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Endurance Time Testing Using the NCAR Snow Machine: Reconciliation of Outdoor and Indoor Tests of Type IV Fluids

October 2003

Final Report

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16. Abstract

This report summarizes the progress made in determining the causes for the shorter fluid endurance times of anti-icing fluids for the National Center for Atmospheric Research (NCAR) snow machine compared to outdoor natural tests. The report also sought to determine if a correlation exists between the NCAR snow machine tests and the natural snow tests for the same anti-icing fluids. Outdoor tests were conducted by Aviation Planning Services (APS) and NCAR during the winter of 2000/2001 using several Type IV fluids in which the snowfall rate, plate temperature, and air temperature were recorded every 6 seconds. Using the parameters recorded for the outdoor tests, snow machine tests were conducted for each of the outdoor tests and a comparison between the outdoor and indoor tests was made.

The results showed that the fluids of the indoor snow machine tests consistently fail more quickly than the equivalent outdoor tests. A correlation analysis of the outdoor to indoor data for the NCAR outdoor tests showed a high correlation (0.99), but a 10-minute lower bias for the NCAR snow machine. A similar correlation analysis for the APS outdoor tests with the NCAR indoor tests showed a correlation of 0.89 and a 25% shorter time for the snow machine tests. These results suggest that there is high correlation of the NCAR snow machine results to the outdoor tests, but with a consistent low bias. To evaluate this further, outdoor tests were also conducted inside a wind shield. These results also showed a high correlation, with little to no bias. This suggests that the main cause for the low bias is due to wind effects.

A consistent result of this study was the higher plate temperature for the outdoor tests exposed to the wind compared to the indoor test without wind exposure. A lower plate temperature will change fluid properties, such as viscosity and surface tension, and therefore, affect its flow-off behavior and, consequently, its endurance time. Previous tests have shown that most fluids show longer endurance times for warmer plate temperatures, and thus shorter endurance times observed for the NCAR snow machine are to be expected due to the lower plate temperatures achieved. To reduce the bias, it was suggested to run the indoor snow machine tests at a constant plate temperature simulating the heating affects of the wind. Preliminary results from APS, University of Quebec at Chicoutimi, (UQAC), and NCAR all show much better agreement with the outdoor testing if this constant plate temperature procedure is used.

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EXECUTIVE SUMMARY

This report summarizes the progress made in determining the causes for the shorter fluid endurance times of anti-icing fluids for the National Center for Atmospheric Research (NCAR) snow machine compared to outdoor natural tests. The report also sought to determine if a correlation exists between the NCAR snow machine tests and the natural snow tests for the same anti-icing fluids. Outdoor tests were conducted by Aviation Planning Services (APS) and NCAR during the winter of 2000/2001 using Type IV fluids: Ultra+, Kilfrost ABC-S, and SPCA AD-480 in which the snowfall rate, plate temperature, and air temperature were recorded every 6 seconds. Identical fluids were provided to each laboratory. Using the parameters recorded for the outdoor tests, snow machine tests were run for each of the outdoor tests and a comparison between the outdoor and indoor tests was made. The results showed that the indoor snow machine tests consistently fail more quickly than the equivalent outdoor tests. A correlation analysis of the outdoor to indoor data for the NCAR outdoor tests showed a high correlation (0.99), but a 10-minute lower bias for the NCAR snow machine. A similar correlation analysis for the APS outdoor tests with the NCAR indoor tests showed a correlation of 0.89 and a 25% shorter time for the snow machine tests. These results suggest that there is high correlation of the NCAR snow machine results to the outdoor tests, but with a consistent low bias. To evaluate this further, outdoor tests were also conducted inside a wind shield. These results also showed a high correlation, with little to no bias. This suggests that the main cause for the low bias is due to wind effects.

A consistent result of this study was the higher plate temperature for the outdoor tests exposed to the wind compared to the indoor test without wind exposure. A lower plate temperature will change fluid properties, such as viscosity and surface tension, and therefore, affect its flow-off behavior and, consequently, its endurance time. Previous tests have shown that most fluids show longer endurance times for warmer plate temperatures, and thus shorter endurance times observed for the NCAR snow machine are to be expected due to the lower plate temperatures achieved. To reduce the bias, it was suggested to run the indoor snow machine tests at a constant plate temperature simulating the heating affects of the wind. Preliminary results from APS, University of Quebec at Chicoutimi, and NCAR all show much better agreement with the outdoor testing if this procedure is used.

Additional findings from this study are as follows:

1. The time variation of the snowfall rate plays an important role in determining the endurance time of a fluid, with high rates at the beginning of a test having the most impact. This means that the endurance time of a fluid with a variable snowfall rate does not equal the endurance time determined with the equivalent mean rate.

2. The good correlation of the snow machine times to outdoor times suggests that the current variation of ±10%-25% in the horizontal distribution produced by the snow machine may not significantly affect the endurance time of the fluids.

INTRODUCTION

This report summarizes the progress made in determining the causes for the shorter fluid endurance times of anti-icing fluids for the National Center for Atmospheric Research (NCAR) snow machine when compared to outdoor natural snow tests and to determine if a correlation exists between the NCAR snow machine tests and the natural outdoor snow tests for the same anti-icing fluids.

COMPARISON OF OUTDOOR TO INDOOR SNOW MACHINE TESTS

Previous tests by Aviation Planning Services (APS) and NCAR have both shown that the NCAR snow machine produces fluid endurance times 20% to 50% shorter than observed in outdoor tests. To help resolve the cause for this shorter time, a procedure was devised to conduct indoor tests with the same temperature and snowfall rate as the outdoor tests. The procedure was agreed to during a conference call with APS, University of Quebec at Chicoutimi (UQAC), and NCAR and is given below.

OUTDOOR SNOW TEST PROCEDURE WITH THE NCAR FROSTICATOR PLATE ASSEMBLY (FROSTICATOR PLATE ATTACHED TO A BUCKET ASSEMBLY TO CATCH THE FLUID) AND FROSTICATOR PLATE.

The assembly is placed on top of a mass balance, and the digital output of the mass balance recorded on a computer during snow events. For each test:

1. One liter of fluid is used, with no wait time. The fluids are stored outdoors.
2. Fluid temperature is measured before application.
3. Initial and final Brix of the fluid is measured at the 6″ line.
4. During the test, the following quantities are recorded on the computer every 6 seconds:
    - Air temperature
    - Plate temperature at the 6″ line
    - Snow mass accumulation
5. Wind speed and direction at the 10-meter level are recorded every minute.
6. The condition of the plate are photographed at failure and 5 minutes after failure

The following Type IV fluids were used: Ultra+, Kilfrost ABC-S, and SPCA AD-480. Each lab was provided fluid from the same production run to intercompare outdoor tests between labs (UQAC, APS, and NCAR). The frosticator plate was pointed into the wind at the beginning of the experiment. UQAC performed similar testing except without the NCAR frosticator plate assembly and without pointing the plate into the wind. The outdoor configuration of the tray assembly is shown in figure 1.

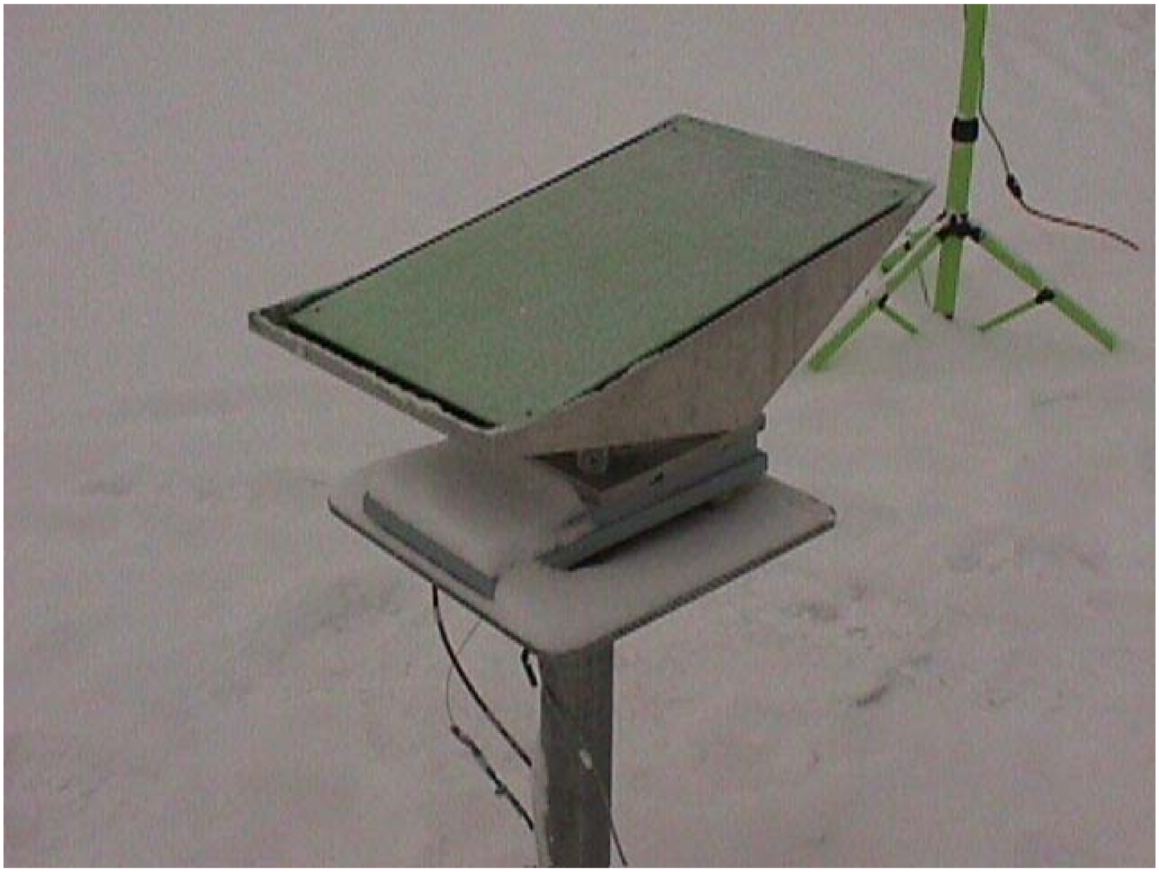

FIGURE 1. NATIONAL CENTER FOR ATMOSPHERIC RESEARCH TRAY ASSEMBLY IN THE OUTDOOR CONFIGURATION

INDOOR TESTING PERFORMED WITH THE NCAR SNOW MACHINE USING THE DATA FROM THE OUTDOOR TESTS.

To eliminate variables, the following outdoor conditions were duplicated for each outdoor test run indoors:

1. Initial fluid temperature
2. Air temperature during the test
3. Snow accumulation rate on the plate

The snow accumulation rate was maintained using a new program designed to produce the same snowfall rate with the NCAR snow machine as actually observed during the outdoor tests. The outdoor mass accumulation file is entered into the snow machine computer, which then uses this data to control the snowfall rate produced by the machine. An example of this rate matching is shown in figure 2.

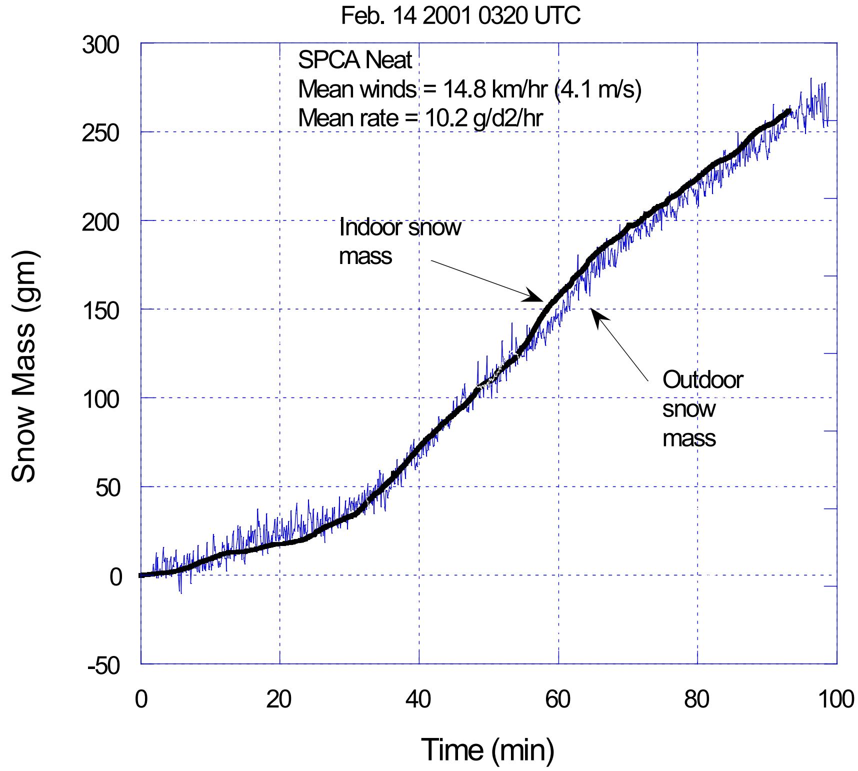

FIGURE 2. EXAMPLE OF INDOOR SNOW MACHINE MATCHING THE OUTDOOR ACCUMULATION RATE
(The solid black curve is the indoor rate and blue line is the outdoor rate.)

In addition, tests were conducted with a constant rate equal to the average rate during the period of the test. The air temperature was maintained manually by controlling a thermostat in the cold room. Accuracy of the air temperature was typically within 0.5ºC of the outdoor measured temperature.

An example of an outdoor test is given in figure 3.

The mass accumulation during the test initially showed a high rate of accumulation until 20 minutes, followed by a low accumulation rate until 60 minutes, and then a higher accumulation rate from 60 minutes to the end of the test. The plate temperature curve follows this trend as well. For instance, during the first 20 minutes, the plate temperature decreases rapidly in response to the high snowfall accumulation. During the low accumulation period between 20 and 60 minutes, the plate temperature levels out to -7°C in response to the low snow accumulation rate and associated low latent heat cooling of the plate. When the rate increases after 60 minutes, the plate temperature drops dramatically to -9°C in association with strong latent heat cooling of the plate. After 70 minutes, the fluid is not able to absorb snow into the fluid, and thus the plate temperature stops dropping and instead starts to slowly increase. Fluid failure occurs when the snow has accumulated over 1/3 of the plate, which in this case takes an additional 45 minutes due to the low rate for this case (6.9 $g/d^2/hr$).

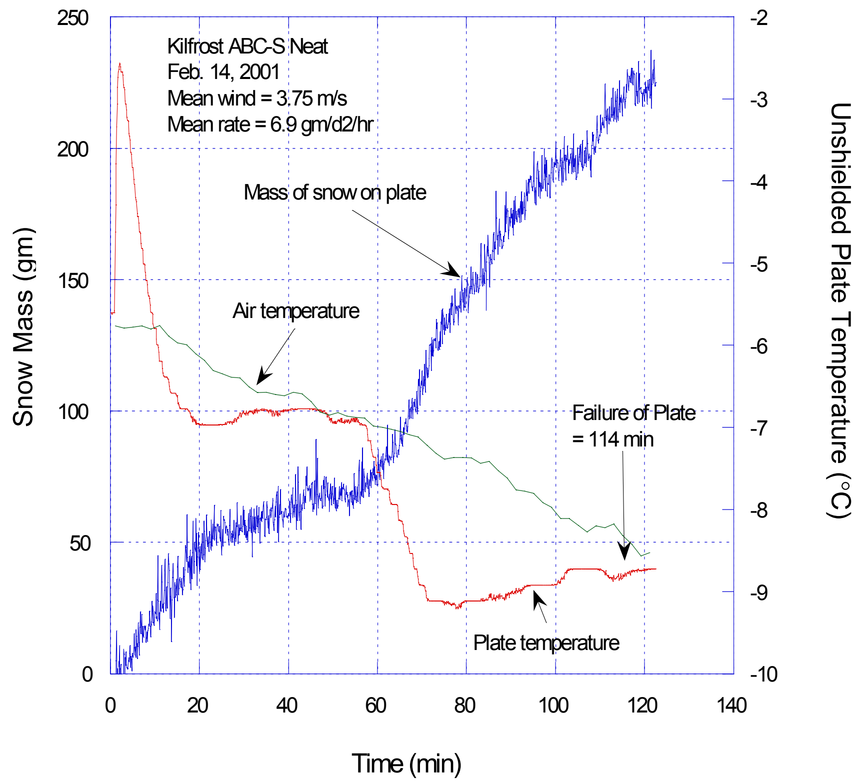

FIGURE 3. EXAMPLE OF AN OUTDOOR SNOW TEST

A summary of the NCAR outdoor and indoor tests is given in table 1.

TABLE 1. COMPARISON OF NCAR OUTDOOR AND INDOOR SNOW MACHINE FLUID ENDURANCE TESTS

Winter 2000/2001	NCAR Tests		1 Liter of fluid applied, no wait										
			Endurance Time (min)				Aver. Snow rate (g/d²/hr)	Aver. Wind Speed		Temp. (°C)	Brix		
			Outdoor		Indoor						Out		In
Date	Fluid	%	Tray	Shield	Actual	Constant		km/hr	m/s		Tray	Shield	
1/16/2001	SPCA	neat	52	46	40	41	12.01	6.5	1.8	-6.1	19.8	20	18.8
1/16/2001	SPCA	neat	160	-	153	137	4.75	3.2	0.9	-5.2	15.0	-	14.0
1/16/2001	SPCA	neat	72	69	61	61	9.63	8.7	2.4	-7.6	19.0	18.8	18.0
1/16/2001	Ultra+	neat	155	140	138	112	4.73	4.1	1.1	-8.4	17.3	-	17.5
2/9/2001	Kilfrost	neat	215	-	-	-	1.41	5.8	1.6	-14.		-	
2/14/2001	Kilfrost	75/25	75	63	62	64	3.39	9.0	2.5	-9.8	19.3	19.5	19.0
2/14/2001	SPCA	neat	89	82	62	53	10.2	14.8	4.1	-4.2	12.8	12.5	14.8
2/14/2001	Kilfrost	neat	113	95	101	92	6.88	13.2	3.7	-7.1	16.3	16.2	18.8
					500 L of fluid								
12/10/2000	Kilfrost	neat	0:17				39.44						
12/10/2000	Kilfrost	neat	0:39		29.8		19.44						22

The APS outdoor tests and endurance times from the NCAR indoor tests simulating the APS outdoor tests are given in table 2.

TABLE 2. COMPARISON OF APS OUTDOOR WITH NCAR INDOOR SNOW MACHINE FLUID ENDURANCE TESTS

APS outdoor NCAR indoor Date	Fluid	Dilution	Endurance Time (min)			Aver. Rate ($g/d^2/hr$)	Aver. Wind Speed		Aver. Air Temp. (°C)	Brix	
			Outdoor	NCAR Indoor							
				Actual	Constant		Km/hr	M/s		Out	Indoor
05Feb1043AM	Ultra+	Neat	49.5	-	-	14.9	9	2.5	-6.8		
14Feb1146AM	SPCA	Neat	111.3	90.6	81.1	7.9	5	1.4	-6.2	12	18
14Feb0209PM	Kilfrost	Neat	82.5	47.5	50.3	12.8	2	.56	-5.3	12	19
14Feb0834PM	SPCA	75/25	78.5	40.9	51.5	8.3	4	1.1	-3.7	12	15
23Feb0118AM	Kilfrost	Neat	103	-	83.3	2.5	12	3.3	-16.5	-	
23Feb0401AM	SPCA	Neat	96.8	-	-	1.1	10	2.8	-16.3		
25Feb0622AM	SPCA	75/25	62.3	41.6	26.0	10.2	12	3.3	-9.7	6	19
25Feb0815AM	Ultra+	Neat	32.2	28.8	21.1	29.2	13	3.6	-7.9	14	17
13Mar0336AM	Kilfrost	75/25	59	50.0	44.9	6.6	13	3.6	-6.6	16	16.3
13Mar0506AM	SPCA	Neat	40.5	31.0	21.5	22.8	16	4.4	-6.1	16	20.3
13Mar0605AM	SPCA	75/25	34.5	24.3	28.8	13.6	16	4.4	-6.0	16	17.3

OUTDOOR AND INDOOR SNOW MACHINE TEST COMPARISONS.

The comparison between the outdoor and indoor test runs for both the NCAR and APS outdoor tests all showed that the indoor test endurance times are shorter than the outdoor tests. In most cases, the constant rate test was shorter than the actual rate test. In the following, detailed results for specific tests are presented to understand these results further.

CASE 1—SPCA NEAT TEST. Figure 4 shows the snow mass accumulation and plate temperature at the 6″ line for the 13Mar01 0506AM APS outdoor test (see table 2 for other details of the test). Note that the indoor snow mass accumulation followed the outdoor accumulation well. The average rate during the test was 22.8 g/d2/hr, and is fairly constant over the period. The indoor fail time was 31 minutes, while the outdoor fail time was 40 minutes. The indoor and outdoor plate temperatures follow each other well until 5 minutes, at which time the outdoor plate temperature stops decreasing and becomes nearly constant, while the indoor temperature continues to decrease until 25 minutes, at which point it starts to increase. The indoor fluid is significantly colder than the outdoor fluid over the duration of the test, reaching a maximum difference at the 25-minute mark (over 3°C cooler). The most likely reason for this behavior is the relatively high wind speed (5.3 m/s) during this test. As a result of the wind, the outdoor plate will warm to the ambient temperature of -6.1°C more rapidly than the indoor plate, which is in nearly calm conditions. It was hypothesized that the reason for the shorter hold time for the indoor test is the colder fluid temperature. Most fluids (except Ultra+) have shorter hold times for colder temperatures. Fluid characteristics affected by the temperature are viscosity, surface tension, and density. It was hypothesized that changes to these quantities due to temperature variations cause more rapid runoff of the fluid and, therefore, less glycol on the plate. Less glycol results in shorter endurance times (snow absorption decreases with a decrease in glycol content). The final Brix of the outdoor fluid was 16, while the indoor fluid final Brix was 20.25. Thus, a secondary factor may have been a discrepancy between failure calls.

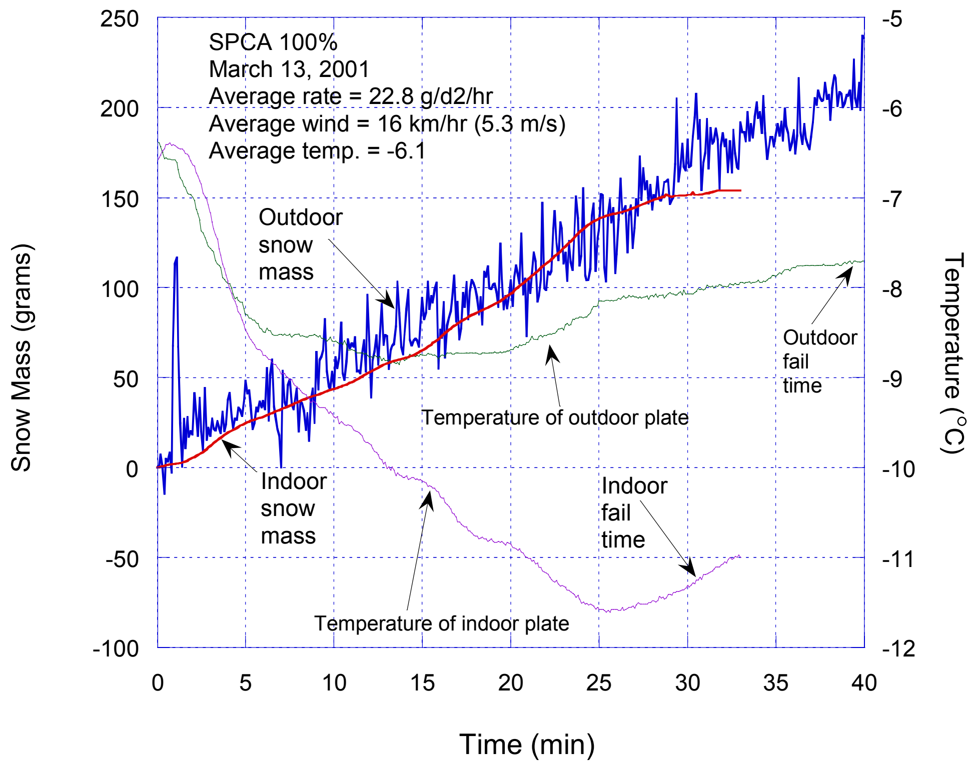

FIGURE 4. COMPARISON OF SNOW MASS AND PLATE TEMPERATURE TIME SERIES FROM THE APS OUTDOOR TEST ON 13MAR01 0506AM USING SPCA NEAT FLUID

CASE 2—SPCA 75/25 FLUID. The average rate for the APS outdoor test presented in figure 5 was 13.6 g/d2/hr. The initial rate, however, was higher during the first 10 minutes of the test. The temperature of the indoor plate decreased from -6° down to -10ºC during this period due to the latent heat released during snow melting. However, the outdoor plate temperature only decreased 1.5ºC from -6.5º to -8.0ºC. The outdoor plate temperature trace flattened out after only 5 minutes, while the indoor trace cooled an additional 2ºC between 5 and 10 minutes. Again, the most likely reason for this behavior is the relatively high wind speed (5.3 m/s) during this test. As a result of the wind, the outdoor plate will warm to the ambient temperature of -6.0ºC more rapidly than the indoor plate, which is in nearly calm conditions. The outdoor failure is longer than the indoor failure in this case (34 minutes versus 25 minutes). This case supports the hypothesis put forward for case 1 that the colder fluid temperature leads to shorter endurance times. In this case, the final Brix for the outdoor fluid test was 16, while the indoor fluid test had a value of 17.25. Thus, the failure call was not a factor in this comparison.

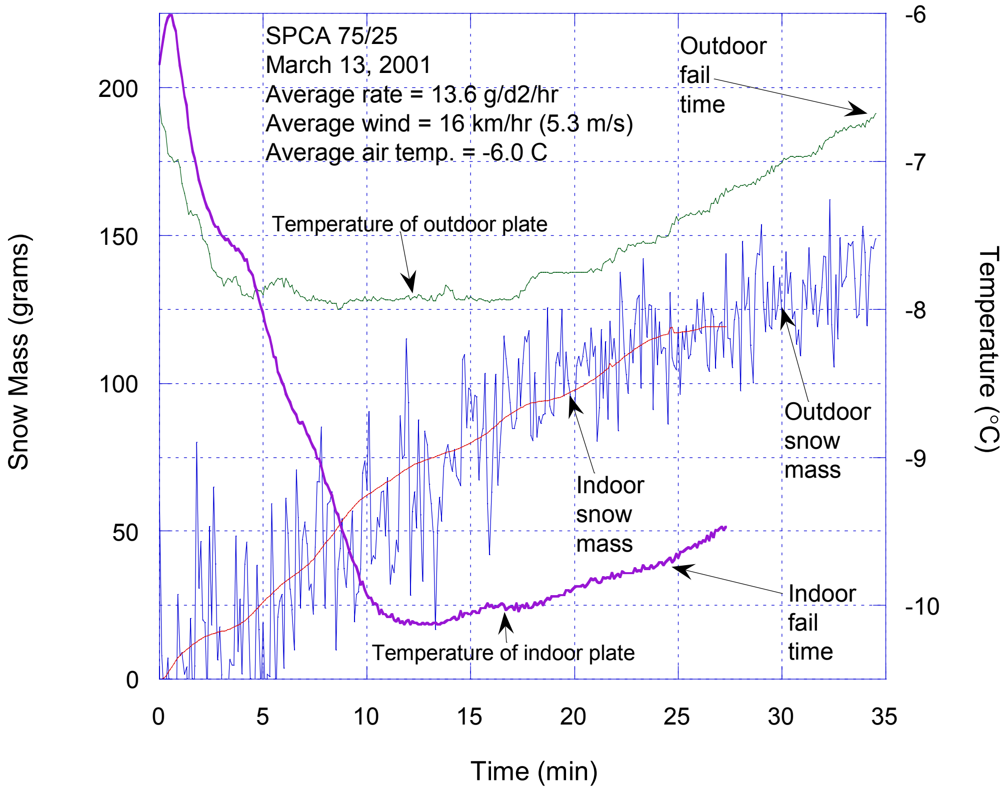

FIGURE 5. COMPARISON OF SNOW MASS AND PLATE TEMPERATURE TIME SERIES FROM THE APS OUTDOOR TEST ON 13MAR01 0605AM USING SPCA 75/25 FLUID

<u>CASE 3—ULTRA+ NEAT TEST</u>. In this case (figure 6), the endurance time for the Ultra+ fluid indoors is within 7 minutes of the outdoor failure (25 minutes indoors versus 32 minutes outdoors) despite a significant temperature difference between the outdoor and indoor fluids. Again, this temperature difference is likely due to the high wind speed (4.3 m/s) during this test, warming the outdoor plate more than the indoor plate. Since the viscosity of Ultra+ increases with decreasing temperature, one might assume that the indoor test should last longer due to more fluid staying on the plate. However, the indoor fluid experiences more shear (since it is not pushed up the plate as in the outdoor test with strong wind), which would lead to a lower viscosity. These two effects may nearly cancel each other out for the indoor test, resulting in a fluid viscosity and runoff similar to the outdoor test. A small difference in endurance time would occur in this case. This hypothesis needs to be further tested, however, to verify this behavior.

The final Brix for the outdoor test was 14, while the indoor test had a final Brix of 17. Thus, the discrepancy in failure times may also be due to a difference in failure call.

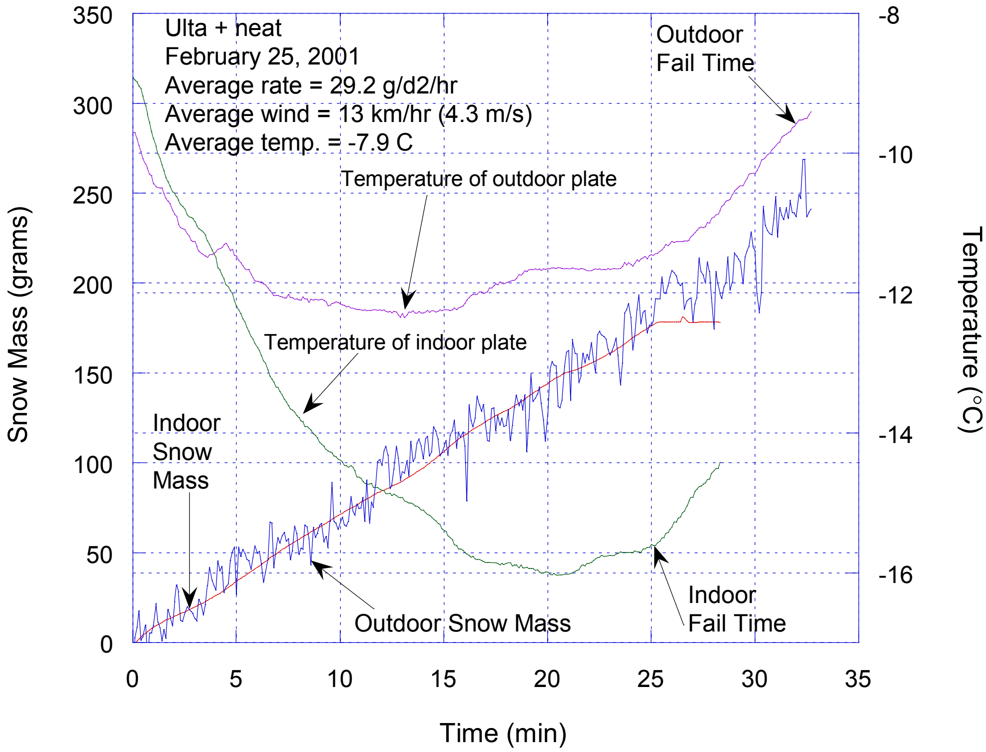

FIGURE 6. COMPARISON OF SNOW MASS AND PLATE TEMPERATURE TIME SERIES FROM THE APS OUTDOOR TEST ON 25FEB01 0815AM USING ULTRA+ NEAT FLUID

CASE 4—ULTRA+ NEAT TEST. In this case (figure 7), the indoor test fails 17 minutes prior to the outdoor test. The indoor test with Ultra+ has a warmer temperature between 20 and 60 minutes. Since Ultra+ viscosity decreases with increasing temperature (in contrast to most other fluids), more fluid would runoff the plate for the indoor test compared to the outdoor test, potentially causing the shorter failure time with the snow machine. The reason for the higher temperatures was the lower rate indoors compared to the outdoor rate during this time period. After 60 minutes, the indoor and outdoor plate temperatures track well. This case is also consistent with the concept that fluid viscosity changes due to plate temperature variations are affecting the fluid runoff and, consequently, the fluid endurance time.

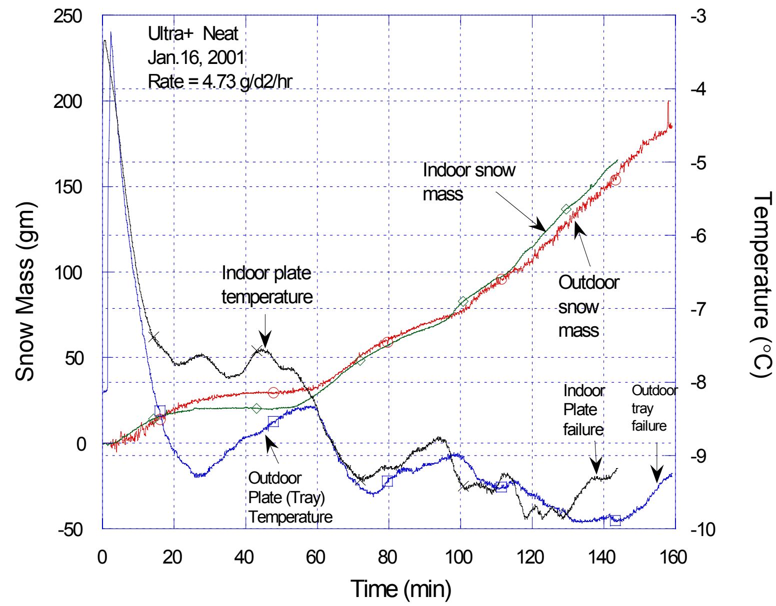

FIGURE 7. ULTRA+ NEAT OUTDOOR AND INDOOR TEST COMPARISON (16JAN01 1106AM)

CASE 5—SPCA NEAT. In this case (figure 8), the indoor fluid failed 11 minutes prior to the outdoor fluid. This is due to the higher plate temperature in the outdoor test, leading to less runoff of the fluid. Wind effects on the plate temperature are clearly evident in this case (3.1 m/s average wind speed).

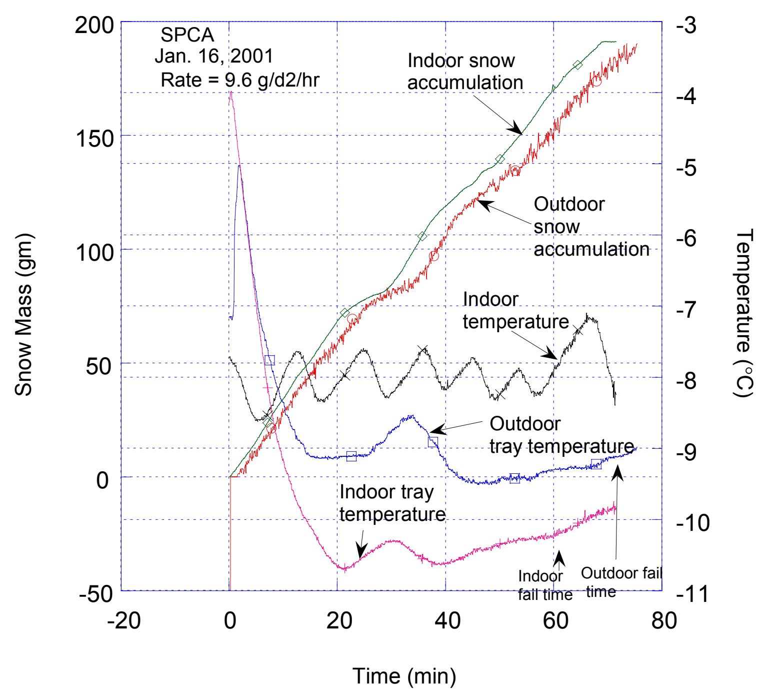

FIGURE 8. SPCA NEAT OUTDOOR AND INDOOR TEST COMPARISON (16JAN01 0939AM)

Figures 9 through 15 present further comparisons of the outdoor to indoor results. These cases all show (1) the indoor failure to be shorter than the outdoor and (2) the plate temperature to be much warmer for the outdoor than the indoor tests. These results further confirm the results presented above regarding the importance of plate temperature in determining the endurance time of a fluid.

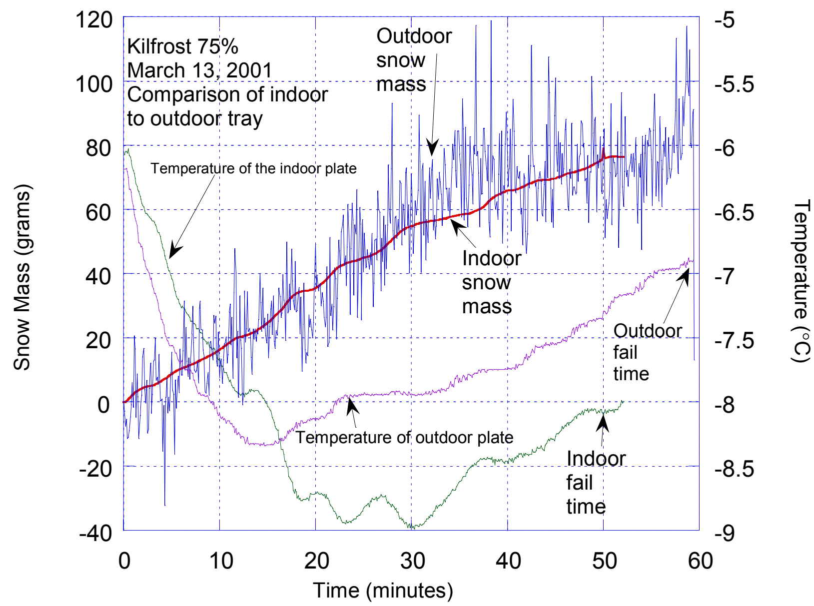

FIGURE 9. KILFROST 75/25 OUTDOOR AND INDOOR TEST COMPARISON (13MAR01 0336AM)

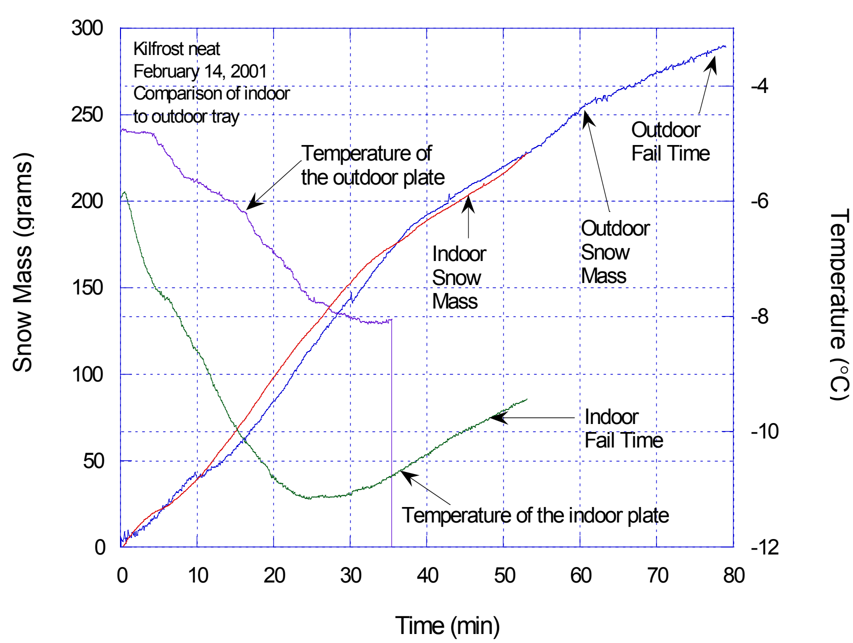

FIGURE 10. KILFROST NEAT OUTDOOR AND INDOOR TEST COMPARISON (14FEB01 0210PM)

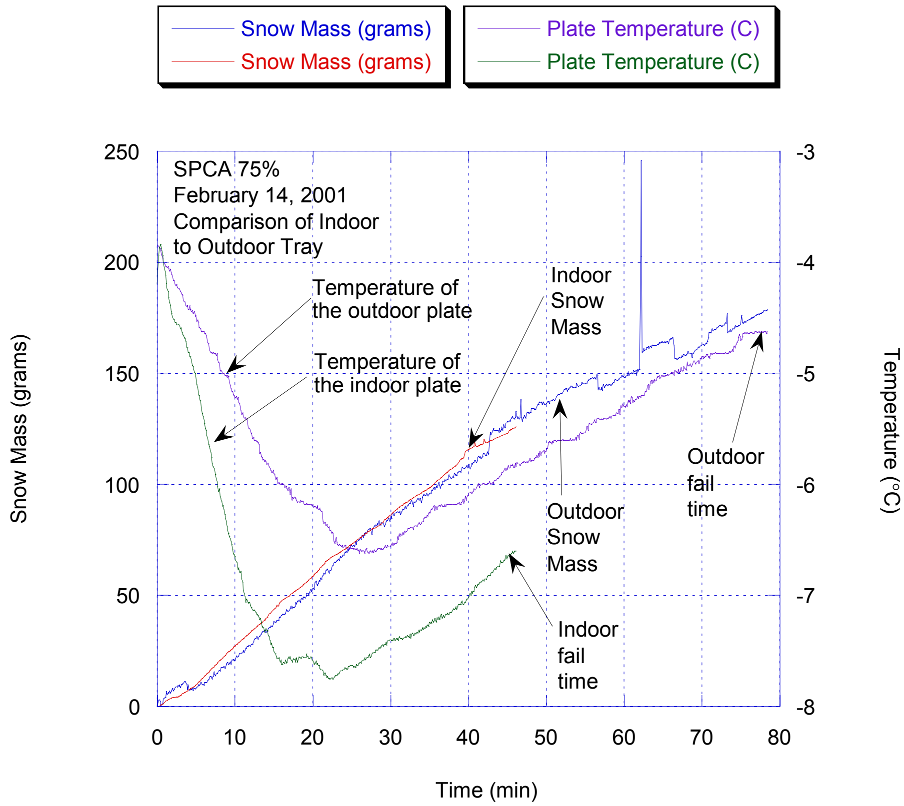

FIGURE 11. SPCA 75/25 OUTDOOR AND INDOOR TEST COMPARISON (14FEB01 0834PM)

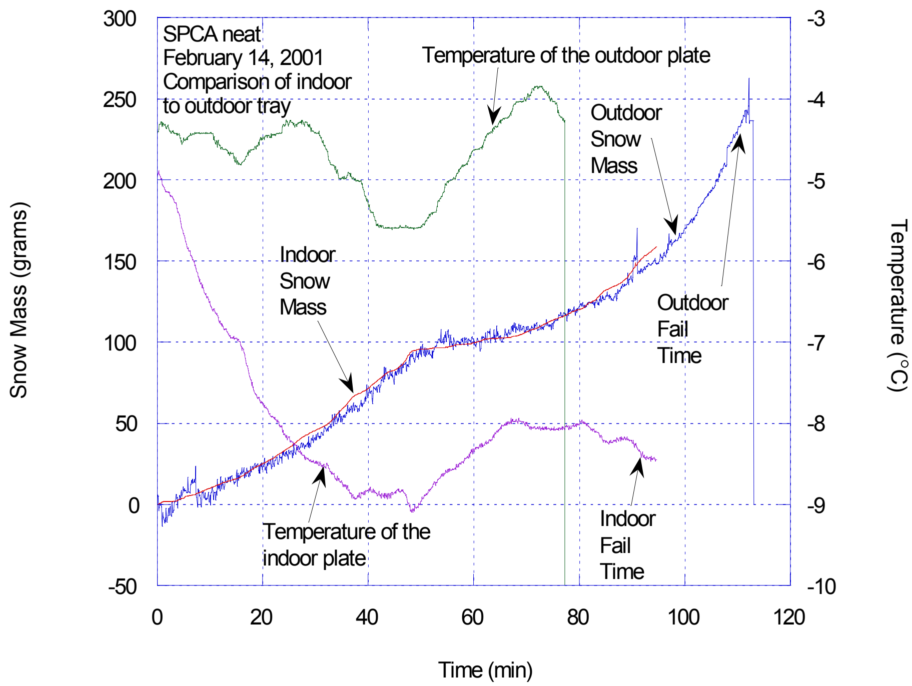

FIGURE 12. SPCA NEAT OUTDOOR AND INDOOR TEST COMPARISON (14FEB01 1147AM)

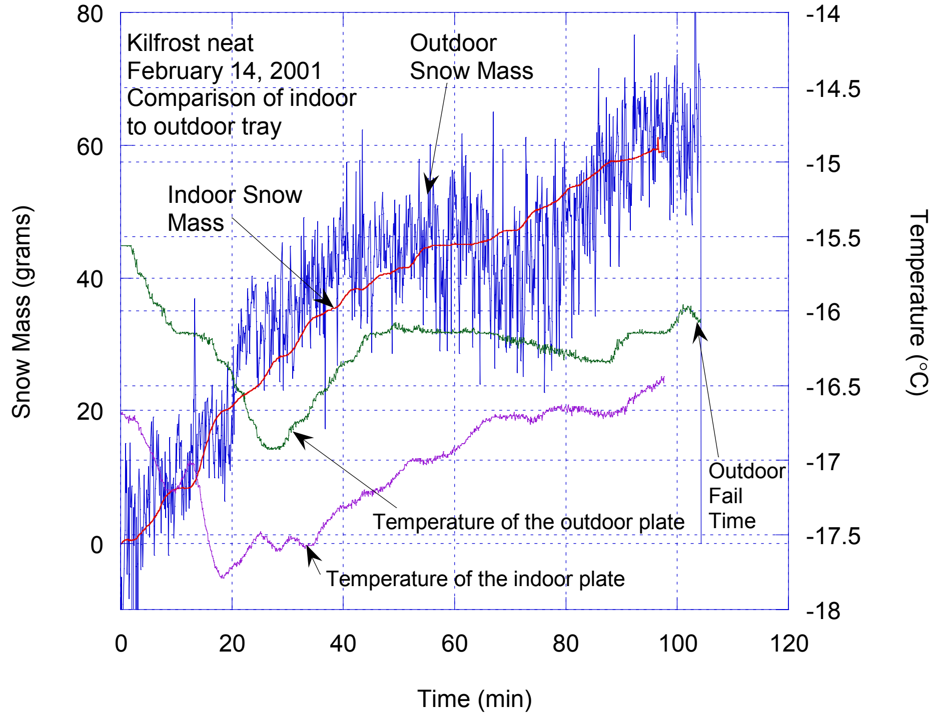

FIGURE 13. KILFROST NEAT OUTDOOR AND INDOOR TEST COMPARISON (23FEB01 0118PM)

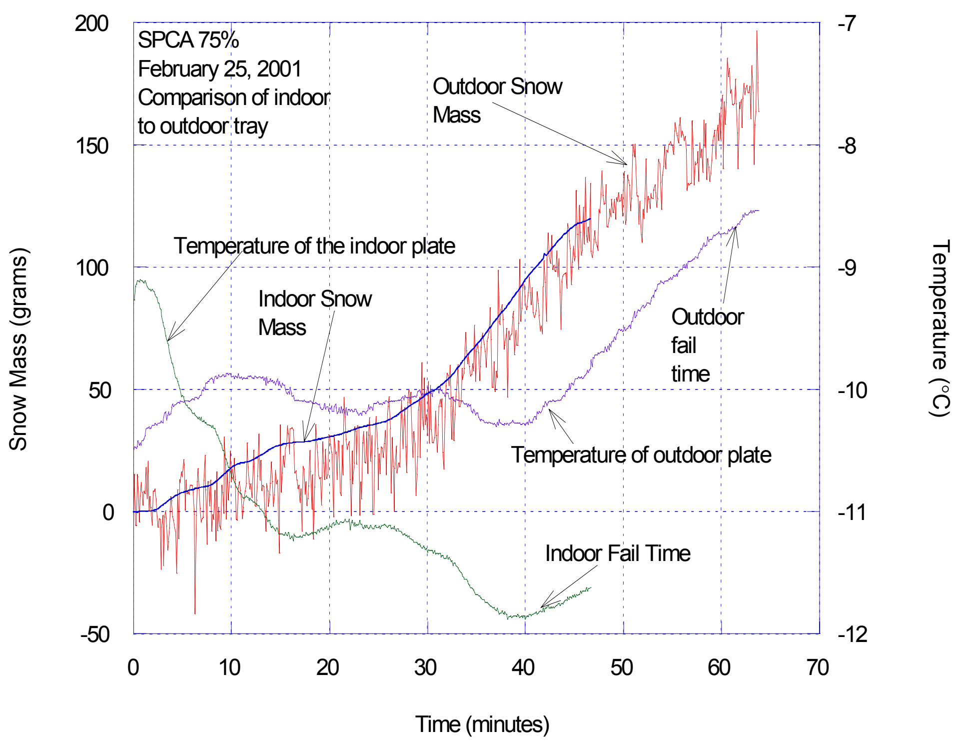

FIGURE 14. SPCA 75/25 OUTDOOR AND INDOOR TEST COMPARISON (23FEB01 0622AM)

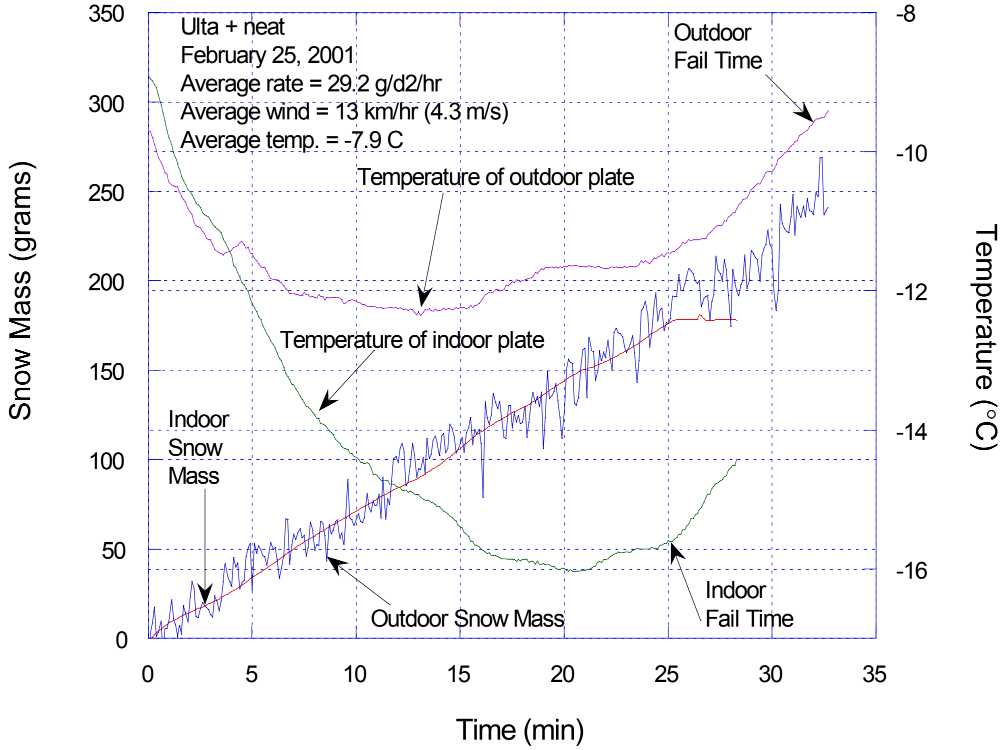

FIGURE 15. UTRA+ NEAT OUTDOOR AND INDOOR TEST COMPARISON (25FEB01 0815AM)

VARIABLE VERSUS LINEAR RATE TESTS WITH THE NCAR SNOW MACHINE BASED ON THE OUTDOOR TESTS.

The role of snowfall rate variability is examined in the following by simulating the outdoor tests with a constant rate and comparing to indoor tests using the actual measured rate.

CASE 6—SPCA 75/25, AVERAGE SNOWFALL RATE VERSUS ACTUAL SNOWFALL RATE. In figure 16, endurance time was compared using the average snowfall rate of 13.6 g/d2/hr versus the actual snowfall rate for the outdoor test presented in case 2. The outdoor rate is higher at the beginning of the test, leading to a colder temperature of the fluid and a more rapid failure (24 minutes) than the case with an average rate (28.8 min). Again, it was hypothesized that this is due to the colder fluid temperature achieved by the actual rate test compared to the constant rate. Since these are both indoor tests, wind is not a factor. Thus, the effect of plate temperature seems to be the cause of the differences in endurance times. The colder fluid most likely runs off the plate faster, leading to shorter endurance times. This test also shows using the mean average snowfall rate for a test does not necessarily represent the endurance time of a fluid experiencing a variable snowfall rate.

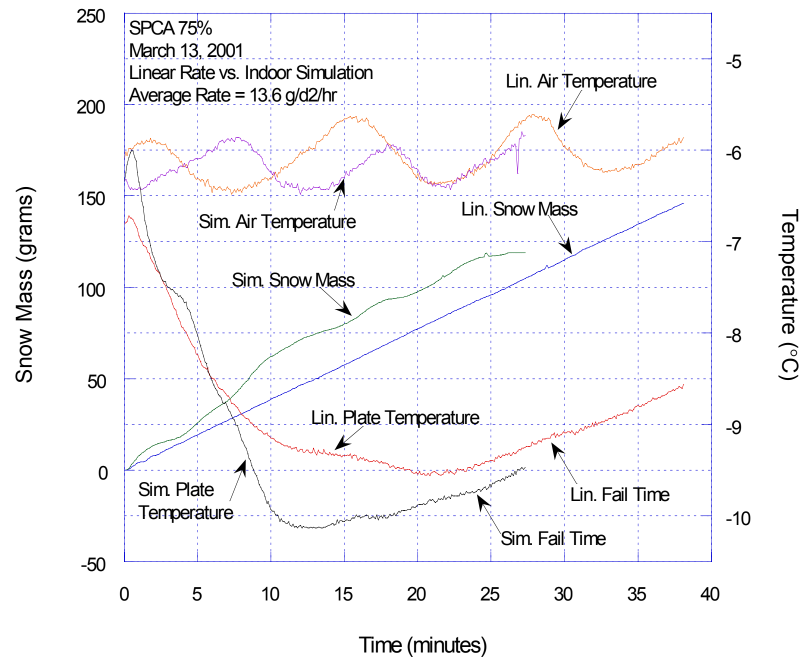

FIGURE 16. COMPARISON OF INDOOR TESTS USING THE AVERAGE SNOWFALL RATE AND THE ACTUAL SNOWFALL RATE FOR SPCA 75/25 13MAR01 0605AM TEST

<u>CASE 7—SPCA NEAT, LINEAR VERSUS VARIABLE RATE TEST</u>. This test (figure 17) shows that the initial high rate from the linear rate run results in a colder fluid and, therefore, a shorter endurance time compared to the variable rate test (both indoor tests). This is consistent with the results from case 10.

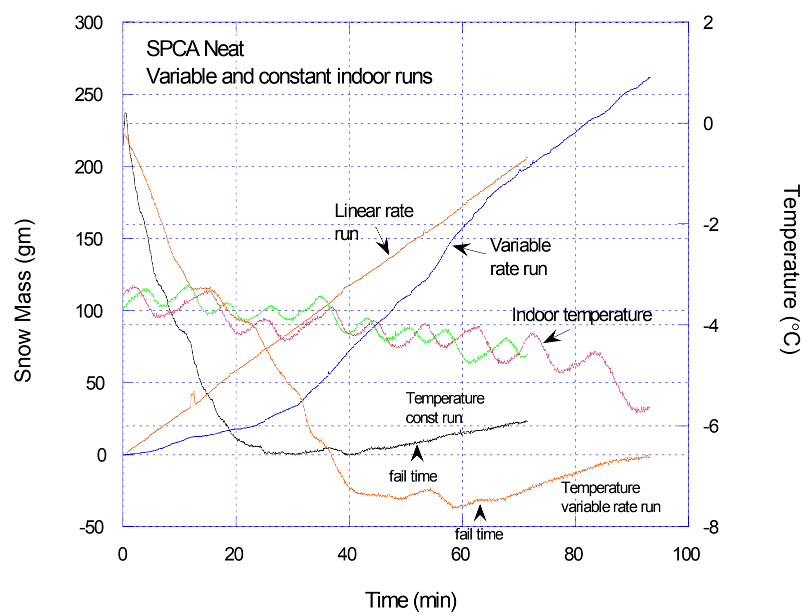

FIGURE 17. LINEAR VERSUS VARIABLE RATE TEST FOR SPCA NEAT (23MAY01 0717PM)

CASE 8—ULTRA +, LINEAR VERSUS VARIABLE RATE TEST (SNOW MACHINE). The variable rate in this test (figure 18) is the same as in case 4. The constant rate test fails first, most likely due to attaining a mass of 155 gm prior to the variable rate test (~30 minutes difference).

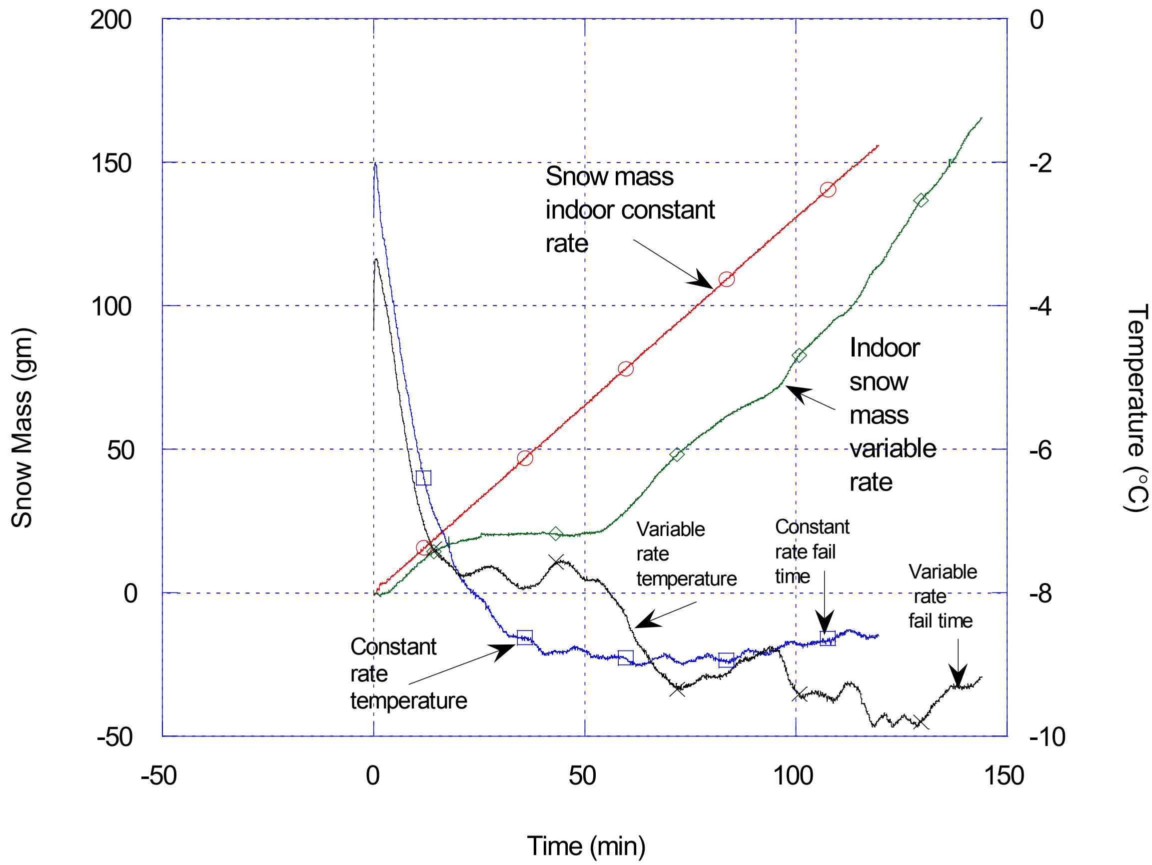

FIGURE 18. LINEAR VERSUS VARIABLE RATE TEST FOR ULTRA+
(Both tests with snow machine on 05Jun01 0840PM)

CASE 9—SPCA NEAT, LINEAR VERSUS VARIABLE RATE TEST (SNOW MACHINE). The variable and linear rate simulations using the snow machine agreed well (figure 19). Since the variable rate does not show large variations, this is reasonable. As a result of the small variability in the variable rate, the plate temperatures are within 1°C.

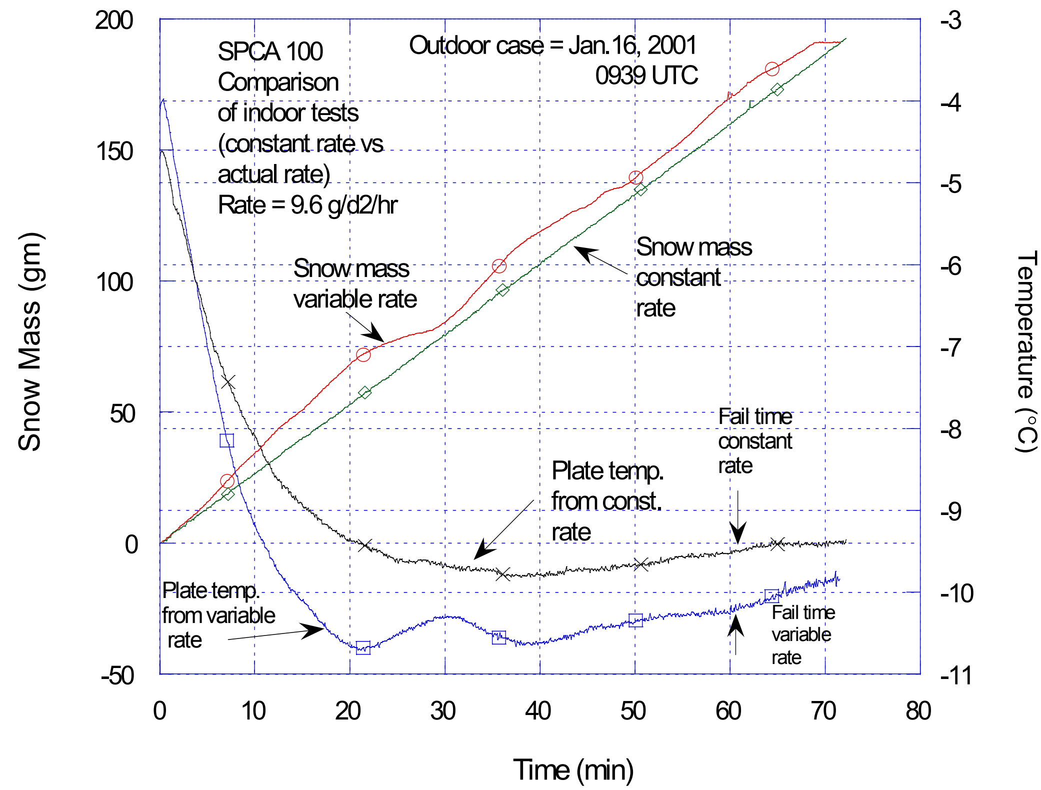

FIGURE 19. LINEAR VERSUS VARIABLE RATE TEST FOR SPCA NEAT
(Both tests conducted with the snow machine on 25Apr01 0514PM)

<u>CASE 10—SPCA NEAT, INDOOR TESTS—LINEAR VERSUS VARIABLE RATE</u>. In this case (figure 20), the linear rate is higher at the beginning of the test, causing the fluid temperature to decrease below the test with the variable outdoor rate. The test with the linear rate also fails before the variable rate test (40 minutes versus 52 minutes for the variable rate test), in contrast to case 6. The amount of snow mass accumulated at the time of failure for the linear case was 130 gm, while the variable rate had nearly 180 gm. Thus, the variable rate case was able to absorb 50 gm more snow than the linear case. This means that the linear rate had less glycol available to absorb the snow, which in turn means that more fluid flowed off the plate during the linear test than the variable rate test. It was hypothesized that the colder fluid temperature produced enhanced fluid runoff.

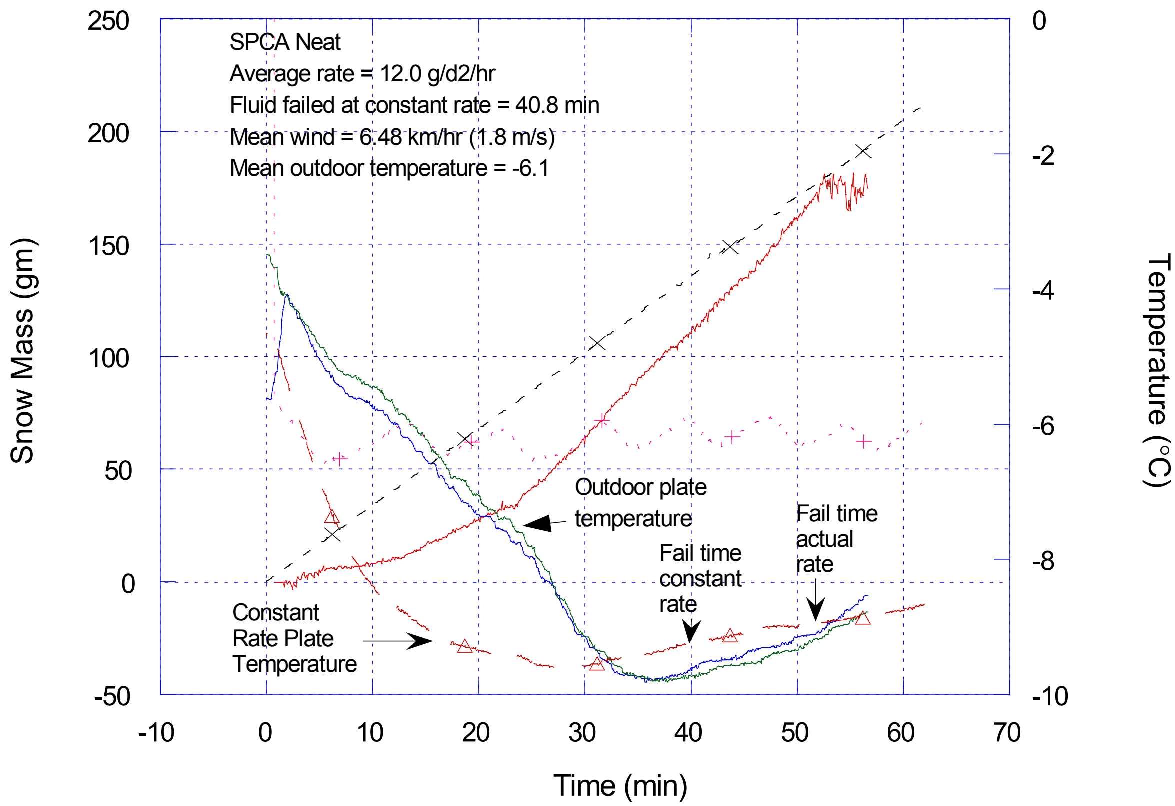

FIGURE 20. COMPARISON OF INDOOR TESTS USING THE AVERAGE SNOWFALL RATE AND THE ACTUAL SNOWFALL RATE FOR SPCA NEAT FLUID FROM 16JAN01 0820AM TEST

COMPARISON OF RESULTS FROM THE WIND SHIELDED, OUTDOOR FROSTICATOR PLATE WITHOUT A TRAY ASSEMBLY TO THE OUTDOOR FROSTICATOR PLATE EXPOSED TO THE WIND WITH A TRAY ASSEMBLY.

To further investigate the effect of wind on the endurance time, simultaneous frosticator tests were run outdoors, one with the frosticator plate attached to the tray assembly and exposed to the wind, and the other with a frosticator plate without a tray assembly but located in a Double Fence Intercomparison Reference (DFIR) wind shield, as shown in figure 21. The difference in endurance time for these tests is an indication of the effect of the wind on the failure of the fluid. In the following, the results of four outdoor tests are described.

FIGURE 21. PHOTOGRAPH OF THE DFIR WIND SHIELD WITHIN WHICH THE FROSTICATOR TEST ASSEMBLY WAS PLACED
(Plate positioned at the center of the shield next to the GEONOR snow gauge.)

Case 11—DFIR SHIELD PLATE FAILURES VERSUS WIND EXPOSURE PLATE FAILURES. In this case (figure 22), the plate in the DFIR shield fails after 82 minutes, while the tray assembly plate exposed to the wind fails in 89 minutes. The mass accumulation trace from the snow gauge located in the DFIR shield agreed well with the mass trace from the tray assembly. Thus, both trays experienced similar amounts and type of snow over the period. The endurance time from the tray in the shield is 7 minutes shorter than the plate outside the shield. The snow machine time is still 25% lower (62 minutes) than the tray in the shield, suggesting that wind effects are still evident with the frosticator plate in the wind shield. As shown, the wind speed for this event is relatively high (5 m/s) and, thus, wind effects inside the shield are likely (typically 50% of the ambient wind).

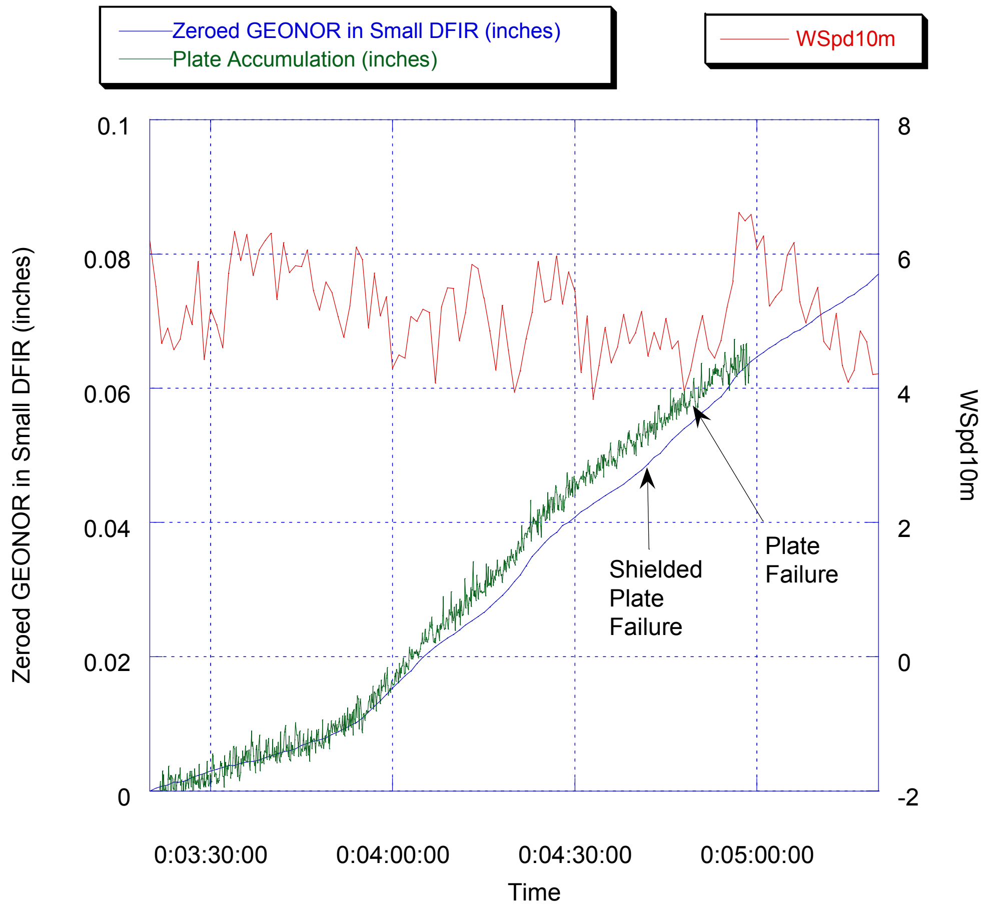

FIGURE 22. TIME SERIES OF MASS ACCUMULATION AND WIND SPEED FOR 14 FEBRUARY 2001 SPCA 100% OUTDOOR FLUID TESTS
(The mass accumulation from the GEONOR snow gauge is indicated by the solid, thin line and the tray assembly snow mass accumulation by the green, high-frequency line.)

The plate temperature trace shown in figure 23, however, shows little evidence of a wind effect, with both temperature traces tracking each other closely. This may be due to compensating factors. Previous testing has shown that the plate on the tray assembly is somewhat shielded from the wind due to the tray. Thus, its temperature will be slightly warmer than a free-standing frosticator plate. On the other hand, the wind in the shield is typically 50% less than the outside wind. Thus, the heating effect of the wind will be less on the plate in the shield. In this particular case, these two effects seem to cancel each other out, resulting in similar temperature traces. Despite the similar temperature traces, the endurance time of the fluid exposed to the higher wind speed was still longer, suggesting a wind effect other than temperature. The Brix at the end of the test for the plate on the tray and the plate in the shield was very similar (~12.5), suggesting that the failure call was not a factor. The Brix of the indoor test, however, was larger, suggesting that it was called too early, bringing the indoor endurance time in closer agreement to the outdoor test.

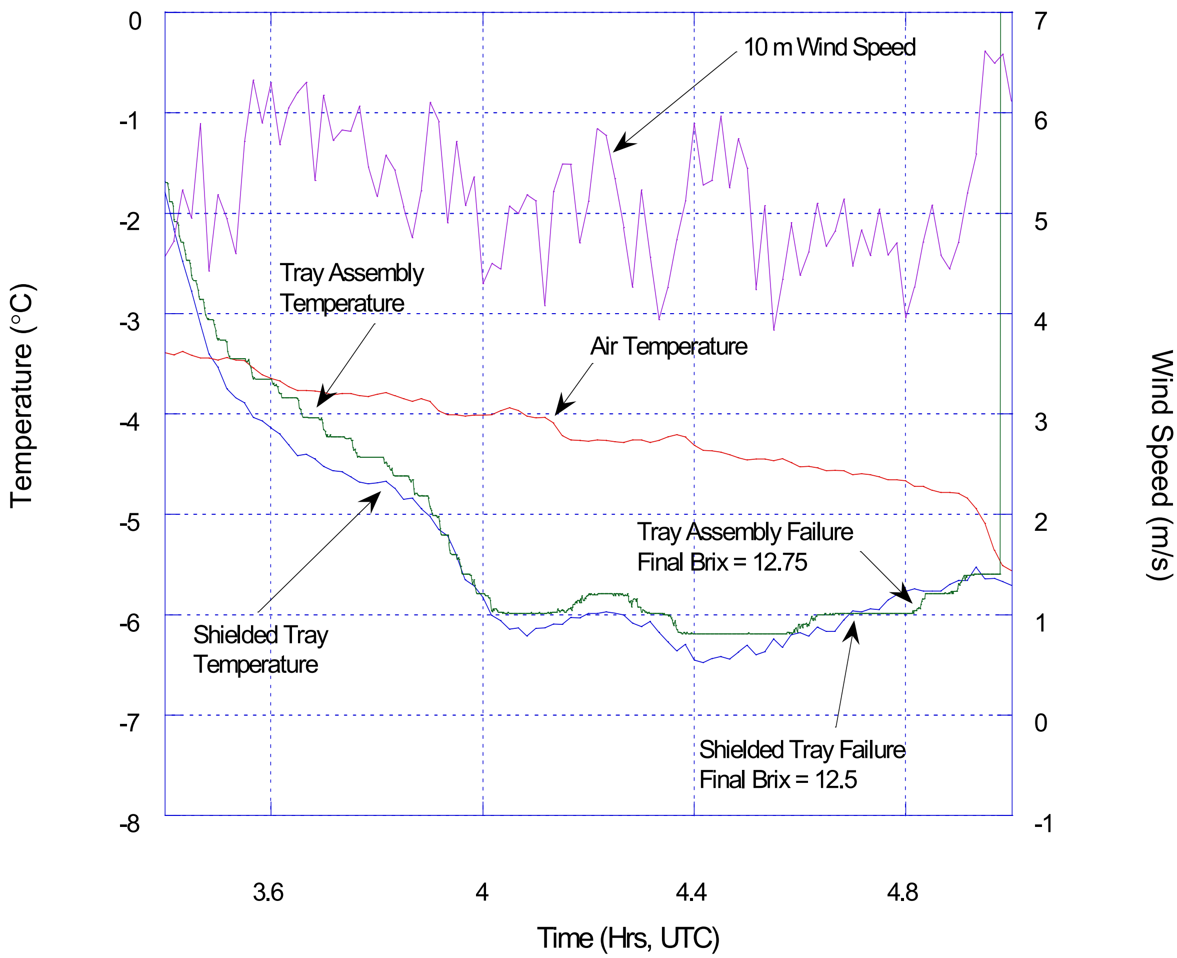

FIGURE 23. TIME SERIES OF AIR, PLATE IN THE SHIELD, AND PLATE ON THE TRAY TEMPERATURE FOR THE 100% SPCA TEST ON 14 FEBRUARY 2001

<u>CASE 12—FAILURES EMPLOYING GEONOR SNOW GAUGE</u>. The mass accumulation trace for the tray assembly and the GEONOR collocated with the free-standing plate in the shield agree well in this case (figure 24), giving evidence that both were exposed to the same snowfall rate. The shielded plate failed earlier (63 min) than the tray assembly plate exposed to the ambient wind (75 min). The indoor fail time (62 min) agrees well with the endurance time of the plate in the shield. This case had a lower wind speed (~ 3 m/s, figure 24) than the previous case, meaning that the wind inside the shield was ~ 1.5 m/s. This result suggests that the indoor snow machine may accurately simulate outdoor snow cases with winds less than 1.5 m/s.

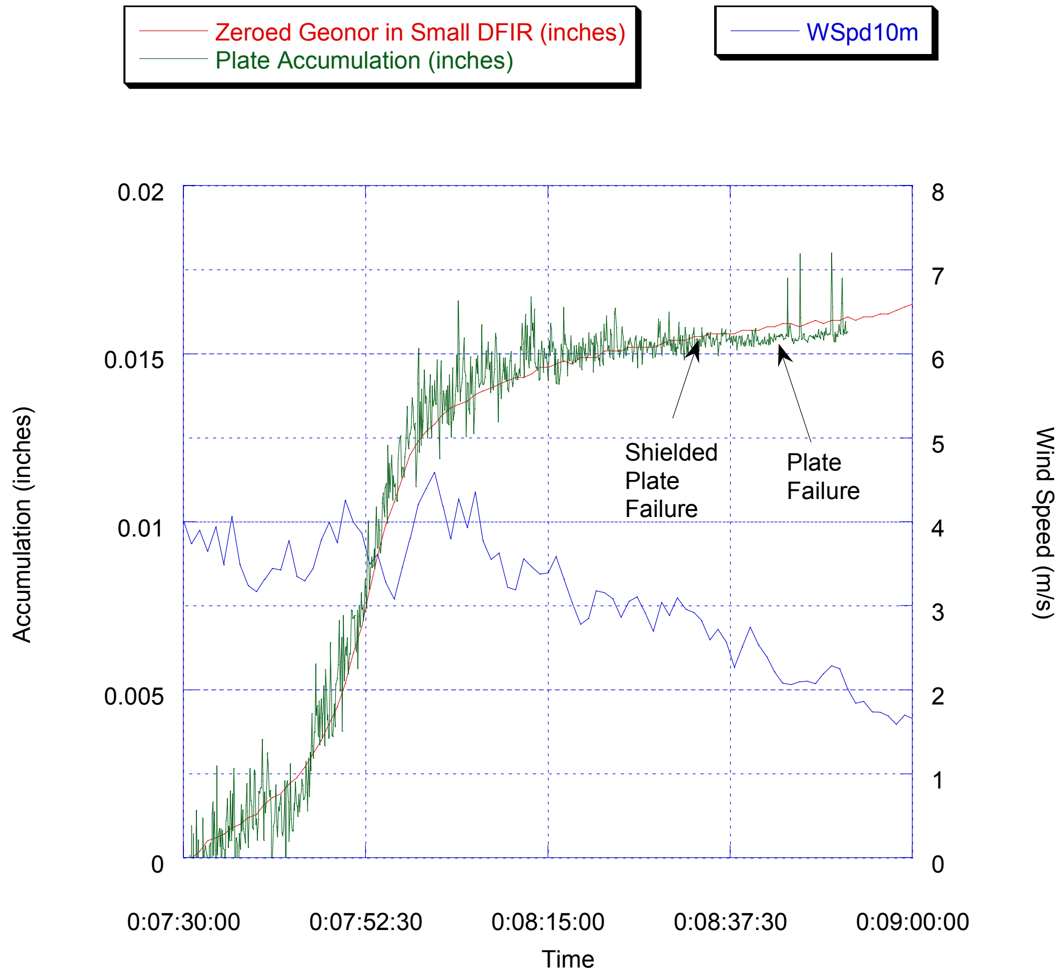

FIGURE 24. TIME SERIES OF MASS ACCUMULATION AND WIND SPEED FOR 14 FEBRUARY 2001 KILFROST 75/25 OUTDOOR FLUID TESTS
(The mass accumulation from the GEONOR snow gauge is indicated by the solid, thin line and the tray assembly snow mass accumulation by the green, high-frequency line.)

The temperature trace for the plate in the shield and the plate on the tray assembly exposed to the full ambient wind is shown in figure 25. Note again that the temperature traces agree well with each other, with the plate in the shield temperature ~ 0.5°C cooler than the outdoor plate. Again, this may be due to compensating effects, as discussed in the previous case. Since the temperature of the plates and snowfall rates are similar, other wind effects must be causing the larger endurance time for the plate on the tray assembly exposed to the wind. The final Brix for the two plates is nearly identical (~ 19.3), thus failure call is not an issue. The indoor Brix is also similar, and thus, the failure call of the plate in the shield and the indoor test were consistent. One factor in this case was the low rate at the very end, making an accurate failure call difficult.

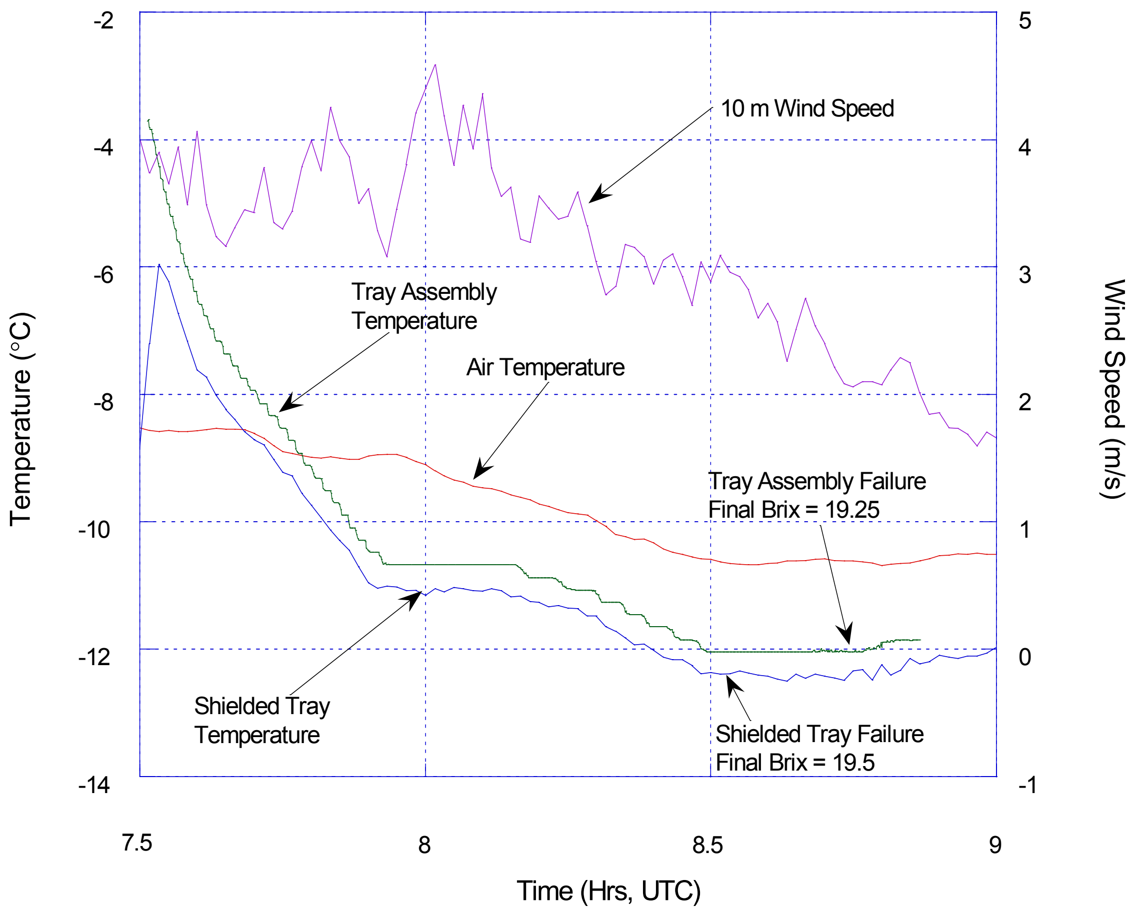

FIGURE 25. TIME SERIES OF AIR, PLATE IN THE SHIELD, AND PLATE ON THE TRAY TEMPERATURE FOR THE KILFROST 75/25 TEST ON 14 FEBRUARY 2001

CASE 13—PLATE TEMPERATURE IN SHIELD VERSUS TEMPERATURES IN WIND. In the case of lighter winds (< 2 m/s for most of the test, figure 26), the frosticator plate in the DFIR shield agrees well with the indoor tests, but is still shorter than the outdoor test by 8 minutes (44 minutes in the shield, 52 minutes outside the shield). The temperature trace for the two tests is nearly identical. However, the mass accumulation on the tray (figure 27) was less than the amount measured by the GEONOR snow gauge in the wind shield where the free-standing frosticator plate was located. Thus, the longer endurance time for the tray is likely due to the lower snow accumulation as compared to the frosticator plate in the wind shield.

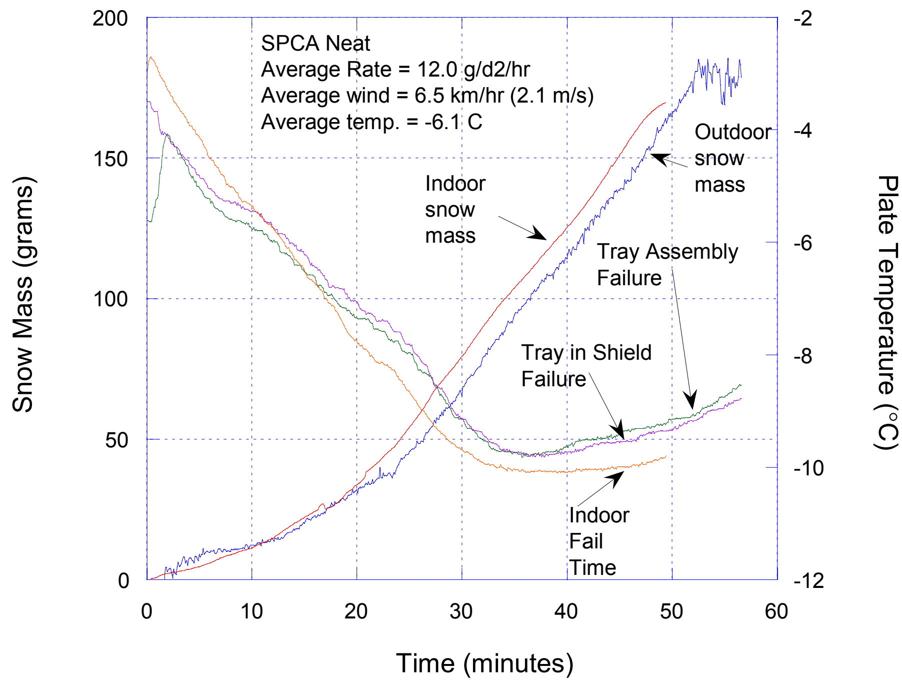

FIGURE 26. COMPARISON OF THE PLATE TEMPERATURE OF THE PLATE IN THE SHIELD, THE TRAY ASSEMBLY IN THE WIND, AND THE INDOOR SNOW MACHINE PLATE TEMPERATURE
(In addition, the indoor and outdoor snow mass accumulation traces is also given.)

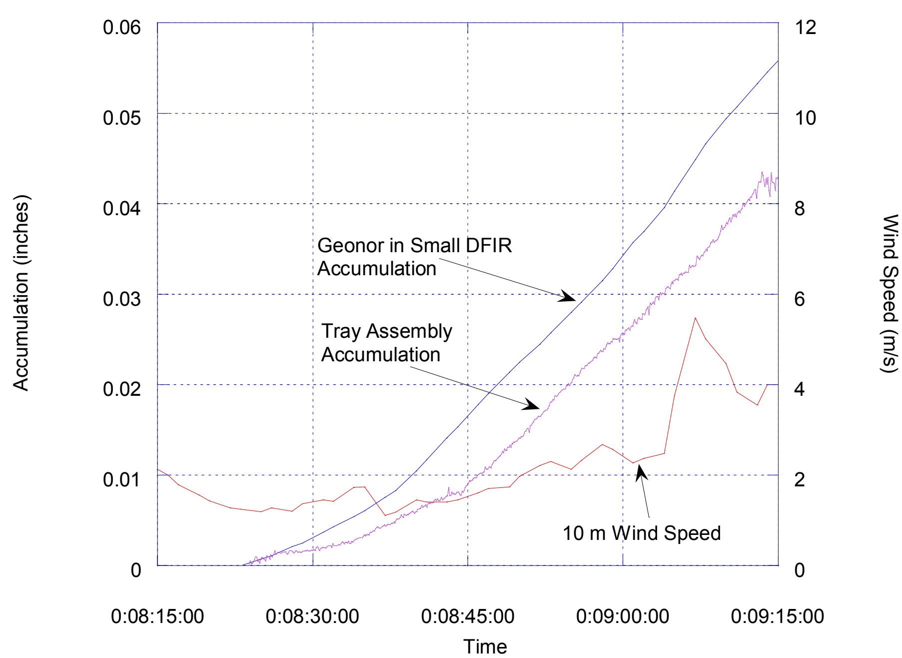

FIGURE 27. MASS ACCUMULATION AND WIND SPEED FOR THE 16 JANUARY 2001 SPCA NEAT FLUID TEST

SUMMARY.

This section discusses the comparison between the free-standing plate in the shield versus the plate on the tray assembly exposed directly to the ambient wind and the indoor snow machine testing.

1. A comparison of the endurance times of the indoor snow machine tests with the endurance times of the plate in the shield (table 1) shows good agreement (figure 28). If the high wind data point is removed (SPCA neat from 14 February 2001, 5 m/s), then the agreement is improved even further. These results suggest that the snow machine can duplicate outdoor snow conditions when the wind speeds are less than ~ 1.5 m/s. For wind speeds higher than this, wind effects need to be taken into account.

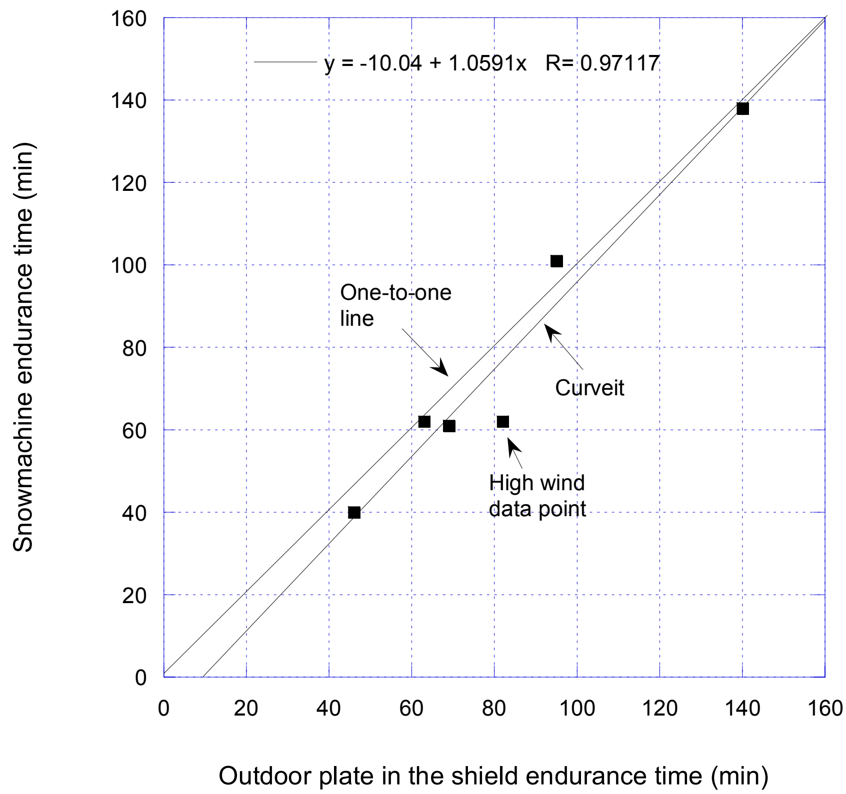

FIGURE 28. COMPARISON OF ENDURANCE TIME OF THE FREE-STANDING PLATE IN THE SHIELD TO THE INDOOR SNOW MACHINE TIMES

2. The results also suggest that there are other wind effects in addition to the plate temperature heating effect that needs to be taken into account in determining endurance time since the plate temperatures were similar from the shielded and unshielded plates in the above tests. These additional wind effects also result in a longer endurance time. Further testing will be required to determine exactly what these additional wind effects are. Candidates include (1) wind holding the fluid on the plate longer due to surface stress, (2) increased snow penetration as a result of wind, causing more rapid melting of the snow and more rapid dilution of the fluid. Since most fluids become more viscous

upon dilution (especially from the neat (100%) concentration), this would decrease the fluid runoff and keep the glycol percentage high, extending the endurance time, (3) increased snow penetration and possible adherence to the plate, leading to blockage of the fluid from running off the plate, and (4) the momentum of the snowflakes themselves may be imparting a force to prevent the fluid from running off the plate.

3. The good agreement between the endurance time from the free-standing plate in the shield and the indoor machine suggests that snow crystal type is not a critical factor, since a variety of snow crystal types (rimed and unrimed dendrites, stellars, needles, plates, columns, and aggregates from 1-10 mm in diameter) were experienced by the outdoor plate, while the indoor plate was only exposed to the artificial snow from the machine. This agrees with recent results from Beisswenger, et al. (2002) using the UQAC snow machine showing that the snow particle size does not significantly affect the endurance time of a deicing or anti-icing fluid.

INDOOR AND OUTDOOR OVERALL TEST COMPARISONS

The comparison of the NCAR outdoor and associated indoor endurance times from the equivalent snow machine tests (figure 29) shows that the indoor tests are highly correlated in the outdoor tests (correlation coefficient 0.99); however, a 10-minute bias seems to exist independent of the overall endurance time. The bias is such that the indoor test is always shorter than the outdoor test. A similar plot of endurance time for plate tests in a shielded environment (wind effects low, figure 28) shows good agreement with the indoor snow machine, suggesting that this bias is due to wind effects. The effect clearly identified in this report is the increased temperature experienced by the outdoor tests as a result of wind heating the plate more effectively than the indoor test performed under near zero wind conditions. One temperature effect is on the fluid viscosity, which in general increases with increasing temperature, resulting in less fluid runoff for warmer plate temperatures. Less fluid runoff leads to a higher percentage of glycol on the plate and longer endurance times. However, the exact functional temperature dependence of viscosity varies widely from fluid to fluid, resulting in a complicated dependence.

The above results also suggest that there are additional wind effects extending the endurance time of fluids based on the comparison of the indoor fluid tests to the tests conducted in the wind shield. An understanding of these additional wind effects will require more investigation.

A comparison of the Brix values (table 1) shows that the failure calls outdoors and indoors are mostly consistent, eliminating failure call as a major source of the bias.

A comparison of the APS outdoor results to the equivalent NCAR indoor results is shown in figure 30.

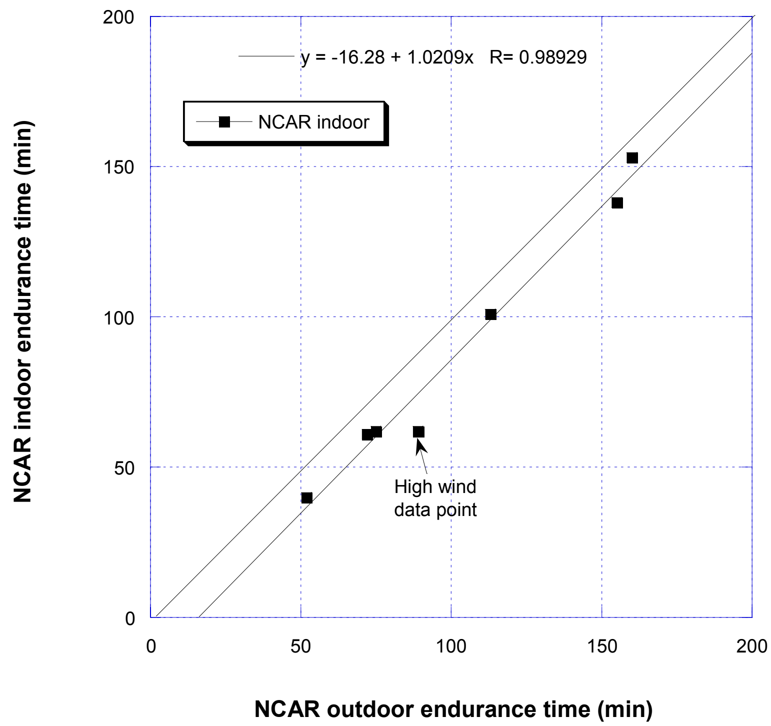

FIGURE 29. COMPARISON OF NCAR OUTDOOR FLUID TESTS FROM TABLE 1 WITH EQUIVALENT INDOOR TESTS

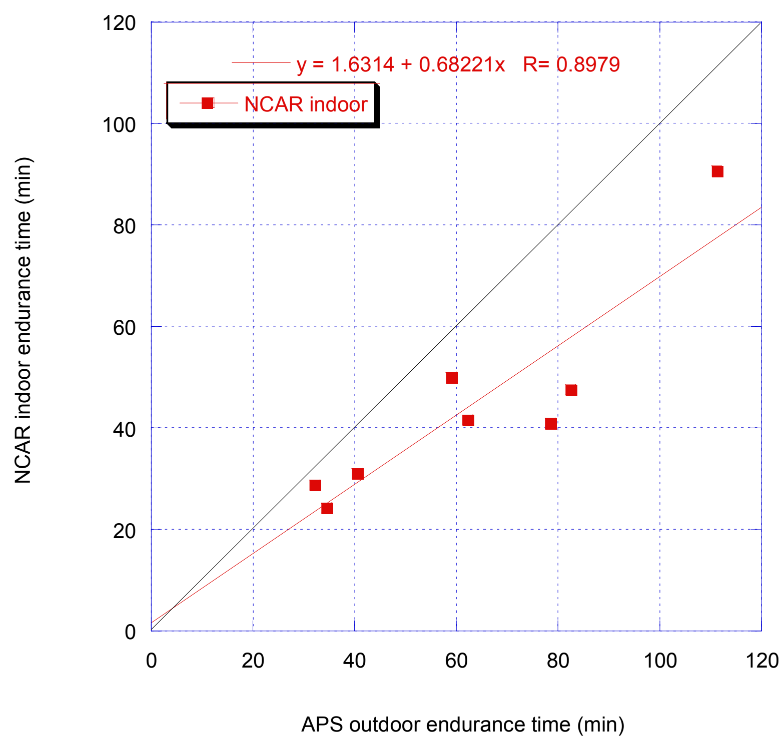

FIGURE 30. COMPARISON OF THE APS OUTDOOR FLUID TESTS WITH INDOOR SNOW MACHINE TESTS UNDER THE EQUIVALENT CONDITIONS

These results show that the endurance time of the NCAR snow machine is on average 25% lower in time than the APS outdoor tests, with a correlation coefficient of only 0.89. These results are in contrast to the comparison to the NCAR outdoor tests in which a constant bias was apparent and a high correlation coefficient of 0.99 achieved (figure 29). The reason for this difference is not readily apparent. Despite the specification of a constant procedure, there may still have been some discrepancy in the NCAR and APS outdoor tests. Of particular concern are the two outlier points, associated with tests of Kilfrost neat on 14 February 2001 and SPCA 75/25 on the same day. The wind for both of these cases is very light (< 1.2 m/s), while the times are nearly a factor of two less for the indoor tests. An examination of the Brix reading at the end of the test for the APS and NCAR tests, however, shows a relatively large discrepancy for one of the data points (see table 2). Thus, part of the discrepancy may be due to the failure call. For instance, one of the data points has a final Brix of 12 (Kilfrost test, 14 February 2001) while the indoor test has a final Brix of 19. From propylene glycol charts, this translates to a glycol percentage of 50% for the NCAR indoor test and only 30% for the APS test. The second data point also has a Brix discrepancy, but only of 3. However, the mass trace for this case showed sudden jumps (figure 11); and thus it was suspected that the data from this case is not entirely reliable. If these two data points are eliminated, the comparison is much improved (figure 31, correlation coefficient 0.98).

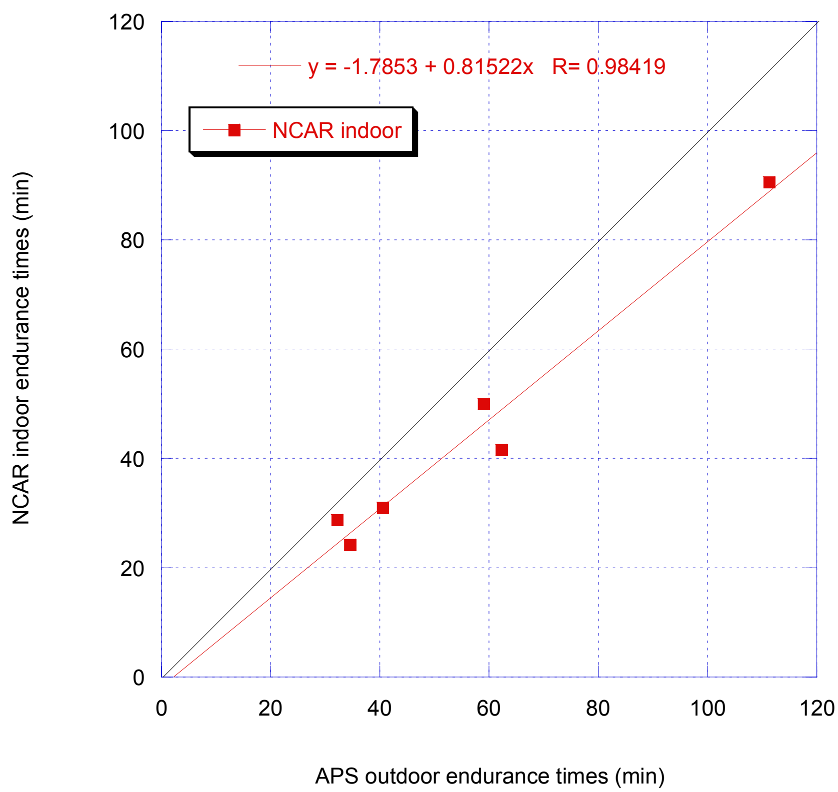

FIGURE 31. COMPARISON OF APS OUTDOOR ENDURANCE TIMES TO NCAR INDOOR EQUIVALENT TESTS WITH THE TWO OUTLIER DATA POINTS IN FIGURE 16 REMOVED

As shown in both the APS and NCAR outdoor and indoor test comparisons, an important factor in the shorter times for the NCAR snow machine is the effect of the wind warming the fluid, slowing the runoff (except for Ultra+ in which the viscosity increases with decreasing temperature). A similar result was obtained in previous indoor snow machine testing, which examined the effect of plate temperature on endurance time. A series of tests with different fluid types in which the plate temperature was allowed to freely cool versus a constant, warmer, prescribed temperature was reported by Rasmussen, et al. (1999). The results showed that for Kilfrost ABC-S, Safewing IV, Octagon MaxFlight, and SPCA AD-480 with an initial plate temperature of -10°C and a rate of 25 $g/d^2/hr$, that the endurance time for the fluid tests run with a constant plate temperature of -10°C was 70%-90% longer than the tests in which the plate temperature was allowed to vary naturally with the snowfall rate. Bernardin, et al. (1997) reported similar trends in endurance times with temperature. The current results are very consistent with these previous studies.

The current results suggest that the NCAR snow machine can be used as a substitute for outdoor testing as long as an appropriate bias can be determined as a function of wind speed. For winds less than 1.5 m/s, the machine can be used in its current configuration. Further testing should be conducted to determine this bias factor as a function of wind speed. One method to account for this bias is to control the plate temperature to the ambient air temperature in order to simulate the heating affect of the wind. Beisswenger, et al. (2002) show that snow machine tests with a constant plate temperature gave the best comparison to the outdoor test data.

The current tests also show that the time variation of the mass accumulation rate is critical to reproduce in order to simulate the plate temperature variation observed.

The good correlation of the snow machine times to the endurance times of the plate in the shield suggests that the current variation of the horizontal distribution of snow in the snow machine of ±10%-25% may not significantly affect the endurance time of the fluids.

The comparison of the linear rate tests to the variable tests shows that the rate at the beginning of the test is most important. If a higher than average rate occurs during the beginning of the test, the fluid temperature is strongly reduced, increasing the fluid runoff and reducing the endurance time. If a lower than average rate occurs during the beginning of the test, the fluid does not cool as much as observed, less runoff occurs, and a longer endurance time is observed (except for Ultra+). Thus, the time variation of the snowfall rate plays an important role in determining the endurance time of a fluid.

RECOMMENDATIONS FOR FUTURE TESTS

1. Conduct fluid tests inside and outside the wind shield at the Marshall test site with identical frosticator plates on tray assemblies. This will allow the snow rate to be determined in the same manner, and the plate geometry to be the same. The difference in these tests should allow for the determination of the wind effect. Conduct equivalent tests with the snow machine and compare the results. Continue to measure Brix at the beginning and end of each test. Record snowflake crystal type for each test.

a. To verify the effect of fluid temperature, the indoor comparison tests to outdoor tests should be conducted in two ways: (1) allow the plate temperature to vary freely and (2) control the plate temperature to the ambient outdoor temperature. This will allow one to determine whether a simple constant temperature test can eliminate much of the observed wind bias by simulating the wind-heating effect directly.

b. Perform the above outdoor and indoor tests on a wider variety of fluids and conditions to confirm the conclusions of this report and to determine the bias factor as a function of wind speed. This will require the construction of additional tray assemblies.

2. Quantify the extent to which fluid runoff is determined by fluid temperature by conducting runs with various fluid temperatures (holding the plate temperature constant) and measuring the runoff rate.

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