A new concept in understanding in-flight icing gathers believers.

Rough Ice

BY JOHN P. DOW SR. AND JOHN MARWITZ

In the early days of aviation, at the advent of thermal ice protection system development, aircraft designers believed that in fighting in-flight icing, the critical variables were the mass of supercooled water that an airplane would transit and the temperature. The measure of mass is liquid water content (LWC). Droplet size of supercooled water, which influences potential icing severity, is measured by the median effective diameter. Droplet size also determines how far back on the airfoil the ice collects. Temperature, mass and location of the ice on the airfoil determine the amount of heat required and the extent of ice protection needed for thermal systems to prevent phase change of water to ice.

Out of the extensive airborne sampling of icing conditions starting in the late 1940s, U.S. Federal Aviation Regulations (FARs) Part 25 Appendix C was developed and defined most of the icing envelope used for certification. While well suited to anti-icing systems, Appendix C does not define the environment adequately to prevent all hazards to deicing systems. Vestiges of this concept of calculating the potential for threats from the development of icing by relying on the measure of mass alone have been slow to be revised, even in the face of icing events to the contrary.

While common usage simplifies the character of the in-flight ice to two descriptors — glaze ice and rime ice — the shape, location, thickness and distribution of ice features, including roughness, are the true discriminators of the effect of ice on aircraft aerodynamics.

Large ice shapes may be problematic, but research is showing that thin, rough ice can have a much greater effect on aircraft performance. These new findings call for a reconsideration of aircraft certification.

This new way to consider icing and its effects began to evolve in 1967 when the University of Wyoming (UW) started operating a variety of state-of-the-art aircraft outfitted for cloud physics work. For the past 40-plus years, UW researchers participated in various weather modification projects, beginning with a search for supercooled liquid water[1], without which there is no weather modification potential.

Data and experience collected in this process inadvertently produced a new concept of in-flight icing: The shape and distribution of the accreted ice, and primarily the roughness, are more significant in terms of performance degradation, by an order of magnitude, than the mass of ice. Pilots often comment on how much ice they are able to handle, creating a misplaced sense of confidence about accretion of lesser thickness that may be far more adverse. Icing severity as often forecast and reported by pilots does not always equate with severity of effect.

Further, the UW observations expanded awareness of the critical factors influencing in-flight icing beyond high LWC to include an understanding of atmospheric temperature and the largest droplets, particularly when considering the performance of deicing systems. There tends to be an "optimum bad" value for each of these parameters: For the flight conditions of the research airplane static air temperature, it is around minus 8 degrees C (18 degrees F). Conditions warming to temperatures well above 0 degrees C (32 degrees F) result in run-back ice — water freezing as it flows — or no ice; at colder temperatures there is mostly ice, no water. Run-back ice can also form ridges aft of ice-protected areas, which can create adverse effects.

The largest "optimum bad" droplet size seems to be around 100 microns in diameter, approximately 2.5 times the thickness of a human hair. These droplets collect on the airfoil in the area of 5 percent to 15 percent of chord. They result in the formation of ice resembling small, pointed "shark's teeth" with the teeth oriented into the local airflow. Smaller droplets collect on the leading edge of the airfoil and cause little

Is Bad Ice

performance degradation. Larger droplets with higher mass inertia and thermal inertia[2] cover the airfoil with a relatively smooth coating of ice, which does not usually significantly degrade the performance of the airfoil.

The "optimum bad" value for LWC is around 0.4 g per cu m. At smaller values of LWC, the rate of ice accretion and rate of performance degradation are low. At high values of LWC, thermal inertia is dominant and, therefore, run-back ice, ice horns and smooth ice occur. And importantly, these droplet sizes can occur either in conditions defined by Appendix C or outside them. However, it was found that specific combinations of droplet size and liquid water content produce the most rapid change in aircraft performance.

Despite a high degree of confidence about the concept, there existed no significant theoretical or icing tunnel data suitable for guidance in the selection and combination of specific, measurable icing parameters. A value was selected — 80VD[3] — as a new parameter to represent the largest droplets, and LWC as the best parameter for cloud composition. The effect of the combined parameters was expressed as simply the first parameter times the second, and the resulting value showed a remarkable correlation to adverse affect on aerodynamic performance. The ice accretion that creates the most adverse conditions is not large.

The massive changes in U.S. icing regulations spawned by the ATR 72 accident at Roselawn, Indiana, on Oct. 31, 1994, finally will be incorporated into an operational airplane 20 years after the event, yet ice roughness in this context has yet to be fully defined or addressed in the FARs, unlike other key milestones in the understanding of icing risk.

Evolution of the regulatory icing envelope defined in Appendix C occurred from 1920 to 1950. There were important milestones in that period.

In 1928, the National Advisory Committee for Aeronautics (NACA) reported "the ice forms in

Two views of distributed-roughness icing, showing the thin layers involved.

University of Wyoming

dangerous amounts only within a small range of temperature below 32 degrees F [0 degrees C].”

Not long after this report, a fatal accident attracted wide attention in the United States. On March 31, 1931, a Fokker F-10 departed Kansas City, Missouri, with an en route stop at Wichita, Kansas, and encountered severe icing. The airplane suffered an in-flight structural wing failure resulting in fatal injuries to all eight occupants, including legendary Notre Dame University football coach Knute Rockne.

The icing aspect of the accident received inadequate attention as a causal factor that forced the airplane into an attitude that resulted in structural failure, the failure becoming the public focus. Nonetheless, it was the first high profile occurrence involving in-flight icing.

After the Fokker accident, and before the natural icing environment was measured or quantified, wind tunnel testing by Eastman Jacobs and Albert E. Sherman demonstrated that the degree of in-flight icing hazard was primarily a function of the location and shape of the accreted ice, and secondarily its mass or thickness. The logic is still sound and its method effective against the shape and/or ridge icing threat.

It wasn’t until 1930 that the “Ice Removing Overshoe,” a predecessor of the pneumatic deicing boot used today, was introduced by B.F. Goodrich, and mechanical systems entered the discussion.

In December 1940, famed Lockheed Aircraft designer Clarence L. (Kelly) Johnson wrote about his wind tunnel research using artificial ice shapes to estimate aerodynamic degradation of stability, control, stall angle and drag. One of Johnson’s conclusions was this: “The icing problem is relatively less severe on large airplanes than on small

Svetlana Bakavets/iStockphoto, Screammm/Dreamstime and Susan Reed

ones.” Johnson’s conclusion on scale was later quantified as the ice thickness (k) to chord (c) ratio or “k/c.” The effects of a certain thickness of ice were less severe for a larger chord (smaller k/c) than a smaller chord (larger k/c).

Researcher J.K. Hardy in 1944 may have been the first to comment on the need for an icing envelope definition, obviously referring to thermal systems: “This [lack] has retarded development, since it has not been possible to analyze the performance of the system under conditions of icing.”

Immediately after World War II, a number of military aircraft gathered data used to form the basis of Appendix C icing condition envelopes still in use. Regulations developed in the early 1950s addressed only pneumatic ice protection systems, however. It was not until 1955 that Amendment 4b-2 to the Civil Aviation Regulations introduced the icing envelopes we have today.

In 1958, the U.S. Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration came into existence, replacing the Civil Aeronautics Authority and NACA, respectively, and the regulations for aircraft were codified in the FARs.

In 1965, FARs Part 25.1419 set forth more comprehensive regulations for transport airplanes and icing condition definitions with no discrimination between thermal systems and mechanical systems; the requirements defined how the applicant would show compliance.

In 1971, FAA Advisory Circular (AC) 20-73 was published. It discussed acceptable means of showing compliance with the icing regulations. For ice protection systems, the concept of impingement limit — or how far back droplets would strike the airfoil surface — was addressed, and the suggested means of designing a compliant system was to use a simple scheme to determine impingement in various flight conditions. The limit of the ice protection system was typically based on how far aft 20-micron and 40-micron diameter droplets would impact the surface. The importance of roughness effects was not recognized or addressed. Thermal anti-ice protection systems predominated in jet transport design.

Groundbreaking research in the academic community started in early 1982 with UW’s work using a Beech King Air 200T. During one notable flight, the drag resulting from in-flight icing reduced the aircraft’s climb capability at maximum power to approximately zero in less than 15 minutes, with airframe buffet indicating stall onset approximately 30 kt above normal uncontaminated stall speed.

While gathering icing data was not part of the UW effort, the airplane performance degradation was so severe that the researchers began an immediate in-depth examination of the recorded cloud physics data and aircraft performance data to understand the cloud characteristics. This was a unique effort to determine a cause and effect relationship. Further, unlike contemporary studies, they recognized the icing variables and associated consequences.

Two potentially hazardous in-flight icing encounters were evaluated. The performance degradation was far greater than was predicted on the basis of LWC or another cloud composition parameter called MVD.[4] The performance degradation comprised an increase in stall speed, a decrease in the coefficient of lift (C_L) and a decrease in climb capability. Both encounters involved substantial numbers of supercooled drizzle droplets (SCDD) in the range of 40–300 microns; the maximum theoretical droplet size in Appendix C's "Intermittent Maximum" envelope is 135.5 microns.

In 1997 and 1998, Ashenden and Marwitz presented additional detailed data from 13 flights in the UW King Air. They presented analysis of performance degradation in conditions of freezing drizzle, freezing rain, warm rain, SCDD, SCDD with high LWC, mixed phase clouds of ice and water, and ice-only clouds.

Change in drag rate, or how quickly drag increased, was selected as the best measure of one aerodynamic hazard because a dramatic increase in drag occurred when the MVD was between 10 and 200 microns. The increase in drag was sometimes large and sometimes small. That is, for a given MVD there was a large range in how rapidly drag increased, but flight experience indicated that the largest droplets combined with the LWC had the most adverse effect on aircraft.

Analyzing flight data, it became clear that the UW pilots inadvertently had flown through freezing rain four times without incident. A number of other experienced pilots related similar experiences in which they had occasionally landed in freezing rain, taxied up to the hangar, and needed assistance from ground personnel to open a cabin door sealed shut by a coating of glaze ice.

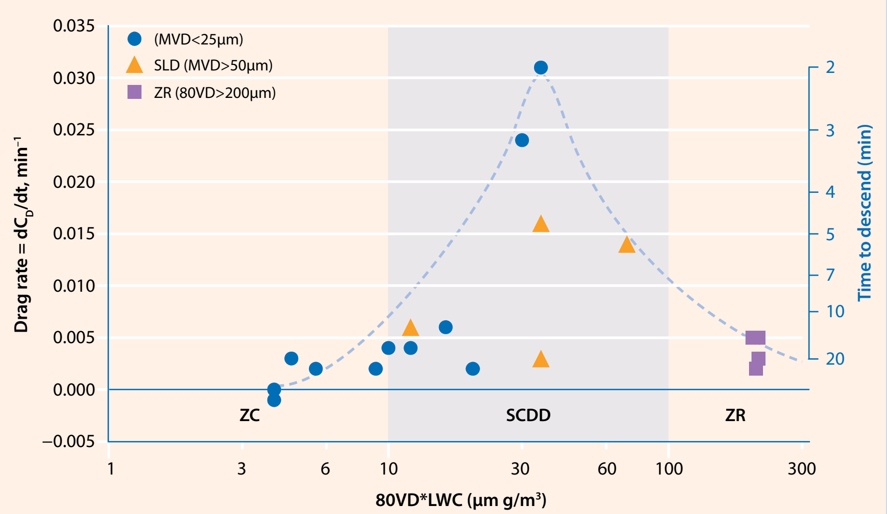
Freezing raindrops are large, greater than 500 microns. This size droplet has large inertial mass and thermal inertia, compared with other droplets. Freezing raindrops, therefore, penetrate the airflow surrounding the airfoil to hit the wing, but do not freeze on contact. Rather, they strike the airfoil, spread downwind and coat the entire aircraft with glaze ice.[5] The coating of ice is rather smooth, and the airfoil is just slightly larger and slightly heavier. The airfoil is still fairly efficient, and the weight of the ice coating is not a significant factor.

The UW researchers found that as the largest droplets increased in size above approximately 30 microns in diameter, the accreted ice from SCDD was not a solid or monolithic formation but formed into the shape of shark's teeth, similar to 10–20 grit, or grain per inch (2.5 cm), sandpaper.

This implied that the thermal inertia of SCDD is small. The smaller SCDDs, therefore, freeze on contact. The obvious deduction was that as the droplets get larger and/or the LWC increases, the thermal inertia will prevent freezing on contact and the ice will tend to be relatively smooth, glaze ice.

The problem was to identify a specific environment that would represent these mass and thermal inertial regulating processes. The parameter selected was the product of 80VD and total LWC. This product was abbreviated as 80VD*LWC and the accompanying graph was produced (Figure 1). Notably, the peak in the curve near 40 would be the same if 80VD on the Y axis was 400 microns and LWC on the X axis was 0.1 g per cu m, or if the Y axis was 100 microns and the X axis was 0.4 g per cu m.

Drag Rate vs. 80VD*LWC



C_D = coefficient of drag; LWC = liquid water content ; min = minutes; µm = micron;
MVD = median volumetric diameter; SCDD = supercooled drizzle droplets;
SLD = supercooled large droplets; ZC = freezing cloud drops; ZR = freezing rain drops

Source: John P. Dow Sr. and John Marwitz

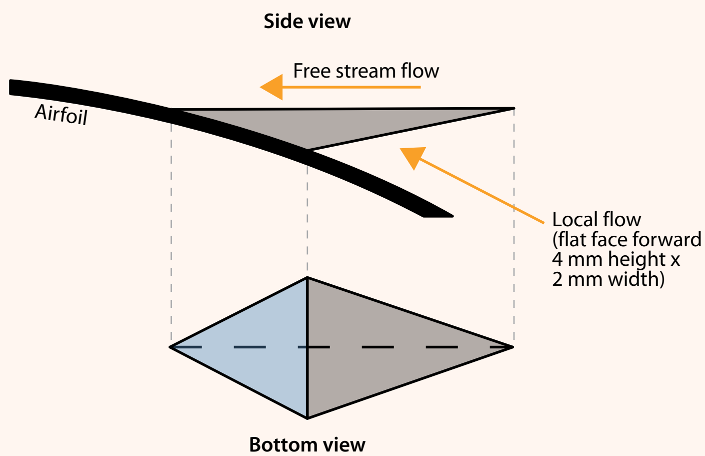
Figure 1

The figure's vertical axis has a second scale showing the time until descent was required to prevent a stall. The C_D for a clean aircraft is approximately 0.045, based on clean aircraft tests, and the C_D when the aircraft has no more climb capability is 0.12. Therefore, the time to a forced descent is inversely related to drag rate.

The worst case shows that the aircraft would be forced to descend in two minutes. These infrequent but consistent conditions contrasted with more common in-flight icing encounters, those involving supercooled cloud droplets and encounters with freezing rain, in which the pilot had roughly 20 minutes to recognize the threat and respond. The major counterintuitive finding has been that this most-adverse condition is not related to the thickness of the ice formation. Therefore, the practice of associating icing severity and threat with only the thickness of ice accumulation is seriously flawed.

Atmospheric conditions that form a shape are better understood by viewing the shape itself. Specifically, a stylized drawing (Figure 2) can depict critical parameters of these distributed elements on the order of only 2 to 4 mm (0.08 to 0.16 in) in length covering 15 to 30 percent of the airfoil surface area.

Stylized Representation of 'Shark's Teeth' Distributed Ice Elements



Source: John P. Dow Sr. and John Marwitz

Figure 2

From 1991 to 1994, the FAA focused on the hazards and remedies for ice-contaminated tailplane stalls. One recommendation was to expand research into conditions beyond Appendix C into freezing rain and drizzle. One reason for the research was that pilots had no means to identify when the icing conditions were beyond the certification envelope and so, beyond the capabilities of the ice protection system.

Initially, the FAA concluded that, in consideration of resources available, "This does not appear to be a program that should be supported at this time." However, a little more than a month later, the Roselawn ATR 72 crash occurred. The airplane was in a holding pattern at an altitude above the freezing level. The flaps were extended in SCDD conditions.

The crew operated the ice protection system, but the reduced angle of attack associated with the flap extension and the large droplets impinging aft of the deicing boots allowed ice growth from droplets running back from the leading edge. This resulted in a sharp-edged ice ridge forming aft of the boots, where it could not be removed, and forward of the ailerons. This ice ridge eventually caused the ailerons to self-deflect to the right-wing-down position; the crew could not regain control, and the crash killed all the occupants.

As a result of this accident, researchers launched an icing tanker test focused on SCDD large droplet conditions. The work by ATR, the U.S. National Transportation Safety Board, FAA, UW and the U.S. Air Force rapidly identified the principal causal factor of the accident. The drag increase — with this form of ice on this airplane in these conditions — was untypically low at 5 percent, plus or minus 5 percent. The industry was then focused again on the size, location and shape of the ice.

The FAA required a quarter-round piece of wood, flat side forward, to be tested just in front of the ailerons. This was termed the "stick test" and employed the principle of the same kind of "protuberance" used six decades earlier, but applied this time for identifying control issues rather than just lift degradation.

As a result of the post-accident research, the FAA issued airworthiness directives that brought attention to the visual cues associated with the droplets of the Roselawn icing conditions. The larger droplets in the test provided distinctive visual cues. However, distributed roughness elements from smaller, yet hazardous-sized, droplets may not present the same visual cues, nor would they form large ice shapes.

During the Roselawn accident investigation, the phrase "supercooled large drop" (SLD) was coined. SLD was defined to refer to drop sizes where MVD exceeded 50 microns, i.e., outside the Appendix C envelope. The problem with this phrase is it includes both SCDD and freezing rain.

On Jan. 7, 1997, an Embraer EMB-120 crashed in Monroe, Michigan, U.S., near Detroit, with fatal injuries to all 29 occupants. Neither droplets outside the definitions in Appendix C nor a long exposure were likely. The most probable ice present was thin and rough and not a ridge, as in the Roselawn accident.

In addition to the Monroe accident, there have been a disturbing number of other accidents paradoxically involving thin ice or small amounts of roughness on airplanes equipped with deicing boots, and not all of these have been in the droplet size region beyond the certification requirements.

On Aug. 16, 2006, the FAA issued AC 20-73A. It introduced a revised concept of assessing ice protection that suggests some of these issues be addressed during certification. While distributed-roughness effects are discussed, the shapes are derived from the icing tunnel, which is not typically representative of natural SCDD conditions and resulting shapes.

Distributed-roughness icing can form within or outside the icing conditions described in Appendix C. The primary mechanism for distributed-roughness icing formation seems to involve a deposition of droplets ranging in size greater than the larger size droplets of the 40 to 109 micron range in Appendix C. This deposition process must be long enough to form a grid or matrix of distributed elements and subsequent ice shape formation, but not so long as to allow the distributed elements to merge into a monolithic shape.

Accordingly, the LWC of the larger droplets can be low. The matrix elements are close but do not touch, and the initial effect of this formation is neither visually extraordinary nor of noticeable aerodynamic consequence. The mechanism of formation is not totally understood, but the data describing the results have been observed and documented.

The visual appearance of distributed-roughness icing formation may be innocuous, with a thickness or element height less than 1/8 in (0.32 cm). If this occurs on a black deicing boot, part of this formation may appear gray. There may be other ice formed at the leading edge as well. While this icing forms quickly and usually is not effectively removed by deicing boots, once outside the cloud, the adverse effects of the small elements, disproportionate to their size, tend to diminish as quickly as they occurred.

Precise effects of ice roughness element shape remain to be determined. Common types of solid geometric shapes are used in icing effects research, but the rapid onset of degradation of aerodynamic characteristics in distributed roughness — without change in location of the ice on the airfoil or the formation of large sizes — strongly suggests sharp-edge features and shape play an essential role. This infrequent condition can result in a hazardous ice shape that is two to five times thinner than even that recommended for operation of deicing boots. Moreover, distributed-roughness icing is not effectively removed even if the deicing boots are operated, or if thermal anti-icing use is delayed.

More work needs to be done to fully define this problem, but it is imperative that flight crews realize that a major performance degradation can be caused in a fairly short time by a relatively small amount of ice that cannot be countered by most deicing systems, with smaller airfoils being more susceptible to severe effects than larger airfoils. And, finally, aircraft certification standards and guidance must be reconsidered.

John P. Dow Sr. is a consultant in aircraft certification and icing with more than 25 years of experience in airplane icing issues relating to airplane certification and accident investigation.

John Marwitz is professor emeritus, University of Wyoming and president, Wyoming Weather Inc.

Notes

1. Supercooled liquid water can exist in the liquid phase at temperatures as cold as minus 40 degrees C (minus 40 degrees F).
2. Water at a temperature slightly below freezing must reject approximately 80 calories per gram to change state from liquid to solid (ice). This takes a discrete amount of time for the heat transfer process and is referred to as "thermal inertia."
3. The proposal was to begin with the common cloud measurement called the "droplet spectrum cumulative mass 80th percentile diameter, in microns," abbreviated as 80VD.
4. The measurement is called the "droplet spectrum cumulative mass 50th percentile diameter, in microns," abbreviated as MVD.
5. Freezing rain has a low freezing fraction, a measure of the fraction of water that freezes on the surface area it strikes. A freezing fraction of 1.00 means all the water that impacts a surface freezes on that area. A freezing fraction of 0.0 means none of the water impacting an area on the surface freezes there.