

Fluid Ice Protection Systems

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16. Abstract Fluid ice protection systems are being installed on several new generation aircraft. There are many new considerations that must be taken into account when fluid ice protection systems are used. This Technical Note addresses the fluid ice protection system from the perspective of certification and presents a compendium of information for use by Federal Aviation Administration (FAA) certification engineers, Aircraft Certification Offices (ACO's) and others.			
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PREFACE

This Technical Note was prepared with the help of the Federal Aviation Administration (FAA) Regions and Aircraft Certification Offices (ACO's). Special thanks go to Ralph Rissmiller, Jr. of the Wichita ACO whose contributions were so extensive that he is a co-author. Thanks also to Jess Lewis from the Central Region for his helpful comments that compared the draft of the Technical Note and the draft of AC 23.1419-XX "Certification of Small Airplanes for Flight in Icing Conditions." Thanks also to Mark Quam from the Northwest Mountain Region who contributed with his comments. Also Terry Barnes from the Seattle ACO for help in the effect of contamination on the Natural Laminar Flow (NLF) airfoils

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EXECUTIVE SUMMARY

Fluid ice protection systems have been used with varying degrees of success on many diverse aircraft. The systems' success in providing ice protection for the wings and empennage of several European general aviation aircraft has sparked an interest by American manufacturers and has led to the Federal Aviation Administration's (FAA) certification of an American made turbojet business aircraft employing this type of ice protection system. Aircraft ice protection (system) certification requires that the aircraft demonstrate a capability for safe operations throughout its approved envelope when subjected to the icing conditions of Appendix C, FAR 25. This, in turn, dictates that information on many of the aircrafts operational modes, systems, subsystems, and components that are affected by operations in icing conditions be obtained and evaluated during the certification process. Since fluid ice protection systems are relatively new to the United States aircraft industry, the type and amount of relevant information needed for the FAA certification engineers and Aircraft Certification Offices (ACO) for the certification of aircraft fluid ice protection is not readily available in a concise form.

This Technical Note discusses fluid ice protection systems and the problems and concerns they bring to the aircraft icing certification process. Also, it presents methodologies and other information, for alleviation of these concerns and for use in validation of ice protection system performance to ensure safe aircraft operations in known supercooled cloud icing conditions.

INTRODUCTION

HISTORY.

Fluid Ice Protection Systems have been used with varying degrees of success on such diverse aircraft as Russian helicopters, British business jets, and United States (U.S.) general aviation aircraft. The majority of these fluid systems have been employed in propeller ice protection systems. However, the successful use of fluid ice protection systems on the wing and tail surfaces of several aircraft in Great Britain has sparked the interest of several American aircraft manufacturers. The major portion of this Technical Note will concern itself with airframe fluid ice protection systems.

The British Civil Aviation Authority (CAA) has certified several aircraft for flight into known icing conditions in which a fluid system under the trade name of TKS was used. These aircraft range from the British Aerospace HS-125 to the Beech Duchess (BE-76). Also, the Federal Aviation Administration (FAA) has certified the Cessna Model S550 with a TKS System. Its certification was received in late 1984. The Beech Starship has applied to obtain FAA certification for flight into known icing conditions and plans to employ a fluid ice protection system. Also, an application for a Supplemental Type Certificate (STC) has been received for approval for flight into known icing conditions utilizing the TKS system for two single-engine aircraft. These aircraft, the Beech Model 33 and the Cessna Model 206, are unique to the icing certification arena in that both are equipped with normally aspirated reciprocating single engines.

Bleed-air systems, popular on turbine powered aircraft through the mid 1980's, are no longer the automatic choice. The fuel consumption and power penalties associated with using bleed-air cause higher specific fuel consumption than desired for new generation aircraft. The pneumatic boot systems that have been used on reciprocating and turbopropeller aircraft have exhibited a tendency to seriously deteriorate the aerodynamic performance of the new generation natural laminar flow (NLF) airfoils by creating a discontinuity in the surface at the aft edge of the boot, which can trip the boundary layer, causing it to become turbulent. Under these conditions, the laminar flow exists over only a small percentage of the chord of the wing, i.e., less than 10 percent mean aerodynamic chord (MAC), when possibly 65 percent could be achieved with a smooth surface. The drag penalties associated with this low percentage of laminar flow is not readily accepted. Some advanced NLF airfoils have been designed to be more tolerant of surface steps, and to insure that the maximum lift coefficient will not decrease significantly with transition to turbulent flow near the leading edge. These airfoils, however, still exhibit a large drag increase when the extent of laminar flow is significantly decreased.

FUTURE.

Recent advances in aircraft systems, combined with changes in the world political climate have created some trends within the aviation industry that the FAA must respond to. Some of these trends that will affect the certification of aircraft for flight into known icing conditions are:

1. Improved and additional systems are being added to single engine aircraft. Turbocharged piston engines combined with pressurized cabins have increased the potential of the single engine aircraft to the point where operators routinely

expect to operate in most flyable conditions including known icing conditions. The manufacturers also realize that the operators of single engine aircraft are possibly more cost conscious than operators of multi-engine aircraft, so ice protection systems which offer cost advantages over other competing systems are of particular interest.

2. The increased cost of petroleum products in the mid and late 70's has heightened the concern of aircraft fuel efficiency. The aviation industry has responded with new designs to increase fuel efficiency.

The fluid ice protection system provides a solution for two problems associated with the above trends; i.e., the fluid system is, in some cases, less expensive than the conventional wing ice protection system and it also provides a very clean wing aerodynamically, which in turn may contribute to increased fuel efficiency. However, the system presents its own new considerations.

Natural Laminar Flow (NLF) wings are being developed for some next generation aircraft because they exhibit decreased drag characteristics. However, these wings are more sensitive to airflow disruptions than the conventional turbulent flow wings. These disturbances can be produced by small protrusions such as insect accumulation on the leading edges or the small discontinuities caused by paint edges or minor inservice damage. Recent studies also suggest that heavy rain, and in some cases, condensation, may cause the same type of disturbances. These disturbances can cause significant increases in stall speed, significant reductions in the coefficient of lift, control problems at low airspeed, or flight loads in excess of those expected with laminar airflow. There is no reason to believe that the fluid used in fluid ice protection systems would cause any problem, if it remains a liquid. The possible consequences of these changes in the aerodynamic characteristics has caused the National Aeronautics and Space Administration (NASA) to conduct research flights to better understand this phenomenon. The possibility exists that fluid ice protection systems could be used to keep the wings aerodynamically clean in flight and reduce the problems associated with the contamination of NLF wings. Also, it now appears that the fluid ice protection system may be used to reduce the possible problems associated with heavy rain by employing a fluid, other than Freezing Point Depressant Fluid (FPD), that decreases the surface tension of water.

Other mentions of possible uses of this type of system include a combination of boundary layer control over the entire wing. One concern has been the possibility of dirt or other contaminants blocking the holes perforated in a wing or other airfoils for boundary layer control purposes. A fluid type system could be used to keep these holes clean. If that were the case, then the fluid system could possibly be employed for ground anti-ice operation, too.

The schedule requirements of most modern aircraft require that it be capable of flying in almost any weather. This requirement is most obvious for airline operations, because nearly all transport category aircraft are capable of flight in supercooled cloud icing conditions. Most smaller aircraft being developed today are designed with the same type of requirement in mind. Therefore, the ACO's will be seeing new and different types of aircraft ice protection systems on the aircraft that manufacturers present for icing certification. The wing fluid ice protection system is a different type of ice protection system than those certified by the FAA in the past. Therefore, this technical note addresses the wing fluid ice protection system and the problems it brings to personnel associated with the aircraft icing certification process.

THEORY

There are several chemicals that, when mixed with water, lower the waters' freezing point. Glycol, alcohol, calcium chloride, nitric acid, sodium, sodium chloride, among others (reference 1), exhibit this characteristic. The most common chemicals used in the aviation industry for in-flight and ground deicing or anti-icing are glycol and alcohol. Glycol's freezing point in pure form is approximately 10° Fahrenheit (F) depending upon the type of glycol. When pure glycol is mixed with water, the freezing point lowers to approximately -10° to -40° F for a 50/50 mixture depending upon the type of glycol. A fluid ice protection capability for an airfoil can be achieved by the appropriate mixing of glycol based fluids and cloud supercooled water droplets on the leading edge of an aircrafts' airfoils.

Fluid ice protection systems designed for leading edges use porous panels that exude the ice protection fluid undiluted and as supplied by the manufacturer onto the surface where the fluid mixes with impinging supercooled water droplets. This results in a mixture that will contain FPD fluid and water, and possibly ice particles that are swept aft and off the airfoil surface by aerodynamic forces. This ice protection capability involves several variables that determines the type of ice protection. The variables include the amount of supercooled water droplet striking the wing, the amount of ice protection fluid exuding on the wing surfaces, and the temperatures. A typical arrangement is shown in figure 1.

FLOW REQUIRED.

There are three different ice protection modes and two thresholds associated with fluid systems (figure 2). They are:

1. Natural Deice Threshold
2. Natural Deice Mode
3. Anti-ice Threshold
4. Anti-ice Mode
5. Deice Mode

The above three modes of the airframe ice protection fluid system are in order of increasing fluid flow (though not necessarily total fluid usage). The ice protection fluid flow rate and the amount of water impingement determines the ice protection mode of the fluid system.

At the present time, there are basically two methods used to predict the required flow rates. One method is described in ADS-4 and a second method is described in an American Institute of Aeronautics and Astronautics (AIAA) publication (reference 2). The latter has been used in at least one Certification Program (reference 3). These methods are described later in this technical note.

NATURAL DEICE THRESHOLD.

The natural deice threshold occurs during a gradual transition between no ice protection and the natural deice mode where there is a period of ice building and shedding. If the time between shedding is long enough, the ice protection system can be said to be not working or not providing ice protection. Using the work from reference 4, this time between shedding has been shown to vary from 2 to 7 minutes. The practical considerations for this time will have to be addressed during the certification process to ensure that no hazard or loss of intended function occurs.

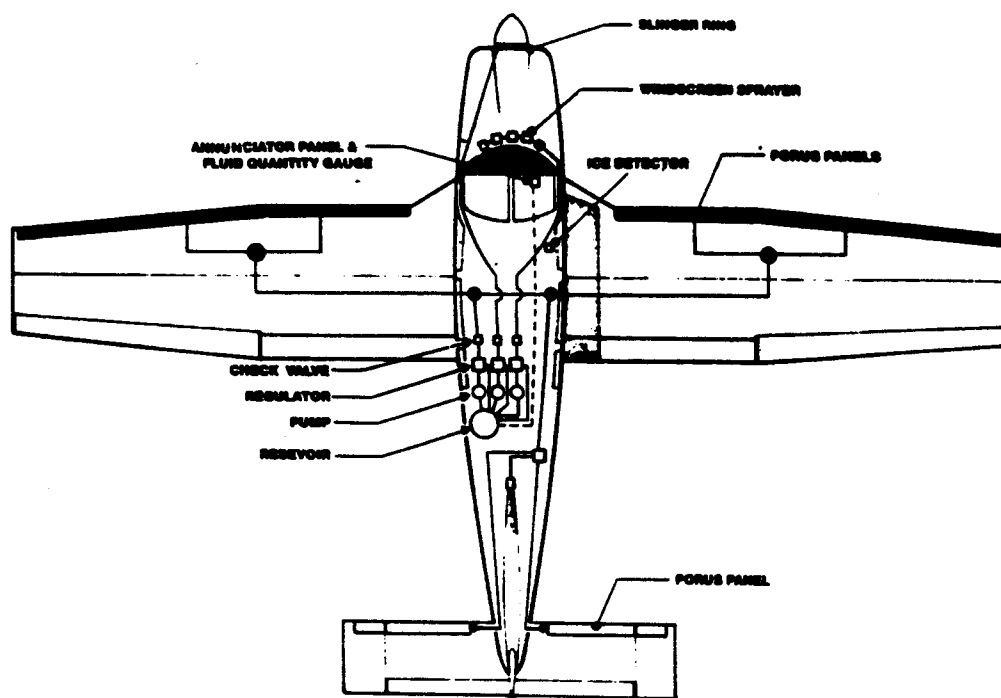


FIGURE 1. TYPICAL ARRANGEMENT OF FLUID ICE PROTECTION SYSTEMS COMPONENTS FOR A LIGHT SINGLE-ENGINE AIRCRAFT

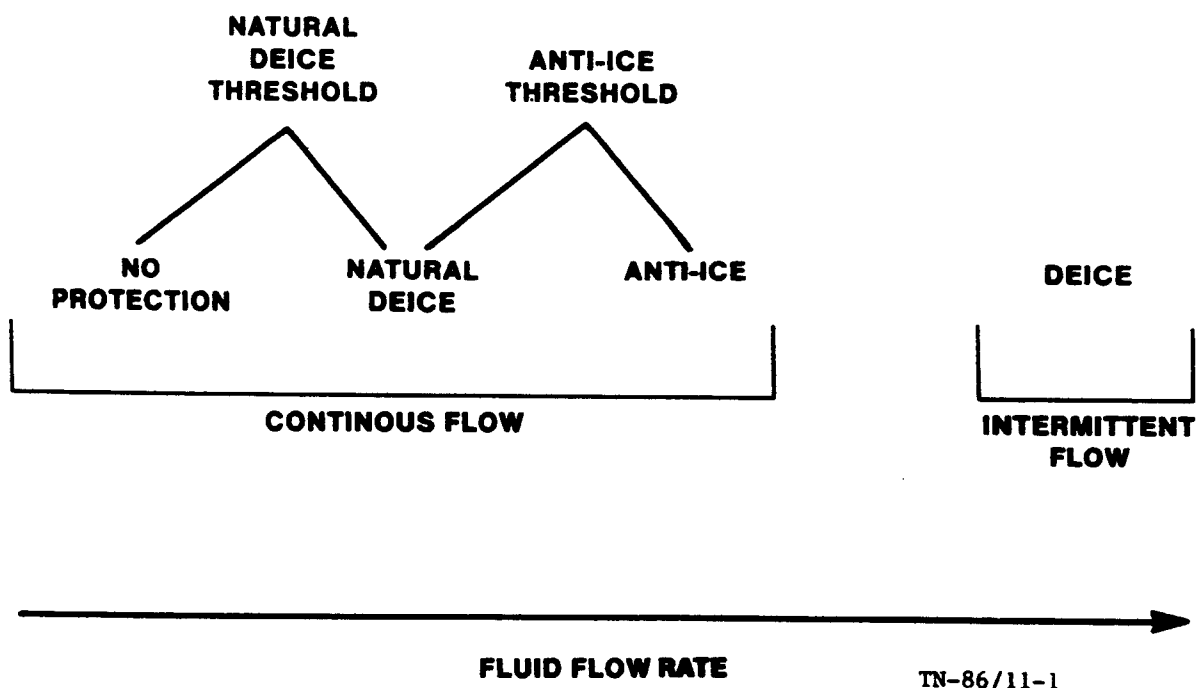


FIGURE 2. FPD FLUID FLOW RANGES

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NATURAL DEICE MODE.

The natural deice mode is a condition that requires the wing fluid ice protection system to be operating before the aircraft has appreciable ice accumulations. The fluid flow rate is lower than required for anti-icing. This lower flow rate allows the freezing point depressant fluid and water mixture at the leading edge to form small spanwise strips of ice along the leading edge stagnation point. The ice will be swept away by aerodynamic forces periodically in the natural deice mode.

ANTI-ICE THRESHOLD.

There is a gradual transition between the anti-ice mode and the natural deice mode. The anti-ice mode has an FPD fluid flow rate that is sufficient to prevent any ice from forming on the leading edge. If the fluid flow rate is decreased, there is a point where small accumulations of ice begin to form, this is the anti-ice threshold. As the flow rate is decreased (or the amount of water impinging on the airfoil increases), the amount of ice forming will increase. The ice will at first be swept away very rapidly and be imperceptible to the eye. As this transition continues, the ice will begin to form along the leading edge in spanwise bars and be swept away by the airflow every few minutes. At this point, the transition has been completed from the anti-ice mode to the natural deice mode.

ANTI-ICE MODE.

The anti-ice mode is a condition such that the FPD fluid and the supercooled cloud droplets water mixture on the leading edge has a freezing point low enough to prevent any freezing on the leading edge or any other surface of that airfoil. Ice is never allowed to adhere to the surface being protected.

DE-ICE MODE.

The deice mode is a condition where ice is allowed to build before the fluid ice protection system is turned on. This allows ice to accumulate which has a bond to the wing surface. When the fluid ice protection system is turned on, a flow is introduced between the ice and the surface to weaken the bond to the extent that ice shedding occurs. There is evidence to suggest that it may not be possible to deice a surface in this manner under some conditions. The testing of the fluid ice protection system should confirm that it operates satisfactorily in the deice mode over the full range of operating conditions that the aircraft is expected to encounter, if certification for deice mode operations is desired.

The flow rate for the deice mode is the highest, but that does not mean it requires the most fluid for an icing encounter. Total fluid requirements for the deice mode may be less than the anti-ice mode if the time between deicing cycles is long enough.

ICE PROTECTION AREAS

The fluid systems used for in-flight anti-icing or deicing are usually only designed for protection of the leading edge of the airfoil. Normally FPD fluid is exuded from a distribution panel that covers the leading edge of the wing. However, in some instances, the wing serves as the distribution panel and is made of a suitable material in which many holes are drilled. The holes may be formed by

different methods but one of the methods used at the present time involves using lasers to drill holes nominally 0.0025 inch in diameter, with 0.035 inch between centers. This arrangement yields about 800 holes per square inch.

AIRFOILS (WINGS AND EMPENNAGE).

The airfoil section usually considered for ice protection systems includes wings, horizontal and vertical stabilizers, canards, winglets, etc. The wing, horizontal and vertical stabilizers have usually been considered one of the primary surfaces to deice or anti-ice. When wing fluid ice protection systems are used they are normally used on the leading edges, but not always. A NASA Lockheed C-140 Jetstar (reference 5) has a spray nozzle mounted inside the Krueger leading edge flap. This nozzle sprays a mixture of water and propylene glycol methyl ether (PGME). Its purpose is to keep the laminar flow section clean of foreign matter and ice.

ANGLE-OF-ATTACK LIMITS. The design and installation of a fluid wing ice protection system must take into account the expected angles-of-attack. This is necessary so that the impact areas of the water droplets can be protected (figure 3). If water droplets impinge on unprotected areas and ice accretes, severe problems may develop. An example of a fatal accident attributed to this phenomenon involving a Beech King Air during climb-out is cited in reference 5. Although some pilots are taught that during climb, the best course of action when encountering icing conditions is to climb as rapidly as possible, it is not stressed that the entire under-wing area may become exposed to ice accretion which the pilot may not be able to see or be aware of.

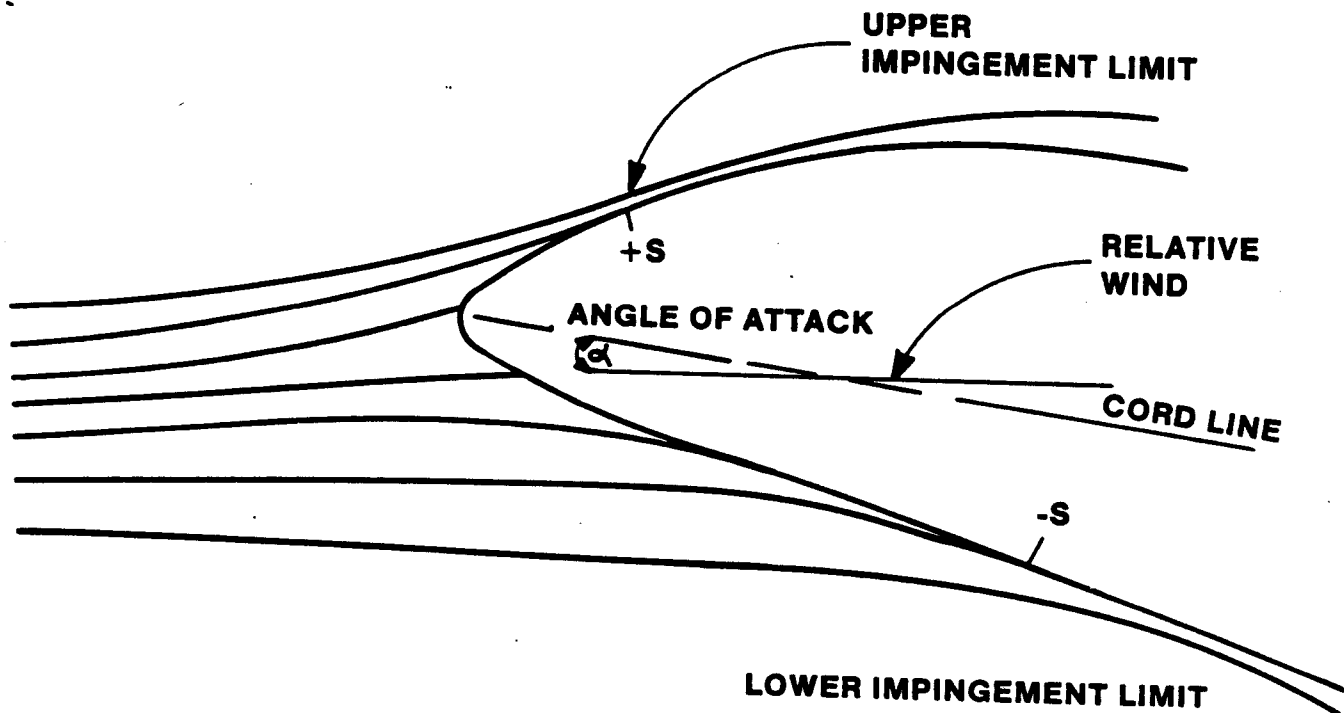


FIGURE 3. WATER DROPLETS IMPINGEMENT LIMITS

The NTSB report on the Beech King Air accident relates the following:

The computer-derived flight performance for N456L indicates that normal climb speed (160 KIAS) or higher was maintained until the aircraft ascended to about 8,800 feet. After ascending through that altitude, the airspeed decreased to near the minimum airspeed of 140 KIAS for flight in sustained icing conditions. This reduction in airspeed indicates that ice was collecting on the airframe and suggest that the flightcrew either: (1) attempted to maintain the normal rate of climb by increasing the pitch attitude (and the angle-of-attack), which resulted in a decrease in the airspeed, or (2) attempted to expedite the climb through the icing conditions by reducing the airspeed to or near the minimum icing penetration speed, thereby increasing the rate of climb.

However, the performance data also show that the airspeeds used above 8,800 feet resulted in substantially less-than-normal climb performance and resulted in higher angles-of-attack than the 4-degree angle identified as critical by the manufacturer's icing certification analysis. The higher angles-of-attack at 140 KIAS were a direct function of the aircraft's high gross weight, because for a maximum gross weight in unaccelerated flight a 4-degree angle-of-attack would occur near 140 KIAS. Additionally, the reductions of airspeed below 140 KIAS and the attendant higher angles-of-attack would have permitted ice to accumulate on the underside of the airfoil surfaces aft of the deicing boots. Finally, since neither the additional weight of ice accumulations nor airfoil distortion caused by ice contamination was accounted for in the flight performance computation, the above angles-of-attack for the associated airspeeds would have increased progressively as ice accumulated on the airframe. Also, the increasing angles-of-attack would have increased rapidly the rate of ice accumulation to the point where further ascent was not possible.

Therefore, the Safety Board concludes that the overweight condition of the aircraft, in conjunction with flight at 140 KIAS and below, and the severity of the icing conditions combined to permit ice to accumulate rapidly on the unprotected surfaces of the wing. Further, since these accumulations could not be removed by the deicing boots, the wing airfoil eventually was severely distorted, and the aircraft's capability to maintain level flight was destroyed.

The fluid ice protection system may provide additional protection to areas behind the leading edge because of the runback of the FPD fluid if it is rich enough. The design and installation of the porous leading edge must take into account the expected angles-of-attack, so that ice protection can be provided above and below all possible stagnation points/lines. The design should allow for enough fluid flow in both directions from the stagnation point to assure that the flow of the fluid mixture (FPD and supercooled water droplets) is at or above the required concentration. For example, at a high angle-of-attack, the majority of the glycol fluid will go to the upper side of the airfoil, when in reality, more fluid is needed on the lower surface. The lack of fluid flowing to the underside could possibly contribute to large ice buildups that are not readily visible to the pilot of a low-wing aircraft and vice versa.

Therefore, the consideration of all operational angles-of-attack is vital to the safe operation of fluid ice protection and should be addressed in design and certification. Also, consideration should be given to best rate of climb, best climb angle, and any manufacturer recommended icing cloud penetration speeds.

Also, in a climb through icing conditions, a higher airspeed than normal with a resulting lower angle-of-attack should be considered. In fact, it may not be feasible to protect the airfoil for all angles-of-attack that the aircraft can operate at. Therefore, appropriate limitations should be placed in the airplane flight manual to alert the pilot of these limitations of the aircraft.

AREA OF THE WING TO BE PROTECTED. The areas to be protected can include several different areas which require different approaches. The design may include areas that must be protected at different times. As an example, the area in front of the engines may require anti-ice protection while other areas may be deiced only after a buildup has occurred.

CLOGGING WITH INSECTS, WAX, ETC. The clogging of holes in the porous leading edge material of fluid ice protection systems is of concern. However, in a recent test by the NASA Langley Research Center there was no problem associated with clogging by insects. During these test, a fluid ice protection system equipped aircraft was flown at low level above the marshes in the vicinity of the Langley Research Center. The primary purpose of these test was to determine if the fluid ice protection system was capable of protecting laminar flow airfoils from accumulation of insect debris that would affect performance, stability, or control. The report (reference 7) indicates that FPD systems may provide protection against insect contamination using very small fluid flow rates and a 80/20 percent Monoethylene Glycol (MEG)/water solution.

ENGINES.

Engine ice protection has always been considered important, in fact, on many light airplanes only the engine is protected. Ice protection systems associated with turbojet engines have been centered around anti-icing rather than deicing, because of potential damage caused by ice ingestion, and possible balance or airflow problems caused by buildup of ice on engine blades or inlets.

INLETS, SPINNERS, AND GUIDE VANES. Methods used in the past to provide ice protection for inlets, spinners, and guide vanes of a gas turbine engine have predominantly been thermal anti-ice systems. The heat required has generally come from one of two sources; i.e., bleed-air or electric. Both of these sources use engine power, the bleed-air anti-ice uses hot gasses from one of the compressor stages, and the electric anti-ice uses power from an engine-driven generator.

A problem associated with ice protection of turbine engines is the release of chunks of ice by deice type ice protection systems. These ice chunks may cause damage as they pass through the engine. Ice protection systems which operate in this manner include the pneumatic boot systems, electromagnetic impulse deicing systems, and thermal or fluid systems used in the deice mode. Considerable care will be necessary in this area because as engines become more fuel efficient they may become less tolerant of ice ingestion. This area may be considered under the broad category of foreign object damage (FOD) during engine certification, however, prudence dictates that this condition be investigated during airframe certification activities.

PROPELLER. There are basically two types of ice protection systems used on propellers; i.e., thermal and fluid. The thermal systems are usually electric and require a slip ring mechanism to conduct electricity to the heater elements on the base of the propellers. In the fluid systems, the FPD fluid is exuded through a hub dispenser and centrifugal force causes the fluid to be slung along the propeller surface. The propellers of piston and turbo-prop aircraft have used fluid ice protection systems for many years. The most popular propeller fluid system is the alcohol slinger systems; however, the potential fire hazards associated with alcohol do present problems.

WINDSCREEN.

The systems now used to provide ice protection for the windscreen are the thermal and fluid ice protection systems. The thermal ice protection systems are normally electric or hot air. The electro-thermal ice protection systems employ either a conductive film or wire grid which is built into the inside of the outer panel of the windscreen, or they employ an additional transparent plate which is heated by conductive film or wire grid that is mounted in front of the windscreen. The hot air ice protection systems usually use bleed-air from the turbine engine compressor section or hot air from a heater muff. The hot air is blown over or through panels on to the windscreen. The fluid type is usually a spray-bar type arrangement using either alcohol or ethylene glycol which is sprayed onto the windscreen. Systems using alcohol have the hazard of using a flammable fluid and precautions must be taken, for example, routing of electrical cables and location of arc producing switches require special considerations.

ROTORS.

There have been several experimental test programs in which a fluid ice protection system was employed to protect helicopter rotors. As yet, these systems have met with limited success. Also, there have been several military attempts to use this system, including successful results by the Soviets. Because of the difficulty of obtaining information on Soviet military aircraft, there is a lack of specific knowledge in this case. However, Soviet transport helicopters of around the 1965-70 vintage did employ a fluid ice protection system, and there are some indications that a recent large transport helicopter uses a fluid system.

Other work (reference 9) was done by the U.S. Army in the early 60's. However, this did not lead to a fluid system being used on any U.S. Army helicopters that were fielded. The Army's experimental system used a slinger ring to transfer the fluid from a fixed nozzle at the rotor hub to the rotating blade (figure 4). Similar arrangements were also employed on the tail rotor. A UH-1 helicopter had this experimental system installed in 1960-1961. However, this system encountered difficulties with even distribution of the FPD fluids over the airfoil surfaces that could not readily be corrected.

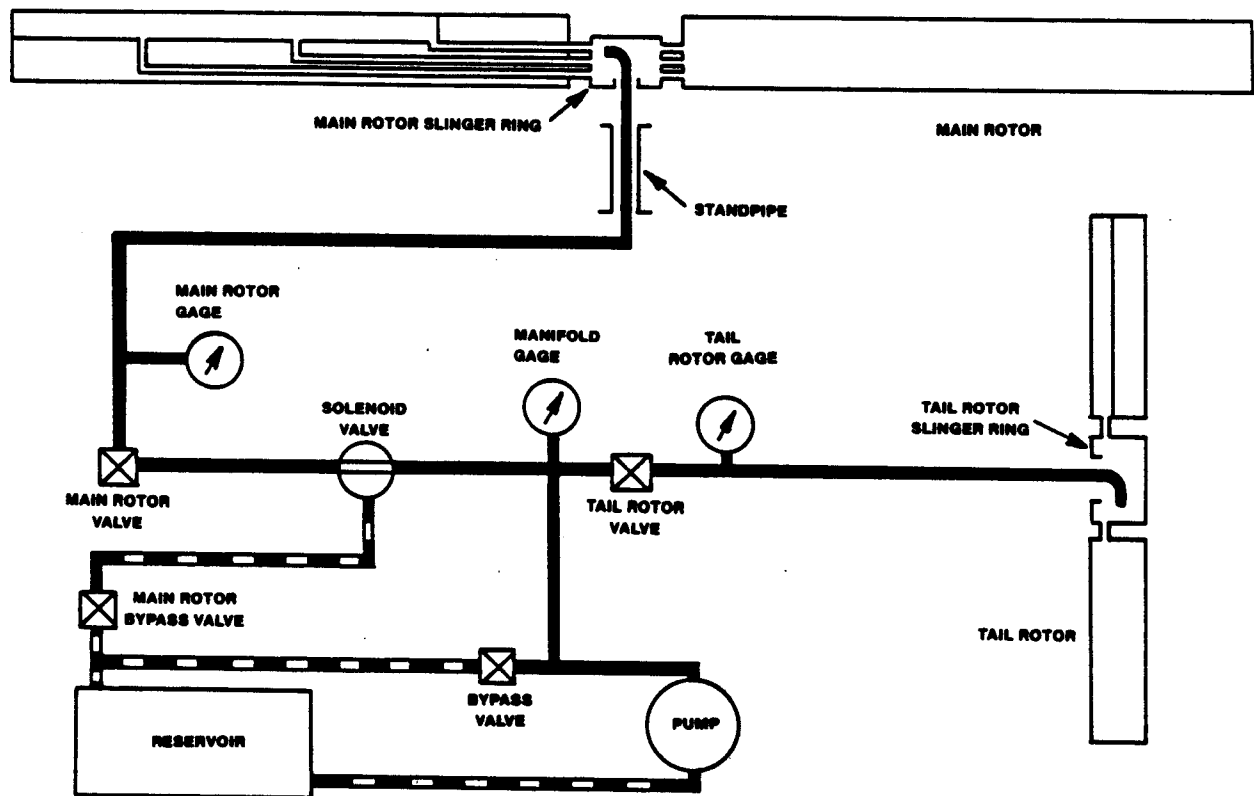


FIGURE 4. SCHEMATIC OF HELICOPTER FLUID ICE PROTECTION SYSTEM
(REFERENCE 9)

FUSELAGE.

The fuselage has not been considered an important surface to protect from ice accumulations, because the surfaces generally run parallel to the airflow so the ice does not accrete. The exceptions to this are the antennas and other objects that protrude into the airstream, for example nose, radomes, instrumentation. These usually have a high ice collection efficiency and in icing encounters these items sometimes shed ice or break off under extreme conditions. The loss of an antenna will probably cause loss of communication or navigation radios, but a more serious hazard exist if the ice sheds into an engine. Therefore, the trajectory of shed ice from protrusions must be considered, with the attendant possibility that ice protection may be necessary for some of these compartments or certain areas of the fuselage.

NOSE-CONE/RADOME.

The nose-cone/radome of an aircraft may need protection for several reasons. These include the prevention of ice shedding and damaging an aircraft engine or other aft-mounted components of the aircraft, and the clearing of radomes to ensure that performance of equipments such as weather radar, radios, and doppler navigation systems are not affected.

CERTIFICATION CONSIDERATIONS

RELIABILITY.

Ice protection system reliability is essential for safe flight in icing conditions. Depending upon the certification basis of a particular aircraft (FAR 23, 25, 27, 29), the method(s) for demonstrating acceptable reliability of the ice protection system may vary.

FAR 23.1309, for the Normal, Utility, and Acrobatic category airplane, makes a significant distinction between single-engine and multi-engine aircraft. FAR 23.1309(c) requires that equipment, systems, and installations of a single-engine airplane be designed to minimize hazards to the airplane in the event of a probable malfunction or failure. FAR 23.1309(b) requires that for multi-engine airplanes these same equipment, systems, and installations must be designed to prevent hazards to the airplane in the event of a probable malfunction or failure.

FAR 25.1309, for the Transport category airplanes, requires that the occurrence of any failure conditions that would reduce the capability of the airplane to cope with adverse operating conditions be improbable, and that compliance with this requirement be shown by analysis, and where necessary, by appropriate ground, flight, or simulator tests. A detailed reliability study, including fault/failure analysis should be conducted to determine the effects of equipment malfunctions or failures of the ice protection system.

FAR 27.1309, for the Normal category rotorcraft and FAR 29.1309, for the Transport category rotorcraft require that systems be designed to prevent hazards to the rotorcraft in the event they fail.

There are individual failures or malfunctions that could render portions or all of the fluid ice protection system inoperative or unuseable. These failures, which may be manifested in various components, include:

1. Electrical System — Alternator/generator failure, alternator/generator control unit failure, drive belt/coupling failure, field wire open or shorted, circuit breaker failure, bus fault, and control circuitry failure.

2. Distribution System — Open tubing or coupling, crushed tubing, blocked flow divider failed or damaged distribution panel, or pump failures.

In accomplishing the reliability studies, it is necessary to determine and investigate the consequences of each component failure that could occur. This evaluation should consider not only the mode of failure or malfunction but also the failure rates for the various components. Since any malfunction or failure that renders components of the ice protection system inoperative when the aircraft is in icing conditions and cannot readily exit that environment, constitutes a hazard to the airplane, this analysis must be carefully conducted.

After accomplishing a detailed analysis of the various failure modes, the designer must evaluate the consequences of these failures and take appropriate measures to achieve the necessary level of safety for that installation. Such steps might include redundant components, reversionary operating modes, backup systems, alternate procedures, etc., or various combinations of them.

REQUIRED FLOW RATE DETERMINATION.

Determination of the flow rate necessary to provide the desired anti-ice/de-ice protection is a significant design requirement. Prediction of the required fluid flow rate used on recent certification programs involved both theoretical analysis and review of NASA icing tunnel test data (references 2 and 8).

Anti-ice protection is provided by maintaining a glycol-water solution on the leading edge of the wing that mixes with water droplets as they impact on the leading edge. In order to attain anti-ice protection, the resulting solution must have a glycol mass fraction (glycol mass fraction - the percent of glycol by weight in the solution) high enough to prevent any freezing. Freezing is not allowed to occur on the leading edge and on the upper and lower airfoil surfaces as the fluid flows aft along these surfaces. As the flow rate is decreased below the anti-ice threshold, ice formation will gradually increase until continuous bars (bars - formations of ice that form spanwise that are approximately 1/2-inch wide and approximately 1/4-inch thick) are formed spanwise on the leading edge before being swept away by aerodynamic forces every few minutes. This latter mode is called natural de-icing.

Precise determination of the anti-icing threshold (natural deice/anti-ice transition) flow rates is difficult, due to the subjective nature of the task. For example, small flecks may form at the stagnation point and be swept away, while other areas along the wing will be anti-iced with no flecks of ice and still other areas may have patches of ice that are being shed from the leading edge. This difficulty is compounded because at certain combinations of temperature, airspeed, and liquid water content, the change is much less clearly defined.

Determination of deicing threshold (deice/no deice transition) flow rates is significantly more difficult than for the anti-ice threshold. This is principally because there is no clear definition of such a threshold, since any flow rate that adequately fills the distribution panel should provide a deice cycle of some period.

The predicted fluid flow rates can be calculated using the analytical method contained in AIAA-84-0023 (reference 2), which was developed subsequent to the 1980-1981 NASA icing tunnel tests of the fluid ice protection system. This method is based upon calculation of the local maximum water collection efficiency factor (figure 5), (β MAX), and is outlined below:

1. Calculate (β MAX) as a function of airfoil shape, airspeed, air density, drop diameter, and angle-of-attack using a reasonably accurate 2-D water droplet trajectory computer code.

$$E = \frac{\Delta Y_o}{H}$$

$$\beta = \frac{d Y_o}{d S}$$

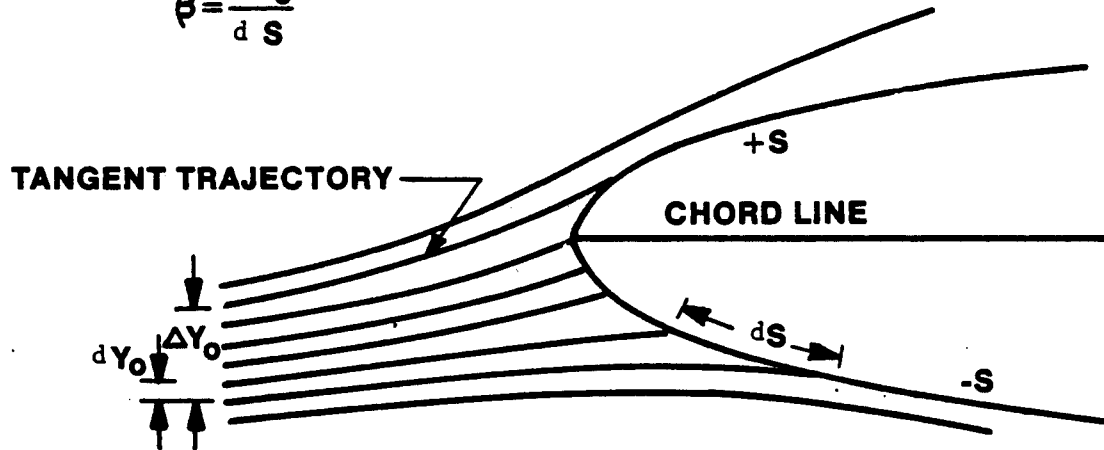


FIGURE 5. DEPICTION OF TOTAL AND LOCAL COLLECTION EFFICIENCY DETERMINATION

2. Calculate the water catch rate, M_w , from the equation:

$$M_w = .0031 (\beta \text{ MAX}) (\text{LWC}) (V_t), \text{ where}$$

LWC = liquid water content (gm/m^3),

V_t = true airspeed (knots)

$$M_w = \frac{\text{gm}}{(\text{min}) (\text{cm}^2)}$$

3. Determine the glycol mass fraction, G , required to produce a solution with a freezing temperature equal to the average between the ambient and the stagnation temperature.
4. Calculate the fluid flow required to achieve the necessary glycol mass fraction, G , given a water catch rate, M_w , using the equation:

$$W = \frac{(G) (M_w)}{(X-G)}$$

where,

X = initial glycol mass fraction of the solution as it is pumped through the porous panel.

An alternative method of predicting fluid flow rates using a modification of techniques described in ADS-4 is discussed next. This method uses a different method to calculate the overall collection efficiency factor, E_m , (figure 4) while the ADS-4 method used an empirical method based on the determination of the overall water collection efficiency factor E_m , the method presented below uses a mathematical determination of E_m . This modified method (reference 2) is outlined below:

1. Calculate E_m as a function of airfoil shape, airspeed, air density, drop diameter, and angle-of-attack using a reasonably accurate 2D water droplet trajectory computer code.
2. Calculate the rate of water impingement on the airfoil from the equation:

$$M_w = (V_t)(LWC)(E_m)(h/c)/S_u - S_l$$

where,

LWC = liquid water content (gm/m^3),

V_t = true airspeed (knots),

h/c = ratio of projected airfoil height to cord,

S_u = tangent trajectory impingement limit on upper surface,

S_l = tangent trajectory impingement limit on lower surface,

3. Determine the glycol mass fraction, G , required to produce a solution with a freezing temperature equal to the datum temperature. This temperature, as defined in ADS-4, represents the temperature of an unheated surface in icing, described as the "wet air boundary layer" temperature. This temperature is a function of airspeed, ambient temperature, and altitude.
4. Calculate the fluid flow required to achieve the glycol mass fraction, G , given the water catch rate M_w by the equation:

$$W_f = (G)(M_w)/(X-G)$$

where,

X = the initial glycol mass fraction of the solution as it is pumped through the porous panel.

DISPLAYS.

Appropriate displays and annunciations should be provided to enable the flight crew to determine the status of the ice protection system at all times.

MALFUNCTION OR FAILURE ANNUNCIATION.

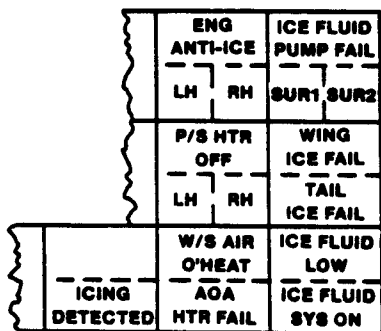
The pilot should be provided with adequate annunciation of various ice protection system malfunctions or failures. These should include such events as FPD fluid pump failure, lack of adequate fluid flow to leading edge panels, FPD fluid distribution malfunction, etc. These annunciations would typically be caution (amber) lights displayed in the cockpit. Alternate methods may require pilot observation of the wing leading edge or other similar procedures for monitoring system operation. If malfunction annunciations are predicted on fluid pressure at different points of the fluid distribution system, careful selection of pressure switch setting is necessary to assure annunciation of a failure in cold weather while avoiding unwanted indications in warmer conditions (due to the significant variation in fluid viscosity with temperature).

FLUID QUANTITY INDICATOR.

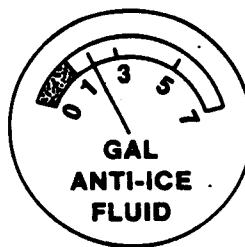
The very nature of a fluid ice protection system is such that there is only a finite duration of ice protection fluid available. It is therefore necessary to provide the pilot with a means to know how much fluid is in the reservoir and enable the pilot to readily determine how long the fluid remaining in the reservoir will last. Conversely, if there are situations where the aircraft may be dispatched with less than full fluid in the reservoir, there should also be a chart or table to allow the pilot to determine how much fluid he must carry for a given flight.

LOW FLUID CAUTION INDICATOR.

All airplanes incorporating an expendable fluid ice protection system should incorporate some means or system which clearly provides a low fluid level caution indication to the pilot (figure 6), approximately 15 minutes prior to fluid exhaustion. This time should be based on the highest flow rate or if possible, the present flow rate of the fluid ice protection system.



**ANNUNCIATOR PANEL
(ICE PROTECTION)**



**ANTI-ICE FLUID
QUANTITY GAUGE**

FIGURE 6. ANNUNCIATOR PANEL AND ANTI-ICE FLUID QUANTITY GAUGE

ICE DETECTION.

Since fluid ice protection systems are generally designed as anti-ice systems, a reliable means to provide the pilot with an immediate indication of icing conditions should be provided. Depending upon the airplane and the ice protection system requirements, such a system may be a relatively simple visual means or could be an electronic sensor.

VISUAL. Several means of visual detection of icing conditions have been used. These may range from a protruding item in the forward area of the airplane that is readily visible to the pilot, to small lights pointed at carefully selected locations on the windshield. The important items of concern are: (1) to determine that the location selected accumulates ice prior to any other area of the airplane, (2) that it is easily observable by the pilot, and (3) that it is readily visible and usable during both day and night conditions.

ICE DETECTION SENSOR. Various ice detection sensor systems are presently available. These systems, such as the rotating drum/scrapper, the hot wire probe, and the Rosemount probe have all demonstrated acceptable performance for detection of icing conditions. These sensors use different techniques for detecting accumulation of ice, but each presents a clearly visible annunciation of icing conditions to the pilot prior to appreciable accumulation of ice on the airplane.

ANTI-ICE VERSUS DE-ICE CAPABILITIES.

The fluid ice protection system is intended to normally operate in an anti-ice mode; i.e., sufficient FPD fluid is provided to the leading edge to prevent any ice formation. In more severe icing conditions, the system operates in a natural deicing mode; that is, the FPD fluid flow rate is not sufficient to prevent all ice accumulation but rather allows continuous building and shedding of a thin spanwise bar of ice which forms along the stagnation line.

System performance during tanker and natural icing tests has been consistent with the results of NASA icing tunnel tests for anti-ice and natural deice operation, provided the fluid system was on and operating prior to accumulation of ice on the leading edge. If, however, appreciable ice was allowed to accumulate prior to initiating fluid flow, activation of the system would not remove the accreted ice even after 20 to 30 minutes of operation. This inability to remove accumulated ice was not consistent with NASA icing tunnel test.

Based upon the potential inability to remove significant accumulated ice within a reasonable (few minutes) time frame, future certification programs should include not only demonstration of system performance when turned on before or immediately upon entering icing conditions, but also after allowing appreciable ice to accumulate on the airframe before activating the ice protection system. Depending upon the demonstrated performance, consideration should be given to including a reliable ice detector as part of the system. Fluid ice protection systems should be approved as anti-ice systems that must be activated immediately upon observation or detection of icing conditions unless satisfactory deice performance is demonstrated.

REQUIRED FLUID DURATION DETERMINATION.

Determination of the required fluid duration (and thus the capacity of the fluid reservoir) should be made as early as possible in the program since it is a major

factor and will significantly affect design of the system. The fluid system uses consumables, and therefore, requires that FPD fluid be carried during all flight conditions. There is also the possibility of running out of FPD during an icing encounter, which in turn requires immediate action to ensure the safe continuation of the flight. While the first inclination may be to simply require sufficient fluid to last for the maximum endurance capability of the particular airplane, this has been considered an unreasonable requirement, considering the extent of the icing envelope prescribed in Appendix C of FAR 25, and the operational environment of the airplane.

In recent programs, two different requirements have been addressed, one relating to airframe protection and the other to engine protection. A number of factors should be considered in determining the minimum fluid duration that must be provided. The following discussion addresses several significant items that should be considered when establishing fluid duration requirements.

Jet aircraft generally operate outside the icing environment for the majority of their flights, and are typically exposed to icing conditions only during climb, descent, holding, approach and landing operations. Holding times at busier terminals have been in excess of 45 minutes. The FAA has required that the airplane's tolerance to continuous ice accumulation (at 0.5 gm^{-3} LWC for 45 minutes) on its unprotected surfaces be evaluated under holding pattern conditions.

Aircraft operating at lower altitudes, such as reciprocating engine and some turbopropeller powered airplanes and helicopters, can be exposed to the icing environment over a greater portion of their flight profile. Correspondingly, the system endurance should be consistent with this operating environment.

The following flight profile considerations were used in reviewing and establishing FPD fluid duration requirements for small business Jet airplanes:

1. For turbojet powered airplanes and turbopropeller powered airplanes with a maximum operating altitude above 30,000 feet:

- a. Takeoff and climb above 22,000 feet (ice protection operating 15 minutes), cruise (ice protection off), descent (ice protection operating 17 minutes), hold (ice protection operating 45 minutes), approach and landing (ice protection operating 10 minutes) for a total of 87 minutes of ice protection system operation.

- b. Takeoff and climb above 22,000 feet (ice protection operating 15 minutes), cruise (ice protection off), descent (ice protection operating 17 minutes), approach and missed approach (ice protection operating 15 minutes), climb above 22,000 feet (ice protection operating 15 minutes), cruise to alternate (ice protection off), descent (ice protection operating 17 minutes), approach and landing (ice protection operating 10 minutes) for a total of 89 minutes of ice protection system operation.

2. For reciprocating engine powered airplanes and turbopropeller powered airplanes with a maximum operating altitude of 30,000 feet and below:

a. Takeoff and climb to 15,000 feet (ice protection operating 15 minutes), cruise (ice protection operating 60 minutes), descent (ice protection operating 15 minutes), hold (ice protection operating 45 minutes), approach and landing (ice protection operating 10 minutes) for a total of 145 minutes of ice protection system operation.

b. Takeoff and climb to 15,000 feet (ice protection operating 15 minutes), cruise (ice protection operation 60 minutes), descent (ice protection operating 15 minutes), approach and missed approach (ice protection operating 15 minutes), climb to 10,000 feet (ice protection operating 10 minutes), cruise to alternate (ice protection operating 15 minutes), approach and landing (ice protection operating 10 minutes) for a total of 140 minutes of ice protection system operation.

Based upon review of the various factors pertinent to establishing endurance requirements for expendable fluid ice protection systems, the following durations were considered appropriate:

1. For turbojet powered airplanes and turbopropeller powered airplanes with a maximum operating altitude above 30,000 feet, sufficient fluid must be provided for continuous maximum flow operation for a minimum of 90 minutes or 15 percent of the maximum endurance of the airplane, whichever is greater. A fluid quantity indicator and low fluid level caution (approximately 15 minutes remaining) shall be installed in the cockpit visible to crew.

2. For reciprocating engine powered airplanes and turbopropeller powered airplanes with a maximum operating altitude of 30,000 feet and below, sufficient fluid must be provided for continuous maximum flow operation for a minimum of 150 minutes or 20 percent of the maximum endurance of the airplane, whichever is greater. A fluid quantity indicator and low fluid level caution (approximately 15 minutes remaining) shall be installed in the cockpit visible to crew.

FLUID CHARACTERISTICS.

There are two fluids commercially available for the TKS fluid ice protection system. These fluids, Canyon Industries AL5 (DTD-406B) and TKS80, are of slightly different composition; AL5 being comprised of 85 percent mono-ethylene glycol, 10 percent deionized water, and 5 percent isopropyl alcohol, and TKS80 being comprised of 80 percent mono-ethylene glycol and 20 percent deionized water. At the present time in the United States, AL5 is the more readily available fluid.

According to reference 11, ethylene glycol is considered toxic for humans and precautions are advised when handling it. The lethal dose for 50 percent of the human population is 1.4 milliliters per kilogram, in other words, a 150-pound person would die from drinking less than four ounces of pure ethylene glycol. Swallowing small amounts of ethylene glycol may cause abdominal discomfort, pain, dizziness, and have other effects on the central nervous system or the eyes. Also, the inhalation of ethylene glycol vapors may cause headaches and throat irritations.

The icing tunnel tests conducted by NASA (reference 10) included a comparison of the performance of the AL5 and the TKS80 fluids. Their results indicated approximately equivalent performance at warmer temperatures (25° F), but showed approximately 20 percent higher flow rate was necessary when using TKS80 at colder

temperatures (5° F). While this difference cannot be readily explained through comparison of the freezing temperature profiles of the two fluids, it should be considered during certification evaluation.

Current FPD fluids (figure 7) become a gel at very cold temperatures (approximately -60° F). The temperature extremes to which the airplane will be subjected (including the certification temperature limits applicable to the airplane) should be considered in evaluating the reservoir and plumbing installations. In order to ensure ice protection availability following prolonged flight at cold temperatures, system operation should be evaluated after being turned off for at least 90 minutes with the outside air temperature (OAT) at or near the minimum temperature at which the airplane is certified for operation.

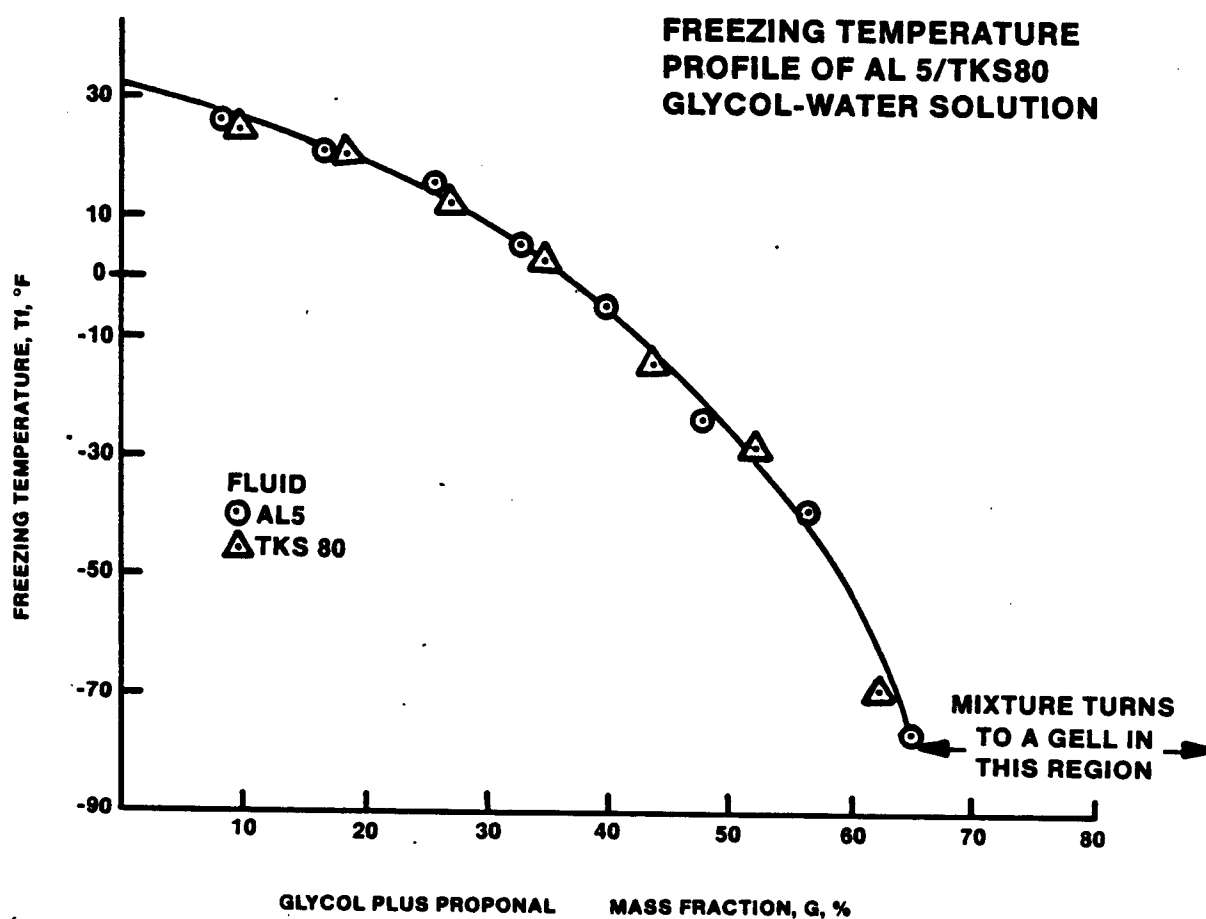


FIGURE 7. FREEZING TEMPERATURE OF AL5 AND TKS80 GLYCOL-WATER SOLUTION

Flammability tests were conducted by the British CAA for a variety of deicing fluids including TKS-80, DTD-406B (AL5), MIL-A-8243C, and isopropyl alcohol. In order to assess the potential fire/explosion hazard with these fluids, fine mist aerosols of each were sprayed onto two ignition sources. One ignition source was a small bunsen burner flame and the other a spark plug operating at about 4 hz. Excluding the isopropyl alcohol, which is a flammable fluid, none of these fluids

exhibited a tendency to ignite (except for occasional slight localized "flashes" when DTD-406B was sprayed into an open flame). Neither TKS-80 or DTD-406B (AL5) are considered to be a flammable fluid. However, the applicant must verify this on each occasion.

The necessity and importance of assuring that materials and components on the aircraft are not effected by the FPD fluids is very important. Some of the areas where concern has been expressed are:

1. The typical piston engine that would have a fluid anti-icing system on the propeller would also have many accessories. There is some concern about the effect that the FPD fluids would have on these accessories. The accessories include the electrical generators which have insulation and other material that might be affected by the FPD fluids. The manufacturer must show compatibility for each accessory.

2. There is also concern about the turbine engines ingesting the FPD fluids. There is concern about the fluid ingestion on aft mounted engines or engines mounted so that they ingest the runback or shed fluids resulting from airframe deicing or anti-icing operations. This concern should be addressed during certification.

3. There is also concern about the effect FPD fluids have on loaded silver or gold electrical contacts. The concern is especially apparent in areas of the aircraft where an atmosphere very high in oxygen is present. This concern should be addressed during certification.

WINDSCREEN CONSIDERATIONS.

The tendency of the fluid to reduce visibility through the windscreen can create problems if the pilot needs outside visual reference, such as during landing. It is an important consideration and the pilot should be warned that this may happen if the windscreen ice protection system is used during approach or landing, or other conditions where visual reference is required. Visual reference through the windscreen may be impaired and the side windows may be the only visual reference they will have during landing. If the system is a deice system, two factors that must be known are (1) the time required for the windscreen to clear and (2) the effective time. The time to clear should be determined during certification. The effective time is the time that the windscreen provides the pilot with good visibility; i.e., the amount of time between the clearing of the fluid so the pilot can see, and the time that icing-over of the windscreen reoccurs. Should either of these times be found unacceptable during certification, an alternate windscreen ice protection method is recommended.

DEMONSTRATION OF ACCEPTABLE PERFORMANCE.

The capabilities of the complete ice protection system to adequately protect the airplane throughout the continuous maximum and intermittent maximum icing envelopes of Appendix C of FAR 25, should be demonstrated through analysis and a combination of instrumented dry air, and simulated and natural icing tests.

DRY AIR. Fluid coverage and spreading characteristics should be evaluated by taking photographs of the airfoil surfaces with colored fluid being pumped through the system. Fluid coverage should be checked over the range of maximum to minimum angles-of-attack expected in service, considering all weight, center of gravity, airspeed and airplane configuration conditions.

Adequate fluid duration should be determined by measuring the pump FPD fluid output rate and dividing the number of usable gallons by the output rate. This duration is verified in-flight by running the reservoir completely dry and noting fluid duration. Proper illumination of and the warning time provided by the low fluid caution should also be observed during this evaluation. Also, determine that the usable gallons is not reduced during all expected flight attitudes, for example takeoff or landing.

Dry air tests with artificial ice shapes should be accomplished to verify satisfactory handling qualities, stability, stall characteristics and speeds, minimum control speed, and performance capability for ice accumulations associated with unprotected surfaces and the deice mode. Proper operation of the anti-ice system should be verified following prolonged flight or exposure (>90 minutes) at the minimum operational temperature approved for the airplane to insure that the system operates properly. In addition, if the system is operated at an extremely low temperature it is conceivable that the FPD fluid may freeze on the wing and cause degraded system and airfoil performance.

ICING TEST. Prior to conducting natural icing tests, the capability of the fluid ice protection system to prevent and/or remove ice accumulation should be evaluated. Using an icing tanker, tunnel, or other device, various sections of the wing and horizontal stabilizer may be immersed in the ice cloud under measured conditions to observe system performance at points within the Appendix C FAR 25, icing envelopes. Additionally, these tests can be used to evaluate the adequacy of the proposed fluid flow rates. During the course of this evaluation, the ability of the system to remove ice that has accumulated prior to system activation should be checked.

Instrumented natural icing tests should be conducted to demonstrate the adequacy of the entire airplane ice protection system. Several icing encounters encompassing a variety of atmospheric conditions including natural conditions, should be evaluated. Throughout these tests, the observed performance of the system should be compared to that predicted for the existing environment. Ice accumulation on unprotected surfaces is compared to the predicted ice shapes used in dry air tests. The ability of the ice detection system to alert the flight crew of icing conditions prior to accumulation of ice on the airframe is evaluated. The performance of the fluid ice protection system in actual icing conditions should be consistent with that predicted by analysis.

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APPENDIX A
RELATED DOCUMENTS

APPENDIX

RELATED DOCUMENTS

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