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# Aircraft Anti-Icing Fluids Endurance Under Natural and Artificial Snow: a Comparative Study

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**Abstract** – *The usage of De-Icing and Anti-Icing fluids is the most common method recognized to protect aircraft on the ground from freezing and frozen contaminants. The snow endurance times, which means the duration that a fluid can protect the vehicle from snow accumulations, is currently determined outdoor under natural conditions. To replace this expensive and very impractical method, the Anti-Icing Materials International Laboratory developed snow machine was used to perform a comparative study. In this first study, three commercial fluids were tested at various snow intensity rates under artificial snow generated with the snow machine in a cold chamber to validate the testing procedure and investigate the way forward. The results obtained were then positively compared to natural snow endurance times. They were also compared with natural snow regression curves, showing similar trends. This study demonstrated the great potential of this method showing the necessity of pursuing this investigation.* ***Copyright © 2022 The Authors.***

***Keywords**: Aircraft, De/Anti-Icing Fluids, Ground De-Icing, Icing, Snow*

## I. Introduction

Winter brings many different conditions that can seriously affect aircraft operations [1]. Frozen and freezing precipitations occurring at lower temperatures may accumulate on critical aircraft surfaces, impeding their performances [2]. Historically, a fatal accident, which occurred in the late 1980s, has changed the operational methods on how the aircraft are deiced and anti-ice in Canada. It was concluded that the main cause of the crash was the presence of snow on the aircraft. The crew did not request proper deicing and the frozen contaminants prevent the aircraft to gain sufficient altitude during takeoff [2], [3]. Aircraft AMS1424 [4] deicing Type I fluids and AMS1428 [5] Type II, III and IV anti-icing fluids are glycol based products, generally used to remove and to prevent accumulations over the aircraft surfaces while taxiing on the ground. Anti-icing fluids have been developed to protect the aircraft for a limited period of time and then be removed aerodynamically while the aircraft take-off [2]. In order to be qualified and approved by the governmental instances, the different fluids used currently have to pass through several endurance and acceptance tests. Those tests cover from the stability, the compatibility, and the environmental information to the endurance of the product under freezing and frozen contaminants and the aerodynamic acceptance. All the tests are included in the Society of Automotive Engineering (SAE) documents [4]-[7]. Since the main method recognized for the de/anti-icing of aircraft on the ground is based on the use of liquid glycol products [8]-[10], Transport Canada started to produce, in the early 1990', an annual document named the "Transport Canada Holdover Time (HOT) Guidelines." The equivalent is also published by the USA Federal Aviation Administration (FAA). This document provides the Hold Over Time Tables (HOTs) of commercially available products under different conditions of precipitation that may occur during winter.

Those HOTs are obtained by regression from endurance time under multiple freezing and frozen precipitation. They vary in terms of temperature and intensity in order to cover the ranges that occur under real conditions. Some of the conditions are simulated with indoor tests, such as light freezing rain and freezing drizzle. However, some tests are conducted outdoor, under natural conditions, such as snow. With the random occurrences that characterize outdoor conditions-including various intensities, presence of wind, and mixed precipitation conditions-it can be hard and very expensive to cover the range of possible conditions. To accelerate the completion of test programs, and reduce costs, Transport Canada has begun research on the use of artificial snow machines. One such apparatus is owned by the Anti-icing Materials International Laboratory (AMIL). Natural snow is composed of crystals of various geometries formed directly from water vapor at a temperature below 0 °C [11]-[13]. During their formation in the atmosphere, the air contains fine particles of water in its gaseous form. When the relative humidity reaches 100% and the air is cooled, clouds form. The water droplets and ice crystals found in clouds have average diameters of one hundredth of a millimeter [11]-[13]. For

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an ice crystal to form from vapor, the temperature must be below -60 °C, a temperature typically reached at altitudes between 9 and 12 km [11]-[14]. One of the elements facilitating the formation of the first crystals is the presence, in the clouds, of various contaminants, such as sand particles, pollen, dust, bacteria or contaminants resulting from human activity such as volatile chemicals.

These contaminants act as nuclei agents, causing instability in the vapor and thus allowing solidification in different forms, depending on supersaturation and air temperatures [15]. Ice crystals solidification then causes them to fall and grow into different shapes. The main shapes consist of diamond dust, stellar dendrites, sectored plates, columns and needles, capped columns, triangular crystals, split stars and split plates, twinned crystals, twelve-sided snowflakes and double stars, chandelier crystals, spatial dendrites, and rimed snowflakes. Each geometry is obtained as a function of the formation temperature as well as the supersaturation of water in the air, air density and relative humidity.

Several researchers have, for hundreds of years, classified and analyzed all possible forms of flakes according to atmospheric conditions [12]-[16]. Furukawa proposed a diagram that detailed the morphologies of the obtained snowflakes as a function of both water supersaturation and temperature based on the research of Ukichiro Nakaya. In the course of taking more than 3000 photographs in a few years, Nakaya classified snow crystals into some 40 morphological categories [15]. The studies regarding the shapes of the snowflakes have been undertaken by several research groups upon the years [12]-[14], [16], [17]. The most recent, Vasquez-Martin et al. (2020), used a ground-based in situ instrument, the Dual Ice Crystal Imager (D-ICI). The D-ICI takes dual high-resolution images (side and top view) that enable a better shape classification than if there was only one image per particle. From these images, they determined the particle size, cross-sectional area, area ratio, and aspect ratio of individual particles to name a few. Their analysis allowed to obtain 135 shapes of snowflakes including 34 new shapes, never observed by other researchers. Artificial snow generation is widely used by the ski industry to extend the season. The most used artificial snow generation apparatus employs a technique to spray cold water through an air-injected nozzle in sub-zero temperatures. The created snow consists of ice particles ranging from 100 to 500 µm. The shape of these particles is normally like beads, in contrast to natural snowflakes, which are hexagonal, plates or needles.

Artificially created snowflakes are formed from liquid water droplets that solidify from the outside to the inside, taking the shape of a bead. Artificial snow machines used by the ski industry are designed to produce impressive amounts of snow, but the shape of the snowflakes does not represent the snow conditions that affect aircraft [18], [19]. Laboratory testing found in the literature uses snow gathered from natural conditions or generated artificially beforehand to simulate a snowfall. In Dalle and Admirat [20], the snowfall is generated using an open loop wind tunnel having a wind speed ranging from 3 m/s to 15 m/s at near 0 °C temperatures. The snowfall is obtained by a treadmill that injects snow particles into the airflow. Snow particle size is controlled by a multi-comb cylinder that breaks the biggest particles into smaller ones. The snow particles are projected onto a collector where only a fraction of the snow adheres. The rates are adjustable, ranging from 8 mm/hr to 30 mm/hr. The snow density depends on several factors; the main factors are wind speed, relative humidity, and initial snow characteristics.

The density usually ranges from 100 kg/m$^3$ to 400 kg/m$^3$. This method is usually to evaluate the impact of wet snow accretion upon non-complex structures specifically on non-energized conductor. In Saito et al. [21], the same principle is applied, but without a wind generation system. They used a treadmill that projects the artificially generated snow onto an inclined collector. In this case, the snow is not broken into smaller particles, and sometimes agglomerated parts reach the collector substrate. Schleef et al. used more representative artificial snow using supersaturation by blowing cold air over a heated water basin [22]. The moist airstream is propelled into a chamber where it cools and the nucleation of ice crystals is promoted on stretched nylon wires. A box is placed underneath to collect the resulting snow as it falls naturally. The obtained snow can then be used in other apparatus to simulate a proper snowfall.

To evaluate the performance of aircraft de/anti-icing fluids, two snow machines have been developed, which are included in the Aerospace recommended practice of the Society of Automotive Engineering (SAE) ARP5485B [23]. The first one is the Anti-Icing Material International Laboratory (AMIL) Snow Machine, presented and described later in this present paper. A few studies have been completed by the AMIL to design this snow machine and investigate potential improvements [24]-[28]. Those preliminary tests have shown that unlike outdoor tests, indoor tests require more energy, so the plate needs to be heated to improve results. It also helps to propose a method to determine the endurance time using the energy profile of heat. Finally, numerical modelling has been performed to understand the behaviour of de/anti-icing fluids subjected to snow [29], [30]. The results were promising and demonstrated the necessity of performing this correlation study with outdoor snow results. The second is the NCAR-FAA Indoor Snow Machine, which consists of a system that generates artificial snow in a laboratory from an ice core [31]. It has been designed specifically to operate in a laboratory cold chamber for testing aircraft de/anti-icing fluids under controlled conditions. The snowflakes are produced using an ice cylinder shaved with a rotating carbide bit. The resulting flakes then fall over the test plates covered with the de/anti-icing fluid. The flakes fall approximately 2.5 m to the bottom of the device, reaching their terminal velocity. The resulting fine ice shavings mimic natural snow in size, distribution, fall velocity, density, and Liquid Water Equivalent (LWE).

The density of the flakes obtained can be varied from

0.1 g/cm$^3$ to 0.5 g/cm$^3$. The intensity is measured and controlled using the Liquid Water Equivalent (LWE) through a scale placed under the test plate. The intensity can be varied from nearly 0 g/dm$^2$/h to 80.0 g/dm$^2$/h. The main advantage of this apparatus is that it does not need to transport real or artificial snow since it comes directly from an ice cylinder. However, the geometry of the flakes may lead to results that do not reflect exactly what occurs in real environments while the fluid is absorbing the contaminant. Even if those two methods are included in the ARP5485, none of the two are accepted yet as a substitute for natural snow in the aircraft de/anti-icing fluid regulations. The Type II, III and IV fluids developed and used by the industry are very complex non-Newtonian fluids. To help with the understanding of the different phenomenon involved in the fluid flow off and snow dilution, numerical modeling will be an interesting aspect to consider. Few researches have been lead on the modeling of non-Newtonian fluids in the literature [32]-[37]. The information provided in these scientific papers will allow the development of a complete model to explain the phenomenon observed in the trials presented in this article. Particular attention will be paid to the flow of these fluids in an anti-icing mode, which has been briefly studied in the past [32], [34]. In recent years, researchers have put a lot of effort into understanding the behavior of non-Newtonian fluids used for aircraft anti-icing [38]-[43]. The modeling of such fluids requires the involvement of several physical parameters that vary according to the variable climatic conditions [38], [39]. Koivisto et al. have done extensive research to understand new aspects of the aerodynamic behavior of these fluids [39]-[43]. Modeling of these fluids has allowed understanding previously unexplored aspects of de-icing and flow-off properties. Although the progress made by the researcher is impressive, there is still a lot of work to be done in order to understand precisely the effect of deposition, absorption and melting of snow in those fluids in order to produce a consistent model reproducing the observed behaviors. Such models will undoubtedly lead to improved products and increased safety in this transportation area. Modelling concerning snow accumulation over the ground anti-icing fluids have also been briefly explored by AMIL in the past [44]-[46]. The very preliminary results obtained for a flat plate similar to those used experimentally gave interesting conclusions on the different theory to consider for further modelling. A new proposed model should include thermodynamic and diffusion theories while considering the principles of absorption, melting and dilution of snow in the fluids.

The purpose of this article is to present a first comparative study of endurance times obtained under natural and artificial snow in order to validate the testing procedure and then investigate the way forward. First, AMIL's unique artificial snow test machine is presented in details. In addition, the process to generate the artificial snow in a specialized cold room is also described as well as the protocol to perform the artificial snow tests. The criteria to define fluid failure and determine endurance time is also detailed. Then the test conditions obtained by Transport Canada under natural snow testing are shown and the selection of the conditions for indoor testing is done. Testing is performed with the snow machine under artificial snow and the results are compared with those obtained by Transport Canada for equivalent conditions. A correlation and regression analysis is presented in order to better understand the artificial snow test relation to natural snow. The final goal of this research is to obtain correlation between the two methods to substitute the costly and impractical method of outdoor measurements.

The conclusion presents the different recommendations to study and improve the snow machine, artificial snow generation and test method in the comprehensive research project to be initiated after this preliminary study and test assessment.

## II. Materials and Methods

### *II.1. Snow Generation*

Before testing, artificial snow has to be generated to fill the distribution box of the snow machine. The snow is generated in AMIL's snow chamber, a specialized cold room dedicated to snow generation and testing under snow storm conditions. This 3-m high insulated cold room can generate temperature ranging from -38 °C to +5 °C. The dual chilling system allows to keep the temperature constant throughout the precipitation. Snow is obtained in the cold chamber at a low temperature of -25 °C by freezing droplets of about 25 µm generated by fine spray hydraulic nozzles [47]. With the spaying, the air becomes supersaturated with water and then the artificial snow crystals are formed upon contact with the ground. The obtained snow is an artificial rime of constant size of 1 to 2 mm. The density of this artificial snow is about 0.25 g/cm$^2$. The obtained snow can be stored for a period of up to two weeks in a freezer or inside the room itself. Prior to a test, the snow is sifter to avoid any sintering.

### *II.2. Snow Machine Apparatus and Test Procedure*

The AMIL snow machine is presented in Fig. 1 and with additional pictures in [47]. The cold room in which the snow machine is installed is set to the test temperature at least 12 h before each test. The snow and fluid to be tested are also placed in the room at the same time to make sure they have reached test temperature when the test is started. Snow density is also measured twice every day to validate the conformity of the snow used for the test by weighting a graduated cylinder filled with the snow. The precipitation is generated by an auto feeding system that moves along the 15° inclined 30 cm per 50 cm test plate. The snow comes from the top box and reaches a rotating cylinder grooved with small cavities.

Fig. 1. Snow machine distribution system

The snow falls from the cylinder when the filled cavities reach the bottom, pushed by air feed at a low pressure (15 psi). The rotation speed of the cylinder is computer-controlled to obtain the intensity targeted for the test. For a higher intensity, the cylinder rotates faster.

Intensity is measured in real-time, with the scale placed under the test plate. The apparatus is limited to a maximum of 30 g/dm$^2$/h, close to the maximum values usually tested outdoor.

A heater mat is installed underneath the test plate to maintain thermal equilibrium.

It has been shown during the development of the snow machine that the absorption of snow by the fluid lowers the plate temperature below the actual test temperature, a phenomenon not observed outdoor. To better simulate outdoor testing, the heater mat is used to maintain the plate at test temperature, better mimicking the outdoor phenomenon [28].

Before starting the test, the plate temperature controller is set at the test temperature for the heater mat to maintain the plate at the test temperature for the duration of the test. Once the snow box is filled with sifted snow, the box is installed in the distribution system and fluid is poured on the plate, starting from the top.

Distribution box is refilled with sifted snow as necessary during the test. The test target intensity is input into the software and the actual mass of snow precipitated on the plate is recorded throughout the test, using a scale placed under, as well as the air temperature using thermocouples. The camera video surveillance system is also started to record the test.

Observation of the fluid state is constantly made in person and via the camera surveillance system. Failure of the fluid is determined according to ARP5485 [23]. The failure corresponds to the time when 30% of the surface of the fluid is covered with white snow, determined visually by the tester, as required in the standard. At first, the snow particles are absorbed by the fluid, resulting in a diluted fluid/water mixture. As the water ratio increases, the fluid mixture becomes less viscous, facilitating its flow off from the inclined plate. The elimination of the fluid from the plate and constant increase of water absorbed lead to the saturation of the fluid mixture, where it can no longer absorb and melt the snow particles.

Then, a slush-like mixture starts to accumulate at the air/fluid interface of the fluid and finally white snow simply falls and lays on top of the slush mixture and failure is called when 30% of the plate is covered with this white snow. Once the fluid has failed and the test is completed, time before failure is recorded and data acquisition is stopped. The real intensity obtained is determined from the real-time weighting of the snow mass distributed over the plate and data recorded during the test is gathered.

### *II.3. Test Conditions and Natural Snow Test Results*

Before starting the tests with the Artificial snow machine, natural snow results provided by Transport Canada are analyzed. The test conditions performed with the snow machine are set to match the conditions obtained by Transport Canada during their natural snow test campaign conducted during winter 2020-2021, in conformity with their habitual methods, as specified in the ARP5485B [26].

Their tests have been performed with the same fluids and same fluid batches as those received at AMIL and allows a direct comparison between natural and artificial snow tests.

The tests were performed with the standard test procedure used for outdoor natural snow conditions for aircraft ground de-icing/anti-icing endurance time testing [23]. With the very complex chemical nature of those fluids, tests with different batches of same fluid brand could have led to difference in viscosity resulting in different performances and difficult comparison of the results. The tests conditions for the results gathered by Transport Canada are presented at Table I, Table II and Table III, in function of different fluids. Due to time limitations, only three conditions per fluid were selected for testing and are identified in bold in the tables. The other conditions are still used to compute regression curves. Tests at each test conditions were repeated two to three times to assess the repeatability of the experiment.

TABLE I
NATURAL SNOW TEST CONDITIONS WITH TYPE II FLUID

| Test Identification | Temperature (°C) | Precipitation Rate (g/dm$^2$/h) | Endurance Time (min) |
|---|---|---|---|
| TII-1(N) | -5.3 | 2.7 | 324 |
| TII-2(N) | -1.5 | 3.7 | 319 |
| **TII-3(N)** | **-5.8** | **6.9** | **150** |
| **TII-4(N)** | **-5.4** | **9.1** | **112** |
| **TII-5(N)** | **-5.2** | **14.4** | **63** |

TABLE II
NATURAL SNOW TEST CONDITIONS WITH TYPE III FLUID

| Test Identification | Temperature (°C) | Precipitation Rate (g/dm$^2$/h) | Endurance Time (min) |
|---|---|---|---|
| TIII-1(N) | -5.5 | 2.7 | 97 |
| **TIII-2(N)** | **-5.3** | **6.4** | **56** |
| TIII-3(N) | -3.1 | 8.1 | 48 |
| **TIII-4(N)** | **-5.1** | **12.2** | **34** |
| **TIII-5(N)** | **-5.7** | **26.6** | **19** |

TABLE III
NATURAL SNOW TEST CONDITIONS WITH TYPE IV FLUID

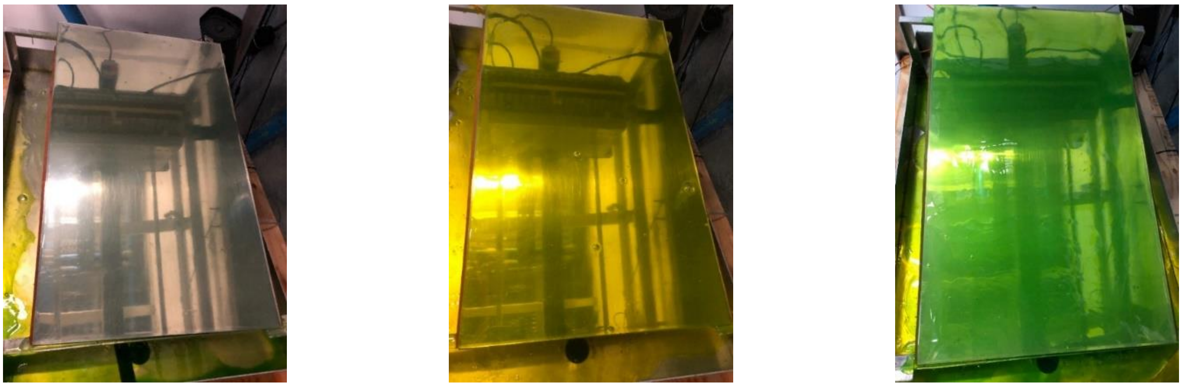
| Test Identification | Temperature (°C) | Precipitation Rate ($g/dm^2/h$) | Endurance Time (min) |
|---|---|---|---|
| TIV-1(N) | -4.4 | 2.2 | 224 |
| **TIV-2(N)** | **-5.7** | **5.4** | **128** |
| TIV-3(N) | -5.4 | 8.7 | 105 |
| **TIV-4(N)** | **-5.2** | **13.6** | **79** |
| **TIV-5(N)** | **-5.9** | **25.0** | **51** |

## III. Artificial Snow Test Results

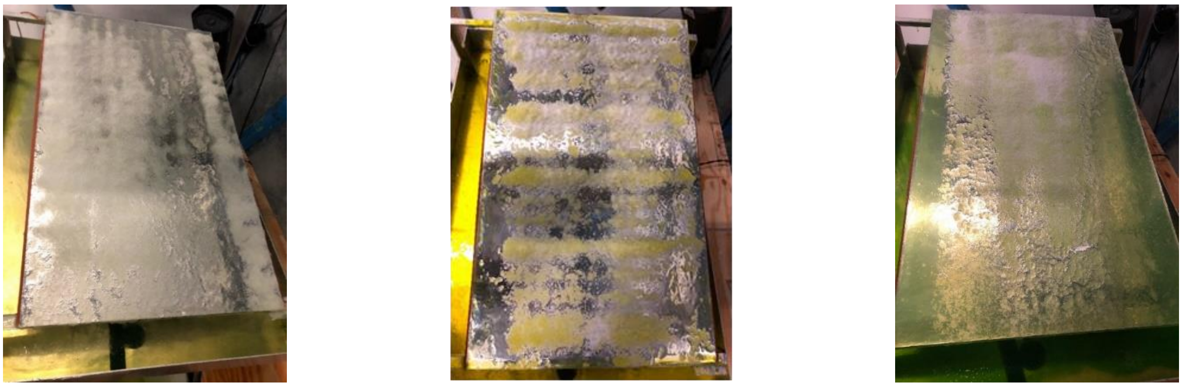
Before starting the precipitation, the fluid is poured onto the plate and spreads over the whole surface (Figs. 2). Due to its coloration, the Type II fluid is difficult to see on the picture. Snow is distributed on the fluid with the snow machine and the heater mat, installed underneath the flat plate, maintains the plate at test temperature. At the end of the test, the test rate obtained during the test is computed with the evolution of the weight of snow on the plate throughout the test measured with a scale installed underneath the setup. Test is stopped when the fluid fails, as determined per the ARP 5485 [23]. Examples of fluid failure are presented at Figs. 3 for the Type II fluid after 180 min at 7.1 $g/dm^2/h$, the Type III fluid after 23 min at 27.1 $g/dm^2/h$ and the Type IV fluid after 96 min at 14.0 $g/dm^2/h$. The results obtained for all the test repetitions performed at the different test conditions with the Type II fluid are presented at Table IV. When comparing the test rates targeted at the beginning of the tests with the real test rates measured, the maximum difference obtained is 4.4%. At a targeted test rate of 6.9 $g/dm^2/h$, the endurance time obtained with the artificial snow is 182 ± 2 min, while at 9.1 $g/dm^2/h$ it is 112 ± 2 min and at 14.4 $g/dm^2/h$ it is 86 ± 1 min. The results obtained for all the test repetitions performed at the different test conditions with the Type III fluid are presented at Table V. The test rates obtained for each test are within 5.6% of the targeted test rates, except for one test repetition at 9.8%.

For test TIII-3(A)-2, the precipitation rate could not be measured due to a problem with the electronic file.

However, there is no reason to believe that the precipitation rate obtained for this test would be outside the discrepancy obtained for the other testing. For the Endurance Time, at a targeted test rate of 6.4 $g/dm^2/h$, the endurance time obtained with the artificial snow is 57 ± 2 min, while at 12.2 $g/dm^2/h$ it is 30 ± <1 min and at 26.6 $g/dm^2/h$ it is 23 ± 4 min. The last fluid tested is an Ethylene Glycol based Type IV fluid. The results obtained for all the test repetitions performed at the different test conditions are presented at Table VI. The test rates obtained for each test are within 6.8% of the targeted test rates. For the Endurance Time, at a targeted test rate of 5.4 $g/dm^2/h$, the endurance time obtained with the artificial snow is 183 ± 4 min, while at 13.6 $g/dm^2/h$ it is 93 ± 3 min and at 25.0 $g/dm^2/h$ it is 61 ± 5 min.


(a) (b) (c)

Figs. 2. (a) Type II, (b) Type III and (c) Type IV fluid spread on the test plate


(a) (b) (c)

Figs. 3. Failed (a) Type II fluid (b) Type III fluid and (c) Type IV fluid

TABLE IV
ARTIFICIAL SNOW TEST RESULTS FOR TYPE II FLUID

| Test Identification | Temperature (°C) | Target Precipitation Rate (g/dm$^2$/h) | Measured Precipitation Rate (g/dm$^2$/h) | Endurance Time (min) |
|---|---|---|---|---|
| TII-1(A)-1 | -5.8 | 6.9 | 7.1 | 180 |
| TII-1(A)-2 | | | 7.2 | 184 |
| TII-2(A)-1 | -5.4 | 9.1 | 9.5 | 110 |
| TII-2(A)-2 | | | 9.4 | 112 |
| TII-2(A)-3 | | | 8.9 | 113 |
| TII-3(A)-1 | -5.2 | 14.4 | 14.8 | 86 |
| TII-3(A)-2 | | | 14.2 | 85 |

TABLE V
ARTIFICIAL SNOW TEST RESULTS FOR TYPE III FLUID

| Test Identification | Temperature (°C) | Target Precipitation Rate (g/dm$^2$/h) | Measured Precipitation Rate (g/dm$^2$/h) | Endurance Time (min) |
|---|---|---|---|---|
| TIII-1(A)-1 | -5.3 | 6.4 | 6.4 | 59 |
| TIII-1(A)-2 | | | 6.7 | 55 |
| TIII-2(A)-1 | -5.1 | 12.2 | 12.1 | 30 |
| TIII-2(A)-2 | | | 13.4 | 30 |
| TIII-3(A)-1 | -5.7 | 26.6 | 27.1 | 23 |
| TIII-3(A)-2 | | | N/A | 26 |
| TIII-3(A)-3 | | | 25.1 | 19 |

TABLE VI
ARTIFICIAL SNOW TEST RESULTS FOR TYPE IV FLUID

| Test Identification | Temperature (°C) | Target Precipitation Rate (g/dm$^2$/h) | Measured Precipitation Rate (g/dm$^2$/h) | Endurance Time (min) |
|---|---|---|---|---|
| TIV-1(A)-1 | -5.4 | 5.4 | 5.2 | 186 |
| TIV-1(A)-2 | | | 5.6 | 179 |
| TIV-1(A)-3 | | | N/A | >170 |
| TIV-2(A)-1 | -5.2 | 13.6 | 14.3 | 90 |
| TIV-2(A)-2 | | | 14.0 | 96 |
| TIV-2(A)-3 | | | 14.3 | 94 |
| TIV-3(A)-1 | -5.9 | 25.0 | 26.7 | 56 |
| TIV-3(A)-2 | | | 24.6 | 66 |
| TIV-3(A)-3 | | | 25.9 | 60 |

## IV. Discussion

### IV.1. Test Variability

During the test campaign, each test condition has been repeated at least twice and up to three times to assess the experimental variability. Variability is observed in the test rate obtained, which slightly varies each test from the intensity targeted at the beginning. Table VII shows that for each of the test conditions, the test rate obtained during a test is within 5.1% for all repetitions performed at the same conditions.

This result shows that it is possible to accurately generate a targeted test rate with the snow machine and the developed computer software. Table VIII presents the variability of the endurance time obtained for each test conditions. The variability obtained in the artificial snow results within a test condition is below 10% for all the conditions tested except at 26.6 g/dm²/h with the Type III fluid, which is 15.4%. For that test, the endurance times obtained are low (26 minutes and less), which means a few minutes' difference results in a large variation in percentages.

Also, this test was the first performed in the test campaign which means that the experience with the snow machine was low and could have led to minor manipulation errors. Considering this, the experimental variability for the artificial snow tests can be set at 10%, at least when the endurance time is 30 minutes and above.

TABLE VII
TEST RATE (INTENSITY) EXPERIMENTAL VARIABILITY

| Test Identification | Number of Repetition (#) | Variability (%) |
|---|---|---|
| TII-1(A) | 2 | 2.3 |
| TII-2(A) | 3 | 5.1 |
| TII-3(A) | 2 | 3.8 |
| TIII-1(A) | 2 | 3.7 |
| TIII-2(A) | 2 | 1.1 |
| TIII-3(A) | 3 | 4.1 |
| TIV-1(A) | 2 | 0.7 |
| TIV-2(A) | 3 | 3.2 |
| TIV-3(A) | 2 | 2.1 |

TABLE VIII
ENDURANCE TIME EXPERIMENTAL VARIABILITY (ARTIFICIAL SNOW)

| Test Identification | Number of Repetition (#) | Variability (%) |
|---|---|---|
| TII-1(A) | 2 | 1.1 |
| TII-2(A) | 3 | 1.3 |
| TII-3(A) | 2 | 0.6 |
| TIII-1(A) | 2 | 3.5 |
| TIII-2(A) | 2 | <0.1 |
| TIII-3(A) | 3 | 15.4 |
| TIV-1(A) | 2 | 1.9 |
| TIV-2(A) | 3 | 3.2 |
| TIV-3(A) | 2 | 8.2 |

### IV.2. Artificial Snow vs. Natural Snow Endurance Time

Artificial snow tests have been performed with the snow machine in the cold room with three different fluids (Type II, Type III and Type IV) at different test conditions. The endurance times obtained are compared with the endurance times obtained at equivalent conditions during natural snow tests to assess the correlation between artificial and natural snow results.

The test rates (intensities) obtained during each artificial snow tests were slightly different than for the matching natural snow test, which can lead to difference between the results. However, except for one test, the test rates were all within 5.6% of the targeted test rates corresponding to the natural snow test rates. This low deviation should have a small impact on the correlation and is neglected in this analysis. Table IX presents the comparison between the artificial and natural snow endurance time results. Except for two test conditions, the artificial snow endurance time results are within 21.3% of those obtained with under natural snow conditions, showing a good correlation. The other two tests have a difference of 35.7% and 42.6%, which are less in agreement with the natural snow endurance times. Plots of the artificial vs natural snow endurance time are presented at Fig. 4, Fig. 5 and Fig. 6.

A picture-perfect theoretical correlation value corresponds to a 1:1 ratio between the artificial and natural snow results, which is represented by the straight black line. The plots show that for the Type II and III fluids, the linear regression is close to the optimal value of 1 with values of 1.14 and 1.01 respectively. However, for the Type IV fluid the regression is not as close with a value of 1.32. This larger discrepancy is created by the results obtained at the lower intensity (5.4 g/dm$^2$/h).

These results show that the artificial snow tests correlate, within 21.3%, with the natural snow tests for the grand majority of the test conditions performed with all three fluids.

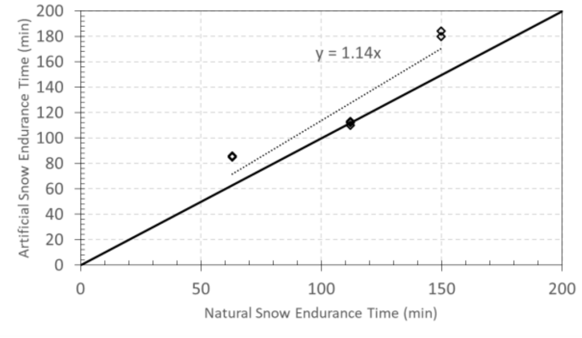


Fig. 4. Type II Artificial and Natural Snow Endurance Time comparison (with a linear full black line representing a 1:1 comparison)

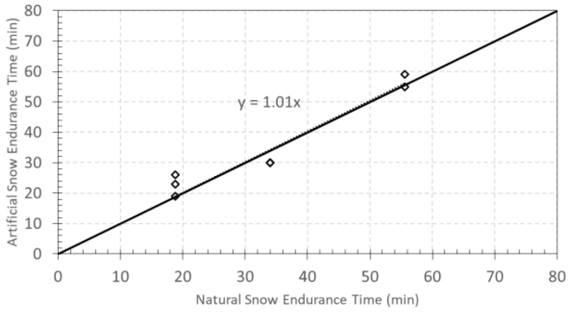


Fig. 5. Type III Artificial and Natural Snow Endurance Time comparison (with a linear full black line representing a 1:1 comparison)

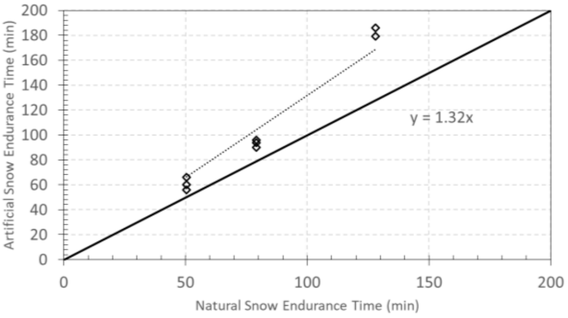


Fig. 6. Type IV Artificial and Natural Snow Endurance Time comparison (with a linear black line representing a 1:1 comparison)

TABLE IX
AVERAGE ENDURANCE TIME (ARTIFICIAL SNOW VS. NATURAL SNOW)

| Test Identification | Natural Snow Endurance Time (min) | Artificial Snow Endurance Time (min) | Difference (%) |
|---|---|---|---|
| TII-1 | 150 | 182 | 21.3 |
| TII-2 | 112 | 112 | -0.3 |
| TII-3 | 63 | 86 | 35.7 |
| TIII-1 | 56 | 57 | 1.8 |
| TIII-2 | 34 | 30 | -11.8 |
| TIII-3 | 19 | 23 | 19.3 |
| TIV-1 | 128 | 183 | 42.6 |
| TIV-2 | 79 | 93 | 18.1 |
| TIV-3 | 51 | 61 | 19.0 |

Considering the slight test rate differences and artificial snow test experimental variability, these results are considered acceptable. For the Type III fluid, all its artificial snow endurance times are within 20% of the natural snow endurance time and correlation can be established for that fluid. This was expected considering that this fluid is a thicker, less complex fluid, with lower aerodynamic performances on aircraft. For the two test conditions where variation exceeds 21.3%, a deeper investigation should be done to try to understand this additional difference.

Not enough information is available on the natural snow testing to draw a definitive conclusion for now.

More parameters should be investigated, like wind speed, particle sizes, etc., as well as the variation of all the important parameters throughout a single test (variation of intensity, temperature, etc. during those outdoor tests).

Also, the most important parameters to successfully define correlation between the two test procedures is still missing and should be deeply investigated, which is the natural snow test variability.

This value needs to be well defined in order to be able to define with certainty correlation between the two tests.

It is still too early in the stage of this project to state whether sufficient correlation is obtained to replace natural snow tests with artificial snow testing. Also, a correlation criterion still needs to be defined (i.e. What is an acceptable correlation) with the regulators, and is this correlation fluid dependent (specific for each fluid brand). There is also the possibility that the correlation is obtained with a correlation coefficient which would need to be defined.

### IV.3. Regression Curve Analysis

Regression analysis is used to determine and generate hold over timetables for all the fluids currently used by the industry, as per ARP5485 from the endurance times determined experimentally [23]. The data obtained in this study are analyzed in a similar manner to investigate correlation between both test methods from a regression perspective. A power law regression is generated with all the data obtained under natural snow conditions for each fluid, as required by the industry standards. The regression curve, as well as the data obtained with artificial snow, is presented in Fig. 7 for the Type II fluid. Table X and Table XI compare the endurance time calculated with the regression curve and the experimental endurance time obtained with natural snow and artificial snow respectively.

The maximum difference between the regression curve and the natural snow results is 16.9% (between the natural results and the regression curve generated with those same results), while it is 33.3% for the artificial snow results.

The data and regression curve for the Type III fluid are presented at Fig. 8. The endurance times calculated with the regression curve and the experimental endurance time obtained with natural snow and artificial snow are compared at Table XII and Table XIII.

TABLE X
TYPE II NATURAL SNOW ENDURANCE TIME VS. REGRESSION CURVE

| Precipitation Rate (g/dm$^2$/h) | Regression Curve Prediction (min) | Natural Snow Endurance Time (min) | Difference (%) |
|---|---|---|---|
| 2.7 | 377 | 324 | -14.1 |
| 3.7 | 273 | 319 | 16.9 |
| 6.9 | 144 | 150 | 3.9 |
| 9.1 | 109 | 112 | 3.2 |
| 14.4 | 68 | 63 | -7.1 |

TABLE XI
TYPE II ARTIFICIAL SNOW ENDURANCE TIME VS. REGRESSION CURVE

| Precipitation Rate (g/dm$^2$/h) | Regression Curve Prediction (min) | Artificial Snow Endurance Time (min) | Difference (%) |
|---|---|---|---|
| 7.1 | 140 | 180 | 28.6 |
| 7.2 | 138 | 184 | 33.3 |
| 8.9 | 111 | 113 | 1.8 |
| 9.4 | 105 | 112 | 6.7 |
| 9.5 | 104 | 110 | 5.9 |
| 14.2 | 69 | 85 | 23.6 |
| 14.8 | 66 | 86 | 30.4 |

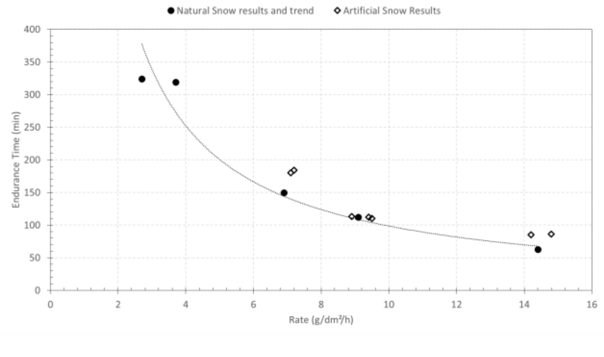


Fig. 7. Regression curve for Natural snow tests with Type II fluid and corresponding Artificial snow Results

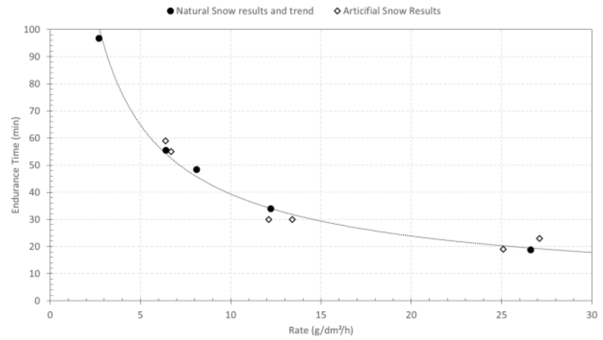


Fig. 8. Regression curve for Natural snow tests with Type III fluid and corresponding Artificial snow Results

TABLE XII
TYPE III NATURAL SNOW ENDURANCE TIME VS. REGRESSION CURVE

| Precipitation Rate (g/dm$^2$/h) | Regression Curve Prediction (min) | Natural Snow Endurance Time (min) | Difference (%) |
|---|---|---|---|
| 2.7 | 101 | 97 | -4.2 |
| 6.4 | 54 | 56 | 2.5 |
| 8.1 | 46 | 48 | 5.7 |
| 12.2 | 34 | 34 | -0.3 |
| 26.6 | 19 | 19 | -3.3 |

TABLE XIII
TYPE III ARTIFICIAL SNOW ENDURANCE TIME VS. REGRESSION CURVE

| Precipitation Rate (g/dm$^2$/h) | Regression Curve Prediction (min) | Artificial Snow Endurance Time (min) | Difference (%) |
|---|---|---|---|
| 6.4 | 54 | 59 | 8.7 |
| 6.7 | 53 | 55 | 4.8 |
| 12.1 | 34 | 30 | -12.5 |
| 13.4 | 32 | 30 | -5.9 |
| 25.1 | 20 | 19 | -6.3 |
| 27.1 | 19 | 23 | 19.9 |

The maximum difference between the regression curve and the natural snow results is 5.7%, while it is 12.5% for the artificial snow results, except for one test.

One test shows a difference of 19.9%, but the endurance time for this test is small leading to a high percentage of variation for a small difference of 4 minutes.

The regression curve for the Type IV fluid and the natural and artificial snow test results are presented at Fig. 9. The endurance time calculated with the regression curve and the experimental endurance time obtained under natural snow and artificial snow conditions are shown at Table XIV and Table XV. The maximum difference between the regression curve and the natural snow results is 5.5%, while it is 38.2% for the artificial snow results.

Regression curves can be a powerful tool to determine hold over timetables from a set of experimental endurance time data.

TABLE XIV
TYPE IV NATURAL SNOW ENDURANCE TIME VS. REGRESSION CURVE

| Precipitation Rate (g/dm$^2$/h) | Regression Curve Prediction (min) | Natural Snow Endurance Time (min) | Difference (%) |
|---|---|---|---|
| 2.2 | 227 | 224 | -1.2 |
| 5.4 | 132 | 128 | -3.3 |
| 8.7 | 99 | 105 | 5.5 |
| 13.6 | 76 | 79 | 3.8 |
| 25.0 | 53 | 51 | -4.5 |

TABLE XV
Type IV Artificial Snow Endurance Time vs. Regression Curve

| Precipitation Rate (g/dm$^2$/h) | Regression Curve Prediction (min) | Artificial Snow Endurance Time(min) | Difference (%) |
|---|---|---|---|
| 5.2 | 135 | 186 | 37.4 |
| 5.6 | 130 | 179 | 38.2 |
| 14.0 | 75 | 96 | 28.3 |
| 14.3 | 74 | 94 | 27.2 |
| 14.3 | 74 | 90 | 21.8 |
| 24.6 | 53 | 66 | 23.6 |
| 25.9 | 52 | 60 | 15.9 |
| 26.7 | 51 | 56 | 10.2 |

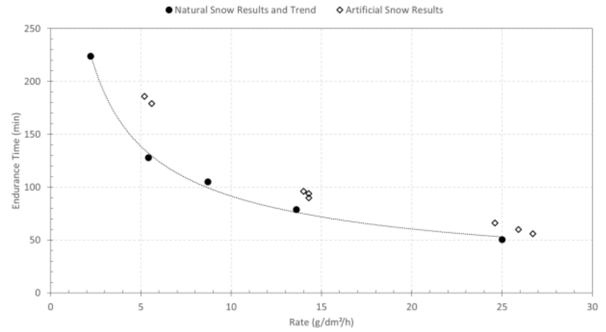


Fig. 9. Regression curve for Natural snow tests with Type IV fluid and corresponding Artificial snow Results

It can be observed that with this method each data point will have a variation from the curve prediction, even the natural snow data from which the curves have been generated. The natural snow shows a discrepancy of up to 16.9% with its own regression curves, while the discrepancy of the artificial snow is up to 38.2% with curves obtained from the natural snow data (not generated with its own set of data). The artificial snow endurance time obtained with the snow machine could be considered in agreement with the regression curve and correlating with the natural snow tests. However, to assess and confirm this correlation, additional natural snow test data should be obtained and analyzed with the regression curve generated in this study to see what level of discrepancy can be obtained when adding new natural snow data that was not used to generate the regression curves. It is expected that, when compared to a regression curve generated with a different set of data, the new natural snow results, even if obtained under the same test conditions and experimental protocol, would show a higher discrepancy than the natural snow results used to generate those regression curve, probably up to levels similar to those obtain with the artificial snow machine, demonstrating a correlation between the two methods.

## V. Conclusion

The snow machine developed and improved at AMIL was used to perform artificial snow endurance tests to recreate a set of data obtained under natural snow conditions. The test conditions were set to match those of the natural snow tests to perform a direct correlation of the results between the two test methods. The results obtained with the artificial snow correlated within 21.3% with the natural snow tests for the grand majority of the test conditions performed with all the fluids tested. Those results were considered acceptable considering the slight differences in test rates obtained with artificial snow, as well as the artificial snow test variability. Only two test conditions exceeded that discrepancy and a deeper investigation should be done to understand this larger gap, especially towards the outdoor snow conditions test variability, which is not well established. The artificial snow results were also compared to power law regression curves generated with the data obtained under natural snow conditions as currently done in the industry to develop the hold over timetables. The artificial snow endurance time also showed good agreement and similar trends with the regression curves generated with the natural snow endurance time. Not enough information was available on the natural snow testing to draw a definitive conclusion on the correlation of the artificial snow tests. More parameters that could influence the tests (wind speed, particle sizes, etc.) should be investigated as well as the variation of the test conditions throughout a single test (variation of intensity, temperature, etc.). The most important information missing to successfully define correlation between the two test procedures is the natural snow test variability.

This value needs to be defined in order to be able to define correlations between the two tests. The same thing can be said to assess the conformity of the artificial snow results with the regression curve technique currently used to generate the hold over timetables. This project lays the important ground work for a new comprehensive project that will be initiated with Transport Canada in order to propose an improved artificial snow test method (snow formation and distribution, thermal equilibrium, physico-chemical interaction) that provides reliable correlation with the outdoor natural snow tests. The first objective will be to perform outdoor natural snow directly on the outdoor test platform at AMIL to observe, analyze and fully understand the process and phenomena involved in outdoor natural snow endurance tests and gather additional data. The second objective will be the investigation of Indoor Snow Tests and Artificial Snow Machine Improvement. In this objective artificial snow formation (i.e. temperature of formation, liquid water content, density, size of the crystals) will be studied as well as investigation of other influent test parameters (wind speed, particle size, etc.) with the final objective of obtaining an acceptable correlation to replace or assist natural snow tests. A numerical model of the snow absorption and fluid flow off will also be developed to assist in this next task. The numerical model will be based on the previous models initiated at the laboratory while including all the new development made on the modeling of non-Newtonian fluids. A validated numerical model including the different aspects of endurance time testing, will be of great help in improving the correlation between natural and artificial snow tests.

This model will also be of great use to the fluid designer in their attempt of increasing the endurance time of the products.

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