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Fluid Endurance Time Tests Using the NCAR Snow Machine: Ethylene Glycol-Based Type II and IV Fluids, Type I Fluids, and Conditions Near and Above 0°C

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16. Abstract

This report summarizes the results of three investigations of the use of the National Center for Atmospheric Research (NCAR) Snow Machine in anti-icing fluid endurance time tests. The first investigation focused on its performance for ethylene glycol-based Type II and Type IV fluids; the second examined its suitability for testing Type I fluids, and the third examined its suitability for testing at temperatures near and above 0ºC.

Endurance time tests of Type II and IV fluids conducted in 2004 using the snow machine showed that it gave results that generally compared well with results from outdoor tests at the same conditions for all fluids except the only ethylene glycol-based fluid tested, ULTRA+. However, the number of tests was limited, and some had highly varying conditions. This report presents the results of subsequent ULTRA+ tests conducted to determine if the poor performance was more likely due to factors such as variable wind speed or direction, snowfall rate, or possibly experimental error, or to an inherent flaw in the snow machine for this particular fluid type. Additional tests showed good agreement between outdoor endurance time tests and with the snow machine tests, suggesting that discrepancies in previous tests were likely due to highly variable outdoor environmental conditions and possibly to experimental error.

The snow machine had not previously been used for endurance time tests of Type I fluids, which have significantly different properties than Type II and IV fluids. Modifications were made to the snow machine, and new procedures were implemented for endurance time tests with Type I fluids. Two fluids were evaluated and their endurance times compared to the holdover times in current Type I holdover time tables. The comparison showed agreement within experimental error, indicating that when properly configured, the snow machine is suitable for endurance time tests of Type I fluids.

The snow machine has more commonly been used to determine endurance times of anti-icing fluids for “cold” temperatures rather than “warm” temperatures around 0°C. Type II Kilfrost® ABC 2000 tests conducted during 2006 were primarily designed to demonstrate that the snow machine could be configured to conduct tests at temperatures between -3°C and 0°C and above 0°C. The tests demonstrated that the snow machine could be used to conduct endurance time tests for these temperatures by appropriately controlling the plate temperature.

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LIST OF ACRONYMS

AMIL	Anti-Icing Materials International Laboratory
APS	APS Aviation, Inc.
ARP	Aerospace Recommended Practice
FAA	Federal Aviation Administration
FY	Fiscal year
HOT	Holdover time
LWE	Liquid water equivalent
NCAR	National Center for Atmospheric Research
OAT	Outside air temperature
UCAR PG ADF	UCAR propylene glycol-based SAE Type I aircraft deicing fluid
UCAR EG ADF	UCAR Ethylene glycol-based SAE Type IV aircraft deicing fluid
UQAC	Université du Québec à Chicoutimi

EXECUTIVE SUMMARY

This report summarizes the results of three investigations of the use of the National Center for Atmospheric Research Snow Machine in anti-icing fluid endurance time tests. The first investigation focused on its performance for ethylene glycol-based Type II and Type IV fluids, the second examined its suitability for testing Type I fluids, and the third examined its suitability for testing at temperatures near and above 0ºC.

Endurance time tests of Type II and IV fluids conducted in 2004 using the snow machine showed that it gave results that generally compared well with results from outdoor tests with the same conditions for all fluids except the only ethylene glycol-based fluid tested, ULTRA+. The snow machine endurance times exceeded the outdoor endurance times for all tests by 25% or more, and exceeded the longest outdoor endurance time by 50%. However, the number of tests was limited, and some had highly varying conditions. This report presents the results of subsequent ULTRA+ tests conducted to determine if the poor performance was more likely due to factors such as variable wind speed or direction, snowfall rate, or possibly experimental error, or to an inherent flaw in the snow machine for this particular fluid type. Additional outdoor tests were compared to snow machine tests for the same conditions and showed good agreement, suggesting that the current version of the snow machine is able to adequately perform endurance time tests with ethylene glycol-based fluids and that discrepancies in previous tests were likely due to highly variable outdoor environmental conditions and possibly to experimental error.

The snow machine had not previously been used for endurance time tests of Type I fluids, which have significantly different properties than Type II and IV fluids. Experiments were conducted to evaluate the ability of the snow machine to perform endurance time tests of Type I fluids. Modifications were made to the snow machine, and new procedures were implemented for testing these fluids. Two fluids (UCAR™ propylene glycol-based SAE Type I aircraft deicing fluid and UCAR Ethylene glycol-based SAE Type IV aircraft deicing fluid) were evaluated and the endurance times compared to the holdover times in current Type I holdover time tables. The comparison showed agreement within experimental error, indicating that, when properly configured, it is suitable for endurance time tests of Type I fluids.

The snow machine has more commonly been used to determine endurance times of anti-icing fluids for "cold" temperatures (i.e., below 5°C) rather than "warm" temperatures (i.e., approximately 0°C). Currently, there is interest in comparing endurance times at conditions above 0°C with those between -3° and 0°C. Tests conducted in 2006 were primarily designed to demonstrate that the snow machine could be configured to conduct tests at the warm temperatures involved. It was decided to test Type II Kilfrost® ABC 2000 fluid during this initial work since it is widely used in Europe for snow conditions above 0°C. The tests demonstrated that the snow machine could be used to conduct above 0°C snow tests by appropriately controlling the plate temperature. Results with Type II Kilfrost ABC 2000 showed ~10% longer endurance times at temperatures above 0°C compared to -3°C. Testing with a free-floating plate temperature showed strong sensitivity to wind speed heating effects. Further testing is required to determine endurance time gains for other qualified fluids for the above 0°C condition.

1. INTRODUCTION.

This report summarizes the results of three investigations of the use of the National Center for Atmospheric Research (NCAR) Snow Machine in anti-icing fluid endurance time tests. The first investigation focused on its performance for ethylene glycol-based Type II and Type IV fluids, the second examined its suitability for testing Type I fluids, and the third examined its suitability for testing at temperatures near and above 0ºC.

The snow machine has been in development for a number of years with the goal of demonstrating the snow machine's ability to reproduce frosticator plate endurance time tests of Type II and IV anti-icing fluids and Type I fluids for snow conditions (Rasmussen, et al., 1999, 2003, 2006). These tests have been conducted in natural, outdoor conditions. Anti-icing fluid tests with the snow machine during fiscal year (FY) 2004 focused on a comparison of outdoor fluid tests to indoor tests using a constant frosticator plate temperature for a given snowfall rate (Rasmussen, et al., 2006). The variability in earlier comparisons of outdoor to indoor tests (Rasmussen, et al., 2003) was attributed to the greater variability of plate temperature for the indoor tests compared to outdoor tests. The plate temperature variation for the indoor snow machine tests was due mainly to plate cooling caused by the latent heat used in the melting of the snowflakes as they fell into the fluid (Rasmussen, et al., 2003). Higher snowfall rates result in greater cooling and latent heat release due to the higher mass rates. The indoor tests were conducted in an environment with low wind velocity (<0.5 m/s), whereas the outdoor tests were conducted with significantly higher wind velocities. Thus, in the outdoor tests, the cooling effect of the latent heat release by melting was offset by the heating effect of the wind. As a result, the outdoor plate temperature was warmer than the indoor plate temperature. To account for the indoor snow machine test effect, the outdoor plate temperature data from NCAR and APS Aviation, Inc. (APS) outdoor tests were analyzed as a function of snowfall rate and a linear relationship was established. During FY04, the indoor snow machine tested this relationship for qualified fluids for that year. Over 80 tests were conducted by NCAR, and similar numbers by APS and the Université du Québec à Chicoutimi (UQAC). APS used an NCAR Snow Machine, while UQAC used their snow machine. The results showed reasonably good agreement among the three snow machines in terms of endurance time for all fluids tested (within ±25% in terms of overall endurance time), except for ULTRA+ Type IV fluid, for which larger differences were noted. ULTRA+ was the only ethylene glycol fluid tested; the rest were propylene glycol fluids, and only a few ULTRA+ outdoor data points were available for comparison. To investigate the discrepancy further, additional tests were conducted during FY05.

The tests described in the previous paragraph were for Type II and IV fluids. For the snow machine to be qualified for all fluid types, the snow machine was also evaluated for Type I fluids during FY05.

After consideration at the 2004 SAE G-12 Holdover Times Subcommittee meeting, the above 0°C row in the holdover time tables was removed due to the similarity of the holdover times in the -3° to 0°C row to those for the above 0°C conditions, and the more limited test data for the latter. Some European operators, however, questioned the removal of the above 0°C row due to the high frequency of snowfall events above 0°C and the need for additional time for certain operations. Outdoor tests showed wide scatter for these warm conditions, so the outdoor tests to evaluate the differences in performance between the two temperature ranges were not conclusive. Since the snow machine tests can be controlled to a much higher degree than the outdoor tests, the snow machine was used to determine whether the difference between the endurance times for conditions above 0°C are significantly different than those for -3° to 0°C. This was the primary activity during FY06. Thus, the key activities with the snow machine for FY05 and FY06 were:

- Conduct additional ULTRA+ Type IV outdoor fluid tests and compare the results with indoor snow machine tests.

- Demonstrate the ability of the snow machine to be used for Type I fluid endurance time tests.

- Determine the difference in endurance time for snow conditions above 0°C and conditions between -3° to 0°C.

2. ULTRA+ TESTS WITH THE SNOW MACHINE.

Round-robin fluid tests with constant plate temperature were conducted with the Snow Machine by NCAR and APS (and by UQAC/Anti-Icing Materials International Laboratory (AMIL) using their snow machine) in FY04 (Rasmussen, et al., 2006). The tests were designed to compare results from previous outdoor fluid tests conducted by APS. Over 100 cases with a wide variety of fluids and conditions were tested. The round-robin indoor tests required that the plate be maintained at a constant temperature throughout the individual experiments to simulate the wind heating on the plates that was observed during the outdoor tests. The fluid temperatures for the indoor tests were adjusted to the ambient air temperature measured at the beginning of each outdoor test. APS chose endurance time tests that had a wide range of temperature and snowfall rates, and removed the tests with the largest fluctuations in snowfall rate. Results from the round-robin tests showed that the snow machine tests conducted by NCAR agreed with the outdoor tests for all fluids except ULTRA+ (figure 1). The snow machine endurance times tended to exceed the outdoor endurance time by 25% or more for all tests and exceeded the longest outdoor endurance time by 50%. The outdoor tests with ULTRA+ had some of the greatest variability in snowfall rate of those retained by APS for the round-robin tests. Previous tests have shown larger scatter in the endurance times that had highly varying conditions. Thus, further ULTRA+ tests were conducted to determine if this poor performance was due to the outdoor test conditions, such as variable wind speed or direction or variable snowfall rate, or was due to an inherent flaw in the snow machine for this particular fluid type.

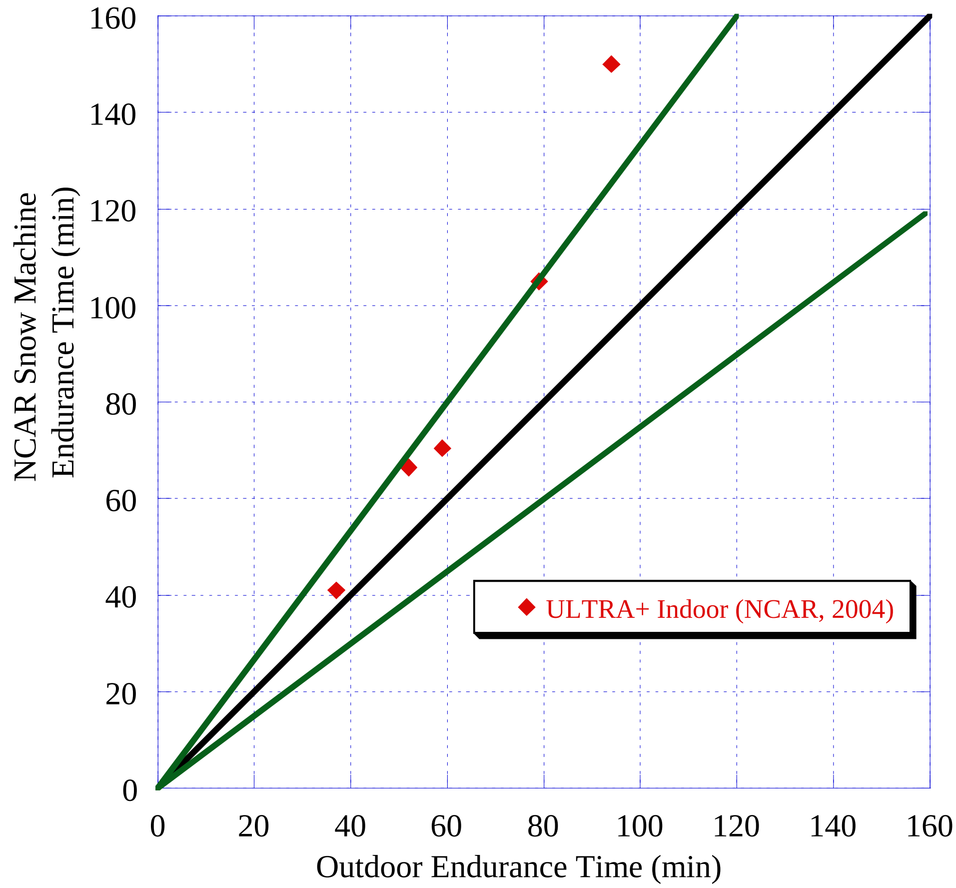

Figure 1. Comparison of Outdoor Endurance Times to the Snow Machine Endurance Times Resulting From the Round-Robin Tests During 2004 (The green lines represent the ±25% error bar for the data.)

2.1 THE NCAR OUTDOOR ULTRA+ TESTS.

The ULTRA+ outdoor tests were conducted at the NCAR Marshall Field Site during the winter of 2004/2005. Endurance time tests were conducted using setup and procedures similar to previous years (Rasmussen, et al., 2003). This consisted of placing the collection system (a frosticator plate mounted on top of a collection bucket) onto a mass balance that automatically recorded the accumulated snow mass landing on the frosticator plate every 6 seconds. The fluid mass ran into the bucket, so no mass change occurred due to fluid running off the plate (see figure 2). By monitoring the mass of the system every 6 seconds, snow accumulation and rate onto the plate were well documented. (The snow machine system used this accumulation rate to duplicate the snow conditions observed outdoors for the comparison tests.) The plate was rotated into the wind at the beginning of the test. Two test plates were used side-by-side in each experiment to ensure consistency of failure calls, a key improvement to previous outdoor tests.

Figure 2. Example of Setup Used for Outdoor Endurance Time Tests

On March 13, 2005, a snow event occurred in Marshall, CO, and three tests with paired plates were run on that day (figures 3-5). Figure 3 shows results for the two plates for Test 1. The initial fluid temperature was 8°C and the outside air temperature (OAT) was -3°C. Liquid water equivalent (LWE) snowfall rates (~19 $g/dm^2/hr$) remained steady throughout the test. Failure time between the two plates differed by only a minute-and-a-half. Figure 4 shows results for the two plates for Test 2. LWE rates of ~13 $g/dm^2/hr$ were fairly consistent until the end of the test when increased wind speeds caused increased noise in the mass readings. Figure 5 shows results for the two plates for Test 3. LWE rates of ~20 $g/dm^2/hr$ and OAT of -4.5°C remained steady throughout the test.

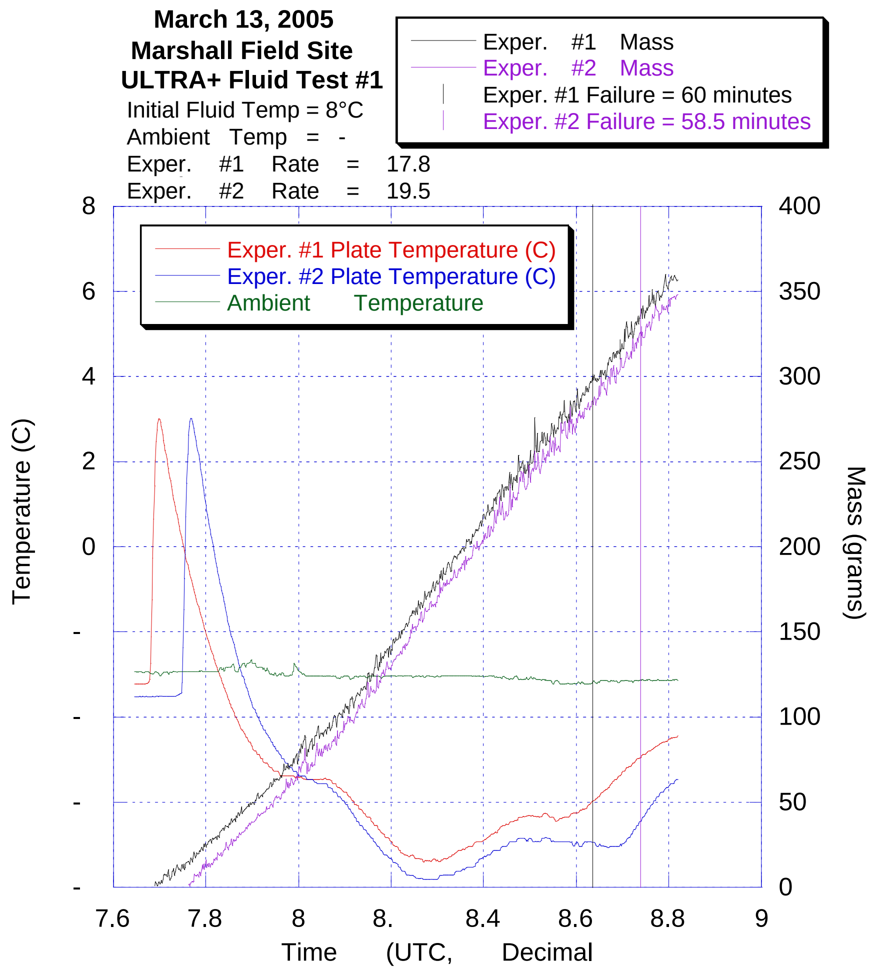

Figure 3. Endurance Time Test 1 Performed at Marshall, CO, on March 13, 2005

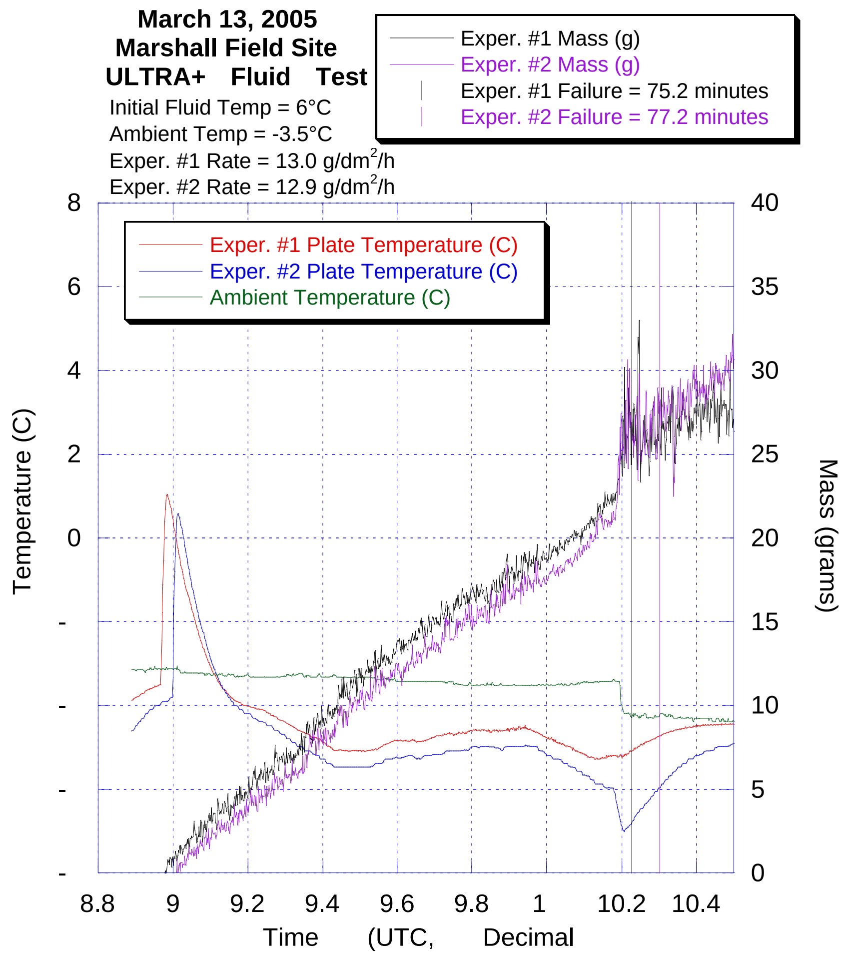

Figure 4. Second Endurance Times Test Performed at Marshall, CO, on March 13, 2005

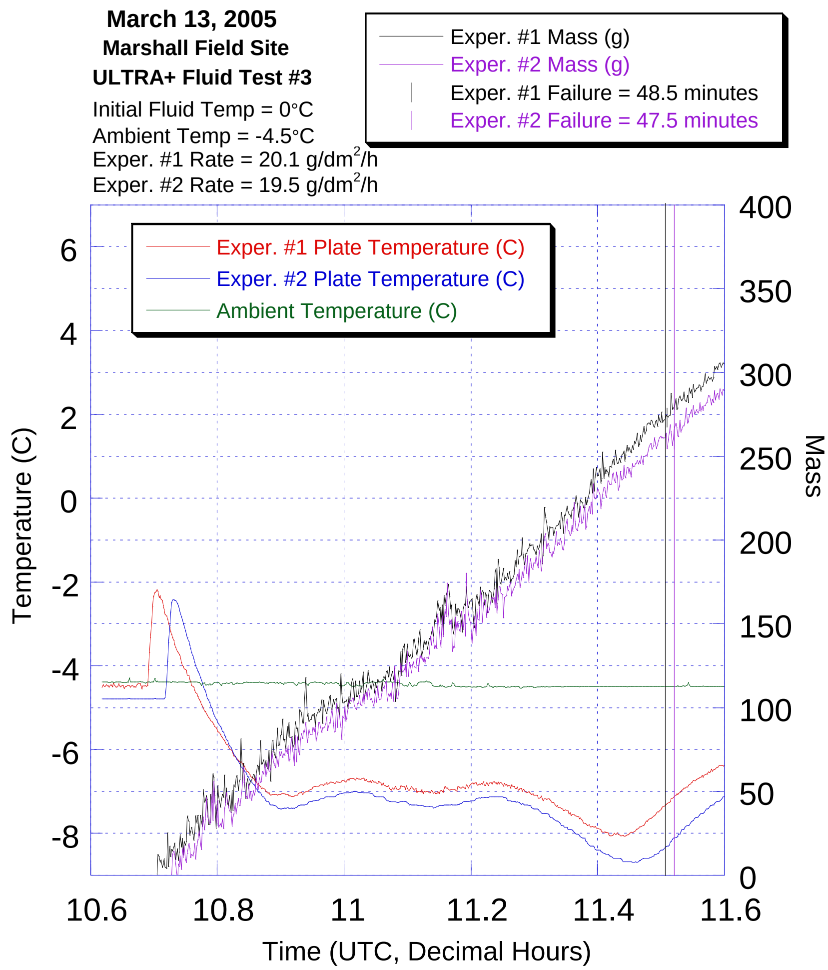

Figure 5. Third Endurance Times Test Performed at Marshall, CO, on March 13, 2005

2.2 INDOOR SIMULATION WITH THE SNOW MACHINE OF OUTDOOR TESTS.

Since each pair of outdoor endurance time tests agreed, one endurance time test was chosen from each pair to be simulated in the snow machine. The ULTRA+ fluid tests were identically conducted to the 2004 tests.

The room temperature was maintained at approximately 2°C colder than the plate temperature to prevent the heating of the plate by the air. The constant plate temperature setting was calculated using the same relationship between plate temperature and snow fall rate, as shown in figure 6. The average temperature drop is subtracted from the ambient temperature based on the snowfall rate, which results in the constant plate temperature setting for the indoor experiment.

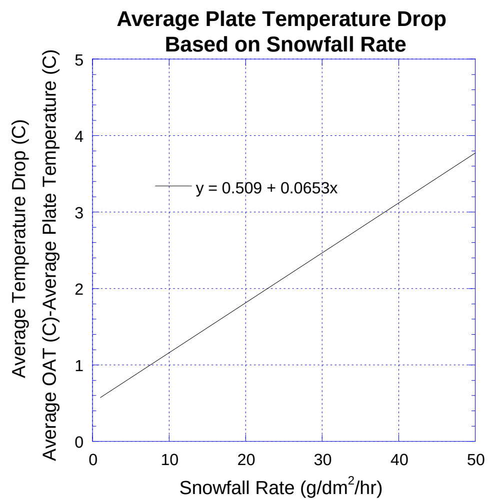

Figure 6. Curve Used to Determine Constant Plate Temperature From Snowfall Rate

Figure 7 shows an example of an indoor simulation. The snow machine simulation of outdoor Test 3 showed excellent agreement with the outdoor data. The rate for this experiment was 20.1 g/dm^2/hr. A constant plate temperature of -6.3°C was used. The outdoor endurance time was 48.5 minutes, and the snow machine-simulated endurance time was 46.5 minutes. This gave a difference in endurance times of only 2 minutes, well within the margin of error.

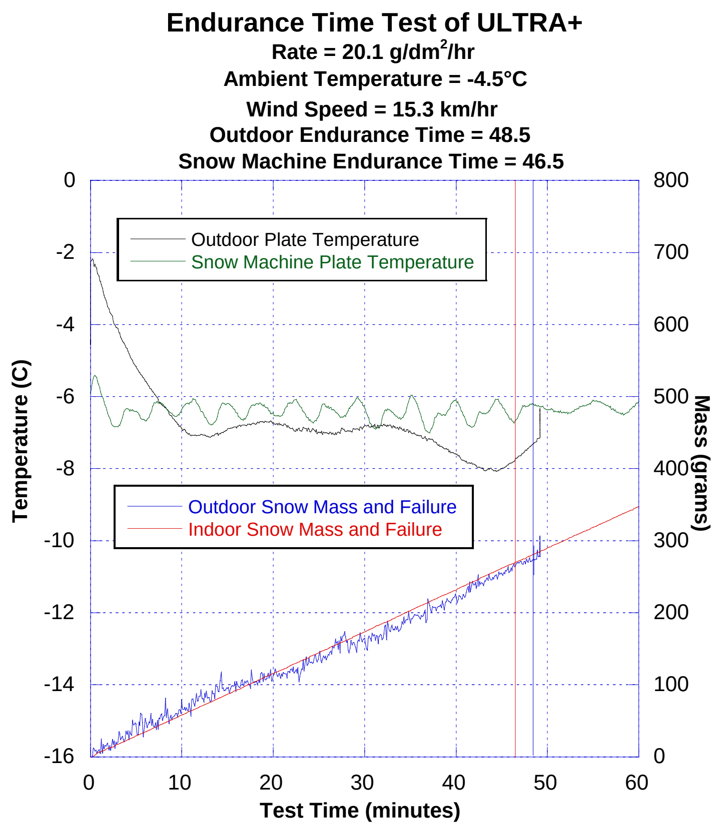

Figure 7. Comparison of Outdoor and Snow Machine Endurance Times for Outdoor Test 3

2.3 RESULTS FROM SNOW MACHINE TESTS OF ULTRA+.

A comparison of the test results from 2005 with the results from the round-robin tests from APS and NCAR in 2004 (figure 8) shows that most of the snow machine endurance times (conducted by APS and NCAR) fall within the ±25% margin of error, with the exception of a few outliers. The three new data points, in particular, fall very close to the 1:1 line, and suggest that the outliers obtained in the previous tests are likely due to experimental error and possibly to highly variable outdoor conditions, such as wind direction and wind speed.

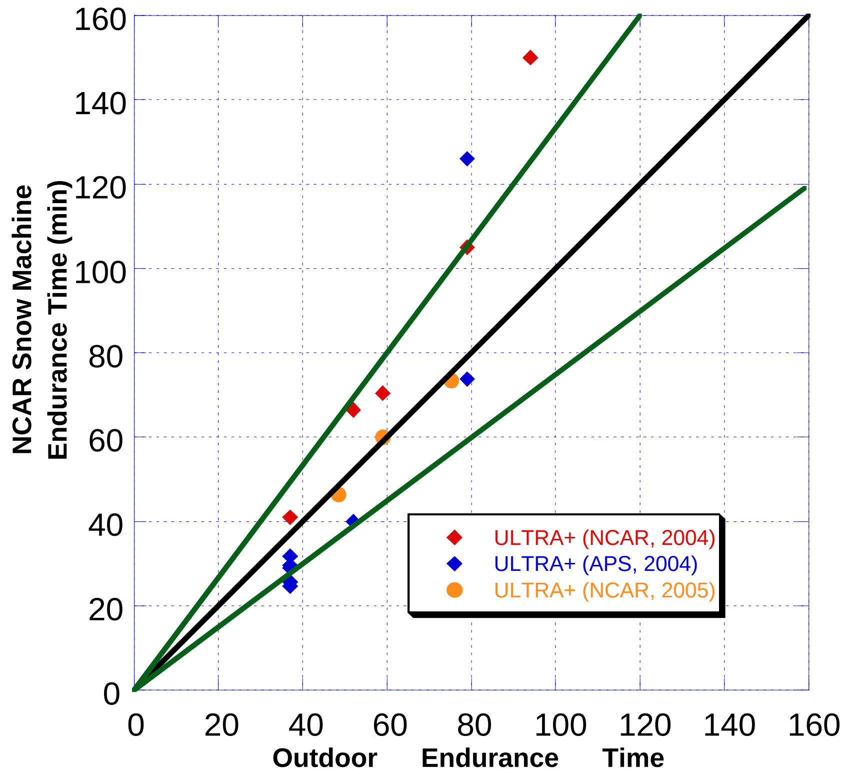

Figure 8. Comparison of Outdoor Endurance Time to the Snow Machine Endurance Time

3. TYPE I FLUID TESTS.

Experiments were run on Type I deicing/anti-icing fluids using the snow machine to evaluate the snow machine's ability to perform endurance time tests of Type I fluids. Modifications were made to the snow machine, and new procedures were implemented for testing these fluids. Two fluids (UCAR™ propylene glycol-based SAE Type I aircraft deicing fluid (UCAR PG ADF) and UCAR ethylene glycol-based SAE Type IV aircraft deicing fluid (UCAR EG ADF)) were evaluated against the current Type I Holdover Time (HOT) tables.

3.1 MODIFICATIONS TO THE SNOW MACHINE TO SUPPORT TYPE I FLUID TESTS.

Based on procedures for the Type I fluid outdoor tests, modifications were made to the snow machine tray assembly. The tray assembly used for Type II and IV fluids tests (figure 9) was modified by adding a cold-soak box (figure 10) to the tray assembly. The cold-soak box design was based on the specifications from SAE Aerospace Recommended Practice (ARP) 5485, which describes its use in Type I fluid outdoor tests. The cold-soak box is an aluminum box insulated with a layer of 1-inch-thick Styrofoam. Unlike the regular tray assembly, the interior aluminum box is in direct contact with the test plate. The test plate remains at a 10-degree angle to allow fluid to run off. Modifications to the code used to run the snow machine were required to account for the larger surface area when using the new cold-soak box. A fluid spreader was also built based on specifications from SAE ARP 5485. The fluid spreader, a PVC pipe cut lengthwise with holes drilled in the bottom, was used to ensure even distribution of the fluid over the test plate.

Figure 9. The Tray Assembly Used to Test Type II and IV Fluids

Figure 10. The New Cold-Soak Box Used to Test Type I Fluids

3.2 TYPE I FLUID TEST PROCEDURE.

Type I fluids were tested using the following procedure.

1. The Type I fluid was diluted with normal tap water so that the freezing point temperature of the diluted fluid is 10ºC below the ambient temperature specified for the endurance time test.

2. The diluted fluid was heated to a temperature of 60° to 62°C using a double boiler and then stored in an insulated container.

3. A small amount of fluid was applied at ambient temperature to the test plate to remove any contamination and to ensure the fluid spread over the entire plate.

4. The fluid spreader was positioned over the top portion of the plate, and heated fluid was poured from the insulated container into the spreader.

5. Once the fluid was fully applied to the plate, the spreader was removed and the experiment began.

6. Visual fluid failure was called once a third of the plate was contaminated by snow/ice.

Brix measurements were not attempted due to the lack of thickness of the fluid and the effect of test plate contact on the snow machine auto-rate calculation.

3.3 ENDURANCE TIME TESTS.

The endurance time tests conducted with the Type I fluids were based on conditions from the Federal Aviation Administration (FAA) HOT table for Type I fluids. Tests were conducted based on the worst conditions found within each cell of the HOT table. This produced a list of 16 possible tests using a combination of four temperatures (-3°, -6°, -10°, and -25°C) and four precipitation rates (3, 4, 10, and 25 g/dm²/hr). Examples of the results from these tests are shown in figures 11 and 12. The decrease in plate temperature over time for both fluids under the same conditions is shown to be in good agreement. The figures also show that endurance times generated by the snow machine are very close to the HOT guidelines.

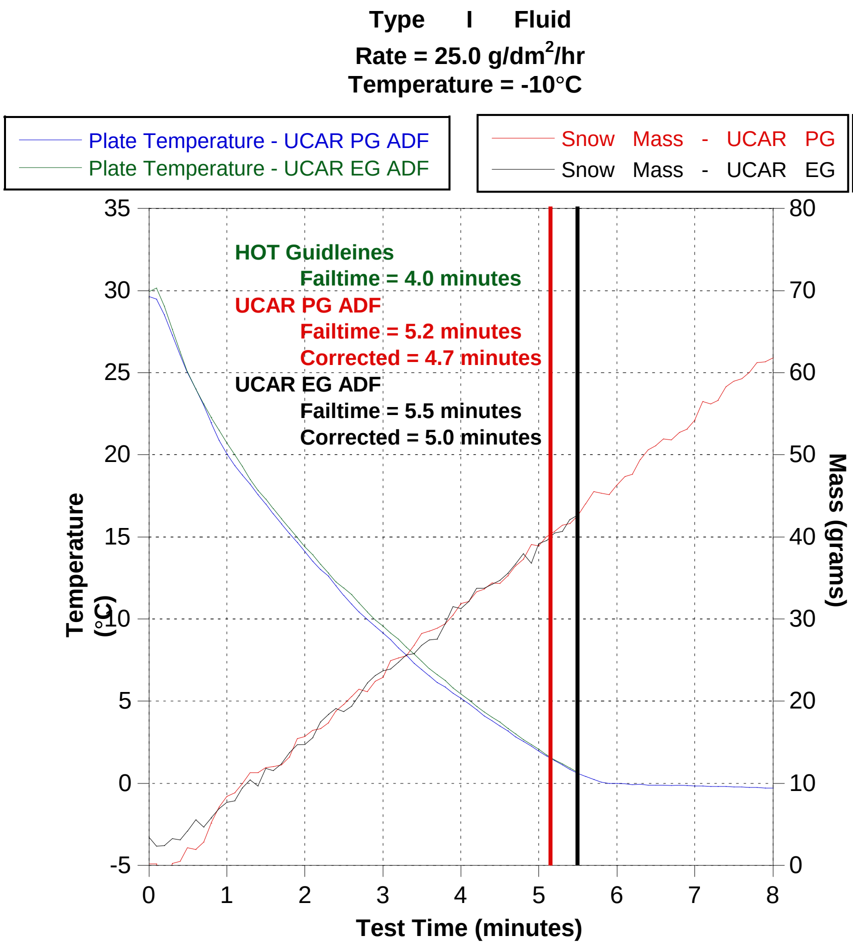

Figure 11. Results From Endurance Time Tests for UCAR PG ADF and UCAR EG ADF for an Air Temperature of -10ºC and a Rate of 25 g/dm²/hr

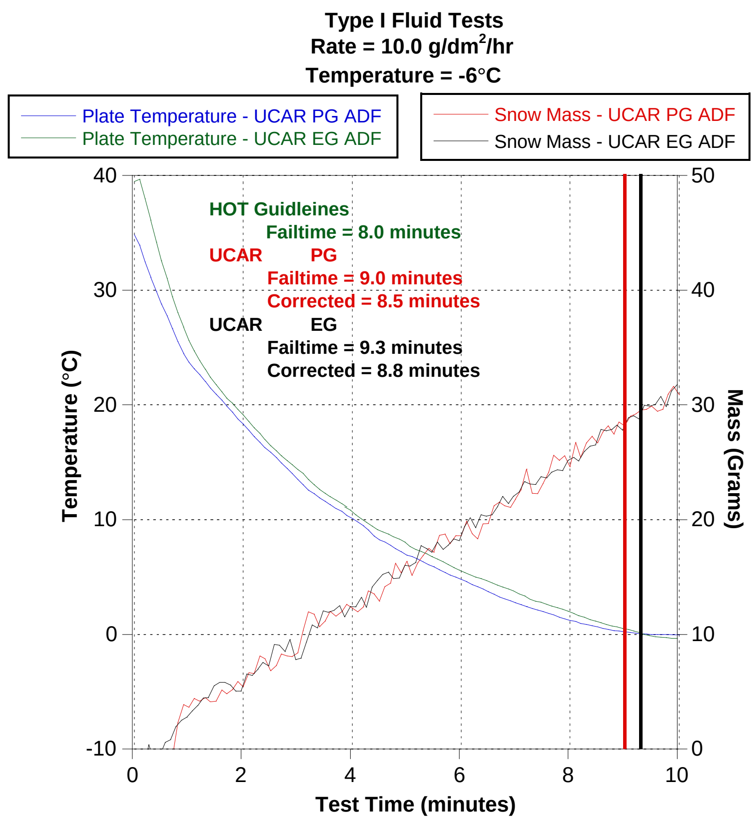

Figure 12. Results From Endurance Time Tests for UCAR PG ADF and UCAR EG ADF for an Air Temperature of -6ºC and a Rate of 10 g/dm²/hr

3.4 COMPARISON OF INDOOR AND HOT TABLE ENDURANCE TIMES.

Figure 13 shows a scatter plot of the snow machine endurance times against those from the HOT guidelines. Results show good agreement between the Type I HOT table endurance times and the snow machine measured endurance times within an error bar of 25%. The correlation coefficient for both fluids is close to 0.93.

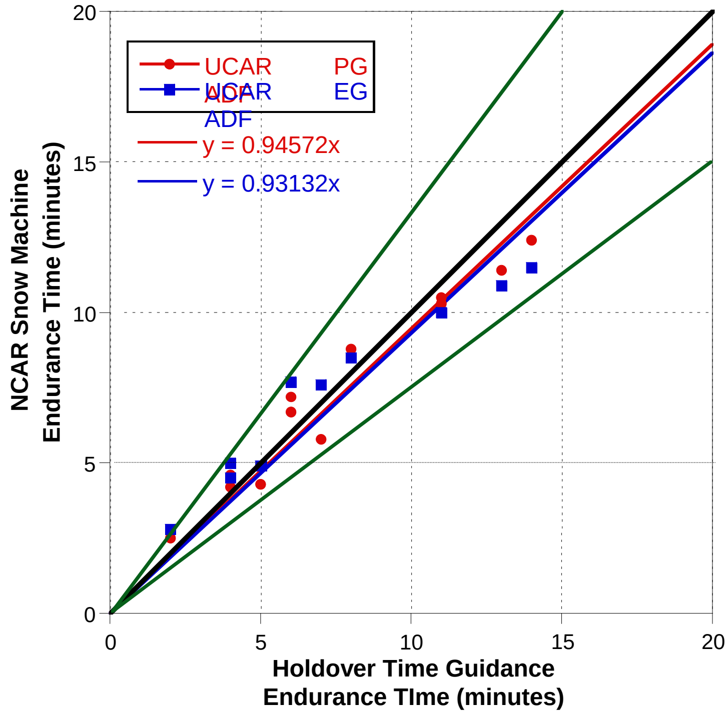

Figure 13. Comparison of HOT Guidelines and Snow Machine Endurance Times
(Error lines of 25% are given in green.)

A comparison of endurance times is given in table 1. Endurance times in black are from the FAA HOT guidelines. The endurance times in bold blue were generated using the worst endurance time available from the indoor snow machine tests of the two different Type I fluids. The results show that the snow machine is in good agreement with the HOT guidelines. Figure 13 and table 1 suggest that the snow machine may be slightly biased towards shorter endurance times but remains within the margin of error.

Table 1. Holdover Time Table for Type I Fluids

Outside Air Temperature		Approximate Holdover Times Under Various Weather Conditions (hours: minutes)		
°C	°F	Very Light Snow	Light Snow	Moderate Snow
-3 and above	27 and above	0:18-0:22 **0:xx - 0:xx**	0:11 - 0:18 **0:10 - 0:xx**	0:06 - 0:11 **0:06 - 0:10**
below -3 to -6	below 27 to 21	0:14-0:17 **0:12 - 0:xx**	0:08 - 0:14 **0:08 - 0:12**	0:05 - 0:08 **0:04 - 0:08**
below -6 to -10	below 21 to 14	0:11-0:13 **0:10 - 0:11**	0:06 - 0:11 **0:07 - 0:10**	0:04 - 0:06 **0:04 - 0:07**
below -10	below 14	0:07-0:08 **0:05 - 0:xx**	0:04 - 0:07 **0:04 - 0:05**	0:02 - 0:04 **0:02 - 0:04**

4. TYPE II FLUID TESTS AT 0°C.

A comparison of the endurance time of anti-icing fluids for conditions above 0°C and between -3° and 0°C can assess possible benefit to retaining the above 0°C row in the HOT tables. The tests during FY06 were designed primarily to demonstrate that the snow machine could be configured to conduct such tests at the warm temperatures involved. It was decided to test Type II Kilfrost ABC 2000 during the initial work since it is a widely used fluid in Europe for snow conditions above 0°C.

4.1 SNOW MACHINE CONFIGURATION FOR ABOVE 0°C TESTS.

At first glance, snow tests for conditions above 0°C seem contradictory; snow typically melts immediately in the fluid or on the wing if the temperature of either is above 0°C, thus making the use of deicing fluids unnecessary. However, the latent heat cooling effect of the melting snow cools the wing and deicing fluid to temperatures below 0°C, even when the ambient air temperature is above 0°C. Under this condition, anti-icing fluids are indeed necessary. For the tests, it was assumed that the worst condition for the above 0°C row occurs when the ambient temperature is 0°C. It was also assumed that the latent heat cooling effect as a function of snowfall rate is approximated by the curve shown in figure 6, which was estimated from direct plate temperature measurements during outdoor tests. Thus, for a rate of 10 $g/dm^2/hr$, the plate temperature would be -1°C, while for a rate of 25 $g/dm^2/hr$, the plate temperature would be -2°C. To compare the results for the -3° to 0°C row, tests at colder plate temperatures were also conducted. Again, assuming that the worst ambient temperature condition is -3°C for the -3° to 0°C cell in the HOT, two additional tests were conducted: the first at 10 $g/dm^2/hr$ with a plate temperature from figure 6 of -4°C, and the second at 25 $g/dm^2/hr$ with a plate temperature of -5°C. In all the tests, the ambient cold room temperature was kept below -5°C or colder for the snow machine to properly produce snow (at warmer temperatures, the snow becomes very sticky and clogs up the snow machine).

4.2 RESULTS OF THE ABOVE 0°C TESTS.

Figure 14 shows an above 0°C test using a rate of 25 $g/dm^2/hr$ and plate temperature of -2°C. The plate temperature oscillates about -2°C as the plate heater turns on and off to maintain the plate temperature. At the fluid failure, these oscillations dampen, indicating that snow is no longer being absorbed into the fluid. Figure 15 shows the above 0°C test for a rate of 10 $g/dm^2/hr$ and plate temperature of -1°C. Again, the same dampening of the oscillation in plate temperature is noted at the end of the experiment. Figure 16 shows a plot of the power supplied to the plate heater during the experiment in figure 15. As with the plate temperature plot, the oscillations in the plate heater power continue until the end of the experiment when the fluid fails and the amount of power needed to heat the plate drops off significantly. This is in agreement with previous results, suggesting that the power consumption to heat the plate may be a useful indicator of fluid failure (Rasmussen, et al., 2006).

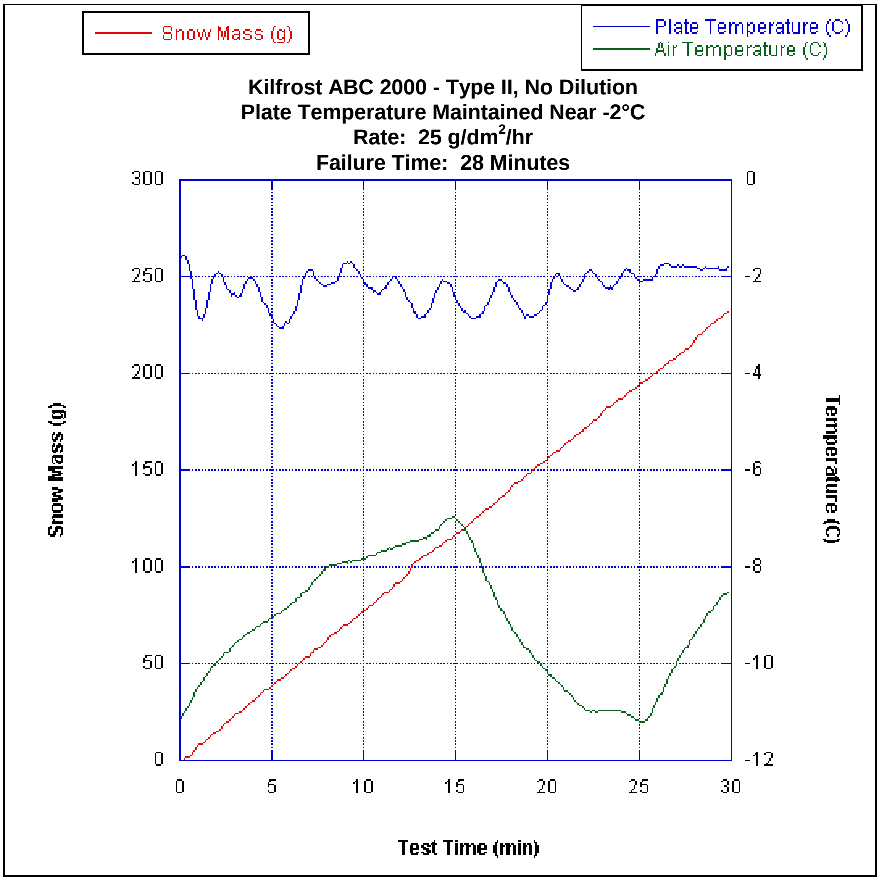

Figure 14. Type II Kilfrost ABC 2000 Experiment for the Above 0°C Condition for a Rate of 25 g/dm^2/hr and Plate Temperature Held Constant Near -2°C

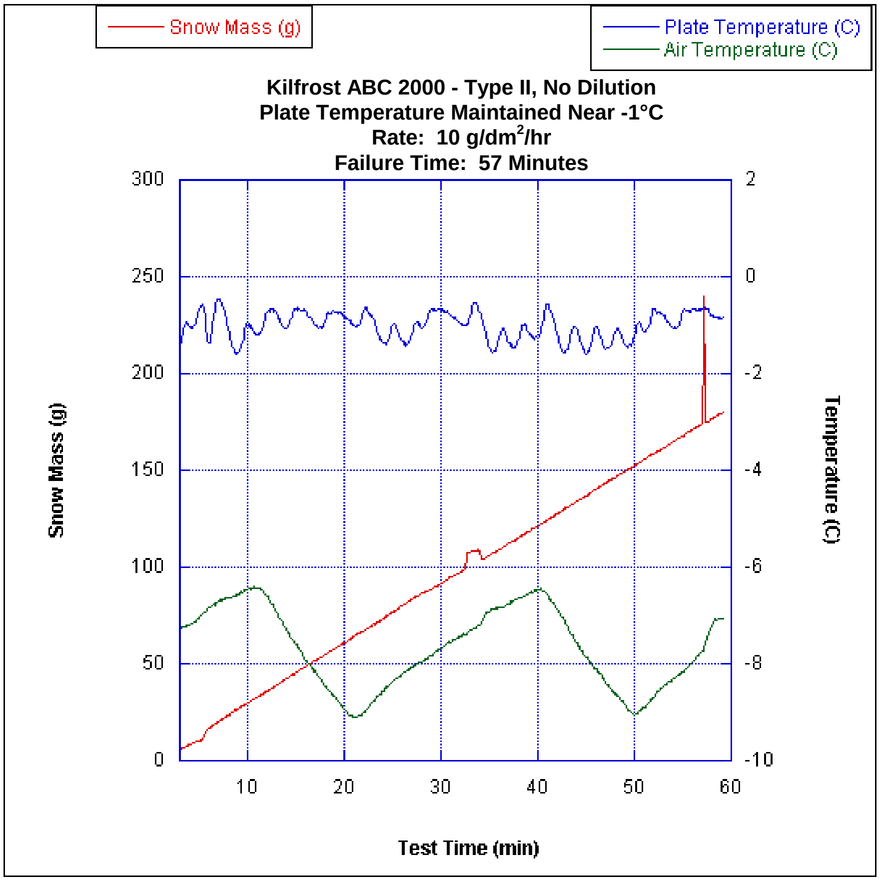

Figure 15. Type II Kilfrost ABC 2000 Experiment for the Above 0°C Conditions for a Rate of 10 g/dm^2/hr and Plate Temperature Held Constant Near -1°C

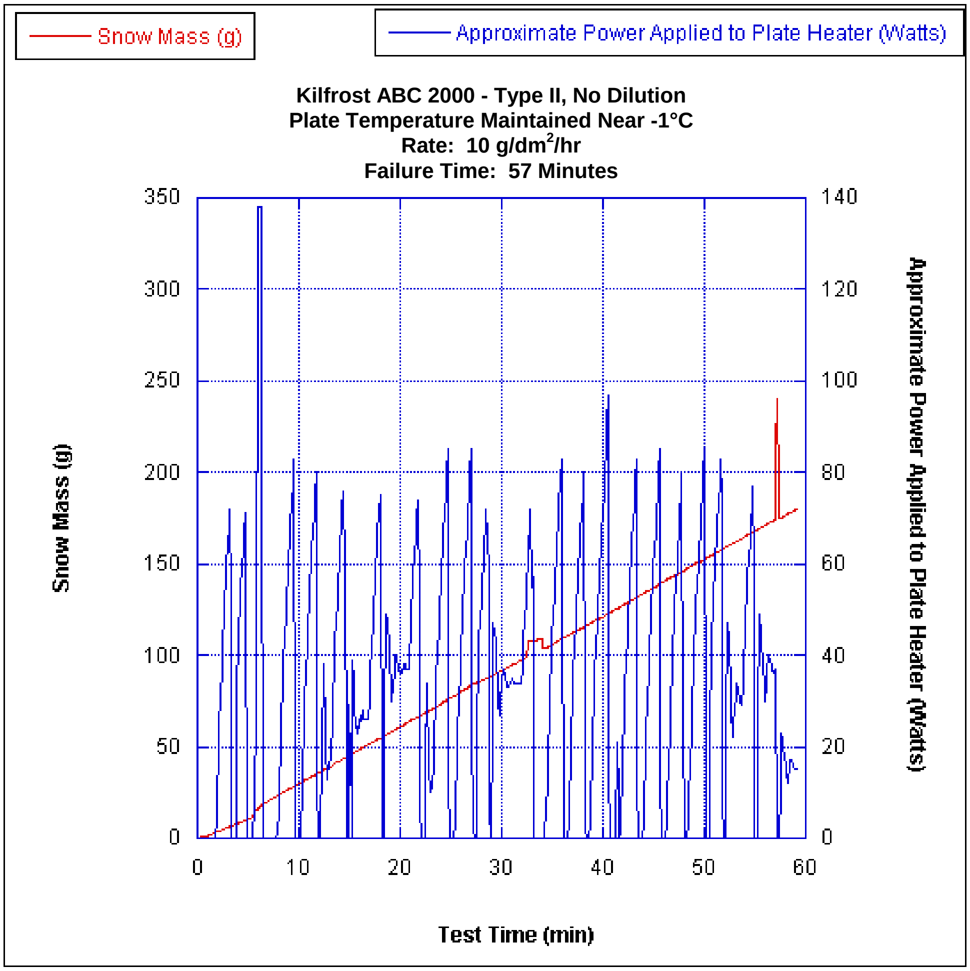

Figure 16. Type II Kilfrost ABC 2000 Experiment With the Power Applied to Maintain the Plate Temperature at -1°C

4.3 COMPARISON OF THE ABOVE 0°C TO THE -3° TO 0°C TESTS.

Comparison of the above 0°C tests to the -3° to 0°C tests shows that the 0°C tests had, on average, a 10% longer endurance time than the -3° to 0°C tests (table 2). Further tests with more fluids are needed to confirm this result.

Table 2. Endurance Time Comparison (minutes)

Snowfall Rate	10 g/dm^2/hr	25 g/dm^2/hr
Above 0°C	27 min (-1°C plate temperature)	57.5 min (-2°C plate temperature)
-3° to 0°C	25 min (-4°C plate temperature)	53 min (-5°C plate temperature)

4.4 TYPE II FLUID TESTS ABOVE 0°C WITH FREE-FLOATING PLATE TEMPERATURE.

To examine the expected endurance time under low wind conditions near 0°C, an additional experiment was performed using a free-floating plate temperature with Type II Kilfrost ABC 2000. In this experiment, the fluid was heated to +1°C and applied to the plate. Figure 17 shows the results of a test with a snowfall rate of 25 gm/dm^2/hr. The failure time was 13 minutes, and the plate temperature dropped over 9°C during the experiment. The endurance time was over 50% shorter than for the constant plate temperature test (13 minutes versus 28 minutes), showing the strong impact of wind heating on controlling HOT. Further tests should be conducted to investigate this sensitivity in the future.

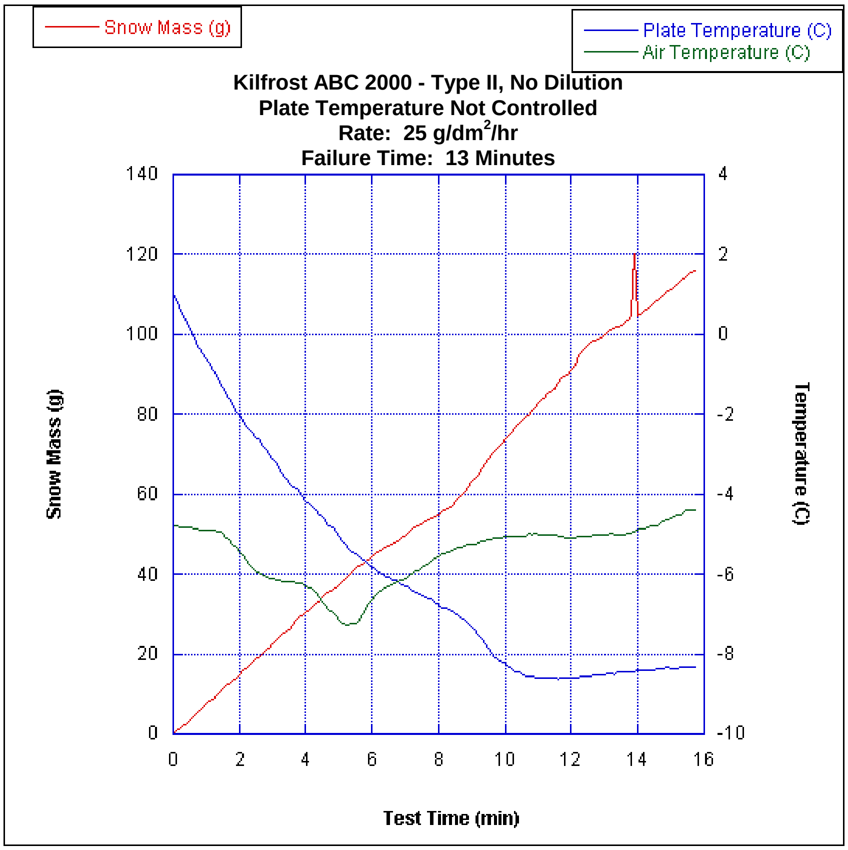

Figure 17. Type II Kilfrost ABC 2000 Applied at +1°C at a Rate of 25 g/dm^2/hr With a Free-Floating Plate Temperature

5. SUMMARY.

The findings of the three investigations discussed in this report are as follows:

- Additional outdoor tests with ULTRA+ and comparison to snow machine tests for the same outdoor conditions showed excellent agreement; this suggests that the current version of the snow machine is able to adequately perform endurance time tests for

ULTRA+ and that discrepancies in previous tests were likely due to highly variable environmental conditions and experimental error.

- A comparison of Type I fluid endurance times determined with the snow machine and current published holdover times for Type I fluids in the FAA HOT table showed agreement within experimental error.

- It was demonstrated that the snow machine could be used to conduct above 0°C snow tests by controlling the plate temperature appropriately. Results with one fluid (Type II Kilfrost ABC 2000) showed ~10% longer endurance times at temperatures above 0°C compared to -3°C. Testing with a free-floating plate temperature showed strong sensitivity to wind speed heating effects. Further tests will be required to determine endurance time gains for other qualified fluids for the above 0°C condition.

6. BIBLIOGRAPHY.

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