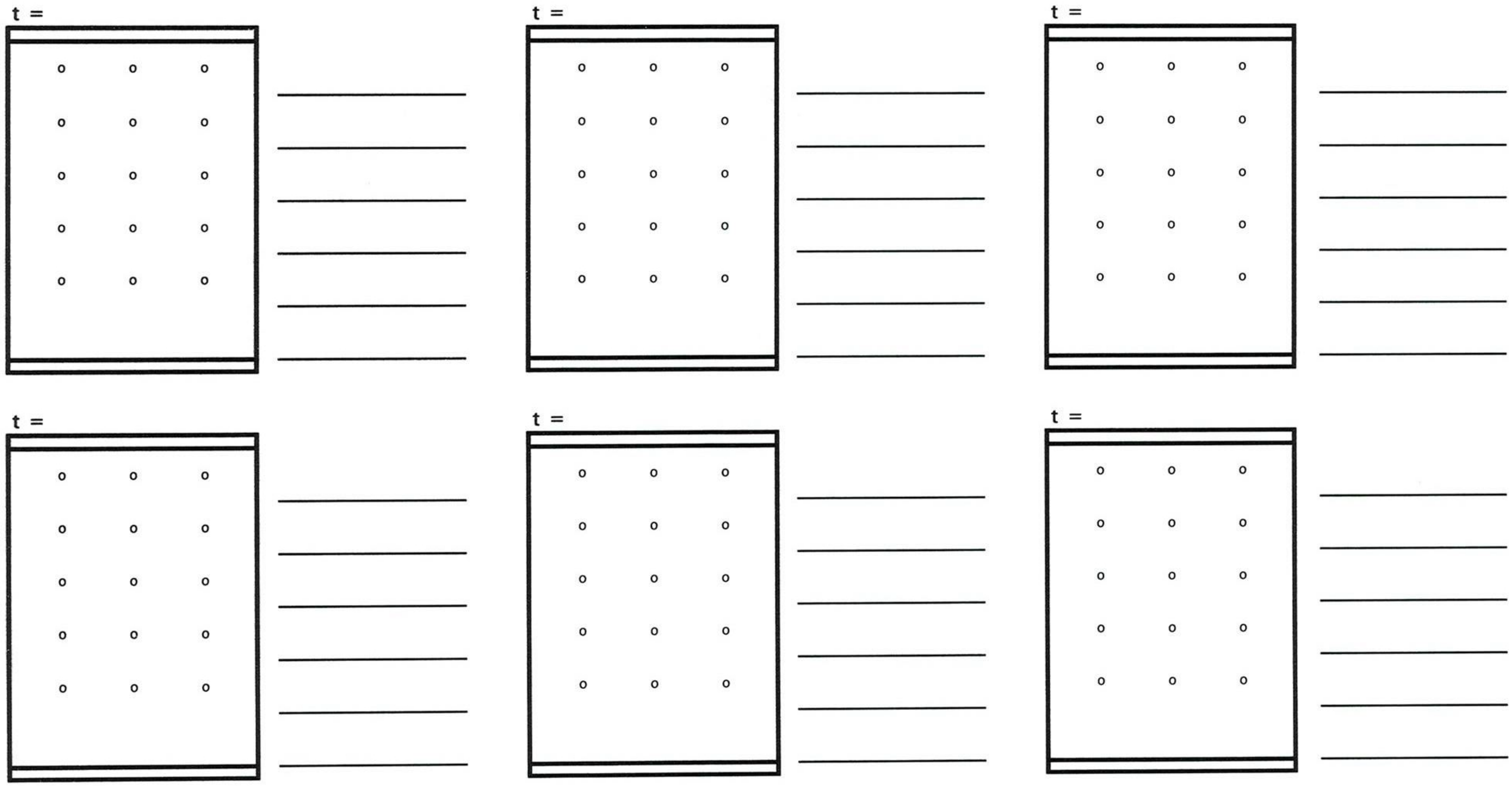
File:g:\cm1380\procedur\nat_snow\PFORM5
At: Data Form 11/16/2005

TABLE D-3

SUBJECTIVE APPEARANCE OF FLUID FAILURE

Date: ____________ Time: ____________ Plate Location: ________

Run #: ____________ Fluid Name: ____________ Fluid Dilution: ________



Note: Ensure observations made at t=0, 1st failure, 5th crosshair, whole plate
Make observations on C/FIMS

cm1514\report\doc_fail\SUBJ_EVL
At: Evaluation
11/16/2005

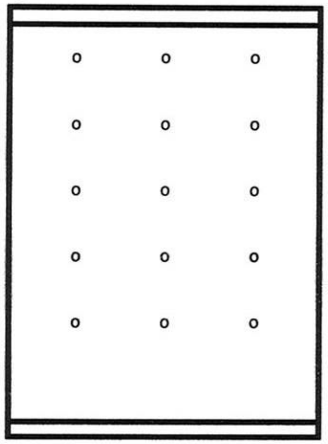
TABLE D-3A

ADHERENCE OF FLUID FAILURE

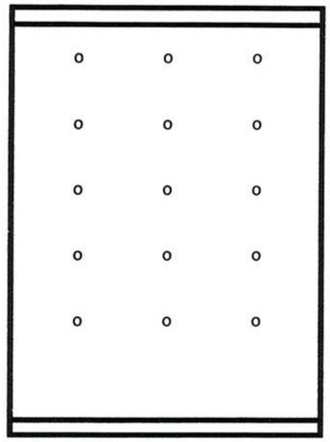
Date: ____________ Time: ____________ Plate Location: ________

Run #: ____________ Fluid Name: ____________ Fluid Dilution: ________

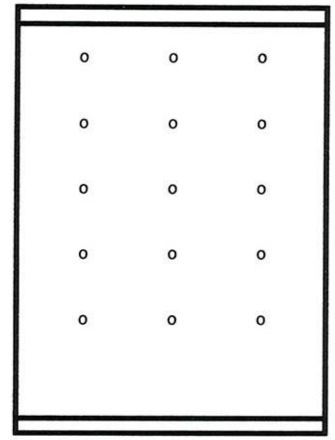
t =



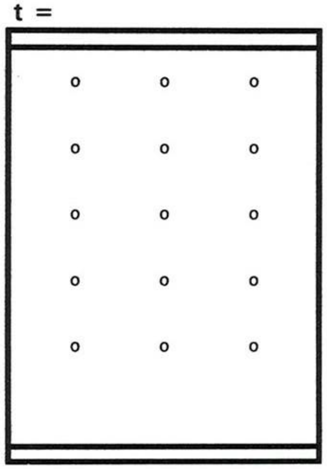
t =



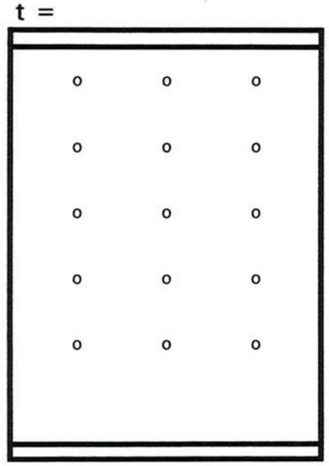
t =



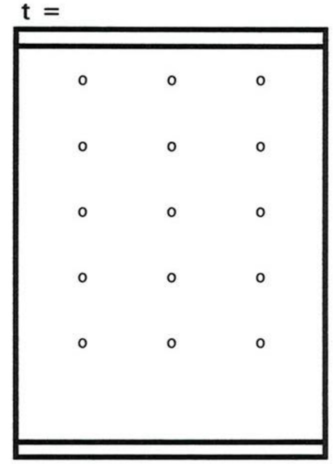
t =



t =



t =



Note: Ensure observations made 5th crosshair, whole plate
Make observations on C/FIMS

TABLE D-4

METEO/PLATE PAN DATA FORM

REMEMBER TO SYNCHRONIZE TIME WITH AES - USE REAL TIME

VERSION 5.0 Winter 97/98

LOCATION: **DATE:** **RUN # :** **STAND # :**

HAND HELD VIDEO CASSETTE #:

PLATE PAN WEIGHT MEASUREMENTS *

PAN #	t TIME BEFORE (hr:min)	t TIME AFTER (hr:min)	w WEIGHT BEFORE (grams)	w WEIGHT AFTER (grams)	COMPUTE RATE (△ w*4.7/△t) ($g/dm^2/h$)

*measurements every 15 min. and at failure time of each test panel.

METEO OBSERVATIONS **

TIME (hr:min)	TYPE (Fig. 4) ZR, ZL,S, SG IP, IC, BS, SP	CLASSIF. (See Fig. 3)	If SNOW, WET or DRY

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

TEMPERATURE AT START OF TEST __________ °C

WIND SPEED AT START OF TEST __________ kph

WIND DIRECTION AT START OF TEST __________ °

COMMENTS : ______________________________

____

____

____

	PRINT	SIGN
WRITTEN & PERFORMED BY :	__________	__________
VIDEO BY :	__________	__________
TEST SITE LEADER :	__________	__________

TABLE D-5

FLUID THICKNESS ON FLAT PLATES

DATE: ____________________ **OAT (°C):** ____________________

RUN NUMBERS: ____________________ **PERFORMED BY:** ____________________

LOCATION: ____________ **WRITTEN BY:** ____________________

THICKNESS (mil)							
Plate:		Fluid:		Plate:		Fluid:	
Fluid Application Time:				Fluid Application Time:			
TIME	**1" LINE**	**6" LINE**	**12" LINE**	**TIME**	**1" LINE**	**6" LINE**	**12" LINE**

TABLE D-6

VISCOSITY SAMPLING FORM

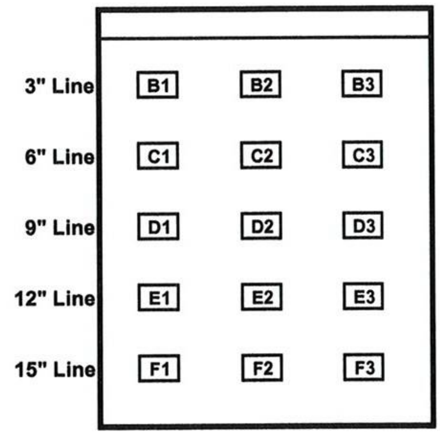
Location: CEF Ottawa

Date: July , 1998

Run #: ____________

Temperature: ____________ (°C)

Precip Type: ZR-, ZD



Time	Fluid	Plate #	Sample Location	Bottle #	Viscosity

Table D-7

BRIX SAMPLING FORM

Location: CEF Ottawa **Date:** , 1999

Run #: ___________ **C/FIMS #:** ___________

Ambient Temperature: ___________ (°C) **Precip Type:** **ZR-, ZD**

Plate Location:

1	2	3	4	5	6
7	8	9	10	11	12

Fluid: ______________________ **Initial Brix:** ___________

Time	Brix Top	Brix Bottom	Average Brix

cm1380/procedure/nrc/BRIX2
At: G. Form
11/16/2005

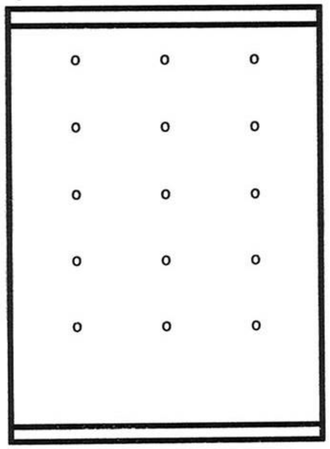
TABLE D-8

ADHERENCE OF FLUID FAILURE

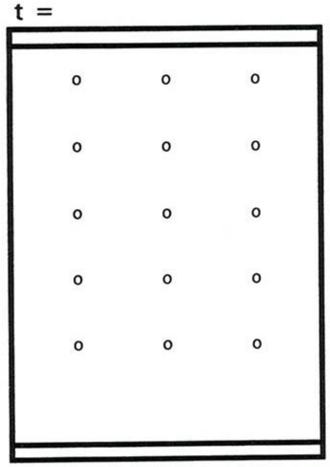
Date: ______________ Time: ______________ Plate Location: __________

Run #: ______________ Fluid Name: ______________ Fluid Dilution: __________

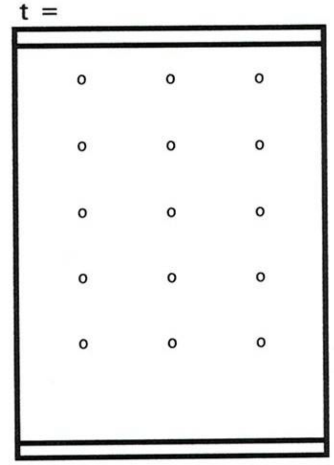
t =



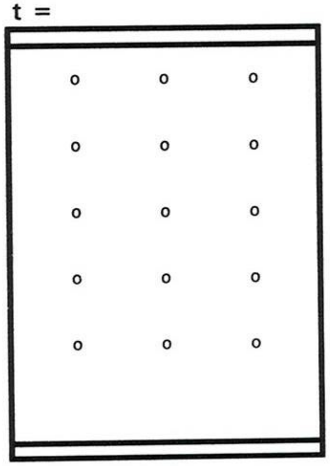
t =



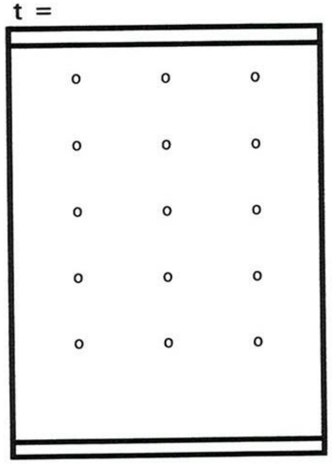
t =



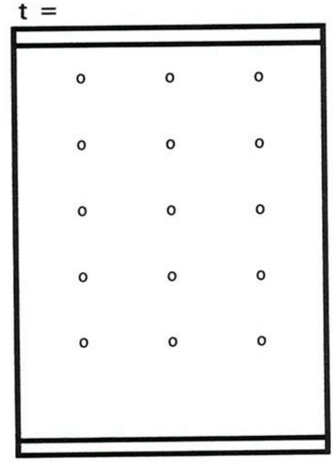
t =



t =



t =



Note: Ensure observations made 5th crosshair, whole plate
Make observations on C/FIMS

cm1514/procedur/dof/ADHER - app d
At: Adherence
11/16/2005

TABLE D-9

DOCUMENTATION OF FAILURE

General Form (Every Run)

Location: CEF Ottawa **Date:** July , 1998 **Time:** ______________

Run #: ________ **Ambient Temperature:** __________ (°C) **Precip. Type:** ZR-, ZD

Run Objective:

____

____

Plate Location:

1	2	3	4	5	6
7	8	9	10	11	12

Plate Documentation:

	1	2	3	4
Fluid Type/Mix				
C/FIMS				
RVSI				
Cox				
Adherence				
Brix				
Thickness				
Viscosity				
Description				
Photo				
Video				

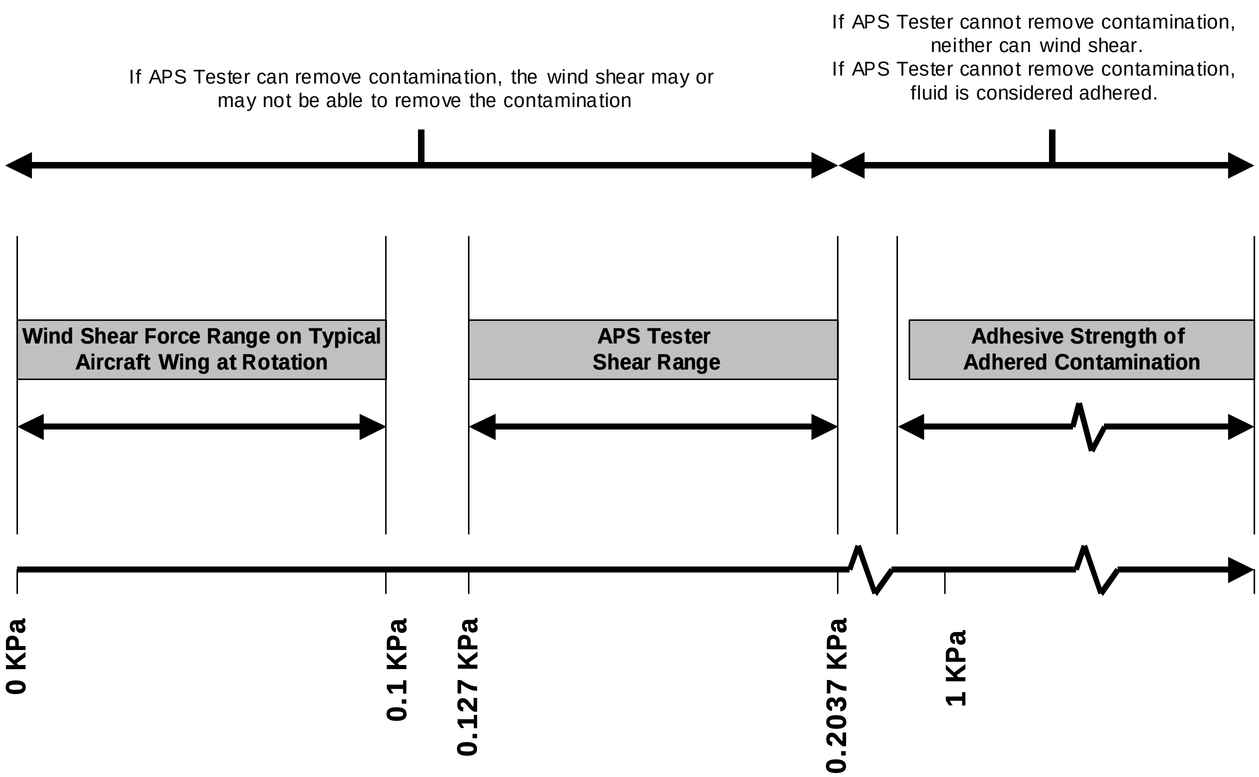
APPENDIX E

EVALUATION OF INSTRUMENT TO DETERMINE ADHESION OF CONTAMINATION TO WING SKIN

ANALYSIS OF ADHERENCE TESTER

The adherence tester exerts a shearing force in the range 1.274×10^{-4} to 2.037×10^{-4} MPa. According to the report of Optima, 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 range number 1 because both the tester and the wind will shear off the failed de/anti-icing fluid. Also in range number 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.

APS TESTER, WIND SHEAR, AND CONTAMINATED FLUID ADHESIVE STRENGTH RANGES



Adherence Tester Force Analysis

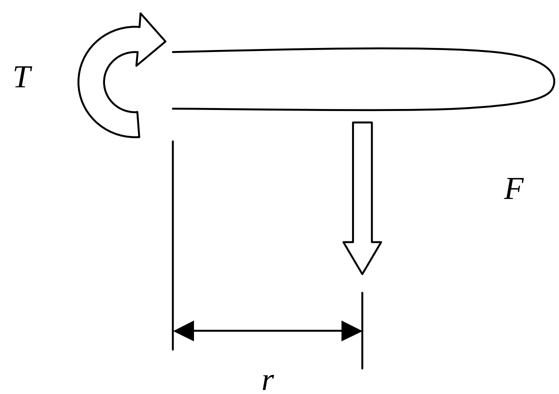
The Adherence Tester exerts a force on the ice particle through the filament. This force can be calculated from the tester motor ratings; namely, the output power, P_{out}, and the shaft rotational speed, ω,

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

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 $\omega = 6500$ Hz

Therefore, the torque is

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

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 $1.274\text{x}10^{-4}$ to $2.037\text{x}10^{-4}$ 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.