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Common Snowfall Conditions Associated with Aircraft Takeoff Accidents

Roy Rasmussen* and Jeff Cole†
National Center for Atmospheric Research, Boulder, Colorado 80307
R. K. Moore‡
United Airlines, Denver, Colorado 80249
and
Murray Kuperman§
United Airlines, San Francisco, California 94128-3800

Snowfall and surface meteorological data from five takeoff accidents related to inadequate deicing or antiicing are examined. Despite common values of liquid-equivalent snowfall rate, temperature, and windspeed, the visibility varied widely. The common values of liquid-equivalent snowfall rates are consistent with recent studies showing that the water content of the snow is the primary factor responsible for the failure of deicing fluids to protect an aircraft from reicing. Liquid-equivalent rates, however, are not available to pilots in real time, and so they instead rely on their own vision or a National Weather Service snowfall intensity estimate based on visibility to estimate snowfall rate. It is shown that snow intensity estimates based on visibility alone can often mislead pilots into thinking that conditions are not as bad as they actually are. We define the hazard as high-visibility–high-snowfall-rate conditions. Nighttime conditions lead to a factor of two increase in visibility during snowfall as compared to daytime, also contributing to the high-snowfall-rate–high-visibility condition. Wind is shown to result in an enhanced accumulation of snow on a wing when an aircraft is facing downwind and stationary due to the approximate 10 deg angle of the wing to the horizontal. Nearly all of the accidents also occurred during the peak snowfall period of a storm in association with snowbands.

I. Introduction

THE accumulation of snow on an aircraft prior to takeoff represents a significant safety hazard due to the possible loss of lift and increase in drag caused by rough ice. An accumulation of as little as 0.8 mm of rough ice on an upper wing surface can result in a 25% loss of lift and increase in drag during takeoff rotation.[1] To avoid this, aircraft are usually deiced and antiiced prior to takeoff. Deicing is usually performed with a heated type 1 fluid, and antiicing with a type 2 or 4 fluid. These fluids, however, are only able to protect aircraft from reicing during active snow conditions for limited amounts of time, depending on the fluid type and concentration and a number of other factors such as liquid equivalent snowfall rate, temperature, and snow type. The time of protection is defined as the holdover time, and approved tables of holdover time as a function of various forms of precipitation such as snow, freezing rain, and fog are required by the Federal Aviation Administration (FAA) to be used in any ground deicing program implemented by commercial airlines.

In this paper we examine snowfall and surface meteorological conditions associated with five aircraft takeoff accidents related to inadequate deicing or antiicing. The motivation for this work is to better understand the type of snow and surface weather conditions leading to hazardous icing conditions for aircraft on takeoff. The results reveal an intriguing similarity of liquid-equivalent precipitation rate, temperature, and windspeed for all five accidents. Visibility, however, was found to vary widely. In Sec. II we examine snowfall and surface weather conditions associated with the five accidents. Section III provides an analysis of the time of occurrence of the accidents in relationship to the passage of snowbands. Finally, a summary and operational implications are given in Sec. IV.

II. Snowfall and Surface Weather Conditions Associated with Five Takeoff Accidents

In Table 1 we present the snowfall and surface weather conditions associated with five commercial aircraft accidents in which ice accumulation on critical aircraft surfaces due to snow was identified as a major contributor to the accident by the National Transportation Safety Board (NTSB) and for which we were able to obtain sufficient surface meteorological data.

The data were obtained from National Climatic Data Center archives of National Weather Service (NWS) hourly surface weather data at the relevant airport using the observation time closest to the time of the accident. Other details in Table 1 such as the accident time and type of deicing fluid used were obtained from NTSB accident reports for each of these accidents. Note that four of the cases were deiced with a type 1 fluid, whereas the remaining case was not deiced at all. The liquid equivalent (LE) precipitation rate was obtained from the NWS standard Belfort gauge with an Alter windshield. The data from this gauge are recorded on a chart recorder, in terms of inches of water. An observer takes a measurement from the chart recorder every hour after scraping off any snowfall that may have accumulated on the sidewalls of the gauge down into the catchment bucket. An example of the chart recorder data from the LaGuardia snowgauge on 22 March 1992 from 1400 to 2400 Eastern Standard Time is shown in Fig. 1. We also examined the chart record to ensure that the data recorded by the observer were correct. The visibilities in Table 1 were taken from the NWS observer estimate just prior to the accident. In most cases the visibility observation was taken within 20 min of the accident.

A number of common elements emerge from Table 1. First, note that the LE precipitation rates are nearly identical, with a low of 0.08 in./h and a high of 0.1 in./h. Second, note that the windspeeds are fairly similar for each case, ranging from 8 to 13 kn. Third, the temperatures observed are close to freezing, ranging from 25 to 31°F. These results suggest that this particular combination of

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*Scientist, Box 3000, Research Applications Program.
†Associate Scientist, Box 3000, Research Applications Program.
‡Aircraft De/Antiicing Instructor, Ramp Services, Denver International Airport, Denver, CO.
§Senior Staff Engineer, Engineering Standards, SFUG, San Francisco International Airport.

Table 1 U.S. jet transport takeoff (TO) icing accidents in snow conditions

Accident location	Date	Accident time (Z)	Aircraft type	Aircraft deicing	Time between deicing and takeoff, min	Fluid type	Precipitation rate, in./h (obs period)	Liquid equivalent precipitation type	Visibilty, mile	Wind speed, kn (Wind direction, deg)	Temperature, °F (°C)
▲ Newark, NJ (Newark International)	27 Nov. 78	1650Z	DC-9	No	——	——	0.095 in./h (1600–1700Z)	Light snow and fog	0.50 (at 1600Z)	8 (30)	27 (−3.9)
● Boston, MA (Logan International)	16 Feb. 80	1908Z	BB-253F	Yes	45–60[a]	1	0.08 in./h (1800–1900Z)	Light snow and fog	2.0 (at 1854Z)	11 (330)	30 (−1.1)
▼ Washington, DC (National)	13 Jan. 82	2100Z	B-737	Yes	50[a]	1	0.09 in./h (2000–2100Z)	Moderate snow	0.38 (at 2000Z)	8 (20)	25 (−3.9)
◆ Denver, CO (Stapleton)	15 Nov. 87	2115Z	DC-9	Yes	27[a]	1	0.10 in./h (2100–2200Z)	Moderate snow	0.5 (at 2100Z)	10 (30)	26 (−3.3)
■ Flushing, NY (LGA)	23 March 92	0235Z	F-28	Yes	35[a]	1	0.10 in./h (0200–0240Z)	Light snow	0.75 (at 0200Z)	13 (70)	31 (−0.6)

[a]Exceeds present Society of Automotive Engineers Aerospace Materials Specification 4737 holdover time guidelines for type 1 fluids.

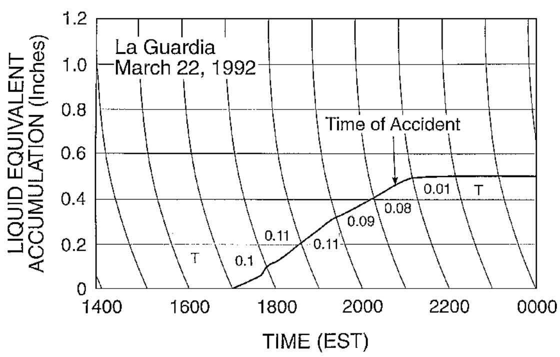

Fig. 1 Liquid equivalent snowfall accumulation as a function of time from LaGuardia Belfort snowgauge: solid line indicates snow accumulation in inches of water, time of the accident indicated, T indicates trace amounts of melted snow, and the numbers along the curve indicate the hourly snow accumulations determined by the observer.

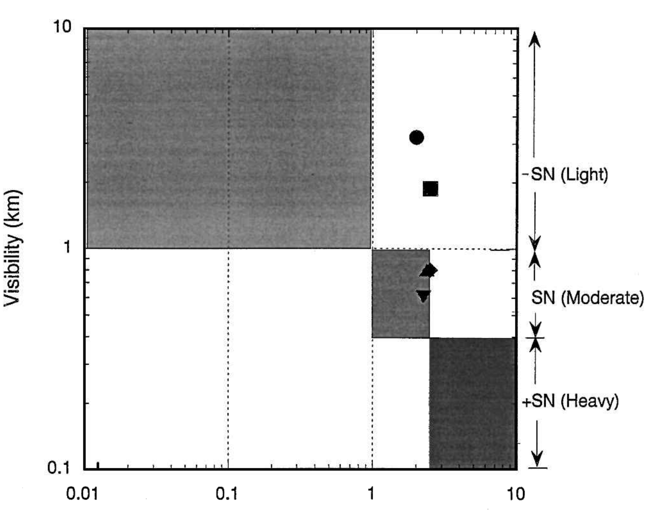

Fig. 2 Liquid equivalent snowfall rate in millimeters per hour vs visibility in kilometers for the five accidents using the data from Table 1; right-hand side indicates NWS visibility criteria for light, moderate, and heavy snowfall intensity.

meteorological conditions may be very conducive to the buildup of hazardous ice accumulations on critical aircraft surfaces.

In the following subsections we examine these three common snowfall and surface weather factors in more detail.

A. Analysis of the Common LE Precipitation Rates and Wide Variation in Visibility

As was mentioned, the LE snowfall rates were very similar during all five accidents. In contrast to snowfall rate, no common visibility value is apparent for these cases. Figure 2 presents a plot of visibility vs precipitation rate using the data in Table 1. We note from Fig. 2 that the visibility from these cases ranges from 0.38 to 2.0 miles, whereas the snowfall rate is nearly constant. Because the NWS defines snowfall intensity based on visibility, with light snowfall occurring when the visibility is greater than $\frac{5}{8}$ mile, moderate intensity when the visibility is less than or equal to $\frac{5}{8}$ mile or greater than $\frac{1}{4}$ mile, and heavy when the visibility is less than or equal to $\frac{1}{4}$ mile, the snowfall intensities during these accidents ranged from light to moderate snowfall intensity, as indicated in Fig. 2. In Fig. 3 we compare the accident data to previous observations of the relationship between snowfall rate and visibility as summarized by Rasmussen et al.[2] The data points represent simultaneous visibility and snowfall rate data collected at the Marshall outdoor test site in Boulder, Colorado, by Rasmussen et al.[2] The snowfall rate was obtained from an Electronics Techniques Incorporated instrument systems 12-in. automatic weighing snowgauge with a resolution of 0.01 in. of water, and the values of visibility from a collocated HSS VPF-730 visibility sensor. The visibility data were collected every minute and averaged over the time period of the snowgauge data. The dashed line represents a curve containing the data points by Fujiyoshi et al.[3] The scatter in the accident data agrees well with the scatter in previous observational studies on the relationship between snowfall rate and visibility. Studies by Poljakova and Tretjakov,[4] Lillesaeter,[5] Mellor,[6] Warner and Gunn,[7] O'Brien,[8] Bisyarin et al.,[9] Muench and Brown,[10] and Stallabrass[11] all show similar scatter in the visibility snowfall rate relationship.[2] Indicated on the right-hand side of Fig. 3 are the NWS snowfall categories for snowfall intensity based on visibility. The results show that the visibility from both the accidents and prior observations have a nearly order of magnitude variation at the critical snowfall rate of 0.1 in./h, and that this variation spans the NWS visibility defined snowfall intensity categories of S−, S, and S+. Thus, visibility is not a good indicator of liquid equivalent snowfall rate. Because recent results[12,13] have shown that the LE snowfall rate determines the holdover time available for a given fluid type and concentration, the use of visibility-based snow intensities of light, moderate, and heavy can be misleading to pilots and ground crews during snow conditions.

To understand this result further, Rasmussen et al.[2] developed theoretical expressions for the relationship between snowfall rate and visibility as a function of various snow types (wet or dry), and as a function of the 27 different ice crystal types (dendrite, plates, needles, etc.). A selected number of these theoretical relationships are compared to the accident data in Fig. 4. Again, the scatter in the accident data is similar to the range in theoretical curves for the various snow and crystal types, suggesting that visibility is not always a reliable indicator of snowfall rate. As shown from both the observations and theory, visibility can be misleading in many cases. We define the hazard as *high-visibility–high-snowfall rate conditions*. The types of snowfall that can result in high visibility during high snowfall rates, from both observations and theory (Fig. 4), are wet snow, snow with rimed crystals (cloud droplets accreted on ice particles similar to rime ice on an aircraft), snow consisting of

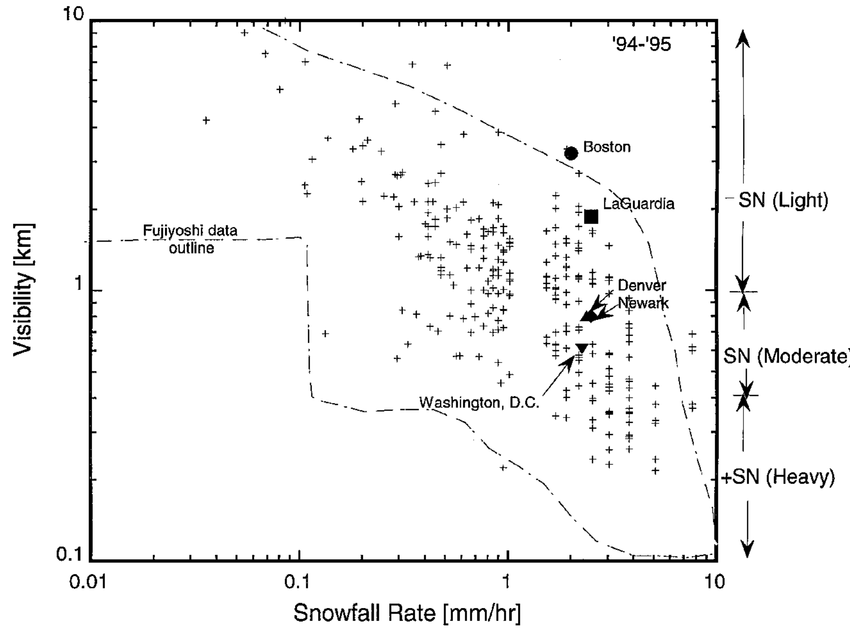

Fig. 3 Comparison of 94/95 NCAR Marshall field site visibility and snowfall data (plus symbols) and Fujiyoshi et al.[3] data (dashed line) to the accident data, bold symbols give the snowfall rate-visibility pairs for the various accidents listed in Table 1.

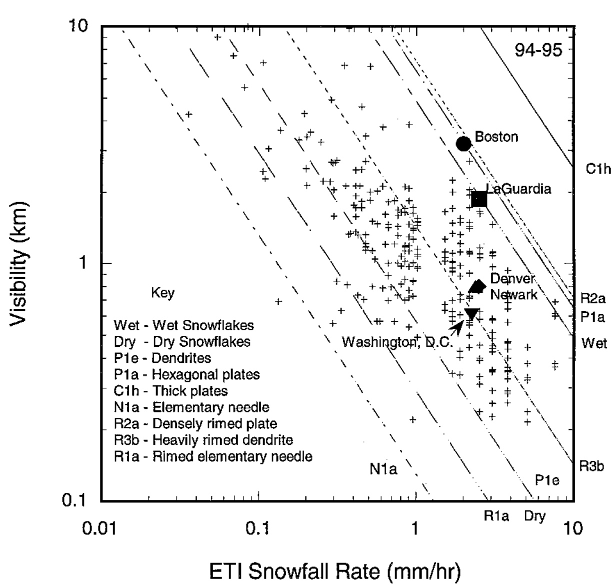

Fig. 4 Theoretical relationship between visibility and snowfall rate from observations and theory, collected at NCAR Marshall field site during the winter of 1994/1995 and plotted as plus symbols [theoretical curves are presented for dry and wet aggregated snow, dendrites (Ple), hexagonal plates (P1a), thick plates (C1h), elementary needles (N1a), densely rimed plate (R2a), heavily rimed dendrite (R3b), and rimed elementary needles (R1a)], the bold symbols give the snowfall rate-visibility pairs for the various accidents listed in Table 1.

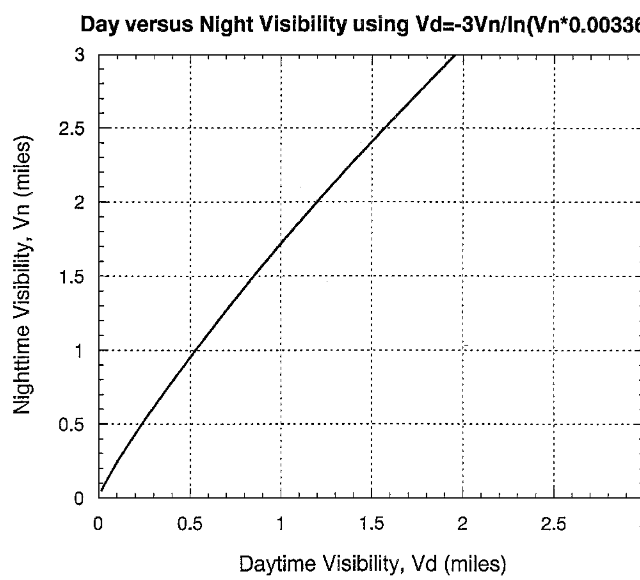

Fig. 5 Nighttime visibility vs daytime visibility for the same extinction coefficient σ using the ASOS equations for day and night visibility.[2]

single snow crystals of compact shape (vs aggregated snowflakes containing 2–100 single snow crystals), and snow pellets.[2] These types of snow particles can lead to high visibility even during high snowfall rates due to their relatively small cross-sectional area and relatively higher terminal velocity as compared to dry, fluffy snow of low density.

Note that the high visibility during the LaGuardia accident was also noted by the first officer of the aircraft. He described the snowfall as "not heavy, no large flakes."[14] Because he did not have access to real-time measurements of LE precipitation rate, the only way he could make a judgement that the snowfall rate was not heavy was by his own vision or the NWS report of light snow intensity. He even notes that there were no large flakes. As mentioned, snowfall with no large flakes leads to a high visibility for a given snowfall rate. In addition, the LaGuardia weather observer characterized the snow as "wet," which also results in a high visibility and high snowfall rate, as mentioned earlier.[2]

An additional factor in the LaGuardia accident was that it occurred at night (Table 1). Rasmussen et al.[2] have shown that visibility increases at night by approximately a factor of two compared to day for visibility ranges less than 3.0 miles for the same liquid equivalent snowfall rate. This is due to the different types of light scattering occurring during the day and night. Figure 5 shows the relationship between day and night visibility for the automatic NWS Automatic Surface Observing System (ASOS) weather system. This is the current operational system providing automatic estimates of snowfall intensity based on visibility at airports and other locations. As can be seen, nighttime visibility is roughly a factor of two higher than the daytime visibility for all visibilities less than 3 miles. Thus, the light snow intensity reported at night during the LaGuardia accident

Table 2 Modified visibility criteria for snow intensity based on temperature and day or night

		ASOS visibility, statute mile					
Condition	Temperature, 0°C	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	1	$1\frac{1}{4}$	$>1\frac{1}{4}$
Snow	<-1	Heavy	Moderate		Light		
Daytime	≥ -1		Heavy	Moderate		Light	
Snow	<-1		Heavy	Moderate		Light	
Nightime	≥ -1		Heavy			Moderate	Light

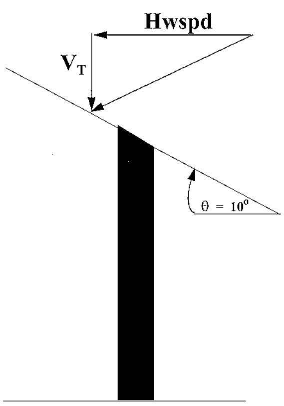

Fig. 6 Schematic of the angled snowflake collection surface at the NCAR/Marshall test site, Hwspd is the horizontal windspeed and V_T the snowflake terminal velocity.

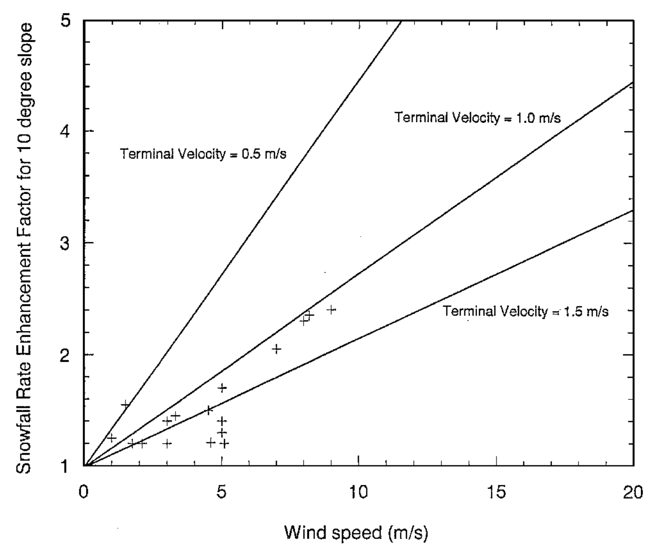

Fig. 7 Precipitation enhancement factor for a 10-deg tilted surface facing into the wind as a function of windspeed from Eq. (4) for various snowflake terminal velocities (solid lines, terminal velocity indicated) and from tilted pan measurements (plus symbols).

should likely have been moderate or even heavy instead of light. The visual estimate of snowfall intensity by the first officer gave him a false sense of security that the conditions were not that bad, when the conditions were actually similar to previous takeoff accidents in snow. Thus, deicing operators should not rely on visibility at night to estimate snowfall rate, and should increase the NWS reported snow intensity to the next higher category to compensate for the factor of two higher visibility at night. A suggested method for doing this is shown in Table 2. Also shown in Table 2 is a compensation for wet snow conditions.

Note that none of the accidents had snowfall rates greater than 0.1 in./h. We speculate that at higher rates, conditions become so severe that either the airport shuts down or special attention is paid to deicing operations. At the lower rates reported during the accidents, the relatively higher visibility can give the impression that conditions are not as bad as they actually are.

B. Common Windspeed

Another common factor in all these accidents is the relatively similar moderate winds observed (between 8 and 13 kn). Wind can effect the heat transfer between the air and a wing, as well as the snowfall accumulation rate on critical aircraft surfaces if the surface is inclined to the horizontal as in the case of the upper surface of a commercial transport wing, which typically angles down toward the trailing edge by as much as 10 deg with respect to the ground. In the following, we consider the potential enhanced snowfall accumulation due to wind effects.

Because the snowfall accumulation on a given surface is determined by the component of snowflake motion perpendicular to the surface, the snowflake mass flux to a given surface (see Fig. 6) can be written as

$$\text{mass flux} = P_s = \text{IWC} * V_{\perp} \tag{1}$$

$$\text{mass flux} = \text{IWC} * [V_T \cos(\theta) + \text{Hwspd} * \sin(\theta)] \tag{2}$$

where the ice water content (IWC) is in gm^{-3} of the snow, $V_{\perp}$ is the component of snowflake velocity perpendicular to the wing or inclined surface, V_T is the snowflake terminal velocity, Hwspd is the horizontal windspeed, and θ is the angle of the inclined surface relative to horizontal. In the last equation we took the perpendicular component of the snowflake velocity that consists of a contribution from both the snowflake terminal velocity and the horizontal motion of the snowflake associated with the ambient windspeed. Equation (2) shows that the mass flux to a surface oriented at 0 deg to the horizontal is just the IWC (gm^{-3}) of the snow times the average terminal velocity of the snowfall (assuming that the airflow around the surface is not affecting the snowflake trajectory appreciably). If, on the other hand, the surface is inclined from the horizontal as a wing is, then the horizontal wind increases the mass flux of snow to the inclined surface by a factor proportional to $\sin(\theta)$ times the windspeed and reduces it by a factor of $\cos(\theta)$ times the snowflake terminal velocity. For a typical wing, θ is equal to 10 deg leading to the following equation:

$$P_s = \text{IWC} * (0.985 V_T + 0.174 * \text{Hwspd}) \tag{3}$$

If we consider the enhancement factor over the accumulation on a horizontal surface, we can write the following equation, which is only a function of Hwspd, snowflake terminal velocity, and angle θ:

$$E_f = P_s(\theta)/P_s(\theta = 0) = \cos(\theta) + \sin(\theta) * (\text{Hwspd}/V_T) \tag{4}$$

In Fig. 7, Eq. (4) is plotted for $\theta = 10$ deg for various typical snowflake terminal velocities. Note that the enhancement factor can reach a factor of 2.0 for a windspeed of 6 m s^{-1} (12 kn) and a typical V_T of 1.0 m s^{-1}. The enhancement factor is actually slightly less than 1.0 at windspeeds less than 0.1 m s^{-1} due to the cosine factor.

To verify this equation, we conducted tests at the Marshall outdoor test site using rectangular plates of area 30×50 cm^2 with a lip height of 1 cm. One pan was inclined at 0 deg, while a second pan located a few inches away was inclined at 10 deg from the horizontal facing into the wind. Wind and temperature data were automatically recorded with a surface weather station while the rectangular pans were exposed to snowfall for an hour. Snowfall accumulation in the pan was determined using an accurate mass balance with a relative resolution of 0.1 gm. Type 2 deicing fluid was used to coat the inside of the pan prior to the test to avoid snow blowing out of the pan during the test. Data are plotted as the crosses in Fig. 7. The enhancement is consistent with the theoretical predictions, and suggests that the mean snowfall terminal velocity is close to 1.0 m s^{-1} as suggested. This value of terminal velocity is very typical of those observed during the tests using the Precipitation Occurrence Sensing System,[15] which uses a vertically pointing Doppler radar, and of previous snowflake terminal velocity studies in the literature.[16]

For the windspeeds observed during the aircraft accidents, (4–6 m s^{-1}), the enhancement factor ranges from 1.75 to 2.0. Thus, if an aircraft is waiting in line to take off and pointed downward (wind blowing from trailing edge to leading edge), the accumulation of snow on a wing can be significantly increased. If, on the other hand, the aircraft is taxiing at the same speed and direction as the wind, this effect is negated. Thus, the highest snow accumulation occurs while the aircraft is waiting in line for takeoff.

Another potential effect of windspeed is to cause preferential icing of one wing over the other, leading to asymmetrical lift and drag forces on takeoff. In the extreme this may result in the aircraft going into an uncontrolled roll. During the LaGuardia accident[14] the aircraft took off at an angle of 60 deg into the wind (wind at 70 deg, direction of takeoff 130 deg magnetic). Thus, when the aircraft taxied to the takeoff runway, the wind was hitting the trailing edge of the right wing preferentially, with the left wing shielded from the wind by the aircraft fuselage. Thus, the roll experienced just after rotation while still in ground effect[14] may have been caused by one wing receiving more snow accumulation than the other. These results suggest that the direction of the wind may be important in determining the asymmetric nature of the snow accumulation on an aircraft on the ground.

C. Common Values of Temperature

The temperatures near freezing (between 25 and 31°F) in all five accidents suggest that wet snow may have been present. As was mentioned, wet snow can produce high-visibility–high-snowfall-rate conditions due to the reduction in cross-sectional area and increase in terminal velocity of the crystals.

Snowfall rates at temperatures near freezing are also larger than at colder temperatures. In Fig. 8 we present a stratification of snowfall rates as a function of temperature from data collected by a GEONOR snowgauge at the National Center for Atmospheric Research (NCAR) Marshall Test Site. As can be seen, the highest snowfall rates occur at temperatures closest to 32°F (0°C). We have also examined snowfall intensity at Denver, Chicago, and New York, and the same relationship holds. Thus, snowfall conditions near 32°F are particularly hazardous due to the more frequent occurrence of high rates and the partial melting of the crystals leading to the misleading condition of high visibility and high snowfall rates.

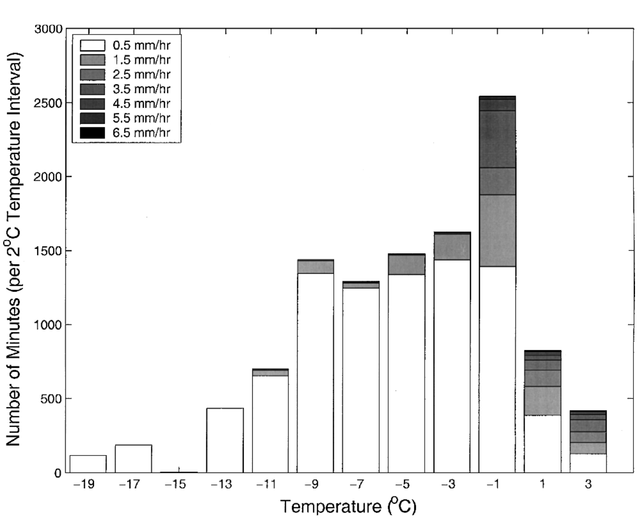

Fig. 8 Frequency of snowfall rate as a function of temperature (data were collected during the winter of 1996/1997 from a GEONOR snowgauge located in Boulder, Colorado), height of the grey shaded bar indicates the number of minutes of the particular rate; the clear bar indicates the frequency of rates between 0 and 0.5 mm/h.

III. Occurrence of Accidents During Period of Peak Snowfall Intensity

A time series of the precipitation intensity from each of the accidents is shown in Figs. 9–13, as well as an indication of the time of the accident. Figures 9–13 all show that the accidents occurred near the time of peak snowfall intensity of the snowstorms. These peak intensity periods are often associated with particular bands of snow, as shown in a meteorological analysis of the Denver accident by Rasmussen et al.[17] With the recent deployment of modern, Doppler radars by the NWS, it is now possible to use the operationally available radar reflectivity data of 1-km horizontal resolution to monitor the location and motion of these potentially hazardous snowbands. The passage of these bands over the airport should be of particular interest to deicing operators due to their potential hazard, and the resulting increased deicing operations likely to be required due to the higher snowfall rates associated with these bands. A system to monitor and forecast the motion of these bands, as well as provide real-time LE snowfall rates every minute, called Weather Support to Deicing Decision Making (WSDDM), has recently been developed at NCAR with FAA funding.[18] These types of systems can help deicing operators identify and anticipate conditions of high

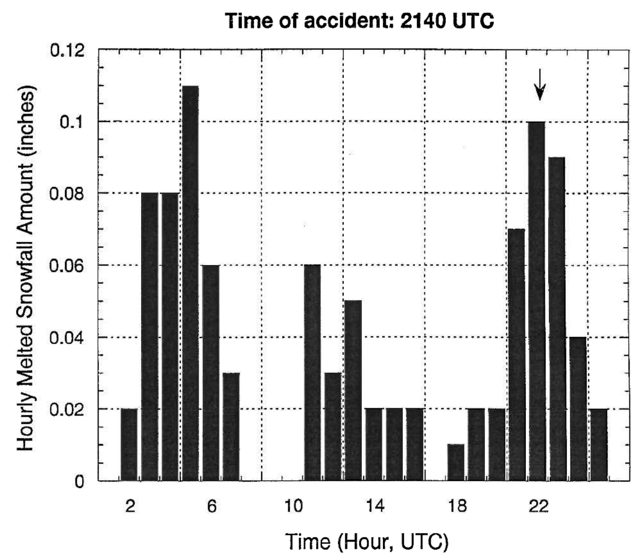

Fig. 9 Hourly melted snowfall amounts as a function of universal time, coordinated for the 15 November 1987 Denver accident; the downward pointing arrow indicates the time of the accident.

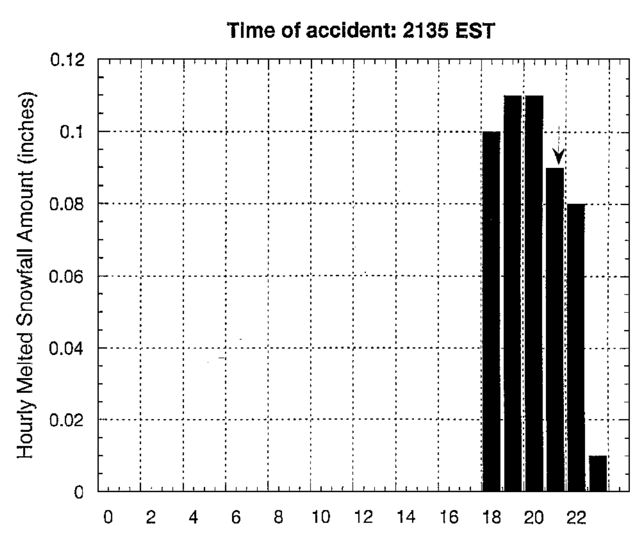

Fig. 10 Hourly melted snowfall amounts as a function of Eastern Standard Time for the 22 March 1992 LaGuardia accident; the downward pointing arrow indicates the time of the accident.

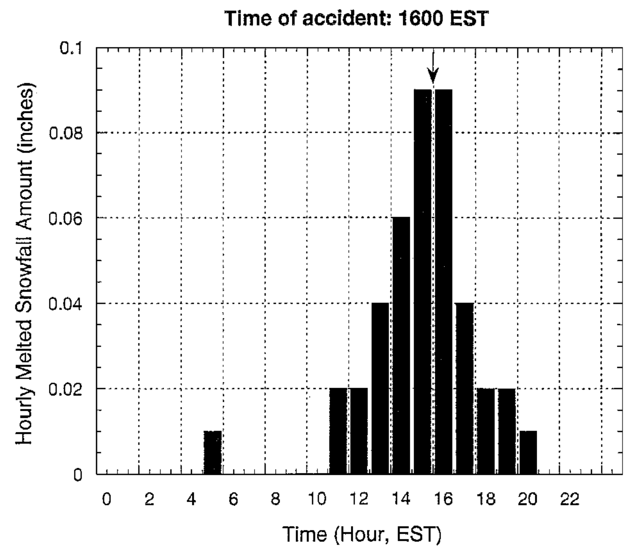

Fig. 11 Hourly melted snowfall amounts as a function of Eastern Standard Time for the 13 January 1982 Washington, DC accident; the downward pointing arrow indicates the time of the accident.

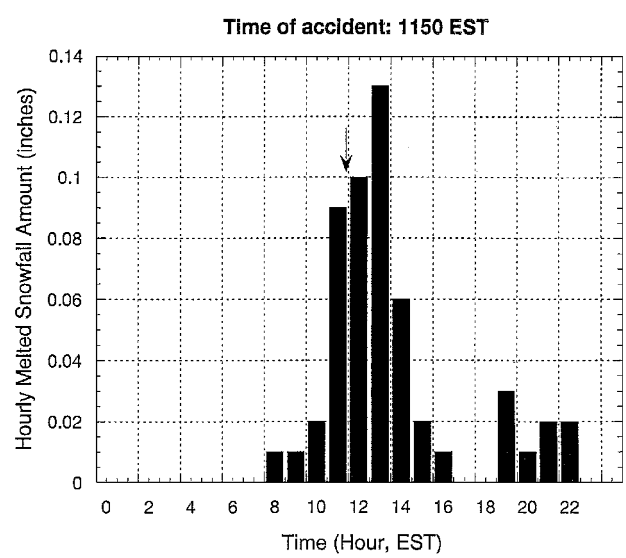

Fig. 12 Hourly melted snowfall amounts as a function of Eastern Standard Time for the 27 November 1978 Newark accident, the downward pointing arrow indicates the time of the accident.

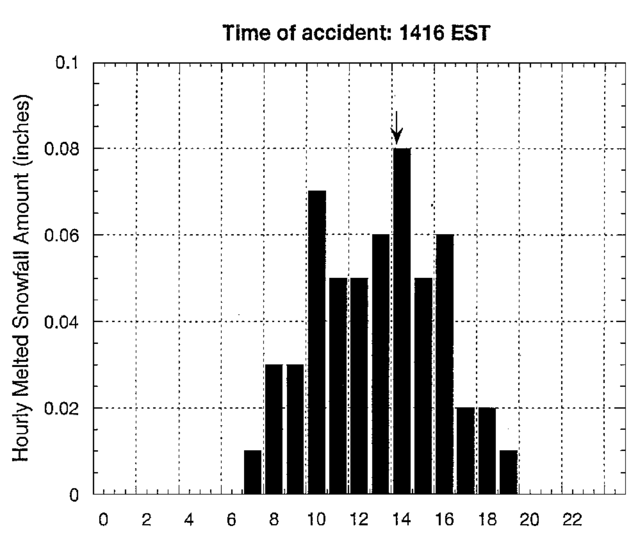

Fig. 13 Hourly melted snowfall amounts as a function of Eastern Standard Time for the 16 February 1980 Boston accident, the downward pointing arrow indicates the time of the accident.

LE snowfall rates, as well as winds and temperatures, providing for safer and more efficient operations.

IV. Conclusions

The data from five ground deicing accidents reveal that common snowfall and surface weather meteorological conditions were associated with accidents in which snowfall was a factor. In particular, the LE snowfall rate was between 0.08 and 0.1 in./h, the temperature between 25 and 31°F, and the windspeed between 8 and 13 kn. This result suggests that these particular conditions may lead to the buildup of hazardous ice accumulation on exposed aircraft surfaces.

On the other hand, visibility was shown to vary widely among the aircraft accidents (from 0.38 to 2.0 miles), suggesting that visibility is not always a reliable estimator for snowfall rate. This was shown to be particularly true for the LaGuardia accident, where the visibility was relatively high, leading to the false impression by the first officer of the aircraft that the snowfall rate was "not heavy"and the NWS to categorize the snowfall rate as light.[14] Visibility is a relatively poor metric for estimating snowfall rate due to the wide variety of snow particle sizes and shapes. Rasmussen et al.[2] have shown that wet snow, snow with rimed crystals, and snow consisting of single, unaggregated compact crystals lead to conditions of high-visibility and high-snowfall rate. Because it is difficult to predict when these crystals are most likely to occur, the use of visibility to estimate liquid equivalent snowfall rate is discouraged. In addition, Rasmussen et al.[2] showed that the visibility at night is twice as high as the visibility during the day for the same snowfall rate due to the difference in light scattering. Because operationally available snow intensity estimates from the NWS are based on visibility, moderate snow intensity during the day can be reported as light snow intensity during the night for the same LE snowfall rate. This result is true for an observer making a measurement of visibility, as well as for the NWS automated ASOS system, which attempts to duplicate the observer. Because the LaGuardia accident occurred at night, this effect may have been a factor in that accident as well. Thus, deicing operators should not rely on visibility at night to estimate snowfall rate, and should increase the NWS reported snow intensity to the next higher category to compensate for the factor of two higher visibility at night.

An analysis of the effect of windspeed on snow accumulation showed that wind can increase snow accumulation on surfaces inclined to the horizontal and facing into the wind by a linear function of windspeed. For a typical wing inclined at 10 deg and the aircraft facing downwind and stationary, the snowfall accumulation could be enhanced by a factor of two for a windspeed of 6 m s^{-1} (12 kn) (wind blowing from the trailing edge to the leading edge of the wing). Windspeeds during the accidents discussed ranged from 4 to 6 m s^{-1} (8 to 13 kn), leading to possible enhancement factors of 1.75-2.0.

The orientation of the plane with respect to the wind was shown to potentially lead to asymmetric accumulation of snow on one wing vs another, leading to unstable conditions during takeoff.

The occurrence of the accidents at temperatures near 32°F was also observed. This temperature band may be particularly hazardous due to the occurrence of wet snow that can lead to the misleading conditions of high snowfall rate and high visibility, and due to the high frequency of heavy snowfall rates near 32°F. Thus, special attention should be paid when the conditions are close to freezing.

Finally, most of these accidents occurred during the peak precipitation rate of the snowstorm in association with snowbands, such as the Denver case.[17] New weather systems such as the WSDDM system[18] take advantage of the newly available WSR-88D radar data and real-time snowgauges to provide deicing operators real-time information on the current and expected location of these potentially hazardous snowbands and the likely liquid equivalent snowfall rates associated with them.

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