Icing problem is a serious threat for which the best solutions may be years away

Our ability to accurately forecast inflight icing conditions lags behind the forecasting of other hazardous meteorological conditions. Interim and long-term measures are necessary to correct this situation.

STEVE GREEN
AIR LINE PILOTS ASSOCIATION, INTL.

IT IS INTERESTING to note that of the many meteorological threats that a Zeppelin airship commander of the Great War faced, structural icing was one of the most menacing. For him, this was a pure performance problem: ultimately the ice simply added more weight than he had ballast to let go, and he descended — slowly, but with little choice in the matter of landing sites.

In 1919, the North Atlantic was first flown non-stop by Capt. John Alcock and Lt. Arthur Whitten Brown in a Vickers Vimy. During the flight, structural icing partially impeded movement of the flight controls, but the real threat came from ice choking the engine air intakes. On several occasions during the crossing, Brown, who was navigating, crawled out on the wings with a penknife and set to work removing the ice from the air intakes.

And so it has gone since powered flight began. Along the way, inflight icing has claimed innumerable lives through innumerable accidents. Indeed, because of its unique ability to completely disappear from the scene after an accident (particularly if there has been a fire), icing may be behind many more accidents than we know.

Alcock and Brown had the constant reminder of an open cockpit to keep them alert to the icing threat. Today, in the comfort of a modern "glass" cockpit where the only moving air is that coming from the eyeball vents, it is easy to overlook the icing threat, even if only for a moment. Moreover, after having gained considerable personal experience in the icing environment with no hint of difficulty, many line pilots may be comfortable in thinking that the problem has been reduced to a routine and manageable one with modern aircraft equipment, weather forecasting and reporting.

They are wrong.

With two exceptions, that of microburst or other wind shear within a thunderstorm cloud, and volcanic ash, no other meteorological phenomena are so capable of compromising aircraft performance so rapidly. Structural icing can change the shape of the airfoil. The resulting new airfoil will have drag, lift, and pitching moment characteristics which may not meet the requirements of the design or the mission. The increase in drag and loss of lift can make continued flight hazardous, if not literally impossible.

But beyond performance, icing is the only phenomenon capable of compromising control. It can reduce the effectiveness of the control surfaces or change the aerodynamic balance designed into them. Such a change can manifest itself in radically altered control forces, changes in stability (even to the point of its becoming divergent, and the aircraft becoming unstable) and possibly even uncommanded deflection of a control surface.

The routine acceptance of operations in icing conditions, despite the potential threat, is perhaps best explained by the great increase in short-haul flight operations. This expansion in air traffic has completely outpaced the industry's ability to forecast, nowcast[1] or even provide on-site (i.e. *in-situ*) detection of serious icing conditions. The result is a high volume of successful operations salted with a few very unsuccessful ones, and yet remarkably little pragmatic understanding of what made those few so unsuccessful and how such events might be avoided in future. However, as the industry strives toward greater aerodynamic efficiency as well as lower manufacturing, maintenance and operational costs, the volume of air traffic continues to increase. This can only lead to the elevation of a risk that is already unacceptable.

Interestingly, the thunderstorm presents a serious threat to aviation, yet its recognition and management are quite a bit better developed than is the case with inflight icing. Perhaps this is because the thunderstorm comes equipped with some convenient handles with which to get hold of it. The conditions which cause thunderstorms are limited and fairly well understood. The meteorological parameters necessary to feed a reliable predictive algorithm are not difficult to measure and indeed this is done on a routine basis. Thus, thunderstorm forecasts have a reputation for reliability not enjoyed by forecasts of other threatening phenomena.

The thunderstorm also presents a structure that is easily recognized by weather radar. This allows a validation of forecasts through ground-based equipment, leading to a type of nowcasting (convective SIGMETs[2]) that is well recognized and respected for its reliability. Further, this same technology allows the on-board detection of thunderstorms ahead of the aircraft.

So, when dealing with thunderstorms, the pilot is presented with:

- a forecast which, in past experience, has frequently been confirmed by either visual or radar detection of the predicted thunderstorms, thus giving the pilot a good degree of confidence in forecast accuracy;
- a nowcast based on the real-time detection of thunderstorms; and

1. Nowcast is a meteorological term defined by the World Meteorological Organization as "a description of current weather and a short-period (up to two hours) forecast".

2. Convective SIGMETs are issued in North America; elsewhere warnings of all specified hazard weather phenomena, including thunderstorms, are issued as SIGMETs.

•a weather radar system which provides significant information about the storm at a considerable distance ahead of the aircraft, allowing a strategic response in en-route flight planning rather than a tactical one.

The addition of forward-looking windshear detection equipment will further refine these strategic resources.

The situation presented by inflight icing is considerably more difficult. The meteorological parameters required for a forecast algorithm are not as easy to obtain nor are they routinely measured. The use of those parameters that are available has restricted the type of algorithm that can be used, thus limiting the accuracy of the resulting forecast and leading to an imprecise spatial and temporal validity. Consequently, there is a poor relationship between the forecasts and actual weather. In fact, there is not much difference between an en-route icing forecast and the conclusion that most pilots draw upon stepping out of their front door on a chilly morning and noting clouds.

For nowcasting, there is a reliance on pilot reports (PIREPs[3]). Because the spatial and temporal movement of icing conditions are not easy to predict, the validity of a PIREP transmitted from 10 miles or 10 minutes away from the event is questionable. Moreover, the terminology used in icing PIREPs is somewhat less than useful.

In terms of either predictive or reactive detection, the pilot currently relies on being able to see and assess icing severity. This is a questionable state of affairs at the end of the 20th century, indicating little advance in the technology since that time when Alcock and Brown had difficulty deciding when Brown should crawl back out onto the wing with his penknife. Still today there is no such thing as on-board predictive detection; indeed, there is not even a reactive detection system in use that is capable of differentiating between the supercooled large droplets (SLD) and the certification droplet described by U.S. Federal Aviation Regulation (FAR) Part 25. Thus, the pilot has no way of detecting supercooled large droplets until some degree of accretion is observed, and to do this, the pilot of course must be able to see the critical surface. Today, many wings are not visible from the cockpit, and the most insidious collector of ice, the tailplane, never has been visible. Glaze ice has been shown to be visually undetectable to someone looking directly at the wing in broad daylight and, of course, this whole method of detection must also be used at night.

Icing severity index

We cannot begin to unravel this entire issue without an objective method of measuring inflight icing. At present, the criteria that are used share essentially one objective — determining whether ice has accumulated in any amount. Beyond that, the definitions used by the present index are entirely subjective, using terms such as "may create a problem," "occasional," "short encounters," "potentially hazardous," and "fails to reduce or control the hazard." These terms are intended for pilot interpretation and application; however the system apparently assumes a uniformity of interpretation that may well be impossible. For example, what exactly is the hazard, or range of hazards, indicated by the terms "potentially hazardous" and "fails to reduce or control the hazard"? For that matter, what degree of likelihood is conveyed by the term "potentially"? How often is "occasional"? Is the "problem" referred to in the definition of light icing the same as the "hazard" referred to in the definitions of moderate and severe icing? What is that "problem"?

Moreover, even after we address the variability in the interpretation of these terms, we are still left with the variability of their application to different types of aircraft. For any given set of quantified icing conditions, the effect on each aircraft will depend on that aircraft's size, speed, airfoil characteristics, configuration, and ice protection systems. Even slight variations in angle of attack (AOA) may noticeably change the impingement limits observed by the pilot. A slight variation in the total air temperature (TAT) may noticeably change the type of ice observed (rime, clear or a combination of the two) and the shape that is observed. A fully evaporative anti-ice system may safely manage a level of liquid water content that another aircraft, at identical AOA and TAT but with a pneumatic de-ice boot, is unable to cope with. Any of these variations can seriously change the performance effects, and thus the "hazard" or "problem" that is observed and reported.

If we step back and consider the spatial and temporal mobility of icing conditions, the variable aircraft-specific response to such parameters as AOA and TAT, and the interpretive variability, both linguistic and cultural, of the official terminology, the severity of the dilemma becomes clear. It can become impossible for one pilot to relate the severity of any particular icing report (or forecast) to a specific aircraft, at a specific location, at a specific time.

It can be impossible for a pilot to relate the severity of any particular icing report or forecast to a specific aircraft at a specific location and time.

So what is the line pilot to do? The decision that has the highest probability of being correct, and which most fortuitously happens to be the one favoured by the financial side of the organization, is to take-off and see what happens.

Most aircraft are, however, fitted with ice protection equipment and the line pilot is often led to believe that the aircraft is certificated for all icing conditions. The flight manual simply states that the aircraft is certificated for flight in icing conditions, and makes no reference to icing conditions for which it might not be certificated. In any event, the line pilot is confident that he or she will be able to detect those conditions which exceed the aircraft's capabilities (severe icing) in plenty of time to change altitude or course, or, heaven forbid, turn around.

The first piece in a solution to all of this is the development of an icing severity index which takes into account the parameters that define an icing environment: temperature, liquid water content, and droplet size distribution. This might be referred to as a graduated parametric severity index, and one could be defined today. The difficulty lies with using such an index. To begin with, liquid water content and

3. PIREPs in North America, AIREPs elsewhere.

droplet size are not readily measured on a routine basis. The basic data that is available to the meteorologist does not include these parameters; they must instead be inferred through the use of numerical models. Secondly, the line pilot is at present not equipped with any method of measuring these two parameters. So it is difficult for the pilot to relate the icing conditions and the resulting accumulation to any parametrically objective index.

Yet for any technological approach to the icing problem, a graduated parametric severity index is essential. Numerical forecast models, differential attenuation radars and piezoelectrically vibrated ice detectors, among other things, are not going to function particularly well using terms such as "occasional," "potentially hazardous," or "may create a problem."

In flying today's modern aircraft, many line pilots may be comfortable in thinking that the icing problem has been reduced to a routine and manageable one.

The ICAO Air Navigation Commission in 1991 reviewed the results of a consultation with selected States on the need for, and feasibility of, developing quantitative airframe icing criteria. The results indicated near unanimity on the need to develop such criteria and general agreement on the feasibility of such an endeavour. However, the study indicated a broad spectrum of concerns regarding how to use such an index. Two of those concerns were aircraft certification and the application of icing forecasts.

Ideally, a graduated parametric severity index should evolve to establish a range of icing intensity levels that are directly related to temperature, liquid water content and droplet size distribution. This index should initially provide the operational criteria for the development of forecasting algorithms. It should also provide a broad criterion for the development and certification of aircraft and their ice protection systems. Finally, it should provide a criterion for the development of on-board ice detection systems. Eventually, forecasts and nowcasts should be written and broadcast using the index's terminology. Aircraft operational limitations in the flight manual should use the terminology. And the pilots' real-time information provided in the cockpit describing the severity of ice accretion at critical locations around the airframe should also use it.

A pilot would then be able to relate an aircraft's capabilities to both the icing forecast and nowcasts, and to icing actually encountered. In much the same way as thunderstorms are now treated, icing conditions could begin to be realistically addressed in both the planning and the execution phases of the flight.

In the ICAO study of 1991, the United States took the position that icing certification need not use a graduated severity index because current certification practices covered nearly the entire range of natural icing. It commented:

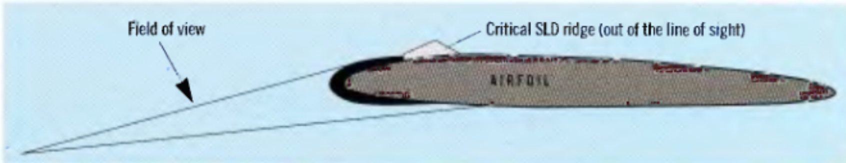
Current aircraft certification practices in the United States do not take account of various levels of icing intensity. The United States has taken the conservative approach that for an aircraft to safely operate in any icing environment, it must be equipped, and so certified, to safely handle all but severe icing environments. Thus, applications for certification must decide whether or not they want their aircraft designs to be certificated for flight into known icing conditions. Once such an applicant decides to seek icing certification for an aircraft type, airworthiness authorities then certificate that aircraft type to the complete environmental envelope (virtually the maximum operational icing scenario) as defined in regulations such as the United States Federal Aviation Regulations or the Joint Airworthiness Regulations. Once certificated, the aircraft flight manual will state the operating procedures and any appropriate limitations.

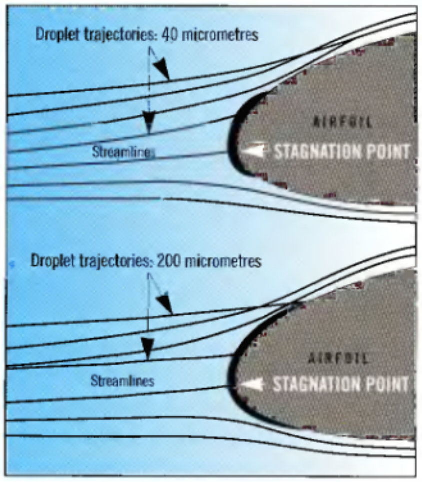
Implicit in this position is the idea that the "complete environmental envelope" (virtually the maximum operational icing scenario) need not include severe icing environments. Probably no single concept has done more to impede the development of icing knowledge in the operational community and, thus, research and development into better forecasting and operating technologies.

This concept may be invalid for three reasons. Firstly, the assumption that large-drop environments such as freezing rain and freezing drizzle could easily be forecast and avoided has been found deficient. Secondly, there may be a type of icing environment which displays a drop size distribution not adequately covered by FAR Part 25 (Appendix C). The typical broad-size drop distribution may contain substantially more large drops than previously considered, while still maintaining a relatively nominal median volume diameter (MVD). Examples of this type of distribution have been observed behind the U.S. Air Force icing tanker as well as in the natural environment in a University of Wyoming study and by the National Research Council of Canada. Finally, research is now beginning to emerge showing that large droplet environments may be specific to particular geographic areas. One such area may be the Canadian Maritimes. The Canadian freezing drizzle experiment identified at least 21 out of 80 cases in which the aggregate MVD exceeded 40 micrometres[4].

A graduated parametric severity index must cover the entire range of possible icing environments; it must be particularly

4. Also known informally as microns.





The portion of a wing visible from the cockpit of many aircraft (above) does not include the critical upper surface where a ridge of ice caused by supercooled large droplets may develop. The size of supercooled droplets (left) affects the severity and location of wing icing in flight. Larger droplets penetrate the streamlines more easily and impact the wing farther aft.

capable of describing those environments for which aircraft are not certificated. These environments, the "exceedance" environments, may be highly dependent upon local topography and meteorology; they may exist far more frequently in limited geographical areas than they do on average in the atmosphere overall. Yet, for short-haul operations, they become very significant. The pilot of a short-haul aircraft is far more interested in the characteristics of a local area than in the mean data collected nationwide. If both certification and operating rules are to apply globally, these local environments must be considered as critical design cases. The severity index that is adopted must have sufficient scope to describe them.

Further work such as the Canadian freezing drizzle experiment is needed to support the characterization of these exceedance environments. Perhaps then the concept that severe environments need not be considered part of the "complete environmental envelope" can be left by the wayside. This can only benefit a range of pilots, from those operating short-haul aircraft from places such as Chicago and Minneapolis to those operating helicopters from North Sea oil platforms.

The management of the inflight icing problem

Within the last year, there has been a great deal of discussion on the possibility of improving the algorithms used to generate an icing forecast. Indeed, the U.S. Federal Aviation Administration (FAA) has required forecasts of en-route freezing drizzle and freezing rain in at least one airworthiness directive. During the process of implementing these requirements, the difficulty of forecasting these types of conditions has become clear. While very broad, general forecasts of icing conditions have some statistical chance of validity in at least part of the specified area, a forecast that demands a very high degree of spatial resolution and a certain degree of parametric resolution, as well, is probably not going to coincide much with actual inflight experience.

In order to develop the inflight icing forecast properly, it must be evaluated in terms of how it will be used. From the outset, it should be understood that forecasts of spatially specific weather hazards generally do not possess the accuracy required to make a suspension of operations mandatory. For example, operations are not suspended solely on the merit of a forecast indicating thunderstorms, tornadoes, or severe turbulence. A forecast of low visibility is, in itself, enough to cause a suspension of operations; however, weather systems that produce low visibility are typically both widely homogeneous and indicated by directly measured parameters. Further, U.S. regulations allow for such a forecast to be mitigated by actual weather observations that do not support the forecast.

The forecast of a spatially specific weather hazard does not, therefore, automatically lead to the suspension of flight operations. It is used instead to allow for flight planning which takes into account the higher probability of an actual encounter with such a condition. For example, in the case of a thunderstorm, a forecast will not suspend the operation; however it will cause both the captain and the dispatcher to require the loading of extra fuel, either for the purpose of diverting to an alternate or, at least, for en-route holding while the storm passes over the destination. Similarly, a forecast for severe turbulence above flight level (FL) 330 will not result in a suspension of operations above FL 330; however, the fuel load may be planned for flight at FL 290 (nominally a less fuel-efficient altitude).

Such operational use of forecasts for thunderstorms and severe turbulence is acceptable because both enjoy some degree of real-time detection. For many years, the industry has presumed that similar real-time detection existed for inflight icing. This may not be the case. One research report mentioned encountering conditions that were particularly insidious because the usual indications of icing (such as visible ice on the leading edges, windows, antennas, etc.) indicated that the accumulation was relatively minor. These conditions resulted in a severe performance penalty causing the research pilot to abandon the experiment. They occurred on two different flights nearly a year apart, and were later associated with a droplet spectrum from 40 to 300 micrometres. Another research flight was also abandoned due to a severe performance penalty. In this case, a researcher stated that the pilot reported little visible icing on the leading edges of the wings. After landing, however, ice accretions were found on the underside of the wings and on the engine cowling. Yet another research report mentions that in icing conditions, a power increase is required to maintain altitude and airspeed due to the increase in total aircraft drag. Countless pilots have indeed experienced such an increase in drag; but interestingly, no such drag increase was noted by the flight data recorder recovered from the American Eagle ATR-72 that crashed from wing icing in October 1994 at

continued on page 25

Steve Green is a member of the Accident Investigation Board at the Air Line Pilots Association, Intl. (ALPA), and is the team leader of that organization's inflight icing certification project. He flies the Boeing 727 for a major U.S. airline.

This article is an adaptation of a paper presented at the 34th aerospace sciences meeting and exhibition of the American Institute of Aeronautics in Reno, Nevada in January 1996.

Icing problem a serious threat

continued from page 8

Roselawn, Indiana, United States. Subsequent flight testing at Edwards Air Force Base in December 1994 confirmed that no power increase was required to carry the ice accretion which could lead to aileron hinge moment reversal.

The problem is with us now, and yet the best solutions may be years away. Consequently, there are two paths to follow simultaneously to bring about both interim short term and, some day, optimum long-term relief.

As with the thunderstorm, the optimum management of the inflight icing problem would be a strategic one. This would involve a reliable forecast algorithm capable of achieving adequate spatial, temporal and parametric resolutions to the degree needed for operational planning purposes. It would involve a method of predictive detection similar to that in use today for thunderstorms and soon to be in use for wind shear. Indeed, both the concepts of differential-attenuating radar and of multiple field-of-view laser radar (or lidar) have shown some promise of viable techniques for predictively detecting some of the necessary parameters from which the presence of actual icing can be inferred. An ideal goal to consider is the development of an on-board radar system which would be capable of detecting not only thunderstorms but also predictively detecting wind shear and inflight icing as well.

Yet, if an on-board predictive detection system were developed, it would probably have a relatively short operational range. The gap between an operationally useful forecast and a short range predictive detection system could be filled by the development of ground-based detection systems which could identify the necessary parameters from which icing in the terminal area, and perhaps in the en-route area, could be inferred. To assist in this effort, a better understanding of why and how an icing environment is sustained may be required. Since continuous real-time observation from the ground has proved difficult in past experiments, it may be useful to develop an understanding of how a particular icing environment initiates, how it moves (if it does), and how it dissipates. This knowledge could then be used to make short-term predictions of the location and duration of an icing environment based on intermittent observation from the ground, the aforementioned airborne platform or, perhaps, a satellite platform.

The interim solution involves a state-of-the-art reactive detection system. There are at present at least two approaches to this. The most elegant solution would be a method of aerodynamic performance monitoring in which the ratio of turbulent to steady components of the local flow velocity is determined at various points along the wing. Monitoring the turbulence intensity ratio would give the pilot an objective indication of the wing's performance, regardless of the source or amount of contamination. A second solution, less elegant but perhaps somewhat closer to realization, involves the installation of a pulse echo or vibrating probe type of ice detector flush with the airfoil just aft of the Appendix C criteria impingement limit point. This device would again provide the pilot with an objective indication of impingement or runback accretion aft of the protected area. Such an indication would represent a reliable method of identifying either an SLD environment or the presence of runback ice in very-near-freezing environments.

These methods have also been suggested as a means of automatically operating pneumatic deicing boots. This type of installation, flush with the airfoil within the protected area, could provide information to the pilot regarding icing conditions which exceed the ice protection system's capabilities.

In any event, pilot reports based on such reactive detection systems would provide better, more uniformly objective information regarding en-route icing than those issued at present. While their spatial and temporal validity would still be unknown, their parametric component could be compared to a standard reference (Appendix C). A scatter plot of this type of report over time would give a following pilot considerably more information than he or she has today.

Conclusion

The present approach to the operational problem posed by inflight icing is an antiquated tactical approach which is highly dependent on some very subjective information which, in fact, the pilot of a modern transport aircraft probably cannot obtain. The system has an unacceptable rate of failure when compared to the systems in use for other spatially specific weather hazards.

The complete solution to the operational problem must include the development of a graduated parametric icing severity index. This type of index should be based on liquid water content, droplet size distribution and temperature.

The optimum approach to the operational problem is a strategic one. Both en-route and terminal area forecasts of icing conditions must achieve adequate spatial, temporal and parametric resolutions to allow changes in operational planning. Methods of predictive detection must be developed and implemented so that both ground-based and on-board detection can be used to validate the forecast and plan an operational response to the conditions before they are entered. Such a system would, in concert with a high resolution forecast, allow safe operation in close proximity to all degrees of inflight icing.

The interim approach to the operational problem is a tactical one. This requires accurate, objective detection of ice accretion which exceeds that used for certification on both the protected and unprotected surfaces of the aircraft. This type of threat information would allow the pilot to make tactical decisions in a timely and informed manner, and would allow inclusion of more objective and useful information in a pilot report than is possible today. □

Inflight icing research

continued from page 11

Sometimes, however, drizzle is formed by cloud droplets coalescing, which can occur at temperatures above or below freezing. In this case, freezing drizzle may exist aloft but the algorithm will not indicate it. The written forecaster's guide supplies information on how to diagnose such an event.

As a result of this research, new inflight icing advisories issued