The Question of Experience in Icing Operations

S.D. Green
Air Line Pilots Association

One of the most perplexing statistics to come out of recent icing incident investigations is the average experience of the flight crews involved. It turns out to be something on the order of 5500 hours. Often the crew has substantial time in type; the captain of the EMB-120 which crashed at Detroit in 1997 had 5300 hours, 2600 in type[1]. His first officer had 2600 hours total time and 1100 of that in type. The captain and first officer involved in the Roselawn accident had 7900 hours and 5300 hours total time, respectively, with 1600 and 3200 in type[2]. The captain of the ATP involved in the Cowly incident in 1991 had 8700 hours total with 1300 in type; the first officer had 900 total with 650 in type[3]. Last year, the captain of a Saab 340 which fell out of a holding pattern due to icing in Australia, losing 2600 feet prior to recovery, had over 13,000 hours total; 3500 of it was in type[4].

There is a widely held belief in aviation that experience is an essential factor in the equation leading to safety. Yet it is difficult to define precisely what experience is, what shades it comes in, and how it contributes to safety. The image called forth may have more to do with the spirit of rugged individualism which prevails in aviation history and in which pilots take great pride. Yet the question of how we know what we know often remains obscure.

If we examine what we know about inflight ice accretion and how we know it, we may end up with more questions than we have answers for. Nevertheless, the confidence that most pilots have in this knowledge is unabated. Vigeant-Langlois and Hansman[5] in 1999 evaluated the decisions of 89 pilots who typically operate aircraft which are certificated for flight in icing. Of this group, 84% reported occasional to extensive experience in icing. 87% reported that they had a comfortable to familiar understanding of aircraft icing. These pilots responded to simulated icing scenarios used to evaluate five different data display concepts. Of those who made "good" decisions (which resulted in optimal icing avoidance or escape), the level of comfort with those decisions ranged from 40% who were very comfortable and 39% comfortable to about 4% who were uncomfortable. Interestingly, of those who made "poor" decisions (which resulted in penetration of severe icing conditions), 36% were very comfortable with their decisions and 39% were comfortable; 8% were uncomfortable. No correlation appeared to exist between quality of avoidance decisions and the comfort level with those decisions. This study is most interesting since pilots were presented with organized information about the icing conditions, in formats of a better quality than is presently available in real operations. Yet many still made poor decisions, and were unable to evaluate the quality of their decisions when they made them.

In fact, there is little doubt introduced by the published information which is commonly available to the pilot. The Airman's Information Manual definition for rime ice is "rough, milky, opaque ice"; clear ice is defined as "glossy, clear, or transluscent ice". One company operating manual states that, “Clear ice...generally conforms to the shape of the structure to which it freezes and, therefore, is slow to distort the form of the leading edge and wing.” Another manual states that, “If an airfoil is thin and highly streamlined, ice forming on it is more likely to assume its shape than if it were blunt nosed.” Many operating manuals contain statements such as,"boot operation must be delayed until 1/4 to 1/2 inch of ice has accreted to avoid ice bridging".

Further inquiry into these statements yields an amazing absence of substance.

Ice Bridging

In 1995, Render and Jenkinson[6] interviewed a number of pilots in Great Britain. All were familiar with ice bridging, and operated their deicing boots accordingly. Yet none had ever seen it. At a 1997 FAA sponsored conference regarding ice bridging, no manufacturer reported ever seeing it during flight test[7]. A review of the NASA Aviation Safety Reporting System data yields no records which attribute an icing event to ice bridging.

In 1956, Dean Bowden[8] conducted research for the NACA on the performance of pneumatic deicing systems. In the introduction to his paper, he described the failings of older, low pressure systems. He wrote that, besides auto inflation and drag rises during the inflated phase, "...the de-icing performance of the [early] boots was not always reliable, and occasionally an ice cap would not be shed from the wing leading edge.". Bowden went on the write that these problems had been dealt with, by 1956, through the use of a new type of boot consisting of "a large number of small spanwise tubes operating with a high inflation pressure". He investigated the performance of a pneumatic boot in a variety of icing conditions, including both rime and glaze icing conditions. He demonstrated that, for the system which he tested, a one minute cycle period usually produced the minimum average airfoil drag increase when compared to a four minute cycle.

The investigation did find that for lower ice accretion rates, the four minute cycle yielded lower average drag than the one minute cycle. However, the difference in this case was only 2 to 6 percent. For higher ice accretion rates, the 1 minute cycle was clearly superior. Within this observation lies a truth which may explain the origin of delayed boot operation.

A pneumatic boot does a more efficient job of shedding ice if the ice is allowed to develop to some specified thickness. B.F. Goodrich[9] pointed out that "Generally, the percentage of ice removed from a leading edge increases if the ice is allowed to reach a "recommended" thickness before cycling the system." This leads to a cleaner wing with less drag early in the intercycle period, but only for a brief time. Later in the intercycle period, the wing becomes contaminated; the longer the period, the greater the contamination and resultant drag increase. It is not surprising that Bowden found the one minute cycle to be optimum for most conditions. While the overall ice shed is less efficient, the lower drag during the later portion of a short intercycle period dominates the higher drag in the early phase of the period.

A wing with unremoved ice yielded significantly greater drag increases over time. Bowden's data indicates that in a glaze ice condition, airfoil drag can double from the clean value in eight minutes, and double again in another 5 minutes. Albright, et.al[10]., in 1981 found drag to increase by over 400% over the uncontaminated airfoil value during a 15 minute exposure to conditions similar to Bowden's, although with a different airfoil.

It is important to note that the drag increases cited represent airfoil section drag only, and do not include induced drag or drag resulting from the rest of the airplane. When considered as a whole, the increase in total airplane drag would not be as severe. But it can easily be severe enough. In the 1991 icing upset event at Cowly, England, the official report[3] indicates that the [airplane] drag coefficient increased roughly 40% in less than 2 minutes during an encounter with glaze ice, leading to a stall.

Nowhere in his report does Bowden discuss the formation of ice bridges, regardless of cycle period or icing condition. He apparently did not see any bridging during the experimental work. But what is more interesting is that in his introductory summary detailing the shortcomings of early pneumatic systems, he addresses many specific problems, including "occasionally an ice cap would not be shed from the wing leading edge"...but he does not describe the mechanism of bridging.

B.F. Goodrich[9] has also commented that they are not aware of any experience with ice bridging. This includes work in natural icing or their icing wind tunnel, and also includes testing with 1 or 3 minute system cycle periods. While they have worked with many manufacturers who have adopted automatic cycling of their boots, Goodrich is not aware of any subsequent reports of ice bridging associated with an automatic system.

Interestingly, the United States Army Air Corp Pilot Information File[11], updated to March 1, 1944, makes no mention of ice bridging. The document was published to "promote safe flying and operational efficiency", and to keep pilots aware of "the results of current research...".In the section covering wing deice boot operation, the instructions state that, "Turning the de-icer valve "ON" automatically starts a motor on the distributor valve, causing the de-icer shoes to be inflated and deflated alternately, breaking the ice from the shoes." This clearly references an automatic system, and it is not airplane specific; yet there is no guidance regarding its usage except to turn it on and then turn it off prior to landing.

In any event, while no accidents or incidents resulting from ice bridging have appeared in data collected to date, such is not the case for flight crews who delay operation of the ice protection system. In a set of 72 events involving multi-engined aircraft (derived from NTSB, ICAO, Eurice, Transport Canada and Flight Safety Foundation accident and incident reports) in which the flight crew was aware of ice accretion, and in which the status of the ice protection system could be determined, 23 took place before the system was operated.

This includes the ATP upset at Cowly, England in 1991 and nearly all of the EMB-120 events, as well as others. Yet there are many events in which nothing is known of either flight crew awareness or ice protection system status. This is usually due to a lack of survivors and a lack of adequate recorders.

Collection Efficiency

The development of an ice shape requires a freezing process which takes place after the droplet impinges on the wing. The character of the ice shape is predominantly determined by the mass of water, the size of individual droplets, the efficiency of droplet collection, and the temperatures of the air, the droplets, and the wing. These factors make up the thermodynamic parameters of the freezing process. Changes in any of them change the process and the ice shape.

One of the more critical factors is the efficiency with which the wing collects liquid water. The area swept by the wing is roughly equivalent to the maximum thickness of the wing section. Within this area, the question is how much liquid water can move out of the way before the wing passes through? There are two factors which influence the answer. One is droplet size. Larger droplets have more mass, more inertia and are less prone to move out of the way. Smaller droplets are lighter and more easily follow the motion of the air ahead of the wing.

The second factor is how much warning does the wing provide? Subsonic wings generate a pressure wave ahead of their physical structure. A larger, thicker wing will create a larger wave, providing more energy and time to move water droplets aside. A thinner wing will produce less of a wave, leading to more liquid water remaining in the way as it passes. Thus, smaller, thinner wings, or other objects, are much more efficient ice collectors than larger wings.

This explains why horizontal stabilizers, propeller blades, antennae and ice evidence probes are usually the first to accrete ice. However, there is no reason to believe that an efficient collector of ice will necessarily develop a "streamlined" ice shape. The right temperature conditions will generate very unstreamlined shapes. And the more efficient collection ability of the smaller wing will enable those shapes to be larger, thus more critical, relative to wing size.

Clear Ice

In the engineering community, inflight ice accretions are generally described as either rime, glaze, or mixed ice. There is no reference to clear ice in common use. Further, none of these ice accretion descriptions are based on opacity; they are based on physical shape. This is because it is the shape, not the opacity, which causes changes in aerodynamic behavior.

In this context, glaze ice has long been known to be the most detrimental. It results from a relatively slow freezing process, which allows liquid water to transport from the impingement point to some point downstream. Typically, this transport distance is quite short, but, depending on the thermodynamics of the transport flow, it can be sufficiently long to allow "runback" to points aft of the protected areas.

In many cases, though, the water flows only a short distance before freezing, leading to ridges of ice immediately downstream of the stagnation region at the leading edge. These small ridges provide ice dams, blocking additional flow and leading to the growth of large, often craggy protrusions known as "ram's horns". The result is substantial flow separation and turbulence. Lift and drag are degraded, often quite seriously.

Glaze ice very rarely conforms to the shape of the leading edge. The USAAF Pilot Information File in 1944 described it as building out "from the leading edges in a mushroom shape that spoils the airfoil..." It may or may not be transluscent or clear. In some cases it can be very clear, and thus difficult to detect. In other cases, it may be quite rough. Bowden described it as "slightly rougher and more irregular" than rime. The term "clear" ice can be misleading.

Rime ice has a reputation for being less detrimental. This is a pretty loose generalization. The relatively uniform layer of roughness created by riming the leading edge can have substantial aerodynamic effects. Some research has noted that the effects of small roughness can be as detrimental as glaze horns. Trunov and Ingelman-Sundberg[12] in 1979 reported that, with respect to the Vickers Viscount tailplane, "an ice roughness equivalent to 1/1,300 of the chord length reduced the maximum lift and altered the elevator hinge moment dramatically, almost as much as the large ice deposits did." Bowden[8] also found drag increases with a standard roughness of .00046-chord (about 1/32 of an inch on a 5 foot chord). Generally, these increases were greater than that for residual ice. Thus, the statement that glaze ice shapes are the most detrimental does not suggest that rime shapes are not detrimental. There is really no reliable and predictable relationship between the type of ice and the resulting degradations.

Presently, the FAA[13] is involved in a major effort to develop an understanding of what features define a critical ice shape. The location aft of the leading edge, the thickness of the ice, the size of the roughness elements, and the height and angle of any horn shape all play important roles in the aerodynamic effects that will be encountered. Small variations in these features can substantially change the resulting effects. Moreover, different ice shapes can create completely different effects, more than one of which can be dangerously detrimental. So it is possible, on a given wing, for one ice shape to have little effect at the wing root but have significant effects near the tip. Another shape may have more significant effects near the root. One shape may influence drag more than lift; another, depending on chordwise location, ridge height, angle, etc., may predominantly affect control hinge moment. All of these effects will vary with angle of attack.

It is instructive, then, to consider that while researchers are conducting extensive batteries of tests in wind tunnels and icing tunnels to understand the effects of variations in the critical features of ice shapes, many line pilots believe they can discriminate a dangerous ice accretion simply by visual inspection.

Freezing Rain/Freezing Drizzle

Nearly all Part 121 Operations Specifications contain authorization for takeoff and landing in light or moderate freezing drizzle or light freezing rain. These ops specs are based on holdover times for de-icing/anti-icing fluids; since holdover times for heavy freezing drizzle, moderate and heavy freezing rain are not published, there are no ops specs approving operation in those conditions.

Yet most turboprop airplanes in Part 121 service have an Airworthiness Directive[14] which specifically describes freezing rain and freezing drizzle as manifestations of supercooled large droplets (SLD). The ADs point out that there is a strong relationship between such conditions and severe icing. Further, the FAA[15] has stated in other publications that no airplane, turboprop or otherwise, has been certificated for flight in freezing drizzle or freezing rain. Taken together, these statements paint concrete yet conflicting pictures, allowing misconception to develop.

The engineering standard used for design and certification in icing conditions, known as FAR Part 25, Appendix C, does not contain a characterization of freezing precipitation of any type or intensity, although it is likely that some larger drops fall within the Appendix C definitions. In itself, this does not constitute a prohibition on flight in these conditions. However, freezing precipitation was not considered in the design of the ice protection system. FAA policy[15] is to normally consider droplets only as large as 40 microns to determine the chordwise extent of ice protection; freezing precipitation droplets can be as large as 1000 microns or more. The ice resulting from freezing precipitation was not considered in handling and performance evaluations. In fact, virtually nothing is known about the airplane's characteristics with ice accreted due to freezing precipitation. This makes a rather strong case for the icing resulting from freezing precipitation to fall into the category of ice referred to in FAR 121.629(a) as "icing conditions...that might adversely affect the safety of the flight.", which requires that the pilot in command not continue to operate or land in those conditions.

So while a great deal is known about the performance of fluids in these conditions, nothing is known about the aerodynamic characteristics with ice accreted in these conditions. Thus, beginning at rotation, the flight crew is operating in an environment which has not been explored by the manufacturer or by the FAA during certification. Freezing rain can extend upwards of 7000 feet above the surface; freezing drizzle up to at least 12,500 feet[16], and can be found at much higher altitudes.

And where did the ops specs get an approval for landing...in conditions only approved because of fluid performance? This type of specific yet wholly unsubstantiated operating approval is the key to understanding why icing accidents happen to experienced crews. The ops specs are quite specific regarding the required equipment and certification for Category II and III landings. The approval to takeoff and land in freezing precipitation conveys the same sense of certainty, when none exists.

The point is not that all intensities of freezing precipitation pose a demonstrated hazard to all airplanes. The point is that many are suspected to, and that without data providing the same standard of safety in these conditions as is already provided in the design conditions, it is simply not appropriate to carry passengers into such conditions.

The Effects of Angle of Attack

The mechanics of how an ice accretion affects the wing can be insidious. Pilots have used the cue of increased drag for ages to detect ice accretion otherwise unseen, or to estimate the accretion's severity. Slight additional power requirements indicate slight drag increases, and this may be interpreted to mean "slight" ice accretions. Many pilots thus allow the relationship of ice, drag and time to develop a mental picture of icing that is characterized by a linear growth of degradations over time. This is certainly the most visible consequence of ice accretion, and repeated exposure to it can lead to a rather concrete conceptualization of ice effects. But without a comprehensive understanding of the different ways ice affects an airfoil, the mental picture is incomplete. Even with this understanding, the routine exposure to drag increases while never encountering other degradations is tailor-made for complacency. There is in fact nothing in the pilots routine experience to indicate the dominant role played by angle of attack.

This classic mental picture starts one down the wrong path in at least two ways.

First, there is no particular relationship between the magnitude of a drag increase and other aerodynamic degradations. It is not possible to determine, based on the severity of a drag rise, whether other things such as lift coefficient will be affected, or when. In fact, the drag itself may not be present prior to the development of other serious degradations. A complete shift in aileron hinge moment occurred during the ATR accident at Roselawn, Indiana in 1994[2]. At the same time, no drag rise that was detectable to the flight crew was recorded on the DFDR. The relationship of power to airspeed remained virtually unchanged.

Second, drag effects are probably more closely related to changes in angle of attack than time. Gray and von Glahn[17] in 1953 concluded that "Relatively small formations of glaze icing...increased the drag coefficient of the airfoil over the range of conditions studied by less than 27 percent following a 30 minute icing period, except for the simulated landing approaches." With regard to landing approaches, "A glaze ice formation on the leading edge section for a simulated approach condition, during which the airfoil attitude is increased from 2 to 8 [degrees] angle of attack, caused a severe increase in drag coefficient of over 285 percent over the bare airfoil drag at 8 [degrees] angle of attack and was accompanied by a shift in the position of the momentum wake that indicated incipient stalling of the airfoil." Bowden[8] in 1956 found that rime ice accreted at a 0 degree angle of attack increased airfoil section drag by 27%. However, when the angle of attack was increased to 4.6 degrees, the same ice shape increased section drag by 122%, compared to a 65% increase found with a rime ice shape accreted while at 4.6 degrees angle of attack. Albright[10] reported that after accreting glaze ice for 10 minutes at an angle of attack of 7.8 degrees, the angle was increased to 10 degrees. The result was an increase in drag from 322% of the bare airfoil to 665%.

As in the discussion earlier, these drag increases represent airfoil section, not airplane, drag. But the point is clear. Drag rises may be directly related to changes in angle of attack <u>after</u> the ice is accreted.

In a set of 164 icing accidents worldwide, 122 took place during the approach and landing phases of flight. This may be due to the effects of ice while increasing angle of attack during those phases.

Most pilots understand that ice accretions can cause premature flow separation from the wing, thus reducing the stall angle of attack. But there is more to this concept. The wing is normally designed to achieve a favorable flow separation during an uncontaminated, or clean wing, stall. The designs that most pilots develop stall experience with are relatively benign, typically developing flow separation from the trailing edge forward during the stall development. Based on the tail effectiveness, many will not truly stall before the tail dominates the pitching moment and forces the nose down. This is a very desirable design feature, and is present in some form even with higher performance aircraft. Thus, it is likely that a large majority of pilots have little or no experience with the less friendly types of stall that have been designed out of the airfoil.

However, ice accretions can add spoiler like protrusions into the boundary layer; they can effectively change the airfoil camber; or they can tighten the leading edge radius. These effects easily lead to stall behavior that is not at all benign. Rapid onset of separation, sharp breaks and complete stall can be encountered. Instead of a trailing edge separation dominating the stall development, the separation may initiate at or near the leading edge. A separation bubble may develop over a portion of the wing, shifting the region of pressure recovery aft until it suddenly influences the aerodynamic balance of a flight control. Complete flow separation may occur before any aerodynamic warning occurs. The gentle break that many pilots associate with stall may instead be a very abrupt, harsh break.

The insidious nature of this lies with the departure of aerodynamic characteristics from the linear part of the curve to the non-linear.

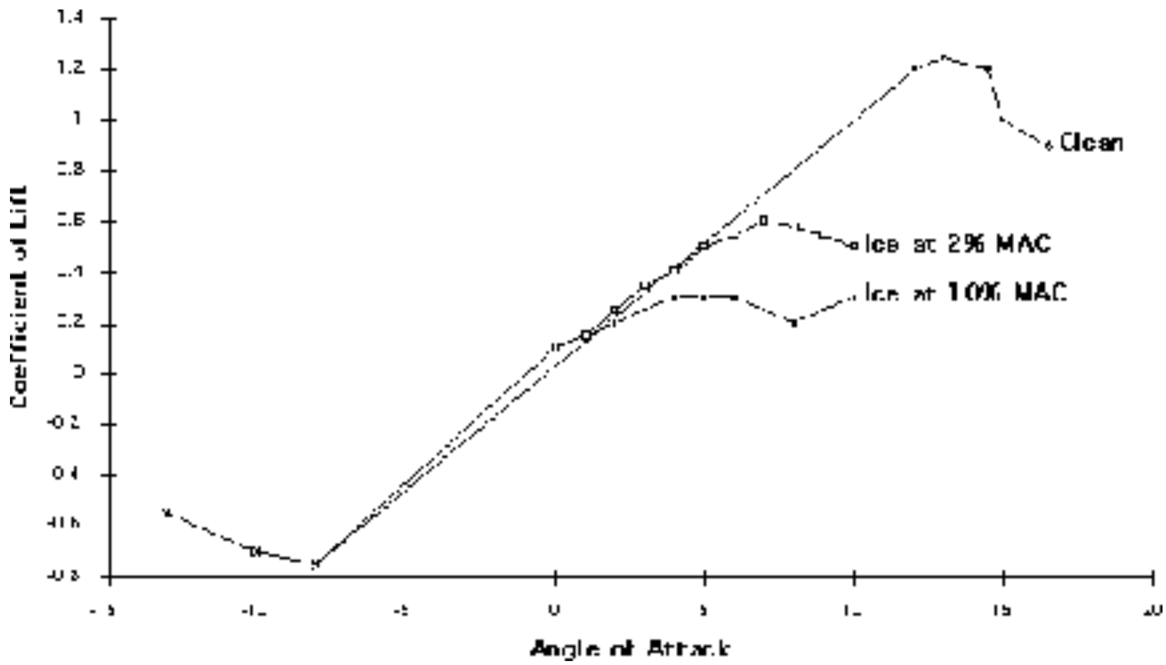

Figure 1 - C_L Effects with Small Step Shape

In Figure 1, the curves representing coefficient of lift are plotted for a clean wing and a wing with an artificial step shape located at 2% MAC and 10% MAC. This particular airfoil was a modified NACA 23012, and the data was developed by Bragg et.al[18], in 1998. The important thing to note is that, up to the point where the curve reaches a maximum and bends downward, the straight, or linear, segments more or less overlap. This is not always the case; often the linear portion representing a contaminated wing will rise at a slightly different slope. However, in any case, the aerodynamic behavior of the airfoil may not feel very different to the pilot from the clean wing case...until the divergence is reached. In the case plotted in Figure 1, the wing is performing pretty much the same at 5 degrees angle of attack with a step shape at 2% as it is while clean. At 7 degrees angle of attack, it is not the same at all.

In experimental flight test work, it is quite common to approach an unknown point in small, careful steps. By working up to the point or region in question, flight test personnel hope to detect indicators of a "cliff", or radical change in flight characteristics, before actually encountering it. This is not a great deal different from the methods that a line flight crew might use to evaluate an unknown or potentially dangerous flight condition. Therein lies the trap.

The more successful experience a pilot gains in icing, the more he may believe in his ability to evaluate ice accretions for handling and performance degradations. Unfortunately, the subtle warnings that many perceive will be seen or felt prior to a major upset...simply

So with operations specifications which imply a certification that does not exist, a misleading definition of the most detrimental ice type, an ice protection system operated more or less on myth, a belief in the ability to visually assess a hazardous ice shape, and an expectation of clear, plentiful warning before an upset...the experienced pilot suffers a handicap few could surmount. In the last few years, since the tragedies of Roselawn and Detroit, the industry and authorities around the world have been working to improve the design and certification of airplanes approved for operation in icing conditions, and to improve the terminology used by all interests. For the present time, the line pilot' best approach to this problem is to adopt a cautious skepticism. He should be wary of what his experience has taught him. Although it is somewhat of an icon within our profession to believe that with suitable experience, we become seasoned, wise, confident and charmingly crusty, we often forget that by default, those of us who have survived to become experienced have not acquired the experience of those who did not survive. Thus we are not afforded a clear perspective on whether our survival is due to wisdom or just to the good humor of the gods. The true wisdom of the seasoned pilot is to not overestimate his experience.

References

1. National Transportation Safety Board, *Inflight Icing Encounter and Uncontrolled Collision with Terrain, Simmons Airlines, d.b.a. American Eagle Flight 4184, ATR-72-212, N401AM, Roselawn, Indiana, October 31, 1994,* NTSB AAR-96-01, July,1996.

2. National Transportation Safety Board, *Inflight Icing Encounter and Loss of Control, Comair Flight 3272, EMB-120RT, N265CA, Monroe, Michigan, January 9, 1997,* NTSB AAR-98-04, November,1998.

3. U.K. Air Accidents Investigation Branch, *Report on the incident to British Aerospace ATP, G-BMYK, 10 miles north of Cowly, near Oxford, on 11 August 1991,* Aircraft Accident Report 4/92, 1992.

4. Australian Bureau of Air Safety Investigation, *Incident at Eildon Weir, Victoria, 11 November 1998,* Interim Factual Report 199805068.

5. Vigeant-Langlois, L. and R.J. Hansman, Jr. *The Influence of Icing Information on Pilot Strategies for Operating in Icing Conditions,* Paper No. AIAA-2000-0365, AIAA 38th Aerospace Sciences Meeting and Exhibit, Reno, NV, United States, January 2000.

6. Render, P.M. and L.R. Jenkinson, *An Investigation into Ice Detection Parameters for Turboprop Aircraft,* Paper No. AIAA-95-0751, AIAA 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV, United States, January 1995.

7. Proceedings; FAA/NASA Airplane Deicing Boot Ice Bridging Workshop, Ohio Aerospace Institute, Cleveland, Ohio, November 18, 1997.

8. Bowden, Dean. *Effect of Pneumatic De-icers and Ice Formations on Aerodynamic Characteristics of an Airfoil,* NACA Technical Note 3564, February, 1956.

9. Sweet, D., *B.F. Goodrich Ice Protection Systems*, Proceedings; FAA/NASA Airplane Deicing Boot Ice Bridging Workshop, Ohio Aerospace Institute, Cleveland, Ohio, November 18, 1997.

10. Albright, A., D. L. Kohlman, W. G. Crawford and P. Evanich, *Evaluation of a Pneumatic Boot Deicing System on a General Aviation Wing Model,* NASA TM-82363, June, 1981.

18. Lee, S., H.M. Gurbacki, M.B. Bragg, and E. Loth, *An Experimental and Computational Investigation of Spanwise-Step-Ice Shapes on Airfoil Aerodynamics,* Paper No. AIAA-98-0490, AIAA 36th Aerospace Sciences Meeting and Exhibit, Reno, NV, United States, January 1998.