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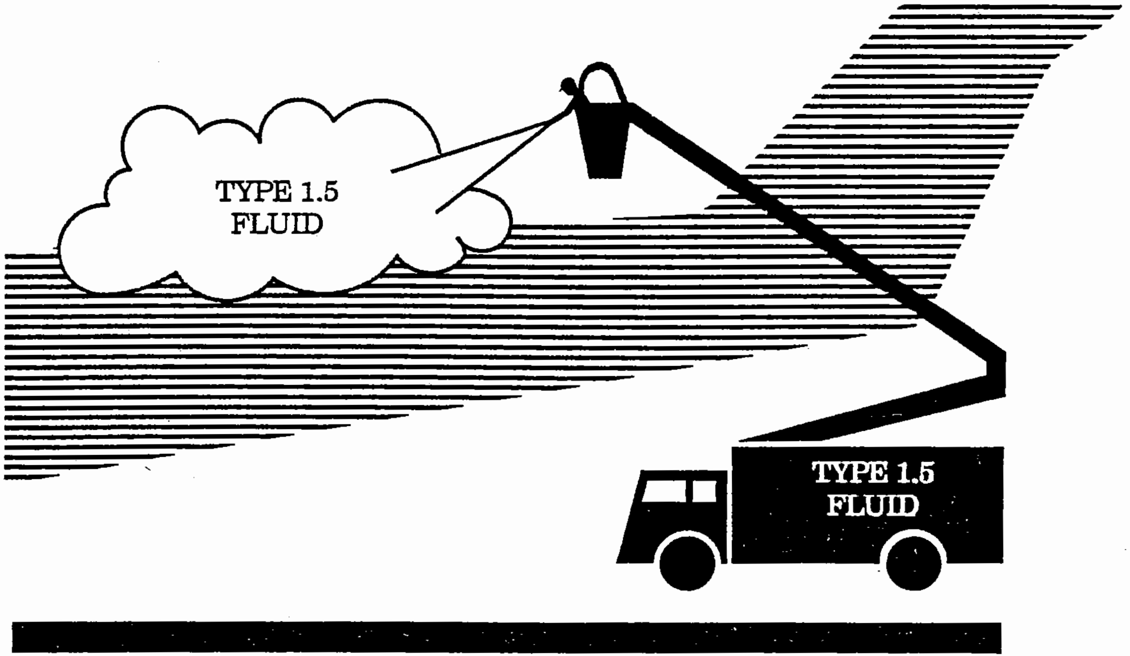
Aircraft Ground De/Anti-icing Fluid Holdover Time Field Testing Program for the 1991-1992 Winter



Prepared for

Transportation Development Centre
Policy and Coordination
Transport Canada

by

Aviation Planning Services Ltd.

August 1992

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

Un sommaire en français de ce rapport est inclus.

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16. Abstract

The objective of this study was to manage, conduct and analyze holdover time tests used to assess the time effectiveness of Type 1.5 anti-icing fluids. Testing was carried out at two Canadian sites, namely Dorval, Quebec and St. John's, Newfoundland. Test procedures consisted of pouring anti-icing fluids onto clean aluminum plates, exposing the plates to either natural or artificial precipitation, and recording the elapsed time to the end condition. Four anti-icing fluids were tested. It was hypothesized that failure time was affected by such variables as precipitation, temperature, humidity, wind and fluid thickness.

A total of 261 natural snow test points and 42 artificial snow test points were collected. While a significant amount of data scatter exists when analyzing the entire data set, restricting the analysis to calm wind tests exposes a potentially significant relationship between failure time and rate of precipitation. Continued refinement of the testing process should support or disprove the relationship.

Testing also investigated the potential use of an ice detector in making the failure determinations. While only three such tests were performed, sufficient promise was exhibited by the results to justify further study.

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16. Résumé

Le but de cette étude était d'organiser et de mener des essais visant à mesurer la durée de l'effet de certains antigivre de type I.5 et dén analyser les résultats. Les essais ont été menés sur deux sites canadiens, à savoir Dorval (Québec) et St.John's (Terre-Neuve). Le mode opératoire a consisté à verser l'antigivre sur des plaques d'aluminium propres, à les exposer à diverses formes de précipitations, naturelles ou artificielles, et à mesurer le temps écoulé jusqu'à l'apparition de l'état final. Quatre antigivre ont été ainsi testés. L'hypothèse de départ était que la durée de l'effet est une variable dépendante de la précipitation, de la température, de l'humidité, de la vitesse du vent et de l'épaisseur d'antigivre.

En tout, 261 mesures ont été obtenues à partir de sites de neige naturelle, et 42 à partir de sites de neige artificielle. Malgré la forte dispersion observée dans l'analyse de l'ensemble des résultats, il reste que, en réduisant la portée des essais pour ne s'intéresser qu'à l'effet dans des conditions de vent calme, une corrélation significative a pu être décelée entre durée de l'effet et taux de précipitation. Par l'affinement de la méthode d'essai, il sera possible de déterminer si cette corrélation se vérifie ou non.

Le capteur essayé à titre de témoin s'est montré très utile dans la détermination de la durée de l'effet, et, bien que trois essais seulement aient été faits avec ce capteur, les résultats sont suffisamment prometteurs pour justifier de plus amples recherches.

17. Mots clés

aéronef, sol, antigivre, fluide, durée, temps, essai, précipitation, aile, plaque, données, dégivrage,capteur

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0. EXECUTIVE SUMMARY

At the request of the Transportation Development Centre (TDC) of Transport Canada and the FAA Technical Centre, Aviation Planning Services (APS) undertook a study to manage, conduct and analyze holdover time tests used to assess the time effectiveness of the commercially produced anti-icing fluids known as Type I.5 fluids.

The project involved the participation of a number of de/anti-icing fluid manufacturers, the National Research Council (NRC), Atmospheric Environment Services (AES), Transport Canada Aircraft Services and Air Canada. Testing was carried out at two sites in Canada, Dorval, Québec and St. John's, Newfoundland.

Generally, the testing consisted of pouring anti-icing fluids onto clean, inclined flat aluminum plates, exposing the plates to various winter precipitation conditions and recording the time elapsed before the plates reached a defined end condition. Some testing was also performed on a curved plate and a wing section. A modified Instrumar IM101 ice sensor was mounted on a flat plate to investigate its possible use in the testing process. Lastly, some testing was done under artificial snow conditions on a ski hill at Mont Rigaud, Quebec.

The end condition was defined as the point in time when snow (or freezing rain) was no longer being absorbed, or accommodated by the fluid. This was to be when snow was seen to be resting, or bridging, on top of the fluid, above a complete crosshair when viewed from the front of the test stand (perpendicular to the plates). The failure time for each individual crosshair was recorded, resulting in up to 15 failure points for each test plate.

Failure time could be affected by any or all the following recorded variables: total precipitation, rate of precipitation, type of precipitation, ambient temperature, relative humidity, wind speed, fluid thickness, type of fluid, and test location, as well as the subjectivity of the tester. Other variables not included in this list may also play a role.

0.1 Data Collection

During the 1991-1992 test season, APS received 72 natural snow test data forms from the two sites, and 20 artificial snow test data forms. Each form contained data for up to six flat plates, or four flat plates and a curved plate or for two test sections on a wing. In total, these data forms contained 261 natural snow test points and 42 artificial snow test points. Ninety-nine points were not used because either a failure did not occur or the tests were aborted due to problems experienced with plates and/or meteorological equipment.

All testing was done using Type I.5 fluids provided by Union Carbide, Octagon, Kilfrost and Hoechst. The majority of the tests were carried out using Union Carbide's 250-3 anti-icing fluid in order to obtain a reasonably sized data set without the additional complication of fluid type.

0.2 Meteorological Analysis

With the assistance of Atmospheric Environment Services Canada, the Consultants were able to obtain relatively detailed meteorological information for both sites. This data was used to determine days on which testing could have taken place. The actual days when testing was done were compared against these days. Results indicated improvements in coverage at both Dorval and St. John's over the previous testing year.

A computerized meteorological data acquisition system was installed at Dorval, and used to study the changes in the meteorological parameters during a storm. The system provided data every ten seconds over the entire winter. Temperature and relative humidity were observed to change slowly over time while wind speed and precipitation rates fluctuated quite rapidly. Tests during periods of moderate precipitation were shown to also contain short bursts of very heavy precipitation.

0.3 Data Analysis

The analysis of the collected data was multi-faceted. Plots of failure time against each of the other variables failed to unearth any strong direct relationships. However, this analysis did discover what appears to be a failure envelope when comparing failure time to rate of precipitation.

More useful information was gained by reducing the scope of the data set to tests under certain specific conditions. By plotting the failure time against the precipitation rate for tests when the average wind speed was less than five kph, a significant correlation was indicated. A regression curve on the these points had the descriptive function $\mathbf{Y = 73.5X^{-0.43}}$, where Y refers to the failure time and X refers to the rate of precipitation (in $g/dm^2/hr$).

A multi-variate statistical analysis was performed on the Union Carbide 250-3 data collected at Dorval. The analysis found that the log of the failure time was dependent on the precipitation rate, temperature, wind speed and fluid thickness. The non-linear relationship accounted for 68% of the variation in the data. In itself, 68% is not a very satisfactory value of $\mathbf{R^2}$, the multiple coefficient of determination, especially if the resulting equation is to be used as a predictor. However, this value is almost 20% above the best value obtained during the 1990-1991 testing season and, in that sense, shows significant promise. An analysis on tests where the wind was less than five kph showed that the log of the failure time was most dependent on the precipitation rate and relative humidity. While this relationship accounted for over 90% of the variation in the data, it should be stressed that this was obtained from a small number of data points and is applicable over a very limited range of conditions.

Precipitation rates under artificial snow conditions were high - above 22.5 g/dm^2/hr. Once failure began to occur somewhere on the plate, the rest of the plate followed very quickly. A layer of crusty snow or ice would form on top of a thin layer of fluid. Failures occurred at the bottom of the curved plate first and progressed upwards while failures on the wing first occurred at the leading edge.

The modified IM101 ice sensor was also tested under artificial snow conditions. The sensor results showed a great deal of promise. In all three tests there was a sharp decline in values returned by the sensor just prior to a visual failure. The final values for the sensor at the time a visual failure was called were all within 8% of each other.

0.4 Future Testing

It is precisely because one eventually wants to understand holdover that future testing should be continued outdoors. It is not possible to generate "natural conditions" in a cold chamber. Unfortunately it is also not possible to control the outdoor conditions themselves.

The key unsatisfactory element which remains in the procedure is the lack of a clear, precise, objective method of measuring the failure point. The subjectivity which remains in this very important test activity is most likely responsible for a good deal of the scatter which is unaccounted for. Testing of the IM101 ice sensor should continue and could end the subjectivity in determining the failure time.

A cylinder or half cylinder test section may be a way to easily investigate the effects of precipitation on the leading edge of a wing. Performing these tests alongside the flat plates may provide grounds for a correlation between the two types of test sections. The benefits are that it may be easier for other interested parties to obtain a cylinder of a pre-determined diameter than it would be to obtain an aircraft wing.

0. SOMMAIRE

Mandatés par le Centre de développement des transports (CDT) de Transports Canada, et le FAA Technical Centre, les Services de planification en aviation (SPA) ont entrepris d'organiser et de mener ainsi d'analyser les résultats des essais visant à mesurer la durée de l'effet des agents antigivre sur le marché connus sous le nom de fluides type I.5.

Les chercheurs ont fait appel à des fabricants d'agents dégivrants et antigivre, au Conseil national de recherches Canada (CNRC), au Service de l'environnement atmosphérique (SEA), aux services de la navigation aérienne de Transports Canada et à Air Canada pour mener à bien ces essais sur deux sites canadiens, un à Dorval (Québec) et un à St.John's (Terre-Neuve).

Règle générale, les essais ont consisté à verser un agent antigivre sur des plaques d'aluminium propres inclinées, à exposer ces plaques à diverses formes de précipitations hivernales et à mesurer le temps écoulé jusqu'à l'apparition d'un état dit final. Des essais ont également été faits sur une plaque incurvée et un profil d'aile. Un capteur de givre IM101 modifié a été fixé à une des plaques planes afin de vérifier son utilité durant les essais. Enfin, quelques essais ont été faits sous une neige artificielle à Mont Rigaud (Québec)

Lors d'un essai, on considérait que l'état était final lorsque la neige (ou le verglas) n'était plus absorbée par le fluide recouvrant la plaque, c'est-à-dire lorsqu'on observait de la neige reposant ou faisant comme un pont sur la plaque au-dessus d'un des fils en croix marqués, ce dernier étant vu perpendiculairement à la plaque. Le temps écoulé était alors mesuré pour chacun des 15 fils en croix marqués sur chaque plaque.

Les variables indépendantes qui peuvent agir séparément ou simultanément sur la durée de l'effet produit par les agents essayés sont multiples : la quantité totale de précipitation, le taux de précipitation, sa nature, la température ambiante, l'humidité relative, la vitesse du vent, l'épaisseur de l'agent, la nature de celui-ci, le lieu de l'essai et la subjectivité du chercheur. D'autres paramètres non pris en compte peuvent avoir eu une influence sur les résultats obtenus.

0.1 Collecte de données

Au cours de la saison 1991-1992, SPA a reçu 72 procès-verbaux provenant des deux sites et 20 autres provenant du site de neige artificielle, chacun consignant les mesures relatives à un maximum de six plaques, ou quatre planes et une incurvée ou deux profils de voilure. Soit, en tout, 261 mesures provenant des sites de neige naturelle et 42 des sites de neige artificielle. Quatre-vingt-dix-neuf mesures étaient inutilisables parce que l'essai avait été soit interrompu soit raté pour raison de difficultés techniques ou météorologiques.

Les agents mis en oeuvre ont été de type I.5 fabriqués par Union Carbide, Octagon, Kilfrost et Hoechst. Dans la plupart des essais c'est l'antigivre 250-3 de Union Carbide qui a servi, afin de pouvoir obtenir un ensemble de données de taille raisonnable sans faire intervenir la complication supplémentaire de type d'agent.

0.2 Analyse météorologique

Grâce à la collaboration du Service de l'environnement atmosphérique, les chercheurs ont pu obtenir des données météorologiques assez détaillées concernant les deux sites d'essai. Ces données ont servi pour compter le nombre de jours durant lesquels des essais auraient pu être faits. À l'issue de la période d'essais, les chercheurs ont comparé ce nombre à celui durant lequel les essais avaient effectivement eu lieu. Les résultats ont montré une augmentation dans le nombre de jours couverts, par rapport aux résultats précédents, tant à Dorval qu'à St.John's.

Un système informatisé d'acquisition de données météorologiques a été installé à Dorval. Il a servi à déceler les changements paramétriques au cours des tempêtes hivernales, les données étant saisies et enregistrées une fois toutes les dix secondes durant tout l'hiver. Il a été constaté que la température et l'humidité relative évoluaient lentement, alors que la vitesse du vent et le taux de précipitation évoluaient assez rapidement. Les observations faites durant des averses d'intensité moyenne ont mis en évidence des épisodes d'averses très intenses mais de courte durée.

0.3 Analyse des données

Cette analyse a été de type multicritères. Aucune des courbes montrant la durée de l'effet en fonction de chacun des paramètres pris en compte n'a mis en évidence une quelconque corrélation directe et convaincante. Toutefois, les chercheurs ont découvert, sur la courbe de durée de l'effet en fonction du taux de précipitation, une limite inférieure et une limite supérieure formant ce qui semble être une enveloppe.

Des données plus intéressantes ont pu être obtenues en réduisant la portée des essais pour ne s'intéresser qu'à l'effet sous certaines conditions précises. Sur la courbe de durée de l'effet en fonction du taux de précipitations, alors que la vitesse moyenne du vent était inférieure à 5 km/h, une corrélation significative a pu être décelée. Une courbe de régression réunissant tous ces points s'est dessinée, correspondant à l'équation $Y = 73{,}5X^{-0.43}$, où Y est la durée de l'effet et X le taux de précipitation (en $g/dm^2/h$).

Les données recueillies à Dorval sur l'antigivre 250-3 d'Union Carbide ont été soumises à une analyse statistique multivariée. Les résultats montrent que la valeur logarithmique de la durée de l'effet est une variable dépendante du taux de précipitation, de la température, de la vitesse du vent et de l'épaisseur de l'agent. Les variations dans les données ont pu être expliquées à concurrence de 68 p. 100 par cette relation non linéaire. Or, 68 p. 100 ne constitue pas une valeur très satisfaisante de R^2 qui est le coefficient de détermination multiple, surtout si l'équation qui en résulte doit servir d'indicateur prévisionnel. Cependant, cette valeur se situe à presque 20 p. 100 au-dessus de la valeur la plus satisfaisante obtenue durant la saison précédente de sorte que, dans un certain sens, elle est prometteuse. L'analyse statistique des résultats alors que la vitesse du vent était inférieure à 5 km/h a montré que la valeur logarithmique de la durée de l'effet subissait l'influence prépondérante du taux de précipitation et de l'humidité relative. Bien que les variations dans les données ont été expliquées à concurrence de 90 p. 100 par cette relation linéaire, il faut souligner qu'elle n'est fondée que sur un nombre restreint de mesures et qu'elle ne peut s'appliquer que dans des conditions très étroites.

Avec la neige artificielle, les taux de précipitation ont été élevés, soit supérieurs à 22,5 $g/dm^2/h$. Une fois que l'effet cessait de se manifester en un point de la plaque, il ne tardait pas à cesser sur toute la plaque, laissant une croûte neigeuse ou glacée se former par-dessus une couche mince d'antigivre. Dans le cas de la plaque incurvée, l'effet cessait de se manifester d'abord vers le bas, et progressait ensuite vers le haut, alors que sur le profil d'aile, l'effet cessait d'abord au droit du bord d'attaque.

Le capteur IM101 modifié, essayé sous une neige artificielle, a donné des résultats très prometteurs. Dans les trois essais effectués, une chute brutale des valeurs mesurées a été observée, et ce juste avant que la cessation de

l'effet ne puisse se constater visuellement. Au moment où la fin de la durée s'observait visuellement, les dernières valeurs mesurées par le capteur se situaient dans une plage de 8 p. 100 les unes des autres.

0.4 Essais futurs

C'est précisément parce qu'on veut approfondir les paramètres déterminant la durée de l'effet produit par les antigivre que les essais à venir doivent se tenir à l'extérieur. Une chambre froide ne peut pas reproduire les conditions naturelles, alors qu'à l'extérieur la maîtrise de celles-ci nous échappe malheureusement.

L'élément essentiel qui reste encore à maîtriser est celui de l'objectivité et pour cela il est nécessaire de disposer d'une méthode d'observation exempte de toute ambiguïté. C'est au facteur de subjectivité qu'il faut attribuer la forte dispersion observée dans les résultats. Il est recommandé de poursuivre les essais avec le capteur IM101 de manière à pouvoir éliminer le facteur de subjectivité nuisible aux observations.

Un profil cylindrique ou semi-cylindrique pourrait constituer un moyen aisé d'observer l'effet de la précipitation sur le bord d'attaque d'un profil d'aile, à condition de mener parallèlement des essais sur les plaques planes de manière à pouvoir établir si une corrélation existe entre ces deux formes de profil. L'avantage de cette façon de procéder est qu'il est plus facile à des tiers de disposer d'un cylindre d'un certain diamètre que d'une voilure d'aéronef.

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LIST OF ACRONYMS

A/D	Analog to Digital (converter)
AES	Atmospheric Environment Services (Canada)
APS	Aviation Planning Services Ltd.
CASP	Canadian Atlantic Storms Program
FAA	Federal Aviation Administration (USA)
NRC	National Research Council
RH	Relative Humidity
SAE	Society of Automotive Engineers
TC	Transport Canada
TDC	Transportation Development Centre
UCAR	Union Carbide

1. INTRODUCTION

At the request of the Transportation Development Centre (TDC) of Transport Canada and the FAA Technical Centre, Aviation Planning Services (APS) undertook a study to manage, conduct and analyze holdover time tests used to assess the time effectiveness of the commercially produced anti-icing fluids known as Type I.5 fluids.

In the last decade, a number of fatal aircraft accidents have occurred at take-off during periods of freezing precipitation or precipitation which could contaminate aerodynamic surfaces; in several of these accidents the effectiveness of ground de/anti-icing has been suspect. Until fairly recently in Canada, aircraft were deiced using only Type I deicing fluids, in various dilutions. While excellent for removing ice and snow which has already accumulated on the wings of aircraft, Type I fluids do not offer any sort of extended duration protection against further ice build up. Lengthy queues for take-off at congested airports, with the accompanying longer anti-icing protection requirement led to examination of the use in North American of the European anti-icing fluids known as Type II fluids. While these fluids do provide increased protection against freezing precipitation, when compared with Type I fluids, their rheological properties are such that the fluids themselves result in aerodynamic penalties for aircraft with relatively low takeoff speeds. Most commuter and general aviation aircraft fit into this category.

Type I.5 fluids were developed to supply commuter aircraft with increased protection from precipitation without the aerodynamic penalties associated with the more viscous Type II fluids.

The need for field testing of the fluids was identified over three years ago and has been addressed through various programs with varying levels of success. Following a series of meetings in 1988-1989 on holdover time, held under SAE auspices, with many major airlines and de/anti-icing fluid manufacturers, Air Canada and the

Transportation Development Centre took the initiative to develop a small field test program for the 1989-1990 winter season to determine the fluid time effectiveness under real precipitation conditions. The results were unsatisfactory for a number of reasons that were subsequently addressed at a TDC sponsored meeting of the SAE Ad Hoc Committee Working Group (Aircraft Ground Deicing Tests), June 6th, 1990, in Montreal. Agreement was reached on standardized test equipment, procedures and the scope of the data to be collected during the 1990-1991 winter. The results of the 1990-1991 world wide testing program, which concentrated on Type II fluids, were published by Aviation Planning Services Ltd. in the Transport Canada report TP11206E, Aircraft Ground De/Anti-Icing Fluid Holdover Time Field Testing Program for the 1990-1991 Winter.

Testing during the 1991-1992 winter was on a smaller scale and had a slightly redirected focus. Type I.5 fluids were the only fluids tested with specific concentration on a locally manufactured fluid. The intention was not to carry out extensive tests of all Type I.5 fluids, but rather to gain a better understanding of the variances between fluids and, most importantly, to improve test methods, gain better insight into the real-world modes of fluid failure and to gain some understanding of the precipitation conditions that rapidly compromise the fluids.

The test activities included collecting short time interval meteorological information via a computerized data acquisition system at Dorval Airport (Montreal, Quebec) and the field testing of Type I.5 fluids at two Canadian Airport sites, Dorval and St. John's, Newfoundland. The testing at St. John's was performed in conjunction with CASP II, the Canadian Atlantic Storms Program, supervised by Atmospheric Environment Services, Canada. At Dorval, in addition to flat plate testing, curved plates and wing sections were included. Two series of artificial snow (snow gun) tests, the last of which included preliminary testing of an ice sensor, were carried out using the snow making equipment at Mont Rigaud, a local ski hill, near Montreal.

The success of the project depended heavily on the collaboration of the FAA, de/anti-icing fluid suppliers, the NRC, AES, Transport Canada Aircraft Services and Air Canada. The influence and assistance of TDC was instrumental in achieving this cooperation.

Section 2 of the report outlines the testing procedures and equipment requirements with special emphasis on the problems experienced with both. Subsequent sections describe the data received, in terms of where it was collected and under what sort of conditions, outline deficiencies and subjectivities in the data, and deal with the analysis of the data, through failure curves, fluid thickness analyses and a purely statistical analysis. The final sections provide a discussion of future testing and conclusions, based on both the testing experience and the data analysis.

2. METHODOLOGY

The methodology description will be sub-divided into six sections dealing with: testing sites; test procedures and data forms; equipment; fluids; personnel and participants; and analysis of results.

2.1 Testing Sites

The field testing for the 1991-1992 winter was performed at two airport sites; Dorval, Quebec and St. John's, Newfoundland. Fine scale meteorological data, using a computerized data acquisition system, was collected at Dorval. The Dorval site was in operation from the middle of January until mid-April, 1992. St. John's was operational from the 22nd of January until the 15th of March, 1992 to coincide with the CASP program.

2.2 Testing Procedures and Data Forms

Generally, the testing consisted of pouring deicing fluids onto clean test sections, exposing the test sections to various winter precipitation conditions and recording the times elapsed before the test sections reached the end condition. Test sections were: flat aluminum plates, inclined at 10°; curved aluminum plates with a 10 foot or 3.048 m radius of curvature to approximate a full scale wing surface; and a wing section (approximated by a horizontal stabilizer of a Super King Air). Four flat plates, the curved plate and the wing section are depicted in Photo 2.1. Additional flat plate testing was performed incorporating an ice sensor, which measured electrical properties of whichever substance was present on the sensor head.

PHOTO 2.1 - Test Sections

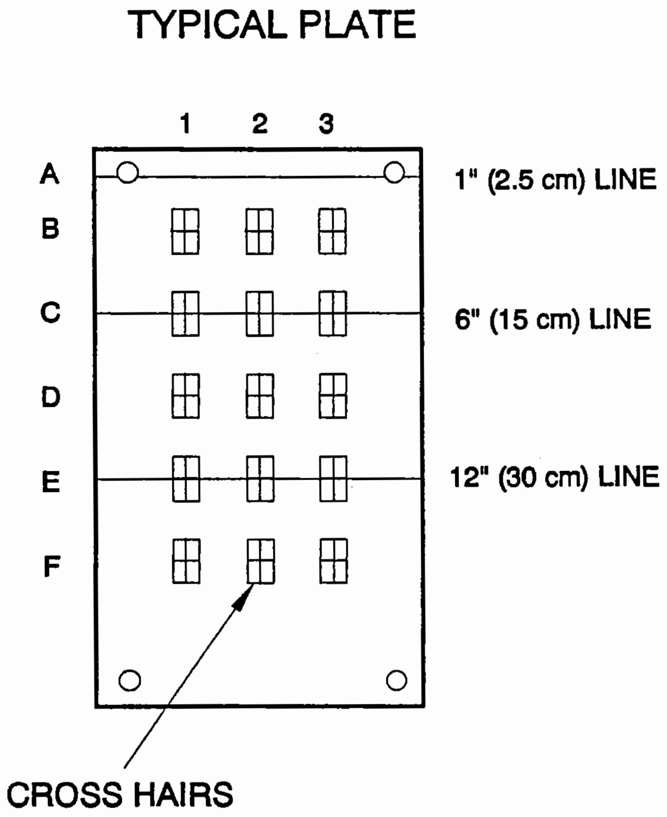
Complete details of the actual test procedures supplied to the program participants are provided in the Appendix, while a brief list of the required steps follows:

- Orient test stand to face into wind;
- Ensure test sections are clean and install on stand;
- Cover stand with a plastic tarp and allow panels to cool to outside temperature;
- Pour fluids slowly and evenly over entire test section surface until saturated;
- Allow fluids to settle on panels for ten minutes, measure fluid thickness at 2.5 cm (1 inch), 15 cm (6 inch) and 30 cm (12 inch) lines using a wet film thickness gauge;
- Expose test sections to precipitation and continue monitoring until final end condition (see below) is reached on all plates or 60 minutes has elapsed;
- Clean plates with isopropyl alcohol and begin entire procedure again.

The plates were marked with three lines, at the 2.5 cm, 15 cm and 30 cm points of the plate (when measured from the top of the plate). The plates were also marked with 15 crosshairs. These crosshairs were used in determining whether end conditions were achieved. Figure 2.1 depicts the markings on a typical flat plate.

As mentioned in the Introduction, the procedure evolved from the experiences of various test programs for the 1989-1990 and 1990-1991 winter seasons. In the report of the 1990-1991 program, the subjectivity of the test end conditions was mentioned as a key reason for the scattered nature of the resulting data. It was decided to eliminate two of the previous end conditions: freezing at the one inch line, which was found to often be misinterpreted, and

FIGURE 2.1
FLAT PLATE MARKINGS



loss of gloss - a condition where the fluid was said to have failed when it lost its reflective properties - which was a rather nebulous condition and was often associated with high failure times. The remaining end condition, obscuration of crosshairs by snow or ice, was more rigidly defined. In 1990-1991 testing, this end condition was satisfied when five of the fifteen crosshairs on a plate were obscured from the tester's view. Testing experience showed that the visibility of the crosshairs depended on the time elapsed since the crosshairs had been marked, the manner in which the markings were applied, and from which angle the markings were viewed as well as the type and density of snow falling. The 1991-1992 end condition was defined as the point in time when snow (or freezing rain) was no longer being absorbed, or accommodated by the fluid. This was to be when snow was seen to be resting or bridging on top of the fluid, above a complete crosshair, when viewed from in front of the test stand (perpendicular to the plates). The failure time above each individual crosshair was recorded resulting in up to 15 failure points for each test plate. Tests in which all 15 crosshairs did not fail within the 60 minute limit were terminated. It was felt that it would be more advantageous to begin a new test than to spend valuable precipitation time waiting for the failure of crosshairs well down the plate (note that 1990-1991 failure conditions were mostly based on five crosshairs).

A similarly spaced pattern of crosshairs was marked on the curved plate and the wing section and similar failure measurements were recorded.

The end condition is still subjective in nature, although perhaps less so than in the past. It was still possible for different individuals to make different determinations as to the time the end condition was reached. To remove all subjectivity the use of an ice sensor to provide the trigger for determining end conditions was investigated and eventually included during the final artificial snow testing period. Discussion of the sensor is included in Sections 2.3 and 5.8.

In addition to the natural condition testing, two sets of artificial snow testing were also performed. All test sections were subjected to the artificial snow produced by a snow gun at a local ski hill. The test procedures and end conditions were as described above.

All data recorded during testing was recorded on supplied data forms, which are also included in Appendix A. The Dorval meteorological data was automatically recorded and stored on a computer.

2.3 Equipment

The equipment list and specifications are also included in the Appendix. Equipment was required to record precipitation, temperature, wind speed, relative humidity and fluid thickness. As meteorological data at St. John's was provided by AES using their own equipment, all discussion in this section will focus on the Dorval equipment.

Previous years' testing in North America employed a heated rain/snow gauge tipping bucket to measure precipitation. The model registered a "tip" for every gram per square decimetre of snow that fell (which equated to 0.1 mm of liquid precipitation). This proved to be too coarse for most of the precipitation conditions measured. A light to medium snow fall would register only 4 or 5 tips over a one hour period. A model used in Europe (an ombrometer) had a resolution 20 times finer than the North American model. The ombrometer counted "drops" as opposed to "tips" and registered a "drop" for every .05 grams per square decimetre of precipitation. This unit was adopted for use in the 1991-1992 testing program. The high resolution of the ombrometer should not be confused with accuracy. Significant winds may result in the ombrometer and the test section receiving different amounts of precipitation.

The ombrometer was connected to a central computer via a serial cable. Similarly connected were an anemometer to measure wind speed, and temperature and humidity probes. It should be noted that the 90% response time for the RH meter used in 1990-1991 was 45 minutes whereas the one employed for this testing season had a 90% response time of one second.

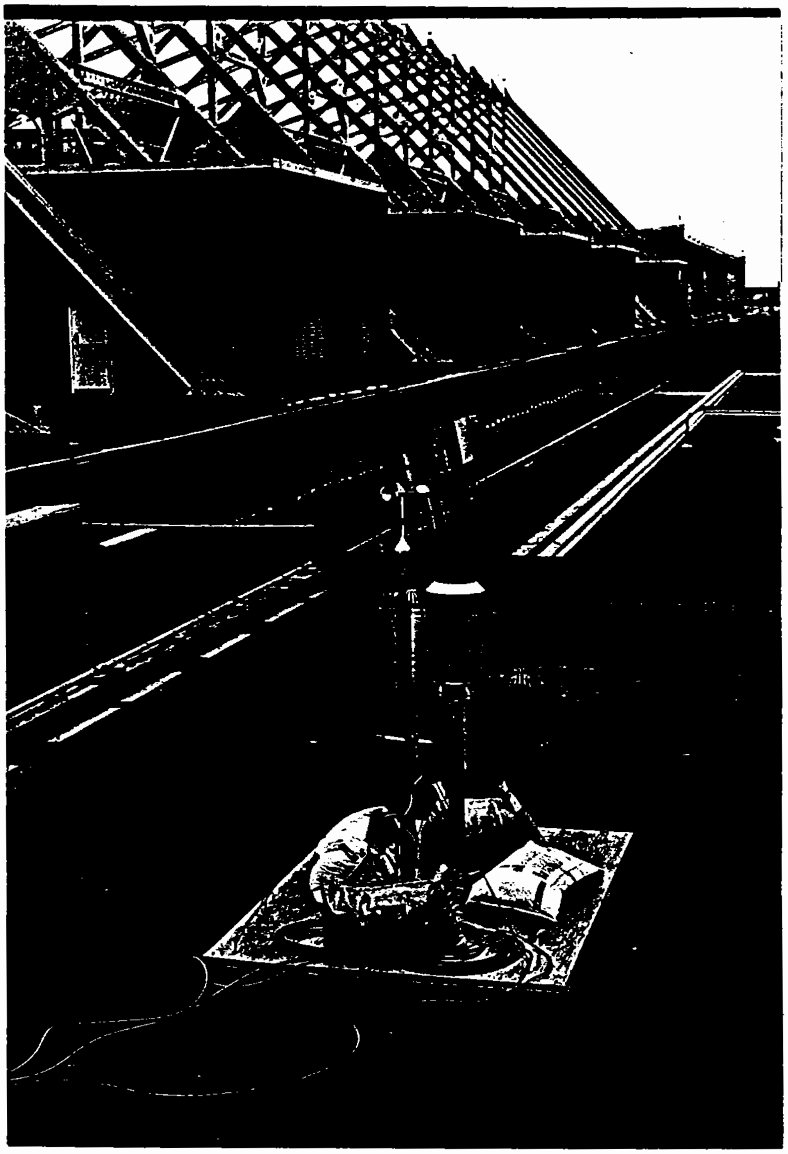
The ombrometer drop count, wind speed, temperature and relative humidity were all sampled every ten seconds. This sampling also continued when no other testing occurred to provide a more complete meteorological picture. The meteorological station used at Dorval is depicted in Photo 2.2.

While the quantity and quality of the meteorological data exceeded, by a wide margin, that collected during previous years, some problems were experienced.

Power surges provided "hiccups" in the data. The "hiccups" were seen as extreme values of individual data records and affected each of the four parameters. One record would indicate a wind speed of six miles per hour and a temperature of -3 degrees celsius and the next would indicate a wind speed of 400 miles per hour and a temperature of -340 degrees celsius. The severe nature of the "hiccups" allowed for relatively simple manual correction.

Under extremely cold weather conditions, the exit nozzle of the ombrometer had a tendency to freeze up. This caused a back up into the ombrometer and cast doubt upon the accuracy of some of the data. Further investigation resulted in two tests being removed from the data base because of this problem. The cause was that the exit nozzle was made of plastic as opposed

PHOTO 2.2 - Meteorological Station



to metal and did not conduct the heat being produced by the ombrometer's own heater.

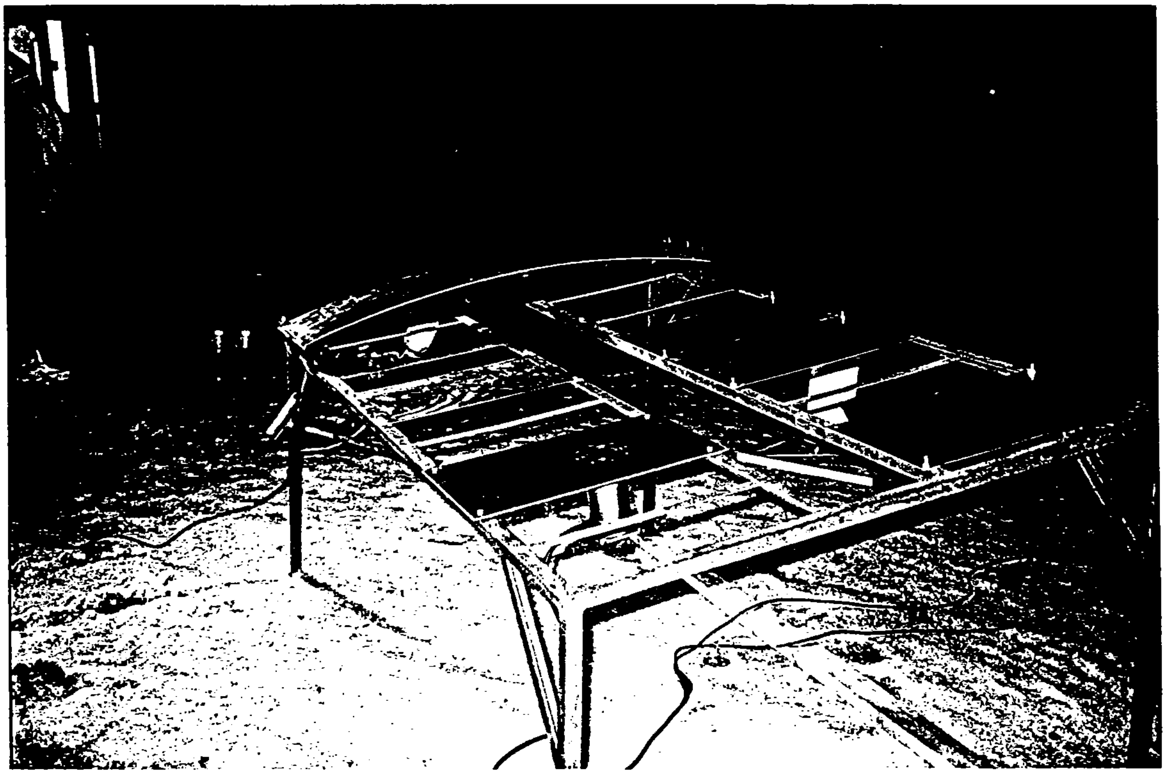
Lastly, a ten minute power failure caused the loss of data from one test. The installation of an uninterruptable power source and a line conditioner should remove both power failures and power surges as areas of concern during future testing.

The ice sensor used at the end of the year was a modified IM101 sensor obtained from Instrumar Ltd of St. John's, Newfoundland. The sensor was attached to a flat plate as shown in Photo 2.3. The sensor measured the admittance of what was directly above the sensor head, be it air, water, fluids, ice, snow, etc. Further discussion of the ice sensor and its implications is left for Section 5.8.

2.4 Fluids

As mentioned, only Type I.5 fluids were tested. The fluids were provided by Union Carbide, Kilfrost, Octagon and Hoechst. Since there are no qualification tests defined for Type I.5 fluids, as yet, it was surmised that the variance between fluids could be substantial. Therefore, it was decided that since basic understanding was the key goal of the program, performing the majority of testing on a single fluid would provide a wider database from which to draw conclusions. Union Carbide 250-3 was selected solely because of Union Carbide's proximity to the Dorval site and APS offices. This proximity became a key positive element when, on a couple of occasions, the testing fluid supply was exhausted. Additional fluids were collected and placed on site within a matter of hours.

PHOTO 2.3 - Ice Sensor (Attached to Flat Plate)



2.5 Personnel and Participants

The sites were staffed mainly by university students. The local site at Dorval, was also staffed and supervised by the APS staff. This APS involvement was critical in giving the analysts a thorough understanding of the intricacies and potential problems with the data collection process. The main difficulty with respect to staffing in previous years was the inability to cover a suitable number of snow periods, especially nighttime snowfalls. This was solved by having a greater number of participants available for testing and by instituting a sliding pay scale which compensated testers more during the nighttime than during the day. Both of these solutions were in place at Dorval during 1990-1991 testing and as a result the site collected almost half of all the data for the worldwide program.

2.6 Analysis Methodology

Before all the collected data was analyzed (Sections 3, 4 and 5), the raw data underwent some manipulation and verification, specifically to correct or remove any errors from the meteorological data acquisition. The individual data parameters and the units used in the final analysis are listed below.

- Precipitation rate - ($g/dm^2/hr$) averaged over test
- Precipitation rate - ($g/dm^2/hr$) averaged over last ten minutes
- Total precipitation - (g/dm^2)
- Air temperature - (°C) averaged over test
- Wind speed - (kph) average over test
- Wind speed - (kph) maximum during final ten minutes
- Film thickness at 2.5 cm line - (mils; 1 mil = .001 inches)
- Film thickness at 15 cm line - (mils)
- Film thickness at 30 cm line - (mils)

- Time to failure of each crosshair - (min.)

The analysis was performed in different stages which were driven by various deadlines. The initial focus was on the meteorological data (Section 5) and general data descriptions (Section 3) which were presented at a TDC meeting in early May, 1992 and the FAA International Conference on Aircraft Ground Deicing held May 28-29, 1992 in Washington, D.C. A general analysis consisting of examining various failure time versus precipitation and precipitation rate curves was performed for the SAE Ad Hoc Committee meeting of June 30-July 1, 1992 in Dallas, Texas.

The final, complete analysis, which includes the above along with more detailed scatter charts, two variable scatter plots and film thickness and statistical examinations, is contained in this report.

3. DESCRIPTION OF DATA

This section provides a description of the data collected: the quantity of data received, from where and for which fluids; and distributions of the basic weather parameters such as temperature, precipitation, wind speed, and humidity over the range of the tests collected.

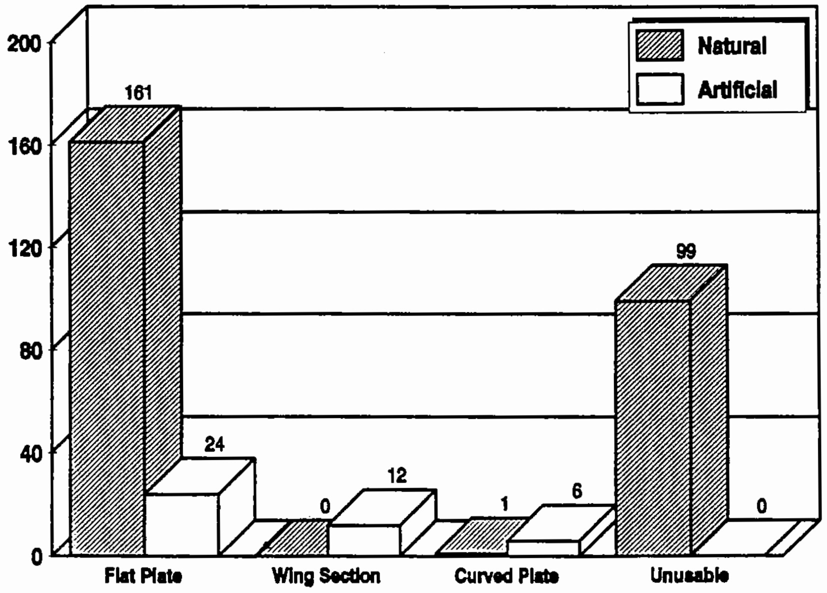
3.1 Usable and Unusable data

During the 1991-1992 test season, APS collected 72 natural snow test forms, from the two sites, and 20 artificial snow test forms. Some of the tests (i.e. flat plate and curved plate) were performed concurrently, indicating that fewer than 92 test runs were performed. Each form contained data for up to six flat plates, or four to six flat plates and a curved plate, or a wing section. Table 3.1 provides a breakdown of the test runs by site and by test section. As shown in Figure 3.1, these data forms contained a total of 261 natural snow test points and 42 artificial snow test points. A total of 99 points were not used because either the tests were aborted due to problems experienced with the plates and/or meteorological equipment, or failure did not occur during the test run. It should be specifically noted that Table 3.1 and Figure 3.1 show a very low number of curved plate and wing section tests relative to the number of flat plate tests. Both of these test sections were added during the testing season and required modification or construction of support and covering equipment. Both were thus tested, in natural snow conditions, on a very limited basis (the wing section on only one test day and the curved plate slightly more often) and failure was only reached once on the curved plate.

TABLE 3.1
SUMMARY of TESTS
91-92 Season

	DORVAL	St. John's
Natural Snow Tests		
Flat Plate	28	9
Curved Plate	1	N/A
Wing Section	1	N/A
Not Usable	17	16
Artificial Snow Tests		
Flat Plate	6	N/A
Curved Plate	6	N/A
Wing Section	6	N/A
Ice Sensor	2	N/A

FIGURE 3.1
DATA SUMMARY
DORVAL, 91-92 SEASON



3.2 Distribution of Fluids Tested

As mentioned in Section 2.4, Union Carbide fluid 250-3 was chosen for a majority of the tests. In fact, 250-3 accounted for 85% of the collected data points, with Octagon, Kilfrost and Hoechst accounting for the remaining 15%. The actual distributions are shown in Figure 3.2. The ratios for fluids used in St. John's were not the same. This is discussed in Section 5.5.

3.3 Frequency of Average Precipitation Rates

Figure 3.3 shows the distribution of average precipitation rates recorded at Dorval. The average rates were calculated by dividing the total precipitation recorded from start of test to time of failure by the failure time. As noted previously, (Section 2.2) up to fifteen failures were recorded for each plate. For clarity, a single crosshair was chosen as the reference point for these precipitation rate calculations. The point chosen was the middle crosshair on the second line from the top of the plate - crosshair C2, as shown in Figure 2.1. This frequently corresponds to the fifth crosshair failure point used in the 1990-1991 testing. This C2 crosshair was used as the reference point for all other time dependent calculations in this section, unless otherwise noted.

A key consideration when examining Figure 3.3 is that all fluid qualification tests are performed at a steady rate of 5 grams/square decimetre/hour. This figure shows that 46% of the precipitation rates were in excess of this value. Section 4 discusses this further and highlights the fact that most precipitation is anything but "steady".

FIGURE 3.2
DISTRIBUTION OF FLUIDS
TYPE I.5 FLUIDS

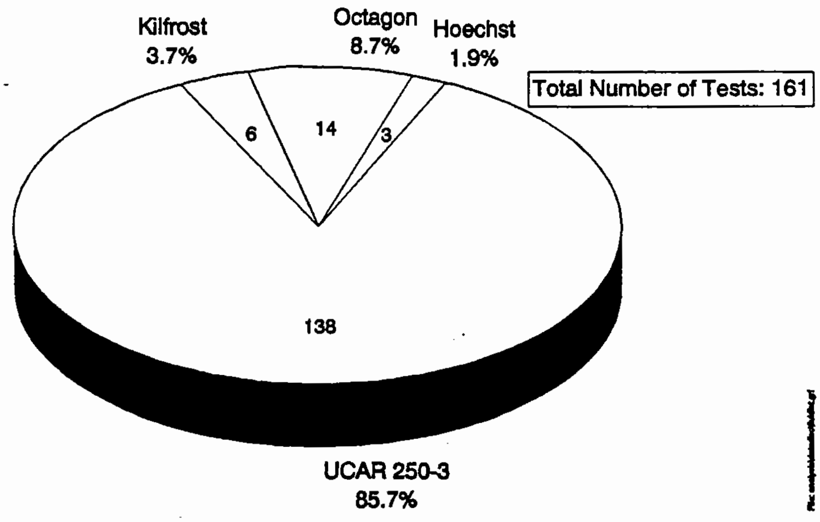
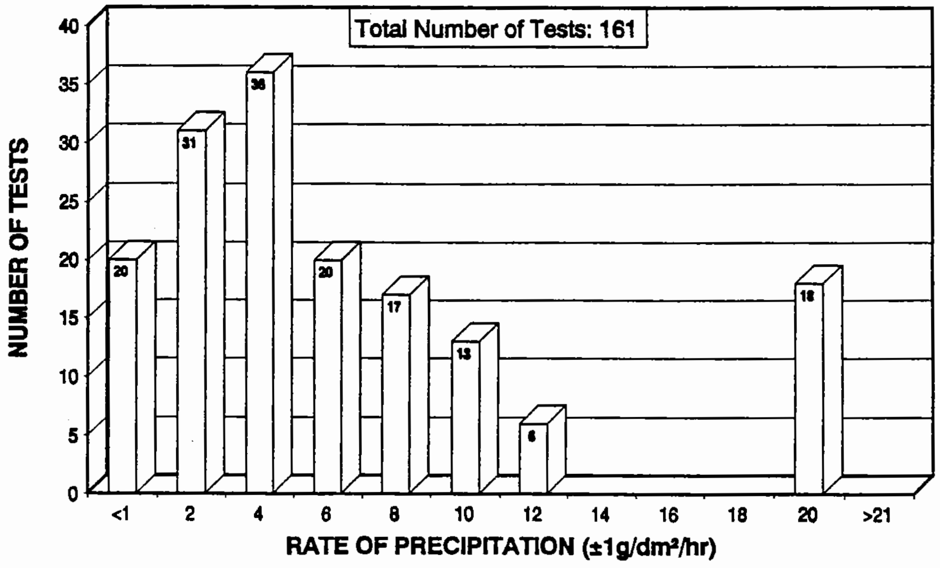


FIGURE 3.3
DISTRIBUTION OF PRECIPITATION RATES
TYPE I.5 FLUIDS



3.4 Frequency of Other Meteorological Conditions

The distribution of meteorological factors such as temperature, relative humidity and wind speed are presented in Figures 3.4, 3.5 and 3.6, respectively. All values are averages based on the data collected at Dorval. Air temperatures were not extreme. The coldest average during a test was ⁻10.3 °C and the warmest was 0.5 °C. 24% of the tests had average air temperatures within half a degree of the freezing point. The distribution of average relative humidity in Figure 3.5 was as expected - mainly high values with an average of 82% RH. Figure 3.6 gives some insight into the prevalence of wind during precipitation conditions - 48% of the tests had average winds above 10 kph including 14% above 15 kph. While these averages may not seem excessive, it should be noted that, like precipitation, wind is rarely constant and an average wind speed does not preclude the existence of gusts three or four times the average. This is apparent in Figure 3.7 which shows the distribution of maximum recorded wind speed during the tests. The ten second sampling interval of the anemometer may have failed to capture some of the gusts and therefore, it is still possible that the maximums depicted here were actually exceeded. However, the maximum recorded wind speeds averaged around 25 kph with some tests experiencing maximums above 50 kph.

3.5 Distribution of Failure Times

The distributions of failure times at various crosshairs are shown in Figures 3.8 through 3.12. Figure 3.8 is based on failures of the B2 point, the middle of the first line of crosshairs, Figure 3.9 is based on the C2 point, and so on. Failures based on the middle crosshair of the fifth line, F2, are shown in Figure 3.12. For an analysis of failure times advancing down the plate from line B to line F to be meaningful, the failures must also occur in this

FIGURE 3.4
DISTRIBUTION OF AIR TEMPERATURES
TYPE I.5 FLUIDS

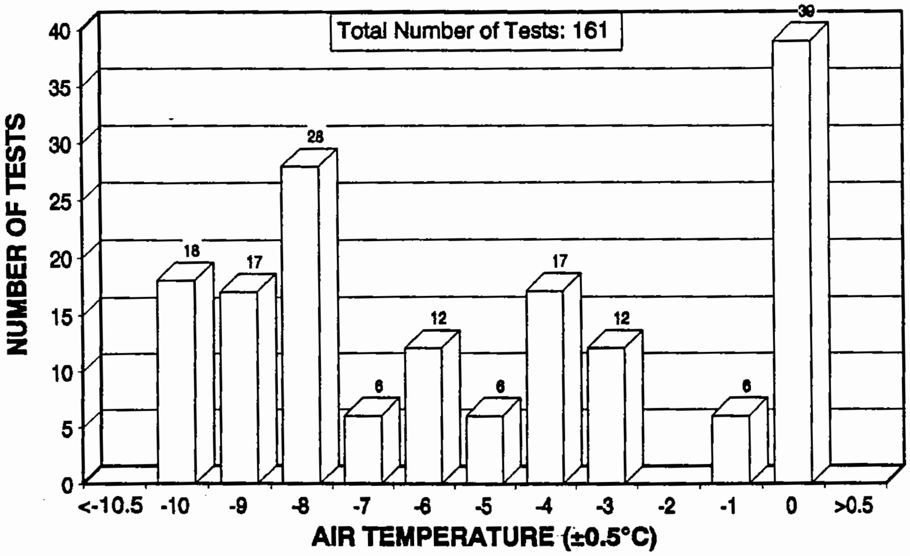


FIGURE 3.5
DISTRIBUTION OF RELATIVE HUMIDITY
TYPE I.5 FLUIDS

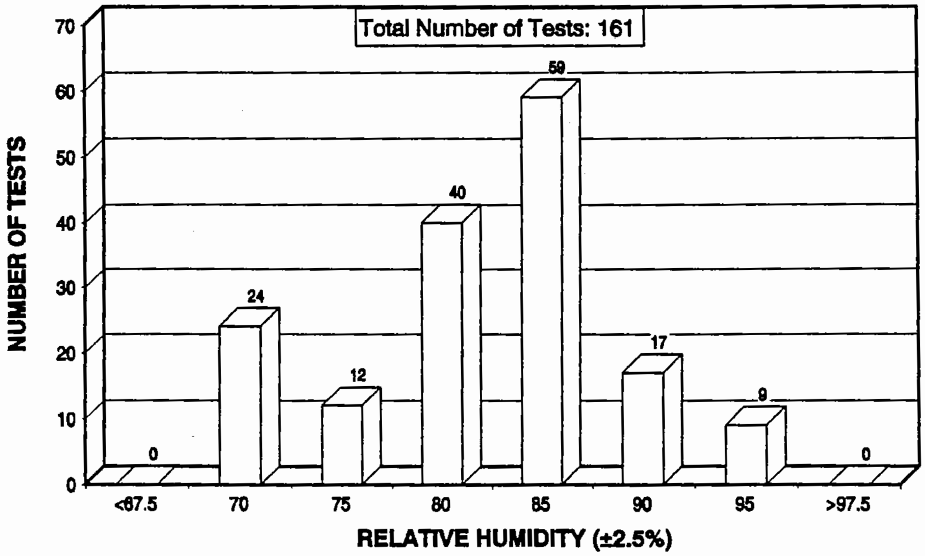


FIGURE 3.6
DISTRIBUTION OF AVERAGE WIND SPEED
TYPE I.5 FLUIDS

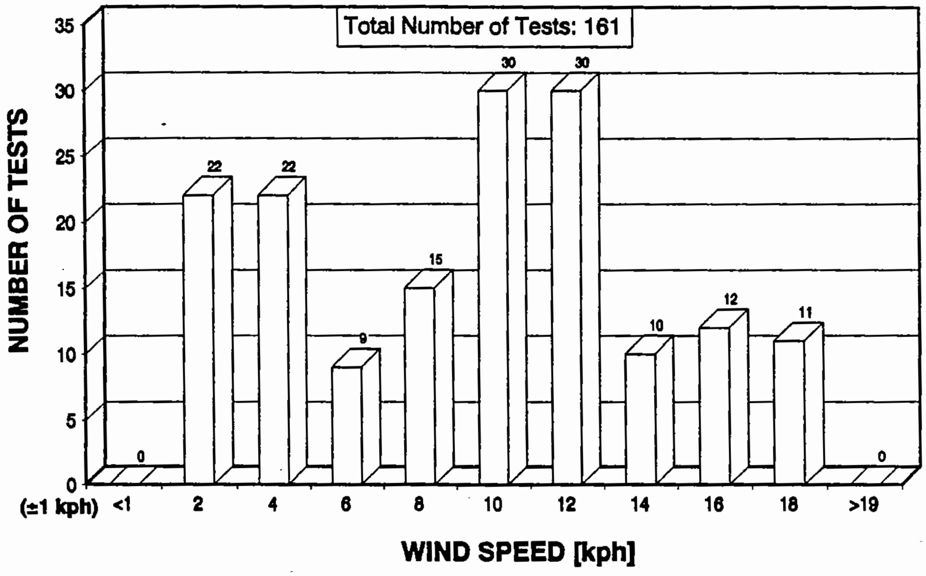


FIGURE 3.7
Distribution of Maximum Recorded Wind Speed
TYPE I.5 FLUIDS

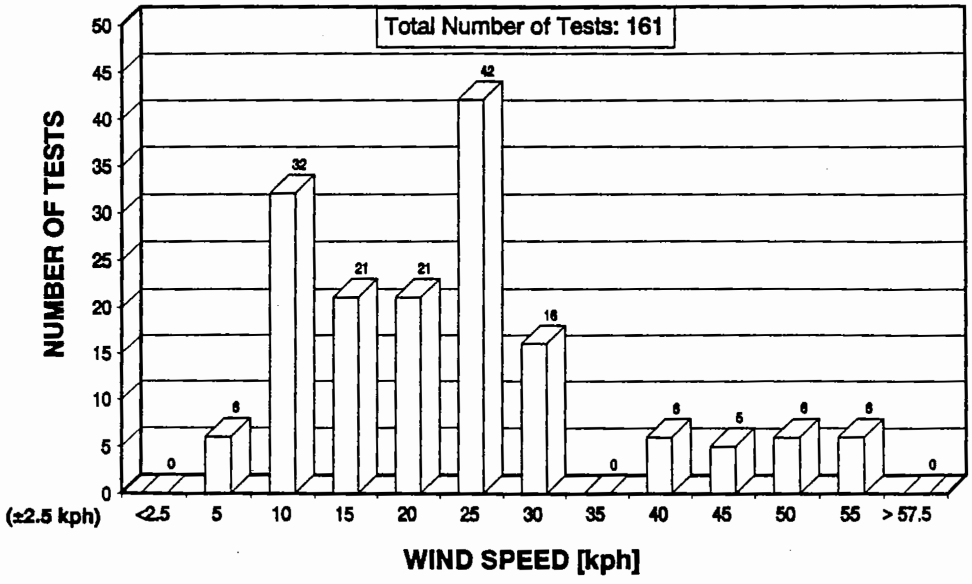
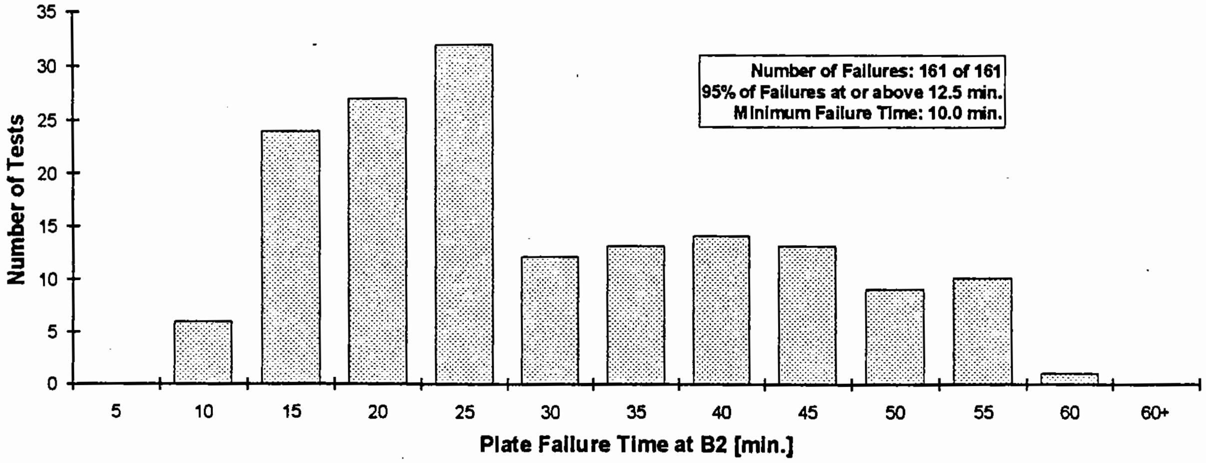


FIGURE 3.8
DISTRIBUTION of FAILURE TIMES at B2



Note: Failure Time ±2.5 min.

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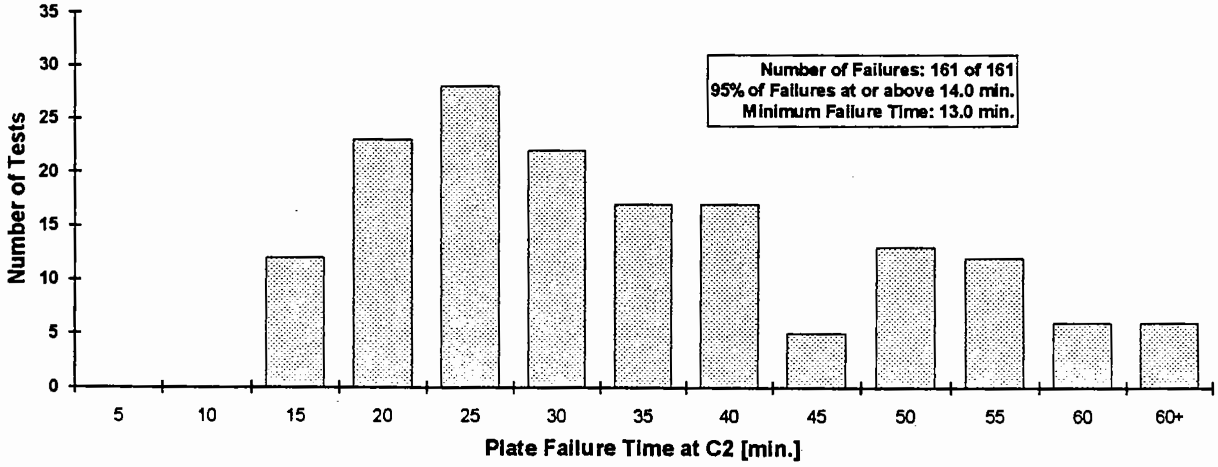
FIGURE 3.9
DISTRIBUTION of FAILURE TIMES at C2



Note: Failure Time ±2.5 min.

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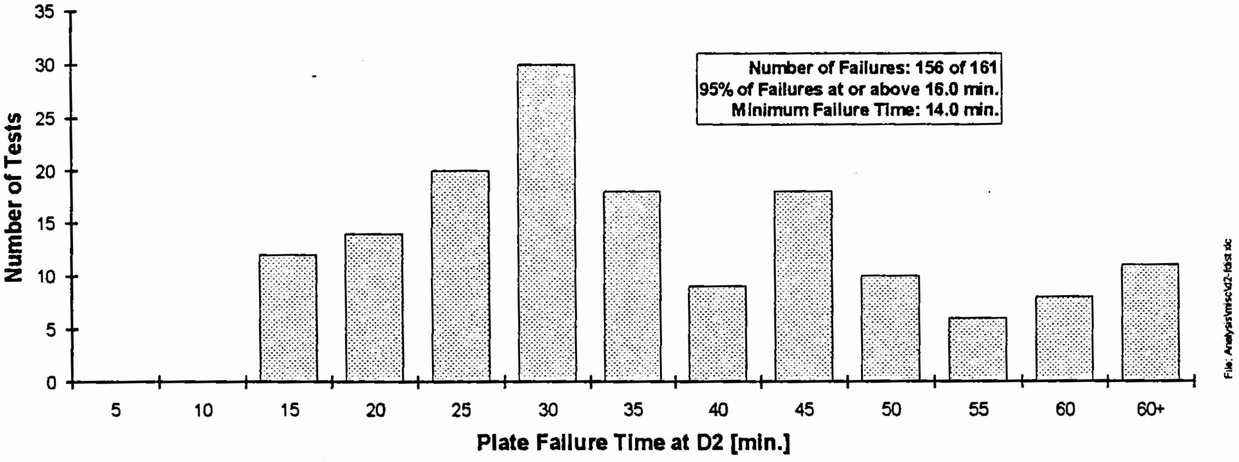
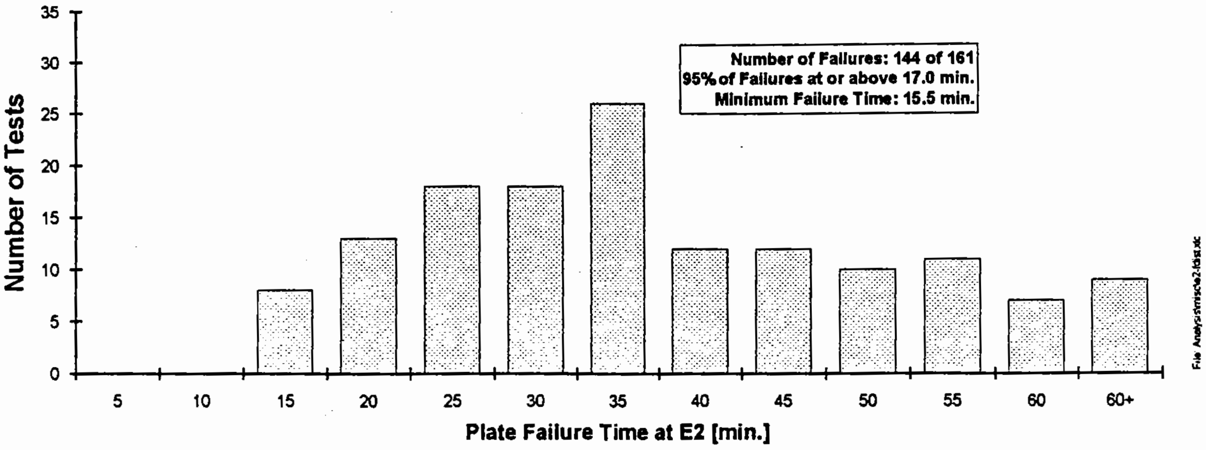
FIGURE 3.10
DISTRIBUTION of FAILURE TIMES at D2



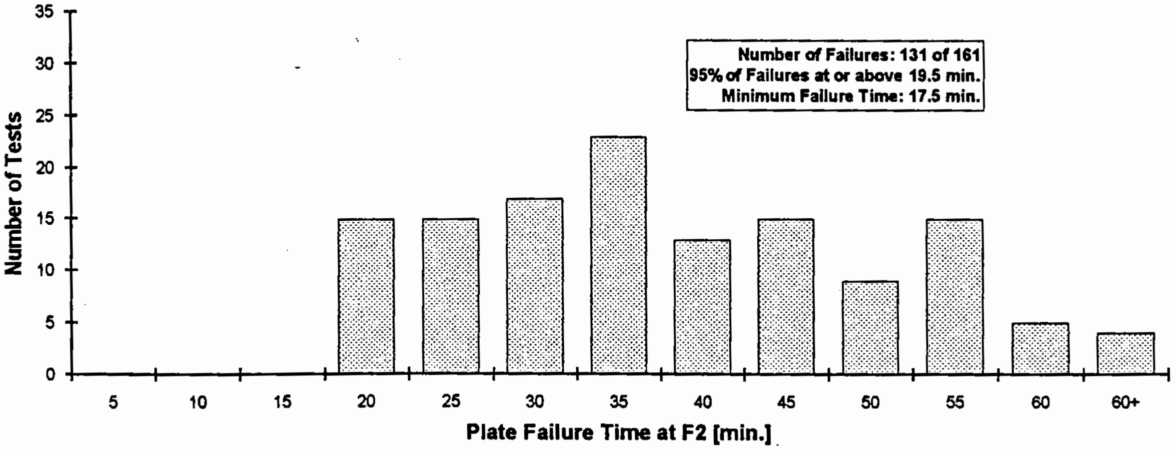
Note: Failure Time ±2.5 min.

FIGURE 3.11
DISTRIBUTION of FAILURE TIMES at E2



Note: Failure Time ±2.5 min.

FIGURE 3.12
DISTRIBUTION of FAILURE TIMES at F2



Note: Failure Time ±2.5 min.

File: Analysis\misc\f2-dist.xls

progressively downward manner, beginning at the top of the plate. This, in fact, was the case in over 98% (158 out of 161) of the tests recorded. The "number of failures" decreases as the graphs progressively move down the plate from line B to line F. This is an indication that some tests were terminated more than one hour before the entire plate failed. The interesting point to note about the series of graphs is that the 95% lower limit (i.e. the time above which 95% of failures occurred) and the minimum failure time recorded both increase steadily while progressing down the plate, yet both still remain below 20 minutes.

4. METEOROLOGICAL ANALYSIS

This section looks at meteorology with two different objectives. Section 4.1 presents an analysis comparable to one in the 1990-1991 report which describes the success achieved in performing tests, that is, how many days when testing could have occurred, and on how many of these days testing actually occurred.

Section 4.2 presents an analysis which looks at the storms themselves. The improvements in the meteorological equipment implemented at the Dorval site made it possible to obtain a much higher calibre of meteorological data which, in turn, allowed deeper study of the different elements constituting a winter storm.

4.1 Summary of Test Success

With the assistance of Atmospheric Environment Services Canada, the Consultants were able to obtain relatively detailed meteorological information for both sites. This AES data was used in order to maintain continuity with previous years' testing.

As with previous years, precipitation of three $g/dm^2/hr$ (or 0.3 mm/hr of water), averaged over the precipitation period, was set as the minimum precipitation requirement for a day to be defined as testable. This limit, which equates to about 0.3 cm of snow per hour, is likely insufficient to yield a successful test by itself. However, the inherent fluctuations during an extended period of precipitation should result in a productive test period. This analysis examined the weather data to determine those days which satisfied this criterion.

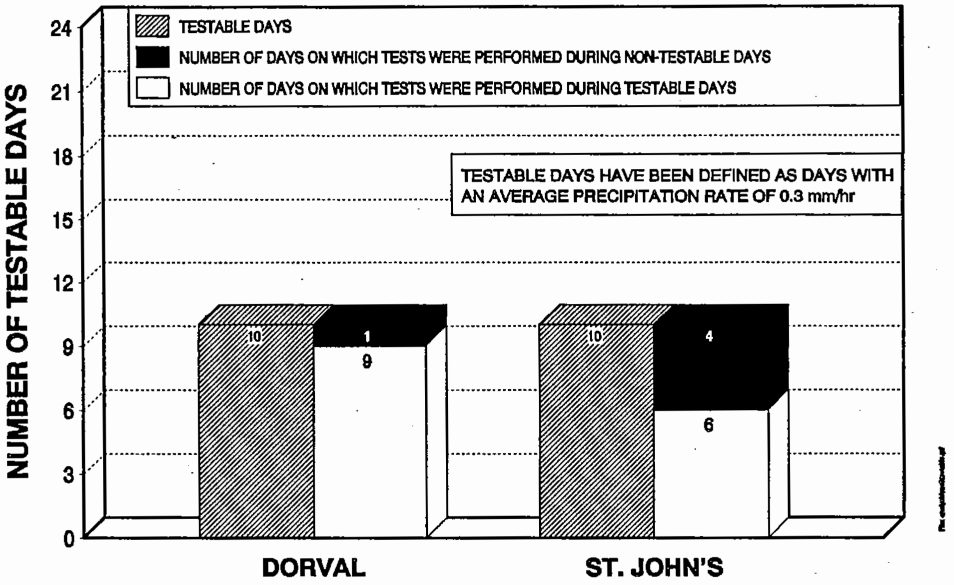
With this minimum limit, it was determined that both Dorval and St. John's experienced a total of ten testable days over their respective periods of operation. The levels of success are presented in Figure 4.1. Both sites recorded an improvement over the 1990-1991 season's results. The Dorval site tested on 90% of testable days, up from 77%, while the St. John's site tested on 60% of testable days, a marked increase from 12%. Days classified as testable may have been missed due to inaccurate forecasts, unavailability of test personnel or, in one case, a lack of test fluids. Both sites also tested on days which were classified as non-testable. These tests did not always provide useful results and, for the St. John's test centre, may have been due to the relative inexperience of test personnel.

4.2 Detailed Analysis

This analysis is not meant to provide an in-depth examination into the mechanics and dynamics of winter storms. Instead, it looks at the meteorological data while trying to understand what patterns are present during these storms and what range of variation exists among the various parameters, with a specific concentration on precipitation.

Distributions of the various meteorological elements present during testing were presented in Sections 3.3 and 3.4 and displayed values which were averaged over the length of the test. Figures 4.2 through 4.4 display the detailed temperature, relative humidity and wind speed graphs for a single test day, February 15th, 1992. There is limited variation in both the temperature and relative humidity profiles, with any significant changes occurring gradually. Figure 4.4 shows very clearly that the opposite is true for wind speed. In the 1990-1991 testing season, wind speed was only recorded at the beginning and at the end of a test. With this knowledge, it is possible to imagine both readings occurring during either particularly calm periods or particularly brisk periods, the end result being a totally misleading wind reading. The

FIGURE 4.1
NUMBER OF TESTABLE DAYS
JANUARY 1992 TO MARCH 1992



TESTABLE DAYS HAVE BEEN DEFINED AS DAYS WITH AN AVERAGE PRECIPITATION RATE OF 0.3 mm/hr

Figure 4.2
Sample Temperature Profile

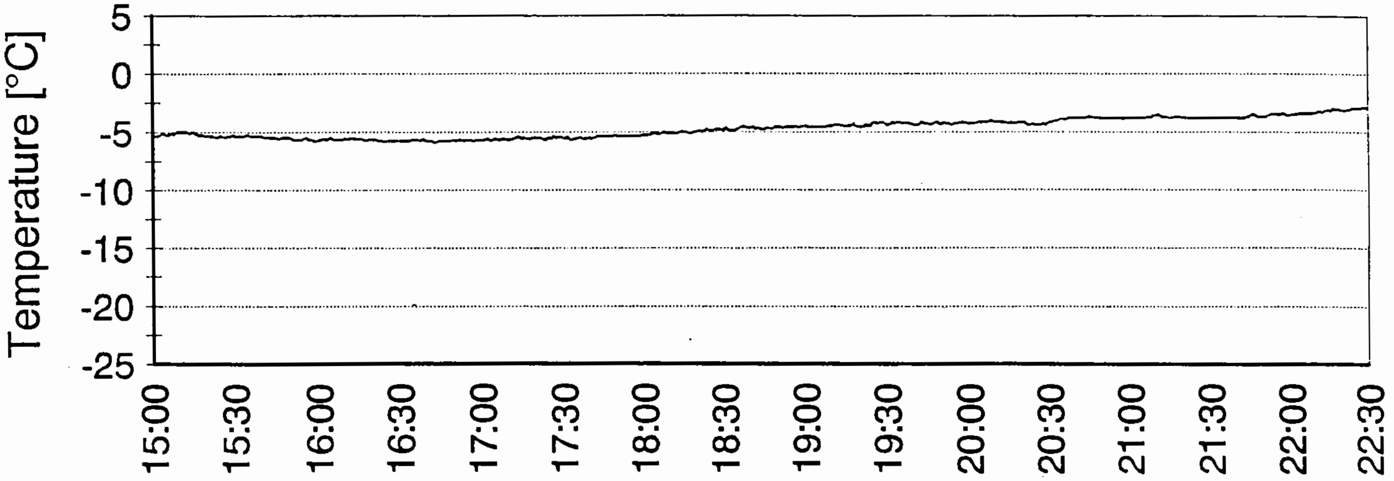


Figure 4.3
Sample Relative Humidity Profile

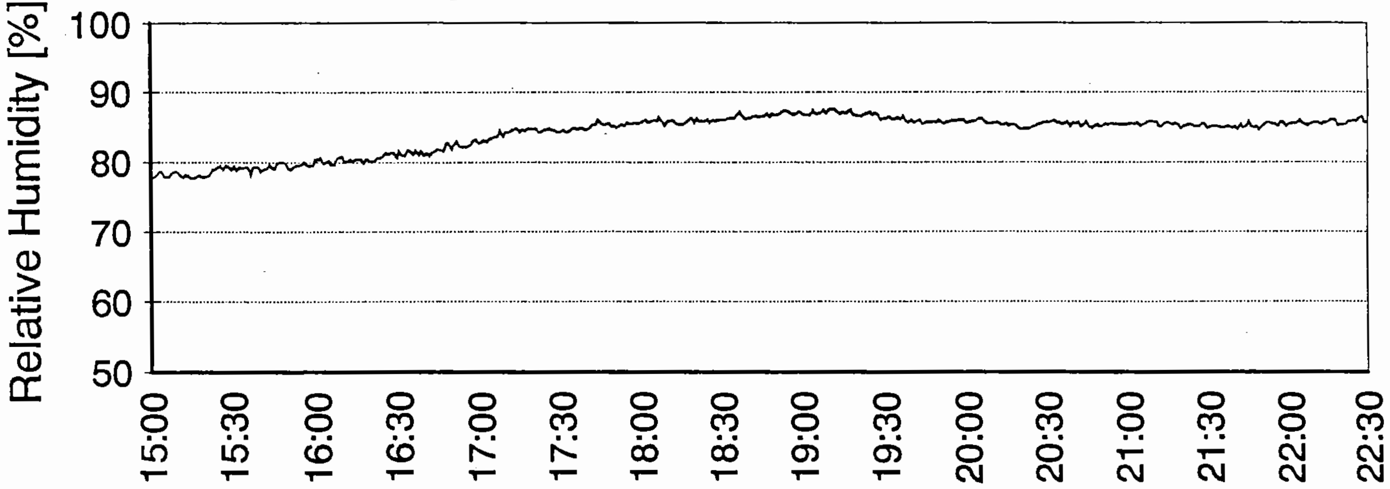
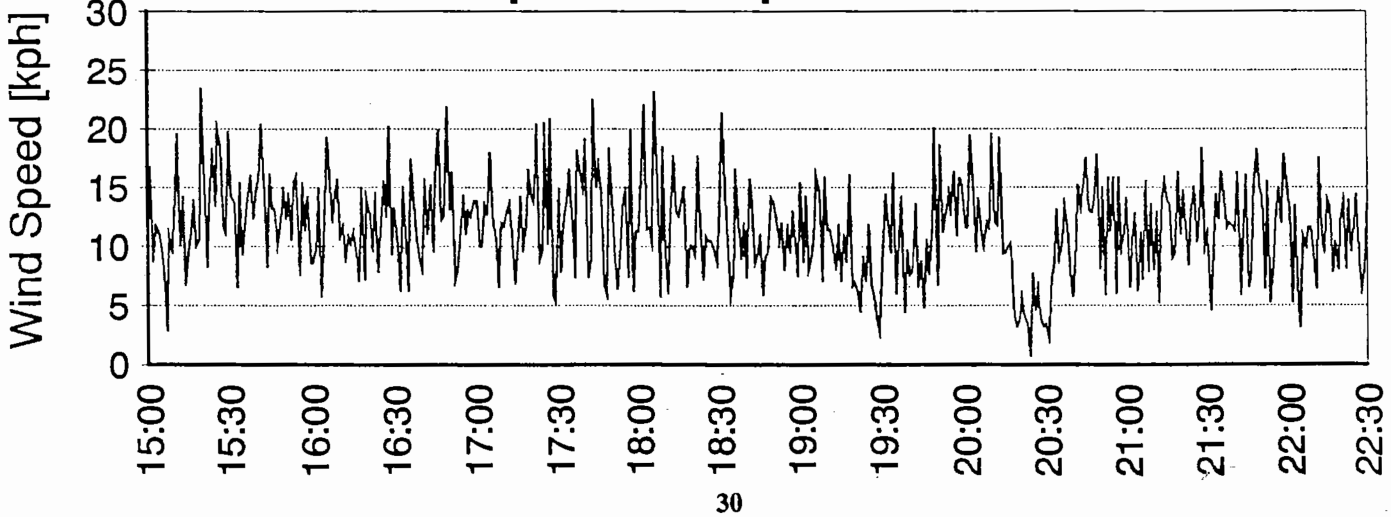


Figure 4.4
Sample Wind Speed Profile



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improvement in the wind measuring equipment and procedure is very obvious and its importance will become evident in Section 5.

The behaviour of precipitation during a test is probably the most important meteorological characteristic from the point of view of fluid failure. Figure 4.5 displays the calculated precipitation rates over the same February 15th test day as Figures 4.2 to 4.4. On Figure 4.5, each point represents a one minute average precipitation rate. The uncertainty surrounding the encircled test point was caused by a comment noted on one of the test forms. At time 20:20, the tester noted that the precipitation gauge discharge tube was blocked. In clearing this tube the tester may have disturbed the dropping mechanism which, in turn, may have resulted in an inaccurate precipitation count at that time. Despite this uncertainty, the rest of the profile should be considered as valid.

Fluid qualification tests normally occur under a constant precipitation rate of 5 $g/dm^2/hr$. While the average precipitation rate over the entire period was 7.8 $g/dm^2/hr$, one minute average peaks of over four times this value did occur. While some periods of precipitation do not have as great a variability as this sample day, it seems evident that the fluid qualification precipitation rates do not faithfully reproduce a natural snow profile.

Figure 4.6 displays the accumulated precipitation over the same test period. This accumulated precipitation was then analyzed in a somewhat convoluted manner. While there are currently no standard cold chamber endurance requirements for Type I.5 fluids, the Type II standard is 30 minutes before failure at 5 $g/dm^2/hr$. This equates to a total of 2.5 g/dm^2 of precipitation. Figure 4.7 was created by identifying, at each minute, the period of time elapsed immediately before that minute, required for 2.5 grams of total pre-

Figure 4.5
Precipitation Rate vs Time
(Dorval, 15 Feb., 92)

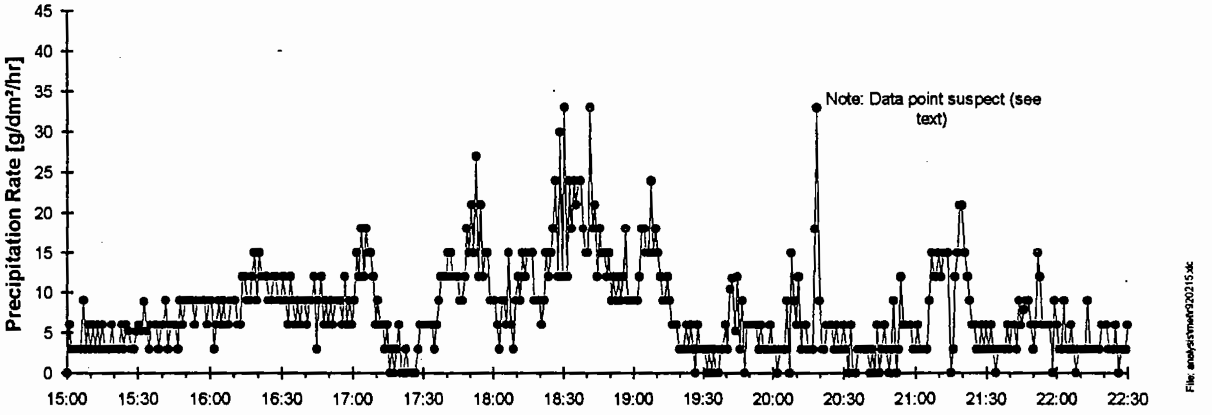
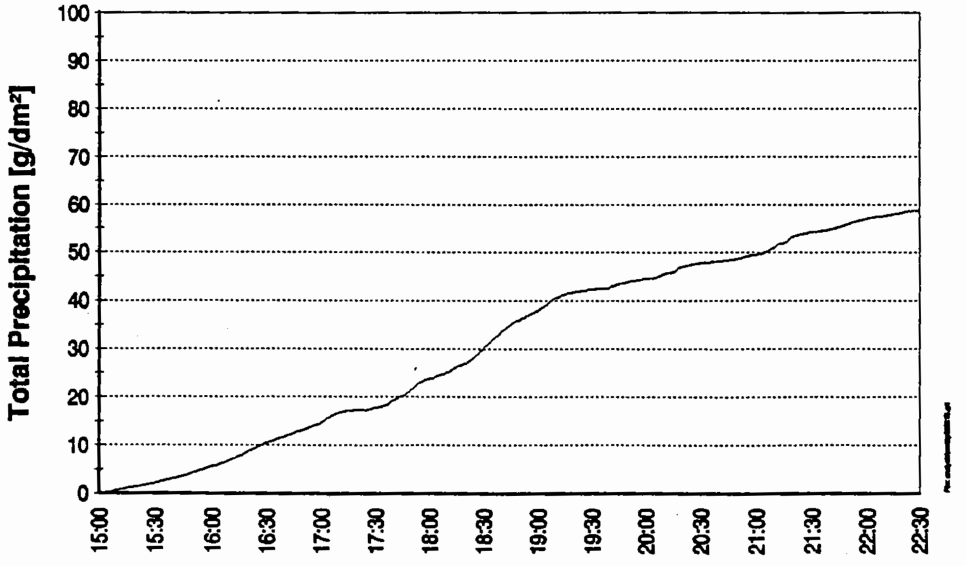


Figure 4.6
Total Precipitation vs Time
(Dorval, 15 Feb., 92)



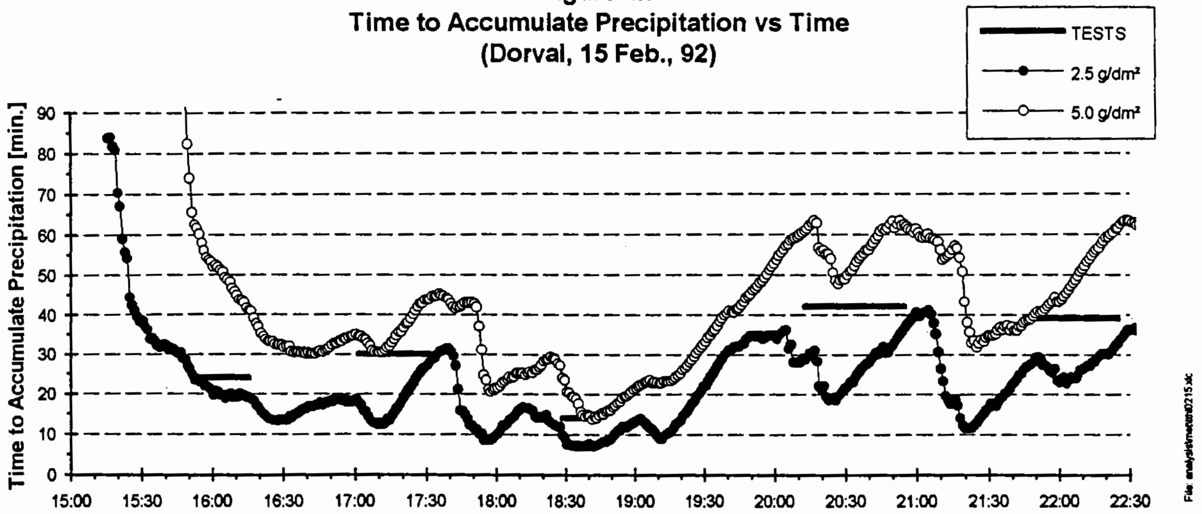


Figure 4.7
Time to Accumulate Precipitation vs Time
(Dorval, 15 Feb., 92)

precipitation to be accumulated. On the resulting curve, higher precipitation is associated with shorter accumulation times. Figure 4.7 also contains a curve with the time to accumulate 5 g/dm^2 of precipitation, or twice the qualification value. Lastly, the duration of individual tests was overlaid onto the chart. The solid, horizontal lines signify that a test was performed between the times indicated on the horizontal axis and the location along the vertical axis is the duration of the test.

Figure 4.7 is significant in two ways. First, the data shows that natural precipitation profiles are not faithfully reproduced in the qualification procedure. Precipitation amounts of double the qualification value were accumulated in less than half the qualification time, as occurs at approximately 18:40 on Figure 4.7. Secondly, the method of determining plate failure is such that it usually required in excess of 2.5 g/dm^2 of precipitation to trigger the failure. This is shown in more detail in Section 5.1.

5. ANALYSIS

A number of analyses were performed on the data described in Section 3. This section describes the methodology and the results of the analysis. The two sites were analyzed separately due to the differences in the data collection methods. The results of the curved plate and wing section tests are also analyzed separately.

The first phase of the analysis, presented in Section 5.1, attempted to graphically ascertain whether there were any clearly visible relationships between failure of the fluid over the crosshairs and any of the other variables. In Section 5.2 a similar graphic approach is used to investigate bivariate relationships. A purely statistical analysis of the data is contained in Section 5.3. Section 5.4 consists of similar analyses on the data collected at St. John's, Newfoundland. The behaviour of the other Type I.5 fluids is discussed in Section 5.5. A comparison between the results of this year's analyses and those performed on 1990-1991 data is presented in Section 5.6. The results of both curved plate testing and wing section testing are presented in Section 5.7 while the artificial snow testing analysis is displayed in Section 5.8. The limited testing of the ice sensor is also included in Section 5.8. Lastly, the results of the film thickness analysis are presented in Section 5.9.

The intense concentration on the Dorval site is due to the increased confidence in this data because of the higher degree of control exercised over the site, the quality of the meteorological data, and the greater quantity of test data. It should also be reiterated that aside from the analysis and discussion in Section 5.5, all data refers to Union Carbide 250-3 fluid only. Because one of the main goals of this study was to attempt to gain a better understanding of fluid behaviour, the exclusion of the other fluids from most of the analysis is justified.

5.1 General Analysis - Dorval Data

For this general, graphical analysis flat plate failure time was plotted against the other variables to determine if there were any explicit relationships between failure and any one variable. A lack of clear relationships is not necessarily negative. It may simply be an indication that any existing relationships are very complex.

5.1.1 Precipitation rate and total precipitation

Figures 5.1 and 5.2 plot the failure time against total precipitation with respect to both the first (B2) and second (C2) lines of crosshairs, respectively. These scatter plots do not indicate any sort of relationship between failure time and total precipitation. Some of the points appear to form radial lines from the plot origin; this is due to these test points having similar precipitation rates, usually collected on the same test day.

Figures 5.3 and 5.4 plot the same plate failure times against the precipitation rates, again with respect to the B2 and C2 failure times, respectively. These scatter plots seem to indicate the existence of a failure envelope involving the rate of precipitation although there is insufficient data to determine if this trend continues beyond a rate of about ten grams per square decimeter per hour. Both C2 plots are shown to maintain continuity with testing from the 1990-1991 season. B2 plots are included because of the results of the fluid thickness analysis (Section 5.9) which indicates a relationship between film thickness near the top of the flat plate and film thickness near the leading edge of the wing section.

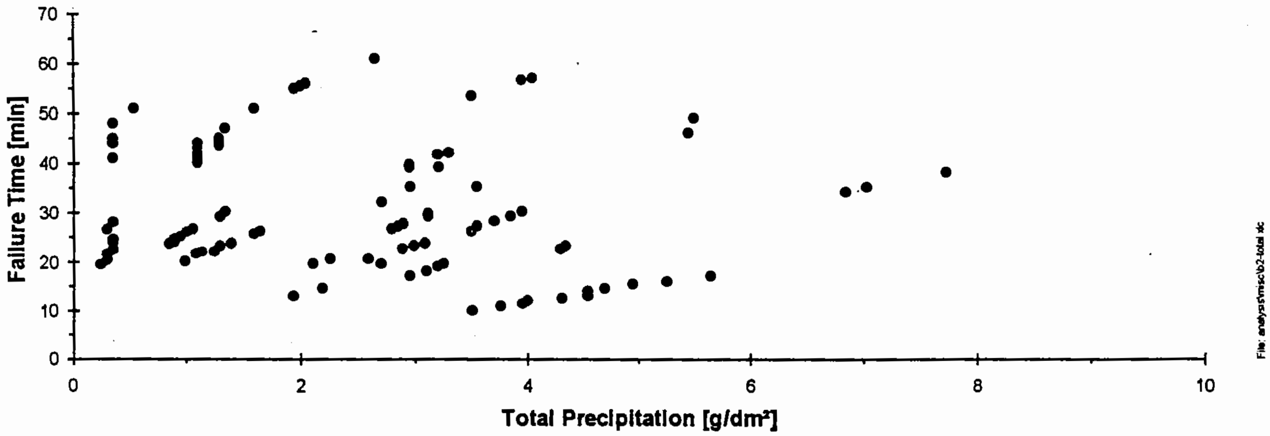


FIGURE 5.1
Failure Time at B2 vs Total Precipitation
(Dorval, UCAR 250-3)

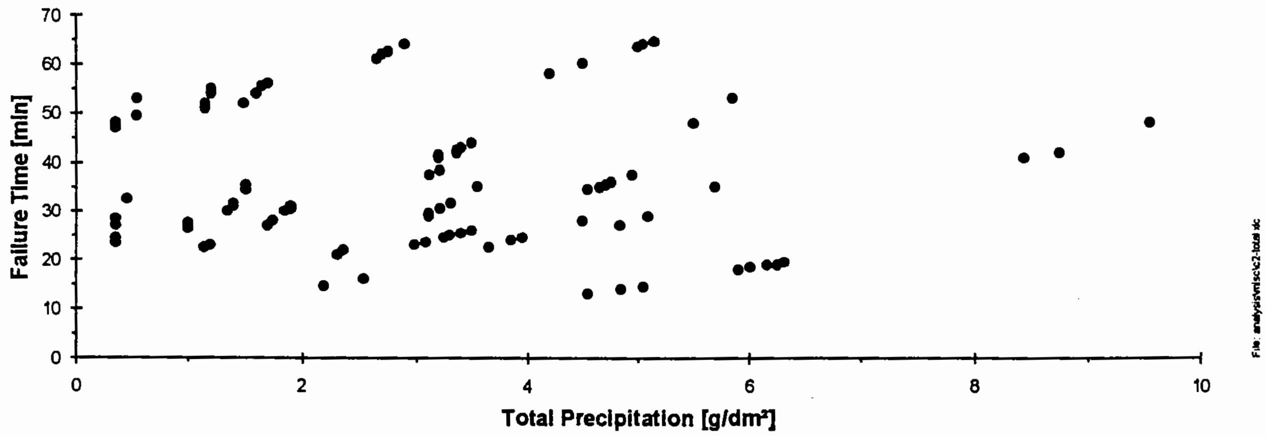


FIGURE 5.2
Failure Time at C2 vs Total Precipitation
(Dorval, UCAR 250-3)

FIGURE 5.3
Failure Time at B2 vs Precipitation Rate
(Dorval, UCAR 250-3)

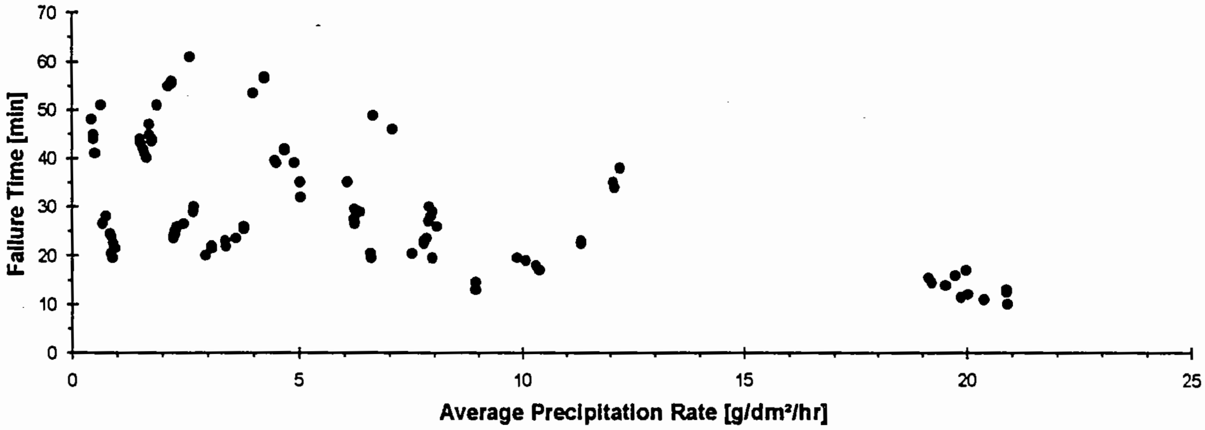
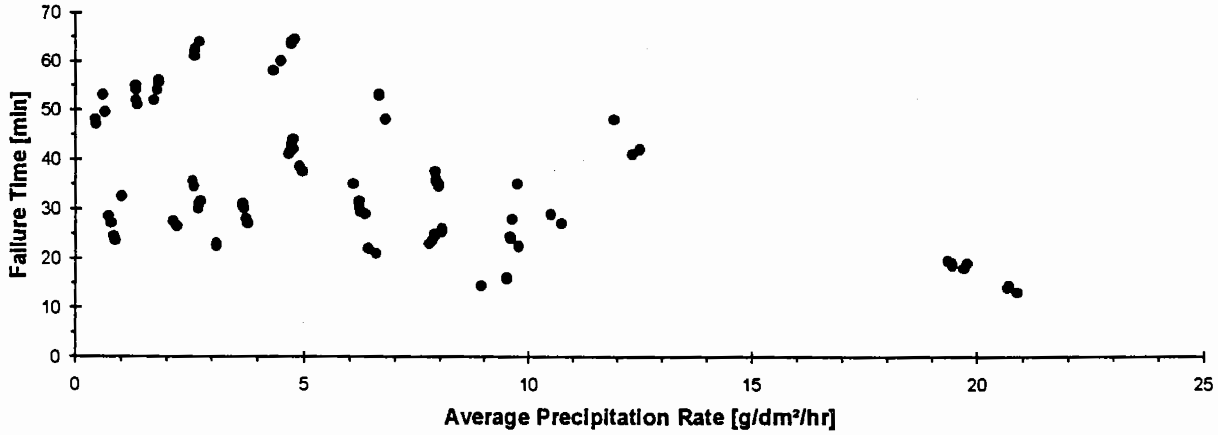


FIGURE 5.4
Failure Time at C2 vs Average Precipitation Rate
(Dorval, UCAR 250-3)



The analysis of the 1990-1991 data used the concept of an effective lower limit curve to provide a minimum failure time for a specific rate of precipitation. While this is a useful way of examining the situation it does not provide as complete a picture as does a failure envelope. What the theoretical failure envelope provides is an upper and lower limit of plate failure time when subjected to specific precipitation rates. Where a failure time lies specifically, within the rather ample envelope, is based on the interactions of all the other variables.

5.1.2 Other data parameters

To determine if any of the other factors had a singular influence on failure time, temperature, relative humidity, wind speed and film thickness were used as the independent variables against the dependent plate failure time. As indicated in Figures 5.5 through 5.7, no single meteorological variable alone has an apparent strong influence on fluid failure.

Figures 5.8 and 5.9 examine film thickness versus plate failure. Figure 5.8 plots film thickness at the six inch (15 cm) line against failure at the C2 point, also at the six inch line. While the majority of the thickness values were either 13, 15 or 17 thousandths of an inch (due to the limited resolution of the measuring device, the failure times seemed fairly impervious to fluid thickness. Figure 5.9 plots film thickness at the one inch (2.5 cm) line against failure at the B2 point, which is located two inches below the one inch line. Again, there does not appear to be any tangible link between fluid thickness and plate failure time within the bounds of the fluid thicknesses tested. What must not be forgotten is that, according to Figures 3.8 through 3.12,

FIGURE 5.5
Failure Time at C2 vs Air Temperature
(Dorval, UCAR 250-3)

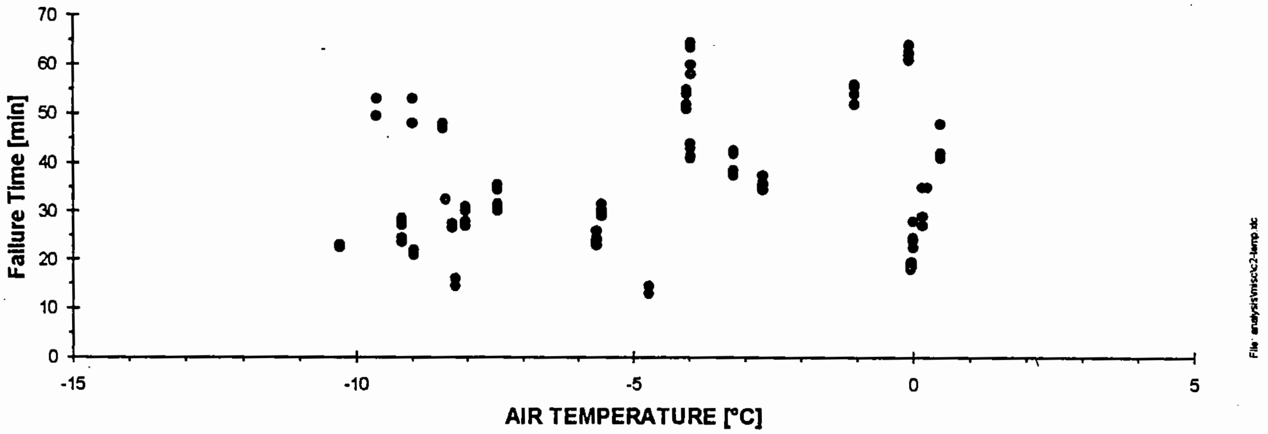


FIGURE 5.6
Failure Time at C2 vs Relative Humidity
(Dorval, UCAR 250-3)

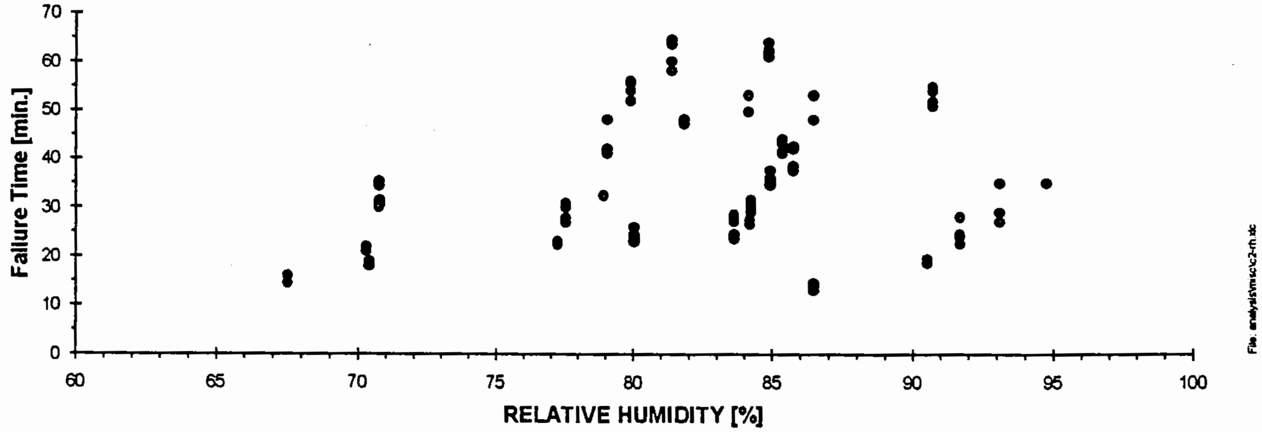


FIGURE 5.7
Failure Time at C2 vs Average Wind Speed
(Dorval, UCAR 250-3)

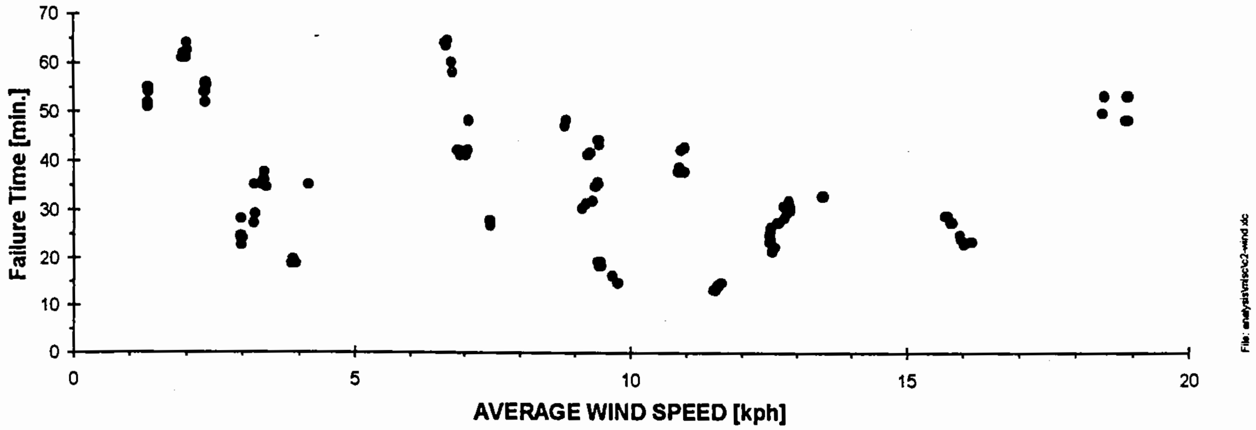


FIGURE 5.8
Failure Time at C2 vs Fluid Thickness at 6" Line
(Dorval, UCAR 250-3)

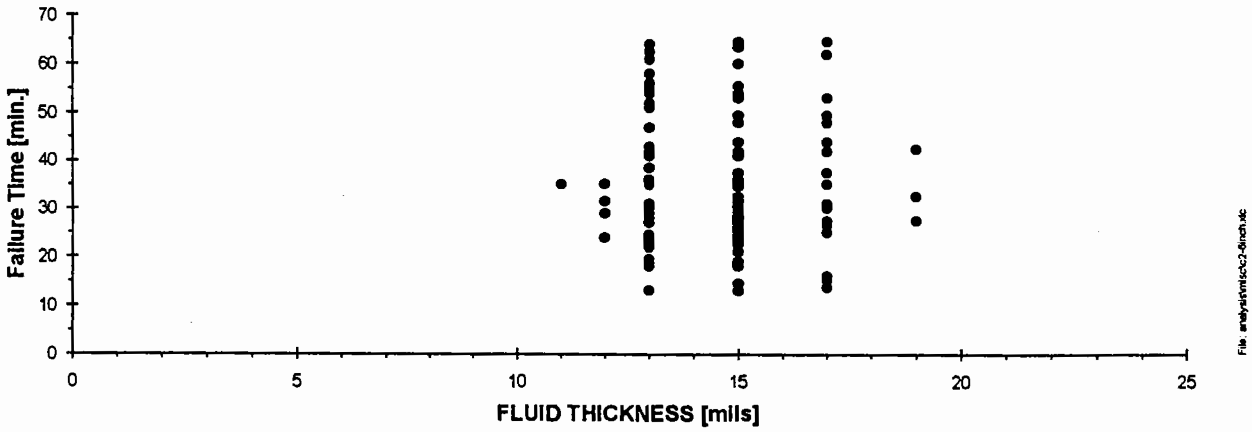
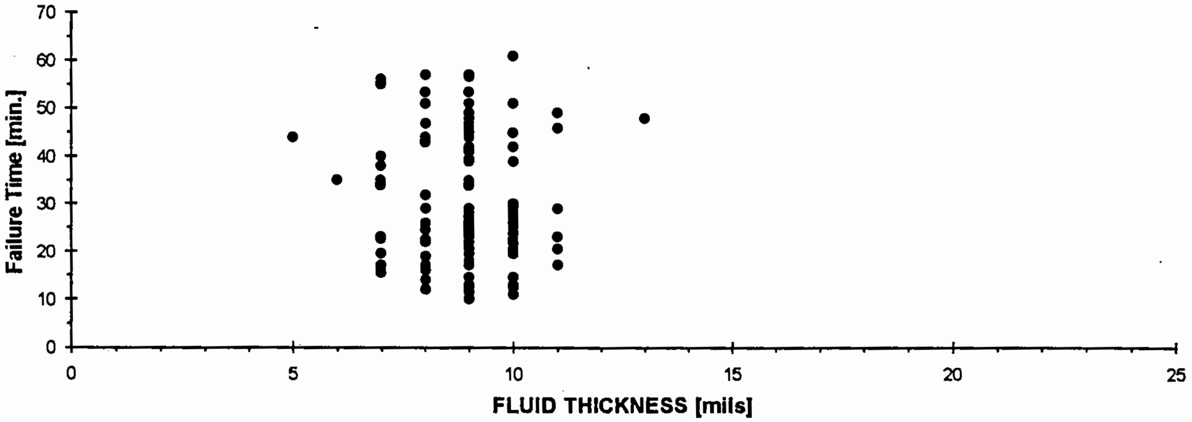


FIGURE 5.9
Failure Time at B2 vs Fluid Thickness at 1" Line
(Dorval, UCAR 250-3)



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failure time increases progressively down the plate. The only measured variable which is different in these cases is fluid thickness.

Therefore, fluid thickness may very well play a role in the plate failure times.

5.2 Secondary Analysis - Dorval Data

This analysis was performed by plotting failure time against either rate of precipitation or total precipitation, and one of the other parameters. The objectives were twofold:

1) to ascertain whether any clear bivariate relationships were visible; or
2) to justify the examination of a narrower stream of data through the identification of suspect data points.

5.2.1 Wind effect

Figures 5.10 and 5.11 were created to examine the effect of wind on the failure times when combined with precipitation. However, what was found was that a more direct failure/precipitation relationship was evident when the wind was factored out of the test. By isolating those tests conducted in calm winds - which for this analysis is assumed to be any test with an average wind speed below five kilometres per hour - Figure 5.12 emerges. Under these conditions, a strong correlation between plate failure and precipitation seems evident (see Section 5.3). Included in Figure 5.12 are the results of a regression performed on the remaining data set in the form of the regression curve and its descriptive function $\mathbf{Y = 73.52\ X^{-0.43}}$, where Y refers to the failure time and X refers to the rate of precipitation. The regression curve

FIGURE 5.10

Plate Failure Times - Wind Effect

(Dorval, UCAR 250-3)

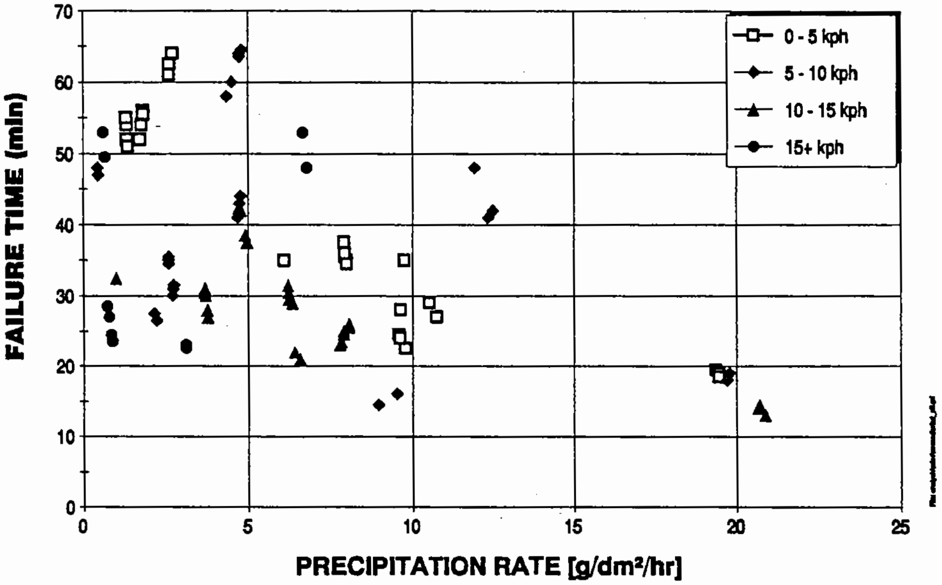


FIGURE 5.11

Total Precipitation Failure - Wind Effect

(Dorval, UCAR 250-3)

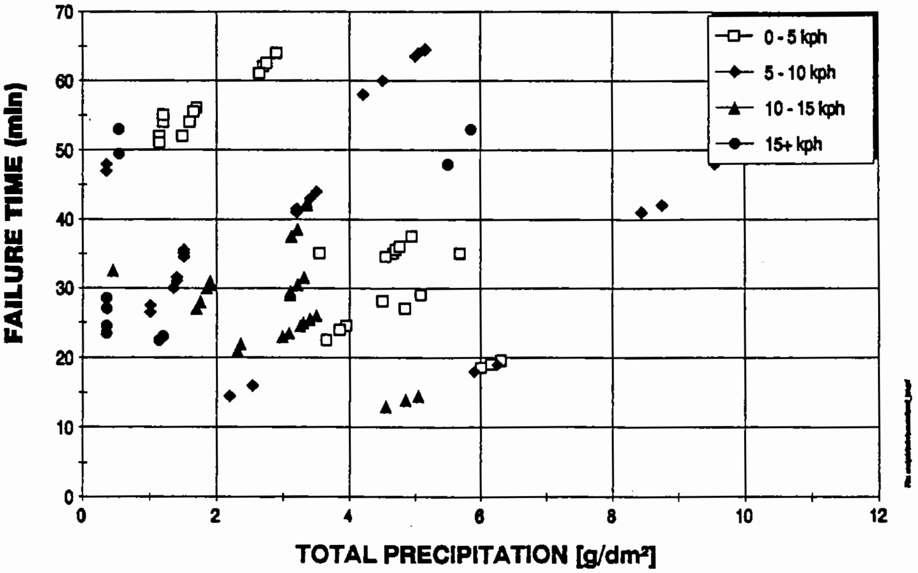
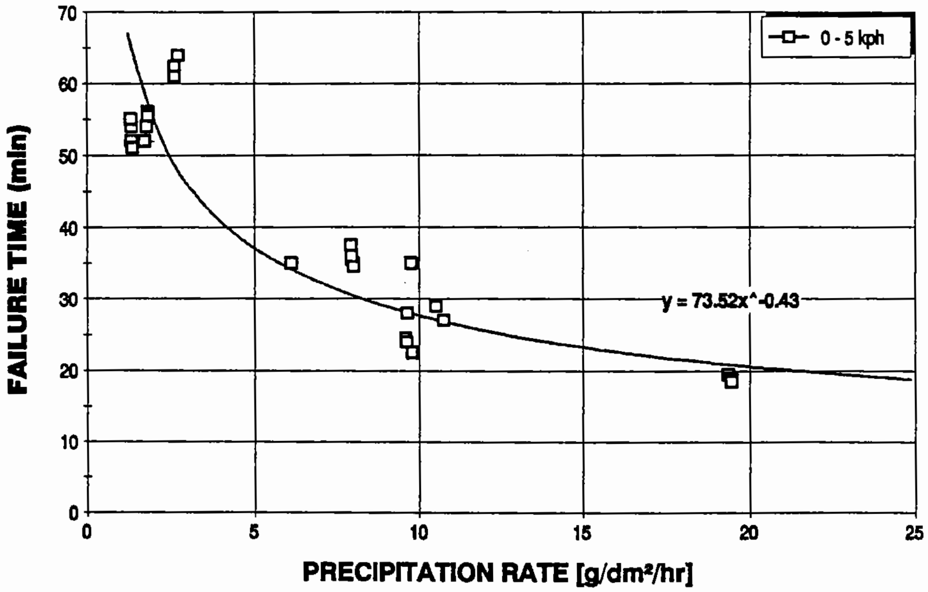


FIGURE 5.12

Calm Wind Plate Failure Times

(Dorval, UCAR 250-3)



indicates that the failure time at the qualification precipitation rate of five grams per decimetre per hour would be 36.8 minutes, although the sparse nature of the collected data can neither support nor refute this value.

When the wind is not calm, the effect of the wind on plate failure time is not clear. This is due to the many different impacts that the wind can have on the plate/precipitation interaction. Some examples are:

- The wind may result in the plates being subjected to a greater amount of precipitation than is recorded by the ombrometer. This could result in relatively low failure times for what seems to be a very low precipitation rate as can be observed in Figure 5.10.
- The wind may result in the plates being subjected to less precipitation than that recorded by the ombrometer. This could occur with swirling winds or winds which change direction midway during a test. This could result in a relatively high failure time for what the ombrometer has recorded as a significant amount of precipitation.
- The wind may either increase or decrease the rate that the fluid flows off the test plates resulting in either shorter or longer failure times.
- The wind effect may shear the fluid on the plates, thus altering fluid viscosity and flow characteristics.

Despite the apparent existence of a direct failure/precipitation relationship under calm wind conditions it must be realized that there are only a limited number of data points which qualify as "calm". Additionally, the other meteorological parameters may play significant roles in failure time, even within the calm wind restriction. Before any defensible conclusions are reached, further analysis is necessary (Section 5.3) and more data is required. Nevertheless, this is the first indication of a potentially useful relationship.

5.2.2 Temperature effect

When failure time is plotted against precipitation rate using temperature as the third variable, the results are as plotted in Figure 5.13. It is initially apparent that those short failure times associated with relatively low precipitation rates were also connected to temperatures below -5°C while the extraneous points with failures above 40 minutes and precipitation rates in the order of 12 grams per square decimetre per hour occurred when the temperature was marginally above the freezing point. There is some amount of scattering within each of the temperature categories but temperature seems to be a meaningful element in the determination of failure time. A more thorough analysis of the temperature effect is left for Section 5.3.

5.2.3 Other variables

Relative humidity and fluid thickness at different locations were also used as categorizing parameters for the failure time versus precipitation graphs. While no useful results were revealed using fluid thickness, high relative humidity (above 90%) seems to show a consistent relationship.

The trend of interest in Figure 5.14 is the apparent failure time/precipitation rate relationship for RH values above 90%. While

FIGURE 5.13

Plate Failure Times - Temperature Effect

(Dorval, UCAR 250-3)

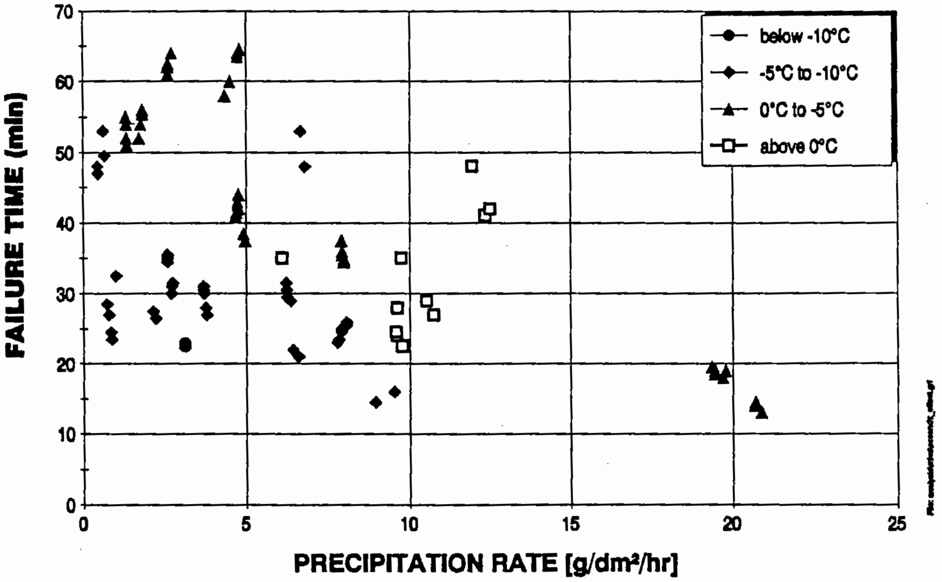
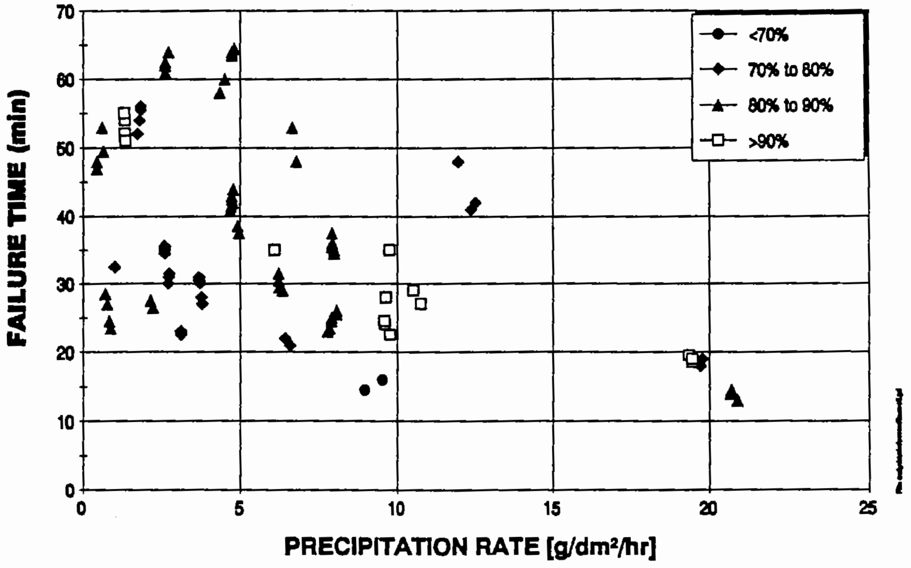


FIGURE 5.14

Plate Failure Times - Humidity Effect

(Dorval, UCAR 250-3)



the relationship may be simply a result of a close correlation with another variable (wind or temperature), the fact that high humidity tests are part of the fluid qualification program makes the behaviour interesting.

While these last three analyses did provide some useful and interesting information, the effects of both wind and temperature or the effects of any other combination of variables should be explored before any preliminary conclusions are reached. With the information obtained in this section, the statistical analysis which follows was performed more effectively and the results have more meaning.

5.3 Statistical Analysis - Dorval Data

The interesting results of the preceding analysis are very useful in providing direction to the statistical analysis. Before delving into multiple regressions or correlations, the variables of interest need to be selected. While parameters such as wind, temperature, humidity and fluid thickness pose no difficulty, a decision must be made as to how precipitation is to be presented. Because precipitation rate is derived directly from total precipitation, both should not be included in the statistical analysis. The apparent relationships discussed in Section 5.2 indicated that precipitation rate may be a more meaningful inclusion in this analysis.

Table 5.1 presents the correlation matrix[1]. The shaded column is of most interest as it describes the correlations between failure time and all of the other variables. It is important to note that for this analysis and the

---

[1] In a correlation matrix, all values lie between -1.00 and +1.00. The closer a value is to one of these extremes, the stronger the linear relationship. A high positive correlation between A and B indicates that as factor A increases, so does B. A very negative correlation indicates that as A increases, B decreases. Correlation values close to zero indicate that there is little linear dependence of B on A or A on B.

TABLE 5.1

CORRELATION MATRIX

DORVAL, UCAR 250-3

	Failure Time @ C2	Precip. Rate - C2	Avg. Temp.	Avg Wind	Relative Humidity	2.5 cm Line	15 cm Line
Precipitation Rate @ C2	-0.576						
Average Temperature	+0.099	+0.501					
Average Wind	-0.208	-0.135	-0.769				
Relative Humidity	+0.176	+0.020	+0.318	-0.299			
2.5 cm Line	-0.131	-0.146	-0.505	+0.469	-0.172		
15 cm Line	-0.003	-0.094	-0.394	+0.398	-0.121	+0.353	
30 cm Line	-0.057	+0.105	-0.144	+0.296	-0.284	+0.286	+0.512

NOTE: 2.5 cm, 15 cm, 30 cm REFER TO MEASURED FLUID THICKNESS AT THOSE LOCATIONS
SOURCE: APS Analysis

regression analyses which follow, the results are only valid **over the range of the data considered**. Low or high correlations may be solely due to the limited range of data for a variable in question. From Table 5.1, the variable with the highest correlation with failure time is precipitation rate.

Multiple regressions were performed, first on the entire 250-3 data set and then on all the "calm wind" data points. A linear regression was first performed but improved results were obtained in the non-linear cases which succeeded it.

5.3.1 Multi-variate linear regression

The general methodology of the regression process was to regress failure time against all the other variables. The least significant variable was removed and the regression was redone with the reduced number of variables. The process continued until only significant variables remained in the predictor equation. The predicted values were compared against the actual recorded variables and the residuals were obtained. Key elements in determining the quality of a regression fit are the $\mathbf{R^2}$ value and the shape of the standardized residual distribution. $\mathbf{R^2}$ is expressed as a percentage and is known as the multiple coefficient of determination. As an example, an $\mathbf{R^2}$ of 50%, as was obtained in the statistical analysis for the 1990-1991 testing period, indicates that the regression equation could account for 50% of the variation in the data. A residual is the difference between the predicted value for a given set of conditions and the actual value as measured. A standardized residual is a residual divided by the standard deviation of the set of predicted values. It is important that the distribution of the set of standardized residuals is normal, or bell shaped.

The multi-variate linear regression performed on this data set did not yield any startling results. The final regression equation for the C2 failure time

$$Time=42.6-2.20*P_{rate}+3.08*Temp+0.595*Wind+1.15*Thick_{6\text{-}inch}$$

has an $\mathbf{R}^2$ of only 56.5% and the standardized residuals are not normally distributed. The significant variables are precipitation rate (**P**$_{\mathbf{rate}}$, in g/dm^2/hr), temperature (**Temp**, in degrees celsius), wind speed (**Wind**, in kph), and film thickness at the 6-inch line (**Thick**$_{\mathbf{6\text{-}inch}}$, in mils). While it is possible to improve the results of the regression by considering only calm wind tests, better results are achieved investigating non-linearities, as is shown in the next sub-section.

5.3.2 Multi-variate non-linear regression

When the data indicates a relationship that is not linear, it is possible to linearize such data and perform a regression on the linearized data set. The analysis in Section 5.2 indicated some logarithmic trends for failure time. Therefore, the log of failure time was regressed against the other variables and the results, even at all wind speeds, were more encouraging.

The resulting predictor equation of this regression is presented below:

$$\log Time=1.64-0.0316*P_{rate}+0.0434*Temp+0.0105*Wind+0.0131*Thick_{6\text{-}inch}$$

For this equation, the multiple coefficient of determination was 68.0% and the distribution of standardized residuals had a more normal appearance. As with the linear regression, the significant variables were precipitation rate, temperature, wind speed, and thickness at the 6-inch (15 cm) line. There are other non-linear possibilities which can be investigated but would not yield superior results with the entire data set. The following sub-section looks only at tests performed during calm wind conditions.

5.3.3 Multi-variate regression - calm wind data

Excluding all tests with average winds above 5 kph reduces the data set to 41 points. These 41 points were analyzed in a number of different ways. The most promising was another logarithmic relationship:

$$\log Time = 2.43 - 0.0260 * P_{rate} - 0.00767 * RH$$

where relative humidity (**RH**, as a percentage) and precipitation rate are the only significant variables. The value of $\mathbf{R^2}$ for this equation is 90.8% although the shape of the standardized residual distribution was not truly normal. While the high $\mathbf{R^2}$ value is encouraging, it is only applicable over a very limited range of data and is thus of limited use. The acceptable data limits are:

- Temperatures between -4.1 and +0.3 °C;
- Wind speeds between 1.3 and 4.2 kph;
- Relative humidity between 80 and 95%;
- Fluid thicknesses between 5 and 10 mils at the one inch line, between 11 and 17 mils at the six inch line, and between 13 and 21 mils at the 12 inch line; and
- Precipitation rates between 1.3 and 19.5 g/dm^2/hr.

It cannot be overemphasized that, while the results are promising, they are based on a small data set for a narrow range of meteorological conditions. Nonetheless, the results are far better than has been achieved in the past and bode well for future testing, if wind speed can be removed or at least restricted to a single direction.

5.4 St. John's Data Analysis

As mentioned previously, the data collected at St. John's, Newfoundland was analyzed separately from the Dorval data. This analysis is presented in this section. The method of analysis is on a more basic level than the method used to analyze the Dorval data. While it was originally hoped that the quantity and quality of the St. John's data would be on a par with the data collected at Dorval, this was not the case on several fronts.

The bane of testing at St. John's continues to be the wind. Gusts above 100 kph are not uncommon. As indicated in Table 3.1, a total of nine successful tests (53 data points) were obtained from the St. John's site. The average winds during those nine tests ranged from a low of 12 kph to a high of over 50 kph with the overall average being in excess of 30 kph. These were the successful tests. Unsuccessful tests were accompanied with comments such as "test stand blew over".

All meteorological data was supplied by AES. While wind speed, temperature and relative humidity were of a high degree of quality, the precipitation measurements were much too coarse for a useful analysis. The precipitation apparatus at the site recorded an event every 10.0 g/dm^2, as opposed to every 1.0 g/dm^2 used in 1990-1991 and to the 0.05 g/dm^2 used at Dorval.

The test site itself was not continuously manned. This led to some fluid delivery difficulties which resulted in Union Carbide 250-3 fluid not being the predominant fluid of the tests. Overall, Octagon was used on 43% of successful tests, 250-3 on 36% of the tests and Hoechst on 21% of the tests. The Kilfrost fluid arrived near the end of the testing season and was not tested successfully.

With no practical measure of precipitation, Figure 5.15 was produced. Figure 5.15 contains the distribution of failure times at the St. John's site. The appearance is not dissimilar to Figure 3.9, which showed the distribution of failure times at the Dorval site (at point C2). While the lack of precipitation is unfortunate in that it made a detailed analysis impossible, the high uncertainty in fluid behaviour due to the substantial winds would have likely resulted in unsatisfactory conclusions.

5.5 Variance Between Fluids

While all of the preceding analysis has focused on the Union Carbide 250-3 fluid, Octagon, Hoechst and Kilfrost fluids were also tested, although in a very limited fashion. While there are too few points of each of these fluids to merit an individual analysis, the test results were combined with the 250-3 results to plot Figure 5.16.

In Figure 5.16, it is apparent that the behaviour of the Hoechst, Kilfrost and Octagon fluids is similar to that of the 250-3 fluid. While an extensive series of tests may show relevant, fine scale differences, this series of tests is sufficient to show that, in all likelihood, we are dealing with similar fluids. As more understanding of the fluids is gained, thorough testing of all fluids should be undertaken to determine the specific differences.

Figure 5.15
Distribution of Plate Failure Times
(St. John's, Type 1.5 Fluids)

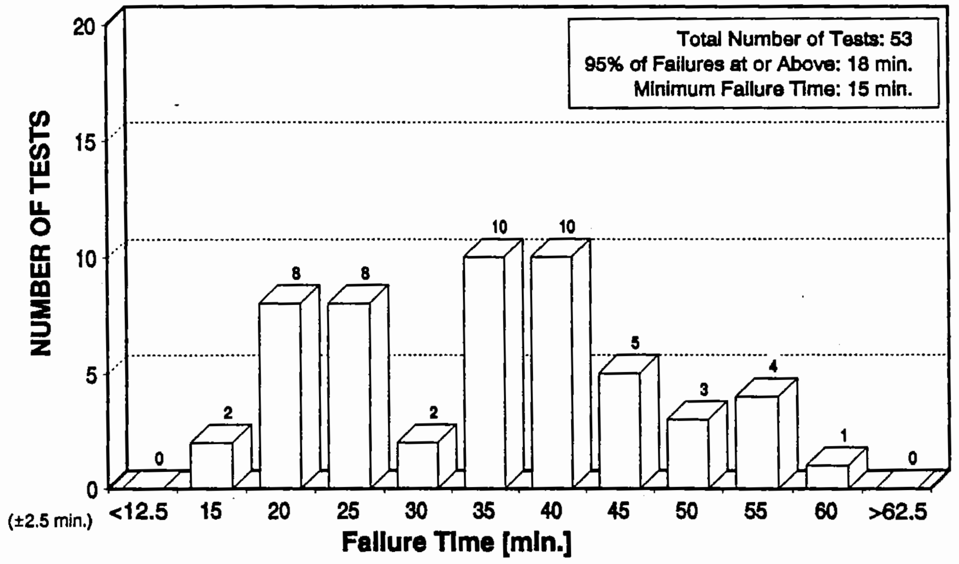
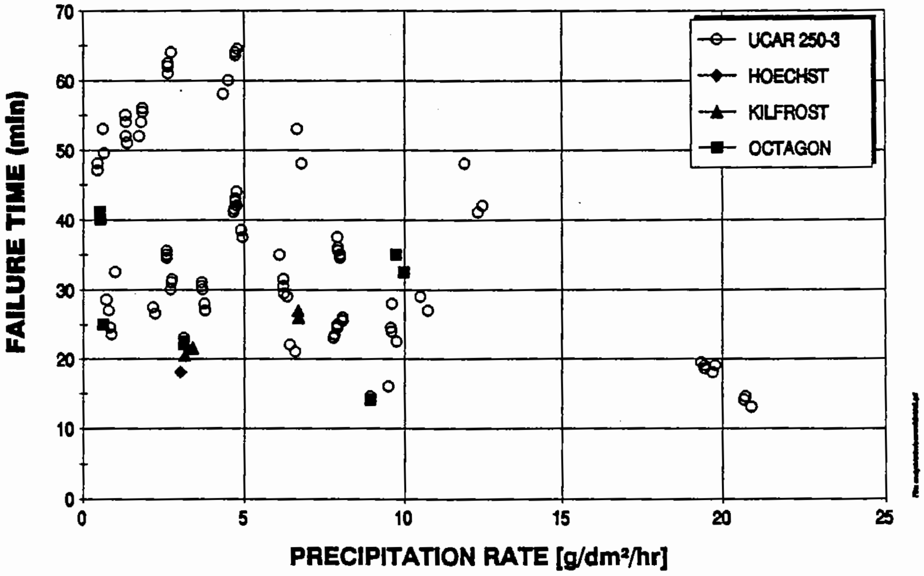


FIGURE 5.16
Plate Failure Times - Fluid Type
(Dorval, All Fluids)



5.6 Comparison with 1990-1991 Results

When comparing results included in this report with those Type I.5 results contained in the 1990-1991 report, some important differences should be noted:

- The visual determination of the end condition was redefined for the testing performed for this report, which means that similar tests performed in different years will have different plate failure times.
- The improvement in meteorological equipment and recording procedures may result in identical meteorological conditions being reported differently for the two years' tests.

With these caveats, it is possible to consider how the two sets of testing are related and whether differences are justifiable.

5.6.1 Tests and testing conditions

1990-1991 testing of Type I.5 fluids consisted of a total of 110 data points, the majority of which were collected at the Dorval site. The 1991-1992 Dorval tests collected 138 UCAR 250-3 data points.

While the maximum precipitation rate recorded during a Type I.5 1990-1991 test approached 30 $g/dm^2/hr$, 10 $g/dm^2/hr$ higher than the maximum collected in the 1991-1992 season, a majority of tests performed in both years were under precipitation rates below 13 $g/dm^2/hr$.

5.6.2 Results

The calm wind condition has produced some of the more meaningful results in the present report. There was insufficient calm wind data collected in the 1990-1991 season (3 points, 1 test), due either to a simple lack of this meteorological condition or to insufficient wind measurements, for this to be a useful way to filter the data. However, with the knowledge gained through the analysis performed for this report, it can be seen that the 1990-1991 calm wind data may follow the same pattern. Figure 5.12, which plotted failure time against precipitation rate for calm wind conditions has been reproduced here, as Figure 5.17, with the 1990-1991 points appended (upper left corner).

Without a foundation from which to work, the statistical analysis performed on the 1990-1991 data was only able to achieve a multiple coefficient of determination ($\mathbf{R^2}$) of 49.0%. The complete regressions performed for this report were able to obtain $\mathbf{R^2}$ values of 56.5% and 68.0% for the linear and logarithmic regressions, respectively. While in the long run, even a 68.0% $\mathbf{R^2}$ is insufficient for predictive capability, it is still a marked improvement over the 1990-1991 results. No calm wind regression was performed on the 1990-1991 data due to an insufficiency of data. The 1991-1992 data did produce a very promising regression on these data points, as discussed in Section 5.3.

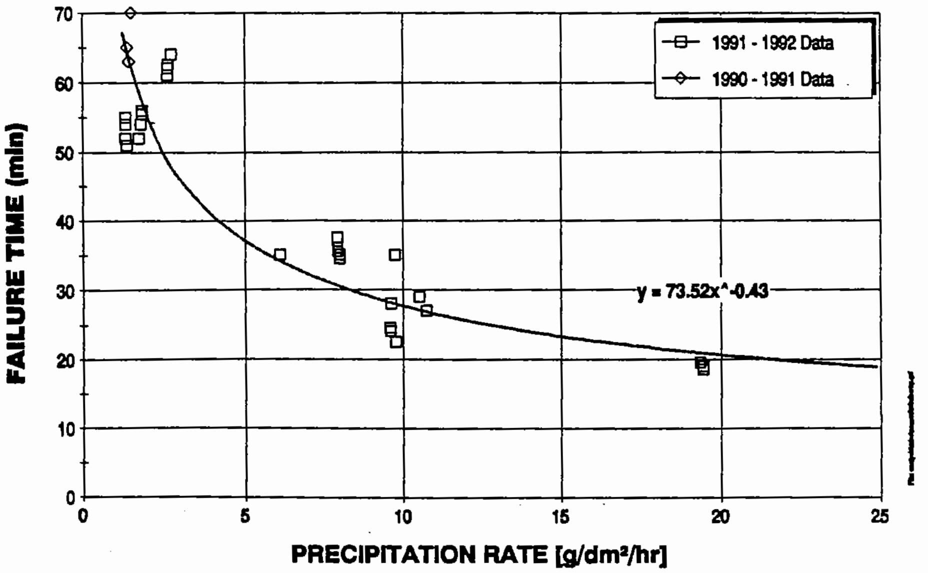
5.7 Curved Plate and Wing Section Testing

As stated in Section 3.1, only one natural snow test performed on the wing section or the curved plate resulted in any sort of failure. This was a curved plate test performed on the very last day of Dorval testing, April 11th, 1992. The lower end of the curved plate began failing after 19 minutes and

FIGURE 5.17

Calm Wind Plate Comparison

(Dorval, UCAR 250-3)



continued upward until the crest of the plate failed after 34 minutes. During this same test, flat plates were failing at between 16 and 22 minutes. The precipitation rate during the test was approximately 20 g/dm^2/hr, which is fairly high. The average ambient air temperature was 0°C, which may have contributed to the wing section, with its greater fluid thicknesses, not failing.

The wing section and curved plates were also tested under artificial snow conditions. This analysis is presented in detail in the next section of the report.

5.8 Artificial Snow Testing Analysis

The artificial snow testing had three important purposes. Because artificial snow can be produced more or less on demand, providing the temperature is below freezing, from an operational standpoint it would be tempting to perform all tests under this precipitation. Given that the precipitation produced is different in size, texture and water content, these tests were performed to examine whether the fluids behave in a similar manner under artificial and natural snows.

The second objective was to determine if the behaviour of the fluids on the three test sections differs greatly under this type of precipitation. This could possibly eventually allow for the extrapolation of flat and or curved plate failure times to aircraft wing failure times.

The third objective was to investigate the possibility of employing the modified IM101 Instrumar ice sensor as a failure determining mechanism. Due to the late arrival of the ice sensor to the testing program, no natural snow tests were performed and therefore, the artificial snow tests were the only means available for a preliminary investigation.

One of the difficulties in generating artificial snow is in obtaining a sufficiently low precipitation rate. The main purpose of such snow guns is to produce as high a precipitation rate as possible. The tests performed for this analysis were performed near the minimum flow rate of the snow gun. The greater the trajectory of the super-cooled water jet spray, the better the quality of snow. However, the difficulty with this is that the higher it was sprayed, the more affected the snow was by any wind which existed. The snow gun was therefore placed a significant distance away from the test stands and required frequent adjustments to maintain a reasonably constant rate of precipitation over the testing area.

Another consideration is that the meteorological equipment used was the same equipment used for the 1990-1991 testing, although the data was manually recorded at a greater frequency than was the case during the 1990-1991 test season. It was impractical to transport the improved meteorological equipment to the ski hill.

5.8.1 Flat plate testing

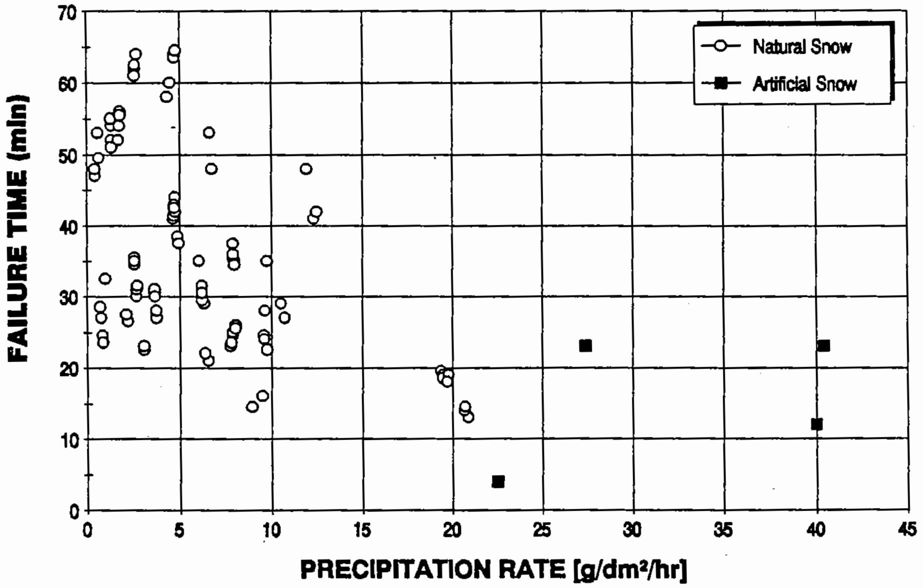
Figure 5.18 appends the 250-3 artificial snow tests to the complete set of UCAR 250-3 natural snow tests. The minimum precipitation rate achieved was about 22.5 $g/dm^2/hr$. Some failure times are not quite as low as might have been expected although they are generally satisfactory when considering the fact that the old meteorological equipment was in use.

The failures which occurred did not mimic the types of failures experienced under natural snow conditions. Once failures began to occur on the plate, the rest of the plate failed very quickly. A typical failure would end with the artificial snow forming a sheet of ice which

FIGURE 5.18

Plate Failure Times - Artificial/Natural Snow

(Dorval/Rigaud, UCAR 250-3)



rested on a very thin layer of fluid. Under slight provocation, the ice would easily slide off the plate. This type of failure did not occur during the natural snow tests. This is attributable to the fact that the artificial snow is essentially ice crystals which can easily fuse together with a slight increase in temperature such as may occur when they enter in contact with the fluids on the plates.

As an important note, unprotected plates exposed to the same artificial precipitation froze over completely and required scraping in preparation for another test.

5.8.2 Curved plate and wing section testing

Unlike the natural snow testing, a curved plate and the wing section were tested during every artificial snow test. Figure 5.19 displays the curved plate failure times at both the crest of the plate ("Upper") and at the crosshairs along the bottom of the plate ("Lower").

One interesting detail with the curved plate is that when sufficient artificial snow had accumulated, it would slide off the plate and leave behind an essentially clean surface but for a thin film of fluid. The failures used to generate Figure 5.19 are with respect to the time of first failure.

A similar chart was produced for the wing section. For Figure 5.20, the time required to fail the leading edge was the time used in determining failure time. Recall that the wing section had two areas used for testing. These are differentiated as Wing 1 (closest to the root of the wing) and Wing 2 (closest to the wing tip). As can be seen, both leading edges failed at the same time.

FIGURE 5.19

Artificial Snow Failure Times - Curved Plate

(Rigaud, UCAR 250-3)

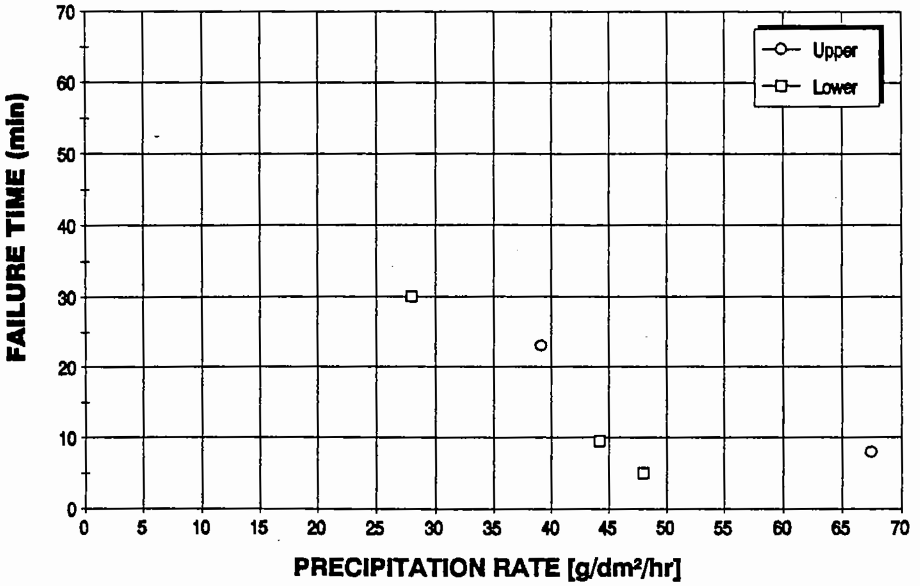
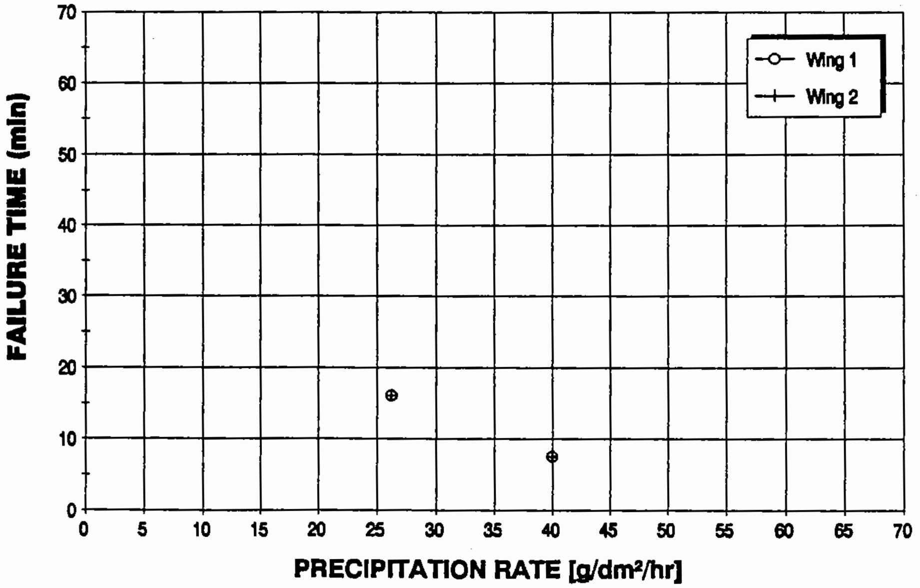


FIGURE 5.20

Artificial Snow Failure Times - Wing Section

(Rigaud, UCAR 250-3)



Combining the results of all test sections under artificial snow conditions onto a single chart produces Figure 5.21. The fact that there is relatively little scatter between all the points can most likely be attributed to the high volumes of precipitation.

5.8.3 Ice sensor testing

Ice sensor testing was potentially the single most important test element of the 1991-1992 field test program. It was unfortunate that the required sensor modifications resulted in it only being available at the end of the testing season. Thus the sensor was only available for a single series of artificial snow testing, and no natural snow testing.

The sensor used in the tests records the admittance (inverse of electrical impedance) of the substance with which it is in contact. The sensor measured admittance and used an A/D converter to return values from 0 to 255. A clean sensor, i.e. one exposed only to air, would register a value of 14 whereas a sensor in contact with thick layer of fluid would register a value in excess of 150. Solid ice would result in a reading of 26.

The sensor was used in only two complete tests. An initial trial run was also recorded where the sensor was operational but the other data collection elements were not. The time history of the sensor readings for this trial run (known as Run 0) and the two complete tests (Run 1 and Run 2) are presented in Figures 5.22, 5.23 and 5.24, respectively. Included on the time history plots are relevant comments pertaining to events such as the fluid being applied, the start of the test and the time a visual failure determination was made according to the standard procedure.

FIGURE 5.21

Artificial Snow Failure Times - All Sections

(Rigaud, UCAR 250-3)

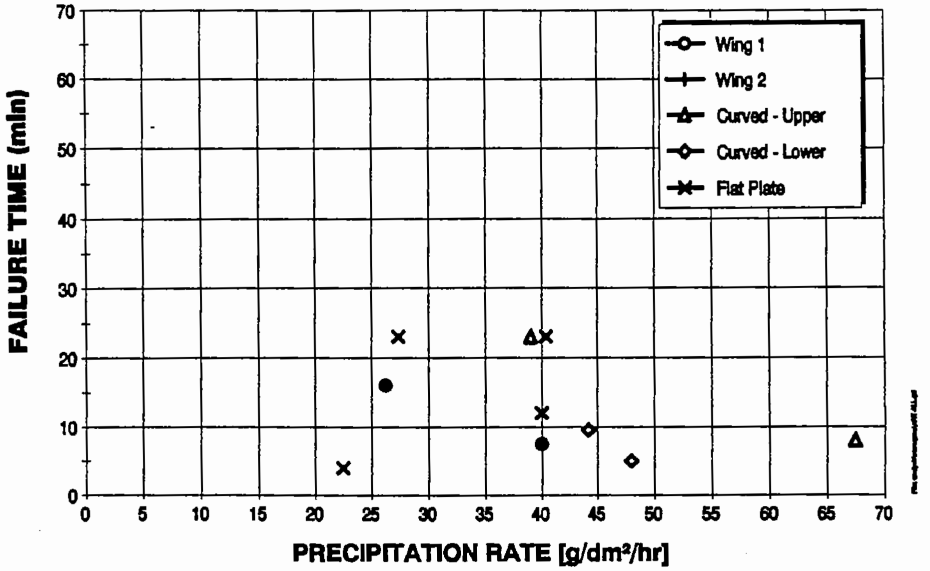


FIGURE 5.22

ICE SENSOR tests - Flat Plate

(Rigaud, Run 0, UCAR 250-3)

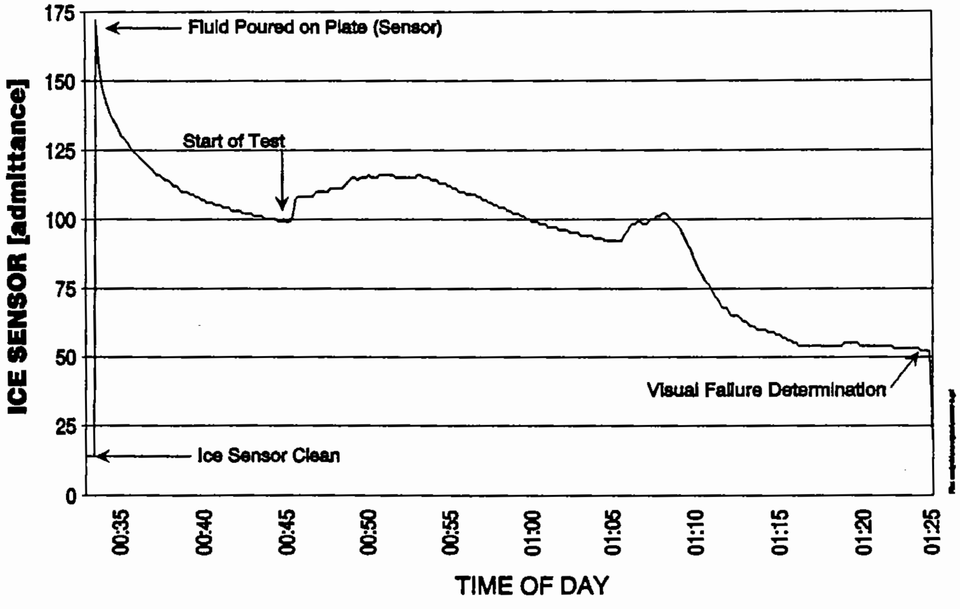


FIGURE 5.23

ICE SENSOR tests - Flat Plate

(Rigaud, Run 1, UCAR 250-3)

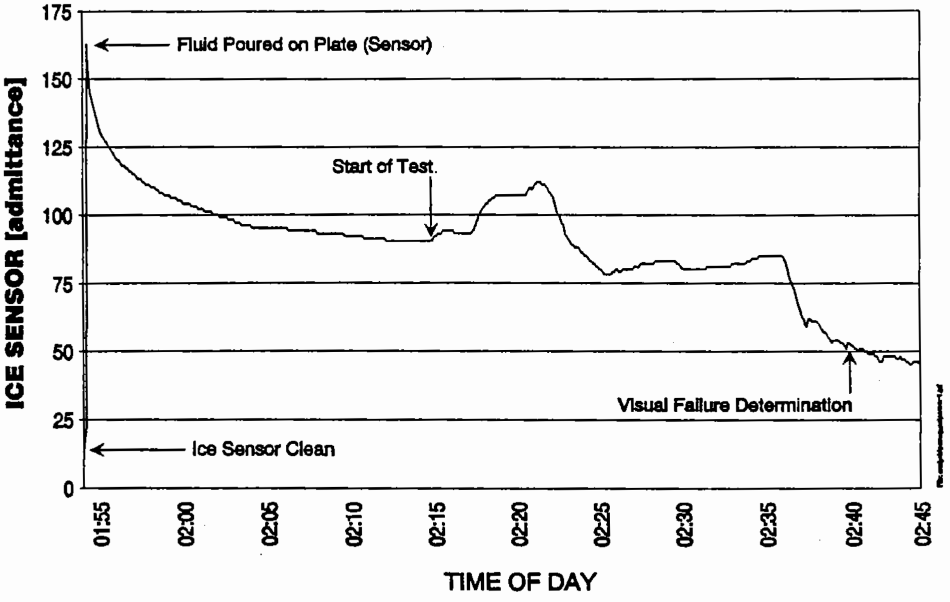
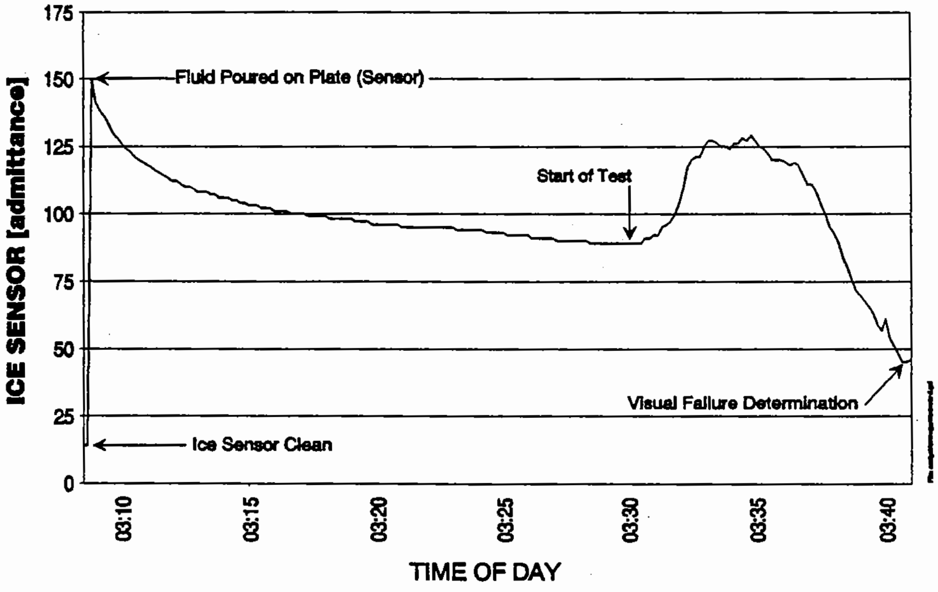


FIGURE 5.24

ICE SENSOR tests - Flat Plate

(Rigaud, Run 2, UCAR 250-3)



In Figure 5.22 the visual failure determination happened seven to eight minutes after the sensor readings stabilized at 52. This could indicate that the actual failure may have taken place earlier but was not detectable on the surface of the fluid. This observation is based on only one test which was also the trial run; future testing should determine if this observation was valid.

All three plots show similar patterns:

- A clean sensor reading of 14;
- A reading of between 150 and 175 once the fluid was applied;
- A gradual decrease in the admittance values before precipitation commenced as the fluid ran off the plate;
- Once exposed to precipitation, there was a definite increase in the admittance readings;
- The increase in admittance levelled off followed by a decrease;
- At a short time before a visual failure determination, there were significant drops in admittance in relatively short periods of time;
- The admittance value corresponding with the visual determination of failure ranged between readings of 46 and 53.

The sharp decrease in admittance before visual failure and the relatively narrow range of admittance at visual failure determination are possibly the solution to the failure determination problems. However, before conclusively stating that this is the case, the fact that all three tests were performed under very similar conditions may explain the similarities. Also, as has been stated, artificial precipitation is not very representative of natural precipitation. Before the use of this particular sensor can be proposed as the failure determining mechanism, a number of natural snow tests must validate its use.

5.8.4 Artificial snow testing - general

While testing under man-made precipitation conditions is not nearly as restricted as testing under natural snow conditions, several disadvantages exist. The snow crystals produced have a significantly higher water content than natural snow flakes and the rates of precipitation tend to be above those found in actual snowfalls. The significance of crystal water content on the fluids is not known and, in the end, may not be a problem. The volume of precipitation produced can probably be regulated under low wind conditions by simply off-setting the test site away from the centre of the artificial storm. This is a very difficult task if there is any wind.

5.9 Film Thickness Analysis

Tests were performed which investigated fluid thickness behaviour in absence of any precipitation. The methodology consisted of applying fluid to a flat plate, the curved plate and the wing section and then measuring the fluid thickness at frequent time intervals over a one hour period. Measurements on the flat plate were taken at the 1" (2.5 cm), the 6" (15 cm) and the 12" (30 cm) lines. Curved plate measurements were taken at seven different lines, each 6 inches (15 cm) apart, beginning at the crest of the curved plate (point of zero slope). Wing section fluid measurements were taken at nine points on the inner marking set (wing 1) and seven points on the outer marking set (wing 2) at six inch (15 cm) increments until the final three measurements which were approximately three inches (7.5 cm) apart. All tests were performed at temperatures below freezing. Four tests were performed on flat plates, three on the curved plate and one on each section of the wing.

Aside from providing general fluid behaviour information, these tests were used to validate a procedural assumption of the testing which was that the fluid thickness would stabilize within ten minutes of being poured onto the plate. Additionally, this testing was useful in establishing whether there were any points of correlation between the fluid thicknesses on the flat plate, the curved plate and the wing section.

5.9.1 Flat plate film thickness

Figure 5.25 presents the measured film thicknesses as a function of time since application. For this Type I.5 fluid, the ten minute cut-off time seems to be fairly valid although the fluid thickness does continue to decrease. The 1990-1991 testing assumed five minutes as a cut-off time. This may be valid for the one inch (2.5 cm) line but not for the 6 inch (15 cm) or 12 inch (30 cm) lines.

5.9.2 Curved plate film thickness

Although seven separate points were measured on the curved plate only three points of interest are included in Figure 5.26 - one six inches (15 cm) from the zero slope crest, one 18 inches (46 cm) from the crest and one 30 inches from the crest or six inches from the bottom of the plate. At a slope of just under 9 degrees, the middle curve on the graph comes the closest to the conditions measured on the flat plate with its slope of 10 degrees. The slopes of the other two curves were 2.9° and 14.3° for the 15 cm and 76 cm lines, respectively.

FIGURE 5.25
FILM THICKNESS ON FLAT PLATE vs TIME
UNION CARBIDE 250-3

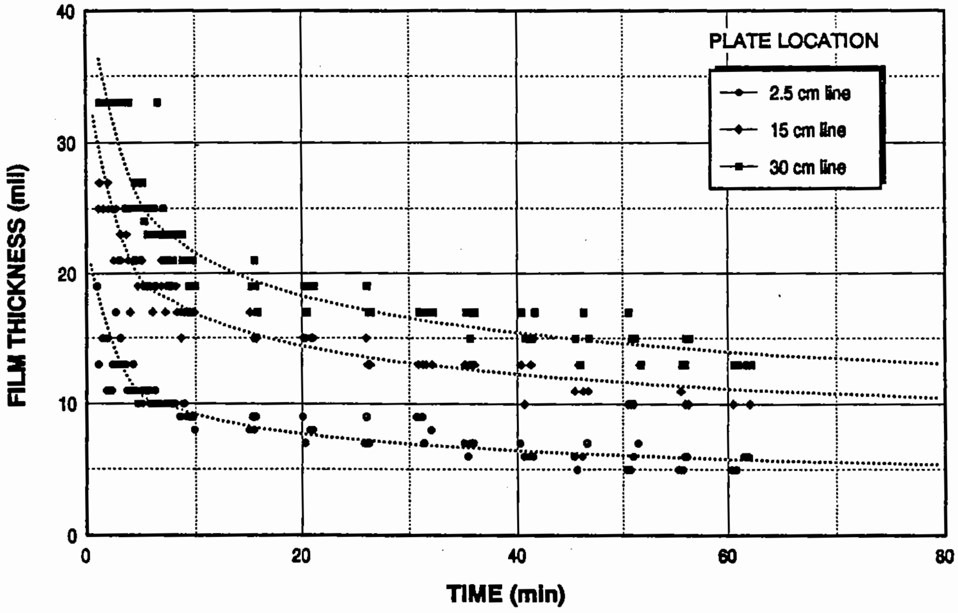
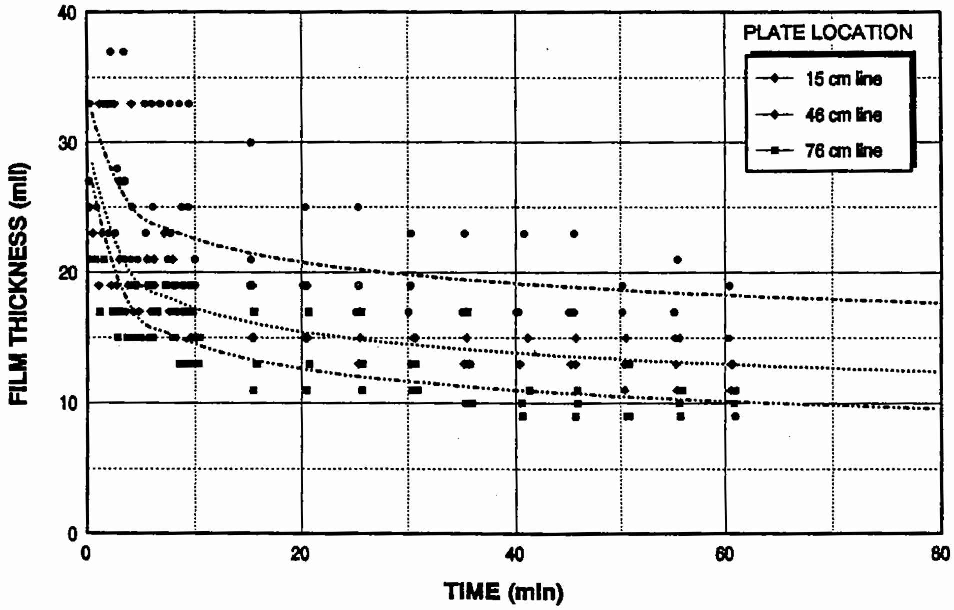


FIGURE 5.26
FILM THICKNESS ON CURVED PLATE vs TIME
UNION CARBIDE 250-3



The wide scatter over the 15 cm line indicates that the film thickness at this near horizontal point is dependent on the amount of fluid applied. The magnitude of the differences decreases as time progresses and the differences themselves are much less significant for the lines lower down on the plate. The values along the 46 cm line are just slightly greater in magnitude than the flat plate's 15 cm line.

5.9.3 Wing section film thickness

Figures 5.27 and 5.28 present film thicknesses for the two segments of the wing section. The two lines indicated were measured at four inches and one inch above the vertical sloped point on the leading edge, respectively. It was not possible to get accurate measurements exactly at the leading edge with the measurement method used (the fluid tended to run onto the gauge). It should also be noted that the scatter of the data is fairly pronounced indicating that the fluid may have tended to flow irregularly. This performance was not unexpected since the wing section was not nearly as smooth and uniform as either the flat plate or the curved plate. The measured thicknesses at the lowest lines of both sections tend to bracket the measured thickness at the flat plate 2.5 cm (one inch) line.

5.9.4 Film thickness - general

The film thickness measurements indicate that there is scope to connect the film thickness behaviours on all three test sections. The six inch line on the flat plate correlates well with the point on the curved plate with the slope closest to the flat plate's 10°. More importantly, the leading edge of the wing, perhaps the most critical surface when considering contamination during takeoff, is closely

FIGURE 5.27
FILM THICKNESS ON WING 1 vs TIME
UNION CARBIDE 250-3

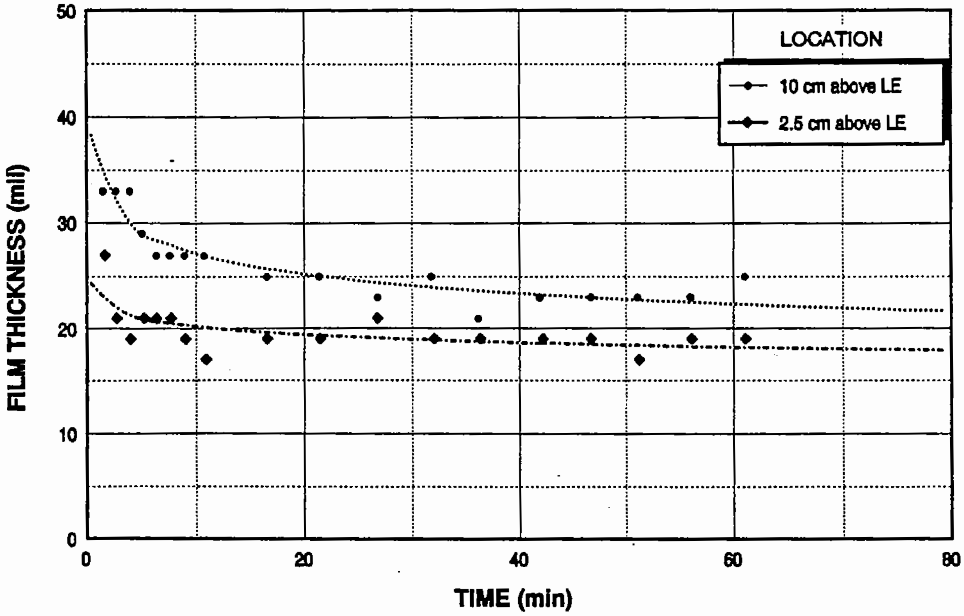
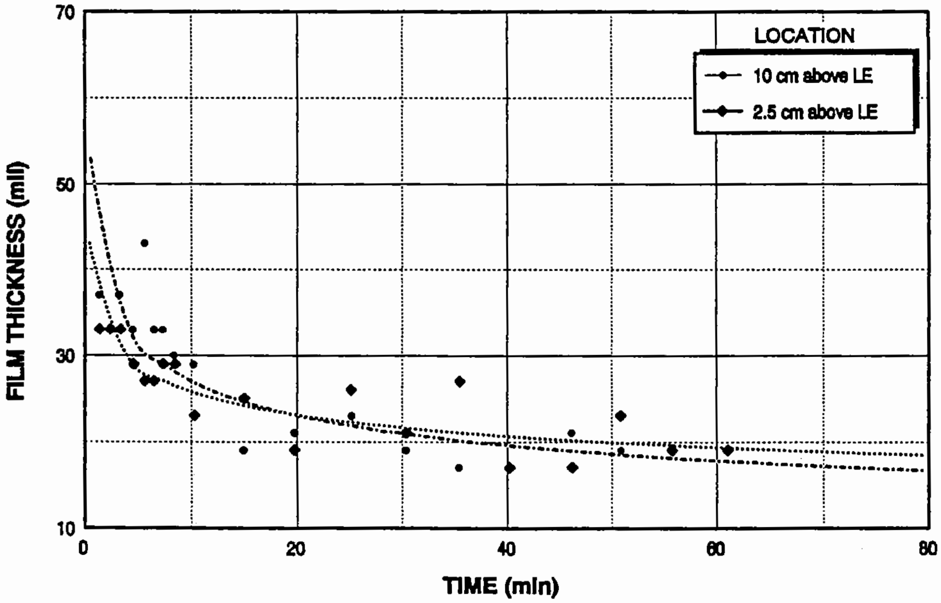


FIGURE 5.28
FILM THICKNESS ON WING 2 vs TIME
UNION CARBIDE 250-3



related to the one inch line on the flat plate. While failures along the one inch line were not recorded during testing, failures at line B should be examined.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE TESTING

As is apparent when comparing the analysis contained in this report with that included in the 1990-1991 report, relationships between the anti-icing fluids and the meteorological parameters are far more evident than was the case in the past. While the improvement in meteorological data collection contributed greatly to this result, a factor not to be overlooked is that the scale of the tests was significantly smaller than in the previous year. Only two field testing sites were active and a single fluid was tested a majority of the time. All the changes implemented in the testing were suggested in the concluding section of the 1990-1991 report. Similarly, changes suggested in this section may also play a pivotal role in improving the quality of the recorded data in future testing.

This section is divided into two sub-sections. The first summarizes conclusions based on this year's testing and analysis and the second suggests procedural and equipment changes which may enhance the quality of future data collection.

6.1 Conclusions

While there was still a substantial amount of scatter contained within the data, that scatter was not too great and, as a result, some key relationships between fluid failure and the other recorded parameters were apparent. This section documents the conclusions, in point form, as they pertain to four specific areas: Procedures and equipment; meteorology; artificial snow testing; and analysis and results.

6.1.1 Procedures and equipment

- The use of the high resolution ombrometer improved the quality of all precipitation data, especially at relatively low rates.
- The computerized data acquisition system installed at the Dorval site provided for the collection of the meteorological data at a more useful sampling rate.
- The film thickness measuring device employed has too coarse a resolution given the fluid thicknesses involved in the testing.
- A wind vane is required to assist in the evaluation of wind effects on the failure times.
- The visual determination of the end condition remains very subjective and may be the major source of the data scatter.
- The limited use of the modified Instrumar ice sensor provided hope that it could be successfully used to determine failure.

6.1.2 Meteorology

- Precipitation, likely the key meteorological data element, does not occur in a fashion which could remotely be called "steady". Orders of magnitude changes in precipitation rate over relatively short time periods are not uncommon under natural precipitation conditions.

- Over this 1991-1992 testing season, a majority of the average precipitation rates were in excess of the laboratory standard 5 $g/dm^2/hr$.

- Wind speed, like precipitation rate, is subject to significant fluctuations in magnitude over short periods of time.

- Changes in temperature and relative humidity usually occur gradually.

- The wind conditions at St. John's, Newfoundland make it an undesirable testing site; it does not produce data that could give basic insights into fluid behaviour. When a greater understanding of fluid failure mechanisms has been gained, St. John's would be a useful site for studying wind effects.

6.1.3 Artificial snow testing

- The artificial snow testing is easy to coordinate and is less restricted by weather conditions.

- The artificial snow has a higher water content and lower air content than most natural snow.

- The artificial snow testing is capable of producing high rates of snowfall which only occasionally occur naturally. If it is possible to correlate natural snow failures and artificial snow failures, the additional high rate data could be very useful.

6.1.4 Analysis and results

- There appears to be a definite relationship between failure time and precipitation rate when only low wind data is studied.

- There are possible relationships between failure time and precipitation rate when either high humidity data or data with temperatures between -5°C and 0°C is examined, although there is significant overlap between these points and the low wind data points.

- The statistical analysis on low wind data was able to account for over 90% of the data variability. The predictor equation is only relevant over a limited range of meteorological conditions and was obtained from a relatively low number of data points.

- There was limited data on the curved plate, and no data on the wing section, under natural conditions. Under artificial snow conditions, the leading edge of the wing section failed before the rest of the wing. This indicates that the curved plate, which is more representative of the top of a wing, may not be a useful test section. A more useful one may be a shape which replicates the leading edge of a wing.

- Clear ice was produced on the wing section by the artificial snow and it was possible to speculate that a pilot would not have been able to discern its existence visually from the cockpit under adverse lighting and weather conditions.

6.2 Future Testing

The positive results obtained due to the improvements in the meteorological data collection can not be overlooked. Any future site at which testing is to occur should be similarly equipped. Despite the positive results obtained, it must be remembered that everything is relative. The results seem exceptional when compared with previous results but the amount of scatter which remains and the degree of uncertainty in the conclusions is still substantially above a desirable level. Future testing should, therefore, be undertaken on the basis that a plan is in place to refine the data even further.

6.2.1 Equipment

The key unsatisfactory element which remains in the procedure is the lack of a clear, precise method of measuring plate failure. The subjectivity which remains in this very important test activity is most likely responsible for a good deal of the scatter which is unaccounted for. The use of an automated sensing device should be a fundamental element of any future testing. If successful, a sensing device would provide the trigger for determining the plate failure time. Removing the subjectivity from the end condition should go a long way towards providing a set of highly correlatable data from which some basic understanding of fluid behaviour can be gained.

In terms of meteorological data, one area which has some uncertainty associated with it is the relative amount of precipitation which the plate is subjected to compared to the amount being registered by the precipitation measuring device. There are various options available to address this problem.

- The addition of a computerized wind vane would be one method of dealing with this problem. While there would still not be a direct correlation between the precipitation recorded and that hitting the plates, knowing wind direction may allow the analysis envelope to be expanded beyond simply a low wind condition.

- Placing a pre-weighed, pre-wetted collector plate (with containment flanges) on the stand beside the other flat plates would provide those doing the analysis with an accurate reading of the total precipitation which the test plates were subjected to. While Section 4.2 of this report provides strong evidence that precipitation is almost never "steady", the collector plate may still provide useful information when used in conjunction with the computerized precipitation measuring device.

- An instrument which measures the concentration of snow in a volume of air has been developed at the National Research Council. This device, known as a Stallabras, sweeps out an annulus of air and records the mass of the precipitation which it collects. Calculations for precipitation rate require both the snow mass concentration, as measured by the Stallabras, and the terminal velocity of the precipitation particles. While certainly a complicated process, the information can provide frequent readings of both the falling and the blowing effects of precipitation.

- The use of a multi-channel ice sensor, such as the one under development by Instrumar and currently being tested by the NRC, should be used in future tests at Dorval. The sensor, which provides additional information, would add to the understanding of fluid failure and facilitate in the calibration of a single channel M101 ice sensor.

Other than improvements in these two areas - plate failure and actual precipitation - there is little else in terms of equipment which is absolutely necessary to continue testing. However, some peripheral equipment may provide some useful information. A forward scatter visibility meter or some less technical method of recording visibility may provide insight.

6.2.2 Procedure and scope of future testing

If the suggested equipment enhancements are acted upon, there would be little change required for the procedures. The visual determination of failure should continue as in future years, although it could be compared to the sensor indications. This is very important in that it appears unlikely that all test sections could be equipped with this sensor. Some means of correlation or calibration must be maintained in the testing.

In terms of scope of testing, some balancing will have to be done between a desire to get detailed information with as little variation as possible in controllable parameters such as fluids tested and number of sites against the practical need to expand testing to obtain a wider base of information. With this understanding, the following recommendations are made:

- Testing should include a small number of samples of Type I, Type I.5 and Type II fluids.

- Montreal (Dorval) should be the main base of testing although setting up two or three Dorval sites in relative proximity to each other would supply more usable data. If other organizations or associations wish to participate, it is suggested that if possible they invest in some or all of the meteorological equipment to ensure that data collected remains useful to the analysis.

- Inclined flat plate testing should continue in order to maintain a link with previous tests.

- Because of the difficulties in accurately recording fluid thickness, it may prove beneficial to perform some testing using a flat horizontal plate with containment flanges where a pre-determined volume of fluid could be poured on the known area. This would result in the test being run with a constant, known thickness of fluid. While this may not be the most realistic test compared with actual fluid application, it may provide further insight into the reasons and the method of fluid failure, something which remains uncertain.

- A cylinder or half-cylinder test section may be a way to easily investigate the effects of precipitation on the leading edge of the wing, without getting a wing itself. Performing these tests alongside the flat plates may provide grounds for a correlation between the two types of test section.

- If a wing section is available, it too could be put to good use. With the wing section, the potential exists for calibrating data collected on other test sections to a "real world" test section.

- A hollow box filled with a liquid such as oil, could be used to simulate cold soaking. The liquid inside the box would need to be cooled sufficiently prior to testing. The surface would need to be monitored during the test.

APPENDIX

TEST PROCEDURES AND EQUIPMENT LIST

FIELD TESTING DE/ANTI-ICING FLUID
HOLDOVER TIME
1991 - 1992

1. SCOPE:

This procedure describes the equipment and generalized steps to follow in order to standardize the method to be used to determine holdover time of anti-icing fluids during inclement weather such as freezing rain or snow.

2. EQUIPMENT

2.1 TEST STAND

A typical test stand is illustrated in Figure 1. There shall be no flanges or obstructions close to the edges of the panels that could interfere with the flow or air or fluids over the panels.

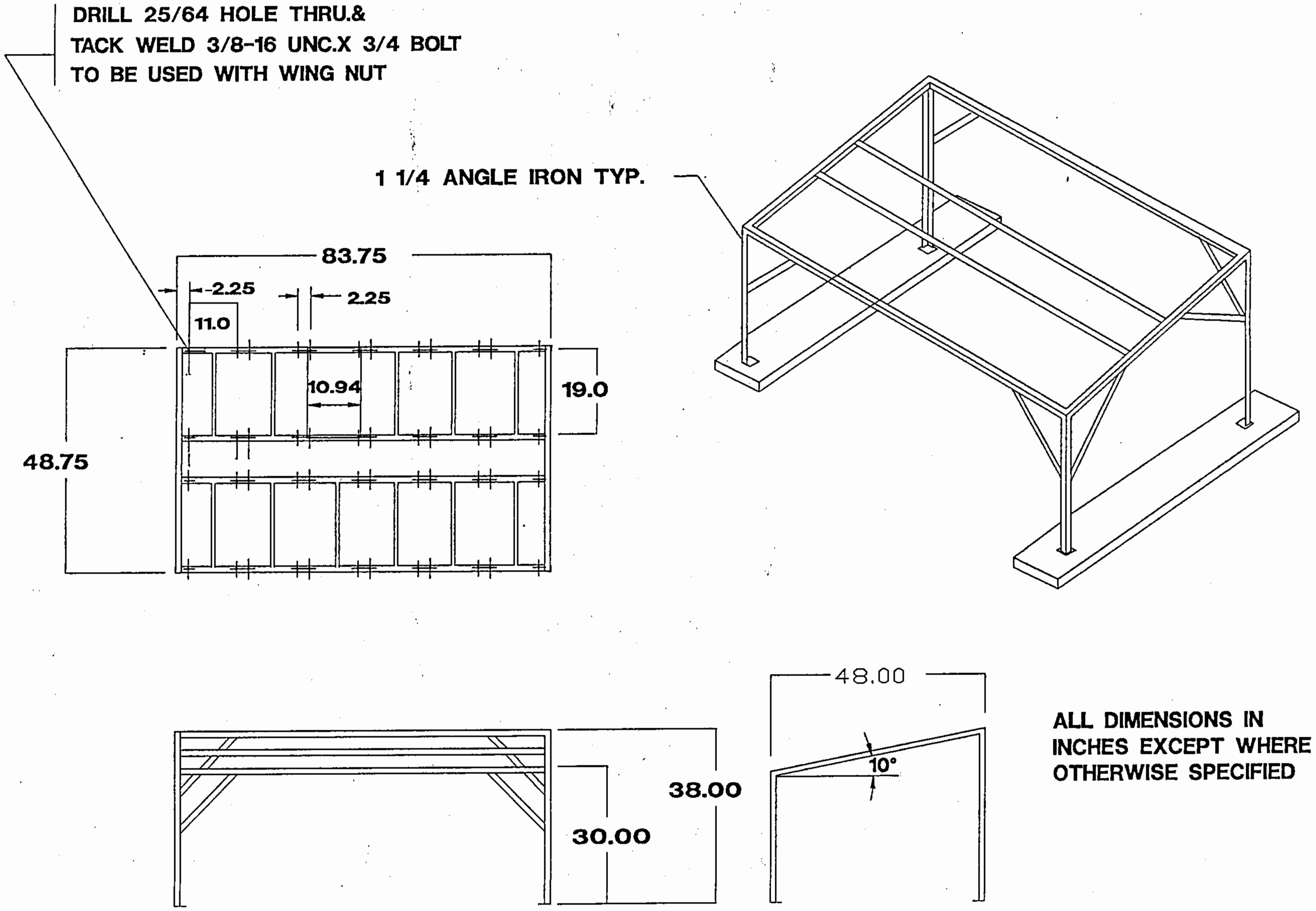
2.2 TEST PANELS

Alclad Aluminum 2024-T6 polished standard roll mill finish 30cm by 50cm by 0.32 cm, for a working area of 25cm by 40 cm.

Each panel shall be marked with lines and crosshairs as shown in Figure 2.

For attachment to the test stand, at least four holes shall be made, spaced along the two sides of each panel; the holes shall be within 2 cm from the panel edge.

FIGURE 1
RACK - DEICING FLUID TEST



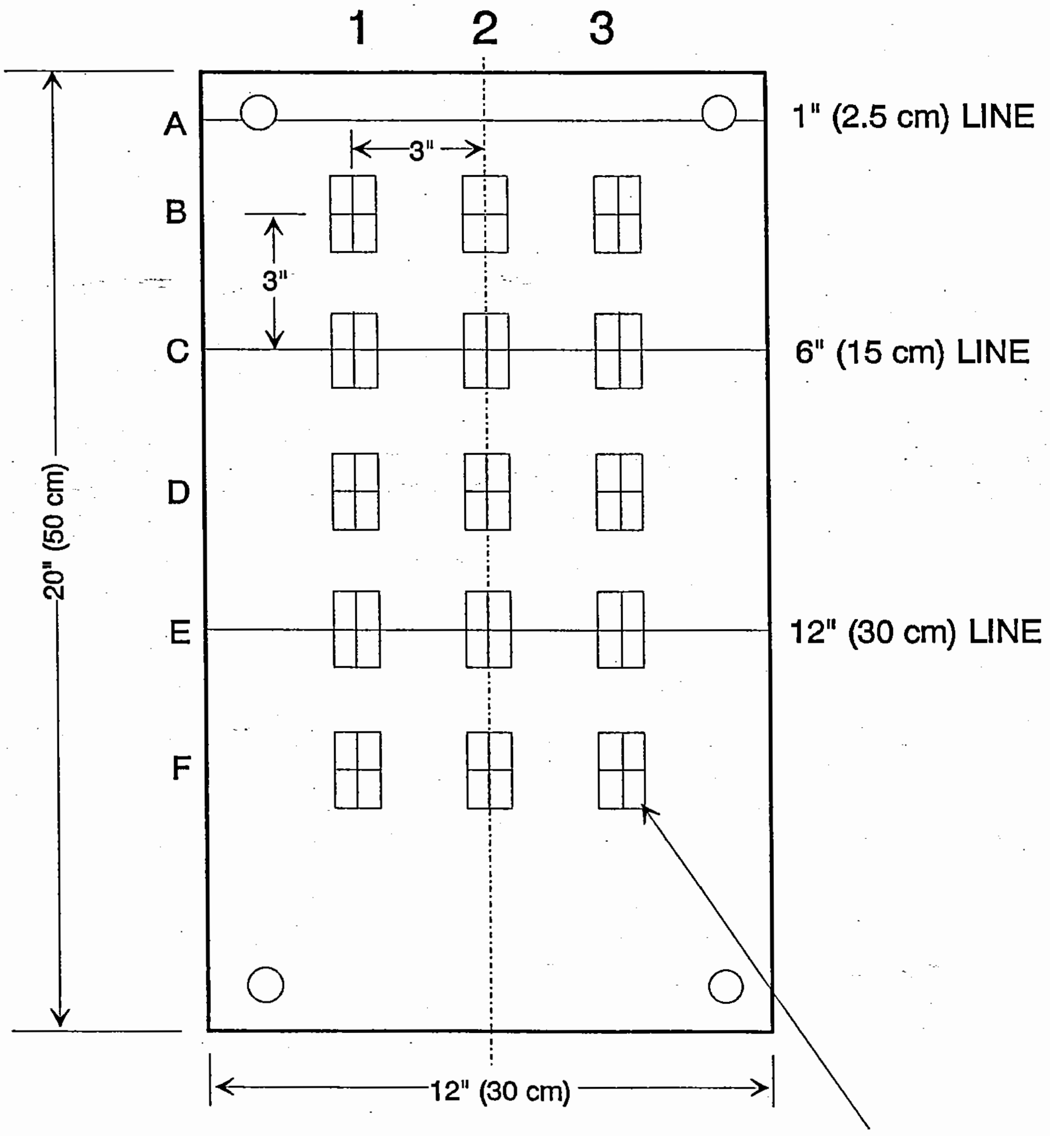
DRILL 25/64 HOLE THRU.&
TACK WELD 3/8-16 UNC.X 3/4 BOLT
TO BE USED WITH WING NUT

1 1/4 ANGLE IRON TYP.

ALL DIMENSIONS IN INCHES EXCEPT WHERE OTHERWISE SPECIFIED

FIGURE 2
FLAT PLATE MARKINGS

TYPICAL PLATE



Cross hairs in a square 2 cm on a side

2.3 FLUID APPLICATION

The fluids should be poured from a 400 ml (1 pint) beaker.

2.4 FILM THICKNESS GAUGE

Painter's wet film thickness gauge (1-60 mil gauge or equivalent).

2.5 METEOROLOGICAL EQUIPMENT

- Thermometer to record outside air temperature.
- Anemometer to record wind speed during the test.
- Relative humidity meter.
- Ombrometer or tipping bucket to measure precipitation during the test

2.6 ADDITIONAL EQUIPMENT

- Covering plastic sheet or tent (sufficiently large to cover back, face, and sides of structure) see photos 1 & 2.
- Stop watch to record failure times.
- Squeegee to remove fluids from the plates.
- Rubberized insulated gloves.

3. DE/ANTI-ICING FLUIDS

Only 100% concentrated fluids shall be used.
The following suppliers are expected to provide fluid:

- Union Carbide
- Hoechst
- Kilfrost
- Octagon

PHOTO 1 - Test stand with plastic tarp covering

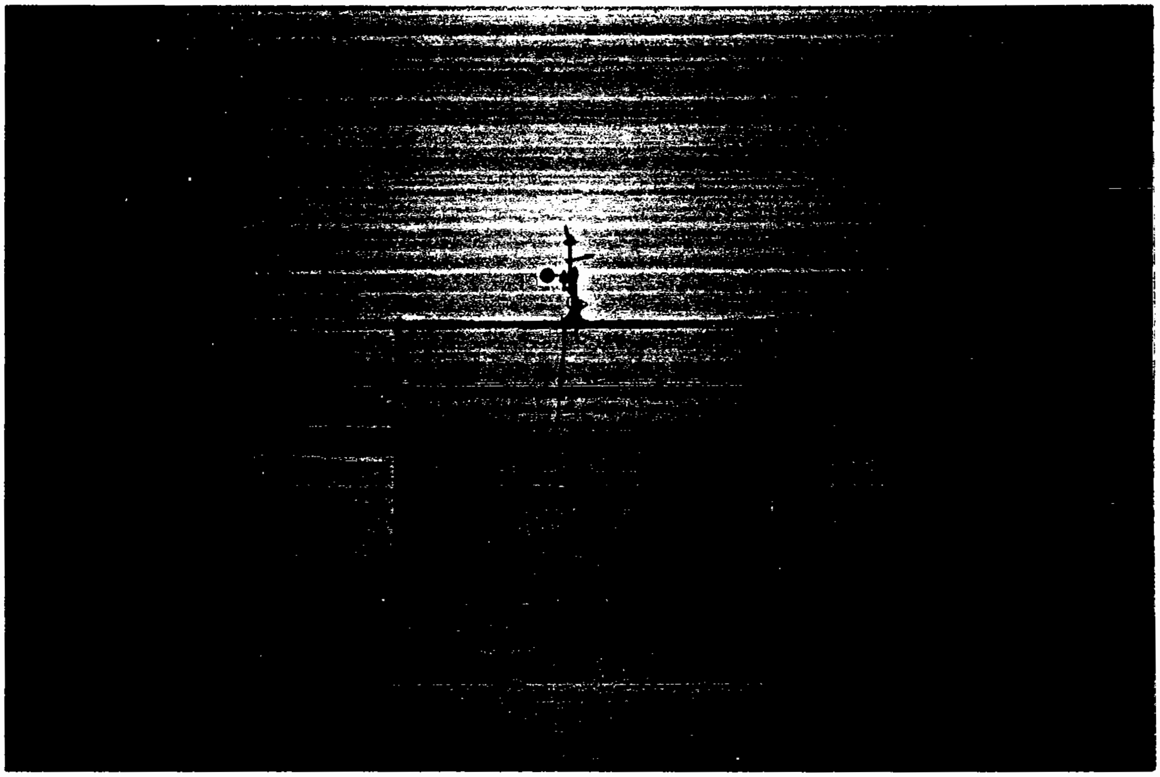
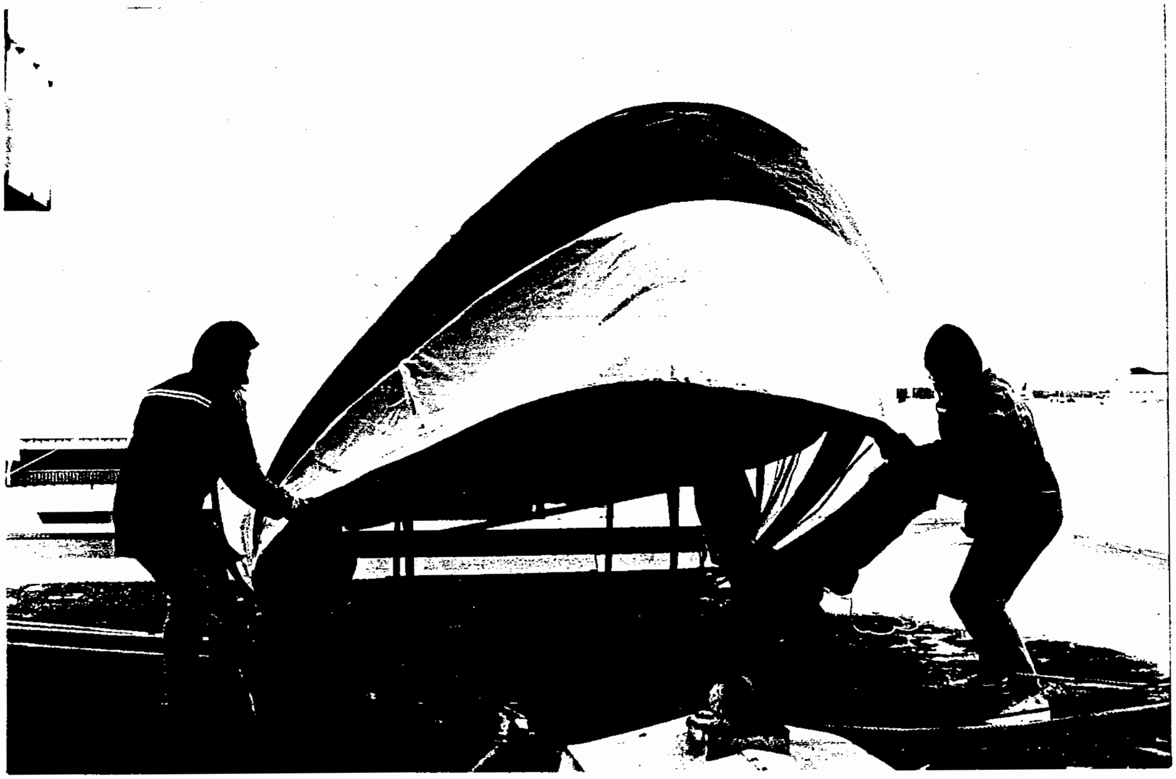


PHOTO 2 - Collapsible tent



4. PROCEDURE

4.1 SETUP

GENERAL

At arrival to the site, synchronize all watches that will be used during the test to the same time, for sites with a computerized meteorological data acquisition system, synchronize to the time being used by the computer. This will aid us in matching holdover data to the meteorological data.

TEST STAND

If there is any wind, orient the test fixture such that the test panels' top surfaces are facing into the wind direction at the beginning of the test.

---> /
WIND PANEL

If the wind shifts during the test, do not move the fixture; simply note the new wind direction and time on the data form.

There should be 6 panels used for testing and a seventh panel which will be used as a control plate. The control plate must be clean, dry and free of all contamination. The six other plates will have the fluid applied to them.

TEST PANEL PREPARATION

Before the start of each day's testing, wash the panels with a solvent such as isopropyl alcohol followed by a wash with an alkali detergent. Rinse thoroughly with water and dry.

Between tests wash the panels with pure glycol and/or isopropyl alcohol and wipe dry.

Place the panels on the fixture and attach to frame screws.

Protect the panels from snow or freezing rain by closing the tent over the stand.

Allow the panels to cool to outside air temperature.

4.2 TESTING

FLUID PREPARATION AND APPLICATION

Before applying fluids, squeegee the panel surface to remove any precipitation or moisture.

Apply the fluid to the panels, commencing at the upper edge of the test panel and working downward to the bottom edge. Always apply fluids to the panels in order, that is panel U, panel V, W, X, Y and Z. Ensure complete coverage by applying the fluid in a flooding manner. Touch up any unsatisfactory spots on any panel.

When all the panels are covered, record the actual time on the test data form in the space "START TIME:". Allow the fluid to settle for 10 minutes for Type II and for Type 1.5 fluids.

After the waiting time has elapsed, measure the fluid thickness at the 2.5, 15 and 30 cm lines (A, C, and E in Figure 2.). Measure at the centre of each line. Begin with panel U and proceed to panels V, W, X, Y and Z in order. Remeasure panel U. With each measurement at the 2.5 cm line, record the time at which the measurement is taken.

USING A CAKE PAN TO RECORD PRECIPITATION

For sites using cake pans to record the total accumulated precipitation, clean and dry the pans. Pour in enough fluid to cover the bottom and wet the sides of the pan. Carefully weigh the pan with the fluid. Record the exact dimensions of the pan needed to calculate the surface area.

Expose the pan to the precipitation at the same time the plates are exposed to precipitation, note the exact time that the pan was exposed. When the test has finished, cover the pan with a clean, dry, solid cover and bring to the scale for weighing. Record the exact time that the pan was covered. Before weighing after the test, clean and dry the outside of the pan and ensure that nothing is on or inside the pan that could distort the weight. Measurement errors can seriously corrupt the usefulness of the results.

MANUAL METEROLOGICAL DATA RECORDING

Air temperature and relative humidity need to be recorded only at the start and end of the test as the changes are gradual. Some relative humidity gauges, such as the L-3310-72 & -74 from Cole-Parmer, have a response time in the order of 45 minutes. Readings should not be taken before this time has elapsed.

Wind speed and direction need to be recorded frequently during the test (every 1-2 minutes). For sites with an ombrometer or tipping bucket, readings should also be taken on a frequent basis as precipitation rates are rarely steady. Record all meterological data on the sheets provided, be sure to note any abnormalities or changes in the data as well as in the precipitation type.

HOLDOVER TIME TESTING

Remove the cover from the stand at soon as possible after the final thickness measurement. Record the actual time (ie. time of day, in 24 hr format) on the data form in the space "**PLATES EXPOSED TO PRECIPITATION AT ACTUAL TIME:**" and reset the stop watch to 0.

Record the elapsed time (from time of exposure to precipitation) in minutes (and half minutes) for each of the three points on the lines B, C, D, E & F to reach the END CONDITION (described below).

Record the time that contamination first occurs on the plate. This is defined when a point failure (same as crosshair failure) occurs anywhere on the plate that is at least 1" from all sides.

Continue testing for 60 minutes or until all five lines have failed. If this has not occurred within 60 minutes, end the test and if the conditions warrant, begin a new test.

END CONDITIONS

A crosshair is considered failed if:

- There is a visible accumulation of snow (not slush, eg. white snow) on the fluid at the crosshair when viewed from the front (ie. perpendicular to the plate). The crosshair does **NOT** need to be obscured (as was the case in the 1990-1991 test season), you are looking for an indication that the fluid can no longer accommodate the precipitation at this point.

or

- Ice (or crusty slush) has formed on the crosshair (look for ice crystals). This condition is only applicable during freezing rain/drizzle or during a mixture of snow and freezing rain/drizzle.

As these determinations are subjective in nature, the following is **very important**:

- Whenever possible, have the same individual make the determination that a crosshair has failed.
- When making such a determination, ensure consistency in the criteria used to call the end of a test.
- Under light snow conditions, snow may sometimes build up on the fluid and then be absorbed later as the fluid accommodates for it. If this occurs, record the first time snow builds up and note (in the comments section) that there was an "un-failure" at a specific crosshair

or line (eg. B3) and the time at which this crosshair or line failed again.

4.3 END OF TEST

At the end of the test as the plate is being cleaned record for each plate any of the following occurrences:

1) There are some frozen patches on the plate itself;
2) A sheet of ice (not necessarily covering a large area) has formed on the fluid itself but has not reached the plate;
3) Any case where the fluid is difficult to remove not covered by cases 1 or 2, eg. The fluid/snow mixture has a paste-like consistency.

Record the type and extent of contamination on the control plate. For example note if the plate is covered in a light fluffy snow, or light ice, or any other distinguishing features of the contamination.

Once the test has ended, wipe the plates and cleanse with isopropyl alcohol and/or pure glycol. Restart the testing procedure and continue as long as the weather conditions warrant.

EQUIPMENT USED AT DORVAL

QTY.	ITEM	DESCRIPTION
1	Ombrometer	Thies Model 5.4031.11.000, resolution 0.005 mm, maximum rate 2 mm/min (24 V DC).
1	Anemometer	Qualimetrics Model 2031, DC Generator ≈ 5.5 mV/mph, 0-100 mph ±1%, with heater model 20201 (115 V AC)
1	Temperature & Humidity	Qualimetrics Model 5124-D, -30°C to 50°C ±0.15%, 0% to 100% RH ±2%
1	Signal Conditioning Modules	Qualimetrics: Enclosure/Power Supply Model 1020 (115 V AC) Ombrometer Module Model 1600 Anemometer Module Model 1202 Temperature Module Model 1419-A Relative Humidity Module Model 1500
1	Computer Interface	Qualimetrics Model 1799-A, RS-232, 1 to 10 channels, 10 sec. to 1 hr. sampling rate.
2	Thickness Gauge	Paul N. Gardner Company
3	Test Stands	2 Flat Plate Stands 1 Stand for Wing Section
1	Tent Cover	Warner Shelter Systems Ltd. Covers flat plate test stand, collapsible with little effort.
	Miscellaneous	Flood Lights (2 x 500 watts). Stop watches. Squeegee. Computer to record meteorological data.

LOCATION: DATE: RUN NUMBER: APS

REMEMBER TO SYNCHRONIZE TIME START TIME: FINISH TIME: CASP

FLUID FILM THICKNESS MEASUREMENTS

		PLATE u	PLATE v	PLATE w
TIME FROM START		: min:sec	: min:sec	: min:sec
THICKNESS	2.5 cm LINE	mils	mils	mils
	15 cm LINE	mils	mils	mils
	30 cm LINE	mils	mils	mils

PLATE x	PLATE y	PLATE z	PLATE u
: min:sec	: min:sec	: min:sec	: min:sec
mils	mils	mils	mils
mils	mils	mils	mils
mils	mils	mils	mils

CONTROL PLATE:

COMMENTS:

PERFORMED BY: ASSISTED BY:

PLATES EXPOSED TO PRECIPITATION AT (ACTUAL TIME):

TIME TO FAILURE FOR INDIVIDUAL CROSSHAIRS (MINUTES)

	u			v			w		
FLUID NAME									
B1 B2 B3									
C1 C2 C3									
D1 D2 D3									
E1 E2 E3									
F1 F2 F3									
TIME TO FIRST CONTAMINATION									
DIFFICULTIES IN REMOVING FLUID (ICE, etc.)									

	x			y			z		
FLUID NAME									
B1 B2 B3									
C1 C2 C3									
D1 D2 D3									
E1 E2 E3									
F1 F2 F3									
TIME TO FIRST CONTAMINATION									
DIFFICULTIES IN REMOVING FLUID (ICE, etc.)									