In-flight icing's hidden threat: the landing flare

On January 8, 1998, a Cessna 340 experienced a hard landing at Bethany, Oklahoma. The airplane had flown from Amarillo, Texas, to Bethany in VMC above the clouds. While being radar vectored for the approach at Bethany, the airplane entered the clouds at about 5000 feet and accumulated light to moderate rime or mixed ice. At the outer marker, the pilot cycled the deice boots, and he maintained a speed of blue line plus 10 knots. At about 25 feet, he reduced power from 23 inches of manifold pressure; the airplane dropped suddenly onto the runway, resulting in substantial damage to the airframe. The pilot reported no operation of the stall warning system; however, the probable cause cites an inadvertent stall. Following the landing, the pilot reported ice still adhering to the unprotected surfaces, and a "very small amount on the boots."

This is a pretty typical icing accident. Following uncontrolled collisions with the ground, hard landings are the second most prevalent outcome attributable to structural icing. Unlike the uncontrolled collision data, hard landing events are generally well documented; almost no one is fatally injured, and the sequence of events and aircraft response is pretty easy to map out. This set of data may give us a window into an obscure and overlooked aspect of aerodynamic icing… drag rise as a function of angle of attack.

Is this graphic actually misleading?

At least as far back as 1955, the effects of icing have been described as "cumulative" in various government and private publications. This is an unfortunate choice of words; in this context, it has always meant that the four forces acting on an aircraft in flight – lift, drag, thrust and weight – are all adversely affected by ice accretion, meaning that less lift will be met with more weight, and that more drag will be met with less thrust.

However, cumulative is actually defined by various dictionaries as "increasing or increased in quantity, degree, or force by successive additions." While this meaning can fit the four forces interpretation, it also strongly suggests a linear relationship between the amount of ice accreted and the aerodynamic effects the ice creates. Indeed, today's version of AC 00-6B, Aviation Weather, bends the use of the term "cumulative" more toward this definition, saying, "Icing is a cumulative hazard. The longer an aircraft collects icing, the worse the hazard becomes."

Of course it does. But for about a hundred reasons – roughness, horn angle, shape, chordwise location – the idea of a linear relationship between ice accretion and aerodynamic effects is just not true. Even more importantly, the cumulative concept, and the typical picture associated with it, depicts the airplane in stable, unperturbed, one G flight, with no motion about any of the three axes, and then paints a picture of what happens when ice is added to the airframe. The cumulative concept never addresses dynamic or transient flight.

Like the lift coefficient, the drag coefficient does not plot a straight line with change in angle of attack; the drag increase between, say, 1 and 2 degrees angle of attack is not going to be the same as it will be between 5 and 6 degrees. At the higher angles, and the higher resulting lift coefficients, the drag increase per unit of angle of attack will be greater. Approaching the stall, it can become quite significant.

Oddly enough, within a couple of months of the CAA publication describing the effects of icing as cumulative, a researcher at the Lewis Flight Propulsion Laboratory at Cleveland named Dean Bowden published a paper titled "Effect of Pneumatic Deicers and Ice Formations on Aerodynamic Characteristics of an Airfoil." In this paper, Bowden described a series of elaborate tests using a NACA 0011 airfoil test section equipped with a pneumatic deicer boot, mounted in an icing research wind tunnel. One of the results he emphasized in his paper was that once ice is accreted on the airfoil, the increase in drag when the angle of attack is increased will far outstrip the drag rise on the clean airfoil with the same change in angle of attack.

Bowden stated that, "A small ice formation accumulated at low angle of attack can increase drag greatly when angle of attack is increased for landing."

More specifically, his data showed that,

Rime ice that formed at 0° angle of attack at 275 miles per hour increased drag by about 25 percent. Increasing the angle to 4.6°, however, resulted in a drag increase of 122 percent of the bare airfoil drag at 4.6°, compared with a 65-percent increase for the same amount of ice accumulated at 4.6°.

Dean Bowden has demonstrated how rapidly drag can increase with ice on an airfoil.

This probably captures the problem in hard landing accidents. What may appear to the pilot as a manageable drag rise due to a very thin layer of rime, or residual ice following boot operation, suddenly becomes an enormous drag rise during the flare maneuver as the angle of attack is increased.

The mechanics of the flare maneuver are a complex mix of aerodynamics, spatial perception and pilot psychology. The latter two tend to be predicated on predictable aerodynamics, specifically a predictable and repeatable total airframe lift-to-drag ratio (L/D). In steady-state gliding flight, the glide angle is purely a function of L/D; the greater the L/D, the shallower the glide angle, and vice versa. The rate of descent is slightly different, being affected by weight and air density, but it will still vary proportionally with L/D. The best glide speed will correspond to the angle of attack at which the best L/D is obtained.

As the flare maneuver is entered, the parameters affecting the aerodynamics of the situation (lift, drag, load factor, etc.) become transient. In his 1975 paper from Princeton University, "The Landing Flare: An Analysis and Flight Test Investigation," Edward Seckel described the flare as "a complicated transient maneuver involving many interrelated and interacting effects." He went on to say, "The most important feature of the flare has turned out to be the airplane's deceleration in the maneuver. If too little, the airplane floats – if too much, it sinks."

The lift to drag ratio is really a measure of how efficiently an airfoil, and the aircraft that it is attached to, use available energy. So another way to look at this problem is from an energy management perspective. The time rate of release of energy is power… horsepower, if you are using those peculiar units. In gliding flight, the total energy available to the pilot is the sum of the kinetic energy represented by airspeed and the potential energy represented by altitude. In order to maintain airspeed, and preserve available kinetic energy, the energy of altitude must be traded off at a time rate equal to the power required to match the drag; this time rate of energy release is the rate of descent. If the drag rises, then the rate of descent must also rise in order to maintain speed. Conversely, the lower the drag generated by the airfoil/airframe, the less altitude must be dissipated to maintain speed… eventually leading to soaring flight.

The airplane enters the flare maneuver with a certain amount of total energy remaining; the maneuver is designed to reduce the rate of descent, thus slowing the release of potential energy. The energy necessary to slow the descent of a several-thousand-pound block of aluminum has to come from somewhere, and the only remaining somewhere, without adding engine power, is the available kinetic energy represented by airspeed. Since the flare maneuver is, if anything, a time-sensitive maneuver, it will demand a certain horsepower… time rate of energy release… to arrest the sink rate. The remaining kinetic energy offsets the deceleration caused by drag, achieving the optimum deceleration described by Seckel. Eventually, the airplane runs out of energy to stay aloft, which hopefully occurs somewhere in the vicinity of the touchdown zone.

Bowden's point is that the drag rise encountered when pitching up into the flare maneuver with a contaminated wing will drastically alter the L/D from that which is normally encountered. While the reduced Cl max resulting from ice contamination may be encountered earlier than expected, resulting in a premature (and often unannounced) stall, it is not necessary to reach that point to experience a hard landing. The radical drag rise resulting from a change in angle of attack with contamination will, from the aerodynamic perspective, push the glide angle, and rate of descent, toward much higher values than the pilot has previously experienced during the same attitude change without ice contamination.

From the energy management standpoint, the radical drag rise will sap the total available kinetic energy at a much greater rate than expected, leading to a rapid deceleration and correspondingly high sink rate. The overall effect will be similar to deploying a drag chute just as the nose is pitched up into the flare.

It is not a linear relationship.

In Advisory Circular 91-74A, Pilot Guide: Flight in Icing Conditions, a drag curve is depicted that is really very similar to the curves in Bowden's paper and, indeed to any drag curve drawn for an ice-contaminated airfoil. For example, nearly every airfoil geometry depicted in Abbott and von Doenhoff's dog-eared old book, Theory of Wing Sections, has a similar drag curve resulting from the "standard" roughness specified by the authors. The plot shown in AC 91-74A clearly shows the ice contaminated drag coefficient going through the roof as angle of attack is increased. Yet the immediately adjacent text seems oblivious to this characteristic, instead repeating a vestige leftover from the cumulative concept, stating that "Drag tends to increase steadily as ice accretes," and later in the text, "The longer the encounter, the greater the drag increase." Both of these statements are true, yet both fail to call attention to the rather considerable threat posed by ice-contaminated drag when the angle of attack is increased close to the ground… a threat clearly depicted in the drag plot.

Seckel describes the control inputs during an optimum flare maneuver as pulling back on the pitch control while simultaneously pulling back, or retarding, the throttle. This is pretty much the way we think of the flare today. However, that may be precisely what you don't want to do when residual or unshed ice remains on the wing.

Rather, the obvious solution to this problem is to rebalance the energy equation by maintaining or adding engine power, driving the drag term down and improving the total airframe L/D when the angle of attack is increased. The difficulty lies with judging the required power, as the actual lift and drag behavior of the contaminated airfoil across the normal angles of attack is anyone's guess. To make the problem more complicated, the power needed may be considerable if the propellers are also contaminated with ice, since the propeller efficiency can be substantially degraded. It is easy to imagine circumstances in which the required power cannot be extracted even if you bend the throttles.

If there's still ice on the wing, should you add power in the landing flare?

In Civil Aeronautics Bulletin No. 25 of January, 1943, which is really B.C. Haynes' book *Meteorology for Pilots*, the author stipulates that (italics added): "If the plane is not equipped with wing boot deicers, turn back to nearest airport and *use power to land* keeping airspeed well above normal landing speed."

Later, he reiterates the same idea, saying:

"Land at the nearest suitable airport but *use power in landing* and, if possible, avoid turns at low altitude."

The emphasis then, as now, is on staying away from the reduced Cl max and inadvertently walking into a premature, unannounced stall. But the technique of using power into the flare and even touchdown probably contributed to preserving the desired energy state during the landing back in the day, whether you had "boot deicers" or not.

We know, from considerable flight testing done by a number of NASA research pilots, including Neil Armstrong, that a pilot can successfully and consistently land an aircraft with an L/D of about 2 to 3, which is pretty low, well below that of any conventional airplane in its normal configuration. We also know that they did this with a lot of extra energy, started the flare very high and aimed for a point a little over half a mile short of the threshold… not for the faint of heart and definitely nowhere to be found in the ATP Flight Test Guide.

For this reason, and all of the other reasons that we have ever learned, we need to keep the airplane as clean of ice contamination as possible during flight. But we also need to be prepared for a very significant drag rise when starting the flare, even with small amounts of residual ice following normal boot operation and to be prepared to counter the drag rise with all of the power necessary until we're an inch or two above the runway.

And being prepared in this case also means to take into consideration the runway surface condition, likely braking action, and the possibility of a slightly long landing if you misjudge the necessary power. Most importantly, being prepared means recognizing that the critical drag rise will not manifest itself until the angle of attack is increased. The approach all the way down to the flare may seem to be well under control… until it isn't.

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Steven D. Green started flying at age 14, and soloed on his 16th birthday in 1972 off runway 9R at

Palm Beach International. He began his airline career flying a Convair 240 for Providence Airlines around the Great Lakes, then flew Metroliners up and down the east coast through the 80s and then all over the world for TWA, Eos and American. Beginning in 1986, he participated in numerous aircraft accident investigations as a representative of the Air Line Pilots Association, including TWA 800. Association with the 1994 Roselawn accident involving Simmons 4184 led to work with ALPA's Inflight Icing Certification Project, as well as the Ice Protection Harmonization Working Group ARAC. He has remained involved with aircraft icing issues, writing a number of papers on the topic and continuing to serve as a consultant to the FAA. He and his wife have lived in Vermont for 27 years, and have two grown sons. He is currently a Boeing 737 captain.
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