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Investigation into Ice Detection Parameters for Turboprop Aircraft

P. M. Render* and L. R. Jenkinson†
Loughborough University of Technology, Loughborough, Leicestershire LE11 3TU, England, United Kingdom

This article summarizes some of the main results from a study into ice detectors for turboprop passenger aircraft. It is concluded that ice detectors do not significantly improve the pilot's ability to detect in-flight icing. The study also identified that ice detection was not the only icing issue for turboprop aircraft. Other issues concern the effectiveness of pneumatic de-icing boots, ice protection on the tailplane, and pilot training.

Introduction

PRIMARY ice detection systems are starting to be fitted to turbofan-powered passenger aircraft. The reasons are mainly economic, but the systems do have the potential of reducing pilot workload and further improving aircraft safety in adverse weather conditions. At present, no primary systems have been fitted to turboprop passenger aircraft, other than the Beech Starship. The case for adding primary ice detection systems to such aircraft is far from proven. The authors have recently completed a study into ice detectors for turboprop passenger aircraft.[1] The study was funded by the United Kingdom's Civil Aviation Authority (CAA). The objectives of the study were as follows.

1) To determine the issues facing operators and airframe manufacturers in the fitting and operation of ice detectors.

2) To determine the capabilities of existing and proposed ice detection systems.

3) To determine the feasibility of conducting a safety/cost benefit analysis of ice detectors, and if such an analysis is possible, to define the methodology to be used.

The need for ice detection was focused on in-flight icing, but ground icing was also considered. This article considers only in-flight icing and summarizes some of the results from the first part of the study, which involved interviews with pilots, operators, and aircraft manufacturers.

During the course of the study it became clear that the provision of ice detectors was not the major issue for turboprop operations in icing conditions. The major issues identified by pilots and operators are covered in the following sections. For airframe manufacturers, certification and test flying in icing conditions are the major concerns. Because of the complexity of the issues, certification and test flying are not covered by this article.

Methodology for Interviews with Pilots

A number of airlines were identified for inclusion in the study. The airlines were chosen because they covered a range of operations (e.g., scheduled and charter passenger services, mail flights, night freighting, etc.), and between them they operated a variety of turboprop aircraft. For each airline a meeting was arranged with personnel identified by the chief pilot. All of the personnel were current commercial pilots, except for two of the chief pilots, who were no longer operational pilots. Depending on the airline, the personnel interviewed included the chief pilot, fleet managers, and line pilots. Frequently, line pilots were met without the presence of their managers. In all, over 20 pilots took part in the study. It must be emphasized that the pilots interviewed were not selected to give a scientifically based sample of the United Kingdom's commercial pilots. However, the pilots interviewed covered a range of experience and backgrounds and are felt by the authors to be a reasonably representative cross section of current commercial pilots.

The meetings took the form of informal discussions typically lasting 2 h. The pilots were informed of the nature of the study and were told that their individual comments would not be attributed to themselves or their airline. The subjects covered in the discussions included 1) the influence of in-flight icing on airline operations, 2) methods used to identify in-flight icing, 3) pilot experience of in-flight icing conditions, 4) pilot understanding of the influence of icing on aircraft characteristics, 5) in-flight ice protection, 6) ground ice detection and protection, and 7) requirements for future ice detection systems. The authors also managed to talk with maintenance personnel working on the Shorts 330/360 and Viscount. As with the pilots the information obtained was used to fill in a questionnaire.

All of the airlines operated at least one type of turboprop aircraft and many of them also operated turbofan/turbojet aircraft. The inclusion of nonturboprop aircraft in the study was deliberate, since it was hoped to ascertain to what extent identified issues were peculiar to turboprop pilots and operators. The turboprop aircraft considered in the study were 1) ATR 42, which is fitted with a Rosemount ice detector. Recent winters in the United Kingdom have been unusually mild, and consequently, the experience of operating the ATR in icing conditions was limited; 2) British Aerospace ATP; 3) British Aerospace Jetstream 31; 4) British Aerospace Jetstream 41, which is fitted with a Rosemount ice detection system; operated by the airline for one winter, so that operational experience in icing was limited; 5) Fokker F27; 6) Fokker 50, at the time of the study the type had only been in service with the airline interviewed for around four months, so that there was little winter operating experience; 7) Shorts SD330/SD360, Lucas rotating cylinder ice detector is fitted; and 8) Vickers Viscount.

Unless stated, the previous aircraft did not have an ice detection system fitted. The nonturboprop aircraft considered in the study were 1) BAC 1-11, Lucas rotating cylinder ice detector is fitted; 2) Boeing 747-400, fitted with a primary ice detection system manufactured by Rosemount; 3) British Aer-

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*Lecturer, Department of Aeronautical and Automotive Engineering and Transport Studies. Member AIAA.

†Senior Lecturer, Department of Aeronautical and Automotive Engineering and Transport Studies. Member AIAA.

ospace 146, Lucas rotating cylinder ice detector fitted; and 4) Fokker 100, Rosemount ice detection system fitted.

With the exception of the Boeing 747-400, the previous turbofan aircraft are only slightly bigger than the largest turboprop aircraft considered, and therefore, some overlap in terms of flight times and routes existed. The 747-400 was deliberately chosen because of its primary ice detection system. The in-service experience of this system was felt to be relevant in helping to determine the merits of primary systems for turboprops.

For the Rosemount detectors, the sensing probe is driven magnetostrictively to vibrate at its resonant frequency of 40,000 Hz. The added mass of the accreted ice causes the resonant frequency to change. When the frequency decreases by an amount corresponding to a certain thickness of ice, the probe is de-iced and the cycle begins again. The Lucas detector has a rotating grooved shaft protruding into the flow. A chisel point is situated close to the shaft. As ice accretes to the shaft it is removed by the chisel. The electric motor that drives the shaft is mounted on a torque-sensing device that switches a signal on the flight deck.

An in-depth analysis of the pilot interviews is given in Refs. 1 and 2.

Discussions with Airframe Manufacturers

Visits were made to four of the main European manufacturers of turboprop aircraft and four other companies were also contacted. The manufacturers included companies that market both turbofan and turboprop types. The manufacturers were initially approached by telephone and a meeting arranged at the company offices. At each meeting a group of engineers and managers were available. One of the difficulties of discussing icing problems with manufacturers lies in the delegation of responsibilities in the company. This means that the aerodynamics department, the systems section, the design team, the airworthiness manager, the flight test section, and the production/service support team are all involved in icing policy. It was impossible and impractical to meet with all of these sections for each company, but fortunately all were represented by the sum of the subgroups. The companies were asked to make available those engineers they felt would have past experience on icing issues and who could explain current company policy. The authors feel that in all of the cases the companies provided an experienced and knowledgeable team. The discussions with the aircraft manufacturers was purposely scheduled to follow the interviews with pilots so that points raised by them could be addressed.

The meetings were arranged as informally as possible and lasted at least 2 h. As with the airlines, the engineers were assured that their individual comments would not be attributed to themselves or their company. In this way it was possible to extend the discussion into potentially commercially sensitive areas and this undoubtedly helped the study. The topics for discussion included 1) the nature and specification of in-flight ice detection; 2) the influence on aircraft characteristics of in-flight icing; 3) the specification and control of in-flight anti-icing and de-icing systems; 4) airworthiness certification issues for in-flight icing; 5) attitude to primary in-flight ice detection systems and specification; 6) ground icing issues; and 7) information, training, and publicity issues.

After the discussion with a manufacturer, the authors compiled the issues into a questionnaire format so that the meeting was recorded in a standardized form.

Pilot Knowledge of Icing

Pilots by their very nature are confident individuals with a professional attitude to their work. Without exception, all of the pilots interviewed felt that regardless of whether or not an ice detector was fitted, they could identify the onset of in-flight icing conditions. Having identified the onset of icing all pilots felt that they could continue to fly their aircraft safely. The authors do not doubt the competence and ability of the pilots interviewed, but it must be recorded that no attempt was made to assess whether or not this level of pilot confidence was justified.

All pilots were respectful of the effects of ice, whether due to in-flight or ground icing. For in-flight icing the attitude of pilots can best be summarized as "All ice is ice, either get rid of it or get out of it." In other words pilots are not interested in the kind of ice (e.g., rime, glaze, etc.), if they identify icing they will attempt to remove it with the aircraft's ice protection system. If they are unsuccessful at removing the ice they will attempt to get out of the icing conditions. For a turboprop pilot this usually means descending to a lower flight level (i.e., warmer air), because the maximum ceiling of the aircraft is likely to be within the icing levels and the ability of the aircraft to climb with ice protection systems switched on is usually poor.

Although most pilots do not worry about identifying different types of icing, it was established that rime ice is by far the most common form of in-flight icing. Freezing rain was very rarely encountered.

Operational Procedures in the Icing Environment

The possibility of in-flight icing is a frequent occurrence in the United Kingdom and Europe, even during summer months. From pilot responses, up to 80% of flights each year need activation of the ice protection system. It must be noted that this does not mean that ice protection systems are working for 80% of the annual flying hours.

All of the turboprop aircraft in the study were fitted with engine and propeller anti-icing systems and with one exception were fitted with pneumatic boot airframe de-icing systems. The exception was the Viscount, which is fitted with a warm air de-icing system. The decision to switch on the anti-icing systems is based on the outside air temperature (OAT) falling to or below a value specified in flight manuals and the presence of visible moisture (i.e., cloud). For most of the turboprop aircraft in the study, pilots reported that the anti-icing systems reduced the available engine torque. As already indicated, this reduction in torque leads to a decrease in climb performance, which can limit the ability of an aircraft to climb through an icing layer.

Airframe de-icing is switched on when in-flight icing is present. All pilots look for visual cues to determine the onset of icing, regardless of whether or not an ice detector is fitted. Pilots look for ice buildup on components such as the windscreen panels, windscreen wipers, wing leading edge, or propeller spinner. On a turboprop aircraft, if the visual cues are missed the pilot may be alerted to the presence of icing by propeller vibration, or by the sound of ice shed from the propeller striking the sides of the fuselage. For pneumatic boot systems, switching on the system is usually delayed until there is sufficient ice buildup on the boot to ensure efficient operation. On the Viscount, the de-icing system is switched on as soon as ice is detected, although some pilots used the system as an anti-icing system and turned it on with the engine and propeller anti-icing.

Except for the ATR-42 and the Jetstream 41, none of the turboprop aircraft in the study rescheduled stall warning in icing conditions. On the ATR an angle-of-attack limitation is switched on when the anti-icing systems are selected. The pilot selects airframe de-icing when the presence of ice is detected either visually or by the Rosemount detector. After switching on the de-icing system, if the ice detector does not detect ice for 5 min the pilot is advised to switch off the de-icing system. The ice detector is advisory and the pilot must decide whether or not to turn off the de-icing system. The anti-icing system is switched off when the pilot is satisfied that the aircraft is clear of potential icing conditions. However, the angle-of-attack limitation still remains in force until the pilot takes the positive action of switching it off. The authors are aware of one occasion where the angle-of-attack limitation was not switched off in clear conditions and a stall warning was given on approach. The Jetstream 41 has a similar system to the ATR.

The primary ice detection system on the Boeing 747-400 is fitted purely for commercial reasons. The purchase cost of the system for an aircraft is recouped every 15 months through fuel savings. These savings come from only having the anti-icing systems switched on when they are required. The system has two Rosemount detectors. Engine anti-ice is automatically turned on at the end of the first cycle to detect ice. If after six cycles ice is still detected the pilots are then advised by a message on the cockpit screens to turn on the airframe anti-icing. The pilots will then use visual inspection of the wing leading edge to decide whether or not to switch on the airframe anti-icing. It should be noted that some airlines have opted for the airframe anti-icing to be activated automatically after the sixth cycle. The system has performed well with no reported failures and no unscheduled maintenance required.

All of the operators issue their pilots with notes on winter operations. These notes are issued annually, prior to the onset of winter. These notes carry information on ground icing, as well as reminding pilots about in-flight icing procedures.

Ice Detection, the Pilot's View

The confidence of pilots in their ability to detect the occurrence of in-flight icing meant that whether or not an ice detector was fitted to an aircraft was not an issue. Pilots who were flying aircraft without ice detectors did not see the need for fitting them and felt that the addition of ice detectors would add nothing to their ability to detect ice. However, some turboprop pilots did concede that ice detectors were useful in alerting the crew to the possibility of icing, particularly in high workload situations, but these pilots would still use visual cues to determine when to activate airframe de-icing. With the exception of Boeing 747-400 pilots, none of the pilots saw any advantage in fitting a primary ice detection system. Pilots want to be actively involved in any decision to turn on ice protection systems because they are concerned about the reliability of the detection system.

Some pilots did see the advantage of an ice detection system for night flying. However, pilots were still confident about anticipating or detecting in-flight icing. Even at night pilots can see visible moisture and in conjunction with the OAT can determine when to select anti-icing. Ice can still be detected on objects close to the cockpit and, with the wing inspection lamps, on the wing leading edge. If visual methods failed, pilots would pick up the presence of ice through performance changes of the aircraft. Some pilots wish to have two wing inspection lamps on aircraft so that either pilot can inspect the wing. This was felt to be particularly important in high pilot workload situations (e.g., approach).

Pilots flying the Shorts 330 and 360 had a mixed response to the fitted ice detector, which was manufactured by Lucas. Some pilots found the detector a reliable indicator of icing, whereas other pilots preferred to rely on visual cues (e.g., windscreen wipers) and their own experience to detect icing. It is interesting to note that this mixed response was in stark contrast to pilots flying turbofan aircraft fitted with Lucas detectors. Turbofan pilots were unanimous in their praise for the accuracy and reliability of the Lucas detectors. This difference between Shorts and turbofan pilots was never fully explained, but may be due to a less than ideal position for the detector on the Shorts aircraft. The detector is located on the underside of the fuselage. Alternatively, the detector may at times be outside its normal operating envelope, where the combination of airspeed, temperature, and atmospheric water content would be unlikely to give a reliable indication of ice. Another possible explanation is the Shorts aircraft being unpressurized, have a ceiling of around 10,000 ft, and consequently, spend a far greater proportion of flight times operating in icing conditions. Therefore, shortcomings in the detector will become more readily apparent to Shorts' pilots than turbofan pilots.

The more modern Rosemount detectors were felt to be reliable at detecting ice, but pilots had usually already detected the presence of ice from visual cues. One turboprop pilot with experience of the Rosemount system suggested that the detector would be more useful if it could indicate the rate of ice buildup.

Ice Detection, the Manufacturer's View

All manufacturers recognized the need to detect ice accretion to the airframe. The attitude to the provision of in-flight ice detection systems on aircraft varied not only between manufacturers, but also on different aircraft types from a particular manufacturer. Some manufacturers felt that such systems did provide an alert to pilots, which assisted in the use of ice protection procedures, whereas others felt that pilots could adequately detect the onset of icing. Even manufacturers who provided ice detectors accepted that a good pilot would often detect ice before, or at the same time, as a detector. For some manufacturers the specification of a detector represented good practice and also provided an insurance against product liability responsibility (i.e., being sued for negligence for not fitting a detector). For similar reasons, a manufacturer who had installed detectors to an earlier aircraft and noted their ineffectiveness, would still be likely to specify ice detectors on a new design.

All manufacturers regarded ice detectors as unreliable. They had experiences in which the detector gave spurious signals and/or late indication of ice. One manufacturer quoted recent difficulties with ice detection due to the interaction of airframe vibrations with the device.

Like pilots, none of the manufacturers felt that ice detection systems should be made primary devices, due mainly to the perceived unreliability of detectors. From experience on an earlier type, one manufacturer had relegated the automatic detector from being a primary system to advisory on a later aircraft type. The manufacturer argued that the fear of icing problems on the earlier configuration had proved to be groundless, which allowed a more relaxed specification for the subsequent type. However, having previously specified ice detection as a primary device, they felt that they could not take the commercial risk of removing the detector completely from the aircraft.

The positioning of the detector is usually decided in consultation with the detector manufacturer. The requirement is for the detector to be outside the boundary layer in freestream air. This usually means that the detector is located on the fuselage, although one manufacturer had fitted the detector on the wing. This choice of location was largely determined by the mechanical considerations of the installation. The detector performance was checked during icing trials and would have been changed if found to be inappropriate. Some support was given to the suggestion that detectors could be used in those areas that the pilot could not visually check (e.g., high wings), but in such circumstances the reliability of the device would need to be better than existing products to give confidence to the pilot. Less support was given to the use of multisensors on the wing surface due to the potential confusion this may cause and the complexity of the logic in the system design. One manufacturer commented favorably on the development of camera scanning devices to visually check the aircraft for ice accretion. All of the manufacturers would like to see better detector devices on the market, as the limited choice of the current designs inhibited their system options.

Manufacturers recognized that pilots use various visual cues to determine ice accretion and quite often identify in the flight manual suitable components to use. In effect, this is using components as a simple ice detector. Manufacturers regard these observations as reliable and accurate, but usually no formal verification is included in the ice certification trials. The development of a simple device for visual observations and validated in-flight tests may be accepted by the manufacturers more readily than the more sophisticated devices currently available. One manufacturer has positioned a visual ice detector just below the cockpit. Flight tests have shown that this is the last location on the aircraft to de-ice. Therefore, the pilot can be confident that the rest of the aircraft is clear of ice. If such simple systems could also pass a signal reliably to the cockpit for pilot alert, this would be regarded as a good advisory ice detection system.

Ice Protection, the Pilot's View

For turboprop pilots, in-flight ice protection is a more important issue than in-flight ice detection. In particular, pilots dislike the pneumatic de-icing boots fitted to most turboprop aircraft. With the exception of one pilot, every pilot who had flown an aircraft fitted with pneumatic de-icing boots wanted a better system. Many pilots expressed a desire for turboprop aircraft to be fitted with anti-icing systems similar to those fitted on many turbofan aircraft.

Flight manuals tell the pilot that the pneumatic de-icing boots should be activated when a certain buildup of ice (typically between 0.25–0.5 in.) has occurred on the boot. The concern for pilots is how to determine this thickness of ice, and so avoid the possibility of ice bridging. Ice bridging occurs when the thickness of ice on the boot is too thin to break away cleanly, leaving a layer of ice to form over the top of the boot. Repeated activation of the boot results in the boot inflating and deflating beneath the layer of ice without the ice breaking away. Pilots use a number of methods to determine ice thickness to help them to decide when to activate the de-icing boots. These methods include the following:

1) The use of a feature on the wing leading edge to estimate ice thickness; not all aircraft have a suitable feature and this method is difficult to use at night or with clear ice. In addition, if the feature is a long way from the cockpit, the accuracy of any thickness measurement is always going to be questionable.

2) As ice builds up on the leading edge of the boot it appears as a white band against the black background of the boot. With experience it is possible to decide when to operate the boots by estimating the width and color intensity of the band. This method is also difficult to use at night and when clear ice is present.

3) Observe the contour of the ice buildup on the wing leading edge and use the shape to estimate ice thickness. This method is also difficult to use at night and when clear ice is present.

4) Estimate the thickness of ice buildup on an object in the freestream airflow (e.g., aileron mass balance). The further away the object is from the cockpit, the harder it is for a pilot to accurately assess ice thickness.

5) Estimate the thickness of ice on an object close to the cockpit (e.g., windscreen wiper blade). With experience the pilot knows that for a certain buildup of ice on the chosen object, the boots should be activated. As it is easier to estimate thickness on a close rather than a distant object, this method is probably more accurate than trying to estimate the thickness of ice on the wing leading edge. However, the pilot does need to know the relationship between the ice thickness on the chosen object and ice thickness on the boot. This relationship is usually handed down from pilot to pilot, but for the Fokker F27, the flight manual tells the pilot to activate the de-icing system when the ice buildup on the windscreen wiper nut reaches a certain thickness. This thickness has been determined from flight testing.

Given the uncertainties of estimating ice thickness it is not surprising that pilots are cautious before activating de-icing systems. One turboprop operator instructs its pilots that upon deciding there is sufficient ice buildup to activate the boots, they should delay activation by 1 min to ensure that the ice buildup is truly sufficient for effective boot operation. On aircraft where the de-icing boots are chordwise (i.e., a number of individual boot sections covering the span of the wing) the pilots will often activate one boot section to see whether the ice breaks away cleanly. If the ice does, they will then activate the whole system. If the ice does not break away cleanly they will not activate the whole system, but wait and then repeat the procedure with another boot. Modern de-icing boots are usually spanwise, and so this procedure is not available to pilots.

Virtually all of the pilots interviewed who had turboprop experience thought that the provision of an ice depth measuring device was desirable. One pilot felt that such a device should be mandatory on all aircraft fitted with pneumatic de-icing boots.

Although all of the pilots were aware of the possibilities of ice bridging, none of them had encountered it. In addition, none of the pilots seemed to know of any colleagues who had encountered ice bridging, apart from one incident involving a light twin engine aircraft. These observations raise an interesting question; is the risk of ice bridging a significant threat in the operational environment? It may be that the threat is very real, and ice bridging has been seen in wind-tunnel tests, but the operational procedures developed by pilots and operators over recent years have minimized its occurrence.

Even when functioning properly, pneumatic boots do not remove all of the ice. After activation of a boot, residual pieces of ice remain on the boot's surface. The amount of residual ice tends to increase as the boot gets older, and this is probably due to roughening of the boot's surface. The treatment of the boot's surface with proprietary products such as Ice-Ex, does improve the shedding characteristics of boots, but does not completely remove the problem. Although the residual ice is not usually detrimental to aircraft performance, pilots do want a system that does consistently get rid of all of the ice.

Another reason for the dislike of pneumatic boots is their perceived unreliability. Two pilots had experienced major problems while operating boots, although one of these incidents had occurred on an aircraft smaller than those considered in this study. Boots frequently suffer from punctures, and as boots are on the minimum equipment list, this means that aircraft can only take off if icing conditions can be avoided. Even in summer, avoiding icing conditions is not always a practical option, and so the aircraft is effectively grounded. Repair of a puncture typically takes 4 h. An indication of the frequency of unscheduled maintenance on boots was given by one airline, which for a fleet of three turboprop aircraft had in three successive months 4, 9, and 5 h of unscheduled maintenance on boots. Anecdotal indication of the reliability of boots came from one senior pilot who claimed that he had once counted 26 patches on the leading-edge boots of one aircraft.

Typically, boots last two to three years and then have to be replaced. This life was typical for all of the operators interviewed and appeared to be independent of aircraft utilization rates. The usual reason for replacement was failure of the boot material, but boots are also susceptible to damage during ground handling. One operator reported that boots had been damaged during overwing refueling, because the fuel hoses had been dragged over the wing leading edge. Typically it takes 24 h to replace a boot, due to the long curing time for the adhesives.

In contrast to the pneumatic boot, the warm air de-icing system on the Viscount was perceived by pilots to be reliable and effective. In this system exhaust air from the two inboard Dart engines is passed through heat exchangers and used to heat ram air from the atmosphere. This ram air is then ducted along the leading edges of the fin, tailplane, and wings and then vented from ports on the surfaces of these components.

In the event of failure on one engine, the remaining inboard engine can supply the entire de-icing system. The only moving parts on the system are the flap valves, which control the amount of air taken from the engine exhausts. These occasionally fail and need to be replaced in a procedure that takes eight man hours. The heat exchanger is a lifed item and is changed as part of regular maintenance. The disadvantage of the system is that it is probably heavier than an equivalent pneumatic boot system. The advantages of the system are that it has few moving parts, it does not require ice thickness to be determined before switching on, and, according to pilots, unlike the bleed air systems fitted to turbofan aircraft there is no noticeable effect on aircraft performance. The true effectiveness of the Viscount system in removing ice has not been assessed, but it does appear that it may be worth evaluating a similar system on future turboprop aircraft.

Ice Protection, the Manufacturer's View

Manufacturers pointed out that they marketed their aircraft to meet competitive cost and performance criteria. They would not wish to introduce an ice protection system that put their aircraft at a disadvantage to their competitors. Ice protection, although regarded as an essential feature, was not a marketing criteria. As such, the manufacturers select a de-icing system that is not too expensive, has least influence on aircraft performance, but still adequately protects the aircraft. There was no evidence of selection on a wider base than this narrow expediency (e.g., including total life cycle costing). For example, overpowering the aircraft to allow a bleed air system was not regarded as a feasible design option. Airframe manufacturers would welcome other systems being made available and were aware of several proposed by equipment suppliers. The pneumatic impulse systems were commented on by manufacturers, but as these are still only at the development stage they could not comment on the possible adoption in new aircraft designs. They were attracted to the simplified mechanical design, but were suspicious about reliability and serviceability aspects. The poor esteem in which the boot system is held, by both airframe manufacturers and airlines, makes the development of alternative systems a high priority.

One manufacturer had used a fluid anti-icing system on an earlier aircraft, but had adopted the boot system on later types. The fluid system was regarded as messy (contaminating the apron tarmac) and vulnerable, due to the possible damage to the porous skin. The system was tested as part of the normal preflight checks and was therefore wet for takeoff. The company would not wish to reintroduce such a system.

All manufacturers were aware of the deficiencies of pneumatic boots. The instructions in the flight manuals for the operation of the boot systems are supplied by the boot manufacturers. This places the responsibility for effective operation of the system on the pilot, who therefore needs to make difficult visual judgments on ice accretion. In this way, the manufacturers have effectively delegated responsibility for de-icing to the equipment suppliers and pilots/operators. Although the requirement to ensure sufficient ice buildup on the boot surface before operation was included in the flight manual, the manufacturers recognized the problems this gave the pilots.

The development pilots for one of the manufacturers had devised a simple indicator to assist them in boot operation. The device had been retained for the production aircraft. Manufacturers often add barber poles to icing trials aircraft to indicate ice depth (up to 3 in.). There is clearly a need for the development of an ice depth indicating device to be used in association with the boot systems. Such equipment will need to be fully validated in certification trials to provide confidence in operation.

The manufacturers had several individual comments to make on boot systems. One felt that the trend to shorter chord boots was a retrograde step, but still accepted the suppliers recommended geometry. All manufacturers recognized the potential for increased drag from the attachment of the boots in the aerodynamically critical leading-edge positions. None had experienced any incident of ice bridging, but one manufacturer confirmed that residual ice remained on the surface of the boot after cycling.

The operators had commented on the poor serviceability of the boot systems and the difficulties encountered in repair and replacement work. The manufacturers understood these difficulties but did not have any data on the detailed effects of such unserviceability on aircraft operations. There was wide variation in the estimated life and replacement times from the manufacturers. Detailed serviceability data did not seem to be passed back to the manufacturers from the operators.

Tailplane Icing

Because of the possibility of tailplane stall, many turboprop aircraft have limitations on flap settings when operating in icing conditions. The limitations are set because the pilot cannot be certain that the tailplane is clear of ice or that the de-icing system on the tailplane is working. On the Viscount the pilot is not allowed to deploy flap unless the leading edge of the tailplane is at a temperature of 50°F or more. In other words, the de-icing system can be seen to be working. The Viscount was the only aircraft in the operator's survey with instrumentation to show that the tailplane de-icing was functioning. To minimize the chance of ice accumulation on the tailplane, one operator told its pilots to cycle the de-icing system immediately prior to selecting flap. Many pilots felt that an ice detection system on the tailplane, or an indication that the tailplane de-icing system is working, would be useful.

There was some support among manufacturers for the development of systems to determine the thickness of ice on the pneumatic boots on the tailplane. However, manufacturers are skeptical of the likely reliability of the system. A better approach would be to give the pilot an indication that the pneumatic boots on the tailplane are functioning correctly. Boot systems on most aircraft include cockpit signals indicating functionality of the system. This often involves the measurement of adequate pressure in the separate subsystems (e.g., inboard and outboard left- and right-hand wing and tail surfaces, a total of five lights). This practice may disguise malfunctioning of some elements of a subsystem. For example, a puncture in one of the tail boots may not reduce the overall pressure sufficiently to signal a warning. The issue of tailplane de-icing system functioning should be addressed by a study to assess the risk and benefits of providing such assurance.

All of the manufacturers used the same de-icing system on the tail surfaces as selected for the mainplane. The importance of the tailplane makes it a possible candidate for anti-icing rather than de-icing systems. A detailed technical and economic analysis on the use of anti-icing systems has not been conducted. Anti-icing systems are accepted for other critical components (engines, intakes, propellers, etc.), but not for tailplane surfaces. Studies should be conducted on the suitability and benefit of such systems.

At least one manufacturer felt that rather than provide improved ice protection on the tailplane, they would rather attempt to design a stall resistant tail surface.

Information and Training

The importance of pilot experience when flying in icing conditions was frequently emphasized during the course of the pilot survey. Experience has already been mentioned in the context of determining ice thickness prior to operation of de-icing boots. Pilots are well practiced in operating procedures for in-flight icing. For example, the operating procedures are covered during renewal of the instrument (IMC) ratings. However, how pilots acquire actual flying experience in severe icing conditions is more haphazard. If trained in the United

Kingdom, pilots will have usually experienced some degree of in-flight icing during their training. Similarly, during line training, pilots will usually encounter some form of in-flight icing. However, it is conceivable for a pilot to be cleared for line flying without having experienced severe or even moderate icing conditions.

All of the pilots interviewed agreed that turboprop pilots had to be more aware of in-flight icing than their turbofan colleagues, because the performance of turboprop aircraft in icing conditions is more marginal than turbofan aircraft. In addition, because turboprop aircraft spend the whole of their flights at potential icing levels, pilots are likely to gain far more experience of icing conditions than their turbofan colleagues. These differences in icing awareness and experience have to be recognized when a pilot switches from a turbofan to a turboprop aircraft. All of the operators recognized the potential problems, particularly when such a switch is at captain level. Some operators of both turbofan and turboprop aircraft overcome these problems by ensuring that all pilots serve as first officers on turboprop aircraft at some point in their flying careers. Such an approach is not possible for airlines that are predominantly turbofan operators. With the incursion of regional jets into the once exclusive preserve of turboprops, more operators are likely to become predominantly turbofan operators, and it will become more likely that pilots with only turbofan experience will be appointed turboprop captains. How to ensure that such captains get adequate icing experience needs to be addressed, and more importantly, care needs to be taken to ensure that first officers and captains, both relatively inexperienced in flying turboprop aircraft in icing conditions, do not fly together.

To give experience and training in handling aircraft in icing conditions it was suggested by pilots that an icing model should be available on simulators. However, the effect of this suggestion would be limited since very little turboprop line training takes place in simulators. The manufacturers could provide aerodynamic and propulsion data for use in simulator design if required. One manufacturer felt that the interrelationship of flap/tailplane performance in icing would be a worthwhile addition to a simulator.

It was also suggested by some pilots that a video on icing issues would be a useful aid during pilot training. In particular, such a video would help to improve the general knowledge of icing of pilots graduating from flying training. The concept was commended by the manufacturers who felt that sufficient photographic material was already available from their icing trials. Such material could be made available for the production of the video if required.

Each manufacturer had accumulated a lot of data on icing from work associated with certification and subsequent incident investigations. This formed the basis for the instructions included in the flight manuals, but these are intentionally kept succinct. Manufacturers do not have responsibility to pass on extra information on icing to operators or to provide training material, but some manufacturers do make such information available through guidance notes and general publications (e.g., house magazine). Provided that they are well written, pilots indicated that they are likely to read these publications. More manufacturers are beginning to recognize the importance of providing additional information on icing, but some manufacturers still remain complacent.

Conclusions

Turboprop pilots are confident in their ability to detect the presence of in-flight icing, regardless of whether or not an ice detection system is fitted. At best, present day ice detectors may provide an alert to pilots in high workload situations. Both pilots and manufacturers agree that the reliability of existing ice detectors make them unsuitable for use as primary systems on turboprop aircraft.

Turboprop pilots do not like pneumatic de-icing boots. They are perceived as unreliable and pilots are always concerned about correctly predicting the thickness of ice buildup on the boot. This concern arises from the fear of ice bridging. From discussions with pilots, airframe manufacturers, and boot manufacturers, there is no evidence to suggest that ice bridging occurs for turboprop aircraft. If ice bridging does not occur, this fact should be communicated to pilots, and consideration should be given to revising the operating instructions for pneumatic boots.

Given the unreliability of pneumatic boots and their high maintenance requirements, aircraft manufacturers should consider using anti-icing systems on the tailplanes of turboprop aircraft.

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