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Comparison of National Center for Atmospheric Research and Aviation Planning Services Snow Machines

December 2012

Final Report

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16. Abstract

Two identical snow-generating machines were developed at the National Center for Atmospheric Research (NCAR) to reproduce outdoor anti-icing fluid test results for snow conditions in a laboratory environment. One machine was upgraded continuously at NCAR, and the other was shipped to Aviation Planning Services (APS) to test the feasibility of using the machine operationally. After 10 years, the APS machine was returned to NCAR, the machine was upgraded and a series of intercomparison tests were conducted to determine whether the calibration of the two machines had drifted apart over time. Height comparison tests were also conducted since the APS machine had to be shortened due to use in a smaller facility at APS. The fluid tests were conducted in accordance with the SAE International standard using Kilfrost® ABC-S Plus and DOW Endurance™ EG-106 type IV anti-icing fluids. In the intercomparison tests, the same procedure was followed for each machine. At the beginning of each test, a brix measurement of the fluid was recorded, and then the fluid was poured onto a frosticator plate. After the fluid had spread over the entire frosticator plate, the ice core translator was turned on, and the test began. Once the fluid failed, the snow machine was stopped, a photograph was taken of the frosticator plate, and a final brix measurement was taken from the anti-icing fluid. Information on the fluid type, rate, air and plate temperatures, failure time, brix measurements, and any comments about the tests were recorded. For the height comparison of the machines, tests were run under the same conditions for each machine but at two different heights. The intercomparison test results showed that the calibration had drifted very little over time between the two machines. The tests of the different NCAR and APS snow machines heights showed that the APS machine had, on average, a 5% to 7% shorter endurance time than the NCAR normal height machine.

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LIST OF ACRONYMS

APS	Aviation Planning Services
ARP	Aerospace Recommended Practices
HOT	Holdover time
NCAR	National Center for Atmospheric Research

EXECUTIVE SUMMARY

Snow holdover times (HOT) for anti-icing fluids are determined by fluid tests under different snowfall rates and ambient air temperatures. The standard procedure for fluid tests for most snow conditions is to conduct the test outdoors in natural snow. 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 fluids using simulated snow in a cold chamber. In 1997, the National Center for Atmospheric Research (NCAR) began developing a new method for fluids tests in a cold-room laboratory environment using a snow-generating machine.

Two identical snow-generating machines were developed at NCAR to perform fluid tests for simulated snow conditions in a laboratory environment. One machine was continuously upgraded at NCAR through 2006, and the other was shipped to Aviation Planning Services (APS) in 1999 to test the feasibility of using the machine operationally. The snow-generating machines provided valuable data on fluid performance at cold temperatures.

After approximately 10 years of use, the APS machine was returned to NCAR, the machine was upgraded and a series of intercomparison tests were conducted to determine whether the calibration of the two machines had drifted apart over time. Since the height of the APS machine had to be shortened because the APS facility was smaller, height comparison tests were also performed. The anti-icing fluid tests were performed in accordance with the SAE International standard using Kilfrost® ABC-S Plus and DOW Endurance™ EG-106, which are both widely used propylene glycol-based type IV anti-icing fluids. In the intercomparison tests, the same procedure was followed for each machine. At the beginning of each test, a brix measurement of the fluid was recorded, and the fluid was poured onto a frosticator plate. After the fluid had spread over the entire frosticator plate, the ice core translator was turned on, and the test began. Once the fluid failed, the snow machine was stopped, a photograph was taken of the failed fluid on the frosticator plate, and a final brix measurement was taken from the anti-icing fluid. Information on the fluid type, rate, air and plate temperatures, failure time, brix measurements, and any comments about the tests were recorded. For the height comparison of the machines, tests were performed under the same conditions for each machine, but at the two different heights. The intercomparison test results showed that the calibration drifted very little over time between the two machines. The height tests of the NCAR and APS snow machines showed that the APS machine had, on average, a 5% to 7% shorter endurance time than the NCAR machine.

1. INTRODUCTION.

1.1 BACKGROUND.

Current methods for determining snow holdover times (HOT) involve testing the fluids under different snowfall rates and ambient air temperatures. Currently, the standard procedure for testing aircraft anti-icing fluid for HOT performance is to conduct the test outdoors in natural snow conditions in accordance with the SAE Aerospace Recommended Practices (ARP) 5485 [1] and ARP 5945 [2]. This procedure, however, means that fluid tests can only be performed during the winter months. This often requires a full winter season before enough data can be acquired at the necessary rates and ambient temperatures to develop the HOT performance specifications for a given fluid.

In 1997, the National Center for Atmospheric Research (NCAR) began developing a new method for anti-icing fluids tests in a cold-room laboratory environment using a snow-generating machine [3]. Indoor laboratory tests with a snow machine can lead to more timely and improved assessments of a fluid's performance using a range of controlled rates and air temperatures, without relying on outdoor snow conditions. Additionally, the tests can be conducted at any time during the year, increasing the confidence in established HOT for fluids and dramatically decreasing the time required for new fluids to be tested.

Two machines were initially developed with the goal of demonstrating the ability to accurately reproduce outdoor fluid test results for snow conditions in a laboratory environment [3-6]. One machine was used for testing fluids at NCAR and the other for testing fluids at Aviation Planning Services (APS). The role of APS was to test the feasibility of using the machine operationally, while the role of NCAR was to continue developing and upgrading the machine, addressing any issues that NCAR or APS encountered. The APS machine was delivered in 1999 and was used until 2009, with the original design specifications except for one modification. The test facility at APS was not tall enough to accommodate the height of the machine, therefore, the machine was shortened by 12 inches. The NCAR machine was continually upgraded from 1999 until 2009 (with most of the upgrades occurring before 2006), using the original height configuration and incorporating features such as better rate control, higher rate capacities, and better snowfall distribution patterns.

1.2 PURPOSE.

In 2009, an electrical short in the artificial snow-generation machine being operated by APS prompted the return of the system for repairs to NCAR. The return of the snow machine from APS to NCAR provided an opportunity not only to repair the machine, but also to upgrade the unit with the latest modifications and then perform intercomparison tests between the two machines. Similar intercomparison tests were conducted in 1999 prior to NCAR delivering a machine to APS, which showed good correlation between the two machines. The new tests would determine whether the calibration of the machines had drifted over time. This would also allow NCAR the opportunity to address any mechanical degradation that may have occurred over the years. A complete list of upgrades to the APS machine is provided in section 2 of this report, as are the results of the intercomparison study.

2. DESCRIPTION OF SNOW MACHINES AND UPGRADES.

The tops and walls of both machines are composed of a polycarbonate plastic material. The snow machines are composed of two stages: the top stage (figure 1), where the snow is generated and the bottom stage (figure 2), which serves as a mounting platform for the top stage and contains the equipment that collects the falling snow. The total height of the NCAR machine is 80 in. (68 in. for the APS machine). Both machines are trapezoidal; the bottom of the lower section is wider (27.6 by 35.4 in.) than the top of the upper section (27.2 by 24.8 in.). The machines generate artificial snow by grinding an ice core that feeds into a horizontally oriented drill bit (figure 3). The drill bit grinds the ice into small shavings and, once calibrated, it produces a size distribution similar to natural snowfall [4]. The machined snow size is calibrated by varying the speed (revolutions per minute) of the drill bit until the desired particle size distribution is acquired; slower speeds produce bigger particle sizes while faster speeds produce smaller particle sizes. The ice core feeds into the drill bit using a translator system controlled by a stepper motor (figure 4). The speed of the stepper motor determines the snowfall rate in the machine, which is controlled through a computer interface. The snow machine is located in a cold room, since the snow machine itself is not refrigerated.

Figure 1. Top Stage of Snow Machine

Figure 2. Bottom Stage of Snow Machine

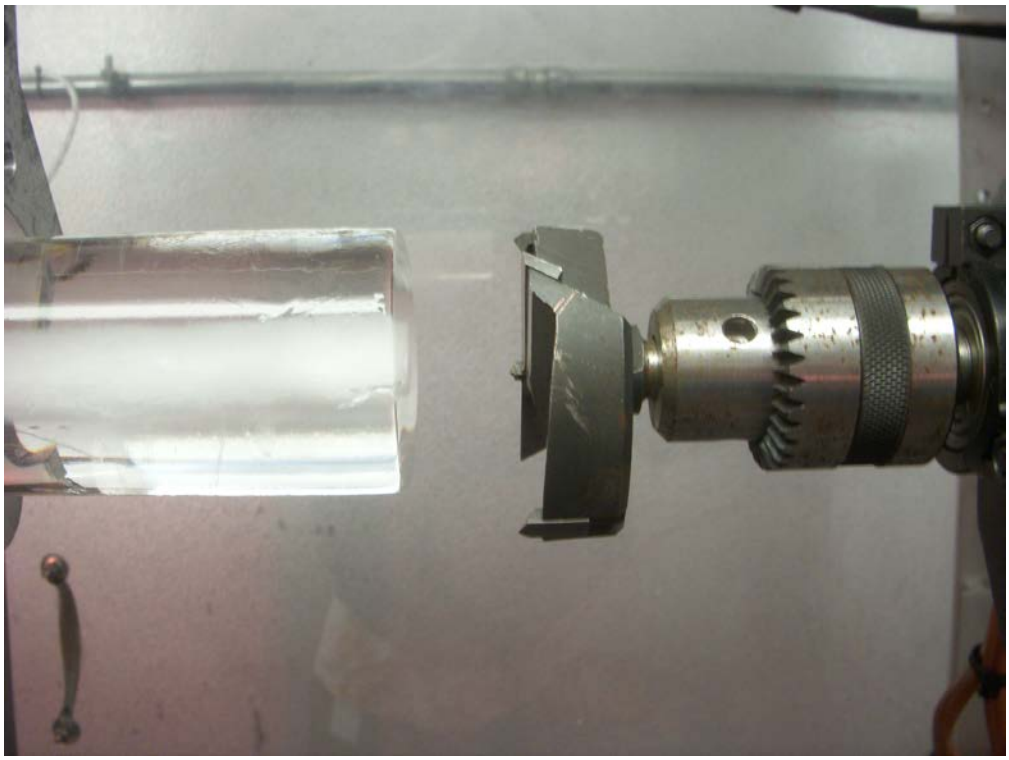

Figure 3. Ice Core and Drill Bit

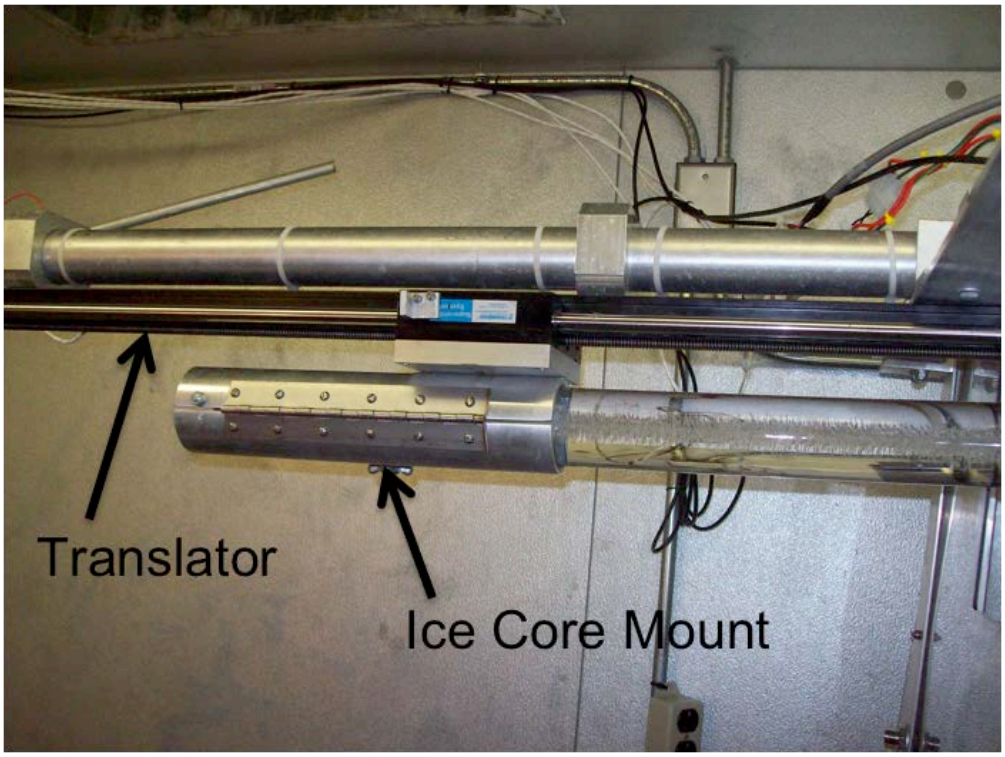

Figure 4. Translator and Ice Core Mount

Snowfall rates are determined through the use of a frosticator plate (measuring 11.8 by 19.7 in.) and bucket assembly mounted on a mass balance (figures 5 and 6). The frosticator plate is the standard test surface used in the determination of HOT. The temperature of the plate can be controlled by a silicone heater affixed to the back of the frosticator plate. Fluid is applied directly to the frosticator plate, which is inclined at a 10° angle to simulate an aircraft wing. The frosticator plate is mounted on top of the bucket assembly, which catches the runoff of the fluid during the tests, keeping the fluid entirely contained within the system. Thus, any change in weight recorded by the mass balance is due entirely to the snow falling on the frosticator plate. As snow falls on the frosticator plate, measurements from the mass balance are taken every 6 seconds, and the change in mass is directly proportional to the snowfall rate. The snow machine can produce snowfall rates from 2.5 g/dm^2/hr (0.25 mm/hr) to over 50 g/dm^2/hr (5.0 mm/hr).

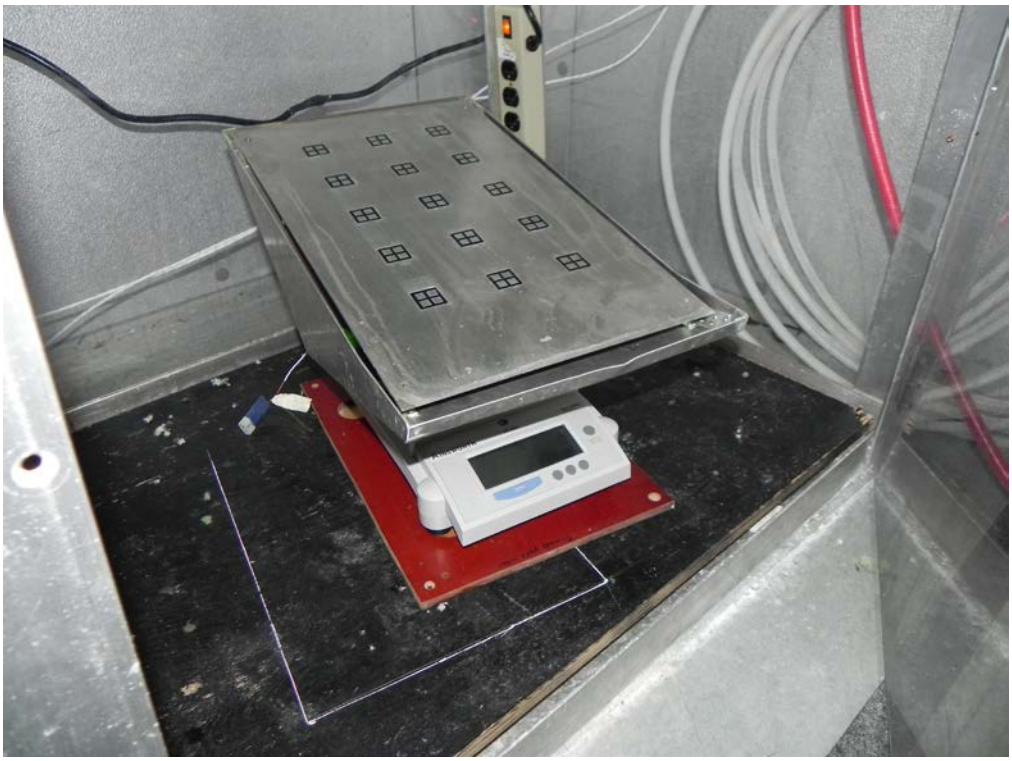

Figure 5. Frosticator Plate and Bucket Assembly on Mass Balance

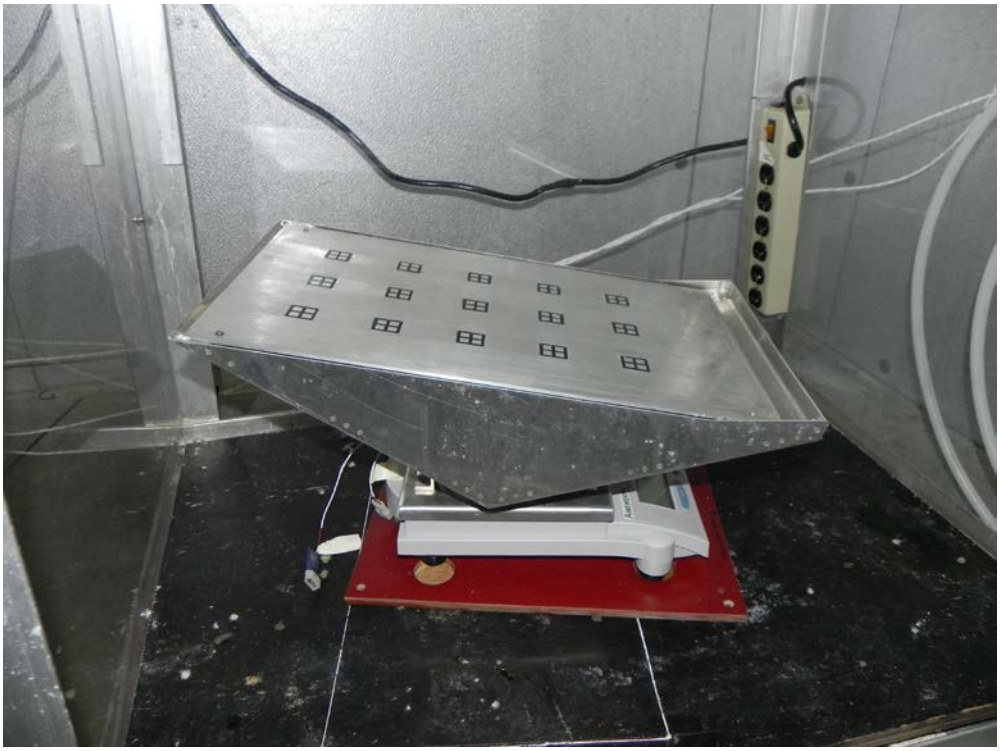

Figure 6. Frosticator Plate and Bucket Assembly on Mass Balance—Side View

To achieve an even snowfall pattern across the frosticator plate, air jets were installed in the machine with air pulsed through them at regular intervals (figure 7). A squeegee system, also shown in figure 7, was also installed at the top of the machine to keep snow from building up and falling in clumps on the frosticator plate during the tests. The machine is controlled through a graphical user interface written in LabVIEW® software (figure 8). The interface allows the user to adjust the snowfall rate, the duration and frequency of the air jet pulses, and the starting and stopping of the air jets, drill bit, and squeegee system. The overall average test rate, 40-second average snowfall rates, and room and frosticator plate temperatures are also shown on the display. Ambient air temperature is controlled via a separate thermostat installed in the cold room.

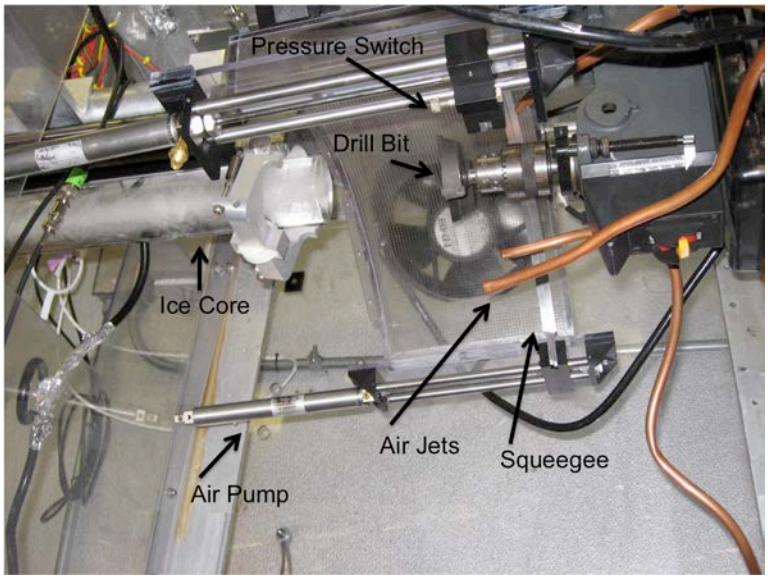

Figure 7. Squeegee System and Air Jets

Figure 8. LabVIEW Control Panel Interface

When the APS snow machine arrived at NCAR, it was upgraded to include all hardware and software advancements made to the NCAR snow machine since 1999. After the upgrades were complete, both machines were identical, except for their height. The upgrades to the APS snow machine included the following:

- The translator arm for the ice core was lengthened, and the stepper motor was replaced with a larger stepper motor capable of producing higher torque and higher snowfall rates.
- The ice core mount was modified to allow faster and easier installation of a new ice core.
- The ice core position was realigned so it was centered on the drill bit.
- The drill press motor, mounting bracket, drive belt, and pulleys were replaced and the motor rewired.
- More economical and readily available steel drill bits were provided in place of the more expensive tungsten carbide drill bits.
- Thicker poly carbonate was used on the top of the machine to accommodate the new motor and light fixtures.
- The lighting in the machine was upgraded to light-emitting diode bulbs, and all power receptacles and power strips were replaced.
- The old wiper system was replaced with the new squeegee system, including new wiring, Teflon® air lines, and valve fittings.
- The air valves to control the airflow in the machine were redesigned with new fittings, cables, and valves.
- All the temperature sensors were calibrated and replaced, if necessary.
- The plate heater was upgraded, and the plate temperature sensors were calibrated.
- The mass balance was repaired and calibrated due to damage it sustained during shipment.
- The electronics control box was upgraded and simplified, and all cabling was replaced.
- The computer was replaced, and a new version of LabVIEW was installed that included upgrades to snowfall rate and plate heater controls.

3. TEST OBJECTIVE.

To determine if the updated APS machine was operating to the specifications established by the NCAR machine, a series of tests were conducted with both machines. Test matrix conditions were developed to cover a range of rates at the two different machine heights. The original test matrix consisted of ten test conditions per machine at two different temperatures for two different types of anti-icing fluids at the NCAR machine height. Ten additional test conditions were also proposed for a shorter machine configuration as well. However, due to time constraints, the test matrix was modified to a smaller set of five test conditions (table 1).

Table 1. Final Test Matrix

Test	Rate ($g/dm^2/hr$)	Temperature (°C)	Fluid	Height	Snow Machine
Anti-Icing Fluid Tests					
1	45.0	-8.0	Kilfrost ABC-S Plus and DOW ENDURANCE EG-106	APS Height	both
2	25.0	-10.0			
3	10.0	-10.0			
Height Comparison Tests					
4	25.0	-10.0	DOW Endurance EG-106	NCAR Height*	APS*
5	10.0	-10.0			

* Note: These tests were also conducted at the APS height and with the NCAR snow machine, using results from test conditions 2 and 3 in column 1.

Since only the top half of the APS machine required repairs and upgrades, only the top half was returned to NCAR. Additionally, all items required for anti-icing fluid tests in the bottom half of the machine were also returned, including all the cabling, the frosticator plate and bucket assembly, the mass balance, and the temperature sensors. The APS snow machine tests were performed with the APS equipment, and the NCAR snow machine tests were performed with the NCAR equipment. The bottom of the NCAR machine was used as a platform for both the APS and NCAR machines during the tests. To simulate the APS snow machine height, the bottom of the NCAR snow machine was raised 12 inches by creating a platform for the frosticator plate and bucket assembly (figure 9). Because of the small amount of space available in the NCAR cold room, only one machine could be tested at a time.

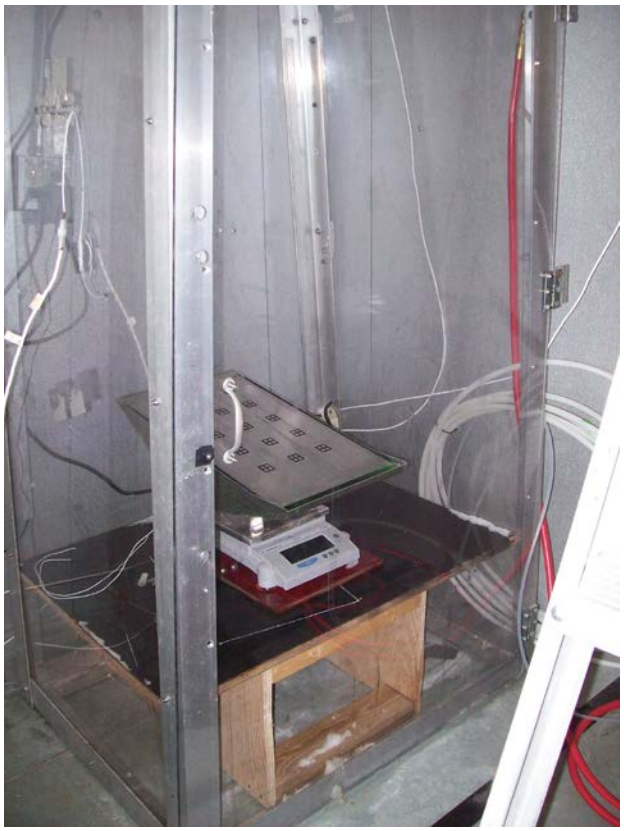

Figure 9. Raised Platform in Base of Snow Machine

4. TEST PROCEDURES.

4.1 SNOW MACHINE DISTRIBUTION CALIBRATION.

Before the actual anti-icing fluid tests were conducted, the snow machines had to be calibrated to ensure an even distribution of snow over the entire frosticator plate. This was accomplished by running distribution calibration tests for each snow machine after installation in the cold room. The plate used for the distribution tests had the same dimensions as the frosticator plate (11.8 by 19.7 in.) but was placed horizontally on top of the frosticator plate and contained ten individual trays (5.9 by 3.9 in.) (figures 10 and 11). Before a distribution test was run, each individual tray was weighed, and the weight was recorded. The snow machine was run at a rate of 25 g/dm^2/hr (2.5 mm/hr) for 10 minutes with the room temperature set at approximately -8°C. Each tray was weighed after the distribution tests. The initial weight was subtracted from the final weight to derive the mass of snow in each tray. The snowfall amounts from the ten trays were then added up for the total amount of snow over the plate and an average accumulation was computed. To find the percent deviation from the average for each tray, the following formula was used.

$$\%\ \text{deviation} = \frac{\text{Snow amount in tray - Average snow amount for all trays over the whole plate}}{\text{Average snow amount for all trays over the whole plate}} \quad (1)$$

Each tray needed to be within ±20% of the average for the distribution to be considered acceptable. Multiple distribution tests were run for each machine until the average percent deviation was met for each tray. If trays were found to be outside that average, the air jets and/or bucket assembly position was modified in the machine to change the distribution pattern. The duration of air jet pulses could also be modified through the LabVIEW interface to further modify the distribution pattern. After any calibration test yielded an acceptable distribution, the test was rerun to confirm the results were reproducible.

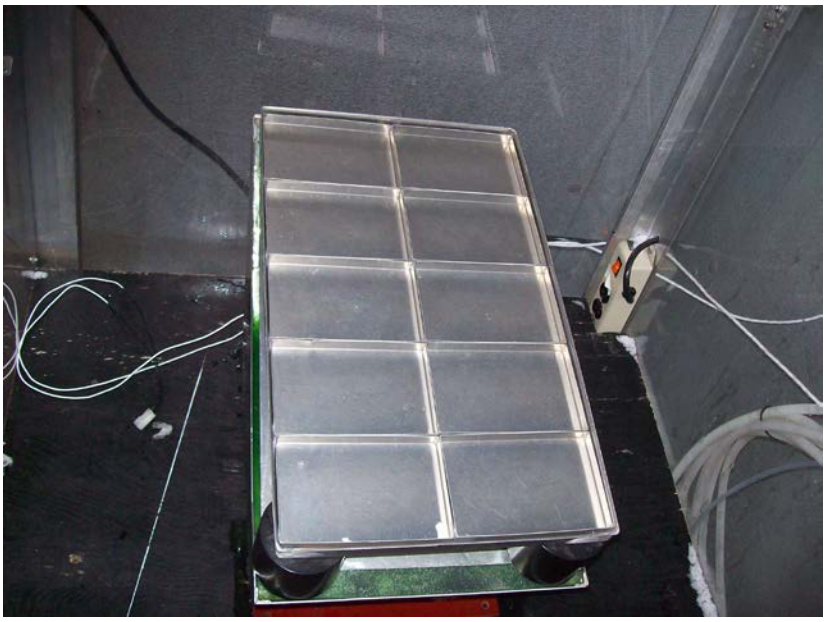

Figure 10. Trays Used for Distribution Tests

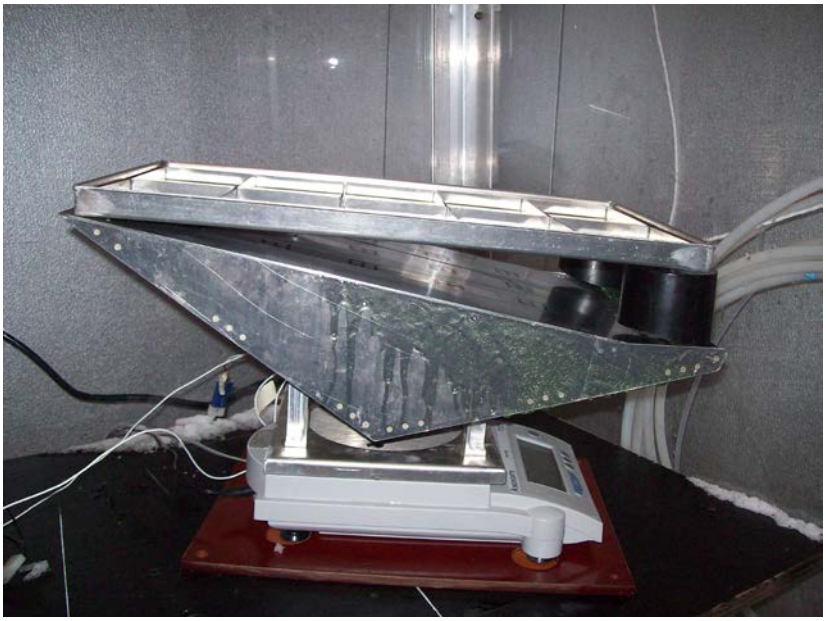

Figure 11. Distribution Trays and Bucket Assembly—Side View

4.2 ANTI-ICING FLUID TESTS.

The anti-icing fluid tests were conducted in accordance with the SAE International standard [1 and 2] and as defined in [7]. The cold room air temperatures varied by ±2.0°C due to the design of the room controls. The plate temperature varied by ±0.1°C and was adjusted throughout the test to minimize the difference from the target temperature. The plate temperature was increased, using equation 2 to account for the absence of wind blowing across the plate in outdoor test conditions [4].

$$\text{Plate Temperature Set Point} = -(\,0.509 + 0.0631 * I\,) - Ta \qquad (2)$$

where I is the snowfall intensity, and Ta is the ambient air temperature.

The initial fluid temperature for all the tests was the same as the air temperature in the cold room (±1.0°C). Kilfrost® ABC-S Plus and DOW Endurance™ EG-106 type IV anti-icing fluids were used for the tests. At the beginning of each test, a brix measurement of the fluid was recorded, and then the fluid was poured onto the upper portion of the frosticator plate and allowed to run down to the bottom. The brix indicates the amount of glycol present in the fluid. After the fluid had spread over the entire frosticator plate, the ice core translator was turned on, and the test began. The test was run until the fluid failed in accordance with SAE guidelines, i.e. the fluid no longer absorbed snow visually from the top of the frosticator plate down one-third of the plate. Once the fluid failed, the snow machine was stopped, a picture was taken of the frosticator plate, and a brix measurement was taken from the anti-icing fluid just below the failure point, one third of the way down the plate. The difference in the brix measurements between the beginning and end of the test showed the degree of dilution of the fluid after it had failed. At the end of the test, information on the fluid type, rate, air and plate temperatures, and any comments about the tests were entered into the data files as comments.

4.3 THE APS SNOW MACHINE TESTS.

Before any anti-icing fluid tests were run, the APS snow machine was calibrated by running the distribution calibration tests described in section 4.1. A total of 22 distribution calibration tests were run over the two-week test period. The shortened height of the APS snow machine made the goal of achieving an acceptable distribution over the frosticator plate more challenging because the snow had less time to be influenced by the air jets.

Thirteen anti-icing fluid tests were run using the APS snow machine, of which seven were determined to be valid. Six tests had software or hardware errors that nullified the results. The description of the valid tests and the resulting failure time, final brix measurements, and test comments are shown in table 2. Additional analyses of the APS machine tests are discussed in section 5.

Table 2. The APS Snow Machine Anti-Icing Fluid Tests

Test	Rate ($g/dm^2/hr$)	Air Temperature (°C)	Plate Temperature (°C)	Fluid Type	Failure Time (minutes)	Final Brix	Comments
1	25.0	-10.0	-12.0	DOW Endurance EG-106	30.3	12.25	Some clumping
2	25.0	-10.0	-12.0	Killfrost ABCS +	26.0	18.50	Room a little warm at the beginning of the test
3	25.0	-10.0	-12.0	Killfrost ABCS +	28.6	19.00	Repeat of test 2, almost whole plate failure, cold room door caused issues with balance
4	10.0	-10.0	-11.0	DOW Endurance EG-106	63.3	14.25	
5	10.0	-10.0	-11.0	Killfrost ABCS +	76.1	19.50	Almost full plate failure
6	45.0	-8.0	-11.0	Killfrost ABCS +	11.1	22.00	Failure called because snow was not being absorbed into the fluid due to high rates
7	45.0	-8.0	-11.0	DOW Endurance EG-106	15.2	14.00	Failure called a little early

4.4 THE NCAR SNOW MACHINE TESTS.

Given time constraints, only ten distribution calibration tests were run for the NCAR snow machine to get an acceptable snow distribution prior to running the anti-icing fluid tests. The distribution tests for the NCAR snow machine at the APS height resulted in a maximum 22% deviation from the average over the whole plate. This was close to the goal of a 20% deviation from average plate distribution. As shown previously, the number of distribution tests conducted on the APS snow machine to get an acceptable distribution with the shortened height made it much more difficult to get the distribution within the 20% deviation from the average, and as a result, the 22% deviation was deemed acceptable for the purpose of the tests.

Six anti-icing fluid tests were run with the NCAR snow machine. Table 3 shows the description of the valid tests along with the failure time, brix measurements, and any test notes. Further discussion and comparison of these results to the APS snow machine are provided in section 5.

Table 3. The NCAR Snow Machine Anti-Icing Fluid Tests

Test	Rate ($g/dm^2/hr$)	Air Temperature (°C)	Plate Temperature (°C)	Fluid Type	Failure Time (minutes)	Final Brix	Comments
1	25.0	-10.0	-12.0	UCAR EG 106	31.9	12.25	
2	25.0	-10.0	-12.0	Killfrost ABC-S +	26.0	17.25	Fluid failure probably called a little early
3	10.0	-10.0	-11.0	UCAR EG 106	62.7	12.00	
4	10.0	-10.0	-11.0	Killfrost ABC-S +	78.7	19.00	Whole plate failure: failed top, bottom-right corner, and middle left
5	45.0	-8.0	-11.0	Killfrost ABC-S +	11.8	21.25	Failure due to snow falling too fast for fluid to absorb, very similar to APS failure
6	45.0	-8.0	-11.0	UCAR EG 106	18.9	13.00	

4.5 HEIGHT COMPARISON.

A comparison of the two different snow machine heights was conducted by using the top of the APS and NCAR snow machines with the bottom half set up for both the shorter APS height (68 in.) and the NCAR machine height (80 in.). A 12-inch platform was used to achieve the APS height and then was removed to run the tests at the NCAR height. Table 4 shows the results of the height comparison fluid tests.

Table 4. The APS and NCAR Snow Machine Height Comparison Tests

Rate	Temperature	Fluid	APS Height		NCAR Height	
			APS Fail Time (minutes)	NCAR Fail Time (minutes)	APS Fail Time (minutes)	NCAR Fail Time (minutes)
25 $g/dm^2/hr$	-10°C	DOW Endurance EG-106	30.3	31.9	33.7	31.9
10 $g/dm^2/hr$			63.3	62.7	67.8	66.2

5. RESULTS AND DISCUSSION.

5.1 COMPARISON OF THE NACR AND APS MACHINES AT THE SAME HEIGHT.

The failure times for the two machines showed excellent agreement for all three rates using both fluid types (figures 12 and 13). The differences are less than 5% in all cases. A scatter plot of the endurance times (figure 14) for the two machines shows a strong one-to-one relationship with a slope of 1.0 and correlation coefficient of 0.996. A histogram of the differences is shown in figure 15.

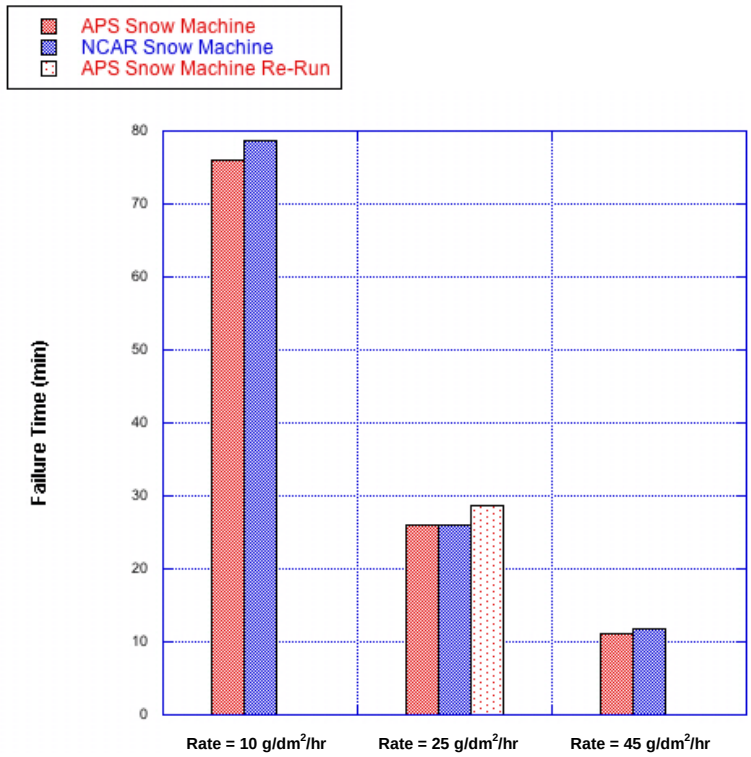

Figure 12. Comparison of Failure Times for Kilfrost ABC-S Plus From the APS and NCAR Snow Machines

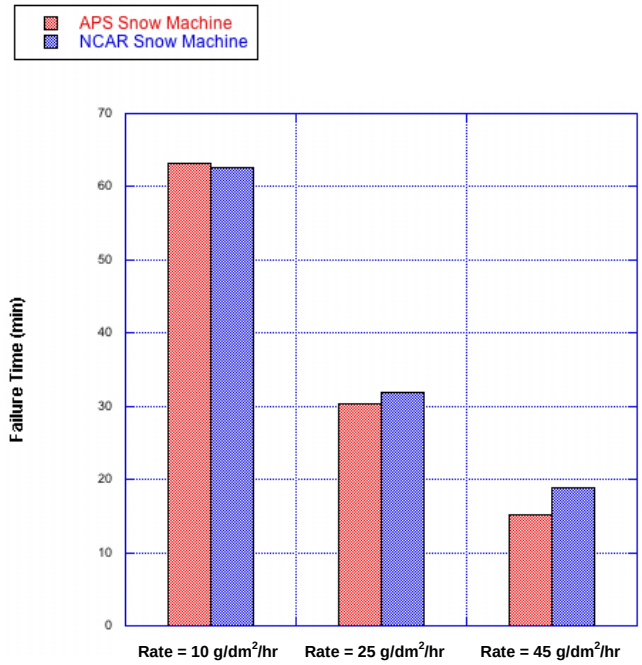

Figure 13. Comparison of Failure Times for DOW Endurance EG-106 From the APS and NCAR Snow Machines

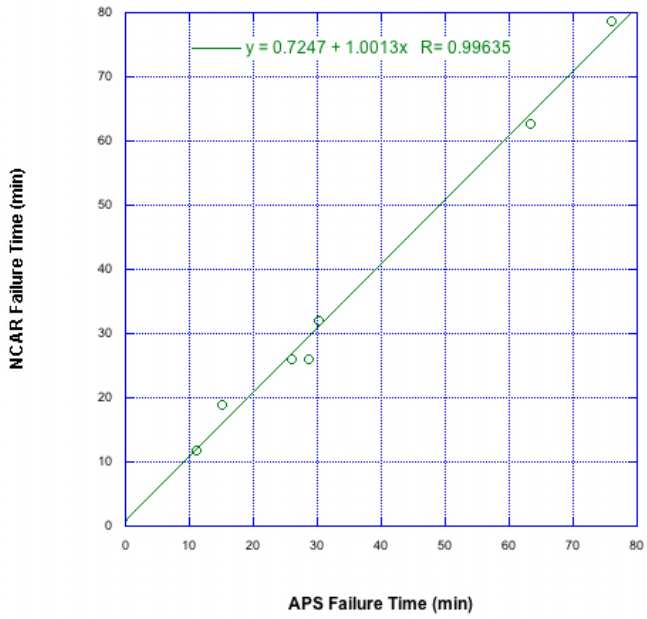

Figure 14. Scatter Plot of APS Snow Machine vs NCAR Snow Machine Fluid Failure Times

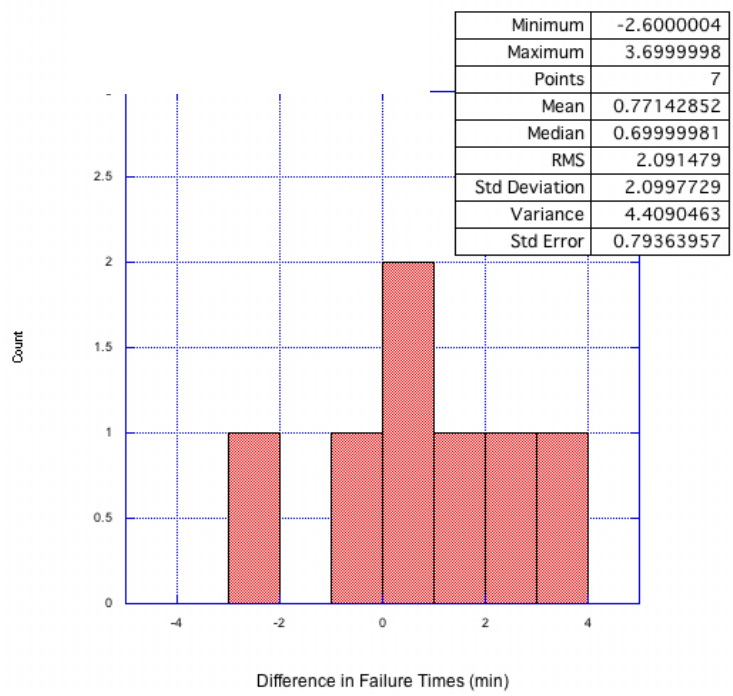

Figure 15. Histogram Plot of the Difference Between the NCAR Snow Machine and the APS Snow Machine Fluid Failure Times With a Table of Some Basic Statistics

Figures 16 through 18 show the comparison of the APS and NCAR snow machines with DOW Endurance EG-106 for a snowfall rate of 10 g/dm^2/hr. The accumulated snow mass during these tests is overlayed in a time series plot in figure 16. The snow mass from the NCAR snow machine plotted in blue shows a short time period at the beginning of the test when there was no snow accumulation on the plate. This was due to an issue with the ice core spinning freely and was quickly resolved by tightening the ice core-casing mount. After this period without snow accumulation, the NCAR snow machine quickly recovered and matched the snow mass from the APS snow machine test (shown in red). The final failure times show this rate drop-off had a negligible effect on the overall test. In figure 17, the time series plot of the snowfall rate similarly shows the rate drop-off from the NCAR snow machine at the beginning of the test with the recovery and demonstrates how well the rates from both machines compared for these tests. The final difference in times was only 0.6 minutes for this test, with the APS machine having the slightly longer fail time.

Pictures of the fluid failures for both machines are shown in figure 18. Some of the differences between the images of the two failures was due to the angle and lighting of the photographs, as well as slightly different distribution patterns. It should be noted that both machines met the plate distribution calibration criterion although there were still differences in the distribution of snow across the plate between the two machines. The focus should be on the similarities between the two images, mainly the buildup of snow across the top and down the center of the plate.

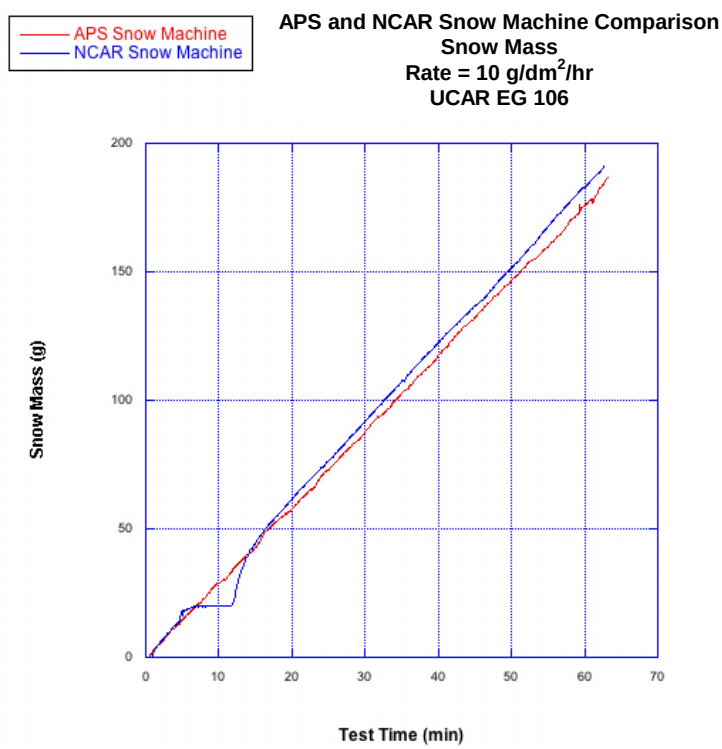

Figure 16. Time Series of the Snow Mass for Tests of the APS and NCAR Snow Machines With DOW Endurance EG-106 at the Rate of 10 g/dm^2/hr

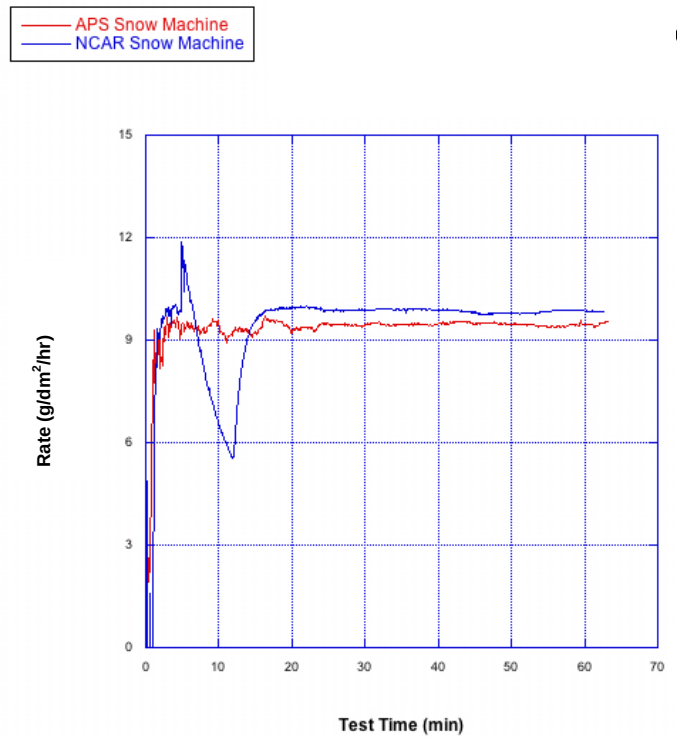

Figure 17. Time Series of the Overall Rate for Tests of the APS and NCAR Snow Machines With DOW Endurance EG-106 at the Rate of 10 g/dm^2/hr

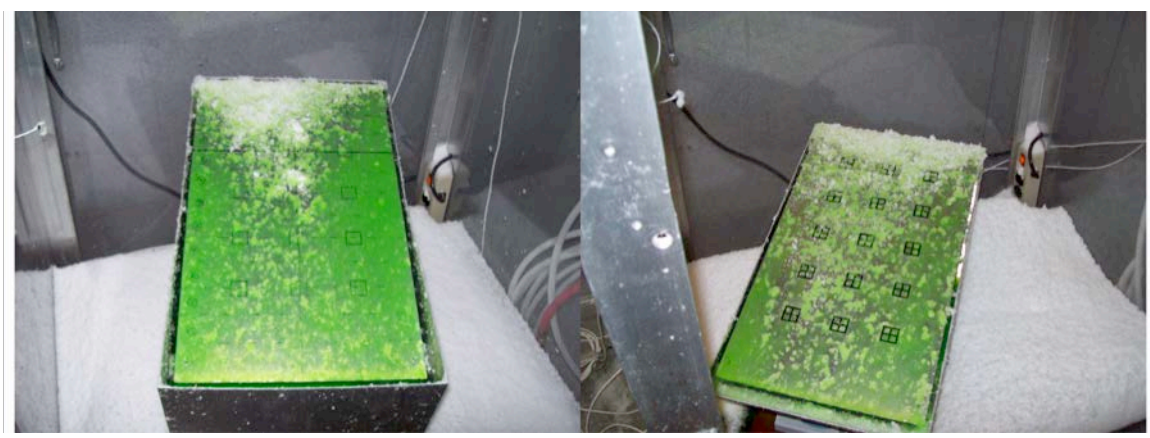

Figure 18. Images of the Fluid Failures From the Test for DOW Endurance EG-106 at the Rate of 10 g/dm^2/hr for the APS (Left) and NCAR (Right) Snow Machines

Figures 19 through 21 show data from the comparison of the APS and NCAR snow machines with Kilfrost ABC-S Plus at a rate of 25 g/dm^2/hr. Figure 19 shows the accumulated snow mass of these test conditions with the APS machine in red and the NCAR machine in blue. The plot shows a slight jump in the accumulation of the APS machine snow mass toward the end of the test due to the machine's mass balance sensitivity to the opening and closing of the cold room door. Aside from the rise in the snow mass, both snow machines compared very well with a difference in failure time of 2.6 minutes. The time-averaged rate from both machines (plotted in

figure 20) shows that the rate from the APS snow machine for these test conditions was slightly less than 25 g/dm^2/hr. Although the failure times of the fluids from both machines are similar, the longer time from the APS machine is likely due to the overall rate being slightly lower throughout the test. Pictures of the fluid failures (figure 21) for both machines show the machines had similar snow distribution patterns, starting at the top and moving down the plate.

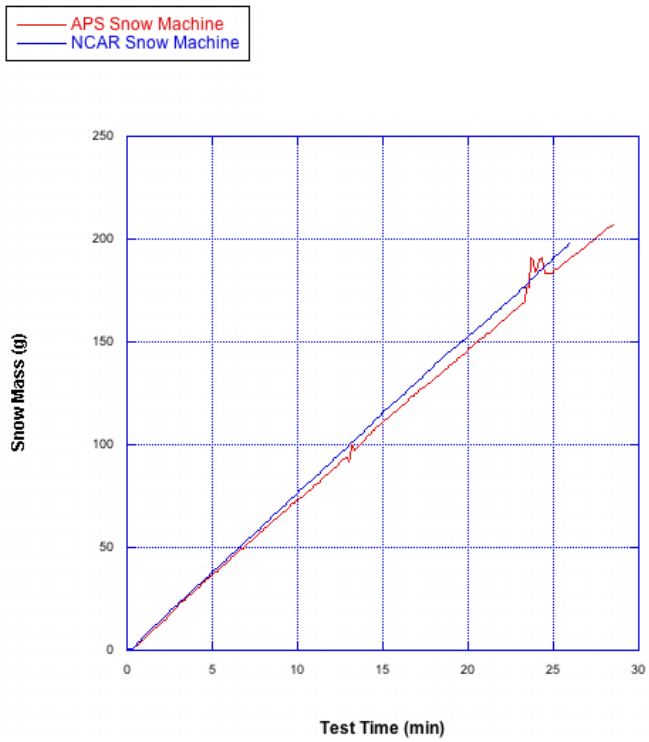

Figure 19. Time Series of the Snow Mass for APS and NCAR Snow Machines Tests With Kilfrost ABC-S Plus at the Rate of 25 g/dm^2/hr

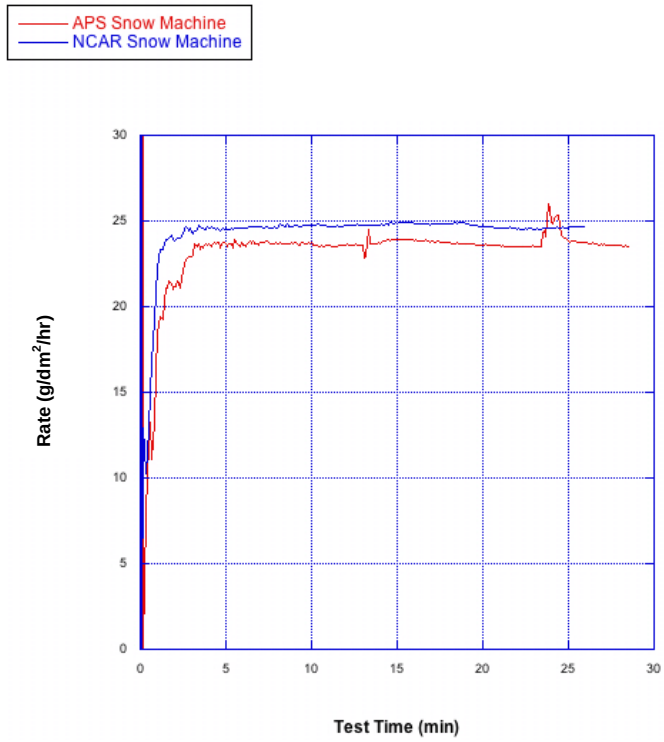

Figure 20. Time Series of the Overall Rate for APS and NCAR Snow Machines Tests With Kilfrost ABC-S Plus at the Rate of 25 g/dm^2/hr

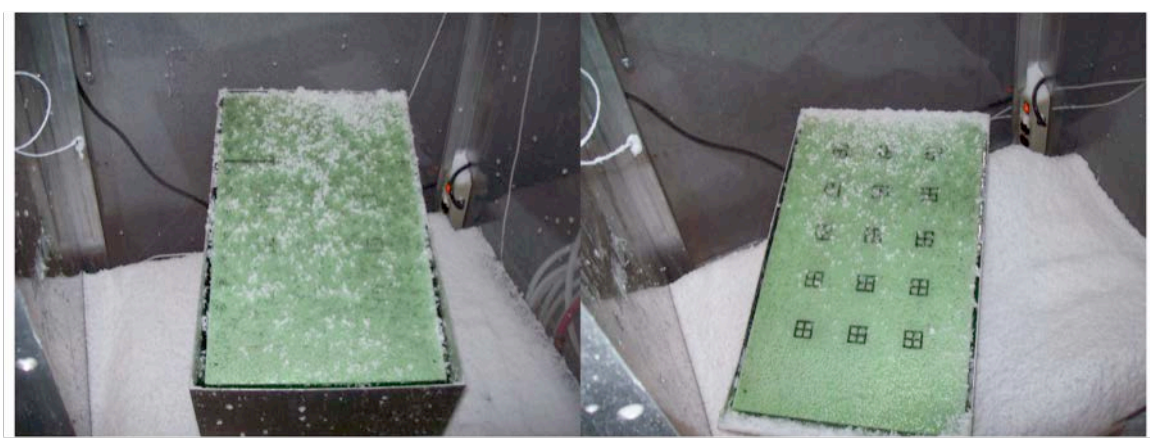

Figure 21. Images of the Failures From the Test for Kilfrost ABC-S Plus at the Rate of 25 g/dm^2/hr for the APS (Left) and NCAR (Right) Snow Machines

5.2 MACHINE HEIGHT COMPARISONS.

For the height comparison of the machines, two sets of tests were performed under the same conditions for each machine, but at the two different heights. Four tests were performed at the NCAR height with DOW Endurance EG-106 anti-icing fluid at rates of 10 g/dm^2/hr and 25 g/dm^2/hr. The tests used in the height comparison for the APS height were taken from the set of tests already run for the machine intercomparison and were not duplicated for the height

comparison tests. Figure 22 shows the fluid failure times for the height comparison tests, with the APS machine at APS height (red), the NCAR machine at APS height (blue), the APS machine at NCAR height (green), and the NCAR machine at the NCAR height (purple). The shorter machine took approximately 5% less time than the full height machine, as shown in figure 22. The plots in figure 23 show a positive bias of 0.07 minutes (y = -0.43 + 1.07x), indicating that the shorter machine took 7% less time.

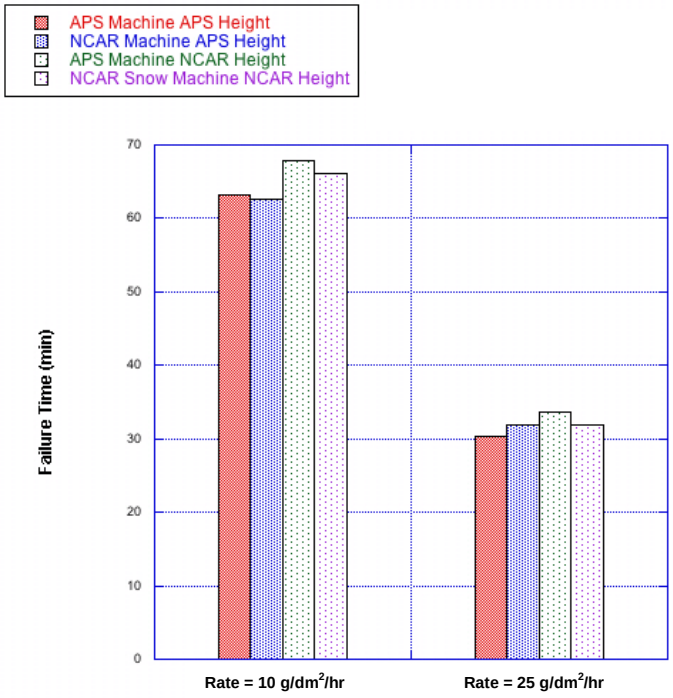

Figure 22. Comparison of Failure Times for the Different Heights of the APS and NCAR Snow Machines Conducted With DOW Endurance EG-106

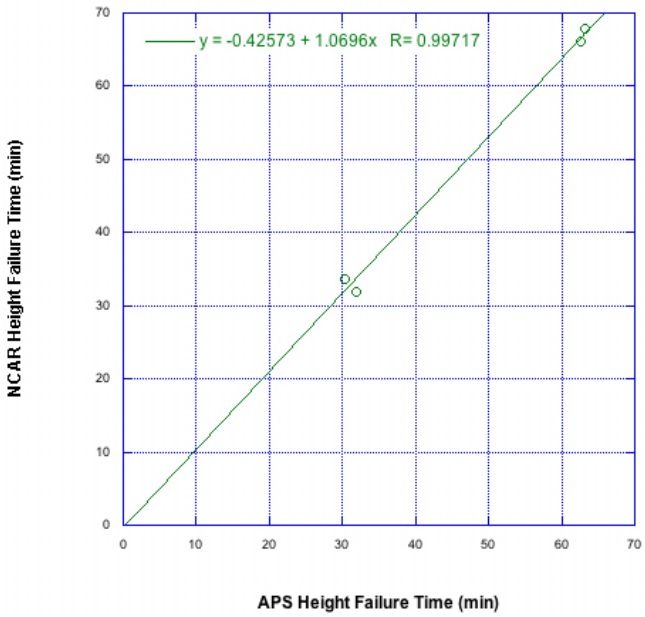

Figure 23. Plot of APS vs NCAR Snow Machine Heights Fluid Failure Times

A time series of the snow mass accumulation for the test runs of the different snow machine heights at a rate of 10 g/dm^2/hr with DOW Endurance EG-106 is shown in figure 24. The red (APS machine) and blue (NCAR machine) lines are from tests run at the APS snow machine height for the machine intercomparison. The green line shows the snow mass from the APS snow machine at the NCAR height. The maximum difference of failure times for this set of tests was 5.1 minutes with the NCAR height running slightly longer. The snow mass accumulation from the normal height simulation is 10% higher than the mass accumulated for the shorter machine, consistent with the longer endurance time of the standard (taller) height machine. The overall rate from all three tests is shown in figure 25. The images in figure 26 show that the failures of the fluids for all three tests have similar snow buildup patterns on the plate.

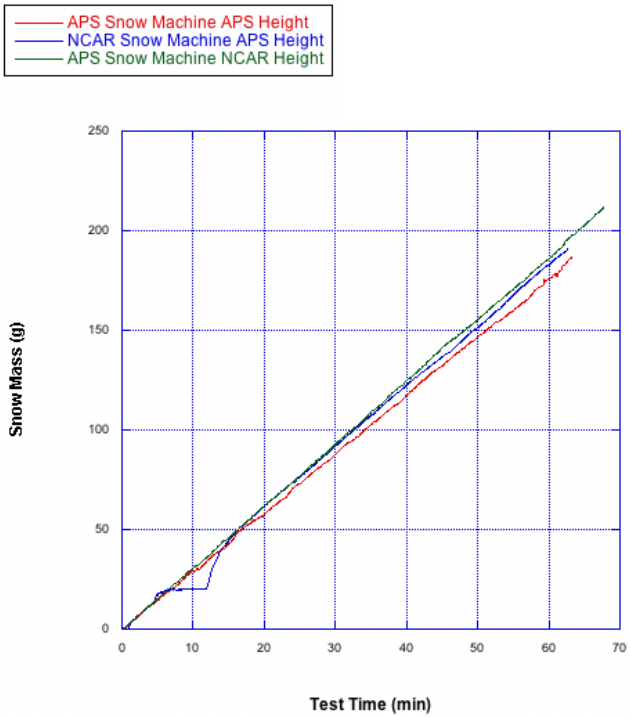

Figure 24. Time Series of the Snow Mass for APS and NCAR Snow Machine Heights Tests With DOW Endurance EG-106 at the Rate of 10 g/dm^2/hr

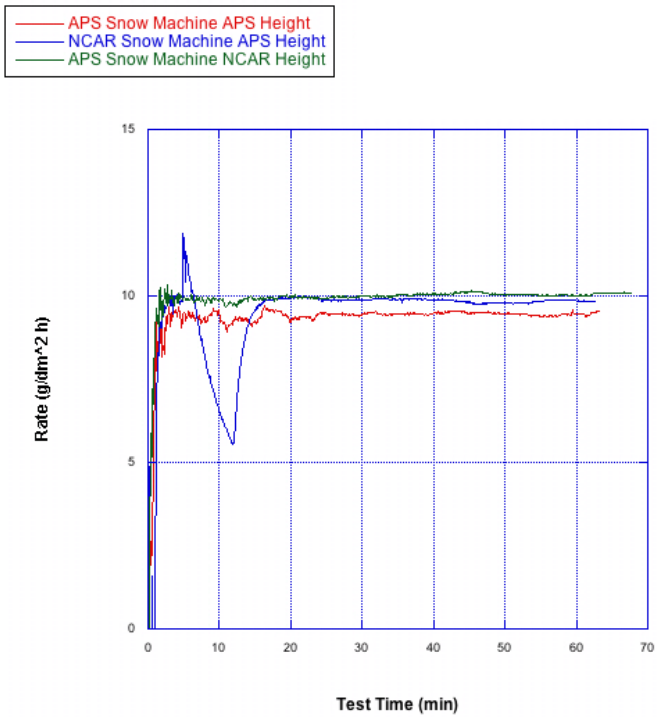

Figure 25. Time Series of the Overall Rate for APS and NCAR Snow Machine Heights Tests With DOW Endurance EG-106 at the Rate of 10 g/dm^2/hr

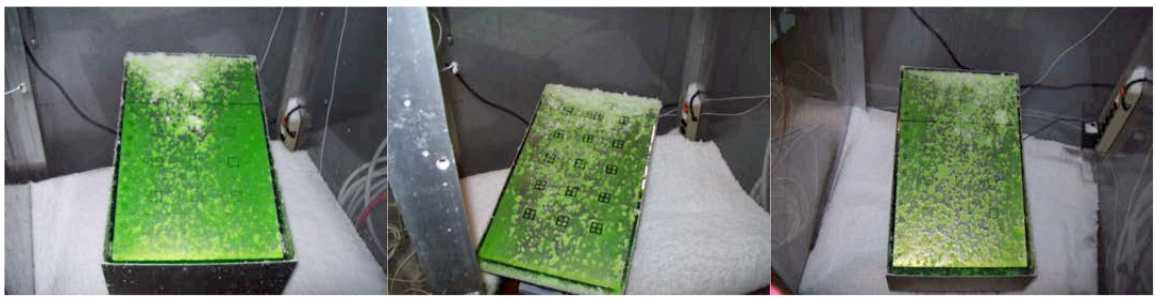

Figure 26. Images of the Failures From the Test for DOW Endurance EG-106 at the Rate of 10 g/dm^2/hr for the APS Snow Machine at APS Height (Left), the NCAR Snow Machine at APS Height (Middle), and the APS Snow Machine at NCAR Height (Right)

Figure 27 shows a time-series plot of snow mass for tests run of the different snow machine heights at a rate of 25 g/dm^2/hr with DOW Endurance EG-106. The red line shows results from a test run at the APS height from the original NCAR machine intercomparison. The green line indicates the snow mass from the APS snow machine at the NCAR height. The difference of failure times for these two tests was 1.8 minutes with the test at the NCAR height running longer. Again, this shows a 6% longer endurance time for the standard height machine over a total endurance time of ~30 minutes. The time-averaged rates from these tests are shown in figure 28 and compare favorably. The images in figure 29 show that the failures of the fluids for these two tests are very similar.

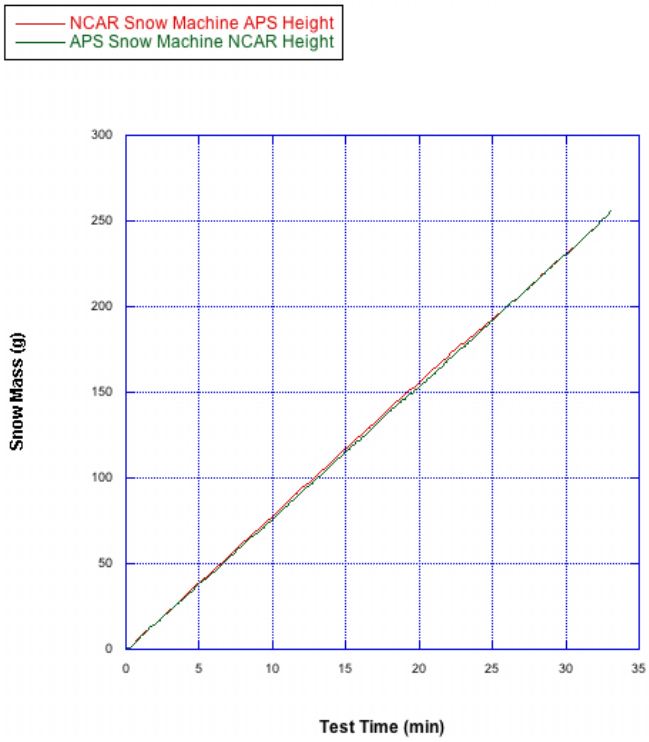

Figure 27. Time Series of the Snow Mass for APS and NCAR Snow Machine Heights Tests With DOW Endurance EG-106 at the Rate of 25 g/dm^2/hr

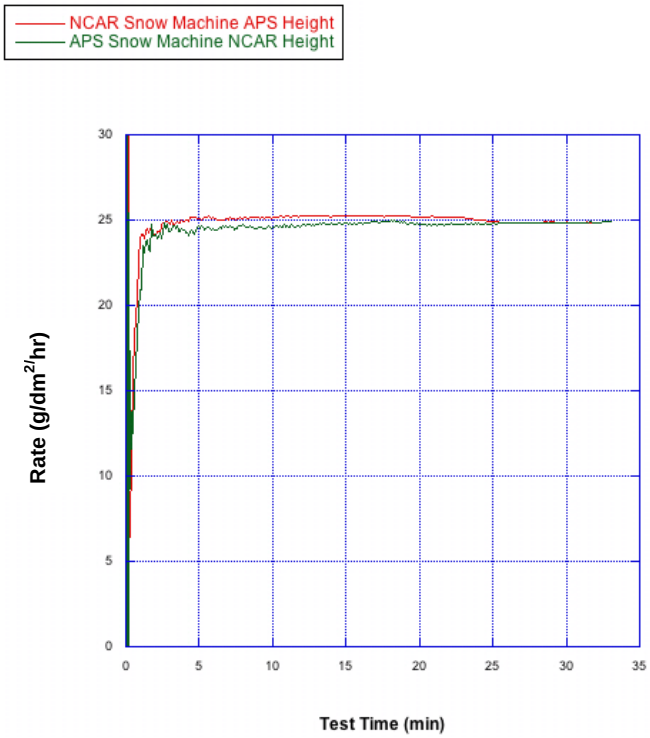

Figure 28. Time Series of the Overall Rate for APS and NCAR Snow Machine Heights Tests With DOW Endurance EG-106 at the Rate of 25 g/dm^2/hr

Figure 29. Images of the Failures From the Test for DOW Endurance EG-106 at the Rate of 25 g/dm^2/hr for the NCAR Snow Machine at APS (Left) and NCAR (Right) Snow Machine Heights

6. CONCLUSIONS.

The fluid test results show that the upgraded APS snow machine and the NCAR snow machine fluid failure times compare extremely well with the differences in failure times for similar test conditions all being within experimental error. Additionally, the testing of the different heights tests of the NCAR and APS snow machines showed that the shorter machine had, on average, a

5% to 7% shorter endurance time than the normal height machine. However, it should be noted that these results are based on only a few comparison tests and further tests would be needed to determine if the variations in times were actually due to the difference in machine height or experimental error inherent in the test procedures. Figure 30 shows a comparison plot of the failure times for all fluid tests of the two machines, including the two height comparisons. The linear regression fit of the data points were very good with R = 0.996. The failure times of the two machines conformed to a nearly one-to-one correlation with a bias of less than 1 minute.

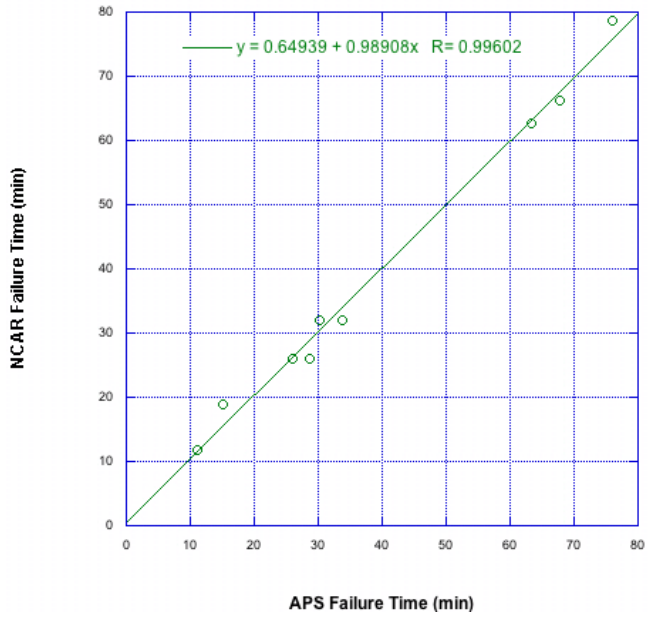

Figure 30. Scatter Plot of all APS vs NCAR Snow Machines Fluid Failure Times

Another observation made during the height comparison was the difficulty in obtaining a good distribution, with 20% deviation from the average snow fall over the plate, for the shorter height of the APS snow machine. This is likely due to the snow having a shorter distance to fall before hitting the plate, giving the air jets less time to randomize the distribution. Installing the air jets in different locations in the snow machine may alleviate this problem.

In conclusion, the comparison showed that the calibration drifted very little over time between the two machines. The NCAR machine was run in its current configuration for several years with the majority of the upgrades to the machine completed before 2006. The high correlation between the upgraded APS machine and the older NCAR machine suggests the calibration is very robust and experiments with one machine should be easily reproducible with very similar results with the other machine.

7. REFERENCES.

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