TP 13133E

DYNAMIC PHYSICAL PROPERTIES OF DE/ANTI-ICING FLUIDS

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Transport Canada

by

Optima Specialty Chemicals and Technology Inc.

November 1997

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Prepared by

Yaman Boluk
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Since the accepted measures in the industry are imperial, they are used equally with metric measures in this report.

OPTIMA SC&T PROJECT TEAM

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Un sommaire français se trouve avant la table des matières.

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16. Abstract

This study monitored the flow and physical properties, such as viscosity and freezing point depression, of de/anti-icing fluids during standard flat plate and aircraft field tests. De/anti-icing fluid samples were collected from flat plate and aircraft test surfaces during field failure tests and the changes in the physical properties of the fluids were measured. Despite the wide range of variations in holdover times as a result of fluctuations in precipitation type and rate and the temperature, failed fluids always reached the same range of viscosity value. At the time of failure, the viscosity of precipitation-contaminated Type IV fluid decreased from the initial viscosity of 36000-45000 mPa to 900-1000 mPa on standard flat plates, 400 mPa on a Boeing 737 wing and 600 mPa on a Fokker 100 wing at sensor spots. Fluid failure times on sensor locations, based on physical property measurements, were longer than first times to failure and to 10% wing failure as recorded by APS. The failure time of fluid on proposed ice sensor locations on Boeing 737 and Fokker 100 aircraft was more in agreement with the 25% wing surface failure time observed by APS. Therefore, the proposed sensor locations on aircraft surfaces must be re-examined and new sensor points more in agreement with first failure time or at least 10% wing surface failure time should be identified.

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16. Résumé

Cette étude a consisté à observer les propriétés rhéologiques et physiques, telles que la viscosité et l'abaissement du point de congélation, des fluides de dégivrage/antigivrage lors d'essais sur plaques planes normalisées et sur aéronefs en milieu réel. Des échantillons de fluides de dégivrage/antigivrage ont été prélevés sur les surfaces d'essai lors d'épreuves de durée d'efficacité en milieu réel, et la modification de leurs propriétés physiques a été mesurée. Malgré la grande variabilité des durées d'efficacité découlant de la diversité des types et des taux de précipitations et des fluctuations de température, la viscosité des fluides, au moment où ils cessaient d'être efficaces, se situait toujours à l'intérieur d'une même fourchette de valeurs. Ainsi, la viscosité du fluide de type IV variait de 36 000 à 45 000 mPa·s à l'application, mais lorsque, chargé de précipitations, il cessait d'être efficace, celle-ci n'était plus que de 900 à 1 000 mPa·s sur les plaques planes normalisées, et de 400 mPa·s et 600 mPa·s, respectivement, aux points d'implantation des capteurs sur une aile de Boeing 737 et sur une aile de Fokker 100. Les durées d'efficacité des fluides, telles qu'établies au moyen des capteurs, se sont révélées supérieures à celles qu'avait enregistrées APS, en prenant comme points de mesure le moment où débutait la cessation d'efficacité du fluide et le moment où celle-ci s'était propagée à 10 % d'une aile d'avion. Les durées d'efficacité mesurées par les capteurs de givrage du Boeing 737 et du Fokker 100 correspondent davantage au temps couru jusqu'à la perte d'efficacité sur 25 % de l'aile, selon les données d'APS. Il y a donc lieu de revoir les emplacements proposés pour la mise en place des capteurs et de déterminer d'autres emplacements plus propices à la détection du moment où le fluide commence à perdre son efficacité ou, à tout le moins, du moment où il a cessé d'être efficace sur 10 % de la surface de l'aile.

17. Mots clés Avion, dégivrage, antigivrage, congélation, givre, neige, durée d'efficacité, écoulement, viscosité	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

This project was initiated in response to a request from the Transportation Development Centre to monitor the flow and physical properties, such as viscosity and freezing point depression, of de/anti-icing fluids during standard flat plate and aircraft field tests. The viscosity of the fluid controls the drainage of de/anti-icing fluid, thus film thickness, on the wing surface. Viscosity of an anti-icing fluid is a function of temperature, shear rate and precipitation absorption. Freezing point depression and ice melting are further critical characteristics of de/anti-icing fluids, which exhibit other important physical property changes during the progression to failure. Therefore, holdover times are not only functions of precipitation conditions, but also functions of these properties of fluids. Optima SC&T Inc. collected de/anti-icing fluid samples from test surfaces during fluid progression to failure tests and measured the change in physical properties. The physical properties and their changes were correlated with field-observed holdover times.

Despite the wide range of variations in holdover times as a result of fluctuations in precipitation type and rate and the temperature, failed fluids always reached the same range of viscosity value. At the time of failure, the viscosity of precipitation-contaminated Type IV fluid decreased from the initial viscosity of 36000-45000 mPa to 900-1000 mPa on the standard flat plate, 400 mPa on a Boeing 737 wing and 600 mPa on a Fokker 100 wing at sensor spots.

Fluid failure times on proposed sensor locations, based on physical property measurements, were longer than times to first failure and 10% wing failure as recorded by APS. Failure times of fluid on ice sensor locations on Boeing 737 and Fokker 100 aircraft were more in agreement with the 25% wing surface failure time observed by APS. Therefore, the proposed sensor locations on aircraft surfaces should be re-examined and new sensor points more in agreement with first failure time or at least 10% wing surface failure time should be identified.

SOMMAIRE

Réalisée à la demande du Centre de développement des transports, cette étude a consisté à observer les propriétés rhéologiques et physiques, telles que la viscosité et l'abaissement du point de congélation, des fluides de dégivrage/antigivrage utilisés lors d'essais sur plaques planes normalisées et sur aéronefs en milieu réel. La viscosité du fluide traduit sa résistance à l'écoulement et détermine donc l'épaisseur du film déposé à la surface de l'aile. La viscosité d'un fluide antigivrage dépend de la température, de la vitesse de cisaillement et de l'absorption des précipitations. L'abaissement du point de congélation et le point de fusion de la glace sont d'autres caractéristiques cruciales des fluides de dégivrage/antigivrage, qui sont le siège d'autres changements importants menant à leur cessation d'efficacité. Ainsi, les durées d'efficacité sont tributaires non seulement des conditions de précipitations mais aussi des propriétés rhéologiques et physiques des fluides. Optima SC&T Inc. a prélevé des échantillons de fluides de dégivrage/antigivrage sur les surfaces d'essai utilisées lors d'épreuves de durées d'efficacité, pour ensuite mesurer le changement de leurs propriétés physiques. Ces données ont été corrélées avec les durées d'efficacité observées en conditions réelles.

Malgré la grande variabilité des durées d'efficacité découlant de la diversité des types et des taux de précipitations et des fluctuations de température, la viscosité des fluides, au moment où ils cessaient d'être efficaces, se situait toujours à l'intérieur d'une même fourchette de valeurs. Ainsi, la viscosité du fluide de type IV variait de 36 000 à 45 000 mPa·s à l'application, mais lorsque, chargé de précipitations, il cessait d'être efficace, celle-ci n'était plus que de 900 à 1 000 mPa·s sur la plaque plane normalisée, et de 400 mPa·s et 600 mPa·s, respectivement, aux points d'implantation des capteurs sur une aile de Boeing 737 et sur une aile de Fokker 100.

Les durées d'efficacité des fluides, telles qu'établies au moyen des capteurs, se sont révélées supérieures à celles qu'avait enregistrées APS en prenant comme points de mesure le moment où débutait la cessation d'efficacité du fluide et le moment où celle-ci s'était propagée à 10 % d'une aile d'avion. Les durées d'efficacité mesurées par les capteurs de givrage du Boeing 737 et du Fokker 100 correspondent davantage au temps couru jusqu'à la perte d'efficacité sur 25 % de l'aile, selon les données d'APS. Il y a donc lieu de revoir les emplacements proposés pour la mise en place des capteurs et de déterminer d'autres emplacements plus propices à la détection

du moment où le fluide commence à perdre son efficacité ou, à tout le moins, du moment où il a cessé d’être efficace sur 10 % de la surface de l’aile.

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1. INTRODUCTION

Following the accident of an F-28 at Dryden in 1989, the commission of inquiry reviewed the airport winter operations and made a series of recommendations. The Dryden Commission Implementation Project (DCIP) of Transport Canada was set up to implement the recommendations of the commission. Together with many other regulatory activities, an intensive DCIP research program on the field testing of deicing and anti-icing fluids was initiated. The test program has been guided by the international air transport sector through the Society of Automotive Engineers (SAE) G-12 Committee on Aircraft Ground De/Anti-icing. One of the main activities of the research program was to substantiate existing Holdover Time (HOT) tables of aircraft de/anti-icing fluids which were recommended by the International Standards Organization (ISO), Association of European Airlines (AEA) and SAE. As a result of the research performed to date, Transport Canada and the US Federal Aviation Agency (FAA) have been introducing holdover time regulations.

The times given in HOT tables were originally established by European Airlines based on the assumptions of fluid properties and anecdotal data. Extensive testing was conducted initially by the DCIP R&D Task Group and subsequently by the Transportation Development Centre (TDC) of Transport Canada. One objective of the research has been to determine the performance of fluids on standard flat plates and aircraft wings under various types of precipitation in order to substantiate the times, and if warranted, to recommend changes.

The first field tests were performed during the 1990-1991 winter season in Canada, the US, Europe and Japan. Subsequently, test procedures have been revised and fluid failure definition has been refined. The SAE G-12 Holdover Time Subcommittee meets regularly every year to review the findings of winter test results and, if necessary, revise the holdover times guideline.

Since 1991, the field test fluid failure data include fluid failure time, precipitation type, precipitation rate, and temperature and wind conditions. The fluid failure time and precipitation conditions were recorded meticulously during field test(1,2,3). In a recent study, the physical changes in an anti-icing fluid have been researched by monitoring the water diffusion into the fluid in a test tube in the laboratory(4). However, there has not been any study available which monitors the changes in physical and flow properties of fluids in the field under natural precipitation before the failure point. The absence of such data makes the analysis of holdover time as a function of precipitation conditions incomplete.

Holdover time of an anti-icing fluid is not only a function of precipitation conditions but one of flow and physical properties of fluids. Viscosity and physical properties such as freezing point repression and ice melting are critical characteristics of de/anti-icing fluids and change with the absorption of freezing precipitates. The holdover potential of fluid under freezing precipitation can be estimated by closely monitoring flow and physical properties from the start to failure point. This is particularly important for ice sensor applications. Ice sensors indicate fluid failure by measuring dielectric or acoustic characteristics. However, what is important for an ice sensor is not only the display of fluid failure but also the prediction of remaining fluid protection time.

Optima SC&T Inc. collected de/anti-icing fluid samples from test surfaces during field failure tests (5) and measured the change in physical properties. The physical properties of fluids and their changes during field failure tests are used.

2. BACKGROUND STUDY

2.1 Type I Fluid

XL 54 was used during field tests as a "ready-to-use" Type I fluid to deice the test plates and airplanes before the application of Type IV fluid. XL 54 is a SAE Type I fluid. It is used by the industry to deice airplanes and remove accumulated snow and other freezing precipitates. Normally it is used hot and it has very limited protection time. Its holdover time under the Water Spray Endurance Test (WSET) is 5 minutes.

XL 54 contains 54% by weight ethylene glycol. It is a Newtonian fluid without any thickener. The refractive index of the fluid is 1.3870, Brix value is 33.2, freezing point is -43°C and viscosity is only 10 mPa.s at 0°C.

2.2 Type IV Fluid

Ultra Plus was used as Type IV anti-icing fluid during testing. SAE Type IV anti-icing fluids are used by industry as protection against freezing rain, frost and snow.

Ultra Flow has a Brix reading of 39.25 which gives glycol concentration of 60% and freezing point lower than -50°C. The non-Newtonian flow characteristic of the fluid is shown in Figure 1. As it is known as non-Newtonian behavior; the viscosity decreases with shear rate (and shear stress). The non-Newtonian behavior of an anti-icing fluid is important for the protection time and lift loss characteristics on aircraft surfaces. When the fluid film on the wing surfaces is thicker, the protection time is longer against freezing precipitation. Thicker fluid films can be accomplished by attaining very high viscosities at low shear rates. On the other hand, at high shear stresses (shear rates as well) the fluid should ideally flow off easily in order to cause minimum lift loss. Therefore, as shear rate increases, viscosity should decrease drastically.

On an inclined wing surface, the fluid flows under the influence of the gravitational force. The fluid thickness is determined by the surface angle and fluid viscosity. The shear stress exerted by gravitational force to the fluid is as follows:

Shear Stress = (Film Thickness)x(Density of Fluid)x(Gravitational Constant)x(Slope of surface)

To use a meaningful fluid viscosity number we have to choose the shear stress (shear rate) which represents the gravitational flow of the fluid on the sloped surface of aircraft wing. The variation in the slope and film thickness on the wing surface makes it impossible to define exact shear stress numbers. However, for fluids with the order of 0.5-1.0 mm film thickness and around 10° sloped surfaces, a 0.1 sec^{-1} characteristics shear rate was chosen. Viscosity of the fluid at 0°C and 0.1 sec^{-1} shear rate was 44500 mPa.s.

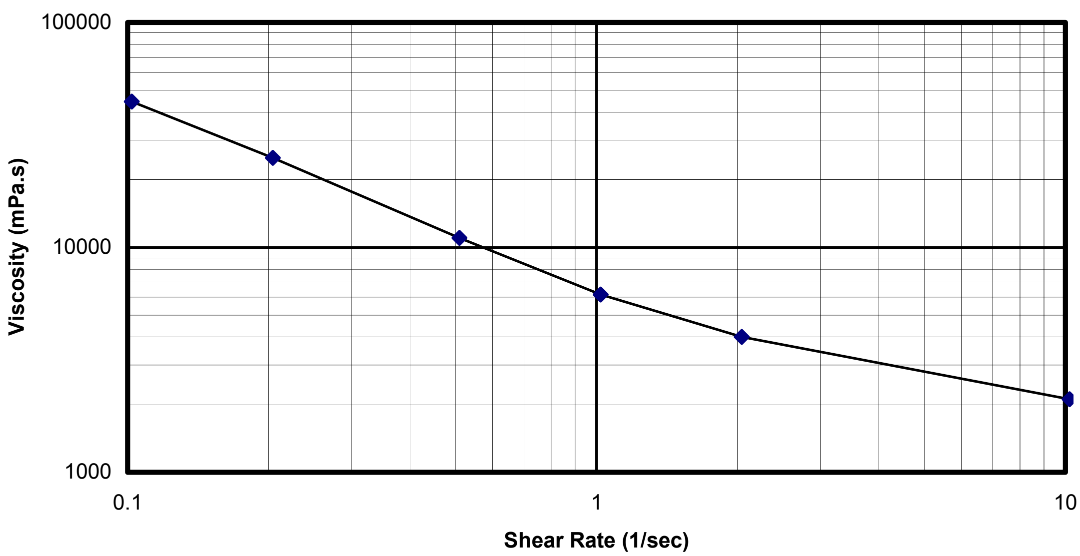

Figure 1. Viscosity vs. shear rate behavior of Ultra Plus at 0°C

3. SAMPLE COLLECTION

Anti-icing fluid samples were collected from flat plate and aircraft wing surfaces at certain time intervals during the field tests. The sampling time intervals were chosen according to the precipitation rate and projected failure time. All of the field tests on flat plates and aircraft wing surfaces were conducted by APS Aviation Inc. Optima SC&T Inc. collected samples from designated spots on the flat plate and wing surfaces.

The flat plate tests were at APS Dorval Test Station. The wing tests were conducted at Dorval Airport (6).

3.1 Flat Plate Tests

Type I and Type IV Fluids samples were collected from the flat plates during 1996/1997 Flat Plate Testing Program. The tests were conducted by APS Aviation Inc., following the test procedure developed by Holdover Time Working Group of the SAE G-12 Committee on Aircraft Ground De/Anti-icing (7,8).

APS Aviation Inc. had reserved tests on two test plates for Optima's sampling program. During each failure test, Optima obtained the first sample of the fluid before the test, the second sample was taken from the first plate during the test. The exact sampling time was decided during the test, based on precipitation intensity and type. The second plate was used to collect the samples when the failure times were called by APS Aviation Inc. at each line.

A minimum of 10 ml of sample is required for viscosity measurements. Therefore, on each test plate the samples were taken at the 7.5 cm, 15 cm and 30 cm lines from the inclined plane upper end. Since it was not possible to collect 10 ml fluid around 2.5 cm line, there were no samples from 2.5 cm line.

3.2 Aircraft Tests

Aircraft wing samples were collected at Dorval Airport while APS Aviation Inc. was conducting the aircraft and plate tests (8).

Optima also collected samples at Allied Signal's four C/FIMS^{TM} ice sensor locations on the wings. Two types of samples were collected from aircraft surfaces. The first was a bulk sample; it was collected to monitor the changes in mean viscosity and refractive index of fluids. Approximately 10-15 ml sample was collected for this purpose.

The second type of sample was collected to monitor the diffusion and penetration of precipitates into the anti-icing fluid. For this purpose, the sample was collected at the surface and through the depth of the fluid. A chemist's syringe was used to collect the samples. To collect the depth samples, the syringe was immersed almost horizontally at the bottom of the fluid and the sample was taken at the wing surface - anti-icing fluid interface. The surface sample was collected again from the top of the fluid. In addition, APS collected fluid samples from the surface of films by contacting a plastic film to the surface and picking the surface layer of the film by capillary forces.

3.2.1 Boeing 737

Figure 2 shows three views of a Boeing 737 aircraft. The sample Wing/Inboard collection location was 4.81 m from the centre of the fuselage and at 43 cm from the leading edge. The sample Wing/Outboard collection location was 8.1 m from the centre of the fuselage and 24 cm from the leading edge.

3.2.2 Fokker 100

Figure 3 shows the views of Fokker 100 aircraft. Sample Wing/Inboard collection point was 4.8 m from the centre of aircraft fuselage and sample Wing/Outboard point was 8.1 m from the centre of aircraft fuselage.

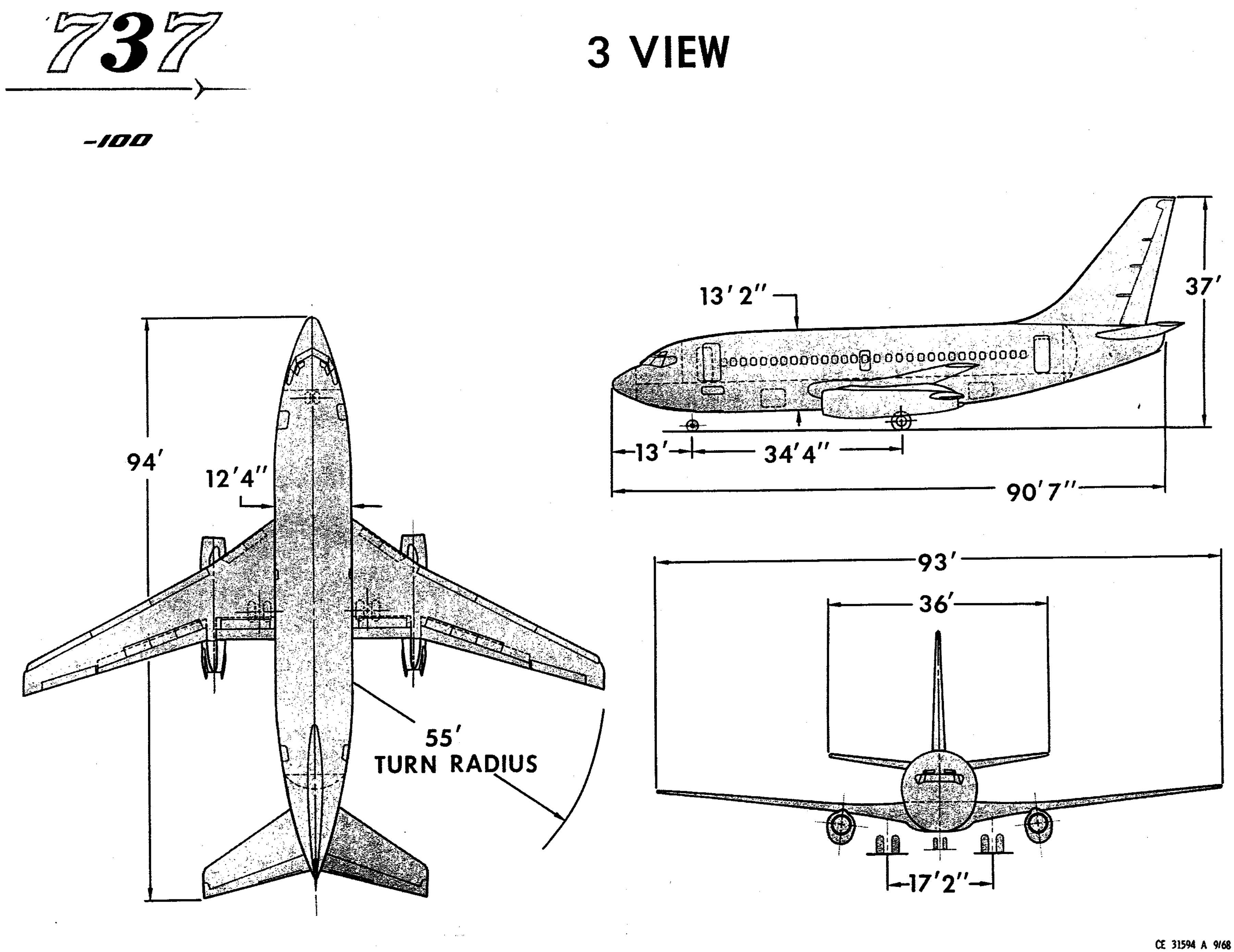

Figure 2. Dimensions of Boeing 737 Aircraft

EXTERIOR DIMENSIONS

Fokker Executive Jet 70

Fokker Executive Jet 100

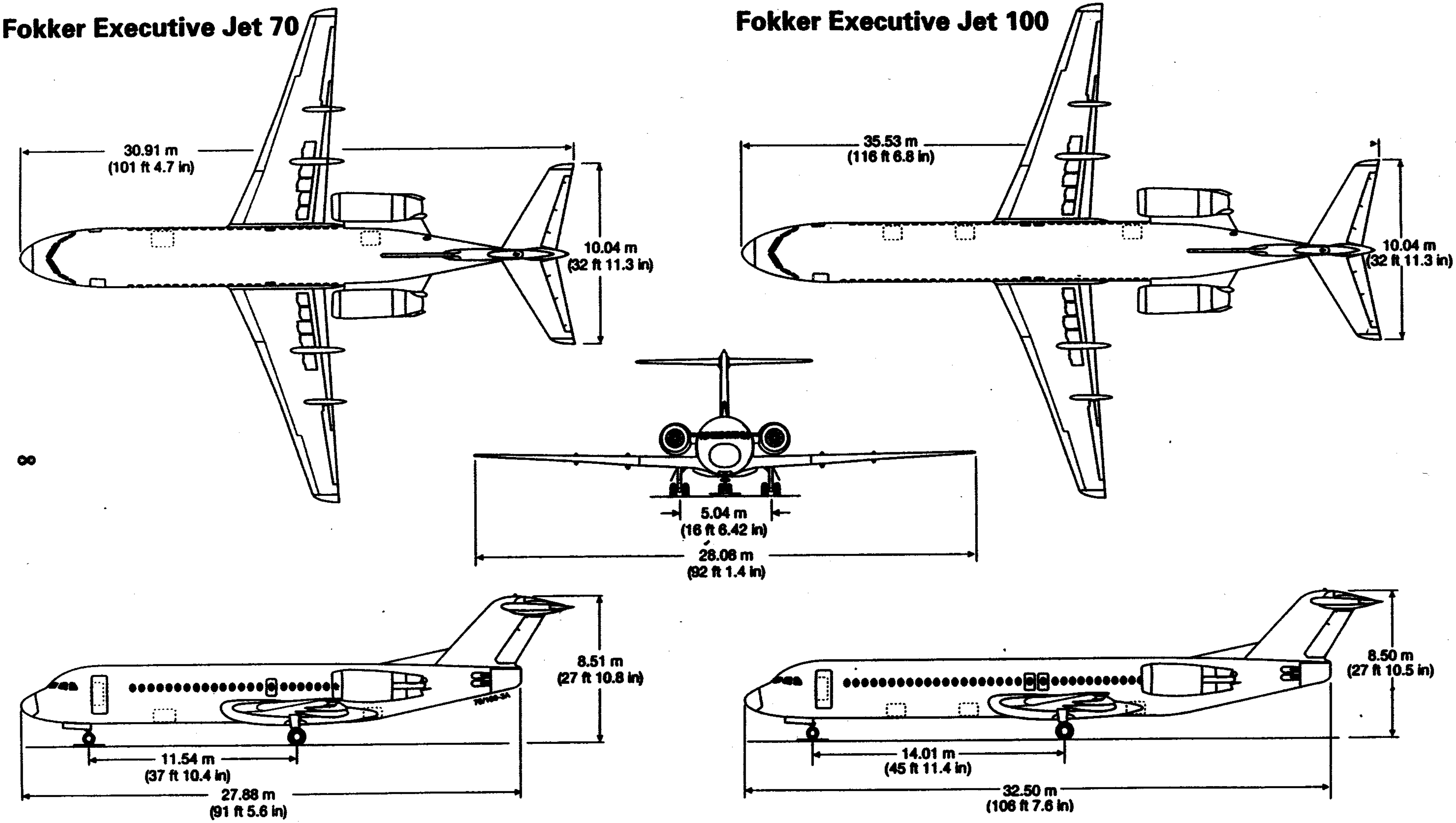

Figure 3. Dimensions of Fokker 100 Aircraft

4. LABORATORY TEST METHODS

4.1 Viscosity

A Brookfield DV-II+ Calculating Digital Viscometer was used for the viscosity measurements. The concentric cylinder geometry with Small Sample Adapter (SSA) and Spindle 31 was chosen for the tests. This geometry has been extremely useful for the viscosity determination of de/anti-icing fluids for two reasons: 1) very low quantity of sample (10 ml) was needed which minimized the quantity of sample collection from test surfaces and assured a uniform temperature in the sample cell; 2) this geometry gave precise shear rate and shear stress definitions in the sample cell. The shear rate range of 0.1-20 sec^{-1} was attained in the cell with Spindle 31 with rotational speed range of 0.3-60 rpm. Viscosity measurements were conducted in accordance to ASTM D2196.

The temperature of the Small Sample Adapter of the viscometer was maintained by using a heat jacketed sample cell attached to an external refrigerated bath/circulator, NESLAB TRE-111 model. NESLAB RTE-111 unit consists of a non-CFC air cooled refrigeration system, circulation pump, seamless stainless steel bath, work area cover and a temperature controller. Digital temperature controller ranges between -25°C and 150°C with a temperature stability of 0.01°C

4.2 Refractive Index

The Brix measurements of the de/anti-icing fluids were measured using Reichart 10431 T/C Hand Refractometer. The T/C Hand Refractometer is designed for rapid and accurate reading of the total dissolved solids in aqueous solutions from a drop or two of sample.

An automatically temperature compensated unit assures accuracy to within approximately ±0.5°C. This unit provides instant reading with fluids at any temperature. The instrument automatically corrects for fluid temperature variance. Model 10431 has the Brix readings 0 to 50° range. The scale reads directly in Brix degrees with the smallest division of 0.25°.

The refractive indexes and glycol concentrations of de/anti-icing fluid samples were calculated from brix degree readings.

5. RESULTS AND DISCUSSION

5.1 Flat Plate Tests

From December 1996 to March 1997 Optima SC&T Inc. participated total of ten (10) flat plate tests in five (5) days at APS Dorval Station. Table 1 lists all of the samples taken during those tests. The first column in Table 1 shows the identification of a test. Individual test days were assigned and identified with P and the number after P. For example, P1 shows the test on day number 1. On some days there was more than one test in a single day. The extension is used in the sample identification to indicate test numbers on a particular day. For example, on day two, there were three experiments, and the tests were identified as P2-1, P2-2 and P2-3.

For aircraft testing, different notations were used to identify tests. Precipitation conditions are also listed with experiment descriptions in Table 1. Changes in physical properties of de/anti-icing fluids and effects of precipitation conditions are discussed in the following section.

Table 1.a Listing of 1996/1997 flat plate tests

ID #	Test Location	Date	Fluid	Plate	HOT Start Time	HOT End Time*	Sample Collection Time**	Air Temperature (°C)	Precipitation Rate (g/dm²/hr)	Wind Speed (km/h)	Wind Direction (°)	Precipitation Type
P1-1	APS Dorval	Dec 19/20	Ultra Plus	X	11:59	n/f n/f n/f	00:29 00:29 00:29	-3	5.95	11	306	Dry Snow
P1-1	APS Dorval	Dec 19/20	Ultra Plus	U	11:59	1:10 1:48 2:22 3:00	 1:48 2:22 3:00	-3	5.95	11	306	Dry Snow
P2-1	APS Dorval	Jan 02/03	Ultra Plus	U	23:24	n/f n/f n/f	0:00 0:00 0:00	-8	5.24	11	65	Dry Snow
P2-1	APS Dorval	Jan 02/03	Ultra Plus	X	23:24	0:33 1:15 1:33 2:06 2:08	 1:15 1:33 2:06 2:08	-8	5.24	11	65	Dry Snow
P2-2	APS Dorval	Jan 02/03	Ultra Plus	U	0:13	 1:43 n/f n/f	 1:43 1:43 1:43	-8	5.24	11	65	Dry Snow
P2-3	APS Dorval	Jan 02/03	Ultra Plus	U	2:15	n/f n/f n/f n/f	3:15 3:15 3:15 3:15	-8	9.17	11	65	Dry Snow
P2-3	APS Dorval	Jan 02/03	Ultra Plus	X	2:15	3:07 3:28 3:40 3:58 4:00	 3:28 3:40 3:58 4:00	-8	9.17	11	65	Dry Snow
P3-1	APS Dorval	Jan 04/05	Ultra Plus	U	0:14	n/f n/f n/f	0:35 0:35 0:35	-2	16.6	15	50	Freezing Rain
P3-1	APS Dorval	Jan 04/05	Ultra Plus	X	0:14	0:55 1:00 1:03 1:11 1:15	 1:00 1:05 n/a 1:15	-2	16.6	15	50	Freezing Rain

* Failure times at 2.5 cm, 7.5 cm, 15 cm, 30 cm, and 38 cm respectively.
** Sample collection times between 7.5 cm 15 cm and 30 cm, and 38 cm respectively.

Table 1.b Listing of 1996/1997 flat plate tests (continues)

ID #	Test Location	Date	Fluid	Plate	HOT Start Time	HOT End Time*	Sample Collection Time**	Air Temperature (°C)	Precipitation Rate (g/dm²/hr)	Wind Speed (km/h)	Wind Direction (°)	Precipitation Type
P3-2	APS Dorval	Jan 04/05	Ultra Plus	X	2:41	n/f n/f n/f	2:53 2:53 2:53	-2	16.6	15	50	Freezing Rain
P4-1	APS Dorval	Jan 09/10	Ultra Plus	U	3:44	n/f n/f n/f n/f	4:05 4:05 4:05 4:05	-9	13.6	10	53	
P4-1	APS Dorval	Jan 09/10	Ultra Plus	X	3:44	4:33 4:43 4:56 5:05	4:43	-9	13.6	10	53	Snow
P4-2	APS Dorval	Jan 09/10	Ultra Plus	U	4:30	n/f n/f n/f n/f	5:00 5:00 5:00 5:00	-9	13.6	10	53	Snow
P4-2	APS Dorval	Jan 09/10	Ultra Plus	X	4:30	5:45 5:55 6:00	5:45 5:55 6:00	-9	13.6	10	53	Snow
P5-1	APS Dorval	Jan31/ Feb01	Ultra Plus	X	21:22	n/f n/f n/f	9:40 9:40 9:40	-6	7.3	9	50	Snow
P5-1	APS Dorval	Jan31/ Feb01	Ultra Plus	U	21:22	22:00 22:35 23:15 23:23	22:35 23:15 23:23	-6	7.3	9	50	Snow
P5-2	APS Dorval	Jan 31 Feb 01	Ultra Plus	X	0:20	n/f n/f n/f	0:50 0:50 0:50	-6	7.3	9	50	Snow

* Failure times at 2.5 cm, 7.5 cm, 15 cm, 30 cm, and 38 cm respectively.
** Sample collection times between 7.5 cm 15 cm and 30 cm, and 38 cm respectively.

5.1.1 P1-1 December 19/20 Test

Table 2 shows the results of the P1-1 test on December 19/20. The test began at 23:59 on December 19. Two test plates, X and U, were used. Plate X was used to take samples 30 minutes after the start of the test; plate U was used to monitor the failure of fluid. Samples were taken when the fluid failed at the specified line. For example, 7.5cm line failed at 1:48 and, the sample was collected at approximately 7.5 cm line at 2:05. As an another example, 15cm line failed at 2:22 and the sample was collected at about 15 cm line at 2:22. The failure time at standard 2.5 cm line was 1:10.

The uncontaminated anti-icing fluid Ultra Plus had 39.50 °Brix refractive index before the test. The viscosity of the fluid at the test temperature (-3°C) was 36000 mPa.s. The viscosity and refractive index of the fluid decreased as water absorption from precipitation into the fluid layer progressed. Figure 4 shows viscosity vs. water content of various fluid samples collected from plates U and X. The samples were taken after 30 minutes and at the failure time from the plates around 7.5cm, 15cm and 30cm lines.

Fluid film thickness is a function of location on the inclined test plate at a particular time. In other words, film thickness decreases from the bottom to the top of the plate. Therefore, some minutes after the start of the test, the amount of adsorbed water decreases from the top to bottom of the plate. Therefore, viscosity, which is the inverse function of water dilution of the fluid, also decreases from the bottom to the top. As it is seen in Table 2 and Figure 4, viscosity and amount of adsorbed water are functions of sampling location on the test plate.

Thirty minutes after the start of the test 7.5cm region has 12200 mPa.s, 15cm region has 19600, and 30 cm region has 22800 mPa.s viscosities at -3°C. These viscosity numbers are high enough to ensure sufficient film thickness and significant protection time.

Table 2. Results of P1-1 test

Date	December 19/20
Type	Flat Plate
Slope	10^0
Location	APS Test Station Dorval
Type of ppt	Dry Snow
Rate of ppt	5.95 $g/dm^2/h$
Temperature	-3 ^0C
Fluid	Ultra Plus
Failure Time	1:10 at 2.5 cm line (71 min)

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^0C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
	23:59	0:00		39.50	62	-50	0	36000	
X	0:29	30	7.5	28.25	45	-31	27	12200	
X	0:29	30	15	29.75	48	-34	23	19600	
X	0:29	30	30	30.75	50	-37	19	22800	
U	2:05	125	7.5	0.00	0	0	100	2	1:48
U	2:22	143	15	5.00	8	-2	87	900	2:22
U	3:00	181	30	6.50	10	-3	84	1000	3:00

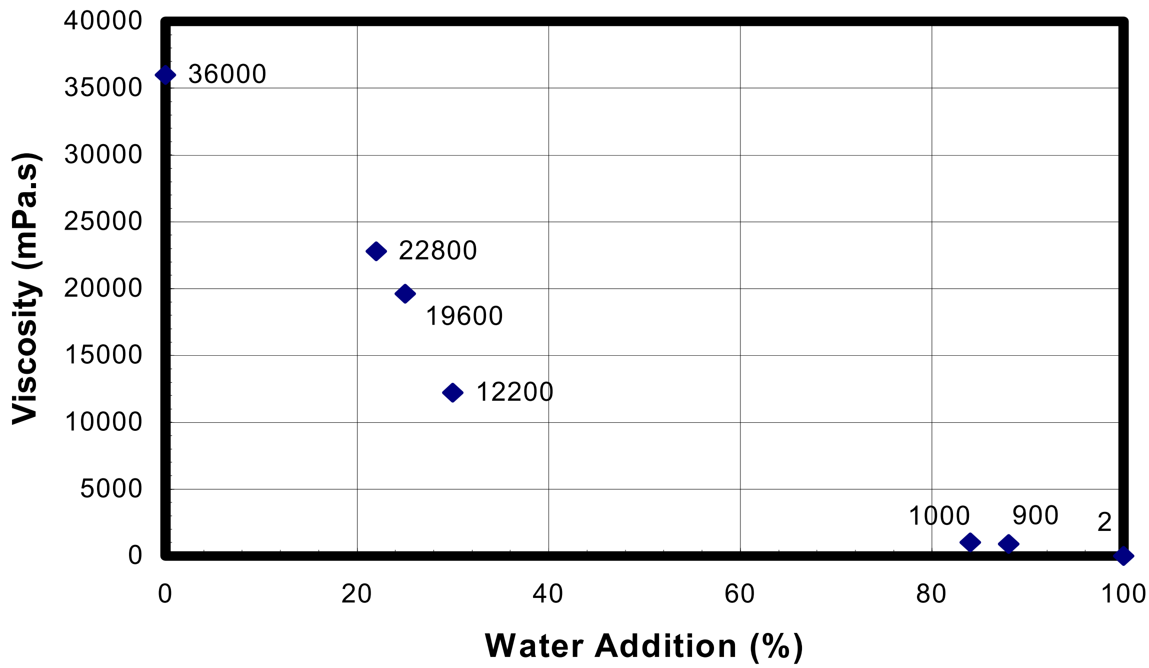

Figure 4. Viscosity of the fluid as a function of adsorption of precipitation during P1-1 test.

On plate U, the absorbed water reached 87% and 84% at 143 minutes on the 15cm line and 181 minutes on the 30 cm line, respectively. The corresponding viscosity values at the failure time were 900 and 1000 mPa.s. The samples around 15cm and 30cm lines were at freezing at -3°C ambient temperature. Their freezing points were -2 and -3°C.

Unfortunately, close to the 7.5cm line, sampling was done at 125 minutes, despite the failure at 108 minutes. Therefore, the exact failure point was missed and water content had reached almost 100%. Since the failure point was missed, the sample from the 7.5 cm line had only 2 mPa.s viscosity, i.e.. the viscosity of slush at -3 °C.

5.1.2 P2-1 January 02/03Test

The first test on January 02/03 was P2-1. Table 3 shows the detailed results of P2-1 on January 02/03. The precipitation conditions, except the air temperature were similar to those of December

Table 3. Results of P2-1 test

Date	January 02/03
Type	Flat Plate
Slope	10^0
Location	Dorval APS Test Station
Type of ppt	Dry snow
Rate of ppt	5.24 $g/dm^2/hr$
Temperature	-8 ^0C
Fluid	Ultra Plus
Failure Time	0:33 at 2.5 cm line (69 min)

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^0C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
	23:24	0		39.25	62	-50	0	39900	
U	0:00	36	7.5	28.25	45	-31	27	10600	
U	0:00	36	15	30.25	49	-36	21	17000	
U	0:00	36	30	31.00	50	-37	19	19500	
X	1:24	120	7.5	10.00	15	-5	76	700	1:24
X	1:40	136	15	9.75	15	-5	76	700	1:40
X	2:06	162	30	9.50	15	-5	76	700	2:06
X	2:06	162	38	9.25	14	-5	77	800	2:06

19/20 P1-1 test. On January 02/03 the air temperature was -8°C as opposed to -5°C on December 19/20. The failure time at standard 2.5cm line was 69 minutes during P2-1.

Because of the lower temperature, -8°C, the viscosity was 39900 mPa.s during the P2-1 test. The amount of absorbed water was 27%, 21% and 19% at the 7.5cm, 15cm and 30cm lines, respectively after 36 minutes of precipitation test; the 7.5 cm, 15 cm, 30 cm and 38 cm lines were failed after 120, 136, 162 and 162 minutes, respectively. Although the failure time was increasing with the distance the physical properties remained almost same at the failure time. The viscosity was around 700-800 mPa.s and water absorption was 76% at failure point. At -8°C ambient temperature, the fluid started to fail at -5°C. Figure 5 shows viscosity vs. water addition data during P2-1 test.

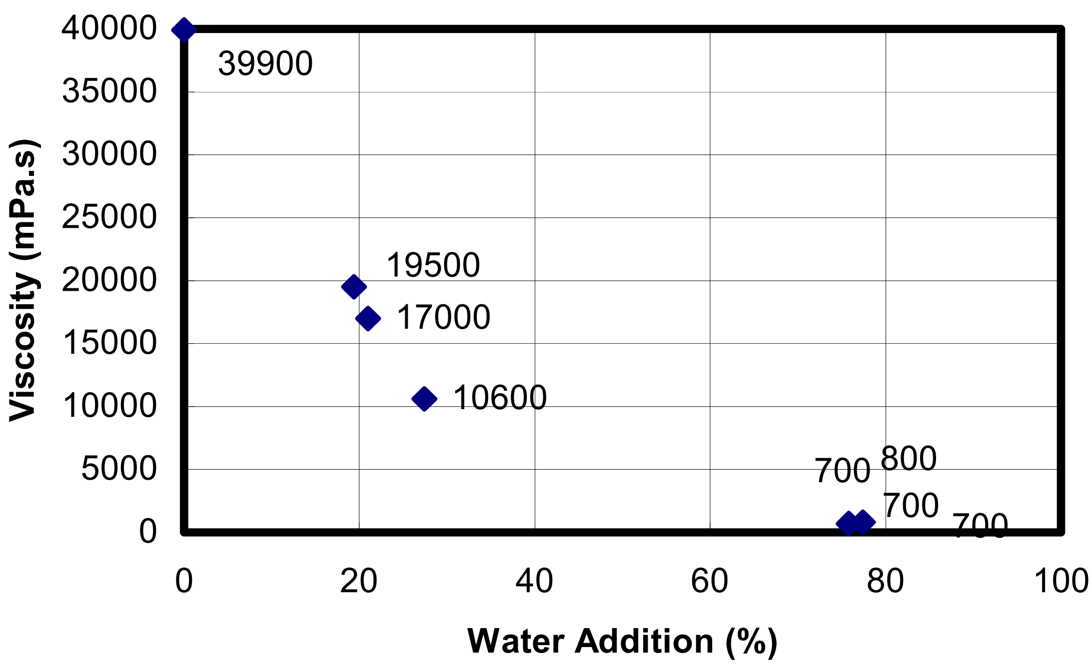

Figure 5. Viscosity of the fluid as a function of adsorption of precipitation during P2-1 test.

5.1.3 P2-2 January 02/03 Test

P2-2 was the second test on January 02/03. Table 4 shows the results. The test was terminated when the ice progress reached 7.5cm after 90 minutes of testing. Again, at the time of the failure the viscosity was 1000 mPa.s around 7.5cm line. The failure line had not yet reached the 15 and 30cm lines on the test plate. On those lines the viscosity was high enough to hold enough anti-icing fluid (glycol). Thus the fluid had enough freezing point depression characteristics and film thickness to protect against incoming precipitation.

5.1.4 P2-3 January 02/03 Test

The third test of January 02/03 was P2-3 (Table 5). It started at 2:15. The 2.5cm standard line failed at 3:07 which resulted 53 minutes holdover time at 9.17 g/dm^2/hr dry snow. At the time of failure the fluid samples have viscosities between 500-1000 mPa.s and water absorption 79-81%. The freezing point of failed samples was -4°C despite the ambient temperature of -8°C.

5.1.5 P3-1 January 04/05 Test

Table 6 shows results of P3-1 which was the first test of January 04/05. During the test the anti-icing fluid absorbed the (16.6 g/dm^2/hr) freezing rain instantaneously and the viscosity of the fluid decreased dramatically. Consequently the diluted anti-icing fluid drained down very quickly from the test plates and left a very thin layer of contaminated fluid, i.e. the remaining fluid on the test plate was very thin and not sufficient to measure the viscosity.

Nevertheless, the samples collected were sufficient for measurement of the °Brix readings of plate samples. In a short time, such as 20 minutes, the glycol concentration dropped from 62% to 33-36% with additional water absorption of 42-47% from freezing rain. Unlike other types of precipitation, the progression of dilution was almost simultaneous and there was no ice progression, glycol and fluid film thickness gradient from the top to the bottom of a sloped surface.

Table 4. Results of P2-2 test

Date	January 02/03
Type	Flat Plate
Slope	10^0
Location	Dorval APS Test Station
Type of ppt	Dry Snow
Rate of ppt	5.24 g/dm^2/hr
Temperature	-8 ^{0}C
Fluid	Ultra Plus
Failure Time	1:43 at 7.5 cm cm line (90

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^{0}C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
	0:13	0		39.25	62	-50	0	39900	
U	1:43	90	7.5	16.00	25	-11	60	1000	1:43
U	1:43	90	15	24.00	38	-23	39	6400	n/f
U	1:43	90	30	25.00	40	-25	35	8300	n/f

Table 5. Results of P2-3 test

Date	January 02/03
Type	Flat Plate
Slope	10^0
Location	Dorval APS Test Station
Type of ppt	Dry Snow
Rate of ppt	9.17 g/dm^2/hr
Temperature	-8 ^{0}C
Fluid	Ultra
Test	3:07 at 2.5 cm line (53 min)

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^{0}C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
	2:15	0		39.25	62	-50	0	39900	
U	3:15	60	7.5	10.50	16	-6	74	1100	
U	3:15	60	15	19.25	30	-15	52	2000	
U	3:15	60	30	20.75	33	-18	47	4800	
U	3:15	60	38	22.00	35	-20	44	4300	
X	3:29	74	7.5	8.00	12	-4	81	500	74
X	3:40	85	15	8.50	13	-4	79	800	85
X	4:00	105	30	7.75	12	-4	81	600	105
X	4:00	105	38	8.75	13	-4	79	1000	105

Table 6. Results of P3-1 test

Date	January 04/05
Type	Flat Plate
Slope	10^0
Location	Dorval APS Test Station
Type of ppt	Freezing rain
Rate of ppt	16.61 g/dm^2/h
Temperature	-1.7^0 C
Fluid	Ultra Plus
Failure Time	0:55 at 2.5 cm line (41 min)

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^{0}C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
control	0:15	0		39.50	62.00	-50	0	46400	
U	0:35	20	7.5	22.50	36.00	-20	42		
U	0:35	20	15	21.00	33.00	-18	47		
U	0:35	20	30	22.00	35.00	-20	44		
U	0:35	20	38	22.00	35.00	-20	44		
X	1:05	50	7.5	2.25	3.00	-1	95		1:05
X	1:05	50	15	1.75	3.00	-1	95		1:05
X	1:15	60	38	1.00	2.00	0	97		1:15

5.1.6 P3-2 January 04/05 Test

The second test on January 04/05 started at 2:41 but was terminated when the freezing rain stopped 12 minutes after the start of the test. A summary of the results is in Table 7.

5.1.7 P4-1 January 09/10 Test

Table 8 shows P4-1 test of January 09/10. After 20 minutes the fluid had enough high viscosity and therefore protection potential against ongoing precipitation. However, at 59 minutes fluid viscosity has decreased to 800 mPa.s and the freezing point (-9°C) has increased to above the ambient temperature and fluid failed at 7.5 cm point.

5.1.8 P4-2 January 09/10 Test

The second test on January 09/10 was P4-2. The viscosity and glycol concentration profile after 30 minutes showed that the top of the plate was closer to failure despite the longer time protection potential of the bottom of the plate.

Samples taken 75 minutes after the start of the test has already failed. The freezing point was -4°C as opposed to ambient temperature of -9°C. Viscosities of slush at -9°C could not be measured.

5.1.9 P5-1 January 31/February 01 Test

Table 10 shows the results of P5-1 from January 31/February 01. On plate X , failure points of 15 cm and 30 cm points were slightly exceeded. Because of that freezing points were increased up to -3°C despite the ambient temperature of -6°C.

5.1.10 P5-2 January 31/February 01 Test

Results are shown in Table 11. There was no failure in the fluid after 30 minutes. The precipitation stopped after the start of the test.

Table 7. Results of P3-2 test

Date	January 04/05
Type	Flat Plate
Slope	10^0
Location	Dorval APS Test Station
Type of ppt	Freezing rain
Rate of ppt	16.6 g/dm^2/hr
Temperature	-1.7^0 C
Fluid	Ultra Plus
Failure Time	No failure (freezing rain stopped)

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^{0}C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
control	2:41	0			62.00	-50	0	53700	
X	2:53	12	7.5	29.00	47.00	-33	24	18600	n/f
X	2:53	12	15	28.75	46.00	-32	26		n/f
X	2:53	12	30	29.50	48.00	-34	23	29400	n/f

Table 8. Results of P4-1 test

Date	January 09/10
Type	Flat Plate
Slope	10^0
Location	Dorval APS Test Station
Type of ppt	Snow
Rate of ppt	13.6 $g/dm^2/hr$
Temperature	-9^0C
Fluid	Ultra Plus
Failure Time	4:33 at 2.5 cm line (49 min)

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^0C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
control	3:44	0		39.50	62.00	-50	0	54300	
U	4:05	20	7.5	28.25	45.00	-31	27	16000	
U	4:05	20	15	29.25	47.00	-33	24	18000	
U	4:05	20	30	30.00	48.00	-35	23	18300	
U	4:05	20	38	31.00	50.00	-37	19	16500	
X	4:43	59	7.5	9.50	15.00	-5	76	800	4:43

Table 9. Results of P4-2 test

Date	January 09/10
Type	Flat Plate
Slope	10^0
Location	Dorval APS Test Station
Type of ppt	Snow
Rate of ppt	13.6 g/dm^2/hr
Temperature	-9^0 C
Fluid	Ultra Plus
Failure Time	5:05 at 2.5 cm line

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^{0}C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Comments
control	4:30	0		39.50	62.00	-50	0	54300	
	5:00	30	7.5	17.25	27.00	-13	56	1300	
	5:00	30	15	20.50	32.00	-17	48	2800	
	5:00	30	30	21.50	34.00	-19	45	2400	
	5:00	30	38	23.50	37.00	-22	40	6300	
			7.5						
	5:45	75	15	7.75	12.00	-4	81		75
	5:55	85	30	8.75	13.00	-4	79		85
	6:00	90	38	9.00	14.00	-5	77		90

Table 10. Results of P5-1 test

Date January 31/February 01
Type Flat Plate
Slope 10^0
Location Dorval APS Test Station
Type of ppt Snow
Rate of ppt 7.3 g/dm^2/hr
Temperature -6^{0}C
Fluid Ultra Plus
Failure Time 22:00 at 2.5 cm line (38 min)

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^{0}C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
control	21:22	0		39.25	62.00	-50	0	48900	
U	21:37	15	2.5	29.25	47.00	-33	24	16500	
U	21:37	15	15	30.75	50.00	-37	19	16800	
U	21:37	15	30	31.25	51.00	-38	18	19700	
X	22:35	73	2.5	11.75	18.00	-7	71		73
X	22:55	93	15	7.25	11.00	-3	82	1800	93
X	23:23	121	30	7.50	12.00	-4	81	600	121

Table 11. Results of P5-2 test

Date	January 31/February 01
Type	Flat Plate
Slope	10^0
Location	Dorval APS Test Station
Type of ppt	Snow
Rate of ppt	7.3 g/dm^2/hr
Temperature	-6^0 C
Fluid	Ultra Plus
Failure Time	No failure

Plate	Real Time	Time (min)	Location (cm)	Brix	Glycol (%)	Freezing Point (^{0}C)	Water Absorption (%)	Viscosity at 0.3 rpm (mPa.s)	Failure Time
control	0:20	0		39.50	62.00	-50	0	48900	
	0:50	30	7.5	36.50	60.00	-50	3	37300	
	0:50	30	15	37.00	60.00	-50	3	38800	
	0:50	30	30	37.00	60.00	-50	3	41600	

5.2 Aircraft Tests

From December 1996 to March 1997, Optima SC&T Inc. participated in six aircraft test days at Dorval Airport. Four were on a Boeing 737 and two were on a Fokker 100 aircraft. Table 12 shows the test conditions and holdover times during these aircraft wing tests. A detailed description of sampling coordinates on aircraft wing surfaces and procedures is given in Section 3, Sample Collection.

5.2.1 ID-1 January 16 Boeing-737 Test

On January 16 there was only Type I fluid spraying test on the aircraft. Since the precipitation rate was low there was no Type IV application. The deicing fluid samples were taken 5 minutes after the spraying. The samples had 36.5 °Brix refractive index which gave -52°C freezing point.

5.2.2 ID 7 January 22 Boeing-737 Test

Table 13.a shows test results of samples taken from the deicing truck and from the B-737 wing surfaces. The truck sample had significantly low viscosity. Viscosity of truck sample was only 6000 mPa.s at the field test temperature (-8.6°C) and 4000 mPa.s at 0°C. A typical Ultra aircraft anti-icing fluid must have a viscosity of 36000 mPa.s at 0°C. On the other hand, the Brix value of truck sample was slightly lower than the typical value of the fluid. It was 37.25 as opposed to the expected value of 39.5. Normally a decrease in viscosity could be due to a dilution by water, or by Type I fluid in the truck or aging of the fluid. A big drop in viscosity along with only a slight drop in refractive index suggested that the viscosity drop was not due to the dilution by water. It was later confirmed by the fluid supplier that aging of the fluid has reduced the viscosity and protection time of the pertinent fluid batch.

Despite the defective nature of the fluid, it was possible to use the data to analyze the failure behavior on the wing. According to APS data (Table 12) the first failure on the wing occurred at 10 minutes and 10% failure occurred at 17 minutes. The failure was at 30 minutes on sensor locations. A viscosity of 1000 mPa.s at 15 minute suggests that there was very little protection potential in the fluid left. As a matter of fact at 30 minutes the freezing point of fluid was only -6°C as opposed to -8.6°C ambient temperature. Furthermore, a viscosity of 500 mPa.s was not enough to hold the fluid on the wing while the precipitation continued. The fluid has completely failed at that moment.

Table 13.b shows another set of samples collected from the surface and depth of fluid on the wing. The top of fluid had 4% lower glycol than the bottom during the precipitation. The difference was due to the slow penetration of precipitation into the anti-icing fluid on the wing.

Table 12. Listing of 1996/1997 aircraft tests

APS ID #	Test Place	Date	A/C Type	A/C Win g	Fluid	Air Temp (°C)	Ppt Rate ($g/dm^2/hr$)	Wind Direction (deg)	Wind Speed (km/h)	Wind Head/Tail / Cross	HOT Start Time	HOT End Time	Wing First Fail (min)	Wing 10% Fail (min)	Wing 25% Fail (min)
1	YUL	Jan 16	B-737	Strbd	XL 54	-0.2	6.6	182	14	cross	4:07	4:53	36	43	45
7	YUL	Jan 22	B-737	Port	XL54/Ultra	-8.6	25.6	40	9	cross	4:30	4:54	10	17	18
12	YUL	Jan 25	B-737	Strbd	XL54/Ultra+	-0.3	1.2	138	15	cross	3:53	n/a	n/f	n/f	n/f
13	YUL	Jan 28	B-737	Port	XL54/Ultra+	-4.3	18.2	163	11	tail	1:54	4:30	36	101	126
17	YUL	Jan 28	B-737	Strbd	XL54/Ultra+	-3.6	13.5	167	10	tail	4:09	5:00	20	51	n/f
18	YUL	Feb 05	F-100	Strbd	XL54/Ultra+	-2.2	18.5	96	7	tail	1:38	2:38	25	42	57
19	YUL	Feb 05	F-100	Port	XL54/Ultra+	-1.9	17.2	101	7	tail	2:14	3:57	7	31	51
29	YUL	Mar 06	F-100	Strbd	XL54/Ultra+	-3.8	8.2	50	17	head	1:30	2:58	27	73	88
34	YUL	Mar 06	F-100	Port	XL54/Ultra+	-4.7	32.7	52	20	cross	3:52	4:27	10	18	23

Table 13.a Results of January 22 ID-7 Boeing-737 Test

Location (1)	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)	Viscosity (2) (mPa.s)
Truck	0	37.25	60	-50	6000
Wing/In	15	21.25	34	-18	1000
Wing/In	30	11.00	17	-6	600
Wing/Out	15	26.50	42	-28	1300
Wing/Out	30	10.75	17	-6	500

Table 13.b Precipitation Penetration Test Results of January 22 ID-7 Boeing-737 Test

Location (1)	Sampling	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)
Wing/In	Surface	10	24.50	39	-24
Wing/In	Depths	10	26.75	43	-28
Wing/In	Surface	20	17.75	28	-13
Wing/In	Depths	20	19.75	31	-16

(1) Sampling Locations: Wing/In 4.81 m from fuselage and Wing/Out 8.1 m from fuselage
(2) Viscosity was measured at -8.6°C.

5.2.3 ID-12 January 25 Boeing-737 Test

ID-12 test was conducted on January 25 on the starboard wing of B-737. The rate of snow precipitation was very low (1.2 g/dm^2/hr). Precipitation almost ceased later. Therefore the fluid did not fail during testing. The fluid thickness on the wing surface was between 1.6 mm - 2.0 mm. As can be seen in Table s14.a and 14.b there was no precipitation contamination in the fluid therefore the physical properties of the fluid were not altered.

Table 14.a Results of January 25 ID-12 Boeing-737 Test

Location (1)	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)	Viscosity (2) (mPa.s)
Truck	0	39.25	62	-50	50800
Wing/In	15	39.00	61.5	-50	49000
Wing/Out	15	39.00	61.5	-50	49000

Table 14.b Precipitation Penetration Test Results of January 25 ID-12 B-737 Test

Location (1)	Sampling	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)
Wing/In	Surface	15	39.25	62	-50
Wing/In	Depths	15	39.50	62.5	-50

(1) Sampling Locations: Wing/In 4.81 m from fuselage and Wing/Out 8.1 m from fuselage
(2) Viscosity was measured at -0°C.

5.2.4 January 28 B-737 Test

There were two samplings on the Boeing 737 aircraft on January 28. ID 13 was the first sampling which was on the port side wing. The second test (ID 17) was done on the starboard side wing.

Table 15.a shows ID 13 sample results from the start to 120 minutes. APS data shows that the fluid's first failure was at 30 minutes and 10% failure was at 101 minutes. However according APS recording failure was at 120 minutes on the sensor locations. The viscosity and brix readings of inboard samples continuously decreased from 46000 mPa.s to 400 mPa.s in 120 minutes. However, outboard samples did not follow the same smooth trend. Viscosity and refractive index values of 25 minute sample were lower than the values of 35 minutes. The viscosity decrease from 55 minutes to 80 minutes was also more drastic at the outboard location.

At the time of failure both inboard and outboard samples had freezing points of -5°C which was almost the ambient temperature (-4.3°C) of testing. The viscosity was 400 mPa.s at the time of failure. As it has been found in previous testing the viscosity was always around 400 mPa.s at the time of failure. The viscosity of flat plate failure was around 900 mPa.s. The difference could be due to the slope differences between flat plate and wing surfaces or due the non-uniform deicing and anti-icing on the airplane.

Table 15.a Results of January 28 ID-13 Boeing-737 Test

Location (1)	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)	Viscosity (2) (mPa.s)
Truck	0	39.25	62	-50	46000
Wing/In	15	33.00	54	-42	21400
Wing/In	25	26.75	43	-28	6400
Wing/In	35	22.50	36	-20	5400
Wing/In	55	18.75	29	-15	2300
Wing/In	80	16.50	26	-12	600
Wing/In	120	9.00	14	-5	400
Wing/Out	15	33.00	54	-42	33700
Wing/Out	25	26.50	42	-28	9400
Wing/Out	35	28.75	46	-32	26500
Wing/Out	55	22.50	36	-20	6200
Wing/Out	80	18.25	29	-14	600
Wing/Out	120	9.25	14	-5	400

(1) Sampling Locations: Wing/In 4.81 m from fuselage and Wing/Out 8.1 m from fuselage
(2) Viscosity was measured at -4.3°C.

Table 15.b Precipitation Penetration Test Results of January 28 ID-13 B-737 Test

Location	Sampling	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)
Wing/In	Surface	10	34.25	56	-46
Wing/In	Depths	10	36.50	60	-50
Wing/In	Surface	20	30.25	49	-36
Wing/In	Depths	20	32.50	53	-41
Wing/In	Surface	30	24.25	36	-20
Wing/In	Depths	30	26.25	39	-23
Wing/In	Surface	50	21.50	34	-19
Wing/In	Depths	50	21.50	34	-19
Wing/Out	Surface	10	33.00	54	-42
Wing/Out	Depths	10	35.00	57	-48
Wing/Out	Surface	20	28.25	45	-31
Wing/Out	Depths	20	29.75	48	-34
Wing/Out	Surface	30	26.25	42	-27
Wing/Out	Depths	30	28.50	46	-32
Wing/Out	Surface	50	23.00	36	-21
Wing/Out	Depths	50	23.00	36	-21

A concentration profile of samples across thickness is given in Table 15.b. The concentration of glycol in the fluid was 4% lower on top of the surface than the bottom at the early stage of testing. However, at minute 50 the concentration gradient across the thickness disappeared. This was due to the decrease in film thickness, and viscosity decrease of the fluid. Therefore, towards the end of the test the precipitation penetrates into the fluid much more quickly than the early stage of the protection process.

The second test of the day was ID-17. Results are shown in Table 16. It was conducted on the starboard side of wing. In this case, as opposed to the previous test the inboard location's refractive index and viscosity values decreased more drastically than the outboard location. The exact cause of these different behaviors is not known. It may be due to non-uniform deicing and anti-icing. Despite the first wing failure at 36 minutes and 10% wing failure at 51 minutes the fluid on sensor locations did not fail yet at 60 minutes. As reported in Table 12, 25% of the wing did not fail.

The concentration profiles were only taken at 20 minutes. The concentration difference between top and bottom was zero at inboard location. The absence of glycol concentration difference was due to the low viscosity of the sample at inboard point. At outboard location surface had 1% less glycol than the bottom location.

Table 16.a Results of January 28 ID-17 Boeing-737 Test

Location (1)	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)	Viscosity (2) (mPa.s)
Truck	0	39.25	62	-50	46000
Wing/In	20	21.5	34	-19	2800
Wing/In	40	17.5	27	-13	1100
Wing/In	60	14.25	22	-9.0	1000
Wing/Out	20	27.00	43	-29	16200
Wing/Out	40	26.50	42	-28	10900
Wing/Out	60	23.00	36	-21	6200

(1) Sampling Locations: Wing/In 4.81 m from fuselage and Wing/Out 8.1 m from fuselage
(2) Viscosity was measured at -4.3°C.

Table 16.b Precipitation Penetration Test Results of January 28 ID-17 B-737 Test

Location	Sampling	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)
Wing/In	Surface	25	24.50	39	-24
Wing/In	Depths	25	24.50	39	-24
Wing/Out	Surface	25	27.75	45	-30
Wing/Out	Depths	25	28.75	46	-32

5.2.5 February 05 F-100 Test

Table 17 shows ID-18 test results from February 05 on starboard wing of Fokker 100. The first failure on the wing was at 25 minutes, 10% of wing failed 42 minutes after and 25% of the wing failed 57 minutes after testing. The physical properties of the fluid reached to failure point on the sensor location after 60 minutes of testing. On Fokker aircraft at sensor location, viscosity was 600 mPa.s at the time of failure. The freezing point of the fluid was still -4°C as opposed to the ambient temperature of -2°C.

Table 18 shows ID-19 test results which was the second test on February 05. It was conducted on port side of the wing. Again, at the time of failure, the viscosity was 600 mPa.s at the test temperature and freezing point was -4°C as opposed to -2°C ambient temperature. The failure time at the sensor was in agreement with 25% of wing surface failure time.

Table 17. Results of February 05 ID-18 Fokker-100 Test

Location (1)	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)	Viscosity (2) (mPa.s)
Truck	0	39.25	62	-50	54900
Wing/In	15	26.00	42	-27	9700
Wing/In	30	20.25	32	-17	1000
Wing/In	60	7.75	12	-4	500
Wing/Out	15	27.25	44	-29	11900
Wing/Out	30	21.00	33	-18	2600
Wing/Out	60	12.00	19	-7	600

(1) Sampling Locations:
(2) Viscosity was measured at -2°C.

Table 18. Results of February 05 ID-19 Fokker-100 Test

Location (1)	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)	Viscosity (2) (mPa.s)
Truck	0	39.25	62	-50	54900
Wing/In	15	30.00	48	-35	29800
Wing/In	30	23.25	37	-22	10400
Wing/In	45	18.50	29	-14	3000
Wing/In	60	16.50	26	-12	1500
Wing/In	75	17.75	28	-13	1800
Wing/In	90	15.25	24	-10	1000
Wing/In	120	8.25	13	-4	600
Wing/Out	15	29.50	48	-34	25600
Wing/Out	30	22.50	36	-20	7600
Wing/Out	45	17.50	27	-13	2100
Wing/Out	60	16.25	25	-12	1400
Wing/Out	75	14.75	23	-10	900
Wing/Out	90	12.00	19	-7	800
Wing/Out	120	6.00	9	-3	600

(1) Sampling Locations:
(2) Viscosity was measured at -2°C.

5.2.6 March 06 F-100 Test

ID-29 was the first test on March 06 (see Table 19). It was conducted on starboard side wing. The first failure of the fluid was 27 minutes but 10% and 25% of the wing were failed at 73 and 88 minutes. However, there was not any failure point detected at sensor location based on physical properties we measured. It was noted during testing that the application of the fluid and film thickness were non-uniform on the wing.

The glycol concentration differences across the thickness were given in Table 19.b. The concentration difference was only 1% across the thickness.

Table 20 shows the port side wing test on March 06 (ID-34). This time the first failure point was at 10 minute and 10% wing failed at 18 minutes and 25% wing failed at 23 minute. Our sampling at 20 minutes showed that despite the low freezing point (-10°C) of fluid, the viscosity was not sufficient to hold the fluid on the wing any more. The viscosity was only 700 mPa.s

Table 19.a Results of March 06 ID-29 Fokker-100 Test

Location (1)	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)	Viscosity (2) (mPa.s)
Truck	0	39.25	62	-50	42000
Wing/In	25	35.50	58	-49	35700
Wing/In	45	29.75	48	-34	25900
Wing/In	65	28.75	46	-32	18100
Wing/In	85	26.75	43	-28	13000
Wing/Out	30	33.00	54	-42	35100
Wing/Out	50	27.00	43	-29	16700
Wing/Out	70	28.25	45	-31	15800
Wing/Out	90	25.25	40	-25	11200

(1) Sampling Locations:
(2) Viscosity was measured at -4°C.

Table 19.b Precipitation Penetration Test Results of March 06 ID-29 Fokker-100 Test

Location	Sampling	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)
Wing/In	Surface	20	n/a		
Wing/In	Depths	20	n/a		
Wing/In	Surface	40	33.00	54	-42
Wing/In	Depths	40	33.00	54	-42
Wing/In	Surface	60	30.75	50	-37
Wing/In	Depths	60	32.25	52	-40
Wing/In	Surface	80	27.25	44	-29
Wing/In	Depths	80	27.50	44	-30
Wing/Out	Surface	20	34.50	56	-46
Wing/Out	Depths	20	35.00	57	-48
Wing/Out	Surface	40	29.00	47	-33
Wing/Out	Depths	40	31.00	50	-37
Wing/Out	Surface	60	29.00	47	-33
Wing/Out	Depths	60	30.00	48	-35
Wing/Out	Surface	80	28.25	45	-31
Wing/Out	Depths	80	28.50	46	-32

Table 20. Results of March 06 ID-34 Fokker-100 Test

Location (1)	Time (min)	°Brix	Glycol (%)	Freezing Point (°C)	+Viscosity (2) (mPa.s)
Truck	0	39.25	62	-50	42000
Wing/In	20	20.50	32	-17	4300
Wing/Out	20	14.75	23	-10	700

(1) Sampling Locations:
(2) Viscosity was measured at - 4°C.

6. CONCLUSIONS

In this test program, the flow and physical properties of a Type IV fluid were monitored on the standard flat plate and various aircraft wings. The viscosity results were measured at the recorded outside air temperatures. Despite the wide range of variations in holdover times as a result of precipitation type and rate and temperature, failed fluids always reached the same range of viscosity value. At failure, the viscosity of contaminated fluid was 900-1000 mPa.s on the standard flat plate, 400 mPa.s on Boeing 737 and 600 mPa.s on Fokker 100 aircraft wing at sensor spots.

The fluid freezing point at the time of the failure is usually the same as the outside air temperature. It is generally believed that the failure of an anti-icing fluid during precipitation can be due to two mechanisms: 1) freezing of fluid film due to decrease in glycol concentration; or 2) not enough protected film left because of fluid film drainage. Therefore, based on the viscosity and freezing point data of failed fluids, it can be concluded that fluid failure was due to the viscosity decrease by dilution and drainage of the protected fluid film.

Fluid failure times on sensor locations based on physical property measurements were longer than first failure time and 10% wing failure time calls recorded by APS. The failure time of fluid on ice sensor locations on Boeing 737 and Fokker 100 aircraft were more in agreement with 25% wing surface failure time observed by APS. Therefore, the proposed sensor locations on aircraft surfaces must be reexamined. Sensors must be installed on locations where the first failure time or at least 10% wing surface failure time were measured by viscosity tests and visual observations.

The viscosity results not only show the convergence of fluid properties at the time of failure but also indicate how much fluid protection time remains before failure under precipitation. When the viscosity value drops below 5000 mPa.s, the residual protection time of the fluid decreases drastically. This argument is only valid for the Type IV fluid tested during the program.

REFERENCES

1. Aviation Planning Services, *Aircraft Ground De/Anti-icing Fluid Holdover Time Field Testing Program for the 1990-1991 Winter,* Transportation Development Centre, Montreal, May 1992, TP11206E.
2. SAE G-12 Main Committee, Aircraft Ground De-Icing Meeting Denver, Colorado, June 1994.
3. SAE G-12 Holdover Time Sub-Committee Meeting, Zurich, Switzerland, May 1996.
4. UQAC, *Fluid Behavior Simulation - Modeling of Water Diffusion in Aircraft Ground De/Anti-icing Fluids for Laboratory Holdover Time: Numerical Prediction,* Transportation Development Centre, Montreal, November 1997, TP13113E (to be published).
5. APS Aviation Inc. *Aircraft Ground De/Anti-icing Fluid Holdover Time Field Testing Program for the 1996/97 Winter, 1996-1997,* TP13131E (to be published), Transportation Development Centre, Montreal, October 1997.
6. APS Aviation Inc*., Experimental Program for Dorval Natural Precipitation Flat Plate Testing, 1996-1997,* November 1996.
7. Holdover Time Working Group of the SAE G-12 Committee on Aircraft Ground De/Anti-icing, *Flat Plate Field Test Equipment and Procedure, 1996-1997..*
8. APS Aviation Inc. *Experimental Program for Simultaneous Aircraft vs. Plate Testing, 1996-1997,* December 1996.