TP 15375E

Final Version 1.0
December 2017

TESTING OF ENDURANCE TIMES ON EXTENDED FLAPS AND SLATS (2016-17)

Prepared for the
Transportation Development Centre
In cooperation with
Transport Canada Civil Aviation
and the
Federal Aviation Administration
William J. Hughes Technical Center

TP 15375E

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by: Marco Ruggi and Benjamin Bernier

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Un sommaire français se trouve avant la table des matières.

PREFACE

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

- To develop holdover time data for all newly-qualified de/anti-icing fluids and update and maintain the website for the holdover time guidelines;
- To evaluate fluid holdover times for snow at very cold temperatures close to -25°C;
- To conduct heavy snow research to determine the highest usable precipitation rate (HUPR) for which operations are permitted;
- To evaluate the effects of deploying flaps/slats, prior to takeoff, on fluid protection times;
- To conduct general and exploratory de/anti-icing research;
- To update the regression coefficient report with the newly-qualified de/anti-icing fluids; and
- To update the source documents used by Transport Canada and the Federal Aviation Administration for the maintenance and publication of the holdover time guidance material.

The research activities of the program conducted on behalf of Transport Canada during the winter of 2016-17 are documented in four reports. The titles of the reports are as follows:

- TP 15372E — Aircraft Ground De/Anti-Icing Fluid Holdover Time Development Program for the 2016-17 Winter;
- TP 15373E — Regression Coefficients and Equations Used to Develop the Winter 2017-18 Aircraft Ground Deicing Holdover Time Tables;
- TP 15374E — Aircraft Ground Icing Research General Activities During the 2016-17 Winter; and
- TP 15375E — Testing of Endurance Times on Extended Flaps and Slats (2016-17).

This report, TP 15375E, has the following objective:

- To conduct comparative testing with two equivalent airfoil models, configured with flaps and slats extended, to isolate and quantify the effects of aircraft orientation and rotation following anti-icing and during taxi on fluid endurance time.

This objective was met by conducting a series of tests at the PET airport test site using two airfoil models in various natural winter weather precipitation conditions.

PROGRAM ACKNOWLEDGEMENTS

This multi-year research program has been funded by Transport Canada with support from the Federal Aviation Administration, William J. Hughes Technical Center, Atlantic City, NJ. This program could not have been accomplished without the participation of many organizations. APS would therefore like to thank the Transportation Development Centre of Transport Canada, the Federal Aviation Administration, National Research Council Canada, and supporting members of the SAE International G-12 Aircraft Ground Deicing Committees.

APS would also like to acknowledge the dedication of the research team, whose performance was crucial to the acquisition of hard data. This includes the following people: Brandon Auclair, Steven Baker, Stephanie Bendickson, Benjamin Bernier, Chloë Bernier, Chris D'Avirro, John D'Avirro, Ben Falvo, Michael Hawdur, Gabriel Maatouk, Philip Murphy, Dany Posteraro, Marco Ruggi, Saba Tariq, David Youssef, and Nondas Zoitakis.

Special thanks are extended to Antoine Lacroix, Howard Posluns, Yvan Chabot, Warren Underwood and Charles J. Enders, who on behalf of the Transportation Development Centre and the Federal Aviation Administration, have participated, contributed and provided guidance in the preparation of these documents.

PROJECT ACKNOWLEDGEMENTS

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Several research reports for testing of de/anti-icing technologies were produced for previous winters on behalf of Transport Canada. These are available from the Transportation Development Centre (TDC). Several reports were produced as part of this winter's research program. Their subject matter is outlined in the preface. The work described in this report was, in part, co-sponsored by the Federal Aviation Administration (FAA).

16. Abstract

Recent research has indicated that early de/anti-icing fluid failure can occur on aircraft flaps and slats if these surfaces are left deployed during the holdover time. The greater surface angles increase the precipitation catch factor and can cause the fluid to flow-off more readily causing a potential for reductions to holdover times. This can pose a problem for operators who deploy flaps/slats prior to anti-icing.

Due to operational concerns, flaps and slats related testing has been ongoing since the winter of 2009-10 and has since included several testing protocols and platforms. For the winter of 2016-17, a new comparative airfoil testing approach was proposed to quantify the effects of aircraft orientation and rotation following anti-icing on fluid endurance time. The information obtained during the winter of 2016-17 would be used to better interpret the data already collected in previous years using flat plates and full-scale aircraft.

After having reviewed each data set collected, the static 20º flat plate data was chosen as the basis of the analysis. It is the largest data set, and is supported by the static full-scale aircraft data. Both of these data sets indicate an expected holdover time of 55% of the baseline 10º plate. In actual operations however, some of the reduction in fluid endurance time resulting from the higher angled surfaces could be offset by the rotation of the aircraft during taxi. Based on the comparative rotating vs. static airfoil testing, the average improvement in fluid endurance time for the rotating surface, referred to as the augmentation factor, is calculated to be 39% of the static surface endurance time. When adjusting the average static flat plate and full-scale results of 55% by a factor of 1.39 to account for rotation, the end result is an expected HOT performance on extended flaps and slats of 76% of the current HOTs.

17. Key Words Endurance Time, Holdover Time, Allowance Time, Flaps, Slats, Deployed Surfaces, Flat Plate, Airfoil, Full-Scale, A300, B737, A319, UPS, Southwest Airlines, Air Canada, Type I, Type II, Type III, Type IV, Taxi Orientation, Rotation During Taxi, Wind Tunnel	18. Distribution Statement Limited number of copies available from the Transportation Development Centre

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

Plusieurs rapports de recherche sur des essais tenus au cours de nombreux hivers, sur les technologies d'antigivrage et de dégivrage, ont été produits pour Transports Canada. Ils sont disponibles au Centre de développement des transports (CDT). Plusieurs rapports ont été produits dans le cadre du programme de recherche de l'hiver en cours. Leur objet est défini à la préface. Les travaux décrits dans le rapport ont été en partie coparrainés par la Federal Aviation Administration (FAA).

16. Résumé

Des recherches récentes ont indiqué que des défaillances prématurées de liquide d'antigivrage ou de dégivrage peuvent se produire sur les volets et les becs de bord d'attaque d'aéronefs, lorsque ces surfaces restent déployées durant la durée d'efficacité. Les angles de surface plus marqués augmentent le facteur de capture de précipitation et peuvent causer plus facilement l'écoulement du liquide, créant ainsi une possibilité de réduction des durées d'efficacité. Cette situation peut causer un problème aux exploitants qui déploient les volets et les becs de bord d'attaque avant l'antigivrage.

En raison de préoccupations opérationnelles, des essais sur les volets et les becs de bord d'attaque ont cours depuis l'hiver de 2009-2010 et, durant cette période, ont utilisé plusieurs protocoles et de plates-formes d'essais. Au cours de l'hiver 2016-2017, une nouvelle méthode comparative d'essais sur les surfaces portantes a été proposée, afin de mesurer les effets de l'orientation et de la rotation de l'aéronef sur la durée d'endurance des liquides, suite à l'antigivrage. L'information obtenue au cours de l'hiver 2016-2017 servirait à mieux interpréter les données déjà recueillies les années précédentes avec des plaques planes et des aéronefs pleine grandeur.

Suite à la révision de chaque ensemble de données recueillies, la plaque plane statique de 20º a été choisie comme base d'analyse. Il s'agit de l'ensemble de données le plus volumineux et il est appuyé par les données recueillies avec l'aéronef statique pleine grandeur. Ces deux ensembles de données indiquent une durée d'efficacité prévue de 55% de celle de la plaque de base de 10º. En mode d'exploitation réelle cependant, une partie de la réduction de durée d'endurance du liquide causée par l'angle plus grand des surfaces pourrait être compensée par la rotation de l'aéronef durant la circulation au sol. Basé sur les essais comparatifs sur les surfaces portantes rotatives et statiques, l'amélioration moyenne de durée d'endurance du liquide dans le cas d'une surface rotative, désignée facteur d'augmentation, a été calculée à 39% de la durée d'endurance sur une surface statique. Lorsqu'on ajuste la moyenne de 55% des résultats sur plaque plane statique et sur aéronef pleine grandeur par un facteur de 1.39 pour tenir compte de la rotation, le résultat donne une performance de durée d'efficacité prévue sur des volets et des becs de bords d'attaque déployés de 76% des durées d'efficacité actuelles.

17. Mots clés Durée d'endurance, durée d'efficacité, marge de tolérance, volets, becs de bord d'attaque, surfaces déployées, plaque plane, surface portante, pleine grandeur, A300, B737, A319, UPS, Southwest Airlines, Air Canada, type I, type II, type III, type IV, orientation de la circulation au sol, rotation en cours de circulation au sol, soufflerie	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

Recent research has indicated that early de/anti-icing fluid failure can occur on aircraft flaps and slats if these surfaces are left deployed during the holdover time. The greater surface angles increase the precipitation catch factor and can cause the fluid to flow-off more readily causing a potential for reductions to holdover times. This can pose a problem for operators who deploy flaps/slats prior to anti-icing.

Due to operational concerns, flaps and slats related testing has been ongoing since the winter of 2009-10 and has since included a multitude of testing protocols and platforms including: wind tunnel testing, flat plate testing, full-scale aircraft validation, and airfoil model testing. For the winter of 2016-17, a new comparative airfoil testing approach was proposed to quantify the effects of aircraft orientation and rotation following anti-icing and during taxi on fluid endurance time. The information obtained during the winter of 2016-17 would be used to better interpret the data already collected in previous years using flat plates and full-scale aircraft.

Test Results

Testing was conducted over several years and resulted in the collection of a variety of datasets, each with a unique set of parameters and limitations as to how the data could be used. After having reviewed each dataset, it was determined that the 20º flat plate data, the full-scale aircraft data, and the rotating vs. static airfoil data were most relevant and should be considered when determining the expected holdover time performance on extended flaps and slats.

The basis of the analysis is the static 20º flat plate data (which is the largest dataset), supported by the static full-scale aircraft data. Both these datasets indicate an expected holdover time of 55 percent of the baseline 10º plate. In actual operations however, some of the reduction in fluid endurance time resulting from the higher angles surfaces could be offset by the rotation of the aircraft during taxi. Based on the comparative rotating vs. static airfoil testing, the average improvement in fluid endurance time for the rotating surface, referred to as the augmentation factor, is calculated to be 39 percent of the static surface endurance time. When adjusting the average static flat plate and full-scale results of 55 percent by a factor of 1.39 to account for rotation, the result is an expected holdover time performance on extended flaps and slats of 76 percent of the current holdover times.

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SOMMAIRE

Des recherches récentes ont indiqué que des défaillances prématurées de liquide d'antigivrage ou de dégivrage peuvent se produire sur les volets et les becs de bord d'attaque d'aéronefs, lorsque ces surfaces restent déployées durant la durée d'efficacité. Les angles de surface plus marqués augmentent le facteur de capture de précipitation et peuvent causer plus facilement l'écoulement du liquide, créant ainsi une possibilité de réduction des durées d'efficacité. Cette situation peut causer un problème aux exploitants qui déploient les volets et les becs de bord d'attaque avant l'antigivrage.

En raison de préoccupations opérationnelles, des essais sur les volets et les becs de bord d'attaque ont cours depuis l'hiver de 2009-2010 et, durant cette période, ont utilisé une multitude de protocoles et de plates-formes d'essais, y compris des essais en soufflerie, des essais sur plaque plane, une validation avec un aéronef pleine grandeur et des essais sur modèle de surface portante. Au cours de l'hiver 2016-2017, une nouvelle méthode comparative d'essais sur les surfaces portantes a été proposée, afin de mesurer les effets de l'orientation et de la rotation de l'aéronef sur la durée d'endurance des liquides, suite à l'antigivrage et durant la circulation au sol. L'information obtenue au cours de l'hiver 2016-2017 servirait à mieux interpréter les données déjà recueillies les années précédentes avec des plaques planes et des aéronefs pleine grandeur.

Résultats des essais

Les essais se sont poursuivis sur plusieurs années et se sont soldés par la collecte d'une variété d'ensembles de données, chacun possédant un ensemble unique de paramètres et de limites sur l'utilisation des données. Suite à la révision de chaque ensemble de données, il a été établi que les données de la plaque plane de 20º, celles de l'aéronef pleine grandeur, ainsi que celles de la surface portante statique comparée à celles de la surface rotative, étaient des plus pertinentes et devraient être prises en considération dans l'établissement de la performance prévue de la durée d'efficacité sur des volets et becs de bord d'attaque déployés.

L'analyse est basée sur les données de la plaque plane de 20º (qui est l'ensemble de données le plus volumineux), confirmées par les données de l'aéronef statique pleine grandeur. Ces deux ensembles de données indiquent une durée d'efficacité de 55 pourcent de la plaque de 10º de base. En mode d'exploitation réelle cependant, une partie de la réduction de durée d'endurance du liquide causée par l'angle plus grand des surfaces pourrait être compensée par la rotation de l'aéronef durant la circulation au sol. Basé sur les essais comparatifs sur les surfaces portantes rotatives et statiques, l'amélioration moyenne de durée d'endurance du liquide dans le cas d'une surface rotative, désignée facteur d'augmentation, a été calculée à

39 pourcent de la durée d'efficacité sur une surface statique. Lorsqu'on ajuste la moyenne de 55 pourcent des résultats sur plaque plane statique et sur aéronef pleine grandeur par un facteur de 1.39 pour tenir compte de la rotation, le résultat donne une performance de durée d'efficacité prévue sur des volets et des becs de bords d'attaque déployés de 76 pourcent des durées d'efficacité actuelles.

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GLOSSARY

AC	Air Canada
APS	APS Aviation Inc.
ARP	Aerospace Recommended Practice
EG	Ethylene Glycol
FAA	Federal Aviation Administration
HOT	Holdover Time
ISO	International Organization for Standardization
MSC	Meteorological Service of Canada
NRC	National Research Council (Canada)
OAT	Outside Air Temperature
PET	Montréal - Pierre Elliott Trudeau International Airport
SAE	SAE International
SWA	Southwest Airlines
TC	Transport Canada
TDC	Transportation Development Centre
UPS	United Parcel Service

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1. INTRODUCTION

Under winter precipitation conditions, aircraft are cleaned with a freezing point depressant fluid and protected against further accumulation by an additional application of such a fluid, possibly thickened to extend the endurance time. Prior to the 1990s, aircraft ground deicing had not been extensively researched. As a result of this need for advancement, the aircraft ground icing research program was developed with the aim of overcoming this lack of knowledge.

Since the early 1990s, the Transportation Development Centre (TDC), Transport Canada (TC) has managed and conducted de/anti-icing related tests at various sites in Canada; it has also coordinated worldwide testing and evaluation of evolving technologies related to de/anti-icing operations with the co-operation of the US Federal Aviation Administration (FAA), the National Research Council (Canada) (NRC), Meteorological Service of Canada (MSC), several major airlines, and deicing fluid manufacturers. There is still limited understanding of some aspects of the hazard and what further can be done to reduce remaining risks posed by the operation of aircraft in winter precipitation conditions. TDC is continuing its research, development, and testing and evaluation program with support from the FAA.

Under contract to the TDC, APS Aviation Inc. (APS) undertook a test program to further advance aircraft ground de/anti-icing research, technology, and information.

1.1 Background

Recent research has indicated that early de/anti-icing fluid failure can occur on aircraft flaps and slats if these surfaces are left deployed during the holdover time. The greater surface angles increase the precipitation catch factor and can cause the fluid to flow-off more readily causing a potential for reductions to Holdover Times (HOTs) (see Figure 1.1). This can pose a problem for operators who deploy flaps/slats prior to anti-icing.

Due to operational concerns, flaps and slats related testing has been ongoing since the winter of 2009-10 and has since included several testing protocols and platforms:

- Wind tunnel testing: High-performance wing model with hinged flap set to 20°;
- Flat plate testing: 10°/20°/35° plates in various configurations and orientations;
- Full-scale validation: Testing with A300 / B737 / A319 (with the support of UPS/SWA/Air Canada); and

- Airfoil model testing: Simple and slatted airfoil testing, both static and with a variety of rotation profiles.

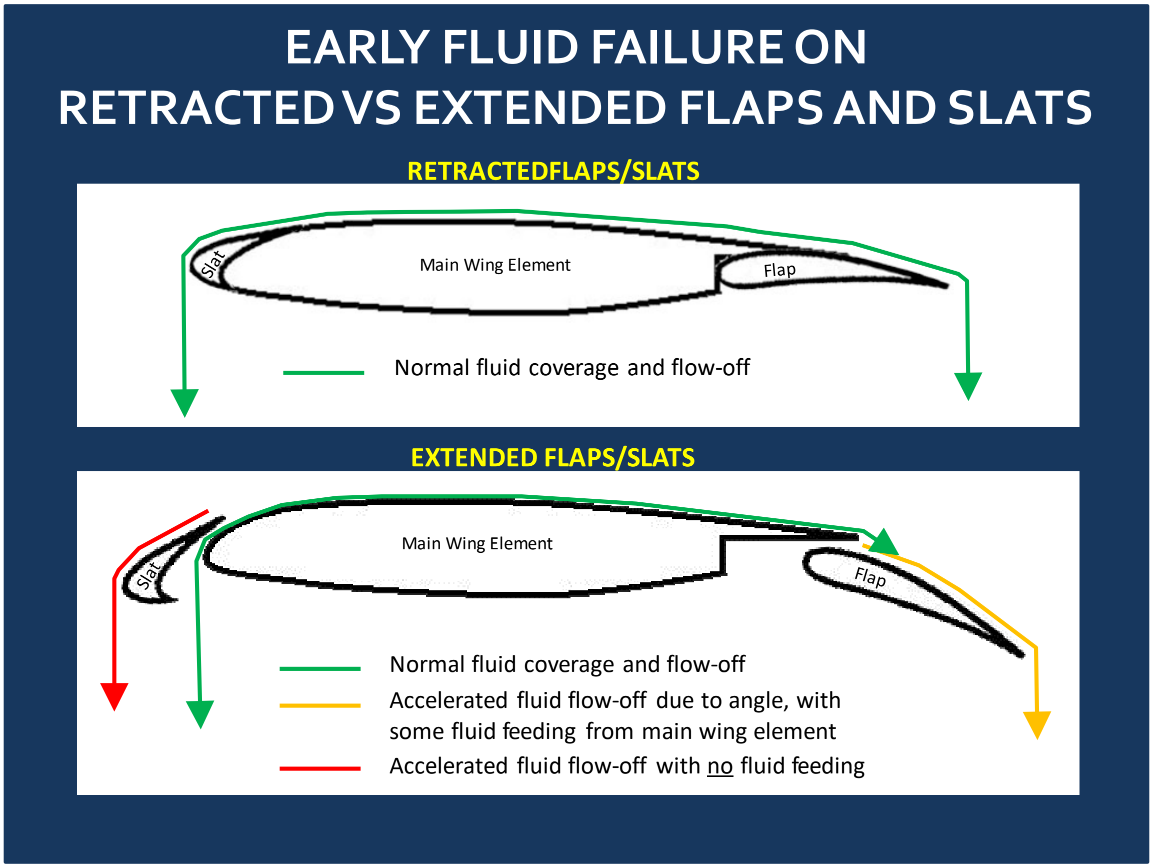

Figure 1.1: Early Fluid Failure on Retracted vs. Extended Flaps and Slats

As of 2011-12, aircraft and airfoil work was conducted with industry support from UPS, Southwest Airlines, and Air Canada. The research was conducted over multiple years, and the TC report, TP 15342E, *Testing of Endurance Times on Extended Flaps and Slats* (1) provides a detailed summary of the most relevant test results up to and including the winter of 2015-16. For analysis purposes, some final values from the report TP 15342E have been included as part of this report.

The data collected up to the winter of 2015-16 contains flat plate, airfoil model and full-scale test data. For the winter of 2016-17, a new comparative airfoil testing approach was proposed to provide information on the effects of aircraft orientation and rotation following anti-icing and during taxi on fluid endurance time. The information obtained during the winter of 2016-17 would be used to better interpret the data already collected in previous years using flat plates and full-scale aircraft.

1.2 Objective

The objective is to conduct comparative testing with two equivalent airfoil models, configured with flaps and slats extended, to isolate and quantify the effects of aircraft orientation and rotation following anti-icing and during taxi on fluid endurance time.

The information obtained during the winter of 2016-17 would be used to better interpret the data already collected in previous years using flat plates and full-scale aircraft.

The sections of the TDC work statement pertaining to the work described in this report are provided in Appendix A.

1.3 Report Format

The following list provides short descriptions of the main sections of this report:

a) Section 2 provides a summary of previous relevant testing results;
b) Section 3 provides a description of the methodology used to carry out the tests;
c) Section 4 provides the 2016-17 testing data log;
d) Section 5 summarizes the airfoil testing results and analysis; and
e) Section 6 provides the conclusions and logic path used to develop guidance.

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2. RELEVANT PREVIOUS TESTING RESULTS

This section provides a summary of relevant previous testing results that were collected from the winter of 2009-10 to 2015-16. For a detailed account of the testing and results described in this Section 2, please refer to the TC report, TP 15342E, *Testing of Endurance Times on Extended Flaps and Slats* (1).

2.1 Flat Plate Testing

HOTs are developed using 10º plates using testing protocols described in the following SAE International (SAE) documents and TC reports: Aerospace Recommended Practice (ARP), ARP5485, *Endurance Time Tests for Aircraft Deicing/Anti-icing Fluids: SAE Type II, III, and IV* (2), ARP5945, *Endurance Time Tests for Aircraft Deicing/Anti-Icing Fluids: SAE Type I* (3), as well as in the TC report, TP 13130E, *Aircraft Full-Scale Test Program for the 1996/97 Winter* (4). Fluid performance on a 10º plate has historically been found to be correlated with fluid performance on full-scale aircraft, whereby 33 percent fluid failure on the 10º flat plate corresponds to first failure on the aircraft.

As part of the previous research, 20º and 35º simple and nested plates were used to simulate aircraft flaps and slats in the extended configuration. The angles selected were based on aircraft schematics and actual aircraft measurements. A total of 386 comparative tests were conducted in both natural snow and simulated freezing precipitation; all tests were conducted in headwind orientation in accordance with standard endurance time testing protocols. Reduction in fluid endurance time on the higher angle surfaces was compared to the baseline 10º plate results.

As testing progressed, focus shifted to the 20º simple plate results as this was found to be best correlated with the full-scale testing fluid failure results; this work is summarized in Section 0. Table 2.1 provides a summary of the average fluid endurance time performance on a 20º plate as compared the baseline 10º plate. Of particular importance is the value for the Type II/IV fluid tests, which was on average 55 percent; Type II/IV fluids are most representative to operations and hence why the majority of the testing was performed with this type of fluid.

Table 2.1: Average 20º Simple Plate Endurance Time Ratio

Fluid Type	# of Tests	Average Ratio (Compared to 10º Baseline Plate)	StdDev of Ratio
I	46	**84%**	17%
III - Hot	27	**72%**	15%
III - Cold	18	**65%**	14%
II/IV	102	**55%**	16%
Total	193		

2.2 Full-Scale Aircraft Testing

In order to validate and support the flat plate testing, full-scale testing was conducted. The objective was to compare the performance of de/anti-icing fluids on full-scale aircraft surfaces with the performance of de/anti-icing fluids on flat plates mounted at 10°, 20º, and 35º in both simple and nested configurations. Testing was conducted during the winters of 2010-11 to 2015-16 in collaboration with United Parcel Service (UPS) Airlines, Southwest Airlines (SWA), and Air Canada (AC).

To better understand the reduction in fluid endurance time experienced on a wing with the flaps and slats in extended configuration, the time when 10 percent of the whole wing demonstrated signs of fluid failure was correlated to the average endurance time of the baseline 10º plate. Table 2.2 and Table 2.3 demonstrate the results for both Type I fluid tests and Type IV fluid tests, respectively.

Of particular importance is the value for the Type IV fluid tests, which was on average 55 percent; Type II/IV fluids are most representative to operations hence why the majority of the testing was performed with these types of fluid. The 55 percent average value shown in Table 2.3 is also in-line with the Type II/IV results obtained from the flat plate testing shown in Table 2.1.

Table 2.2: 10 Percent Wing Failure vs. Standard Plate Failure – Type I Data Only

Run #	Fluid/ Orientation	Normalized Time of 10% Wing Failure (min)	*Non Corrected Time*	AVG. Endurance Time of 10º Plate (min)	Time of 10% Wing Failure as Percentage of 10º Standard Plate Failure (%)
5*	**TI / Head Wind**	35.9	49.0	13.9	258%
6	**TI / Tail Wind**	15.4	23.9	57.1	27%
9	**TI / Tail Wind**	3.4	3.0	16.3	21%
				Average	**102%**
				Average without potential outlier	**24%**

*Potential outlier data point.

Table 2.3: 10 Percent Wing Failure vs. Standard Plate Failure – Type IV Extended Configuration Data Only

Run #	Fluid/ Orientation	Normalized Time of 10% Wing Failure (min)	*Non Corrected Time*	AVG. Endurance Time of 10º Plate (min)	Time of 10% Wing Failure as Percentage of 10º Standard Plate Failure (%)
2	**TIV / Head Wind**	55.7	65.7	89.4	62%
3	**TIV / Head Wind**	33.7	37.0	58.7	57%
4	**TIV / Head Wind**	91.8	85.6	133.0	69%
7	**TIV / Tail Wind**	17.4	12.5	73.1	24%
8	**TIV / Tail Wind**	76.2	68.5	103.7	74%
10	**TIV / Tail Wind**	48.7	38.5	114.3	43%
11	**TIV / Tail Wind**	64.0	64.0	91.0	70%
SWA 1 STBD (Extended)	**TIV / Head Wind**	19.8	20.0	52.2	38%
SWA 2 STBD (Extended)	**TIV / Head Wind**	44.8	31.5	80.4	56%
				Average	**55%**

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3. METHODOLOGY

This section describes the overall approach, test parameters and experimental procedures followed during the winter of 2016-17. For additional information, see the detailed test procedure in Appendix B.

APS measurement instruments and test equipment are calibrated and verified on an annual basis. This calibration is carried out according to a calibration plan derived from approved International Organization for Standardization (ISO) 9001:2008 standards, and developed internally by APS.

3.1 Test Location - APS Montreal P.E.T. Airport Test Site

Fluid endurance time testing during natural snow conditions was conducted by APS personnel at the APS test site (Photo 3.1) located at the Montreal - Pierre Elliott Trudeau International Airport (PET) in Montreal. The location of the test site is shown on the plan view of the airport in Figure 3.1.

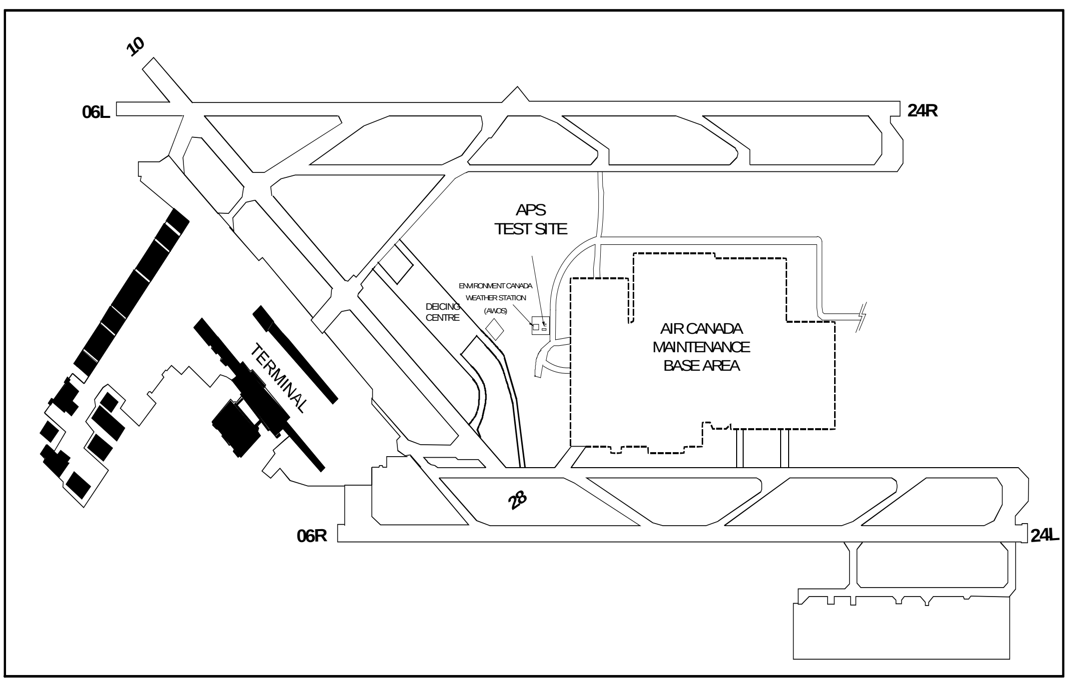

Figure 3.1 Plan View of APS Montreal-Trudeau Airport Test Site

3.2 General Procedure

Comparative testing was conducted using two airfoils which were built to be as close to identical as possible based on the materials and assembly procedures used. In addition, a baseline 10° plate was included in the test setup to record the endurance time according to ARP5485 or ARP5945. A 20° plate was included in the test setup to be used as the plate model best representing the full-scale deployed wing endurance time, and to add to the existing dataset. The airfoils were rotated as per the test plan requirements. The endurance times of the fluid on the four individual surfaces were compared. A diagram showing a top view of the general test setup is included in Figure 3.2. Photo 3.2 and Photo 3.3 demonstrates the general setup at the PET airport test site.

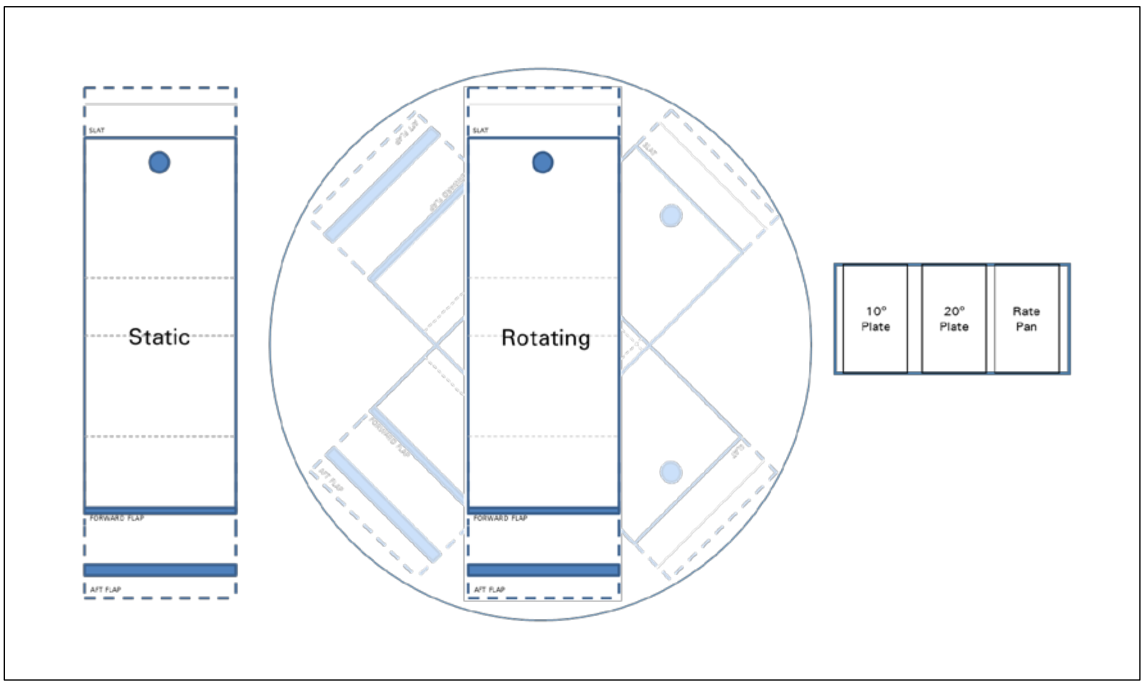

Figure 3.2: Top View of General Test Setup

3.2.1 Airfoil Calibration Testing Procedure

Testing was conducted to verify that both airfoils were equivalent, and that fluid applied to the two models would provide equal fluid endurance times. Testing was conducted using the two slatted airfoils in the same static orientations. Running both airfoils in tandem ensured that natural factors remained the same for both airfoils (temperature, rate, wind speed, snowflake size etc.) The airfoils were not rotated during these tests. The 10° and 20° plates were also included in the test setup.

3.2.2 Wind Direction Sensitivity Study Procedure

Testing was conducted to determine the effect of specific airfoil orientations on fluid performance with the intent of identifying possible orientations that may be associated with increased or decreased fluid endurance times. Testing was conducted using the two slatted airfoils in differing static orientations, the first in headwind configuration, and the second in different static orientations as per the test plan requirements. Running both airfoils in tandem ensured that natural factors remained the same for both airfoils (temperature, rate, wind speed, snowflake size etc.) The airfoils were not rotated during these tests. The 10º and 20º plates were also included in the test setup.

3.2.3 Comparative Static vs. Rotating Airfoil Testing

Testing was conducted to isolate the effect of rotation on airfoil endurance time (while keeping other variables constant). Running both airfoils in tandem ensured that natural factors remained the same for both airfoils (temperature, rate, wind speed, snowflake size etc.). One airfoil remained in headwind position, while the second airfoil was rotated throughout the test; one rotation profile was used for all tests (see Section 3.2.3.1). The magnitude of rotating effect was derived through comparison of static airfoil vs. rotating airfoil endurance time results. The 10º and 20º plates were also included in the test setup.

3.2.3.1 Airfoil Orientation Sequencing

An analysis conducted by Southwest Airlines provided a wind rose output of typical aircraft orientations for the time period following de/anti-icing until takeoff. APS conducted a post analysis and indicated that the general head / cross / tail orientation breakdown for the recorded operations could be simplified to 20 percent / 40 percent / 40 percent respectively in order to facilitate testing procedures. Further details can be found in the TC report, TP 15342E, *Testing of Endurance Times on Extended Flaps and Slats* (1).

To minimize the potential error in orientation sequencing due to under or over estimation of the fluid endurance time, the airfoil orientation sequencing was done in a continual 20-minute rotation cycle. Airfoil rotations were performed at the 4, 12, and 20-minute mark of each cycle. This rotation timing and the use of repeating cycles ensured the 20/40/40 headwind/crosswind/tailwind orientation ratios were maintained as closely as possible. Figure 3.3 illustrates an example of the airfoil orientation for a test in which the expected HOT is 60 minutes.

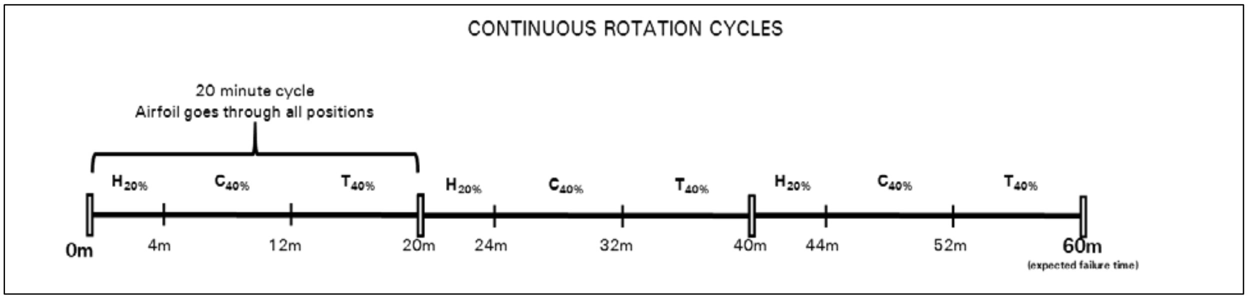

Figure 3.3: Airfoil Orientation Sequencing – Example of 60-minute Expected Holdover Time

3.3 Data Forms

The data forms used for the various test objectives are provided in the respective procedures described in Appendix B.

3.4 Test Surfaces

3.4.1 Test Plates

Flat plate endurance time testing was conducted using standard aluminum test plates. These test plates were positioned in different configurations using specially manufactured aluminum stands to achieve the desired angles. A schematic of a test plate is shown in Figure 3.4.

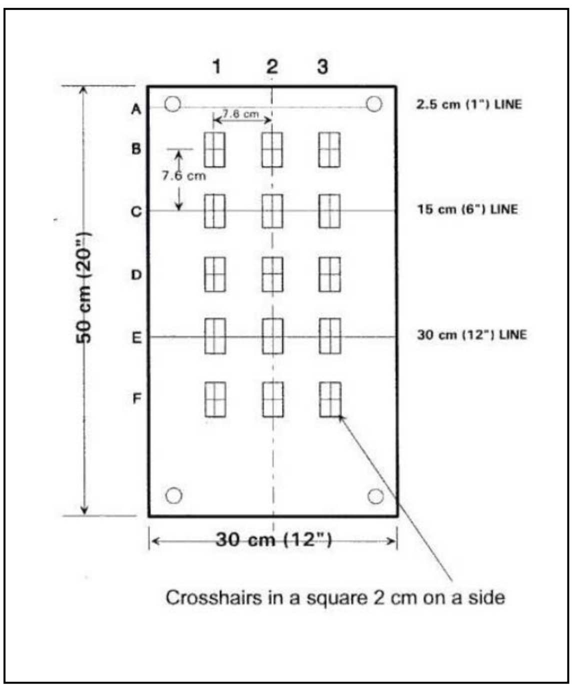

Figure 3.4: Schematic of Standard Holdover Time Test Plate

3.4.2 Fokker F28 Airfoil

TC currently owns two F28 airfoil models. One of these models was retrofitted by Southwest Airlines in 2014-15 to have slats and flaps modelled after those found on a Boeing 737. The second F28 model was modified in 2015-16 by M1 Composites using the same schematics and procedures used by Southwest Airlines, with the goal of creating an equivalent surface. The airfoils were able to be rotated during testing to simulate the rotation during aircraft taxi. The modified airfoils measured 2.8 meters (9 feet 2 inches) length, 0.8 meters (2 feet 8 inches) width, and the leading gap size was 0.2 mm (0.007 inches). Figure 3.6 provides the schematic which was designed by Southwest airlines and used as the basis for the modification of both airfoils. For the purpose of data logging in Table 4.2, Airfoil #1 refers to the airfoil modified by SWA, and Airfoil #2 refers to the airfoil modified by M1 Composites.

3.5 Equipment

The test equipment for standard HOT testing was used to conduct the flap and slat evaluation and are described for the respective procedures in Appendix B. The following subsections briefly describe some of the equipment used.

3.5.1 Wet Film Thickness Gauge

Wet film fluid thickness measurements were recorded during endurance time tests. Figure 3.5 shows the schematic of the wet film thickness gauges.

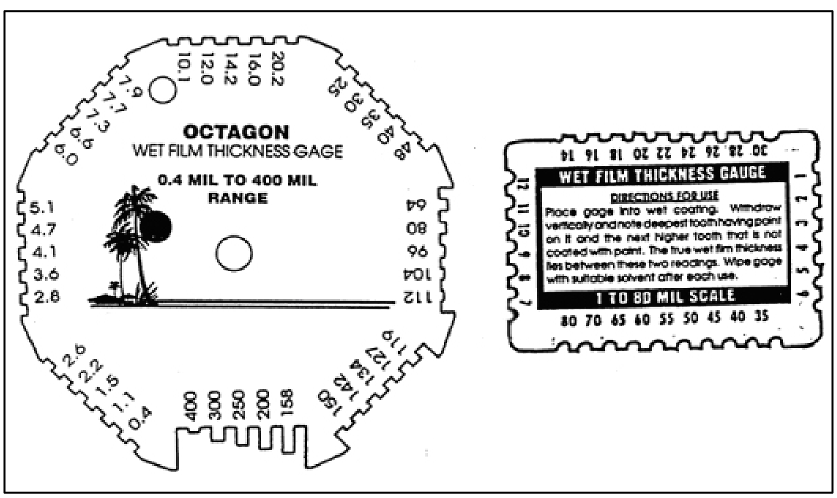

Figure 3.5: Wet Film Thickness Gauges

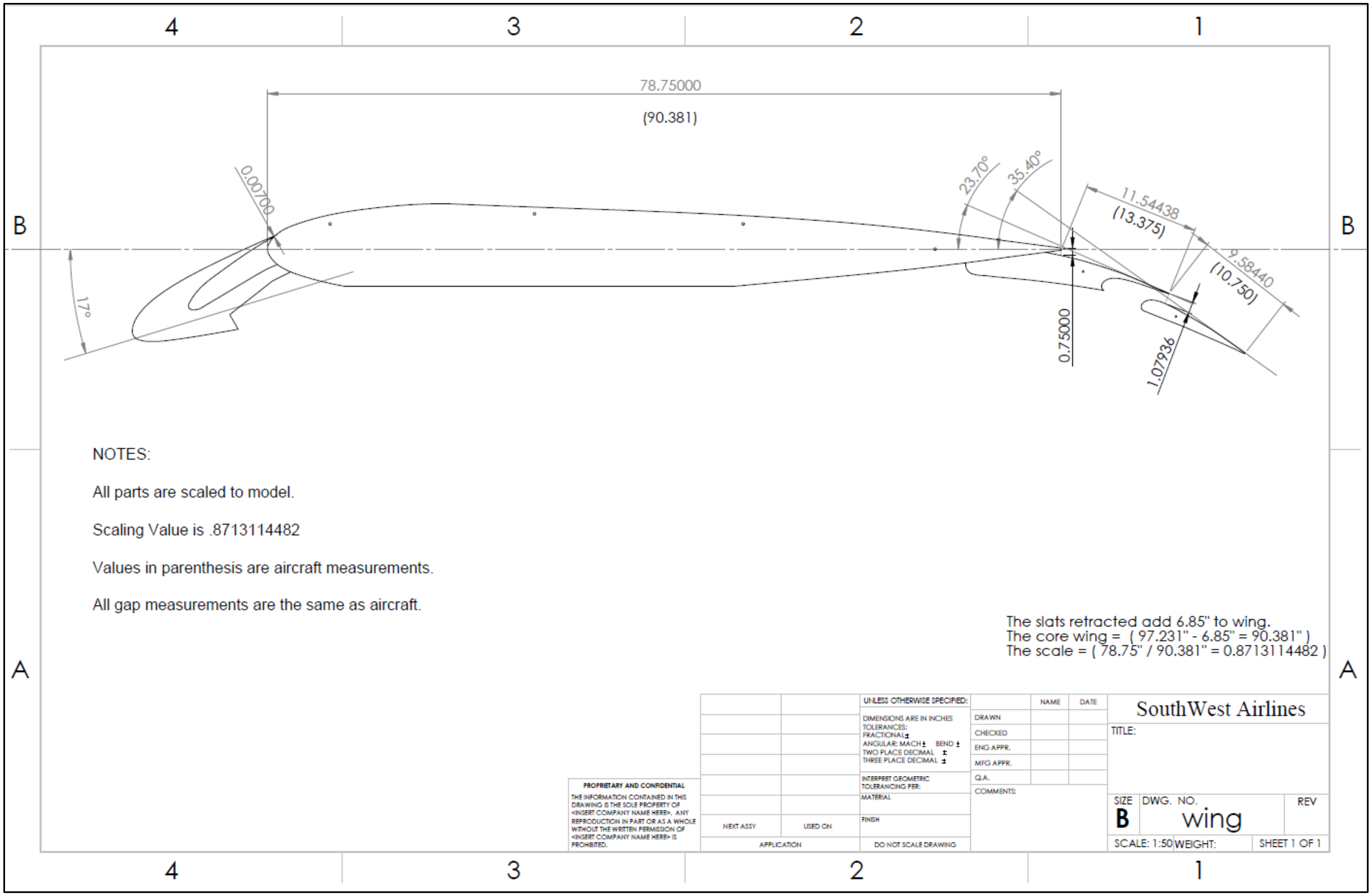

Figure 3.6: Modified Airfoil Schematic Designed by Southwest Airlines

3.5.2 Brixometer

Brix measurements provided data relevant to the fluid concentration; measuring Brix monitors fluid dilution. Figure 3.7 shows the schematic of a hand-held Brixometer which measures refractive index.

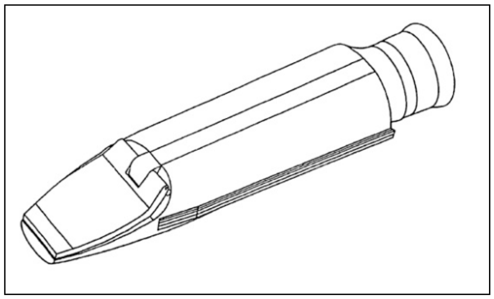

Figure 3.7: Hand-Held Brixometer

3.5.3 Video and Photo Equipment

Canon Powershot Digital ELPH cameras were used to obtain high-resolution photographs of the testing. In addition, some short HD videos were taken with the same cameras whenever required. The high resolution photos are available on the APS server and can be made available upon request.

3.6 Fluids

Based on discussions which included TC/FAA/APS and industry, primarily Airlines for America (A4A), it was agreed that primary objective testing would utilise only two Type IV fluids in order to minimize testing variables and facilitate comparative analysis. In addition some samples of Type I and Type II fluid were also obtained. Mid-production viscosity fluid samples were requested. Table 3.1 provides a summary of the viscosity information for the testing fluids received. A surplus sample of Kilfrost ABC-S Plus was also used to conduct some early wind direction sensitivity testing and was coded as “Type IV PG – E”.

Table 3.1: Testing Fluids - Receiving and Viscosity Information for Fluids Received

Manufacturer	Fluid	Dilution	Batch #	Litres Received	Viscosity Details					
					Method Type	Method (a-n)	Production Min	Production Max	Mfr Stated Viscosity	APS Measured Viscosity
Clariant Produkte	Octaflo EF Concentrate	Concentrate	U71E000857	150	n/a	n/a	n/a	n/a	n/a	n/a
Clariant Produkte	Safewing MP II FLIGHT	100/0	DEG4 145492	200	AS	a	6,000	14,000	10,920	11,200
Cryotech Deicing Technology	Polar Guard Advance	100/0	PGA161216PA	780	AS	a	8000	16,200	14,400	14,400
Dow Chemical Company	UCAR™ Endurance EG 106	100/0	D268GAC000	520	MFR	h	29,500	47,800	43,390	37,500
Dow Chemical Company	UCAR™ Endurance EG 106 2nd Shipment	100/0	D268GAC000	480	MFR	h	29,500	47,800	43,390	40,591

Photo 3.1: APS Test Site - View of the Office Trailer and Reefer Trailer from the Test Pad

Photo 3.2: Outdoor Airfoil Setup Example #1

Photo 3.3: Outdoor Airfoil Setup Example #2

4. TESTING DATA AND LOGS

In this section, only the testing data collected during the winter of 2016-17 is presented. For a detailed account of previous testing and results, please refer to the TC report, TP 15342E, *Testing of Endurance Times on Extended Flaps and Slats* (1).

4.1 Airfoil Testing Log

A summary of the test runs conducted is presented in Table 4.1. The detailed log is presented in Table 4.2 and provides a summary of the airfoil tests conducted at the PET airport test site during the winter of 2016-17. The test log also includes the flat plate 10º and 20º data which served as the baseline and comparative surrogate to the aircraft, respectively. It should be noted that the run and test numbering follows the sequential numbering from the previous related research dating back to 2009-10, and consequently begins in this table at Run #199 and Test #SN365. Sections 4.2, 4.3, and 4.4 provide details on how the adjusted endurance time, relative ratio, and augmentation factor were calculated. For a detailed account of previous testing and results, please refer to the TC report, TP 15342E, *Testing of Endurance Times on Extended Flaps and Slats* (1).

Table 4.1: Summary of Test Runs Conducted

Test Objective	# of Test Runs
Airfoil Calibration	5
Wind Direction Sensitivity Study	5
Comparative Static vs. Rotating Airfoil Testing	47

Table 4.2: Test Log

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
199	11-Dec-16	SN635	Snow	I	Type I PG - A	32.0	HEAD	Calibration	10°	34.8	34.8	0.9	15.5	-4.8	100%	N/A	4	14.75
199	11-Dec-16	SN636	Snow	I	Type I PG - A	32.0	HEAD	Calibration	20° Simple	29.5	22.5	0.7	15.6	-4.8	64%	N/A	4	15.5
199	11-Dec-16	SN637	Snow	I	Type I PG - A	32.0	HEAD	Calibration	Slatted Airfoil #1	13.3	10.0	0.7	16.0	-4.9	29%	N/A	3	13.75
199	11-Dec-16	SN638	Snow	I	Type I PG - A	32.0	HEAD	Calibration	Slatted Airfoil #2	13.4	10.1	0.7	15.9	-4.9	29%	N/A	3	13
200	12-Dec-16	SN639	Snow	II	Type II PG - B	100/0	HEAD	Calibration	10°	138.8	138.8	6.9	19.3	-4.3	100%	N/A	65	13.5
200	12-Dec-16	SN640	Snow	II	Type II PG - B	100/0	HEAD	Calibration	20° Simple	94.5	73.2	5.4	20.7	-4.3	53%	N/A	35	10
200	12-Dec-16	SN641	Snow	II	Type II PG - B	100/0	HEAD	Calibration	Slatted Airfoil #1	81.3	57.7	4.9	20.9	-4.2	42%	N/A	28	9.5
200	12-Dec-16	SN642	Snow	II	Type II PG - B	100/0	HEAD	Calibration	Slatted Airfoil #2	86.5	64.0	5.1	20.8	-4.2	46%	N/A	40	9
201	12-Dec-16	SN643	Snow	II	Type II PG - B	100/0	HEAD	Calibration	10°	47.3	47.3	19.6	16.0	-4.2	100%	N/A	70	16
201	12-Dec-16	SN644	Snow	II	Type II PG - B	100/0	HEAD	Calibration	20° Simple	41.5	38.7	18.3	15.9	-4.2	82%	N/A	40	13.75
201	12-Dec-16	SN645	Snow	II	Type II PG - B	100/0	TAIL	Calibration	Slatted Airfoil #1	46.3	44.2	18.7	16.0	-4.2	93%	N/A	50	20
201	12-Dec-16	SN646	Snow	II	Type II PG - B	100/0	TAIL	Calibration	Slatted Airfoil #2	47.3	46.1	19.1	16.0	-4.2	97%	N/A	45	18.5
202	12-Dec-16	SN647	Snow	II	Type II PG - B	100/0	HEAD	Calibration	10°	60.5	60.5	22.1	18.8	-4.2	100%	N/A	96	16.5
202	12-Dec-16	SN648	Snow	II	Type II PG - B	100/0	HEAD	Calibration	20° Simple	38.5	42.0	24.1	18.8	-4.2	69%	N/A	40	13
202	12-Dec-16	SN649	Snow	II	Type II PG - B	100/0	CROSS (SB)	Calibration	Slatted Airfoil #1	41.0	45.2	24.4	18.7	-4.2	75%	N/A	65	16.5
202	12-Dec-16	SN650	Snow	II	Type II PG - B	100/0	CROSS (SB)	Calibration	Slatted Airfoil #2	46.0	49.6	23.8	18.8	-4.2	82%	N/A	60	15.25

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
203	12-Dec-16	SN651	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	10°	201.5	201.5	6.4	11.4	-3.3	100%	N/A	70	7.5
203	12-Dec-16	SN652	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	20° Simple	133.8	125.0	6.0	12.6	-3.5	62%	N/A	40	9.25
203	12-Dec-16	SN653	Snow	II	Type II PG - B	100/0	CROSS (SB)	Sensitivity	Slatted Airfoil #1	113.5	94.2	5.3	13.2	-3.6	47%	N/A	35	10.5
203	12-Dec-16	SN654	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	Slatted Airfoil #2	104.5	85.2	5.2	13.3	-3.6	42%	N/A	35	12
204	12-Dec-16	SN655	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	10°	265.0	265.0	3.5	14.7	-3.5	100%	N/A	70	-
204	12-Dec-16	SN656	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	20° Simple	195.5	177.5	3.2	13.4	-3.2	67%	N/A	40	-
204	12-Dec-16	SN657	Snow	II	Type II PG - B	100/0	CROSS 45° (SB)	Sensitivity	Slatted Airfoil #1	163.0	144.7	3.1	12.4	-3.0	55%	N/A	50	9.5
204	12-Dec-16	SN658	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	Slatted Airfoil #2	180.0	159.8	3.1	12.9	-3.1	60%	N/A	45	7.5
205	12-Dec-16	SN659	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	10°	130.0	130.0	8.7	16.2	-4.9	100%	N/A	70	14.5
205	12-Dec-16	SN660	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	20° Simple	99.0	89.1	7.8	17.0	-4.8	69%	N/A	45	12
205	12-Dec-16	SN661	Snow	II	Type II PG - B	100/0	TAIL	Sensitivity	Slatted Airfoil #1	126.0	119.9	8.3	16.5	-4.9	92%	N/A	35	8.25
205	12-Dec-16	SN662	Snow	II	Type II PG - B	100/0	HEAD	Sensitivity	Slatted Airfoil #2	67.0	54.8	7.1	17.8	-4.8	42%	N/A	35	11.5
206	17-Dec-16	SN663	Snow	IV	Type IV PG - E	100/0	HEAD	Sensitivity	10°	103.5	103.5	5.5	21.7	-13.9	100%	N/A	50	19.75
206	17-Dec-16	SN664	Snow	IV	Type IV PG - E	100/0	HEAD	Sensitivity	20° Simple	55.0	51.4	5.2	21.5	-14.0	50%	N/A	30	19
206	17-Dec-16	SN665	Snow	IV	Type IV PG - E	100/0	CROSS 135° (P)	Sensitivity	Slatted Airfoil #1	105.2	105.7	5.6	21.7	-13.9	102%	N/A	35	27.25
206	17-Dec-16	SN666	Snow	IV	Type IV PG - E	100/0	HEAD	Sensitivity	Slatted Airfoil #2	56.2	52.9	5.2	21.5	-14.0	51%	N/A	35	19.5
207	17-Dec-16	SN667	Snow	IV	Type IV PG - E	100/0	HEAD	Sensitivity	10°	N/A	150.0	4.2	21.2	-12.4	N/A	N/A	65	20

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
207	17-Dec-16	SN668	Snow	IV	Type IV PG - E	100/0	HEAD	Sensitivity	20° Simple	78.0	77.6	4.2	22.7	-13.0	N/A	N/A	45	19.75
207	17-Dec-16	SN669	Snow	IV	Type IV PG - E	100/0	CROSS 45° (P)	Sensitivity	Slatted Airfoil #1	85.5	83.3	4.1	22.6	-12.9	N/A	N/A	35	18
207	17-Dec-16	SN670	Snow	IV	Type IV PG - E	100/0	HEAD	Sensitivity	Slatted Airfoil #2	60.5	67.6	4.7	22.7	-13.1	N/A	N/A	40	21.75
208	22-Dec-16	SN671	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	187.3	187.3	5.5	9.1	-0.1	100%	N/A	70	1
208	22-Dec-16	SN672	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	142.5	103.7	4.0	9.4	-0.1	55%	N/A	50	1
208	22-Dec-16	SN673	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	127.3	84.9	3.7	9.5	-0.1	45%	1.06	50	0.25
208	22-Dec-16	SN674	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	121.8	79.9	3.6	9.5	-0.1	43%	N/A	45	0.5
209	22-Dec-16	SN675	Snow	I	Type I PG - A	19.0	HEAD	Calibration	10°	DNF	DNF	3.7	4.5	0.1	N/A	N/A	6	0.25
209	22-Dec-16	SN676	Snow	I	Type I PG - A	19.0	HEAD	Calibration	20° Simple	DNF	DNF	3.7	4.4	0.1	N/A	N/A	3	0.25
209	22-Dec-16	SN677	Snow	I	Type I PG - A	19.0	HEAD	Calibration	Slatted Airfoil #1	DNF	DNF	3.7	4.5	0.1	N/A	N/A	5	0.25
209	22-Dec-16	SN678	Snow	I	Type I PG - A	19.0	HEAD	Calibration	Slatted Airfoil #2	DNF	DNF	3.7	4.4	0.1	N/A	N/A	4	0.25
210	29-Dec-16	SN679	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	72.0	72.0	15.2	19.1	-3.2	100%	N/A	55	11
210	29-Dec-16	SN680	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	65.9	55.0	12.7	19.1	-3.2	76%	N/A	35	9.25
210	29-Dec-16	SN681	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	69.5	63.1	13.8	19.1	-3.2	88%	1.18	30	8
210	29-Dec-16	SN682	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	65.5	53.5	12.4	19.0	-3.2	74%	N/A	40	6.5
211	29-Dec-16	SN683	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	79.3	79.3	22.4	18.3	-1.9	100%	N/A	70	5.75
211	29-Dec-16	SN684	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	22.9	41.7	40.7	16.5	-2.2	53%	N/A	50	12.75

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
211	29-Dec-16	SN685	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	23.6	42.8	40.6	16.5	-2.2	54%	0.99	50	9
211	29-Dec-16	SN686	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	23.8	43.3	40.8	16.5	-2.2	55%	N/A	55	5.5
212	29-Dec-16	SN687	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	240.8	240.8	5.5	22.6	-0.9	100%	N/A	70	2.25
212	29-Dec-16	SN688	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	115.5	139.2	6.6	21.5	-1.2	58%	N/A	45	5
212	29-Dec-16	SN689	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	100.7	127.0	7.0	21.6	-1.2	53%	1.01	45	N/A
212	29-Dec-16	SN690	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	99.3	125.8	7.0	21.6	-1.2	52%	N/A	40	N/A
213	29-Dec-16	SN691	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	N/A	284.5	4.3	23.8	-0.1	N/A	N/A	60	8.75
213	29-Dec-16	SN692	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	159.8	157.9	4.3	25.4	-0.1	N/A	N/A	40	3.5
213	29-Dec-16	SN693	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	153.5	137.8	3.9	25.5	-0.2	N/A	N/A	45	0.5
213	29-Dec-16	SN694	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	155.7	143.4	4.0	25.5	-0.2	N/A	1.04	45	0.25
214	31-Dec-16	SN695	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	88.8	88.8	10.7	21.8	-9.5	100%	N/A	50	16.5
214	31-Dec-16	SN696	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	64.3	56.5	9.4	20.5	-9.5	64%	N/A	35	15.5
214	31-Dec-16	SN697	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	62.0	53.0	9.1	20.4	-9.5	60%	N/A	30	15.25
214	31-Dec-16	SN698	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	83.1	80.8	10.4	21.5	-9.5	91%	1.52	30	15.25
215	31-Dec-16	SN699	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	112.6	112.6	9.2	29.6	-10.1	100%	N/A	60	17
215	31-Dec-16	SN700	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	73.2	63.7	8.0	29.9	-10.1	57%	N/A	40	16.75
215	31-Dec-16	SN701	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	61.8	50.0	7.4	29.9	-10.1	44%	N/A	35	17

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
215	31-Dec-16	SN702	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	101.5	96.1	8.7	29.7	-10.1	85%	1.92	35	16
216	3-Jan-17	SN703	Freezing Rain	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	245.0	245.0	4.8	24.0	-1.9	100%	N/A	60	N/A
216	3-Jan-17	SN704	Freezing Rain	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	224.3	177.4	3.8	23.5	-2.0	72%	N/A	35	1
216	3-Jan-17	SN705	Freezing Rain	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	227.7	187.6	4.0	23.6	-2.0	77%	N/A	35	0.5
216	3-Jan-17	SN706	Freezing Rain	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	237.8	225.0	4.6	23.8	-1.9	92%	1.20	35	0.5
217	3-Jan-17	SN707	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	84.6	84.6	18.5	25.6	0.3	100%	N/A	80	1.5
217	3-Jan-17	SN708	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	44.0	40.8	17.2	25.5	0.3	48%	N/A	45	3.5
217	3-Jan-17	SN709	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	34.6	30.9	16.6	25.5	0.3	37%	N/A	50	3.25
217	3-Jan-17	SN710	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	49.0	45.5	17.2	25.5	0.2	54%	1.47	45	1
218	4-Jan-17	SN711	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	89.8	89.8	19.6	21.0	-0.1	100%	N/A	80	2.75
218	4-Jan-17	SN712	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	45.0	43.3	18.9	22.4	0.0	48%	N/A	60	6.75
218	4-Jan-17	SN713	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	37.0	33.5	17.8	22.6	0.0	37%	N/A	80	7.75
218	4-Jan-17	SN714	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	52.0	51.3	19.4	22.2	0.0	57%	1.53	80	2
219	4-Jan-17	SN715	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	176.1	176.1	10.2	19.7	-1.1	100%	N/A	80	4
219	4-Jan-17	SN716	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	63.2	77.8	12.6	19.2	-0.6	44%	N/A	50	3
219	4-Jan-17	SN717	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	64.6	80.1	12.7	19.2	-0.6	45%	N/A	50	3.25
219	4-Jan-17	SN718	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	82.5	112.1	13.9	19.6	-0.7	64%	1.40	45	4.25

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
220	10-Jan-17	SN719	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	189.7	189.7	5.9	36.0	-2.1	100%	N/A	45	5.25
220	10-Jan-17	SN720	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	134.8	107.3	4.7	34.3	-2.6	57%	N/A	30	6.25
220	10-Jan-17	SN721	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	114.5	74.0	3.8	33.3	-2.8	39%	N/A	35	4.75
220	10-Jan-17	SN722	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	127.0	92.7	4.3	34.0	-2.7	49%	1.25	30	5.25
221	10-Jan-17	SN723	Ice Pellets	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	N/A	309.7	3.4	39.7	-0.1	N/A	N/A	65	10.5 @ 23:35
221	10-Jan-17	SN724	Ice Pellets	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	207.9	189.1	3.1	39.7	-0.2	N/A	N/A	45	1
221	10-Jan-17	SN725	Ice Pellets	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	164.6	160.7	3.3	39.8	-0.5	N/A	N/A	45	1.75
221	10-Jan-17	SN726	Ice Pellets	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	202.7	186.1	3.1	39.7	-0.2	N/A	1.16	50	0.5
222	17-Jan-17	SN727	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	177.1	177.1	8.5	28.7	-5.2	100%	N/A	60	11.25
222	17-Jan-17	SN728	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	118.5	85.6	6.1	29.2	-5.2	48%	N/A	35	12.25
222	17-Jan-17	SN729	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	117.6	83.7	6.0	29.3	-5.2	47%	N/A	40	12.5
222	17-Jan-17	SN730	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	154.5	136.4	7.5	28.9	-5.2	77%	1.63	40	10.75
223	18-Jan-17	SN731	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	277.7	277.7	4.7	26.0	-4.4	100%	N/A	70	8.25
223	18-Jan-17	SN732	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	193.3	155.5	3.8	26.3	-4.5	56%	N/A	45	9
223	18-Jan-17	SN733	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	124.5	120.0	4.5	25.6	-4.7	43%	N/A	35	9
223	18-Jan-17	SN734	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	162.9	138.7	4.0	26.3	-4.6	50%	1.16	40	7.75
224	18-Jan-17	SN735	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	199.6	199.6	9.2	24.4	-3.8	100%	N/A	65	9.25

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
224	18-Jan-17	SN736	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	113.3	91.1	7.4	25.1	-3.9	46%	N/A	50	8.5
224	18-Jan-17	SN737	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	84.6	67.2	7.3	25.2	-4.0	34%	N/A	45	7.75
224	18-Jan-17	SN738	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	108.3	85.8	7.3	25.2	-4.0	43%	1.28	45	4.75
225	18-Jan-17	SN739	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	239.3	239.3	5.7	22.5	-4.2	100%	N/A	70	7
225	18-Jan-17	SN740	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	99.8	153.8	8.7	23.1	-3.6	64%	N/A	50	7.25
225	18-Jan-17	SN741	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	73.5	133.8	10.3	23.1	-3.6	56%	N/A	55	8.25
225	18-Jan-17	SN742	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	114.5	162.6	8.1	23.0	-3.7	68%	1.22	60	4
226	24-Jan-17	SN743	Freezing Rain	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	148.4	148.4	14.7	40.8	-2.6	100%	N/A	70	5.25
226	24-Jan-17	SN744	Freezing Rain	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	102.5	78.5	11.3	41.2	-2.7	53%	N/A	45	5
226	24-Jan-17	SN745	Freezing Rain	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	96.8	68.5	10.4	41.7	-2.7	46%	N/A	40	3.75
226	24-Jan-17	SN746	Freezing Rain	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	110.5	88.9	11.8	41.1	-2.6	60%	1.30	40	3.25
227	24-Jan-17	SN747	Ice Pellets	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	75.0	75.0	22.9	42.1	-2.7	100%	N/A	80	5
227	24-Jan-17	SN748	Ice Pellets	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	38.9	37.3	21.9	42.6	-2.5	50%	N/A	60	3
227	24-Jan-17	SN749	Ice Pellets	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	38.5	37.2	22.1	42.5	-2.5	50%	N/A	60	3.25
227	24-Jan-17	SN750	Ice Pellets	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	52.9	49.1	21.2	42.7	-2.6	65%	1.32	60	4
228	24-Jan-17	SN751	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	64.0	64.0	38.1	42.2	-3.5	100%	N/A	70	9
228	24-Jan-17	SN752	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	27.2	29.1	40.9	39.2	-3.4	45%	N/A	60	11

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
228	24-Jan-17	SN753	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	27.3	28.9	40.4	39.1	-3.4	45%	N/A	60	9
228	24-Jan-17	SN754	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	34.3	38.1	42.4	39.7	-3.4	60%	1.32	65	9.5
230	1-Feb-17	SN755	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	176.8	176.8	2.5	23.4	-13.2	100%	N/A	35	21.25
230	1-Feb-17	SN756	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	90.7	97.2	2.7	24.8	-13.4	55%	N/A	24	21.25
230	1-Feb-17	SN757	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #1	82.8	84.5	2.5	24.8	-13.4	48%	N/A	28	23.25
230	1-Feb-17	SN758	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #2	99.7	108.5	2.7	24.7	-13.4	61%	1.28	35	19.25
232	7-Feb-17	SN759	Snow/Ice Pellets	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	129.3	129.3	11.2	37.3	-9.7	100%	N/A	40	12.25
232	7-Feb-17	SN760	Snow/Ice Pellets	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	85.8	54.1	7.1	37.9	-9.9	42%	N/A	35	11.5
232	7-Feb-17	SN761	Snow/Ice Pellets	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	105.3	82.6	8.8	37.5	-9.8	64%	1.70	35	18
232	7-Feb-17	SN762	Snow/Ice Pellets	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	71.4	48.5	7.6	38.5	-9.9	37%	N/A	35	17.25
233	12-Feb-17	SN763	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	40.8	40.8	19.3	30.4	-9.7	100%	N/A	45	17.75
233	12-Feb-17	SN764	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	29.1	29.5	19.5	30.5	-9.8	72%	N/A	35	18
233	12-Feb-17	SN765	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	47.5	46.4	18.8	30.2	-9.7	114%	1.62	40	16.75
233	12-Feb-17	SN766	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	28.6	28.7	19.3	30.5	-9.8	70%	N/A	35	15
234	12-Feb-17	SN767	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	56.2	56.2	18.4	25.7	-8.7	100%	N/A	70	17.75
234	12-Feb-17	SN768	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	35.1	34.7	18.1	26.2	-8.9	62%	N/A	45	17
234	12-Feb-17	SN769	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	58.7	58.5	18.3	25.6	-8.7	104%	1.82	55	16.25

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
234	12-Feb-17	SN770	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	32.7	32.0	18.0	26.3	-8.9	57%	N/A	45	17.75
235	12-Feb-17	SN771	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	59.4	59.4	23.2	20.0	-7.2	100%	N/A	96	14.25
235	12-Feb-17	SN772	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	25.1	25.7	23.8	21.8	-7.6	43%	N/A	60	13.75
235	12-Feb-17	SN773	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	27.6	28.2	23.8	21.7	-7.5	48%	1.16	70	12.5
235	12-Feb-17	SN774	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	23.8	24.4	23.8	21.9	-7.6	41%	N/A	65	12.25
236	12-Feb-17	SN775	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	86.2	86.2	20.0	15.6	-5.9	100%	N/A	104	9
236	12-Feb-17	SN776	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	35.5	34.3	19.4	16.8	-6.5	40%	N/A	65	12.75
236	12-Feb-17	SN777	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	33.2	33.0	19.9	16.9	-6.5	38%	1.16	65	12
236	12-Feb-17	SN778	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	26.9	28.4	21.2	17.1	-6.6	33%	N/A	80	15.5
237	12-Feb-17	SN779	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	46.1	46.1	34.0	15.9	-4.4	100%	N/A	104	11
237	12-Feb-17	SN780	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	24.3	23.4	32.8	15.7	-4.5	51%	N/A	60	12
237	12-Feb-17	SN781	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	22.6	21.4	32.3	15.7	-4.5	47%	1.14	70	12
237	12-Feb-17	SN782	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	20.2	18.7	31.5	15.7	-4.5	41%	N/A	60	11.25
238	12-Feb-17	SN783	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	73.8	73.8	21.6	18.2	-3.4	100%	N/A	N/A	12
238	12-Feb-17	SN784	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	35.7	45.4	27.5	18.0	-3.5	61%	N/A	N/A	15.5
238	12-Feb-17	SN785	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	52.3	59.1	24.5	18.0	-3.4	80%	1.24	N/A	12.75
238	12-Feb-17	SN786	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	37.6	47.8	27.5	18.0	-3.5	65%	N/A	N/A	10.75

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
239	12-Feb-17	SN787	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	79.1	79.1	19.7	21.7	-3.3	100%	N/A	70	10.5
239	12-Feb-17	SN788	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	49.6	45.2	17.9	21.3	-3.3	57%	N/A	50	11.5
239	12-Feb-17	SN789	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	48.2	43.7	17.8	21.2	-3.3	55%	1.20	40	11
239	12-Feb-17	SN790	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	40.9	36.3	17.5	20.7	-3.3	46%	N/A	45	12.5
240	12-Feb-17	SN791	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	63.3	63.3	28.0	21.9	-3.4	100%	N/A	70	10.75
240	12-Feb-17	SN792	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	34.2	33.4	27.3	21.9	-3.4	53%	N/A	50	11
240	12-Feb-17	SN793	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	41.3	41.4	28.0	21.6	-3.4	65%	1.29	45	9.5
240	12-Feb-17	SN794	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	33.1	32.1	27.1	21.6	-3.4	51%	N/A	50	10.75
241	12-Feb-17	SN795	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	81.8	81.8	21.9	26.1	-3.5	100%	N/A	80	8
241	12-Feb-17	SN796	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	29.7	35.3	26.0	24.2	-3.5	43%	N/A	60	9.5
241	12-Feb-17	SN797	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	42.9	49.7	25.4	25.1	-3.5	61%	1.42	60	6
241	12-Feb-17	SN798	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	29.4	34.9	26.0	24.2	-3.5	43%	N/A	55	8
242	13-Feb-17	SN799	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	79.0	79.0	22.7	25.8	-4.1	100%	N/A	80	8
242	13-Feb-17	SN800	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	31.3	34.0	24.7	25.3	-3.9	43%	N/A	60	9
242	13-Feb-17	SN801	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	40.0	44.5	25.3	25.4	-3.9	56%	1.48	55	6.5
242	13-Feb-17	SN802	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	27.7	30.1	24.7	25.3	-3.9	38%	N/A	60	8.25
243	13-Feb-17	SN803	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	121.5	121.5	9.6	24.4	-4.9	100%	N/A	80	8.5

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
243	13-Feb-17	SN804	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	53.2	64.7	11.6	24.7	-4.6	53%	N/A	60	8
243	13-Feb-17	SN805	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	53.0	66.5	12.0	24.9	-4.6	55%	1.19	60	6.25
243	13-Feb-17	SN806	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	35.0	55.9	15.3	25.1	-4.5	46%	N/A	55	7.25
244	14-Feb-17	SN807	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	105.8	105.8	8.5	12.9	-4.2	100%	N/A	70	8.5
244	14-Feb-17	SN808	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	51.0	60.3	10.0	13.4	-4.4	57%	N/A	45	9.5
244	14-Feb-17	SN809	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	55.7	64.8	9.9	13.4	-4.5	61%	1.11	60	9.5
244	14-Feb-17	SN810	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	50.8	58.4	9.8	13.4	-4.4	55%	N/A	55	10
245	15-Feb-17	SN811	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	N/A	227.5	4.7	13.2	-3.6	N/A	N/A	60	11.0 @ 3:38
245	15-Feb-17	SN812	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	141.0	153.8	5.2	12.6	-3.7	N/A	N/A	40	9
245	15-Feb-17	SN813	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	124.0	128.4	4.9	12.6	-3.7	N/A	0.97	40	9
245	15-Feb-17	SN814	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	126.3	131.9	5.0	12.6	-3.7	N/A	N/A	40	9
246	14-Mar-17	SN815	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	114.5	114.5	11.4	41.6	-9.0	100%	N/A	80	11.75
246	14-Mar-17	SN816	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	66.8	43.6	7.5	40.6	-9.1	38%	N/A	55	12.5
246	14-Mar-17	SN817	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	91.5	75.5	9.4	40.7	-9.1	66%	1.83	65	12.75
246	14-Mar-17	SN818	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	64.0	41.2	7.4	40.6	-9.1	36%	N/A	60	11
247	14-Mar-17	SN819	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	59.3	59.3	23.9	48.9	-8.7	100%	N/A	96	11.25
247	14-Mar-17	SN820	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	29.8	25.4	20.4	45.7	-8.9	43%	N/A	60	12.25

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM^2/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
247	14-Mar-17	SN821	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	46.1	43.9	22.8	48.2	-8.8	74%	1.90	65	12.5
247	14-Mar-17	SN822	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	27.3	23.1	20.2	45.6	-8.9	39%	N/A	70	12
248	14-Mar-17	SN823	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	66.3	66.3	22.4	52.5	-8.2	100%	N/A	112	12
248	14-Mar-17	SN824	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	30.2	22.9	17.0	51.7	-8.4	35%	N/A	60	11.75
248	14-Mar-17	SN825	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	46.8	43.0	20.6	52.4	-8.3	65%	1.93	65	10.5
248	14-Mar-17	SN826	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	29.7	22.3	16.8	51.7	-8.4	34%	N/A	65	11.5
249	14-Mar-17	SN827	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	51.5	51.5	32.0	51.7	-8.0	100%	N/A	112	11
249	14-Mar-17	SN828	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	20.0	18.4	29.4	52.5	-8.0	36%	N/A	65	11
249	14-Mar-17	SN829	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	41.3	40.2	31.1	52.2	-8.0	78%	2.03	70	9.25
249	14-Mar-17	SN830	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	21.5	19.8	29.5	52.5	-8.0	39%	N/A	70	13.25
250	14-Mar-17	SN831	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	84.8	84.8	26.5	40.7	-8.3	100%	N/A	65	12.5
250	14-Mar-17	SN832	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	37.3	38.6	27.5	43.6	-8.2	46%	N/A	50	14.5
250	14-Mar-17	SN833	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	68.3	69.3	26.9	40.6	-8.3	82%	1.77	50	16.5
250	14-Mar-17	SN834	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	37.8	39.2	27.5	43.7	-8.2	46%	N/A	50	13.25
251	14-Mar-17	SN835	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	32.7	32.7	47.6	47.8	-8.1	100%	N/A	104	11.25
251	14-Mar-17	SN836	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	13.9	15.2	52.1	45.9	-8.1	47%	N/A	80	13.75
251	14-Mar-17	SN837	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	25.5	26.4	49.3	47.0	-8.1	81%	1.21	70	10.25

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
251	14-Mar-17	SN838	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	20.4	21.8	50.8	46.4	-8.1	67%	N/A	96	13.25
252	14-Mar-17	SN839	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	30.2	30.2	43.3	57.8	-7.8	100%	N/A	119	11.5
252	14-Mar-17	SN840	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	13.7	14.2	45.1	57.5	-7.8	47%	N/A	80	12.75
252	14-Mar-17	SN841	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	26.6	26.8	43.7	57.7	-7.8	89%	1.55	96	11.25
252	14-Mar-17	SN842	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	16.7	17.3	45.0	57.5	-7.8	57%	N/A	96	13.75
253	14-Mar-17	SN843	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	27.0	27.0	47.6	58.0	-7.9	100%	N/A	119	10.5
253	14-Mar-17	SN844	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	12.3	12.4	48.1	58.0	-7.9	46%	N/A	80	11.75
253	14-Mar-17	SN845	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	23.8	23.9	47.7	58.0	-7.9	89%	1.50	80	11
253	14-Mar-17	SN846	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	15.7	16.0	48.3	58.0	-7.9	59%	N/A	96	10.75
254	14-Mar-17	SN847	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	10°	43.2	43.2	37.0	45.9	-8.2	100%	N/A	80	15.25
254	14-Mar-17	SN848	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	20° Simple	24.8	26.2	39.1	47.5	-8.2	61%	N/A	60	14.5
254	14-Mar-17	SN849	Snow	IV	Type IV PG - C	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	37.8	39.1	38.3	46.5	-8.2	90%	1.35	65	14.75
254	14-Mar-17	SN850	Snow	IV	Type IV PG - C	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	27.4	29.0	39.2	47.4	-8.2	67%	N/A	70	15
255	15-Mar-17	SN851	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	73.9	73.9	17.6	17.2	-7.7	100%	N/A	119	12.25
255	15-Mar-17	SN852	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	32.4	39.2	21.3	19.2	-7.7	53%	N/A	70	13
255	15-Mar-17	SN853	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	52.3	58.0	19.6	18.6	-7.7	79%	1.48	70	11.5
255	15-Mar-17	SN854	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	32.3	39.2	21.4	19.2	-7.7	53%	N/A	65	12.5

Table 4.2: Test Log (cont'd)

RUN	DATE	TEST #	CONDITION	FLUID TYPE	FLUID	BRIX	STAND ORIENTATION	TEST OBJECTIVE	TEST SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	PRECIP RATE (G/DM²/H)	WIND SPEED (KM/H)	OAT (°C)	ENDURANCE TIME RELATIVE RATIO	AUGMENTATION FACTOR (ADJ. ET ROT / ADJ. ET STAT)	THICKNESS @ 5 MIN (MM)	BRIX @ FAIL (°)
256	15-Mar-17	SN855	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	84.4	84.4	12.0	16.5	-7.5	100%	N/A	96	12
256	15-Mar-17	SN856	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	33.8	36.1	12.9	15.3	-7.6	43%	N/A	55	12.75
256	15-Mar-17	SN857	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	56.4	57.6	12.3	15.8	-7.5	68%	1.49	70	9
256	15-Mar-17	SN858	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	36.4	38.8	12.8	15.3	-7.6	46%	N/A	65	13.25
257	15-Mar-17	SN859	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	10°	78.4	78.4	12.1	17.5	-7.2	100%	N/A	104	12
257	15-Mar-17	SN860	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	20° Simple	42.6	45.3	12.9	17.4	-7.3	58%	N/A	55	12
257	15-Mar-17	SN861	Snow	IV	TYPE IV EG - D	100/0	ROTATING	Rotating vs Static	Slatted Airfoil #1	46.8	50.0	13.0	17.3	-7.3	64%	1.33	60	10.75
257	15-Mar-17	SN862	Snow	IV	TYPE IV EG - D	100/0	HEAD	Rotating vs Static	Slatted Airfoil #2	36.2	37.5	12.6	17.5	-7.3	48%	N/A	60	14

4.2 Adjustment of Endurance Times to Compensate for Variation in Precipitation Rates

During natural snow conditions, the precipitation rate will fluctuate over the course of a test. When conducting comparative tests, it is necessary to adjust the measured endurance times to compensate for variations in precipitation rates. This is done by adjusting the measured endurance time for each test by a linear ratio, which is determined by the average rate of precipitation measured over course of each individual test as compared to the average rate during the baseline test. The endurance times were adjusted based on a linear relationship in the following formula:

$$Adjusted\ Endurance\ Time = Actual\ Endurance\ Time\ \ x\ \ \frac{Rate\ of\ Precip}{Avg\ Rate\ of\ Precip\ of\ Baseline\ Test(s)}$$

An example of this calculation is shown in Table 4.3.

Table 4.3: Example of Normalization of Endurance Times to Compensate for Variation in Precipitation Rates

TEST #	SURFACE	Start Time (Local)	Fail Time (Local)	ENDURANCE TIME (MIN)	PRECIP RATE (g/dm²/h)	ADJUSTED ENDURANCE TIME CALCULATION	ADJUSTED ENDURANCE TIME (MIN)
SN671	10° (Baseline)	7:14:40	10:22:00	187.3	5.5	=5.5/5.5x187.3	187.3
SN672	20° Simple	7:14:30	9:37:00	142.5	4.0	=4.0/5.5x142.5	103.7
SN673	Airfoil Rotating	7:13:45	9:21:00	127.3	3.7	=3.7/5.5x127.3	84.9
SN674	Airfoil Static Head	7:13:15	9:15:00	121.8	3.6	=3.6/5.5x121.8	79.9

4.3 Calculation of Relative Ratios

In order to better understand the performance of the individual surfaces as compared to the baseline 10º plate, a relative ratio analysis was conducted. For each test, the "Ratio" was calculated using the following formula:

$$Endurance\ Time\ Relative\ Ratio = \frac{Test\ Surface\ Adjusted\ Endurance\ Time}{Baseline\ 10^{\underline{o}}\ Plate\ Adjusted\ Endurance\ Time}$$

An example of this calculation is shown in Table 4.4.

Table 4.4: Example of Relative Ratio Calculation

TEST #	SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	ENDURANCE TIME RELATIVE RATIO CALCULATION	ENDURANCE TIME RELATIVE RATIO
SN671	10° (Baseline)	187.3	187.3	=187.3/187.3	100%
SN672	20° Simple	142.5	103.7	=103.7/187.3	55%
SN673	Airfoil Rotating	127.3	84.9	=84.9/187.3	45%
SN674	Airfoil Static Head	121.8	79.9	=79.9/187.3	43%

4.4 Calculation of Augmentation Factor

The "augmentation factor" was developed to quantify the operational benefit provided by changing wind orientation during taxi. For each rotating airfoil test, the "augmentation factor" was calculated using the following formula:

$$Augmentation\ Factor = \frac{Rotating\ Airfoil\ Adjusted\ Endurance\ Time}{Static\ Airfoil\ Adjusted\ Endurance\ Time}$$

An example of this calculation is shown in Table 4.5.

Table 4.5: Example of Relative Ratio Calculation

TEST #	SURFACE	ENDURANCE TIME (MIN)	ADJUSTED ENDURANCE TIME (MIN)	AUGMENTATION FACTOR CALCULATION	AUGMENTATION FACTOR
SN671	10° (Baseline)	187.3	187.3	N/A	N/A
SN672	20° Simple	142.5	103.7	N/A	N/A
SN673	Airfoil Rotating	127.3	84.9	=84.9/79.9	1.06
SN674	Airfoil Static Head	121.8	79.9	N/A	N/A

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5. FLAT PLATE TESTING RESULTS AND ANALYSIS

In this section, the airfoil testing data collected during the winter of 2016-17 is analysed and discussed.

5.1 Airfoil Slat Gap Sizing

An issue was noted during the first test event while attempting to complete a calibration test (airfoils both oriented into headwind). A large variation in the failure patterns was observed on the two airfoils. For both airfoils, the gap was set at 0.18 mm, however, due to the undulations in the aluminum sheeting used in construction, there were sections where the target gap size was not achieved. It was also observed that the failure patterns on the two airfoils matched where the gap size was equal, indicating that the variation was a direct result of the gap sizing. Photos included in Appendix C demonstrate the fluid failure patterns during this test. It should be noted that the data from this preliminary endurance time test was omitted from the test log in Table 4.2, due to the different configuration of the slat as compared to the other tests.

The preliminary results indicated that variations in the gap size, especially for gap sizes smaller than the fluid thickness, can have large impacts on the comparative test results. Both airfoils had slats designed in a way that they could be moved and set to desired gap sizes, but both models had limitations relating to the accuracy of that gap. For comparative testing, a larger gap was determined to be preferable since it reduced the impact of the variations in gap size on fluid failure.

Information provided by airframe manufacturers (not included here to maintain confidentiality) indicated that gap size can vary based on aircraft type and service life, and can be much larger than 0.18 mm (up to 35 mm in some cases). It was also determined that the fluid thickness on the airfoil leading edge typically settles to around 0.50 to 1.00 mm shortly after application, especially during precipitation. Based on this information, because the goal that the airfoils used for testing be as generic as possible with respect to fluid failure, it was decided that the gap size of the airfoils would be increased to a minimum of 1.00mm. Taking into account the gap size variations caused by the undulations of the aluminum sheeting, this consistently resulted in measured gap sizes of 1.00-1.20 mm on both airfoils. This was deemed necessary to reduce variability and increase repeatability in the testing while ensuring the airfoils configuration remained representative of operational aircraft.

To verify and validate the use of the 1.00 mm gap size, fluid thickness tests were conducted with a surplus batch of Type I and Type IV fluid in inventory. The results demonstrated similar fluid thickness profiles on both airfoils after fluid application; equal or within 10 percent after 30 min for Type IV fluids, and less than 0.1 mm difference for Type I fluid. The fluid thickness data is included in Appendix C.

5.2 Airfoil Calibration

Testing was conducted to verify that both airfoils were constructed the same, and that fluid applied to the two models would provide equal fluid endurance times, assuming all other variables remain constant. A total of three tests were conducted with Type II PG – B fluid. In addition, two Type I tests were attempted but were not successful (the first due to a procedural issue, and the second due to a lack of fluid failure), and therefore were not analysed. It should be noted that these tests were completed at the beginning of the testing season prior to the arrival of Type IV fluid samples, and this is why the testing was attempted only with Type I and Type II fluids.

For the three tests conducted with Type II PG – B fluid, the results were compared to identify any differences in fluid performance. Table 5.1 demonstrates the calibration test results obtained with Type II PG – B fluid (which is assumed to be a good surrogate for Type IV fluids as well). The results indicated that the difference in fluid performance on the two airfoils is within 10 percent, thus within an acceptable tolerance that can be attributed to experimental error.

Table 5.1: Calibration Test Results

Calibration Tests				
Orientation	**Test #'s**	**Airfoil #1 (SWA) Adjusted Endurance Time (min)**	**Airfoil #2 (M1) Adjusted Endurance Time (min)**	**% Difference**
Head/Head	SN641/642	57.7	64.0	10%
Tail/Tail	SN645/646	44.2	46.1	4%
Cross (SB)/Cross (SB)	SN649/650	45.2	49.6	9%
			Average	**8%**

5.3 Wind Direction Sensitivity Study

Testing was conducted to determine the effect of specific airfoil orientations on fluid performance with the intent of identifying possible orientations that may be associated with increased or decreased fluid endurance times. A total of five tests were completed, three with Type II PG – B fluid, and two with a surplus batch of Type IV PG – Z fluid which remained from previous research activities. Type I testing was not attempted.

For the five tests conducted, the results were compared to quantify the effect of orientation on fluid performance. Table 5.2 demonstrates the sensitivity study test results obtained. The results indicated that there is little difference in fluid endurance time when the airfoils are oriented into the wind (between 270° and 90°) as compared to the baseline headwind oriented airfoil. An increase is apparent once the airfoil is oriented out of the wind (between 90° and 270°) as compared to the baseline headwind oriented airfoil. These results are summarized in Figure 5.1.

Table 5.2: Sensitivity Test Results

Sensitivity Tests				
Orientation	**Test #'s**	**Oriented Adjusted Endurance Time (min)**	**Headwind Adjusted Endurance Time (min)**	**% Increase in ET (versus Headwind)**
Head 0° /Head	SN641/642	57.7	64.0	10%
Cross 45° (SB)/Head	SN669/670	83.3	67.6	23%
Cross 90° (SB)/Head	SN653/654	94.2	85.2	10%
Cross 135°/Head	SN665/666	105.7	52.9	100%
Tail 180°/Head	SN661/662	119.9	54.8	119%

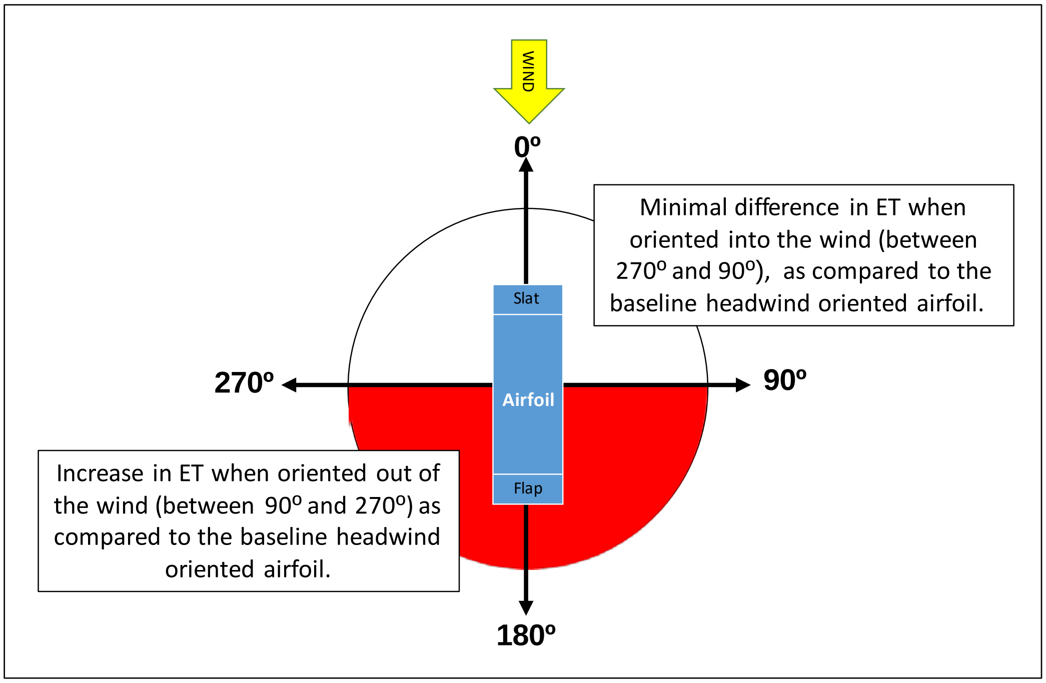

Figure 5.1: Summary of Wind Direction Sensitivity Results

5.4 Comparative Static vs. Rotating Airfoil Testing

Testing was conducted to isolate the effect of rotation on airfoil endurance time (while keeping other variables constant). A total of 47 tests were conducted, 42 of which were conducted in snow conditions. Table 5.3 and Table 5.4 provide a distribution of the tests by fluid type and by condition.

Table 5.3: Test Count Sorted by Fluid Type

Fluid Type and Condition	# of Tests Runs
Type IV EG - D	**21**
Snow	20
Ice Pellets	1
Type IV PG - C	**26**
Snow	22
Freezing Rain	2
Ice Pellets	1
Snow/Ice Pellets	1
Total Tests Runs	**47**

Table 5.4: Test Count Sorted by Condition

Fluid Condition and Type	# of Tests Runs
Snow	**42**
Type IV EG – D	20
Type IV PG - C	22
Freezing Rain	**2**
Type IV PG - C	2
Ice Pellets	**2**
Type IV EG – D	1
Type IV PG - C	1
Snow/Ice Pellets	**1**
Type IV PG - C	1
Total Tests Runs	**47**

It should be noted that testing was only conducted with Type IV fluids, whereas previous research focused primarily on Type II and IV fluids. Additional testing with Type I, II, and III fluids could be conducted to further substantiate the applicability of these results.

5.4.1 Relative Ratio Analysis

In order to better understand the performance of the individual surfaces as compared to the baseline 10° plate, a relative ratio analysis was conducted for each surface of each test run (see Section 4.3 for additional details). The average of the relative ratios from Table 4.2 was calculated for each of the surfaces tested and is demonstrated in Table 5.5 and Table 5.6 for the snow data, and other freezing precipitation data, respectively.

Table 5.5: Average Relative Ratio Analysis of Snow Data

SNOW DATA		
Test Surface	**Test Count**	**Average Ratio of the Surface Compared to the 10º Baseline Plate**
10° Plate	42	100%
20° Plate	42	52%
Airfoil Rotating	42	68%
Airfoil Static (Headwind)	42	48%

Table 5.6: Average Relative Ratio Analysis of Other Freezing Precipitation Data

OTHER FREEZING PRECIPITATION DATA		
Test Surface	**Test Count**	**Average Ratio of the Surface Compared to the 10º Baseline Plate**
10° Plate	5	100%
20° Plate	5	54%
Airfoil Rotating	5	70%
Airfoil Static (Headwind)	5	52%

The snow data shows that the 20º plate average ratio was 52 percent of the 10º plate, comparable to the average 55 percent result seen in previous flat plate testing as described in Section 2.1. This indicates that the two datasets are comparable, as the 20º results remain relatively consistent.

The static airfoil results show the average ratio was 48 percent, slightly lower than the full-scale testing results in Section 2.2. This indicates the airfoil may generate slightly shorter endurance times as compared to the full-scale aircraft tested. This supports the decision to use the comparative dataset only to isolate the effect of rotation on airfoil endurance time, rather than to simply evaluate the rotating airfoil results at face value.

5.4.2 Augmentation Factor Analysis

The augmentation factor analysis was developed to quantify the operational benefit provided by changing wind orientation during taxi (see Section 4.4 for additional details). The average of the individual augmentation factors from Table 4.2 was calculated for the rotating airfoil and is demonstrated in Table 5.7 and Table 5.8 for the snow data, and other freezing precipitation data, respectively. Note that the augmentation factor is only calculated for the rotating airfoil (hence why the other cells are listed as N/A).

Table 5.7: Average Augmentation Factor Analysis of Snow Data

SNOW DATA		
Test Surface	**Test Count**	**Average Augmentation Factor**
10° Plate	42	N/A
20° Plate	42	N/A
Airfoil Rotating	42	139%
Airfoil Static (Headwind)	42	N/A

Table 5.8: Average Augmentation Factor Analysis of Other Freezing Precipitation Data

OTHER FREEZING PRECIPITATION DATA		
Test Surface	**Test Count**	**Average Ratio of the Surface Compared to the 10° Baseline Plate**
10° Plate	5	N/A
20° Plate	5	N/A
Airfoil Rotating	5	134%
Airfoil Static (Headwind)	5	N/A

The test results indicate that the average augmentation factor is 139 percent for snow conditions, and 134 percent for other freezing precipitation conditions. The freezing precipitation data is limited, therefore, the snow results are considered to be more representative for this analysis. In fact, if looking at both datasets combined, the average remains 139 percent for the combined 47 tests.

The majority of the research described in this report has been conducted with Type II/IV fluids in snow conditions, with a comparatively limited Type I and Type III, as well as freezing precipitation dataset. Additional testing with Type I and Type III fluids in both snow and freezing precipitation conditions, as well as limited additional testing with Type II/IV in freezing precipitation conditions would be beneficial to further substantiate the results; this could potentially be done with flat plates to facilitate execution.

5.5 Other Analysis Approaches Explored

At the request of industry, several other analysis approaches were explored. These additional approaches served as a “sensitivity analysis” and ultimately provided more confidence in the selected interpretation of the data collected (see Section 6 for details). The following sections provide a brief summary of the different analysis approaches explored and the observations made.

5.5.1 Regression Based Analysis of Rotating vs. Static Airfoil Data

The fluid endurance time data collected with the various surfaces (10º and 20º plates, and static and rotating airfoils) was analysed as a function of the measured temperature and rate of precipitation. A regression analysis was performed based on the methodology used for developing HOTs. Using the generated regression equations, the regression predicted endurance times at select temperatures and rates of precipitation could be calculated and compared. Appendix C contains the regression analysis results for each surface, separated by fluid type tested. In addition, an augmentation factor was calculated using different approaches comparing the regression outputs of the rotating airfoil to the static airfoil at various points. The results of this analysis supported the augmentation analysis approach described in Section 5.4.2.

5.5.2 Effect of Wind Speed, OAT, and Rate

A similar regression analysis to Section 5.5.1 was conducted, however also included wind speed as a variable. The p-value results were evaluated to determine the significance level of wind speed, Outside Air Temperature (OAT), and rate. In general, the results indicated that the OAT and rate were of statistical significance to all surfaces tested. The results also indicated that wind speed was of statistical significance to the 20º plate, static airfoil and rotating airfoil surfaces, but was less significant for the 10º plate. This result supports why the regression methodology for developing HOTs historically includes only rate and OAT as variables. Wind speed is thought to have a greater effect on the 20º plate, static and rotating airfoil surfaces, due to the higher angled surfaces experiencing a greater catch factor in high wind conditions. Appendix C includes an analysis of the augmentation factor versus wind speed, which shows a good correlation; as wind speed increases, so does the augmentation factor.

5.5.3 Effect of Gap Size on the Slat

The fluid performance on the airfoil with the gap set to 0.18 mm versus 1.00 mm was compared using some limited data available from previous year with the smaller 0.18 mm setting. The data indicated that the 1.00 mm gap would provide slightly shorter endurance times as compared to the 0.18 mm gap, as would be expected. However, because both airfoils experienced the same decreases in fluid performance when the gaps were set equally, and because the data was being used only for comparative purposes (evaluating the difference in performance on the static airfoil vs. the rotating airfoil), this effect of the gap size did not influence the final analysis.

5.5.4 Fluid Type and Fluid Specific Performance

Based on a review of data from previous years testing, fluid specific performance was not a significant factor in the comparative analysis, however there were some differences in the behaviour of propylene and ethylene glycol (EG) based Type IV fluid products. TC and FAA concluded that a generic one-size-fits-all analysis approach was still preferred due to limitations in data collected, and to limit complexities in guidance development.

5.5.5 Effect of Time Spent in Respective Orientation Analysis

The augmentation factor analysis described in Section 5.4.2 was presented to industry, and an industry request was made through A4A to evaluate the effect of time spent in headwind on the overall augmentation factor and resulting expected impact on holdover time. The rationale for the request was that time spent in headwind, crosswind, and tailwind should have been 20 percent, 40 percent, and 40 percent respectively, however the actual time spent in each orientation during a given test may have varied depending on at which point during the rotation cycle the test concluded. Appendix C includes some analysis details relating to this issue.

The analysis indicated that the headwind and crosswind time ratios were slightly overrepresented, and that those orientations were most prone to early fluid failure. Normalizing the ratios back to 20 percent, 40 percent, and 40 percent would have a net effect of increasing the augmentation factor. This approach was discussed, however TC/FAA concluded that additional wind direction sensitivity data (see Section 5.3) would be required to support any adjustments based on this type of analysis. Additional testing would be beneficial in better determining the effect of specific airfoil orientations on fluid performance. The intent of the additional testing should be to identify orientations associated with increased or decreased fluid endurance times. Additional data could provide more information into the influence of orientation and rotation on fluid endurance time, and support further analysis related to the calculation of the augmentation factor.

5.6 Southwest Airlines Wind Rose Data Re-Analysis

Industry, through A4A, requested a review of the Southwest Airlines provided wind rose data that led to the calculation of the 20/40/40 headwind, crosswind, tailwind ratios, the details of which are in the TC report, TP 15342E, *Testing of Endurance Times on Extended Flaps and Slats* (1). The 20/40/40 ratio was originally selected as a generic representative ratio model. The proposal from industry was that the wind rose data should have been divided into four equal segments of 45° each (rather than the three equal 60° segments that were used), which would have resulted in a 15/50/35 ratio. This approach was discussed, however TC/FAA concluded that additional wind direction sensitivity data (see Section 5.3) would be required to support any adjustments based on this type of analysis. As described in Section 5.5.5, additional data could provide more information into the influence of orientation and rotation on fluid endurance time, and support further analysis related to the calculation of the augmentation factor. In addition, the time spent in the deicing bay from the start of HOT until brake release was not included in the original Southwest Airlines wind rose analysis, and depending on the airport configuration, this could further increase the time spent in headwind and crosswind.

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6. CONCLUSIONS AND LOGIC PATH TO SUPPORT GUIDANCE DEVELOPMENT

This section describes the conclusions and the logic path that was developed and used to synthesize the different datasets collected in support of guidance development.

6.1 Summary of Relevant Datasets

The following sections provide a top level summary of the relevant datasets and how they pertain to guidance development.

6.1.1 Flat Plate Testing

Flat plate models have been used to develop holdover times since the early 1990's. Use of flat plate models was determined to be the best method to collect a large dataset in a variety of conditions; these tests were relatively inexpensive and easy to conduct. The industry requested side-by-side testing with full-scale aircraft be conducted to validate the use of the flat plate models selected for this research. The flat plate data collected showed the 20º plate to be representative of full-scale aircraft. This was later supported by the results of full-scale testing requested by industry. The 20° plate was therefore selected as the best possible surrogate model based on the different flat plate models evaluated. The results demonstrated that the expected Type II/IV holdover times on a 20º plate would be 55 percent of those on the baseline 10º plate (see Section 2 for more details).

6.1.2 Full-Scale Aircraft Testing

Full-scale testing was conducted to validate the use of the flat plate models. This type of testing was very difficult to perform, mainly due to the coordination required and the various parties involved including airports, operators, deicing services, etc. As a result, only a limited number of full-scale tests were performed. The data collected supported the flat plate results, indicating that the extended configuration reduced fluid endurance time, and also validated the use of the 20º plate model as a suitable surrogate test model. The results (see Section 2.2 for more details) demonstrated that the expected Type II/IV holdover times on the full-scale aircraft with flaps and slats extended would be 55 percent of the baseline 10º plate (see Section 2 for more details).

6.1.3 Comparative Static vs. Rotating Airfoil Testing

Airfoil model testing was conducted to supplement the full-scale tests which were conducted in a static position. The airfoils could be rotated and therefore the data gathered could be used to isolate the effect of airfoil rotation on fluid endurance time. The airfoils were large size models, with a moderate difficulty level for testing, primarily due to the larger fluid quantities required. The test results indicated that the average augmentation factor is 139 percent, based on a comparison of the rotating versus static airfoil endurance time results.

6.2 Logic Path to Support Guidance Development

Testing was conducted over several years and resulted in the collection of a variety of datasets, each with a unique set of parameters and limitations as to how the data could be used. After having reviewed each dataset, it was determined that the 20º flat plate data, the full-scale aircraft data, and the rotating vs. static airfoil data were most relevant and should be considered when determining the expected HOT performance on extended flaps and slats.

The basis of the analysis is the static 20º flat plate data (which is the largest dataset), supported by the static full-scale aircraft data. Both these datasets indicate an expected holdover time of 55 percent of the baseline 10º plate. In actual operations however, the aircraft would be rotating during taxi to the runway, which could offset some of the reduction in fluid protection resulting from the higher angled surfaces. Based on the comparative rotating vs. static airfoil testing, the average improvement in fluid protection time for the rotating surface, referred to as the augmentation factor, is calculated to be on average 39 percent of the static surface endurance time. When adjusting the static flat plate and full-scale results of 55 percent by a factor of 1.39 to account for rotation, the end result is an expected HOT performance on extended flaps and slats of 76 percent of the current HOTs. Figure 6.1 provides a graphical demonstration of the logic path used to determine the expected HOT performance of fluids when applied to aircraft configured with extended flaps and slats.

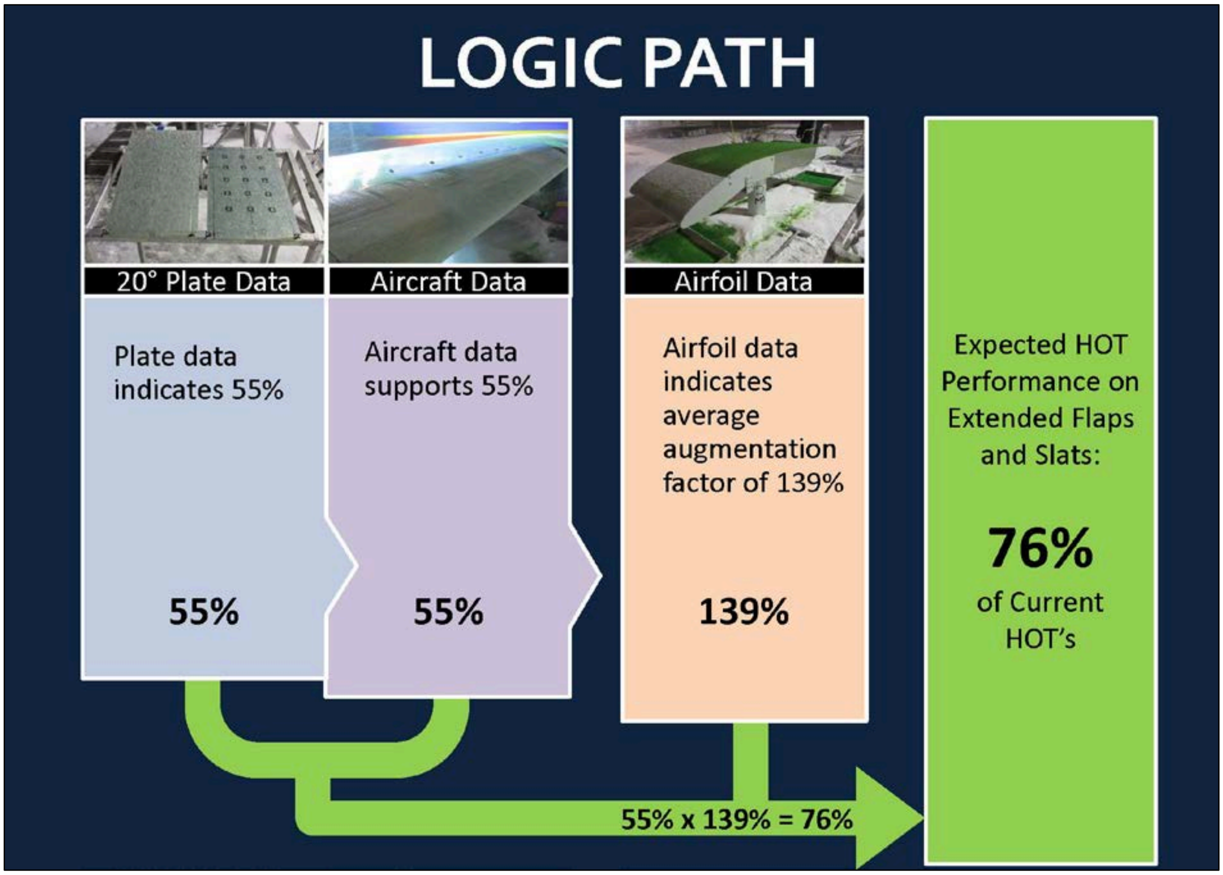

Figure 6.1: Data Analysis Logic Path

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REFERENCES

1. Asnytska, E., Bernier, B., Bernier, C., Youssef, D., Zoitakis V., *Testing of Endurance Times on Extended Flaps and Slats*, APS Aviation Inc., Transportation Development Centre, Montreal, December 2016, TP 15342E, 138.

2. SAE International Aerospace Recommended Practice 5485A, *Endurance Time Tests for Aircraft Deicing/Anti-icing Fluids: SAE Type II, III, and IV*, July 2007.

3. SAE International Aerospace Recommended Practice 5945, *Endurance Time Tests for Aircraft Deicing/Anti-Icing Fluids: SAE Type I*, July 2007.

4. D'Avirro, J., Chaput, M., Dawson, P., Hanna, M., Fleming, S., *Aircraft Full-Scale Test Program for the 1996/97 Winter*, APS Aviation Inc., Transportation Development Centre, Montreal, December 1997, TP 13130E, 180.

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APPENDIX A

TRANSPORTATION DEVELOPMENT CENTRE WORK STATEMENT EXCERPT: AIRCRAFT & ANTI-ICING FLUID WINTER TESTING 2016-17

TRANSPORTATION DEVELOPMENT CENTRE
WORK STATEMENT EXCERPT
AIRCRAFT & ANTI-ICING FLUID
WINTER TESTING 2016-17

4.2 Evaluation of Endurance Times on Deployed Flaps and Slats - Flat Plate and Model Testing - Priority 1

a) Review previous results from flat plate, airfoil, and full-scale testing conducted by APS;

b) Modify procedure and methodology, as required, based on TC/FAA and industry consultations;

c) Modify second airfoil model with flaps and slats for testing;

d) Order necessary fluid samples and measure viscosities;

e) Conduct testing on airfoils at P.E.T. test site. The test matrix will be determined following consultations with TC and FAA and will consist of both comparative airfoil testing and a sensitivity testing based on wind direction with respect to the model. The target is 20-35 Type II/IV tests and 10-14 Type I tests;

f) Analyze the data collected;

g) Evaluate current guidance material regarding flap configuration against results obtained and develop/modify guidance material if necessary; and

h) Report the findings and prepare presentation material for the SAE G-12 meetings.

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APPENDIX B

PROCEDURE: FLAPS AND SLATS RESEARCH – COMPARATIVE AIRFOIL TESTING WINTER 2016-17

CM2480.003

PROCEDURE:

FLAPS AND SLATS RESEARCH – COMPARATIVE AIRFOIL TESTING

Winter 2016-17

Prepared for

Transportation Development Centre
Transport Canada

and

Federal Aviation Administration
William J. Hughes Technical Center

Prepared by: Ben Bernier and Marco Ruggi

Reviewed by: John D'Avirro

December 15, 2016
Final Version 1.0

PROCEDURE:
FLAPS AND SLATS RESEARCH – COMPARATIVE AIRFOIL TESTING

Winter 2016-17

1. BACKGROUND

Anti-icing fluid applied to a wing with deployed flaps and slats can quickly flow off, resulting in a reduced fluid thickness layer, and consequently may shorten fluid holdover times (see Figure 1.1). In addition, the higher angles surfaces are subject to higher precipitation rate catch in wind conditions. Due to operational concerns, flaps and slats related testing has been ongoing since the winter of 2009-10 and has since included a multitude of testing protocols and platforms:

- Wind tunnel testing: High-performance wing model with hinged flap set to 20°;
- Flat plate testing: 10°/20°/35° plates in various configurations and orientations;
- Full-scale validation: Testing with A300 / B737 / A319 (with the support of UPS/SWA/Air Canada); and
- Airfoil model testing: Simple and slatted airfoil testing, both static and with a variety of rotation profiles.

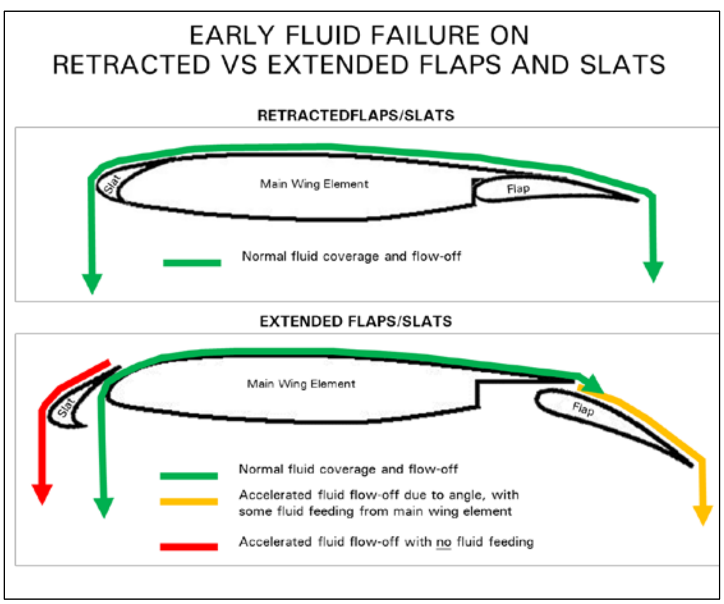


Figure 1.1: Fluid Failure Progression on Flaps and Slats

The data package available to date now contains flat plate, airfoil model and full-scale test data. For the winter of 2016-17, a new comparative airfoil testing approach using is being proposed to facilitate interpretation of results and to support development of guidance. The testing approach will include a wind direction sensitivity study as well as comparative static vs. rotating airfoil tests. This procedure includes the methodology and test plan for the testing to be conducted during the winter of 2016-17.

2. OBJECTIVE

The objective is to conduct comparative testing with two equivalent airfoil models to isolate and quantify the effect of orientation and rotation on endurance times.

3. METHODOLOGY

3.1 General Procedure

Comparative testing will be conducted using two airfoils which were built to be as close to identical as possible based on the materials and assembly procedures used. In addition, a baseline 10º plate (or box for Type I fluids) will be included in the test setup to record the endurance time according to ARP 5485 or ARP 5945. A 20º plate (or box for Type I fluids) will be included in the test setup and used as the surrogate plate model best representing the deployed wing protection time, and to add to the existing growing data set. General holdover time testing protocols will apply, however the following provides an overview of the specific testing procedure:

1. Ensure airfoils are correctly positioned with respect to the wind as per the test plan requirement;
2. Verify with a feeler gauge that the gap distance between the trailing edge of the slat and the hard leading edge is at least 1 mm;
3. Ensure the 10º and 20º plates are positioned into the wind;
4. Ensure rate of precipitation is being measured approximately every 10-minutes just before, throughout, and just after the test (or every 5-minutes in moderate snow conditions);
5. Apply fluid to all surfaces simultaneously. Thickened fluids should be applied by pouring the fluid on the surface, Type I fluids should use a spreader or sprayer due to the large surface area. Note: Type III fluid testing is not planned for 2016-17. Typically, it will require 14 L of Type II/IV fluid to

properly coat each airfoil (this may be as high as 20 L if it is cold and the fluid is very viscous). For Type I fluids, 2.5 L will be applied (this correlates to 1 L/m²), however discussion is ongoing about increasing the quantity to be in line with the 0.5 L applied to a cold soak box in outdoor snow testing which translates to 3.3 L/m², or 8.25 L on each airfoil;

6. Rotate the airfoils (if applicable) as per the test plan requirements. A looping PowerPoint show with has been developed and will be used to facilitate the timing of the rotations through sound and visual cues;
7. Measure fluid thickness 5-minutes after fluid application, and fluid brix at the time of failure;
8. Record the time of first failure, 10 percent failure, and full failure (if practical) on the airfoil models;
9. Record the time of standard plate failure (1/3 of the plate) for the 10° and 20° surfaces; and
10. Compare the results from the four different test models.

A diagram describing showing a top view of the general test setup is included in Figure 3.1.

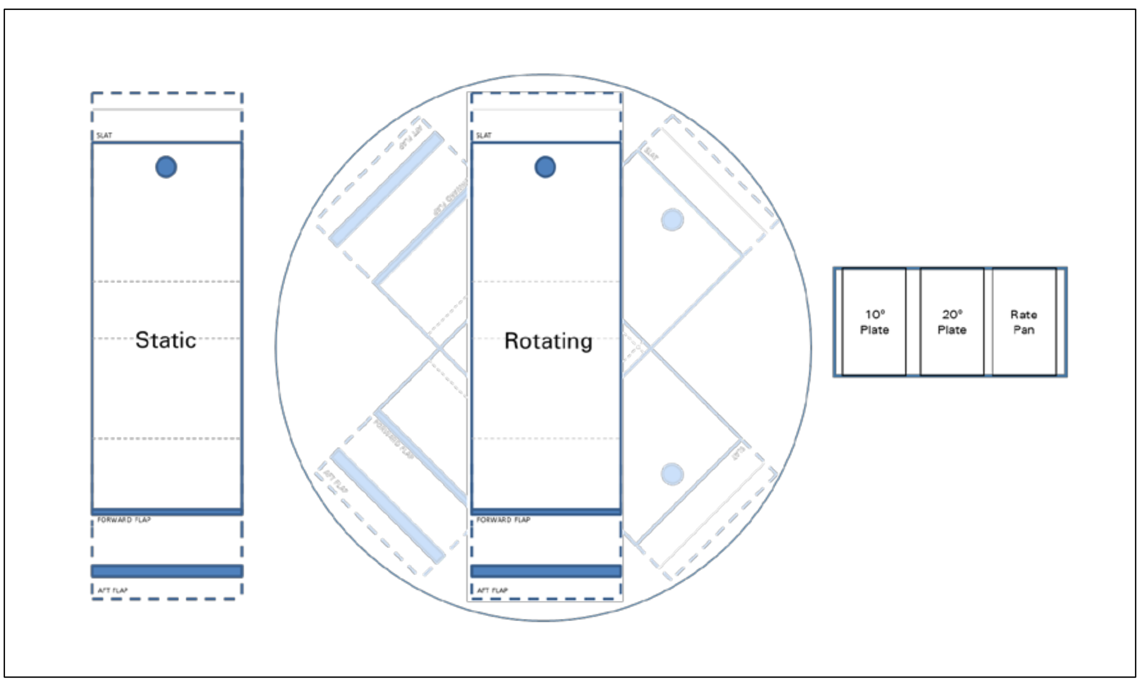


Figure 3.1: Top View of General Test Setup

3.2 Airfoil Calibration Testing

Testing will be conducted to verify that both airfoils are constructed equally, and that fluid applied to the two models will provide equal fluid protection times. Testing will be conducted using the two slatted airfoils in the same static orientations. Running two airfoils in tandem will ensure that natural factors remain the same for both airfoils (temperature, rate, wind speed, snowflake size etc.) The airfoils will not be rotated during these tests. A baseline 10º and 20º plate will also be included in the test setup.

3.3 Wind Direction Sensitivity Study

Testing will be conducted to determine the effect of specific airfoil orientations on fluid performance with the intent of identifying possible orientations that may be attributed to increased or decreased fluid protection times. Testing will be conducted using the two slatted airfoils in differing static orientations, the first in headwind configuration, and the second in different static orientations as per the test plan requirement. Running two airfoils in tandem will ensure that natural factors remain the same for both airfoils (temperature, rate, wind speed, snowflake size etc.) The airfoils will not be rotated during these tests. A baseline 10º and 20º plate will also be included in the test setup.

3.4 Comparative Static vs. Rotating Airfoil Testing

Testing will be conducted to isolate the effect of rotation on airfoil endurance time (while keeping other variables constant). Running two airfoils in tandem will ensure that natural factors remain the same for both airfoils (temperature, rate, wind speed, snowflake size etc.). One airfoil will remain in headwind position, while the second airfoil will be rotated throughout the test; one rotation profile will be used for all tests. The magnitude of rotating effect will be derived through comparison of static airfoil vs. rotating airfoil endurance time results. A baseline 10º and 20º plate will also be included in the test setup.

3.5 Airfoil Orientation Sequencing

An analysis conducted by Southwest Airlines provided a wind rose output of typical aircraft orientations following de/anti-icing until takeoff. APS conducted a post analysis and indicated that the general head / cross / tail orientation breakdown for the recorded operations could be simplified to 20 percent / 40 percent / 40 percent respectively for facilitate testing procedures.

To minimize this potential error in orientation sequencing due to under or over estimating the fluid HOT, the airfoil sequencing will be done in a continual 20-minute rotation cycle. The continuous 20-minute cycle will ensure the headwind 20 percent, crosswind 40 percent, and tailwind 40 percent orientation ratios are maintained. To do so, the rotations must be completed every 4, 8, and 8 minutes in order to maintain the 20/40/40 ratio for a 20-minute cycle. In the case of Type I fluids, if the expected HOT is less than 20-minute, consideration will be given to halving the rotation cycle to 10-minutes total (i.e. 2, 4, and 4 minutes) or shorter if required. Figure 3.2 demonstrates an example of the airfoil orientation for a test in which the expected HOT is 60-minutes.

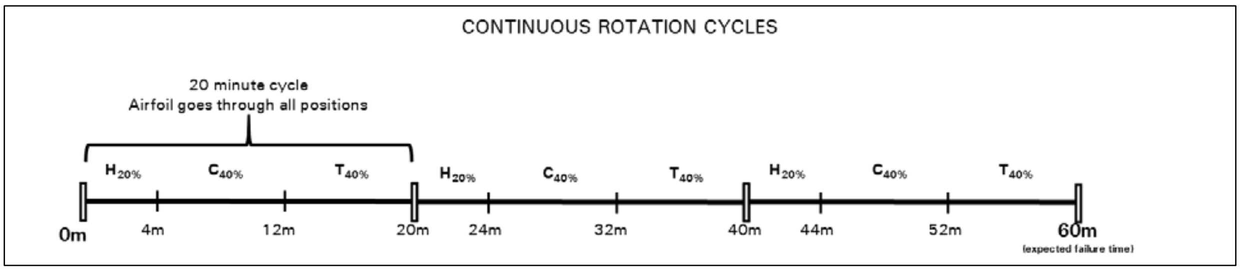


Figure 3.2: Airfoil Orientation Sequencing – Example of 60-minute Expected Holdover Time

4. TEST PLAN

Testing is to be conducted in natural snow conditions. It should be noted that the test runs are not specific to precipitation rate or outside temperature, however a variety of different conditions are preferred. The test plan for the winter of 2015-16 is included in Table 4.1. Tests #1-6 address the calibration testing objective, tests #7-16 address the wind direction sensitivity study, and tests #17-61 address the comparative static vs. rotating airfoil testing objective.

Consideration will be given to replacing the headwind airfoil in tests # 17-61 with a second rotating airfoil in order to collect a larger data set of rotating airfoil tests. The decision to proceed with this change will depend on the preliminary analysis of the static airfoil tests collected during tests #1-16.

Table 4.1: Test Plan for Winter 2016-17

TEST #	PRIORITY	OBJECTIVE	MODEL ORIENTATION OR ROTATION SEQUENCE			CODED FLUID	COMMENTS
			AIRFOIL #1	AIRFOIL #2	10° AND 20° PLATES		
1	1	Calibration	Headwind 0°	Headwind 0°	Headwind 0°	Type IV PG - C	Serves for sensitivity also
2	1	Calibration	Headwind 0°	Headwind 0°	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
3	1	Calibration	Crosswind 90°	Crosswind 90°	Headwind 0°	Type IV PG - C	
4	1	Calibration	Crosswind 90°	Crosswind 90°	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
5	1	Calibration	Tailwind 180°	Tailwind 180°	Headwind 0°	Type IV PG - C	
6	1	Calibration	Tailwind 180°	Tailwind 180°	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
7	3	Sensitivity	Headwind 0°	Headwind 0°	Headwind 0°	Type IV PG - C	Serves for calibration also
8	1	Sensitivity	Headwind 0°	45° to Wind	Headwind 0°	Type IV PG - C	
9	3	Sensitivity	Headwind 0°	45° to Wind	Headwind 0°	Type IV PG - C	
10	1	Sensitivity	Headwind 0°	Crosswind 90°	Headwind 0°	Type IV PG - C	
11	3	Sensitivity	Headwind 0°	Crosswind 90°	Headwind 0°	Type IV PG - C	
12	1	Sensitivity	Headwind 0°	135° to Wind	Headwind 0°	Type IV PG - C	
13	3	Sensitivity	Headwind 0°	135° to Wind	Headwind 0°	Type IV PG - C	
14	1	Sensitivity	Headwind 0°	Tailwind 180°	Headwind 0°	Type IV PG - C	
15	3	Sensitivity	Headwind 0°	Tailwind 180°	Headwind 0°	Type IV PG - C	
16	3	Sensitivity	Headwind 0°	45°, 90°, or 180° (TBD)	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
17	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
18	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
19	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
20	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
21	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
22	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
23	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
24	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
25	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
26	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	
27	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
28	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
29	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
30	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
31	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
32	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
33	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
34	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
35	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind
36	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - C	Consider pairing with EG106 and eliminate headwind

*** Consider replacing with second rotating airfoil test, pending analysis of head wind airfoil data.

Table 4.1: Test Plan for Winter 2016-17 (cont'd)

TEST #	PRIORITY	OBJECTIVE	MODEL ORIENTATION OR ROTATION SEQUENCE			FLUID	COMMENTS
			AIRFOIL #1	AIRFOIL #2	10° AND 20° PLATES		
37	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
38	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
39	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
40	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
41	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
42	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
43	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
44	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
45	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
46	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type IV PG - D	Consider pairing with PGA and eliminate headwind
47	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
48	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
49	1	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
50	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
51	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
52	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
53	2	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
54	3	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
55	3	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
56	3	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type I PG - A	Do in light snow when TII/IV not feasible
57	4	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type II PG - B	
58	4	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type II PG - B	
59	4	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type II PG - B	
60	4	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type II PG - B	
61	4	Static vs. Rotating	Headwind 0° ***	Rotating 20/40/40 - 20-min Cycles	Headwind 0°	Type II PG - B	

*** Consider replacing with second rotating airfoil test, pending analysis of head wind airfoil data.

5. EQUIPMENT

Standard holdover time testing equipment will be used for the conduct of these tests. In addition, the following specific items will be required:

- Two airfoils fitted with slats and flaps;
- Catch basins to collect fluid overflow during fluid application throughout the test (can use spare holdover time test stand catch pans);
- Large 3 litre jugs to apply anti-icing fluid; and
- Fluid spreader or backpack sprayer to apply deicing fluid.

6. PERSONNEL

A minimum of three people will be required for the conduct of these tests:

1. Overall coordinator, photography, and responsible for calling failures on all surfaces;
2. Fluid application on airfoil #1 and data documentation; and
3. Fluid application on airfoil #2 and measurements.

Ideally additional support from one or two persons is available at the start of the tests for fluid application.

7. FLUIDS

Testing will be performed with commercial fluids of production range viscosity (for comparative testing). The fluid selection was based on operator feedback regarding commonly used in U.S. and Canadian operations. Fluids quantities required have been ordered specifically for these tests and are described in Table 7.1. Fluid viscosity measurements will be conducted using the Brookfield viscometer and the falling ball upon receipt. Spot checks of fluid viscosity may be conducted periodically throughout the season as requested by Transport Canada or the Federal Aviation Administration; this will likely be done using only the falling ball method.

Table 7.1: Fluid Requirements

Fluid	Fluid Type	Dilution	Test Count	Fluid Required*
Type I PG - A	PG-Based Type I	10°B	14	168L
Type II PG - B	PG-Based Type II	100/0	5	200L
Type IV PG - C	PG-Based Type IV	100/0	20	800L**
Type IV PG - D	EG-Based Type IV	100/0	10	400L

*Prepared volume – not concentrate volume. Type II/IV approx. 40L per test, Type I approx. 12L per test.
**An additional 600L of fluid will be held on "reserve" by the fluid manufacturer in the event extra fluid is required.

8. DATA FORM

Comparative airfoil tests will require the use of a data form, which can be found in Attachment 1. Each test run will require the completion of this form.

9. PHOTOS

Photo documentation is an important part of the data collection. At the time of each plate failure, airfoil first failure, or airfoil 10 percent failure, nine photos should be taken as demonstrated in Figure 9.1. Special care should be given to taking photos in proper sequence to facilitate future analysis.

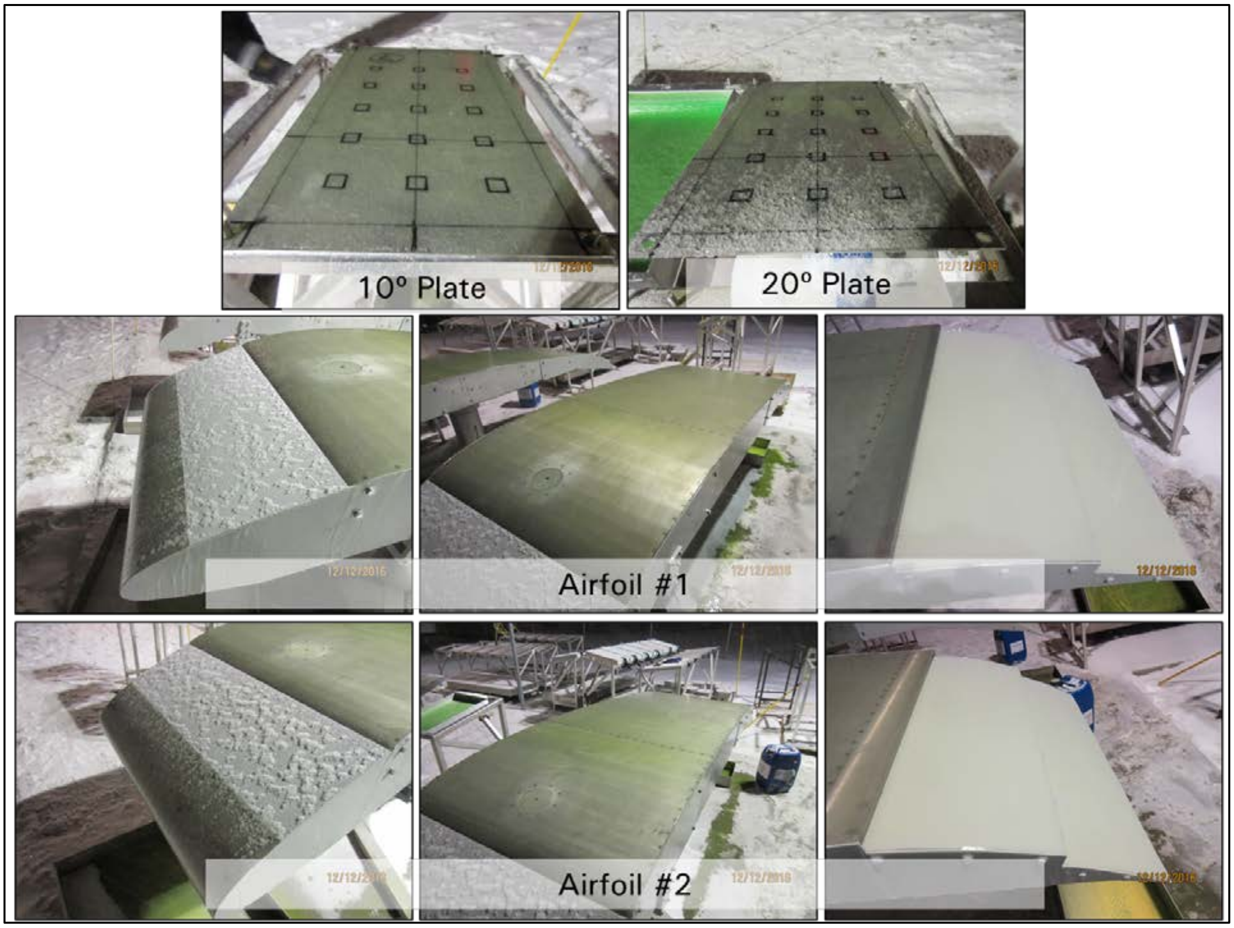


Figure 9.1: Example of Photos Required at Each Failure Event

Attachment 1: Airfoil End Condition Data Form

FLAPS AND SLATS RESEARCH
AIRFOIL END CONDITION DATA FORM

Test Plan # _________ Run # _________

EC HOURLY DATA
RECORDED AT END OF POUR TIME

TIME OF EC OBSERVATION

____

TEMP _______ °C

WIND SPEED _____km/h

WIND DIRECTION _______.

FLUID INFORMATION
Fluid Name:

Batch #:

Fluid Type:

Fluid Dilution:

Liters used:

Initial Brix:

Initial Temp:

ROTATION SEQUENCE
H = Headwind, C = Crosswind, T = Tailwind

Start Time:

20-minute Rotation Sequence = Hx4-min, Cx8-min, Tx8-min

Orientation	Start Time	60-min Checklist
Headwind 4-min		
Crosswind 8-min		
Tailwind 8-min		
Headwind 4-min		
Crosswind 8-min		
Tailwind 8-min		
Headwind 4-min		
Crosswind 8-min		
Tailwind 8-min		

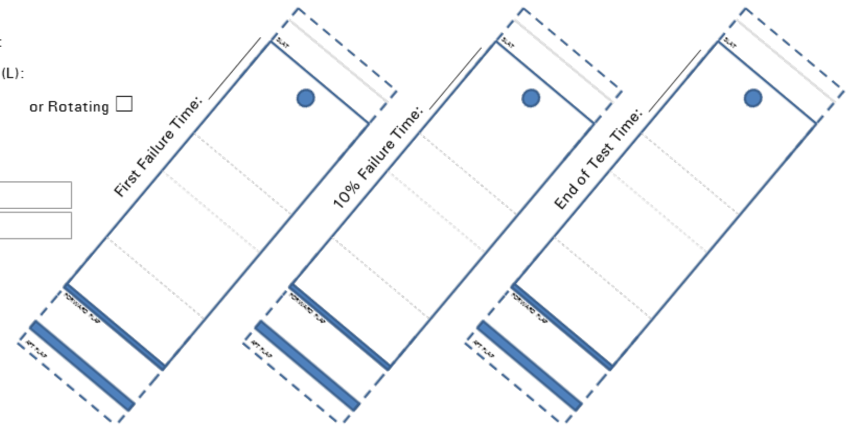
AIRFOIL #1
Time of Fluid Application:

Quantity of Fluid Applied (L):

Static (Position) ☐ or Rotating ☐

TH @ 5 MINS

BRIX @ FAILURE



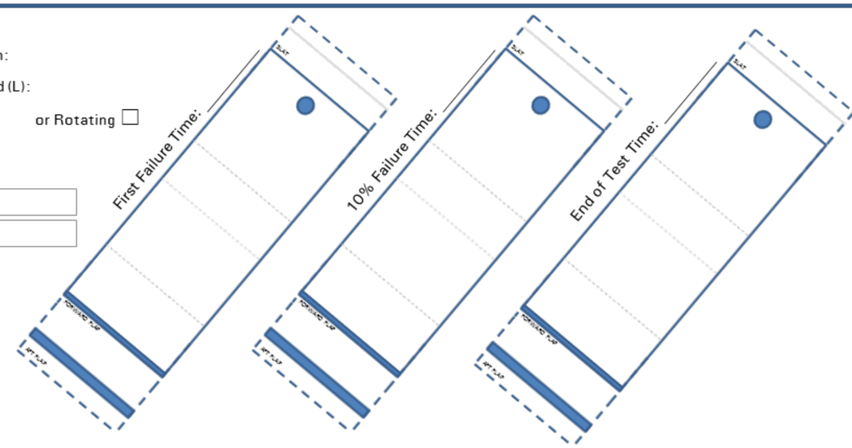
AIRFOIL #2
Time of Fluid Application:

Quantity of Fluid Applied (L):

Static (Position) ☐ or Rotating ☐

TH @ 5 MINS

BRIX @ FAILURE



PLATES (Headwind)
Time of Fluid Application:

	10°	20°
Time of Fluid Failure:		
TH @ 5 MINS		
BRIX @ FAILURE		

Comments:____________________

____

____

____

☐ Check if more on other side

Date: ______________

Recorded by: ______________

Testers: ______________

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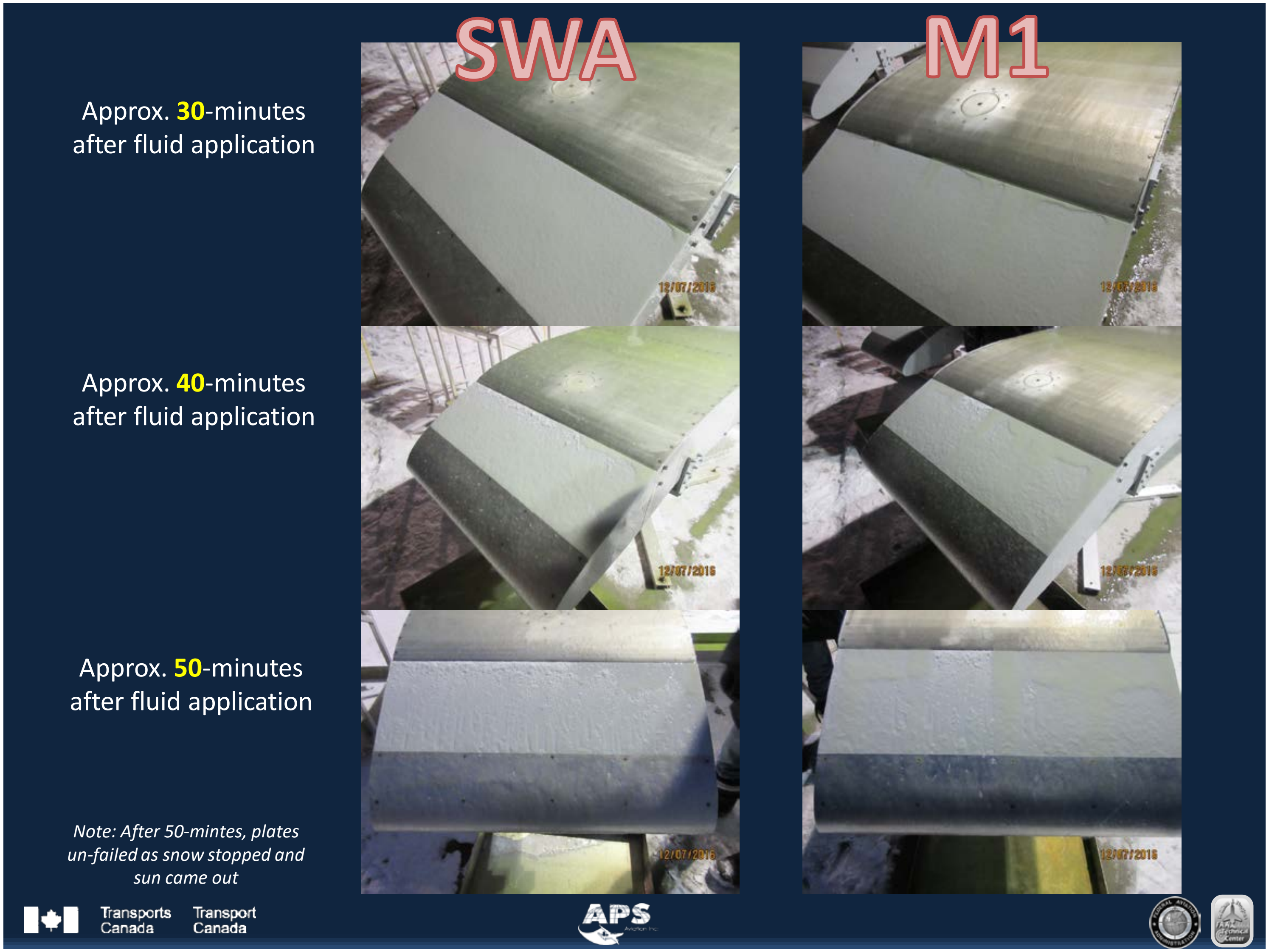
APPENDIX C

ADDITIONAL ANALYSIS
(FOR INFORMATION PURPOSES ONLY)

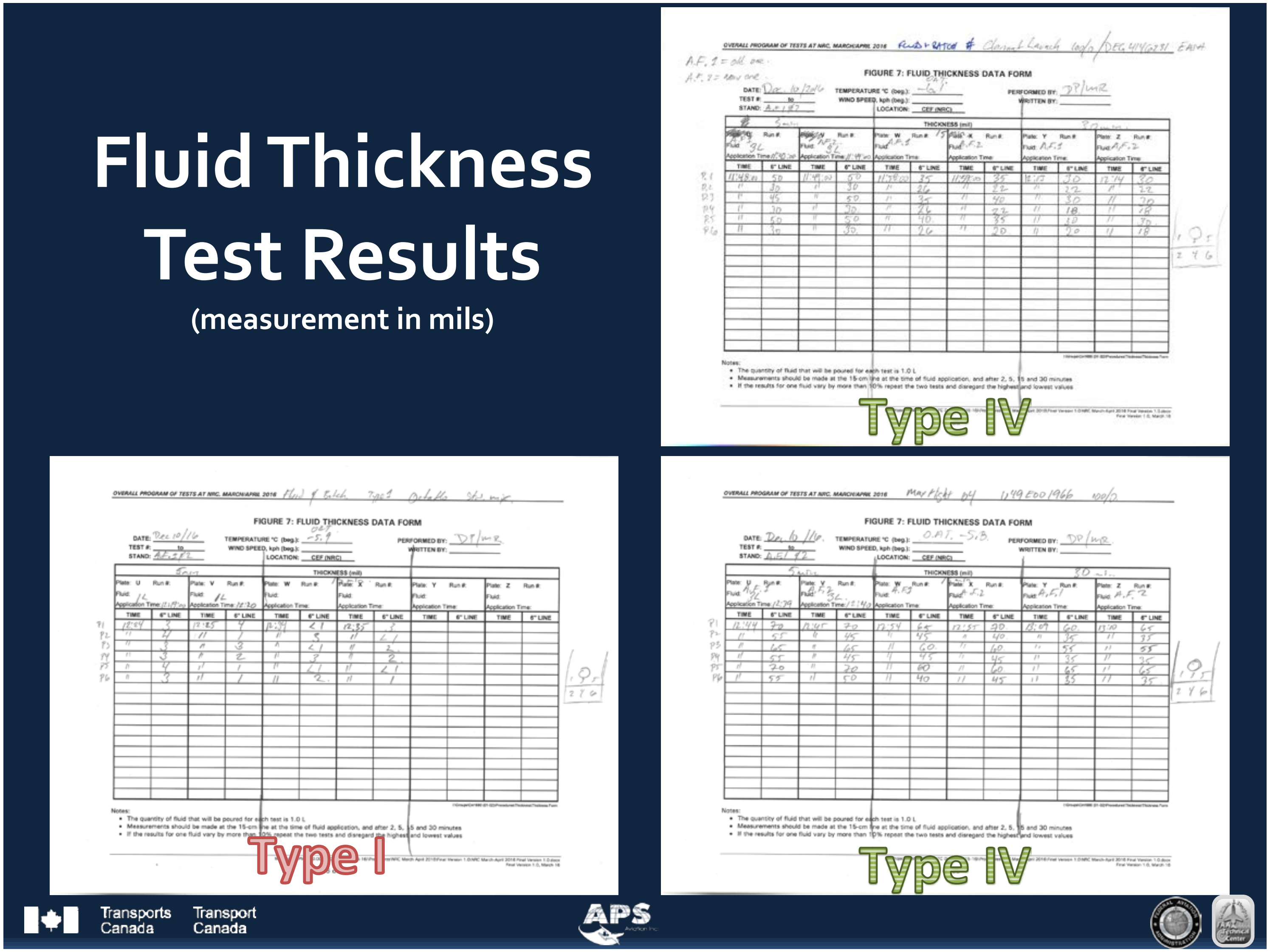
Airfoil Gap Sizing Testing and Evaluation
Regression Based Analysis of Rotating vs. Static Airfoil Data
Augmentation Factor Versus Wind Speed Analysis
Time Spent in Respective Orientation Analysis

Airfoil Gap Sizing Testing and Evaluation

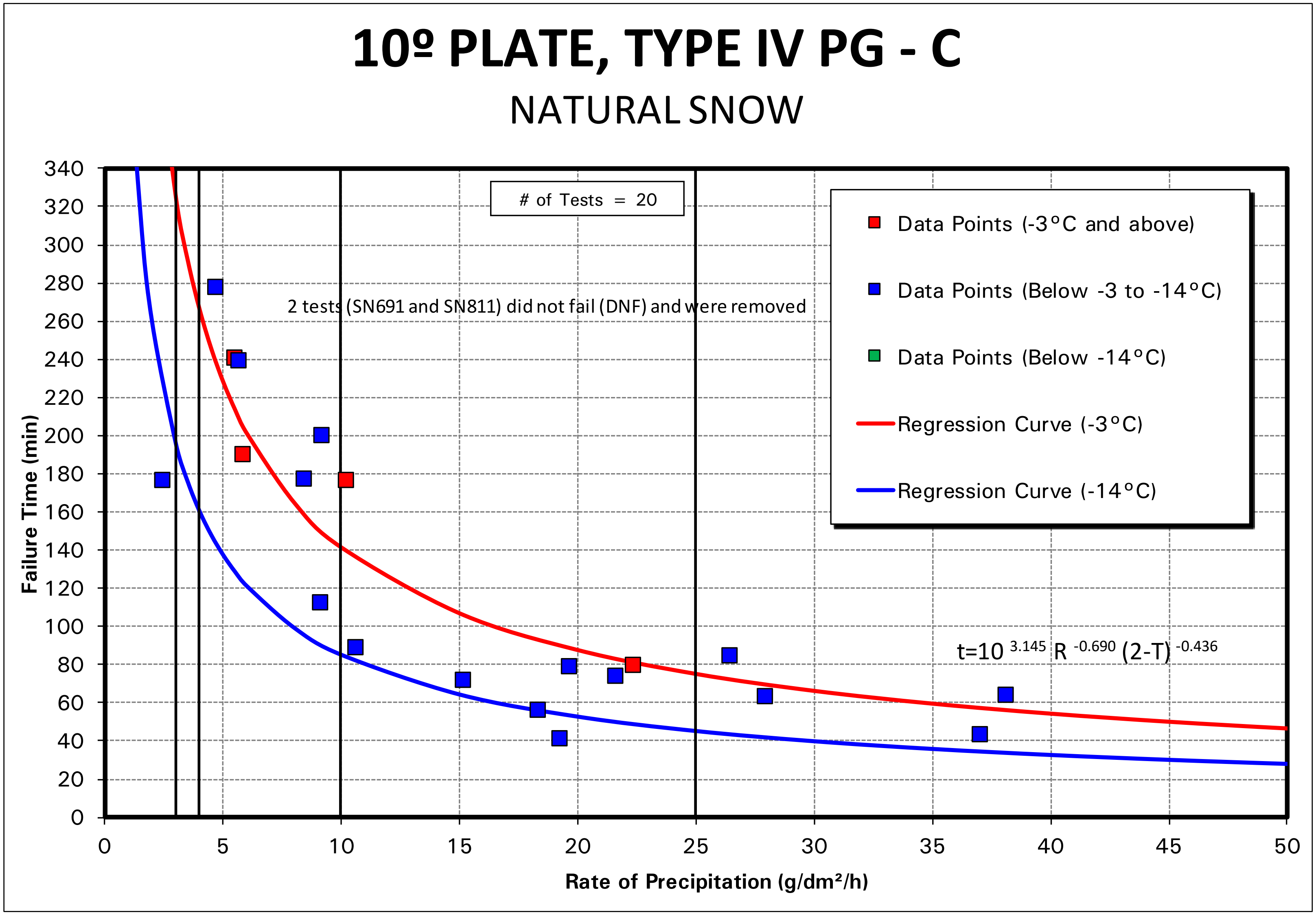
Comparison of fluid failure on airfoil with gaps set to 0.18mm, but error in setting can be up to 0.2mm or more due to undulations in aluminum sheeting.

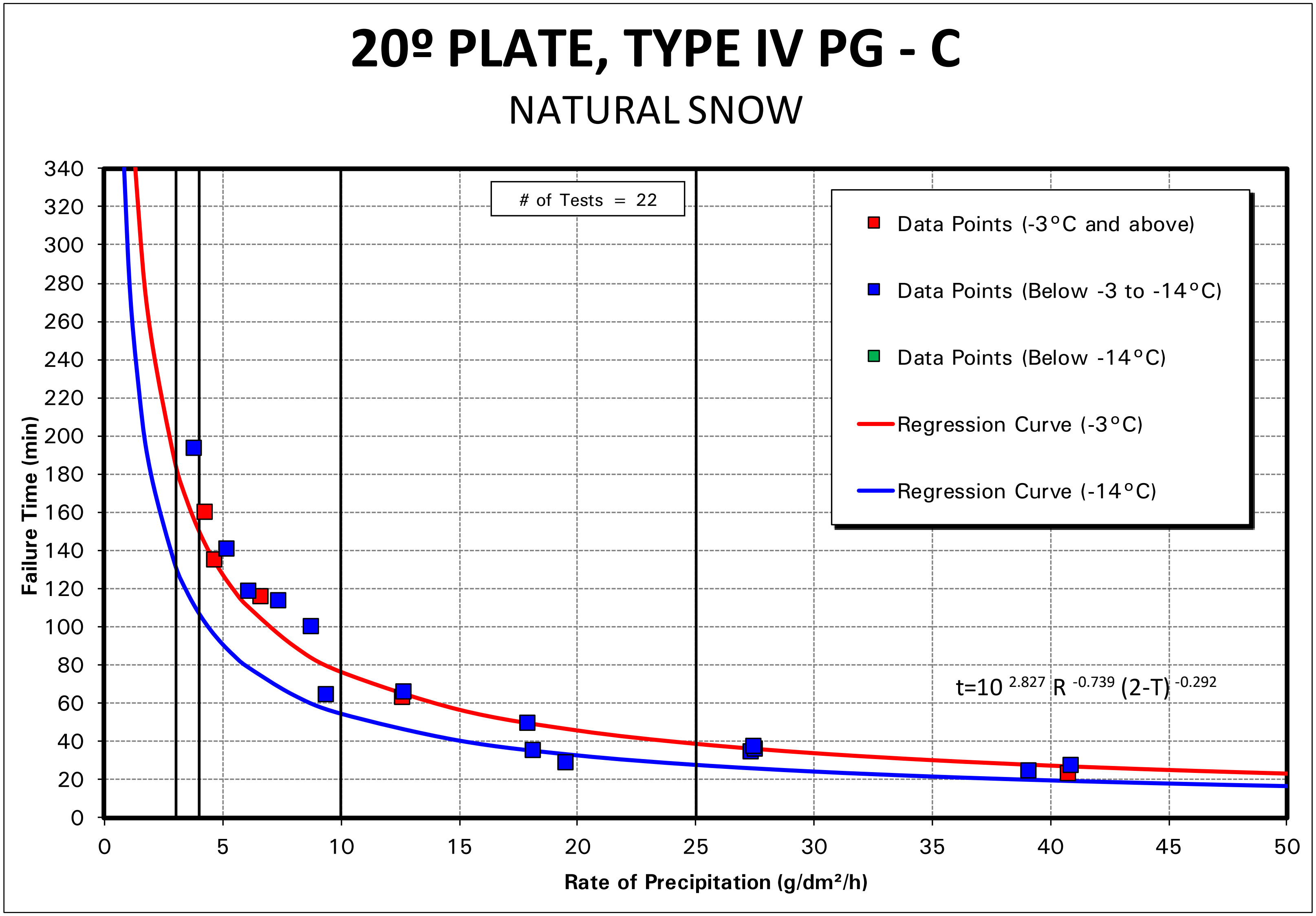


Summary of comparative fluid thickness testing results on airfoils with gaps set to 1mm.

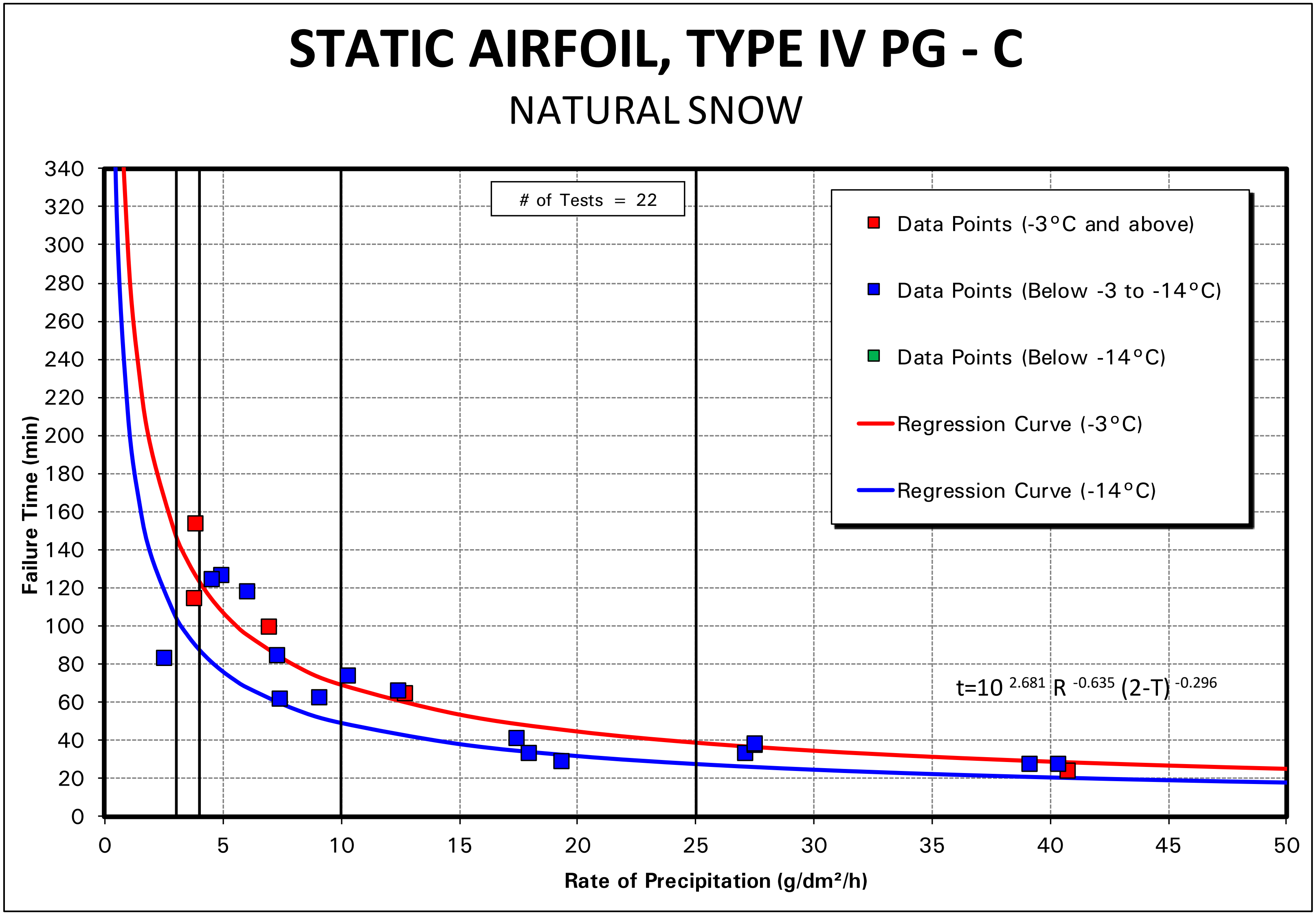


Regression Based Analysis of Rotating vs. Static Airfoil Data

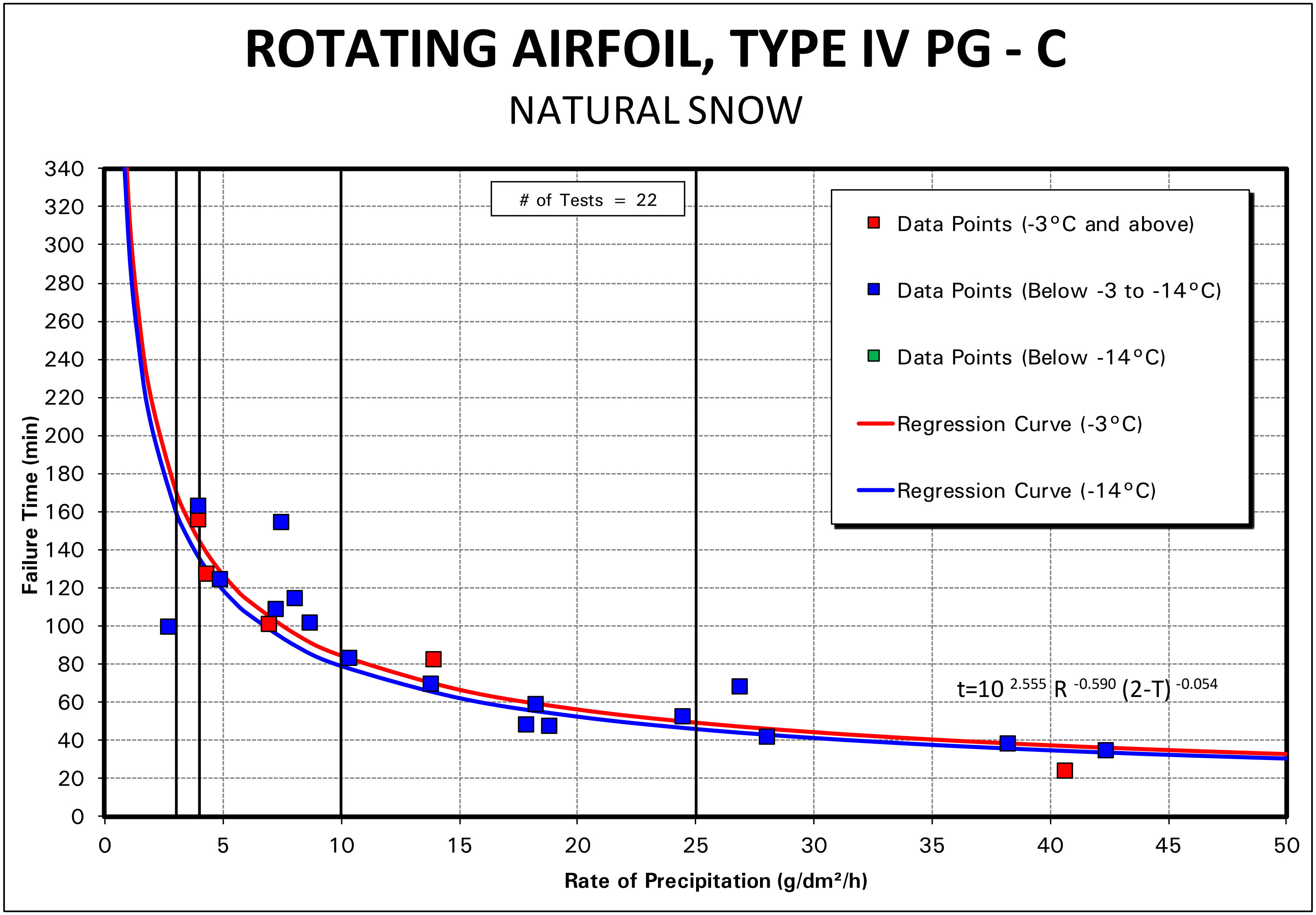

10º PLATE, TYPE IV PG - C
NATURAL SNOW
# of Tests = 20
2 tests (SN691 and SN811) did not fail (DNF) and were removed
Data Points (-3°C and above)
Data Points (Below -3 to -14°C)
Data Points (Below -14°C)
Regression Curve (-3°C)
Regression Curve (-14°C)
t=10 3.145 R -0.690 (2-T) -0.436
Failure Time (min)
Rate of Precipitation (g/dm²/h)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
5
10
15
20
25
30
35
40
45
50



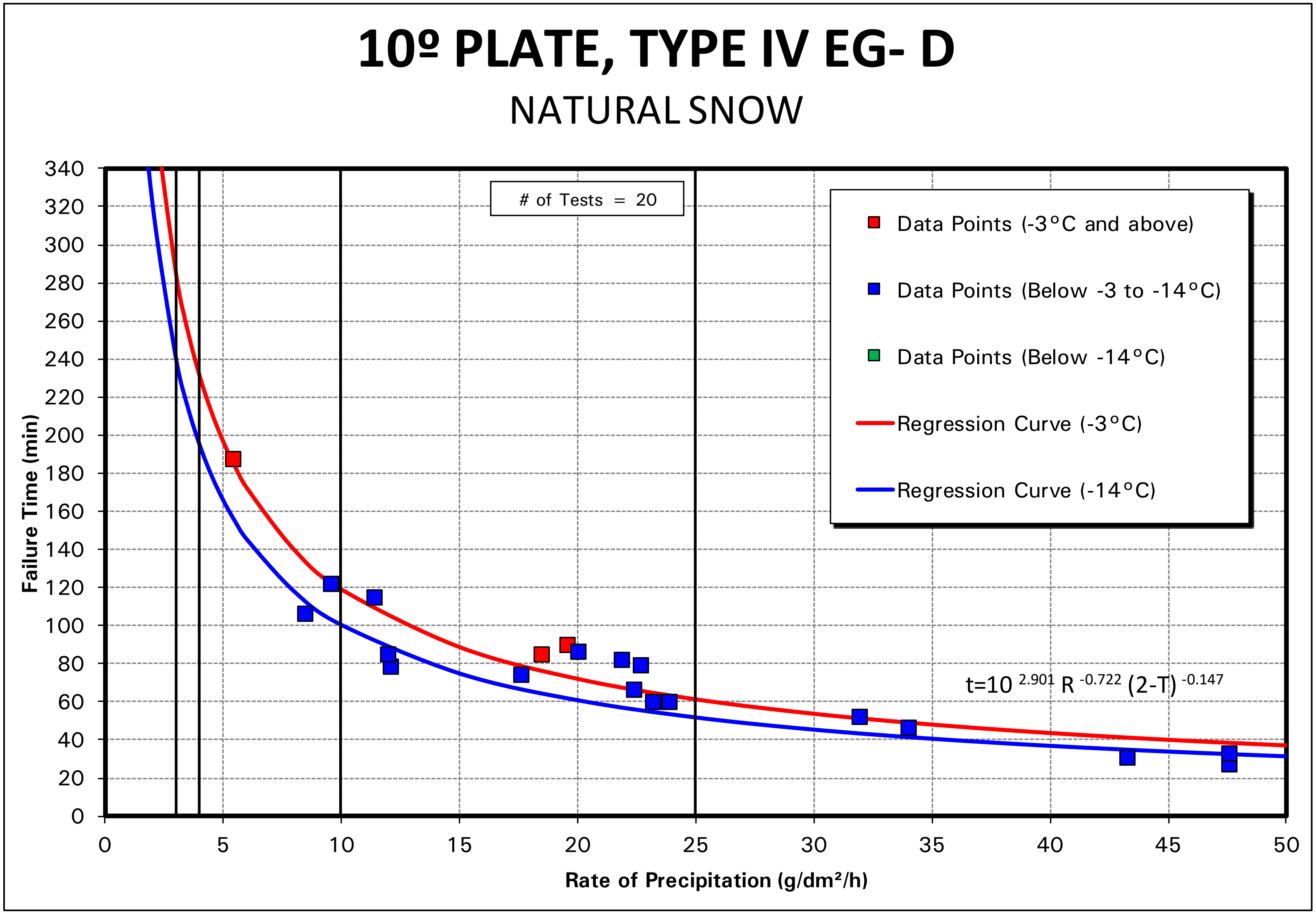
20º PLATE, TYPE IV PG - C
NATURAL SNOW
# of Tests = 22
Data Points (-3°C and above)
Data Points (Below -3 to -14°C)
Data Points (Below -14°C)
Regression Curve (-3°C)
Regression Curve (-14°C)
t=10 2.827 R -0.739 (2-T) -0.292
Failure Time (min)
Rate of Precipitation (g/dm²/h)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
5
10
15
20
25
30
35
40
45
50



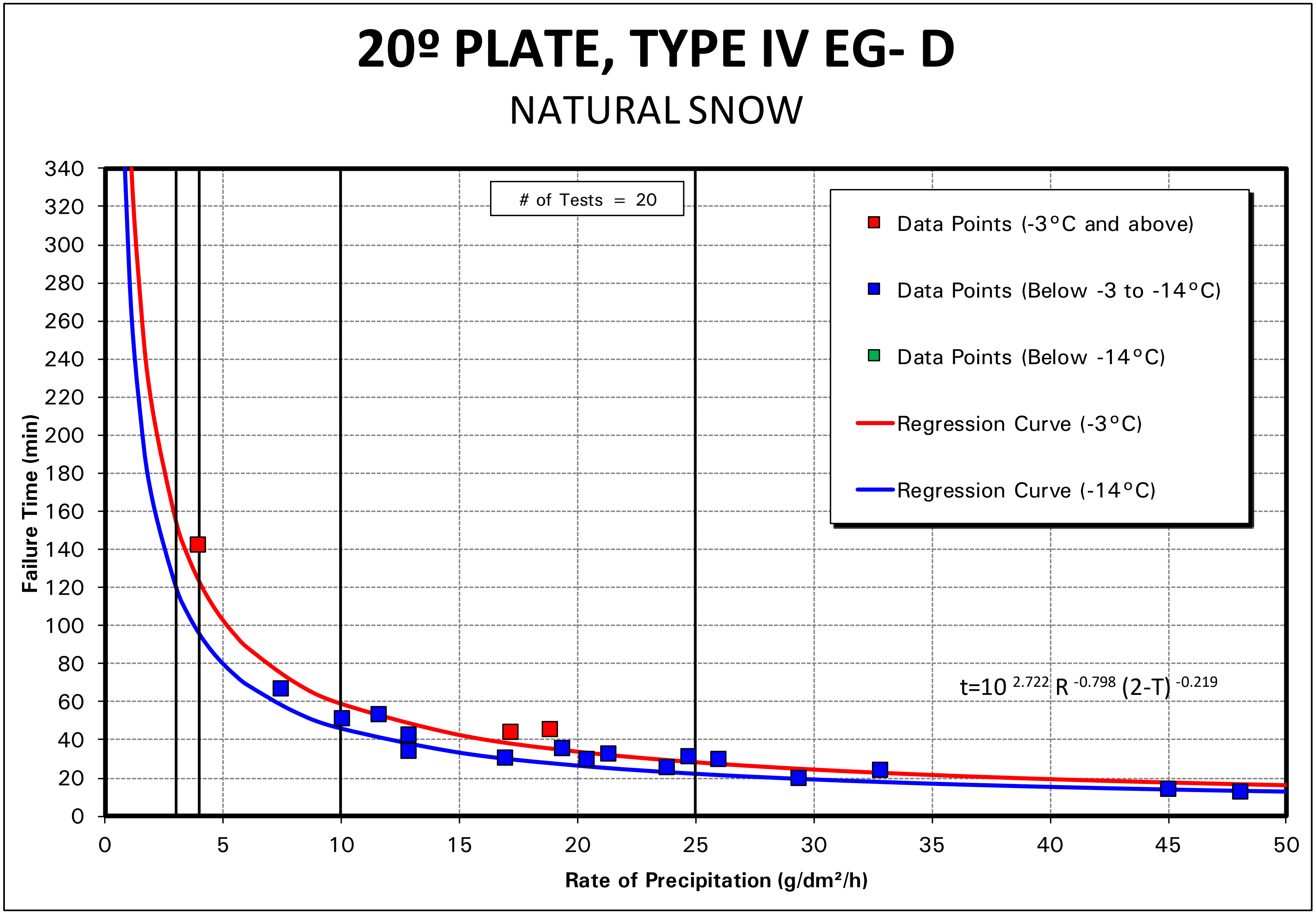
STATIC AIRFOIL, TYPE IV PG - C
NATURAL SNOW
# of Tests = 22
Data Points (-3°C and above)
Data Points (Below -3 to -14°C)
Data Points (Below -14°C)
Regression Curve (-3°C)
Regression Curve (-14°C)
t=10 2.681 R -0.635 (2-T) -0.296
Failure Time (min)
Rate of Precipitation (g/dm²/h)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
5
10
15
20
25
30
35
40
45
50

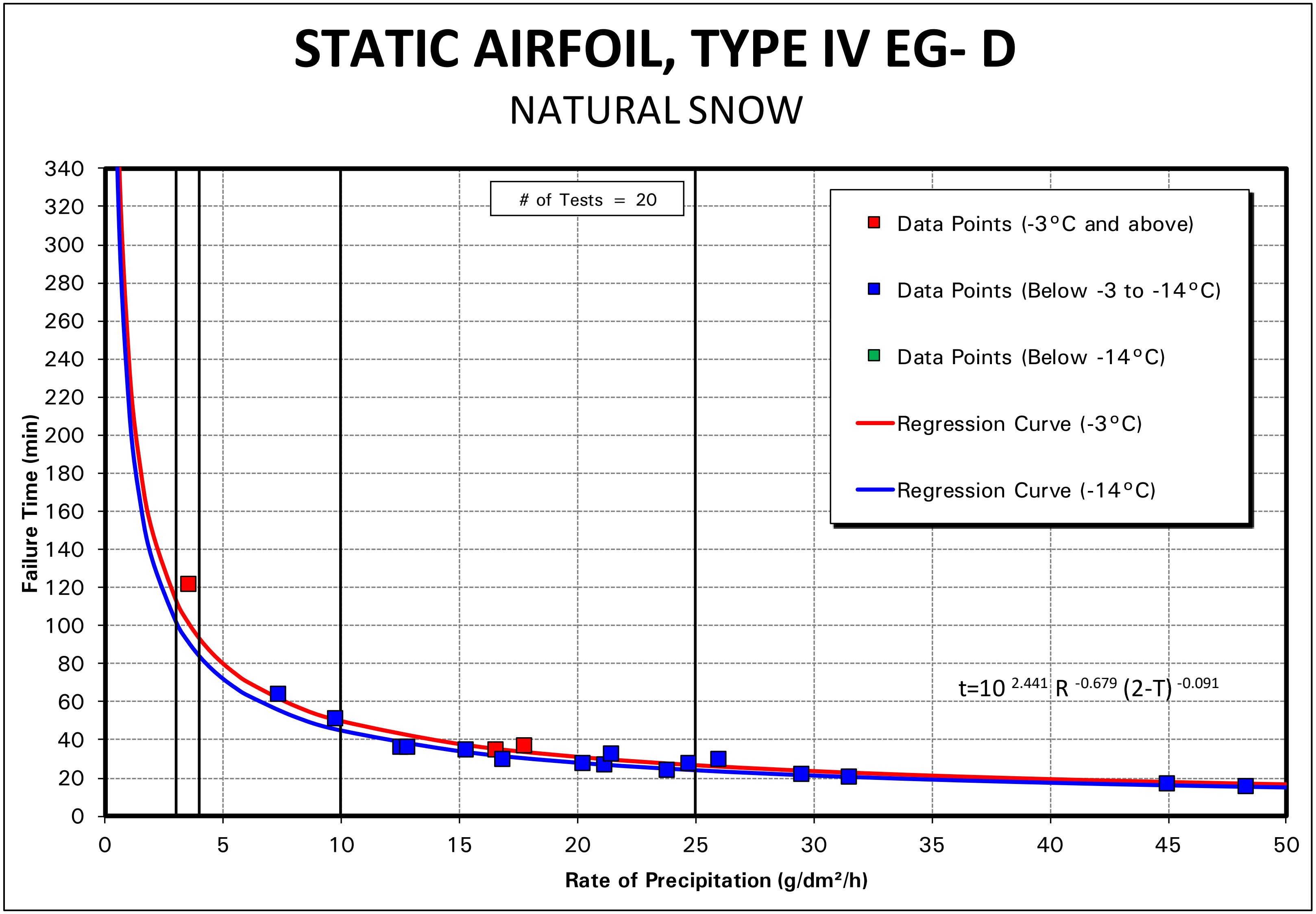


ROTATING AIRFOIL, TYPE IV PG - C
NATURAL SNOW
# of Tests = 22
Data Points (-3°C and above)
Data Points (Below -3 to -14°C)
Data Points (Below -14°C)
Regression Curve (-3°C)
Regression Curve (-14°C)
t=10 2.555 R -0.590 (2-T) -0.054
Failure Time (min)
Rate of Precipitation (g/dm²/h)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
5
10
15
20
25
30
35
40
45
50

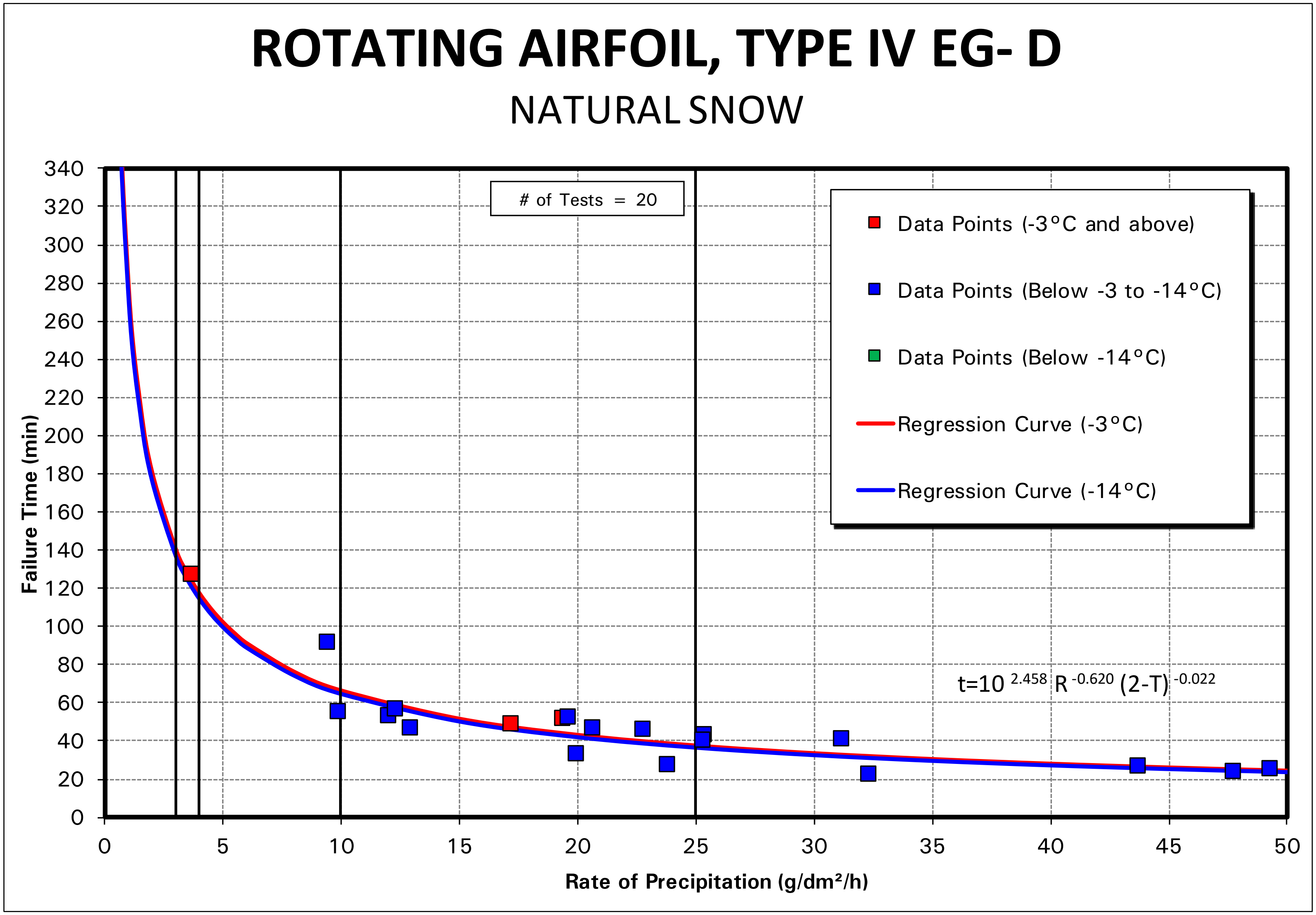


10º PLATE, TYPE IV EG- D
NATURAL SNOW
# of Tests = 20
Data Points (-3°C and above)
Data Points (Below -3 to -14°C)
Data Points (Below -14°C)
Regression Curve (-3°C)
Regression Curve (-14°C)
t=10 2.901 R -0.722 (2-T) -0.147
Failure Time (min)
Rate of Precipitation (g/dm²/h)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
5
10
15
20
25
30
35
40
45
50


20º PLATE, TYPE IV EG- D
NATURAL SNOW
# of Tests = 20
Data Points (-3°C and above)
Data Points (Below -3 to -14°C)
Data Points (Below -14°C)
Regression Curve (-3°C)
Regression Curve (-14°C)
t=10 2.722 R -0.798 (2-T) -0.219
Failure Time (min)
Rate of Precipitation (g/dm²/h)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
5
10
15
20
25
30
35
40
45
50



STATIC AIRFOIL, TYPE IV EG- D
NATURAL SNOW
# of Tests = 20
Data Points (-3°C and above)
Data Points (Below -3 to -14°C)
Data Points (Below -14°C)
Regression Curve (-3°C)
Regression Curve (-14°C)
$t=10^{2.441}\ R^{-0.679}\ (2-T)^{-0.091}$
Failure Time (min)
Rate of Precipitation (g/dm²/h)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
5
10
15
20
25
30
35
40
45
50


ROTATING AIRFOIL, TYPE IV EG- D
NATURAL SNOW
# of Tests = 20
Data Points (-3°C and above)
Data Points (Below -3 to -14°C)
Data Points (Below -14°C)
Regression Curve (-3°C)
Regression Curve (-14°C)
t=10 2.458 R -0.620 (2-T) -0.022
Failure Time (min)
Rate of Precipitation (g/dm²/h)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
5
10
15
20
25
30
35
40
45
50

Augmentation Factor Analysis Based on Regression Results				
Method	**Type IV PG-C Augmentation Factor (A)**	**Type IV EG-D Augmentation Factor (B)**	**Average of (A) and (B)**	**Confidence Level**
Evaluated at 8 HOT condition Limits (-3, -14ºC and 3, 4, 10, 25g/dm²/h)	140%	136%	138%	Medium - Limited # of evaluation points therefore can be biased
Evaluated at Average OAT and Rate of All Rotating Airfoil Tests	133%	144%	139%	Low - Single point evaluation and highly sensitive to small OAT or rate shifts
Manual Integral Evaluating Every OAT from 0 to -14ºC and Rate from 3 to 25g/dm²/h	138%	139%	139%	High - Covers a large set of OAT's and Rates and representative of conditions where data was collected
average:	137%	140%	138%	

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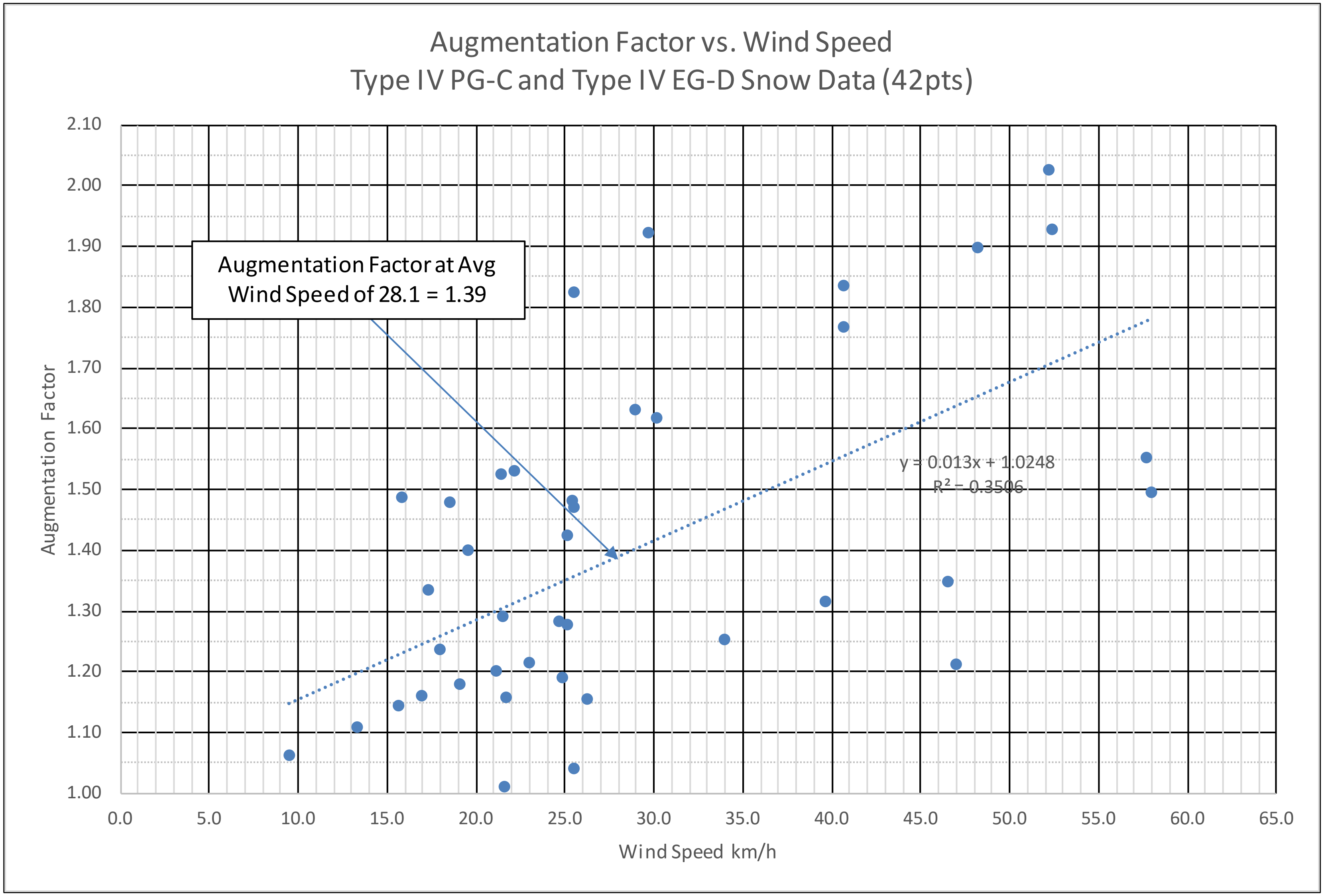
Augmentation Factor Versus Wind Speed Analysis



Augmentation Factor vs. Wind Speed
Type IV PG-C and Type IV EG-D Snow Data (42pts)
Augmentation Factor at Avg Wind Speed of 28.1 = 1.39
y = 0.013x + 1.0248
R² = 0.3506
Augmentation Factor
Wind Speed km/h
2.10
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0

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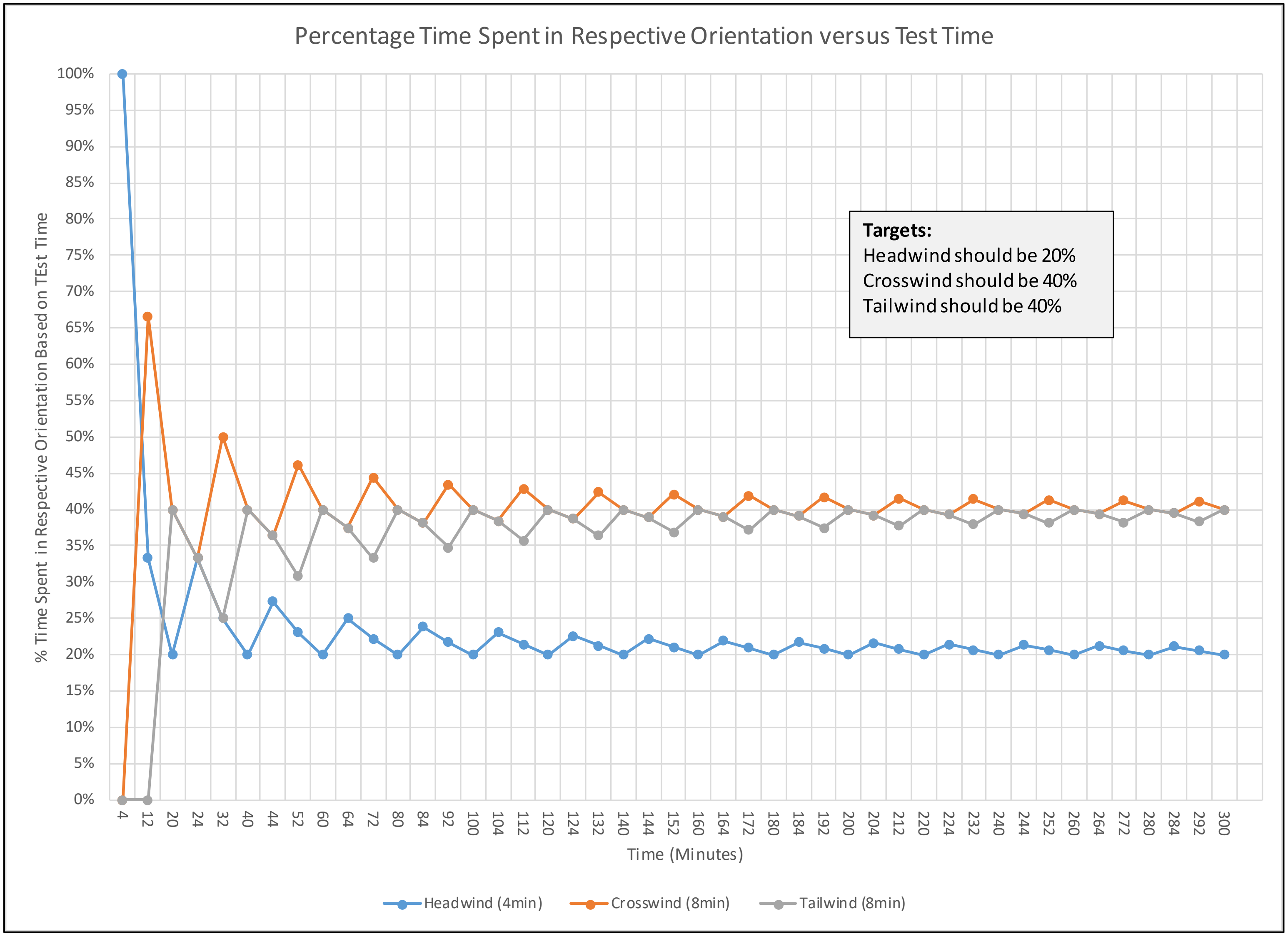
Time Spent in Respective Orientation Analysis

Comparison of Target % Time Spent in Each Orientation Versus the Average Actual % Time Spent in Each Orientation

Airfoil Orientation	Target % Time Spent in Orientation	Average Actual % Time Spent in Orientation
Headwind	20%	23.7%
Tailwind	40%	40.7%
Crosswind	40%	35.6%


Percentage Time Spent in Respective Orientation versus Test Time
% Time Spent in Respective Orientation Based on TEst Time
Time (Minutes)
Targets:
Headwind should be 20%
Crosswind should be 40%
Tailwind should be 40%
Headwind (4min)
Crosswind (8min)
Tailwind (8min)