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ADVISORY CIRCULAR

Subject: Turbojet, Turboprop, Turboshaft, and Turbofan Engine Induction System Icing and Ice Ingestion

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This advisory circular (AC) provides guidance for demonstrating compliance with the engine induction system icing and engine installation ice requirements of Title 14 Code of Federal Regulations (14 CFR) parts 23, 25, 27, 29, and 33. This AC discusses the icing environments depicted in appendices C and O of part 25, appendix C of part 29, and appendix D of part 33. This AC discusses turboshaft engine installations, but not the rotary wing aircraft they are installed on.

If you have suggestions for improving this AC, you may use the Advisory Circular Feedback form at the end of this AC.

for Colleen M D'Alessandro
Kim Smith,
Acting Manager, Engine & Propeller Directorate
Aircraft Certification Service

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1. **Purpose**.

a. This advisory circular (AC) provides guidance for demonstrating compliance with the engine induction system icing and engine installation ice requirements of Title 14 Code of Federal Regulations (14 CFR) parts 23, 25, 27, 29, and 33. This AC discusses turboshaft engine installations, but not the rotary wing aircraft they are installed on. See ACs 20-73A, AC 27-1B, and AC 29-2C for additional guidance on engine installation icing issues for rotary wing applications.

b. This AC, 20-147A, replaces AC 20-147, dated February 2, 2004. Applicants should use this AC as their primary guidance concerning icing issues for engines and engine installations for parts 25 and 33, other guidance on the subject notwithstanding. For part 23 airplanes, AC 23-16A takes precedence on engine installation icing compliance guidance. For parts 27 and 29 rotorcraft, ACs 27-1B, and 29-2C, respectively, take precedence on engine installation guidance (that is, §§ 27.1093 and 29.1093). Additionally, AC 20-73A contains useful information on the understanding and characterization of the icing environment, but it should not be viewed as guidance on engine icing methods of compliance discussed in this AC. It should be noted that neither supercooled large droplet (SLD) (refer to appendix O of part 25) nor Ice Crystals (refer to appendix D of part 33) icing environments are currently required for turboshaft engines and their aircraft installations. It should also be noted that the SLD (refer to appendix O of part 25) icing environment is currently not required for turbine engine induction systems (refer to § 25.1093) on part 25 airplanes with a maximum takeoff weight equal to or greater than 60,000 pounds, or for part 23 airplanes.

2. **Applicability**.

a. The guidance provided in this document is directed to engine and airframe manufacturers, modifiers, and foreign regulatory authorities.

b. This material is neither mandatory nor regulatory in nature, and it does not constitute a regulation. It describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations. The FAA (we) will consider other methods of demonstrating compliance that an applicant (you) may elect to present. Terms such as “should,” “shall,” “may,” and “must” are used only to ensure the applicability of this particular method of compliance when the method in this document is used. This guidance is derived from extensive FAA and industry experience in determining compliance with the relevant regulations. If we determine that following this AC would not result in compliance with the applicable regulations, we will not be bound by the terms of this AC, and we may require additional substantiation as the basis for finding compliance.

c. This material does not change, create any additional, authorize changes in, or permit deviations from existing regulatory requirements.

3. Cancellation. AC 20-147, Turbojet, Turboprop, and Turbofan Engine Induction System Icing and Ice Ingestion, dated 2/2/04, is canceled.

4. Related Regulations.

a. Part 23, Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes, §§ 23.901(d)(2), 23.1093, and 23.1419.

b. Part 25, Airworthiness Standards: Transport Category Airplanes, §§ 25.1091, 25.1093, 25.1419 and 25.1420.

c. Part 27, Airworthiness Standards: Normal Category Rotorcraft, §§ 27.1093.

d. Part 29, Airworthiness Standards: Transport Category Rotorcraft, §§ 29.1093.

e. Part 33, Airworthiness Standards: Aircraft Engines, §§ 33.68, 33.77(c), 33.77(e), 33.89(b), and 33.78.

5. References and Related Reading Material.

a. AC 20-73A, “Aircraft Ice Protection”, dated 8/16/2006.

b. AC 23-16A, “Powerplant Guide for Certification of Part 23 Airplanes and Airships”, dated February 23, 2004.

c. AC 23.1419-2D, “Certification of Part 23 Airplanes for Flight in Icing Conditions”, dated April 19, 2007.

d. AC 27-1B, “Certification of Normal Category Rotorcraft”, dated September 30, 2008.

e. AC 29-2C, “Certification of Transport Category Rotorcraft”, dated September 30, 2008.

f. AC 33-2B, “Aircraft Engine Type Certification Handbook”, dated June 30, 1993.

g. U.S. Department of Transportation. Federal Aviation Administration. Report No. FAA-RD-77-76, “Engineering Summary of Powerplant Icing Technical Data”, by G. D. Pfeiffer and G. P. Maier, dated July 1977.

h. U.S. Department of Transportation. Federal Aviation Administration. Report No. FAA-RD-77-78, “Engineering Summary of Powerplant Icing Technical Data”, dated July 1977.

i. U.S. Department of Transportation. Federal Aviation Administration. Report No. DOT/FAA/AR-97/66, August, 1998. “Snow and Ice Particle Sizes and Mass Concentrations at Altitudes Up To 9 km (30,000 ft)”, by R. K. Jeck.

j. U.S. Department of Transportation. Federal Aviation Administration. Report No. DOT/FAA/AR-09/13, “Technical Compendium from Meetings of the Engine Harmonization Working Group”, by R. Mazzawy, dated April 2009.

k. U.S. Department of Transportation. Federal Aviation Administration. Report No. DOT/FAA/AR-03/48, MAY 2003. “Assessment of Effects of Mixed-Phase Icing Conditions on Thermal Ice Protection Systems”, by Kamel Al-KHalil.

l. Royal Aircraft Establishment (Farnborough) Technical Note No: Mech. Eng. 283. “The Analysis of Measurements of Free ice and Ice/Water Concentrations in the Atmosphere of Equatorial Zone”, by Ian I. McNaughton, B.Sc., Dip. R.T.C., dated 1959.

m. “The Icing of an Unheated Non-rotating Cylinder in Liquid Water Droplet-Ice Crystal Clouds”, by E. P. Lozowski, J. R. Stallabrass & P. P. Hearty, National Research Council Canada Report LTR-LT-96, dated February 1979.

n. “Further Icing Experiments on an Unheated Non-rotating Cylinder”, LTR-LT-105, by J.R. Stallabrass and P. F. Hearty, dated November 1979.

o. “Snow Concentration Measurements and Correlation with Visibility”, by J. R. Stallabrass, AGARD Conference Proceedings No. 236 Icing Testing for Aircraft Engines, dated April 1978.

p. “The Estimation of Snowfall Rate Using Visibility”, by Rasmussen, R.M., J. Vivekanandan, J. Cole, B. Myers, and C. Masters, 1999: Journal of Applied Meteorology, 38, 1542-1563.

q. “Calibration and Acceptance of Icing Wind Tunnels, Aerospace Recommended Practice (ARP) 5905”, issued 2003-09: Society of Automotive Engineers.

r. “Appendix D – An Interim Icing Envelope”, by R. S. Mazzawy and J. W. Strapp, SAE 2007-01-3311, dated September, 2007.

6. Background.

a. The induction system icing requirements of §§ 23.1093, 25.1093, 27.1093, 29.1093 and of § 33.68 are to provide protection for flight into icing with no adverse effect on engine operation or power. Propulsion systems that meet these requirements when operated in accordance with the aircraft flight manual, have generally demonstrated safe operation upon exposure to natural icing environments.

b. The successful demonstration of the test conditions outlined in the regulation is intended to address many potential engine power conditions. These conditions include aircraft flight conditions, and environmental conditions that could otherwise prove to be costly and difficult to realistically test.

c. A direct comparison between the severity of compliance requirements for icing versus compliance requirements for rain and hail is inappropriate. In § 33.68, the regulation references appendices C and O of part 25, and appendix D of part 33. The environmental threats depicted in all of these appendices have occurred. However, operators have also encountered icing conditions that are more severe. Indeed, the probable occurrence rate of encountering the icing conditions depicted in appendix C of part 25 or 29 is far greater than the remote threat posed by the rain and hail environmental conditions depicted in appendix B of part 33. As a result of these differences in rates of occurrence, as well as fundamental differences of environment and corresponding assumed in-flight profiles, a comparison of compliance requirements across different threat types will be flawed, incongruous, and ultimately inappropriate.

d. The icing environments described in this AC are considered probable to encounter. Appendices C and O of part 25 and appendix C of part 29, address 99% of supercooled droplet icing conditions; they are based on atmospheric icing data. Additionally, the probability of exceeding both liquid water content (LWC) and median volume diameter (MVD) while operating at or below the temperature specified in both appendices C, of parts 25 and 29 is estimated at approximately 10^{-3} encounters for each flight; thus a probable encounter. Appendix D of part 33 is derived from the available flight data (see reference in paragraph 5.j. of this AC) and represents a 99% ice crystal condition based on the current data.

e. Finally, the icing environments depicted in each of the referenced appendices define single cloud lengths in terms of 17.4 nautical miles, while nature doesn’t provide icing clouds so discretely. Experience has shown that actual icing environment can be a combination of conditions. For example, as depicted in appendix C of parts 25 and 29, a continuous maximum cloud followed by an intermittent maximum cloud, followed by a continuous maximum cloud, and so on, is probably what a natural environment demonstrates. To account for this difference between natural icing environments and the environments depicted in the appendices, this guidance effectively provides an equivalent icing condition that is representative of multiple clouds in sequence.

f. The body of this AC is arranged in three areas corresponding to the applicable parts (that is, §§ 33.68, 33.89(b), 33.77, 23.1093, 25.1093, 27.1093, and 29.1093). The first area addresses part 33 induction system icing compliance guidance (§ 33.68 compliance), in paragraph 9 of this

AC. The second area addresses engine ice slab ingestion compliance guidance (§ 33.77 compliance), in paragraph 10 of this AC. The third area addresses installation icing requirements under parts 23, 25, 27, and 29, in paragraph 11 of this AC.

g. The icing conditions depicted in appendix O of part 25, and appendix D of part 33 are not applicable to turboshaft engines or their installations. Turboshaft engines need only comply with the icing conditions depicted in appendix C of part 29.

h. The icing conditions depicted in appendix O of part 25 are not applicable to turbine engine induction systems on part 25 airplanes with a maximum takeoff weight equal to or greater than 60,000 pounds, or on part 23 airplanes. Turbine engine induction systems on part 25 airplanes with a maximum takeoff weight equal to or greater than 60,000 pounds need only comply with the icing conditions depicted in appendix C of part 25, appendix D of part 33, and in falling and blowing snow within the limitations established for the airplane for such operation.

7. Definitions. The following are defined for the purpose of this AC:

a. <u>Auto-Recovery Systems</u>. Engine systems that ensure that engines operate just before or immediately after an upset (that is, power loss or stall) without operator intervention. Auto-recovery systems include auto-relight systems, stall recovery systems, and other engine system intended to recover the operability of an engine following a flameout, surge, stall, or a combination of these.

b. <u>Freezing Fraction</u>. The ratio or percentage of water that impacts a surface and freezes. The freezing fraction is defined as a number between 0 and 1, and will determine the type of ice formation.

c. <u>Cloud Extent Factor</u>. The distance that a cloud extends vertically (vertical extent) or horizontally (horizontal extent). Vertical extent is normally measured in feet while horizontal extent is measured in nautical miles. The cloud extent factor is a dimensionless number, which uses the length of a cloud to determine an average liquid water content across the cloud.

d. <u>Highlight Area</u>. The area bounded by the leading edge of the nacelle inlet. This may be different for turboshaft installations where complex inlet schemes are utilized.

e. <u>Ice Formations</u>. These result from the impact of supercooled water droplets on propulsion system surfaces; formations are classified as follows:

(1) <u>Glaze Ice</u>. A clear, hard ice, which forms at temperatures close to (but below) freezing, in air with high liquid water content and large droplet sizes. Droplets impacting the surface do not freeze immediately, but run back along the surface until freezing occurs. Glaze ice typically has a non-aerodynamic shape and is more susceptible to aerodynamic forces that result in shedding. Glaze ice typically has both a lower freezing fraction and lower adhesive properties than rime ice. Glaze ice is often a concern for static hardware while rime ice is often a concern for rotating hardware.

(2) Rime Ice. A milky white ice which forms at low temperatures, in air with low liquid water content and small droplet sizes. Rime ice typically forms in an aerodynamic shape, on both rotating and static engine hardware. The freezing fraction is high for rime ice, typically approaching a value of 1.0. Rime ice typically has greater adhesion properties than glaze ice but often a lower density. Adhesion properties increase with lower temperature up to a test point where no additional adhesion is gained with additional lower temperature.

(3) Mixed or Intermediate Ice. A combination of glaze and rime ice which forms with rime patches slightly aft of the glaze ice portions. This ice forms at temperatures, liquid water contents, and droplet sizes between those that produce rime and glaze ice.

f. Ice Shed Cycles. The time period required to build up and then shed ice on a propulsion system surface for a given power and icing condition. A shed cycle can be identified visually (for example, with high-speed cameras, and engine instrumentation such as vibration pickups, temperature probes, pressure probes, speed pickups, etc.). For rotating surfaces, such as fan blades, the ice shed cycle is strongly influenced by rotor speed and the adhesive strength of ice to the surface. In general, ice adhesive strength increases as surface temperature decreases.

g. Icing Conditions. These meteorological conditions are defined by the following parameters:

(1) Liquid Water Content (LWC). The concentration of liquid water in air, typically expressed in grams of water for each cubic meter of air.

(2) Median Volume Diameter (MVD). The drop diameter which divides the total water volume present in a droplet distribution in half (that is, half the water volume is in larger drops and half the volume in smaller drops). Note the MVD used in appendix O of part 25, and appendix D of part 33, is equivalent to the MED in appendix C of parts 25 and 29 for an assumed Langmuir type droplet distribution.

(3) Mean Effective Diameter (MED). Similar to MVD. See definition of MVD.

(4) Median Mass Dimension (MMD). The particle size (sphere of equivalent mass) which divides the total ice mass present in an ice particle distribution in half (that is, half the ice mass is in larger particles and half the ice mass is in smaller particles).

(5) Total Temperature. The ambient temperature plus the ram rise. For icing testing in test cells, the total engine inlet temperature includes static temperature of the cloud as depicted in appendices C and O of part 25, appendix C of part 29, and appendix D of part 33, plus the assumed flight airspeed.

(6) Static Temperature. The ambient temperature calculated from the local measured total temperature on the aircraft, minus the temperature rise from velocity effects. Appendices C and O of part 25, appendix C of part 29, and appendix D of part 33 temperatures are assumed to be static ambient temperatures.

h. Power Loss Instabilities. These are caused by engine operating anomalies. These types of anomalies could include non-recoverable or repeating surge, stall, rollback, or flameout, which can result in engine power or thrust cycling. A rotating compressor stall is one kind of power loss instability that might be acceptable, upon review with the FAA: if it is not noticeable to the flight crew, and if it does not result in unacceptable stresses or operability effects either at steady-state conditions, or during acceleration.

i. Scoop Factor (concentration factor). The ratio of the nacelle inlet highlight area (A_H) to the area of the captured air stream tube (A_C) [scoop factor = A_H/A_C]. Scoop factor compares the liquid water available for ice formation in the engine inlet, to that available in the low-pressure compressor or engine core, as a function of aircraft forward airspeed and engine power condition. The scoop factor effect depends on the droplet diameter, the simulated airspeed, and the engine power level, as well as the geometry and size of the engine. This may be different for turboshaft installations where complex inlet schemes are utilized.

j. Serious Loss of Power or Thrust. A non-recoverable or repeating engine surge, stall, rollback, or flameout occurrence, which can result in noticeable engine power or thrust loss.

k. Stabilized Operation. This is when the engine demonstrates steady, reliable, and smooth operation while operating at the test condition (that is, during multiple ice build or shed cycles, if ice is accreting), and during throttle or power transients. Engine operation is considered stabilized when measured engine parameters are not changing, or when a regular repeatable shed cycle has been demonstrated through the recording of measured engine parameters with stabilized ice accretions.

l. Stabilized Ice Accretion. A condition when ice accretion is not increasing on any engine part, or when the accreting ice has demonstrated a regular shed cycle when viewed by a video camera or instrumentation indication.

m. Sustained Power Loss. A permanent loss in engine power or thrust. Typically, sustained power loss is calculated at rated takeoff power. See definitions below on “Temporary Power Loss” and “Momentary Power Loss” for power or thrust losses that are not sustained.

n. Descent Idle Engine Speed. An altitude-dependent, minimum flight-idle engine speed that is generally in effect from the top of descent (TOD) to where the approach phase of flight begins. This is typically when flaps are deployed and idle speed increases for an approach. Since this is different for turboshaft installations, the applicant can propose appropriate criteria.

o. Momentary Power Loss. A short-duration reduction in engine power or thrust associated with a transient event (for example, ice shedding).

p. Noticeable. A tactile feeling during an event, or the use of typical engine test instrumentation or flight deck instrumentation (such as, N_1, N_2, vibrations, exhaust gas temp) to indicate an event.

q. Temporary Power Loss. A reduction or loss in engine power or thrust occurring during an icing encounter; this may be related to the effects of ingesting supercooled water or ice particles, or possibly the effects of ice accumulation within the flowpath. The amount of temporary power loss should be communicated to the installer from the engine manufacturer.

r. Power rollback. An uncommanded reduction in engine rotor speeds, and subsequent loss of power and power control.

8. Discussion.

a. An icing encounter, including a prolonged encounter, should neither cause a significant increase in workload, nor elicit concern from the flight crew. Additionally, an icing encounter should not result in damage to the engine, its systems or subsystems, loss of performance or an operability deficiency, or any other compromise of compliance with the engine certification basis. Relevant changes in bill of material hardware or software made during the compliance program should be re-evaluated with respect to icing.

(1) The engine should have sufficient durability to operate through prolonged or repeated environmental icing encounters without special operational or maintenance interventions. For example, operational procedures to assist ice shedding, such as throttle manipulation or power change, should not be used to comply with the in-flight icing requirements of parts 23, 25, 27, 29 and 33.

(2) The applicant may provide procedures for engine throttle manipulation or power change (for example, power run-ups) to shed ice accumulated during ground operations. These procedures will be used as in-service ground operation recommendations, although they would be mandatory if used during the compliance demonstration of §§ 33.68, 23.1093, 25.1093, 27.1093, and 29.1093.

(3) Applicants should ensure they collect sufficient data to demonstrate regulatory compliance. Video or photographic coverage may be useful for supplementing test results. In addition, applicants should determine the most critical measured parameters which indicate ice accretion and shedding within the engine. These parameters provide critical data for showing regulatory compliance during the compliance plan. In addition they help validate the critical point analysis (CPA) assumptions and demonstration intent. The parameters may include both visual and instrumented indications that need to be monitored during the icing test to show acceptable operation in icing conditions.

(a) This demonstration should include stabilized ice accretion (that is, stabilized operation) with either no ice buildup or no additional ice buildup on the engine or nacelle inlet. Normal engine control system responses during the ice accumulation process (for example, isochronous control responses to accreting ice) are acceptable if no sustained power losses are encountered. Any significant temporary power loss during operation in icing conditions should be reported to the installer by the engine manufacturer.

b. Mixed Phase or Glaciated Atmospheric Conditions. The FAA and the aviation community have recently become aware of the potential effects of mixed phase icing conditions. They occur when mixtures of supercooled liquid water droplets and ice particles (mixed phase) or ice crystals alone (glaciated) exist in a cloud, often around the outskirts of a deep convective cloud formation. Ice crystal icing conditions exist when all the liquid water particles in the cloud have frozen into ice particles. Mixed phase and ice crystal icing has caused more than 100 turbine engine power losses. Compliance methodologies for these conditions are being introduced in this AC for the first time for turbojet and turbofan engines. These conditions do not apply to turboshaft engines.

(1) Traditionally, industry has considered the susceptibility of turbine engines to mixed phase or ice crystal conditions as minimally consequential, with two exceptions: (1) pronounced inlet bends (such as particle-separator inlets) or inlet flow reversals, and (2) high solidity, high turning front stage compressor stators. Industry has recognized the inlet bends are a concern since that is where inlet flow can stagnate and accumulate ice. Similarly, industry has recognized that high solidity, high turning front stage compressor stators are a concern because stator airfoils are susceptible to non-aerodynamic ice buildup. These flowpath blockages and significant turns can result in accretion zones and core airflow blockage from ice accretion.

(2) Recently, operators have reported service experience on fixed wing applications with icing within the engine core stream due to mixed phase and glaciated atmospheric conditions. These reported service events included ice crystal accretion within the engine’s flowpath and within engine inlet probes, including temperature and pressure probes. This ice accretion has produced significant adverse impacts, including uncommanded engine power rollback or flameout, with occasional core hardware damage.

(3) Operators have also reported total air temperature (TAT) probe malfunctions during many of these engine icing events. A heated TAT probe malfunction is a known indicator of ice crystals. Ice accumulation within the TAT probe produces a false TAT of air temperature near 32^0 Fahrenheit (0^0 degrees Celsius). Ice detection systems should be evaluated for these conditions.

(4) Events attributed to icing within the engine core stream due to mixed phase or ice crystal conditions, and TAT probe malfunctions, suggests that ice crystal icing is of greater concern than originally thought. The root cause of these events can be traced to ice buildup within the core flowpath of the affected engine. In general, these events occur near convective clouds at ambient temperatures warmer than the international standard atmosphere, and outside the icing envelopes depicted in appendices C and O of part 25, and appendix C of part 29.

(5) We have established appendix D of part 33 to define the mixed phase or glaciated atmospheric envelope.

c. Auto-Recovery Systems. Compliance with §§ 33.68 and 33.77 is intended to demonstrate no flameout, sustained power loss, surge or stall, or rundown will occur when operating in icing conditions. The auto-recovery provides protection in-service against multiple forms of power loss. However, auto-recovery protections should not be relied on during the compliance demonstration because auto-recovery systems are back-up devices. For additional information about the use of auto-recovery systems when demonstrating compliance to §§ 33.68 and 33.77, see paragraphs 9.p., and 10.f.(5) of this AC. For additional information on auto-recovery systems when demonstrating compliance to §§ 23.1093, 25.1093, 27.1093, and 29.1093, see paragraph 11.p.(3)(a) of this AC.

d. Application of Cloud Extent Factors for § 33.68 Compliance Tests. Cloud extent factors are depicted in appendices C and O of part 25, appendix C of part 29, and appendix D of part 33. The horizontal cloud extent factor is a dimensionless number, which relates the length of a cloud to an average LWC across the cloud. It is used in the CPA to assess the probable icing content during various aircraft mission and performance analyses.

(1) Typically, the average LWC of a cloud is less for longer clouds. The horizontal cloud extent factor is not intended to be used to limit the severity of exposure to icing conditions, assuming the aircraft will be required to operate in that condition. For example, when in a holding pattern which may require repeated passes through a severe icing environment, or continuously remain in that severe environment, the horizontal cloud extent factor should not be applied.

(a) Engines and their inlet systems should demonstrate continuous operation in icing conditions without regard to time. Typically, an applicant assumes multiple clouds in their CPA, with a cloud extent factor equal to 1.0. This is because actual cloud extent factors are not a consideration for most engine operations, particularly in an aircraft hold pattern. This approach assures proper engine and induction system operation within the atmospheric conditions depicted in appendices C and O of part 25, appendix C of part 29, appendix D of part 33, and as experience indicates, in actual icing environments. The following are some additional factors to consider:

1. These cloud extent factors are also applicable to airframe flight profiles. Airplane applicants use the cloud extent factors depicted in the appendices during their evaluation of the straight-line flight portion of their compliance demonstration. However, engines and induction systems have historically not been limited to or evaluated against a specific aircraft flight profile when considering icing environments. Instead, they are evaluated for unlimited operation in icing.

2. While appendix C of parts 25 and 29 define supercooled clouds, appendix O of part 25 includes freezing precipitation (that is, rain and drizzle).

3. Appendix D of part 33 depicts ice crystals and mixed conditions (meaning, a mixture of supercooled water droplets and ice crystals). The cloud extent factor depicted in appendix D of part 33 relies primarily on limited data derived from the reference in paragraph 5.k. of this AC. The data covers several geographical regions including eastern Asia where ice crystal-related service events are prevalent.

9. Induction System Icing and Operation Test (§§ 33.68 and 33.89(b)).

a. Critical Point Analysis (CPA). A CPA is an analytical method utilizing engine test data to show an engine meets the certification requirements of part 33. This method derives critical test points from the collection and analysis of data on icing effects on engine performance.

Compliance with § 33.68 includes identifying, through analysis, the critical operating test points for icing within the declared operating envelope of the engine. A CPA should include consideration of the icing conditions depicted in appendix C of parts 25 and 29, and as we gain experience, in appendix D of part 33. A CPA should relate these appendices with the aircraft speed range and engine powers defined by the engine manufacturer. It should also include a prolonged flight operation in icing (for example, in-flight hold pattern), or repeat icing encounters. These combined elements within the CPA should identify the most critical operational icing conditions.

(1) The applicant (you) should ensure that analysis is supported by test data. Your CPA should also include environmental and engine operational effects on accumulation, accretion locations, and the most critical engine operating conditions for ice shed and ingestion. You may propose conditions outside the requirements of the appendices (for example, recommending conditions that are more severe based on actual service experience). You may also supplement a CPA with development test data (for example, wet and dry testing with thermocouple components).

(2) Your CPA should include ice accretion calculations that account for freezing fraction and aerodynamic effects of the ice as it moves into the air inlet. For example, water ingestion into the fan module and core inlets, water impingement rates for critical surfaces, forward aircraft airspeed effects, engine configuration effects such as inter-compressor bleed, and altitude effects (such as bypass ratio effects). The CPA should also include an energy balance of critical engine surfaces (for example, latent heat and heat of fusion effects, metal-to-ice heat transfer effects, and ice insulating effects).

(3) For anti-iced parts, the CPA should identify a critical test point determined from energy balance calculations of required heat loads, and encompassing the range of possible combinations of icing condition and engine power. In glaze ice conditions, assessing the effects of non-aerodynamic ice formations and their shedding is more complex. FAA Report number FAA-RD-77-78, titled "Engineering Summary of Powerplant Icing Technical Data", provides additional guidance on performing a critical test point icing analysis.

b. Test Versus Analysis. The CPA is not meant to replace testing. Rather, it provides a means to predict critical test points. The CPA test points can replace the standard table points defined in Tables 1 and 2 of § 33.68, when applicants can show they are equivalent. Otherwise they supplement the standard certification test points. Today's analysis tools are greatly improved over their predecessors; however, experience has shown the CPA is best used to predict the critical icing conditions for a given design, then use them in conjunction with the standard certification test points for certification compliance test purposes. Please note, even if the FAA concurs with a type certificate holder's generic CPA method, this does not constitute our acceptance of the resulting critical icing test points for future certification projects. The content of an icing certification program for any given certification project will be evaluated on a case-by-case basis.

c. Test Facilities. Facility limitations or weather can delay § 33.68 compliance demonstrations. These delays may often be avoided by using national and international icing test facilities. National and international icing test facilities for accomplishing engine icing compliance testing include the United States Air Force (USAF) McKinley Climatic Lab in Florida, the Arnold Engineering Development Center (AEDC) in Tennessee, and the Canada's National Research Council in Ottawa, the Global Aerospace Center for Icing and Environment (GLACIER), and GE Aviation Engine Testing, Research and Development Centre (TRDC) in Winnipeg. In Europe, there is the Delegation Generale Pour L'Armement (DGA) Aero Engine test facility in France. Other test facilities are likely to become available in the future as test capabilities improve.

(1) When considering any icing facility, the capability to provide simulated cloud conditions that meet the requirements of § 33.68 should be thoroughly considered. Critical items that that you should also consider are:

(a) A description of the icing facility, including the spray system arrangement, spray nozzle(s), water flow system, airflow system, and test facility operation.

(b) Instrumentation should include facility operation monitoring, cloud simulation, and cloud property determination.

(c) Air/water flow operating map.

(d) Psychrometrics.

(e) Pre-test icing rig functional checks.

(f) Facility test procedures.

(g) Test data measurement accuracy and capability description.

d. Elements of CPA. Your CPA should address, at minimum, the following icing issues:

(1) Ice Shed Damage. Shed ice can cause engine damage if it impacts an engine surface with sufficient mass and velocity. The following types of damage are common, and you should include them in your CPA with an assessment of each:

(a) First Stage of Compressor (example, fan). Various rotating and non-rotating parts of the fan module, or first stage compressor section for non-fan engines, are susceptible to ice shed damage. For example, acoustic panels, fan rub strips, and fan blade tips are susceptible to ice shed from the inlet sensor(s), spinner, and the fan blade root.

(b) Since engine icing compliance testing is performed in test cells and not actual flight conditions, the effects of ice density, hardness, and adhesion strength as it sheds should be assessed to realistic flight conditions. For example, in realistic flight conditions the ice shed cycle for rotating surfaces such as fan blades, or first stage compressor blades for non-fan engines, is strongly influenced by the rotor speed and the adhesive strength of the ice to the surface. The adhesive strength of ice generally increases with decreasing surface temperature.

The ice thickness and the rotor speed at the time of the shed, defines the impact threat. Available data typically shows that shedding from unheated rotating and static parts can be quite variable and difficult to predict. This is due to uncertain factors such as adhesion strength properties, local thermodynamic properties, and ice structure (such as ice bridging). In some cases, applicants have utilized consistently demonstrated shedding trends in their CPA, as opposed to absolute values, since there is often uncertainty in precise shed predictions.

(c) When determining the critical conditions for fan module damage, the surface temperature, exposure time, and rotor speed are important considerations, as well as atmospheric icing conditions and scoop factor. In particular, extended operation in a holding condition power level during very cold and continuous maximum icing conditions will maximize the adhesion of ice on rotating first stage compressor or fan components. This can result in large ice accretions and resulting sheds which can damage the engine or cause power loss.

(2) Compressor Damage. When ice formations on static components shed, they often result in damage. This type of damage generally occurs on the first blade set in the high-pressure compressor (that is, intermediate pressure compressor for three spool engines, or first stage of compression for conventional turboshaft engines). Establishing the critical conditions for these glaze ice accretions requires careful consideration, since they occur at specific limited conditions of low freezing fractions, over a range of local mach numbers and air densities. The critical conditions may not occur during any of the power settings discussed in this AC (for example, flight-idle, 50% and 75% of maximum continuous or 100% maximum continuous); consequently, you should evaluate the power setting at the critical condition. Finally, since icing is a common environmental condition, you should evaluate any engine compressor damage that results from ice testing against the possibility of multiple occurrences.

(3) Engine Operability and Compressor Rematch. Ice shed from upstream components may enter the core compressor. The presence of ice, or water from melted ice, in the gas path may cause engine component cycle changes. The engine should be capable of accelerating from minimum flight-idle to takeoff power, and should demonstrate takeoff power set procedures on the ground at any icing condition, without unacceptable power loss or power loss instabilities. Ice sheds should not result in flameout, rollback, or surge. Any anomalous engine behavior should be raised to the FAA Engine or Aircraft Certification Office (ECO or ACO) for evaluation, and if found acceptable, it should be documented in the engine's installation manual. You should consider as part of the CPA, the engine accelerations and decelerations relative to operability challenges (for example, surge and stall). Assume that the minimum engine bleed schedule allowed for the condition being tested minimizes the operability margin. CPA testing should demonstrate those conditions where the minimum operability margin is expected.

(4) Core and Booster Ice Blockage. Ice accretion on internal engine vanes from glaze ice accretions may affect airflow capacity and rematch of the engine cycle. This should be considered in your CPA. For engine powers that can sustain flight, you should reconcile ice accretion through a demonstration of several ice build shed cycles. Show that there are no adverse operating effects from ice builds or sheds.

(5) Sensor Fouling. Ice accretion and blockage of control sensors can result in erroneous engine pressure and temperature measurements. Critical sensors include inlet total pressure and temperature probes, and inter-compressor temperature probes. A power loss or power loss instability could result if erroneous measurements are used by the engine control system's control law to establish power or thrust ratings, or if used to schedule other systems required to operate the engine (for example, variable stator vanes). Critical sensors should be designed to operate when exposed to the conditions defined in 33.68 and the associated appendices, with minimal ice accretion and no erroneous measurements that would result in an unacceptable operating characteristic, such as a power loss. In accordance with 33.68 icing requirements, turboshaft engines need only be evaluated against the environmental icing conditions depicted in appendix C of part 29. The effects of installation on the local icing conditions at the probe should be accounted for in all types of applicable installations. Additionally, ice accretion on upstream sensors can shed and cause engine damage to downstream rotating hardware. You should evaluate engine inlet probes for supercooled droplet icing susceptibility, as well as ice crystal icing susceptibility.

e. Test Point(s) Selection. Test points selected for a supercooled droplet environment should address the applicable icing envelopes depicted in appendices C and O of part 25, and appendix C of part 29. Test points for an ice crystal icing environment should be representative of the meteorological conditions depicted in appendix D of part 33. Typically, the supercooled droplet test points include those defined in the regulation (either § 33.68 or § 25.1093) and any additional test points identified as part of your CPA. You should consider pertinent service experience as well as the anticipated use of the aircraft when selecting critical icing test points. Do consider the following when constructing an icing test matrix:

(1) Section 33.68, Acceptable Means of Compliance. The engine should be capable of operating acceptably under the meteorological conditions depicted in appendices C and O of part 25, and appendix C of part 29, covering the engine operating envelope defined in § 33.68(b)(2)(ii)(B), and under the conditions of ground icing defined in § 33.68(d). Section 33.68(c) permits eliminating specific standard certification test points so long as you choose to run a similar CPA test condition that is more severe in terms of ice accretion mass at critical engine locations or to produce an equivalent level of safety to the standard test points.

(2) Rotorcraft Turboshaft Engines. Engines installed on rotorcraft present their own unique conditions. Holding phase test conditions are not applicable to turboshaft applications. Therefore, turboshaft engine testing should include test conditions that address prolonged hover or continued operation in a relatively small area of operation. For example, prolonged operations in the local vicinity of the airport or possibly local operations around oil rigs at sea. This may require additional test, analysis, or both, to show installation configuration dilution benefits in prolonged operations, based on the aircraft induction system design.

f. Table 1 of § 33.68 Icing Conditions.

(1) The supercooled LWC shown in Table 1 of § 33.68 represents ambient icing conditions for an open inlet ground test facility or equivalent, within the inlet duct of a direct connect test

facility. An analysis of local enrichment for flight effects, as would normally be done for a CPA LWC, is not necessary for the table points.

(2) For Table 1 test conditions 1 and 2, applicants should run the engine under both rime and glaze icing conditions. You should test under both conditions for at least 10 minutes each at 100%, 75%, and 50% maximum continuous power, and for 10 minutes at a flight-idle. Follow each power setting with a snap acceleration to takeoff power. If ice is building at the end of 10 minutes at the three higher power settings, continue running the test point until the engine demonstrates stabilized building and shedding, or until the engine no longer operates satisfactorily.

(3) Table 1, conditions 1 and 2 are intended to partially represent a broad test matrix of environmental and engine operating conditions to be used when showing compliance with § 33.68. This test matrix includes power settings from idle to 100% maximum continuous. They are representative of exposure to conditions typical of both high altitude where rime ice formations occur, as well as conditions typical of low altitude where glaze ice formations often occur.

(a) Icing conditions are normally run for a minimum of 10 minutes for all engine powers that can sustain level flight, or longer if the natural engine ice shed cycle is not established. Special consideration and tests should be conducted to adequately demonstrate engine inlet screens and inlet air passages that might accumulate snow or ice due to restrictions or contours. At low power, such as idle descent power, the required time period is limited to 10 minutes. The rime icing condition should be run at an engine speed associated with top of descent operation for fixed wing aircraft, as depicted in appendix C of part 25. The glaze icing condition should be run at the minimum engine speed associated with lower altitudes at the end of the descent phase of flight for fixed wing applications. Applicants for rotorcraft applications should propose an appropriate flight profile to address this low power test period duration.

(4) Conditions 3 and 4 (holding phase). The engine should continue to meet part 33 requirements while demonstrating it can operate indefinitely in a flight hold pattern under icing conditions. Guidance on test durations and procedures to achieve this are outlined throughout this AC. The test program for turbofan and turboprop applications should include test point conditions (for example, icing conditions and power settings) to address the effects of prolonged exposure in icing conditions that are typical of in-flight holding patterns.

(a) Condition 4 in Table 1 represents a rime icing condition that is typically encountered on transport category airplanes. Condition 3 in Table 1 represents a mixed rime and glaze icing condition that was originally derived from the European Union’s JAR-E ice requirements of LWC, temperature, and droplet size. The engine and inlet should be capable of prolonged exposure to the conditions specified in Table 1. For fixed wing aircraft, a 45-minute test exposure will typically demonstrate several ice shed cycles. You should follow each accretion point for condition 3 and 4 with a snap acceleration to takeoff power. To demonstrate unlimited icing operation, the engine should exhibit stabilized operation at the conclusion of the 45-minutes test condition, prior to the snap acceleration.

(5) For All Conditions. Engine operation in all icing conditions should be uneventful, uninterrupted, and without any significant adverse effects. It should also include the ability to continue in operation and accelerate and decelerate normally without adverse operational effects. Some power reduction is acceptable at idle power settings in icing conditions, due to the cycle effects of pumping ice and water; however, all other operation should be unaffected.

(a) You should determine what parameters need to be monitored to determine the stabilized operation of the engine during the icing test. Engine operation is considered stabilized either when measured engine parameters are not changing, or when a regular, repeatable shed cycle has been demonstrated through the recording of measured engine parameters. Variations in measured parameters are acceptable during the performance of the ice test, as long as the long-term trend (typically the duration of several shed cycles) is stable and not trending upwards or downwards.

(b) Engines with manually activated icing protection systems (including systems for probes), should be tested. You may test these systems by stabilizing the engine for at least 2 minutes in the icing atmosphere (1-minute for turbo shaft engines) with the protection systems off (that is, prior to turning the icing protection system on). Conduct this test at flight-idle and above. Doing so simulates the delay expected for the pilot to recognize the icing condition.

(c) Fully automatic systems may use an appropriate delay. Systems that are automatic and controlled by the full authority digital electronic engine control (FADEC) do not require the 2-minute delay in the ice protection system demonstration. Where the engine’s anti-icing system relies on an ice detector to indicate the presence of icing conditions, a delay in the anti-ice selection is likely. Therefore, delayed selection testing should still be demonstrated.

(d) Stable engine operation should occur under the tested icing conditions. A stable engine operation is intended to address both stabilized ice accretion and shed cycles during steady-state engine operation. Ice accretions are considered stabilized when either ice is not forming on any engine part or the accreting ice has demonstrated a regular shed cycle when viewed by a video camera, or as indicated by instrumentation. Engine operation is considered stabilized when the measured engine parameters are not changing, or a regular and repeatable shed cycle has been demonstrated through the recording of measured engine parameters. You may provide a justification to the FAA for a performance change while operating a steady-state test point. Momentary performance changes such as a thermodynamic engine response to shed ice ingestion may be acceptable. These momentary performance changes are due to an ice shed which can momentarily affect the thermodynamic cycle.

(6) Turboprop and Turboshaft Engines Equipped with an Inlet Screen. You may perform engine icing tests utilizing the aircraft inlet system or alternately with a bellmouth. Some airframe installations utilize an inlet screen, which in some cases is included as part of the testing for the part 33 compliance demonstration. The inlet screen compliance demonstration for icing may be addressed separately from the § 33.68 engine ice compliance testing. If addressed separately, then you should note the requirement for an engine inlet screen in the engine installation manual.

(a) If the inlet screen is not addressed under § 33.68, then compliance could be demonstrated under the installation requirements of §§ 23.1093, 25.1093, for turboprop, and §§ 27.1093, or 29.1093, for turboshaft installations. Icing testing that utilizes inlet screens should demonstrate acceptable operation, including multiple shed cycles representative of long-term or unlimited operation in icing conditions. Protruding or unusual inlet features may require specialized tests or analysis to assure they don't adversely affect operations in icing conditions.

(b) At the conclusion of each steady-state icing test point, the engine should be accelerated to takeoff power (throttle or power lever movement of one second or less) or shedding should be induced by other methods, depending on the critical shed methodology. The throttle or power lever motion should be the most critical when considering the ice shed effects on engine operability. In some cases, a quick deceleration before accelerating to takeoff power may be more critical to the ice shed effects on engine operation. Assess this effect and account for your assessment in your test proposal.

g. Section 33.68(d) – Ground Operation. Section 33.68(d) provides two icing test points that represent freezing fog conditions; a falling or blowing snow icing encounter during ground operation; and a supercooled large droplet (SLD) test point that represents freezing rain or drizzle. The SLD condition is similar to freezing fog in terms of ambient temperature range and the LWC levels. However, the larger droplets can penetrate farther back on the surface of the engine spinner with the potential for ice shedding into the fan blades.

(1) The ground-fog icing, SLD, and falling or blowing snow demonstrations of § 33.68(d) should continue for at least 30 minutes, or until acceptable operation is demonstrated. If you cannot achieve acceptable operation then you should demonstrate the periodic engine speed run-ups. These run-ups will become mandatory in the engine operating manual and aircraft flight manual for operating in these icing conditions, since they were required to comply with the icing testing requirements. Turboshaft engines do not need to address SLD conditions.

(2) Falling and Blowing Snow. Service experience has shown that compressor damage occurs as a result of exposure to prolonged periods of falling snow ingestion during ground operation. Based on our review of service events we have found that airports have continued to operate with falling snow concentrations that result in 0.25 mile or less visibility (about 0.9 gm/$m^3$of snow). While visibility in snow can be a poor indicator of precipitation rates (see reference in paragraph 5.o. of this AC), the following calculation is based on equivalent rainfall rate and gives a similar result as the 0.25 mile visibility criteria:

(a) Visibility and Snow Fall Rates. The maximum precipitation rate for moderate snow is equivalent to 2.5 millimeters per hour (mm/hr) of rainfall over approximately 30 minutes. Using a typical fall speed for snow of 0.8 meters per second (m/s), this translates into a snow/ice concentration of 0.9 gm/m^3. From a Transport Canada data set of 338,000 minutes of snowfall data, the 95% and 99% values were 2 and 4 mm/hr respectively, showing that a 2.5 mm/hr threshold provides an extreme value of snowfall rates. Holdover time tables for de-icing fluids are only good for the extreme values of moderate snow, defined as 2.5 mm/hr (or a visibility of ¼ of a statute mile). This is equivalent to the engine certification levels described here.

(b) Engine core icing service events in snow conditions confirm the critical snow accretion temperature range is 25^0 to 32^0 Fahrenheit (-4^0 to 0^0 Celsius). The engine service events have demonstrated that a snow environment is conducive to ice accretion behind the fan in front compressor stages of the engine, at low engine power. The engine test for snow conditions was developed to represent the engine conditions where snow can form accretions aft of the fan on the core inlet and first stages. You should choose a temperature within the range provided above to achieve icing behind the fan.

h. Ground Idle Demonstrations. Section 33.68 requires operation at ground idle setting for at least 30-minutes under the icing conditions defined in § 33.68(d), followed by acceleration to takeoff power or thrust. Since a broad temperature range is provided within the regulation, you should identify the most critical temperature, as determined by the CPA, and target that range. The CPA analysis can be used to demonstrate that colder conditions are less critical to the engine's operation than the CPA condition that is demonstrated during ground icing tests. Turboprop and turboshaft engine inlet screen icing compliance demonstrations may be addressed separately from the § 33.68 engine ice compliance testing. If so, you should note the requirement for an engine inlet screen in the engine installation manual. We recommend you give special attention to these inlet features:

(1) Unless data is provided indicating otherwise, the minimum ground idle engine speed will be considered the most critical engine operating condition. Unless a more critical ground operating speed is identified, you should show that the engine continues to perform acceptably at its minimum ground idle speed attainable within all icing conditions. This test demonstration generally establishes the maximum allowable ground icing operation time for the engine. In addition, this test usually establishes the maximum allowable time in the engine operation instructions between engine run-ups to shed ice. This time may be prescribed as a single duration or, if supported by test conduct and results, the maximum time interval allowed between performing a repetitive, intentional, ice shedding engine run-up procedure. You should demonstrate stabilized ice accretion, either naturally or with run-ups, to achieve a ground icing taxi time which is appropriate for long taxi times in icing conditions.

(2) Engine ice shed characteristics (for example, period, extent, location(s)) during the duration of the § 33.68(d) test demonstration, should be examined (that is, by means of visual and/or suitable engine flowpath instrumentation) to determine the engine's natural (unassisted by operator input) tendency to shed compressor system rotating and static surface ice accumulations as well as the effectiveness of any intentional (that is, prescribed, operator initiated) ice shedding engine run-up procedure(s). Understanding these natural and, if applicable, assisted ice shedding characteristics will aid in determining the necessary ground operational limitations in icing requirements (for example, total and periodic exposure durations, prescribed procedures) for the engine.

(3) The resulting substantiated ground operating procedure in icing must be included in the engine's operating instructions. If required, the applicable aircraft flight manual should specify the maximum total time allowed for ground icing operation and, if appropriate, the maximum time period between run-ups consistent with the compliance test demonstration.

Alternate run-up procedures are also acceptable if you can show these will result in acceptable engine acceleration to takeoff power.

i. Ice Crystal Icing (part 33 turbofan and turboprop, only).

(1) Ice crystal icing conditions that are hazardous to turbine engines are found in and around cloud formations containing deep convection, in scales ranging from isolated and organized convective cells and complexes, to tropical storms (for example, monsoons, hurricanes, typhoons). Information on the mixed phase icing condition is located in the reference shown in paragraph 5.i. of this AC. Total water content (TWC) up to 5 gm/m^3 can exist at these high altitudes, composed mostly of ice crystals. The maximum size of ice particles within convective weather clouds can be up to 10 mm or larger, but mass is typically concentrated at a much smaller median mass diameter of approximately 200 microns.

(2) Appendix D of part 33 defines compliance requirements in terms of ice crystal and mixed phase icing environments. This mixed phase environment extends beyond the icing envelopes depicted in appendices C and O of part 25 or appendix C of part 29. TWC concentration levels in appendix D of part 33 are based on predicted “adiabatic” condensation rates in convective storm updrafts. This has been shown to be a reasonable upper estimate based on available flight test data, mostly from the 1950s. However, the accuracy of these flight test data is no longer adequately traceable, and the flight patterns adopted were not optimum for deriving TWC extent (cloud length) statistics. Therefore, the TWC extent probability of 99% put forth by appendix D is likely increasingly conservative with increasing cloud length. Until a more comprehensive mixed phase and glaciated atmospheric envelope is defined from flight test data using modern cloud instrumentation to determine TWC and ice crystal size measurement, appendix D of part 33 should be treated as the critical ice crystal icing condition when demonstrating compliance for § 33.68. Likewise, applicants should evaluate engine inlet probes for the conditions depicted in appendix D of part 33.

j. Test Setup Considerations. The LWC levels depicted in appendices C and O of part 25 and appendix C of part 29 are intended as supercooled droplet ambient icing conditions. Tests may be conducted with a simulated cloud which is produced outside of the inlet and ingested into the engine. Under such a test environment, the LWC within the inlet ducting should replicate the engine operating conditions of an airplane in icing conditions at actual airspeeds. The inlet icing concentration or dilution effect is dependent on droplet size, engine fan speed (for turbofan engines), and simulated forward airspeed. For example, engine operation at idle descent power with simulated forward airspeed that is less than flight speed, due to facility limitations, might require a compensating increase in the test level of LWC concentration above what is depicted in appendices C and O of part 25. This increase would be greater for larger supercooled droplet diameters. The engine size is also a variable that affects the difference in the LWC inlet concentration between flight conditions and the engine test environment, with small engines potentially needing the greatest compensation. Rotorcraft engine applications may have different criteria and applicants should propose a test that addresses those specific turboshaft installation issues.

k. Direct Connect Inlet Engine Test Facilities. Icing tests that provide a simulated icing cloud by direct connection of facility piping to the front flange of the engine, where no inlet air spillage is allowed, may cause test facility effects to alter the test parameters (for example, LWC and MVD). You must provide the FAA with data that demonstrates the simulated test conditions are representative of an installed engine operating in the icing environments as depicted in appendices C and O of part 25 and appendix C of part 29, as applicable. Suitable data may be direct measurement data concerning LWC within the inlet, or an acceptable validated analysis of water droplet trajectories for the test setup. In some cases, you may need to adjust the LWC to address any effects of the test setup (for example, non-uniformity across the engine face).

l. Testing in Mixed Phase or Glaciated Atmospheric Conditions (part 33 turboprop and turbofan engines only).

(1) Flight testing is a method of demonstrating engine operation in icing conditions, particularly mixed phase or glaciated atmospheric conditions. Under these conditions, two important flight test considerations are: the measurement of ambient meteorological data, and the ability to correlate the measured engine performance to a more severe icing point. To address the correlation, it is necessary that you have a fully instrumented engine with temperature sensors strategically located in the core flow passage. This instrumentation will collect data during the icing environment encounter. Since the environment encountered may not be as severe as the levels needed, scaling of the measured data to show satisfactory engine operation at the more severe point should be attempted to the extent possible. Any proposals for scaling should be supported by data from experiments, and the scaling approach should be conservative.

(a) An accurate measurement of the ambient meteorological condition is essential. Past engine flight tests in this environment demonstrated that a combination of LWC probe, TWC probe, particle sizing and imaging probe, ice accretion detector, and TAT probe are necessary to fully characterize the ambient environment.

(b) An onboard real-time meteorological data display with GPS positioning capability is also helpful to find high ice crystal concentration areas. This allows the pilot to position the aircraft for the test. Since testing around a thunderstorm elevates the risk level of a flight test, an on-site rapid data reduction capability would give a timely indication if the test objective is met, and minimizes the number of flights into this hazardous environment.

(2) Simulation of the Critical Mixed Phase and Glaciated Atmospheric Condition in a Ground Icing Facility. As indicated in the reference shown in paragraph 5.i. of this AC, facility simulation of ice crystal icing conditions is difficult and not currently done routinely. It is not known how well any facility simulation method actually replicates the natural environment. Consequently, no testing standard for this icing condition currently exists. Therefore, ground simulation to demonstrate compliance to the ice crystal icing certification requirements will be evaluated on a case-by-case basis until uniform industry standards are developed.

m. Test Results and Compliance Issues. During all icing tests (that is, supercooled droplet, or ice crystal icing), the engine should operate without accumulating ice that would adversely affect engine operation. Accumulating ice can adversely affect engine operation (for example, flameout, surge, stall, run-down, high vibrations, slow acceleration, or lack of throttle or power lever response), or can cause a sustained loss of power or thrust. Additionally, the applicant should accurately monitor icing test point conditions. Video surveillance or other instrumentation may provide the means to identify any source of ice damage, especially in those instances where test apparatus may also shed ice (for example, icing nozzles, special test instrumentation, or icing tunnel walls).

(1) Sustained Loss of Power or Thrust and Power Loss Instabilities. The engine should not experience a sustained power loss while operating at approved ratings in icing conditions.

(2) Temporary Power Loss. Temporary power losses below engine power and thrust ratings selected under § 33.8 are acceptable if you show that the engine has a sufficient margin to avert any power loss instability, such as rollback, surge, stall, high vibrations or flameout.

(3) Momentary Power Loss. Momentary power loss caused by pumping or processing of ice debris through the fan module and compressor during the ice shed ingestion process is usually acceptable. Any accepted temporary or momentary power loss or temporary high vibrations must be documented in the engine installation manual.

n. Mechanical Damage. The engine should not exhibit more than limited engine damage from any cause because of § 33.68 icing testing. Some limited damage can be acceptable if the resultant power loss is minor. Additionally you must fully account for cumulative damage from repeat encounters. Limited engine damage will be considered acceptable provided you satisfy the following criteria:

(1) Continued In-Service Use. You should evaluate any resultant damage and demonstrate that it does not affect the engine performance for continued in-service use. This includes both continued safe operation, with no imminent failures expected, and no significant power loss.

(2) Sustained Power Losses. The engine should not experience any sustained power loss beyond 1.5% (that is, the nominal accepted level considered to be within measurement capability).

(3) Temporary or Momentary Power Loss. Temporary or momentary power loss should be reviewed by both the airframe and engine manufacturer to assess installed operational impact. Any resultant temporary or momentary power loss, or high vibrations found acceptable by the FAA during the compliance demonstration, should be recorded in the installation manual by the engine manufacturer.

(4) Validation Basis. Analytical tools used to substantiate the criteria for determining acceptable damage should demonstrate an acceptable validation basis. For example, validation could utilize engine tests or rig tests to substantiate the accuracy of results. An acceptable analytical tool validation basis includes test data which yield conservative results.

(5) Engine Damage. Damage to the engine or engine components as a result of icing compliance testing should not exceed the maintenance manual limits. Cumulative damage for

repeated encounters should be considered part of this assessment. Any damage findings should be brought to the attention of the FAA for approval.

(6) High Vibrations. You must ensure that high vibrations are assessed for the specific aircraft installation. The acceptability of high vibrations is evaluated by the airframer. Bring high vibrations to the attention of the ACO or ECO approving the engine; it will contact the ACO approving the engine installation before the final approval, and inform them of this condition. Any high vibrations should be included in the installation manual by the engine manufacturer.

(7) Communication of Results. The installation and operating manuals required by § 33.5 should provide information describing all engine conditions observed during engine certification icing tests. Prior to these tests, the engine manufacturer should provide the FAA with a process to evaluate the acceptability of any potential damage that could occur during icing tests.

(a) Natural icing flight tests are conducted to demonstrate compliance with §§ 23.1093, 25.1093, 27.1093, or 29.1093; they require an FAA preapproved process for evaluating damage resulting from icing tests. Also, if periodic engine power run-ups are used to minimize icing damage during the ground icing operation demonstration defined in § 33.68(d), then the applicant must document the run-up procedure. Complete documentation must contain a description of the run-up requirements and the required run-up intervals, and it must be contained in the operation manual as mandatory within icing conditions. Prior to demonstration, the engine manufacturer should coordinate the proposed run-up shedding procedures with the airplane manufacturer, so as to assure that procedures are practical and appropriate for the intended operations.

(b) Any acceptable power loss anomalies from for example, ice accretion, ice shed, water runback and refreeze and shed, and the effects on performance and operation, should be documented in the installation manual. Both the engine certifying ACO and the installing ACO should carefully evaluate any high vibrations induced from ice accretions during ice testing. These vibrations should be documented by the engine manufacturer in the engine's installation manual.

o. Engine Systems. Applicants may use an automatic engine control system to initiate an ice protection system to meet the requirements defined in § 33.68, provided that system operation does not result in potential crew action. Examples of engine characteristics that may be noticeable to the flight crew are exhaust gas temp fluctuations, large speed fluctuations, or audible surging. Further, any engine control system required for engine ice protection certification under part 33 should not react adversely with other aircraft systems, aircraft handling qualities and performance, or human factor considerations.

(1) Any unacceptable adverse interactions may result in the engine being deemed un-installable under parts 23 or 25 airplanes or parts 27 or 29 rotorcraft. Critical issues which you must address include: crew interface, uncommanded thrust or power changes, thrust or power setting, asymmetric engine behavior, pilot workload and appropriate flight deck indication and procedures, the effect on aircraft handling, pilot ability, and human factors. Additionally, any

engine system required to show compliance under § 33.68 should meet the following requirements:

(a) System Reliability. Demonstrate the capability of the system for reliably sensing the conditions, which enables the engine system function, throughout the approved operating envelope.

(b) Dispatch. The engine system function should be available for all dispatch configurations. The system should be configured in its most critical dispatch state for certification icing tests.

(c) Electronic Faults. Applicants should demonstrate that engine system functions will not be lost due to any probable electronic fault(s).

(d) Other Environmental Testing. Engine system functions should not be affected when the system and any associated electronic systems are exposed to the required operating environments, including high intensity radiated fields (HIRF) and lightning.

(e) Power Requirements. For those systems powered solely with a dedicated engine alternator (either directly or using another engine system such as a FADEC), applicants should demonstrate the system sensing and performance function at minimum certified rotor speeds. Minimum certified engine speed is the minimum idle rotor speed achievable anywhere in the icing envelope.

p. Auto-Recovery Systems. Auto-recovery systems should not be needed under § 33.68 testing since these icing conditions are considered to be within the engine’s certified operational envelope and a probable encounter. The intent of § 33.68 is to certify engines to perform and operate reliably in the icing conditions depicted in appendices C and O of part 25, appendix C of part 29, and appendix D of part 33, as applicable.

(1) Auto-recovery systems are considered back-up devices that are only needed following rare ice ingestion events resulting from icing conditions outside appendices C and O of part 25, appendix C of part 29, and appendix D of part 33. If auto-recovery systems activate during the icing test, then the applicant should alert the installing ACO of the activation. Auto-recovery systems are not the primary protection for continued safe engine operation during normal ice sheds or accretion while operating in icing conditions depicted in appendices C and O of part 25, appendix C of part 29, and appendix D of part 33.

(2) Therefore, applicants may perform the § 33.68 compliance testing with auto-recovery systems enabled, but the systems should not activate during the § 33.68 test sequence. Additionally, continuous ignition should not be selected during the § 33.68 compliance testing. To assure non-activation of an enabled auto-recovery system, the applicant should have displayed an instrumented signal that monitors the auto-recovery system activation. If activation monitoring cannot be accomplished, then disabling the auto-recovery system will be necessary.

q. Operation Instructions. Any operating procedure (for example, ground run-up procedures) required to ensure continued operational compliance with ground icing conditions or falling and blowing snow evaluated under § 33.68(d), and the installation requirements of §§ 23.1093(b)(1)(ii), 23.1093(b)(2), 25.1093, 27.1093(b)(1)(ii) or 29.1093(b)(1)(ii), should be communicated to the installer in the operating instructions as a requirement. The requirement for each applicable operating procedure should further be included in the limitation section of the airplane flight manual. It may be necessary to coordinate with the installer on these procedures to ensure that they can be effectively implemented in-service. The installer may translate the operating instructions into a procedure tailored at the airplane level if it results in an operation that is equivalent to the demonstrated operating procedure. An equivalent operation should be conservatively representative of the demonstrated operating procedure.

r. Special Considerations for Mixed Phase and Glaciated Atmospheric Conditions (part 33 turbofan and turboprop only). Part 33 requirements for the type certification approval of engines operating in an ice crystal environment are located in § 33.68, and appendix D of part 33. These requirements have been developed in response to service events. The root cause of these events can be traced to ice buildup within the core flow path of the affected engines. Engine inlet probe blockage and the resulting signal corruption should also be analyzed. Adverse effects created by this type of icing on the engine include un-commanded rollback of power or flameout, as well as compressor stall and core hardware damage.

(1) Ice crystals have only been recognized as a threat to turbine engines in recent years. In response, the FAA has worked with industry to develop standards that address this threat. During this process, we found that although capabilities are developing, the present ice crystal tools and test techniques have not been fully developed and validated sufficiently. Therefore, we developed a phased-in approach to address the ice crystal threat during an engine type certification program. The following paragraphs describe this phased-in approach.

(2) New engines must address the known in-service experience in ice crystal environments (for example, core damage and engine flameout events). Until ice crystal tools and test techniques have been developed and validated, the engine manufacturer should use a comparative analysis to specific field events. This analysis approach should show that new engine cycle or design features, or both, will result in acceptable engine operation.

(3) Acceptable operation includes the absence of rollback, rundown, stall, flameout, and unacceptable compressor blade damage as described earlier in paragraph 8.a of this AC. Additionally, we recommend the engine manufacturer incorporate developed and validated technology as it becomes available, and work toward a full engine test substantiation of operation in ice crystal environments.

(4) Long-term, we anticipate an acceptable demonstration will eventually include a CPA of an ice crystal environment as depicted in appendix D of part 33. All engine power levels, including in-flight idle operation, will be evaluated in these conditions. The critical conditions will be demonstrated to the FAA through a combination of testing and validated analysis using the latest tools and technology when proposing the compliance methodology. Computational

tools to be used in this analysis would be calibrated by either rig calibration test data or engine test measurements.

s. Comparative Analysis Guidance for Ice Crystal Icing (part 33 turbofan and turboprop only).

As stated earlier, until ice crystal tools and test techniques have been developed and validated, the engine manufacturer should use a comparative analysis to specific field events. This analysis should show the new engine cycle or design feature, or both, would result in an acceptable engine operation when subjected to the ice crystal environment depicted in appendix D of part 33. This comparative analysis should consider both suspected susceptible design features, as well as mitigating design features.

(1) Susceptible Design Features. These features could include:

(a) Stagnation points which could provide an increased accretion potential.

(b) Exposed core entrance (as opposed to hidden core).

(c) High turning rates in the inlet, in the booster and core flowpath (particularly compound turning elements).

(d) Protrusions into the core flowpath (for example, bleed door edges and measurement probes).

(e) Unheated surfaces on booster and front core stages.

(f) Narrow vane-to-vane circumferential stator spacing leading to a small stator passage hydraulic diameter.

(2) Mitigation Features. These susceptible design features can be significantly mitigated by one or more of the following design features. Mitigating design features could include:

(a) Heated surfaces in the fan, booster, and forward core compressor stages.

(b) Elevated rotor speeds.

(c) Hidden core entrance.

(d) Low frontal cross-sectional area on flowpath probes.

(e) Inter-compressor bleed scheduling to remove both the ice crystal media and any up-stream shedding, from the flowpath.

(f) Circumferential spacing of stators set to enhance tolerance to ice blockage (generally denoted by the hydraulic diameter of the stator passage).

(g) Increasing core compressor airfoil tolerance to soft-body damage. Soft-body damage is typically airfoil bending, whereas hard-body damage results in tearing and fracture.

(3) <u>Similarity to Engines Proven Safe to Operate in Mixed Phase or Glaciated Atmospheric Conditions (part 33)</u>. Although ice crystal icing conditions are hazardous to turbine engine operation, severe incidents involving this type of meteorological condition are not common. Many currently certified engine designs have been proven by their field service experience to be safe to operate in these conditions. New engine designs that are similar to those of proven engine designs are allowed to show compliance by comparative analysis.

(a) Several steps are required to demonstrate compliance by similarity analysis. First, you should identify the baseline (certified) engine, and supply evidence that this engine is safe to operate in mixed phase or glaciated icing conditions. This evidence can be field service experience and/or a certification report.

(b) Second, identify the icing-pertinent engine features that may influence mixed phase or glaciated ice accretion within the target (certifying) engine; then compare them to the baseline engine. This comparison should establish that the new engine model is less than or equally susceptible to icing as the baseline model.

(4) <u>Comparative Analysis Versus CPA</u>. A comparative severity analysis should be performed to show the operational envelope of the target engine does not make it more susceptible to ice crystal icing than the baseline engine. As the icing community's knowledge improves through research, in the long term applicants should perform a CPA to fully assess ice crystal icing. This severity analysis should consider both environmental and engine operational effects on accumulation, accretion locations, as well as ice shedding.

(5) <u>Innovative or Novel Designs</u>. If the new engine cycle or design feature, or both, contains innovative design ideas such that a comparative analysis with current engines and specific engine events is not possible, then you should demonstrate that the innovative feature(s) will not be susceptible to any adverse effects of operating in an ice crystal environment. Such a demonstration entails a two part process. In part one you should document the physical basis regarding why this design would result in acceptable operation in ice crystals. In part two you should generate physical evidence to substantiate the claims of part one. For purposes of substantiation, water particles may be used instead of ice crystals. However, data collected with water particles should be corrected to account for ice crystal characteristics, including liquid to solid phase thermodynamic effects. The use of water to simulate crystals will be re-evaluated by the FAA as ice crystal test techniques improve through research and development.

Table A. Example Steps That May Be Used

Part 1	**Part 2**
Discuss consequences of ice accretion.	Identify test article (engine or component).
Identify design features that promote tolerance to critical ice accretion.	Establish test conditions promoting ice accretion (with allowance for use of liquid water if testing with ice crystals is not feasible).
Discuss consequences of ice crystals on promotion of ice accretion.	Evaluate tolerance of new design features over a range of test points.

t. Compliance Considerations (part 33). Engine icing events in an ice crystal environment appear to be associated with accretion of ice deeper in the compressor, as compared to supercooled droplet environments where accretion occurs farther forward.

u. Ice Crystal Accretion Explanation. The accretion process is believed to be a result of ice crystals passing through the engine inlet and into the front compressor stages. This process continues until the local conditions within the engine are conducive to forming a liquid layer on vane and blade surfaces. Once the local conditions are conducive to the formation of a liquid layer, the vane and blade surface condition allows impinging crystals to melt and stick to the liquid layer and accrete on the surface. This is a combination of conductive and convective heat transfer from ice melting, evaporation, and surface contact.

(1) The combination of both the liquid water and solid ice crystal draw significant heat away from the impinged surface. An impingement surface that was initially as high as 120^0 Fahrenheit (49^0 Celsius) can be cooled down to 32^0 Fahrenheit (0^0 Celsius) by this dual phase ice and water media on the surface.

v. Ice Crystal Icing Assessment (part 33, turbofan and turboprop only). You should assess engine operation across the whole icing envelope. Cruise, hold, and descent power settings should be evaluated in mixed phase and glaciated atmospheric conditions as depicted in appendix D of part 33. Note that no established standardized CPA for ice crystal icing currently exists. However, to aid you, we are recommending some possible CPA point selections described in Table B below. We also recommend applicants use the associated general criteria when selecting proposed conditions to be evaluated.

Table B. General Criteria for Selecting Conditions to be Evaluated

Service History	This suggests that a selection of conditions at high ambient temperatures depicted in appendix D of part 33 icing envelope, are consistent with higher TWC levels. However, lower temperatures might push the accretion aft, where there may be a more critical ice accretion site with lower TWC. Therefore, both high and low temperatures within the envelope should be evaluated.
Power Levels	To promote ice crystal melting, power levels with internal total air temperature within the core flowpath should be between 32^0 Fahrenheit (0^0 Celsius) and approximately 120^0 Fahrenheit (49^0 Celsius). The power level adjusts the accretion site forward or aft within the engine.
High Altitude	High altitude (low air density) allows greater ice accretion mass before shedding from static surfaces.

(1) The operating conditions for this evaluation should be chosen from appendix D of part 33, covering the flight phases to include climb, cruise, idle-descent, and holding. The water contents depicted in appendix D represent the level for a standard exposure distance of 17.4 nautical miles. To adjust the water content level as required, so that it reflects the expected icing exposure period, use the distance scale factor depicted in appendix D. Service experience suggests that straight line exposure distances of 20 to 80 nautical miles may be encountered, as well as holding in cloud. As our understanding of water content in relation to distance flown becomes more precise, this encounter distance may be adjusted. Currently we hold that applicants who test to this greater distance will assure their engines are robust and meet the minimum standards of the regulations.

(2) As noted earlier, ice crystals promote icing at engine sites rearward and at higher local air temperatures than would exist with only supercooled liquid. These rearward internal flowpath accretion sites will also have higher air loads, which can limit ice accretion due to shedding. Therefore, the CPA should consider not only ice accretion, but also the likelihood of ice shedding.

w. Appendix O of Part 25, Water Impingement.

(1) The water impingement region may become greater when encountering the large water droplets depicted in appendix O of part 25. This occurs because larger droplets have greater inertia and follow a more ballistic trajectory less prone to influence by local airflow streamlines that bend to deflect air around an object. A way to illustrate this droplet inertia effect is through the use of the modified inertia parameter variable, K_o, as shown in Figure 1 of this AC (see reference g, in section 5 of this AC. This parameter is a relationship based on the momentum of the droplet, air viscosity, and size scale of the impingement region (with a correction for

Reynolds number). It is used to correlate the streamline effect of the airflow in deflecting a droplet and preventing it from impinging on an object. The equation for K_o is provided below for a droplet with diameter (d) with an upstream velocity (V_o) traveling in an airflow with a viscosity (μ).

(2) The impingement efficiency E_m is simply a decimal fraction of the water droplets that are aligned with an object far upstream that actually do impinge on the surface. For very large droplets, impingement efficiency approaches unity and is progressively less for smaller droplets. Published correlations exist for various object shapes of interest for ice impingement. Such a correlation between K_o and impingement efficiency E_m, is shown below in Figure 1 for several object shapes.

Figure 1. Droplet Impingement Efficiency for Different Shapes

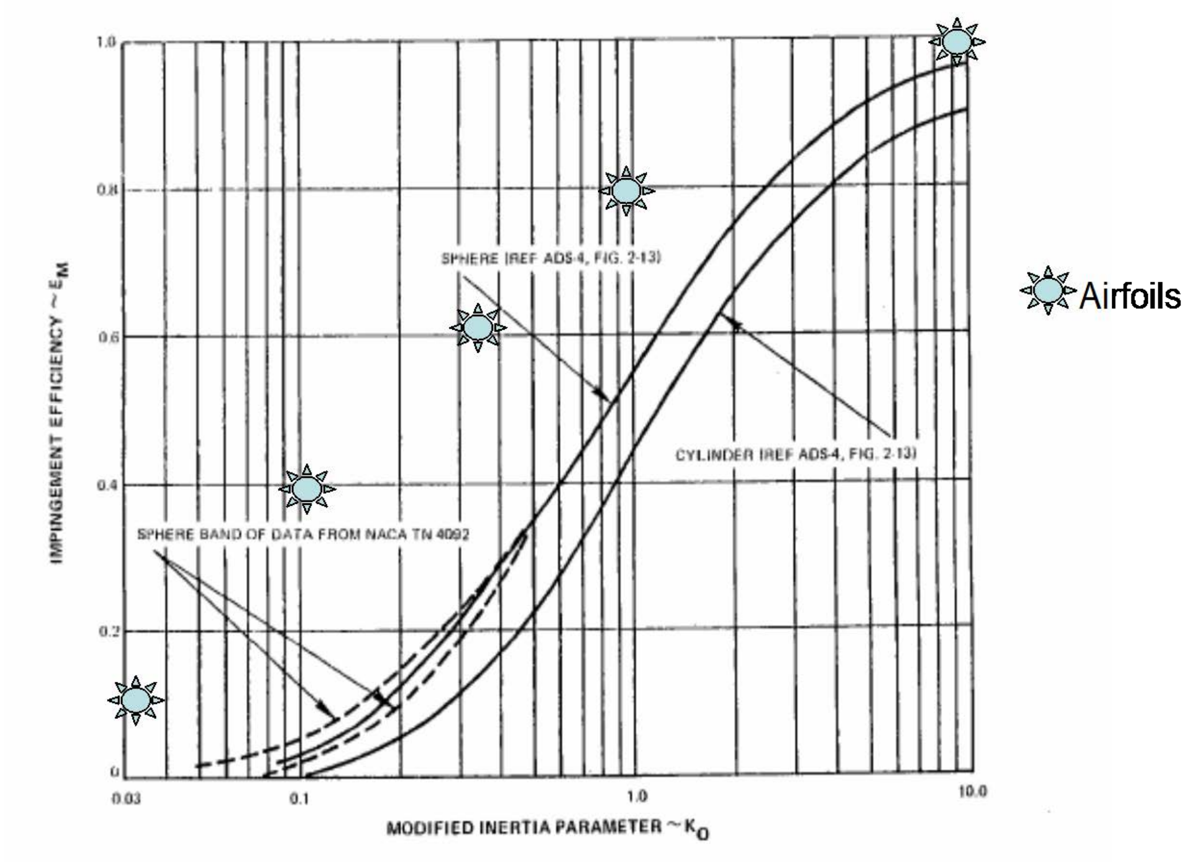


Figure 1a. Definition of Inertia Parameter, Equation 3.10 from Reference 5.g of this AC

Inertia Parameter $K = \frac{2(d/2)^2 \rho_{H20} V_0}{9 L_C \mu}$ (Dimensionless) EQU 3.10

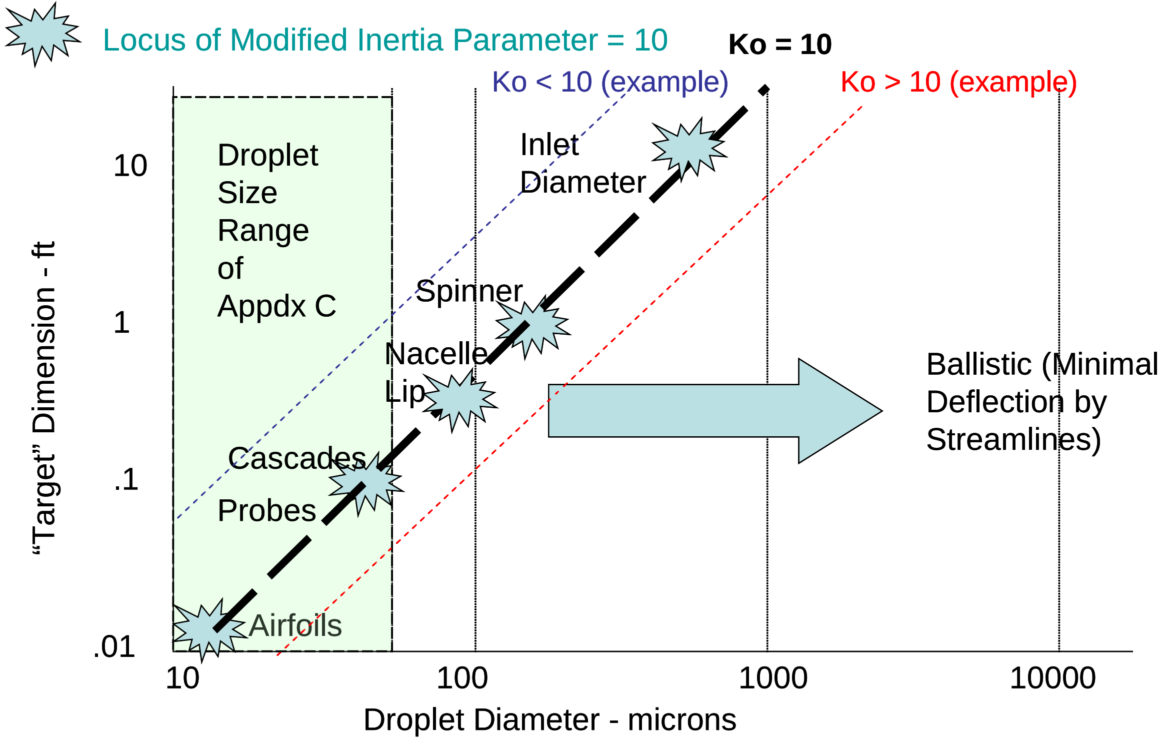
Where Characteristic length L_C of object is:

Airfoils L_C = Chord	Cylinders L_C = Radius
Spheres L_C = Radius	Cones L_C = Base Radius

(3) Lower impingement efficiencies (less than a value of one) are indicative of droplet deflection from the object. When droplets are deflected, they don't accrete on the object. This deflection is caused by streamlines moving around the object. For most shapes, a modified inertial parameter of 10 or greater implies a ballistic path for the droplets. A ballistic path means the droplet does not follow stream lines and can impinge the vane farther back than a non-ballistic droplet. This results in ice accretion farther back on the vane.

(4) Impingement of a supercooled water droplet on a surface is dependent on the droplet size, and the size of the geometric feature. The smaller the drop size and the bigger the feature, the more likely the drop will follow the aerodynamic streamlines around the body and fail to impinge. Larger drops, with more inertia are less likely to follow streamlines, and therefore they will impinge on larger features. In the engine, such features include the inlet and spinner. The applicant must account for the potential impingement of larger drops on engine geometric features of this scale. Figure 2 of this AC illustrates the consequences of encountering the larger water droplets depicted in appendix O of part 25. Figure 2 also shows what happens with target objects of typical size ranges for larger transport engines. The shaded area in Figure 2 covers appendix C of part 25 and appendix C of part 29, as applicable. For a given modified inertia parameter value (K_o) of 10, the droplet size range is seen to behave ballistically for small "target" objects, such as engine airfoils, airfoil cascades, and probes. Consequently, large droplets as depicted in appendix O of part 25 will not significantly affect surface water impingement and resulting ice accretions on small airfoils within engines. For larger targets, however, applicants should anticipate greater impingement on surfaces, for example: the nacelle and engine spinner. Other surfaces unprotected by surface heating systems are also at risk for water impingement by the sized droplets depicted in appendix C of parts 25 and 29, as applicable.

Figure 2. Ballistic Boundary as a Function of Target and Droplet Size



10. Section 33.77, Ice Slab Ingestion.

a. Why the Ice Slab Ingestion Test is Conducted. The intent of the ice slab ingestion test is to demonstrate tolerance to ice ingestion due to shedding from inlet (nacelle) surfaces in the front of the engine. This test also establishes limits for ice released from other aircraft or rotorcraft surfaces during parts 23, 25, 27, and 29 certifications. The dimensions of the test slab are related to engine size (defined by inlet highlight area), based on service experience. Manufacturers of turboshaft engines with complex inlet designs should propose an equivalent inlet highlight area once they have defined the ice slab size. Engine manufacturers should also include in their compliance plan, an analysis of the potential installation effects of the engine induction system.

(1) The engine manufacturer and the installer should closely coordinate the ice slab sizing and density. This coordination ensures that ice accumulation sites on the airframe which can potentially be ingested by the engine are addressed under § 33.77. Airframe locations that should be considered include for example, the inboard section of the wing for an aft fuselage mounted engine, the radome, and antenna. Ice slab ingestion is demonstrated under § 33.77, but must be addressed and shown as acceptable for the installation under §§ 23.901(d)(2), 23.1093, 25.1091(e), 25.1093, 27.1093, or 29.1093 (see paragraph 11 of this AC).

(2) The airframer responsible for the induction system should assess the inlet cowl ice accumulations in accordance with §§ 23.901(d)(2), 23.1093, 25.1093, 27.1093, or 29.1093. They should also provide pertinent test variables to the engine manufacturer for incorporation into a § 33.77 test demonstration. If an application or product inlet has not been selected at the time of engine certification, the engine manufacturer should include in the engine installation manual all pertinent inlet icing assumptions, test data, and results. See paragraph 11 of this AC for installer assessment guidance.

b. Compliance Considerations. Compliance may be demonstrated by the standard engine ice slab test or by using a validated analysis procedure that uses equivalent soft body testing. The test demonstration should use ice slab trajectories aimed at critical engine locations. Applicants should pick locations based on the ice accretion and shed characteristics of the induction system likely to be installed on the engine. The most critical impact location should be tested.

(1) Slab Dimension Considerations. If the engine manufacturer type certificate applicant lacks specific knowledge of the icing characteristics of an aircraft inlet system, it may select test conditions typical of an installation already in-service, in combination with conservative assumptions on the future installation. The ice slab size, thickness, and density defined in the § 33.77 compliance demonstration should be evaluated against parts 23, 25, 27, and 29 engine installation and inlet system icing requirements. Applicants should use a minimum ice slab density equivalent to a 0.9 specific gravity, unless a different value is considered more appropriate (see AC 20-73A, AC 23.1419-2D, AC 25.1419-1, AC 27-1B, or AC 29-2C (or latest revisions) for more guidance on ice shedding).

(2) Engine Test Considerations. Applicants should determine if the ice slab size, thickness, and density are appropriate for the specific engine installation. If appropriate, the test

results of § 33.77 might be used by the airframe manufacturer to comply with the natural icing flight test requirements of §§ 23.1093, 25.1093, 27.1093, and 29.1093. Execution of the ice slab ingestion test typically involves targeting the slab to enter the air stream ahead of the fan, intact, at the outer diameter of the inlet duct. This is intended to mimic the ice release from the inlet and results in impact on the outer diameter of the fan.

c. Validated Analysis with Equivalent Soft Body Tolerance Testing. Compliance may also be shown by a validated analysis procedure that uses appropriate soft body damage testing. If the applicant elects this alternate compliance approach, the engine will be certified for the minimum standard ice slab consistent with the engine inlet area as defined in § 33.77. We recognize that alternate soft body damage testing may, in some circumstances, include objects that are larger than the standard ice slab based on inlet area. However, certification of an ice slab larger than the standard size by this validated analysis method is not currently allowed.

d. Elements of a Validated Analysis. This analytical model may be used alone or in conjunction with the results of a certification medium bird or other soft body ingestion test. A validated analysis must contain sufficient elements to show compliance. These elements may include:

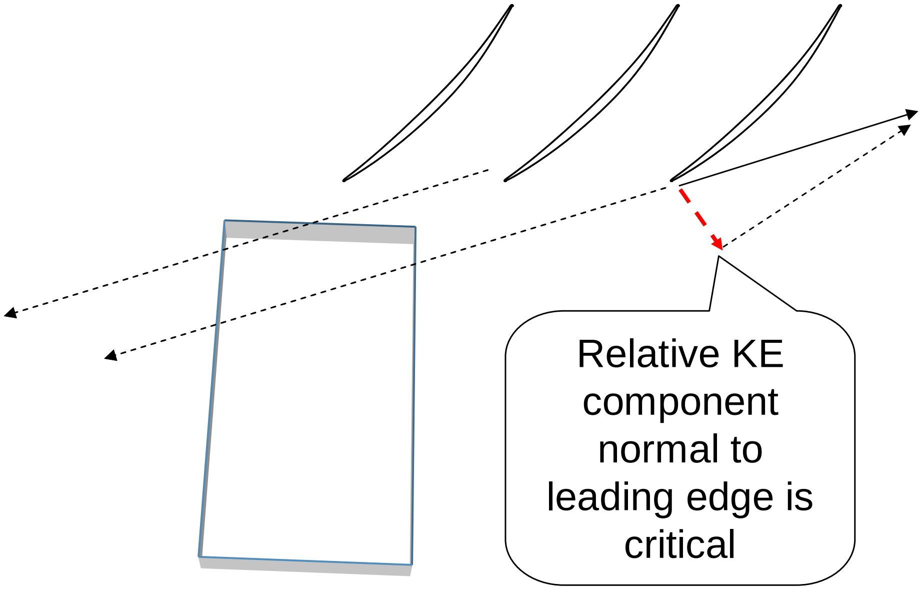
- Full fan (fan engines) or first stage compressor (non-fan engines) blade modeling using the latest techniques such as finite element analysis;
- Blade material properties for yield or failure, or both, as appropriate;
- Dynamic and time variant capability;
- Thrust or power variance prediction if required to account for blade or other damage; and
- Appropriate engine or component testing, or both, with impact at the outer 1/3 of the first stage blade span location. The fan is the first stage blade row for turbofan engines.

(1) The analysis of the ice slab impact on the fan must properly account for critical controlling parameters:

- Relative kinetic energy normal to the leading edge chord;
- Incidence angle – relative slab speed and blade speed;
- Slab dimensions; and
- Slab orientation.

(2) Any predicted power loss or blade damage (distortion, cracking, tearing) must be assessed against the criteria of this AC. Figures 3 and 4 of this AC help describe the contribution of these parameters when establishing the threat to the blade.

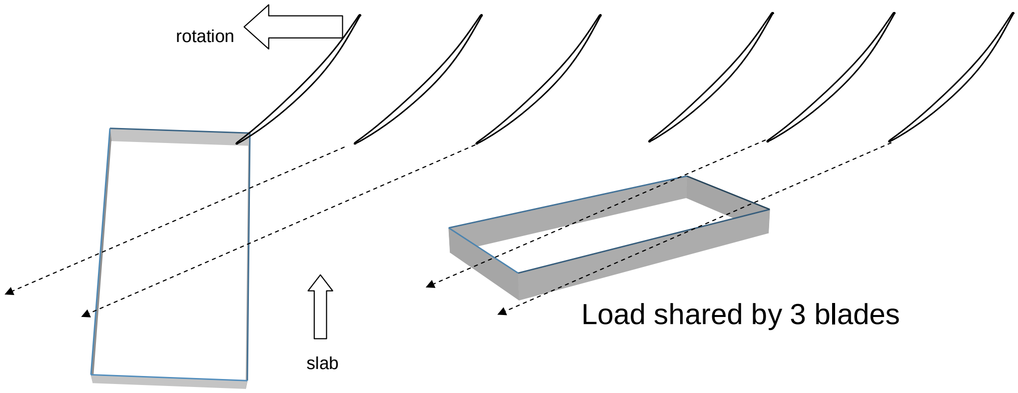
Figure 3. Normal Component of Kinetic Energy of Ice Slab



Relative KE component normal to leading edge is critical

Figure 4. Ice Slab Orientation Effects

Dependent on orientation at fan face the "bite" can be increased substantially



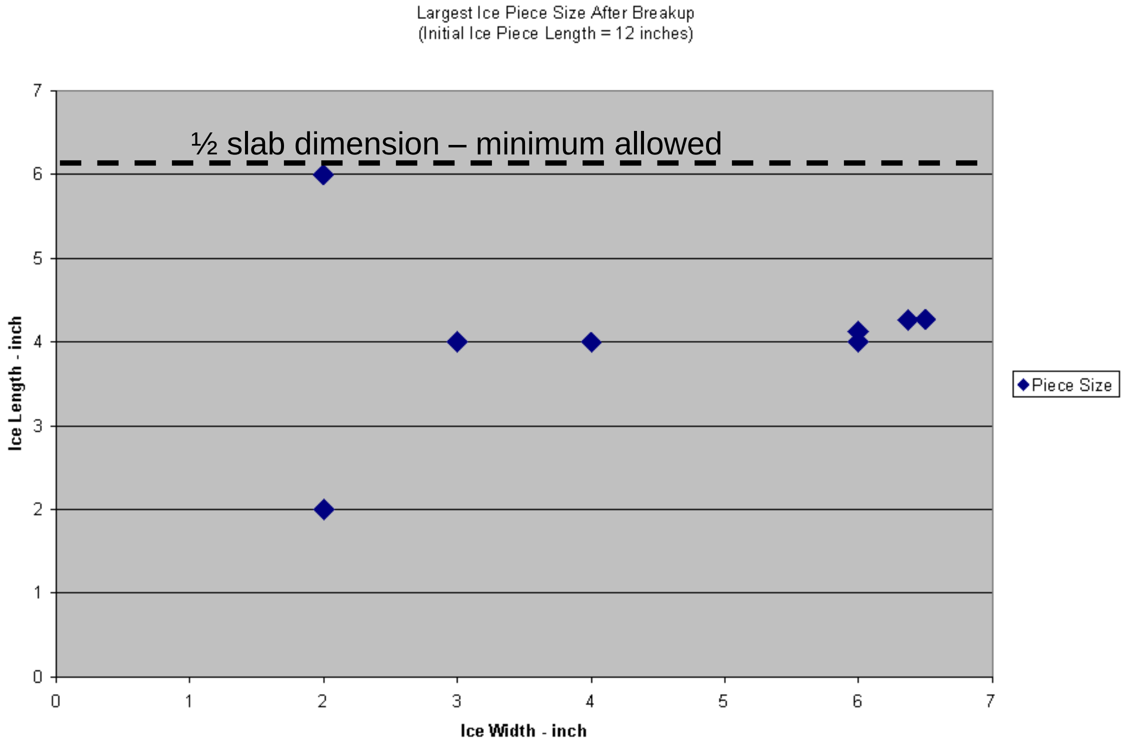
Load shared by 3 blades

Load shared by 6-7 blades

(3) The relative kinetic energy of the ice slab should be determined from an assessment of flight conditions that control engine rotor speed versus ice slab velocity. Engine test results from previous ice slab testing may be used to support the predicted ice slab velocity. The applicant's analysis should assume the most critical orientation, unless they can show that an alternate ice slab orientation is more conservative for ice slab testing purposes.

e. Ice Slab Break Up. Typically, the ice slab breaks into smaller pieces during ingestion. The applicant's analysis should use the largest slab size consistent with a conservative assessment of slab "break up" that can occur within the air stream ahead of the fan. Data derived from a number of tests are included in Figure 5 below. The largest ice piece is typically 1/3 to 1/2 the original size. For compliance by analysis, the applicant should assume 1/2 of the original slab length unless evidence suggests that this is not conservative relative to ice slab testing.

Figure 5. Ice Slab Break Up Experience



f. Test Results. Section 33.77(c) requires that under the conditions in § 33.77(e), ice ingestion must not cause a sustained power or thrust loss, or require the engine to be shutdown. The following paragraphs cover these points in greater detail:

(1) Sustained Power Loss. Applicants should evaluate the impact of any first stage blade bending or damage on potential sustained engine power loss. Power loss associated with blade damage from the slab should be less than 1.5%. As soft body blade damage is common from medium bird ingestion, applicants may use the medium bird ingestion test results to show compliance with this requirement. If the medium bird ingestion test results is less than 1.5% permanent power loss, and no cracks, tears, or blade piece breakout occurs due to a bird introduced at the outer 1/3 of the fan blade span, then the § 33.77 requirement is met.

(a) If power loss exceeds 1.5% when utilizing the bird test, the manufacturer must provide a validated analysis that shows consistency with the bird test results. The manufacturer must also demonstrate the standard ice slab would produce less than the 1.5% power loss.

(b) Applicants must also demonstrate by test that any cracks, tears, or blade piece breakout will not result in “unacceptable sustained power or thrust loss” within 100 flight cycles. This is considered sufficient to allow continued engine use until the next scheduled “A” check for fixed wing applications, or similar inspection periods for rotorcraft applications. Note that any damage resulting from this test must be documented in the engine installation manual.

(2) Engine Operability. Engine damage should not cause surge, flameout, or prevent transient operation.

(3) In-Service Capability. Engine damage should not result in a failure or a performance loss that would prevent continued safe operation during a conservative flight operations scenario. For example, an engine should be able to operate within the time period for an “A” check or greater, if appropriate testing validates a continued period of in-service capability. The period of in-service capability to be demonstrated may vary with installation if the damage is not readily evident to the crew or visible on preflight inspection (for example, tail mounted engine location).

(4) Other Anomalies. Engine damage should not result in any other anomaly (for example, vibration) that may cause the engine to exceed operating or structural limitations.

(5) Auto-Recovery Systems. If during the ice slab ingestion testing under § 33.77, an engine incurs a momentary flameout and auto-relight, then the acceptance of that test is predicated on including the auto-relight system as a required part of the engine’s type design. Furthermore, additional criteria would be required where the ignition system is fully operable before each dispatch. The reason for the additional dispatch criteria is to ensure the ignition system’s critical relight function is reliably available during the next flight. We allow use of the auto-recovery system during § 33.77 certification testing to account for ice accretion and shedding that results from an inadvertent delay in actuating the anti-icing system. We consider this delay to be an abnormal operational result where operability effects, like momentary flameout and relight, may be accepted.

g. Communication of Test Results.

(1) The installation and operation instructions required by § 33.5 should provide information on the size, thickness, and density of the ice slab ingested; any anomalous behavior such as high vibrations, and any affect on the engine’s ability to operate at the commanded power setting or rating. By including the information in the installation manual, you provide these test results to the installer.

(2) The icing certification report addressing § 33.77 compliance should include information regarding ice slab orientation and trajectories, slab breakup, impact locations, descriptions of any resultant damage, as well as all other pertinent data defining the engine's capability or response to the ice ingestion event. Additionally, if the auto-recovery system is required to comply with § 33.77, then the functional state of the recovery system (for example, one igniter inoperative) becomes a limitation that needs to be communicated to the installer via the engine installation manual to ensure compliance with the delayed activation requirements of §§ 23.1093, 25.1093, 27.1093, or 29.1093.

11. Induction System Icing Protection (§§ 23.1093, 25.1093, 27.1093, and 29.1093). Applicants usually use the results of § 33.77 for compliance with §§ 23.1093, 25.1093, 27.1093, and 29.1093, instead of a test demonstration of the 2-minute delayed activation of inlet anti-ice (1-minute for turbo shaft engines). The § 33.77 results have also been used to show compliance with §§ 23.1093, 25.1093, 27.1093, and 29.1093 for other airframe ice sources. The engine manufacturer and the airframer should coordinate closely to ensure the § 33.77 test covers all potential ice sources. Similarly the icing compliance demonstration of § 33.68 should be coordinated with the installer to verify the engine icing compliance demonstration is applicable to the installation icing compliance requirements. The icing conditions depicted in appendix O of part 25 are only applicable to turbine engine induction systems on part 25 airplanes with a maximum takeoff weight less than 60,000 pounds. Turbine engine induction systems on part 25 airplanes with a maximum takeoff weight equal to or greater than 60,000 pounds need only comply with the icing conditions depicted in appendix C of part 25, appendix D of part 33 and in falling and blowing snow within the limitations established for the airplane for such operation.

a. Acceptable Means of Compliance (§§ 23.1093(b)(1), 25.1093(b)(1), 27.1093(b), and 29.1093(b)). As a general rule, engine induction systems should operate continuously in icing conditions without regard to time, as in a hold condition. For fixed wing aircraft, a 45-minute test duration in a standard continuous maximum cloud is an acceptable demonstration of continuous in-flight operation, so long as the test demonstration result isn’t indicating an imminent test criteria failure. An exception would be for low engine power conditions where a sustained level flight is not possible. Even then, a conservative approach must be used when a series of multiple horizontal and vertical cloud extent factors are assumed. The horizontal cloud extent factor is not intended to be used to limit the severity of exposure to those icing conditions where it is reasonable to assume the aircraft will be required to operate.

(1) Applicants must adequately analyze the engine inlet anti-ice system performance and address any potential ingestion hazards to the engine from predicted ice buildup on the engine inlet. This includes runback and lip ice. If an applicant can show that both the inlet anti-ice system performance and the first stage compressor blade (for example, fan blade for turbofan

engines) capability are equivalent to previous certification experience, then certification may be shown through similarity to previous designs.

(2) You must show by analysis, and verify by test, that the engine inlet anti-ice system provides adequate protection under all flight operations. Your analysis should include the conditions shown in Table C of this AC. Note that additional critical points may be needed depending on the specifics of the airplane and engine design. Bleed crossover points may also need to be analyzed, if applicable.

b. Inlet Design Point Selection. If the inlet is evaporative under the critical points in continuous maximum icing conditions, and if it is running wet under intermittent maximum icing conditions (refer to appendix C of parts 25 and 29), then the design is satisfactory. Turbofan and turboprop engine inlet anti-ice systems have historically demonstrated good service experience with inlet anti-ice systems that run wet, when runback ice has been evaluated at the conditions described in Table C of this AC. For turbofan and turboprop inlets that are certified for unlimited operation in icing, runback ice formation is allowed during hold, descent, and diversions under the conditions shown in Table C of this AC. Turbofan and turboprop installers should determine the critical accretion conditions for their inlets in each of the scenarios in Table C below. They should then compare each result to the amount of ice the engine was satisfactorily demonstrated to ingest during engine certification (refer to § 33.77).

Table C. Inlet Lip and Runback Ice (part 33 turbofan and turboprop engines only)

Flight Condition	Descent	Hold	Straight-Line Flight
Icing Design Condition	6500 foot descent through a continuous maximum cloud, as depicted in appendix C of part 25, with a cloud extent factor of 1, followed by an intermittent maximum cloud exposure, as depicted in appendix C of part 25.	45-minute hold in a continuous maximum cloud, as depicted in appendix C of part 25, with a cloud extent factor of 1.	45-minute exposure in a continuous maximum cloud, as depicted in appendix C of part 25, with a cloud extent factor as depicted in appendix C of part 25, followed by an intermittent maximum cloud exposure, as depicted in appendix C of part 25.

c. Addressing Specific Operational Conditions.

(1) Descent. If the engine inlet anti-ice system is not fully evaporative during descent through a continuous maximum cloud as depicted in appendix C of part 25, then the total amount of ice accretion (including inlet lip and runback ice) must be calculated for both the continuous maximum and intermittent maximum icing conditions depicted in appendix C, and for the operating conditions shown in Table C above. Airspeed and scoop factor (if applicable for the inlet design) should be part of this assessment. Ingestion of these calculated quantities of ice buildup for a given condition must not result in more ice ingestion damage (that is, based on slab size or kinetic energy) than the amount of ice the engine was satisfactorily demonstrated to ingest during the engine certification (refer to § 33.77).

(2) Holding. The engine inlet anti-icing system must be capable of safe operation in the cloud conditions depicted in appendix C of parts 25 or 29 for extended operations. The extended holding condition is for 45 minutes (except, 30 minutes is used for parts 27 and 29) at the critical accretion ice conditions for the continuous maximum icing cloud, using a horizontal cloud extent factor of one.

(a) If the inlet is evaporative under continuous maximum icing conditions, and it is running wet under intermittent maximum icing conditions, then the design is satisfactory. This is because the descent condition provides less power to the anti-ice system and will always become the critical accretion condition in intermittent maximum icing conditions.

(b) If the inlet is running wet in a maximum continuous atmospheric condition, then the applicant should calculate the amount of ice that would accumulate during the holding conditions as described in Table C above. The total amount of calculated ice should include runback and lip ice for the condition being analyzed. Ingestion of this ice must not result in more damage than the amount of ice the engine was satisfactorily demonstrated to ingest during engine certification tests (refer to § 33.77). This damage assessment should be based on the kinetic energy at the leading edge of the first stage compressor blade (for example, the fan for turbofan engines), and should include considerations of ice slab size, velocity, density, and compressor (or fan) rotor speed.

(3) Straight-Line Flight. For straight-line flight (for example, cruise, and diversion to alternate airport) the engine inlet anti-icing system should be capable of operating sufficiently to assure safe operation for extended time in icing conditions. The straight-line flight evaluation must be evaluated and may include the use of the cloud extent factor depicted in appendix C of parts 25 or 29. If the inlet is evaporative under continuous maximum icing conditions, and if it is running wet under intermittent maximum icing conditions, then the design is satisfactory. If the inlet is running wet in a maximum continuous atmospheric condition, then the applicant should calculate the amount of ice that would accumulate during the straight-line flight conditions identified in Table C of this AC (that is, continuous maximum exposure followed by an intermittent maximum exposure). Ingestion of these calculated quantities of ice (that is, the total amount of ice including runback and lip ice for the condition) should not result in more ice

ingestion damage than the amount of ice the engine was satisfactorily demonstrated to ingest during engine certification tests (refer to § 33.77).

(4) Running Wet Inlet Anti-ice Systems. For running wet systems, an alternative method of compliance would be to demonstrate the normal (no crew action required) ice build and shed cycles during exposures representative of descent, holding, or straight-line flights (turboshaft engines can propose alternate representative exposures). This may be accomplished through tanker or ground testing, with conservative corrections for water contents consistent with exposures discussed in paragraphs (1) through (3) above. Ingestion of this ice must not result in more damage than the amount of ice the engine has satisfactorily demonstrated to ingest during engine certification tests (§ 33.77). The period of in-service capability to be demonstrated may vary with installation if the damage is not readily evident to the crew or visible on preflight inspection (for example, tail mounted positions). Damage should be reviewed with the FAA and documented in the certification report.

d. Two-minute Delayed Selection of Inlet Anti-Ice Accretion Analysis (part 33 turbofan and turboprop engines only). The § 33.77 testing criteria were developed to account for historical means of compliance regarding the 2 minute delayed selection of inlet anti-ice. For traditional pitot-style engine inlet designs, a part 23 or 25 applicant does not need to consider this scenario if the applicant shows compliance with § 33.77 testing criteria that utilizes a standard slab size.

(1) For inlet designs other than the traditional pitot-style inlets, a 2-minute delay calculation may be required, given that inlet lip ice can form during the delayed activation of the engine inlet anti-ice system. Applicants should calculate the amount of inlet lip ice that forms using a continuous maximum condition depicted in appendix C of part 25, with a cloud extent factor of one. Of the total lip ice, only the ice on the inner barrel side of the stagnation point would be ingested into the engine.

(2) For the 2-minute delay approach, applicants may assume that 1/3 of the ice on the inlet perimeter is ingested as one piece. This assumption is consistent with the historical approach taken by the engine manufacturers. The maximum damage to the fan blade occurs at a high fan speed; the critical condition occurs with the maximum inlet nacelle heat. Therefore, 2 minutes is a reasonable time to include the pilot reaction to select the anti-ice system and, for the engine thereafter, to shed the ice from the inlet perimeter.

e. Extended Operations Performance Standards (ETOPS) (part 25 installations only). If ETOPS certification is desired, the applicant should consider the maximum ETOPS diversion scenarios. For example, if a lightweight two-engine diversion occurs at a 10,000 foot altitude followed by a cabin depressurization, then this puts the airplane into icing conditions that will promote ice buildup. Therefore, the inlet icing should be evaluated. Ingestion of the ice must not result in more ice ingestion damage than has been satisfactorily demonstrated during engine certification ice ingestion (refer to § 33.77).

f. Potential Airframe Ice Sources, Including Inlets. The engine manufacturer should consider the potential installation effects of the engine induction system and work with the installer to ensure that potential ice accretions formed at airframe ice accumulation sites are adequately tested during the engine ice ingestion testing of § 33.77. Fuselage sources of ice accretion include the inboard section of the wing for an aft fuselage mounted engine, and a radome for any installation configuration, to name two. The induction system manufacturer or installer should assess ice accumulations in accordance with parts 23, 25, 27, or 29 (that is, §§ 23.901(d)(2), 23.1093, 25.1093, 27.1093, or 29.1093). They should also provide pertinent test variables to the engine manufacturer for incorporation into the § 33.77 test demonstration. If an application or product inlet has not been selected by the time of engine certification, the engine manufacturer should list all pertinent inlet assumptions, test data, and results in the engine installation manual for use by the future installer.

(1) It is normally sufficient to show that ice accretions from these sites are smaller in size, and therefore have less or equal kinetic energy potential than the ice slab used in § 33.77 testing. As described in paragraph 10.e of this AC, the slab typically breaks into pieces when entering the inlet. For the comparison of airframe ice to the results of the § 33.77 test, it may be assumed that airframe ice sources break in half when entering the inlet.

(2) The applicant may elect to compare the ice based on the kinetic energy of the ice slab. Kinetic energy may be used as an acceptable method for comparing the airframe ice source to the results of the § 33.77 test. Any kinetic energy method must be agreed to by the applicant's ACO.

(3) Demonstration of ice shedding with natural or icing tanker testing can be an acceptable means of compliance for airframe ice that accumulates in front of the engine, while in the conditions depicted in appendix C of part 25 or 29. However, the applicant must demonstrate conservatism relative to long durations in these icing conditions (such as for several successive cloud extent exposures). Ingestion of shed ice during natural or icing tanker testing must not result in more damage than the amount of ice the engine was satisfactorily demonstrated to ingest during engine certification tests (refer to § 33.77). The period of in-service capability to be demonstrated may vary with the installation if the damage is not readily evident to the crew or visible on preflight inspection (for example, tail mounted positions).

g. Wing Sourced Ice for Aft Mounted Engines (part 33 turbofan and turboprop engines, only). Clear ice may occur on the upper surfaces of the wing when cold-soaked fuel (due to aircraft prolonged operation at high altitude) remains in contact with the fuel tanks' upper surfaces after landing, and during time on the ground when the airplane is exposed to conditions of atmospheric moisture (for example, fog, precipitation, and condensation of humid air) at ambient temperatures above freezing. Atmospheric moisture, when in contact with cold wing surfaces, may freeze. If undetected and still present during takeoff, the ice is most likely to shed when the wings flex at takeoff rotation. Simultaneous ice shedding from both wings of an airplane with aft mounted engines has resulted in ice ingestion damage and power loss in both engines during takeoff.

(1) When fuel management procedures allow wing fuel tanks to remain mostly full after landing, cold fuel is in contact with the wing upper skin. As a result, clear ice may form on cold wing surfaces during the time on the ground; this holds true even if conditions remain above

freezing and are not expected to be, or recognized as, icing conditions. Fuel temperature may need to be analyzed, including the effect of fuel schedules and refueling procedures.

h. Aft Mounted Engine Installations. For aircraft with aft mounted engines, applicants should demonstrate that any undetected ice in front of engine inlets is not greater than what was shown during engine and aircraft certification. Applicants should also demonstrate that shedding the ice accumulated due to cold-soaked fuel will not result in hazardous engine operation.

(1) For fixed wing applications, a wing mounted ice detection system may allow minimal accretion prior to alerting the flight crew as long as the accumulated ice thickness is limited to a defined value. This defined value should demonstrate a sufficient margin relative to both engine ingestion (refer to § 33.77) and performance and handling qualities as demonstrated under § 25.1419. The largest clear ice slab area that could be ingested into an engine is the same area as the engine's inlet highlight area. In cases where this large slab is very thin, it may not be possible to reach the engine in one piece. Therefore, consistent with a conservative assessment of slab "break up" that can occur within the air stream ahead of the fan, the applicant may consider the ice slab as multiple pieces. You may evaluate any potential resulting damage to individual engine components, such as fan blades, by comparison to other ice ingestion tests such as the ice slab discussed in paragraph 10 of this AC. Additionally, you may compare the ingestion results to other soft body ingestion test results, such as the 2-inch hail ingestion tests, as long as the mass and kinetic energy effects are accounted for. Finally it may be appropriate to address the potential effect on the engine fan shaft, or other structure, if the combined impact of a large sheet of ice (or multiple pieces) striking many fan blades simultaneously could generate unacceptable loads on the engine components. This might in some instances be addressed by analysis.

i. Compliance with Mixed Phase and Glaciated Atmospheric Conditions Under § 25.1093(b)(1) (part 33 turbofan and turboprop engines only). The results of previous airfoil testing in a mixed phase icing environment indicates these icing conditions do not appreciably accrete on unheated aircraft wings. Furthermore the testing showed mixed phase environment results in the same or less ice accretion than an equivalent amount of supercooled liquid water. The overall power required by the running-wet ice protection system was essentially unchanged between all-liquid and mixed phase conditions.

(1) However, in the running-wet mode, the local power density was much higher around the stagnation area in the mixed phase conditions, compared to the purely liquid conditions. This is due to the power required to offset the thermodynamic heat-of-fusion necessary to melt the impacting ice particles that either fully or partially stick to the surface.

(2) This may also explain why pitot-style inlets have not proved to be susceptible to mixed phase ice accretion within the inlet, and why the compliance methods to § 25.1093 for the icing conditions depicted in appendix C of part 25, have historically adequately addressed those inlets. Engines designed with reverse flow intakes, or with intakes involving considerable changes in airflow direction should demonstrate acceptable operation in the icing conditions depicted in appendix D of part 33. Compliance for pitot-style inlets, without considerable changes in

airflow direction, may be shown through qualitative analysis of the design, and supported by similarity to previous designs that have shown successful service histories.

j. Compliance with the Supercooled Large Drop (SLD) Conditions Under § 25.1093(b)(1) (part 33 turbofan and turboprop engines only). The icing conditions depicted in appendix O of part 25 are not applicable to turbine engine induction systems on airplanes with a maximum takeoff weight equal to or greater than 60,000 pounds.

(1) In-Flight Exposure to Appendix O of Part 25 Conditions.

(a) For airframe ice sources, the installer may use either quantitative or qualitative analysis of the design. The qualitative analysis must be supported by similarity to previous designs that have shown a successful service history in order to have confidence that the historical methodology for certification as represented by § 33.77, Table 1 – "Minimum Ice Slab Dimensions Based on Engine Inlet Size", is appropriate.

1. For engine inlets, compliance may be shown through quantitative or qualitative analysis of the design. Qualitative analysis must be supported by similarity to previous designs that have shown a successful service history. Compliance to the "Large Droplet Condition" of Table 1 of § 25.1093(b)(2), titled "Table 1 - Icing Conditions for Ground Tests", would still be required for ground idle taxi conditions. If similarity is not shown, then an assessment of inlet impingement limits, differing catch efficiency, distribution effects, and water contents depicted in appendix O of part 25 should be accomplished.

2. To demonstrate compliance with § 25.1093, the exposures should be consistent with, but conservative to the aircraft operational approvals, as well as the applicable definitions in Part II of appendix O of part 25, for both the ice protection system and the potential airframe accumulations with respect to shedding.

(2) Ground Taxi Exposure to Appendix O of Part 25 Conditions. The service experience considered for this advisory material indicates that engine fan damage events exist which resulted from exposure to SLD during ground taxi operations. For this reason, an additional compliance condition was added to § 25.1093(b)(2) for a 30-minute, idle power exposure to SLD on the ground. Applicants should include the terminal falling velocity of SLD (for example, freezing rain, freezing drizzle) in their trajectory assessment, relative to the protected sections of the inlet. The 100 micron minimum mean effective diameter (MED) was selected as a reasonable achievable test condition, given current technology. We recommend however, that applicants who choose to certify by analysis, should evaluate engine operation in the icing conditions depicted in appendix O of part 25. This evaluation should include various drop sizes, with the appropriate drop size distribution, to find a critical condition.

k. Natural Icing Flight Tests. Natural icing flight tests are intended to demonstrate that each turbine engine is capable of operating throughout the flight power range of the engine (including idling), without an adverse effect. This includes the accumulation of ice on the engine, inlet system components, or airframe components that would have an adverse effect on the engine operation or cause a serious loss of power or thrust. The icing conditions depicted in appendix O of part 25 are only applicable to turbine engine induction systems on part 25 airplanes with a maximum takeoff weight less than 60,000 pounds.

(1) Based on multiple natural ice engine damage and operability events experienced on natural icing flight tests and in-service airplanes, natural ice encounters must be used to show compliance with §§ 23.1093(b)(1) or 25.1093(b)(1), and in some cases for §§ 27.1093(b)(1) and 29.1093(b)(1). For airplanes that are not intended to be certificated for flight in icing conditions, other methods may be used to replace the natural icing flight tests. When replacing the natural icing flight tests on these airplanes, you can show compliance to § 23.1093(b)(1) by analysis such as ground testing, dry air flight testing, and similarity.

(2) In addition to showing your engine inlet icing analysis model is accurate, several other key issues exist that the natural ice encounter addresses. These include:

- The adequacy of flight crew procedures when operation in icing conditions;
- The acceptability of control indications to the flight crew as the airplane responds to engine fan blade ice shedding during various conditions;
- The performance of the engine vibration indication system, as well as other engine indication systems; and
- The confirmation that the powerplant installation performs satisfactorily while in icing conditions. This powerplant installation is comprised of the engine, inlet, and the anti-ice system.

l. Identification of Ice Source. Applicants should provide a means to identify the source of any ice that may be ingested by the engine during the natural icing certification testing. Special attention should be given to non-representative ice accretions on flight test instrumentation probes or other surfaces forward of the engine during prolonged operation in icing conditions.

m. Icing Test Point Monitoring. The applicant should provide acceptable monitoring of the icing test point condition (that is, LWC, droplet diameter, temperature) for sufficient time exposure to ensure the icing encounter is representative of the environmental icing conditions depicted in appendices C and O of part 25 certification icing conditions, appendix C of part 29, or appendix D of part 33 conditions, as applicable.

n. Compliance. Compliance with §§ 23.1093 or 25.1093 is required even if flight into icing conditions is not intended or approved (§§ 23.1419 or 25.1419 compliance). Applicants must therefore, propose an acceptable icing engine-installation test. The proposed test should include the natural ice encounter criteria. The icing conditions depicted in appendix O of part 25 are only applicable to turbine engine induction systems on part 25 airplanes with a maximum takeoff weight less than 60,000 pounds.

(1) Typically, an adequate test sequence includes three natural fan ice shed cycles at each of the following conditions (inlet anti-ice turned "on"): descent (flight-idle, or anti-ice idle), holding (power set to maintain level flight through a range of anticipated airplane gross weight), and maximum climb, unless a more critical engine power setting exists. These fan shed cycles

should result from natural ice accumulation and shedding, not induced or forced shedding by throttle or power lever excursions or manipulations during each condition.

(2) This test should be conducted at a steady-state engine thrust level. The test may also involve flying through the same icing cloud multiple times (lapping) for the fan to accumulate enough ice for a shed cycle to occur. The airplane may exit the icing conditions between each fan shed cycle as needed to clear any other unprotected airplane surfaces from ice. Applicants should ensure the test engine ignition system is off during the icing conditions. This will avoid masking any adverse engine operating conditions during the natural icing encounter. This may require pulling several airplane circuit breakers to disable the test engine's auto-ignition or recovery system, or both. We recommend that applicants establish engine damage criteria and obtain FAA approval of these criteria before conducting the natural ice encounter test. Our experiences have shown that pass or fail criteria, such as allowable limits of engine damage, are best agreed on before certification testing.

o. Falling and Blowing Snow. Sections 23.1093(b)(1)(ii), 25.1093(b)(1), 27.1093(b)(ii), and 29.1093(b)(ii) require engines to operate satisfactorily in falling and blowing snow throughout the flight power range, and ground idle. Ground idle would include aircraft operations on or around the airport environment, both before and after flight. Accordingly, the effect of ingesting snow during ground operations should be evaluated.

(1) Consistent with service experience, airports continue operations with falling snow concentrations that result in a 0.25 mile or less visibility (about 0.9 gm/m^3, see paragraph 9.g.(2) of this AC). For turbine engines operating in these conditions, in-flight service experience shows that snow sheds from engine or aircraft accumulation sites can cause severe operability affects when ingested by these engines. Typical turbofan or turbojet installations, using simple pitot (straight duct) inlets, have minimal areas for snow accumulation. For these inlets, in-flight icing tests have generally been found to be more critical than snow tests. The applicant should evaluate engine inlets that incorporate plenum chambers, screens, particle-separators, variable geometry, inlet barrier filters (rotorcraft), or any other feature, such as an oil-cooler, struts or fairings, which may provide a potential accumulation site for snow. Further, any airframe accumulation sites upstream of the engine inlet should also be considered by the applicant.

(2) A temperature range of 25^0 to 32^0 Fahrenheit (-4^0 Celsius to $+0^0$ Celsius) is common in a heavy snow environment, and can result in "wet sticky snow" which may accumulate on unheated surfaces (airframe and engine) that are subject to impingement. Engine service events have demonstrated that a snow environment is conducive to ice accretion behind the fan in front compressor stages of the engine, at low engine power. Service experience has demonstrated compressor damage as a result of exposure to prolonged periods of falling snow during ground operation. The new engine test for snow conditions is developed to represent the engine conditions where snow can form accretions aft of the first stage compressor (for example, the fan on turbofan engines) on the core inlet and first stages of the core compressor. The applicant should choose a temperature within the range provided above to achieve icing behind the first stage compressor (for example, the fan for turbofan engines).

p. Test Results. The applicant should carefully consider all evidence of ingestion and damage to the engines, and their potential sources. If damage is incurred, the possible test outcomes include:

(1) Acceptable Damage. The extent of damage is equivalent to or less than what was incurred and accepted during the engine certification testing.

(2) All Systems Operating Normally. The extent of damage is equivalent or less than what was incurred and accepted during the § 33.68 tests.

(3) Delayed Activation of Induction System Anti-Icing. If ice ingestion tests under § 33.77 do not adequately represent the particular airframe installation, then the delayed anti-icing system activation test should be considered (caution should be used and all safety precautions exercised). For this condition, the acceptance criteria described in paragraph 10 of this AC should be used. The airframe manufacturer still must consider all potential ice shedding sites (for example, inboard wing and radome).

(a) Similar to the § 33.77 ice slab ingestion test compliance, the use of engine auto-ignition and recovery systems are allowed when showing compliance with the delayed activation tests of parts 23, 25, 27, or 29, as long as these automatic systems cannot be easily turned off by the flight crew.

(b) The difference in anti-iced inlets versus de-iced inlets is significant. Anti-iced inlets are designed so that no ice accretes on the inlet while operating in icing conditions. De-iced inlets allow some ice accretion, but are designed for a cyclic shedding of ice from the engine inlet into the engine. De-iced inlets typically incorporate, as part of their design, an inlet particle-separator that stops the ingestion of ice into the core of the engine. Engine auto-recovery systems should not be a compensating design feature utilized to minimize the negative effects of an inadequate particle-separating inlet that is not in full compliance with §§ 23.1093, 25.1093, 27.1093, or 29.1093.

(4) Damage From Testing in Non-Representative Icing Conditions. When damage results from icing test conditions that fall significantly outside the icing envelopes depicted in appendices C and O of part 25, appendix C of part 29, or appendix D of part 33, or when the flight test is conducted in an abnormal manner and results in excessive ice shed damage, this may result in a test failure relative to the pretest pass or fail criteria. Any abnormal conditions should be discussed with the FAA to determine if the test can be deemed “passed”. An example of an abnormal operation is flying with one engine at idle while the aircraft is operated in level flight.

(5) Unacceptable Damage. The icing test conditions are representative of in-service encounters, but the resultant airframe or engine ice sheds caused damage that exceeded the acceptance criteria described in paragraph 8.a.(1) of this AC.

q. Compliance for Auxiliary Power Unit (APU) Installations. Compliance for an auxiliary power unit (APU) installation is demonstrated under §§ 23.901(f), 25.901(d) or 29.901(d), but

APUs must also be addressed and shown as acceptable for installation under §§ 23.1093(b), 25.1093(b) or 29.1093(b) (see section 11 of this AC). An essential APU is used to provide air and/or power necessary to maintain safe aircraft operation. A non-essential APU is used to provide air and/or power as a matter of convenience and may be shut down without jeopardizing safe aircraft operation. The icing conditions depicted in appendix O of part 25 are not applicable to APU induction systems on airplanes with a maximum takeoff weight equal to or greater than 60,000 pounds.

(1) Non-Essential APU. An applicant for a transport category airplane with a non-essential APU installation that is restricted from use in icing conditions is not required to show compliance with § 25.1093(b). This includes the icing conditions depicted in appendices C and O of part 25, appendix D of part 33, and in falling and blowing snow conditions. An applicant for a transport category airplane with a non-essential APU installation that is not restricted from use in icing conditions or falling and blowing snow must show compliance with § 25.1093(b). To do this, you must demonstrate that the APU's operation will not affect the safe operation of the airplane when subject to those conditions, both on the ground and in-flight.

(2) Essential APU. An applicant for a transport category airplane with an essential APU installation is required to demonstrate that it can safely operate in natural icing conditions, both on the ground and in-flight. Thus, if you are applying for a transport category airplane icing approval with an essential APU installation, you must show compliance with § 25.1093(b). This includes the icing conditions depicted in appendices C and O of part 25, and appendix D of part 33, and in falling and blowing snow within the limitations established for the airplane for such operation.

(a) Acceptable operation of an APU in the icing conditions depicted in appendix C to part 25 should be demonstrated using the same compliance methods for turbine engine installations described in this AC.

(b) Acceptable operation in the icing conditions depicted in appendix O to part 25 and appendix D to part 33, should be demonstrated using the same compliance methods for turbine engine installations described in this AC. However, many transport category airplane APU installations have an inlet located in the empennage section of the airplane fuselage that can generate a shadowing effect, and thereby prevent large icing droplets (SLD) and ice crystals from entering the APU inlet. For this type of installation, the § 25.1093 compliance for the icing environment depicted in appendix O to part 25 and appendix D to part 33, may be demonstrated by an acceptable validated analysis. To be acceptable, a validated analysis should show that icing conditions depicted in appendix O to part 25 and appendix D to part 33, are adequately addressed by the compliance demonstration for the conditions depicted in appendix C to part 25.

(c) APU compliance with the falling and blowing snow conditions, within the limitations established for the airplane for such operation, should be demonstrated using the same compliance methods for turbine engine installations described in this AC.

12. Conclusion. Although applicants may conduct representative tests under §§ 33.68, 33.77, 23.1093, 25.1093, 27.1093, and 29.1093, flight test events during aircraft certification may still occur which appear inconsistent. In all likelihood, these results will not be inconsistent when evaluated based on the scope, intent, and limitations of the certification testing. Only through appropriate test criteria, appropriate critical point selection, reliable instrumentation, and adequate documentation, can the impact of icing on turbine engines be fully addressed. Because of the relative frequency with which operators experience icing encounters, and because of the potential adverse impact on safety, we recommend all applicants adopt a conservative approach when establishing icing testing plans and demonstrations of compliance.

APPENDIX A

Reference: Low engine speed part 33 compliance testing
(part 33 turbofan and turboprop engines only)

1. The Federal Aviation Administration (FAA; us), Engine and Propeller Directorate, Standards Staff, ANE-110, has been requested to provide a position relative to test time duration during § 33.68 icing tests at non-flight sustainable engine speeds. The following paragraphs provide a technical rationale for the standardized compliance test times for Appendix C conditions. The FAA's position has traditionally been, and continues to be, that engines are held to a higher standard than aircraft for icing certification and the engines must demonstrate unrestricted and unlimited operation in icing conditions. Therefore, during the § 33.68 compliance test demonstration, engines must remain on-point until stable operation is demonstrated.

Some applicants have described this requirement as being burdensome when operating the engine at non-flight sustainable rotor speeds (meaning, below lightweight hold engine operation). In response to this observation, the FAA has developed criteria that allow for a reasonable test period and termination time for icing testing at non-flight sustainable engine speeds. It is emphasized that this criteria is *only* applicable to icing testing when the engine is operating at non-flight sustainable engine speeds.

2. The maximum intermittent maximum liquid water content (LWC) severity depicted in appendix C of part 25 is over three times more severe than the continuous maximum LWC. Due to the significant differences in severity between intermittent maximum and continuous maximum icing conditions depicted in appendix C of part 25, two separate criteria have been considered. They are: (1) short test sequences for the more severe intermittent maximum conditions, and (2) longer test sequences for continuous maximum conditions.

3. Appendix C of part 25, paragraph (a) - Continuous Maximum Icing Conditions. In an effort to preserve flight safety in icing conditions, the FAA strives to retain a margin of safety through suitable demonstrations of compliance. We have established the criteria for part 33 icing testing through conservative assessments, the better to ensure that compliance demonstrations *are* reflective of real world conditions. Our rationale is detailed below.

a. Conservative test perspective. Engine designs should be capable of operations exceeding the single cloud definitions depicted in appendix C of part 25. A robust design is necessary, since an encounter of LWC at a stated inlet temperature, at any mean effective diameter (MED) is a probable event for the cloud length specified. This expected occurrence rate is too frequent to be addressed by tests durations based on a single cloud extent. Thus for demonstration of compliance with § 33.68, we use a test duration representative of multiple cloud extents.

b. Conservative test period: icing test demonstrations at non-flight sustainable speeds. The FAA has developed a conservative methodology for assessing the worst case condition to be expected in service (that is, long descent loiter). The following analysis is intended to show the rationale behind the test duration we have selected for low engine speed testing under § 33.68. This analysis is not based on expected or representative flight profiles or typical icing conditions.

(1) A typical descent gradient for pilots is 3 miles horizontal transit for every 1000-foot vertical descent (15.8:1 gradient). Approximately, this works out to a 60-mile descent initiation test point for a 20,000-foot descent, with a nominal descent slope of about 3.6 degrees. If a conservative 2-degree descent slope is considered, then the descent initiation would start at 120 miles out for a 22,000-foot vertical descent. A total descent altitude of 22,000 feet above ground level (agl) was used because Appendix C goes from sea level to 22,000 feet, although it is recognized that icing occurs at altitudes greater than 22,000.

(2) In order to convert a descent gradient into a meaningful descent rate in feet each minute, a horizontal airspeed must be assumed. For this conservative analysis, an average horizontal air speed of 220 knots (250 miles per hour) is assumed. This average airspeed is for the complete descent through all 22,000 feet, and assumes periodic head winds and profile variations for all types of fixed wing aircraft. This makes the assumption more conservative for transport category aircraft and less conservative for small lightweight propeller aircraft. This is a conservative approximation above 10,000 feet agl, where speed is not limited.

(3) At a 2-degree descent gradient and 220 knots (250 mph) horizontal air speed, the result of these inputs is about a 750 feet descent each minute from 22,000 feet, for a total time of 30 minutes. Consequently, when stabilized operation has not been demonstrated, it is reasonable that engine manufacturers should test engines at flight-idle and up to engine speeds that result in non-sustainable flight (that is, less than light hold power) for a total of not more than 30-minutes of continuous maximum icing operation in the conditions depicted in appendix C of part 25.

4. Appendix C of part 25, part 1, paragraph (b) - Intermittent Maximum Icing Conditions. The intermittent maximum icing conditions depicted in appendix C of part 25, are more severe than the continuous maximum conditions. Just as the previous continuous maximum discussion provides for multiple cloud extents in a series, the same philosophy will be applied here for intermittent maximum conditions, to assure robust design demonstrations. The increased severity of an intermittent cloud depicted in appendix C, in conjunction with the reduced horizontal and vertical extents of these clouds in appendix C, necessitates a proportionately reduced maximum compliance test demonstration period.

The FAA has a very long and successful historical experience base for compliance test demonstrations in intermittent maximum icing conditions. This historical basis has shown that a 10-minute test period has been sufficient. Additionally, the 10-minute period would represent about five to ten sequential intermittent maximum clouds on a horizontal extent basis, depending on aircraft speed, as depicted in appendix C of part 25.

6. Conclusion: Appendix A of this AC provides the rationale for the standard test time durations described in this AC and the icing rule (14 CFR 33.68). In summary, shorter compliance test demonstration periods have been rationalized here for low power descent conditions and for intermittent maximum conditions where there are shorter cloud extents.

APPENDIX B

Advisory Circular Feedback Information

If you have comments or recommendations for improving this advisory circular (AC), or suggestions for new items or subjects to be added, or if you find an error, you may let us know about by using this page as a template and 1) emailing it to 9-AWA-AVS-AIR500-Coord@faa.gov or 2) faxing it to the attention of the AIR Directives Management Officer at 202-267-3983.

Subject (insert AC number and title) Date: (insert date)

Comment/Recommendation/Error: (Please fill out all that apply)

An error has been noted:

Paragraph ____________________

Page ______

Type of error (check all that apply): Editorial:-----Procedural-----

Conceptual____

Description/Comments:____

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Recommend paragraph ______ on page ______ be changed as follows:
(attach separate sheets if necessary)

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In a future change to this advisory circular, please include coverage on the following subject:
(briefly describe what you want added attaching separate sheets if necessary)

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Name: __________________________