

LS-197

ICING: ACCRETION, DETECTION, PROTECTION

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1. INTRODUCTION

Icing conditions present an adverse environment to aircraft. In flight, the most common icing hazards are clouds containing supercooled water droplets, clouds with mixtures of supercooled droplets and ice crystals, and freezing rain. On the ground, icing hazards include freezing rain, freezing drizzle, freezing fog, falling or blowing snow, frost, slush, and humid air.

The adverse effects of icing on aircraft operations are described below. Ice contamination on wings and tails reduces maximum lift coefficient and stall angle of attack, and increases stall speed and drag. During takeoff, ice on wings has caused wing stall and serious stability and control problems with nearly every kind and size of aircraft, resulting in pitch up, rolloff, and crash. During approach or landing, the combination of extended wing flaps and ice on the horizontal tail has caused tailplane stall, resulting in uncommanded pitchovers with some aircraft. Ice contamination on propulsion system components—such as air intakes, engine nacelles, inlet ducts, propellers, fan blades, spinners, inlet guide vanes, and helicopter rotor blades—reduces propulsive efficiency and adds to aircraft drag. For smaller fixed-wing aircraft, the combination of reduced lift, increased drag, and reduced propulsion efficiency can result in the loss of the capability for level flight, and the aircraft will execute an uncommanded descent. For helicopters, increased rotor drag caused by ice can result in required torque exceeding available engine torque, and the helicopter will execute an uncommanded descent. Iced rotors can also cause retreating blade stall, resulting in an uncontrolled rolloff. Furthermore, iced rotors will cause more rapid descents during autorotation. Pieces of ice shed from wings, propellers, rotors, or engine nacelles can cause structural damage to the airframe or engine, or cause engine flameout. Ice on aircraft instrumentation can give wrong airspeed indications or wrong engine pressure ratios that lead to improper engine power settings. Ice accretion on antennas, struts, wheels, and external stores adds weight and drag to the aircraft. Ice can cause destructive vibration of parts such as antennas and wing struts.

Anytime an aircraft flies through visible moisture at outside air temperatures below about 5 °C, there's a good chance that ice will form on the aircraft components. In-flight icing conditions normally occur from ground level up to 22,000 ft, but pilots have reported icing at altitudes as high as 40,000 to 50,000 ft. On aircraft in flight, ice forms on the leading edges of wings, tails, engine nacelles, spinners, etc. At temperatures near freezing (0 °C), in-flight ice is clear (glaze) and horn-shaped, while at colder temperatures, it is white and opaque (rime) and spear-shaped. On grounded aircraft,

freezing precipitation covers all the upper surfaces of the aircraft. Ice on grounded aircraft can take several forms: frost, wet snow that freezes, freezing rain that turns into clear ice, slush that freezes, or moisture from humid air that condenses on cold-soaked wings and freezes to clear ice.

Five methods are used to protect against ice

1. Keep water wet—apply heat continuously
2. Evaporate water—apply more heat continuously
3. Melt ice—apply heat intermittently
4. Mechanically remove ice—crack, debond, and expel the ice with pneumatic deicers or impulse deicers
5. Chemically prevent ice or melt ice—apply freezing point depressant fluids

In that ice protection systems have been used successfully since the 1940's, it would seem reasonable to expect that all the icing technology problems have been solved by now. However, new problems continually arise, because the use of new technologies in modern aircraft have a ripple effect on ice protection. Also intense global economic competition forces airplane manufacturers to optimize overall airplane performance while minimizing airplane capital costs, operating costs, and maintenance costs, and ice protection must be included in this optimization process.

The global aircraft industry and its regulatory agencies are currently involved in three major icing efforts: ground icing; advanced technologies for in-flight icing; and tailplane icing. These three major icing topics correspondingly support the three major segments of any aircraft flight profile: takeoff; cruise and hold; and approach and land. In this lecture, we will address these three topics in the same sequence as they appear in flight, starting with ground deicing, followed by advanced technologies for in-flight ice protection, and ending with tailplane icing.

2. GROUND OPERATIONS AND HAZARDS IN CONDITIONS CONDUCTIVE TO ICING

Aircraft ice contamination caused by freezing precipitation during ground operations poses a potential hazard for takeoff and subsequent flight. Airplane manufacturers do not design their airplanes to take off with ice on critical surfaces, nor does the FAA/JAR certify them to take off under such conditions. Airplane manufacturers fully support the "Clean Aircraft Concept" and warn that it is imperative not to attempt takeoff unless the pilot is certain that all critical surfaces of the aircraft are clear of ice. The Federal Aviation Regulations

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(FAR) Sections 121.629, 91.209, and 135.227 *prohibit* a pilot from taking off with ice contamination. Section 121.629 Operations in Icing Conditions states:

No person may take off an aircraft when frost, snow, or ice is adhering to the wings, control surfaces, or propellers of the aircraft.

Deicing and anti-icing fluids are available to protect aircraft from ground icing. Deicing fluids remove ice from aircraft but do not prevent freezing. Anti-icing fluids prevent precipitation from freezing on the aircraft for a limited period of time (holdover time). The FAA requires operators to develop and use an FAA-approved aircraft ground deicing program and specifies checks and inspections to ensure a clean aircraft at takeoff.

2.1 Effects of Roughness on Wing Aerodynamics

On takeoff, the predominant effect of ice contamination is on the lifting characteristics of the wing. Figure 1 shows conventional plots of lift coefficient versus angle of attack (AOA) for a clean wing and a contaminated wing. The plots show that contamination reduces both the maximum lift coefficient and the angle of attack for maximum lift (stall angle).

Figures 2, 3, and 4 (from Ref. 1, 2, and 3, respectively) provide a comprehensive and valuable collection of wind tunnel and flight test data that quantifies the percent loss in maximum lift as a function of nondimensional roughness height, k/c . Percent loss in maximum lift is defined as:

$$\frac{100 \times (\text{maximum lift clean} - \text{maximum lift contaminated})}{\text{maximum lift clean}}$$

These last three figures present somber evidence that contamination causes a significant loss in aerodynamic performance for both slatted and unslatted wings. Unslatted wings refer to wings without leading edge devices extended. Slatted wings refer to wings with extended/deflected leading edge devices such as a slat. (In this paper, we will denote unslatted wings as "hard" wings.) Brumby's correlation for the entire upper surface covered with roughness (Fig. 2) brackets the data from all three figures and can be considered an upper limit on percent loss in maximum lift for hard wings and tails. On the last three figures, the data from Boeing, Fokker, and McDonnell-Douglas for slatted wings at higher k/c values show much lower losses in maximum lift coefficient than does Brumby's correlation.

Figure 5 (Ref. 3) shows that loss in angle of attack to stall varies nearly linearly with nondimensional roughness height, k/c . Figures 2 to 5 together contain enough information to get a representative estimate of the effects of roughness on wing or tail aerodynamics. They should prove useful to those concerned about icing problems during both takeoff and landing.

The data presented in Fig. 2 to 5 include data taken at both subscale and flight Reynolds numbers. Reference 3 presents data that demonstrates that testing must be done at chord Reynolds numbers of 5×10^6 or higher to achieve percent loss of maximum lift results representative of full-scale flight.

Figure 4 shows that even a small nondimensional roughness height of 5×10^{-4} , which is comparable to about a 0.2 mm roughness height on a small jet transport wing, can reduce maximum lift of a hard wing by 35 percent and angle of attack for maximum lift (stall angle) by about 6° . Percent increase in stall speed, the operationally more significant parameter, can be estimated as about half the percent loss in maximum lift coefficient. So for the present example, a 35 percent loss in maximum lift translates to an 18 percent increase in stall speed. For a normal takeoff run with this amount of contamination on the wings, V_2 (takeoff safety speed) would be less than stall speed, which means that the wings could not generate enough lift to take off.

Several times thus far, we have mentioned that ice contamination on the lifting surfaces (i.e., wings and tails) reduces maximum lift and stall AOA and increases stall speed and drag. Typically, a modern transport is required for certification to have about a 13 percent stall speed margin at takeoff, which is to say that its normal safe takeoff speed, V_2 , is 13 percent higher than its 1g stall speed for the clean wing takeoff configuration. Landing speeds are typically about 23 percent higher than stall speed for the clean wing landing configuration.

Although ice contamination increases form drag it does not appreciably affect drag on large transports. However, if the angle of attack is high enough to stall the wing, the wing form drag becomes appreciable and may double the aircraft drag. On smaller aircraft, ice on exposed landing gears and wing struts could contribute appreciably to airplane drag.

2.2 Effects of Ground De/anti-icing Fluids on Wing Aerodynamics

When ground deicing or anti-icing fluids are present on the wing during the takeoff run, the fluid surface becomes unstable and develops a waviness which is, in effect, a form of roughness that contaminates the wing. So, even though these fluids can protect against the large aeroperformance losses caused by ice roughness, the fluids themselves could potentially cause performance penalties during takeoff. In the 1980's and early 1990's, the Boeing Airplanes Company demonstrated both in wind tunnel tests and in flight tests that these fluids do cause measurable losses in maximum lift coefficients (Ref. 4). These results were confirmed by the von Karman Fluid Dynamics Institute in Brussels, Belgium, under a grant from the Association of European Airlines (AEA) (Ref. 5).

Remarkably, these studies demonstrated that the loss in maximum lift coefficient correlated with the boundary layer displacement thickness measured at the trailing edge of the wing's fixed element. Professor Mario Carbonaro from the von Karman Institute used this correlation to develop a cost effective Aerodynamic Acceptance Test for the qualification of Type I and Type II fluids. The test measures the growth in boundary layer displacement thickness at the trailing edge of a flat plate covered with the fluid and located on the test section floor of a specially designed wind tunnel. A correlation exists that defines an acceptable upper limit on displacement thickness over a range of temperatures. Fluids that exceed the upper limit fail the acceptance test and are rejected. (Keep in mind that the acceptable upper limit on displacement thickness is directly correlated with the acceptable upper limit on loss in maximum lift.)

Only two wind tunnel facilities are currently approved to conduct this test: one is located in Europe at the von Karman Institute and the other is in North America at the University of Quebec at Chicoutimi. References 4 and 5 discuss the Boeing and von Karman Institute aerodynamic studies on ground deicing fluids. And Ref. 6 describes the aerodynamic acceptance test and its rationale, which was approved by the Aerospace Industries of America (AIA) and the Association Europeenne des Constructeurs de Materiel Aerospacial (AECMA).

The acceptable upper limit on loss in maximum lift derives from the criterion for stall speed margin at takeoff safety speed, V_2 . The airplane manufacturers and the regulatory agencies recognized that the fluid imposed a *transitory* loss in maximum lift, since the fluid completely flows off the wing shortly after rotation (except for a very thin residual film that remains for much longer). Although authorities require a 13 percent stall speed margin for clean wings, they accepted a ten percent stall speed margin for fluid-covered wings because the fluid effect is transitory. To meet the minimum 10 percent stall speed margin, the percent loss in maximum lift coefficient must not exceed 5.24, which establishes the acceptance test criteria. We shall work through the arithmetic to show that a 5.24 percent loss in maximum lift coefficient results in a 10 percent stall speed margin. Using the rule of half, a 5.24 percent loss in maximum lift coefficient causes a 2.62 increase in stall speed. Therefore, we have the identity

$$V_{1g \text{ stall fluid}} = 1.0262 * V_{1g \text{ stall clean}}$$

The required safe takeoff speed, V_2 , is

$$V_2 = 1.13 * V_{1g \text{ stall clean}}$$

which means that the airplane takes off with a 13 percent stall speed margin when the wing is clean and dry.

Assuming no adjustment is made to V_2 for the presence of fluid on the wing (i.e., V_2 remains constant), use the first equation to substitute $V_{1g \text{ stall fluid}}/1.0262$ for $V_{1g \text{ stall clean}}$ in the second and obtain

$$V_2 = 1.13 * (V_{1g \text{ stall fluid}}/1.0262)$$

or

$$V_2 = 1.10 * V_{1g \text{ stall fluid}}$$

Thus the fluid-contaminated airplane takes off with a transitory 10 percent stall speed margin. Nearly all aircraft in the jet transport category were found to be able to accept this transitory loss in stall speed margin without any takeoff adjustments, but there were a few aircraft for which adjustments had to be made, such as by offloading passengers or cargo when fluids were used.

The Type II anti-icing fluids were designed for use on jet transports that have rotation speeds of about 110 kt, and they are not recommended for aircraft with rotation speeds below 85 kt. This is explained further in section 2.4.2.

2.3 Effects of Wing Contamination on Takeoff Characteristics

References 1 and 2 give good descriptions of the typical effects of contamination on airplane takeoff characteristics.

Fokker Aircraft engineers acquired data from wind tunnel tests of wing sections and airplane half models with roughness distributed uniformly over the entire wing upper surface and also from flight tests with simulated rime ice and sandpaper roughness on the leading edge of the wing. They made use of this data in an engineering flight simulator of the Fokker 100 (Ref. 2). Figure 6 shows the lift versus AOA curves for the clean and contaminated wing, along with stick shaker AOA and roll control boundaries. When the clean aircraft is rotated 3° per second the peak AOA was approximately 10.5°. The clean aircraft would still have about a 2.5° margin before stick shaker activation and a 5.5° margin to stall AOA. The aircraft with contaminated wings will stall at about 9°, or about 1.5° below the aircraft's target angle of attack.

Van Hengst (Ref. 2) pointed out that the clean airplane gives a slow progression of wing flow separation that starts inboard and moves toward the wing tips as AOA is increased, thereby ensuring exceptionally good roll control throughout a stall test maneuver. The manner in which a contaminated wing will stall is unpredictable and, therefore, extremely dangerous because the inherent good stalling characteristics of the clean wing are lost. Unequally distributed contamination over both wings will most likely further aggravate the situation, causing an asymmetric stall accompanied by violent roll. In addition, significant increase in drag develops during rotation as the wing goes into stall.

As Ref. 1 and 2 noted, stall of a contaminated wing is usually accompanied by either a pitch up or a pitch-down tendency of the aircraft, both of which tendencies will likely lead to over-rotation of the aircraft. A pitch-up tendency directly leads to over-rotation, driving the wing deeper into the region of stall where airframe buffet occurs. A pitch-down tendency is noticed by the pilot after rotation when the aircraft fails to gain sufficient climb rate and customary height. The pilot's normal response is to increase the elevator input, which action will over-rotate the aircraft and again lead to airframe buffet.

The moment of airframe buffet is the pilot's first indication that something is wrong. Fokker studies showed that the pilot would not notice the reduced acceleration caused by the contamination drag or the accompanying slight increase in takeoff run, and therefore, the pilot would not be alerted that something was wrong with the aircraft.

With clean wings, aircraft drag is low enough to ensure climb capability at the required climb angle at V_2 (takeoff safety speed) with one engine inoperative. However, with contaminated wings, the stalled wing may double aircraft drag, and even with all engines operative at take-off thrust, climb capability may be lost.

As mentioned above, the Fokker 100 wing is designed for flow separation to first occur inboard and then, as angle of attack increases, progress towards the wing tip. For the clean wing, inboard wing flow separation occurs at 16° AOA when maximum lift is reached, and flow separation does not affect roll control until an AOA of 19° is reached (Fig. 6). For the contaminated wing, the slow progression of flow separation towards the wing tip is lost, and uncontrollable roll may develop at an AOA as low as 10°, just 1° beyond the AOA for maximum lift of the contaminated wing.

In the Fokker 100 engineering simulator studies for a symmetrically distributed roughness of a thickness that caused

wing stall at 9°, an altered takeoff technique was found that achieved a successful simulator takeoff if the peak angle of attack were 8.5°. It was also found, however, that this was achieved at the expense of significantly increased runway distance.

Van Hengst concluded from these simulator studies that: "With the lack of any means of relating the amount of contamination in ground icing conditions to its effect on the aerodynamics of the aircraft, this flight simulation study shows that **NO TAKE-OFF SHOULD BE ATTEMPTED UNLESS IT IS FIRST ASCERTAINED THAT ALL CRITICAL SURFACES OF THE AIRCRAFT ARE FREE OF ICE, SNOW OR FROST DEPOSITS.**"

2.4 Characteristics of Ground Deicing and Anti-icing Fluids

We shall begin this section with definitions of the terms "aircraft deicing" and "aircraft anti-icing". "Aircraft deicing" is a procedure that *removes* frost, ice, snow, or slush from the aircraft in order to provide clean surfaces. Deicing involves spraying the surfaces with hot water or hot water/glycol mixtures.

"Aircraft anti-icing" is the procedure that *protects* clean surfaces of the aircraft against the formation of frost, ice, and accumulations of snow or slush for a limited period of time (holdover time). Anti-icing involves spraying the clean surfaces with thickened glycol-based fluids that can protect against freezing precipitation for a *limited* time (holdover time). The international aviation community has accepted the AEA's coding of these deicing and anti-icing fluids as Type I and Type II, respectively. Type I and Type II fluids must meet rigorous physical, chemical, and aerodynamic acceptance specifications before they can be qualified for use in aircraft operations. Although the AEA, SAE, and ISO have cooperated to develop a comprehensive set of specifications and qualification tests for these fluids, some minor differences exist between the three organizations' specifications. Therefore the fluid is prefixed by the letters AEA, SAE, or ISO, as for example, SAE Type I or ISO Type II, etc.

Unfortunately, some confusion could develop over fluid terminology because there are also Mil Spec Type I and Type II fluids, which are similar, but not identical, to the SAE/ISO/AEA Type I fluids. These Mil Spec fluids will not be discussed herein. (For further clarification, see the discussion by M.S. Jarrell starting on p 243 of Ref. 7.)

2.4.1 SAE/ISO/AEA Type I Fluids

Type I fluids, in their undiluted (neat) formulation, usually contain a minimum of 80 percent glycol. These fluids are easily stored and handled. They are eutectic with the minimum freezing point occurring approximately at a mixture of 60 percent glycol and 40 percent water by volume. Their viscosity is a function of temperature but not of fluid shear, and therefore they are said to exhibit Newtonian behavior. Type I fluid viscosity is relatively low except at very cold temperatures, where the viscosity depends significantly on the type of glycol used. This low viscosity allows Type I fluids to readily flow off aircraft surfaces, leaving only a thin layer of protection against freezing precipitation. They have limited effectiveness when used for anti-icing purposes. Monoethylene glycol, which has been widely used in the United

States, has a low viscosity over the range of expected operating temperatures. Diethylene, triethylene, and propylene glycol-based fluids are used in Europe and are becoming more common in North America. Compared with monoethylene glycol, when these latter fluids are used undiluted, their viscosity is higher and increases faster with decreasing temperatures. If applied undiluted to the wing at the colder temperatures, their viscosities are high enough to cause unacceptably high aerodynamic penalties at takeoff. Diluted with water, these latter fluids have acceptable aero penalties; therefore, they should always be used in the diluted formulation for deicing aircraft.

2.4.2 SAE/ISO/AEA Type II Fluids

Type II fluids have markedly improved anti-icing capabilities compared with Type I fluids. These fluids contain at least 50 percent glycol in their neat form. They exhibit non-Newtonian behavior, which means that their viscosity strongly depends on shear as well as on temperature. Their viscosity decreases strongly with increasing shear stress. This non-Newtonian behavior is achieved by adding thickeners composed of long polymer chains. When the airplane is stationary and wind speeds are low, the Type II fluid film on the wing is gel-like and therefore thicker than Type I films. Its greater thickness allows it to absorb more freezing precipitation before ice crystals begin adhering to the wing. During the takeoff run and climbout (at rotation speeds over 85 kt), air flowing over the wings shears the fluid and reduces its viscosity to near that of a Type I fluid, and it readily flows off the wing.

Type II fluids are sensitive to storage tank materials and handling equipment. Therefore, special tank materials are used to prevent fluid vapors from corroding the tanks; and pumps, nozzles, and piping are designed to avoid degrading the fluid (i.e., the polymer chains must not be broken up by the shearing action of pumping and pressure drop) before it settles on the aircraft surfaces.

Type II fluids were developed for typical commercial transports that have rotation speeds of about 110 knots. During the takeoff run, high viscosity fluids, such as Type II fluids, develop a wavy surface that in effect is a form of surface roughness that degrades aerodynamic performance. The high takeoff run speeds of the large transports help shear the fluid and reduce its viscosity, and the long takeoff runs (about 25 sec) provide time for most of the fluid to flow off the wings before rotation. These fluids are not intended for commuters and general aviation aircraft whose rotation speeds are usually less than 85 knots and whose takeoff run times are about 15 sec. One commuter manufacturer found that its aircraft would have to be held on the ground for about 30 sec during the takeoff run to ensure adequate fluid runoff from the wings and tails; otherwise, the aircraft would not rotate because the residual fluid caused excessive lift loss on the tail (Ref. 8). **THE OPERATOR OF AN AIRPLANE SHOULD CONSULT THE AIRPLANE MANUFACTURER FOR RECOMMENDATIONS REGARDING THE USE OF TYPE I AND TYPE II FLUIDS.**

2.4.3 Holdover Time

"Holdover time" is the estimated time the anti-icing fluid will prevent frost, ice, snow or other forms of freezing precipitation from forming or accumulating on the protected surfaces

of an aircraft. Holdover time is estimated to be the time interval between when the fluid was applied and when ice crystals became visible in the fluid, for a given intensity and type of freezing precipitation and outside air temperature or wing surface temperature.

Tables of holdover times were first developed by the AEA on the basis of tests in the laboratory and in real winter conditions, and from years of experience of several European airlines. These holdover time tables have served as a guideline to pilots in Europe, where there have been no takeoff accidents attributable to ground icing for over 20 years. The original AEA tables have been modified by the international SAE G-12 Committee on Aircraft Ground Deicing Fluids, which had access to additional test results in real winter conditions in the United States and Canada. These adjusted tables are presented in Figs. 7 and 8 for Type I and Type II fluids, respectively (Ref. 9). While the AEA tables give only one protection time, the SAE tables give two protection times: a lower time and an upper time. This range serves to remind the user that protection times depend on many factors.

The SAE tables should not be separated from the procedures document (SAE ARP 4737), since the holdover times depend upon following the proper procedures, cautions, and caveats given in that document. The two cautionary notes given in the tables are worth repeating here:

CAUTION: The times of protection represented in this table are for general information purposes only and should be used only in conjunction with a pre-takeoff inspection.

CAUTION: The time of protection will be shortened in heavy weather conditions, high wind velocity and jet blast may cause a degradation of the protective film. If these conditions occur, the time of protection may be shortened considerably. This is also the case when the fuel temperature is significantly lower than OAT.

These two cautions reveal the complexity and challenge the pilot in command faces in making a final determination as to whether it is safe to take off.

2.5 FAA Rulemaking on Ground Icing

On July 21, 1992, the FAA announced that it would issue a Notice of Proposed Rulemaking that would require each airline to have an FAA-approved ground deicing program in place by the next winter (Ref. 10). The proposed rule would require airlines to provide training for pilots and other personnel on the detection of wing ice and provide for establishment of limits on how long an airplane can be exposed to snow or freezing rain before it had to be inspected or deiced again. The FAA would also change operational procedures for controlling the flow of aircraft on the ground to reduce the time aircraft have to wait in line for takeoff after being deiced. The FAA would also encourage the use of the longer-lasting AEA Type II anti-icing fluid, which is thicker and stays effective longer than Type I. The FAA would also help finance the construction of deicing pads on taxiways to further reduce the time between deicing and takeoff. For airports that historically had experienced takeoff delays due to heavy winter operations, the FAA would encourage airport,

airline, and air traffic control officials to jointly develop deicing plans tailored to their specific airport.

On November 1, 1992, revised FAR 121.629 became effective. It requires the operator to develop an FAA-approved aircraft ground deicing program and implement it when weather conditions are conducive to ground icing. *These plans are highly individualized to the particular operator at the given airport and must be approved by the FAA's Principal Operations Inspector or Principal Maintenance Inspector for the airport.*

The FAA-approved aircraft ground deicing program must include (Ref. 2, 11):

1. Procedures to determine the existence of conditions conducive to icing of aircraft on the ground.
2. Sound management, training of flight and ground crews, qualification of all affected personnel, and assignment of specific responsibilities.
3. Specific checks and inspections during the deicing process.
4. A pre-takeoff check or inspection within 5 min of takeoff. Using supportable holdover time tables, the operator must establish a holdover time for the applied deicing or anti-icing fluid under the existing precipitation conditions and outside air temperature.

FAR 121.629 allows operators to:

1. Develop and use FAA-approved alternative procedures such as ice detectors.
2. Elect to not operate in ground icing conditions if so stated in its Operations Specifications.
3. Dispatch and take off with slight amounts of frost (up to 3 mm) on underwing surfaces in the vicinity of cold-soaked fuel cells if approved by the FAA Aircraft Certification Office.

Operational procedures acceptable to the FAA as set out in FAR 121.629 are summarized below:

1. A pre-flight external aircraft icing check must be performed by qualified ground personnel immediately following applications of aircraft de-icing and anti-icing fluids. This check determines whether the critical surfaces are free of frost, ice or snow before push-back or taxi, and the results of the checks are communicated to the pilot in command. The aircraft should be released for take-off as soon as possible.
2. A pre-takeoff check is required within 5 min of takeoff anytime conditions conducive to ground icing exist and/or anytime the aircraft has been deiced or anti-iced and a holdover time established.
3. *If the pre-takeoff check occurs within the holdover time, the pilot or designated crew member (co-pilot or flight engineer) normally checks from inside the cockpit or cabin, whichever provides the best vantage point. The pilot in command may require the assistance of qualified ground personnel to assist in the pre-takeoff check.*

4. If the pre-takeoff check occurs after the holdover time is exceeded, the pilot in command must make a pre-takeoff contamination inspection. Depending upon the agreement between the FAA and the operator (which would take into account the type of aircraft and other factors) this inspection may range from observing the wings from some vantage point inside the aircraft to an external inspection by a licensed inspector. The FAA prefers external inspections, which might include observation from a high vantage point using binoculars, or actual touching of the aircraft surfaces.

An alternative action that could be taken if holdover time is exceeded is to re-deice/anti-ice the wings, control surfaces and other critical surfaces and establish a new holdover time.

5. An Airworthiness Directive (AD) on pre-takeoff ground icing inspections has been published for each of three specific aircraft types. Actions to be taken for these aircraft if holdover time is exceeded are as follows:

- a. On the F28 and DC-9-10 (hardwing aircraft) and on the MD 80/88 (aircraft with cold-soaked wings), conduct the check from outside the aircraft in accordance with an FAA-approved method as set forth in the AD. The operator must include a tactile check of selected portions of the wing leading edge and upper wing surface.
- b. On those aircraft for which an AD exists for pre-takeoff ground icing inspections, the manufacturer may offer alternative methods to establish that the critical surfaces are not contaminated.

For the hardwing aircraft, such methods might include: on-ground operation of the wing thermal anti-ice system; an abrasion strip which is rough when no ice is present and smooth when covered with ice, such that when an inspection rod is run over the strip, vibrations are felt when the strip is clean, but no vibrations are felt when the strip is covered with ice; a paint stripe or special reflective surface for a background that clearly shows up ice when it is present; improved lighting; surface ice detectors; or surface boundary layer flow sensors.

For cold soaked wings, existing methods include: wing tufts placed near the fuel cells such that when the tufts are probed with a long stick, the tufts will move when ice is absent, but will be frozen in place when ice is present; or surface ice detectors placed near the fuel cells.

If the FAA approves an alternative method, they will issue a replacement AD, which will define the allowable alternative inspection methods. A replacement AD has been issued for the F28 that allows the external tactile inspection to be replaced by the use of black paint stripes on the wing at selected locations in conjunction with an external visual inspection.

FAR's 125.221, 125.287, 135.227, 135.345, and 135.351 were revised and became effective December 1, 1993. They require:

1. The operator to develop and use FAA-approved, airplane type specific procedures for performing required pre-takeoff contamination checks or an approved alternate procedure for assuring the clean aircraft concept.

2. Initial and recurrent training and testing for pilots regarding procedures and ground operations in icing conditions.
3. A pre-takeoff contamination check within 5 min of takeoff.

FAR 125 and 135 allow:

1. Voluntary application of FAR 121 rules, summarized above, to FAR 125 and 135 operations.
2. Use of supportable holdover time tables with anti-icing fluids to assist in departure planning.
3. Takeoff with slight underwing frost formations if FAA approved.

As a result of these revised FAR's, FAA personnel, airline operators, traffic controllers, and airport authorities have been aggressively developing and implementing procedures to minimize aircraft takeoff hazards in icing conditions. The SAE G-12 Committee, airplane manufacturers, and fluid manufacturers have also supported the activity. These actions have resulted in significant improvements in the ground deicing/anti-icing technologies as summarized below (Ref. 11):

1. New and improved AEA/SAE/ISO Type II anti-icing fluids and procedures are now in prevalent use in North America and in Europe. If used properly, these fluids give longer protection.
2. Holdover time tables now exist that can be used in concert with other methods of assuring the clean aircraft concept. Although not yet fully validated, these tables, with proper training and guidance, can reduce flight crew confusion and workload.
3. New aerodynamic test data and experimental qualification methods ensure that deicing/anti-icing fluids do not themselves impose unacceptable aerodynamic penalties during takeoff.
4. Many operators and airports are now using either permanent or mobile deicing and anti-icing facilities located very near the departure end of runways. This method offers enormous benefits, including last minute assurances of a clean aircraft at takeoff, minimized operations time and fuel consumption, and avoidance of aircraft having to return to a maintenance or service area for re-deicing/anti-icing if ice formations were detected during pre-takeoff inspections. At many airports, where it is not yet feasible to locate spray facilities at the departure end of runways, other alternatives exist.

There is still room for improvement of the SAE holdover time tables. Better scientific methods are needed to obtain and analyze holdover time data, and to quantify the weather conditions. Ideally, the pilot needs a way to quantify the weather conditions and to put this quantified information into a computer program that will output a more accurate estimate of holdover time.

Instruments are needed that will help the pilot determine if ice has formed on the wings at the time of the pre-takeoff check. The instruments should be able to survey the entire upper wing surface; ice detectors that sample ice at discrete points on the wing are probably not sufficient.

And finally, operators should be encouraged to locate deicing facilities near the departure end of runways so that the aircraft can be deiced, and without further delay, start the takeoff run. Fortunately, there is a trend toward airports opting for end of runway deicing when it is feasible.

3. ADVANCED TECHNOLOGY FOR IN-FLIGHT ICE PROTECTION

Even though aircraft ice protection technology matured in the 1940's, icing technology problems still continue to arise. Most of these problems have arisen either because modern aircraft have incorporated new technologies that have a ripple effect on the ice protection systems or because global economic competition has intensified the need to further optimize aircraft performance and to minimize development, capital, operating, and maintenance costs. And the aircraft ice protection system enters into these optimization strategies. In this section we briefly discuss in-flight icing and the advanced icing technologies being globally pursued by researchers, manufacturers, and regulatory agencies. Among these advanced technologies are advanced ice protection concepts and advanced computer codes.

Figure 9 shows the components of an aircraft that require ice protection.

3.1 Protection Against In-Flight Ice

Before discussing approaches to ice protection, we need to define "anti-icing" and "deicing" systems. *Anti-icing* systems prevent ice from forming either by using an evaporative system that applies enough heat to evaporate all the surface water deposited by cloud droplets, or by using a running wet system that applies just enough heat to prevent the water from freezing. With the running wet system, the water would run back in the form of rivulets that would cover the entire upper surface of the wing. To prevent the rivulets from freezing, the entire upper surface would have to be heated; but this arrangement would require far more energy than an evaporative system and would greatly complicate the design of the wing. Therefore, running wet systems are usually reserved for use on engine inlets with short duct runs. On some aircraft, anti-icing is accomplished with freezing point depressant fluids (usually mixtures of glycol and water) which are oozed out through a porous panel on the leading edge of the wing or other component.

Deicing systems allow ice to build to some prescribed thickness, and then the system is actuated to remove the ice. This is normally a repetitive or cyclic process of ice growth and ice removal. Thus, those wings and tails protected with deicing systems must be designed to tolerate the aerodynamic penalties imposed by the expected maximum thickness of ice that would accrete before actuation.

The ideal protection against icing would be to anti-ice all components that collect ice. The simplest way to do this would be to heat the surface and evaporate all the water. Unfortunately, this approach is not practical because no aircraft can economically provide the required thermal energy from the available on-board heat sources, which are hot compressor bleed air, engine waste heat, and electricity.

A more realistic approach is to protect only critical components, and design the airplane to tolerate some ice on the other components. Today's modern jet transports utilize compressor

bleed air to anti-ice engine nacelles and critical sections along the wing span. Because today's high by-pass-ratio engines can deliver only a limited amount of compressor bleed air, aircraft manufacturers anti-ice as little as 40 percent of the wing span, and allow the other 60 percent to accrete ice during an icing encounter. Reference 12 gives an illustration that shows the percentage of wing span that is anti-iced on each of Boeing's aircraft.

Jet transport manufacturers use wind tunnels to test aircraft models with simulated ice shapes attached to the leading edge of the wings and tails. From these tests they learn how the ice affects handling characteristics and stability and control, and determine which parts of the wings and tails can be left unprotected. To verify their wind tunnel results, they apply simulated ice shapes to a real aircraft and flight test it in clear air.

Some airplane manufacturers have found from their airframe integration studies that fuel burn during cruise can be reduced by eliminating the ice protection on the empennage (thus avoiding heavy and complex ducting that carries bleed air from the engines to the tail) while making the tail sections larger to tolerate the expected ice. Other manufacturers have found that the best way to reduce fuel burn is to electrothermally deice the tail, which allows them to reduce tail size, and in turn, reduce weight and drag penalties.

Business jets usually employ the same approach to ice protection as the larger jet transports, but turboprop and general aviation aircraft must employ a significantly different approach. Their power margins are so small that only their propellers and engine intake lips are electrothermally anti-iced and the remaining critical components are deiced either with expandable pneumatic boots or with electrothermal deicers.

Pneumatic boots are attractive because they require very little power, are lightweight, and are reasonably priced. One drawback usually cited for pneumatic boots is that for effective ice removal, they must not be activated until about one quarter to one half inch of ice accretes on them. This procedure prevents "ice bridging," which sometimes occurs when boots are expanded with smaller thicknesses of ice. Several inflations may be required to remove the bridged ice, during which time ice continues to accumulate on the cap and further degrades aerodynamic performance. Airplanes that are certified for flight into icing with pneumatic boots must be designed to tolerate the additional one-quarter to one-half inch of ice.

3.2 Advanced Impulse Deicers

The last decade has seen the development of alternatives to the conventional electrothermal and pneumatic boot deicers. These are the electromagnetically and pneumatically actuated mechanical impulse deicer systems: EIDI (electromagnetic impulse deicing); EESS (electro-expulsive separation system); EDI (electromagnetic deicing strip); and PIIP (pneumatic impulse ice protection) (Ref. 13). These systems produce a rapid impulse that cracks, debonds, and dynamically expels the ice. Unlike the slowly expanding conventional pneumatic boots, which rely on aerodynamic forces to remove ice, the impulse systems accelerate the iced surface up to 1000 g's, and inertially eject the ice as the surface snaps back. The inertial ejection process can remove ice layers as thin as 0.75 mm (Ref. 14). With these thinner ice layers, the

aerodynamic penalties for ice contamination are correspondingly reduced, and in addition, the ejected ice particles are very small. The small particles make the impulse deicers attractive for application to engine inlets, where ingested particles must not damage the engine components. Their power requirements are quite low—about equal to the power consumed by the aircraft's landing lights or about one percent of an electrothermal anti-icing system or ten percent of an electrothermal deicing system. Although somewhat heavier than conventional pneumatic deicers, their weights still appear competitive.

The PIIP, invented and manufactured by BFGoodrich Deicing Systems, Inc., is the only impulse system which is being applied commercially today—on only one aircraft, the Grob GF-200. The electromagnetic impulse systems have proved effective in removing ice, but their relative complexity and uncertain life expectancy have apparently discouraged any airframer from using them thus far, but manufacturers can produce them for the aviation market right now.

Lynch, et. al., have expressed concern about the aerodynamic penalties that would be imposed on jet transports by the use of the advanced impulse deicers, which can limit ice thickness to only 0.75 mm (Ref. 3). In their experimental studies on the effects of roughness on airfoil aero performance, they found that "...reductions in maximum lift capability on configurations without leading-edge devices extended are very large, even for extremely small leading-edge ice (roughness) buildups. For example, roughness heights of around 0.005 in. [0.127 mm] would result in reductions in the maximum-lift capability of 20 percent at the critical spanwise stations on the wing or tail of a representative 200-seat transport. Obviously, the concern is even greater for smaller aircraft. Increasing the leading-edge roughness size to at least 0.03 in. [0.762 mm], perhaps the minimum ice buildup that can be reliably eliminated by a deicing system, would result in losses in maximum lift capability of up to 40 percent for the 200-seat aircraft. If the wing or tail surface areas for a particular configuration are sized by maximum lift capability, then corresponding increases in surface areas would be required, with all the attendant performance penalties (drag, weight, etc.)."

For slatted airfoils, Lynch, et. al., say: "Lower percentage losses in maximum-lift capability due to leading-edge ice buildups are experienced if the ice buildup occurs on an extended/deflected leading-edge device such as a slat. The maximum penalty for the 0.03 in. [0.762 mm] ice buildup on a slat would be about 10 percent at typical landing flap settings. However, the penalty could well be near 20 percent on the wing for lower takeoff flap settings, or for a tail (without deflected flaps). Again, these penalties would all be increased for smaller aircraft."

It appears that because of the engine manufacturers' continuing quest to improve engine performance, their next generation of high by-pass-ratio turbofan jet engines will provide little or no excess bleed air for thermal anti-icing. Therefore, those involved in ice protection technology have been forced to consider efficient *deicing* systems as a possible alternative to the conventional thermal anti-icing systems. The above conclusions, by a major aircraft manufacturer, will likely create controversy and confusion about the future markets for impulse deicers—the *first new ice protection concept to be demonstrated in about 40 years*. This issue needs further

discussion and clarification by all the major aircraft and engine manufacturers. And perhaps there is need for flight tests of a modern jet transport with simulated roughness applied on its wings and tails to correlate two-dimensional wing section results with full-scale three-dimensional flight test results.

3.3 Physical Characteristics of Ice Accretion

As mentioned earlier, the shape of ice accreted on the unprotected portion a wing or other component depends on the atmospheric environment (outside air temperature, liquid water content, and droplet sizes), the flight conditions (airspeed and AOA), and the component geometry (size, cross-section, and sweep). Rime ice and glaze ice were mentioned in the Introduction as two extremes of icing shapes, but actually there is a continuum of icing shapes that range from rime at the coldest temperatures to glaze at the warmest. In rime ice formation, the droplets freeze upon impact and trap air in between the frozen droplets, causing the ice to appear white and opaque. In glaze ice formation, the droplets impact the surface and form a water film that partly freezes at the droplet impact site and partly runs back along the chord to freeze farther aft. Glaze ice is clear like refrigerator ice. Between the extremes of rime and glaze, the ice shape gradually changes from a pointy shape to a single- or double-horned shape, and these in-between shapes are referred to as mixtures of rime and glaze, or as mixed icing. In the mixed regime, the ice formed near the stagnation region is usually clear glaze while the ice farther aft, where heat transfer is higher, has an opaque rime appearance. Figure 10 (Ref. 15) illustrates how total temperature affects the ice cross section when all other atmospheric and flight conditions are held constant.

Liquid water content, droplet size, and air speed also affect the ice shape, and increasing any or all of the above will increase the amount of water deposited on the surface and move the ice shape towards the glaze end of the spectrum. Increasing airspeed presents two opposing influences on ice shape: the increased convection heat and mass transfer encourages freezing while the increased kinetic heating discourages freezing. But ultimately, a speed or Mach number will be reached, beyond which kinetic heating will dominate and ice will not form. This explains why the wings of fighter aircraft are not ice protected.

Component size and shape also affect the ice shape. Relative to their size, smaller components accrete more ice than do larger components. This is illustrated in Fig. 11. This size dependence has great significance to aircraft ice protection system design requirements. For example, the wings of a C-5A aircraft are so large that only a small strip of ice would accrete on them, and as a result, the C-5A's wings do not require ice protection.

Size dependence is very important to smaller aircraft flying in icing conditions. It is frequently the case that even though the wing appears to be free of ice, the tailplane has collected enough ice to adversely affect its aerodynamics, particularly during approach and landing. To deal with this problem, pilots often look for ice accretion on the smallest object they can see, for example, the windshield wiper blade. If the windshield wiper is picking up ice, pilots know they are in icing conditions and should either turn on the ice protection systems or get out of the icing clouds.

Another parameter affecting ice shape is sweep on wings or any other component. Sweep causes spanwise flow of air along the leading edge, which in turn causes ice to form scallops or lobster tails. These ice shapes have a spanwise periodicity that has not been satisfactorily explained or predicted by analysis (Ref. 16). Although they look grotesque, their effect on aerodynamic performance may be no worse than that of the glaze horns on unswept wings. In fact it has been suggested that the scallops may act as turbulence generators and help keep the flow attached.

3.4 Advanced Computer Codes

As in every other aircraft technology area, computer codes are heavily used in aircraft icing to support design, development, and certification. Although the final proof in the icing certification process will always be through flight testing in natural icing conditions, manufacturers hope that computer code calculations can replace some of the flight testing. Icing flight testing is regarded by the entire aircraft industry as risky, costly, lengthy, and resource intensive.

Today, computer codes are used extensively throughout the aircraft industry to design ice protection systems or to predict ice accretion shapes on unprotected surfaces. For example, about 100 organizations in the United States are using NASA's LEWICE ice accretion code. Codes developed by ONERA in France and the DRA in Great Britain give comparable results and are heavily used throughout Europe. Other organizations also have ice prediction codes in various stages of development. Most of these codes are considered research codes, which means that while they are not fully validated, they are the best codes available and are very useful to those who have experience with them and understand their limitations. But, they are still being improved and validated through the development of advanced numerical methods, through the development of advanced physical models obtained from fundamental physics experiments, and through comparisons with new data from basic experiments and operational experience.

The codes most often employed in aircraft icing include 1) flow codes, 2) droplet trajectory codes, 3) ice accretion prediction codes, 4) electrothermal deicer design/analysis codes, 5) anti-icing ice protection system design codes, 6) iced airfoil aeroanalysis codes, and 7) helicopter rotor and propeller performance-in-icing codes.

3.5 Ice Accretion Predictions

Since this lecture is time-limited, we are unable to discuss the details of the computer codes. The interested reader should consult Ref. 17, which give more details and more references. In this section we will briefly discuss the LEWICE ice accretion prediction code. Figure 12 shows the modeling approach in LEWICE. The code consists of three main elements: 1) flowfield prediction; 2) water droplet trajectory prediction; and 3) ice accretion prediction. The flowfield code normally used is a potential flow panel code, although LEWICE can accommodate Navier-Stokes or Euler or compressible potential flow solvers. The droplet trajectory code uses results from the flowfield code to calculate the flux of water impinging on the leading edge region of the airfoil. The ice accretion code solves a thermodynamic energy balance and a mass balance on surface control volumes that coincide with the panel elements on the airfoil as shown on Fig. 13. LEWICE cycles through the three elements to calculate an ice shape for a given time increment or time step.

Then the flowfield is recomputed for the new ice covered airfoil, the droplet trajectories are recomputed, and a new layer of ice is computed for a time step. This process is repeated until all the of time steps add up to the total exposure time.

LEWICE is most accurate in predicting the colder ice shapes, and less accurate for the warmer ice shapes. At the colder temperatures, the droplets freeze upon impact and the accuracy of the ice shape prediction is determined primarily by the accuracy of the droplet trajectory prediction. Fortunately, droplet trajectory codes have good accuracy. At the warmer temperatures, the water only partly freezes at the droplet impact site, and the unfrozen water runs aft and eventually freezes. *At these warmer temperatures, the shape of the ice is controlled by heat transfer to the surrounding air.* The lower prediction accuracy for the warmer temperatures is attributed primarily to the lack of good heat and mass transfer prediction models for ice-roughened surfaces. Another source of inaccuracy is the limitation of the physical model of the icing process.

As just noted, central to the heat balance on the water at the warmer temperatures is the prediction of convective heat and mass transfer from the water surface to the air flowing over the surface. It is helpful to keep in mind that the air flowing over the airfoil is the sink for heat and mass. Thus, when water freezes on the surface, its heat of fusion is transferred to the surrounding air by convection heat transfer and by evaporative cooling through convective mass transfer.

The surface of ice is covered with roughness. This roughness does not affect the heat and mass transfer in the laminar boundary layer, but it does affect the transition location and the heat and mass transfer in the turbulent boundary layer. Turbulent heat transfer correlations and analytical models exist for standard sandgrain surface roughness that is about 10 percent or less of the boundary layer displacement thickness. Unfortunately, ice roughness is usually thicker than the boundary layer displacement thickness, and therefore, there are no validated correlations or analytical models for heat transfer over ice-roughened surfaces. Lacking anything better, the ice accretion prediction codes use the sandgrain roughness models and ignore the fact that they were validated only for roughness heights much less than the displacement thickness.

3.6 Basic Studies in Support of Computer Codes

In spite of their limitations, the computer codes are being used successfully by those who have had experience with them and know their limitations. Yet, it is obvious that there exists a need for further basic studies to improve the numerical techniques and the physical models of heat and mass transfer and of the ice accretion growth process. Basic numerical studies to improve the numerical stability of the LEWICE ice accretion code are being conducted at NASA Lewis. For LEWICE, it has been found that predicted warm ice shapes are sensitive to the number of time steps that make up the total exposure time. For the current version of LEWICE, about five time steps is optimal. More time steps can lead to instabilities in the ice shape, such that the results do not converge to a single ice shape as would be expected with finer and finer time increments. Bidwell (Ref. 18) has succeeded in writing a numerical algorithm that eliminates the shape instability, and his results converge to a single ice shape as time step increment is reduced.

NASA Lewis is conducting basic experimental research to better understand how ice shapes develop under various icing conditions and how ice roughness develops and affects laminar-to-turbulent transition and heat and mass transfer. One objective is to quantify ice roughness and correlate it with the cloud and flight conditions. Other objectives are to conduct experiments that will aid in developing heat and mass transfer correlations and analytical models for flow over iced surfaces and mass transfer correlations and analytical models for flow over smooth surfaces.

3.7 Experimental Icing Simulation

Good experimental icing simulation facilities such as icing wind tunnels and in-flight spray tankers are essential because they are more productive, more economical, and far safer than flight testing in natural icing conditions. Since smaller aircraft and helicopters have limited range, they must wait for the icing weather to come to their test sites. This waiting has extended icing flight trials over several winters, and has driven up the cost for icing certification. Longer-range aircraft fly long distances to where ice is forecasted, but the cost per flight hour of these aircraft is very high, and the manufacturer works hard to control these costs.

Figure 14 shows the closed-loop circuit of the NASA Lewis Icing Research Tunnel (IRT). Two unique components of the IRT are its heat exchanger that refrigerates the air and its water spray system that uses air-blast nozzles to produce supercooled clouds. The IRT can produce the desired test conditions any time of the year regardless of the weather outside. Because of its uniqueness and versatility, the IRT is one of NASA's most heavily utilized wind tunnels, logging about 1000 hr of test time annually.

4. ICE CONTAMINATED TAILPLANE STALL (ICTS)

We ordinarily associate the hazards of in-flight icing with wing ice, knowing from our earlier discussions that 2 mm thick ice roughness can increase stall speed by 18 percent and reduce stall angle by 6°. But we are not as aware that even thinner roughness on the tailplane leading edge can cause potentially catastrophic tailplane stall during approach or landing, when the wing flaps are extended. Ice contaminated tailplane stalls during approach or landing have caused some airplanes to go into a steep dive. And if this happened at low altitude, the chances of recovering from the dive were slim to none.

Figure 15 shows the catastrophic flight path and aircraft attitudes of the Vickers Viscount that crashed at Stockholm in January 1977 (Ref. 19). "The broken curve" according to Dr. Martin Ingleman-Sundberg, "shows the flight path that might have been attained, in spite of the stall, if the pilots had managed to keep the yoke back."

According to Mr. John Dow (Ref. 20), from the FAA's Small Airplanes Directorate, "Sixteen known or suspected ICTS accidents occurred worldwide to turboprop-powered transport and commuter category airplanes, resulting in 139 fatal injuries." The FAA has issued eight Airworthiness Directives (ADs) against five airplane types in commercial service in response to ICTS related accidents and incidents. Although turboprop aircraft had the highest number of ICTS accidents and incidents, the problem is not limited to a specific size or configuration of airplane. Indeed, a worldwide survey revealed that piston, jet, and non-U.S. Type Certificated

aircraft accounted for an additional twenty accidents and incidents in which ICTS was considered a likely factor.

4.1 Uncovering ICTS Problems

By early 1991, the European Joint Airworthiness Authorities (JAA) had developed and published (Ref. 21) a required flight test maneuver that they believe identifies aircraft with ICTS problems. In this maneuver, the airplane (with specified tail ice contamination) is pitched over at a prescribed pitch rate to a load factor of zero "g". If the airplane remains in control, and the stick force characteristics are within defined limits, then the airplane stability and control characteristics with ice on the tailplane are judged acceptable by the JAA. The FAA has adopted the JAA's zero "g" maneuver in principle and has required it be performed as part of the icing certification process on a selective basis to date.

Some airplane manufacturers' test pilots believe the pushover to zero "g" maneuver is too dangerous and not a maneuver that pilots would intentionally do in normal operations. But the airworthiness authorities have been successful in getting compliance from the manufacturers and believe that it is currently the best maneuver to uncover ICTS problems. Generally, the manufacturer will use a cautious approach by starting with, say, a pushover to one-half "g". And in some cases, the one-half "g" maneuver has uncovered the ICTS problem.

Although acknowledging that the zero "g" maneuver poses high risk for test pilots, aircraft operators point out that even in normal operations, if the pilot's approach was high or fast, he might push over to get to the glide slope, or if the approach was slow, he might push over to pick up speed. In either case, that would be pushing the airplane towards zero "g". The operators would like these problems to be found by the highly skilled test pilots and fixed by the manufacturer rather than be encountered unexpectedly by the journeyman pilot. But everyone agrees that it would be beneficial to better understand what happens during the pushover maneuver and to use that knowledge to develop lower risk methods to identify ICTS problems.

4.2 Screening of Turboprop Airplanes for ICTS

Two recent international workshops sponsored by the FAA have alerted the aviation community to the seriousness of ICTS. Numerous articles about ICTS have been published subsequently in magazines read by pilots. Both the FAA and the manufacturers have responded with a new and concerted effort to 1) identify the causes of tailplane stall, 2) prevent it by design, 3) discover and fix it before the airplane is certificated for icing, and 4) educate pilots on how to avoid it in flight operations,

An important recommendation that came from the first workshop was that the FAA should screen all turboprops used in Part 121 or 135 operations for susceptibility to ICTS. The FAA responded by contracting with Mr. Pete Hellsten, a consultant in aircraft design, to develop an analytical method and apply it to the thirty-one turboprop airplanes that the FAA identified in the Part 125 or 135 categories. In the study, the FAA and Mr. Hellsten analyzed cruise, approach, and landing configurations at speeds from stall to V_{FE} ; they assumed a forward center-of-gravity and made calculations for both one "g" and zero "g" load factors; and they also analyzed each of the above combination of conditions for both clean tails and

tails contaminated with standard roughness. In discussing Hellsten's work (Ref. 22) herein, we present results only for tails contaminated with standard roughness.

4.3 Wing and Tail Aero Characteristics for Approach and Landing

For the purpose of explaining his analytical approach, Mr. Hellsten used the average geometry of the 31 turboprop configurations to develop a generic or "paper" airplane. Although not an actual airplane, the generic airplane was a good representation of the study. We will use the data from Hellsten's analysis of this generic airplane to illustrate the changes in wing and tailplane operating characteristics during approach and landing (this viewpoint was first adopted by Dr. Ingleman-Sundburg in Ref. 19).

Figure 16 shows plots of wing lift coefficient versus wing angle of attack for the cruise, approach, and landing configurations. Superimposed on these plots are the operating points for cruise, approach, and landing. Starting with a cruise speed of 200 kt (point 1), the pilot decreases speed to 126 kt (point 2) while increasing the wing AOA from 2.5° to 9.5° . Next, the pilot deploys half flaps and lowers wing AOA to 7° (point 3) and then further decreases speed to 114 kt while increasing wing AOA to 9.5° (point 4). Finally, the pilot extends full flaps and lowers wing AOA to 4.5° (point 5). Eventually the pilot reduces speed and increases wing AOA while slowing to touch down.

Several aircraft responses accompany the deployment of flaps. First, when the flaps are initially deployed, say at point 2, the wing AOA has not yet changed, and the airplane is lifted because it is temporarily operating on the half-flap lift curve at an AOA of 9.5° . This effect is termed "ballooning". Second, the deployed flaps move the center of pressure farther aft on the wing, causing a nose-down pitching moment. Third, the extended flaps increase the wing downwash angle, which in turn increases the AOA on the tail and produces a greater downward force on the tail. The pilot compensates for these effects by moving the yoke to trim out the airplane. During the trim adjustment, the nose pitches down to a lower wing AOA and the tail pitches up to a higher tail AOA. During the upward motion of the tail there is an increased downward relative velocity on the tail which further increases the tail AOA. The critical moment occurs when deploying full flaps because this results in the largest trim adjustment to get to the smallest wing AOA (point 5) and, conversely, to the largest tail AOA. This is the critical point where tail stall margin is least and tail stall might occur.

The above discussion also illustrates a dilemma that the pilot can get into: If the pilot suspects that wing ice contamination has increased the wing stall speed and he increases speed to compensate, the wing AOA will decrease, but the tail AOA will increase. The increased tail AOA might possibly reduce tail stall margin to the point where a sudden downburst or nose-down pitch could stall the tail. **IT IS IMPORTANT THAT THE PILOT KNOW AND FOLLOW THE MANUFACTURER'S RECOMMENDATION IN THIS SITUATION AND FLY IT BY THE BOOK.**

By interpolating the data of Hellsten, we were able to deduce the wing and tail operating characteristics for the six points shown in Fig. 16. The wing and tail configurations for these points are given in Fig. 17. Hellsten defines the wing and tail

stall margins as $(C_{L_{max}} - C_L)$ and $(C_L - C_{L_{min}})$, respectively. These margins are given on Fig. 18 for the six points on Fig. 16. (Figure 18 also shows stall margins for the zero "g" analysis, which will be discussed later). As expected, the tail stall margin is least at point 5 but does not seem excessively small. It would be difficult to draw any conclusions from the results shown in Fig. 18 about the susceptibility of this generic airplane to ICTS. These stall margins, however, are for the trimmed airplane and do not account for transients such as the nose down pitch rates or downgusts or control inputs that might temporarily increase tail AOA and push the lift margin to zero or negative.

Just as the JAA had found that the zero "g" flight test maneuver was the best discriminator of ICTS, Hellsten also found that his calculated response of an aircraft to the zero "g" maneuver correlated best with the airplane's actual ICTS history. Hellsten's study of the thirty-one turboprops showed that when his analysis predicted that an airplane had a negative or just slightly positive tail stall margin for the zero "g" maneuver, that airplane was likely to be susceptible to ICTS. During the pitchover maneuver, the wing loading is zero (zero lift) and the large nose-down pitching moment coming from the flaps is balanced by a large download or negative lift on the tail. The predicted tailplane configurations, lift coefficients, and stall margins during the zero-"g" maneuver are shown in the bottom of Fig. 18 for three airspeeds: V_{stall} , $1.3*V_{stall}$, and V_{FE} . The predicted stall margins for the zero "g" maneuver range from a low of 0.04 at V_{stall} to a high of 0.07 at V_{FE} . The tailplane was contaminated with standard roughness. These slightly positive stall margins put the generic airplane in the susceptible range for ICTS.

The results of Hellsten's screening analysis are summarized in Fig. 19, which is a histogram of the calculated tailplane stall margins for each of the 31 airplanes during the zero "g" maneuver for standard roughness contamination on the tail (Ref. 23). Hellsten's analysis predicted that eighteen of the 31 turboprop airplanes had stall margins that were either negative or just slightly positive. Of these 18 airplanes 13 have known histories of ICTS. The remaining 13 airplanes outside the susceptible range (meaning they have substantial positive stall margins) have no histories of ICTS. These findings gave the FAA confidence that they were heading in the right direction with this screening process. The FAA is currently working with the manufacturers of these 18 potentially susceptible airplanes to verify the methodology developed by Hellsten.

The question naturally arises as to whether certain design features distinguished airplanes that are not susceptible to ICTS. Hellsten found that those airplanes having no history of ICTS problems either had properly trimmed movable horizontal stabilizers or had tails with inverted camber. But, Dow cautioned that not all aircraft with movable tailplanes or cambered tails were free of ICTS problems. Hellsten also observed that the more effective wing flap systems (i.e., more Fowler motion) cause more nose-down pitching moment, thus requiring more negative lift on the tail to trim out the flaps and thereby driving the tail further toward stall. Although the use of movable stabilizers or cambered tails appear to be steps in the right direction, Hellsten cautioned that there is no simple answer to what works or doesn't work. The designer must go through the details of the design.

4.4 Stick Forces Caused by Stall of Fixed-Incidence Tailplanes

In a number of turboprop ICTS incidents or accidents, it was found that after the pilot extended full flaps, the stick lurched forward with such force that the pilot, or both the pilot and co-pilot, had to use all their strength to pull it back (on large turboprops, as much as 400 lb were required). This occurred on airplanes with fixed incidence tailplanes that had aerodynamically balanced elevators without power boosting. When the tailplane stalled, the separated flowfield redistributed the pressure over the elevator and caused an enormous downward hinge moment on it (Ref. 19). The problem is not a complete loss of elevator authority when the tailplane stalls, but rather the problem is the inability to detect the stall (stick lightening or vibration or tail buffeting) soon enough and to muscle the stick back so that the elevator is moved from the down to the up position. Even though the tail is stalled, it apparently can develop sufficient downward lifting force to prevent a dive.

4.5 Operating in Known or Suspected Icing Conditions

If you are in known or suspected icing conditions, you must be keenly aware of the deleterious effects of ice contamination on both wing and tailplane aeroperformance and the resulting reduction in airplane handling qualities and stability and control. Keep in mind that because the tailplane is smaller than the wing, ice can accumulate on the tail before you can actually see it on the wings or elsewhere; and relative to its size, the tailplane ice coverage will be thicker and extend farther aft than the ice on the wing (see Fig. 10). The bottom line is that the tail will accumulate more ice and be less tolerant of it than the wing. Also, on airplanes equipped with pneumatic boots for ice protection, remember that the smaller leading edge radius of the tail renders the tail boot less effective than the wing boot in removing ice. Thus the tail boot may have to be exercised more often than the wing boots; **BUT HERE YOU SHOULD FOLLOW THE AIRPLANE AND PNEUMATIC BOOT MANUFACTURER'S RECOMMENDATIONS.**

Several recommendations came from the two tailplane icing conferences and from subsequent articles published in pilot magazines. Some recommendations involved operational strategies that should help prevent an ice contaminated tailplane stall or help recover from one. There is an important caveat to any recommendation or guideline published here or elsewhere: **READ YOUR AIRPLANE FLIGHT MANUAL AND FOLLOW THE AIRPLANE MANUFACTURER'S RECOMMENDATIONS; THEY OVERRIDE ANYTHING THAT IS PRINTED HERE.**

The following partial, but representative, list of the guidelines for avoiding or recovering from ICTS was published recently by Manningham (Ref. 24):

After checking with the manufacturer and the FAA, consider the following guidelines to avoid tailplane icing and its worst consequences:

Know the level of icing for which your airplane is certified and never intentionally fly into icing conditions which exceed that level.

Never fly in known icing conditions with any anti-icing or deicing components inoperable.

When you observe ice on the wing, assume that there is even more ice on the tail and that it will have a more profound effect.

Use pneumatic boots and other deicing and anti-icing components strictly according to manufacturer's recommendations. Hangar tales and rumors never provide better operating procedures than those who make and test the equipment. If you have a question, talk to the manufacturers directly.

In icing conditions, make the landing approach with something less than full flaps. Half flaps or less are about right. Ask your manufacturer. Check the applicable ADs [Airworthiness Directives]. [Have a firm hold on the stick, and if your airplane has a fixed incidence tailplane with aerodynamically balanced elevators and no power boosting, anticipate the possibility that it could lurch forward with great force.]

In icing conditions be circumspect about adding speed for the final approach to compensate for ice on the wings. Every knot of speed added to prevent wing stall is a knot closer to tail stall... Fly the approach by the numbers if your airplane is one of those at greatest risk. [Adding speed lowers wing AOA and raises tail AOA, thus reducing tail stall margin to the point where a sudden downburst or nose-down pitch could stall the tail.]

If you do encounter pitch problems on final approach in icing conditions, muscle the elevator to the position you want, and it will provide adequate control to avoid a pitchover. The problem is not elevator authority but hinge moment and, therefore, control forces that you can overcome with muscle.

Be alert and wary during flap changes. Make final flap selection at least 1,000 ft above ground level so that any uncommanded pitchover will occur with enough altitude to recover.

If you experience an uncommanded pitchover during or shortly after flap selection, immediately return the flaps to the previous setting.

If the aircraft is high and fast on final approach, go around and try again. Several uncommanded pitchovers have been reported by pilots who attempted to slow rapidly with max flaps.

Tailplane icing is a real and serious threat to all airplanes, but especially to mid-sized, propeller-driven airplanes. Conversely, tailplane icing need not threaten your flight safety if you: (1) are aware of the potential, (2) limit final flap settings in icing conditions, and (3) maintain vigilance during the final approach.

It takes just the right combination of a number of factors that can momentarily increase the tail's AOA and trigger a tail stall. These factors include tail ice accumulation (and, maybe, not very much of it), deployment of flaps, higher airspeeds, low airplane AOA, nose-down pitch, forward center of gravity, headwind gusts, sideslips, downdrafts, etc. But by studying the above guidelines **AND FOLLOWING THE**

AIRPLANE AND ICE PROTECTION MANUFACTURER'S RECOMMENDATIONS, you should be well prepared to cope with ICTS.

We will conclude this section on ICTS by repeating Manningham's succinct advice:

The classic tail icing pitchover occurs on final approach as the flaps move to an increased setting. Appropriate pilot action is to use all necessary force to pull back on the yoke while returning the flaps to their previous setting. If you can remember the contents of this paragraph, you will have retained virtually all of the important information regarding tail icing.

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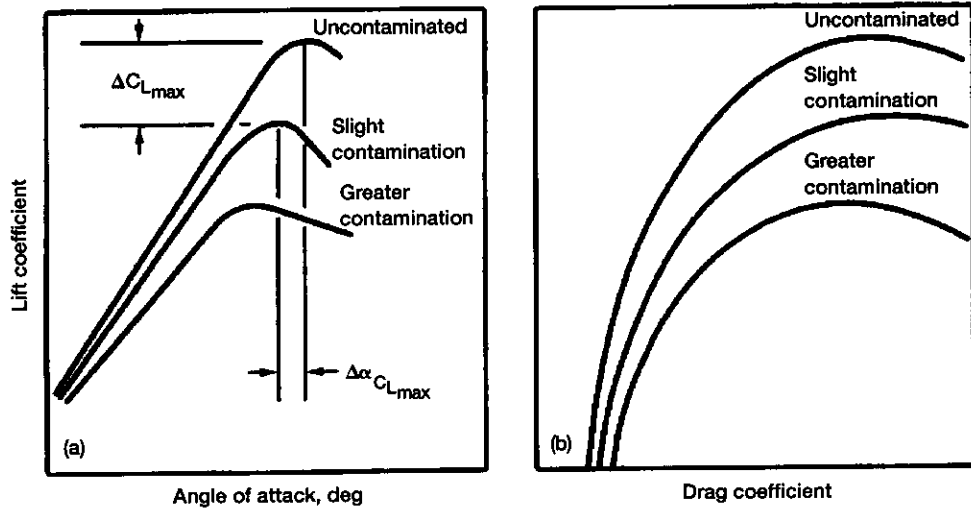


Figure 1.—Effect of wing ice contamination on lift and drag coefficients (ref. 1). (a) Lift coefficient. (b) Drag coefficient.

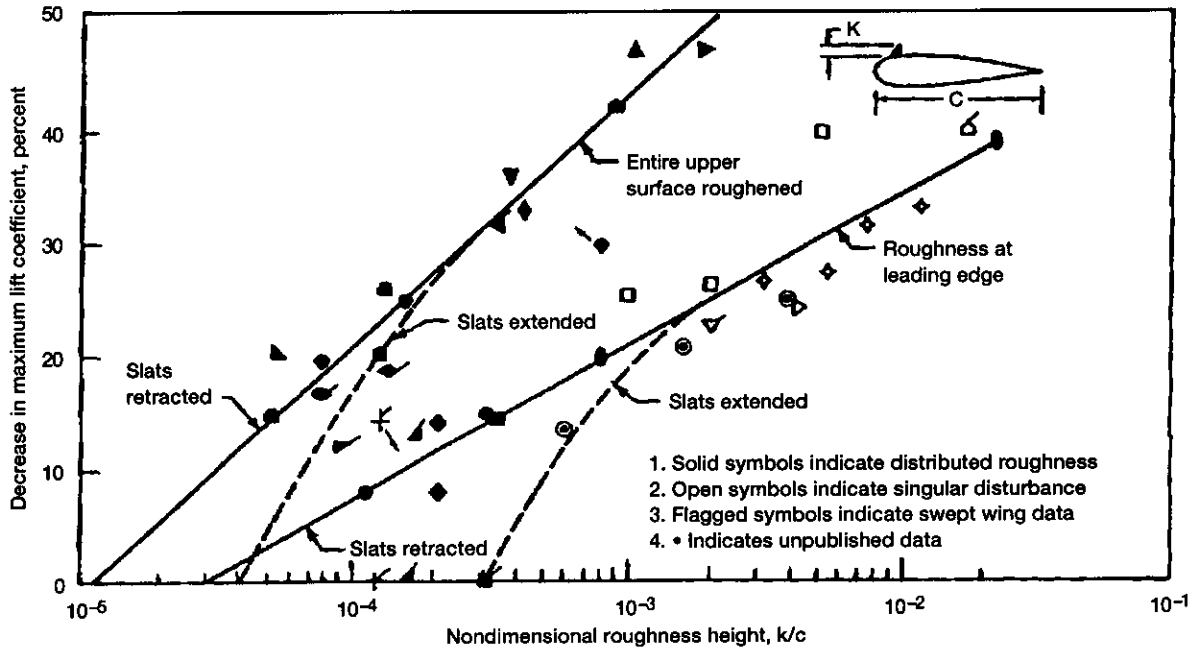


Figure 2.—Correlation of the effect of wing surface roughness on maximum lift coefficient (ref. 1).

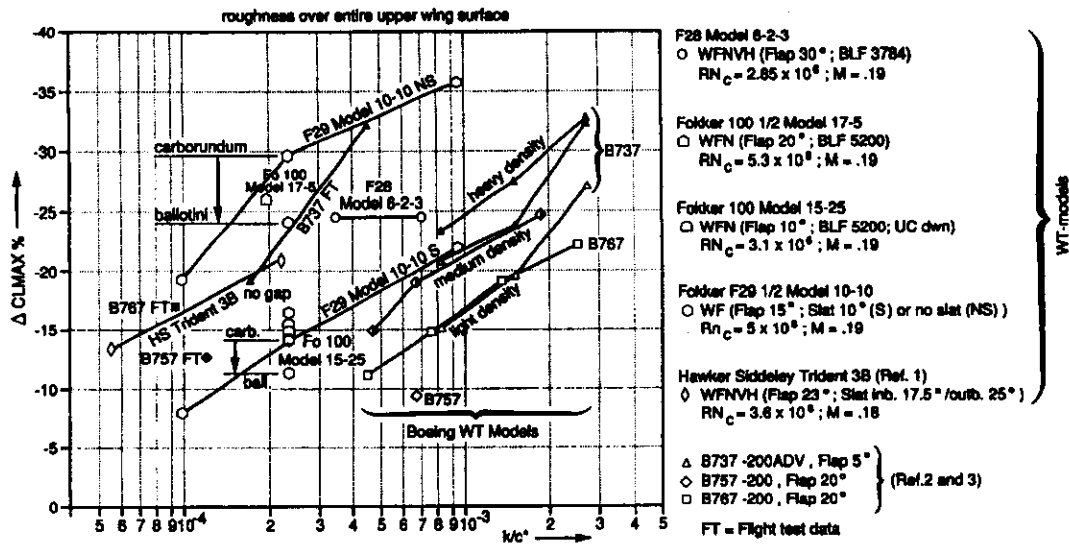


Figure 3.—Effect of roughness on maximum lift coefficient (ref. 2).

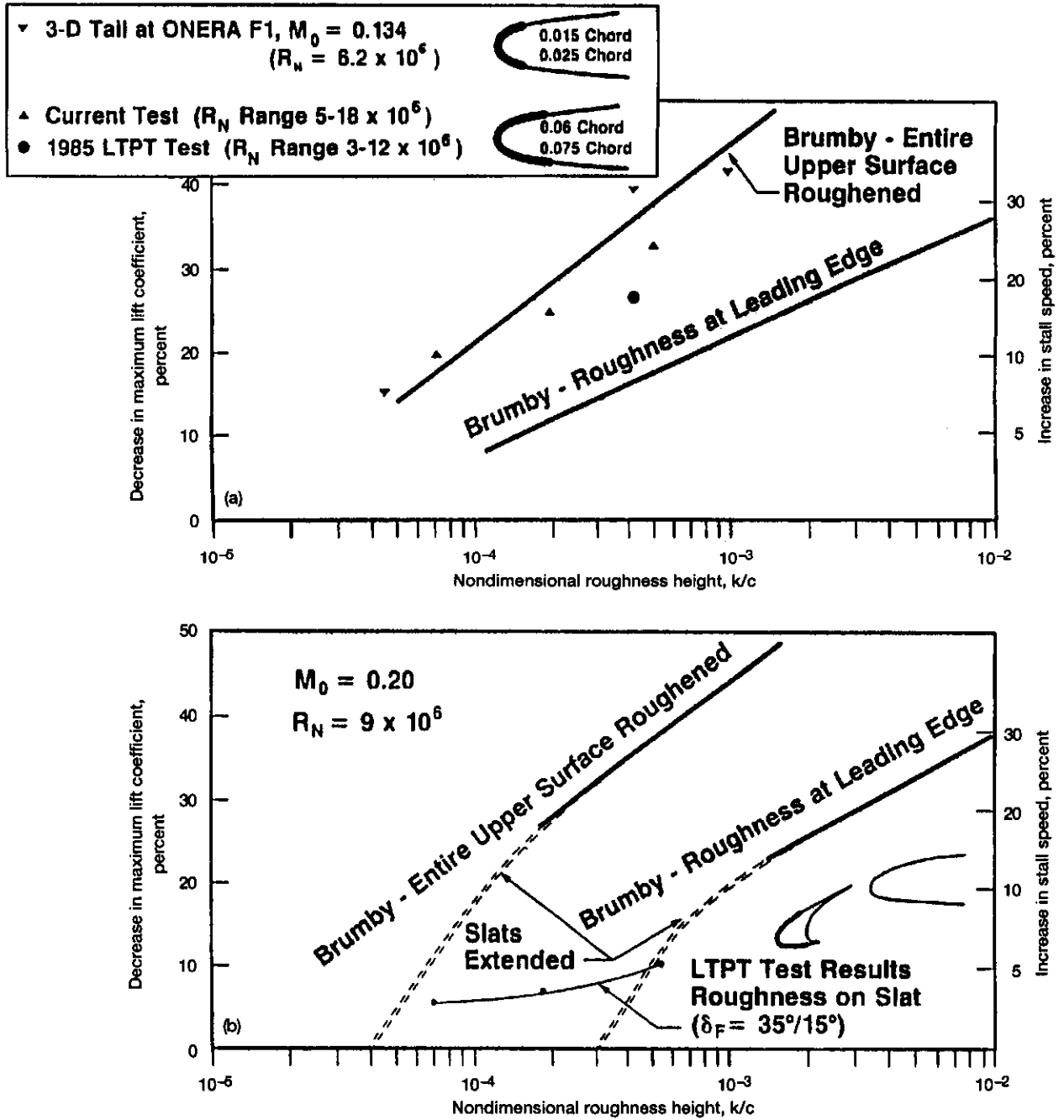


Figure 4.—Effect of roughness on maximum lift (ref. 3). (a) Single element airfoil and tail. (b) Four element airfoil.

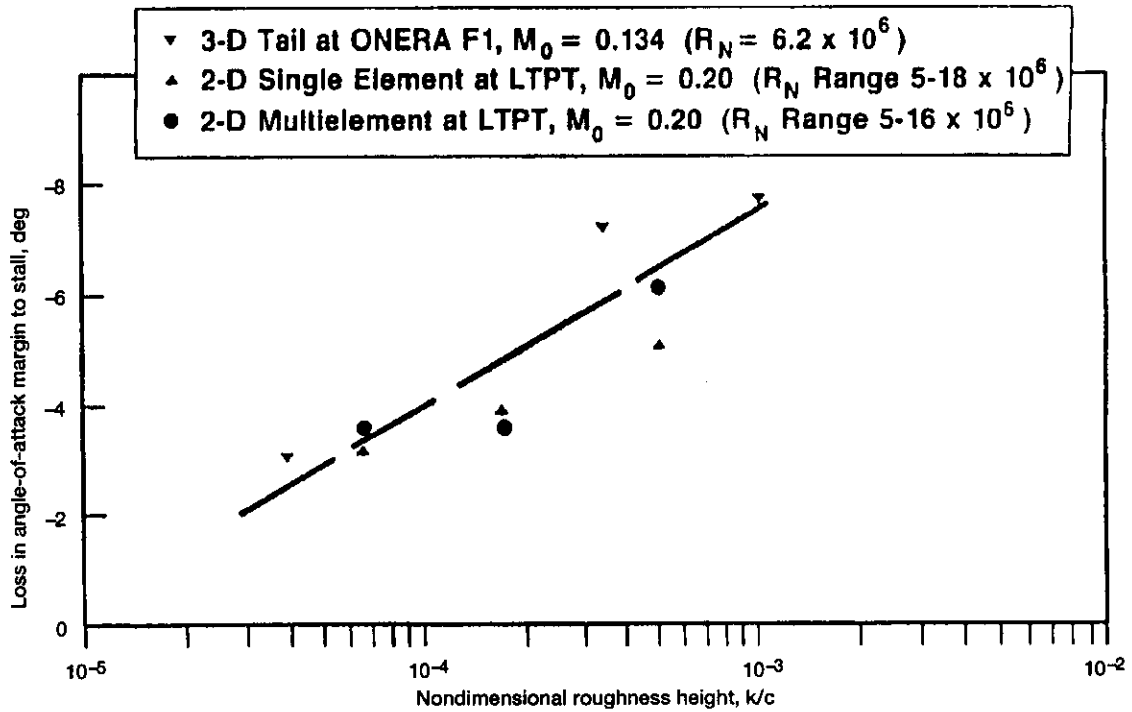


Figure 5.—Effect of roughness on loss of angle-of-attack margin to stall (ref. 3).

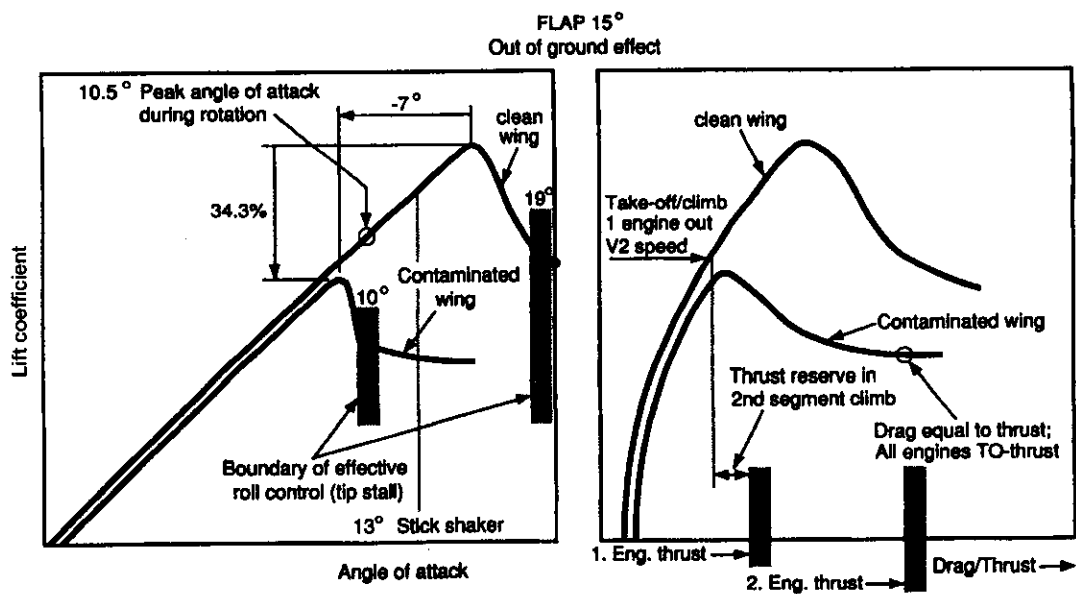


Figure 6.—Effect of wing contamination on aircraft lift and drag (ref. 2).

THE RESPONSIBILITY FOR THE APPLICATION OF THESE DATA REMAINS WITH THE USER AND SHOULD ONLY BE USED IN CONJUNCTION WITH THE SAE METHODS DOCUMENT (SEE CAUTIONS)

FP of SAE Type I Fluid Mixture Must be at least 10 °C (18 °F) below OAT

OAT		Approximate Holdover Times Under Various Weather Conditions (hours:minutes)				
°C	°F	Frost	Freezing Fog	Snow	Freezing Rain	Rain on Cold Soaked Wing
0 and above	32 and above	0:18-0:45	0:12-0:30	0:06-0:15	0:02-0:05	0:06-0:15
below 0 to -7	below 32 to 19	0:18-0:45	0:06-0:15	0:06-0:15	0:01-0:03	
below -7	below 19	0:12-0:30	0:06-0:15	0:06-0:15		

°C = Degrees Celsius
 °F = Degrees Fahrenheit
 OAT = Outside Air Temperature
 FP = Freezing Point

CAUTION: THE TIMES OF PROTECTION REPRESENTED IN THIS TABLE ARE FOR GENERAL INFORMATION PURPOSES ONLY AND SHOULD BE USED ONLY IN CONJUNCTION WITH A PRE-TAKEOFF INSPECTION.

CAUTION: THE TIME OF PROTECTION WILL BE SHORTENED IN HEAVY WEATHER CONDITIONS. HIGH WIND VELOCITY AND JET BLAST MAY CAUSE A DEGRADATION OF THE PROTECTIVE FILM. IF THESE CONDITIONS OCCUR, THE TIME OF PROTECTION MAY BE SHORTENED CONSIDERABLY. THIS IS ALSO THE CASE WHEN THE FUEL TEMPERATURE IS SIGNIFICANTLY LOWER THAN OAT.

Figure 7.—Guideline for holdover times anticipated for SAE Type I fluid mixture as a function of weather conditions and OAT (ref. 9).

THE RESPONSIBILITY FOR THE APPLICATION OF THESE DATA REMAINS WITH THE USER AND SHOULD ONLY BE USED IN CONJUNCTION WITH SAE METHODS DOCUMENT. (SEE CAUTIONS)

OAT		SAE Type II Fluid Concentration Neat-Fluid/Water (Vol %/Vol %)	Approximate Holdover Times Under Various Weather Conditions (hours:minutes)				
°C	°F		Frost*	Freezing Fog	Snow	Freezing Rain	Rain on Cold Soaked Wing
0 and above	32 and above	100/0	12:00	1:15-3:00	0:25-1:00	0:08-0:20	0:24-1:00
		75/25	6:00	0:50-2:00	0:20-0:45	0:04-0:10	0:18-0:45
		50/50	4:00	0:35-1:30	0:15-0:30	0:02-0:05	0:12-0:30
below 0 to -7	below 32 to 19	100/0	8:00	0:35-1:30	0:20-0:45	0:08-0:20	
		75/25	5:00	0:25-1:00	0:15-0:30	0:04-0:10	
		50/50	3:00	0:20-0:45	0:05-0:15	0:01-0:03	
below -7 to -14	below 19 to 7	100/0	8:00	0:35-1:30	0:20-0:45		
		75/25	5:00	0:25-1:00	0:15-0:30		
below -14 to -25	below 7 to -13	100/0	8:00	0:35-1:30	0:20-0:45		
below -25	below -13	100/0	Use of SAE Type II for anti-icing below -25 °C (-13 °F) must maintain 7 °C (13 °F) buffer, and the fluid shall conform to the lowest operational use temperature/aerodynamic acceptance limitation (see para. 6.3.1.1.2). Consider use of SAE Type I where SAE Type II fluid cannot be used.				

°C = Celsius

°F = Degrees Fahrenheit

OAT = Outside Air Temperature

VOL = Volume

* = For maintenance purposes

CAUTION: THE TIMES OF PROTECTION REPRESENTED IN THIS TABLE ARE FOR GENERAL INFORMATION PURPOSES ONLY AND SHOULD BE USED ONLY IN CONJUNCTION WITH A PRE-TAKEOFF INSPECTION.

CAUTION: THE TIME OF PROTECTION WILL BE SHORTENED IN HEAVY WEATHER CONDITIONS. HIGH WIND VELOCITY AND JET BLAST MAY CAUSE A DEGRADATION OF THE PROTECTIVE FILM. IF THESE CONDITIONS OCCUR THE TIME OF PROTECTION MAY BE SHORTENED CONSIDERABLY. THIS IS ALSO THE CASE WHEN THE FUEL TEMPERATURE IS SIGNIFICANTLY LOWER THAN OAT.

Figure 8.—Guideline for holdover times anticipated for SAE Type II fluid mixture as a function of weather conditions and OAT (ref. 9).

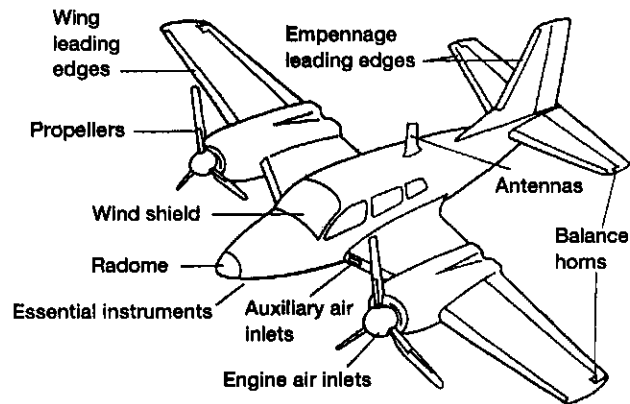


Figure 9.—Aircraft ice protection.

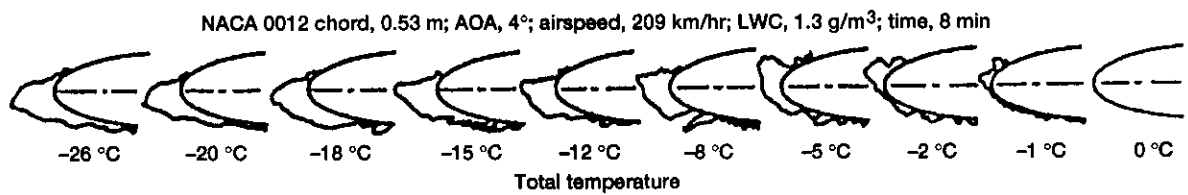
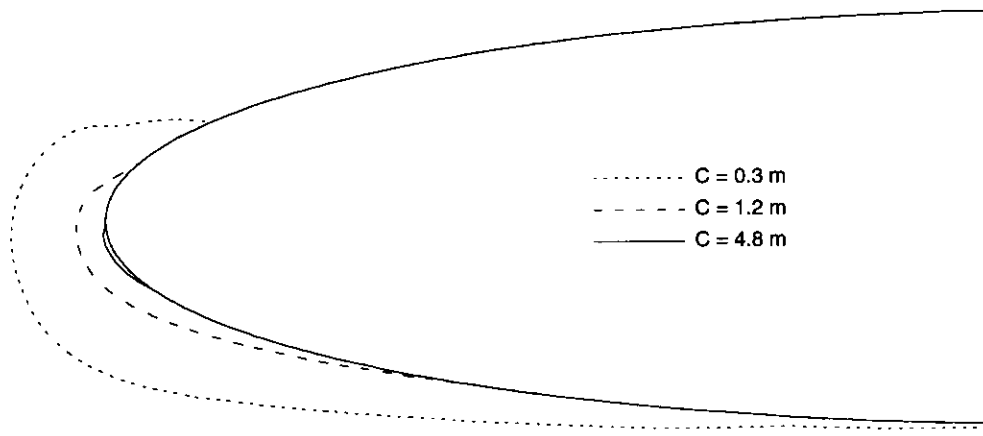


Figure 10.—Effect of total temperature on ice shape development (ref. 15).



NACA 0012 airfoil; AOA, 4°; airspeed, 252 km/hr; LWC, 0.35 g/m³; MVD = 20 μm; time, 10 min

Figure 11.—Effect of airfoil size on ice coverage.

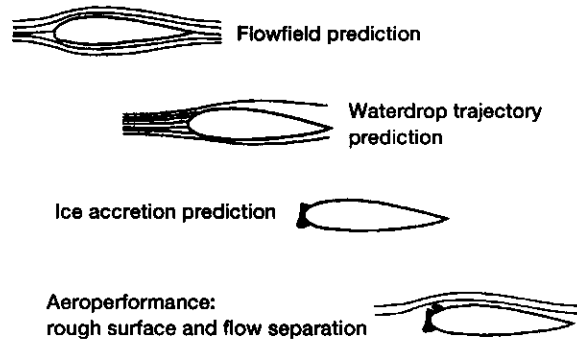


Figure 12.—Ice accretion modeling approach.

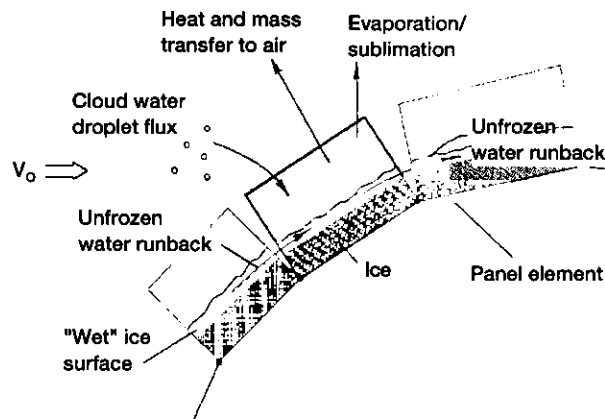


Figure 13.—Control volume approach for ice accretion model.

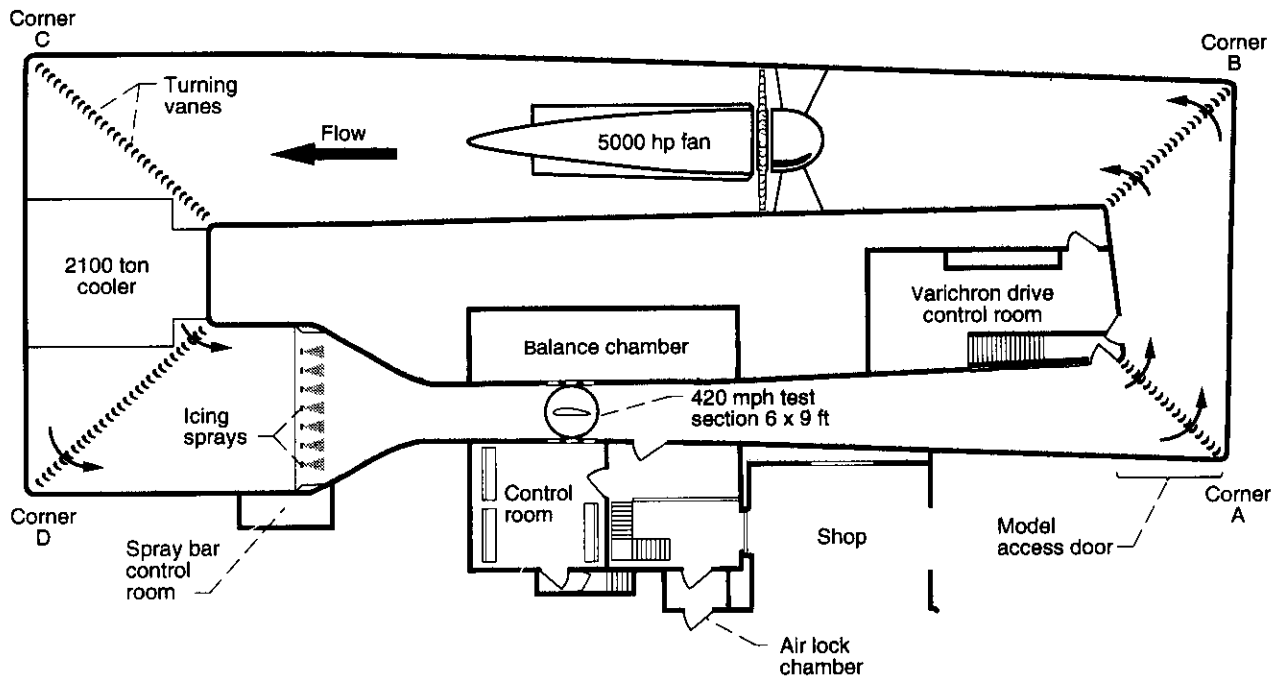


Figure 14.—Schematic of the NASA Lewis Research Center Icing Research Tunnel (IRT).

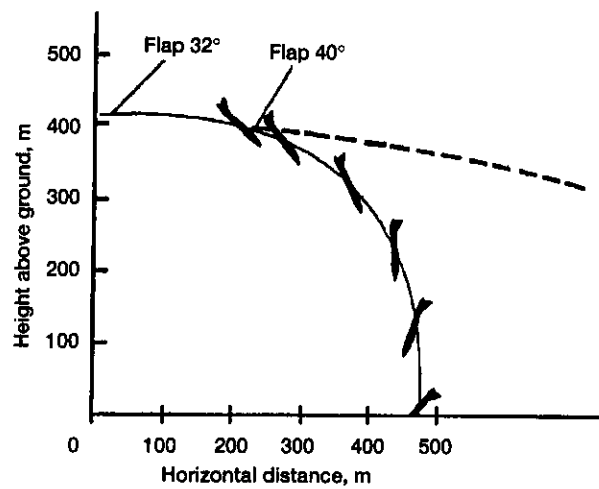


Figure 15.—Catastrophic flight path of Vickers Viscount accident in Stockholm, Sweden on January 1977 (ref. 19).

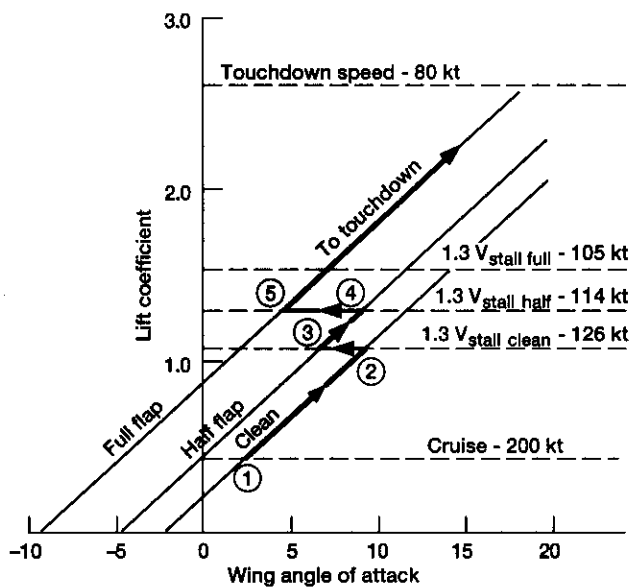


Figure 16.—Angle-of-attack conditions for P. Hellsten's generic turboprop airplane (ref. 22).

	Condition (fig. 16)	Flaps	Wing AOA, deg	Wing downwash, deg	Tail AOA, deg	Elevator deflection, deg	Tail, C_L	Airspeed, kt
Trimmed aircraft	1	Clean	2.3	1.4	-1.5	2.3	0	200
	2	Clean	9.5	3.8	3.1	-3.4	0.04	126
	3	Half	7.0	3.8	-2.0	1.1	-0.07	126
	4	Half	9.5	4.8	-0.2	-0.8	-0.05	114
	5	Full	4.4	4.8	-4.9	3.1	-0.22	114
	6	Full	18.1	9.6	4.2	-7.5	-0.075	80
Zero "g" pushover	VFE	Full		0	-14.8	15.1	-0.29	145
	$1.3 V_s$	Full		0	-15.8	16.3	-0.29	105
	V_s	Full		0	-17.3	18.3	-0.29	80

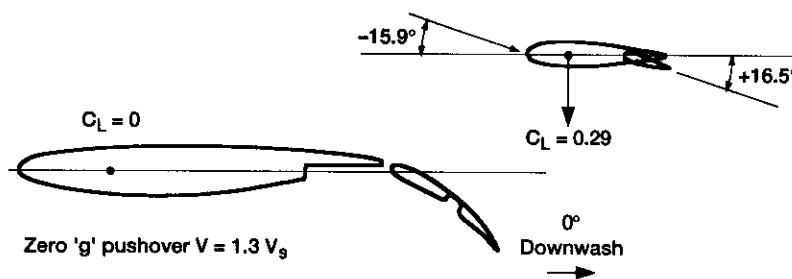


Figure 17.—Wing and tail configurations for the flight conditions shown on figure 16 (ref. 22).

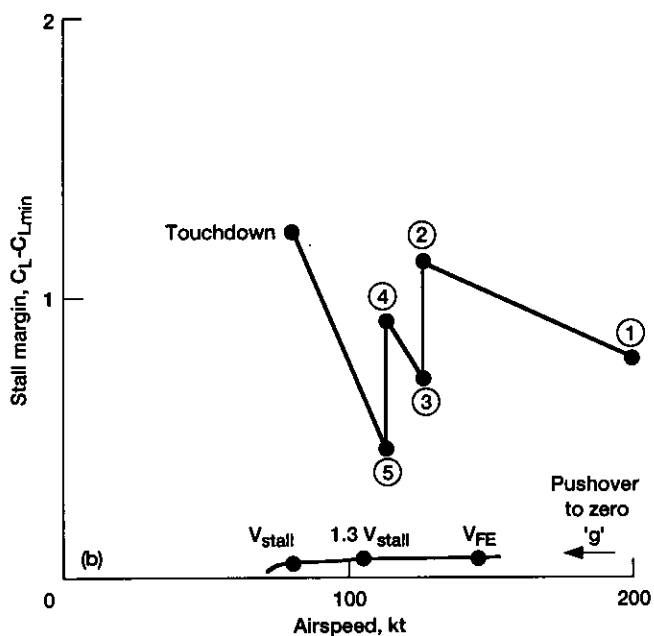
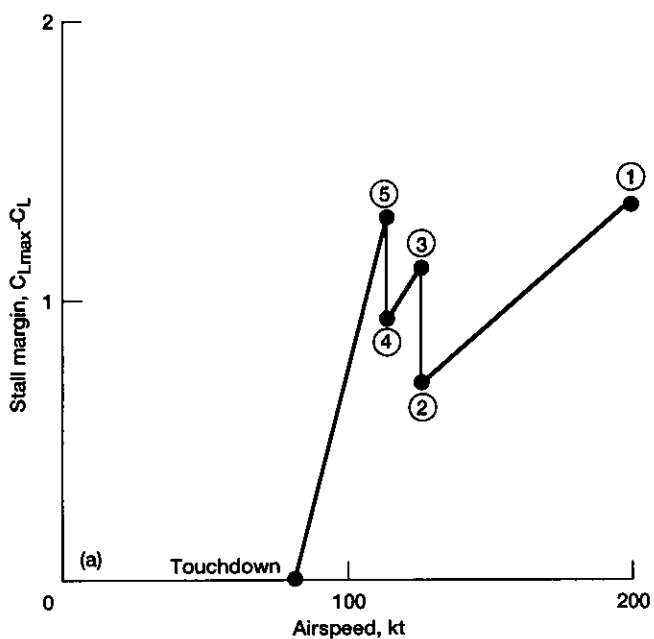


Figure 18.—Stall margins for the flight conditions shown on figure 16 and for the pushover to zero 'g' maneuver (ref. 22). (a) Wing. (b) Tail.

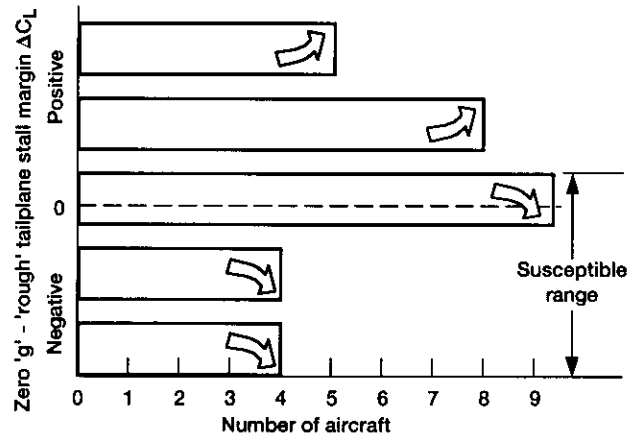


Figure 19.—Predicted zero 'g' 'rough' tailplane stall margins for thirty-one Part 121/135 Turboprop Aircraft (ref. 23).