INFLIGHT ICING: THE HANDLING EVENT

By F/O Steve Green (TWA)

On Feb. 21, 1951, a Curtiss C-46 operating at night encountered icing conditions more severe than anticipated. The crew attempted to return to the departure point, but the aircraft was unable to maintain altitude. The crew executed a forced landing alongside a highway in mountainous terrain, destroying the aircraft but incurring only minor injuries.

On Jan. 15, 1977, almost 26 years later, at Stockholm, Sweden, a Vickers Viscount pitched over and entered a vertical dive while on final approach 5 kilometers from the runway. The aircraft hit terrain in a near 90-degree nose-down attitude, fatally injuring all 22 people on board. The Swedish accident was determined to be the result of tailplane stall due to ice accretion.

The Curtiss crew was certainly aware of the effect that ice was having on their aircraft, and that awareness led them to the decision to make an off-airport landing. On the other hand, the Viscount crew was clearly unaware of the effect that ice would have on their aircraft when they configured for landing. This distinction is characteristic of two different types of inflight icing events: the "performance" event and the "handling" event.

The performance event is characterized by drag and lift penalties that predominate and thus appear as reduced airspeed and rate of climb, and a reduced ability to maintain altitude.

The handling event is characterized by changes in the aircraft's stability and control that often appear before the performance penalties become apparent.

Ice accretions can affect the aerodynamic forces and moments responsible for the aircraft's normal stability and control characteristics. A handling event in its mildest form involves changes in the airplane's longitudinal or lateral stability. A handling event in its worst form, and possibly with very little warning, invokes wingtip stall and/or tailplane stall, and for aircraft with manually operated flight controls, critical changes in control surface hinge moment.

Ice-induced degradations in stability and control are always a function of the angle of attack (AOA) of the lifting surface involved, whether it be the wing or the tailplane. Consequently, these degradations typically occur when something has happened to change the AOA, such as changes in configuration, power, or airspeed.

Ice accretions that affect the stability and control of the airplane may be very small and rather unspectacular in appearance. Because of the autopilot's willingness to try to single-handedly manage these disturbances, up to a point, the crew is often unaware of a developing instability or control degradation until the autopilot gives up and hands the pilot a very serious and rapidly deteriorating problem.

The tailplane

In his book *Spitfire: A Test Pilot's Story*, Vickers test pilot Jeffrey Quill observed that, in aerodynamics, "stability can be simply defined as the tendency of an aircraft when disturbed from a condition of steady flight to return to that condition when left to itself. Conversely, instability is the tendency of the aircraft to diverge further away from the condition of steady flight if once disturbed.

"The vital importance to the pilot of having positive stability is obvious," Quill noted. "For instance, if he wishes to raise the nose of his aircraft a small amount...perhaps to aim his guns...but the aircraft itself decides to bring the nose up further than he wants before he has time to check it, he will have great difficulty in aiming."

Quill was instrumental in developing and testing the Supermarine Spitfire during the late 1930s and throughout World War II. The basic Spitfire had marginal longitudinal stability, and Quill and his colleagues expended considerable effort to protect that stability as the airplane evolved.

By itself, instability does not mean the aircraft cannot be flown. But Quill's point regarding difficulty in aiming applies to all forms of precision flightpath control, the kind expected in air carrier operations. In particular, it applies to flightpath control during operations.

Quill goes on to state that providing "a sufficiency of inherent longitudinal stability in an aircraft is therefore an essential task for the designer; and in aircraft of a conventional layout, it is normally obtained by the use of a fixed tailplane at a distance behind the main wing. The effectiveness of the tailplane depends on its aerodynamic qualities and its distance behind the aerodynamic center of the mainplane."

Aerodynamic qualities are precisely the characteristics most affected by structural icing.

The horizontal stabilizer normally operates as an inverted wing. In a steady trimmed flight condition, it must develop low pressure on the underside, creating a nose-up moment that balances the nose-down "pitching moment" produced by the wing as a function of the distance between the center of lift and the center of gravity. If the airplane is upset from this steady condition and pitches above its center of gravity, the stabilizer develops a restoring moment proportional to the extent of the upset. Thus, the farther from trimmed flight the airplane is pitched, the more powerful the restoring moment.

The stabilizer's performance is a function of its local AOA. Because the wake of the wing always affects the tail,

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the local AOA of the tail is a function of the wake characteristics, including downwash from the wing. Both flap deflection and propeller wash influence the nature of the wake.

Increased airspeed leads to a reduction in the wing's positive AOA. However, to provide the download required during most phases of flight, the stabilizer is already operating at a negative AOA. All other things being equal, the pitch-down translation that reduces the wing AOA also increases the negative AOA of the tail.

The stabilizer's performance is also a function of the camber of the stabilizer-elevator airfoil—nose-up elevator increases the camber, and nose-down decreases it. To keep the wing and tail forces balanced, increased airspeed also requires a nose-down elevator deflection, which effectively decambers the stabilizer. This decambering can aggravate flow separation under the right conditions.

Certain designs provide the pilot with control over the tail AOA independent of the wing AOA. A full-flying stabilizer, such as that used on the T-38, Piper Cherokee, and Lockheed L-1011, allows the pilot primary control over the tail incidence angle to vary the tail AOA and thereby adjust the lift generated by the stabilizer. A trimmable stabilizer allows the pilot secondary control over the stabilizer incidence angle, resulting in control of the tail AOA.

The control forces required to deflect the elevator from a trimmed condition depend on the "hinge moments," which develop when the elevator is deflected from the trimmed condition.

In *Flying Qualities and Flight Testing of the Aeroplane*, British test pilot Darrol Stinton gives the simplest definition I have yet seen: "Hinge moments are caused by the centres of pressure of the moving surfaces acting at a distance from their hinges." Elevator deflection, because it influences the pressure field around the stabilizer, influences the hinge moment. Ideally, the more one deflects the elevator, the more powerful the hinge moment driving the elevator back toward the trail position. Thus, the hinge moments provide a restoring force for the elevator as well as control "feel." If the center of pressure of either the fixed or moving surface wanders about inappropriately, so does the hinge moment.

With ice on the stabilizer, the airplane's "aerodynamic qualities" are no longer ensured. The stabilizer's ability to provide positive stability may be compromised. The elevator hinge moment may change magnitude or even direction. Most importantly, such a compromise to the tail may not affect the complete operating envelope for a particular configuration. For example, in a given flap configuration, normal stability may be sensed until a power increase or a nose-down correction is applied. At that point, the stabilizer flow may begin to separate, seriously degrading stability and changing elevator hinge moment characteristics.

Hydraulically powered flight controls are capable of managing the elevator (or aileron) regardless of the hinge moment being developed. Airplanes so equipped do not suffer uncommanded control movements due to hinge moment reversals, nor can the pilot get any buffet or force feedback cues. However, such airplanes can still experience degraded stability and handling qualities due to ice contamination on the stabilizer, and tailplane stall is not impossible.

Moreover, if the airplane is equipped with either a full-flying stabilizer or a trimmable stabilizer, the pilot's normal use of stabilizer incidence-angle adjustments may reduce tailplane vulnerability to ice-induced flow separation, but not necessarily eliminate it.

Because FAR Part 25 contains stringent requirements for longitudinal stability, very, very few pilots have the opportunity to fly a longitudinally unstable airplane. Virtually all of us spend our entire careers, including military high-performance time, in aircraft that are either fundamentally or artificially stable. Little prepares us for the time when the autopilot hands us an airplane that has substantially degraded stability and is, furthermore, well into the process of swapping ends; or the time when a slightly more-aggressive-than-normal correction pushes us over a cliff and the aircraft becomes uncontrollable.

Because of the autopilot's willingness to try to single-handedly manage these disturbances, up to a point, the crew is often unaware of a developing instability or control degradation until the autopilot gives up and hands the pilot a very serious and rapidly deteriorating problem.

Twin Otter research at NASA

On Oct. 28, 1997, I had the opportunity to fly NASA 607, the well-instrumented and rather venerable de Havilland of Canada Twin Otter based at the National Aeronautics and Space Administration Lewis Research Center at Cleveland-Hopkins. (See "Over the Falls in a Twin Otter," February.) The aircraft was equipped with "boot failure" artificial ice shapes on the leading edge of the horizontal stabilizer. This shape is a small, double ram's horn type of shape. It is based on FAR 25 Appendix C ice accretion on the stabilizer if the deice boot is inoperative (or, for some reason, not operated).

The test plan was designed to allow the guest pilot to explore, under controlled circumstances, the effects of power, airspeed, and flap angle on the longitudinal flight characteristics of an airplane with ice on the tail. Each variable was investigated with a set of test points that gradually developed the flow separation condition at the tail. Perhaps the most important aspect of this program for me was the opportunity to fly an airplane in a configuration and flight condition in which it was *not* longitudinally stable.

De Havilland has, for quite some time, prohibited operation of the Twin Otter in icing conditions with the flaps deployed beyond 10 degrees—for good reason. As we flew through flap transition, from 0 to 37 degrees, at a constant airspeed of 80 knots, we could see a step-by-step development of flow separation at the tail, with the resultant degradation in longitudinal stability. This illustrated the direct control that flap deflection has on downwash angle, and thus the wake in which the horizontal stabilizer must always operate. Flap retraction can directly reduce the AOA of the tail and restore stabilizer performance.

We flew the speed transition at a constant flap setting of 37 degrees. Beginning at 65 knots with normal stability and control response, we accelerated gradually to 85 knots.

By 85 knots, it was apparent that something was very wrong with pitch control. The difference between 65 and 85 knots represented a reduction in wing AOA. This resulted in an increase in the effective AOA of the tail, which in this case, crossed into a region where the flow began to separate from the stabilizer. The condition was aggravated by the decambering effect of the additional down elevator required as speed was increased. Reducing speed reduced the AOA of the tail and restored the stabilizer's performance.

We flew the power transition at a flap deflection of 30 degrees and an airspeed of 80 knots. When we began with zero torque and added power up to the flight maximum, the effects were equally clear. As we increased the power, stability degraded noticeably. This may be a result of the effect that propeller wash itself has on the wake behind the wing, or it may be the result of the effect that the propeller wash has on the wing and its downwash.

The actual mechanism is not clear yet; indeed, to some extent it may be unique to the Twin Otter. Additional work is necessary to determine if this relationship is applicable to other designs or configurations. In the Twin Otter's case, increasing power aggravates the flow separation at the tail. Reducing power can assist in reattaching flow to the tail surfaces, and restoring tailplane performance.

The degradation in stability manifests itself in unique changes in the airplane's pitch behavior. The separated airflow under the tail causes the elevator to begin buffeting erratically.

This is very obvious to a pilot who has his or her hands on the controls. But the elevator, not the airframe, is buffeting. Consequently, the buffeting is not at all discernible if the safety pilot—or the autopilot—is holding the controls. A pilot cannot feel it through the "seat of the pants" or detect it at all except through the direct feedback that manual flight provides.

Furthermore, this elevator buffeting can feel remarkably similar to a stickpusher when the pusher is resisted to the point of clutch slippage. However, mistaking it for a stickpusher, or conversely mistaking a stickpusher for elevator buffet, can quickly lead to loss of control and loss of the aircraft.

When the pilot makes a pitch-down input, the instability becomes apparent. The nose pitches down much too quickly; the elevator seems excessively sensitive. Whereas a nose-down pitch translation can ordinarily be stopped simply by releasing forward pressure on the yoke, in this case the nose will continue down until the pilot applies back pressure to the yoke. The airplane has become longitudinally unstable.

As the tail flow separation develops further, the pilot realizes that the elevator itself is not behaving normally. The elevator buffeting becomes much worse. The control yoke pulls hard in the hands of the pilot, who must apply considerable back pressure to maintain a neutral control column position.

This is the phenomenon of hinge moment reversal. When the flow separation under the tail has developed to the point of disturbing the pressure field under the elevator, the elevator hinge moment changes dramatically.

Significant back pressure by the pilot may be required to maintain a neutral elevator; depending on the size of the elevator, these pull forces can reach a couple of hundred pounds.

In spite of all of this, however, the elevator is still an effective control surface. The hinge moment may have shifted or reversed, but nose-down elevator still means that the nose is going to go down.

To me, one concept was most significant. The instability that may result from certain ice accretions can rapidly amplify a normally corrective pitch input into a pilot-induced oscillation (PIO).

For example, a pilot who is flying a typical ILS in IMC will be making continuous corrections to the glidepath through the pitch control system. Each correction represents a slight departure from the trimmed condition, and the pilot makes these corrections expecting that the airplane's positive stability will react to the correction to place the airplane where the pilot wants it—"aiming his guns," if you will.

But when the airplane's tail is not performing properly, the less-positive, neutral, or negative stability that the pilot encounters results in poor glidepath control. The natural response is slightly more aggressive pitch inputs.

When the airplane manages to drift above the glidepath, the pilot pushes the nose over. This decambers the tail.

With the ice accretion present, decambering with the elevator may initiate flow separation on the underside of the stabilizer.

As a result, the airplane pitches down quite a bit farther than the pilot expected it would, which causes the pilot to respond with a mighty pull to overcome the tucking nose. This upward elevator deflection actually recambers the tail, allowing the flow to reattach.

After a noticeably abnormal delay in control response, the nose pitches back up—way up, because the tail is now fully functioning and responding to that mighty pull. The rapid pitch-up leads the pilot to the final straw—an even more aggressive pushover. This results

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in a much larger decambering of the tail, the flow separates completely, the nose tucks over firmly, and now the required pull forces can be overwhelming.

In the real world, this all occurs on a dark and stormy night within 2,000 feet of the ground—probably lower. The effect is obvious.

On Dec. 21, 1963, a Convair 440 crashed on approach to Midland, Tex. According to the accident report, "The crew conducted an ILS approach. Witnesses reported that immediately after the aircraft broke out of the overcast, it began a series of up-and-down pitch oscillations, with the third downward pitch continuing until the aircraft struck the ground, where it was destroyed by post-accident fire."

The accident was attributed to ice-contaminated tailplane stall.

That this scenario would develop during the final stepdown of a non-precision approach, or at breakout at minimums, would be virtually assured due to the more radical pitch changes required. Clearly, how the pilot flies precision maneuvers with ice on the tail is critical. The pilot has control over both stabilizer camber, through elevator inputs, and over the wing wake characteristics that affect the tailplane, through flap management and power control. But the pilot has to be sensitive to the effects of structural ice on stability, and on the demands the maneuver places on stability.

Flight with known or suspected ice accretions on the tail should probably be approached in much the same way as descending a mountain trail blindfolded. Taking small, careful steps is wiser than striding along as though you could see clearly on a sunny day.

The wing

Another type of handling event is every bit as dangerous and challenging as tailpane stall. This is a tip stall of the wing. The tip stall can have two dramatic effects. First, the aileron may be unable to correct a dropping wing; the ailerons may be fully deflected in the direction opposite the roll with no effect. Second, with respect to aircraft equipped with unpowered controls, the aileron hinge moment may reverse. These events are not mutually dependent, and may occur independently.

The mechanics are much the same as those for the tail, except that the flow separation occurs on the outboard upper surface of the wing.

While the wing is typically slightly twisted so that the wing stall occurs inboard first, the thickness of the wing and taper of its chord may work to the opposite effect when contaminated with ice. A sharp leading edge radius collects ice much more efficiently than a blunter leading edge radius.

Thus, a thicker section of wing may not ice up in the same way as a thinner section. (This is one reason why B-747s typically don't have icing problems—and why the tail may have critical ice on it when the wing does not.) The result may be a flow separation beginning at the outboard leading edge of the wing, in front of the aileron, before anything happens inboard.

The chord length also influences how the flow separation develops. A shorter chord at the tip may react to a given ice shape differently than a broader chord at the root. If flow separation at the tips develops to the point of disturbing the aileron hinge moment, the unbalanced aileron may deflect rapidly. This is sometimes referred to as "aileron snatch."

Mechanics of hinge moment changes

Dr. Michael Bragg of the University of Illinois, one of the leading researchers in inflight icing stability and control, has identified a significant difference between the stall of a clean airfoil and the stall of an airfoil contaminated with a step or horn type of ice shape located just aft of the leading edge.

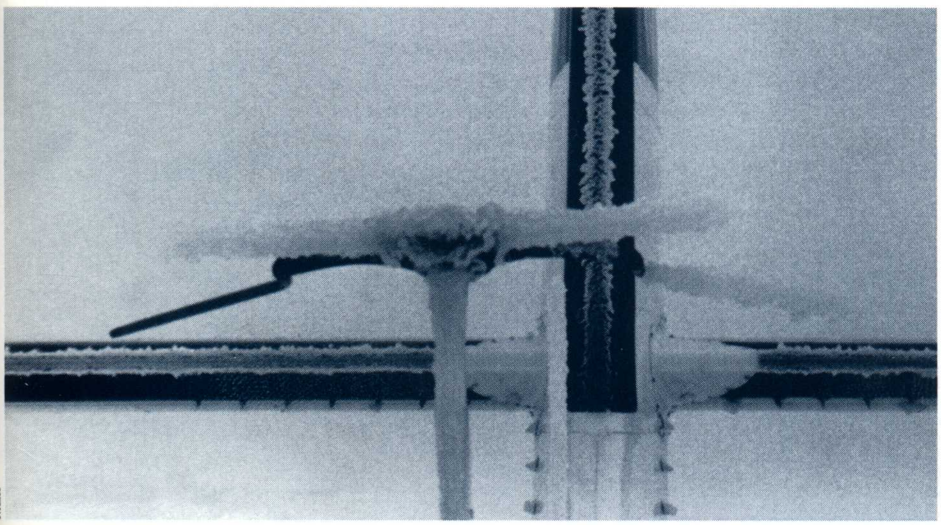
The clean case produces a trailing-edge stall, in which the flow separation begins at the trailing edge and propagates forward. This may also be the case with some ice roughnesses and distributions. In the case of one-quarter-inch step or small horn-shaped contaminations, however, the stall develops as a "thin wing" type of stall, beginning at the leading edge of an uncontaminated diamond-shaped airfoil.

For an iced wing, the stall develops at the ice shape protuberance near the leading edge. The flow separation propagates aft from this point.

In the thin airfoil stall case, the lift generated just ahead of the trailing edge is much greater than in either the unstalled or trailing edge stall cases, because of the pressure distribution that the aftward advancing separation bubble forces. This greater trailing edge lift seriously alters the control surface hinge moment, causing the control surface (aileron or elevator) to deflect toward the suction side of the airfoil.

Something else occurs during thin wing stall. As the flow separation bubble progresses aft, the wing becomes "aft loaded." The center of pressure travels aft, significantly increasing the pitching moment. This may precede the hinge moment shift. It is not clear how this would manifest itself, or if it is even a universal characteristic.

Bragg's research has so far been lim-



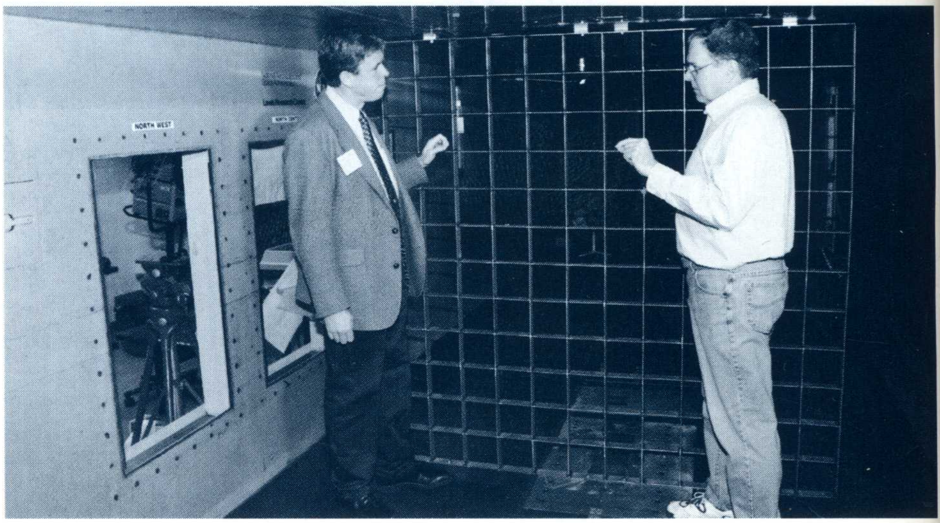
NASA

DHC-6 Twin Otter flown by NASA Lewis Research Center test pilots picks up a load of light rime. Note growing double ridge of ice accretion on the horizontal stabilizer and the vertical fin.

ited to one-quarter-inch step and small horn type ice shapes. Yet the thin wing stall mechanism may not be limited to these shapes, or require even a dimension as large as one quarter inch.

In 1979, the Russian-Swedish research team of Trunov and Ingelman-Sundberg reported that on the particular airfoil that the Vickers Viscount horizontal stabilizer used, 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." On a 5-foot chord, that is an ice shape with a roughness of 0.046 inch. Trunov and Ingelman-Sundberg had good reason to choose the Viscount as a test article; the previously mentioned Viscount accident at Stockholm had occurred during the period in which they were planning their research.

F/O Green (left) and NASA engineer Bill Sexton discuss the workings of the NASA Lewis Research Center's unique Icing Research Tunnel, which has been operational since 1944.



The critical ice shape

One of the most controversial issues in aircraft design is how much ice, and what shape of ice, will be most critical to a particular wing design. The traditional approach to ice accretion is that the bigger and uglier the shape, the nastier its effect on the airfoil. Yet during the 1930s, wind tunnel research by Jacobs began to show that even small accretions that were placed in the proper chordwise location could have serious effects.

The subsequent work of Trunov and Ingelman-Sundberg in the 1970s and Bragg's work since the ATR 72 crash at Roselawn, Ind., in 1994, have sparked considerable debate within the aviation industry today about just what the "critical" ice shape is. Is it the "big ugly" ice shape, or something else, perhaps the shape known as "sandpaper" ice? While developed for design and certification reasons, this discussion is enormously important from the pilot's perspective.

Over the years, pilots have developed a variety of methods for determining when to operate the aircraft's ice-protection systems. In the case of airplanes that have leading edge pneumatic boots, the pilot may use a manufacturer's recommendation to wait until one-quarter- to one-half-inch ice thickness accumulates on the wing to optimize boot efficiency. In the case of thermally anti-iced airplanes, the pilot may use almost anything—ice on the windshield wiper nut, ice on the chicken splitter, the howl from the upper VHF antenna, etc.

Virtually none of these techniques, including the one-quarter- to one-half-inch concept, has any basis in flight testing. At a recent meeting addressing the phenomenon of ice bridging, one manufacturer admitted placing the one-quarter- to one-half-inch criterion in the AFM only because it was "traditional."

Virtually all of these techniques will tolerate what may be sandpaper ice before the pilot is supposed to operate the ice-protection system. Without reliable ice-detection systems coupled with clear, tested guidance from the manufacturer, the period between initial accretion and initial deicing becomes very arbitrary, based only on visual assessments of ice severity. But the wing may appear to have negligible accretion while the tail has a critical accretion. The wing may not even be visible.

One regional airline uses airspeed decays of 5 to 10 knots as an indication that the flight crew should operate the deice boots—yet there is no reason to presume that a significant rise in drag accompanies the formation of critical ice.

In the case of the ATR 72 that crashed at Roselawn, Ind., in 1994, the data did not indicate a significant drag rise before the upset; the airspeed remained relatively constant throughout the period in which the ice was accreting. This condition was repeated later during icing tanker tests at Edwards Air Force Base.

Thus, the period of time between initial ice accretion and the initial operation of the ice-protection system naturally results in some ice accretion. This period might be referred to as the "deice pause." Yet the absence of a complete definition for the critical ice shape throughout the airplane's configuration envelope may lead to this period being one of considerable vulnerability to ice-induced changes in stability and control.

A Flight Safety Foundation review of icing accidents contains numerous references to ice accretion thicknesses that would be considered nominal in line operations. The DC-9-10 series is well known for its inability to tolerate more than 0.015 inch of ice on the leading edge of the wing. A Twin Otter crashed in Alaska apparently due to an ice accretion of 0.2 inch. A Beech 200 crashed in Michigan, with 0.5 inch of ice found on the horizontal stabilizer. A Dornier D-28 Skyservant experienced a tailplane stall on approach; after successfully landing following recovery with flap retraction, the pilot discovered one-sixteenth to one-eighth of an inch of rime ice on the stabilizer (see "ALPA Mailbag," page 8, the letter from Capt. Opel). In this case, the aircraft was equipped with a full-flying tail. Finally, the aforementioned Convair 440 accident revealed 0.5 inch of rime ice accreted on the surviving wing. The crew had elected not to operate the ice-protection system during the approach.

Recently, the subject of ice bridging

has come under much investigation, and this work continues. A number of turboprop manufacturers have changed their boot operation procedures to remove the "deice pause" and to require boot operation continuously and immediately at the first indication of ice accretion. The Airplane Flight Manual must be the final authority with regard to this consideration.

The deice pause may apply to turbojet aircraft as well. Many operators use the ice-protection system in a deice manner after allowing the aircraft to initially accrete ice. But how much ice? What is a valid indication of ice on a flying surface? Recently, a Canadian Airlines Boeing 767 experienced a tailstrike after landing from a nonprecision approach. Analysis of the digital flight data recorder revealed an increase in drag and a loss of lift between the minimum descent altitude (MDA) and landing that could not be explained. However, the Transport Safety Board of Canada was curious about the effects that the light freezing drizzle reported at the surface might have had—particularly since the crew had not operated the wing ice-protection system. Yet this crew had observed no ice accretion on the windshield, windshield wipers, etc., and indeed, ice accretion could not be verified after the incident.

SLD has been formally defined as supercooled water droplets up to and including freezing drizzle and freezing rain and larger than the maximum 50 microns that manufacturers consider in design and certification. No icing environment that has not been considered in design and certification should be considered safe for line operations. Numerous ADs have appeared regarding these conditions, and ALPA has issued several Safety Alerts as well.

The pilot should

- look for unusual ice accretions on prop spinners, wings, and other structures;
- look for any accretion aft of the boots and other protected areas; and
- consider any amount of clear or mixed ice as suspect.

Above all, the pilot must remember that the autopilot can keep secrets. Taking advantage of icing conditions as a time to practice one's hand-flying skills may be wise. This will allow the earliest possible sensing of changes in stability and control, and it will eliminate the potentially fatal time delay between upset and pilot intervention.

When encountering the above conditions, the pilot must start thinking "no protection" immediately and remember that SLD accretions have been identified as leading directly to handling events in the past. The Roselawn accident was one such case. In any event, no manufacturer has considered SLD ice accretions when assessing the critical ice shape for a particular wing or tail.

Summary

In the final analysis, the most damning thing about structural icing is that techniques that lessen the effects of one handling phenomenon actually aggravate the other. For example, applying an arbitrary speed additive during an approach in icing conditions may adversely affect the AOA of the tail; on the other hand, not applying the same additive may adversely affect the wing.

This aspect becomes extremely critical during recovery from an upset, when the techniques for recovery from a roll upset are virtually the exact opposite of the techniques for recovery from a pitch upset. In the case of a roll upset, a firm pitch-down to immediately reduce the AOA of the wing and roll inputs as necessary to level the wings, coupled with adding power and extending the flaps to a setting known to be safe, is entirely appropriate.

Yet each of these steps may dangerously aggravate a tailplane stall. In that case, a firm pitch-up, to recamber the tail, coupled with retracting the flaps to a setting known to be safe and reducing power, is appropriate.

The best approach to avoiding the handling event is to absolutely minimize contamination of the airfoils, both wing and tail. This requires carefully managing the flightpath to avoid icing conditions whenever possible. It also requires prompt, correct, and extensive use of the aircraft's ice-protection systems. NASA has noted that during Twin Otter flights in natural icing conditions, several boot cycles are often needed to clear all the ice; but that once this is achieved, allowing the boots to continue cycling automatically maintains an acceptably clean wing. Clean airfoils (wing and tail) are the best insurance against the handling event.

When operating in icing conditions, you should be continuously aware of the airplane's longitudinal stability, trim requirements for configuration, control "feel" (hinge moments) and responsiveness in both pitch and roll axes. You should be particularly alert for abnormal changes in handling qualities during configuration changes. In any circumstance, if the airplane starts acting up as configuration changes, go back to a configuration that is known to be safe, with normal handling qualities.

Be prepared to fly the airplane. While ice accretions can seriously affect the handling qualities and flight control hinge moments, the flight controls themselves typically remain effective. Even if it requires all of the strength that both pilots can muster, the airplane can be flown through most hinge moment reversals if the flight controls are put where they need to be to get the AOA corrected.

Above all, the pilot must remember that the autopilot can keep secrets. Taking advantage of icing conditions as a time to practice one's hand-flying skills may be wise. This will allow the earliest possible sensing of changes in stability and control, and it will eliminate the potentially fatal time delay between upset and pilot intervention.

Jeffrey Quill captured the essence of stability by concluding that, "all in all, a proper degree of positive longitudinal stability is a basic necessity in any aeroplane controlled by manually operated aerodynamic surfaces. It follows that in aeroplanes such as the Spitfire, which were entirely manually controlled, any inherent instability was unacceptable and potentially dangerous."