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Aviation Research Division
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New Jersey 08405

# Investigating the Discrepancies in Aircraft Anti-Icing Fluid Endurance Times Derived by the Indoor Snow Machine Versus Natural Outdoor Snow Conditions

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Final Report

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16. Abstract

This report summarizes progress made in determining the causes for the shorter fluid endurance times of aircraft anti-icing fluids produced by the National Center for Atmospheric Research (NCAR) snow machine compared to outdoor tests in natural snowfall conditions. This report will examine these discrepancies and the potential reasons they occur. Outdoor tests were conducted by NCAR personnel during the winter of 2014/2015 at the Marshall Field test site. Snowfall rate, plate temperature, wind speed/direction, and air temperature were recorded every minute during anti-icing fluid tests using the Type IV fluid Kilfrost ABC-S Plus. Based on the results from the outdoor tests, indoor snow machine simulations were designed and conducted to verify the observations from the outdoor experiments.

Outdoor testing focused on determining whether wind effects were the reason for the shorter endurance times. Typical testing of fluids is performed outdoors using freestanding aluminum plates, whereas the indoor testing is conducted using an aluminum plate recessed in a bucket assembly designed to capture and hold the fluid as it runs off the plate. It was hypothesized that the endurance times from the freestanding plates are more impacted by winds than the plate in the bucket assembly. To test this hypothesis, a series of outdoor experiments were designed using the Double Fence Intercomparison Reference shield, which significantly reduces the ambient wind speed while still allowing for testing in natural snowfall conditions. The results of the outdoor testing are presented, along with some preliminary results, using a new indoor testing technique.

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| | |
|---|---|
| DFIR | Double Fence Intercomparison Reference |
| HOT | Holdover time |
| LWE | Liquid water equivalent |
| NCAR | National Center for Atmospheric Research |

# EXECUTIVE SUMMARY

Determining snow holdover times (HOTs) for aircraft de/anti-icing fluids involves testing the fluids under different snowfall rates and ambient air temperatures. The standard procedure for testing aircraft anti-icing fluid for HOT performance for most snow conditions is to conduct the test outdoors in natural snow conditions per the SAE ARP5485 & ARP5945. However, some snow conditions occur infrequently in natural conditions, in particular snow at cold temperatures, and it is valuable to have the capability to test in a cold chamber in simulated snow for these conditions. In 1997, the National Center for Atmospheric Research (NCAR) began developing a new method of testing anti-icing fluids in a cold-room laboratory environment using snow-generating machines. Indoor laboratory tests with a snow machine can result in more timely and improved assessments of a fluid's performance using a range of controlled rates and air temperatures, eliminating the need to wait on unreliable outdoor snow conditions. In addition, the testing can be conducted at any time during the year, increasing the confidence in established HOTs for fluids and dramatically decreasing the time required for new fluids to be tested.

Before the snow machine system can be used to determine the HOTs of more snow conditions, its capability must be assessed, enhanced as necessary, and the improved capability evaluated. Currently, the NCAR snow machine is producing shorter fluid endurance times of aircraft anti-icing fluids compared to outdoor tests in natural snowfall conditions. Outdoor tests were conducted by NCAR personnel during the winter of 2014–2015 at the Marshall Field test site to examine these discrepancies and the potential reasons they occur. Based on the results from the outdoor tests, indoor snow machine simulations were designed and conducted to verify the observations from the outdoor experiments.

After completing the simulations of the outdoor tests, it was concluded that four factors caused the indoor simulations to provide shorter HOTs:

1. Snow bridging from the tray assembly to the frosticator plate in the snow machine
2. Wind effects on the plate temperature
3. Snowfall rate effects on the plate temperature
4. Snow particles bouncing off the fluid

Snow bridging from the tray assembly to the frosicator plate appears to be the main reason for the discrepancies in fluid failure times. Preliminary snow machine tests showed encouraging results when using a raised frosicator plate. Fluid failure times increased in length, bringing the times closer to what is expected based on the currently published HOT tables. Higher and lower rates and temperatures and additional fluids need to be tested to determine the true effects of raising the frosticator plate.

## 1. INTRODUCTION

The National Center for Atmospheric Research (NCAR) snow machine has been under development since the mid-1990’s with the goal of demonstrating the machine’s ability to reproduce outdoor endurance time tests of Type I deicing fluids and Type II and Type IV anti-icing fluids for snow conditions [1–5]. These tests are typically conducted in natural, outdoor snowfall conditions in which the snowfall rate and ambient air temperature can vary during the period of testing. The snow machine allows for indoor testing in a controlled laboratory environment where both the snowfall rate and air temperature can be controlled.

The variability of outdoor to indoor tests was attributed to the strong variability of the plate temperature for the indoor tests as compared to the outdoor tests [3]. The plate temperature variation of the indoor snow machine tests was mainly because of the plate cooling that resulted from the latent heat removal from the fluid and the plate used to melt the snowflakes as they were absorbed into the fluid [3]. Higher snowfall rates result in greater cooling and latent heat removal from the fluid/plate because of the higher mass rates. Because of the removal of heat from the fluid/plate to melt the snowflakes, the fluid/plate temperature would drop below ambient temperature in low wind speeds. This is especially true for the indoor tests that were conducted in an environment with little or no horizontal wind velocities. Figure 1 shows an example of a prior indoor test using the snow machine. The initial fluid temperature was warmer than ambient, causing the plate temperature to also be above ambient; however, the plate temperature can be seen dropping after the start of the experiment and continuing to drop below ambient temperature approximately 7 minutes after the beginning of the test. By the time the fluid fails, the plate temperature is almost 2° colder than ambient.

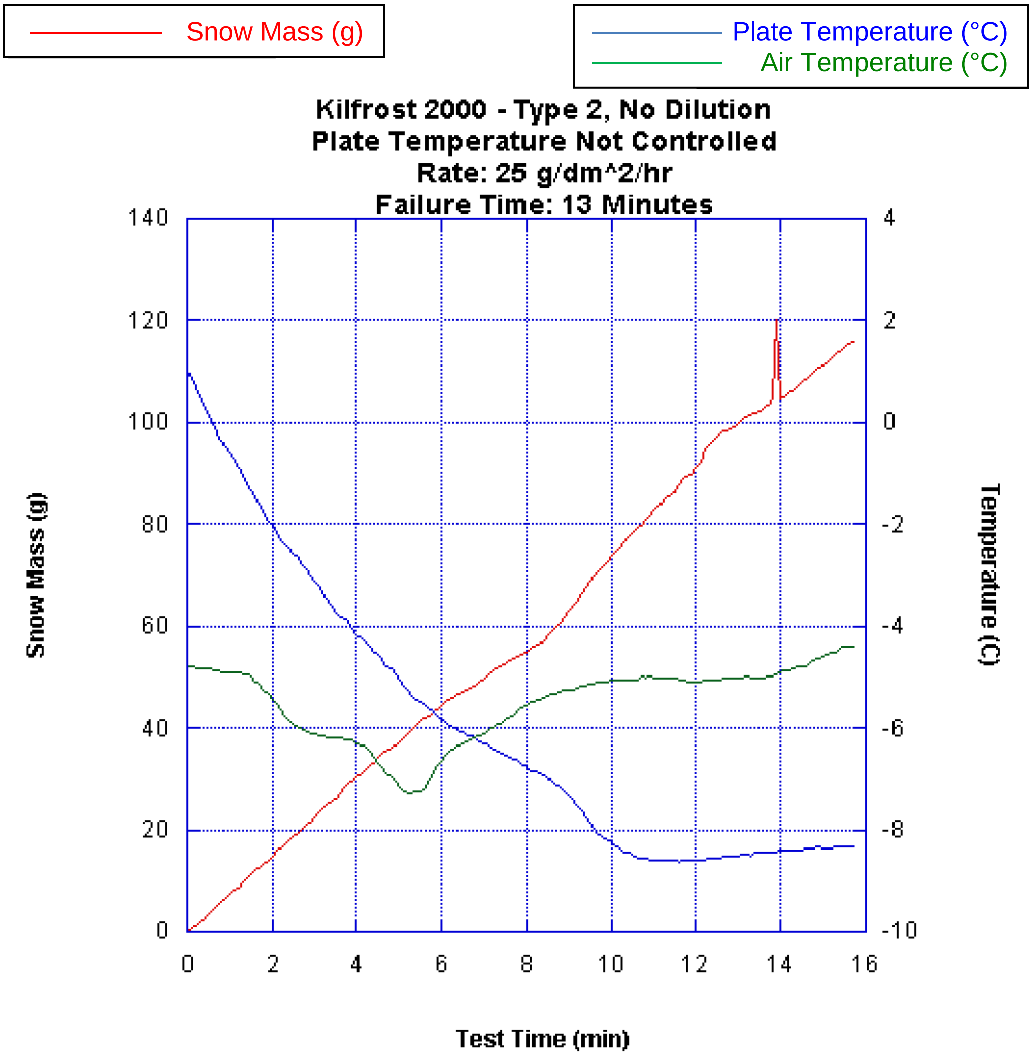

**Figure 1. Example of prior snow machine test showing the plate temperature relative to ambient temperature**

In 2004, anti-icing fluid testing with the NCAR snow machine focused on a comparison of outdoor versus indoor fluid tests using a constant frosticator plate temperature for a given snowfall rate [4]. This constant plate temperature technique, which maintained the plate temperature at ambient air temperature using a heater affixed to the back of the plate, was derived to adjust the indoor failure times to more closely match the outdoor failure times. This technique did not work consistently because the discrepancies between the indoor versus outdoor failure times were not well understood.

Unlike the indoor tests, the outdoor tests were subjected to wind velocities. Therefore, it was hypothesized that, as the temperature of the outdoor plates decreased below ambient temperatures (because of the latent heat released from the fluid and plate to melt the snow in the fluid), the heating of the plate and fluid from the wind (which contained air that was warmer than the fluid and plate) offset the degree of cooling of the fluid as the wind moved over both the top of the fluid and the bottom of the plate. As a result, the actual outdoor plate temperature could remain warmer than the indoor plate temperature under the same temperature and snowfall rate conditions. The addition of this heat from the wind would allow for longer holdover times (HOTs) of the fluid when tested outdoors versus indoors. To test this, an outdoor experiment was designed using the indoor bucket assembly with the plate raised above the assembly, allowing it to experience conditions similar to those of the standard outdoor test plates. Furthermore, a standard indoor bucket assembly was placed inside a Double Fence Intercomparison Reference (DFIR) shield to allow for outdoor testing in relatively low wind conditions, similar to what would be experienced in the snow machine. A third standard indoor bucket assembly was also deployed outside the DFIR as a direct comparison to the bucket assembly with the raised plate.

## 2. OUTDOOR VERSUS INDOOR TESTING PROCEDURES

The standard procedure for outdoor testing involves the use of freestanding polished aluminum "frosticator" plates measuring 30 x 50 cm. Each plate is 0.3-cm thick and is sloped at a 10-degree angle to simulate an aircraft wing (see figure 2). The fluid testing procedures summarized here are based on the SAE document ARP5485 [6]. The plates are turned so that they face into the wind at the beginning of each test, and a liter of anti-icing fluid is poured over them. The plates are then left exposed to the natural snowfall conditions. As the fluid begins to lose its ability to absorb the precipitation, snow will begin to build up on top of the fluid until approximately 1/3 of the plate has snow on top of the fluid. This indicates the fluid's failure to continue providing protection against snow and ice buildup. To determine the snowfall rates, special rate pans are used that are coated in glycol and exposed to the same snowfall conditions as the frosticator plates. These rate pans have the same dimensions as the frosticator plates and contain a small 1-cm-high lip around the outer edge of the pan, which prevents the precipitation and glycol from running out of the pan. These pans are weighed before exposing them to snowfall conditions and then placed outside. The pans are swapped every 10 minutes with a new set and weighed to get their final weights. The difference in weight is then used to determine the 10-minute snowfall rate. An example of the rate pan is shown on the left side in figure 2 with a giant "2" written in the pan.

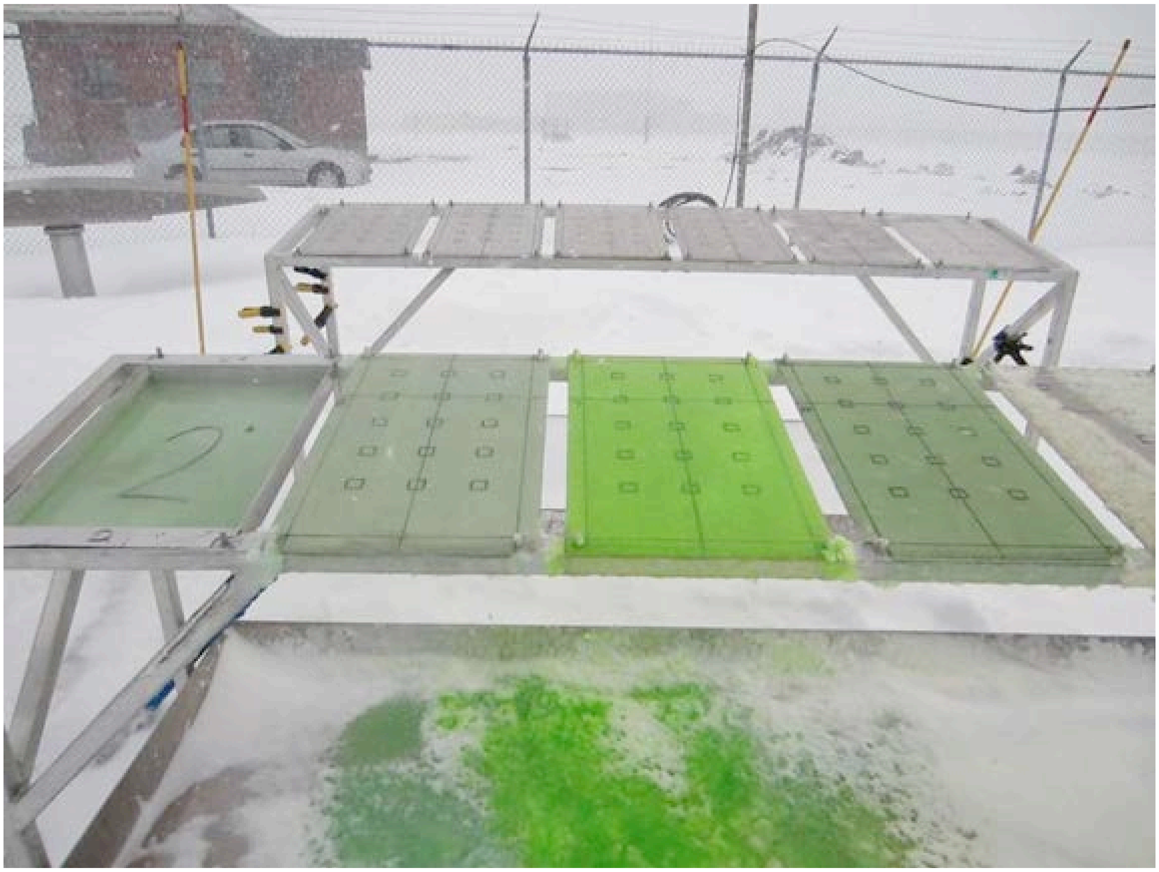

**Figure 2. Outdoor frosticator plates used for anti-icing fluid testing and the corresponding rate pan, shown at far left with a drawn-in "2"**

Indoor testing of fluids using the snow machine cannot be performed in the same manner as the outdoor tests. Controlling the snowfall rate using the snow machine requires real-time measurements of the added snowfall mass using a mass balance placed under the frosticator plate. Using the outdoor technique would allow fluid to drip off the plate and would result in a loss of mass. The snow machine design uses a tray assembly that the frosticator plate rests on, which collects the fluid dripping off the plate (see figure 3). The tray assembly is slightly wider and longer than the frosticator plate, which minimizes the chances of snow collecting on the tray assembly and not on the plate. The tray assembly and frosticator plate are placed on a mass balance from which the computer takes measurements every 6 seconds and uses those measurements to adjust to the snowfall rate. With the fluid contained on either the frosticator plate or in the tray assembly, any change in mass is attributed to the addition of the snow falling on the fluid.

**Figure 3. Indoor frosticator plate and tray assembly on a mass balance in the snow machine**

## 3. OUTDOOR EXPERIMENTAL DESIGN

To determine the effects of wind on the combined tray/frosticator combination (henceforth referred to as the frosticator assembly), an outdoor experiment was designed that incorporated the use of a DFIR shield (see figure 4). The DFIR is considered to be the most effective shield at slowing the horizontal winds and helping remove the effect the wind has on precipitation (snow in particular) [7]. Using this shield allows for outdoor testing in low-to-no-wind conditions, similar to what would be experienced with the indoor snow machine. The Marshall Field Instrument Test Site, just south of Boulder, Colorado, has several DFIR shields and was chosen as the site to conduct the experiments.

**Figure 4. The DFIR shield**

Three frosticator assemblies were used in this experiment. One standard frosticator assembly, such as the one typically used in the snow machine, was installed outside of the DFIR shield on the predominant upwind side during precipitation events to minimize the effects the shield would have on snow in the free-stream air (see figure 5). A second frosticator assembly was also installed in the free-stream environment, but the frosticator plate was modified and raised 15 cm above the tray, allowing the wind to move freely beneath the plate (see figure 6). This second assembly is also referred to as the “tall assembly.” A third standard frosticator assembly was located inside the DFIR shield (see figure 7). All of the frosticator plates had temperature probes connected to the back of the plates that took measurements of the plate temperature every minute. These measurements can be correlated to wind speed to see if the temperature of the plate remains higher for the assemblies outside the DFIR during higher wind events versus the temperature of the plate inside the DFIR. Each frosticator assembly resided on a mass balance to record the increase in snow mass throughout an event. Two R.M. Young Company wind sensors were also used in the experiment to record wind speed and direction during events; one was installed inside the DFIR shield and the other near the free-stream frosticator assemblies. Two webcams were also used (one inside the DFIR and one outside) to view and record photographs of the frosticator assemblies during events.

**Figure 5. The outdoor standard frosticator assembly used in the free-stream environment**

**Figure 6. The outdoor tall frosticator assembly used in the free-stream environment**

**Figure 7. The standard frosticator assembly used in the DFIR shield**

## 4. OUTDOOR TESTING PROCEDURES

Before each event, the stands that held the frosticators were checked to confirm they were level and any necessary corrections were made by adjusting the guy wires holding them in place. The mass balances were placed on the stands and connected to a computer that collected the data via an RS-232 serial connection. Once the balances were connected and the mass measurements zeroed, the frosticator assemblies were added and the plate temperature probes connected to a datalogger that recorded the plate temperatures and wind speeds. The frosticator plate angles were also checked to confirm they were sloped at a 10° angle. The wind sensors and webcams were permanently installed and required no additional setup before events. Once everything was connected and operational, the fluid was prepared for application to the frosticator plates.

For these experiments, the fluid used was Kilfrost ABC-S Plus, a Type IV anti-icing fluid. The fluid was stored in a trailer at the Marshall site, which was not environmentally controlled and was allowed to remain near outdoor ambient temperature. Fluid was poured into 1-liter bottles before each experiment and the temperature and Brix measurement of each liter were taken. After these measurements were recorded, the fluid was then taken to the frosticator assemblies. The assemblies would be turned so that the sloped plates faced into the wind and the fluid was poured across the top of each plate, allowing it to run down and cover the surface. The fluid on the three plates was applied at the same time, requiring three people to be on hand for each test. Once the fluid was poured (usually within 1 minute), the time would be noted and the experiment commenced.

The plates were checked regularly throughout the event. Failure of the fluid was called when approximately one-third of the plate was covered in snow that had not been absorbed into the fluid within 30 seconds of collecting on the fluid. At this time, the failure time of the fluid would be noted and another Brix measurement would be taken just below the one-third-failure point in the fluid. Once the fluid on all three frosticator plates had failed, the plates were cleaned off and prepared for another round of testing if the storm continued. If the trays contained fluid from two tests, they would be emptied out, the frosticator assemblies would be replaced on the balances, and they would again be checked for proper leveling. Another test would then begin once the fluid temperatures and Brix measurements had been taken and the frosticator assemblies were turned to face into the wind.

## 5. OUTDOOR TESTING SUMMARY

Testing for the winter season began in late December 2014. The initial tests indicated the expected pattern between the two frosticator assemblies located outside the DFIR shield. Typically, the standard frosticator assembly plate would fail more quickly than the tall assembly plate in the free-stream wind, indicating that the hypothesis regarding the wind adding heat to the tall assembly may be correct. The DFIR frosticator assembly plate sometimes failed sooner and sometimes later than the other plates, depending on the snowfall rate and the horizontal wind speed. This was attributed to the DFIR assembly experiencing a different collection efficiency of snow than the other two plates because of the difference in wind speeds, though this was not investigated in great detail because of other issues described in section 6. From December until April, 37 experiments were conducted. The data were filtered at the end of the season to remove cases in which the fluids did not fail (which accounted for nearly one-third of all events), the winds changed direction more than 90° during a given experiment, and fluid failure calls may have been missed. Table 1 lists the 14 events that passed the filter. Average wind speeds (inside and outside the DFIR), average ambient air temperatures, average snowfall intensities derived from a co-located hotplate precipitation gauge, and failure time in minutes are shown in the table.

**Table 1. List of all valid fluid test events from the Marshall site (events for which multiple tests occurred throughout the day have letters appended after the dates)**

| Date | DFIR Failure (m) | Tall Failure (m) | Standard Failure (m) | Air Temp (°C) | Ambient Wind Speed (m/s) | DFIR Wind Speed (m/s) | Snowfall Rates |
|---|---|---|---|---|---|---|---|
| 20141229 | 116 | 139 | 93 | -10 | 2.5 | 0.5 | L |
| 20150201 | 68 | 157 | 114 | -5 | 2 | 0.5 | VL-H |
| 20150204 | 83 | 89 | 86 | -5 | 1.5 | 0.25 | L-M |
| 20150216a | 61 | 66 | 60 | -2.8 | 1 | 0.25 | M-H |
| 20150216b | 67 | 97 | 62 | -3.5 | 3 | 0.25 | H |
| 20150216c | 100 | 151 | 100 | -3.8 | 2 | 0.25 | L-M |
| 20150221a | 46 | 70 | 69 | -4.8 | 6 | 1.5 | H |
| 20150221b | 62 | 89 | 81 | -5.4 | 5 | 1 | M-H |
| 20150222a | 134 | 172 | 152 | -6.7 | 3.5 | 1 | L-M |
| 20150222b | 105 | 172 | 157 | -8.7 | 3.5 | 1 | M |
| 20150222c | 75 | 90 | 63 | -12 | 1.5 | 0.25 | L-M |
| 20150225a | 89 | 108 | 96 | 0.2 | 3 | 1 | L-H |
| 20150225b | 68 | 88 | 68 | -2.6 | 2.5 | 0.5 | L-H |
| 20150226 | 65 | 84 | 76 | -2.9 | 5 | 1.25 | VL-H |

VL = very light; L = light; M = moderate; H = heavy

## 6. ANALYSIS AND SELECTED CASE STUDIES

An uncommon snowfall event occurred with moderate rates and relatively little to no winds on February 16, 2015 (20150216a in table 1), followed by a similar event on February 25, 2015 (20150225b in table 1). These cases were anticipated to be good calibration tests between the three frosticator assemblies because it was expected that all three should give the same failure times. However, the results of the tests indicated that the failure times were not the same, and that the standard plates inside and outside the DFIR failed at the same time, whereas the raised plate took a slightly longer time to fail.

### 6.1 FEBRUARY 16 CASE STUDY (20150216A)

The February 16, 2015 event proved to be extremely useful in understanding the discrepancies between the tall and the standard frosticator assemblies located outside the DFIR. Wind speeds throughout the test were lower (<3 m/s) than the average 3–5 m/s typically experienced during snow events at Marshall. The test began at approximately 0520 UTC (2220 MST) on February 16 (February 15, MST). Figure 8 shows the wind speed, ambient air temperature, and liquid water equivalent (LWE) snowfall amounts during the test. There was a brief spike in wind speed up to 2.5 m/s after the start of the test, but the wind speeds fell after that and remained mostly near or below 1 m/s throughout the rest of the test. Ambient temperature remained steady near -3° C. Snowfall liquid equivalent amounts from a co-located GEONOR all-weather precipitation gauge in a DFIR shield are also shown. During the course of the test, the GEONOR accumulated nearly 2 mm of precipitation, indicating an average rate of 2 mm/h (20 g/dm2/h), which indicates snowfall intensities in the moderate category (see table 2).

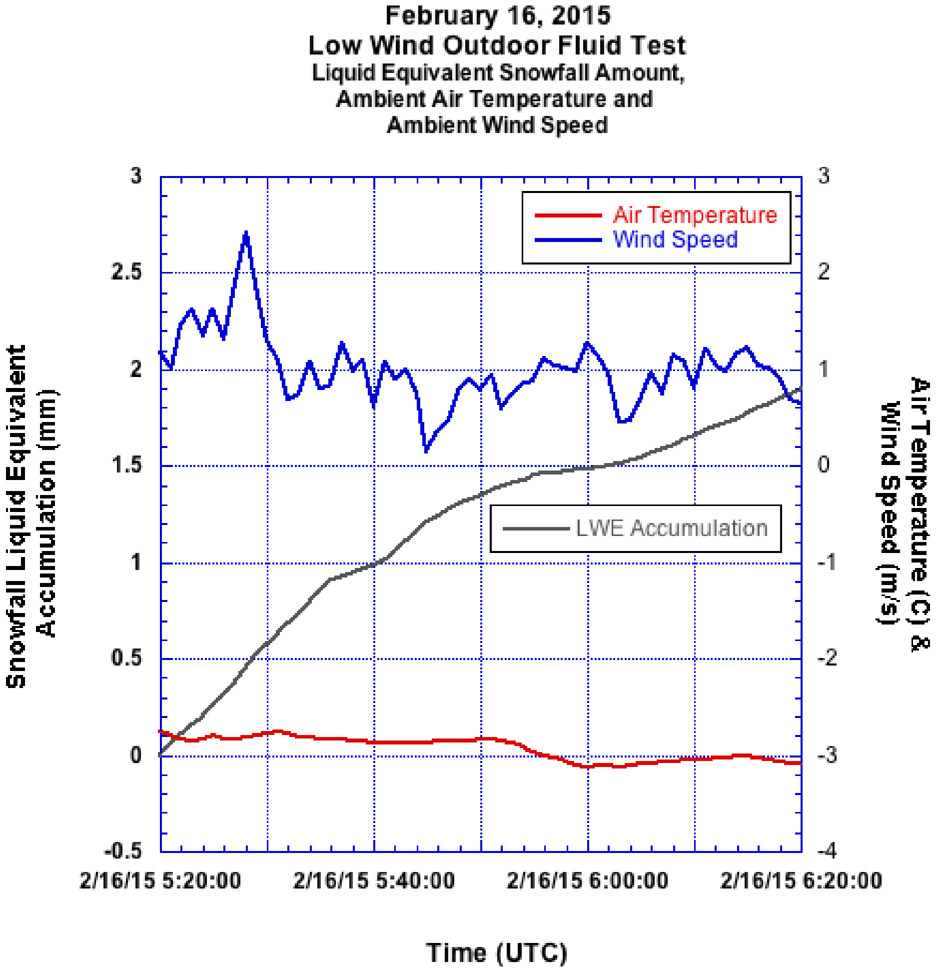

**Figure 8. Ambient wind speed during the first outdoor test on February 16, 2015**

**Table 2. Snowfall intensities and the corresponding snowfall liquid equivalent rates**

| Snowfall Intensities | Liquid Equivalent Snowfall Rates (mm/h) | Liquid Equivalent Snowfall Rates (g/dm$^2$/h) |
|---|---|---|
| Very Light | <0.4 | <4 |
| Light | 0.4–1.0 | 4–10 |
| Moderate | 1.0–2.5 | 10–25 |
| Heavy | >2.5 | >25 |

Figure 9 shows the temperature of each of the frosticator plates as compared to the ambient air temperature and the snowfall accumulation. All three plates cool below ambient temperature relatively quickly after the fluid has been applied and remain below ambient throughout the remainder of the experiment. Figure 9 shows that the plate temperatures appear well-correlated to the change in snowfall rate. As the accumulation rates increase (indicated by the accumulation trace getting steeper), the temperature of the fluid decreases more quickly. At 0535 UTC and 0550 UTC, the snowfall accumulation trace becomes less steep, indicating a decrease in snowfall rates. The plate temperatures respond accordingly and begin to warm until the rates increase again. Eventually, towards the end of the experiment, the fluid begins to lose its capacity to absorb the snow and begins to warm toward ambient, though the snowfall rate increases again. This provides further evidence that the fluid has failed and is no longer able to pull latent heat from the plate to continue melting the snow.

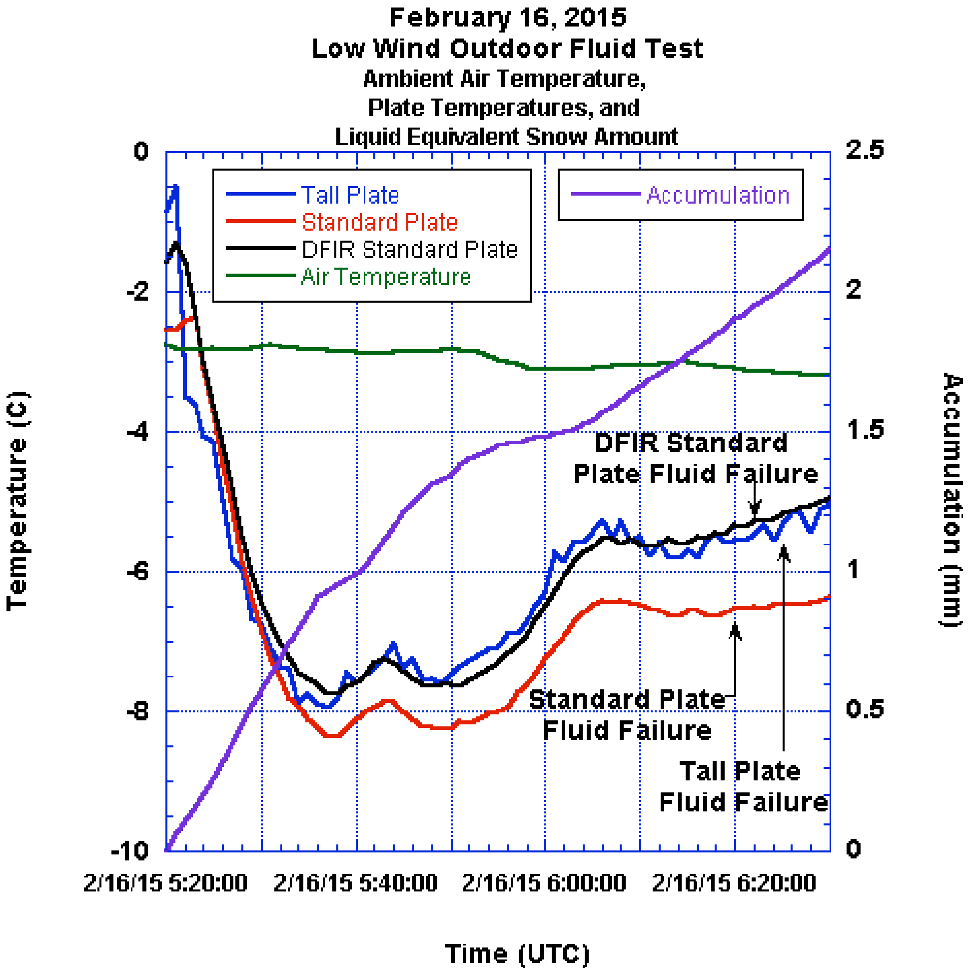

**Figure 9. Frosticator plate temperatures, ambient air temperature, and snowfall mass from the February 16, 2015 (20150216a) event**

When examining the plate temperature traces in figure 9, the tall frosticator plate temperature appeared noisier than the other two. Figure 10 shows the tall frosticator plate temperature and the ambient wind speed. Though there does not appear to be a strong correlation between the two (i.e., wind spikes increase the plate temperature and vice versa), the variability in the wind does appear to match the increased variability in the temperature of the plate. This may indicate that wind does have an effect on the plate, but not as strong as the snowfall rate.

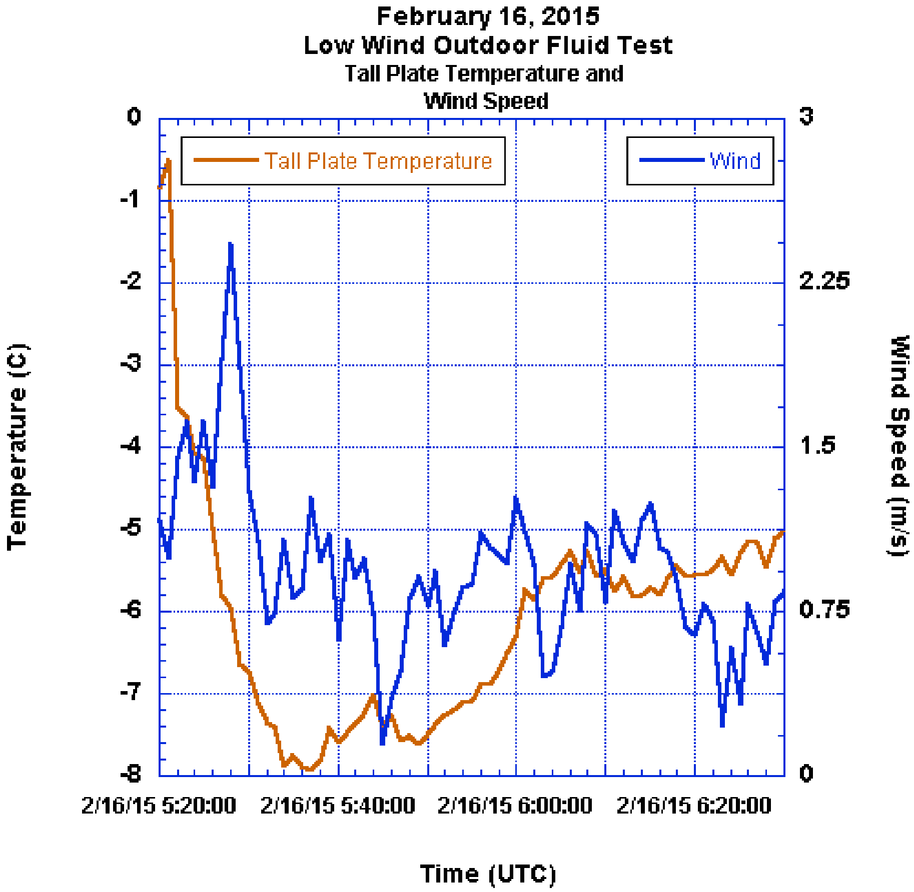

**Figure 10. Tall frosticator plate temperature and ambient wind speed from the February 16, 2015 (20150216a) event**

Throughout the course of the event, the fluids were checked regularly to monitor their behavior. At 0550, 30 minutes after the start of the event, it was observed that the standard frosticator assemblies (both inside and outside the DFIR) were already showing a buildup of snow at the top of the plate (see figure 11). At the same time, the tall plate still showed almost no indication of any snow contamination buildup (see figure 12). Because both frosticator assemblies outside the DFIR were being subjected to the same snowfall rates, low ambient wind speeds, and temperatures, there should not be any meteorological reason why one plate would exhibit snowfall buildup and not the other. By 0622 UTC, the fluid on the standard frosticator assemblies had both failed; however, the fluid on the tall frosticator assembly continued for nearly an additional 5 minutes before failing.

**Figure 11. Snow buildup/fluid failure beginning near the top of the standard frosticator assembly at 0550 UTC**

**Figure 12. Photograph of the tall frosticator assembly taken at the same time as the photograph in figure 11 showing almost no snow accumulation at the top of the plate**

On closer inspection of the standard frosticator assemblies, it appeared that the earlier fluid failures might be caused by snow building up in the gap between the tray and the frosticator plate at the top of the frosticator assembly. Figure 13 shows a close-up view of the top of the standard frosticator assembly. Because of the relatively shallow depth of the tray assembly behind the frosticator plate, it was theorized that snow falling on this portion of the tray would begin to build up on the edge of the tray and bridge the gap between the tray and the frosticator plate. The snow that built up in this gap would begin to absorb the fluid near the top of the plate, causing a thinning of the fluid near the top of the plate, which would lead to an early failure of the fluid.

**Figure 13. Close-up view of the top of the standard frosticator assembly showing the shallow gap between the tray and the frosticator plate**

## 6.2 FEBRUARY 25TH CASE STUDY (20150225B)

On February 25, 2015, another snowfall event occurred with conditions nearly identical to the case presented from February 16th, which allowed for some additional comparisons between all assemblies.

Similar to the February 16th event, the ambient air temperature remained very close to -3°C throughout the test (see figure 14). Wind speeds were a little higher during the test, averaging approximately 2 m/s, but dropped below 1 m/s for periods toward the end of the experiment. Snowfall LWE accumulations during this experiment were higher at the beginning and then dropped off significantly before picking up again toward the end of the experiment. Overall, average rates were close to 2 mm/h (20 g/dm2/h), which were again similar to what was experienced during the February 16th event.

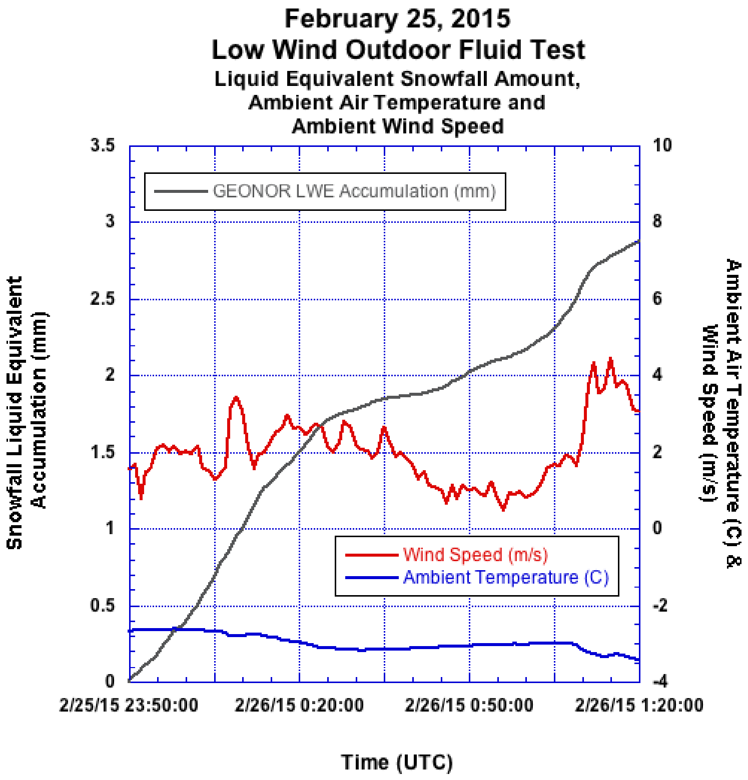

**Figure 14. The ambient wind speed during the first outdoor test on February 25, 2015**

The frosticator plate temperatures were again examined and compared to the snowfall rate (see figure 15). Unfortunately, the tall frosticator assembly plate temperature probe malfunctioned during this test and plate temperature for this assembly was not recorded. However, when examining the standard plate temperatures, a similar pattern to the February 16 event can still be seen. The plate temperatures appear strongly correlated to the snowfall rates. During this event, the fluid on both standard frosticator assemblies failed at the same time (approximately 66 minutes after the start of the test). The fluid on the tall frosticator plate took an additional 20 minutes to fail. Because the winds were higher for this event, it is possible that the winds helped increase the plate temperature, leading to a longer fluid failure time of the tall plate; however, without the plate temperature data, this cannot be stated for certain.

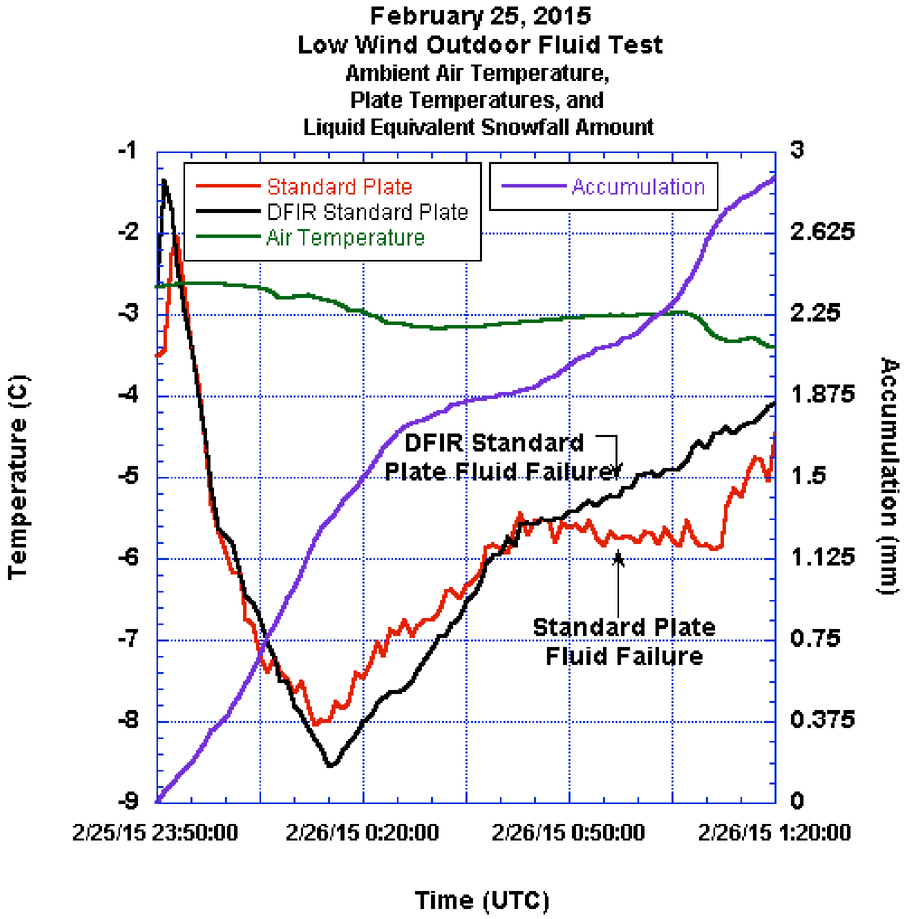

**Figure 15. Frosticator plate temperatures, ambient air temperature, and snowfall mass from the February 25, 2015 (20150225b) event**

The fluids were checked regularly throughout the experiment and, similar to the February 16 test, the fluid on the standard frosticator assemblies was observed to have snow buildup at the top of the plate sooner than the fluid on the tall frosticator assembly. Because this behavior was observed again during this test, it is more likely that the cause of the early fluid failures in the snow machine may was actually the snow bridging at the top of the plate, which leads to a premature failure of the fluid.

## 7. INDOOR SNOW MACHINE TESTING

After reviewing the outdoor test data, a series of experiments using the snow machine were developed to test the tall frosticator assembly against the standard frosticator assembly. These tests required using constant snowfall rates at fixed ambient air temperatures and duplicating the tests for both the tall and the standard frosticator assemblies. To prevent snow from falling into the tray beneath the plate on the tall frosticator assembly (thereby creating abnormally higher rates, as measured by the mass balance), the plate height was adjusted downward so that it was only a few centimeters above the tray assembly (see figure 16).

**Figure 16. The modified height frosticator assembly used for testing in the snow machine (the standard assembly is shown to the right to emphasize the differences)**

Beginning in the spring of 2015, the snow machine underwent a major software upgrade to bring the system up to date with Microsoft® Windows® 7. This also required a significant upgrade of the LabVIEW™ code, which is used to run the snow machine, because the base LabVIEW code was 11 years out of date. New mass balances were needed because the ones being used were wearing out from age and wear and tear after being used in the cold. The older balances were no longer being manufactured and the company had no replacement models for them. Another company was located that could provide balances with similar specifications, but hardware modifications were required for the balances to work accurately in the cold environment. A significant amount of time was dedicated to working out the software bugs in the system and modifying the mass balances to reliably operate in the cold room environment. For this reason, only four tests were conducted indoors with the snow machine using both the tall and the standard frosticator assemblies. Table 3 summarizes the tests conducted in the snow machine.

**Table 3. List of completed snow machine tests at constant rates and air temperatures**

| Test # | Air Temperature (C) | Rate ($g/dm^2/h$) | Failure Time (minutes) | Tray Assembly |
|---|---|---|---|---|
| 1 | -20 | 25 | 15.8 | Tall Plate |
| 2 | -20 | 25 | 10.9 | Standard Plate |
| 3 | -20 | 10 | 29.2 | Tall Plate |
| 4 | -20 | 10 | 23.7 | Standard Plate |

Though only four tests were completed, the results were encouraging regarding the discrepancies in fluid failure times. Figure 17 shows the results of tests 1 and 2 for a snowfall rate of 2.5 mm/h (25 g/d2/h). The snow mass accumulation was relatively constant between the two tests, but the standard frosticator assembly had a shorter failure time by approximately 5 minutes. Though the fluid applied to the standard plate was slightly warmer at the beginning of the experiment, it still failed more quickly than the fluid on the tall frosticator assembly. Fluid temperature can have an effect on the failure time, particularly if it is significantly warmer or colder than air temperature; therefore, the fluids are usually kept near ambient temperature to remove this variable during testing.

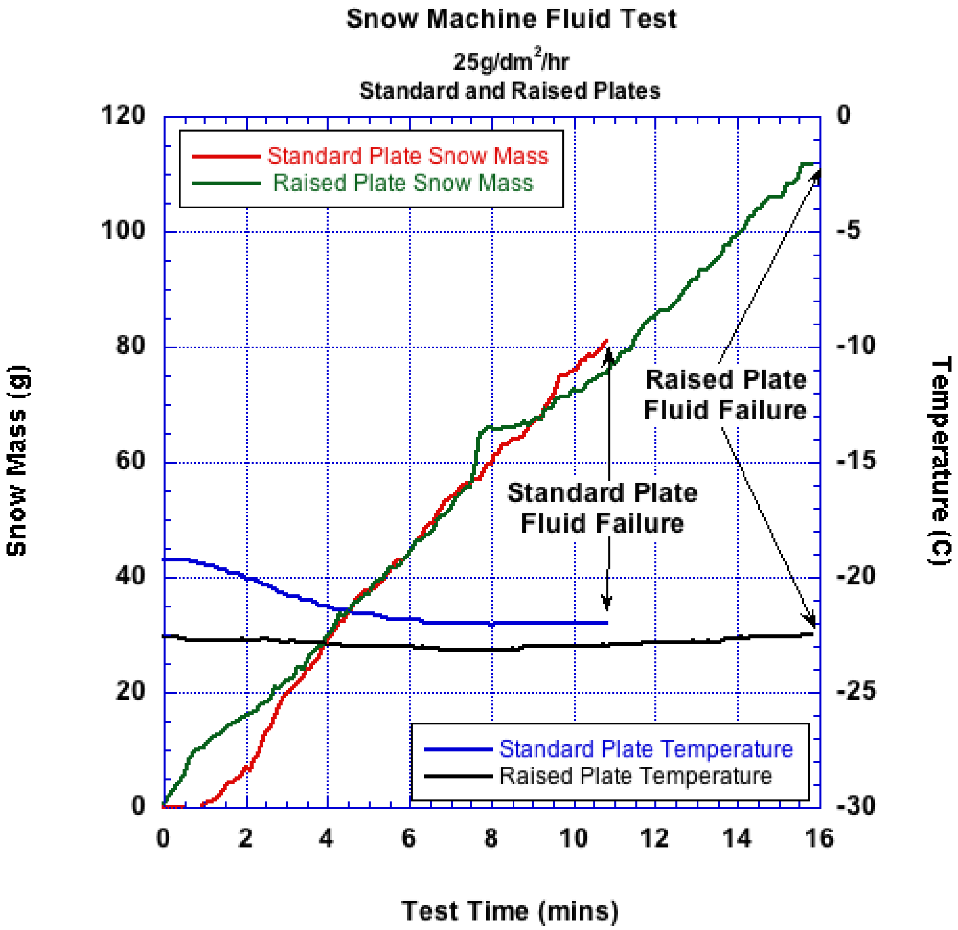

**Figure 17. Indoor fluid tests at a constant rate of 2.5 mm/h (25 g/dm2/h) at -20° C**

Figure 18 shows the results of tests 3 and 4 using a snowfall rate of 1 mm/h (10 g/d2/h). As with the prior tests, the standard frosticator assembly fluid failed approximately 5 minutes before the fluid on the tall frosticator assembly.

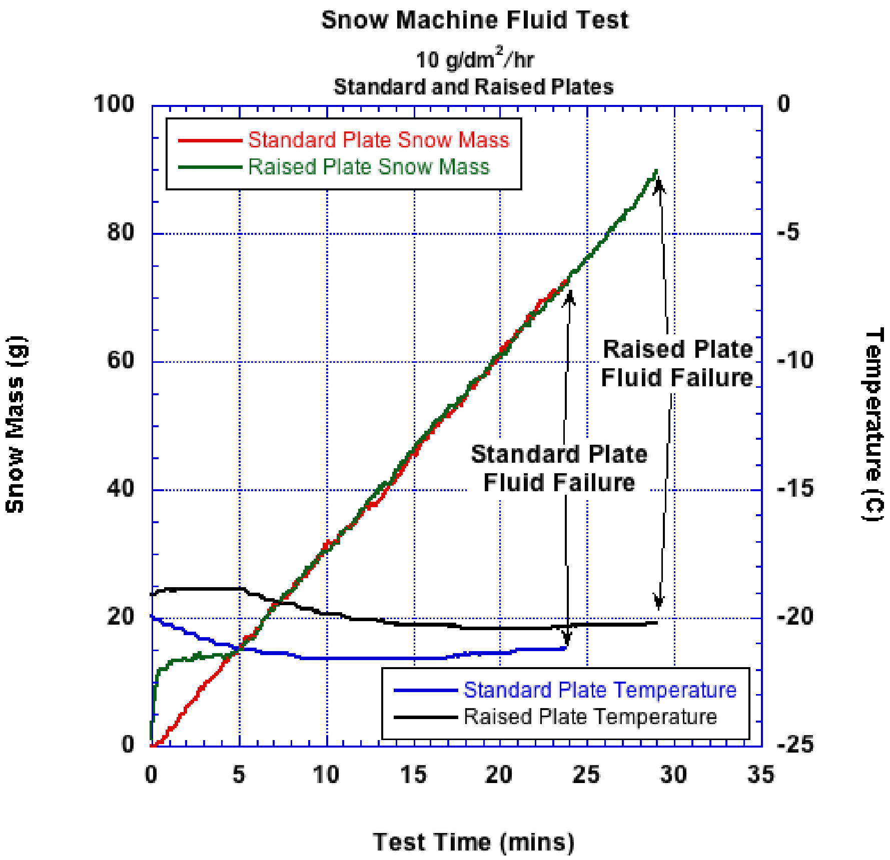

**Figure 18. Indoor fluid tests at a constant rate of 1.0 mm/h (10 g/dm2/h) at -20 °C**

After the tests were completed, the fluid failure times were compared to the HOT guidelines for the Kilfrost ABC-S Plus fluid. This chart was not viewed prior to the tests to prevent any biases when determining fluid failures. Figure 19 shows the HOTs as a function of snowfall rate/intensity and ambient air temperature. A rate of 2.5 mm/h (25 g/dm2/h) is considered the threshold between moderate and heavy rates. At a temperature of -20°C, the holdover chart indicates that the fluid should last for 15 minutes. The fluid on the tall frosticator assembly failed at exactly 15 minutes, whereas the fluid on the standard frosticator assembly failed after nearly 11 minutes. For the rate tests conducted at 1.0 mm/h (10 g/dm2/h), which is the threshold between light and moderate rates, the chart indicates that the fluid should last for 30 minutes. The fluid on the tall frosticator assembly failed at 29 minutes, whereas the fluid on the standard frosticator assemblies failed at 24 minutes. Though there are only two comparison tests conducted at one ambient air temperature, the results indicate that the shorter fluid failure times from the snow machine may indeed be a function of the frosticator assembly design, and raising the plate slightly may help eliminate this particular problem. Raising the plate also appears to have brought the failure times closer to what is indicated in the official holdover chart for this fluid. Further testing still needs to be conducted to determine whether raising the plate in the snow machine will lead to fluid failure times closer to what is experienced outdoors.

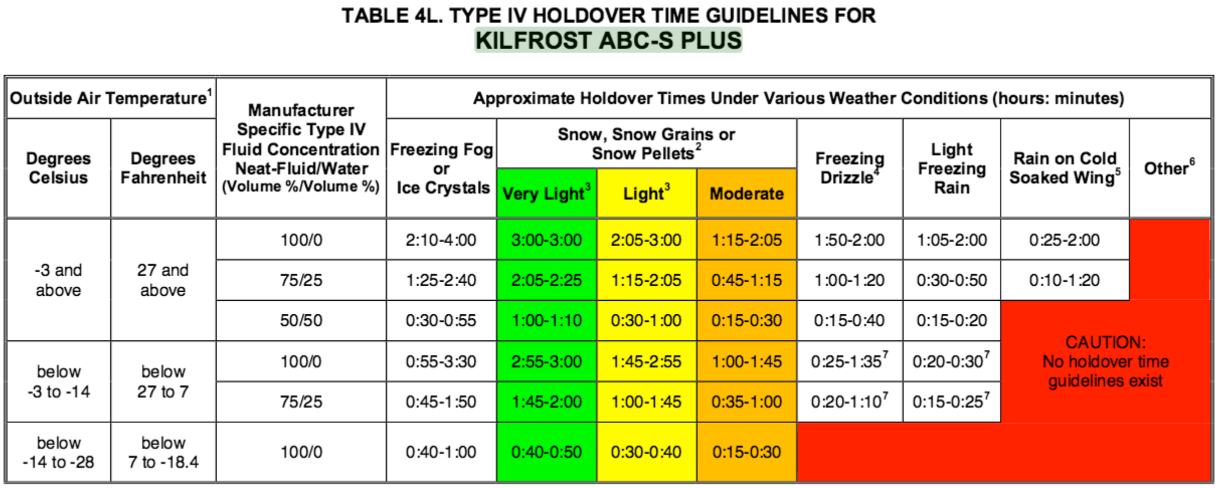

TABLE 4L. TYPE IV HOLDOVER TIME GUIDELINES FOR
KILFROST ABC-S PLUS

| Outside Air Temperature[1] | | Manufacturer Specific Type IV Fluid Concentration Neat-Fluid/Water (Volume %/Volume %) | Approximate Holdover Times Under Various Weather Conditions (hours: minutes) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Degrees Celsius | Degrees Fahrenheit | | Freezing Fog or Ice Crystals | Snow, Snow Grains or Snow Pellets[2] | | | Freezing Drizzle[4] | Light Freezing Rain | Rain on Cold Soaked Wing[5] | Other[6] |
| | | | | Very Light[3] | Light[3] | Moderate | | | | |
| -3 and above | 27 and above | 100/0 | 2:10-4:00 | 3:00-3:00 | 2:05-3:00 | 1:15-2:05 | 1:50-2:00 | 1:05-2:00 | 0:25-2:00 | CAUTION: No holdover time guidelines exist |
| | | 75/25 | 1:25-2:40 | 2:05-2:25 | 1:15-2:05 | 0:45-1:15 | 1:00-1:20 | 0:30-0:50 | 0:10-1:20 | |
| | | 50/50 | 0:30-0:55 | 1:00-1:10 | 0:30-1:00 | 0:15-0:30 | 0:15-0:40 | 0:15-0:20 | | |
| below -3 to -14 | below 27 to 7 | 100/0 | 0:55-3:30 | 2:55-3:00 | 1:45-2:55 | 1:00-1:45 | 0:25-1:35[7] | 0:20-0:30[7] | | |
| | | 75/25 | 0:45-1:50 | 1:45-2:00 | 1:00-1:45 | 0:35-1:00 | 0:20-1:10[7] | 0:15-0:25[7] | | |
| below -14 to -28 | below 7 to -18.4 | 100/0 | 0:40-1:00 | 0:40-0:50 | 0:30-0:40 | 0:15-0:30 | | | | |

**Figure 19. The 2015/16 HOT table for the Kilfrost ABC-S Plus fluid[1]**

## 8. OTHER OBSERVATIONS

In the course of testing outdoors, another observation was made regarding the interaction of the snow particles with the fluid. In higher wind conditions (wind speeds > 3 m/s), it was observed that some of the snow particles hitting the fluid would bounce. They would sometimes bounce higher on the plate and stick to the fluid, whereas other times they would bounce off the plate altogether. This behavior occurred regardless of whether the fluid had just been poured or was nearing failure. The photographs in figures 20 and 21 attempted to capture the bouncing particles. These can be seen as white streaks oriented from the lower left to the upper right of the image, whereas the normal snowfall (and streaking pattern) was from the upper left to the lower right. This is particularly noticeable in figure 21. This behavior implies that the collection efficiency of the fluid is not 100% in higher wind speeds and may also be another indication of why the outdoor tests last longer (because of snow bouncing off) than the indoor tests.

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[1] The image is taken from the Winter 2015-2016 FAA Holdover Time Guidelines. Current issue can be found here: http://www.faa.gov/other_visit/aviation_industry/airline_operators/airline_safety/deicing/

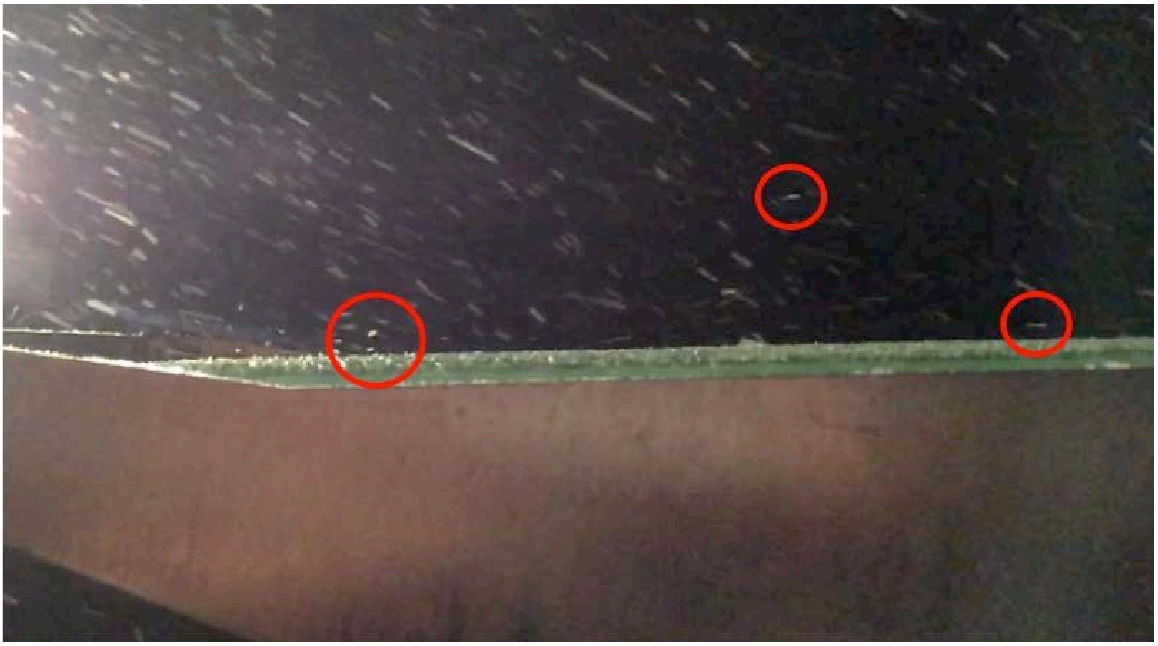

**Figure 20. Photograph of snow particles bouncing (noted by streaks moving anti-parallel to the free-stream particles) when they hit the fluid surface**

**Figure 21. Another photograph of snow particles bouncing (noted by streaks moving anti-parallel to the free-stream particles) when they hit the fluid surface (this was taken immediately following fluid application)**

## 9. CONCLUSIONS

After completing the outdoor and indoor testing, there appear to be four potential reasons why the outdoor tests are lasting longer than the indoor tests:

1. Frosticator assembly design
2. Wind effects on plate temperature
3. Snowfall rate effects on plate temperature
4. Snow particles bouncing off of the plate

The first (and likely the most important) reason is the design of the existing frosticator assembly used in the snow machine. The preliminary snow machine tests showed encouraging results when using the modified-height frosticator plate. More testing needs to be completed, but the fluid failure times did increase in length, bringing the fluid failure times closer to what was expected based on the currently published holdover time tables. Higher and lower rates and temperatures and additional fluids need to be tested to determine the true effects of raising the frosticator plate.

Wind effects, related to the addition of heat to the plate and fluid, have not been ruled out. The frosticator plate temperatures show a strong correlation to snowfall rate, but a weak correlation to wind speeds for the events shown. However, it should be noted that these events were low-wind-speed events, and the correlation would not be expected to be high for them. Other events were analyzed, but many of the higher wind-speed events also had temperature and snowfall rate variations that impacted fluid performance, making it difficult to narrow in on just the effects of wind. This issue may better be addressed in the lab using fans below the plate to simulate wind effects while temperature and snowfall rate remain constant.

Lastly, the effect of snow particles bouncing off the fluid in higher winds may also contribute to longer failure times in natural snow conditions. Beyond observing this phenomenon, no actual measurements were taken to determine how much snow might be lost because of bouncing. This does, however, indicate that failure times may also be a function of higher winds creating a lower collection efficiency of the fluid and needs to be investigated further.

## 10. REFERENCES

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