Federal Aviation Administration – Regulations and Policies
Aviation Rulemaking Advisory Committee

Transport Airplane and Engine Issue Area
Ice Protection Harmonization Working Group

Task 2 – Review National Transportation Safety Board

Task Assignment

[Federal Register: December 8, 1997 (Volume 62, Number 235)]
[Notices]
[Page **64621**-64623]
From the Federal Register Online via GPO Access [wais.access.gpo.gov]
[DOCID:fr08de97-107]

DEPARTMENT OF TRANSPORTATION

Federal Aviation Administration

Aviation Rulemaking Advisory Committee; Transport Airplane and Engine Issues; New Tasks

AGENCY: Federal Aviation Administration (**FAA**), DOT.

ACTION: Notice of a new task assignment for the Aviation Rulemaking Advisory Committee (ARAC).

SUMMARY: Notice is given of new tasks assigned to and accepted by the Aviation Rulemaking Advisory Committee (ARAC). This notice informs the public of the activities of ARAC.

FOR FURTHER INFORMATION CONTACT:
Stewart R. Miller, Manager, Transport Standards Staff, ANM-110, **FAA**, Transport Airplane Directorate, Aircraft Certification Service, 1601 Lind Ave. SW., Renton, WA 98055-4056, telephone (425) 227-2190, fax (425) 227-1320.

SUPPLEMENTARY INFORMATION:

Background

The **FAA** has established an Aviation Rulemaking Advisory Committee to provide advice and recommendations to the **FAA** Administrator, through the Associate Administrator for Regulation and Certification, on the full range of the **FAA**'s rulemaking activities with respect to aviation-related issues. This includes obtaining advice and recommendations on the **FAA**'s commitment to harmonize its Federal Aviation Regulations (FAR) and practices with its trading partners in Europe and Canada.

One area ARAC deals with is Transport Airplane and Engine issues. These issues involve the airworthiness standards for transport category airplanes in 14 CFR parts 25, 33, and 35 and parallel provisions in 14 CFR parts 121 and 135. The corresponding European airworthiness standards for transport category airplanes are contained in Joint Aviation Requirements (JAR)-25, JAR-E, and JAR-P, respectively. The corresponding Canadian Standards are contained in Chapters 525, 533, and 535 respectively.

The Tasks

This notice is to inform the public that the **FAA** has asked ARAC to provide advice and recommendation on the following harmonization tasks:

Task 1. As a short-term project, consider the need for a regulation that requires installation of ice detectors, aerodynamic performance monitors, or another acceptable means to warn

flightcrews of ice accumulation on critical surfaces requiring crew action (regardless of whether the icing conditions are inside or outside of Appendix C of 14 CFR Part 25). Also consider the need for a Technical Standard Order for design and/or minimum performance specifications for an ice detector and aerodynamic performance monitors. Develop the appropriate regulation and applicable standards and advisory material if a consensus on the need for such devices is reached. (Schedule: September 1998, Reach agreement on proposed rule; January 1999, NPRM package delivered to **FAA** from ARAC; March 1999, Publish NPRM; March 2000, Publish Final Rule.)

As long-term projects:

Task 2. Review National Transportation Safety Board recommendations A-96-54, A-96-56, and A-96-58, and advances in ice protection state-of-the-art. In light of this review, define an icing environment that includes supercooled large droplets (SLD), and devise requirements to assess the ability of aircraft to safely operate either for the period of time to exit or to operate without restriction in SLD aloft, in SLD at or near the surface, and in mixed phase conditions if such conditions are determined to be more hazardous than the liquid phase icing environment containing supercooled water droplets. Consider the effects of icing requirement changes on 14 CFR part 23 and part 25 and revise the regulations if necessary. In addition, consider the need for a regulation that requires installation of a means to discriminate between conditions within and outside the certification envelope. (Schedule: September 1999, Reach technical agreement; January 2000, NPRM package delivered to **FAA** from ARAC; March 2000, Publish NPRM; March 2001, Publish Final Rule.)

Task 3. Propose changes to make the requirements of 14 CFR 23.1419 and 25.1419 the same (Schedule: September 1999, Reach technical agreement; January 2000, NPRM package delivered to **FAA** from ARAC; March 2000, Publish NPRM; March 2001, Publish Final Rule)

Task 4. Harmonize 14 CFR Secs. 23.1419, 25.1419, 25.929, and 25.1093 and JAR 23.1419, 25.1419, 25.929, and 25.1093. (Schedule: September 1999, Reach technical agreement; January 2000, NPRM package delivered to **FAA** from ARAC; March 2000, Publish NPRM; March 2001, Publish Final Rule)

Task 5. Consider the effects icing requirement changes may have on 14 CFR Secs. 25.773(b)(1)(ii), 25.1323(e), 25.1325(b) and revise the regulations if necessary. (Schedule: September 1999, Reach technical agreement; January 2000, NPRM Package delivered to **FAA** from ARAC; March 2000, Publish NPRM; March 2001, Publish Final Rule (if necessary)).

Task 6. Consider the need for a regulation on ice protection of angle of attack probes (Schedule: September 1999, Reach technical agreement; January 2000, NPRM package delivered to **FAA** from ARAC; March 2000, Publish NPRM; March 2001, Publish Final Rule (if necessary)).

Task 7. Develop or update advisory material pertinent to items 2 through 6 above. (Schedule: October 2000, Advisory material package delivered to **FAA** from ARAC; March 2001, Publish advisory material).

If ARAC determines rulemaking action (e.g., NPRM, supplemental NPRM, final rule, withdrawal) should be taken, or advisory material should be issued or revised, it has been asked to prepare the necessary documents, including economic analysis, to justify and carry out its recommendation(s).

ARAC Acceptance of Tasks

ARAC has accepted these tasks and has chosen to assign them to a new Ice Protection Harmonization Working Group (IPHWG) under the Transport Airplane and Engine issue. The new working group will serve as staff to ARAC to assist ARAC in the analysis of the assigned tasks. Working group recommendations must be reviewed and approved by ARAC. If ARAC accepts the working group's recommendations, it forwards them to the **FAA** as ARAC recommendations.

The IPHWG will coordinate with the Flight Test Harmonization Working Group, other harmonization working groups, organizations, and specialists as appropriate. Other affected groups, organizations, and specialists may include but not be limited to the Powerplant Installation Harmonization Working Group, Engine Harmonization Working Group, General Aviation Manufacturers Association (GAMA), human factors specialists, and meteorologists. Coordination with the Flight Test Harmonization Working Group will be necessary to ensure that the IPHWG does not initiate work on issues already being addressed by the Flight Test group. Coordination with GAMA will be necessary to ensure that the proposed NASA Advanced General Aviation Transport Experiment project is considered throughout the process of accomplishing the short and long term projects. The IPHWG will request ARAC assignment of tasks to existing working groups if necessary. The IPHWG will identify to ARAC the need for additional new working groups when existing groups do not have the appropriate expertise to address certain tasks.

Working Group Activity

The Ice Protection Harmonization Working Group is expected to comply with the procedures adopted by ARAC. As part of the procedures, the working group is expected to:

1. Recommend a work plan for completion of the tasks, including the rationale supporting such a plan, for consideration at the meeting of ARAC to consider Transport Airplane and Engine Issues held following publication of this notice.
2. Give a detailed conceptual presentation of the proposed recommendations, prior to proceeding with the work stated in item 3 below.
3. For each task, draft appropriate regulatory documents with supporting economic and other required analyses, and/or any other related guidance material or collateral documents the working group determines to be appropriate; or, if new or revised requirements or compliance methods are not recommended, a draft report stating the rationale for not making such recommendations.
4. Provide a status report at each meeting of ARAC held to consider Transport Airplane and Engine Issues.

Participation in the Working Group

The Ice Protection Harmonization Working Group will be composed of experts having an interest in the assigned tasks. A working group member need not be a representative of a member of the full committee.

An individual who has expertise in the subject matter and wishes to become a member of the working group should write to the person listed under the caption FOR FURTHER INFORMATION CONTACT expressing that desire, describing his or her interest in the tasks, and stating the expertise he or she would bring to the working group. The request will be reviewed by the assistant chair, the assistant executive director, and the working group chair, and the individual will be advised whether or not the request can be accommodated.

The Secretary of Transportation has determined that the formation and use of ARAC are necessary and in the public interest in connection with the performance of duties imposed on the **FAA** by law.

Meetings of ARAC will be open to the public. Meetings of the Ice Protection Harmonization Working Group will not

be open to the public, except to the extent that individuals with an interest and expertise are selected to participate. No public announcement of working group meetings will be made.

Issued in Washington, DC, on November 24, 1997.

Joseph A. Hawkins,
Executive Director, Aviation Rulemaking Advisory Committee.
[FR Doc. 97-32034 Filed 12-5-97; 8:45 am]
BILLING CODE 4910-13-M

Mr. Craig R. Bolt
Assistant Chair, Aviation Rulemaking
Advisory Committee
Pratt & Whitney
400 Main Street, Mail Stop 162-14
East Hartford, CT 06108

Dear Mr. Bolt:

We are changing task 2 assigned to the Ice Protection Harmonization Working Group because of an oversight when we initially assigned the task.

Engine installation and engine icing requirements are in Title 14, Code of Federal Regulations, parts 25 and 33, respectively. When we assigned the task, we addressed part 25 icing requirements, but we failed to adequately address part 33 engine icing requirements. Modifications to part 33 engine icing requirements may be necessary to ensure engines certificated under part 33 can be installed on part 25 airplanes certificated to the new supercooled large droplet icing environment.

As written, task 2 allows the Aviation Rulemaking Advisory Committee (ARAC) to recommend rulemaking development for part 33, but it does not allow ARAC to provide the exact regulatory language. By correcting this oversight, ARAC can provide regulatory language as well as harmonize the language with the European Aviation Safety Agency certification specifications.

Therefore, we are revising the task to read as follows:

> Review National Transportation Safety Board recommendations A-96-54, A-96-56, and A-96-58, and advances in ice protection state-of-the-art. In light of this review, define an icing environment that includes supercooled large droplets (SLD), and devise requirements to assess the ability of aircraft to safely operate either for the period of time to exit or to operate without restriction in SLD aloft, in SLD at or near the surface, and in mixed phase conditions if such conditions are determined to be more hazardous than the liquid phase icing environment containing supercooled water droplets. Consider the effects of icing requirement changes on 14 CFR part 25 ***and part 33*** and

> revise the regulations if necessary. In addition, consider the need for a regulation that requires installation of a means to discriminate between conditions within and outside the certification envelope.

Sincerely,

Anthony F. Fazio
Director, Office of Rulemaking

ARM-209:EUpshaw:fs:12/2/04:DOCS #22073
cc: ARM-1/20/200/209; AIR-1; ANM-110; ANE-100
ANM-98-518-A

Recommendation Letter

Pratt & Whitney
400 Main Street
East Hartford, CT 06108

Pratt & Whitney
A United Technologies Company

March 7, 2005

Federal Aviation Administration
800 Independence Avenue, SW
Washington, D.C. 20591

Attention: Mr. Nicholas Sabatini, Associate Administrator for Aviation Safety

Subject: ARAC Tasking, Ice Protection Harmonization Working Group, Federal Register, December 8, 1997.

Reference Letter: TAEIG to FAA, same subject, dated November 4, 2005 (attached).

Dear Nick,

The reference letter from TAEIG transmitted the Ice Protection Harmonization Working Group Report on Task 2 relating to SLD and ice crystal environments. Minor revisions have been made to the report as outlined in revision tracking sheet of the report and the report is being resubmitted to the FAA as Revision A.

The reference letter also indicated that the IPHWG would be providing recommendations for future research into analytical tools and test techniques relating to SLD and ice crystals. These recommendations are also attached. As stated in the reference letter, TAEIG strongly endorses the recommendation for continued research.

Sincerely,

Craig R. Bolt

C. R. Bolt
Assistant Chair, TAEIG

Copy: Dionne Krebs – FAA-NWR
Mike Kaszycki – FAA-NWR
John Linsenmeyer – FAA-Washington, D.C., ARM-207
Jim Hoppins – Cessna
TAEIG Distribution List

Pratt & Whitney
400 Main Street
East Hartford, CT 06108

Pratt & Whitney
A United Technologies Company

November 4, 2005

Federal Aviation Administration
800 Independence Avenue, SW
Washington, D.C. 20591

Attention: Mr. Nicholas Sabatini, Associate Administrator for Aviation Safety

Subject: ARAC Tasking, Ice Protection Harmonization Working Group, Federal Register, December 8,1997

Dear Nick,

The Transport Airplane and Engines Issues Group is pleased to forward the attached report from the Ice Protection Harmonization Working Group as an ARAC recommendation. The report addresses Task 2 of the reference tasking statement and provides recommended regulatory and advisory material changes relating to SLD and ice crystal environments. The package has been prepared with the support of the Flight Test HWG, the Powerplant Installation HWG and the Engine HWG and would affect 14 CFR 25 and 14 CFR 33. The Working Group did not obtain consensus on all aspects of the report. The minority and majority views are fully documented in the submittal.

The IPHWG notes that the maturity level of analytical tools and test techniques to address the SLD and ice crystal environment are lacking in many aspects, particularly compared with the analytical and test techniques available to address compliance demonstrations for the existing Appendix C icing envelope. Accordingly, the IPHWG strongly recommends that the FAA and NASA continue to fund efforts for development and validation of icing simulation methods (analytical and testing). The IPHWG will be providing the FAA a recommended roadmap for this research effort by the end of 2005.

TAEIG strongly endorses the recommendation for continued research while the ARAC recommendation progresses through the rulemaking process. TAEIG believes this will be critical in order to assure a viable and effective means of compliance at the time the rule is promulgated. TAEIG requests that prior to issuance of an NPRM on this subject, that a Phase 4 review be conducted with the IPHWG. This review is needed to ensure maximum linkage to the progress made in the proposed research activity to the actual NPRM.

TAEIG would like to commend the working groups involved for their outstanding effort on this very challenging topic.

Sincerely yours,

Craig R. Bolt

C. R. Bolt
Assistant Chair, TAEIG

Copy: Dionne Krebs – FAA-NWR
Mike Kaszycki – FAA-NWR
John Linsenmeyer – FAA- Washington DC, ARM-207
Jim Hoppins- Cessna
TAEIG Distribution List

IPHWG Task 2 WG Report 18SEP05.pdf

COPY

U.S. Department
of Transportation

**Federal Aviation
Administration**

800 Independence Ave., S.W.
Washington, D.C. 20591

MAY 22 2006

Mr. Craig R. Bolt
Assistant Chair, Aviation Rulemaking
Advisory Committee
Pratt & Whitney
400 Main Street, Mail Stop 162-14
East Hartford, CT 06108

Dear Mr. Bolt:

This is in reply to your March 7, 2006 letter, transmitting Revision A of the Ice Protection Harmonization Working Group (IPHWG) report on Task 2, dated December 2005. Your letter also transmits recommendations from the Transport Airplane and Engine (TAE) Issues Group for research related to Supercooled Large Droplets (SLD) and ice crystal environments. We acknowledge the need for SLD and ice crystal research to improve the engineering tools available for showing compliance with the ARAC-recommended rules.

I wish to thank the Aviation Rulemaking Advisory Committee (ARAC), the members associated with TAE Issues, and the TAE working groups that provided resources to develop the revised report and recommendation. The revised IPHWG report will be placed on the ARAC website at: http://www.faa.gov/regulations_policies/rulemaking/committees/arac/.

We consider your submittal of the revised IPHWG report as completion of Task 2 of our November 24, 1997, tasking statement. We shall keep the committee apprised of the agency's efforts on this recommendation through the FAA report at future TAE meetings.

Sincerely,

Margaret Gilligan

Nick Sabatini
Associate Administrator for Aviation Safety

23 December 2005

Cessna
A Textron Company

IN REPLY, REFER TO
L374-44-05-005

Mr. Craig R. Bolt
Assistant Chair
Advisory Committee on Transport Aircraft Engines Issues
400 Main Street
East Hartford, CT 06108

Re: L374-44-05-003, dated 19 September 2005 (Submittal of Task 2, Rev. n/c)
L374-44-05-004, dated 19 December 2005 (Submittal of Task 2, Rev. A)

Dear Mr. Bolt:

This letter is provided for submittal of the Ice Protection Harmonization Working Group (IPHWG) Engineering Tool Development Roadmaps in support of Task 2.

As outlined in the original submittal letter (L374-44-05-003), interim means of compliance exist for the SLD and mixed phase/ice crystal rulemaking recommended by the IPHWG, but there is a need for further development and improvement of the engineering certification tools. To meet this need NASA (with cooperation from international research organizations) has developed a SLD roadmap which details a plan for continued development of icing simulation tools. The FAA Technical Center has sponsored development of a mixed phase/ice crystal roadmap that will similarly provide a plan for continued technology development steps required to mature the technology for certification of engines. Both roadmaps are complete and are submitted as enclosures to this letter.

The IPHWG (as well as FTHWG, PPIHWG and EHWG) strongly recommend that the FAA and NASA continue to fund efforts for development and validation of icing simulation methods (analytical and testing). This type of technology development will contribute to public safety by increasing certification confidence as well as ensure robust designs with respect to these types of icing conditions.

CONCLUSION

In conclusion this package is recommended to be approved by TAEIG for transmittal to the FAA with a recommendation for continued support and development of both SLD and mixed phase/ice crystal engineering tool development.

Sincerely,

Jim Hoppins
Co-Chair Ice Protection
Harmonization Working Group

cc:	Robert Park	FTHWG
	Franck Iannarelli	FTHWG
	Andrew Lewis-Smith	PPIHWG
	Jeanne Mason	PPIHWG
	Jerry McRoberts	EHWG
	Robert Mazzawy	EHWG

Task 2 Working Group Report on Supercooled Large Droplet Rulemaking

---

Prepared by:

Ice Protection Harmonization Working Group (IPHWG)

With Recommendations from:
Flight Test Harmonization Working Group (FTHWG)
Powerplant Installation Harmonization Working Group (PPIHWG)
Engine Harmonization Working Group (EHWG)

Revision A - December 2005

Revision Tracking

Revision A - December 2005

Location of change	**Description**
Table of Contents	Updated as required
Appendix K of WG report Page K-55 through K-58	Removed interim placeholder comments and inserted language on an example certification using visual cues (revisions as marked).
Appendix N of WG report Page N-43	Added section A1.4.1.3 discussing visual detection means and recognition times and removed interim placeholder comments (revisions as marked).

TABLE OF CONTENTS

Table of Appendices

Table of Appendices (continued)

Table of Appendices (continued)

Table of Appendices (continued)

Table of Figures

Table of Tables

Abbreviations & Acronyms

Item	**Description**
μm	Micron (one millionth of a meter)
AMS	American Meteorological Society
APM	Aerodynamic performance monitor
Appendix C	14 CFR 25, Appendix C
Appendix X	Proposed 14 CFR 25 new appendix with "X" as a placeholder until specific Appendix is assigned.
CAD	Computer Aided Design
CANICE	Canadian Ice Accretion Code
CAST	Commercial Aviation Safety Team
CFD	Computational Fluid Dynamics
CIP	Current Icing Potential
CPA	Critical Point Analysis
Dmax	Maximum diameter dropsize within a distribution
EHWG	Engine Harmonization Working Group
FMC	Flight Management Computer
FSAT	Flight Standards Information Bulletin for Air Transportation
FTHWG	Flight Test Harmonization Working Group
FZDZ	Freezing Drizzle
FZDZ/G	Freezing Drizzle with an MVD greater than 40μm
FZDZ/L	Freezing Drizzle with an MVD less than 40μm
FZRA	Freezing Rain
FZRA/G	Freezing Rain with an MVD greater than 40μm
FZRA/L	Freezing Rain with an MVD less than 40μm
IPHWG	Ice Protection Harmonization Working Group
IPS	Ice Protection System
JSIT	Joint Safety Implementation Team
k/c	Indicator of relative roughness, k=roughness height, c=chord dimension
LEWICE	Ice Accretion simulation code produced by NASA Glenn, Icing Branch
LOC	Loss of control
LWC	Liquid Water Content
MED	Mean Effective Drop Diameter
MMD	Median mass dimension
MMEL	Master Minimum Equipment List
MSC	Meteorological Service of Canada
MSL	Mean sea level
MTOW	Maximum Take-off Weight
MVD	Median Volume Diameter
NCAR	National Center for Atmospheric Research
PIREPS	Pilot Weather Reports
PMS	Particle Measurement System
PPIHWG	Powerplant Installation Harmonization Working Group
SLD	Supercooled large drops
STC	Supplemental type certificates
SWC	Stall Warning Computer
TWC	Total water content, liquid water content plus ice water content
VFR	Visual Flight Rules
WAT	Weight, Altitude Temperature limits
ZL	Freezing Drizzle
ZR	Freezing Rain

<u>ATTENTION</u>: This Working Group Report was written with the assumption that three icing rules, which have been proposed by ARAC to the FAA, have become final rules by the time that this report is developed into an NPRM. If those three rules are not final at that time, the NPRM will need to be revised to reflect the status of the proposed draft rules. The three rules are: §§25.21(g); 25.1419(e), (f), (g), and (h); and 121.321.

This Working Group Report contains references to the Joint Aviation Authorities (JAA). The report was coordinated with IPHWG members who participated as representatives of the JAA. Coordination with EASA has not been accomplished.

1. BACKGROUND:

This section "tells the story."

- It should include all the information necessary to provide context for the planned action. Only include information that is helpful in understanding the proposal -- no extraneous information (e.g., no "day-by-day" description of Working Group's activities).
- It should provide an answer for all of the following questions:

A. SAFETY ISSUE ADDRESSED/STATEMENT OF THE PROBLEM

(1) What prompted this rulemaking activity (e.g., accident, accident investigation, NTSB recommendation, new technology, service history, etc.)? What focused our attention on the issue?

On October 31, 1994, an accident involving an Aerospatiale Model ATR72 series airplane occurred in which icing conditions, believed to include freezing drizzle drops, were reported in the area. The FAA, Aerospatiale, the French Direction Général de l'Aviation Civile, Bureau Enquete Accident, National Aeronautics and Space Administration, National Transportation Safety Board, and others have conducted an extensive investigation of this accident. This investigation led to the conclusion that freezing drizzle conditions created a ridge of ice on the wing's upper surface aft of the deicing boots and forward of the ailerons. It was further concluded that the ridge of ice resulted in uncommanded roll of the airplane. The atmospheric conditions (freezing drizzle) that may have contributed to the accident are outside of the icing envelope specified in Appendix C of part 25 of the Federal Aviation Regulations (14 CFR part 25) for certification of the airplane. Freezing rain is an atmospheric condition that also is outside of the icing envelope. The FAA has not required that airplanes be shown to be capable of operating safely in freezing drizzle or freezing rain icing conditions.

NTSB Safety Recommendations

The NTSB issued various safety recommendations to the FAA following the Model ATR72 accident. One of the recommendations, A-96-56, states in part that:

> If safe operations in certain icing conditions cannot be demonstrated by the manufacturer, operational limitations should be imposed to prohibit flight in such conditions and flightcrews should be provided with the means to positively determine when they are in icing conditions that exceed the limits for aircraft certification

Another recommendation, A-96-54, states:

> Revise the icing criteria published in 14 Code of Federal Regulations (CFR), parts 23 and 25, in light of both recent research into aircraft ice accretion under varying conditions of liquid water content, drop size distribution, and temperature, and recent developments in both the design and use of aircraft. Also, expand the appendix C icing certification envelope to include freezing drizzle/freezing rain and mixed water/ice crystal conditions, as necessary.

In response to the NTSB safety recommendations, the FAA tasked the Aviation Rulemaking Advisory Committee (ARAC), by notice published in the Federal Register on December 8, 1997 (62 FR 64621), to do the following:

> . . . consider the need for a regulation that requires installation of ice detectors, aerodynamic performance monitors, or another acceptable means to warn flightcrews of ice accumulation on critical surfaces requiring crew action (regardless of whether the icing conditions are inside or outside of appendix C of 14 CFR part 25).

and to:

> . . . define an icing environment that includes supercooled large drops (SLD), and devise requirements to assess the ability of aircraft to safely operate either for the time to exit or to operate without restriction in SLD aloft, in SLD at or near the surface . . . .

(2) What is the underlying safety issue to be addressed in this proposal?

The Part 25 and Part 33 airworthiness rules identify icing conditions (14 CFR 25, Appendix C) upon which approval of airplane operations in icing conditions is based. Appendix C conditions do not include supercooled large drops conditions (which include freezing drizzle and freezing rain), nor does it cover mixed phase and ice crystal icing conditions. The operating rules do not prohibit operations in supercooled large drop conditions or mixed phase and ice crystal icing conditions. The accident and incident history indicates that flightcrews of certain types of aircraft have had power losses and in some cases lost control of their aircraft in such conditions.

(3) What is the underlying safety rationale for the requirement?

Many airplanes have operated without incident in these conditions. However, the performance and handling safety margins are not known for these operations. A required safety margin should be established to help ensure the safety of operations in these conditions.

(4) Why should the requirement exist?

The proposed rule would expand the certification icing environment to include certain freezing drizzle and freezing rain conditions in which an airplane must be capable of safely operating either for the time to exit or without restriction. The proposed rule would require specified safety margins when operating in these icing conditions. Additionally the proposed rule would expand the engine and installation certification icing environment to include certain mixed phase and ice crystal icing conditions.

(5) Concerns with the proposed rule.

NASA is developing codes and test methods to provide airplane manufactures with a means of compliance with the proposed rule. However, the distribution of the NASA products is limited to US companies. This will result in non-US companies being limited in the methods that can be used to comply with the proposed rule. Having all possible means of compliance available to all airplane companies will improve aircraft safety not only in the US but worldwide. Therefore, the IPHWG recommends that NASA take the necessary steps to ensure their aircraft icing products are available to all airplane companies worldwide.

B. CURRENT STANDARDS OR MEANS TO ADDRESS

(1) If regulations currently exist:

(a) What are the current regulations relative to this subject? (Include both the 14 CFR's and JAR's.)

None of the current FAA 14 CFR 25, 14 CFR 33 rules addresses safe operations in freezing drizzle and freezing rain or mixed phase and ice crystal icing conditions JAR E and JAR 25 JAR (EASA) 25 guidance materials do define a mixed phase/ice crystal environment that has had application to pitot probes and engine inlets (ex. AMC 25.1419).

Certification Regulations

The current certification icing regulations that are applicable to transport category airplanes for flight in icing conditions are contained in Title 14, Code of Federal Regulations (14 CFR) part 25 (§§ 25.21(g),25.773, 25.929, 25.1093, 25.1323, 25.1325, 25.1419) and JAR 25.773, 25.929, 25.1093, 25.1323, 25.1325, 25.1419. Both 14 CFR 25.1419 and JAR 25.1419 require that an airplane must be able to safely operate in the continuous maximum and intermittent maximum icing conditions of 14 CFR part 25, Appendix C and JAR 25, Appendix C. Also, icing certification requirements exist for engines in Part 33, sections 33.68 for induction system icing and section 33.77 for ice slab ingestion. Some of the other regulations that address flight in icing conditions require the affected equipment operate to various extents of the icing conditions defined in Appendix C while others do not specify the icing conditions that must be considered.

Appendix C characterizes continuous maximum and intermittent maximum icing conditions within stratiform and cumuliform clouds. Appendix C defines icing cloud characteristics in terms of mean effective drop diameters, liquid water content, temperature, horizontal and vertical extent, and altitude. Freezing drizzle and freezing rain precipitation are not included as these environments typically contain mean effective diameters that are larger than the cloud mean effective drop diameters defined in Appendix C. Consequently, these icing conditions containing freezing drizzle and freezing rain are not considered during the certification of the airplane’s ice protection system, and exposure to these conditions could result in hazardous ice accumulations because the larger diameters typically impinge farther aft on airfoil surfaces. Also, mixed phase and ice crystal icing conditions are not currently considered during the certification of the engine, and exposure to these conditions could result in hazardous ice accumulations within the engine that could result in engine damage and power loss.

Operating Regulations

There are relevant regulations that apply to airplane operations in icing conditions, which are found in 14 CFR part 91 (“General Operating and Flight Rules”), 14 CFR part 121 (“Operating Requirements: Domestic, Flag, and Supplemental Operations”), and 14 CFR part 135 (“Operating Requirements: Commuter and On Demand Operations and Rules Governing Persons on Board Such Aircraft”).

Specifically, § 91.527 (“Operating in icing conditions”) and § 135.227 (“Icing conditions: Operating limitations”) address limitations in icing conditions for aircraft operated under these rules.

Specific requirements regarding exiting hazardous icing conditions are found in § 121.629(a) (“Operation in icing conditions”) which states:

> No person may dispatch or release an aircraft, continue to operate an aircraft en route, or land an aircraft when in the opinion of the pilot in command or aircraft dispatcher (domestic and flag operations only), icing conditions are expected or met that might adversely affect the safety of the flight.

Also, § 121.341 ("Equipment for operations in icing conditions") requires the installation of certain types of ice protection equipment and wing illumination equipment.

14 CFR 121.321 requires airplanes with less than 60,000 lbs maximum takeoff weight and equipped with reversible flight controls for the pitch and/or roll axis to exit icing conditions when the airplane is operated in supercooled large drop conditions conducive to ice accumulation aft of the airframe's protected areas. The regulations require either a substantiated visual cue or a caution level alert to the flightcrew when the airplane is operated in supercooled large drop conditions conducive to ice accumulation aft of the airframe's protected areas.

(b) How have the regulations been applied? (What are the current means of compliance?) If there are differences between the 14 CFR and JAR, what are they and how has each been applied? (Include a discussion of any advisory material that currently exists.)

Advisory material such as JAA interim policy and FAA issue papers are discussed in the section 1.b.(2)(a) of this report.

(c) What has occurred since those regulations were adopted that has caused us to conclude that additional or revised regulations are necessary? Why are those regulations now inadequate?

Investigation of the 1994 accident described above resulted in the NTSB, JAA, FAA, and others concluding that the existing icing conditions used for certification are not adequate. The FAA issued § 121.321 to improve the safety of certain existing airplanes when operated in supercooled large drop conditions not considered by the certification regulations. This proposed rule addresses the safe operation in supercooled large drop conditions of all future part 25 airplanes. Section 1.b.(2)(b) of this report contains a full discussion on the inadequacies of the existing rules. Additionally, there have been documented cases of over 100 ice crystal and mixed phase engine events, with six occurrences of multi-engine flameouts, during the period of 1988 through 2003. During this same period there were 54 aircraft level events of SLD icing engine damage where 56% occurred on multiple engines on an aircraft and two events resulted in an air-turn-back.

(2.) If no regulations currently exist:

(a) What means, if any, have been used in the past to ensure that this safety issue is addressed? Has the FAA relied on issue papers? Special Conditions? Policy statements? Certification action items? Has the JAA relied on Certification Review Items? Interim Policy? If so, reproduce the applicable text from these items that is relative to this issue

As a result of activities following the above-mentioned ATR accident in 1994, the FAA issued a series of Airworthiness Directives (ADs) to minimize the potential hazards associated with operating certain airplanes in severe icing conditions. [Amendment 39-9698, AD 96-09-22 (61 FR 20674, May 7, 1996) is typical of these ADs.] The ADs require certain airplanes to exit icing when the conditions exceed the capabilities of the ice protection equipment.

Additionally, JAA interim policy INT/POL/25/11 “Severe Icing Conditions” and FAA generic issue paper “Roll Control in Supercooled Large Droplet Conditions” have been applied for new certifications on aircraft equipped with unpowered roll axis controls and pneumatic de-icing boots. The interim policy and issue paper do not address operation of other types of aircraft in freezing drizzle and freezing rain conditions. The interim policy and issue paper are intended to provide some protection against loss of control by providing for means of detection and exiting from freezing drizzle and freezing rain conditions. However, they are not intended to certify an airplane for unrestricted flight in supercooled large drops or any other conditions which are outside of the Appendix C icing envelope.

See Appendices A, B, and C of this report for copies of a typical AD, the FAA generic issue paper, and the JAA interim policy.

The FAA has been working with engine manufacturers to identify means to understand ice crystal icing conditions effects on engine operation and develop mitigation design techniques and validated analytical and test techniques for these conditions. Although JAR-E 780(d) provides consideration for ice crystal icing conditions, in practice, engine manufacturers have not provided objective pre-certification evidence of substantiated operation in these conditions.

(b) Why are those means inadequate? Why is rulemaking considered necessary (i.e., do we need a general standard instead of addressing the issue on a case-by-case basis?)

It is important that all airplanes operate safely in freezing rain and freezing drizzle conditions as well as mixed phase and ice crystal icing conditions. However, the JAA interim policy and FAA Airworthiness Directives and issue paper are only applicable to airplanes with unpowered roll controls and pneumatic deicing boots. The § 121.321 rule only addresses airplanes operated under Part 121 that have a MTOW less than 60,000 lbs and are equipped with unpowered roll or pitch controls.

The scope of these actions are also limited because they do not address the underlying safety concern of the unknown performance and handling safety margins for airplanes operating in freezing drizzle or freezing rain or mixed phase and ice crystal conditions. Requirements resulting from these actions are not comparable to those established by the addition of part 25 §25.21(g) that defined safe performance and handling qualities for flight in part 25 Appendix C icing conditions.

The ADs are intended to minimize the potential hazards associated with exposure of the identified airplane types to severe icing conditions by having the flightcrews exit icing conditions when certain visual cues are observed.

The FAA issue paper and the JAA interim policy were intended to address the safety concern of possible roll upset. The large drop icing environment and the dynamics of ice accretion in such conditions were not well understood at the time the policies were issued. Therefore the tests only address possible roll upset due to a ridge of ice aft of the protected area and forward of the ailerons. Extensive research and analyses have been performed to characterize freezing drizzle and freezing rain icing conditions and the resultant definition of the supercooled large drop icing environment differs from the interim environment contained in the issue paper and interim policy. It is recognized that airplanes could develop ice shapes other than those addressed by the issue paper and interim policy which could result in unsafe operations. Also, other considerations in addition to the roll control anomaly identified by the 1994 accident, such as engine operability and other airplane flying qualities, should be addressed when evaluating airplane airworthiness during flight in icing.

The § 121.321 rule only partially addresses the concern of airplanes operating in icing conditions that exceed Appendix C conditions. The rule is not performance based but instead identifies specific conditions (icing conditions conducive to ice accretions aft of the protected area) from which the airplane must exit. Like the AD's, the rule minimizes the potential hazards associated with exposure of the identified airplanes to severe icing conditions.

No aircraft, including those affected by these ADs, policies, or operations rule, are evaluated for potential performance and handling problems when exposed to freezing drizzle and freezing rain.

New and modified airplanes approved for flight in icing conditions, except those limited by the Issue Paper and JAA interim policy, are permitted to operate in freezing drizzle and freezing rain icing conditions, based on recommendations of the airplane manufacturers and decisions of the airplane operators. Operators of future airplanes limited by the Issue Paper and JAA interim policy, will suffer a commercial disadvantage relative to operators of airplanes not subjected to these requirements when these icing conditions exist. There are no airworthiness requirements, similar to those established by the addition of part 25 §25.21(g), for safe flight in freezing drizzle and freezing rain that may be used by affected airplane manufacturers or operators to demonstrate that their airplanes are unfairly limited from such operations, and thereby be relieved of the commercial disadvantage. Conversely, there are no requirements to determine if those airplanes not affected by the Issue Paper and JAA Interim policy should so be limited.

The proposed standards for SLD and mixed phase icing conditions effects on engines were developed when industry, EASA, Transport Canada, and the FAA combined together as an engine and engine installation subgroup under the Ice Protection Harmonization Working Group. A thorough review of service experience in conjunction with meteorological data has allowed a joint approach to developing standards for these icing conditions. This group has developed propulsion rules and guidance material that will be phased in as the industry advances in its understanding of these weather conditions. For Propulsion systems, SLD is addressed in proposed rule changes for 14 CFR Part 33, sections 33.68 and 33.77, and 14 CFR Part 25, section 25.1093. Mixed phase and ice crystal conditions are addressed in proposed rule changes for 14 CFR Part 33, section 33.68, and 14 CFR Part 25, section 25.1093. Guidance material has been developed and is proposed in a revision to AC 20-147. The JAA has previously had ice crystals (glaciated ice) addressed under JAR-E 780(d), but with no specific definition of the environmental threat or related ACJ guidance material defining acceptable means of compliance.

2. DISCUSSION OF PROPOSAL

This section explains:

- *what the proposal would require,*
- *what effect we intend the requirement to have, and*
- *how the proposal addresses the problems identified in Background.*
- *Discuss each requirement separately. Where two or more requirements are very closely related, discuss them together.*
- *This section also should discuss alternatives considered and why each was rejected.*

A. SECTION-BY-SECTION DESCRIPTION OF PROPOSED ACTION

(1) What is the proposed action? Is the proposed action to introduce a new regulation, revise the existing regulation, or to take some other action?

Propose a new part 25.1420 regulation, a new part 25 Appendix X, and a new Part 33 Appendix D. In addition, revise §§25.773, 25.903, 25.929, 25.1093, 25.1323, 25.1325, 33.68, 33.77 and 121.321. See Appendix M of this report for details on the proposed revisions to Part 25 sub-part B.

Note that paragraph (b) of the proposed part 25.1420 requires “one, or more as found necessary, of the following methods must be used:” The words “as found necessary” will be applied in the same way as they are applied in §25.1419(b). During the certification process the applicant will demonstrate compliance with the rule using a combination of analysis and test(s). The applicant’s means of compliance will consist of analysis and the amount and types of testing they find are necessary to demonstrate compliance with the regulation. The applicant will choose to use one or more of the tests identified in paragraphs (b)(1) through (b)(5). Although the applicant may choose their means of compliance, it is ultimately the FAA (EASA) which must make a finding that the applicant has performed sufficient test(s) and analysis to substantiate compliance with the regulation. Similarly, the words “as required” which appear in (b)(3) and (b)(5) will result in the applicant choosing the means of compliance that is necessary to support the analysis but the authorities will make a finding whether the means of compliance is acceptable.

Additionally note that following the proposed 14 CFR § 25.21(g) icing certification performance and handling qualities requirements in 14 CFR part 25 Appendix C icing conditions, similar requirements are proposed for the icing conditions of Appendix X, including defining the ice accretions needed for showing compliance with the proposed revised 14 CFR § 25.21(g) requirements for Appendix X. The proposed ice accretions are defined in part II of the proposed Appendix X.

(2) If regulatory action is proposed, what is the *<u>text</u>* *of the proposed regulation?*

<u>Proposals 1 through 25 - 14 CFR 25 Sub-Part B:</u>

See Appendix M of this report for Proposals 1 through 25 relative to 14 CFR 25, subpart B

<u>Proposal 26 - New Part 25.1420 Regulation:</u>

§25.1420 Supercooled large drop icing conditions
(a) If certification for flight in icing conditions is desired, in addition to the requirements of §25.1419 the airplane must be capable of (a)(1), (a)(2) or (a)(3).
(1) Operating safely after encountering Appendix X conditions:

(i) There must be a means provided to detect that the airplane is operating in Appendix X; and

(ii) Following detection, the airplane must be capable of operating safely while exiting all icing conditions.

(2) Operating safely in a portion of Appendix X as selected by the applicant.

(i) There must be a means provided to detect that the airplane is operating in conditions that exceed the selected portion of Appendix X; and
(ii) Following the exceedance of the selected portion of Appendix X, the airplane must be capable of operating safely while exiting all icing conditions.

(3) Operating safely in the icing conditions of Appendix X.

(b) To establish that the airplane can operate safely as required in paragraph (a), an analysis must be performed to establish that the ice protection for the various components of the airplane is adequate, taking into account the various airplane operational configurations; and one, or more as found necessary, of the following methods must be used:

(1) Laboratory dry air or simulated icing tests, or a combination of both, of the components or models of the components.
(2) Laboratory dry air or simulated icing tests, or a combination of both, of models of the airplane.
(3) Flight tests of the airplane or its components in simulated icing conditions, measured as required to support the analysis.
(4) Flight tests of the airplane with simulated ice shapes.
(5) Flight tests of the airplane in natural icing conditions, measured as required to support the analysis.

(c) For an airplane certificated in accordance with (a)(2) or (a)(3) the requirements of 25.1419(e), (f), (g), and (h) must be met for the selected portion or all of Appendix X as applicable.

Proposal 27 - New Part 25 Appendix X

Part 25, Appendix X

Appendix X consists of two parts. Part I defines Appendix X as supercooled large drop (SLD) icing conditions in which the drop median volume diameter (MVD) is less than or greater than 40 μm, the maximum mean effective drop diameter (MED) of Appendix C continuous maximum (stratiform clouds) icing conditions. For Appendix X, supercooled large drop icing conditions consist of freezing drizzle and freezing rain and can consist of precipitation in and/or below stratiform clouds. Part II defines ice shapes used to show compliance with 14 CFR § 25.21(g) requirements for continuous flight or for flight in a portion of Appendix X.

PART I – METEOROLOGY

Appendix X icing conditions are defined by the parameters of altitude, vertical and horizontal extent, temperature, liquid water content, and water mass distribution as a function of drop diameter distribution.
a. Freezing Drizzle (Conditions with spectra maximum drop diameters from 100μm to 500 μm)

1. Pressure altitude range: 0 to 22,000 feet MSL
2. Maximum vertical extent: 12,000 feet
3. Horizontal extent: standard distance of 17.4 nautical miles

4. Total liquid water content (cloud and precipitation):
   Note: LWC based on horizontal extent standard distance of 17.4 nm.

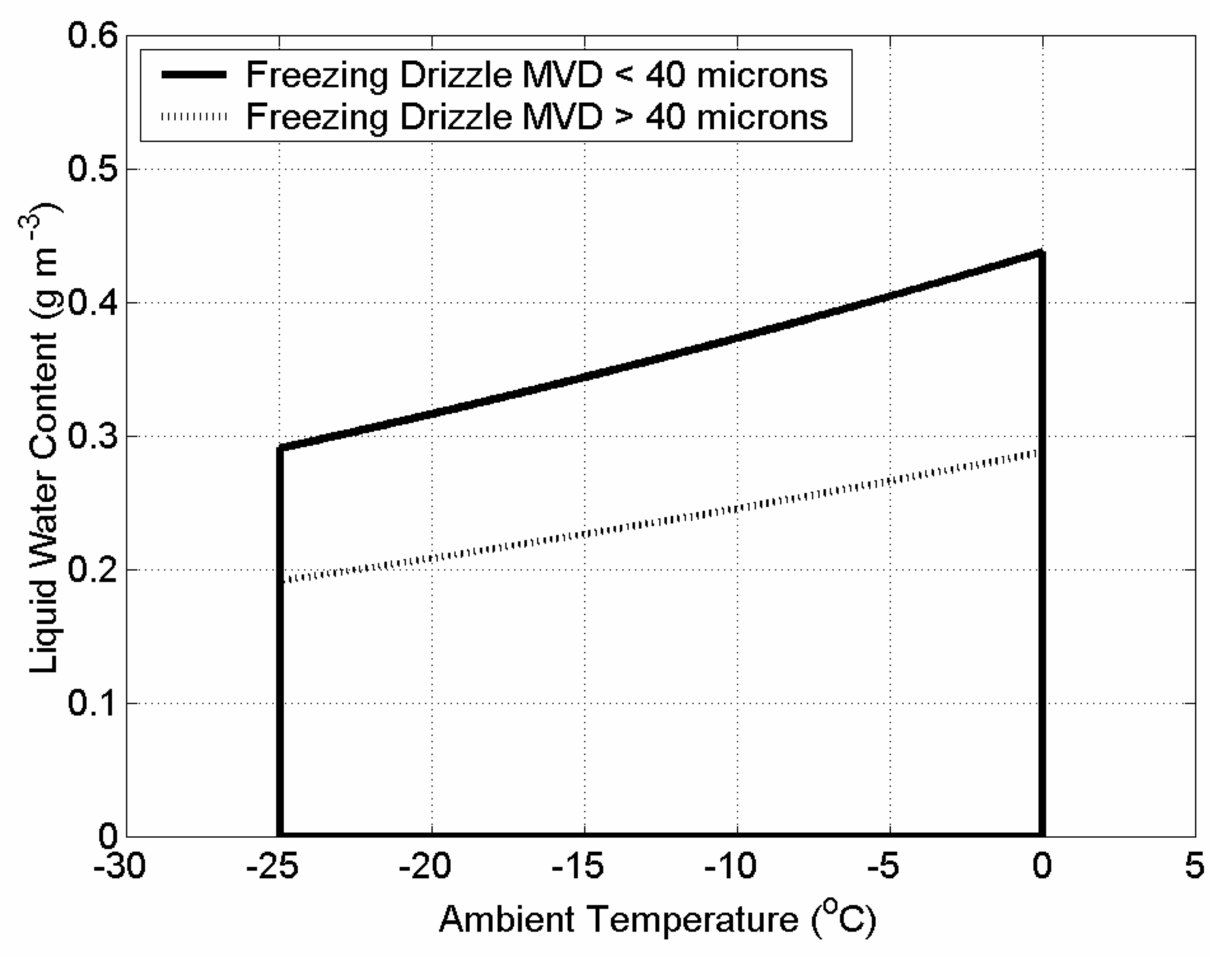


Figure 1 - 14 CFR 25, Appendix X, Freezing Drizzle, Liquid Water Content

5. Drop diameter distribution:

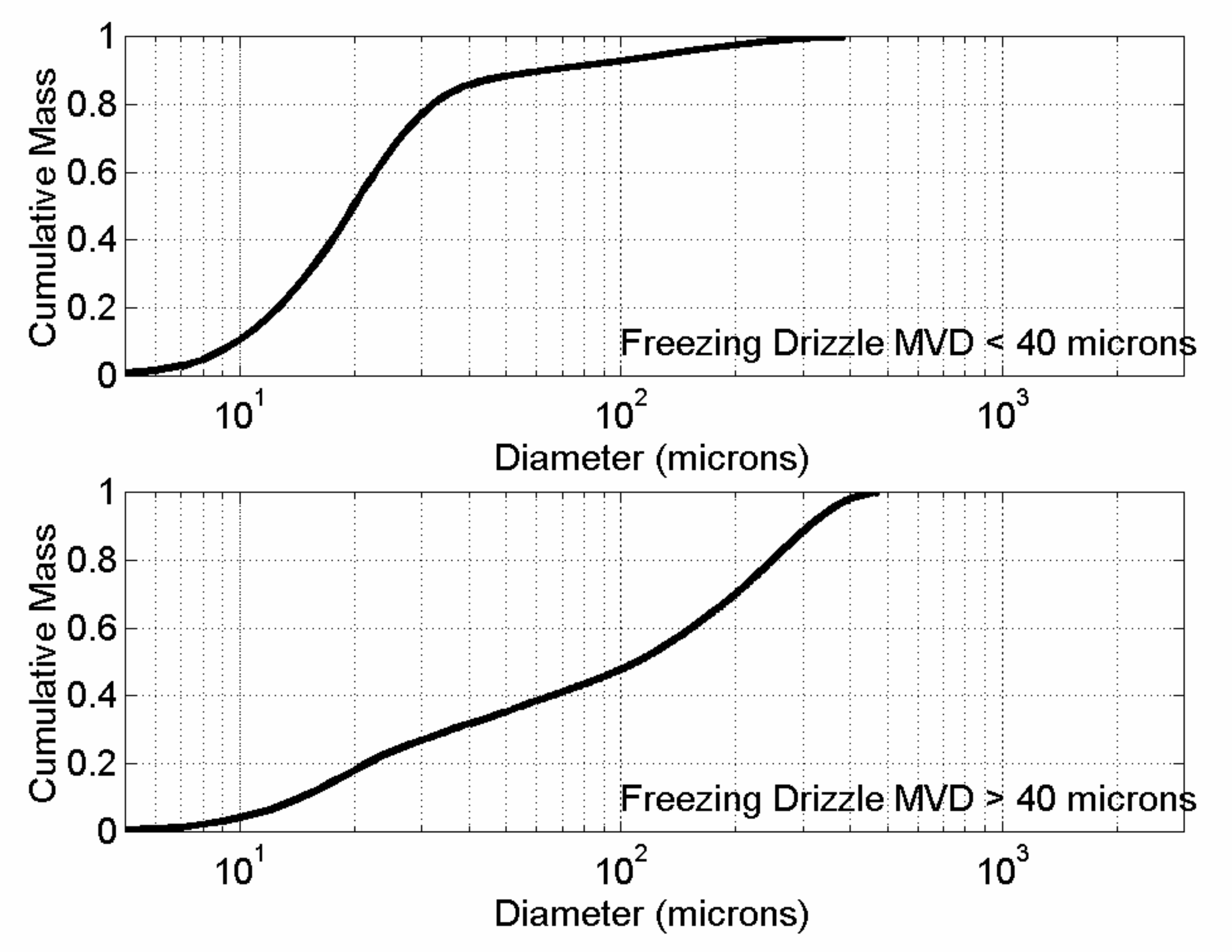


Figure 2 - 14 CFR 25, Appendix X, Freezing Drizzle, Drop Diameter Distribution

6. Altitude and temperature envelope:

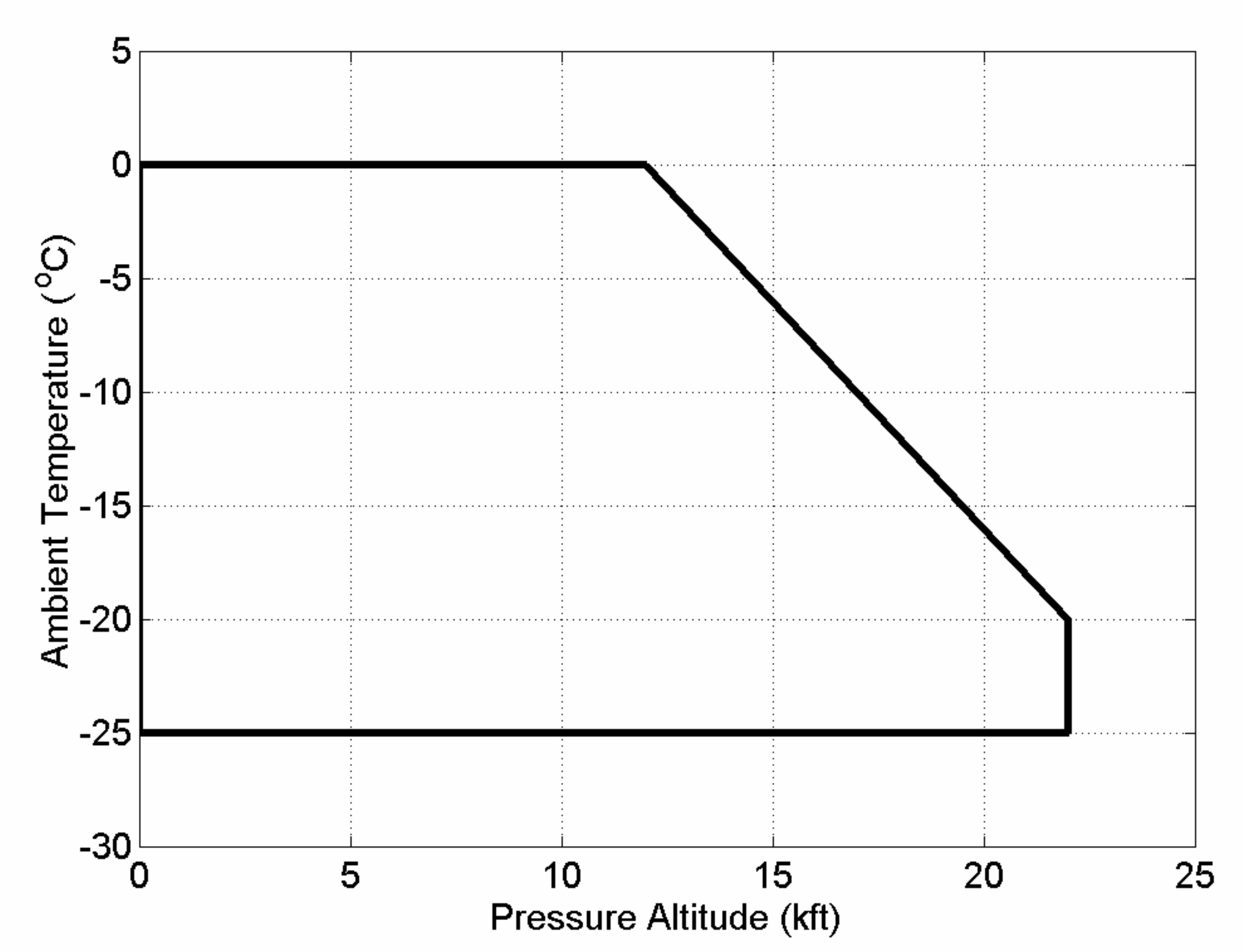


Figure 3 - 14 CFR 25, Appendix X, Freezing Drizzle, Temperature and Altitude

b. Freezing Rain (Conditions with spectra maximum drop diameters greater than 500 µm)

1. Pressure altitude range: 0 to 12,000 ft MSL
2. Maximum vertical extent: 7,000 ft
3. Horizontal extent: standard distance of 17.4 nautical miles
4. Total liquid water content (cloud and precipitation)
   Note: LWC based on horizontal extent standard distance of 17.4 nm.

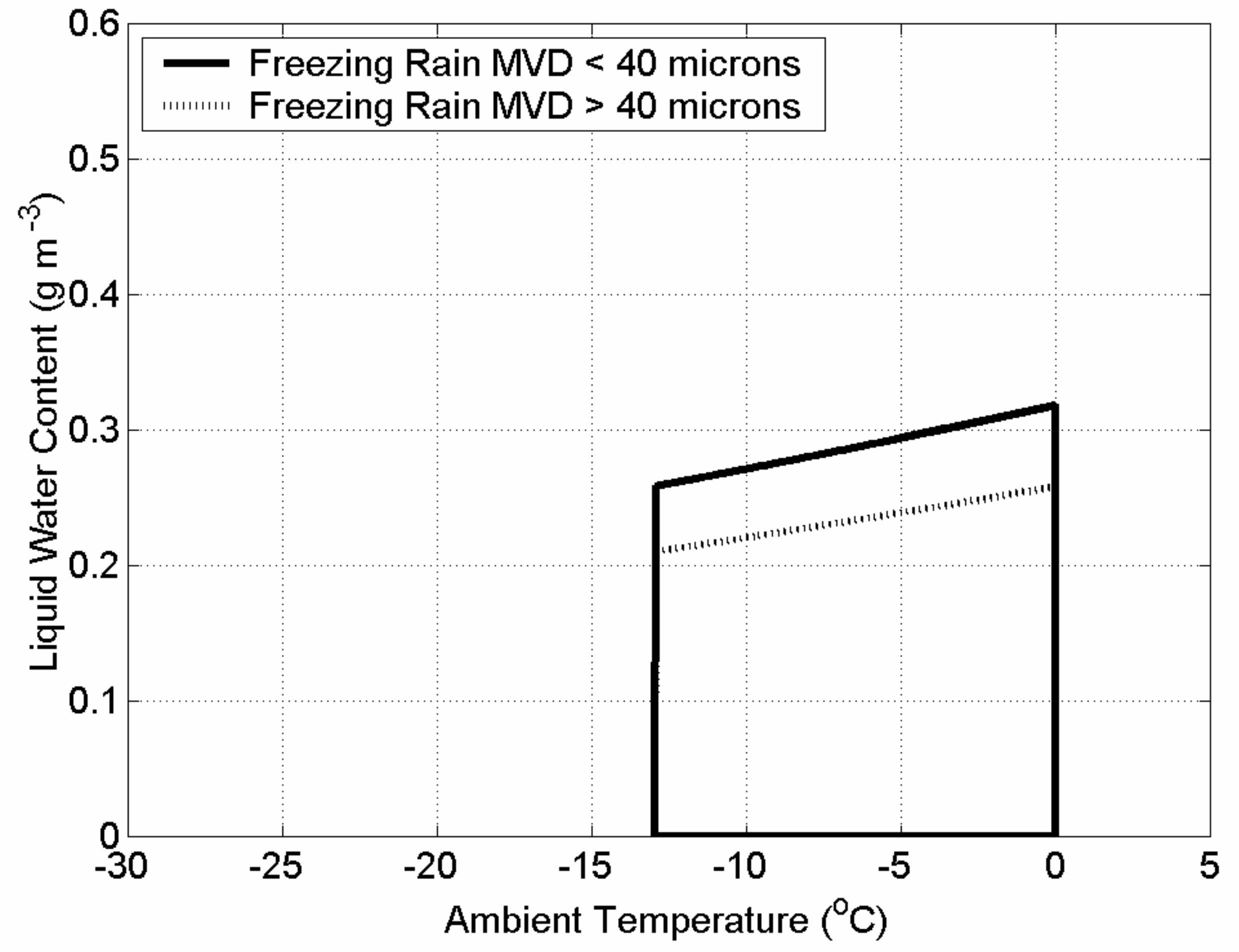


Figure 4 - 14 CFR 25, Appendix X, Freezing Rain, Liquid Water Content

5. Drop Diameter Distribution

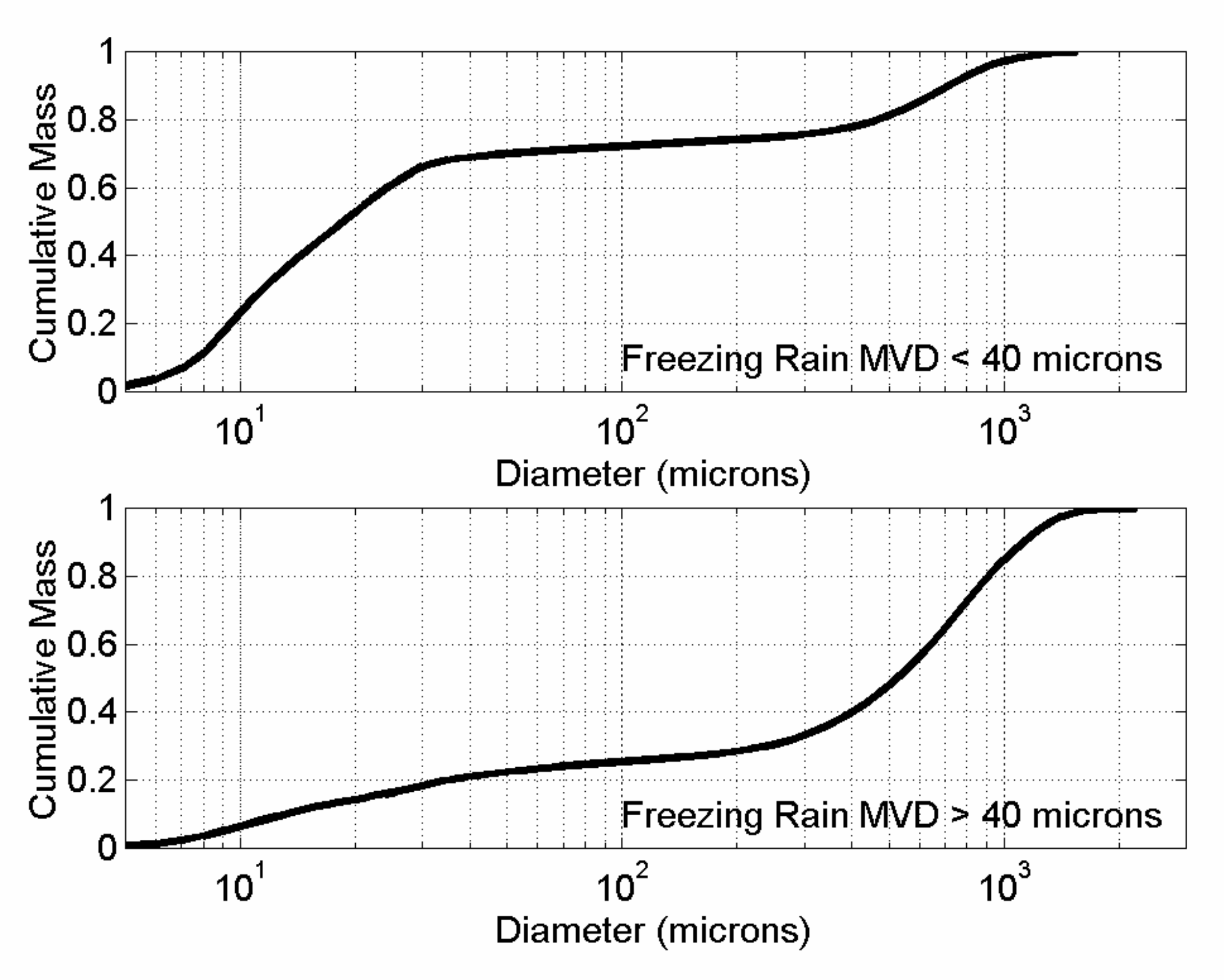


Figure 5 - 14 CFR 25, Appendix X, Freezing Rain, Drop Diameter Distribution

6. Altitude and temperature envelope:

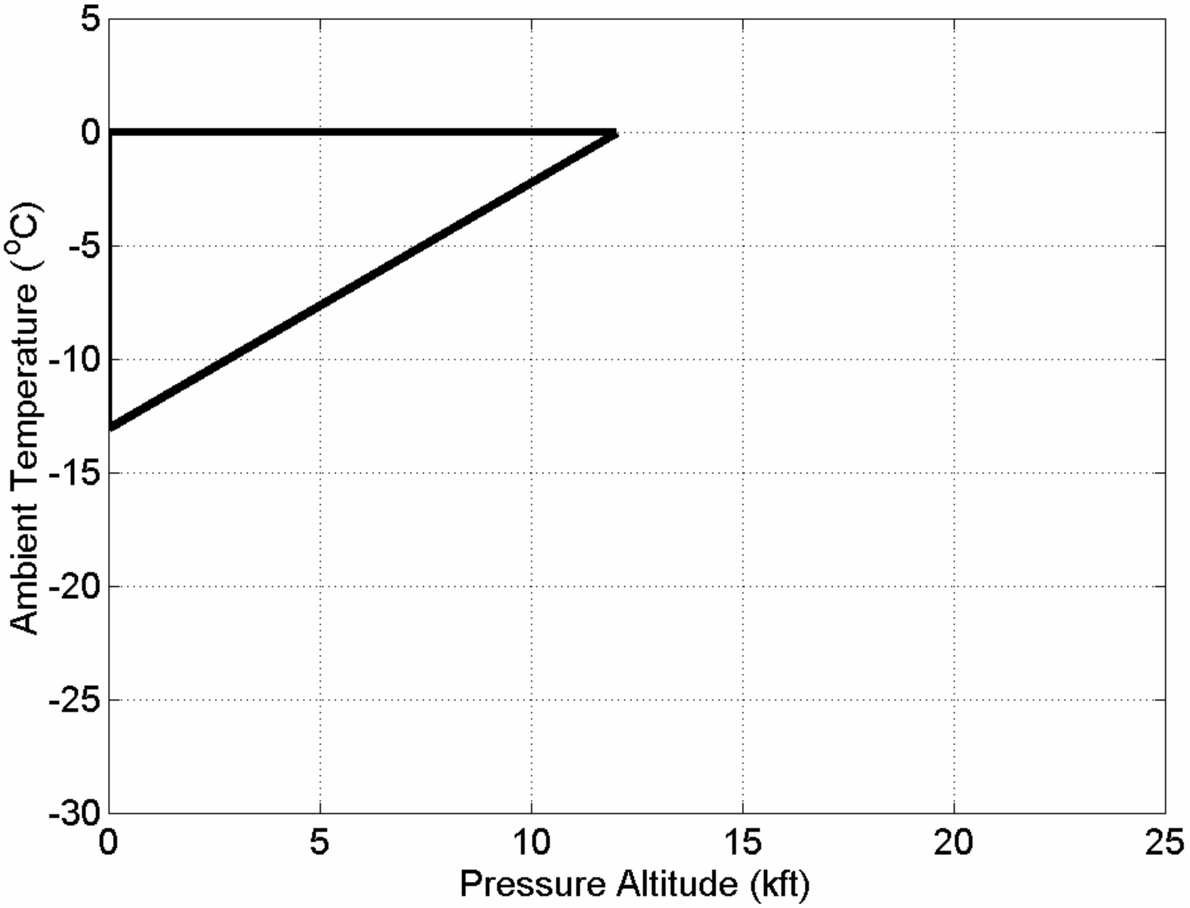


Figure 6 - 14 CFR 25, Appendix X, Freezing Rain, Temperature and Altitude

c. Horizontal extent

The liquid water content for freezing drizzle and freezing rain conditions for horizontal extents other than the standard 17.4nm can be determined by the value of the liquid water content determined from Figure 1 or Figure 4, multiplied by the factor provided in Figure 7.

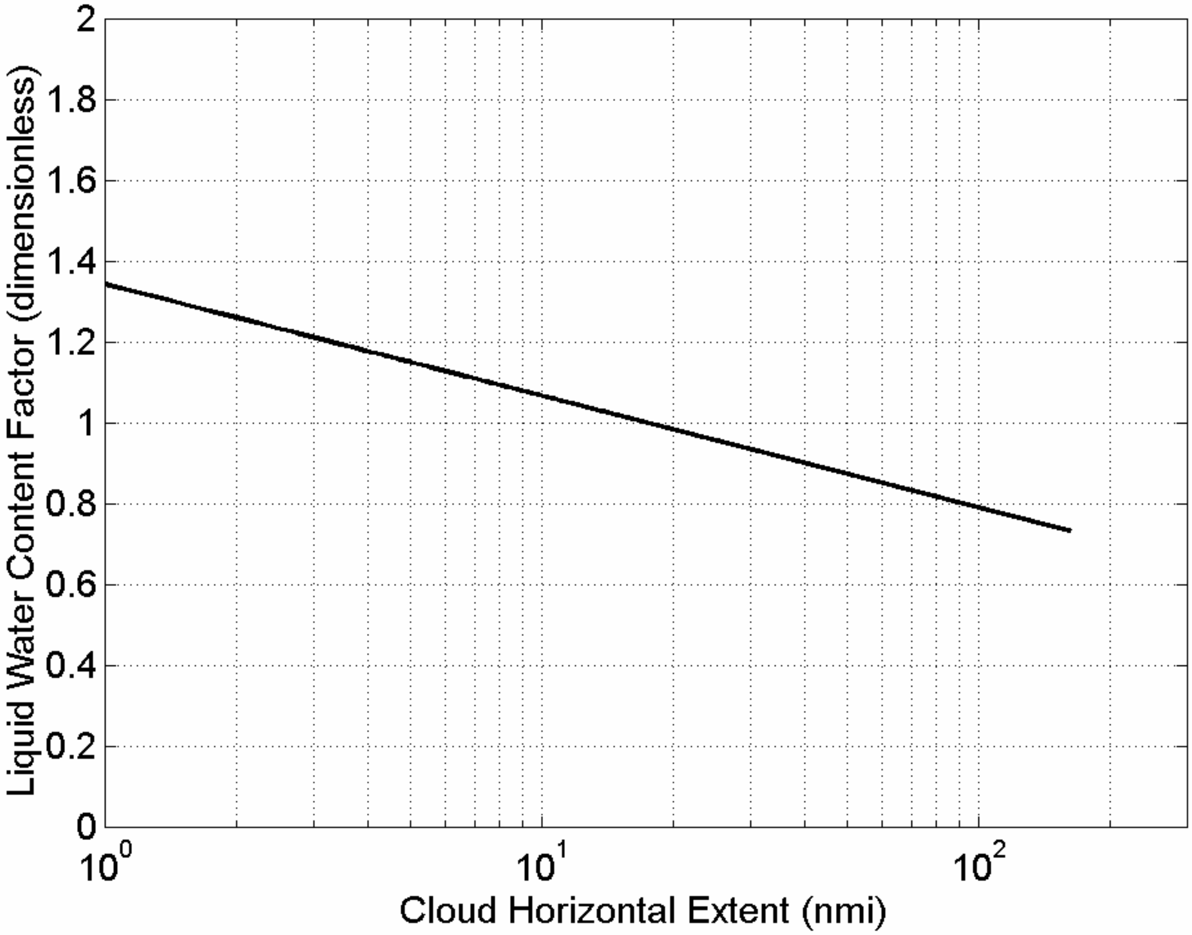


Figure 7 - 14 CFR 25, Appendix X, Horizontal Extent, Freezing Drizzle and Freezing Rain

PART II – AIRFRAME ICE ACCRETIONS FOR SHOWING COMPLIANCE WITH SUBPART B

a. General

14 CFR §25.21(g) states that if certification for flight in icing conditions is desired, the requirements of subpart B must be met (except as specified otherwise) with the ice accretions of part II of Appendix C and part II(b) of this appendix. The most critical ice accretion in terms of handling characteristics and performance for each flight phase must be determined, taking into consideration the atmospheric icing conditions of part I of this appendix, and the flight conditions required by §25.21(g) (for example, configuration, speed, angle of attack, and altitude).

b. Ice accretions

(1) Certification for Appendix X icing conditions defined in Part I of this appendix, or a portion thereof, as required by §§ 25.1420(a)(2) and 25.1420(a)(3).

(a) Takeoff Ice

Takeoff ice is most critical ice accretion on unprotected surfaces, and any ice accretion on the protected surfaces appropriate to normal ice protection system operation, occurring between liftoff and 400 feet above the takeoff surface, assuming accretion starts at liftoff.

(b) Final takeoff ice

Final takeoff ice is the most critical ice accretion on unprotected surfaces, and any ice accretion on the protected surfaces appropriate to normal ice protection system operation, between 400 feet and 1,500 feet above the takeoff surface, assuming ice accretion starts at liftoff.

(c) En route Ice

En route Ice is the most critical ice accretion on the unprotected surfaces, and any ice accretion on the protected surfaces appropriate to normal ice protection system operation, during the en route flight phase.

(d) Holding Ice

Holding ice is the most critical ice accretion on the unprotected surfaces, and any ice accretion on the protected surfaces appropriate to normal ice protection system operation, resulting from 45 minutes of flight within the 17.4 nautical miles cloud horizontal extent standard distance during the holding phase of flight.

(e) Approach ice

Approach ice is the more critical ice accretion of the following:

(i) Ice accumulated during descent from the maximum vertical extent of the icing environment described in part I of this appendix to 2,000 feet above the landing surface in the cruise configuration, and transition to the approach configuration and maneuvering for 15 minutes at 2,000 feet above the landing surface.
(ii) Holding ice as defined by Part II b(1)(d).

(f) Landing Ice

Landing ice is the more critical ice accretion of the following:
(i) The ice accretion defined by Part II b(1)(e)(i)) plus ice accumulated during a descent from 2,000 feet above the landing surface to a height of 200 feet above the landing surface with a transition to the landing configuration, a go-around maneuver, beginning with the minimum climb requirements of 14 CFR § 25.119, from a height of 200 feet above the landing surface to 2,000 feet above the landing surface, maneuvering for 15 minutes at 2,000 feet above the landing surface in the approach configuration, and a descent to the landing surface (touchdown) in the landing configuration.
(ii) Holding ice as defined by Part II b(1)(d).

(g) Ice accretion for the takeoff phase

For both unprotected and protected surfaces, the ice accretion may be determined by calculation, assuming the icing conditions described in part I of this appendix, and that:

(i) Airfoils, control surfaces, and, if applicable, propellers are free from frost, snow, or ice at the start of takeoff,
(ii) The ice accretion begins at liftoff,
(iii) The critical ratio of thrust/power-to-weight,
(iv) Failure of the critical engine occurs at V_{EF}, and
(v) Crew activation of the ice protection system is in accordance with a normal operating procedure provided in the Airplane Flight Manual in accordance with § 25.1581(a)(1), except that after commencement of the takeoff roll no crew action to activate the ice protection system should be assumed to occur until the airplane is 400 feet above the takeoff surface.

(h) Ice accretion before normal system operation

Ice accretion prior to normal system operation (pre-activation ice) is the ice accretion formed on the unprotected and normally protected surfaces before the activation and effective operation of any ice protection system. The ice accretion includes that accumulated during the detection of the icing condition, during activation of the ice protection systems, and during the period required for the ice protection systems to become fully effective in performing their intended functions.

(i) Failure ice

Failure ice is the critical holding ice on unprotected surfaces, as defined by paragraph part II b(1)(d) of this appendix, plus the critical ice accretion on protected surfaces accumulated during 22.5 minutes of exposure to the critical icing conditions of part I of this appendix (total accumulation limited to 45 minutes). If failure of the ice protection system is unannounced or if Airplane Flight Manual procedures do not call for exiting icing conditions following an ice protection system failure, the failure ice is the same as the ice accretion normally considered for unprotected surfaces. For airplanes certificated in accordance with 25.1420(a)(1) failure ice need not be considered. For airplanes certificated in accordance with 25.1420(a)(2) failure ice need only be considered for the selected portion of appendix X.

(2) Certification for detecting and exiting the icing conditions defined in part I of this appendix, as required by §§ 25.1420(a)(1) and 25.1420(a)(2).

For determining detect-and-exit ice accretions, pre-existing ice accretions may exist from operations in approved icing conditions prior to encountering the icing conditions requiring an exit. For aircraft certified under 25.1420(a)(2), these pre-existing ice accretions should be based on the approved portion of Appendix X as determined in paragraph part II b(1) of this appendix. For aircraft certified under 25.1420(a)(1), the pre-existing ice accretions should be based on Appendix C.

(a) En route detect-and-exit Ice

En route detect-and-exit Ice is en route ice, as defined by paragraph part II b(1)(c) of this appendix (25.1420(a)(2) certifications) or by paragraph part II (a)(3) of 14 CFR part 25 Appendix C (25.1420(a)(1) certifications), as applicable, plus pre-detection ice, as described by paragraph part II b(2)(e) of this appendix, and the ice accumulated during the transit of one standard cloud horizontal extent (17.4 nautical miles) of the icing environment described in part I of this appendix and one standard cloud horizontal extent (17.4 nautical miles) of the continuous maximum icing environment described in Appendix C of 14 CFR part 25.

(b) Holding detect-and-exit Ice

Holding detect-and-exit ice is holding ice, as defined by paragraph part II b(1)(d) of this appendix (25.1420(a)(2) certifications) or by paragraph part II (a)(4) of 14 CFR part 25 Appendix C (25.1420(a)(1) certifications), as applicable, plus pre-detection ice, as described by paragraph part II b(2)(e) of this appendix, and the ice accumulated during the transit of one standard cloud horizontal extent (17.4 nautical miles) of the icing environment described in part I of this appendix and one standard cloud horizontal extent (17.4 nautical miles) of the continuous maximum icing environment described in part I of 14 CFR part 25 Appendix C. The total exposure to the icing conditions need not exceed 45 minutes.

(c) Approach detect-and-exit ice

Approach detect-and-exit ice accretion is the more critical of the following:

(i) Ice accumulated during descent from the maximum vertical extent of the icing environment described in part I of this appendix to 2,000 feet above the landing surface in the cruise configuration (25.1420(a)(2) certifications) or descent from the maximum vertical extent of the maximum continuous icing environment described in part I of 14 CFR part 25 Appendix C (25.1420(a)(1) certifications), as applicable, transition to the approach configuration, plus pre-detection ice, as described by paragraph part II b(2)(e) of this appendix, and the ice accumulated during the transit at 2,000 feet above the landing surface of one standard cloud horizontal extent (17.4 nautical miles) of the icing environment described in part I of this appendix and one standard cloud horizontal extent (17.4 nautical miles) of the continuous maximum icing environment described in part I of 14 CFR part 25 Appendix C.

(ii) Holding detect-and-exit ice as defined by Part II b(2)(b).

(d) Landing detect-and-exit ice

Landing detect-and-exit ice accretion is the more critical of the (i) or (iii):

(i) Approach ice, as defined by paragraph part II b(1)(f)(i) of this appendix plus a descent from 2,000 feet above the landing surface to the a height of 200 feet above the landing surface with a transition to the landing configuration (25.1420(a)(2) certifications) or approach and landing ice in 14 CFR part 25 Appendix C icing conditions as described by ii of this section (25.1420(a)(1) certifications), as applicable, plus pre-detection ice, as described by paragraph part II b(2)(e) of this appendix, and the ice accumulated during an exit maneuver, beginning with the minimum climb requirements of 14 CFR part 25 Section 25.119, from a height of 200 feet above the landing surface through one standard cloud horizontal extent (17.4 nautical miles) of the icing environment described in part I of this appendix and one standard cloud horizontal extent (17.4 nautical miles) of the continuous maximum icing environment described in part I of 14 CFR part 25 Appendix C.

(ii) Approach & Landing ice in the maximum continuous icing conditions described in part I of 14 CFR part 25 Appendix C is the ice accumulated during a descent from the maximum vertical extent of Appendix C part I maximum continuous icing conditions to 2,000 feet above the landing surface in the cruise configuration, and transition to approach configuration and maneuvering for 15 minutes at 2,000 feet above the landing surface, a descent from 2,000 feet above the landing surface to the a height of 200 feet above the landing surface with a transition to the landing configuration.

(iii) Holding detect-and-exit ice as defined by Part II b(2)(b).

(e) Ice accretion before detection of Appendix X icing conditions (pre-detection ice)

Ice accretion before detection of Appendix X conditions which require exiting per 25.1420(a)(1) and (a)(2), is the ice accretion formed on the unprotected and normally protected surfaces or on pre-existing ice. The pre-detection ice must consider the ice accumulated during the period required to detect the icing conditions (considering the provided means of detection) followed by two minutes of ice accumulation to represent the period for the flight crew to reference and implement prescribed procedures to exit the icing conditions including coordination with air traffic control.

(3) Use of conservative ice accretions

To reduce the number of ice accretions needed to show compliance with 14 CFR §25.21(g), the most conservative ice accretion may be used.

-----------------------END OF APPENDIX X------------------------

REVISED REGULATIONS

(Note: new words are in **bold**)

Proposal 28 - Reserved

Proposal 29 - Sec. 25.773 – Pilot compartment view

Sec. 25.773(b)(1)(ii): The icing conditions specified in **Appendices C and X** ~~§ 25.1419~~ if certification ~~with ice protection provisions~~ **for flight in icing conditions** is ~~requested~~ **desired.**

Proposal 30 - Section 25.903 - Engines

Add section (a)(3)

(3) Each turbine engine must comply with one of the following:

(i) Section 33.68 of this chapter in effect on [insert effective date of final rule], or as subsequently amended; or

(ii) Comply with § 33.68 of this chapter in effect on February 23, 1984, or as subsequently amended before [insert effective date of final rule], unless that engine's ice accumulation service history has resulted in an unsafe condition; or

(iii) Comply with § 33.68 of this chapter in effect on October 1, 1974, or as subsequently amended prior to February 23, 1984, unless that engine's ice accumulation service history has resulted in an unsafe condition; or

(iv) Be shown to have an ice accumulation service history in similar installation locations which has not resulted in any unsafe conditions.

Proposal 31 - Sec. 25.929 – Propeller deicing

Sec. 25.929(a): **If certification for flight in icing is desired.** ~~For airplanes intended for use where icing may be expected~~, there must be a means to prevent or remove hazardous ice accumulations **that could form in the icing conditions specified in Appendices C and X of this part**, on propellers or on accessories where ice accumulation would jeopardize engine performance.

Proposal 32 - Sec. 25.1093 – Induction system icing protection

Revise section (b) Turbine Engines.

Each engine, with all icing protection systems operating, must:

1. Operate throughout its flight power range, in continuous maximum and intermittent maximum icing conditions as defined in Appendix C, Appendix X of Part 25 of this chapter, and Appendix D of Part 33 of this chapter, in falling and blowing snow within the limitations established for the airplane for such operation, including the minimum descent idling speeds in icing, without the accumulation of ice on the engine, inlet system components or airframe components that:

- ***I. Adversely affects installed engine operation or that causes a permanent loss of power or thrust ; or unacceptable increase in operating temperature; or cause an airframe/engine incompatibility; or***
- ***II. Results in unacceptable temporary power loss or engine damage; or***
- ***III. Causes a stall, surge, or flameout or loss of engine controllability (for example, rollback).***

2) Idle for a minimum of 30-minutes on the ground in the following icing conditions shown in Table 25.1093-1 [sic: ref. Table 1 of this report]***, unless replaced by similar test conditions that are more critical. These conditions must be demonstrated with the available air bleed for icing protection at its critical condition, without adverse effect, followed by an acceleration to takeoff power or thrust. During the idle operation the engine may be run up periodically to a moderate power or thrust setting in a manner acceptable to the Administrator. The applicant must document any demonstrated run ups and minimum ambient temperature capability during the conduct of icing testing in the limitations section of the Aircraft Flight Manual (AFM).***

Condition	***Total Air Temperature***	***Water Concentration (minimum)***	***Mean Effective Particle Diameter***	***Demonstration***
1. Rime ice condition	***0 to 15 °F (-18 to -9 °C)***	***Liquid - 0.3 gm/m3***	***15-25 microns***	***By test, analysis or combination of the two.***
2. Glaze ice condition	***20 to 30 °F (-7 to -1 °C)***	***Liquid - 0.3 gm/m3***	***15-25 microns***	***By test, analysis or combination of the two.***
3. Large droplet condition	***15 to 30 °F (-9 to -1 °C)***	***Liquid - 0.3 gm/m3***	***100 microns (minimum)***	***By test, analysis or combination of the two.***

Table 1 - "Table 25.1093-1"

Proposal 33 - Sec. 25.1323 – Airspeed indicating system

> Sec. 25.1323(e): Each system must have a heated pitot tube or an equivalent means of preventing malfunction due to icing **conditions specified in appendices C and X of this part**.

Proposal 34 - Sec. 25.1325 – Static pressure system

> Sec. 25.1325(b): . . . and that the correlation between air pressure in the static pressure system and true ambient atmospheric static pressure is not changed when the airplane is exposed to the continuous and intermittent maximum icing conditions defined in appendix C **and the icing conditions defined in appendix X** of this part.

Proposal 35 - Section 33.68 - Induction System Icing

Each engine, with all icing protection systems operating, must:

A. Operate throughout its flight power range, including the minimum descent idling speeds, in icing conditions as defined in Appendix C, Appendix X of Part 25 of this chapter, and Appendix D of Part 33 of this chapter without the accumulation of ice on the engine components that:

1) ***Adversely affects engine operation or that causes an unacceptable permanent loss of power or thrust or unacceptable increase in engine operating temperature; or***
2) ***Results in unacceptable temporary power loss or engine damage; or***
3) ***Causes a stall, surge, or flameout or loss of engine controllability (for example, rollback). The applicant must account for in-flight ram effects (for example; scoop factor amplification, water temperature, air density) in any critical point analysis or test demonstration of these flight conditions.***

B. Operate throughout its flight power range (including minimum descent idling speeds in icing) in continuous maximum and intermittent maximum icing conditions as defined in Appendix C, and Appendix X of Part 25 of this chapter. In addition,:

1) ***It must be shown through Critical Point Analysis (CPA) that the complete ice envelope has been analyzed, and that the most critical points must be demonstrated by engine test, analysis or a combination of the two to operate acceptably. Extended flight in critical flight conditions such as hold, descent, approach, climb, and cruise, must be addressed, for these ice conditions.***
2) ***It must be demonstrated by engine test, analysis or a combination of the two that the engine can run for a duration that achieves the following compliance requirements:***
    (a) At engine powers that can sustain level flight:

A duration that achieves repetitive, stabilized operation in part 25, Appendix C and in large droplet icing conditions of part 25, Appendix X.

(b) At engine power below that which can sustain level flight:

  i. Demonstration in altitude flight simulation test facility:

  A duration of 10 minutes consistent with a simulated flight descent of 10000 ft (3 km) operation in Continuous Maximum icing conditions, plus 40 percent liquid water content margin, at the critical level of airspeed and air temperature, or

  ii. Demonstration in ground test facility:

  A duration of 3 cycles of alternating icing exposure corresponding to the LWC levels and standard cloud lengths in Intermittent Maximum and Continuous Maximum icing conditions, at the critical level of air temperature.

C. In addition to complying with paragraph B. of this section, the following conditions shown in Table 33.68-1 [sic: ref. Table 2 of this report]***, unless replaced by similar CPA test conditions that are more critical or produce an equivalent level of safety, must be demonstrated by engine test:***

Condition	***Total Air Temperature***	***LWC (minimum)***	***Median Volume Droplet Diameter (+/- 3 microns)***	***Duration***
1. Glaze ice conditions	***21 to 25 °F (-6 to -4 °C)***	***2 gm/m3***	***25 microns***	***(a) 10-minutes for power below sustainable level flight (idle descent). (b) Must show repetitive, stabilized operation for higher powers (50%, 75%, 100%MC).***
2. Rime ice conditions	***-10 to 0 °F (-23 to –18 °C)***	***1 gm/m3***	***15 microns***	***(a) 10-minutes for power below sustainable level flight (idle descent). (b) Must show repetitive, stabilized operation for higher powers (50%, 75%, 100%MC).***
3. Glaze ice holding conditions (Turboprop and turbofan, only)	***Turbofan, only: 10 to 18 °F (-12 to –8 °C) -------------------- Turboprop, only: 2 to 10 °F (-17 to –12 °C)***	***Alternating cycle: 0.3 gm/m3 (6 minute) 1.7 gm/m3 (1 minute)***	***20 microns***	***Must show repetitive, stabilized operation (or 45 minutes max)***
4. Rime ice holding conditions (Turboprop and turbofan, only)	***Turbofan, only: -10 to 0 °F (-23 to –18 °C) -------------------- Turboprop, only: 2 to 10 °F (-17 to –12 °C)***	***0.25 gm/m3***	***20 microns***	***Must show repetitive, stabilized operation (or 45 minutes max).***

Table 2 - "Table 33.68-1"

D. Idle for a minimum of 30-minutes on the ground in the following icing conditions shown in Table 33.68-2 [sic: ref. Table 3 of this report]***, with the available air bleed for icing protection at its critical condition, without adverse effect, followed by an acceleration to takeoff power or thrust. During the idle operation the engine may be run up periodically to a moderate power or thrust setting in a manner acceptable to the Administrator. The applicant must document any demonstrated run ups and minimum ambient temperature capability during the conduct of icing testing in the engine operating manual as mandatory in icing conditions. The applicant must demonstrate, with consideration of expected airport elevations, the following:***

Condition	***Total Air Temperature***	***LWC (minimum)***	***Mean Effective Particle Diameter***	***Demonstration***
1. Rime ice condition	***0 to 15 °F (-18 to -9 °C)***	***Liquid - 0.3 gm/m3***	***15-25 microns***	***By engine test***
2. Glaze ice condition	***20 to 30 °F (-7 to -1 °C)***	***Liquid - 0.3 gm/m3***	***15-25 microns***	***By engine test***
3. Snow ice condition	***26 to 32 °F (-3 to 0 °C)***	***Ice - 0.9 gm/m3***	***100 microns (minimum)***	***By test, analysis or combination of the two.***
4. Large droplet glaze ice condition	***15 to 30 °F (-9 to -1 °C)***	***Liquid - 0.3 gm/m3***	***100 microns (minimum) 3000 microns (maximum)***	***By test, analysis or combination of the two.***

Table 3 - "Table 33.68-2"

E. The applicant must demonstrate by test, analysis or combination of the two acceptable operation in ice crystals and mixed phase icing conditions throughout the Part 33, Appendix D icing envelope throughout its flight power range, including minimum descent idling speeds.

Proposal 36 - Section 33.77 - Foreign object ingestion ice

(a) Compliance with the requirements of this paragraph shall be demonstrated by engine ice ingestion test or by validated analysis showing equivalence of other means for demonstrating soft body damage tolerance.

(b) [Reserved]

(c) Ingestion of ice under the conditions of ***this section may not --***
(1) Cause an immediate or ultimate unacceptable sustained power or thrust loss; or
(2) Require the engine to be shutdown

(d) For an engine that incorporates a protection device, compliance with this section need not be demonstrated with respect ***to ice formed forward of the protection device if it is shown that--***
(1) Such ice is of a size that will not pass through the protective device;
(2) The protective device will withstand the impact ***of the ice and***
(3) ***The ice*** stopped by the protective device will not obstruct the flow of induction air into the engine with a resultant sustained reduction in power or thrust greater than those values required by paragraph (c) of this section.

(e) Compliance with paragraph (c) of this section may be shown by engine test under the following ingestion conditions:
(1) The minimum ice quantity will be established by the engine size as defined in Table 33.77 [sic: ref. Table 4 of this report] ***– dimensions should be linearly interpolated based on actual hilite area***
(2) The ingestion velocity will simulate ice being sucked into the engine from the inlet
(3) Engine operation will be at the maximum cruise power or thrust ***unless lower power is more critical***

Inlet Hilite area (sq inch)	Thickness (inch)	Width (inch)	Length (inch)
0	0.25	0	3.6
80	0.25	6	3.6
300	0.25	12	3.6
700	0.25	12	4.8
2800	0.35	12	8.5
5000	0.43	12	11.0
7000	0.50	12	12.7
7900	0.50	12	13.4
9500	0.50	12	14.6
11300	0.50	12	15.9
13300	0.50	12	17.1
16500	0.5	12	18.9
20000	0.5	12	20.0

Table 4 - "Table 33.77 Minimum Ice Slab Requirements Based on Engine Inlet Size"

Proposal 37 - 14 CFR Part 33 Appendix D – Mixed Phase and Ice Crystal Icing Envelope (Deep Convective Clouds)

Ice crystal conditions associated with convective storm cloud formations exist within the 14 CFR Part 25 Appendix C Intermittent Maximum Icing envelope (including the extension to -40 deg C) and the Mil Standard 210 Hot Day envelope. This ice crystal icing envelope is depicted in Figure D-1. [sic: refer to Figure 8 of this report].

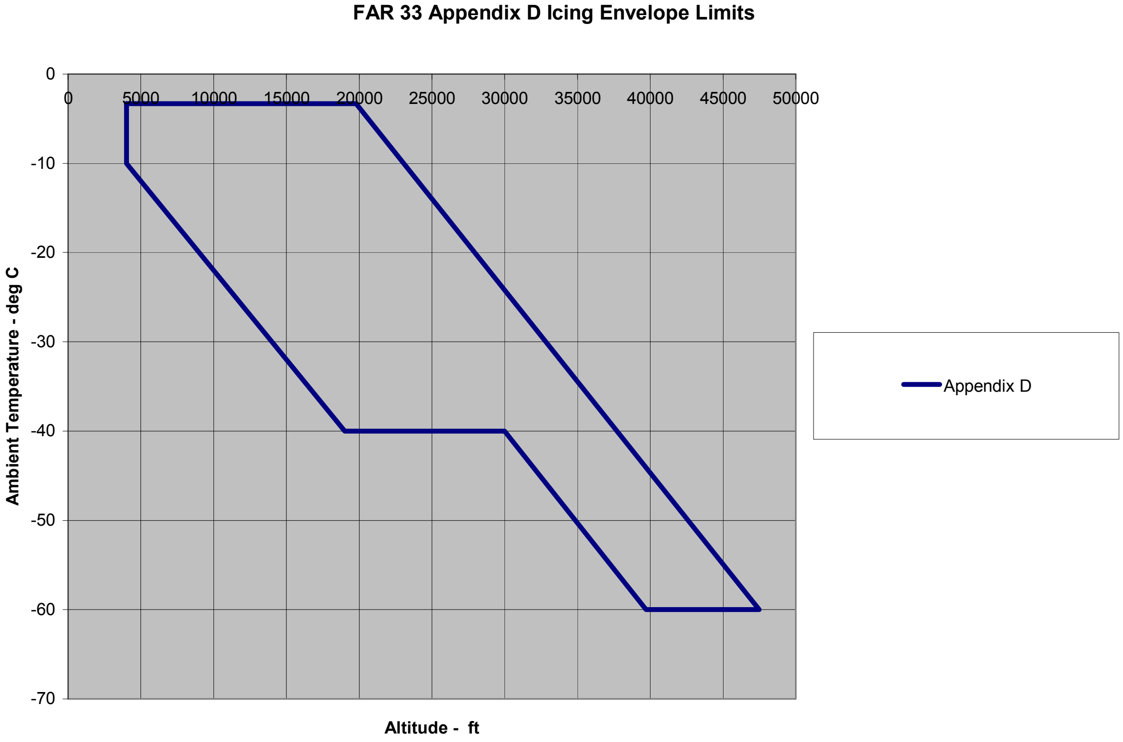


Figure 8 - 14 CFR Part 33, App. D, Figure D-1 Convective Cloud Ice Crystal Envelope

Within the envelope, total water content (TWC) in gms/m3 have been assessed based upon the adiabatic lapse defined by the convective rise of 90% relative humidity air from sea level to higher altitudes and scaled by a factor of 0.65 to a standard cloud length of 17.4 nautical miles. TWC is displayed for this distance over a range of ambient temperature within the boundaries of the ice crystal envelope in Figure D-2 [sic: refer to Figure 9 of this report].

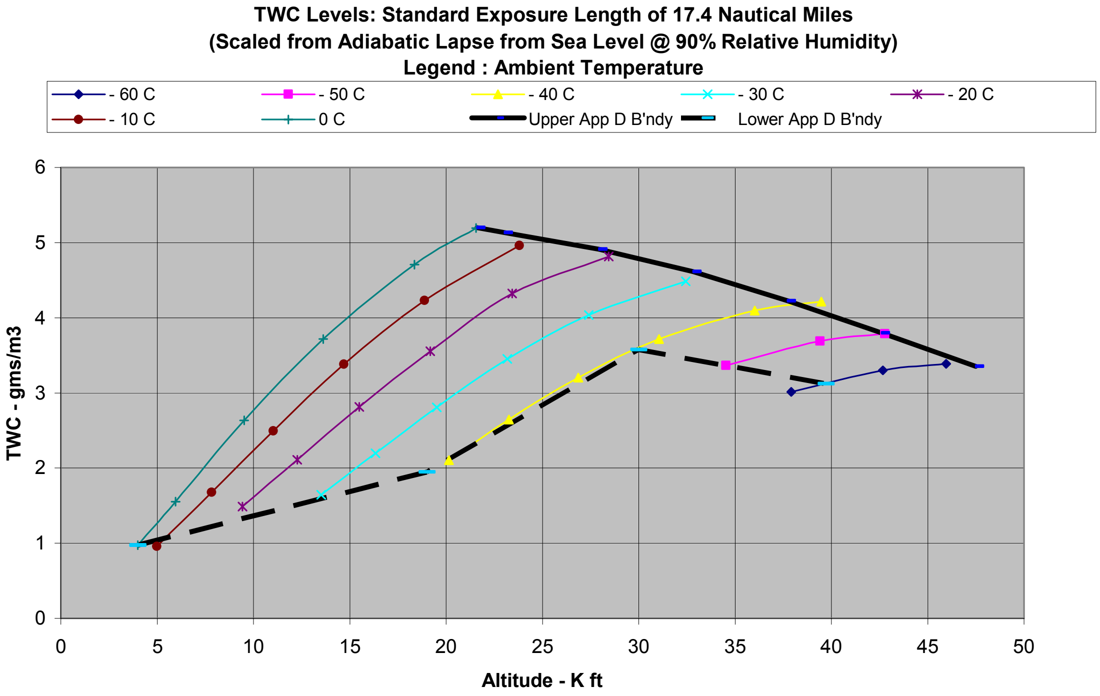


Figure 9 - 14 CFR Part 33, App. D, "Figure D-2" Total Water Content

Ice crystal size median mass dimension (MMD) range is 50 - 200 microns (equivalent spherical size) based upon measurements near convective storm cores.

The TWC can be treated as completely glaciated except as noted in the Table D-1 [sic: refer to Table 5 of this report].

Temperature Range – deg C	Horizontal Cloud Length	LWC – gm/m3
0 to -20	</= 50 miles	</=1.0
0 to -20	Indefinite	</=0.5
< -20		0

Table 5 - 14 CFR 33, App. D, "Table D-1" Supercooled Liquid Portion of TWC

The TWC levels displayed in Figure D-2 [sic: refer to Figure 9 of this report] represent TWC values for a standard exposure distance (horizontal cloud length) of 17.4 nautical miles that must be adjusted with length of icing exposure. The assessment from data measurements in References 1 supports the reduction factor with exposure length shown in Figure D-3 [sic: refer to Figure 10 of this report].

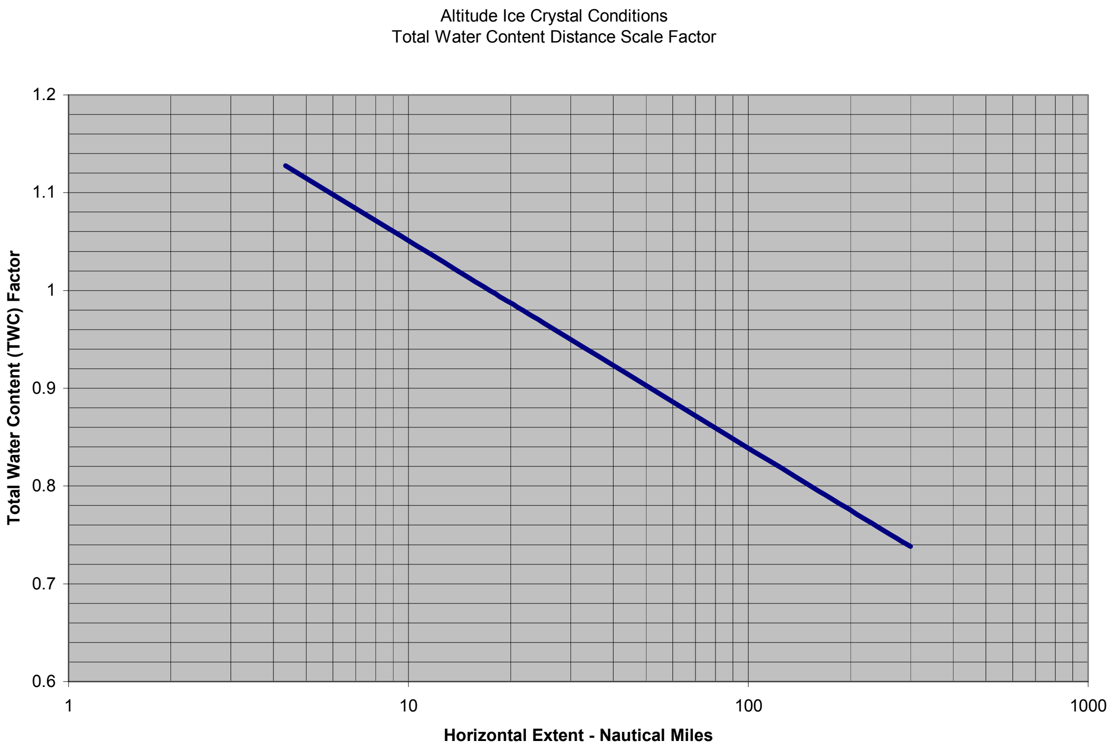


Figure 10 - 14 CFR Part 33, App. D, "Figure D-3" Exposure Length Influence on TWC

Proposal 38 - Sec. 121.321 – Operations in Icing Conditions

Sec 121.321: After [a date 24 months after the effective date of the final rule], no person may operate an airplane with a maximum certified takeoff weight less than 60,000 pounds in conditions conducive to airframe icing unless it complies with this section ***or 25.1419 Amendment 25-xx, and 25.1420, 25.773, 25.903, 25.929, 25.1093, 25.1323, and 25.1325 Amendment 25-xx.***

(3) If this text changes current regulations, what change does it make? For each change:
What is the reason for the change?
What is the effect of the change?

The proposed 25.1420 text changes the icing environment used to evaluate safe operation of the airplane in icing conditions. The reason for the change is that the accident history of some aircraft has shown that the current icing environment requirements are inadequate. The effect of the change is to require: evaluation of safe operation in the revised icing environment; and, if necessary, a means to differentiate environmental icing conditions and development of exit procedures.

The proposed 25.1420 extends the requirements of 25.1419(e), (f), (g), and (h), regarding the activation and operation of airframe ice protection systems, to the certificated portion of Appendix X icing conditions. These requirements are not applicable to non-certificated Appendix X icing conditions because 25.1420(a) requires a method to identify these conditions and safely exiting the conditions.

Current knowledge suggests that large-droplet dynamic phenomena such as breakup and splashing can reduce the amount of ice that forms. These mechanisms can contribute to mass leaving the airfoil surface after impact and smaller droplets (either from breakup or splash-off) not impinging. This can lead to substantial amounts of water in SLD conditions not staying on the airfoil.

As has been widely documented, ice ridges may form due to the impingement and freezing of large drops aft of protected areas. However, there is experimental evidence indicating that, in some conditions, in particular when the total air temperature is near the freezing point or at low freezing fractions, aft ice accretions may result from runback ice or ice migration (ice-on-surface movement), as well as from direct drop impingement. Ice migration has been observed in videos of icing tunnel experiments at total air temperature near the freezing point and is characterized by ice-buildup that initially grows at or near the leading edge, then slides aft due to aerodynamic forces overcoming ice-to-airfoil adhesion forces. The videos indicate that the ice migration can contribute to the potential for development of ice ridges behind protected areas. Drop impingement onto such formations would result in their enlargement.

If certification for flight in icing is desired, part 25 requires that the airplane must be capable of safe operation in icing conditions. The airplane and its components are considered during flight in icing certification programs. There are several rules in part 25 (§§25.773, 25.929, 25.1093, 25.1323, and 25.1325) which reference icing requirements for specific components. Since these rules reference Part 25, Appendix C icing conditions or generically mention icing conditions, the proposed expansion of icing conditions to be considered for safe operation of the airplane necessitates revisions to these rules. The effect of the changes is to require that certain components function properly when exposed to Part 25, Appendices C and X icing conditions.

The proposed part 25 Appendix X provides definitions of supercooled large drop icing conditions (freezing drizzle and freezing rain) addressed by the proposed §25.1420 and the proposed revisions of §§25.773, 25.929, 25.1093, 25.1323, and 25.1325. The supercooled large drop icing conditions described in the proposed part 25 Appendix X are the icing meteorological conditions in which the airplane must either safely operate unrestricted or safely exit following detection. Appendix X includes supercooled drops larger than those considered by current icing regulations. These larger drops will impinge and freeze farther aft on airplane surfaces and may affect the airplane's performance, flying qualities, engine and systems operation. The Appendix X icing conditions may affect design considerations of airplane ice protection provisions.

Sections 25.929 and 25.1323 generically reference icing instead of specifically mentioning Appendix C. Historically the icing conditions of Appendix C have been considered as applicable to these rules. For clarity, the rules are revised to specifically reference Appendices C and X.

Section 25.1419 requires that the airplane be able to safely operate in all of the conditions specified in Appendix C. Section 25.1420 allows substantiation that the airplane is able to safely operate in all of Appendix X, a portion of the Appendix X, or detect SLD and exit icing conditions. Airplanes certificated to a portion of Appendix X must have a method to detect that the airplane is operating in conditions which exceed the selected portion of Appendix X. Airplanes certificated to a portion of Appendix X or certificated to detect and exit Appendix X conditions may encounter a range of Appendix X conditions while exiting icing. It is not practical to certificate probes, components, or engines to varying portions of Appendix X. Therefore the icing regulations for probes, components, and engines (§§25.773, 25.929, 25.1093, 25.1323, and 25.1325) will be modified to reference Appendix X rather than the icing conditions specified in §25.1420. The wording is chosen to preclude the interpretation that the components may be certificated for only the certificated portions of Appendix X conditions.

Section 25.773(b) is only applicable if there are ice protection provisions. Future airplanes may be capable of safely operating in icing conditions without ice protection provisions. Therefore, the rule is also being revised to apply to those airplanes certificated for flight in icing.

Section 25.929 is also being modified to clarify the meaning of the words, "for airplanes intended for use where icing may be expected." The intent is for the rule to be applicable to airplanes certificated for flight in icing. The regulation is being revised to clarify this intent.

Section 121.321 is being modified to remove the requirement to comply with the rule providing the airplane complies with certain part 25 regulations.

Section 121.321 addresses two issues: when to activate the ice protection system and when to exit icing conditions.

Section 25.1419 Amendment 25-xx addresses when the ice protection system must be activated. An airplane that is certificated to this amendment level would comply with this aspect of §121.321. Section 121.321 partially addresses the concern of airplanes operating in icing conditions that exceed Appendix C conditions. The part 121 rule is not performance based but instead identifies specific conditions (icing conditions conducive to ice accretions aft of the protected areas) from which the airplane must exit. The rule does not allow the option of substantiating that the airplane can safely operate in icing conditions conducive to ice accretions aft of the protected areas.

The proposed §25.1420 is a performance-based rule that would allow for substantiation that the airplane can be safely operated in Appendix X icing conditions and that the flight crew need not exit icing conditions when Appendix X conditions are encountered.

Section 25.1420(a)(1) requires a method to detect that the airplane is operating in Appendix X; following detection, the airplane must be capable of operating safely while exiting all icing conditions.

When complying with §25.1420(a)(2), certification may be requested for portions of Appendix X, such as for freezing drizzle only or for specific phases of flight. Following detection, the airplane must be capable of operating safely while exiting all icing conditions. Certification for a portion of Appendix X (§25.1420(a)(2)) or detect and exit from Appendix X (§25.1420(a)(1)) requires that substantiated methods be provided to alert flight crews when those portions of Appendix X are exceeded (§25.1420(a)(2)) or Appendix X conditions are encountered (§25.1420(a)(1)).

Certification to Appendix X (§25.1420(a)(3)) requires that the airplane operate safely throughout Appendix X.

An airplane that is certified to proposed §25.1420 would not need to comply with Part 121.321(c), which requires certain airplanes to exit icing conditions conducive to ice accumulations aft of the protected areas.

The proposed 33.68, 33.77 and 25.1093 text changes the icing environment used to evaluate safe operation of the installed engine in icing conditions. The reason for the change is that the incident history of some aircraft has shown that the current icing environment requirements are inadequate. The effect of the change is to require an evaluation of safe operation in the revised icing environment. Engine and engine installation certification to Appendix X of part 25 and Appendix D of part 33 requires that the plane operate safely throughout these icing envelopes. Acceptable compliance methods are proposed within a revised AC 20-147. The proposed text change to 25.903 is consistent with the current § 25.903, and allows flexibility for installation of pre § 33.68 certification basis engines into new aircraft applications at the FAA's discretion.

(4) If not answered already, how will the proposed action address (i.e., correct, eliminate) the underlying safety issue (identified previously)?

This is answered in section 1.a(4) of this report in response to the question, "Why should the requirement exist?"

(5) Why is the proposed action superior to the current regulations?

The proposed action is superior to the current regulations because it requires airplanes to be able to safely operate in supercooled large drop icing conditions, and for engines, in ice crystal and mixed phase conditions. These conditions have resulted in flightcrews losing control of their aircraft and in some cases in engine power loss, and are not addressed by the current regulations. The JAA interim policy, FAA issue paper, and FAA Airworthiness Directives, and part 121 operations rule address a portion of the safety issue. However, as noted in section 1.b.(2)(b), there are limitations associated with the JAA and FAA actions.

Similar to rulemaking that added §25.21(g) to define airplane performance and handling qualities that ensure safe flight in part 25 Appendix C icing conditions, appropriate part 25 Subpart B requirements have been defined to ensure safe flight in the freezing drizzle and freezing rain icing conditions defined by Appendix X. These requirements apply to all part 25 airplanes and permit determination of airplanes that must be limited, in part or completely, from operations in supercooled large drop icing conditions. Subsequently, part 25 Subpart B requirements that ensure safe flight in icing are comparable for both part 25 Appendices C and X.

Considerations have been given to engine and engine installation, pilot compartment view, propeller, and air data instrumentation ice protection requirements to ensure safe flight in freezing drizzle and freezing rain as defined by Appendix X. These requirements have been revised to address inadvertent exposure to supercooled large drop icing conditions, even if the airplane is certified for operation in a limited portion of Appendix X or certified to operate safely while exiting Appendix X.

Preliminary definitions of the supercooled large drop icing environment provided by the Issue Papers and the JAA Interim Policy on Severe Icing Conditions are replaced by a new part 25 Appendix X that resulted from extensive research and analyses performed by the Meteorological Service of Canada, the National Aeronautics and Space Administration, the FAA, and others. Appendix H of this report summarizes the development of the new part 25 Appendix X, and a more detailed description is provided in DOT/FAA/AR-04/7.

B. ALTERNATIVES CONSIDERED

(1) What actions did the working group consider other than the action proposed? Explain alternative ideas and dissenting opinions.

Alternate Means of Addressing Tasking

Research is ongoing to address avoidance operations in supercooled large drops. The use of terminal area radar and sensors for detection and characterization of icing conditions and holding areas is being developed. These have limited capability to determine supercooled large drops in between terminals or holding areas and could not provide avoidance information to flight crews for these areas. In addition, in development are airborne radars and sensors that would allow identification of supercooled large drop conditions in sufficient time for avoidance. Although active, these developments are not mature enough to provide sufficient aircraft protection over the entire flight operations area.

Additionally, icing diagnostic and predictive weather tools have been developed that can provide information on icing and SLD potential, with acceptance of the icing diagnostic tool by the Aviation Weather Center. Internet access to these experimental tools can be used to provide flight planning information guidance for avoidance of SLD conditions. However, aircraft safety margins for inadvertent flight in such conditions are not addressed.

- Aerodynamic Performance Monitor as an Alternative to § 25.1420 and Part 25 Appendix X

The working group considered the use of aerodynamic performance monitors (APMs) to detect sources of boundary layer instabilities similar to those caused by ice accretions. The logic is that flightcrews would be alerted to take precautionary actions once the wing or a control surface's boundary layer conditions had reached a safety threshold, regardless of what caused the boundary layer disturbance. Several attempts have been made to investigate the feasibility of APMs on civil aircraft. Currently no APMs are used on commercial aircraft and there is little operational experience to establish confidence in the system's capabilities. The working group concluded that APM's are not sufficiently mature to support a rule based on its technology. However, the rule is written broadly enough to allow the use of an APM as a means of compliance should the APM's reach the maturity required to obtain approval for installation on a Part 25 airplane.

Alternative Concept Relative to Caution Information

The working group evaluated whether the proposed §25.1420 should contain a requirement similar to §25.1419(c). Paragraph 25.1419(c) requires that caution information, such as an amber caution light or equivalent, must be provided to alert the flightcrew when the anti-ice or de-ice system is not functioning normally. (Amdt. 25-72, July 20, 1990). In the preamble to Amendment 25-72 it is stated:

> One commenter suggests that the requirement of proposed §25.1419(b)(3) for flightcrew caution indication is unnecessary as system failure indication requirements are adequately covered by §25.1309(c). The FAA concurs that such indication would be required by current §25.1309(c) in the absence of a specific rule, such as proposed §25.1419(b)(3). The general nature of §25.1309(c), however, introduces a degree of uncertainty as to its applicability to specific airplane systems. It is, therefore, considered appropriate to retain the specific requirement of proposed §25.1419(b)(3).

It should be noted that the proposed §25.1419(b)(3) became §25.1419(c) in the final rule. The working group found that in the years since amendment 25-72 was adopted, §25.1309(c) has been interpreted as applying to any airplane system that can experience unsafe system operating conditions. The uncertainty that existed in 1990 no longer exists. Paragraph 25.1309(c) does apply to ice protection systems. Therefore, the proposal for §25.1420 does not contain the requirement for caution information as contained in §25.1419(c).

Necessity to Flight Test in Natural Appendix X Conditions

Another area of extended debate within the IPHWG regards the topic of whether flight testing in natural icing conditions should be required. The discussions centered on the difficulty of performing certification testing within Appendix X and the ability to use the simulation methods as a means of demonstrating the effects of Appendix X conditions. For a more detailed discussion, see Appendix D of this report.

Necessity of a Means to Determine Exceedance of Appendix X

The tasking states: "In addition, consider the need for a regulation that requires installation of a means to discriminate between conditions within and outside the certification envelope." This topic was debated within the working group and a consensus was achieved that a means for discrimination of conditions outside the certification envelopes is not necessary. See Appendix E for a detailed statement of the final consensus position.

Exclusion of Aircraft with Certain Design Features

Airbus, Boeing, and Embraer, with a supporting statement from Cessna, have put forth a Minority Position advocating exclusion from §25.1420 for aircraft with specific design features. The rationale for the position of these manufacturers is that large transport aircraft still in production have experienced no accidents and few incidents as a result of flying in SLD conditions. Therefore, the imposition of new, burdensome and costly certification requirements for flight in SLD conditions for these types of aircraft is unwarranted as no safety improvement can be expected. These manufacturers have proposed that aircraft with the following three design features be excluded from compliance with §25.1420: (1) gross weight in excess of 60,000 lbs (27,000 kg); (2) irreversible powered flight controls; and (3) wing leading-edge high-lift devices. It is the intent of these manufacturers that all three of these design features would be required to qualify for exclusion. The details of this position are included in Appendix F of this report.

Certification to a Portion of Appendix X

Two minority positions against the option for an applicant to certify to a portion of Appendix X (§25.1420(a)(2)) were submitted, and consensus of these positions was not achieved. Both minority positions address aspects of the appropriate use of Appendix X for certification. See Appendix G of this report for the position statements.

Potential Benefits of §25.1420

Embraer, with the support of the Regional Airline Association, holds a minority view of the applicability of some of the accidents identified for potential use in the economic analysis. See Appendix I of this report for the position statements.

Necessity for an AFM Statement Concerning Cumuliform Cloud Large Droplet Icing

Proposed 14 CFR 25 Appendix X was derived from flight data obtained in stratus clouds. As such, information on large droplet icing that may be present in cumuliform clouds is not defined. See Appendix L of this report for the minority and majority position statements on this issue and Appendix H of this report for more information on the development of the proposed 14 CFR 25 Appendix X.

(2) Why was each action rejected (e.g., cost/benefit? unacceptable decrease in the level of safety? lack of consensus? etc.)? Include the pros and cons associated with each alternative.

Necessity to Flight Test in Natural Appendix X Conditions

See Appendix D of this report.

Necessity of a Means to Determine Exceedance of Appendix X

See Appendix E of this report.

Exclusion of Aircraft with Certain Design Features

The position advocating exclusion from §25.1420 for aircraft with specific design features was rejected since the basis of excluding aircraft with the specified design features may not be applicable for future airplane designs. The design features of future and innovative airplanes are unknown. Therefore, the effectiveness of the proposed design features to ensure safe operation in icing conditions, including freezing drizzle and freezing rain, is unknown. Safe in-service experience for current airplanes with the proposed design features will not ensure safe flight for future new and innovative airplane with similar design features. For this reason, airplane airworthiness requirements typically do not include exclusions unless those exclusions are addressed by other more appropriate regulations or if the requirement is not applicable to a specific type of engine or airplane. (Examples of appropriate exclusions include turbojet versus reciprocating engines, and land based versus water based airplanes.) See Appendix F of this report for the full response.

Certification to a Portion of Appendix X

See Appendix G of this report.

Potential Benefits of §25.1420

See Appendix I of this report.

Necessity for an AFM Statement Concerning Cumuliform Cloud Large Droplet Icing

See Appendix L of this report.

C. HARMONIZATION STATUS

(1) Is the proposed action the same for the FAA and the JAA?

Yes for large drop aspects. Mixed phased icing relative to §§ 25.1323 & 25.1325 will be addressed by IPHWG Task 5.

For 14 CFR 33 engine icing requirements, the rules are somewhat different. The objective is to maintain equivalency, just as has been the case historically.

(2) If the proposed action differs for the JAA, explain the proposed JAA action.

No difference is anticipated, but the JAA, now EASA is currently making their final determination of their proposed actions.

(3) If the proposed action differs for the JAA, explain why there is a difference between FAA and JAA proposed action (e.g., administrative differences in applicability between authorities).

No difference is anticipated with respect to large drops. For 14 CFR 33 engine rules, the JAA/EASA is expected to maintain equivalency to FAA rules, and not direct similarity. This equivalency allows for all manufacturers to continue their equivalent methods of compliance demonstrations.

3. COSTS AND OTHER ISSUES THAT MUST BE CONSIDERED

The Working Group should answer these questions to the greatest extent possible. What information is supplied can be used in the economic evaluation that the FAA must accomplish for each regulation. The more quality information that is supplied, the quicker the evaluation can be completed.

A. COSTS ASSOCIATED WITH THE PROPOSAL

(1) Who would be affected by the proposed change? How? (Identify the parties that would be materially affected by the rule change – airplane manufacturers, airplane operators, etc.)

Airplane manufacturers of new Part 25 airplane type certificate programs, engine manufacturers of new Part 33 engine type certificate programs and applicants for type certificate amendments, supplemental type certificates (STCs), or amended STCs that involve significant changes to the ice protection system, airframe, or engines would be required to provide additional substantiation.

(2) What is the cost impact of complying with the proposed regulation? Provide any information that will assist in estimating the costs (either positive or negative) of the proposed rule.
(For example:
What are the differences (in general terms) between current practice and the actions required by the new rule?

- *If new tests or designs are required, how much time and costs would be associated with them?*
- *If new equipment is required, what can be reported relative to purchase, installation, and maintenance costs?*
- *In contrast, if the proposed rule relieves industry of testing or other costs, please provide any known estimate of costs.*
- *What more-- or what less -- will affected parties have to do if this rule is issued?*

> ***NOTE**: "Cost" does not have to be stated in terms of dollars; it can be stated in terms of work-hours, downtime, etc. Include as much detail as possible.)*

See Appendix I for the accidents and incidents relevant to this proposed rule.
See Appendix J for an estimate of the costs.

B. OTHER ISSUES

(1) Will small businesses be affected? *(In general terms, "small businesses" are those employing 1,500 people or less. This question relates to the Regulatory Flexibility Act of 1980 and the Small Business Regulatory Enforcement Fairness Act of 1996.]*

APO to determine.

(2) Will the proposed rule require affected parties to do any new or additional recordkeeping? If so, explain. *[This question relates to the Paperwork Reduction Act of 1995.]*

No.

(3) Will the proposed rule create any unnecessary obstacles to the foreign commerce of the United States -- i.e., create barriers to international trade? *[This question relates to the Trade Agreement Act of 1979.]*

No.

(4) Will the proposed rule result in spending by State, local, or tribal governments, or by the private sector, that will be $100 million or more in one year? *[This question relates to the Unfunded Mandates Reform Act of 1995.]*

APO to determine.

4. ADVISORY MATERIAL

a. Is existing FAA or JAA advisory material adequate? Is the existing FAA and JAA advisory material harmonized?

No.

b. If not, what advisory material should be adopted? Should the existing material be revised, or should new material be provided?

New advisory material is proposed as part of this report.

c. Insert the text of the proposed advisory material here (or attach), or summarize the information it will contain, and indicate what form it will be in (e.g., Advisory Circular, Advisory Circular – Joint, policy statement, FAA Order, etc.)

A new combined Advisory Circular to address §25.1419 and §25.1420 icing requirements has been drafted and will be submitted as a separate document. It is intended to replace the current AC 25.1419. The AC contains information necessary to clarify the icing guidance for certification to Appendix C and the new Appendix X. The current release of AC 25.1419 contains materials that provide direction relative to compliance to subpart B requirements for icing. Upon recommendation of the FTHWG, the subpart B aspects were removed from the IPHWG-drafted Advisory Circular.

The subpart B aspects for compliance to both §25.1419 as well as §25.1420 are to be addressed in the materials prepared by the FTHWG in association with AC 25.21-1. The AC prepared by the IPHWG focuses on the icing environment and systems compliance aspects.

The engine and engine installation aspects are to be addressed in a revision to AC 20-147.

APPENDIX A - TYPICAL AIRWORTHINESS DIRECTIVE ON SEVERE ICING

PART 39 - AIRWORTHINESS DIRECTIVES

1. The authority citation for part 39 continues to read as follows:

Authority: 49 USC 106(g), 40113, 44701.

§ 39.13 - [Amended]

2. Section 39.13 is amended by adding the following new airworthiness directive:

96-09-26 FOKKER: Amendment 39-9602. Docket 96-NM-21-AD.

Applicability: All Model F27 Mark 100, 200, 300, 400, 500, 600, and 700 series airplanes and Model F27 Mark 050 series airplanes, certificated in any category.

NOTE 1: This AD applies to each airplane identified in the preceding applicability provision, regardless of whether it has been modified, altered, or repaired in the area subject to the requirements of this AD. For airplanes that have been modified, altered, or repaired so that the performance of the requirements of this AD is affected, the owner/operator must request approval for an alternative method of compliance in accordance with paragraph (b) of this AD. The request should include an assessment of the effect of the modification, alteration, or repair on the unsafe condition addressed by this AD; and, if the unsafe condition has not been eliminated, the request should include specific proposed actions to address it.

Compliance: Required as indicated, unless accomplished previously.

To minimize the potential hazards associated with operating the airplane in severe icing conditions by providing more clearly defined procedures and limitations associated with such conditions, accomplish the following:

(a) Within 30 days after the effective date of this AD, accomplish the requirements of paragraphs (a)(1) and (a)(2) of this AD.

NOTE 2: Operators must initiate action to notify and ensure that flight crewmembers are apprised of this change.

(1) Revise the FAA-approved Airplane Flight Manual (AFM) by incorporating the following into the Limitations Section of the AFM. This may be accomplished by inserting a copy of this AD in the AFM.

"WARNING

> Severe icing may result from environmental conditions outside of those for which the airplane is certificated. Flight in freezing rain, freezing drizzle, or mixed icing conditions (supercooled liquid water and ice crystals) may result in ice build-up on protected surfaces exceeding the capability of the ice protection system, or may result in ice forming aft of the protected surfaces. This ice may not be shed using the ice protection systems, and may seriously degrade the performance and controllability of the airplane.
>
> • During flight, severe icing conditions that exceed those for which the airplane is certificated shall be determined by the following visual cues. If one or more of these visual cues exists, immediately

request priority handling from Air Traffic Control to facilitate a route or an altitude change to exit the icing conditions.

- Unusually extensive ice accreted on the airframe in areas not normally observed to collect ice.

- Accumulation of ice on the lower surface of the wing aft of the protected area.

- Accumulation of ice on the propeller spinner farther aft than normally observed.

• Since the autopilot may mask tactile cues that indicate adverse changes in handling characteristics, use of the autopilot is prohibited when any of the visual cues specified above exist, or when unusual lateral trim requirements or autopilot trim warnings are encountered while the airplane is in icing conditions.

• All icing detection lights must be operative prior to flight into icing conditions at night. [NOTE: This supersedes any relief provided by the Master Minimum Equipment List (MMEL).]"

(2) Revise the FAA-approved AFM by incorporating the following into the Procedures Section of the AFM. This may be accomplished by inserting a copy of this AD in the AFM.

"THE FOLLOWING WEATHER CONDITIONS MAY BE CONDUCIVE TO SEVERE IN-FLIGHT ICING:

• Visible rain at temperatures below 0 degrees Celsius ambient air temperature.

• Droplets that splash or splatter on impact at temperatures below 0 degrees Celsius ambient air temperature.

PROCEDURES FOR EXITING THE SEVERE ICING ENVIRONMENT:

These procedures are applicable to all flight phases from takeoff to landing. Monitor the ambient air temperature. While severe icing may form at temperatures as cold as -18 degrees Celsius, increased vigilance is warranted at temperatures around freezing with visible moisture present. If the visual cues specified in the Limitations Section of the AFM for identifying severe icing conditions are observed, accomplish the following:

- Immediately request priority handling from Air Traffic Control to facilitate a route or an altitude change to exit the severe icing conditions in order to avoid extended exposure to flight conditions more severe than those for which the airplane has been certificated.
- Avoid abrupt and excessive maneuvering that may exacerbate control difficulties.

- Do not engage the autopilot.

- If the autopilot is engaged, hold the control wheel firmly and disengage the autopilot.

- If an unusual roll response or uncommanded roll control movement is observed, reduce the angle-of-attack.

- Do not extend flaps during extended operation in icing conditions. Operation with flaps extended can result in a reduced wing angle-of-attack, with the possibility of ice forming on the upper surface further aft on the wing than normal, possibly aft of the protected area.

- If the flaps are extended, do not retract them until the airframe is clear of ice.

- Report these weather conditions to Air Traffic Control."

(b) An alternative method of compliance or adjustment of the compliance time that provides an acceptable level of safety may be used if approved by the Manager, Standardization Branch, ANM-113, FAA, Transport Airplane Directorate. Operators shall submit their requests through an appropriate FAA Principal Operations Inspector, who may add comments and then send it to the Manager, Standardization Branch, ANM-113.

NOTE 3: Information concerning the existence of approved alternative methods of compliance with this AD, if any, may be obtained from the Standardization Branch, ANM-113.

(c) Special flight permits may be issued in accordance with sections 21.197 and 21.199 of the Federal Aviation Regulations (14 CFR 21.197 and 21.199) to operate the airplane to a location where the requirements of this AD can be accomplished.

APPENDIX B - FAA ISSUE PAPER ON ROLL CONTROL IN SLD CONDITIONS

ISSUE PAPER

PROJECT: GENERIC AIRPLANE COMPANY
Model XYZ

ITEM: S-2
STAGE: 2

REG. REF.: §§ 21.16, 21.21(b)(2), 25.1419

DATE: June 25, 1998

NATIONAL
POLICY REF.: ANM-100 Memorandum dated July 23, 1997 (Signed: Ron Wojnar)

ISSUE STATUS: OPEN

SUBJECT: Roll Control in Supercooled Large Droplet Conditions

BRANCH ACTION: ANM-111, 112

Based on GIP # S-x13

COMPLIANCE
TARGET: Pre-TC

Known Unsafe Condition

STATEMENT OF ISSUE:
The requirements for the certification of an airplane with ice protection provisions are defined in º 25.1419. The current regulation requires that an airplane with ice protection provisions must be able to safely operate in the conditions defined in the Federal Aviation Regulations, part 25, appendix C. The regulation is not adequate to address freezing drizzle and freezing rain conditions (hereafter called supercooled large droplets or SLD) that are outside of the appendix C envelope.

BACKGROUND:
On October 31, 1994, an Aerospatiale ATR-72-212 was involved in an accident in which severe icing conditions were reported in the area. During extensive testing the accident profile was replicated by ice shapes developed from testing in an icing cloud having droplets in the size range of freezing drizzle at a temperature near freezing. This condition created a ridge of ice aft of the deicing boots and forward of the ailerons, which resulted in uncommanded motion of the ailerons and rapid roll of the aircraft.

The National Transportation Safety Board recommended that the FAA develop a test procedure to identify unsafe aileron hinge moment characteristics. The procedure described herein is the procedure used during the FAA's program to screen airplanes for susceptibility to aileron control anomalies. The airplanes that were evaluated in the program are used in regularly scheduled passenger service equipped with non-powered controls and pneumatic deicing boots.

FAA POSITION:
The FAA has identified the susceptibility to loss of control following exposure to supercooled large droplets as an unsafe condition that may exist on other airplanes. The FAA is particularly concerned with airplanes with non-powered flight controls, since non-powered flight controls do not have the physical advantage of hydraulic or electrical power to assist the pilot in overcoming the large control forces that may exist from differential pressure resulting from flow separation over the roll control surfaces.

The FAA proposes to test airplanes with non-powered roll controls and pneumatic deicing boots for susceptibility to roll control anomalies in certain supercooled large droplet conditions. This test is not intended to certify an airplane for flight in supercooled large droplets or any other conditions which are outside of the appendix C icing envelope.

The following test is proposed:

a. Tests and analyses must show that the airplane characteristics meet the criteria specified in paragraph b. following a 20 minute icing encounter:

1. with supercooled droplets having maximum diameters of approximately 400 μm (microns),
2. an LWC (liquid water content) of approximately 0.6 grams per cubic meter[1],
3. a median volumetric diameter of approximately 170 microns[2],
4. temperatures near freezing such that runback conditions exist at the stagnation line[3], and
5. at holding speeds and approved holding configurations.

b. When manually flying the airplane:

1. The pilot roll force to counter any uncommanded roll control surface deflection may not exceed 50 pounds with two hands available for control, and
2. the airplane must not exhibit a hazardous degradation of flying qualities. Rapid control force onset, unsteady and oscillatory forces must be considered carefully as these dynamic conditions may be hazardous even though the peak force may be less than the static limit.

c. The tests and analyses in paragraph a. must consider the effects of asymmetric shedding of the ice.

---

[1] For this condition, the LWC strongly affects the rate at which the ice feature develops. A higher LWC results in more rapid formation of the ice feature while a lower LWC results in a slower formation of the ice feature. The LWC should be adequate to produce an ice feature during the exposure interval that will start to self shed and then reform.

[2] The cloud physics instrumentation, calibration, and data processing methodologies must be acceptable to the FAA.

[3] For this test, temperature is a critical factor. Not only is the temperature critical to the development of the ice shape and dimension, static air temperature excursions above freezing, although short in duration, can reverse the ice accretion process.

d. There must be a means for the flightcrew to determine when the airplane has entered into a supercooled large droplet environment, to enable the crew to take appropriate action.

e. There must be appropriate crew information provided in the airplane flight manual that describes the limitations and procedures to be observed while exiting the supercooled large droplet environment. The FAA finds the limitations and procedures contained in AD 96-09-25 are an acceptable means of compliance with this paragraph. These limitations and procedures include but are not limited to:

1. visual cues that the airplane is in severe icing conditions,
2. prohibition on the use of the autopilot when the visual cues are observed,
3. all icing detection lights operative prior to flight into icing conditions at night,
4. immediate exiting of the severe icing conditions, and
5. if the flaps are extended, do not retract them until the airframe is clear of ice.

Note: For paragraph e.5., the retraction of the flaps is contingent upon the aircraft having a means to determine if the airframe is clear of ice.

f. One means of compliance with paragraphs a., b., and c. is to perform a high speed taxi test to evaluate control wheel force characteristics that may result from flow separation over the roll control surfaces induced by an artificial ice shape as described below. The testing should include the following:

1. Installation of a one-inch high quarter-round molding, flat side forward, located on the upper surface of the wing, at the chord position aft of the active portion of the boots and forward of the non-powered roll control surfaces (i.e. ailerons and/or inflight spoilers) that produces the most adverse lateral wheel force.
2. Locate this shape in front of the roll control surfaces on one wing only. As a minimum the shape must cover the entire span of the roll control surface.
3. Perform high speed taxi tests with the flaps retracted and at various angles of attack. The maximum angle of attack should be obtained at the highest takeoff weight such that the airplane does not become airborne.
4. Measure the forces required to maintain wings level.
5. Extrapolate the maximum forces obtained from the high speed taxi tests to the maximum speeds expected while in holding conditions. In most cases the maximum forces will occur at the maximum angle of attack achieved during the high speed taxi tests.
6. The extrapolated forces may not exceed 50 pounds with two hands available for control.

7. Airplanes equipped with non-powered inflight spoilers may require tunnel or flight testing to evaluate the effect on airplane control and handling characteristics.

APPENDIX C - JAA INTERIM POLICY ON SEVERE ICING CONDITIONS

Policy Paper Number : INT/POL/25/11 Issue 1 Date: 01.10.98

Subject : Severe Icing Conditions

Regulation affected : JAR 25.1419

Problem:

A fatal accident and some incidents related to loss of aeroplane control have raised the concern that aeroplane operating in certain meteorological conditions can accrete ice, not only aft of the protected areas but also on the underwing airfoil surface. This may result particularly in lateral control difficulties due to disturbed flow over the control surfaces and (or) drag penalties. This JAA Interim Policy focuses on the hazard of sudden handling qualities degradation resulting from Ice accretion downstream the protected area on the overwing.

The meteorological conditions involved so called large supercooled droplets, are outside the conditions defined in Regulation part 25, Appendix C.

An inadvertent encounter of such conditions may result in an unsafe condition that must be addressed.

This issue is particularly of interest for aircraft equipped with pneumatic de-icing boots and lateral axis non powered flight control system.

JAA Policy:

As long as, Severe Icing Conditions, so called large supercooled droplets are not defined in the required atmosphere of JAR-25 Appendix C used for certification, means must be provided to the crew to detect these conditions and procedures to exit them are to be established.

The JAA consider that the following issues must be addressed:

1.) Means for the flight crew to determine when the aeroplane has inadvertently entered Severe Icing Conditions.

2.) Assessment of the design to ensure that the aeroplane can safely exit such environment (susceptibility to loss of control leading to an unsafe condition).

3.) Crew information that describes the limitations to be observed while exiting such environment.

4.) Means for the crew to determine when the hazard no longer exists.

5.) Appendices:

Appendix A: provides guidance for Freezing drizzle (ZL) and freezing rain (ZR) included in Severe Icing Conditions addressed by this CRI.

Appendix B: provides guidance material on means to demonstrate acceptable handling qualities in case of inadvertent encounter of Severe Icing Conditions.

APPENDIX A

[sic: Refers to Appendix A of INT/POL/25/11]

For guidance in the definition and representative characteristic values of freezing drizzle and freezing rain the under mentioned document may be used.

"REPRESENTATIVE VALUES OF ICING RELATED VARIABLES ALOFT IN FREEZING DRIZZLE AND FREEZING RAIN".
Richard K. JECK
March 1996
DOT/FAA/AR-TN 95/119
FAA
Technical Centre
Atlantic City International Airport, NJ 08405

The hereafter set of values are extracted from the above mentioned document but for accurate details about how these values have been originated and could be used, refer to the FAA document.

Due to the few amount of measurement, the meteorological statistics/data are preliminary but focused on the under mentioned characteristics.

Freezing drizzle (ZL):
Dropsize diameter range 50 to 500 micron meters,
Ambient temperature between 0 and -11ºC,
Liquid water content 0.1 (0.3 g/m3 maximum),
Altitude range up to 12 500/17 000 ft.

Freezing rain (ZR):
Dropsize diameter range 500 up to 2.000/4000 micron metres,
Ambient temperature between 0 and -11ºC,
Liquid water content 0.1 up to 0.3 g/m3 for 1000 micron-meters RMVD (Raindrop Median Volume Diameter),
Altitude range up to 7.000 ft
Horizontal extend about 100 Miles,
Depth of ZR layer about 6 to 8000 ft.

APPENDIX B

[sic: Refers to Appendix B of INT/POL/25/11]

Guidance Material for

AIRPLANE CERTIFICATION IN CASE OF INADVERTENT SEVERE ICING ENCOUNTER OF CONDITIONS OUTSIDE THE "APPENDIX - C" ATMOSPHERE:

Large Supercooled Droplets (Freezing drizzle and freezing rain)

The guidance material outlines an acceptable means of compliance with the above mentioned requirements.

To establish that the aeroplane can safely exit inadvertent Severe Icing, the applicant must:

- Determine if conditions (in terms of droplet size diameter, liquid water content, temperature) outside the Appendix C can lead to an unsafe situation and

- Demonstrate by an agreed selection of means of compliance (analysis, test in simulated icing conditions, test in dry air with artificial ice shapes, test in measured natural icing conditions,...) that the aeroplane can safely exit such non-authorised conditions.

  For that purpose, the most critical Ice accretions in terms of shape, thickness and location should be established for each flight phase to determine the combinations which have the most adverse effect on handling qualities to be flight tested.

  The applicant should apply the method consisting in:

- Ice shape determination either by test in simulated Icing Condition (tanker test or wind tunnel or analysis) or using the arbitrary defined Ice shape "Quarter Round/One Inch/high/flat side forward."

- Wind tunnel test in dry air with the above agreed artificial Ice shape and location to determine the most critical flight conditions/flight characteristics effects.

- In flight evaluation with the agreed Artificial Ice Shape using the following criteria:

While flying the airplane to assess handling qualities, at speeds up to the maximum anticipated for holding or for flap configurations (VFE), the criteria about flight characteristics specified below are applicable. Manoeuvres should include constant airspeed level banked turns up to 40º either direction, 30º to 30º rolls in both directions using up to full lateral control wheel throw, and wing level deceleration down to the stall warning.

-1 <u>When manually flying the aeroplane</u>:

There shall be no hazardous degradation of the handling qualities of the airplane. The pilot roll forced needed to maintain lateral control during the aforementioned manoeuvres may not exceed 50 lbs. (22,7 daN) with two hands available for control.

-2 <u>When Auto pilot is engaged</u>:

Any uncommanded control surface movement occurring during the manoeuvres specified above with the Autopilot connected during entry into the manoeuvre, then disconnected after establishing the maximum Autopilot coupled bank angle for normal operation or 40º, whichever is less; or disconnected with the maximum roll rate is established when changing the direction of bank angle with the Autopilot heading control (in both directions); or disconnected at stall warning during a deceleration with Autopilot in attitude hold and heading hold mode, must not result in the following:

- bank angle of more 60º,
- a load on any part of the structure greater than its limit or beyond 2g,
- a normal acceleration less 0g,
- a roll force greater than 50 lbs (22,7 daN) during the recovery action,
- an excessive altitude loss,
- hazardous degradation of the handling qualities of the airplane,
- engagement or disengagement of a mode leading to hazardous consequences.

Recovery action should be initiated:
- until three seconds after recognition point for straight flight
- until one second after the recognition point for manoeuvring flight (turns included).

Influence of power setting should be evaluated.

APPENDIX D - ACCEPTABLE COMPLIANCE METHODS FOR APPENDIX X CONDITIONS (NATURAL ICE FLIGHT TESTING NECESSITY)

NECESSITY TO FLIGHT TEST IN NATURAL APPENDIX X CONDITIONS

The requirement to flight test the airplane in Appendix X conditions was a major issue when drafting the proposed §25.1420. There is a requirement to flight test in natural Appendix C conditions to show compliance to §25.1419. The only specified method of compliance that is required in the proposed §25.1420 is analysis. The analysis must be supplemented by at least one type of test. The proposed rule lists the tests, and natural icing Appendix X flight tests is one of them. The group recognizes that flight testing in natural Appendix X conditions is not as practical as in Appendix C conditions, and substantiated tools could be used to show compliance to §25.1420 for most airplane configurations. After considerable discussion, concerns for requiring flight testing in Appendix X natural icing conditions were addressed by modifications to the proposed rule and AC. The working group concluded that the tools must be substantiated and that there may be some configurations or design features that would warrant natural Appendix X flight tests. Guidance on these critical issues are contained in the draft AC. This appendix provides a history of the issue including the background, key points from both sides of the issue, a Minority Position, and the Majority Response.

INITIAL AUTHORITIES' POSITION

The initial position of the FAA, JAA, and Transport Canada was that flight testing in measured natural Appendix X conditions was required to show compliance to §25.1420.

The rationale was as follows:

Although there is some variability in the various manufacturers' methods for certification for flight in icing conditions, the fundamentals are similar. Each manufacturer typically uses a variety of analysis and test methods to optimize the airplane and ice protection systems design. For compliance with 14 CFR/JAR 25.1419, the following means are used in addition to analysis and flight in measured natural icing conditions:

- Wind Tunnel / Icing Tunnel Tests
- Dry Air and Simulated Ice Shape Flight Tests
- Artificial Icing Flight Tests
- Ancestor Airplane Comparison (Similarity Analysis)

NOTE: The FTHWG proposed AC 25.21-1 identifies similar means of showing compliance to the 25.21(g) requirement.

These means of compliance have limitations with regard to Appendix X icing conditions. For example:

- Engineering tools, such as software for CFD, computer aided design analysis (CAD), aerodynamics, and drop and ice accretion effects (LEWICE, CANICE, CFD, etc.), may be used in conjunction with testing of scale, or full-size, models of the airplane or its components in wind tunnels and icing tunnels to confirm the analysis results. However, the current software codes and icing tunnels typically address Appendix C simulations for drop impingement and ice accretion effects. The applicability of the engineering tools to Appendix X icing conditions has not been verified.

- There are variations in the Appendix C ice shapes produced in different icing tunnel facilities that cannot be explained. These differences are expected to continue in Appendix X icing conditions.

- Airborne icing tankers can only produce an icing plume of a consistent drop distribution and liquid water content over a limited area. The test area of the plume may not adequately expose the areas of the airplane that are of interest. There are also concerns of low humidity effects, ambient temperature, uniformity of the plume relative to liquid water content, and drop spectra.

- Ancestor airplane data has been utilized to support new models where sufficient similarity exists between derivative models. However, the use of ancestor airplane data can only be applied for certification to Appendix X after at least one airplane model has been certificated to Appendix X. Otherwise, the data that would be used to support a similarity analysis would not exist.

As required by 14 CFR 25.1419, flight tests in measured natural icing conditions, along with at least one other test method, are required to verify the ice protection analysis, to check for icing anomalies, and to demonstrate that the ice protection system and its components are effective. It is important to note that these tests are conducted with the airplane and its ice protection system (IPS) operating as a complete system, not as a series of discrete components. The natural icing flight tests demonstrate that the components function properly when installed and interact together as a system to perform their intended function in normal operating modes and in failure cases. Confirmation of the AFM Normal and Abnormal procedures is also carried out, including demonstrating adequate performance and handling of the airplane in measured natural icing conditions. Some recent examples of problems found during measured natural icing flight tests that were not accounted for by other tests and analyses include:

- Asymmetric ice accretions on the wing and horizontal tail.
- Ice accretions that affected air data probes.
- A tendency for ice build up on the elevator horn after ten minutes in a hold. The ice prevented elevator movement and caused autopilot disconnect and a 10º pitch up in a turn (the airplane had reversible flight controls).
- Water reaching the brush block area of the propeller deicing system that caused brush block/slip ring hydroplaning and loss of power to propeller deicing boots.
- Unexpected ice accretions.

These Appendix C “Lessons Learned” can apply to Appendix X conditions. Some additional concerns for Appendix X that can only be evaluated by flight testing in measured natural icing conditions include:

- Ice accretions aft of the protected surfaces.
- Experience has shown that SLD ice accretions on the far aft portions of the radome can occur. These ice accretions could affect the accuracy of the angle of attack vanes used by stall warning and stick pusher systems. Flight deck airspeed indications may also be affected.
- Qualitative performance checks of propeller airplanes are done in natural Appendix C icing conditions because intercycle propeller ice shapes are not tested and propeller codes do not account for runback ice. The need to evaluate intercycle propeller ice shapes and runback ice in Appendix X conditions will exist and natural icing flight tests will likely continue to be the only means of examination.
- Nacelle cooling inlets may be blocked or partially blocked and this may affect thrust or power (maximum engine power or thrust cannot be obtained due to over-temperature).

- Antennae that do not build up significant ice in Appendix C can do so in Appendix X. Communication and navigation systems would have to be checked with the ice accretions on the antennae. Similarly, systems such as the weather radar, fuel venting, bleed air cooling, and APU performance may be affected in Appendix X icing conditions.

- Unexpected ice accretions on aircraft surfaces and an ice accretion on surfaces not predicted by icing simulation methods e.g. ice on fuselage, nacelle, pylons, etc.

Airplane icing certification is recognized as a complex task. Even though the aviation industry has been using 14 CFR 25.1419 and Appendix C standards for decades and the tools used for certification have matured, flight tests in measured natural icing conditions are still considered a valuable engineering tool and continue to identify areas of design or operating procedures where improvements can be made. The authorities see no reason why Appendix X should be treated differently than Appendix C.

INITIAL MANUFACTURERS' POSITION

The airplane manufacturers examined the practicality of certification testing in natural SLD conditions. They concluded that there are multiple issues that contribute to the difficulty and hence the practicality of certification testing in natural SLD conditions and that natural icing flight tests in Appendix X conditions should not be required.

Encounter Probability

One issue that has been brought up repeatedly in IPHWG deliberations is the probability of encountering the SLD conditions. The Meteorological Service of Canada (MSC) research data indicates that SLD are a relatively frequent event and can be found readily. However, this indication is biased by the definition of SLD that has been used to reach this conclusion. At the May, 1996, FAA International Conference of Aircraft Inflight Icing, a working group deliberated on the current knowledge of the SLD environment. Co-Chairs for this working group were George Isaac (MSC) and Richard Jeck (FAA Technical Center). In the published proceedings of this event, one of the consensus items was that the definition of SLD was "any droplets larger than 50 microns diameter."

As has been previously brought before the working group, this definition does not consider the drop distribution effects of icing clouds. In a previously presented technical paper,[4] it was proposed that the definition of SLD as drops greater than 50µm should stand. However, it was also recommended that agreement should be reached on the definition of "SLD conditions". This new term would address distribution effects and align more closely with today's Appendix C. This agreement has not been reached and is a contributing factor in the discussion on the practicality of flight-testing in SLD conditions.

The concept of the drop distribution is inherent in the definition of the current certification icing envelopes with the term "mean effective diameter" (MED). This term[5] is associated with the rotating multi-cylinder method for sampling cloud properties and requires the assumption of a specific drop distribution. FAA research has shown that the historic use of MED is in general agreement with the term Median Volume Diameter (MVD) as used today. It follows that the concept of the drop distributions has long been associated with the current certification icing envelopes.[6] The most commonly used distributions are the Langmuir & Blodgett distributions "A" through "E" ("A" is monotonic and "E" has the widest range of drop sizes).

To illustrate the point relative to the probability of encountering SLD, consider a 20µm MED condition assuming the Langmuir & Blodgett "E" distribution. Per the definition, 5 percent of the liquid water content (LWC) is contained in drops of ~54µm (2.71*20=54.2µm). Given that the distribution contains drops in excess of 50µm, it would be classified as SLD per the 1996 definition. However, this 20µm distribution is well within current certification envelopes and is a probable icing condition.

However, it is unlikely that an airworthiness authority would accept a 20µm MVD encounter as a certification test representative of flight in SLD conditions. As an example, consider a wing system designed with the aft protection limits set at the 40µm or 50µm impingement limit (mono-distributed as discussed in current AC20-73 and ACJ25.1419). Using the Langmuir "E" distribution, only 5 percent of the water even has the potential for accreting behind the protected area due to the drop size exceeding the 50µm protection limit. The remaining 95 percent of the water (smaller drops) will not have sufficient inertia to impinge behind the

---

[4] Anil D. Shah, Michael W. Patnoe and Ervin L. Berg: Engineering Analysis of the Atmospheric Icing Environment Including Large Droplet Conditions, SAE 2000-01-2115

[5] Richard Jeck: Terminology for Droplet Size Measurements, (Icing Information Note -August 1994),

[6] Such as: FAA ADS-4, DOT/FAA/CT-88/8-1, FAA AC20-73, FAA AC25.1419, and JAA ACJ25.1419.

protected areas directly. An additional reduction factor is the effect of the distribution of the local collection efficiency. The local collection efficiency approaches zero at the aft edges of the protected area as shown in Figure D-1. Using the example, the local collection efficiency near the protection limits is less than 1 percent. Assuming the flight conditions noted in the figure, the theoretical maximum accumulation potential is approximately 0.012 inches film thickness over a 10-minute exposure.[7] This analysis has some simplifying assumptions[8] but provides an order of magnitude estimate to help illustrate the point.

The purported purpose of natural ice flight testing evaluations is as follows:

> The primary purposes for flight testing an airplane equipped for flight in icing conditions is to evaluate such degradation, and to determine the flying qualities remain adequate and that performance levels are acceptable for this flight environment[9]

and

> to consolidate the results obtained from flight testing with artificial shapes.[10]

In addition, this evaluation of degradation effects is listed among “significant” items in Transport Canada AMA 525/5 (September, 1996). However, given the slight amount of ice accretion behind the protected areas in the example, it is unlikely than any meaningful evaluation of degradation effects could be performed.

This effect indicates that the real acceptance threshold for a SLD certification test would require significantly larger drop sizes and/or significantly higher water contents in the large drops. In fact, the real acceptance threshold will likely be closer to the 50µm MVD, 135µm maximum drop size distribution proposed in the previously referenced technical paper.[4] The result of this line of reasoning is that the reduced

---

[7] Using maximum accumulation potential methods such as Eq. 2-29 and Eq. 2-30 of DOT/FAA/CT-88/8-1, "Aircraft Icing Handbook".

[8] Does not account for any runback, assumes ice growth normal to surface, assumes clean efficiency characteristics, conversely does not account for splash effects which would reduce accumulation potential.

[9] FAA/AC 25.1419-1, Certification of Transport Category Airplanes for Flight in Icing Conditions, 8/18/99.

[10] JAA/NPA 25F-219, Flight in Icing Conditions Acceptable Handling Characteristics and Performance Effects, May 1996.

acceptance envelope for SLD certification validation testing (relative to the 1996, 50μm definition) would greatly decrease the probability of encountering such conditions.

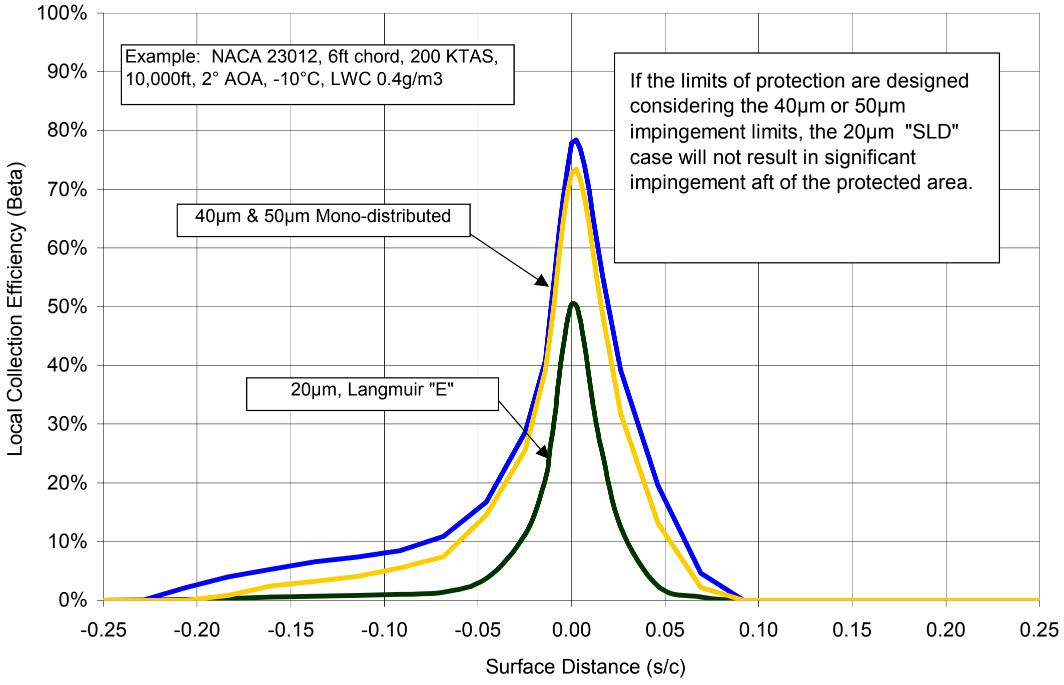


Figure D-1 - Example Impingement Characteristic

Previous Testing Experience

It has been reported[11] that previous attempts to perform development and/or certification testing in SLD conditions were of limited success. The testing involved installation of an ice detector positioned to alert to the presence of ice behind the protected areas. The devices were installed on two flight test airplanes and seven in-service airplanes in normal revenue service over the winter of 1997-1998. During the evaluation only two unusual icing encounters (characterized as “severe large droplet icing encounters”) were experienced. It was later reported[12] that three successive winter flight test campaigns were flown on company-owned aircraft, as well as evaluations of in-service experience, in the US and Europe for this same purpose. The flight tests were unsuccessful for a variety of reasons including, “[t]he rarity of severe SLD icing encounters.”

---

[11] FAA letter dated 12/14/98 response to NTSB recommendation A-96-59

[12] FAA letter dated 3/28/00 response to NTSB recommendation A-96-59

In addition, there is other evidence that the successful pursuit of SLD conditions is improbable. It was reported to the IPHWG that the NASA SLD data collection for the 1998-1999 flight season was not productive due to the inability and difficulty of locating and sampling significant SLD conditions. This was approximately a six-week program dedicated to the pursuit of SLD conditions for data collection. No data was collected due to either extinction of the conditions before arrival, lack of significant SLD conditions, or data issues due to instrumentation problems. This was a research program where the aircraft was put on station awaiting weather patterns conducive to SLD conditions. This program had access to significant meteorological resources, such as frequent forecasts and in-flight updates through a satellite telephone. A typical certification program would likely not have this level of meteorological support. This would decrease the probability of success.

As a practical matter, aircraft certification programs would incur a large expense to station an aircraft for an extended period to await SLD weather patterns to move into the test region. This expense would not only include aircraft flight and crew costs but would also include costs associated with accompanying flight test engineer(s), maintenance personnel, inspection personnel (both company and FAA delegates) to release the aircraft for flight, and likely a photographer to document the process. These expenses are aside from the logistics of hotels, meals, and car rentals that would be required for an extended test period. For certification testing, icing conditions are commonly “chased” based on available meteorological data (including NCAR products and pilot reports). The ability to forecast SLD conditions is much less mature than currently available icing products. Pilot Reports (PIREPS) will be of limited use since there is no requirement to distinguish SLD conditions from conventional icing encounters. In addition, the success of “chasing” a particular icing condition is heavily influenced by aircraft range, speed, and service ceiling. Due to the transient nature of icing, aircraft with limited range, speed, or service ceiling have a decreased probability of reaching the reported icing conditions before the conditions dissipate.

These factors provide actual flight test evidence of the difficulty in finding SLD conditions that would provide a significant validation of SLD conditions.

Variability of Conditions

Representative distributions have been presented to the IPHWG that demonstrate the wide range of drop sizes and distributions present in the SLD environment. This range of distributions can provide a substantial amount of water in small drops and a relatively few large drops. Conversely, the distribution can provide a relatively large population of large drops with virtually no small cloud-sized drops.

Current certification encounters have no firm criterion for acceptability of the extent and intensity.

- AC20-73 states:

  To establish the airplane's tolerance to the continuous accumulation of ice on unprotected surfaces, flight tests should explore stratiform icing clouds (Continuous Maximum Fig. 1) for a period of time representative of today's air traffic "holding" conditions . . . . It is recommended that the tests include a continuous exposure for at least 45 minutes.

- AC25-7A states:

  The amount of ice on the airplane should be representative of what would be accumulated in a 45 minute hold in icing conditions prior to approach and landing (typically, one to two inches on the unprotected wing leading edge surfaces has been found acceptable for this testing).

- JAA advisory materials NPA 25F-219 state: “with natural glaze ice . . . various quantities of ice on unprotected surfaces (between 0 and 3 inches).”

Although not a specific criteria, the above guidance typically drives the testing towards the warm, small-drop corner of the Appendix C (Figure 1) liquid water content envelope with no horizontal extent adjustment. The primary variable sought is water content. Temperatures are a function of water content and altitudes are taken as available considering sufficient ground clearance for safety.

Given the potential variability of SLD ice shapes due to distribution effects, the presence of large drops alone may not provide adequate confidence to certification engineers that the conditions have been validated. This forces the potential candidate for SLD certification to pursue not only water content but also a specific distribution, again considering sufficient altitude for safe evaluation. Given that the SLD conditions tend to be low-altitude events, pursuing water content, altitude, and distribution effects reduces the probability of finding adequate SLD conditions beyond the limits of practicality. Accounting for this variation in distribution effect is best suited to analytical methods.

Instrumentation Requirements

Research flights have carried extensive instrumentation for particle classification/sizing. As an example, the Canadian MSC Convair carries the following Particle Measurement Systems (PMS) sizing equipment:

• PMS FSSP 100 3-45 µm	Drop concentration/size
• PMS FSSP 100 5-95 µm	Drop concentration/size
• PMS 2D-C Mono 25-800 µm	Hydrometeor conc./size
• PMS 2D-C Grey 25-1600 µm	Hydrometeor conc./size
• PMS 2D-P Mono 200-6400 µm	Hydrometeor conc./size

This equipment is carried in addition to any for water content and temperature measurement requirements. The instrumentation probes require expert attention to maintain calibration and ensure functionality. The difficulty in maintaining this instrumentation was a contributing factor in the previously reported unsuccessful NASA research flight testing to obtain SLD data. Maintaining this quantity of equipment, both from reliability and calibration standpoints, would be a significant burden for an applicant and would require highly specialized skills. It has been reported to the IPHWG that post-processing of the data from these instruments is critical to accurately quantify the conditions and ensure that ice-contaminated conditions are understood. The data processing from SLD encounters is very time consuming and has taken months within the research environment to complete sufficient post-flight processing and analysis required to determine the full extent of the conditions. The aircraft certification environment is a fast-paced, costly environment where it would be extremely difficult to justify such program delays. Maintaining this quantity of equipment, both from a reliability and a calibration standpoint, would be a significant burden for an applicant.

Test aircraft typically require modification to provide the structural support required for particle measurement systems for Appendix C certifications. Suspending pylon mounted, multiple 35- to 50-pound devices on an airframe is not a trivial task, particularly on small transport category aircraft. This effort would require significant design and analysis support. The modification includes extensive analysis to determine local drop trajectory effects and additional engineering to perform aero-elastic stability analysis. Requiring the multiple ranges of PMS would require multiple hard mounting points. This extensive aircraft modification effort would be a significant expense.

This quantity of instrumentation represents state of the art as applied to quantifying large drop conditions. However, imposing this level of instrumentation requirement for an SLD certification effort is extreme and contributes to the impracticality of testing in natural SLD conditions.

Risk Mitigation

Most manufactures have stringent safety process in place to reduce the risk of experimental flight testing. While many airplanes are derivative in nature and have extensive service history, this cannot be assumed while proposing new certification rulemaking. With the low-altitude nature of SLD icing, increased risk would be present due to the lack of altitude for recovery in the event of an upset. Taking an unproven aircraft design into an SLD condition and performing any type of maneuver testing would represent excessive risk for flight test personnel. Most manufacturers will require some method of risk reduction. Wind tunnel testing is commonly used, as is dry air flight testing with simulated ice shapes. Dry air flight testing with “built-up” shapes allows for testing with varying degrees of contamination to assess and reduce risk before flights with the full-span, representative ice shapes.

These simulated ice shapes will likely be the result of analysis and icing tunnel tests. This analysis can consider a wide variety of conditions to determine critical ice shapes. The simulated ice shapes can be flown with sufficient altitude and in VFR conditions that allow safe recovery in the event of an upset. If this risk mitigation process is based on sufficiently validated simulation tools, the risk is mitigated not only for experimental flight test but also for in-service encounters with such conditions. This removes the necessity for testing in natural SLD conditions.

Simulation

The best alternative to flight tests in natural icing testing is through the increased use of simulation. This simulation would take the form of analysis or physical testing such as icing wind tunnels, icing tankers, dry-air wind tunnels, and dry-air flight testing with simulated ice shapes. Each form of simulation has particular strengths that can be used to resolve particular areas of concern relative to SLD environments. The primary areas of interest particular to SLD conditions include:

- Impingement aft of protected areas (potential hinge moment and stall handling effects)
- Ice shapes on unprotected areas ($C_{L_{max}}$, C_M, and C_D)
- Verification of exit cues (visual or device based)
- Performance effects (drag from extended accretion areas)[13]

Each of these areas of concern can be addressed through simulation methods. The following discussion provides examples of the simulation techniques and the relationships to the areas of interest.

Analytical Simulation

Analytical simulation methods include impingement and accretion models based on computational fluid dynamics. There are existing Appendix C tools which are in the process of being modified to account for large drop effects. Part of the development process includes validation of the large drop physics. These methods have the potential of simulating impingement and accretion aft of the protected areas, as well as resulting shapes on unprotected areas. Analytical simulation appears to provide the best method of accounting for the variability in drop distributions that are present in nature. Once the SLD ice accretions are defined, aerodynamic results could be obtained through wind tunnel or dry-air flight testing.

In addition to determination of resultant SLD ice shapes, analytical simulation provides the capability to examine impingement relative to visual icing cues and analyze the location of detection devices for any detrimental local flow effects. This will become more accurate when the

---

[13] The issue of performance (power margins relative to drag rise) in SLD conditions is a lesser concern for many transport category aircraft. Large-scale aircraft are less susceptible to all icing conditions due to the reduced collection efficiency of the airfoils. High-speed aircraft (large or small scale) typically have significant power margins when operating at low altitude holding speeds where the large droplets would likely be encountered.

SLD physics are incorporated (e.g., splashing). For aircraft where performance effects could be a concern,[13] analytical techniques have the potential to predict SLD accretion areas over the total airframe. For aircraft that have potentially limited performance, these SLD accretion areas could potentially be used in estimating overall aircraft drag decrements. The accretion areas could be used with other proven methods (such as wind tunnels or dry-air flight testing) to determine aircraft performance effects.

The ability to analytically simulate complex physical conditions continues to grow at a rapid rate due to the rapid growth in computer hardware capabilities. This trend will likely continue and provide increasingly realistic simulation of icing effects.

Icing Tunnel Tests

Icing tunnels are likely to be the primary method of predicting ice accretions aft of protected areas, as well as ice shapes on unprotected areas. This method has the ability to combine the effects of thermal systems, such as runback, with potential accretion due to SLD. The icing tunnels will likely be limited in cloud size and in the ability to simulate distribution effects. However, the distribution effects could conceivably be addressed through superposition of large and small drop effects (time/LWC scaled) or for accretions behind protected areas through LWC scaling (time) of water catch for the area of interest. The defined SLD ice accretions could then be use to determine aerodynamic results through wind tunnel or dry-air flight testing.

Icing tunnels could conceivably be used to examine impingement limits relative to fuselages or windscreens with scale models. While scaling SLD icing shapes is still an emerging area, scaling of drop inertia effects and subsequent impingement limits is in a more mature state. This technique could be used to examine visual icing cues, validate location of detection devices, and determine total SLD accretion areas that could be used in drag estimates.

Icing Tanker Testing

The use of an icing tanker would provide high confidence in local icing effects. Tankers typically have limited cloud sizes, but they can produce clouds of approximately four to eight feet. A plume of this size is sufficient to examine local icing effects relative to large drop impingement. This technique could potentially be used in a manner similar to icing tunnel testing with respect to ice shape development on unprotected areas and on areas behind protection zones. The plume could be applied to sections of the airframe (four to eight feet at a time) to examine any potential hinge moment or $C_{L_{max}}$ effects. Alternately, the testing could be used to define simulated ice shapes to evaluate aerodynamic effects. This method also has the advantage of being able to combine the effects of thermal systems (such as runback) with direct accretion to simulate the resulting ice accumulations. Similar to previous discussion, this method could be used to estimate SLD accretion areas that could be used in drag estimates (if required).[13]

Wind Tunnel and Dry-Air Flight Testing

The use of wind tunnel and dry-air flight testing has long been used as a cornerstone of ice protection system development and certification. The primary differences between Appendix C and SLD conditions are in the formation of the ice shapes. Once the shapes are defined, the testing methods for aerodynamic degradation would be the same. These are mature techniques with no new development required.

Current Appendix C icing regulations such as 14 CFR §25.1419 and JAR 25.1419 require the use of multiple methods of compliance. Simulation of SLD conditions will likely be similar as it may take a combination of a couple of methods to adequately represent the conditions and determine the degradation effects.

The realities of a new aircraft development and certification program are such that early evaluation of icing effects via simulation is not only desirable but essential. While program practices vary among manufacturers, the following illustrates a general timeline for a large aircraft manufacturer prior to first flight of a new aircraft model.

Activity	Time Frame PRIOR TO FIRST FLIGHT
Preliminary estimate of ice shapes for dry-air wind tunnel testing (is/can be a factor in establishing final configuration)	5-10 yrs (all new) 3-5 yrs (derivative)
Preliminary IPS design	5-10 yrs (all new) 3-5 yrs (derivative)
Final estimate of ice shapes & dry-air wind tunnel testing	2-3 yrs
Final IPS design	2-3 yrs
Preliminary icing data for onboard computers (AFM, FMC, SWC, etc.) and simulator database	0-2 yrs

Table D-1 - Large Manufacturer Development Timeline

Between the time of first flight of the aircraft until the time that it is certified, data for the systems, onboard computers, and simulator are finalized. Flight-testing for icing certification (either in natural icing or with manufactured ice shapes) has primarily become a “declare and verify” effort. It is expected that there will be no surprises during flight test which will require substantial re-analyses of the pre-flight data. Should a manufacturer be required to wait until AFTER the aircraft is flying to assess the icing effects, clearly there would be a substantial risk of the unknown placed upon the manufacturer. This is particularly true in the case of SLD, where today there is relatively little upon which to base pre-flight analyses. Waiting until the aircraft flies to investigate ice accretion is highly impractical and unrealistic. It is essential that tools and methods be available to estimate SLD ice accretion and assess its effects prior to first flight.

Relation to current §25.1419

Much of the previous working group discussion has centered on the current requirements of §25.1419 relative to testing in natural icing conditions. This requirement was imposed by Amendment 25-23 in 1970. In the preamble materials, the stated reason for this change is: “The current state of the art and current practice indicate that the flight tests in measure natural atmospheric icing conditions specified in paragraph (c)(4) are necessary in all ice protection system certification programs . . . .”

This precedent indicates that the decision to require natural icing tests should be based on the confidence level of the simulation techniques that could alternatively be used. The simulation tools and capabilities that NASA, et al., are developing for SLD are planned to be validated tools. In fact, many of the large drop effects (such as splashing) are being developed through physical testing which also serves as validation points for that particular aspect of the large drop physics. Another factor to be considered is that the proposed simulation tools are not completely new techniques; they are a continued progression of current Appendix C simulation techniques.

In addition, there is a precedent to not require testing in specific conditions throughout the Appendix C envelopes. In AC 25.1419-1 it states:

> Past experience indicates that flight testing in natural Intermittent Maximum icing conditions may be accompanied by severe turbulence and possible hail encounters that could extensively damage the test airplane. When design analyses show that the critical ice protection design points (i.e., heat loads, critical ice shapes, accumulation, and accumulation rates, etc.) are adequate under these conditions, and sufficient ground or flight test data exist to verify the analysis, the flight test in intermittent maximum conditions may not be necessary.

Given this precedent, it follows that natural SLD conditions could be treated in a manner analogous to the Appendix C Intermittent Maximum conditions without requiring flight tests in such conditions.

Conclusion

There are multiple factors that contribute to the impracticality of testing in natural SLD conditions. As presented, the primary factor is the difficulty in locating such conditions on demand in the time constraints of a certification program. Other factors include:

- Perceptions on the availability of SLD have been biased by the use of differing definitions to discriminate such conditions.
- Previous flight test experiences in SLD conditions illustrate the difficulty in finding SLD conditions that would be adequate to validate the aerodynamic degradation predictions.

- Requiring natural SLD flight-testing with current state-of-the-art particle measurement technology would be excessively burdensome for applicants.

- The risk of flight in SLD (either without restriction or continuously) can be effectively mitigated with simulated shapes through wind tunnel or dry-air flight testing.

- A precedent has been established to not require testing within potentially hazardous icing conditions by the allowance of validation methods other than natural icing flight tests for Appendix C Intermittent Maximum conditions.

In summary, a requirement for flight testing in natural SLD conditions would be impractical and an excessive burden on airframe manufacturers with no significant increase in the level of safety. The value added by such an exercise would not approach the cost of the testing. There are other methods of mitigating the risk such that natural ice flight testing is not required. The alternative methods of validating SLD conditions can be designed to be conservative and reliable through steady-state, controlled testing. This has the added benefit of providing a more rigorous validation than a random encounter in natural SLD conditions. Therefore, it is recommended that certification flight tests in natural SLD conditions not be required in the proposed IPHWG Task 2 rulemaking.

AUTHORITIES' RESPONSE

The authorities' response to the issues raised by the manufacturers was as follows:

Probability of Encountering Appendix X Conditions

The IPHWG has moved away from the 1996 definition of SLD conditions. As described in the September 2003 version of the draft AC 23.1419/1420, distributions with maximum drop sizes (Dmax) less than 100 µm are now classified as Appendix C. For a given temperature, the FZDZ/L water content at 110 µm is approximately four times the water content of an Appendix C, Continuous Maximum, 40 MVD Langmuir E distribution, see Figure D-2. With SLD conditions defined with a Dmax of greater than or equal to 100 µm, SLD conditions were encountered 4 percent of the time during SLD research flights conducted from 1995 to 2000. Encountering SLD icing conditions 4 percent of the time is less probable than encountering icing 24 percent of the time. However, 4 percent of the time is not improbable. Applicants may have to relocate to geographical areas where the probability of encountering SLD icing conditions is higher, as they similarly do to find Appendix C icing conditions.

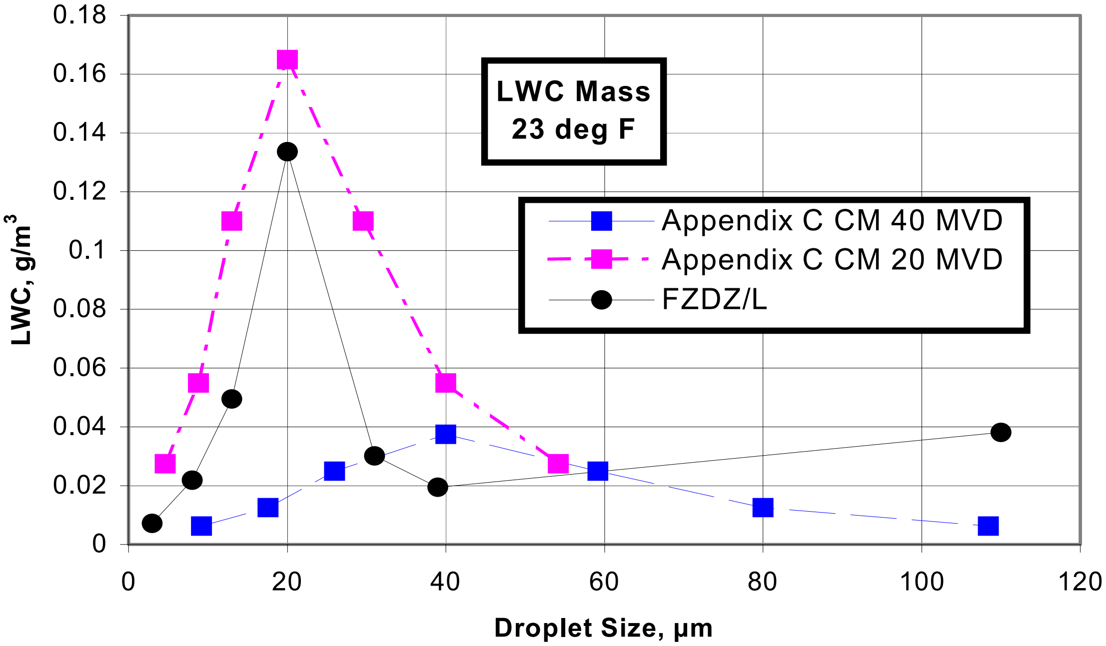


Figure D-2 - LWC as a Function of Drop Size

The authorities concede that finding SLD conditions that will be meaningful may take a longer time than Appendix C conditions.

However, the authorities have comments on several of the statements:

"A typical certification program would likely not have this level of meteorological support." This statement was made in reference to a research program that, *"had access to significant meteorological resources, such as frequent forecasts and in-flight updates through a satellite telephone*."

It is recognized that manufacturers may not have in-house weather support, but they typically contract a company to provide this service in real time to the test team. A manufacturer has already utilized such a contractor and found icing conditions every time that they looked for it.

"The ability to forecast SLD conditions is much less mature than currently available icing products. Pilot Reports (PIREPS) will be of limited use, since there is no requirement to distinguish SLD conditions from conventional icing encounters." Freezing rain can be predicted and tools, such as the Current Icing Potential (CIP), are available on the internet to assist in finding SLD conditions. This tool represents a big improvement over what was available only a few years ago. It is undergoing refinement to make it less conservative, which will be a benefit to flight testers. It is hoped that by the time §25.1420 becomes effective, the SLD forecast capabilities of CIP will be just as mature as current icing products. In 2004, the PIREP format will include an "airplane effects" code that will include "severe." Although "severe" does not differentiate between SLD and conventional icing encounters, it does represent conditions that exceed the capabilities of the airplane's ice protection system, which could be an indication of SLD conditions.

An acceptable Appendix X natural icing flight test program has not been defined. However, it may not be too different from current Appendix C natural icing flight testing. Specific Appendix C LWC/drop size/temperature points cannot be targeted due to the improbability of finding specific conditions. AC 25.1419-1 states: "At least one exposure to icing conditions within the part 25, Appendix C, continuous maximum icing envelope should be obtained." Many times now it is difficult to judge the acceptability of an Appendix C encounter. For this reason the draft AC 20-73A will have appendices that provide tools for such determination. The authorities concede that Appendix X may be different since specific drop spectra are defined.

Instrumentation Requirements

The authorities agree that the instrumentation required to measure Appendix X conditions is more extensive than that currently required for Appendix C. Efforts are underway to develop Appendix X instrumentation that is appropriate for certification. Commercial resources are currently available to measure Appendix X icing conditions. Equipment for measuring Appendix X icing conditions may also be rented. Some manufacturers may contract this service for Appendix C certifications. Analysis is required to mount Appendix C equipment on test airplanes. This would not be different for Appendix X equipment. For small airplanes, instrumentation can be mounted on a larger chase airplane.

Risk Mitigation

Although freezing rain may be concentrated at lower altitudes, it is anticipated that flight testing in Appendix X would not be different than Appendix C. Maneuvers such as stall approaches would be accomplished in VFR conditions and at a safe altitude after desired ice accretions are obtained. One of the objectives of natural icing flight test would be to evaluate the whole system (for example, propeller) as well as to look for unexpected places where ice can collect. In this regard, flight testing with simulated ice shapes mitigates the risk of natural icing flight tests but is not a replacement for natural icing flight tests.

Simulation Tools

The authorities agree that simulation tools need to be developed and validated in order to be a means of compliance. The simulation tools will be required to mitigate risk to the manufacturer regardless of whether natural icing flight tests in Appendix X are required.

Relation to §25.1419

The authorities agree that the decision to require natural icing tests should be based on the confidence level of the simulation techniques. It should be pointed out that the authorities believe that Appendix C natural icing flight tests are required regardless of whether natural Appendix X flight testing is required. To reiterate the comment under “Simulation Tools,” validation of the simulation tools is critical if they are to be used in lieu of natural Appendix X icing flight test. For an airplane certificated to the entire Appendix X icing envelope, the authorities do not agree that flight testing in Appendix X is analogous to flight testing in intermittent maximum icing conditions. Flight testing in intermittent maximum icing conditions is not done because there is sufficient data to verify the intermittent maximum icing conditions analysis. The conditions are avoided due to non-icing hazards such as lightning and turbulence. Some manufactures do test in intermittent maximum icing conditions. Natural icing tests in Appendix X icing conditions are analogous to testing in Appendix C maximum continuous icing conditions since they are both related to operations in stratiform clouds.

Authorities Conclusions:

The authorities fully appreciate the difficulties that the manufacturers face with respect to flight testing in natural icing in Appendix X conditions. This includes the aspects of probability of encounter, variability of conditions, instrumentation requirements, and risk mitigation. The authorities have taken into account these factors in determining the need for natural icing flight test in Appendix X but have to point out that the safety objectives must be achieved for flight in Appendix X, and flight testing in natural icing can only be not required if adequate alternative means are validated and employed satisfactorily.

MAJORITY WORKING GROUP POSITION

NASA has obtained natural ice shapes in SLD icing conditions. This information will contribute to a validation database for assessing SLD icing simulation methods. NASA will be using these inflight ice shapes for validating their SLD icing simulation methods. This would be useful during a certification program. However, it is not required prior to the rule, and a means of compliance using icing tankers and tunnels may be used as a verification method.

The rule language "as found necessary" was not intended to force applicants to perform testing in natural icing conditions. Acknowledging the difficulties in flight testing in natural Appendix X conditions, the majority of the IPHWG agree that flight testing in natural Appendix X conditions would not be required as in §25.1419 for Appendix C icing conditions. Flight testing in natural Appendix X icing conditions was then considered as one of the available methods to support the required analysis.

Flight testing in natural Appendix X conditions should not be necessary if:

1. The design analyses show that the critical ice protection design points (i.e., heat loads, critical ice shapes for performance and handling qualities, accumulation, and accumulation rates, etc.) are adequate under the conditions of Appendix X and various airplane operational configurations; and

2. The analyses performed for item 1. are accomplished with methods that have been validated for Appendix X icing conditions (see paragraphs (c) and (d)); and

3. Adequate analyses and/or tests are accomplished if there is a need to evaluate more than one airplane component simultaneously. As examples, the evaluation of airplane performance with propeller and airframe ice accretion, asymmetric ice accretions due to propeller wash, engine performance with inlet (including cooling) ice accretions, or stall warning and characteristics with ice accretion that affects air data used by stall protection systems; and

4. If the airplane is a derivative and is being certificated for flight throughout Appendix X icing conditions, the service record of ancestor airplanes does not include a pattern of accidents or incidents due to in-flight encounters with Appendix X conditions; and either

5. Flight testing and/or dry air wind tunnel testing with simulated Appendix X ice shapes shows performance and handling qualities characteristics that meets the requirements of § 25.21(g); or

6. The aircraft approval being sought is limited to exiting from Appendix X conditions § 25.1420(a)(1).

(c) At least two different methods of predicting Appendix X ice accretions should be shown to provide similar results (ice accretion thickness, location). One method should be either an icing wind tunnel or icing tanker test.

(d) Similarity analysis may be used if the methods used on similar designs were validated as in (c).

MINORITY POSITION OF AIRBUS, BOEING, EMBRAER AND SAAB

Airbus and Boeing remain the minority IPHWG members on this issue. In their view, the Majority Working Group Position presented above is somewhat misleading regarding the AC language: “Flight testing in natural Appendix X conditions should not be necessary if . . . .” Even Airbus and Boeing agree that if the numerous criteria are satisfied, then natural icing flight testing should not be necessary. However, that is not the point. The primary reasons for sustained disagreement with the majority are that the criteria remain overly burdensome in terms of cost and resources to be expended by the manufacturers, and they believe that a flight test program in natural Appendix X conditions is more likely to result in an extensive research project than an airplane certification.

Airbus and Boeing maintain that at the time of release to the user community, any one of the engineering tools currently being developed for determining Appendix X ice shapes should be validated/substantiated to such a degree that it is acceptable to the authorities and thus not require the use of two methods. While it is likely that for some period of time, applicants may find it prudent to use more than one tool, eventually enough expertise will be developed that applicants may have sufficient confidence in a single method, yet the rule will still require two. Boeing does not believe that the natural SLD ice shapes obtained by NASA will be of much value for them since the research airplane utilized by NASA is not at all similar to Boeing’s large jets. This opinion is supported by the current situation with NASA’s Appendix C ice-shape generation CFD codes, e.g., Lewice 2.0: it has not been validated for large, high-speed airplanes. The experimental data range used for validation by NASA is limited to a wing chord length of 78 inches but the wing chord of the 737-300, for example, is approximately 135 inches; the highest Reynolds Number is 13 million, whereas the in-flight Reynolds Number for Boeing airplanes ranges from approximately 20 to 40 million; the wings of NASA’s Twin Otter aircraft are not swept, whereas those of all large modern aircraft are swept. Given these exceedances of the validation data, whether LEWICE 2.0 generates ice shapes that correlate with those accreted in natural Appendix C conditions is unknown, and thus Boeing does not utilize the LEWICE 2.0 code for certification purposes. There is no reason to believe that the situation will be improved for Appendix X. Validation of NASA’S LEWICE 2.0 code utilized an extensive icing tunnel ice-shape database including modern airfoils; however, no such extensive database exists or is planned for NASA’s Appendix X code validation. Unfortunately, based upon historical experience with Appendix C certifications, Airbus and Boeing believe that it will be many years and numerous certification attempts before the authorities will accept even a combination of two methods of determining Appendix X ice shapes without natural icing flight test validation performed with the airplane model for which certification is sought.

The potential for natural icing flight testing in Appendix X conditions to be "found necessary" at the discretion of the authorities is an unacceptable business situation. The Airbus and Boeing view is that the manufacturers should have the liberty and responsibility of determining which means of compliance are appropriate for their situation. They must not be burdened with the uncertainty that at the final hour of a certification program, the authorities will declare that natural icing flight testing in Appendix X conditions is necessary and therefore required. The rationale presented in the "Initial Manufacturers' Position" remains valid. Airbus and Boeing stand by that position.

Notwithstanding the majority's contention that the phrase "as found necessary" is not intended to force the applicant to perform natural icing flight testing in Appendix X conditions, the fact is that the language remains in the proposed rule. If the majority sincerely accepts that natural icing flight testing in Appendix X conditions is merely one of the acceptable additional means of compliance and is not intended to be required, then they should be amenable to deleting the phrase "as found necessary" rather than stating in guidance material that they don't actually intend for it to be necessary. Another good-faith alternative would be to incorporate into the rule itself language similar to the "should not be necessary if . . . " provision from the Majority Working Group Position and proposed AC (of course, changing "should not be" to "is not" and removing the stipulation for the use of at least two methods of predicting ice shapes).

Failure to achieve full group consensus on this issue stems from a fundamental difference of opinion that has not changed since the beginning of this effort: the authorities (or the majority) believe that the proposed new rule for Appendix X conditions is necessary to improve safety for all Part 25 airplanes; Airbus and Boeing do not believe that safety will be improved for large jet transports. Therefore, although some additional burden may be acceptable when the rule is first implemented, care should be taken to eliminate the potential for unnecessary long-term undue burden.

MAJORITY RESPONSE TO MINORITY POSITION (ALPA, CAA/UK, CESSNA, FAA/FAA TECH CENTER, METEOROLOGICAL SERVICES CANADA, NASA, TRANSPORT CANADA/TRANSPORT DEVELOPMENT CENTER)

Criteria Overly Burdensome

The minority state, “the criteria remain overly burdensome in terms of costs and resources . . . .”

The working group has prepared cost and benefit information to be considered in the economic evaluation. If the benefits outweigh the costs, the proposed rule will not be considered overly burdensome.

Extensive Research Project

The minority state, “that a flight test program in natural Appendix X conditions is more likely to result in an extensive research project than an airplane certification.”

The Majority Working Group Position acknowledges the difficulties in flight testing in natural Appendix X conditions. Since natural icing flight test are controversial, the majority of the working group developed and agreed upon the conditions when the natural Appendix X conditions would not be necessary.

Ice Shape Determination

1. The minority believes that it will be many years and certification attempts before the authorities will accept a combination of two methods of determining ice shapes without natural icing flight tests.

The majority does not concur. The Majority Working Group Position of when flight testing in natural Appendix X conditions should not be necessary has been included in the proposed AC. The authorities concur with the proposed AC, which provides options other than icing flight tests to verify Appendix X ice shapes. The development of the methods for determining the ice shapes is expected to be incremental relative to existing Appendix C capabilities. This should be able to be accomplished in a shorter time frame than that required for the development of Appendix C methods.

2. The minority states that, “any one of the engineering tools currently being developed for determining Appendix X ice shapes should be validated/substantiated to such a degree that it is acceptable to the authorities and thus not require the use of two methods.”

The majority acknowledges that government entities are actively pursuing the development of engineering tools for use in determining Appendix X ice shapes. However, it is ultimately the applicant’s responsibility to substantiate that the engineering tools employed during certifications are valid. The manufacturers cannot and should not expect that the government will deliver a package that does not require additional verification effects by the manufacturer.

3. The minority states: “While it is likely that for some period of time, applicants may find it prudent to use more than one tool, eventually enough expertise will be developed that applicants may have sufficient confidence in a single method yet the rule will still require two.”

The majority interprets this to mean that the minority would like the rule changed to only require one tool. The majority does not concur. The rule requires two methods: analysis and, as found necessary, one or more types of tests. The requirement for more than one method is similar to the existing icing rule § 25.1419. The AC 25.1419-1A and the proposed AC for this rule provide guidance on the use of similarity analyses that allows an applicant to take advantage of past certifications by applying the previous substantiation to another program. The use of similarity analyses has been successfully used on many programs. There have been cases where a manufacturer has substantiated compliance with § 25.1419 based on a similarity analysis and no additional testing was required for the new program. The majority believes that the use of similarity analyses for compliance with § 25.1420 will result in similar reductions in testing as experience with Appendix X certification programs increases. There is no need to revise the rule as suggested by the minority.

“As Found Necessary”

1. The minority position states: ‘The potential for natural icing flight testing in Appendix X conditions to be “found necessary” at the discretion of the authorities is an unacceptable business situation.’

This appears to imply that the authorities will arbitrarily decide that natural icing flight tests in Appendix X conditions is necessary. The majority believe that adequate explanations have been provided in the Working Group Report and the advisory material so the rule may be applied without ambiguity regarding the meaning of the words, “as found necessary.” The Working Group Report, which provides information to be included in the preamble to the proposed rule, contains an explanation of the words “as found necessary.” The report states, in part:

> The words “as found necessary” will be applied in the same way as they are applied in § 25.1419(b). During the certification process, the applicant will demonstrate compliance with the rule using a combination of analysis and test(s). The applicant’s means of compliance will consist of analysis and the amount and types of testing they find are necessary to demonstrate compliance with the regulation. The applicant will choose to use one or more of the tests identified in paragraphs (b)(1) through (b)(5). Although the applicant may choose their means of compliance, it is ultimately the FAA (EASA) which must make a finding that the applicant has performed sufficient test(s) and analysis to substantiate compliance with the regulation.

As mentioned above, the working group has developed AC material that identifies when flight testing in Appendix X conditions should not be necessary. The majority of the working group, which includes the authorities, concurs with the proposed AC.

2. The minority has interpreted the AC language to mean that with regard to flight testing in natural icing conditions, the majority “don’t actually intend for it to be necessary.”

The majority finds this to be an incorrect interpretation of the AC language. The advisory material simply explains when fight testing in Appendix X should not be necessary.

3. The minority proposes that the language in the AC be included in the rule.

The majority does not concur. Including the language from the AC into the rule would unnecessarily increase the complexity of the rule.

<u>Safety Not Improved for Large Jet Transports</u>

The minority position brings up the issue of the applicability of the rule. This issue is addressed in Appendix F of this Working Group Report.

APPENDIX E - NECESSITY OF A MEANS TO DETERMINE EXCEEDANCE OF APPENDIX X

NECESSITY OF A MEANS TO DETERMINE EXCEEDANCE OF APPENDIX X

The tasking statement requires: "In addition, consider the need for a regulation that requires installation of a means to discriminate between conditions within and outside the certification envelope." For aircraft certified for detect and exit under §25.1420(a)(1) and (a)(2), a method to discriminate between conditions within and outside of the certification envelope is required by the rule language and clarified in the advisory material. This discussion addresses aircraft certified under §25.1420(a)(3) and the necessity for a means to discriminate conditions outside of Appendix X.

Appendix X characterizes the SLD environment in terms of an engineering design standard. The database used for developing Appendix X consists of measurements made in wintertime stratiform clouds. No measurements were made in cumulus clouds. Convective flows within cumulus clouds are known to produce higher liquid water (LWC) contents than stratiform clouds. Appendix H of this report provides more detail on why it was reasonable to develop Appendix X using wintertime stratiform cloud data only.

The IPHWG proposed Advisory Circular AC 121-XX contains the following statements: “The Appendix C conditions were designed to include 99% of icing conditions. Evaluation of icing data has indicated that the probability of encountering icing outside of Appendix C droplet conditions is on the order of 10–2”.

The IPHWG has proposed to use the 99th percentile of liquid water content (LWC) for Appendix X. Therefore, for Appendix X encounters the probability of LWC values greater than Appendix X is on the order of 10–2.

There are other mitigating considerations that are conservative aspects of an ice protection system certification program. For example, the probability of being in icing is assumed to be one for certification purposes. Ice shapes described in Part II of Appendix X for use in demonstrating compliance with the airplane handling and performance requirements of 14 CFR § 25.21(g)(2) & (g)(4) are defined to provide a conservative assessment of the icing effects to ensure an acceptable level of safety. Holding operations are assumed to last for extended durations, typically at the most critical water catch point. Current and future advisory material considers the hold to occur within a 17.4 nm cloud extent which produces a high LWC. The critical water catch point is typically a very specific set of conditions and conservative assumptions such as aircraft weight, holding airspeeds, and ambient temperatures. The probability of an aircraft simultaneously achieving or exceeding these design assumptions is not quantifiable but is conservative. Many certification programs have further conservative factors such as assuming minimum system tolerances such as minimum pressure regulators or temperature controller set points.

CONCLUSIONS

No definitive quantitative analysis can be performed to show that the hazard of flight in conditions beyond certification limits meets commonly accepted probabilities for catastrophic events. However, given the conservative factors described above, the IPHWG believes that the probability of exceeding the limits for aircraft certification is sufficiently low to prevent a catastrophic event, and a means to alert flight crews when 14 CFR part 25 Appendix X icing conditions are exceeded is not needed.

APPENDIX F - RULE APPLICABILITY BASED ON AIRCRAFT DESIGN FEATURES

POSITION STATEMENT SUPPORTING EXCLUSION FROM §25.1420 FOR AIRPLANES WITH CERTAIN DESIGN FEATURES

(Airbus, Boeing, Embraer, Cessna[14])

Overview

The current airworthiness requirements of 14 CFR/JAR Part 25 for flight-in-icing certification have proven to be sufficient to provide the desired level of safety for certain transport-category airplanes. The position of Airbus, Boeing, Embraer, and Cessna[14] ("the major airplane manufacturers") is strongly supported by the safety record of the class of airplanes proposed for exclusion, which today routinely fly in icing conditions both within and outside of Appendix C. Compliance with the proposed new certification requirements of §25.1420 to address icing environments including supercooled large droplet conditions ("SLD") would be extremely costly, and no safety improvement can be expected. Consequently, the major airplane manufacturers contend that there is no justification for making either the certification requirements or the certification process more burdensome for these types of airplanes.

Introduction

The Ice Protection Harmonization Working Group ("IPHWG") assembled accident and incident databases of events in SLD conditions that are considered relevant to the proposed §25.1420 ("relevant" meaning that had it been in place at the time, the proposed regulation could have prevented the event). Review of the databases revealed that airplanes of certain types or with certain design features have experienced no accidents and very few incidents due to in-flight icing, either inside or outside of Appendix C environments. It is therefore reasonable to conclude that no increase in safety with regard to in-flight icing need be achieved for these types of airplanes. The major airplane manufacturers thus propose the concept of "exclusionary design features," with the intent that future airplane designs which incorporate these features be exempt from demonstrating compliance with proposed §25.1420.

The major airplane manufacturers propose three primary exclusionary design features, discussed in greater detail below: size, irreversible powered flight controls, and wing leading-edge high-lift devices. The intention of the major airplane manufacturers is that in order to qualify for exemption from proposed §25.1420, an airplane should have all three of these main features. However, there are other design features that warrant consideration for exemption as well.

---

[14] See appended Cessna position statement.

Requirements for Flight-in-Icing Certification

The icing certification rules were established in the 1940's after World War II. The certification process was subsequently defined by gradual development of the advisory material. The 14 CFR/JAR requirement is that an airplane be able to operate safely when flying in icing conditions. Compliance is shown by evaluating the ice protection system ("IPS") design and the airplane's performance when subjected to an environment defined by design icing envelopes known as 14 CFR/JAR Part 25, Appendix C. Advisory material provides guidance on the conservative critical ice shapes to be considered when showing compliance. Ice accretion associated with a 45-minute holding scenario has often been found to result in the most critical ice shapes per Appendix C, and historically this ice measured a nominal 3 inches at the upper horn and has come to be known as "3-inch ice." Both 3-inch simulated ice shapes and natural accretion of as much as 3 inches on the wing leading edge are commonly used for flight testing to show compliance.

It is often quite difficult to accrete 3 inches of ice in natural Appendix C conditions. Natural icing conditions generally do not match the Appendix C conditions which generated the critical ice shapes. Appendix C conditions are a statistical definition where each point is defined by 3 icing parameters for a given size cloud: mean effective diameter ("MED," droplet size), air temperature, and liquid water content ("LWC"). Icing clouds seldom provide an environment adequate for achieving a 3-inch accumulation during a certification flight test, and as a result, the airplane is often flown for several hours (rather than 45 minutes) and the authorities accept a lesser accumulation. In-flight assessment of the actual shape and thickness is very difficult and results are approximate. These difficulties are compounded by another factor relative to natural ice flight testing for certification compliance: measurement of CLmax with a naturally iced wing. Generally, natural buffet or buffet generated by the accreted ice causes the ice to break off or shed in parts, resulting in inconsistent measurements. For these reasons, more and more reliance has come to be placed upon dry-air wind tunnel and flight tests with simulated ice shapes. By manufacturing ice shapes out of a light-weight material (e.g., wood, plastic, or foam) and bonding them onto airplane leading edges, it is possible to make a consistent assessment of airplane behavior with ice accretion; flight tests can take place in a quiet atmosphere. Preceding dry-air tests, it remains necessary to define the critical ice shapes. Ground simulation techniques and the emergence of computational fluid dynamic ("CFD") computer codes assist in determination of the critical ice shapes. This has assisted the transition away from reliance upon natural icing flight testing as the primary means of certification compliance.

An airplane certified for flight in icing today typically has no environmental limitations on its in-flight operation in icing conditions. Since Appendix C does not describe all icing conditions encountered by airplanes in flight, and given recent meteorological data as to the probability of encountering various conditions, the conclusion can be made that many airplanes safely fly today, and have for decades, in SLD conditions described by the proposed Appendix X. As they are flying safely, it must be the case that certification compliance to Appendix C conditions is conservative enough that the conditions of Appendix X do not pose a greater or additional threat. Airplanes also take off today in icing conditions outside of Appendix C, i.e., freezing drizzle and light freezing rain, with no limitation on vertical or horizontal extent of the conditions after takeoff. No accidents nor incidents have occurred due to takeoff and subsequent flight in these conditions. Therefore, for airplanes possessing the exclusionary design features, certification for flight in icing using Appendix C conditions for design of the IPS and determination of the critical ice shapes should be considered an equivalent method of compliance providing global protection (or “equivalent protection”) for all icing encounters.

At an FAA symposium in 1969 regarding review of the Appendix C icing criteria, William Lewis stated:

> Since these criteria have stood the test of use, and since the total of experience with existing aircraft is more comprehensive than any data-collecting program, it is suggested that the future changes in criteria be based primarily on operating experience rather than on meteorological data.

This opinion is very much in unison with the assertion of the major airplane manufacturers – that the current large transport category airplanes, a fleet of nearly 20,000, already demonstrate safe operation in icing.

Exclusionary Design Features

The major airplane manufacturers propose that airplanes possessing a combination of all three specific design features be exempt from demonstrating compliance with the proposed §25.1420. The three exclusionary design features are:

1. Size. Size has a direct bearing on an airplane’s susceptibility to the adverse effects of ice accretion. From Appendix 3 of the draft AC 25.21(g):

   > The size of an airplane determines the sensitivity of its flight characteristics to ice thickness and roughness. The relative effect of a given ice height (or ice roughness height) decreases as airplane size increases.

Notwithstanding the difficulty of defining the limit between “larger” and “smaller” airplanes, review of the icing safety record reveals the facts:

- Zero in-flight accidents with larger airplanes[15]
- Numerous fatalities from accidents of smaller airplanes.

The advantage of size with regard to in-flight icing considerations is well known based upon decades of testing and experience and does not have to be re-proven.

Based upon review of the accident/incident database, it is proposed that size be an exclusionary design feature for airplanes with gross weight in excess of 60,000 pounds (27,000 kilograms). There is no compelling rationale for the choice of 60,000 pounds other than it being the threshold used for the IPHWG’s proposed operating rule §121.321. Wing chord or other such parameters would no doubt be better technical criteria but, as was decided for §121.321, a simple weight threshold is easier to implement.

2. Irreversible Powered Flight Controls. The use of irreversible powered flight controls is another factor that reduces an airplane’s susceptibility to SLD conditions. The concern that SLD accretions can produce hinge moment or other anomalous control force/trim effects is not applicable to such systems. Since the loads generated at the control surfaces are reacted against the actuator and its mounting, changes in these loads cannot be transmitted through the cockpit controls. The use of irreversible powered flight controls is implicitly related to reduced airplane susceptibility. The choice of irreversible flight controls is related to the aerodynamic loads on the control surfaces. The high loads that require powered flight controls are typical of high speed or large-scale airplanes. The high-speed characteristic requires significant power that results in significant power margins at the low speeds typical of low altitude operations within the icing environment. The scale issue is discussed in item 1 above.

3. Wing Leading-Edge High-Lift Devices. For wings without ice contamination, wing leading-edge high-lift devices (e.g., slats, Krueger flaps) provide a considerable increase in the maximum lift coefficient, CLmax, compared to fixed leading edges. When contaminated with ice,

---

[15] Regarding the 28 March 1989 McDonnell Douglas DC-8-73F accident, this airplane type would not qualify for the proposed exemption since it does not have the proposed required design features (no wing leading-edge devices nor irreversible powered flight controls).

wings equipped with these devices have smaller relative CLmax losses due to ice accretion than are suffered by wings with fixed leading edges. This reduced sensitivity to the adverse effects of ice accretion is applicable to the critical takeoff, initial climb, approach, and landing phases of flight.

Significant facts associated with the proposed exclusionary design features should be pointed out.

- Manufacturers of airplanes with the proposed exclusionary design features tend to apply an IPS to fewer and fewer lifting surfaces. As airplanes have grown in size, it has been found to be unnecessary to protect the entire wing leading edge and the leading edges of the horizontal and vertical tails. For example, the B777 IPS protects only three out of seven wing leading-edge slats, less than half of the span, and does not protect the tails at all. As a precautionary measure for flight testing, the A380 prototype design incorporates protection for only one wing slat out of eight; the production airplane is intended to have no IPS for the wings and tails.

- The safety record of today's commercial jet airplane types that would qualify for the proposed exclusion shows not one single accident due to SLD icing conditions. As of 31 December 2001, there were approximately 16,144 airplanes, 7 manufacturers, and 33 types of these airplanes in service. The cumulative departures were 396 million, registering approximately 645 million flight hours. These metrics are impressive, with not one accident due to SLD icing conditions.

There are other design features which may have a positive effect on mitigating performance degradation due to ice accumulation. Such features should be considered as potentially providing a level of safety equivalent to the three primary exclusionary design features.

a. Configuration or Airfoil Design. The configuration of an airplane's critical surface may be such that degradation due to icing effects falls within the operational design envelope. For example, some tails are designed to provide full functionality with critical ice accretion. Some airfoil designs are less susceptible to icing effects than others. The scale of a leading-edge radius has a dramatic effect on collection efficiency and the resulting ice accretion, as shown by the comparison among the thickness of ice collected during the same test on the following Airbus airplane parts: Beluga wing tip, 3 inches; wing root, 1.5 inches; upper front fuselage, zero. This result is not unique and is indisputable. It may be explained by the experimental fact that water droplets are susceptible to bursting when subjected to the shear forces that appear in front of any leading edge, due to the bending of flow lines. Another finding is the spectrum of droplets after the burst: larger droplets split into thousands of very small ones which are easily carried away by the airflow and never hit the airframe. This type of "protection by design" would likely have to be evaluated on a case-by-case basis.

b. Stall Protection Devices. An airplane equipped with a stall protection device such as a "slat gapper" (a device that automatically extends leading-edge slats from a sealed to a slotted position, typically when the airplane reaches a specific angle of attack) is likely able to generate a greater CLmax with ice accretion than the uncontaminated wing with sealed slats. The extension and gapping of the slats increases the maximum lift capability of the wing and may provide effective protection against degradation in stall performance or characteristics.

c. Thermal Ice Protection System. The accident/incident database revealed that most airplane types that have had accidents in SLD conditions did not have a thermal IPS or, at least, not one that was prudently activated. The greatest advantage of a thermal IPS is achieved when it is designed as an evaporative system and operated as an anti-icing system to prevent ice accretion.

Conclusion

Airplanes possessing the proposed exclusionary design features enjoy an exemplary safety record with regard to in-flight icing. Tribute for this must be given to the current certification standards and methods, which are successful for these types of airplanes. This success demonstrates the validity of the concept of "equivalent protection" afforded by using the current Appendix C as the environmental icing standard for means of compliance. Given actual flight activity, it is clear that current icing certification standards adequately protect many airplanes against any type of icing encounter, including SLD conditions as described by proposed §25.1420 Appendix X.

The major airplane manufacturers contend that the current icing certification process is not only adequate for these types of airplanes, it is already overprotective; each new version of more stringent certification requirements penalizes new airplanes relative to previous ones, which have proven to be safe as certified to the previous requirements. The major airplane manufacturers therefore consider it unnecessary and unacceptable to impose the requirements of §25.1420 upon these types of airplanes. Such a change to icing certification cannot be justified by any safety benefit but would be enormously costly. With the growing challenges of economics within the aviation industry, it is more important than ever to invest for safety improvements in the most productive manner. Further, the IPHWG's rulemaking activities with regard to SLD, as assigned by TAEIG in Task 2, are not consistent with the recommendations of the Commercial Aviation Safety Team, which has determined that the operational data support application of an expanded icing envelope only to airplanes without thermal anti-icing systems.[16] Burdening all airplanes with certification efforts that result in no significant increase in safety does not benefit the flying public and is contrary to the purposes of ARAC rulemaking.

Cessna Position Statement

As a manufacturer of small-scale Transport and Normal Category airplanes, a scale-based discriminator will not include most Cessna products. However, it is recognized that there is technical justification for the reduced susceptibility of certain airplanes based on scale and other design features. Cessna is supportive of the recognition that airplanes with certain design features are less susceptible and will have a reduced safety benefit as a result of large drop rulemaking. It is also recognized that improved operating procedures and training is a major factor in increasing safety in icing conditions, whether in Appendix C or large droplet conditions and independent of certification or specific operating rules (Part 121, 135 or 91).

---

[16] The following excerpts are from the Commercial Aviation Safety Team - Loss of Control Joint Safety Implementation Team's Implementation Plan for Criteria for Flight in Icing Conditions for New Airplane Designs (emphasis added):

> Safety Enhancement: **New designs for airplanes not equipped with evaporative systems accommodate flight in an expanded icing envelope** and additional de-ice/anti-ice system malfunctions.
>
> Output 1: Regulations and guidance materials are in place that adopt the principles embodied in the final reports of the ARAC Ice Protection Harmonization Working Group and the ARAC Flight Test Harmonization Working Group **to establish new icing certification criteria, for airplanes not equipped with evaporative systems**, that include performance and handling qualities requirements for the following: Residual ice; Intercycle ice; Delayed anti-icing/de-icing system activation; De-icing/anti-icing system malfunction.
>
>> Actions:
>>
>> 1. **The ARAC Ice Protection Harmonization Working Group publishes expanded icing envelope**.
>>
>> 2. The ARAC Flight Test Harmonization Working Group publishes recommendations that address airplane performance and handling characteristics in icing conditions.

MAJORITY POSITION - RESPONSE TO EXCLUSION FROM §25.1420 FOR AIRCRAFT WITH CERTAIN DESIGN FEATURES

(ALPA, CAA/UK, FAA/FAA Tech Center, Meterological Services of Canada, NASA, SAAB, Transport Canada/Transport Development Center)

Background

The existence of SLD icing conditions, consisting of freezing drizzle and freezing rain, is unquestioned. Transport airplanes, regardless of airplane size, weight, high-lift configuration design, or flight control system design, routinely operate or may be inadvertently exposed to these icing conditions. Yet, during the approval of the airplane for flight in icing conditions, transport airplanes are not required to show compliance with minimum airworthiness requirements that would ensure safe operation in these SLD icing conditions. The safety margins when operating in these conditions are unknown.

While some transport airplane manufacturers remain silent on the operation of their aircraft in SLD icing conditions, others recommend that their airplanes not be operated in SLD icing conditions. For example, Gulfstream states the following in the operations manual for their GI-GV airplanes: "Under no circumstances will flights be planned through forecast or known severe icing conditions. . . . Flight in freezing rain or freezing drizzle should be avoided."

Assessments by the FAA, TC, ALPA, and the National Safety Transportation Board (NTSB) of transport airplane operational experiences in SLD indicate that the 14 CFR part 25 Appendix C icing conditions standards are no longer sufficient and that the icing conditions standards of 14 CFR part 25 should be expanded to include SLD icing conditions and mixed-phase icing conditions, if mixed-phase icing conditions are found to be more hazardous than the liquid SLD icing conditions. These assessments and decisions are congruent with a statement made relative to 14 CFR part 25, Appendix C, at a 1969 FAA symposium by William Lewis, a National Advisory Committee for Aeronautics' researcher, who contributed to the information used to establish Appendix C:

> Since these criteria have stood the test of use, and since the total of experience with existing aircraft is more comprehensive than any data-collecting program, it is suggested that the future changes in criteria be based primarily on operating experience rather than on meteorological data.

Action by the FAA to expand the 14 CFR part 25 icing condition standards to include SLD is "based primarily on operating experience."

Beyond the assessment by the NTSB and the FAA of the safety history of transport airplane operations in SLD icing conditions, , the transport airplane operational experience in SLD icing conditions is further mired in related confused industry practices and unclear information provided to pilots relative to deciding when operating their airplane in SLD icing conditions is safe. Annually, the FAA issues a Flight Standards Information Bulletin for Air Transportation (FSAT) that provides de/anti-icing fluid holdover protection guidelines in freezing drizzle and light freezing rain for ground operations. Even though the de/anti-icing fluid holdover time guidelines explicitly state that the fluids do not provide protection during flight, some flight crews interpret the inclusion of light freezing rain fluid protection guidelines in the FSAT as an FAA approval for flight operations in SLD icing conditions. Action by the FAA to expand the 14 CFR part 25 icing condition standards to include SLD will address operational issues associated with flightcrews lacking clear guidelines for when operation in freezing rain would be safe or unsafe.

Issue No. 1- *Exclude airplanes that have the following:*

1. *Weight greater than 60,000 pounds,*
2. *Equipped with irreversible flight controls, and*
3. *Wing leading edge high-lift devices.*

Response No. 1

The response to the minority proposal to exclude airplanes with specific characteristics or design features is addressed in two parts: first, a general response addressing whether it is appropriate to limit the applicability of a certification requirement; secondly, a response to some of the specific design features that are proposed to be used to limit the applicability of the proposed rule.

General

Part 25 prescribes airworthiness standards for the issue of type certificates, and changes to those certificates, for transport category airplanes. In general, specific airworthiness standards are defined with the intent of ensuring safety of flight. These standards state airworthiness objectives or absolute requirements, and have been formatted to be generally applicable to future airplane designs. Typically, a limit is included in the airworthiness requirements when the requirement applies to a specific configuration class, such as: reciprocating or turbojet engines; propeller or turbojet powered airplanes; land or sea airplane; nose or tail wheel landing gear; high-lift devices retracted or extended.

Limiting the applicability of an airworthiness requirement is only appropriate when there is high confidence that the boundary of the applicability can be appropriately chosen. To evaluate the confidence in the proposed boundary one must consider if there are unknown factors involved. For example, the safety record of large aircraft may be due in part to the prevalence of safety equipment that are not typically installed in smaller airplanes, a situation that may change due to improved technology and changes in the economy that could drive the removal of the equipment on future airplanes. Another example would be the unknown effect of future new, modified, or innovative airplane designs and modifications on past operational experience. These two examples illustrate that we cannot predict with confidence that the past service experience of airplanes with specific design features will be applicable to future designs.

Historically the FAA has not limited the applicability of icing requirements contained in part 25. Recent Aviation Rulemaking Advisory Committee (ARAC) activities have followed this philosophy. The Flight Test Harmonization Working Group (FTHWG), consisting of industry and government specialists of Europe, North America, and South America, was tasked on June 10, 1994 (59 FR 30082), to recommend to the ARAC new or revised requirements and compliance methods related to airplane performance and handling characteristics in part 25, Appendix C, icing conditions. ARAC has recommended to the FAA proposed rulemaking drafted by the FTHWG, commonly referred to as §25.21(g), et al. These proposed airworthiness requirements are applicable to all transport category airplanes, regardless of size, weight, high-lift configuration design, or flight control system design.

The Ice Protection Harmonization Working Group (IPHWG) has requested support from the FTHWG relative to devising requirements to assess the ability of airplanes to safely exit or operate without restriction in Appendix X SLD icing conditions. The IPHWG has proposed that the FTHWG generally extend the proposed requirements of §25.21(g), et al., to Appendix X SLD icing conditions.

Operations in Appendix X SLD icing conditions are expected to result in airplane performance degradations and adverse changes in airplane stability and control different than, and potentially greater than, those resulting from operations in part 25, Appendix C. Limiting the applicability may result in degraded airplane performance and handling qualities relative to the airworthiness standards that have been relaxed in the proposed in §25.21(g), et al. Therefore, limiting the applicability of the proposed §25.1420 would result in the unacceptable situation of requiring higher levels of safety for certain airplanes and lower levels of safety for other airplanes with regard to performance, stability, and control in icing conditions.

Weight

Airplane takeoff weight is suggested as a design feature that reflects the alleviating effect of airplane size on the adverse aerodynamic effects of ice accretion. However, the ratio of wing and control surface sizes to airplane weight varies between airplane designs. Also, the chord of wings and control surfaces vary with the aspect ratio of these surfaces. Therefore, airplane takeoff weight is not a consistent indicator of lifting and control surface size or chord.

The proposed 14 CFR §25.21(g), et al., recognizes the beneficial effects of airplane size, relative to the adverse effects of ice accretion, by the establishment of airplane performance thresholds at which airplane performance degradations resulting from ice accretion must be included in the airplane performance requirements of subpart B of 14 CFR part 25. The proposed 14 CFR §25.21(g), et al., establishes thresholds for when ice-related degraded airplane performance must be addressed. This benefits larger airplanes since the adverse aerodynamic effects of ice accretions diminish as the airplane size increases. Airplane size is also addressed by the diminished effects of ice accretion on large airplanes relative to the ice contaminated stability and control requirements proposed by §25.21(g), et al. Actual substantiation of the effects of airplane size on the aerodynamic effects of ice accretion, as is required by the proposed §25.21(g), et al., is considered more encompassing and appropriate than inferring benefits based on takeoff weight. The proposed 25.21(g), et al., currently requires analysis based on 14 CFR Appendix C icing envelopes. The larger drops in SLD conditions will yield impingements, and ice accretions, further aft than Appendix C conditions, along with potentially different accretions in the leading edge area. These SLD shapes and locations have not been quantified in terms of performance degradation and handling qualities, and they need to have the same evaluation expected of Appendix C ice shapes to assure safe operations.

Irreversible Flight Controls

Irreversible flight controls will provide protection against uncommanded motion of a flight control surface due to a ridge of ice aft of the protected area and in front of the flight control surface. However, this is not the only concern in SLD icing conditions. An irreversible control surface may not be deflected by the SLD accumulation but the aerodynamic efficiency of the control is likely to be degraded by the presence of SLD icing in front of the control surface. Moreover, the thinner outboard wing sections are in general more susceptible to collecting ice than the thicker inboard wing sections, and the chord of the airfoil decreases outboard, which makes the outboard sections more sensitive for ice accretion. Thus, especially SLD ice accretion might change the stall characteristics of the wing in the direction of wingtip stall.

Wing leading edge high-lift devices

The aerodynamic benefits resulting from wing leading edge high-lift devices are well known. The leading edge high-lift devices afford wing boundary layer control that delays wing stall to higher angles of attack. Airplane performance benefits can be realized since many performance margins defined by subpart B of 14 CFR part 25 are predicated on stall speed. However, any aerodynamic benefits attributed to the devices in icing conditions would not be present when the devices are stowed for the cruise configuration.

Arguments have been made that airplanes with leading edge high-lift devices are less sensitive to leading edge surface roughness. However, maintenance and repair requirements of 14 CFR part 41 and the requirements of 14 CFR §121.629, and similar other operating rules, ensure that airplane surface finishes are maintained to manufacturers' standards and ensure that transport airplane surfaces are free of adhering ice prior to takeoff. Also, means used for demonstrating compliance with 14 CFR part 25, subpart B, provide for using the most adverse of allowable tolerances, such as equipment tolerances and surface finishes, for those demonstrations. The issues of surface smoothness and the adverse aerodynamic effects of non-smooth surfaces are addressed by compliance with existing regulations and conformance with existing certification practices.

The benefits of various leading edge high-lift device designs relative to leading edge surface roughness may vary. A significant portion of these benefits are due to boundary layer control resulting from a well-designed slot between the leading edge high-lift device and the basic wing leading edge. Some leading edge slats are not slotted for takeoff but instead are extended and deflected to increase wing area and leading edge camber for improved high-lift performance. Airplanes with these features may exhibit the same sensitivity to leading edge surface roughness as "hard wing" airplanes. The takeoff position of slats may be automated, with the slat extended and sealed at takeoff operational attitudes and further extended and deflected, opening a slot at the slat trailing-edge, as stall angles of attack are approached. Such slat designs may provide tolerance to wing leading surface roughness. The level of surface roughness tolerance provided by such designs may vary.

High confidence in limiting a rule based on the presence of wing leading edge high-lift devices cannot be achieved because of the variations in these devices. Wing leading edge high-lift device designs include: slats that may be slotted or sealed to the basic wing leading edge, over or under deflected, deflection and slotting of the slat that may be automated as a function of stall warning or airplane angle of attack; Krueger flaps that may be slotted or sealed to the wing leading edge, flexed to optimum curvature or conformed to the wing's leading edge lower surface; vortilons or some other vortex creating devices; or some other innovative device. In addition the spanwise extent of ice protection for transport airplanes with leading edge high-lift devices varies from 100 percent for some early turbo-jet airplane slats to the span of two slats for later airplane designs and to none for Krueger flaps. The variations in the designs lead to varying degrees of aerodynamic benefit. Without defining these specific performance benefits associated with the above designs, it is indeterminate as to the potential safety margins for SLD conditions.

A comprehensive review of the effects of ice accretion on airplane aerodynamics published in 2001 by Frank T. Lynch and Abdollah Khodadoust[17] states that there is very little applicable data available addressing the possible range of maximum lift penalties which could be caused by "large" in-flight ice accretions on multi-element high-lift wings. A well know correlation of the effect of wing surface roughness on maximum lift coefficient by Ralph E. Brumby,[18] indicates that for roughness at the leading edge, the maximum lift benefits afforded by slats, relative to "hard wing" designs, no longer exists for k/c greater than approximately 0.0015. SLD ice is often rougher than Appendix C ice. On a large transport aircraft this kind of rough SLD ice may result in adverse aerodynamic effects.

Use of wing leading edge high-lift devices to limit the applicability of the draft 14 CFR §25.1420 is considered inappropriate since: the adverse aerodynamic effects of icing must be addressed for all phases of flight and airplane configurations; the variability of wing leading edge high-lift device and airplane ice protection designs (and associated benefits that may be attributed to utilization of the devices); and, the lack of applicable data available that address the aerodynamic benefits resulting from the devices during flight in icing.

Issue No. 2 – *Exclude airplanes with other design features (configuration of airfoil design, stall protection devices, thermal ice protection system)*

Response No. 2

Airplane design features may exist that mitigate the adverse effects of ice accretion on airplane performance and stability and control, such as leading edge sweep, airfoil camber and thickness distribution, and stall margins. However, the mitigation may vary, depending on the attributes of the design feature. Since the value of mitigation varies with specific airplane design features, consideration of these design features should be recognized when decisions are made relative to the extent of needed ice protection and when compliance with airworthiness standards is demonstrated.

---

[17] Lynch, Frank T. and Khodadoust**,** Abdollah, "Effects of ice accretion on aircraft aerodynamics," *Progress in Aerospace Sciences,* Vol. 37, p. 730, 2001.

[18] Reinmann, John J., "Icing: Accretion, Detection, Protection, "*AGARD Lecture Series 197, "Flight in an Adverse Environment,"* AGARD-LS-197, November 1994, p. 4-14.

Below are comments on some of the specific design features the minority has proposed to be used to limit the applicability of the proposed rule.

Configuration or Airfoil Design

The minority states that larger drops split into thousands of small ones, which never hit the airframe. Although understood for other applications (e.g., ink jet printing and fuel atomization), the bursting of large water drops because of shear forces as the drops approach surfaces and the bouncing and splashing of large drops is an emerging area of icing physics research. The science of large droplet shear and break-up dynamics is not well understood, and there is no current research that defends the notion of droplets bursting into thousands of very small ones for the speed, leading edge radius, and droplet sizes involved. The claim cannot be substantiated at this time. It would not be appropriate to limit the applicability of a rule without a better understanding of large drop icing physics and any potential impingement effects on airfoil surfaces.

Thermal Ice Protection System

The design of thermal ice protection systems varies with respect to coverage and capability. Running wet systems are becoming more prevalent as heat sources become scarce with the use of high by-pass ratio engines, resulting in runback ice aft of the protected surfaces. Runback ice can exacerbate ice accretion resulting from SLD icing conditions. Also, thermal ice protection system coverage is becoming less extensive as the size of airplanes increases and as the heat sources become scarce with the use of high by-pass ratio engines, resulting in more unprotected surfaces that would be exposed to SLD icing conditions. As such, the benefits of thermal ice protection systems may vary and offer little confidence as a basis for limiting the applicability of the proposed 14 CFR § 25.1420

Issue No. 3 – *Extremely costly and there are no benefits for the airplanes that are proposed to be excluded.*

Response No. 3

A cost/benefit analysis has not been accomplished. Therefore the majority does not concur that it is possible to conclude that the costs would outweigh the benefits for the airplanes that are proposed to be excluded from the Task 2 SLD rule.

Identification of benefits would need to consider:

1. That the past service history may not predict future service experience with respect to safe operations in icing because there is a trend toward minimizing the areas protected from ice accretions and increasing the areas which run wet rather than minimizing the protected surface wetness by evaporation of the impinging cloud drops.

2. Zero accidents or incidents do not mean that sufficient safety margins are always maintained.

The majority acknowledges that the manufacturer would incur costs to comply with the proposed rule.

Issue No. 4 – *An aircraft certificated for flight in icing typically has no environmental limitations on its in-flight operation in icing conditions. Certain airplanes already safely fly in icing conditions of proposed Appendix X. Since they are safely flying the certification compliance to Appendix C conditions is conservative enough that the conditions of Appendix X do not pose a greater or additional threat.*

Response No. 4

The majority concur that certain large transport *aircraft* presently operate without environmental limitations on their in-flight icing operation. These *aircraft* have been designed and certified according to Appendix C. Thus, compliance with Appendix C may provide some measure of conservatism. However, it is not known if this conservatism results in a safety margin that is appropriate for operation in all icing conditions of Appendix X. The general trend for new *aircraft* designs is to further improve airplane efficiency by reducing the protected areas, reducing the amount of heat, changing the mode of the thermal IPS from evaporative anti-icing to running-wet de-icing systems etc. Therefore, the majority does not concur that current practices ensure future airplanes will have an acceptable safety record in Appendix X icing conditions.

The safety margin for Appendix X conditions afforded by compliance with Appendix C would be dependent upon the specific airplane and the means of compliance. Therefore, without determining the effect of Appendix X on the performance and handling for each airplane, the majority does not concur that it is possible to state that compliance with Appendix C is sufficient to ensure that Appendix X does not pose a greater or additional threat to safe operations.

Issue No. 5 – *Task 2 is not consistent with recommendations of the Commercial Aviation Safety Team (CAST), which determined that the operational data support application of an expanded icing envelope to only airplanes without thermal anti-icing systems.*

Response No. 5

The majority concur that there is an inconsistency. This issue references the CAST Loss of Control (LOC) Joint Safety Implementation Team (JSIT) implementation plan for safety enhancement No. 39. The implementation plan is based upon recommendations from the CAST LOC Joint Safety Analysis Team (JSAT). The LOC JSAT only looked at three icing accidents, all of which involved airplanes equipped with pneumatic deicing boots. With such a limited evaluation, no data was examined to justify a decision regarding the adequacies or inadequacies of a thermal anti-icing system or aircraft size. Under issue No. 2, the majority explains why this proposed rule should not be limited to airplanes without thermal ice protection systems.

Issue No. 6 – Cessna Position Statement

a. There is technical justification for the reduced susceptibility of certain aircraft based on scale and other design features.

b. Supportive of recognition that aircraft with certain design features are less susceptible and will have a reduced safety benefit as a result of supercooled large drop rulemaking.

c. Improved operating procedures and training is a major factor in increasing safety in icing conditions.

Response Nos. 6.a and 6.b

The Cessna position statement does not propose the exclusion of certain aircraft from the proposed SLD rule. As stated in response No. 2, the majority concurs that airplane scale and other design features help reduce the effect of icing. However, these design features must be evaluated on a case-by-case basis. The majority concurs that airplanes with certain design features may have reduced susceptibility.

Response No. 6.c

The Cessna position statement does not propose specific operating procedures or training that should be implemented. However, the majority does concur with the general statement that operating procedures and training are important factors that improve the safety in icing conditions.

APPENDIX G - CERTIFICATION TO A PORTION OF APPENDIX X

MINORITY POSITION REGARDING CERTIFICATION TO A PORTION OF APPENDIX X

(ALPA, Metrological Services of Canada)

The Appendix X rule and AC provide for “certification with a range of techniques for example, limiting the range of liquid water contents, or potentially water contents in a specific drop size.” The AC further requires “the ice shapes developed for the portion of the envelope should account for the icing conditions in terms of drop distribution and water content . . . .” There is no guidance for either an applicant or an approving authority for how to apply the four spectra and their individual LWC’s in the Appendix X rule to “account for the icing conditions” in any proposed limited environment.

Using Appendix X, ALPA does not believe it is possible to know how any proposed limited condition relates to actual SLD icing environments. There are no “envelopes” in Appendix X to determine what spectrum or LWC should be used to represent the chosen “portion of the envelope” for a partial spectrum or limited LWC certification. Appendix X contains four “average spectra” which were not designed or demonstrated to represent actual SLD environmental data for other drop sizes or other LWC’s than those contained in Appendix X.

Perhaps AC material could be developed to show a validated method to derive spectra and LWC for use to certify to a portion of Appendix X. Use of the SLD database would be necessary to validate the method as representing actual SLD conditions, over any proposed range of drop sizes and LWC’s, to the same degree as does Appendix X. Such a process would be necessary to insure valid ice shapes and provide consistent safety levels in various certification programs.

Certification to a portion of Appendix X based on limited LWC’s or drop sizes should be removed from the advisory material, since Appendix X provides no way to relate such a proposal to actual SLD icing environments. Accurate representation of the environment is essential to provide accurate airplane ice shapes for determining the performance and handling quality impact of SLD.

MAJORITY RESPONSE

(Airbus, Boeing, CAA/UK, Cessna, Embraer, FAA/FAA Tech Center, NASA, SAAB, Transport Canada/TDC)

The majority of the IPHWG recommend that certification to a portion of Appendix X be retained. Specific AC language has been added in an attempt to reach a consensus position but the Working Group has been unable to resolve the dissenting opinion. In particular, the AC acknowledges that initial certifications to a portion of Appendix X will likely include all of freezing drizzle or all of freezing rain, or will be restricted by phase of flight. The AC material also discusses some potential concepts that could be used to accomplish certification to a portion of Appendix X but, as the minority position suggests, does not provide specific examples. However, the AC does provide guidance that for limited certifications, ice shapes will be developed for the portion of the envelope for which the aircraft is approved, as well as “detect and exit” ice shapes, and that the ice shapes should account for the icing conditions in terms of drop distribution and water content. Additionally, the shapes will need to be related to the proposed method of identifying the icing conditions for the portion that requires exiting. Language was added to the AC to clarify that certifications to a portion of Appendix X should consider the methods used for developing Appendix X, with a reference to a detailed report to be released by the FAA Technical Center. Further, proposed advisory material discusses that the AFM Limitations section should contain appropriate limits that consider the certification assumptions with respect to approved portions of Appendix X. As such, if an aircraft is only approved for a portion of the freezing drizzle environment and an operator is unable to distinguish that portion prior to dispatch (for example, the exiting icing cue is an inertia based, in-flight cue only), the aircraft may have to be limited from dispatching into any freezing drizzle. These changes to the proposed advisory materials, in addition to the rule language, constitute a performance-based approach to defining how to certify to a portion of Appendix X.

Eliminating the alternative for certification to a portion of Appendix X creates a more prescriptive rule that has the potential for disproportionately restricting the flight operations of future aircraft. Future aircraft designs could potentially accommodate portions of Appendix X; however, it is not possible to design all transport category aircraft to operate unrestricted in the full SLD environment. Removing certification to a portion removes any benefit for manufacturers to certify for a part of the Appendix X envelopes if the aircraft can safely operate therein. The ability to certify to a portion of the environment allows manufacturers to certify to as large an icing envelope as safely possible. This provides a balance of economic pressures (aircraft operators desire to dispatch with a minimum of restrictions), yet provides a consistent level of safety (with established margins) via the type certification process.

In addition, the ability to certify to a portion of Appendix X provides incentive for technology development relative to both detection of conditions requiring exit and the design of protection systems. The desire expressed in the Minority Position to provide a validated method for certification to a portion of Appendix X in the AC materials is not consistent with allowing potential for future development of techniques and compliance methodologies. As stated previously, some example concepts are provided in the AC but a fully defined method will likely not be available until an applicant chooses to certify with this option. As with many new types of certification efforts, extensive negotiations between the applicant and the authorities will likely be necessary, and engineering judgment will be applied based on the performance-based guidance in the rule.

Conclusion

The rule language was specifically drafted to be performance-based and not prescriptive. The majority of the IPHWG recommend that allowance of certification to a portion of Appendix X is needed to accomplish the overall goal of improving safety in icing conditions while balancing the practical aspect of allowing aircraft to dispatch in as wide an operating envelope as safely possible. The majority of the IPHWG accept that the performance-based rule language and the added draft advisory material provide sufficient guidance to future applicants and regulatory personnel regarding certification to a portion of Appendix X and are therefore sufficient to address the concerns raised by the Minority Position.

MINORITY POSITION AGAINST CERTIFYING TO FREEZING DRIZZLE OR FREEZING RAIN USING A SUBSET OF THE APPENDIX X CURVES

(Meteorological Service of Canada, ALPA)

The four spectra with associated LWC limits were developed to describe the entire Appendix X environment as it could be determined by all of the measurements available, rather than producing a continuous envelope that covered all SLD conditions. A manageable number (four) of curves were selected to allow tests using codes, icing tanker, and wind tunnel simulations. During development of these spectra, partial certification to a portion of Appendix X was not considered. Later it was proposed that a manufacturer might want to certify to freezing drizzle (ZL) or freezing rain (ZR) by using one or two of the four Appendix X curves. However, the curves were not designed or selected for this purpose. As an example, all of the four spectra contain some cloud droplets. They do not necessarily represent ZL or ZR extreme drop spectra that might be observed below cloud at the surface. In addition, airport observers do not identify freezing drizzle or freezing precipitation using the precise criteria used to develop these curves, so this could pose a problem. For example, freezing drizzle is defined by the surface observer as containing drops between 200 and 500 microns, and the rainfall rate should not be greater than 1 mm/hr. However, it is very difficult for a surface observer to identify freezing drizzle visually and distinguish it from freezing rain.

Table G-1 below shows the in-flight aircraft data used to develop Appendix X in terms of 50, 75, 95, 99 and 99.9 percent values of precipitation rate. It also shows the freezing drizzle and freezing rain precipitation rates, measured every minute using a heated gauge with the occurrence of freezing drizzle or rain as being reported by the ground observer. The surface data were obtained from an analysis performed by Transport Canada for several stations in Quebec, and contain 3,692 minutes of freezing drizzle and 10,833 minutes of freezing rain. Obviously, the gauge data shows higher precipitation rates for the extreme cases of freezing drizzle than the in-flight data. The values are also outside of the definition of the extreme value of 1 mm/hr to be used by the surface observer as the definition of freezing drizzle. This is not very surprising. The surface observer needs to quickly estimate the drizzle/rain distinction using visual cues which are difficult to use, and precipitation rates are naturally highly variable, especially on a time scale of minutes. The extreme drizzle rates as measured by the gauge were probably incorrectly classified by the observer who classified them as freezing drizzle when they should have been classified as freezing rain. Based on the data in Table 2, in excess of 25 percent of the surface observations of freezing drizzle would exceed the maximum criteria of Appendix X for freezing drizzle because the observer had misidentified freezing rain as freezing drizzle.

The logical use of a partial certification to Appendix X for freezing drizzle or rain would be to allow the aircraft to take off or land in such conditions using the surface reports of precipitation type made by an observer. Given that Appendix X was not designed for manufacturers to be able to certify to only freezing drizzle or freezing rain, the surface observer definitions of freezing drizzle and rain are different than those used for Appendix X, and the fact that extreme values of surface observations of freezing drizzle fall well within the freezing rain envelope, it would not be prudent to allow certification to freezing drizzle or freezing rain alone using Appendix X.

		50%	75%	95%	99.0%	99.9%
Method	Type	Precipitation Rate mm/hr				
In-Flight	ZL	0.03	0.07	0.26	0.60	1.13
Gauge	ZL	0.26	1.0	2.0	3.2	4.7
In-Flight	ZR	0.50	1.1	2.1	3.2	4.5
Gauge	ZR	0.67	1.7	3.3	4.3	6.0

Table G-1 - Comparison of In-flight versus Ground Observations

Note: Shows the 50, 75, 95, 99, 99.9% precipitation rate values of freezing drizzle and freezing rain as determined from the in-flight data of Appendix X and observations at the ground using heated gauges and the reports of precipitation type by the surface observer.

MAJORITY RESPONSE

(Airbus, Boeing, CAA/UK, Cessna, Embraer, FAA/FAA Tech Center, NASA, SAAB, Transport Canada/TDC)

The majority of the IPHWG support the concept of certification to a portion of Appendix X. Discussion of the motivation for retaining the ability to certify to a portion is contained in the above IPHWG majority position relative to the ALPA position statement against certification to a portion. This position statement will focus on the concerns raised by the Minority Position relative to certifying to a portion of Appendix X and to the difficulty in differentiating between freezing drizzle and freezing rain at the terminal areas.

Certification to a portion of Appendix X

The minority position states that during the development of Appendix X, certification to a portion was not considered. The majority of the IPHWG do not agree with this statement, as use of a portion was inherent in the concept from the early stages. A review of the concept proposal presented to and approved by TAEIG in February of 2002 contains early draft rule language and states: "Operating safely in Appendix (X) to an extent as determined by the applicant." As such, certification to a portion has been intended since concept approval. During much of the development of the draft SLD rule language and supporting documentation, some of the IPHWG focused on development of Appendix X as part of the Meteorology sub-working group and may have not been fully aware of the draft rule intent of allowing approval of ice protection provisions for a portion of Appendix X.

The majority of the IPHWG acknowledges that freezing precipitation is a continuum of many drop sizes and liquid water contents. To characterize the environment, measurements of the freezing precipitation were stratified into four categories, based on the maximum drop size contained in the spectra of each measurement. Measurements containing maximum drop sizes of less than 500 µm, but greater than the maximum drop sized commonly considered as a cloud drop size (100 µm), were defined as freezing drizzle. The maximum drop size of 100 µm is consistent with the use of the Langmuir D distribution for the Appendix C stratiform cloud maximum average drop size. Measurements containing maximum drop sizes greater than 500 µm were defined as freezing rain. These definitions of freezing drizzle and freezing rain were selected to be consistent with accepted meteorological definitions of these recognized types of precipitation. The two categories were further divided to sub-categories having drop mean volume diameters greater than or less than 40 µm. The Appendix C stratiform cloud maximum mean effective drop size was used as a boundary for maximum average cloud drop size. The descriptors used for characterizing Appendix X therefore stratify the continuum of freezing precipitation into commonly accepted regimes of freezing drizzle and freezing rain. The database used for characterizing the freezing precipitation environment can be thoughtfully and carefully stratified using other definitions. Freezing drizzle and freezing rain are each characterized by two curves. By definition, each set of two curves completely describes the two different precipitation types, and each set may be used independently of the other set.

Differentiating between freezing drizzle and freezing rain at the terminal areas

The Minority Position warns that ground-based diagnosis of freezing precipitation may be inaccurate for takeoff and landing of airplanes in a portion of Appendix X and is not compatible with measurements of freezing precipitation contained in the Appendix X data base. The proposed 14 CFR § 25.1420 addresses safe in-flight airplane operations in Appendix X and does not address terminal area freezing precipitation diagnosis and reporting. Ground-based observations of freezing precipitation were not included in the Appendix X database. Information from ground-based observations were only used to justify the coldest temperatures recorded for freezing precipitation, and ground-based measurements of precipitation rates were used to ensure that the measured in-flight precipitation rates were compatible. This comparison of the precipitation intensities provided confidence that airplane deicing and anti-icing practices did not permit dispatch of airplanes into freezing precipitation aloft rates greater than those addressed by Appendix X. Note that ground-based observations of precipitation rates (discussed in the minority position), especially at moderate and high intensities, may be influenced by other effects such as downdrafts, sample volumes, and mixed-phase precipitation. Therefore, the majority of the IPHWG has concerns about the significance of the ground and in flight comparison presented in the minority opinion.

The need for accurate diagnosis of freezing precipitation in the terminal area currently exists for dispatching airplanes for takeoff in freezing precipitation. Reported freezing precipitation is used to restrict takeoff in freezing precipitation that exceed the capability of anti-icing fluids to protect the airplane from ice accumulation during ground operations and the takeoff run. Also, the reported freezing precipitation diagnosis is used to estimate the holdover protection time provided by deicing and anti-icing fluids. Service history shows that the means and procedures used for reporting the category (drizzle or rain) and intensity of freezing precipitation have been adequate for safe airplane takeoff operations following de-icing and anti-icing.

The minority position states that the fall rate for freezing drizzle "should" not be greater than 1 mm/hr. However, the definition in the American Meteorological Society's "Glossary of Meteorology" states that the fall rate is "usually" not greater than 1 mm/hr. The minority position also states that "it is very difficult for a surface observer to identify freezing drizzle visually and distinguish it from freezing rain." However, an expert consulted by the majority states that impact behavior is generally accepted as a reliable indicator in distinguishing between drizzle drops and raindrops.

The minority position relies heavily on a single study analyzing data from "several stations in Quebec." No other studies are cited, and no evidence is provided to show that a single limited study in one geographical area should be taken as representative. The study reports some drizzle rates substantially higher than 1 mm/hr, which as noted is a value usually not exceeded, but not a strict upper bound, in the AMS definition. The minority then states the high rates are "probably" due to rain being "incorrectly classified" as drizzle. The use of the word "probably" acknowledges that other factors may be considered in interpreting the results. One such factor is wind. An expert consulted by the majority stated that wind can have a much more dramatic effect on fall rates for drizzle than for rain, due to the much smaller mass of drizzle drops. Thus, two drizzle events characterized by the same liquid water content might have substantially different fall rates.

The majority acknowledges that misdiagnosis can occur in discriminating between freezing drizzle and rain, and supports improvements in practices and technology to improve reporting accuracy. However, it believes that the conservatism inherent in the certification practices will result in safe operations.

The certification process for Appendix X has many cumulative conservative assumptions that support the overall level of safe operations. For example, in addition to the use of the 99 percent liquid water content (LWC) levels, the vertical extents are defined as 12,000 ft. The vertical extent is defined by the combined icing environment of the cloud and the precipitation levels below the cloud. This results in the use of 99 percent LWC over the full 12,000 ft. Previous IPHWG deliberations determined that the mean vertical extents are closer to 3,500 ft and 2,900 ft for freezing drizzle and freezing rain, respectively. As such, the majority of actual encounters in the terminal area will not approach the 12,000 ft limit defined in Appendix X, nor will they approach the 99 percent LWC values. Additional conservatism is applied in that every takeoff is planned based on engine-out performance; this has the effect of decreasing the aircraft’s vertical climb rates and increases the duration of the exposure to the Appendix X environment. These combined procedures for assessing the environmental and operational processes for certification provide a conservative evaluation.

Aircraft certificated for a portion of Appendix X will have a means to determine exceedance conditions. The result of this situation would be that exceedance cues would be present and would trigger an exit from the restricted portion of the SLD environment. The results of an aircraft taking off into a freezing rain encounter that was misidentified as freezing drizzle would not be significantly different than those associated with an inadvertent encounter with freezing rain aloft. This type of operation would not result in an unsafe condition as the aircraft will have been evaluated with accretions simulating a detect and exit scenario from all icing conditions. The end result will likely cause an increase in the number of diversions, or other operational considerations, but will not result in an unsafe condition. Data has been provided regarding the economic impact of diversions for use in the rulemaking process (see “Recurring Costs” section of Appendix J of this Working Group Report).

The majority of the IPHWG believes that current observing and reporting definitions, when properly applied, are sufficient to accurately distinguish between freezing drizzle and freezing rain, (the difference in impact behavior of drizzle drops and raindrops is itself a reliable indicator). Furthermore, the majority of the IPHWG also believe that the conservatism built into the certification process is sufficient to offset any safety concerns at this time.

APPENDIX H - DEVELOPMENT OF 14 CFR PART 25 APPENDIX X & 14 CFR PART 33 APPENDIX D

This appendix provides discussion of the development of the 14 CFR Part 25 Appendix X and 14 CFR Part 33 Appendix D. Detailed information concerning the development of these appendices will be published as FAA Technical Center reports.

14 CFR PART 25, APPENDIX X

Appendix X was derived from a database containing in-situ measurements of supercooled large drop (SLD) icing conditions by suitably instrumented research aircraft. Data from many research campaigns, in various geographic locations and over several years, were used. All data was screened for quality and combined to form a database maintained at the FAA's Wm. J. Hughes Technical Center. This database was used to determine the spatial aspects of SLD icing conditions, such as altitude and temperature ranges. Concerns about significant amounts ice crystals in traditionally measured liquid water content (LWC) data, and the desire to more precisely define SLD drop spectra and LWC values, resulted in a subset of more precise, multiple sensor data from recent Meteorological Service of Canada (MSC) and the National Aeronautics and Space Administration (NASA) research flights being used for these purposes. This insured both the widest applicability and the greatest confidence in the critical details for the Appendix X environment. See following references for more information.

GENERAL

The relationship between Appendix C and Appendix X icing conditions is limited. The data measured to produce Appendix X was taken in wintertime stratus cloud formations. As such, the Appendix X conditions are most closely associated with the stratus conditions used to define the existing Appendix C, Continuous Maximum conditions. Nearly all of the data contained in the IPHWG SLD icing conditions database are related to wintertime, stratiform cloud conditions. It is known, however, that supercooled large drop icing conditions are generally plentiful in warm season, vigorously growing convective clouds (Cumulus Congestus, Towering Cumulus, Cumulonimbus) above the freezing level. Changnon, et al. (1991), report that for large, growing convective clouds in Illinois: "Typical in cloud results at –10 °C reveal multiple updrafts that tend to be filled with large amounts of supercooled drizzle and raindrops." This means that airplanes penetrating the cores of these clouds in the 0° C to –20° C temperature range can expect to encounter intense bursts of SLD icing. The horizontal extent of individual cores is on the order of Appendix C Intermittent Maximum icing conditions and, as such, the characterization of these cloud penetrations would be an extension of this Appendix C icing condition.

Use of only stratiform cloud data for the airframe aspects is considered acceptable since stratiform clouds predominate during prolonged freezing precipitation conditions, and these conditions are seen as the primary source of reported SLD-related accidents and incidents. In addition, some practical factors that mitigate the need for a characterization of summer SLD icing conditions are:

- The relative ease of visually recognizing or using on-board weather radar to avoid strong convective cloud activity
- Operating procedures that limit exposure to such conditions, as well as the relative brevity of inadvertent exposures (at least in Cumulus Congestus and Towering Cumulus clouds).

The in situ data obtained for determining Appendix X were divided as follows:

- Measured icing conditions with an MVD less than 40 μm and a maximum drop size of less than 100 μm were excluded from the Appendix X definition (categorized as Appendix C icing conditions).
- Measured icing conditions with an MVD less than 40 μm and a maximum drop size between 100 μm and 500 μm were classified as freezing drizzle, MVD < 40 μm.
- Measured icing conditions with an MVD greater than 40 μm and a maximum drop size between 100 μm and 500 μm were classified as freezing drizzle, MVD > 40 μm.
- Measured icing conditions with an MVD less than 40 μm and a maximum drop size greater than 500 μm were classified as freezing rain, MVD < 40 μm.
- Measured icing conditions with an MVD greater than 40 μm and a maximum drop size greater than 500 μm were classified as freezing rain, MVC > 40 μm.

SLD icing conditions are defined by Appendix X, including freezing drizzle and freezing rain. The two types of freezing precipitation are further divided into conditions in which the drop median volume diameters are either less than or greater than the 40 μm, the largest mean effective diameter of Appendix C continuous maximum icing conditions. This format follows recommendations by A. D. Shah, M. W. Patnoe, and E. L. Berg, SAE 2000-01-2115, "Engineering Analysis of the Atmospheric Icing Environment Including Large Droplet Icing Conditions." Dividing the freezing drizzle and freezing rain into these two categories approximates freezing precipitation icing conditions where most of the supercooled water mass is either in or outside of an Appendix C stratiform cloud.

Appendix X consists of measured data that was divided into drop distributions within these four icing conditions. These conditions were averaged to produce representative distributions for each condition.

The water content versus drop size relationships defined in 14 CFR 25, Appendix C, Figures 1 and 4, are defined in terms of mean effective drop diameter. By definition, this acknowledges the distributed nature of drop sizes around a mean or median value. However, Part 25 does not require specific distributions that must be considered for Appendix C icing conditions. As referenced in DOT/FAA/CT-88/8-1 "Aircraft Icing Handbook" and AC 20-73A, commonly assumed single-mode distributions such as Langmuir & Blodgett have been used to represent the range of drop sizes and associated water contents in a specific Appendix C icing condition.

The distributions assumed for Appendix C icing conditions are inappropriate for freezing precipitation icing conditions since SLD icing conditions typically consist of significant portions of small and large drops and a bi-modal distribution of drop sizes. Use of the Langmuir & Blodgett type of distributions for determining the drop size intervals do not adequately define the bi-modal nature of freezing precipitation. Consequently, the distributions of drop sizes are defined as part of Appendix X. The need to include the distributions comes from the larger amount of mass in the larger drop diameters of Appendix X. The water mass of the larger drops will impinge further aft on surface leading edges than that of Appendix C. Ice accretion resulting from this water catch must be considered relative to its effects on safe flight of the airplane.

The variation among freezing precipitation drop diameter distributions is very large. Subdividing freezing drizzle and freezing rain allowed selection of the four average drop diameter distributions that are representative of the total range of drop distributions. Appendix X drop diameter distributions are shown as cumulative mass distributions.

Also, the maximum values of freezing drizzle and freezing rain liquid water content decrease with decreasing temperature as defined in 14 CFR 25, Appendix X, figures 1 and 4, respectively. Following the same standard as 14 CFR 25, Appendix C, the values of total liquid water are selected at the standard icing condition horizontal extent of 17.4 nautical miles (20 statute miles).

The maximum vertical extent of 12,000 feet for freezing drizzle includes the cloud layer and any drizzle precipitation below the cloud. The maximum altitude of freezing drizzle is the same as that of an Appendix C continuous maximum icing cloud, 22,000 feet (Appendix X, figure 3). Freezing drizzle has been reported at temperatures as cold as -13° F (-25°C).

The maximum vertical extent of freezing rain is 7,000 feet. The maximum altitude of freezing rain is 12,000 ft. Freezing rain has been reported at temperatures as cold as 8.6° F (-13°C).

The liquid water contents of continuous freezing drizzle and freezing rain conditions decrease with increasing horizontal extents. Horizontal extents of exposures in FZDZ and FZRA can be anywhere from a brief encounter to an extended encounter. The use of the Appendix X f-factor is the same as for the Appendix C f-factor, which is discussed in Appendix N of AC 20-73A.

TOTAL WATER CONTENT VERSUS LIQUID WATER CONTENT

For approximately 40 to 50 percent of the in-situ measurements in icing conditions between -5° C and –30° C, some ice crystals exist in the cloud and the cloud may be considered as mixed phase. The fraction of all liquid cloud in-situ measurements increases as the temperature approaches 0° C, and the fraction of glaciated or all-ice clouds increases as the temperature approaches –30° C. However, the portion of mixed-phase cloud measurements remains near 40 to 50 percent. These mixed-phase clouds tend to cluster near liquid fractions 1 or 0.

The total water content (TWC) consists of both the liquid water content (LWC) and ice water content portions of the cloud. However, removing the glaciated clouds, and just considering the all-liquid and all-mixed-phase clouds, the probability distributions of both TWC and LWC as a function of temperature are very similar. The 90 to 95 percent values are almost the same. Since Appendix X includes extreme water content values, it does not appear that there would be a significant difference between using TWC or LWC.

GEOGRAPHICAL RESTRICTIONS

The current archive used to produce representative spectra and extremes for LWC for Appendix X consists of data collected at a few locations in North America, such as the Great Lakes area, Canadian east coast, and the Canadian Arctic. The larger database maintained by the FAA was used to produce the extremes for altitude limits, and temperature ranges for Appendix X include measurements from more locations (e.g., Colorado, Alaska, California, and Kansas), with a limited amount of data outside of North America. Observed data provided by NCAR (National Center for Atmospheric Research) was also considered in the development of the temperature ranges used in Appendix X. There are known differences between geographical areas. For example, maritime areas have larger drops and lower drop concentrations. The frequency of occurrence of SLD conditions also varies by location according to recent climatology studies, and this has been confirmed by aircraft measurement campaigns. There is evidence that a high frequency of occurrence of SLD occurs in the southern tip of South America and in Europe. However, there are very few in-situ measurements from these areas. The micro-physics of large droplet formation are the same and it is not expected that the drop diameter distributions would be greatly affected. Therefore, the existing data is considered sufficient for rulemaking.

PROBABILITY OF OCCURRENCE

The MSC in-situ icing database shows that the SLD icing conditions with MVD greater than 40 µm represent an average of 6 percent of the in-flight time. In maritime areas, this percentage rises to 20 percent of in-flight time. These percentages cannot be used to represent the probability of occurrence of SLD icing conditions because these flights were directed into areas with icing that were expected to contain SLD. Consequently, the true probability of occurrence of SLD icing conditions would be lower. For example, the frequency of occurrence of freezing precipitation at the ground represents approximately 1 percent of the time averaged over the winter season for most of Canada, with greater values occurring in the Great Lakes area (2 percent) and in Newfoundland (5 percent).

Climatology studies performed by the National Center for Atmospheric Research (NCAR) for North America show that the annual average frequency of occurrence of SLD ranges from 0.4 to 5 percent of the time in a spatial column over a measuring station. This study indicates significant variations in probability of SLD icing conditions with geographic location and season (e.g., in northern Canada or Alaska, SLD icing conditions are most prevalent during the summer season). In the December to March time period, in the Great Lakes area where most of the Canadian data were obtained, the NCAR frequency of occurrence was approximately 3 percent in a spatial column over each surface measuring site. For sites on the western coast of Alaska for the same December to March time frame, the percentage rises to 6 to 8 percent.

Determining the actual occurrence of SLD icing conditions in the atmosphere is difficult using the data sets available. It is recognized that there are large geographical differences and changes with season. However, to a first approximation, the probability of occurrence of SLD icing conditions for any particular location in North America, representing the altitude ranges between 0 and 15,000 feet which airplanes normally encounter upon takeoff and landing, is typically 1 to 5 percent over a winter season for a large part of the continent.

Currently, airport observers cannot accurately identify the differences between freezing drizzle and freezing rain. The precipitation conditions at the ground are primarily out of cloud. Appendix X is an engineering design standard that considers freezing drizzle and freezing rain aloft, and the four spectra selected contain cloud droplets. This can lead to differences between dispatch standards and conditions tested during the certification process. However, the working group considers this difference to be acceptable for an engineering design standard due to the limited exposure during transition between ground freezing precipitation environment and aloft.

APPENDIX X REFERENCES

1. Ashenden, R. and Marwitz, J. D. (1996); "Supercooled Large Droplet Distribution in the Natural Environment and Comparison to Artificial Drizzle from the Air Force Water Spray Tanker", Proc. of the FAA International Conf. On Aircraft Inflight Icing, DOT/FAA/AR-96/81, II, p. 33-43, dated August 1996.

2. Cober, S. G. et al (1995); " Aircraft Icing Measurements in East Coast Winter Storms," Journal of Applied Meteorology, Vol. 34, pages 88-100, dated January 1995.

3. Cober, S.G., G.A. Isaac, A.V. Korolev, and J.W. Strapp, 2001: Assessing cloud-phase conditions. J. Appl. Meteor., 40, 1967-1983.

4. Cober, S. G. et al (2001); "Characterizations of Aircraft Icing Environments that Include Supercooled Large Drops," Journal of Applied Meteorology, Vol. 40, pages 1984-2002, dated November 2001.

5. Cober, S. G. et al.(2003), "Defining Characteristic Cloud Drop Spectra From In-Situ Measurements," AIAA-2003-0561, 41st Aerospace Sciences Meeting & Exhibit, 6-10 January 2003, Reno, NV

6. Cober, S.G., T.P. Ratvasky, and G.A. Isaac, 2002: Assessment of aircraft icing conditions observed during AIRS. AIAA 40th Aerospace Sci. Meeting and Exhibit, Reno Nevada, 14-17 January 2002, AIAA 2002-0674.

7. Cober, S.G., and G.A. Isaac, 2002: Aircraft environments observed in mixed-phase clouds. AIAA 40th Aerospace Sci. Meeting and Exhibit, Reno Nevada, 14-17 January 2002, AIAA 2002-0675.

8. Isaac, G. A. et al (1999); “Canadian Freezing Drizzle Experiment”, AIAA-1999—0492, dated January 11-14, 1999.

9. Isaac, G.A., S.G. Cober, J.W. Strapp, A.V. Korolev, A. Tremblay, and D.L. Marcotte, 2001: Recent Canadian research on aircraft in-flight icing. Canadian Aeronautics and Space Journal, 47, 213-221.

10. Isaac, G.A., S.G. Cober, J.W. Strapp, D. Hudak, T.P. Ratvasky, D.L. Marcotte, and F. Fabry 2001: Preliminary results from the Alliance Icing Research Study (AIRS). AIAA 39th Aerospace Sci. Meeting and Exhibit, Reno Nevada, 8-11 January 2001, AIAA 2001-0393.

11. Jeck, R. K. (1996); “Representative Values of Icing-Related Variables Aloft in Freezing Rain and Freezing Drizzle" Technical note DOT/FAA/AR-TN95/119, 44 pp., dated March 1996.

12. Jeck, R. K. editor; "Data and Analyses Contributing to the Development of Engineering Specifications for Freezing Rain and Freezing Drizzle Conditions for Aviation Purposes," FAA Technical Report DOT/FAA/AR-04/7,To be released.

13. Shah, A. D. et al (1998); "Droplet Size Distribution and Ice Shapes", AIAA 98- 0487, Reno, NV. dated January 12-15,1998.

14. Shah, A. D. et al (2000); "Engineering Analysis of the Atmospheric Icing Environment Including Large Droplet Icing Conditions", SAE 2000-01-2115, dated April 2000.

14 CFR PART 33, APPENDIX D

A data base of commercial service icing events (see Appendix I of this report) in the mixed phase / glaciated environment established that the current FAR Part 25 Appendix C icing envelope with supercooled liquid water droplets does not cover the range of altitude and ambient temperature established by these events. The event conditions are predominately outside FAR Part 25 Appendix C, but appear to be bounded by Mil Std 210A Hot Day temperature limits. Hence, the range of the new FAR Part 33 Appendix D was increased beyond FAR Part 25 Appendix C envelope to the Mil Std 210A temperature limits. A common characteristic in most of these events was the proximity to convective / tropical storm cloud formations, and thus Appendix D is being proposed primarily as a deep convective cloud extension to the current 14 CFR 25, Appendix C intermittent maximum conditions.

To develop Appendix D, a literature search was perfomed which revealed limited data for deep convective atmospheres. For example, a series of airborne measurements of cloud total water content (TWC) were conducted between December 1956 and March 1958 in three tropical locations, resulting in an extensive set of 101 cloud measurement flights with 44.5 hours of in cloud data (McNaughtan data). Most of the more recent data on the properties of mixed phase clouds has been collected by the atmospheric research community, but these studies were not focused on measuring maximum total water content areas of deep convective storms as in the case of the McNaughtan data.

The accuracy of the TWC measurements in all of the above studies is questionable and the traceability and accuracy of the data methods is limited.

As such, an engineering design standard is being proposed that combines facets of the theoretical and experimental data. A theoretical adiabatic lifting of air was used to establish an upper bound on water contents and scaled to the 99% of the McNaughtan data. The events were examined relative to temperature and altitude and were consistent with the Mil-Std hot day boundary. As such, the Mil-Std was used as limiting temperature/altitude condition.

The general slope of the TWC reduction with distance scale was derived from the McNaughtan data set. A standard distance scale of 17.4 nmi was chosen as a normalization point. This distance scale also roughly represents a typical onset time for an engine event after the recognition of a total air temperature (TAT) anomaly, an indicator of the presence of high TWC. The short distance limit of 4.6 nm is the lowest that could be deduced from the McNaughtan data set. It was the opinion of the EHWG that this was adequate given the information in the event database and current technical knowledge of onset time for the engine problem.

Given the limited availability of data, the above engineering design standard approach is recommended to reduce engine events due to the ice crystal environment. EHWG has recommended that a new effort be conducted to collect a data base of tropical convergence zone cloud measurements using modern instrumentation with accurate TWC measurement capability.

14 CFR PART 33, APPENDIX D REFERENCES

1. THE ANALYSIS OF MEASUREMENTS OF FREE ICE AND ICE/WATER CONCENTRATIONS IN THE ATMOSPHERE OF THE EQUATORIAL ZONE, Ian I. McNaughton, B.Sc., Dip. R.T.C., ROYAL AIRCRAFT ESTABLISHMENT (Farnborough) TECHNICAL NOTE No: MECH. ENG. 283, 1959

2. SNOW AND ICE PARTICLE SIZES AND MASS CONCENTRATIONS AT ALTITUDES UP TO 9 KM (30,000 FT), R. K. Jeck, DOT/FAA/AR-97/66, August, 1998.

3. CLOUD MICROPHYSICAL MEASUREMENTS IN THUNDERSTORM OUTFLOW REGIONS DURING ALLIED/BAE 1997 FLIGHT TRIALS, Strapp, J.W., P. Chow, M. Maltby, A.D. Bezer, A. Korolev, I. Stomberg, and J. Hallett, *37th AIAA Aerospace Sciences Meeting and Exhibit*, Jan. 11-14, 1999, Reno, NV. AIAA 99-0498.

APPENDIX I - ACCIDENTS AND INCIDENTS RELEVANT TO THE PROPOSED RULE

The IPHWG examined incidents and accidents to identify those which may be considered in the benefit analysis of the regulatory evaluation. It should be noted that some of these accidents and incidents have been identified as being relevant to the regulatory evaluations of other ARAC recommendations, such as the Part 121 Operations in Icing, Part 25 Activation of Ice Protection, and Part 25 Performance and Handling in Icing Conditions. It will be necessary for the FAA economist to ensure that the benefits associated with an accident or incident are employed in accordance with acceptable practices.

Incidents and accidents of Part 23 airplanes that have 14 CFR §25.1419 in their certification basis have been included in the events considered as relevant. It is the IPHWG's understanding that the FAA economist will use events of these airplanes in the regulatory evaluation. However, not all of the working group concurs with this policy. Some contend that these events are not relevant because it is not believed that future Part 23 airplanes will have a Part 25 icing certification basis.

ICING INCIDENT DATABASE REVIEW

The icing incident database for Task 2 included 81 events. These 81 events were obtained following a review of the NASA Aircraft Safety Reporting System (ASRS) database for the time frame 1988 to 2002, five reports of incidents extracted from the NTSB 3/31/94 Simmons 4184 accident report, one report of an incident that was extracted from the NTSB 1/9/97 Comair 3272 accident report, and incidents from foreign authorities.

Descriptors such as severe ice, freezing rain, freezing drizzle, side window icing, heavy icing, large droplets, SLD, and, for mixed ice conditions, descriptors of sleet, snow, snow grains, and ice were employed in the selection of these events.

In general, the review encompassed both 14 CFR part 23 and 14 CFR part 25 aircraft. However, the preponderance of events pertained to small aircraft (14 CFR part 23). Since the result of Task 2 is to be a Part 25 rule, the group chose to eliminate all part 23 aircraft events as not being applicable to Task 2 (except for those with a 14 CFR §25.1419 certification basis). Several other events were eliminated due to insufficient information. With these eliminations, the number of applicable events was reduced from 81 to 28. This includes 6 events associated with turbojet aircraft, 18 events associated with turbo-propeller aircraft, and one event in which the type of power plant could not be determined. Of these, there were 4 references to mixed conditions (2 each for turbo-propeller aircraft and turbojet aircraft), and six events which occurred outside the U.S.

A review of incidents related to 14 CFR Part 23 aircraft with a 14 CFR § 25.1419 certification basis was conducted. This review yielded 3 incidents involving Part 23 turbo-propeller aircraft and they are included in Table I-1 below. Thus, the final list of 28 incidents potentially applicable to Task 2 is:

Aircraft Type	**Number of incidents**		
	Total	U.S.	Other
Turbo-propeller	18	14	4
Turbo-jet	6	4	2
Un-determined	1	1	0
Part 23 aircraft/w Part 25.1419 Cert. basis	3	3	0

Table I-1 - Applicable Aircraft Icing Incidents

ICING ACCIDENT DATABASE REVIEW

The IPHWG developed an icing accident database in support of Task 2 that included 182 events. These 182 events were obtained after a review of several databases, including the National Transportation Safety Board, Flight Safety Foundation (FSF), Transport Canada, Eurice, and other sources. The accident database covers the time frame from 1940 to 2002.

Descriptors such as severe ice, freezing rain, freezing drizzle, side window icing, heavy icing, large droplets, SLD, and for mixed-ice conditions, descriptors of sleet, snow, snow grains, and ice were employed in the selection of events for the database. There were limited references to “SLD” since most of these accidents occurred prior to the 10/31/94 Roselawn accident and SLD is a term that was coined after that accident. In general, the review encompassed many aircraft of different categories (including two helicopters). However, the preponderance of events pertained to small aircraft (14 CFR part 23).

Since the result of Task 2 is to be a Part 25 rule, the group chose to eliminate all helicopter and part 23 aircraft accidents as not being applicable to Task 2 (except for the part 23 aircraft with a 14 CFR §25.1419 certification basis). Several other events were eliminated due to duplication (4), improper ground deicing (4), and insufficient information (2). With these eliminations, the number of applicable events was reduced from 182 to 42. A further division of these accidents was made for old pre-Appendix C icing certified aircraft and post-Appendix C icing certified aircraft. There were 34 events falling into the old pre-Appendix C category; 18 were deemed to be potentially applicable for Task 2. The Bristol Britannia 253 accident on 2/16/80 was included even though this aircraft had not been properly deiced prior to takeoff. For this particular event the NTSB listed the probable cause of this accident as resulting from an accumulation of ice and snow on the airframe before takeoff and a further accumulation of ice when the aircraft was flown into moderate to severe icing conditions following takeoff (see Table I-2 below).

DATE	AC TYPE	LOCATION	FATAL	INJURY
12/21/47	DC-3A	N. Platte, NE	0	3 Minor
10/4/57	DC-3	Alberta, Canada	0	2 Serious
1/29/63	VISC-810	Kansas City, MO	8	8 Fatal
12/2/78	DC-3	Des Moines, IA	2	2 Fatal
1/16/81	DC-6A	Gambell, AK	0	3 Minor
12/4/40	DC-3A	Chicago, IL	10	3 Serious
10/30/41	DC-3A	Mooreshead,MN	14	1 Serious
4/11/42	DC-3A	LaGuardia, NY	0	2 Serious
10/9/49	C-46E	Cheyenne, WY	3	3 Fatal
1/7/53	C-46F	Fishaven, ID	40	40 Fatal
3/20/53	DC-4	Alvarado, CA	35	35 Fatal
1/20/54	DC-3A	Kansas City, MO	3	3 Fatal
2/26/54	CV-240	Wight, WY	9	9 Fatal
4/6/58	VISC –700	Freelance, MI	47	47 Fatal
3/10/64	DC-4	Boston, MA	3	3 Fatal
3/12/64	DC-3	Miles City, MT	5	5 Fatal
12/27/78	DC-3	Des Moines, IA	0	2 Serious
2/16/80	BRIT-253	Billerica, MA	7	1 Serious

Table I-2 - Applicable Accidents Of Aircraft With Pre-Appendix –C Icing Certification Criteria

Of the eight accidents involving aircraft certificated to Appendix C criteria, six, including two outside of the U.S., were deemed as being potentially applicable for Task 2 (see Table I-3 below).

DATE	AIRCRAFT TYPE	LOCATION	FATAL	INJURY	HULL LOSS
10/31/94	ATR-72	Roselawn, IN	68	0	Yes
3/28/89	DC-8-73	Edmonton, Canada	0	0	No
4/29/93	EMB-120	Pine Bluff, AR	0	13 minor	Yes
1/9/97	EMB-120	Monroe, MI	29	0	Yes
3/19/01	EMB-120	Orlando, FL	0	0	Severe Damage
12/21/02	ATR-72	Pengu Island, Taiwan	2	0	Yes

Table I-3 - Applicable Aircraft Accidents For Aircraft With Appendix C Certification Criteria

MINORITY POSITION ON APPENDIX I OF THE IPHWG WORKING GROUP REPORT (ACCIDENTS AND INCIDENTS RELEVANT TO THE PROPOSED RULE)

(Embraer, with support of the Regional Airline Association)

The airworthiness rules identify icing conditions (14 CFR 25, Appendix C) upon which approval of airplane operations in icing conditions is based. Appendix C conditions do not include supercooled large drops conditions (includes freezing drizzle and freezing rain). The operating rules do not prohibit operations in supercooled large drop conditions. The accident history indicates that flight crews of certain types of aircraft have lost control of their aircraft in such conditions.

The proposed 25.1420 text changes the icing environment used to evaluate safe operation of the airplane in icing conditions. The IPHWG Working Group report identifies as "the reason for the change <u>the accident history of some aircraft has shown that the current icing environment requirements are inadequate</u>". Embraer agrees with this statement; however, the purpose of this document is to clarify that the events related to the EMB-120 aircraft, based on the acceptance criteria used on the accidents screening, should not be considered in the IPHWG benefit analysis. It must be clear that the reasons for the requirement improvement are not associated with the EMB-120 aircraft model.

The IPHWG examined incidents and accidents to identify those which may be considered in the benefit analysis of the regulatory evaluation. Descriptors such as severe ice, freezing rain, freezing drizzle, side window icing, heavy icing, large droplets, SLD, and for mixed ice conditions descriptors of sleet, snow, snow grains and ice were employed in the selection of the events of the database.

The current IPHWG proposal for “Accidents and Incidents Relevant to the Proposed Rule” includes three events with the EMB-120 aircraft (164, 171 and 179), which are presented in Table I-3 above:

Some reasons were also taken into account to consider the elimination of an event from the benefit analysis. They are:

- Inoperative IPS
- IPS not activated
- Improper ground deicing
- Improper pilot actions

All three events with the EMB-120 aircraft considered by the IPHWG as applicable to this benefit analysis should be removed from the Working Group report, as either the IPS was not activated, there was improper pilot action, or both. This is very clear in the NTSB report associated to each event. Below is a summary of each of the events that support our request:

- Pine Bluff

In the Pine Bluff case, as stated in the NTSB report, the probable cause of the accident was: “… [T]he probable causes of this accident were the captain’s failure to maintain professional cockpit discipline, his consequent inattention to flight instruments and ice accretion, and his selection of an improper autoflight vertical mode” .
The report also states that there was no evidence that the crew had turned the IPS ON at any time prior to the loss of control. This is based on the performance analysis performed by Embraer, during the accident investigation, that demonstrated that the loss of performance size wise and time wise was not compatible with all data available for the EMB-120 with the de-ice system activated.

- Monroe

In the Monroe accident, according to the performance analysis performed by Embraer and fully accepted by the NTSB, it was demonstrated that the aircraft boots were most probably not activated prior to the loss of control. FDR data shows that the crew let the airspeed decrease to around 138 KIAS that is much lower than the minimum of 160 KIAS, recommended in the AFM for icing conditions. The NTSB probable causes for this accident are all related with dissemination of information between the aircraft manufacturer, certification authorities and aircraft operators and are not related to the specific icing conditions.
In this accident also, the performance analysis performed by Embraer, during the accident investigation, demonstrated that the loss of performance size wise and time wise was not compatible with all data available for the EMB-120 with the de-ice system activated.

- Orlando

In respect to the Comair 5054 (Palm Beach) accident, the NTSB report concluded that the probable cause of the accident was: "The failure of the flight crew to maintain airspeed during an encounter with severe icing conditions, which resulted in an inadvertent stall, loss of control, and structural damage to the airplane". Although there are indications that the crew had activated the de-icing boots, the "light" mode was probably selected, was not compatible with the severity of the icing encounter.
A series of improper pilot actions were verified during this accident:

  - Pilots ignored evidences of severe icing and did not attempt to leave the icing cloud;
  - Auto pilot was not disengaged as specified in the AFM;
  - Pilots did not pay attention to aircraft speed and let it reach values much lower than the 160 KIAS threshold specified in the AFM for operation in icing conditions
  - According to Embraer analysis of the accident that shows that there was a linear increase in performance degradation for approximately 3 minutes, it is apparent that the de-icing system was activated in "light" mode (three minutes cycle), conflicting with instructions presented in the AFM to select "heavy" (one minute cycle) mode in severe icing conditions.

In none of the incidents/accidents above it was demonstrated that the icing conditions prior to the upsets were outside the FAA Appendix C envelope. The possibility of SLD was discussed and not discarded, but, according to the performance analyses, all events were possible with a severe ice encounter inside the Appendix C conditions.

In addition to that, a series of improvements mandated by FAA/CTA have already been incorporated to the plane, as follows:

  - Modification in the Limitations Section of the AFM, describing the visual cues of severe ice, instructing to immediate leave this ice condition and prohibiting the use of the auto-pilot;
  - Removal of the de-icing system "light" mode (now only the "heavy" mode is available);
  - Installation of an Ice Detection System;
  - Installation of a Low Speed Alarm, which activates whenever ice detection system detects ice or ice protection system is activated and the airspeed with flaps up decreases below the recommended minimum of 160 KIAS.

These improvements by themselves, if available before events involving the listed EMB-120 happened, would have very likely prevented the events involving the EMB-120 aircraft from occurring.

Because the contribution of SLD (if any) to the accidents listed can never be established with absolute certainty, Embraer believes that the only way FAA can construct a defendable benefit estimate is to factor the total benefit from accidents prevented by the percentage contributed by each corrective action that has been or will be implemented. This would allocate the proper credit to each action. Since the FDR data from each accident clearly shows that each airplane was operated for a significant period of time at airspeeds below the 160 KIAS threshold of the low speed alarm, it is clear that the vast amount of benefit would be accrued solely through that system. This would leave only accidents in SLD conditions so severe that the 160 KIAS threshold would be insufficient to prevent stall and loss of control as an accident that would be credibly prevented by the proposed regulation. There is nothing indicating that the events involving EMB-120 would fall in this category, what reinforces Embraer position that the EMB-120 events shall be removed from the list of events relevant to the proposed SLD rule.

As a conclusion, Embraer would like to request the IPHWG to remove the EMB-120 events from the Working Group Report.

REGIONAL AIRLINE ASSOCIATION STATEMENT OF SUPPORT OF EMBRAER MINORITY POSITION

RAA concurs with the Embraer position that with all three of the Emb-120 accidents/incidents, there is nothing to indicate that the icing conditions were outside the current Appendix C envelope and that the Emb-120 events should not be cited as justification for the proposed new rule.

MAJORITY RESPONSE

(ALPA, Boeing, CAA/UK, FAA/FAA Tech Center, MSC, NASA, SAAB, Transport Canada/TDC)

Considering the descriptions of the accidents in the NTSB reports, the three EMB-120 events included in Table 5 were more closely reviewed.

Determining the actual icing conditions after an accident is very difficult. In all 3 events, the NTSB reports did not quantify the icing environments as inside or outside 14 CFR Appendix C envelopes, however, the icing event was believed to have affected the performance and handling of the airplane and the effective operation of the ice protection system. In all three events, NTSB meteorological data showed that conditions in the accident area were conducive to SLD conditions. The screening criteria used was “potential SLD conditions”, since the actual icing conditions for each event were not measured.

Although there was no evidence in the Pine Bluff accident that the flight crew had activated the deicing boots, there was no evidence that they failed to activate the deicing boots. In the Orlando, FL event, the flightcrew did activate the “light” mode of the deicing boots, but the AFM did not specify the mode to be used for severe icing, and in fact stated that ice forming aft of the deicing boots may not be shed using the ice protection systems. The “light” mode was prohibited in the EMB-120 several months later as a result of the Orlando, FL accident. Although not activating de-ice boots in a high LWC Appendix C could cause the performance losses noted in the events, it is also possible that icing conditions outside of Appendix C could cause similar performance losses. It is also possible that operating boots designed to Appendix C conditions may not eliminate ice accretions aft of the boots in SLD conditions.

The majority does not concur with the supporting statement that there was an "absolute" IPHWG criterion for exclusion from the list of accidents for benefit analysis. Failure to activate the IPS was identified as a "basis for possible exclusion" rather an absolute criterion. In cases where it was unclear whether the IPS was activated, the event was not excluded.

Failure to adhere to the AFM operating procedures such as maintaining a minimum airspeed in icing conditions, or failure to be made aware of the latest recommended operating procedures were identified as contributing factors affecting the crew’s performance and ability to safely operate the airplane in these icing conditions. The above improvements (such as improvements to the ice detection systems and AFM procedures) are considered appropriate responses by applicants to Appendix C as well as Appendix X icing conditions. Failure to monitor airspeed in icing conditions is a systemic factor in icing related accidents of airplanes without an auto-throttle, not just in the EMB-120. The accident and history database show that a redesign for the SLD environment may include a stall warning system modification.

The series of incorporated improvements listed by Embraer for the EMB-120 were not a requirement for icing certification when the EMB-120 was certificated, and is not a requirement for Appendix C icing certification. This is direct indication that improvements to the certification requirements are necessary for safe flight in the icing conditions.

It is recognized that rulemaking is in progress that will require adequate stall warning in Appendix C icing conditions. However, if one works through the numbers available in the NTSB reports, one will find that a stall warning reset to provide a 7% margin, as required when the EMB-120 was certificated, with the critical Appendix C ice shapes flight tested, would not have been sufficient. The current part 25 stall warning margin requirement is even lower, 5%. In addition, the Low Speed Alarm referenced by Embraer was designed to the accident FDR data, not part 25 regulations. One would find the Low Speed Alarm of 160 knots activates 20 knots higher than a stall warning designed to CFR Section 25.207. This analysis supports the need for improvements to the icing certification requirements.

The performance analysis that Embraer conducted for the NTSB after the Orlando, FL accident, and included in the public docket for that accident, was reviewed by the group. The analysis showed that the lift loss and drag increase measured in EMB-120 flight testing with critical Appendix C ice shapes could not duplicate the performance losses experienced in the three EMB-120 accident events included in Table 5, and an EMB-120 incident included in Table 3, derived from the flight data recorders. For example, Figure 1 of the NTSB performance group report for the Orlando, FL accident, dated March 13, 2002, showed the following lift losses at the current stall warning shaker angle of attack:

Flight test with critical Appendix C intercycle ice: 20%
Pine Bluff accident: 28%
Monroe accident: 30%
Westair incident: 37%
Orlando accident: 41%

Based upon the above, improvements to the design of the airplane to meet the proposed SLD icing environment rule could be considered as appropriate, thus, the three EMB-120 events were retained in the database to support this Task 2 proposed SLD icing environment rule.

EHWG/PPIHWG REVIEW OF ACCIDENTS AND INCIDENTS

An assessment of worldwide commercial engine service history was conducted for small and large engines covering the period from 1989 through 2003. No accidents were attributed to the effects of SLD or Mixed Phase/Glaciated conditions on engine operation.

The following chart (Figure I-1) displays incidents (defined as specific weather events which affected multiple aircraft) in SLD conditions that resulted in reportable fan damage. The 15 incidents listed resulted in damage to a total of 59 engines. None of the events resulted in an actual threat to continued safety of flight.

Note:
H1 - Engines with SLTO thrust < 20,000 lbs
H2 - Engines with SLTO thrust > 20,000 lbs and < 40,000 lbs
H3 - Engines with SLTO thrust > 40,000 lbs

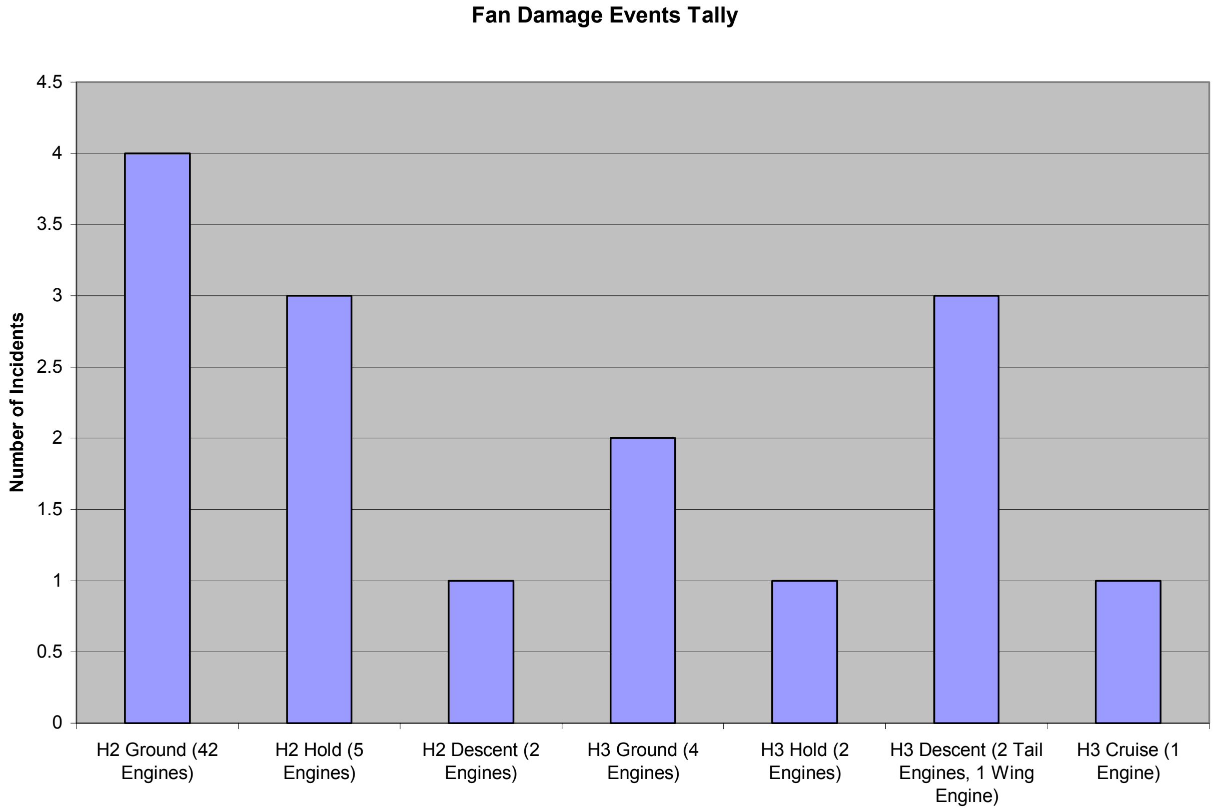


Figure I-1 - Fan Damage Events Tally

The following chart (Figure I-2) displays incidents in Mixed Phase/Glaciated conditions that resulted in reportable rollbacks, flameouts, stalls or engine core damage. The 70 incidents listed affected a total of 97 engines.

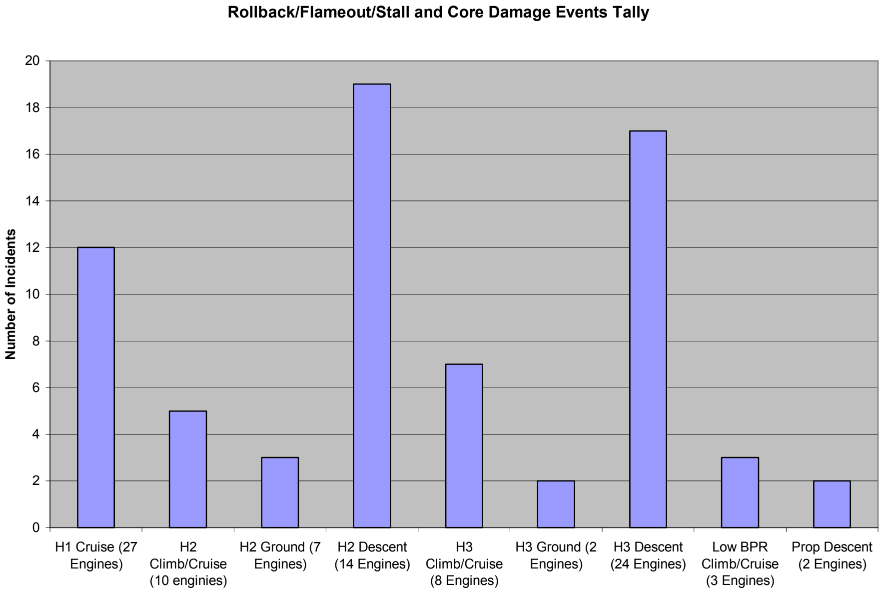


Figure I-2 Rollback/Flameout/Stall and Core Damage Events Tally

APPENDIX J - COST ESTIMATES

GENERAL ASSUMPTIONS

It is admitted among the group that the results of the economic analysis will contain some fairly arbitrary numbers, as experience of existing airplanes cannot be used as a reliable indicator.

Data could be split in three main categories:

-Large transport aircraft operating in full Appendix X ((§25.1420(a)(3))

-Regional aircrafts operating in full or a portion of Appendix X ((§25.1420(a)(3) or (a)(2))

-Commuters / business aircrafts certified with the “detect and exit” option ((§25.1420(a)(1))

There is some indication that the development and certification costs will be roughly the same for all certification options in Appendix X (full, portion of, detect and exit), but the additional operational costs (training, dispatch, diversions, etc.) will be strongly dependant upon the type of certification.

There were no efforts made to identify the costs to government entities associated with the development of the simulation tools (e.g., icing codes, test methods, and facilities development).

The potential overlapping with certification in Appendix C was discussed, without clear conclusions. The costs were provided assuming no benefit from an Appendix C certification applied to an Appendix X certification. There may be some reduction in the cost when considering a combined Appendix C and Appendix X certification program, but this is an unknown factor.

EXAMPLE COSTS

Table J-1 provides example costs that were provided to the IPHWG as representative of expected costs to show compliance to the proposed rule.

	Large Transport Y	Large Transport Z	Regional Transport Aircraft[3]
SLD Ice Detection System Design, Qualification & Certification	$556,800	$600,000	$280,000
Aerodynamic Wind Tunnel Tests	$1,219,200	$800,000	$ 1,202,000
Icing Tunnel Test	$2,020,800	$12,300,000[2]	$456,000
Analysis (icing codes, CFD, ...)	$230,400	n/a	$100,000
Simulated Ice Shapes - Flight Test Campaign	$1,420,800	$1,900,000	$682,000
Icing Tanker - Flight Test Campaign	$2,434,800	n/a	$1,530,000
Natural Ice - Flight Test Campaign	$4,252,800	$4,200,000	$2,555,000
SLD Ice Detect Recurring	$10,000[5]	$10,000[5]	$10,000[5]
Total	$12,135,600[1]	$20,300,000[1]	$6,805,000[1]

Table J-1 - Example Costs

Note 1: Compliance will likely require a combination of the approaches, but individual manufactures will have to determine which exact combination will be required to meet the certification goals of program risk reduction, development and validation of ice shapes, and validation of the methods. It is not possible to predict which combinations will be required. In light of this, a conservative economic analysis would consider the total costs. For derivative aircraft programs that have an ancestor aircraft that has already been certified to Appendix X, it is expected that the program costs could be reduced by 50 percent. For operation in a portion and “detect and exit” aircraft, it should be assumed that 50 percent will use an ice detector to exit and 50 percent will use visual cues. It is estimated that 50 percent of airplane certification programs will require natural icing flight testing.

Note 2: Quote assumes considerably more tunnel testing.

Note 3: These quotes are representative of commuters / business aircraft, as well as regional aircraft.

Note 4: Quotes were normalized to the US dollar assuming an exchange rate of 1.2 US dollar per Euro. Costs are provided in year 2003 US dollars.

Note 5: The Ice Detector could be a detector for activation of the ice protection system and/or for knowing when to exit icing conditions. The large transport manufacturers, whose airplanes will likely be certified in accordance with § 25.1420(a)(3), anticipate installation of an ice detector which will activate the IPS, although the rule allows activation of the IPS based on visible moisture and temperature. There are fuel savings benefits associated with the installation of ice detectors which activate the IPS; conversely, there are fuel-burn penalties associated with activation of the IPS based upon temperature and visible moisture; neither have been accounted for in this Working Group Report.

Note 6: Certifications will be approximately equally divided between unrestricted operation, operation in a portion of X, and detect and exit.

Note 7: For unrestricted aircraft, the majority position is that a system to detect exceedance of Appendix X conditions is not required. The minority position may require some percentage of the aircraft to be equipped with such a system.

ENGINE CERTIFICATION COSTS

- 14 CFR Part 33.68 – Three additional icing test conditions required, cold point plus ground operation in SLD and snow, with allowance for certification in the latter two by analysis and/or in the case of snow by equivalent liquid water). Five additional test conditions (climb, cruise, idle descent, holding, approach) in Mixed Phase/Glaciated icing currently addressed in AC20-147.
- 14 CFR 25.1093- Requirement to demonstrate capability by test or analysis including a 30 minute ground SLD exposure. Expect this will drive one or more experimental test points to validate analysis.

New Equipment Purchases

- Currently, there are limited test facilities for testing with ice crystals. Estimates are being prepared for enhancing ground test facilities for this purpose. An alternate proposal utilizes current test facilities by prescribing an equivalent liquid water test, but requires validation. A technology program to validate that approach is now under consideration. If snow and Mixed Phase/Glaciated tests must use artificial ice crystals, an assessment is required for effects of ice crystal velocity. Existing means for generating artificial ice crystals from spray nozzles provide velocities lower than flight speed. If facilities for producing the ice crystals with adequate velocity to simulate flight speeds are required, they may need to include ice processing and high air pressure equipment.

Industry Relief

- 14 CFR Part 33.77 – Rule changes allow alternate means for certification of soft body impact tolerance associated with ice slab through use of validated analysis and other applicable testing. This will minimize engine ice slab testing for manufacturers having or developing validated analysis procedures. It is anticipated that due to the costs and complexity of developing such analyses only the three large engine manufacturers will be able to make use of this option, while small engine manufacturers will continue to run the ice slab test.

- 14 CFR Part 33.68 – Manufacturers will not be required to test the legacy AC20-147 “Table Points” unless they are more severe than conditions defined by the Critical Point Analysis of icing conditions.
- 14 CFR Part 33.77 and Part 33.68 – Rule changes allow for changes in engine power resulting from ice slab and natural icing tests within the nominal ability to measure this parameter (1.5%).
- Alternate method of compliance by similarity to engines proven safe to operate in mixed phase or glaciated icing conditions: Although it has been established that mixed phase or glaciated 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 design, similar to those proven engines, is allowed to show compliance by similarity analysis.

Additional Requirements

- Validated analysis of engine icing in glaciated environment is required for assessment of this icing threat.
- Manufacturers will have to demonstrate to FAA that they have thoroughly addressed Critical Point Analysis requirements for natural icing in 14 CFR Part 25 Appendix C, the new 14 CFR Part 25 Appendix X and the new 14 CFR Part 33 Appendix D.
- The addition of Appendix X to 14 CFR 25.1093 will require additional analysis of the engine inlet capability in descent and holding conditions
- The addition of Appendix X Ground Test point will require additional analysis of inlet ice accretion on the ground for comparison with 14 CFR 33.77 slab.
- Analysis for 14 CFR 33.77 to show compliance using equivalent soft-body testing may require additional component tests to validate analyses.

	Large Engine A	Large Engine B	Large Engine C	Small Engine
Engine Analysis (Mixed Phase Glaciated)	TBD*	$10,000	**$50,000**[a]	TBD*
Ice crystal facility			**$1,000,000**[b]	
Engine Analysis SLD	TBD*	$10,000*	**$20,000**[c]	TBD*
Engine Icing Tests	TBD**	TBD**	**$600,000**[d]	$500,000
Saved Ice Slab Testing	-TBD***	-150,000***	**-$50,000*** **	N/A
Soft Body Tolerance Analysis	TBD	$182,000	**$50,000**	N/A

Table J-2 - Example Costs/Engines

[a] Mixed phase compliance by analysis is only short term. Considerable research & testing must be done to meet the long-term goals stated in the proposed rule. This work may cost $250,000 or more.

[b] Modifying manufacturer facility to provide an ice crystal cloud estimated to cost approx. $1 million using a known method, however this may not meet requirements and result in more expensive facilities.

[c] If additional test facilities to provide SLD required then investment costs of facility changes estimated at $100,000, additional per program costs ~$50,000

[d] Additional testing in Appendix C atmosphere and new 14 CFR33 Appendix D will result in extra test points, if manufacturers facility cannot be used and altitude facility required costs will be considerably higher

* Rule allowance for ice crystal compliance by similarity reduces cost significantly and promotes designing proven ice crystal-tolerant features into new engines. Comparative analysis done by one engine manufacturer cost $10,000.

** If new engine size is compatible with limited existing test facilities capable of producing ice crystals, or equivalent liquid water can be substituted for ice crystal tests, preliminary estimates from one small engine manufacturer are for $400,000 -$500,000 additional icing test costs for new engine certification program. Estimate from one testing facility with capacity up to 25,000 lb thrust turbofan engine are for $200,000 additional icing test costs for new engine certification program.

***Cost reduction for eliminated ice slab test partially offset by additional soft body tolerance analysis

NOTE: Additional SLD costs for airplane certification associated with 25.1093 rulemaking have not been included in IPHWG cost numbers. Cost information is being assessed and will be provided to the economist as available.

NON RECURRING COSTS (DEVELOPMENT, CERTIFICATION)

Flight tests in natural conditions were identified as being a major contributor to the overall cost. There is no clear visibility on the amount of flight hours that could be needed for certification (low probability for SLD encounters as compared to Appendix C conditions; no requirements defined in terms of MVD, LWC, or exposure times). A large transport aircraft manufacturer evaluated the additional test time at about 100 flight test hours. It is recognized that the accretions obtained during the test campaign may not be sufficient to allow the validation of the icing codes used to generate the critical ice shapes for a full Appendix X certification. The analysis should therefore provide an envelope, with a lower limit corresponding to the minimum to comply and an upper limit which includes extensive flight-testing in natural conditions.

Some other factors need to be considered, such as the rank of application to the new rule (costs associated with the first certifications will likely be significantly higher than subsequent applications) or certification of derivatives (no general rule can be proposed on the nature of the modifications being applied).

For each airplane category assumed (large transport, regional transport, commuter/business), the non-recurring costs can be summarized with the following break down:

1. Minimum Cost to Comply (Lower Limit):

   -Ice detector qualification / certification
   -Analysis (icing codes, CFD)
   -Aerodynamic wind tunnel tests
   -Icing tunnel tests or artificial icing behind a tanker
   -Flight test with simulated ice shapes
   -Documentation (Certification reports, AFM, FCOM,..)

2. Upper Limit:

   - All of the items in No. 1 above, plus
   - Flight tests in natural SLD conditions

Note: The possible overlapping with certification in Appendix C will obviously depend upon the performance penalties which could be required for operation in Appendix X. Costs provided by the manufacturers are based on a scenario in which a specific set of minimum speeds /performance and associated handling qualities tests need to be established for Appendix X operation in addition to Appendix C conditions.

RECURRING COSTS

On the manufacturers' side, introduction of the new rule may lead to major modifications in the ice protection systems (e.g., increased size of protected surfaces requiring additional power; addition of new detection or warning means). An evaluation of these recurring costs is not available.

On the operators' side for the non-recurring costs, a breakdown equally divided into three categories (large, regional, business/commuter) can be envisaged. This is based on the assumption that large transport airplanes will probably apply for certification in all of Appendix X, regional airplanes for full or a portion of Appendix X, and business/commuters for the detect and exit option. The economic analysis should take into account the following consequences:

- Impact on dispatch (performance limited take-offs and payload decrease)
- Diversion by exiting (increased flown distance)
- Diversion to alternate
- Cancelled flight
- Pilot training

Costs associated with the training of Air Traffic Control and weather system personnel also need to be considered.

One large transport manufacturer using available figures (probability to encounter Appendix X conditions, number of airplanes certified to the new rule, estimated proportions in each category) provided an example calculation of the operational costs. The impact on dispatch numbers are based on aircraft certified without restriction or certified for a portion of Appendix X (i.e., WAT limited takeoffs). The diversion and cancelled-flight numbers are based on aircraft certified to detect and exit all or a portion of Appendix X. These estimates are provided in Table J-3.

Table J-3 - Operating Costs

Category	Costs for year one (2007 assumed)
Impact on dispatch (payload)	$113,380
Exit by Diversion	$169,493
Diversion to alternate airport	$16,376,100
Cancelled flights	$5,567,874
Pilot training	not available[2]
Weather/ATC training	not available[2]

Notes:

(1) Assumptions of 1,900 flights per year and 169 new aircraft in 2007.

(2) Pilot training and weather/ATC training costs should be calculable by the FAA economist assuming, for example, one hour of training per person per year.

APPENDIX K - IPHWG RECOMMENDED ADVISORY MATERIALS §§25.1419, 25.1420

ATTENTION: This Advisory Circular is based on the existing AC 25.1419-1 "Certification of Transport Category Airplanes for Flight in Icing Conditions". This draft AC is intended to address existing §25.1419 requirements as well as §25.1420. As part of the revision, Sub-part B related requirements were moved to the FTHWG proposed advisory materials AC 25.21(g).

U.S. Department
of Transportation
Federal Aviation Administration

Advisory Circular

Subject: COMPLIANCE OF TRANSPORT CATEGORY AIRPLANES FOR FLIGHT IN ICING CONDITIONS	**Date:** Draft 5/10/04 **Initiated By:** ANM-110	**AC No: 25-XX** **Change:**

WORKING DRAFT -- NOT FOR PUBLIC RELEASE.

1. PURPOSE.

a. This Advisory Circular (AC) describes an acceptable means for showing compliance with the requirements of § 25.1419, “Ice protection” and § 25.1420, “Supercooled Large Drop Icing Conditions,” of Title 14, Code of Federal Regulations (14 CFR) part 25, commonly referred to as part 25 of the Federal Aviation Regulations (FAR). Part 25 contains the applicable certification requirements for transport category aircraft. The means of compliance described in this document are intended to provide guidance to supplement the engineering judgment that must form the basis of any compliance findings relative to the requirements of §§ 25.1419 and 25.1420.

b. The guidance provided in this document is directed to airplane manufacturers, modifiers, foreign regulatory authorities, and Federal Aviation Administration airplane type certification engineers and their designees.

c. Like all advisory circular material, this AC is not in itself mandatory, and does not constitute a regulation. It is issued to describe an acceptable means, but not the only means, for demonstrating compliance with the requirements for transport category airplanes. Terms such as “shall” and “must” are used only in the sense of ensuring applicability of this particular method of compliance when the acceptable method of compliance described in this document is used. While these guidelines are not mandatory, they are derived from extensive Federal Aviation Administration and industry experience in determining compliance with the pertinent regulations.

d. This advisory circular does not change, create any additional, authorize changes in, or permit deviations from regulatory requirements.

2. APPLICABILITY.

The guidance provided in this AC applies to certification of part 25 transport category airplanes for flight in icing conditions. If certification for flight in icing conditions is desired, the airplane must be able to safely operate throughout the icing envelope of 14 CFR 25, Appendix C. The airplane must also be able to safely operate or exit the icing conditions defined by 14 CFR 25, Appendix X. The certification options available are: 1) to safely operate throughout Appendix X, 2) To operate safely throughout a portion of Appendix X, 3) Limited to safely exiting Appendix X conditions. Sections 25.1419 and 25.1420 set forth the specific airframe requirements for demonstrating compliance with the icing conditions defined in Appendices C and X. Additionally, for other parts of the airplane (i.e., engine, engine inlet, propeller) there are more specific icing requirements and associated guidance defined in the referenced regulations and advisory circulars listed in paragraph 3 below. Some of the icing-related regulations must be complied with, even if the airplane is not certificated for flight in icing (e.g., §§ 25.629(d)(3), 25.903, 25.975, 25.1093, 25.1323(e), and 25.1325(b)). This AC contains information on flight tests for ice protection certification; additional information on flight tests for showing compliance with the airplane performance and handling qualities requirements for icing certification may be found in Advisory Circular 25.21-1. The guidance provided in this AC is applicable to new Type Certificates (TC's), Supplemental Type Certificates (STC's), and amendments to existing TC's for airplanes certified under Part 4b of the Civil Aviation Regulations (CAR) and Part 25, for which approval under the provisions of § 25.1419 is desired.

3. RELATED DOCUMENTS.

a. **Regulations contained in Title 14, Code of Federal Regulations (CFR).**

Section	Title
§ 25.21(g)	Proof of compliance
§ 25.105(a)(2)	Takeoff
§ 25.107(h)	Takeoff speeds
§ 25.111(c)(5)	Takeoff path
§ 25.119(b)	Landing climb: All-engines-operating
§ 25.121(b)(2)(ii), (c)(2)(ii) & (d)(2)(ii)	Climb: One-engine-inoperative
§ 25.123(b)(2)	En route flight paths
§ 25.125(a)(2), & (b)(2)(ii)	Landing

§ 25.143(c),(i), & (j)	General
§ 25.207(b), (e), (f), (h), & (i)	Stall warning
§ 25.237(a)(3)(ii)	Wind velocities
§ 25.253(b)	High-speed characteristics
§ 25.629	Aeroelastic stability requirements
§ 25.773(b)(1)	Pilot compartment view
§ 25.929	Propeller deicing
§ 25.975(a)(1)	Fuel tank vents
§ 25.1093	Induction system icing protection
§ 25.1323	Airspeed indicating system
§ 25.1325	Static pressure system
§ 25.1301	Equipment - Function and installation
§ 25.1309	Equipment, systems, and installations
§ 25.1316(b)	System lightning protection
§ 25.1321	Instruments Installation - Arrangement and visibility
§ 25.1322	Warning, caution, and advisory lights
§ 25.1403	Wing icing detection lights
§ 25.1419	Ice protection
§ 25.1420	Supercooled large drop icing conditions
§ 25.1585	Operating procedures.
Appendix C to part 25	
Appendix X to part 25	

b. **Advisory Circulars (AC).** The AC's listed below may be obtained from the U.S. Department of Transportation, Subsequent Distribution Office, SVC-121.23, Ardmore East Business Center, 3341 Q 75th Avenue, Landover, MD 20785:

Number	Title and Date
AC 20-73A	Aircraft Ice Protection, dated *XX, 2004*.
AC 20-117A	Hazards Following Ground Deicing and Ground Operations in Conditions Conducive to Aircraft Icing, dated December 17, 1982.
AC 20-115B	Radio Technical Commission for Aeronautics, Inc. (RTCA) Document RTCA/DO-178B, dated January 11, 1993.
AC 20-147	Turbojet, Turboprop, and Turbofan Engine Induction System Icing
AC 21-16D	RTCA Document DO-160C, dated July 21, 1998.
AC 25-11	Transport Category Airplane Electronic Display Systems, dated July 16, 1987
AC 25.21-1	Performance and Handling Characteristics in the Icing Conditions Specified in Part 25, Appendix C, dated XX, 2004.
AC 25-22	Certification of Transport Airplane Mechanical Systems
AC 25.629-1	Flutter Substantiation of Transport Category Airplanes
AC 25.1309-1A	System Design Analysis, dated June 21, 1988.

c. **Other FAA Documents:**

Number	Title
DOT/FAA/CT-88/8-1	“Aircraft Icing Handbook,” issued March 1991, updated September 1993
DOT/FAA/AR-04/7	"TBD", dated TBD (Insert Met group paper that is to be written on the derivation of Appendix X)

d. **Industry Documents.** The following RTCA documents can be obtained from Radio Technical Commission for Aeronautics (RTCA), Inc., 1140 Connecticut Ave., NW, Suite 1020, Washington, DC 20036. The following SAE Documents can be ordered from the Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096. The SAE documents to date have not been updated to reflect supercooled large droplet analyses and testing but provide good reference material.

Number	Title
RTCA/DO-178B	Software Considerations in Airborne Systems and Equipment Certification
RTCA/DO-160D	Environmental Conditions and Test Procedures for Airborne Equipment
RTCA/DO-254	Design Assurance Guidance for Airborne Electronic Hardware
SAE/ARP5624	Aircraft Inflight Icing Terminology, to be released
SAE/ARP5903	Droplet Impingement and Ice Accretion Computer Codes, dated, October 2003
SAE/ARP5904	Airborne Icing Tankers, dated 10/2002.
SAE/ARP5905	Calibration and Acceptance of Icing Wind Tunnels, dated September 2003.
SAE ARP1168/4	Ice, Rain, Fog and Frost Protection, dated 7/30/1990
SAE AS5498 (EUROCAE ED-103)	Minimum Operational Performance Specification For Inflight Icing Detection Systems

Signed by:
Manager, Transport Airplane Directorate
Aircraft Certification Service

Contents

Appendices

1. BACKGROUND.

a. Civil Air Regulations (CAR).

(1) Prior to 1953, airplanes were certificated under Part 04 of the CAR. Section 04.5814 required that if deicer boots were installed, then positive means must be provided for the deflation of all wing boots. There were no other references to an airplane ice protection system (IPS) in Part 04.

(2) Part 4b of the CAR was codified on December 31, 1953. The requirement for positive means of deflating deicer boots was incorporated, without change, in § 4b.640. Section 4b.640 stated that, “When an ice protection system is installed, it shall be of an approved type. If pneumatic boots are used, at least two independent sources of power and a positive means for the deflation of the boots shall be provided.” Section 4b.351(b)(ii) provided requirements for pilot compartment vision in icing conditions. Section 4b.406 provided propeller-deicing requirements. Section 4b.461 provided induction system deicing and anti-icing requirements. Section 4b.612(a)(5) required that the airspeed indicating system be provided with a heated pitot tube or equivalent means of preventing malfunctioning due to icing.

(3) Amendment 4b-2, effective August 25, 1955, introduced icing envelopes similar to the current Appendix C to part 25. The graphs added by Amendment 4b-2 (4b-24a, 4b-24b, 4b-24c, 4b-25a, 4b-25b, and 4b-25c) were identical in substance and format to the current Appendix C envelopes with a few exceptions. These envelopes described the liquid water content, the mean effective diameter of droplets, the temperature, and horizontal and vertical extent of the supercooled icing cloud environment. In the figures introduced by Amendment 4b-2, the units of the distances shown on the graphs were expressed in statute miles instead of nautical miles. The Liquid Water Content (LWC), however, is identical between the Amendment 4b-2 figures and the current Appendix C envelopes, if the correction for the difference in value between nautical and statute miles is made. There are two significant differences between the Amendment 4b-2 envelopes and the current Appendix C. The minimum mean effective diameter in the intermittent maximum conditions was 20 µm versus the current 15 µm, and the minimum cloud horizontal extent in the Intermittent Maximum Atmospheric Icing Conditions Variation of LWC Factor with Cloud Horizontal Extent chart was 1.5 statute miles versus the current 2.6 nautical miles (3.0 statute miles).

(4) Amendment 4b-6, effective August 12, 1957, revised the icing envelopes to the current requirements and revised § 4b.461, “Induction system de-icing and anti-icing provisions.” The preamble to the amendment states:

> There are included herein changes which extend the currently effective provisions governing intermittent maximum icing conditions so as to cover conditions which might be critical insofar as the turbine engine induction system is concerned. In this regard, the data are being extended in accordance with NACA Technical Note 2738 and involve a revision of Figure 4b-25a to cover drop diameters as small as 15 µm and a revision of Figure 4b-25c to cover distances down to 3.0 mile. The icing conditions prescribed in the currently effective regulations are applicable in the main to the airframe. The changes being made in section 4b.461 require the turbine powerplant to be subjected to the same icing conditions and require that the induction system be protected to prevent serious engine power loss. A similar requirement is incorporated with respect to certification of turbine engines by an amendment to Part 13 which is being made concurrently with this amendment.

b. Part 25.

(1) Part 4b of the CAR was codified into part 25, effective February 1, 1965. After recodification, with minor editorial changes the content of § 4b.640, Ice protection, became § 25.1419; § 4b.406, Propeller deicing provisions, became § 25.929; § 4b.612(a)(5), Airspeed indicating systems, became § 25.1323(e); § 4b.351(b)(1)(ii), Pilot compartment view, became § 25.773(b)(1)(ii). The § 4b.351 reference to the most severe icing conditions for which approval of the airplane is desired was changed in part 25 to reference the icing conditions specified in § 25.1419. Section 4b.461, Induction system deicing and anti-icing provisions, became § 25.1093.

(2) Amendment 25-5, effective July 29, 1965, revised § 25.1325(b) to require that the correlation between air pressure in the static pressure system and true ambient atmospheric static pressure is not changed when the airplane is exposed to the continuous and intermittent maximum icing conditions defined in Appendix C.

(3) Amendment 25-11, effective June 4, 1967, revised § 25.1585 to require that the Airplane Flight Manual include information on the use of ice protection equipment.

(4) Amendment 25-23, effective May 8, 1970, revised § 25.1419 to require that the effectiveness of the IPS and its components be shown by flight tests of the airplane or its components in measured natural atmospheric icing conditions. Previous to this amendment, flight tests in natural icing conditions were considered as one means of compliance but were not mandatory. Amendment 25-23 also revised § 25.1309 to include additional requirements for certificating equipment, systems, and installations. The regulation was revised to

require a comprehensive systematic failure analysis, supported by appropriate test, to ensure that the safety objectives of the probability of occurrence decrease as the hazard of a failure increases.

(5) Amendment 25-38, effective February 1, 1977, added § 25.1403 to require a means for illuminating or otherwise determining the formation of ice on the parts of the wings that are critical from the standpoint of ice accumulation. The requirement is not applicable if the operating limitations prohibit operations at night in icing conditions.

(6) Amendment 25-43, effective April 12, 1978, added § 25.1326 to require the installation of a pitot heat indication system on airplanes equipped with flight instrument pitot heating systems.

(7) Amendment 25-46, effective December 1, 1978, added § 25.1416 to require specific standards for pneumatic deicer boots.

(8) Amendment 25-72, effective July 20, 1990, transferred § 25.1416 to § 25.1419 for clarification and editorial improvement. In addition, the contents of § 25.1416(c), which required a means to indicate to the flightcrew that the pneumatic deicing boot system is receiving adequate pressure and is functioning normally, were revised to allow the use of the “dark cockpit” concept (i.e., a warning when failure occurs rather than continual pilot monitoring of a healthy system).

(9) Amendment 25-XX, effective xx xx, 200X, §§ 25.21, 25.103, 25.105, 25.107, 25.111, 25.119, 25.121, 25.123, 25.125, 25.143, 25.207, 25.237, and 25.253 were revised to provide performance and handling requirements for safe operation in Appendix C icing conditions. Section 25.1419 was revised to require compliance with § 25.1419 if certification for flight in icing is desired. Prior that revision, compliance with § 25.1419 was only required if the airplane had ice protection provisions. Editorial revisions were made to §§ 25.773 and 25.941 to retain consistency with the changed § 25.1419 and to revise references to changed paragraphs, respectively.

(10) Amendment 25-XX, effective xx xx §25.1419(e), (f), (g), and (h) were added to provide requirements for determination of when to operate ice protection systems to ensure safe operation in Appendix C icing conditions.

(11) Amendment 25-XX, effective xx xx, 200X, introduced Appendix X and § 25.1420, and revised §§ 25.773, 25.929, 25.1093, 25.1323, and 25.1325. The amendment added supercooled large droplet icing conditions that must be considered when an airplane is certificated for flight in icing.

2. DEFINITION OF TERMS. For the purposes of this AC, the following definitions should be used.

NOTE: These definitions of terms are intended for use only with respect to § 25.1419 & § 25.1420

a. ADVISORY ICE DETECTION SYSTEM: An advisory system annunciates the presence of icing conditions or ice accretion. The flightcrew is responsible for monitoring the icing conditions or ice accretion as defined in the AFM, typically using total air temperature and visible moisture criteria, visible ice accretion, or specific airframe ice accretion thickness, and activation by the flightcrew of the anti-icing or de-icing system(s) is necessary. The advisory system provides information to advise the flightcrew of the presence of ice accretion or icing conditions, but it can only be used in conjunction with other means to determine the need for, or timing of, activating the anti-icing or de-icing system.

b. AIRFRAME ICING: Ice accretions on portions of the airplane, with the exception of the propulsion system including the air induction system, on which supercooled liquid droplets may impinge.

c. ANTI-ICING: The prevention of ice formation or accumulation on a protected surface, either:

- by evaporating the impinging water or
- by allowing it to run back and off the surface or freeze on non-critical areas.

d. APPENDIX C ICING CONDITIONS: The environmental conditions defined in Appendix C of 14 CFR Part 25 that are to be used as the engineering standard for icing certification.

e. APPENDIX X ICING CONDITIONS: The environmental conditions defined in Appendix X of 14 CFR Part 25, characterizing SLD conditions, which are to be used as the engineering standard for icing certification.

f. ARTIFICIAL ICE: Real ice, but formed by artificial means, such as a spray rig in a tunnel or by a tanker.

g. AUTOMATIC CYCLING MODE: A mode of operation of the airframe de-icing system that provides repetitive cycles of the system without the need for the pilot to select each cycle. This is generally done with a timer, and there may be more than one timing mode.

h. DEICING: Removal or the process of removal of an ice accretion after it has formed on a surface.

i. DRIZZLE DROP: A drop of water of diameter 100 µm to 500 µm (0.1 – 0.5 mm).

j. FREEZING DRIZZLE (FZDZ): Supercooled drizzle drops that remain in liquid form, and freeze upon contact with objects colder than 0°C.

k. FREEZING PRECIPITATION: Any form of supercooled liquid precipitation that freezes upon impact with the ground or exposed objects, that is, freezing rain or freezing drizzle.

l. FREEZING RAIN (FZRA): Supercooled rain drops that remain in liquid form, and freeze upon contact with objects colder than 0°C.

m. IPS: Ice Protection System

n. ICING CONDITIONS: The presence of atmospheric moisture and temperature conducive to airplane icing.

o. ICING CONDITIONS DETECTOR: A device that detects the presence of atmospheric moisture and temperature conducive to airplane icing.

p. IRREVERSIBLE FLIGHT CONTROLS: All of the force required to move the pitch, roll, or yaw control surfaces is provided by hydraulic or electric actuators, the motion of which is controlled by signals from the flight deck controls. Loads generated at the control surfaces themselves are reacted against the actuator and its mounting and cannot be transmitted directly back to the flight deck controls.

q. LIQUID WATER CONTENT (LWC): The total mass of water contained in liquid drops within a unit volume or mass of air, usually given in units of grams of water per cubic meter (g/m3).

r. MEAN EFFECTIVE DIAMETER (MED): The calculated drop diameter that divides the total liquid water content present in the drop size distribution in half, i.e., half the water volume will be in larger drops and half the volume in smaller drops. The value is calculated, based on an assumed Langmuir drop size distribution, which is how it differs from median volume diameter.

s. MEDIAN-VOLUME DIAMETER (MVD): The drop diameter that divides the total liquid water content present in the drop distribution in half, i.e., half the water volume will be in larger drops and half the volume in smaller drops. The value is obtained by actual drop size measurements.

t. MIGRATING ICE: Ice resulting from the down-stream migration and buildup of ice from wet protected surfaces to areas that cool sufficiently for the migrating ice to adhere to the surface.

u. MONITORED SURFACE: The surface of concern regarding the ice hazard. (e.g., the leading edge of a wing). Ice accretion on the monitored surface may be measured directly or correlated to ice accretion on a reference surface.

v. PRIMARY ICE DETECTION SYSTEM: An ice detection system which is the only means used to determine when the IPS must be activated. The system annunciates the presence of ice accretion or icing conditions and may also provide information to other aircraft systems. A primary automatic system automatically activates the anti-icing or de-icing systems. With a primary manual system, the flightcrew activates the IPS upon indication from the system.

w. RAIN DROP: A drop of water of diameter greater than 500 µm (0.5 mm).

x. REFERENCE SURFACE: The observed (directly or indirectly) surface used as a reference for the presence of ice on the monitored surface. The presence of ice on the reference surface must occur prior to – or coincidentally with – the presence of ice on the monitored surface. Examples of reference surfaces include windshield wiper blades or bolts, windshield posts, ice evidence probes, propeller spinner, and the surface of ice detectors. The reference surface may also be the monitored surface.

y. REVERSIBLE FLIGHT CONTROLS: The flight deck controls are connected to the pitch, roll, or yaw control surfaces by direct mechanical linkages, cables, or push-pull rods such that pilot effort produces motion or force about the hinge line. Conversely, force or motion originating at the control surface (through aerodynamic loads, static imbalance, or trim tab inputs, for example) is transmitted back to flight deck controls.

(1) Aerodynamically boosted flight controls: Reversible flight control systems that employ a movable tab on the trailing edge of the main control surface linked to the pilot's controls or to the structure in such a way as to produce aerodynamic forces that move, or help to move, the surface. Among the various forms are flying tabs, geared or servo tabs, and spring tabs.

(2) Power-assisted flight controls: Reversible flight control systems in which some means is provided, usually a hydraulic actuator, to apply force to a control surface in addition to that supplied by the pilot to enable large surface deflections to be obtained at high speeds.

z. RUNBACK ICE: Ice formed from the freezing or refreezing of water leaving an area on an aircraft surface that is above freezing and flowing downwind to an area that is sufficiently cooled for freezing to take place. This ice type is frequently associated as an unwanted product of thermal deicing systems.

aa. SIMULATED ICE: Ice shapes that are fabricated from wood, epoxy, or other materials by any construction technique.

ab. STATIC AIR TEMPERATURE: The air temperature as would be measured by a temperature sensor not in motion with respect to that air. This temperature is also referred to in other documents as "outside air temperature," "true outside temperature," or "ambient temperature."

ac. SUBSTANTIATED VISUAL CUE: Ice accretion on a reference surface that has been demonstrated by testing to correlate with ice accretion on a monitored surface.

ad. SUPERCOOLED LARGE DROPS (SLD): Supercooled liquid water that includes freezing rain or freezing drizzle.

ae. SUPERCOOLED WATER: Liquid water at a temperature below the freezing point of 0°C.

af. FZDZ/G: A drop diameter distribution that has an MVD greater than 40 μm and includes freezing drizzle and drops with diameters less than 100μm (defined by 14 CFR 25, Appendix X).

ag. FZDZ/L: A drop diameter distribution that has an MVD less than 40 μm and includes freezing drizzle and drops with diameters less than 100μm (defined by 14 CFR 25, Appendix X).

ah. FZRA/G: A drop diameter distribution that has an MVD greater than 40 μm and includes freezing rain, freezing drizzle and drops with diameters less than 100μm (defined by 14 CFR 25, Appendix X).

ai. FZRA/L: A drop diameter distribution that has an MVD less than 40 μm and includes freezing rain, freezing drizzle and drops with diameters less than 100μm (defined by 14 CFR 25, Appendix X).

3. ICING ENVELOPES

a. Background. The Appendix C icing envelopes are unchanged by the addition of Appendix X. See AC20-73A and DOT/FAA/CT-88/8-1 "Aircraft Icing Handbook" for detail on the Appendix C envelopes. Appendix X was defined to provide a representative icing environment for supercooled large drops (SLD), which include freezing drizzle and freezing rain conditions.

Section 25.1420 requires that the airplane operate safely in the SLD icing conditions defined in Part 25, Appendix X. When complying with § 25.1420(a)(1) the applicant must provide a method to detect that the airplane is operating in Appendix X; and following detection, the airplane must be capable of operating safely while exiting all icing conditions. When complying with § 25.1420(a)(2), certification may be requested for portions of Appendix X, such as for freezing drizzle only or for specific phases of flight. Following detection of conditions that exceed the selected portion of Appendix X, the airplane must be capable of operating safely while exiting all icing conditions. Certification for a portion of Appendix X (§ 25.1420(a)(2)) or none of Appendix X (§ 25.1420(a)(1)) requires substantiated methods be provided to alert flight crews when those portions of Appendix X are exceeded (§ 25.1420(a)(2)) or Appendix X conditions are encountered (§ 25.1420(a)(1)). Certification to Appendix X (§25.1420(a)(3)) requires that the airplane operate safely throughout Appendix X.

The four spectra with associated LWC limits were developed to describe the entire Appendix X environment as it could be determined by all the measurements available. Initial certifications to a portion of Appendix X will likely include all of freezing drizzle or all of freezing rain, or be restricted by phase of flight, provided acceptable means are made available to the flight crew to distinguish the portion of Appendix X for which the aircraft is not approved. Certification for a portion of Appendix X allows latitude for certification with a range of techniques; for example, limiting the range of liquid water contents. In doing these type of limited certifications, ice shapes will be developed for the portion of the envelope for which the aircraft is approved as well as for detecting and exiting icing conditions beyond the selected portion.

The ice shapes developed for the approved portion of the envelope should account for the icing conditions in terms of drop distribution and water content and consider the proposed method for identifying the icing conditions that require exiting. The definition of the certificated portion of Appendix X should be based on measured characteristics of the selected icing environment and consistent with the methods used for developing Appendix X. A detailed report on the development of Appendix X is available from the FAA Technical Center, reference report DOT/FAA/AR-04/7, dated xx/xx/xx.

SLD icing conditions are defined by Appendix X, including freezing drizzle and freezing rain. The two types of freezing precipitation are further divided into conditions in which the drop median volume diameters are either less than or greater than the 40 µm, the largest mean effective diameter of Appendix C continuous maximum icing conditions. Appendix X consists of measured data that was divided into droplet distributions within these four icing conditions. These distributions were averaged to produce the representative distributions for each condition.

The icing conditions data were divided as follows:

1. Measured icing conditions with an MVD less than 40 µm and a maximum drop size from 100 µm to 500 µm were classified as FZDZ/L
2. Measured icing conditions with an MVD greater than 40 µm and a maximum drop size from 100 µm to 500 µm were classified as FZDZ/G
3. Measured icing conditions with an MVD less than 40 µm and a maximum drop size greater than 500 µm were classified as FZRA/L
4. Measured icing conditions with an MVD greater than 40 µm and a maximum drop size greater than 500 µm were classified as FZRA/G

The data measured to produce Appendix X was taken in wintertime stratus cloud formations. As such, the Appendix X conditions are most closely associated with the stratus conditions used to define the existing Appendix C, Continuous Maximum conditions. Based on the methods used for Appendix X development, the boundary between Appendix C and Appendix X is Continuous Maximum icing conditions with maximum drop sizes below approximately 100µm. Use of only stratiform cloud data is considered acceptable since stratiform clouds predominate during prolonged freezing precipitation conditions. See FAA Technical Center report DOT/FAA/AR-04/7, dated xx/xx/xx for more information on the development of Appendix X.

The water content versus drop size relationships defined in 14 CFR 25, Appendix C figures 1 and 4 are defined in terms of Mean Effective Drop diameter. By definition, this acknowledges the distributed nature of droplet sizes around a volume median value of assumed drop size distribution. However, Part 25 does not require specific distributions that must be considered for Appendix C icing conditions. As referenced in DOT/FAA/CT-88/8-1 "Aircraft Icing Handbook" and AC20-73A, single mode distributions such as Langmuir distributions have been used to represent the range of drop sizes and associated fractional water contents in a specific Appendix C icing condition.

The distributions assumed for Appendix C icing conditions are inappropriate for freezing precipitation icing conditions since these icing conditions often consist of small and large drops that are bi-modally distributed. Langmuir type distributions cannot capture the bi-modal characteristic. Consequently, the distributions of drop sizes are defined as part of Appendix X. The need to include the distributions comes from the larger amount of mass in the larger drop diameters of Appendix X. The water mass of the larger drops affects the water catch on airplane components, the drop impingement, icing limits, and the ice buildup shape. Ice accretions resulting from the water catch must be considered relative to their effects on safe flight of the airplane.

The distribution of freezing precipitation drop diameters varies greatly. Subdividing freezing drizzle and freezing rain allowed selection of four average drop diameter distributions that are representative of the total range of measured drop distributions. These four distributions are shown as cumulative mass distributions in Appendix X.

Also, the maximum values of freezing drizzle and freezing rain liquid water content decrease with decreasing temperature as defined in Appendix X, figures 1 and 4, respectively. Following the same standard as Appendix C, the values of total liquid water are selected at the standard icing condition horizontal extent of 17.4 nautical miles (20 statute miles).

The maximum vertical extent of 12,000 feet for freezing drizzle includes the cloud layer and any drizzle precipitation below the cloud. The maximum altitude of freezing drizzle is the same as that of an Appendix C continuous maximum icing cloud, 22,000 feet (Appendix X, figure 3). The temperatures are as cold as -13° F (-25°C).

The maximum vertical extent of freezing rain is 7,000 feet. The maximum altitude of freezing rain is 12,000 ft. The temperatures are as cold as 8.6° F (-13°C).

The United States Standard Atmosphere temperature lapse rate with altitude is not appropriate for freezing drizzle and freezing rain. Typically, freezing rain is associated with temperature inversions and freezing drizzle is associated with other deviations from the standard lapse rate. In generating ice shapes for vertical transits through freezing drizzle and freezing rain, the critical temperature should be determined and used for the duration of the vertical exposure.

The liquid water contents of continuous freezing drizzle and freezing rain conditions decrease with increasing horizontal extents. Horizontal extents of exposures in FZDZ and FZRA can be anywhere from a brief encounter to an extended encounter. The use of the Appendix X f-factor is the same as for the Appendix C f-factor, which is discussed in Appendix N of AC 20-73A.

b. Use of Icing Envelopes. The use of Appendix C is addressed in AC 20-73A and is unchanged by the addition of Appendix X. Appendix X is designed to be similar to Appendix C and is used in much the same manner. The principal differences between the use of Appendix X relative to Appendix

C are the need to consider four icing conditions rather than two when determining critical icing conditions and the need to address drop size distributions (DSD).

Applications of DSDs typically require a bin tabulation of the proportion of mass (liquid water content) relative to drop diameter. Tables 1 and 2 represent 10-bin tabulations for the cumulative distributions in Appendix X. The mass proportions for the bins were selected to provide reasonable resolution of the upper range of the distributions. The shaded columns (a) and (b) in the tables contain the values that typically would be input to ice accretion computer codes. For some simulation techniques, different methods of segregating the bins may be appropriate. Different methods should consider the impingement characteristics of the geometry relative to drop size.

Table 1. FZDZ distributions represented using 10 bins.

		FZDZ/L (MVD < 40 µm)			FZDZ/G (MVD > 40 µm)		
	(a)		(b)			(b)	
Bin	Proportion of Mass	Left Boundary Point (µm)	Mass-weighted Midpoint (µm)	Right Boundary Point (µm)	Left Boundary Point (µm)	Mass-weighted Midpoint (µm)	Right Boundary Point (µm)
1	0.100	1	9	10	1	11	15
2	0.200	10	13	16	15	22	36
3	0.200	16	18	20	36	64	106
4	0.200	20	23	27	106	150	197
5	0.100	27	29	33	197	221	247
6	0.050	33	36	40	247	261	276
7	0.050	40	48	66	276	292	309
8	0.050	66	97	137	309	330	354
9	0.025	137	163	202	354	370	390
10	0.025	202	252	388	390	417	473

Note: DSDs in one-micrometer-drop bin resolution are available in electronic files from the William J. Hughes Technical Center.

Table 2. FZRA distributions represented using 10 bins.

		FZRA/L (MVD < 40 μm)			FZRA/G (MVD > 40 μm)		
	(a)		(b)			(b)	
Bin	Proportion of Mass	Left Boundary Point (μm)	Mass-weighted Midpoint (μm)	Right Boundary Point (μm)	Left Boundary Point (μm)	Mass-weighted Midpoint (μm)	Right Boundary Point (μm)
1	0.100	1	7	8	1	9	14
2	0.200	8	10	12	14	35	236
3	0.200	12	15	19	236	399	526
4	0.200	19	25	53	526	645	765
5	0.100	53	255	468	765	833	912
6	0.050	468	534	595	912	957	1008
7	0.050	595	655	718	1008	1066	1129
8	0.050	718	792	883	1129	1197	1288
9	0.025	883	942	1034	1288	1345	1420
10	0.025	1034	1191	1553	1420	1545	2228

Note: DSDs in one-micrometer-drop bin resolution are available in electronic files from the William J. Hughes Technical Center.

c. Effects of Appendix X icing conditions. One of the significant effects of Appendix X icing conditions on aircraft icing physics is the inertia effect of droplet size. When compared with the Langmuir distributions associated with Appendix C cloud drop sizes, the Appendix X drop size distributions have a larger percentage of the total water mass in large drop sizes. The mass of the larger drop sizes has sufficient inertia to overcome the local airflow effect and tend towards straight-line trajectories. The collection efficiency and the impingement limits are both influenced by the inertia between the aircraft flow field and supercooled water droplets as well as the splashing and breakup of the larger drops. In general, smaller drop sizes tend to follow the local streamlines of air as they flow around the airframe. Also, behavior of the water drops are influenced by the scale of the object being considered. Increasing the scale of the object increases the disturbance in flow ahead of the object, which in turn increases the ability of the airflow disturbance to influence the trajectory of the supercooled water droplets (Both Appendix C and Appendix X). This results in decreasing collection efficiency with increases in scale.

The Appendix X icing conditions contain larger drop sizes, have a greater percentage of total liquid water content in the larger drops, and different liquid water contents than the icing conditions of Appendix C. These differences may affect the water collection efficiency and result in impingement limits that are further aft than those determined for Appendix C icing conditions. For more discussion of the effects of droplet size and trajectory influence, see FAA Technical Report DOT/FAA/CT-88/8-1, and AC 20-73A.

An additional effect of the supercooled large drop environment is the variability in the distribution of drop sizes. Ice shapes developed from Appendix C icing conditions sometimes assume uniform drop size distributions with all drops diameters at the MVD (mono-dispersed) because the predicted main ice shapes are not highly sensitive to commonly assumed distributions (such as Langmuir distributions). However, the large variations of drop sizes and the larger percentage of total water contained in the larger drops within Appendix X tends to magnify the effects of distributed drop sizes. The distribution of water drops, or more directly, the percentage of water content contained within certain drop sizes, can affect shapes and runback ice characteristics.

d. Primary Areas of Interest for Appendix X. The primary areas of interest specific to supercooled large droplet conditions include:

(1) Ice shapes on protected areas of lifting surfaces. Appendix X icing conditions may result in a ridge of ice or ice roughness aft of the protected areas.. On aircraft with reversible flight controls, a ridge of ice may result in uncommanded deflections of the control surfaces, which may result in an aircraft upset. Aircraft, independent of the flight control system, may also incur reduced maximum lift and reach the reduced maximum lift at lower angles of attack. Without adjustments to the stall protection system activation schedules, the Appendix X ice buildups can also result in an aircraft upset or stall.

(2) Ice shapes on unprotected areas of lifting surfaces. Ice shapes resulting from Appendix X icing conditions can be more extensive than those from Appendix C icing conditions. When portions of the airfoil leading edge are unprotected, there is potential to affect the performance and handling qualities.

(3) Ice shapes on unprotected airframe regions. Areas of the airframe, which do not accrete ice under Appendix C conditions, should be examined relative to the increased impingement or accretion areas in and potentially larger ice shapes. Issues such as windshield visibility, air data sensor locations, and potential airflow disturbance (for example on airplane nose) from Appendix X accretions that could influence the performance of the air data sensors should be evaluated.

(4) Drag and Power effects. Aircraft may exhibit reduced performance in supercooled large drop conditions due to increased drag and reduced lift due to ice accretions. These accretions may extend further aft on protected areas, extend beyond the protected areas, or occur in areas not typically protected (e.g. extended accretions on fuselage and lower surface of the wing). The ice accretions may be rough and cause large local drag increases. Additionally, thrust effects such those due to bleed penalties from system operations or

degradation of thrust from powerplant losses (e.g. propeller icing) should be addressed. See AC 25.21-1 for more information regarding the evaluation of potential effects on airplane performance.

(5) Engine Considerations. Airframe and air induction system components ice accumulations resulting from Appendix X icing conditions should be evaluated for potential ingestion of the ice by the engine (relative to the requirements of §§ 33.68 and 33.77) and potential blockage effects.

4. CERTIFICATION PLAN. At the start of the design and development effort, the applicant should submit a certification plan to the cognizant FAA Aircraft Certification Office (ACO) for approval. The certification plan should include the following basic information:

a. A general airplane description that includes dimensions, airworthiness limitations, and other data that may be relevant to certification of IPS.

b. IPS description.

c. A compliance checklist that addresses each section of part 25 applicable to the product.

d. Identification of the certification methods for each applicable section of part 25, including a description of analyses and tests, or references to similarity of designs, that the applicant intends for certification of the IPS. These methods of showing compliance should be agreed upon between the applicant and the FAA early in the certification program prior to conducting certification tests.

e. A failure hazard assessment to determine the criticality of the system.

f. If the ice protection or detection systems contain software, software plans, as described in RTCA DO-178B (or another acceptable means of compliance for software).

g. Projected schedules of design, analyses, testing, and reporting.

h. A list of any anomalous 14 CFR part 33 icing certification test results (relative to the requirements of §§ 33.68 and 33.77), if completed, that will require special operating procedures.

i. If the IPS or detection systems contain complex electronic hardware (such as programmable logic devices (PLD) or application specific integrated circuits (ASIC)), plans for providing a level of design assurance of these devices commensurate with their potential contribution to aircraft hazards and system failures, which could result from electronic hardware faults or malfunctions.

5. <u>ANALYSES</u>. The applicant should prepare analyses to substantiate decisions involving the application of selected ice protection equipment. Such analyses should clearly state the basic protection required and the assumptions made, and delineate the methods of analysis used. All analyses should be validated by tests or should have been validated by the applicant on a previous program. To utilize a previously validated methodology, the applicant should substantiate that the methodology is applicable to the new program.

Analytical simulation methods include impingement and accretion models based on computational fluid dynamics. These methods are typically used to evaluate unprotected and protected areas to determine the potential ice accretions. Analytical simulation provides a method of accounting for the variability in droplet distributions. In addition, analytical simulation provides the capability to examine impingement relative to visual icing cues and analyze the location of detection devices for detrimental local flow effects. Thermal characteristics of IPSs relative to icing conditions may also be evaluated using computational simulation.

During the substantiation process of icing simulation tools, cross comparisons should be made with natural icing flight test data, tanker test data, icing tunnel data and analytical codes to show that simulating supercooled large droplets results in equivalent or conservative results. The results of icing tunnel tests, tanker tests and codes should be compared to the results of natural icing flight tests in Appendix C conditions that are required in § 25.1419. Engineering judgment is required in evaluating the results of these comparisons, as most simulation tools are steady-state simulations that are being contrasted with variable natural icing conditions. See AC 20-73A for additional guidance relative to substantiation of the icing simulation tools. The guidance in this paragraph applies to airframe, engines, and propeller icing tools.

a. <u>Analysis of Areas and Components to be Protected</u>. The applicant should examine those areas listed below in evaluating the ability of the aircraft to safely operate in the icing conditions defined in Appendix C and the relevant icing conditions of Appendix X and in determining which components will be protected. An applicant may determine that protection is not required for one or more of these areas or components. If so, the applicant should include supporting data and rationale in the analyses for allowing those areas or components to be unprotected. The applicant should show that the lack of protection does not adversely affect the handling characteristics or performance of the airplane, as required by § 25.21(g), nor the operation and functioning of affected systems and equipment (e.g. pitot probes).

(1) Leading edges of wings, winglets, and wing struts; horizontal and vertical stabilizer; canards; and other lifting surfaces.

(2) Leading edges of control surface balance areas, if not shielded.

(3) Accessory cooling air intakes that face the airstream and/or could otherwise become restricted due to ice accretion. Inlets (including NACA inlets) that are in shadow zones for Appendix C, may accrete ice in the Appendix X conditions.

(4) Antennas and masts.

(5) External tanks.

(6) External hinges, tracks, door handles, and entry steps.

(7) Instruments including pitot tube (and mast), static and dynamic ports, angle-of-attack sensor, and stall warning.

(8) Forward fuselage nose cone and radome.

(9) Windshields and cockpit side windows.

(10) Landing gear.

(11) Retractable forward landing lights.

(12) Ram air turbines.

(13) Ice detection lights, if required for compliance with § 25.1403.

(14) Vortex generators installed on lifting surfaces and the fuselage, and stall improvement devices such as strips, vortilons, and fences.

(15) Any structure that extends into the free stream such as cameras, camera mounts, and video equipment.

Note 1: Ice protection of fuel tank vents, propellers, and engine inlet cowls is addressed by part 25, subpart E – Powerplant.

b. Flutter Analysis. Advisory Circular (AC) 25.629-1A, “Flutter Substantiation of Transport Category Airplanes,” provides guidance for showing compliance with § 25.629. The flutter analyses should reflect any mass accumulations on unprotected and protected surfaces from exposure to Appendices C and, as appropriate, X icing conditions, including any accretions that could develop on control surfaces. Section 25.629(d)(3) requires the consideration of inadvertent encounters with icing for airplanes not certificated for flight in icing conditions.

c. Power Sources. The applicant should evaluate the power sources in the IPS design (e.g., electrical, bleed air, and pneumatic sources). An electrical load analysis or test should be conducted on each power source to determine that it is adequate to supply the IPS plus all other essential electrical loads throughout the airplane flight envelope under conditions requiring operation of the IPS. The effect of an IPS component failure on power availability to other essential loads should be evaluated in accordance with § 25.1309. All power sources that affect engine or engine IPSs for multiengine airplanes must comply with the engine isolation requirements of § 25.903(b).

d. Failure Analyses.

(1) Failure Analysis for § 25.1419 (Appendix C Conditions). Advisory Circular (AC) 25.1309-1A, “System Design Analysis,” provides guidance for demonstrating compliance with the requirements of § 25.1309. Substantiation of the hazard classification of IPS failure conditions is typically accomplished through analyses and/or testing. The failure analysis should include the potential contribution of complex electronic hardware faults and malfunctions to system failure conditions, and classify the hardware assurance level appropriately, see RTCA/DO-254, "Design Assurance Guidance for Airborne Electronic Hardware." The probability of encountering Appendix C icing is considered one for quantitative analysis.

(2) Failure analysis for § 25.1420 (Appendix X Conditions). The application of the system safety principles of § 25.1309 is helpful in determining the necessity of any system requirements to address potential hazards due to the Appendix X environment. The following information provides guidance relative to the application of these principles to the Appendix X conditions. In showing compliance to § 25.1309, the following may be used:

(a) Hazard classification. The process of assessing a hazard classification in showing compliance to § 25.1309 is typically a combination of quantitative and qualitative factors. Assessing the severity of the hazard of an unannunciated encounter with Appendix X conditions for a new aircraft model design is no different. If the design is new and novel and has little similarity to previous designs, a hazard classification based on past experiences may not be appropriate. However, if the new design is derivative in nature, the assessment can consider the specific icing event history of similarly designed aircraft, as well as the icing event history of all conventional design aircraft. When assessing the similarity to previous designs, the specific effects of supercooled large droplet icing should be considered (see paragraph 3.c, “Effects of Appendix X Icing Conditions”).

The following is a qualitative analysis that may be used for determining the hazard classification associated with an unannunciated encounter with Appendix X icing conditions for aircraft that are shown to be similar to previous designs with respect to Appendix X icing effects:

In accordance with the principles of § 25.1309, service history, design and installation appraisals may be used in support of hazard classifications. If a new or derivative aircraft has similar design features to a previously certificated airplane, this service history may be appropriate to support the determination of the hazard classification.

While definitive statistics are not available, a historical perspective can provide some guidance. Many aircraft have been unknowingly exposed to supercooled large droplet conditions. The exposure interval can vary from a brief exposure (such as a vertical transition through a cloud) to a more sustained condition (such as a hold). The severity of the conditions in terms of water content can vary significantly. Therefore, not all encounters with supercooled large droplet conditions may result in a catastrophic event.

For aircraft that are not similar to a previous design, an assessment of the hazard classification may require more analysis or testing to assess the hazard. One method of assessing the hazard would be to consider the effects of ice accumulations similar to those expected for aircraft to be certified under the provisions of §25.1420. These ice shapes may be defined from a combination of analysis, tanker or icing wind tunnel testing. The aerodynamic effects of such shapes could be evaluated with wind tunnel testing or potentially, computational fluid dynamics. See AC 20-73A for additional guidance on assessing the aerodynamic effects of ice buildups. The hazard classification typically takes place early in a certification program. Therefore, a conservative assessment of the hazard may be required until sufficient supporting data is available to reduce the hazard classification.

(b) Probability of Encountering Appendix X. The appendix C conditions were determined on the 99 percentile probability of exceeding the icing conditions (Ref: NACA TN 2738, “A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States”). In other words, the probability of encountering icing outside of Appendix C droplet conditions is on the order of 10^{-2}. Climatology studies for North America indicate that the annual average frequency of occurrence of SLD range from 0.4% to 5% of the time in a 100 km radius column over various stations. Determining the actual occurrence of SLD in the atmosphere is difficult using the data sets available. It is recognized that there are large geographical differences and changes with seasons that influence the probability of SLD occurrence. However, to a first approximation, the probability of occurrence of SLD for any particular location in North America, representing the altitude ranges between 0 and 15,000 ft, which airplanes normally encounter upon takeoff and landing, is typically 1 to 5 percent over a winter season for a large portion of the continent. For operations above 15,000 ft, the occurrence of SLD during the winter is less frequent. These numbers do not account for the full probability of an aircraft encountering supercooled large drops within the 100 km radius of the column. Based on this information, on an annual basis the average probability of 1 x 10^{-2} per flight hour may be assumed for encountering appendix X conditions within a quantitative analysis. The probability should not be reduced based on phase of flight.

(c) Numerical safety analysis. For the purposes of a numerical safety analysis, the applicant may combine the probability of equipment failure with the probability, defined above, of encountering appendix X icing conditions. Therefore, if the applicant can support a hazard level of “hazardous” and considering the above probability of encountering the specified supercooled large droplet conditions (10^{-2}), it follows that the probability of an unannunciated equipment failure should be less than 1 x 10^{-5}.

(d) Assessment of visual cues. Typical system safety analyses do not address the probability of crew actions such as observation of a visual cue prior to performing a specified action. As advised in AC 25.1309-1A, quantitative assessments of crew errors are not considered feasible. When visual cues are the method of detecting Appendix X conditions to determine when to exit, an assessment of the appropriateness and reasonableness of the specific cues should be performed (see paragraph 8.b.(2).(b) of this AC for additional guidance). Reasonable tasks are those for which full credit can be taken because they can realistically be anticipated to be performed correctly when they are required. The task of visually detecting Appendix X conditions should be assessed to determine if it could be performed when required. In part, this is coincident with the substantiation of the specific cues as described in paragraph 13.f. The workload of the visual detection method should be considered in combination with the operational workload during applicable phases of flight. It may be assumed that the flight crew is already aware that the aircraft has encountered icing and the assessment of appropriateness and reasonableness of the task is limited to identifying Appendix X accumulations that require exiting from icing conditions.

e. Similarity Analyses.

(1) In the case of certification based on similarities to other type certificated airplanes previously approved for flight in icing conditions, the applicant should specify the airplane model and the component to which the reference applies. Specific similarities should be shown in the areas of physical, functional, thermodynamic, pneumatic, aerodynamic, and environmental exposure. Analyses should be conducted to show that the component installation, operation, and the effect on the airplane’s performance and handling are equivalent to that of the previously approved configuration.

(2) Similarity requires an evaluation of both the system and installation differences. The differences should be evaluated for their effect on the functionality of the IPS and on safe flight in icing. If there is uncertainty about the effects of the differences, additional tests and/or analyses should be conducted as necessary and appropriate to resolve the open issues.

(3) Section 14 CFR 25.1419(b) requires flight testing in measured natural icing conditions. However, flight test data from previous certification programs may be used to show compliance with 14 CFR 25.1419(b) if it can be shown that the data is applicable to the airplane in question. If there is uncertainty about the similarity analysis, the manufacturer should conduct flight tests in measured natural icing conditions for compliance with § 25.1419(b).

(4) On derivative airplane designs, similarity to previous type designs that have shown compliance to § 25.1420 can be used as a method of compliance if the effects of differences are substantiated. Natural ice flight-testing may not be required for design shown to be similar. As a minimum, the following differences should be addressed:

1. Airfoil size, shape, and angle of attack
2. IPS design
3. Operating altitude, airspeed
4. Center of gravity
5. Flight control system
6. Engine and propeller operation

Note: The applicant must possess all the data to substantiate compliance with applicable regulations, including the data from past certifications upon which the similarity analysis is based.

f. Impingement Limit Analyses. The applicant should prepare a droplet trajectory and impingement analysis of the wing, horizontal and vertical stabilizers, propellers, and any other critical surfaces upon which ice may accrete. This analysis should consider the various airplane operational configurations, phases of flight, and the associated angles of attack. The analysis should establish the upper and lower aft droplet impingement limits that can then be used to establish the aft ice formation limit and the relationship to the IPS coverage.

g. Ice Shedding Analyses. Airframe ice shedding may damage or erode engine or powerplant components as well as lifting, stabilizing, and flight control surface leading edges. Fan and compressor blades, impeller vanes, inlet screens and ducts, as well as propellers, are examples of powerplant components subject to damage from shedding ice. For fuselage-mounted turbojet engines (and pusher propellers that are very close to the fuselage and well aft of the airplane's nose), ice shedding from the forward fuselage and from the wings may cause significant damage. Ice shedding from components, including antennas, of the airplane should cause no damage to engines and propellers that would adversely affect engine operation or cause a serious loss of power or thrust (compliance to 14 CFR 25.1093). Consideration should also be given to airplane damage that can occur due to ice shedding from the propellers.

Control surfaces such as elevators, ailerons, flaps, and spoilers are also subject to damage, especially those constructed of thin metallic, nonmetallic, or composite materials. Currently available trajectory and impingement analyses may not adequately predict such damage. Unpredictable ice shedding paths from forward areas such as radomes and forward wings (canards) have been found to negate the results of these analyses. For this reason, a damage analysis should consider that the most critical ice shapes will shed and impact the areas of concern.

h. Propeller deicing analysis. A propeller deicing analysis should be accomplished. In addition to intercycle ice, the applicant should account for the effect of ice accretions aft of the protected leading edge on propeller efficiency and airplane performance.

i. Pitot Probe Ice Protection**.** Compliance to the TSO qualification standard for electrically heated pitot probes (TSO-C16) is not sufficient by itself in demonstrating compliance to the installation requirements of §§ 25.1309(a), 25.1323, 25.1326, 25.1419, and 25.1420. Section 25.1309(a) requires that the system must perform its intended function under any foreseeable operating condition. Sections 25.1419 and 25.1420 require that an airplane certificated for flight in icing must be able to safely operate in part 25 Appendix C and Appendix X icing conditions, respectively. It is unlikely that the conditions of Appendices C or X that are critical to the air data system equipment will be encountered during flight tests. Consequently, certification programs should supplement the icing flight tests with icing tunnel test and/or tanker test data, as necessary. In-service experience during severe atmospheric conditions has shown that pitot tubes qualified to the older standards have resulted in airspeed fluctuations and even loss of indicated airspeed. As these components must perform their intended function under any foreseeable operating condition, they should be qualified to the Continuous and Intermittent maximum icing conditions defined in FAR 25, Appendix C, and to Appendix X icing conditions.

(1) TSO C16, Air-speed tubes (electrically heated), requires compliance to the performance specifications of SAE Aerospace Standard AS393. SAE AS393A includes a test to demonstrate deicing and anti-icing capability, but only temperature and airspeed are specified. Liquid water content is not specified but it influences heat requirements. Although functioning of pitot probes are evaluated in natural icing conditions during certification test programs, there is no

requirement to flight test at the Appendix C or X icing limits because the low probability of finding those conditions imposes a burden. The airframe manufacturer is responsible for showing the pitot heat is adequate for the Appendix C and Appendix X icing conditions. If not obtained in flight test, analysis or icing tunnel test data should be submitted.

(2) Although Appendices C and X of part 25 only consider the liquid water content of icing conditions, recent cloud characterization research has indicated that approximately 40 percent of icing condition events consist of liquid water drops and ice crystals (mixed-phase icing conditions). Also, glaciated atmospheric conditions are encountered during aircraft operations. The ice crystal environment may be more critical than liquid water for thermal systems since more energy is required to evaporate the ice crystals. Recently, some aircraft manufacturers and foreign certification authorities have required pitot and pitot-static probes to be tested in ice crystal and mixed-phase icing conditions along with supercooled liquid water conditions. As a result, some pitot tube manufacturers now use the icing environment of British Specification (BS) 2G.135, “Specification for Electrically-Heated Pitot and Pitot-Static Pressure Heads,” in addition to the requirements of TSO. Even though the part 25 regulations only address liquid water, it is good design practice to ensure the pitot heat is sufficient for the ice crystal and mixed-phase conditions of BS 2G.135.

j. Stall Warning System Ice Protection. Compliance to the TSO qualification standard for stall warning instruments (TSO-C54) is not sufficient by itself in demonstrating compliance to the installation requirements of §§ 25.1309(a), 25.1419, and 25.1420.

(1) TSO-C54, “Stall Warning Instruments”, requires compliance to the performance specifications of SAE Aerospace Standard AS403A with some exceptions and additions. As in AS393A, the requirements include a test to demonstrate deicing and anti-icing capability, but only temperature and airspeed are specified. The precipitation test conditions of AS-403A include moderate icing conditions for Type II instruments. However, "moderate" is not defined. The same comments from 5.i.(1) apply. The airframe manufacturer is responsible for showing the stall warning heat is adequate for Appendix C and the applicable X icing conditions.

(2) The same comments from 5.i.(2) apply.

k. Runback Ice. Water not evaporated by thermal ice protection systems and unfrozen water during near-freezing conditions (or when the freezing fraction is less than one) may run aft and form runback ice. The resulting runback ice can capture additional mass through direct impingement. Computer codes may be unable to estimate the characteristics (rivulets or thin layers) of the runback water or the resultant ice shapes; however, some codes may be able to estimate the mass of the runback ice. Therefore, runback ice should be determined experimentally. Runback ice should be considered when determining critical ice shapes. Simulated runback ice shapes may be used when evaluating the effects of critical ice shapes. Consideration should be given to potential hazards resulting from the shedding of runback ice.

6. SIMULATED ICE SHAPES and ROUGHNESS AC 25.21-1 contains guidance on the icing exposure during various phases of flight that should be considered when determining simulated ice shapes and surface roughness. The shape and surface roughness of the ice shapes should be developed and substantiated using acceptable methods. Common practices include: use of computer codes for droplet impingement limits and ice shape predictions (see SAE ARP5903), flight in measured natural icing conditions, icing wind tunnel tests (see SAE ARP5905), and flight in a measured controlled simulated icing cloud (e.g., behind an icing tanker, see SAE ARP5904).

a. During holding conditions it should be assumed that the airplane will remain in a rectangular “race track” pattern, with all turns being made within the 17.4 nautical mile icing cloud. Therefore, no horizontal extent correction should be used for this analysis.

b. The applicant should substantiate the drop diameter distribution (mean effective, median volume, spectra), LWC, and temperature that result in the formation of an ice shape that is critical to the airplane’s performance and handling qualities.

c. The ice roughness should be based on icing tunnel, natural icing, or tanker testing.

d. See AC 20-73A for more information on ice shapes.

7. COMPLIANCE TESTS (Flight/Simulation) . The following paragraphs address the major methods normally used to show compliance with the requirements of §§ 25.1419 and 25.1420. These requirements state that the airplane must be able to safely operate in the continuous maximum and intermittent maximum icing conditions described in Appendix C and the appropriate icing conditions described in Appendix X of part 25. The airplane should be shown to comply with the certification requirements when all IPSs are installed and functioning. This can normally be accomplished by performing tests

at those conditions found to be most critical to basic airplane aerodynamics, IPS design, and powerplant functions. All IPS equipment should perform its intended function throughout the entire operating envelope.

The primary purposes of flight testing are to determine that the IPS is acceptably effective and performs its intended functions during flight as predicted by analysis or ground testing and to evaluate any degradation in performance and flying qualities. Performance and handling qualities requirements are identified in § 25.21(g). Flight tests to show compliance with these requirements are addressed in AC 25.21-1. Flight testing also verifies the adequacy of the flightcrew procedures and limitations for the use of the IPS in normal, abnormal, and emergency conditions.

Flight testing is also used to confirm that the powerplant installation as a whole (engine, inlet, anti-ice system, etc.) performs satisfactorily while in icing conditions. In addition, the APU should be evaluated for performance in icing conditions if it performs essential functions. In accordance with part 33, engine icing certification results should also be carefully reviewed prior to any part 25 engine or airframe icing flight tests in order to determine if there were any anomalous results that will require special airplane/engine operating procedures.

Both 14 CFR §§ 25.1419 and 25.1420 require the use of one or more methods of compliance. It is common to use a combination of methods to adequately represent the conditions and determine the degradation effects with sufficient confidence to show compliance.

a. Dry Air Ground Tests. Depending upon the details of the IPS design, some preliminary ground tests of the equipment may be warranted to verify the basic function of each item. Quantitative data may be obtained, as necessary, to verify the system designs. These data include operating temperatures of thermal devices, deicing fluid flow rates and flow patterns for deicing liquid devices, and operating pressures and rates of inflation of pneumatic components.

b. Dry Air Flight Tests with Ice Protection Equipment Operating. Initial dry air flight tests are usually the first flight tests conducted to evaluate the airplane with the IPS operating. The initial dry air tests are conducted to verify that the IPS does not affect the flying qualities of the airplane in clear air and to obtain a thermal profile of an operating thermal IPS. Several commonly used IPSs and components are discussed below to illustrate typical dry air flight test practices. Other types of equipment should be evaluated as their specific design dictates.

(1) Thermal Ice Protection Leading Edge Systems. Dry air flight tests are conducted to verify the system design parameters and thermal performance analyses.

(a) Normally, the system components are instrumented to measure the anti-icing mass flow rate or energy input (for electrical systems), supply air temperature, and the surface temperatures. The dry air test plan generally includes the airplane operating conditions such as climb, holding, and descent phases of a normal flight profile. Since the presence of moisture can affect the surface temperatures, the tests should be conducted where no visible moisture is present.

(b) The measurements of supply air mass flow rate, energy input and air temperature allow the determination of heat available to the system. The adequacy of the IPS then can be demonstrated through a comparison of the measured data to the theoretical analysis over Appendix C and either Appendix X or the portion of Appendix X proposed for compliance with § 25.1420(a)(2). The surface temperatures measured in the dry air, for example, can be useful in extrapolating the maximum possible leading edge surface temperature in-flight, the heat transfer characteristics of the system, and the thermal energy available for the IPS. The supply air temperatures or energy input also may be used to verify that the materials of the IPS were appropriately chosen for the thermal environment.

(2) Pneumatic Leading Edge Boots. Tests should demonstrate a rise and decrease in operating pressures, which results in the effective removal of ice. This pressure rise time, as well as the maximum operating pressure for each boot, should be evaluated throughout the altitude range defined in Appendix C and X. Boots should be operated in flight at the minimum envelope temperature (-22 ^{o}F) of Appendix C Continuous Maximum and Appendix X, to demonstrate adequate performance throughout the entire flight envelope and to demonstrate that no damage occurs during inflation and deflation. The appropriate speed and temperature limitation (if any) on boot activation should be included in the AFM. The inflation of the boots should have no significant effect on airplane performance and handling qualities.

(3) Electrically Heated Propeller Boots. For compliance with the provisions of §§ 25.901(c), 25.903(b), 25.929, and 25.1419(c):

(a) When flight testing in dry air, the following system parameters should be monitored to confirm proper function. It is suggested that system current, brush block voltage (i.e., between each input brush and the ground brush) and system duty-cycles be monitored to ensure that adequate power is applied to the deicers. Surface temperature measurements should be made during dry air tests. These surface temperature measurements are useful for correlating analytically predicted dry air temperatures with actual temperatures, and as a general indicator that the system is functioning and that each deicer is heating.

(b) The system operation should be checked throughout the full r.p.m. and propeller cyclic pitch range expected during flight in icing. Any significant vibrations should be investigated.

(c) Consideration should be given to the maximum temperatures to which a composite propeller blade may be subjected when the deicers are energized. It may be useful to monitor deicer bond-side temperatures. When performing this evaluation, the most critical conditions should be investigated (e.g., airplane on the ground; propellers non-rotating) on a hot day with the system inadvertently energized.

(4) Windshield Anti-Ice. Section 25.773(b)(1)(ii) requires that the airplane must have a means to maintain a clear portion of the windshield in icing conditions specified in §§ 25.1419 and 25.1420. Dry air flight tests should be conducted to verify the thermal analysis. Both inner and outer windshield surface temperature measurements of the protected area may be needed to verify the thermal analysis. Thermal analysis should substantiate that the windshield surface temperature is sufficient to maintain anti-icing capability without causing structural damage to the windshield. An evaluation of the visibility, including distortion effects through the protected area, should be made for both day and night operations. In addition, the size and location of the protected area should be reviewed for adequate visibility, especially during the approach and landing phases of flight.

(5) Pitot-Static and Static Pressure Sources. Section 25.1323(e) requires a heated pitot tube or an equivalent means of preventing malfunction due to icing for each airspeed indicating system. Section 25.1325(b) requires that static pressure ports be designed and located such that the correlation between air pressure in the static pressure system and true ambient atmospheric static pressure is not affected when the airplane encounters icing conditions defined in Appendices C and Appendix X. Section 25.1326 requires an indication system be provided to indicate to the flightcrew when a pitot heating system is not operating. An acceptable indication system may consist of separate lights or crew alert indication on an electronic display for each pitot source. Additional guidance on an acceptable means of compliance with § 25.1326 is provided in AC 25-11. Surface temperature measurements are

typically made for air-data instruments, such as pitot tubes, pitot-static pressure probes, and angle-of-attack probes (if ice protected), during icing wind tunnel tests to verify thermal analyses. The acceptability of the installed air data instrument ice protection should be evaluated during natural or artificial icing tests.

(6) Bleed Air Systems. The effects of any bleed air extraction on engine and airplane performance should be examined and included in the AFM performance data. The surface heat distribution analysis should be verified for varying flight conditions including climb, cruise, hold, and descent. Temperature measurements may be necessary to verify the thermal analyses. In accordance with the provisions of § 25.939(a), the effects of the maximum bleed air for ice protection should have no detrimental effect on engine operation throughout the engine's power range.

c. Dry air flight tests with predicted simulated ice shapes and roughness. The primary function of dry air flight tests with simulated ice shapes is to demonstrate the ability of the airplane to operate safely with critical ice shapes determined in Appendix C and appropriate Appendix X icing conditions. Scale effects and scaled roughness effects should be substantiated using acceptable methods. The specific flight tests used to evaluate airplane performance and handling qualities are addressed in AC 25.21-1. In addition, the effects due to ice accretion on locations forward of pitot-static sensors, angle of attack sensors, and static pressure ports should be assessed.

For failure conditions of the IPS that are not extremely improbable, validation testing may be required (e.g. flight tests, flight simulator, wind tunnel test, validated CFD) to demonstrate that the effect on safety of flight (as measured by degradation in flight characteristics) is commensurate with the failure probability. Dry air flight tests with predicted critical failed IPS ice shapes, which may include asymmetric ice shapes, may be used to demonstrate acceptable operational safety.

d. Icing Flight Tests. Flight tests in measured natural icing and the use of artificial icing tools, such as icing tankers, are normally employed to demonstrate that the IPS performs during flight as predicted by analysis or other testing. They are also used to confirm analyses used in developing the various components (e.g., ice detectors) and ice shapes. In the case of natural icing, testing should be accomplished within the icing conditions of part 25, Appendix C and, if necessary, Appendix X, to corroborate the general nature of the effects on airplane handling characteristics and performance determined with simulated ice shapes (see AC 25.21-1), as well as to qualitatively assess the analytically predicted location and general physical characteristics of the ice accretions. If necessary, there should be a means to measure and record ice accumulations and impingement limits. They can be approximated by various means, e.g., a rod mounted on the airfoil and black paint on the airfoil.

(1) Instrumentation. Sufficient instrumentation should be planned to allow documentation of important airplane, system and component parameters, and icing conditions encountered. The following parameters should be considered:

(a) Altitude

(b) Airspeed

(c) Engine power level or speed

(d) Propeller speed and pitch if applicable

(e) Temperatures that could be affected by ice protection equipment or ice accumulation or that are necessary for validation of analyses, such as:

1. Static air

2. Engine component

3. Electrical generation equipment

4. Surface

5. Structure integrity

(f) Liquid water content. The liquid water content should be measured over the complete water drop size distribution.

(g) Median volume drop diameter and drop diameter spectra. When measurement of the icing environment drop diameter is necessary, instrumentation used for measuring drop sizes should be appropriate for the Appendix C and Appendix X icing conditions. For aircraft to be certified to a portion or all of Appendix X, measurement and recording of drop diameter spectra should be accomplished.

Microscopic measurement of drop impact craters on a gelatin oil or soot slide exposed to an icing cloud may be an impractical method for measuring a median volume drop diameter because of the splashing and bouncing characteristics of large drops. Also, use of gelatin oil or soot slides is impractical for recording the drop diameter spectra of Appendix X type clouds. Median volume diameters and drop diameter distributions are more practically obtained using more sophisticated equipment, such as laser-based drop measuring and recording instruments, or their equivalent. Depending on the drop size measurement capability of the instruments, more than one instrument may be required to measure the expected range of drop diameters. Large drop instrumentation on the test aircraft may not be required if testing is performed with a calibrated icing tanker. Some icing conditions may contain mixed-phase icing (liquid plus ice). The instrumentation should provide the capability to be able to distinguish between liquid drops and ice crystals. The equipment should be calibrated and properly maintained to obtain quality data.

(2) Artificial Icing. Flight testing in artificial icing environments, i.e., behind icing tankers, represents one way to predict ice protection capabilities of individual elements of the ice protection equipment and determine local ice shapes. Due to limited cross-sectional area of the plume, testing is usually limited to components such as, heated pitot tubes, antennas, air inlets including engine induction air inlets, empennage, airfoil sections, and windshields. Calibration and verification of the icing cloud produced by the icing tanker should be accomplished as necessary to meet the test objectives. SAE ARP5904 provides recommended practices for using tanker icing simulations.

The use of an icing tanker can provide high confidence in local icing effects. However, it may be difficult to obtain small drop sizes with some spray nozzles. Therefore, these methods could produce larger ice build-ups and different ice shapes than those observed in natural icing conditions within the icing envelope of part 25, Appendix C. This technique can be used in a similar manner to the icing tunnel testing with respect to ice shape development. The plume may be of sufficient size that it could be applied to sections of the airframe to examine any potential hinge moment or C_{Lmax} effects due to ice accretions behind protected areas for Appendix C or Appendix X icing conditions. This method also has the advantage of being able to combine the effects of thermal systems (such as runback) with direct accretion to simulate the resulting ice accumulations. Tanker simulation could also be used to estimate accretion areas that could be used in drag estimates from extended accretion regions (such as ice accretions extending beyond a radome) during exposures to Appendix X icing conditions. Atmospheric effects such as humidity and drop residence time (time required to bring the drop to static temperature) should be considered in this type of testing.

(3) Appendix C Natural Icing Flight Testing.

(a) Section 25.1419(b) requires measured natural icing flight tests. Flight tests in measured natural icing conditions are intended to verify the ice protection analysis, to check for icing anomalies, and to demonstrate that the IPS and its components function as intended. Advisory Circular 20-73A provides additional information that is useful for planning a natural icing flight test program. Sufficient exposures to icing conditions should be obtained to allow extrapolation to the envelope critical conditions by analysis. Test data obtained during these exposures may be used to validate the analytical methods used and the results of any preceding artificial icing tests.

(b) Past experience indicates that flight testing in natural intermittent maximum icing conditions may be accompanied by lightning strikes, severe turbulence and possible hail encounters that could extensively damage the test airplane. When design analyses show that the critical ice protection design points (i.e., heat loads, critical ice shapes, accumulation, and accumulation rates, etc.) are adequate under these conditions, and sufficient ground or flight test data exist to verify the analysis, the flight test in intermittent maximum icing conditions may not be necessary.

(c) Flight testing in natural icing conditions should also be used to verify AFM procedures for activation of the IPS, including recognition and delay times associated with IPS activation and verify the analytically predicted location and general physical characteristics of the ice accretions. Critical ice accumulations should be observed, where possible, and sufficient data taken to allow correlation with dry air testing. Remotely located cameras either on the test airplane or on a chase airplane have been used to document ice accumulations on areas that cannot be seen from the test airplane's flightdeck or cabin.

(d) For an airplane with a thermal deicing system as the IPS, the applicant should demonstrate the effectiveness of the deicing operation either in artificial icing conditions or during a natural icing flight test certification program. The tests usually encompass the measurements of the surface temperature time history. This time history includes the time the system is activated, the time the surface reaches an effective temperature, and the time the majority of ice is shed from the leading edge. The data should be recorded in the flight test report.

(4) Appendix X Natural Icing Flight Testing. Section 25.1420(a) requires that the airplane operate safely in the SLD icing conditions defined in Part 25, Appendix X.

(a) Unless shown by other means, such as discussed in paragraph 7.d.(4)(b), flight testing in measured natural Appendix X icing conditions may be necessary to:

1. Verify the general physical characteristics and location of the simulated ice shapes utilized for dry-air testing, and in particular, their effects on airplane handling characteristics.

2. Determine if ice accretes on areas not predicted to accrete ice;

3. Verify adequate performance of ice detectors or visual cues

4. Conduct the performance and handling quality tests as outlined in AC 25.21(g).

5. Evaluate the effects of ice accretion not normally evaluated with simulated ice shapes (propeller, antennas, spinners, etc.) and evaluate operation of any critical aircraft system or component after exposure to Appendix X conditions.

(b) Flight testing in natural Appendix X icing conditions should not be necessary if:

1. The design analyses show that the critical ice protection design points (i.e., heat loads, critical ice shapes for performance and handling qualities, accumulation, and accumulation rates, etc.) are adequate under the conditions of Appendix X and various airplane operational configurations; and

2. The analyses performed for item 1. are accomplished with methods that have been validated for Appendix X icing conditions by; i) at least two different methods of predicting Appendix X ice accretions should be shown to provide similar results (ice accretion thickness, location) One method should be either an icing wind tunnel or icing tanker test; or; ii) Similarity analysis may be used if the methods used on similar designs were validated as in (i); and

3. Adequate analyses and/or tests are accomplished if there is a need to evaluate more than one airplane component simultaneously. As examples, the evaluation of airplane performance with propeller and airframe ice accretion, asymmetric ice accretions due to propeller wash, engine performance with inlet (including cooling) ice accretions, or stall warning and characteristics with ice accretion that affects air data used by stall protection systems.

(c) The necessity of flight testing in natural Appendix X icing is reduced for aircraft limiting to exiting from Appendix X conditions per § 25.1420(a)(1) due to reduced exposure to such conditions.

(d) Flight testing in natural Appendix X icing conditions should be accomplished for airplane derivatives whose ancestor airplanes have a service record that includes a pattern of accidents or incidents due to inflight encounters with Appendix X conditions.

e. Fluid Anti-Icing/Deicing Systems. Flight testing should include evaluation of fluid flow paths to confirm that adequate and uniform fluid distribution over the protected surfaces is achieved. Fluid flow paths should be determined when the fluid is mixed with impinging water during system operation. A means of indicating fluid flow rates, fluid quantity remaining, etc., should be evaluated to determine that the indicators are plainly visible to the pilot and that the indications provided can be effectively read. A shutoff valve should be provided in systems using flammable fluids. The fluid anti-icing/deicing systems may be used to protect propellers and windshields as well as leading edges of airfoils. The fluid for windshield fluid anti-ice systems should be tested to demonstrate that it does not become opaque at low temperatures. The AFM should include information so the flightcrew will know how long it will take to deplete the amount of fluid remaining in the reservoir.

f. Icing Wind Tunnel Tests. Icing wind tunnels provide the ability to simulate natural icing conditions in a controlled environment and a variety of conditions within both Appendix C and Appendix X freezing drizzle. This type testing has been used to evaluate ice shapes on unprotected areas as well as the performance of ice protection systems, such as pneumatic deicing or thermal systems, and any resulting protected area accretions, such as intercycle, residual and thermal runback. Aerodynamic effects (such as hinge moments) may also be evaluated in an icing tunnel. Testing in an icing wind tunnel has the ability to combine the performance of the IPS, including runback ice, with any potential ice accretions behind the protected areas due to Appendix X icing conditions. Icing tunnels and scale models may be used, with appropriate scaling corrections, to examine impingement limits relative to fuselages or windscreens with scale models relative to Appendix C and Appendix X icing conditions. While scaling icing shapes is still an emerging area of technology, scaling of droplet inertia effects and impingement limits are in a more mature state. This technique may be used to examine visual icing cues, validate location of detection devices, and determine total accretion areas that could be used in drag estimates (if required).

g. Dry-air wind tunnel tests. Dry-air wind tunnel testing has long been used to determine ice protection requirements. Ice shapes defined by computation, icing tunnels or icing tankers can be used. Scale aerodynamic and roughness effects should be substantiated using methods found acceptable to the authorities.

8. CERTIFICATION TO § 25.1420. Section 25.1420 requires that the airplane operate safely in the supercooled large droplet (SLD) icing conditions defined in Part 25, Appendix X.

Interim SLD tools and test techniques have been developed and are expected to be improved and validated. When 14 CFR Part 25.1419 was issued in 1965, the capabilities for simulating icing conditions in laboratories and in flight, as well as the analyses used to predict ice shapes, were rudimentary or did not exist; thus, reliance was placed upon conservative use of then-existing icing simulation methods, engineering judgment, and flight testing in natural icing conditions to demonstrate compliance with icing requirements. The interim SLD tools and test techniques are an extension of current Appendix C methods, but are not developed to the same level as current Appendix C tools. Progress has been made in freezing drizzle simulation both through calibration of existing icing wind tunnels and refinements of drop impingement and ice accretion computer codes. However, extension of the progress made in freezing drizzle to the freezing rain regime has not been accomplished. Due to these limitations with freezing drizzle and freezing rain methods, reliance on available simulation methods and engineering judgment will be required for finding compliance with 25.1420. Paragraph 7(d)(4) of this AC discusses the use of simulation in lieu of natural icing flight testing in SLD.

a. Certification to § 25.1420(a)(3). For compliance with § 25.1420(a)(3), if the AFM performance data reflects the most critical ice accretion (Appendix C and Appendix X) and no special normal or abnormal procedures are required in Appendix X conditions, then a means to indicate when the aircraft has encountered Appendix X icing conditions is not required.

b. Certification to §§ 25.1420(a)(1) and 25.1420(a)(2). As an alternative to the requirements of § 25.1420(a)(3), applicants have the option of complying with §§ 25.1420(a)(1) or (a)(2), which allows an aircraft to be certified to a limit ranging from Appendix C only to a portion of Appendix X. The boundary may be in terms of any parameters that defines Appendix X and could include phase of flight limits, such as takeoff or holding, in Appendix X or a portion of Appendix X. For example, an airplane may be certificated to takeoff in portions of Appendix X but not certificated to hold in those same conditions. Substantiated means must be provided to inform flight crews when the selected icing conditions boundary is exceeded. Compliance with § 25.21(g) for exiting the restricted Appendix X icing conditions must be shown. The ice shapes to be tested are those that represent the critical icing conditions within Appendix X during recognition and subsequent exit from icing conditions. Methods of defining the selected Appendix X icing conditions boundary should be considered early in the certification process, with concurrence from the appropriate certification authority. See paragraphs 15 of this AC for specific guidance on AFM limitations and operating procedures.

(1). Selection of <u>Appendix X Boundary</u>. As discussed in paragraph 3.c., “Effects of Appendix X Icing Conditions,” the physics of ice accretion is complex. However, some generalizations can be made relative to the effects of supercooled water drop impingement and ice limits. By definition, the modified inertia parameter is a measure of a water drop's inertia relative to an object such as an airfoil. (See FAA Technical Report DOT/FAA/CT-88/8-1, “Aircraft Icing Handbook” for detailed discussion on the icing physics process.) The modified inertia parameter is a dimensionless parameter that relates the major influences on the trajectory of a water drop. These influences are drop size, drop density, local air density, drag forces on a droplet, aircraft velocity, and aircraft scale, and the drop's drag if it's shape is distorted from a sphere by the airflow disturbances caused by the object. Examination of the modified inertia parameter is of interest for the inertia of Appendix X large drops in that increases in the modified inertia parameter typically result in increased collection efficiency and further-aft impingement limits. Also, as discussed in paragraph 3.c of this AC, other influences that affect the object's water collection efficiency, drop impingement and icing limits, ice shape, and runback ice include splashing of the large water drops and break-up of the large water drops when forces on the distorted drop exceeds the surface tension required to hold the drop together. These latter influences become more evident for the larger drops defined in Appendix X. Drop size distributions and the related distribution of water mass are important considerations for water catch, impingement and ice limits as well as runback ice. Consideration of these influences allows comparison of critical icing conditions that can be correlated to ice accretions in aft locations, such as behind protected areas. Conditions with equivalent modified inertia parameters result in similar impingement characteristics.

The modified inertia parameter is commonly used in icing wind tunnel testing to compare high altitude flight conditions to the available low altitude test conditions. To simulate the impingement effects of high altitudes and true airspeeds, larger dropsizes are used at the lower altitude test conditions. As an example, an IPS designed to protect against 50μm drop impingement at 22,000 ft and 200 KCAS (290 KTAS) would be equivalently protected against 76 μm drops at sea level and 200 KCAS (190 KTAS) due to an equivalent modified inertia parameter (ref. 6 foot chord).

(a) Based on these physical processes, selection of an Appendix X icing Conditions boundary based on drop size is difficult to implement. Consideration of the drop inertia effects throughout the flight envelope will likely be required. While technology does not currently exist to discriminate icing conditions based on specific drop sizes (exclusive of inertia effects), methods may be developed in the future to certify in such a manner.

(b) Alternate methods of defining a selected Appendix X icing conditions boundary may also be considered. For example, it may be possible to develop an exit cue such that unrestricted flight in Appendix X freezing drizzle is approved; however, exit is required from Appendix X freezing rain.

(c) See Appendix A of this AC for an example of a certification effort considering a certification to Appendix C only (§ 25.1420(a)(1)) based on droplet size discrimination.

2. Means for Detecting Appendix X boundaries. The means for determining whether the selected Appendix X boundary icing conditions boundary has been exceeded can be substantiated visual cues, an ice detection system, or an aerodynamic performance monitor.

(a) Ice detection systems and aerodynamic performance monitors are discussed in paragraph 11.e of this AC. For compliance with §25.1420(a)(1) it is acceptable to use an ice detection system that detects accretions behind the aircraft's protected areas.

(b) Substantiated visual cues can range from direct observation of ice accretions aft of the airplane's protected surfaces to observation of ice accretions on reference surfaces. The cue should not require the flightcrew to judge the ice to be a specific thickness or size. Examples of visual means are:

- accretions forming on the side windshields,
- accretions forming on the sides of nacelles,
- accretions forming on propeller spinners aft of a reference point,
- accretions forming on radomes aft of a reference point, and/or
- accretions forming aft of the protected surfaces

(i) The visual cues should be developed with the following considerations:

- Visual cues should be within the flightcrew's vision scan area while seated and performing their normal duties.
- The visual cues should be visible during all modes of operation (day, night) without the use of a handheld flashlight.

(ii) During the certification process, the applicant should verify the ability of the crew to observe the visual cues or reference surfaces. The visual cues should be evaluated from the most adverse flightcrew seat locations in combination with the range of flightcrew heights, within the approved range of eye reference point locations, if available. A visual cue is required for both the left and right seats. If a single visual cue is used, it should be visible from either seat. Consideration should be given to the difficulty of observing clear ice. The adequacy of the detection method should be evaluated in all expected flight conditions. Night evaluations can be done with simulated accretions to assess visibility in and out of cloud. Methods used to substantiate visual cues should be agreed to with appropriate certification authorities.

(iii) Such visual cues should be validated by testing in measured natural icing, or otherwise validated through icing tanker testing or potentially through icing wind tunnel tests. The cues should consider the drop distributions of Appendix X, to establish that these cues would be appropriate in the restricted appendix X icing conditions. If a reference surface is used, the applicant should validate that it correlates with ice accumulation on the critical surfaces.

(iv) Appendix X and AC 25.21-1 should be reviewed for guidance on the time required to detect visual ice cues for the ice detection system to activate.

9. <u>PNEUMATIC DEICER BOOTS</u>. Many existing AFM's specify a minimum ice accumulation thickness prior to activation of the deicer boot system. However, the accident and incident history has shown that it is difficult for

flightcrews to use visual means to determine the thickness of an ice accretion. The AFM procedure for boot operation should be to activate the boots at the first sign of ice if an advisory ice detector is installed and not wait for a specific amount of ice to accumulate. If an ice detector is not installed the AFM procedure for boot operation should be to activate the boots based on visible moisture and temperature.

In addition, for applicants that choose to recommend an observable ice accumulation prior to boot activation, this pre-activation ice accretion must be considered when determining critical ice accretions for performance, stability, control, and stall testing.

Note: Activation of the deicing boots typically results in one cycle of inflation and deflation of all boots, but not necessarily at the same time. Some systems are designed such that a complete cycle of the boots does not occur (i.e., some boots are not inflated) if the IPS is "selected off" before the cycle is complete. For these systems, the AFM should include information to warn the flightcrew to select the IPS on for at least one complete cycle of the deicing boots and allow completion of any subsequent cycle previously started. This note is equally applicable to other deicing systems that similarly do not activate all portions of the deicing systems simultaneously.

10. EMERGENCY AND ABNORMAL OPERATING CONDITIONS. Flight tests should be conducted to demonstrate continued safe flight and landing, using appropriate AFM abnormal and/or emergency operating procedures, following failures of the IPS. These demonstrations should be conducted with anticipated ice accumulation on normally protected surfaces. See Appendix C, part 2 and AC 25.21-1 for sub-part B testing with failure ice shapes.

11. ICE AND ICING CONDITIONS DETECTION SYSTEMS. Sections 25.1419(e), (f), (g), and (h) specify requirements regarding the activation of the IPS. These requirements are only applicable to Appendix C icing conditions. Section 25.1420(c) requires compliance with § 25.1419(e), (f), (g), and (h) for the selected portion or all of Appendix X as applicable. Sections 25.1420(a)(1) and (a)(2) require a means to alert the flight crew that they are in Appendix X icing conditions or are in Appendix X icing conditions from which they must exit, respectively.

a. COMPLIANCE WITH § 25.1419(e)(1) and (e)(2).

These sections of the rule provide alternatives to the operation of the IPS based on icing conditions defined in § 25.1419(e)(3). These alternatives require either a primary ice detection system, or substantiated visual cues and an advisory ice detection system.

(1) Ice Detectors

(a) Primary ice detector. A primary ice detector must either alert the flight crew to operate the IPS using AFM procedures or automatically activate the IPS prior to an unsafe accumulation of ice on the airframe, engine components, or engine air inlets. The primary ice detection system must perform its intended function for the airplane configurations, phases of flight, and within icing envelopes of Appendix C and Appendix X. Design of the primary ice detector system should account for reasonable time delays in the activation of the IPS, and should recognize the effects of intercycle ice on deicer surfaces if the ice detector is a component of an automatic deicing system. Laboratory tests should demonstrate the ability of the ice detector to function properly within the entire required icing conditions and airplane operating envelope. Approval of the primary ice detector should include measured natural icing flight tests to verify analyses and laboratory test results, as well as to verify that the ice detector system performs its intended function.

The primary ice detection system may incorporate an ice accretion detector and/or an icing conditions detector. The use of the icing conditions detector may be required if the ice detector fails to detect ice at low freezing fractions at the ice detection sensor, see AC20-73A for details.

(b) Advisory ice detector. The advisory ice detector, in conjunction with another cue, such as visible ice accretion on referenced or monitored surfaces, should advise the flight crew to initiate operation of the IPS using AFM procedures. An advisory system is not the prime means used to determine if the IPS should be activated. When there is an advisory system installed on an airplane, the flight crew has primary responsibility for determining when the IPS should be activated. Analyses and tests similar to those performed for a primary ice detector should be performed for an advisory ice detector to understand its characteristics, limitations, and installation.

(c) Ice Detector System Performance When Installed. The applicant should accomplish a droplet impingement analysis and/or tests to ensure that the ice detector(s) are properly located. It should be shown that under the various airplane operational configurations, phases of flight, and associated angles of attack, that the ice detector is exposed to free-stream water droplets. The ice detector should be located on the airframe surface where the sensor is adequately exposed to the icing environment. Flow field and boundary-layer analyses of candidate installation positions should be accomplished to ensure that the ice detector sensor is not shielded from impinging Appendix C and Appendix X water drops. The ice detection system should be shown to operate in the range of conditions defined by Appendix C and the applicable portion of Appendix X. Sections 25.1419 and 25.1420 also require a combination of tests and analysis to demonstrate the performance of the ice detector and the system as installed on the airplane. This could include icing tunnel and icing tanker tests to evaluate the ice detector performance. Droplet impingement analysis may be used in determining that the ice detector functions properly over the droplet range of Appendix C and the applicable portions of Appendix X when validated through natural or artificial icing tests (e.g. tanker, icing tunnel). It should be demonstrated that the airplane can be safely operated with the ice accretions formed at the time the ice protection system becomes effective, following activation of the ice detector. The detector and its installation should minimize nuisance warnings.

(d) Ice Detector System Safety Considerations. The applicant should consult AC 25.1309-1A for guidance on compliance with § 25.1309. In accordance with the AC, the applicant should accomplish a functional hazard assessment to determine the hazard level associated with failure of the ice detection system. The unannunciated failure of a primary ice detection system is assumed a catastrophic failure condition, unless the characteristics of the airplane in icing conditions without activation of the airframe ice protection system(s) are demonstrated to result in a less severe hazard category. If visual cues are primary, failure of an advisory ice detection system is considered to be minor.

(2) Visual Cues. Visual cues can either be direct observation of ice accretions on the airplane's protected surfaces to observation of ice accretions on reference surfaces. Examples of visual means could be:

- accretions forming on the windshield wiper posts (bolt or blade),
- accretions forming on propeller spinners,
- accretions forming on radomes,
- accretions on the protected surfaces

If accretions on the protected surfaces cannot be observed, consideration should be given to providing a reference surface.

(a) *Field of View.* The visual cues should be developed with the following considerations:

(i) Visual cues should be within the flightcrew's vision scan area while seated and performing their normal duties.

(ii) The visual cues should be visible during all modes of operation (day, night, in cloud).

(b) *Substantiation*. During the certification process, the applicant should substantiate the ability of the crew to observe the visual cues or reference surfaces. The visual cues should be evaluated from the most adverse flightcrew seat locations in combination with the range of flightcrew heights, within the approved range of eye reference point locations, if available. A visual cue is required for both the left and right seats. If a single visual cue is used, it should be visible from either seat. Consideration should be given to the difficulty of observing clear ice. If a reference surface is used, the applicant should validate that it correlates with ice accumulation on the airframe's protected areas. Such visual cues should be validated by testing in measured natural icing.

b. **COMPLIANCE WITH § 25.1419(e)(3).**

This paragraph of §25.1419 provides an alternative to the primary ice detection system and the visual cues plus advisory ice detection system as defined in paragraph §§ 25.1419(e)(1) and 25.1419(e)(2). This alternative requires the operation of the IPS when the airplane is in conditions conducive to airframe icing during all phases of flight.

(1) **Temperature Cue.** The temperature cue used in combination with visible moisture, should be calibrated and be readily available to the flightcrew. A minimum temperature limitation may be required on some types of systems due to equipment temperature limitations (such as elastomer pneumatic de-ice boot systems).

(2) **Airplane Flight Manual (AFM).** The limitations section of the AFM should identify specific static or total air temperature and visible moisture conditions which must be considered as conditions conducive to airframe icing and should specify that the IPS must be operated when these conditions are encountered.

c. COMPLIANCE WITH § 25.1419(f).

This paragraph of § 25.1419 states that the requirements of §§ 25.1419(e)(1), 25.1419(e)(2), and 25.1419(e)(3) are applicable to all phases of flight unless it can be shown that the IPS need not be operated. To substantiate that the IPS need not be operated during certain phases of flight, the ice accretions that form during these phases should be considered when establishing the airplane is able to safely operate in the continuous maximum and intermittent maximum icing conditions of appendix C and the applicable portions of Appendix X.

d. COMPLIANCE WITH § 25.1419(g).

This paragraph of § 25.1419 requires that after the initial activation of the IPS:

(a) the IPS must operate continuously, or

(b) the airplane must be equipped with a system that automatically cycles the IPS, or
(c) an ice detection system must be provided to alert the flightcrew each time the IPS must be cycled.

Some examples of systems which automatically cycle the IPS are:

- A system that senses ice accretion on a detector and correlates it to ice accretion on a protected surface. This system then cycles the IPS at a predetermined condition.
- A system which cycles the IPS based on the use of a timer. Such a system may have more than one cycling time.
- A system that directly senses the ice thickness on a protected surface and cycles the IPS.

A common attribute of the above systems is that the pilot is not required to manually cycle the IPS after initial activation.

Some examples of an ice detection system which alerts the flight crew each time the IPS must be cycled could be the same as the automatic systems as discussed above, except that the system alerts the crew each time the IPS must be manually cycled. The use of a timer (without ice sensing capability) to alert the flight crew to manually cycle the deicers does not meet the requirements of §25.1419(g)(3). For a system that employs the use of a timer, it should be substantiated that the airplane can safely operate with the ice accretions that will form between the time the deicing cycle is completed and the next cycle is initiated. For systems that have more than one cycle time it should be substantiated that the flight crew is able to determine which cycle time is appropriate. The ice shedding effectiveness of the selected means for cycling the ice protection system should be evaluated during testing in natural icing conditions and any inter-cycle and runback ice should be considered when showing compliance with § 25.21(g). See paragraphs 11.a.(1) of this AC for guidance on installed ice detector performance and safety considerations.

e. Compliance with § 25.1420(a)(1) or (a)(2). These paragraphs of § 25.1420 require that a means be provided to flight crew to detect when the selected portion of Appendix X icing conditions is exceeded. Means for determining when the selected portion of Appendix X icing conditions is exceeded may include visual means, ice detectors or an airplane performance monitor.

(1) Ice Detectors. An ice detector system installed for compliance with § 25.1420(a)(1) or (a)(2) is intended to determine when the conditions have reached the boundary of Appendix X for which the airplane has been demonstrated for safe operations. The applicant should accomplish a droplet impingement analysis and/or tests to ensure that the ice detector is properly located to function over the aircraft operational conditions and in Appendix X icing conditions. Analysis may be used in determining that the ice detector is located properly to function over the droplet range of Appendix X when validated considering methods described in SAE ARP 5903. It should be ensured that the system minimizes nuisance warnings when operating in icing conditions.

The low probability of finding conditions conducive to ice accumulation in Appendix X may make natural icing flight tests difficult as a means of demonstrating that the system functions in conditions exceeding appendix C. The applicant may use flight tests of the airplane under simulated icing conditions (icing tanker) or icing wind tunnel tests of a representative airfoil section and ice detector to demonstrate the proper functioning of the system and to correlate the signals provided by the detectors and the actual ice accretion on the surface.

(2) Aerodynamic Performance Monitor (APM). A crew alerting system could be developed using pressure probes and signal processors to quantify pressure fluctuations in the flow field from contamination over the wing surface. The technology exists but a full development is necessary before incorporating into the crew warning system.

12. PERFORM INTENDED FUNCTION IN ICING. All systems and components of the basic airplane should continue to function as intended when operating in an icing environment including, for example:

a. Engines and Equipment. Engines and equipment (such as generators and alternators operating under maximum ice protection load) should be monitored during icing tests for adequate cooling (§ 25.1041) and be found acceptable for this operation (§§ 25.1093 and 25.1301).

b. Engine Alternate Induction Air Sources. Engine alternate induction air sources should remain functional in an icing environment.

c. Fuel System Venting. Fuel system venting should not be adversely affected by ice accumulation.

d. Landing Gear. A retractable landing gear should operate as intended following an icing encounter. Gear retraction should not result in an unsafe indication because of ice accretion.

e. Stall Warning. Ice could form on stall warning and angle-of-attack sensors if these devices are not protected. Therefore, the sensors' functions should be evaluated to ensure operation in the icing conditions of Appendices C and, as appropriate, X. The activation points of artificial stall warning and stall identification systems, if installed, may need to be reset for operations in icing conditions to provide adequate stall warning margins and to prevent inadvertent stalling or loss of control, respectively.

f. Ice Detection Cues. Ice detection cues that the pilot relies on for timely operation of ice protection equipment should be evaluated in anticipated flight attitudes. (See paragraph 8.b.(2) for guidance on substantiated visual cues for compliance with §§ 25.1420(a)(1) or 25.1420(a)(2). Also, see paragraph 11.a.(2) of this AC for guidance on substantiated visual cues for compliance with § 25.1419(e)(2).)

g. Primary and Secondary Flight Control Surfaces. Primary and secondary flight control surfaces should remain operational after exposure to icing conditions. It should be demonstrated that aerodynamic balance surfaces are not subject to icing throughout the airplane's operating envelope (weight, center of gravity, and speed) or that any ice accumulation on these surfaces does not interfere with or limit actuation of the control for these surfaces, including retraction of flaps for a safe go around from the landing configuration.

h. Ram Air Turbine. The ram air turbine should remain operational. It does not need to be tested in natural icing conditions if tested in the icing wind tunnel.

i. Pilot Compartment View. In support of compliance with § 25.773, Pilot compartment view, any obstruction of the pilots’ view due to ice accumulation should be assessed.

13. ICE INSPECTION LIGHT(S). Unless operations at night in icing conditions are prohibited by an operating limitation, § 25.1403 requires that a means be provided for illuminating or otherwise determining the formation of ice on the parts of the wings that are critical from the standpoint of ice accumulations.

a. If the wings cannot be observed by the flightcrew, one acceptable means of compliance with this regulation would be the installation of an ice evidence probe located in a position where the flightcrew can observe the ice accumulation. Formation of ice on the device should be shown to precede or occur simultaneously with the formation of ice on the wings. Consideration should be given to the need for illumination of the ice evidence probe.

b. Ice inspection lights should be evaluated both in and out of clouds during night flight to determine that adequate illumination of the component of interest is available without excessive glare, reflections, or other distractions to the flightcrew. These tests may be conveniently accomplished both in and out of clouds during the airplane certification flight tests. Typically, airplane-mounted illumination has been used as a means of compliance with this regulation. Use of a hand-held flashlight has not been considered acceptable due to the associated workload. The appropriate manual should identify the ice characteristics the flightcrew is expected to observe and the flightcrew action associated with the observation.

14. CAUTION INFORMATION. Section 25.1419(c) requires that caution information be provided to alert the flightcrew when the IPS is not functioning normally. Caution information should be provided if the failure condition of the IPS can result in a hazardous airplane condition. It should be assumed that icing conditions exist during the failure event. The decision to provide the caution information should not be based on the numerical probability of the failure event (i.e., even if a numerical probability analysis indicates the system failure is

improbable or extremely improbable, the caution information should be provided if the failure could result in a hazardous condition). Caution information related to §25.1420 must comply with §25.1309(c).

a. The placement of the sensor(s) used to identify a failure condition should be evaluated to ensure that the sensors are properly located to obtain accurate data on the failure of the IPS.

b. The applicant should submit data to substantiate that the indication system does not give a false indication that the system is functioning normally. For example, if a pneumatic deicing system (boots) requires a specific minimum pressure and pressure rise rate to adequately shed ice, then caution information should be provided if the minimum pressure and pressure rise rate are not attained. If this caution information is not provided, the flightcrew may erroneously believe that the boots are operating normally when, in fact, the boots might not be inflating with sufficient pressure or rate of inflation to adequately shed the ice. The need for caution information should also be considered for the case of ice forming in the pneumatic system that can result in low pneumatic boot pressures or an inadequate pressure rise rate.

15. AIRPLANE FLIGHT MANUAL (AFM). The AFM should provide the pilot with the information needed to operate the IPS, including the following:

a. Operating Limitations Section.

(1) Establishment of any systems limitations when operating in icing conditions. These limitations should address airframe, engine, and equipment ice protection systems, and other systems that may need to be specifically configured for operation in icing conditions. Appropriate icing conditions definitions may need to be provided to ensure proper operation of the related IPS.

(2) Limitations on operating time for ice protection equipment, if these limitations are based on fluid anti-icing/deicing systems capacities and flow rates.

(3) Airplane speed limitations (if any) and minimum temperature for deicing boot operation for airplanes equipped with boots.

(4) Environmental limitations for equipment operations as applicable (e.g., minimum temperature for boot operation or maximum altitude for boot operation).

(5) Minimum engine speed if the airframe IPS does not function properly below this speed.

(6) A list of required placards.

(7) If compliance is based on §§ 25.1420(a)(1) or 25.1420(a)(2), the Limitations section must include a requirement that the flightcrew exit all (Appendix X and C) icing conditions immediately upon recognition that the Appendix X icing conditions exceed the certification boundary. For certification of detection and exit of Appendix X in accordance with § 25.1420(a)(1) and §25.1420(a)(2) the Limitations section should contain appropriate limits that consider the certification assumptions with respect to portion (phase of flight, freezing drizzle, freezing rain, etc.)

b. Operating Procedures Section.

(1) Section 25.1585 requires that operating procedures be provided in the AFM for: (1) normal procedures peculiar to the particular type or model encountered in connection with routine operations, (2) non-normal procedures for malfunction cases and failure conditions involving the use of special systems or the alternative use of regular systems, and (3) emergency procedures for foreseeable but unusual situations in which immediate and precise action by the crew may be expected to substantially reduce the risk of catastrophe. These procedures should include any preflight action necessary to minimize the potential of enroute emergencies associated with the IPS. The system components should be described with sufficient clarity and depth that the pilot can understand their function. Unless flightcrew actions are accepted as normal airmanship, the appropriate procedures should be included in the FAA-approved AFM, AFM revision, or AFM supplement. These procedures should include proper pilot response to cockpit warnings, a means to identify system failures, and the use of the system(s) in a safe manner.

(2) Procedures should be provided to optimize airplane operation during penetration of icing conditions, including climb, holding, and approach configurations and speeds. The AFM should define when the ice protection equipment should be activated consistent with the system operation during certification.

(3) Emergency or abnormal procedures, including procedures to be followed when IPSs fail and/or warning or monitor alerts occur, should be provided.

(4) For fluid anti-icing/deicing systems, information and method(s) for determining the remaining flight operation time should be provided.

(5) For airplanes that cannot supply adequate electrical power for all systems at low engine speeds, load-shedding instructions should be provided to the pilot for approach and landing in icing conditions if pilot action is required.

(6) For compliance with §§ 25.1420(a)(1) or 25.1420(a)(2):

(a) The method used to determine when icing conditions must be exited, must be provided, as well as appropriate failure indications and crew procedures.

(b) The operating procedures section should contain guidance relative to exiting the icing environment.

(c) For certification of certain phases of flight to Appendix X, information defining these restricted phases should be provided. This information should include any aircraft configurations associated with the restricted phases of flight such as flap position, gear extension, or airspeed.

(7) The method for determining when the IPS must be activated must be provided. Information should be provided to indicate that a de-icing system should not be de-activated until the completion of an entire de-icing cycle after leaving icing conditions. An anti-icing system should not be de-activated before leaving icing conditions.

(8) The following statement should be included:
Convective clouds, above the freezing altitude, that are vigorously growing should be avoided since they may contain icing conditions exceeding those for which the aircraft has been certified.

16. GUIDANCE FOR AMENDED TCs, AND STCs

General guidance for amended TCs, and STCs can be found in AC21.101-1/ACJxxx. As stated in its “APPLICABILITY” section, the guidance in this AC applies to any STC or amended TC on an airplane for which the applicant seeks approval under the provisions of §§ 25.1419 and 25.1420. Increases in gross weight, increases in engine power, and propeller changes could affect approval in icing and these areas should be evaluated using this AC as the method of compliance. An applicant wishing to use an alternate means of compliance (AMOC) needs to consult the cognizant Aircraft Certification Office.

For additional guidance, refer to Appendix B of this AC.

Appendix A
Example of Certification to §25.1420(a)(1) using Visual Cues.

To give guidance on the use of Appendix C as a boundary and the determination of substantiated visual cues, the following hypothetical example is used.

The aircraft is a transport category, turbofan aircraft. It is a derivative of an existing type. The existing aircraft has already been type certificated for flight in icing including §25.1419 (Appendix C). The changes in the derivation did not alter the original §25.1419 compliance. The derivative aircraft design is characterized by:

- Cruise altitude above the Appendix C envelope.
- Wing design does not include leading edge devices.
- Ice protection over the full span of wing and tailplane.
- Reversible flight controls on the roll and pitch axes.

AC 25.21-1 contains guidance on compliance with 14 CFR 25, sub-part B requirements and AC 20-147 contains guidance for engine and engine installations. All relevant certification requirements must be met. However for this example only the following aspects will be discussed.

Impingement aft of the protected areas of lifting surfaces.
The aircraft has ice protection over the full span of the wing and horizontal stabilizer with minimal unprotected areas. Since this is a derivative aircraft, the system has already been evaluated and certificated for Appendix C conditions. The aircraft does have reversible flight controls on the roll and pitch axis. An assessment of hinge moment and lift reduction effects is required. See AC 25.21-1 for details on performance and handling qualities guidance.
Impingement aft of the engine inlet protected surfaces. Ice accumulation aft of the engine inlet protected surfaces should be evaluated relative to ingestion of the ice by the engine. For the example, the cumulative mass of this ice is less than that used for demonstrating compliance with § 33.77. Therefore, compliance with 25.1093 will be found based on this known ingestion standard. Refer to AC 20-147 for further information on engine and engine installation certification.

Ice shapes on unprotected areas of lifting surfaces
The aircraft is designed with full span ice protection on the wing and horizontal stabilizer. As such, the unprotected areas (wing tip, stabilizer tip) are a small percentage of the effective airfoil areas. Aerodynamic effects due to the effects of Appendix X accretions on the minimal exposure area is unlikely to be critical, but should be investigated. See AC 25.21-1 for details on performance and handling qualities guidance.

Ice shapes on unprotected airframe regions
Other areas of the airframe (which do not accrete ice under Appendix C

conditions) should be examined relative to the increased impingement and runback on accretion areas related to Appendix X. Issues such as windshield visibility, static port location and potential airflow disturbance from Appendix X accretions that could influence sensors (TAT, pitot, AOA) should be examined. Use of computational fluid dynamic analysis, or icing impingement analysis (icing wind tunnel) combined with a satisfactory field service history on derivative models may be sufficient to alleviate any potential issues.

Air data sensors
Ice protection on air data sensors should be examined to ensure adequate protection for exposure to Appendix X icing conditions.

Design Substantiation
A review of the impingement analysis and runback ice data versus protected area for the wing and horizontal stabilizer indicates that the wing is the critical surface for formation of a potential ridge behind the protected areas in front of the ailerons. The horizontal stabilizer has farther aft protection limits and has sufficient margin with contamination aft of the protected areas. Again, it is assumed that the horizontal stabilizer would be addressed, but will not be presented in this example.

Determination of Exit Cues
The aircraft-operating envelope encompasses all of the Appendix X icing conditions. Climbs and descents should be examined, but due to the transient nature of these encounters, they may not produce the critical accretions for Appendix X.
The recommended procedure for holding in icing conditions should be considered (e.g., whether flaps or landing gear extended). AFM recommended procedures would include this operating information. The case to be evaluated will consider flaps up, gear up configuration. Since ice accretions aft of the protected areas on the upper wing surface are the primary concern in this example, an analysis of the operational conditions will be made to determine the critical flight conditions for such accretions. The conditions considered as critical were determined to be the following:

Highest holding altitude within the conditions of Appendix X that maximizes water catch (typically a function of ram air effects and LWC content at defined static temperatures) Highest true airspeed expected during holding conditions (typically high weight hold speed; produces maximum water catch aft of protected areas upper surface.)

> Note: Other operating conditions should be considered as required to determine the critical conditions.

Through a combination of impingement analysis, analytical ice shape prediction and icing wind tunnel testing, it has been determined that there is potential for an ice ridge to begin to accumulate on the upper wing surface under these operating conditions when there is significant water content in drop sizes above a specific drop size and liquid water content. As such, this will be proposed as a condition to determine when icing conditions must be exited. It should be noted that this dropsize criteria is not a fixed boundary. As an example, at a lower altitude and a similar equivalent airspeed (similar AOA), slightly larger dropsizes are required to produce a similar accretion of ice behind the protected area. However, this combination of drop size, liquid water content, and relative inertia to the aircraft is sufficient to potentially produce accumulations behind the protected areas. See discussion on the modified inertia parameter in paragraph 8.b(1) of this AC and DOT/FAA/CT-88/8-1 Aircraft Icing Handbook, reference section Chap. I, section 2 and Chapter IV, Section 2.2.2.

Determination of visual exit cue
The target boundary will be icing conditions with significant water content in dropsizes greater than the specific drop size determined by analysis and testing under the operating conditions of a high altitude, high speed hold. The target criterion for a visual exit cue is a surface on the aircraft that is readily visible to the flight crew that will indicate water collection in such drop sizes. A CFD analysis of the cockpit/fuselage area has determined that there are perceptible changes in impingement limits along the side windows with increasing drop sizes. The desired visual cue is a specific portion of the windshield as a reference surface that can be correlated to ice accumulation on the wing. Preliminary impingement analysis indicates that this is feasible as there is significant movement of the aft impingement limits on the windshield with increasing drop sizes when the specific flight conditions of interest are considered. Based on this analysis, a specific location on the aircraft side window is proposed as the visible cue to determine when the Appendix X conditions that require exiting icing conditions have been encountered.

Definition of critical ice accretion
It is proposed that the exit cue will be based on the first sign of accretion. It has been determined that an accretion of approximately 1/16-inch is required on the reference surface for the crew to detect it. This reference-surface accretion is then correlated to the specific ice accretion on the monitored surface (behind the leading edge) considering the ice accretion corresponding to the first indication on the reference surface considering recognition time and time to initiate escape as described in AC 25.21-1, Appendix 1. This correlation is based on a combination of analysis and icing wind tunnel testing.

This results in accretion of a 1/8-inch ice ridge behind the protected area at the specific critical operating condition. The difference in ice thickness is due to differences in the local collection efficiencies between the side window and the area aft of the leading edge protected surface. Consideration of additional accretion during the exit from the icing conditions is required to determine the full ice shape to be evaluated for aerodynamic degradation effects.

Evaluation of critical ice accretions

Wind tunnel testing of this critical accretion has determined that there are no hinge moment issues that result in changes in roll forces. However, there is a potential increase in stall speed that must be addressed in the stall warning system. Dry air flight-testing is performed using simulated ice shapes. This flight-testing is performed in a built up manner with limited spanwise exposure to evaluate the effects with minimal safety risk. The stall warning margins are evaluated and result in a modification of the stall warning system to ensure that adequate stall margin exists both for the period prior to detection and during the exit from all icing conditions. See AC 25.21-1 for details on 14 CFR 25, sub-part B compliance.

Validation of the visual cue

The use of the visual cue is to be evaluated and validated through flight-testing with an icing tanker. The tanker is equipped to provide a specific MVD with an associated droplet distribution. As the tanker cannot simulate the full extent of icing conditions within Appendix X, a validation of the specific conditions will be made. A fixed nozzle simulating the specific drop size to be used as the exit cue will be selected.

Icing tanker testing indicates that the side window does begin to accumulate ice at the specific condition considered, which validates the analysis. At slower speeds, the droplets do not have sufficient inertia to reach the side windows. This serves to validate that the visual cue is not overly sensitive and will not result in false indications. Tanker testing also showed good correlation to the predicted ice shapes validating the ice shape behind the protected areas. The location is such that it is adequately illuminated by existing cockpit lighting without glare or reflection and is readily observable by crewmembers.

Exiting from restricted Appendix X icing conditions

Flight tests are performed in accordance with 14 CFR § 25.21(g)(2) and (4) to show that the airplane can safely exit Appendix X icing conditions. See AC 25.21-1 for details on performance and handling qualities guidance.

Appendix B
GUIDANCE FOR AMENDED TC's, AND STC's

The guidance in this AC applies to any STC or amended TC on an airplane for which the applicant seeks approval under the provisions of §§ 25.1419 and 25.1420. Increases in gross weight, increases in engine power, external modifications, and propeller changes could affect approval in icing and these areas should be evaluated using this AC as the method of compliance. An applicant wishing to use an alternate means of compliance (AMOC) needs to consult the cognizant Aircraft Certification Office.

a. These are some examples of modifications (but not limited to the list) for which compliance to icing regulations should be revisited are:

(1) Engine changes
(2) Propeller changes
(3) Engine inlet or accessory inlet changes
(4) Antennae installations or other external modifications
(5) Gross weight increases
(6) Center of gravity envelope increase
(7) Flight envelope increase
(8) Turboprop conversion
(9) Modifications to lifting surfaces
(10) Installation of vortex generators
(11) Modifications to ice protections systems

Besides the guidance on similarity analysis provided in paragraph 5.e, the following guidance on specific modifications should be followed:

b. Engine changes The effects of increased engine power or thrust on airplane handling qualities in icing conditions,§ 25.21(g), should be addressed, as well as compliance to engine induction icing regulations, § 25.1093.

(1) Effects of increased engine power or thrust

(a) Stall Characteristics, Stability, and Control If there is a potential for the increased engine power or thrust to affect airplane handling qualities in icing conditions, flight tests with ice accretions should be conducted as described in AC 25.21-1.

(b) Ice contaminated tailplane stall (ICTS) ICTS should be addressed. See AC25-21-1 for compliance materials on tailplane stall.

(2) Engine induction icing

(a). Similarity - If similarity is used as a method of compliance, it should be supplemented with analysis or testing, or both. In some cases, an analysis that substantiates similarity, along with an installation survey conducted by the engine manufacturer, may be sufficient. The analysis should include:

1. Heat requirements for the inlet lip ice protection, if installed, i.e., no increase in speed envelope;
2. Location of the lip deicer thermostat, if installed;
3. Inlet material to which the deicer is attached (heat sink may be different);
4. Inlet geometry;
5. Engine ignition system; and
6. Engine sensors

Any differences that cannot be addressed by analysis must be addressed by flight testing. The data to be used for similarity, including the data from past certification on which the similarity analysis is based must be available to the applicant and be provided to the FAA at their request.

(b) Falling/Blowing Snow and Ground Ice Fog for Turbine Engines

If similarity will be used as a method of compliance, the certification plan should state to what similarity will be shown. This is important because similarity may be based on a certified installation that does not have falling/blowing snow or ground ice fog in its certification basis. Service experience by itself cannot be used to show compliance. Compliance is normally shown by testing for turboprop installations. With regards to falling and blowing snow, inlets such as the oil cooler as well as the induction system are of concern. The certification plan should identify how compliance with these sections will be shown.

(c) Ice Shedding

Engine compliance data to § 33.77 should be compared between the currently installed engine and the proposed engine. If the ice slab used to show compliance is smaller for the proposed engine, ice shedding from the airframe should be re-addressed. Engine inlet lip ice shedding should be addressed. The amount of ice mass that could be shed should be compared to a similar, approved installation or to Part 33 engine compliance data.

(d) IPS Operation

Bleed air mass flows, pressures and temperatures of the proposed engine and existing, certified engine should be compared. If there is a reduction, the effectiveness of the IPSs must be substantiated.

c. Propeller changes

Section 25.929 requires a means to prevent or remove hazardous ice accumulation on propellers or accessories where ice accumulation would jeopardize engine performance.

The typical analysis report from the deicing boot manufacturer is not sufficient by itself to show compliance to § 25.929. The typical report calculates intercycle ice thicknesses for various flight and icing conditions, but does not calculate the effect on propeller efficiency, which must be done to show no appreciable loss of thrust. For Supplemental Type Certificates, it would be acceptable to show that intercycle ice is equal to or less than the accretions obtained on the same propeller on an airplane that was flight tested in icing conditions and shown to have no appreciable loss in thrust.

The typical deicing boot manufacturer report also contains a caveat that it does not address propeller runback ice. Similarity to another propeller that was flight tested in icing conditions is usually done to address runback. Similarity would include propeller and deicing boot aerodynamic and thermal similarity, deicing timer, propeller RPM, and flight conditions. Note that metal and composite propellers have different thermal masses.

As a final qualitative check for both intercycle and runback ice on new airplane programs, airplane performance is checked during flight tests in icing conditions.

The propeller installation, including spinner and cowl geometry, must be compared to previously tested installations in icing conditions. Changes that could allow moisture to reach the brush blocks must be avoided.

If the proposed propeller is calculated to have higher efficiency than the existing, approved propeller, the guidance under "1. Effects of increased engine power or thrust" under "Engine changes" should be followed.

d. Engine inlet or accessory inlet changes

Guidance is provided in the "Engine changes" section above. It should be noted that § 25.1093 applies to engine oil and accessory cooling inlets as well as induction inlets.

e. Antennae installations or other external modifications

(1) When antennae, cameras, fairings for such installations, or other external installations such as drain masts are installed on aircraft, the installer should show the following:

(a) The predicted ice accretion does not contribute significantly to drag;
(b) There is no ice shedding hazard on downstream structure or engines.
(c) There is no ice related reduction performance of lifting surfaces; and
(d) There is no ice related effect on downstream air data sensors or ice detectors;

(2) A very conservative, simple analysis may be accomplished first to show the objectives (a) and (b). If the conservative analysis fails, the analysis can be refined to determine if the initial analysis was overly conservative. The conservative analysis can assume the following:

(a) The water catch area is the full frontal area of the installation;
(b) Collection efficiency is one.
(c) No runback or evaporation of impinging water.
(d) Assume the shape on blade antenna will be similar to airfoils and the shape on low profile antennae will be single horn shapes.

(3) The applicant should determine the critical icing condition. If the analysis shows a problem, then one or more of the following can be accomplished:

(a) Determine a less conservative collection efficiency either with an ice accretion code or with the FAA "Aircraft Icing Handbook" (DOT/FAA/CT-88/8-1);
(b) Determine less conservative impingement limits by using an icing code, which may reduce the collection area;
(c) Run the full configuration in an icing code to determine if the installation is in a shadow zone.
(d) If drag is a problem, run an ice accretion code to determine a less conservative ice shape.

(4) Flight tests in measured natural icing or with simulated ice shapes should be accomplished to determine if there are any detrimental effects due to the ice accretions if

(a) The installation is upstream of air data sensors or an ice detector; or

(b) The installation is on a lifting surface or

(c) The installation could create a wake on a lifting surface.

Note: The one exception to (b) is fairings. An analysis to show the impact on maximum lift coefficient, in combination with flight tests with no ice accretions, have been accepted in the past.

f. <u>Gross weight increases</u>

(1) The impingement analysis should cover a weight range that is applicable to any increase in gross weight.

(2) The impingement analysis should also evaluate unprotected areas such as fuel vents.

(3) If there is a potential for the increased gross weight to affect airplane handling qualities in icing conditions, flight tests with ice accretions should be conducted as described in AC 25.21-1.

g. <u>Center of gravity envelope increase.</u> Generally, the same guidance used for gross weight increases can be used for center of gravity envelope increases. The one exception is an increase of forward center of gravity limit on airplanes may make an airplane more susceptible to ICTS. This should be addressed by flight testing for airplanes with unpowered, reversible elevators or for airplanes with propellers. An analysis may be acceptable for other configurations.

h. <u>Flight envelope increase</u>

If an increase in maximum operating altitude is applied for, the applicant should demonstrate:

(1) the IPS operating pressures (for pneumatic systems) or temperatures (for thermal air) by dry air testing; and

(2) stall speeds and characteristics with ice accretions if these are shown to be influenced by Mach number

The effect of increased cruise airspeeds and increased altitudes that could affect <u>windshield ice accretion</u>, and adequacy of the <u>windshield heat</u>, should be addressed.

i. Turboprop conversion

If the IPSs use engine bleed air for operation, the pneumatic lines may accumulate more water than the current unmodified type design. This water can subsequently refreeze and block the pneumatic lines, resulting in failure of some or all zones of the pneumatic system. The applicant needs to show that the pneumatic deicing system will continue to function in icing conditions.

The pneumatic deicer operating pressure may also decrease at lower engine RPMs. A minimum engine RPM for acceptable pneumatic operating pressure, which should allow for descent, should be established and published in the AFM/POH.

j. Modifications to lifting and control surfaces

Critical ice accretions (including consideration of pre-activation, intercycle, residual, and runback icing) may have to be re-defined, especially if the changes affect operational wing angle of attack. Stall strips are good collectors of ice and are an example where leading edge ice accretions should be re-defined. If ice accretions are changed or the modifications could affect control power or hinge moments, AC 25.21-1 provides guidance on flight testing.

k. Installation of vortex generators

Vortex generators may accrete ice depending on their location. The applicant should provide data on expected ice accretions. Flight conditions to consider are the hold, descent, and approach. Substantiation on the effects on stall speeds, stall characteristics, and stability and control should be provided.

l. Modifications to ice protection systems

Critical ice accretions (including consideration of pre-activation, intercycle, residual, and runback icing) may have to be re-defined. If ice accretions are changed or the modifications could affect control power or hinge moments, flight testing with simulated ice accretions should be accomplished. AC 25.21-1 provides guidance on flight testing.

APPENDIX L - NECCESSITY FOR AN AFM STATEMENT CONCERNING CUMULIFORM CLOUD LARGE DROPLET ICING

MINORITY POSITION ON THE NECESSITY OF AN AFM STATEMENT CONCERNING CUMULIFORM CLOUD LARGE DROPLET ICING (EXCEEDANCE OF APPENDIX X)

Supported by: ALPA

The addition of an explicit caution concerning convective cloud icing in future aircraft flight manuals is necessary for pilot understanding of aircraft icing capability and to increase the probability of avoidance of conditions which may exceed Appendix X.

With Appendix X certification addressing SLD conditions, pilots will expect safety in known icing conditions; however, with Appendix X addressing only stratiform clouds, that is not necessarily the case. Appendix C certification addresses icing in cumuliform clouds, Appendix X does not. There is a body of evidence (photos, anecdotal reports, and limited data) of icing that is more intense and severe than Appendix C and Appendix X icing. In the modern ATC environment, pilots routinely face decisions concerning penetration of cumuliform clouds and operations near thunderstorms. While pilots understand that numerous hazards are associated with these conditions, without an AFM warning they will not understand that icing certification does not provide the same safe operation in convective cloud icing as it does in other icing. A warning is necessary to insure that this hazard is not dismissed.

Add the following statement to the IPHWG AC, section 16 a.

> Warning: The large droplet icing conditions that may be encountered in or near convective clouds that are vigorously growing above the freezing level are not evaluated in aircraft certification. Such conditions may result in hazardous degradations of aircraft performance and handling characteristics and should be avoided.

{Note: A WARNING is defined as an operating procedure, technique, etc., that may result in personal injury or loss of life if not carefully followed. A CAUTION is an operating procedure, technique, etc., that may result in damage to equipment if not carefully followed. Based on these definitions, a WARNING is proposed.}

This section then reads:

> 16. AIRPLANE FLIGHT MANUAL (AFM). The AFM should provide the pilot with the information needed to operate the IPS, including the following:

a. Operating Limitations Section.

(9) For all aircraft, a requirement to avoid large drop icing associated with convective clouds that are vigorously growing above the freezing level, such as: Warning: The large droplet icing conditions that may be encountered in or near convective clouds that are vigorously growing above the freezing level are not evaluated in aircraft certification. Such conditions may result in hazardous degradations of aircraft performance and handling characteristics, and should be avoided.

MAJORITY POSITION ON THE NECESSITY OF AN AFM STATEMENT CONCERNING CUMULIFORM CLOUD LARGE DROPLET ICING (EXCEEDANCE OF APPENDIX X)

Supported by: Airbus, Boeing, Bombardier, CAA/UK, Cessna, Embraer, FAA/FAA Tech Center, MSC, Saab, Transport Canada/TDC

The majority concurs that there should be information in the AFM to minimize exposure of aircraft to large droplet convective cloud icing conditions that are not considered during certification. However, the use of a Warning or Caution in the Limitations section is not appropriate. For a Warning or a Caution, there should be a good means that will allow the flightcrew to follow the instructions. Since all vigorously growing convective clouds do not appear as red on the weather radar and visual observation is not adequate at night, there is not a good means for the flightcrew to consistently avoid these clouds. It would not be prudent to provide a Warning or a Caution that could lead the flightcrew to become overly concerned about their inability to comply with the instructions. There is not a history of icing accidents in convective clouds. Therefore, it is reasonable to place the information in the procedures section of the AFM where the flightcrew would utilize the information by avoiding these clouds when possible.

In addition, the majority do not concur that the AFM information is necessary for the airplanes that are certificated as detect and exit airplanes because the flightcrew will be provided with a means to know when they should exit icing conditions.

The AC will be revised to include the following information in the procedures section of the AFM:

"Convective clouds, above the freezing altitude, that are vigorously growing should be avoided since they may contain icing conditions exceeding those for which the aircraft has been certified."

APPENDIX M FTHWG RECOMMENDATIONS FOR 14 CFR 25 SUB-PART B

FTHWG Proposed Requirements for Aeroplane Handling Qualities and Performance in Supercooled Large Drop Icing Conditions

Prepared for the IPHWG

Introduction

The rules that the FTHWG proposes for performance and handling qualities for flight in the icing conditions of Appendix X are based upon those developed for flight in Appendix C icing conditions. These proposals address the options identified by the IPHWG for CS/FAR 25.1420; for continued operation in the icing conditions of Appendix X, operation in a portion of Appendix X and for the alternative option of leaving all icing conditions once Appendix X conditions are detected ("detect and exit").

The FTHWG interpretation of "operating safely"

The FTHWG discussed the interpretation of "operating safely", as in CS/FAR 25.1420 proposed by the IPHWG, with respect to the required level of safety and the resulting handling qualities and performance levels.

For CS/FAR 25.1420(a)(2) "operating safely in a portion of Appendix X", the FTHWG quickly came to the conclusion that there is a direct analogy with operation in Appendix C icing conditions (discussed below).

For CS/FAR 25/1420(a)(1) "operating safely after encountering Appendix X conditions" and 25.1420(a)(1)(ii) "operating safely while exiting all icing conditions", the FTHWG considers that these are not failure cases and the temptation to link this text with the phrase "continued safe flight and landing", commonly used in association with system failure conditions of CS/FAR 25.1309, should be resisted. These cases are also discussed below.

The recognition that the "detect and exit" cases of 25.1420(a)(1) are not failure conditions led directly to the decision by the FTHWG to make "detect and exit" for Appendix X an integral part of a certification for Appendix C icing conditions (discussed later).

Continued operation in the icing conditions of Appendix X

For continued operation, the FTHWG considers that little change is required from the requirements for Appendix C. The list of requirements excepted for flight in Appendix C were reviewed and found largely appropriate for Appendix X; the only difference is that CS/FAR 25.121(a) "Performance - Take-off landing gear extended" is not excepted, as the FTHWG cannot at the moment justify an assumption that the accretion in this flight phase can be assumed insignificant, unlike Appendix C. In practice, it is expected that some applicants may prohibit take-off in Appendix X conditions. Otherwise, the rationale behind the requirements is exactly that applied for Appendix C; that for continued operation in icing conditions, there should effectively be no degradation in handling qualities and any degradation in performance should be strictly limited by means of the same thresholds developed for Appendix C. The proposed requirements are thus, with the one exception identified above, identical to those proposed for Appendix C.

The FTHWG also considers that it is worth clarifying that the optional certification for continued operation in the supercooled large drop conditions of Appendix X cannot be obtained independently of certification for operation in the icing conditions of Appendix C.

Continued operation limited to a portion of Appendix X or to a flight phase

The concept of limiting continued operation to a portion of the Appendix X icing conditions is acceptable, provided that there are not too many divisions that could lead to significant human factors issues. The FTHWG advised the IPHWG at an early stage that a division between freezing rain and freezing drizzle would be most practical from an operational standpoint but has accepted a further sub-division to each based on particle size.

The concept of limiting continued operation in Appendix X to specific flight phases, not explicitly stated in CS/FAR 25.1420 but addressed in the IPHWG draft AC, is more difficult. In certification there is a general understanding on what is intended by reference to the different flight phases in terms of aeroplane configuration, speed etc. Operationally, there is not usually such a clear distinction. Take-off and final take-off can be considered a distinct flight phase in that operation in this phase can be authorised or not and a clear go/no go decision can be made on the ground. Otherwise, the only discriminant that can sensibly be recognised by the crew is aeroplane configuration. The holding flight phase is often not the classic manoeuvre recognised in certification and operationally is frequently more akin to low level vectoring. It may, therefore, be unrealistic and potentially unsafe to consider holding, approach and landing as separate flight phases.

To meet the IPHWG request, the proposed Subpart B rules allow a limitation on operation in Appendix X to a "clearly defined flight phase or atmospheric condition" but this requires interpretation in advisory material, a suitably realistic ice accretion scenario and a convincing case from any applicant.

"Detect and exit" from the icing conditions of Appendix X into clear air

The situation regarding the "detect and exit" option is much more complex. One of the key issues is the definition of the appropriate scenarios to be considered and this is given in the proposed Appendix X. It is worth noting that the FTHWG has followed the advice of the IPHWG in assuming that the aeroplane leaves all icing conditions after encountering Appendix X icing conditions and does not continue in Appendix C icing conditions.

"Detect and exit" Appendix X certification integral with Appendix C certification

The "detect and exit" cases of 25.1420(a)(1) are normal flight conditions arising from an inadvertent encounter with Appendix X icing conditions. Hence, the FTHWG considers it appropriate to make "detect and exit" for Appendix X an integral part of any icing certification for Appendix C icing conditions i.e. if an Appendix C icing certification is sought, then "detect and exit" for Appendix X must also be addressed.

Performance and handling qualities for "detect and exit"

Regarding specifically handling qualities and performance, the discussions in the FTHWG addressed the following issues:

- Performance – The FTHWG assumes that the take-off case need not be considered for a "detect and exit" aeroplane. Hence, with the exception of stall speeds, landing speeds and distances and landing climb performance, the FTHWG considers that performance need not be specifically addressed for "detect and exit" certification.

- Handling qualities – The FTHWG proposes, with one exception, that the same handling qualities as for flight in Appendix C icing conditions are retained. That exception is a take-off case, CS/FAR 25/143(c)(1), addressing controllability following engine failure at V_2. No justification for a relaxed standard of handling qualities could be identified, bearing in mind that "detect and exit" is not a failure case and that the aeroplane, once clear of all icing conditions but retaining the ice accretion, may continue in clear air for some time.

- Roll controllability - The FTHWG reviewed the JAA Interim Policy and the FAA ADs published to address roll controllability issues. Several manufacturers gave presentations of their experiences in addressing the FAA ADs. The FTHWG concluded that the existing requirement is adequate to address roll control but there is a need for additional advisory material.

- Additional limitations may be imposed after encountering Appendix X conditions that may be reflected in the certification flight tests.

- Demonstration of compliance - AC/AMC 25.21(g) clarifies that many handling requirements are only required to be addressed in Appendix C if the compliance in non-icing conditions is marginal. It is anticipated that the same philosophy will hold for Appendix X.

- Sandpaper ice, included in the previous Appendix C proposals, does not feature in the Appendix X icing environment.

Entry into icing conditions

- "Prior to normal IPS operation" - The FTHWG presumes that entry directly into Appendix X conditions from clear air cannot be ruled out. Hence the minimal set of "prior to normal IPS operation" handling requirements developed for Appendix C is proposed also for Appendix X. In practice, it may be possible to propose one envelope accretion covering both cases.

- "Prior to detection of Appendix X" – The FTHWG considers that there is a need for a set of minimal requirements to address the ice accreted before crew recognition of accretion in Appendix X conditions. The same requirements as for "prior to normal IPS operation" are proposed but to be related to the means of detection of Appendix X. In practice, it may be possible in this case also to combine with the "prior to normal IPS operation" accretions.

Summary of proposed Subpart B requirements for "detect and exit"

A summary of the Subpart B requirements (as amended by the 25.21(g) Appendix C proposals of NPA 16/2004) applicable to a "detect and exit" certification is given below.

Subpart B Requirements* for D+E App X		**Title**	**Comments**
Exclude:	**Retain:**		
		General	
	25X20	Applicability	No impact in practice
	25.21	Proof of compliance	
	25.23	Load distribution limits	No changes in load distribution and weight and c.g. limits allowed in Appendix X
	25.25	Weight limits	
	25.27	Centre of gravity limits	
	25.29	Empty weight and corresponding centre of gravity	No impact in practice
	25.31	Removable ballast	
	25.33	Propeller speed and pitch limits	
		Performance	
	25.101	General	
	25.103	Stall speed	Necessary for HQ
25.105		Take-off	No take-off performance required for D+E App X
25.107		Take-off speeds	
25.109		Accelerate-stop distance	
25.111		Take-off path	
25.113		Take-off distance and take-off run	
25.115		Take-off flight path	
	25.117	Climb: general	
	25.119	Landing climb: all-engines operating	
25.121		Climb: One-engine-inoperative	No en-route performance required for D+E App X
25.123		En-route flight paths	
	25.125	Landing	

Subpart B Requirements* for D+E App X		Title	Comments
Exclude:	**Retain:**		
		Controllability and Manoeuvrability	
25.143(b)(1),(2), (c)(1)	25.143 not (b)(1),(2), (c)(1)	General	Pushover manoeuvre to same standard as App C. 25.143(c)(1) is a take-off case
	25.145	Longitudinal control	
	25.147	Directional and lateral control	
25.149		Minimum control speed	Engine failure for approach, landing and go-around addressed qualitatively in 25.143(c)(2)&(3)
		Trim	
	25.161	Trim	
		Stability	
	25.171	General	
	25.173	Static longitudinal stability	
	25.175	Demonstration of static longitudinal stability	
	25.177	Static directional and lateral stability	
	25.181	Dynamic stability	
		Stalls	
25.201(c)(2)	25.201, not (c)(2)	Stall demonstration	
	25.203	Stall characteristics	
25.207(c) and (d)	25.207(a),(b),(e),(f)	Stall warning	Same means and margin of stall warning required as for App C. Option for further stick shaker advance for App X requested by manufacturers (in A(M)C).

Subpart B Requirements* for D+E App X		**Title**	**Comments**
Exclude:	**Retain:**		
		Ground Handling Characteristics	
	25.231	Longitudinal stability and control	
	25.233	Directional stability and control	
	25.235	Taxying condition	
	25.237	Wind velocities	
		Miscellaneous Flight Requirements	
25.251(b) thru (e)	25.251(a)	Vibration and buffeting	
	25.253	High-speed characteristics	
	25.255	Out-of-trim characteristics	

* Based on CS-25 as amended by NPA 16/2004

Proposed Amendment to CS 25.21(g) Rule to Accommodate Appendix X

Based on the proposals of EASA NPA 16/2004

Introduction

The proposed requirements addressing flight in the icing conditions of Appendix C (EASA NPA 16/2004 and the corresponding FAA NPRM) require revision to accommodate the proposed Appendix X icing environment.

This paper uses the NPA 16/2004 circulated for comment by EASA as a basis.

Proposed changes to CS 25.21(g) are identified by italic font.

Identification of Amendments

Deletions from and additions to the current CS-25 text to accommodate flight in the icing conditions of Appendix C are shown by strike-through and bolding respectively.

To accommodate the incorporation of Appendix X, further suggested changes to the proposals are shown by italic font.

"...." is used as an ellipsis (with leading and/or trailing text to aid reference) to indicate unchanged text that, for clarity, is not repeated.

Proposal 1

CS 25.21 Proof of compliance

Introduce CS 25.21(g) to read:

"**(g)** ***The requirements of this subpart associated with icing conditions apply only if certification for flight in icing conditions is desired.*** **If certification for flight in icing conditions is desired, the following requirements** ***also*** **apply (see AMC 25.21(g)):**

(1) Unless otherwise prescribed, ***compliance with*** **each requirement of this subpart, except CS 25.121(a), 25.123(c), 25.143(b)(1) and (2), 25.149, 25.201(c)(2), 25.207(c) and (d), and 25.251(b) through (e), must be** ***shown using*** **the ice accretions defined in** ***part II of*** **Appendix C,** ***assuming*** **normal operation of the aeroplane** ***and its ice protection system*** **in**

accordance with the operating limitations and operating procedures *provided* in the aeroplane Flight Manual.

(2) Unless otherwise prescribed, compliance with each requirement of this subpart, except CS 25.105, 25.107, 25.109, 25.111, 25.113, 25.115, 25.121, 25.123, 25.143(b)(1), (b)(2) and (c)(1), 25.149, 25.201(c)(2), 25.207(c) and (d), and 25.251(b) through (e), must be shown using the ice accretions defined in part II(b)(2) of Appendix X, assuming normal operation of the aeroplane and its ice protection system in accordance with the operating limitations and operating procedures provided in the aeroplane Flight Manual.

(*3*) The aeroplane must meet the requirements of CS 25.143(j) and 25.207(h) *after entry into icing conditions and before* the ice protection system *has been activated and is performing its intended function. Compliance must be shown using the ice accretions defined in (i) part II(e) of Appendix C and (ii) part (II)(b)(1)(h) of Appendix X*.

(*4*) *The aeroplane must meet the requirements of CS 25.143(k) and 25.207(i) after entry into the supercooled large drop icing conditions of Appendix X and before the detection of those conditions. Compliance must be shown using the ice accretions defined in part II(b)(2)(e) of Appendix X.*

(5) If, additionally, certification for flight in any portion (whether a clearly defined flight phase or atmospheric condition) of the supercooled large drop icing conditions of Appendix X is desired, unless otherwise prescribed, each requirement of this subpart, except CS 25.123(c), 25.143(b)(1) and (2), 25.149, 25.201(c)(2), 25.207(c) and (d), and 25.251(b) through (e), must be met in those icing conditions. Compliance must be shown using the ice accretions defined in part II(b)(1) of Appendix X, assuming normal operation of the aeroplane and its ice protection system in accordance with the operating limitations and operating procedures provided in the aeroplane Flight Manual.

(*6*) No changes in the load distribution limits of CS 25.23, the weight limits of CS 25.25 (except where limited by performance requirements of this subpart), and the centre of gravity limits of CS 25.27, from those for non-icing conditions, are allowed for flight in icing conditions or with ice accretion."

Proposal 2

Amend CS 25.103 Stall Speed to read:

"(a) The reference stall speed V_{SR} ....

(b) V_{CLMAX} is determined with:

(1) Engines idling, or, if that resultant thrust causes an appreciable decrease in stall speed, not more than zero thrust at the stall speed;

(2) Propeller pitch controls (if applicable) in the take-off position;

(3) The aeroplane in other respects (such as flaps, ~~and~~ landing gear, **and ice accretions**) in the condition existing in the test or performance standard in which V_{SR} is being used;

(4) The weight used when V_{SR} is being used as a factor to determine compliance with a required performance standard;

(5) The centre of gravity position that results in the highest value of reference stall speed; and

(6) The aeroplane trimmed for straight flight at a speed selected by the applicant, but not less than 1.13 V_{SR} and not greater than 1.3 V_{SR}.

(c) Starting from ....

(d) In addition to ...."

Proposal 3

Amend CS 25.105 Take-off to read:

"(a) The take-off speeds described in CS 25.107, the accelerate-stop distance described in CS 25.109, the take-off path described in CS 25.111,~~ and~~ the take-off distance and take-off run described in CS 25.113, **and the net take-off flight path described in CS 25.115**, must be determined ~~–~~

~~(1) At each weight, altitude, and ambient temperature within the operational limits selected by the applicant; and~~

~~(2) In the selected configuration for take-off.~~

in the selected configuration for take-off at each weight, altitude, and ambient temperature within the operational limits selected by the applicant -

(1) In non-icing conditions; and

(2) In icing conditions, if in the configuration of CS 25.121(b) with the *applicable* "Take-off Ice" accretion *specified by CS 25.21(g)*:

(i) The stall speed at maximum take-off weight exceeds that in non-icing conditions by more than the greater of 5.6 km/h (3 kt) CAS or 3% V_{SR}; or

(ii) The degradation of the gradient of climb determined in accordance with CS 25.121(b) is greater than one-half of the applicable actual-to-net take-off flight path gradient reduction defined in CS 25.115(b).

(b) No take-off made .....

(c) The take-off data must be based on .....

(d) The take-off data must include ....."

Proposal 4

CS 25.107 Take-off speeds

Amend CS 25.107(c), 25.107(g) and add a new CS 25.107(h) as follows:

"(c) V_2, in terms of calibrated airspeed, must be selected by the applicant to provide at least the gradient of climb required by CS 25.121(b) but may not be less than -

(1) V_{2MIN};

(2) V_R plus the speed increment attained (in accordance with CS 25.111(c)(2)) before reaching a height of 35 ft above the take-off surface; and

(3) A speed that provides the manoeuvring capability specified in CS 25.143(**h**).

(d) ….

(e) ….

(f) ….

(g) V_{FTO}, in terms of calibrated airspeed, must be selected by the applicant to provide at least the gradient of climb required by CS 25.121(c), but may not be less than -

(1) 1.18 V_{SR}; and

(2) A speed that provides the manoeuvring capability specified in CS 25.143(**h**).

(h) In determining the take-off speeds V_1, V_R, and V_2 for flight in icing conditions, the values of V_{MCG}, V_{MC}, and V_{MU} determined for non-icing conditions may be used."

Proposal 5

Amend CS 25.111 Take-off path to read:

"(a) The take-off path ....

(b) During the acceleration ....

(c) During the take-off path determination in accordance with sub-paragraphs (a) and (b) of this paragraph -

(1) The slope ....

(2) The aeroplane ....

(3) At each point ....,

(i) 1.2% ....

(ii) 1.5% ....

(iii) 1.7% ...., ~~and~~

(4) **The aeroplane configuration may not be changed, except for gear retraction and automatic propeller feathering,** and no change in power or thrust that requires action by the pilot may be made until the aeroplane is 122m (400 ft) above the take-off surface**; and**

(5) If CS 25.105(a)(2) requires the take-off path to be determined for flight in icing conditions, the airborne part of the take-off must be based on the aeroplane drag:

(i) With the *applicable* "Take-off Ice" accretion *specified by CS 25.21(g)*, from a height of 11m (35 ft) above the take-off surface up to

the point where the aeroplane is 122m (400 ft) above the take-off surface; and

(ii) With the *applicable* "Final Take-off Ice" accretion *specified by CS 25.21(g)*, from the point where the aeroplane is 122m (400 ft) above the take-off surface to the end of the take-off path.

(d) The take-off path ....

(e) *Not required for CS-25."*

Proposal 6

Amend CS 25.119 Landing climb: All-engines-operating to read:

"In the landing configuration, the steady gradient of climb may not be less than 3.2%, with -
~~(a)~~ the engines at the power or thrust that is available 8 seconds after initiation of movement of the power or thrust controls from the minimum flight idle to the go-around power or thrust setting (see AMC 25.119~~(a)~~) ~~- and~~

~~(b) A climb speed which is -~~

~~(1) Not less than -~~

~~(i) 1·08 V_{SR} for aeroplanes with four engines on which the application of power results in a significant reduction in stalling speed; or~~

~~(ii) 1·13 V_{SR} for all other aeroplanes;~~

~~(2) Not less than V_{MCL}; and~~

~~(3) Not greater than V_{REF}.~~

(a) In non-icing conditions, with a climb speed of V_{REF} determined in accordance with CS 25.125(b)(2)(i),

(b) In icing conditions with the *applicable* "Landing Ice" accretion *specified by CS 25.21(g)*, and with a climb speed of V_{REF} determined in accordance with CS 25.125(b)(2)(ii)."

Proposal 7

Amend CS 25.121 Climb: One-engine-inoperative to read:

"(a) *Take-off; landing gear extended*. ....

(b) *Take-off; landing gear retracted.* In the take-off configuration existing at the point of the flight path at which the landing gear is fully retracted, and in the configuration used in CS 25.111 but without ground effect~~,~~**:**

(1) The steady gradient of climb may not be less than 2.4% for two-engined aeroplanes, 2.7% for three-engined aeroplanes, and 3.0% for four-engined aeroplanes, at V_2 ~~and~~ with -

(i) The critical engine inoperative, the remaining engines at the take-off power or thrust available at the time the landing gear is fully retracted, determined under CS 25.111, unless there is a more critical power operating condition existing later along the flight path but before the point where the aeroplane reaches a height of 122m (400 ft) above the take-off surface (see AMC 25.121(b)(1)**(i)**); and

(ii) The weight equal to the weight existing when the aeroplane's landing gear is fully retracted, determined under CS 25.111.

(2) The requirements of sub-paragraph (b)(1) of this paragraph must be met:

(i) In non-icing conditions; and

(ii) In icing conditions with the *applicable* "Take-off Ice" accretion *specified by CS 25.21(g)*, if in the configuration of CS 25.121(b) with the "Take-off Ice" accretion:

(A) The stall speed at maximum take-off weight exceeds that in non-icing conditions by more than the greater of 5.6 km/h (3 kt) CAS or 3% V_{SR}; or

(B) The degradation of the gradient of climb determined in accordance with CS 25.121(b) is greater than one-half of the applicable actual-to-net take-off flight path gradient reduction defined in CS 25.115(b).

(c) *Final take-off*. In the en-route configuration at the end of the take-off path determined in accordance with CS 25.111~~,~~**:**

(1) The steady gradient of climb may not be less than 1.2% for two-engined aeroplanes, 1.5% for three-engined aeroplanes, and 1.7% for four-engined aeroplanes, at V_{FTO} ~~and~~ with -

(i) The critical engine inoperative and the remaining engines at the available maximum continuous power or thrust**;** and

(ii) The weight equal to the weight existing at the end of the take-off path, determined under CS 25.111.

(2) The requirements of sub-paragraph (c)(1) of this paragraph must be met:

(i) In non-icing conditions; and

(ii) In icing conditions with the *applicable* "Final Take-off Ice" accretion *specified by CS 25.21(g)*, if in the configuration of CS 25.121(b) with the "Take-off Ice" accretion:

(A) The stall speed at maximum take-off weight exceeds that in non-icing conditions by more than the greater of 5.6 km/h (3 kt) CAS or 3% V_{SR}; or

(B) The degradation of the gradient of climb determined in accordance with CS 25.121(b) is greater than one-half of the applicable actual-to-net take-off flight path gradient reduction defined in CS 25.115(b).

(d) *Approach.* In a configuration corresponding to the normal all-engines-operating procedure in which V_{SR} for this configuration does not exceed 110% of the V_{SR} for the related all-engines-operating landing configuration~~,~~**:**

(1) The steady gradient of climb may not be less than 2.1% for two-engined aeroplanes, 2.4% for three-engined aeroplanes, and 2.7% for four-engined aeroplanes, with -

(i) The critical engine inoperative, the remaining engines at the go-around power or thrust setting;

(ii) The maximum landing weight;

(iii) A climb speed established in connection with normal landing procedures, but not exceeding 1.4 V_{SR}: and

(iv) Landing gear retracted.

(2) The requirements of sub-paragraph (d)(1) of this paragraph must be met:

(i) In non-icing conditions,

(ii) In icing conditions with the *applicable* "Holding Ice" accretion *specified by CS 25.21(g)*; the climb speed selected for non-icing conditions may be used if the climb speed for icing conditions, computed in accordance with sub-paragraph (d)(1)(iii) of this paragraph, does not exceed that for non-icing conditions by more than the greater of 5.6 km/h (3 kt) CAS or 3%.

Proposal 8

Amend CS 25.123 En-route flight paths to read:

"(a) For the en-route configuration, the flight paths prescribed in sub-paragraphs (b) and (c) of this paragraph must be determined at each weight, altitude, and ambient temperature, within the operating limits established for the aeroplane. The variation of weight along the flight path, accounting for the progressive consumption of fuel and oil by the operating engines, may be included in the computation. The flight paths must be determined at **a** ~~any selected~~ speed **not less than V_{FTO}**, with -

(1) The most unfavourable centre of gravity;

(2) The critical engines inoperative;

(3) The remaining engines at the available maximum continuous power or thrust, and

(4) The means for controlling the engine-cooling air supply in the position that provides adequate cooling in the hot-day condition;

(b) The one-engine-inoperative net flight path data must represent the actual climb performance diminished by a gradient of climb of 1.1% for two-engined aeroplanes, 1.4% for three-engined aeroplanes, and 1.6% for four-engined aeroplanes~~.~~ **-**

(1) In non-icing conditions,

(2) In icing conditions with the *applicable* "En-route Ice" accretion *specified by CS 25.21(g)*, if:

(i) 1.18V_{SR} with the "En-route Ice" accretion exceeds the en-route speed selected in non-icing conditions by more than the greater of 5.6 km/h (3 kt) CAS or 3% V_{SR}, or

(ii) The degradation of the gradient of climb is greater than one-half of the applicable actual-to-net flight path reduction defined in sub-paragraph (b) of this paragraph.

(c) For three- or four-engined ...."

Proposal 9

Amend CS 25.125 Landing to read:

"(a) The horizontal distance necessary to land and to come to a complete stop from a point 15m (50 ft) above the landing surface must be determined (for standard temperatures, at each weight, altitude and wind within the operational limits established by the applicant for the aeroplane) **-** ~~as follows~~:

(1) In non-icing conditions,

(2) In icing conditions with the *applicable* "Landing Ice" accretion *specified by CS 25.21(g)* if V_{REF} in icing conditions is greater than V_{REF} in non-icing conditions by more than 9.3 km/h (5 kt) CAS.

(b) In determining the distance in (a):

(1) The aeroplane must be in the landing configuration.

(2) A stabilised approach, with a calibrated airspeed of **not less than** V_{REF}, must be maintained down to the 15m (50 ft) height.

(i) In non-icing conditions, V_{REF} may not be less than:

(**A**) $1.23V_{SR0}$;

(**B**) V_{MCL} established under CS 25.149(f); and

(**C**) A speed that provides the manoeuvring capability specified in CS 25.143(**h**).

(ii) In icing conditions, V_{REF} may not be less than:

(A) The speed determined in sub-paragraph (b)(2)(i) of this paragraph;

(B) 1.23 V_{SR0} with the *applicable* "Landing Ice" accretion *specified by CS 25.21(g)* if that speed exceeds V_{REF} selected in non-icing conditions by more than 9.3 km/h (5 kt) CAS; and

(*C*) A speed that provides the manoeuvring capability specified in CS 25.143(h).

(3) Changes in configuration,….(See AMC 25.125(**b**)(3).)

(4) The landing must….

(5) The landings may....

(c) The landing distance....(See AMC 25.125(**c**).) In addition –

(1) The pressures….

(2) The brakes….(see AMC 25.125(**c**)(2); and

(d) *Not required for CS-25.*

(e) *Not required for CS-25.*

(f) The landing distance data.....

(g) If any device....."

Proposal 10

Amend CS 25.143 Controllability and Manoeuvrability - General to read:

"(a) (See AMC 25.143(a).) The aeroplane must ....

(b) (See AMC 25.143(b).) It must be possible ....

(c) It must be shown that the aeroplane is safely controllable and manoeuvrable with the critical ice accretion appropriate to the phase of flight *specified by CS 25.21(g)*, and with the critical engine inoperative and its propeller (if applicable) in the minimum drag position:

(1) At the minimum V_2 for take-off;

(2) During an approach and go-around; and

(3) During an approach and landing.

(d) The following table prescribes, for conventional wheel type controls, the maximum control forces permitted during the testing required by sub-paragraphs

(a) ~~and (b)~~ **through (c)** of this paragraph (See AMC 25.143(**d**)): ....[Table unchanged]

(e) Approved operating procedures .... that are prescribed in sub-paragraph (**d**) of this paragraph. The aeroplane ....

(**f**) When demonstrating compliance .... that are prescribed in sub-paragraph (**d**) of this paragraph, the aeroplane....

(**g**) When manoeuvring .... (see AMC No 1 to CS 25.143(**g**)), and must .... over-controlling. (See AMC No 2 to CS 25.143(**g**)).

(**h**) (See AMC 25.143(**h**)). The manoeuvring capabilities ....[Table unchanged]

(i) When demonstrating compliance with CS 25.143 in icing conditions -

(1) Controllability *must* be demonstrated with the ice accretion *specified by CS 25.21(g)* that is most critical for the particular flight phase. For aeroplanes with unpowered elevator controls, the "Sandpaper Ice" *of Appendix C* must also be considered in determining the critical ice accretion;

(2) It must be shown that a push force is required throughout a pushover manoeuvre down to zero g or the lowest load factor obtainable if limited by elevator power. It must be possible to promptly recover from the manoeuvre without exceeding 222 N (50 pounds) pull control force; and (Based on FAA/JAA/ALPA position in original FTHWG Appendix C report)

(2) The aeroplane must be controllable in a pushover manoeuvre down to zero g, or the lowest load factor obtainable if limited by elevator power. It must be shown that a push force is required throughout the manoeuvre down to 0.25g. It must be possible to promptly recover from the manoeuvre without exceeding 50 pounds pull control force. (TC position in original FTHWG Appendix C report)

(2) The aeroplane must be controllable in a pushover manoeuvre down to zero g, or the lowest load factor obtainable if limited by elevator power. It must be shown that a push force is required throughout the manoeuvre down to 0.5g. It must be possible to promptly recover from the manoeuvre without exceeding 50 pounds pull control force. (Manufacturers' position in original FTHWG Appendix C report)

(3) Changes in longitudinal control force to maintain speed with increasing sideslip angle must be progressive with no reversals or unacceptable discontinuities. (Based on FAA/JAA/TC/ALPA position in original FTHWG Appendix C report)

(3) Advisory material only (Manufacturers' position in original FTHWG Appendix C report)

(j) For flight in icing conditions *before the ice protection system has been activated and is performing its intended function*, the following apply:

(1) If activation of normal operation of any ice protection system is dependent upon visual recognition of a specified ice accretion on a reference surface, the requirements of CS 25.143 are applicable with the ice accretions *specified by CS 25.21(g)*. (Based on position of group less ALPA in original FTHWG Appendix C report)

(1) If activation of normal operation of any ice protection system is dependent upon visual recognition of ice accretion, the requirements of JAR 25.143 are applicable with the ice accretion defined in Appendix C, Part II(e). (ALPA's position in original FTHWG Appendix C report)

(2) If activation of normal operation of any ice protection system is dependent upon means of recognition other than that defined in sub-paragraph (j)(1) of this paragraph, it must be shown that the aeroplane is controllable in a pull-up manoeuvre up to 1.5g and there is no longitudinal control force reversal during a pushover manoeuvre down to 0.5g with the ice accretions *specified by CS 25.21(g)*.

(k) For flight in icing conditions after entry in the icing conditions of Appendix X but before detection of those conditions, the following apply:

(1) If detection of Appendix X icing conditions is dependent upon visual recognition of a specified ice accretion on a reference surface, the requirements of CS 25.143 are applicable with the ice accretions specified by CS 25.21(g).

(2) If detection of Appendix X icing conditions is by an approved ice detection system, it must be shown that the aeroplane is controllable in a pull-up manoeuvre up to 1.5g and there is no longitudinal control force reversal during a pushover manoeuvre down to 0.5g with the ice accretions specified by CS 25.21(g)."

Proposal 11

Amend CS 25.207 Stall warning to read:

"(a) Stall warning with ....

(b) The warning must be furnished either through the inherent aerodynamic qualities of the aeroplane or by a device that will give clearly distinguishable indications under expected conditions of flight. However, a visual stall warning device that requires the attention of the crew within the cockpit is not acceptable by itself. If a warning device is used, it must provide a warning in each of the aeroplane configurations prescribed in sub-paragraph (a) of this paragraph at the speed prescribed in sub-paragraphs (c) and (d) of this paragraph**. Except for the stall warning prior to normal operation of the ice protection system prescribed in sub-paragraph (h)(2) of this paragraph, the stall warning for flight in icing conditions prescribed in sub-paragraph (e) of this paragraph must be provided by the same means as the stall warning for flight in non-icing conditions.** (See AMC 25.207(b).)

(c) When the speed is reduced ....

(d) In addition to the requirement ....

(e) In icing conditions, when the speed is reduced at decelerations of up to 0.5 m/s^2 (one knot per second), the stall warning margin in straight and turning flight must be sufficient to allow the pilot to prevent stalling (as defined in CS 25.201(d)) when recovery, using the same test technique as for the non-contaminated aeroplane, is initiated not less than 3 seconds after the onset of stall warning, with -

(1) The *applicable* "Holding Ice" accretion *specified by CS 25.21(g)* for the en-route, holding, approach, landing, and go-around high-lift configurations; and

(2) The more critical of the *applicable* "Take-off Ice" and "Final Take-off Ice" accretions *specified by CS 25.21(g)* for each high-lift configuration used in the take-off phase.

(f) The stall warning margin must be sufficient to allow the pilot to prevent stalling ~~(as defined in CS 25.201(d))~~ when recovery is initiated not less than one second after the onset of stall warning in slow-down turns with at least 1.5g load factor normal to the flight path and airspeed deceleration rates of at least 1m/s^2 (2 knots per second), with the flaps and landing gear in any normal position, with the aeroplane trimmed for straight flight at a speed of 1.3 V_{SR}, and with the power or thrust necessary to maintain level flight at 1.3 V_{SR}. **When demonstrating compliance with this sub-paragraph with ice accretions, the same test**

technique as for the aeroplane without ice accretions must be used for recovery.

(g) Stall warning must ....

(h) For flight in icing conditions prior to activation of normal operation of the ice protection system, the following apply:

(1) If activation of normal operation of any ice protection system is dependent upon visual recognition of a specified ice accretion on a reference surface, the requirements of this paragraph except sub-paragraphs (c) and (d) are applicable with the ice accretion*s specified by CS 25.21(g)*. (Based on position of group less ALPA in original FTHWG Appendix C report)

(1) If activation of normal operation of any ice protection system is dependent upon visual recognition of ice accretion, the requirements of this paragraph except sub-paragraphs (c) and (d) are applicable with the ice accretion defined in Appendix C, Part II(e). (ALPA's position in original FTHWG Appendix C report)

(2) If activation of normal operation of any ice protection system is dependent upon means of recognition other than that defined in sub-paragraph (h)(1) of this paragraph:

(i) If stall warning is provided by the same means as for flight in non-icing conditions, when the speed is reduced at rates not exceeding 0.5 m/s^2 (one knot per second), the stall warning margin in straight and turning flight must be sufficient to allow the pilot to prevent stalling, using the same test technique as for the non-contaminated aeroplane, without encountering any adverse characteristics when recovery is initiated not less than 1 second after the onset of stall warning, with the ice accretion*s specified by CS 25.21(g)*.

(ii) If stall warning is provided by a different means than for flight in non-icing conditions, when the speed is reduced at rates not exceeding 0.5 m/s^2 (one knot per second), the stall warning in straight and turning flight must be sufficient to allow the pilot to prevent stalling, using the same test technique as for the non-contaminated aeroplane, without encountering any adverse characteristics when recovery is initiated not less than 3 seconds after the onset of stall warning, with the ice accretion*s specified by CS 25.21(g)*. Additionally, compliance with CS 25.203 must be shown using the demonstration means prescribed by CS 25.201, except that the 1.5 m/s^2 (3 kt) per

second airspeed deceleration rates of CS 25.201(c)(2) need not be demonstrated.

(i) For flight in icing conditions after entry in the icing conditions of Appendix X but before detection of those conditions, the following apply:

(1) If detection of Appendix X icing conditions is dependent upon visual recognition of a specified ice accretion on a reference surface, the requirements of this paragraph except sub-paragraphs (c) and (d) are applicable with the ice accretions specified by CS 25.21(g).

(2) If detection of Appendix X icing conditions is by an approved ice detection system:

(i) If stall warning is provided by the same means as for flight in non-icing conditions, when the speed is reduced at rates not exceeding 0.5 m/s^2 (one knot per second), the stall warning margin in straight and turning flight must be sufficient to allow the pilot to prevent stalling, using the same test technique as for the non-contaminated aeroplane, without encountering any adverse characteristics when recovery is initiated not less than 1 second after the onset of stall warning, with the ice accretions specified by CS 25.21(g).

(ii) If stall warning is provided by a different means than for flight in non-icing conditions, when the speed is reduced at rates not exceeding 0.5 m/s^2 (one knot per second), the stall warning in straight and turning flight must be sufficient to allow the pilot to prevent stalling, using the same test technique as for the non-contaminated aeroplane, without encountering any adverse characteristics when recovery is initiated not less than 3 seconds after the onset of stall warning, with the ice accretions specified by CS 25.21(g). Additionally, compliance with CS 25.203 must be shown using the demonstration means prescribed by CS 25.201, except that the 1.5 m/s^2 (3 kt) per second airspeed deceleration rates of CS 25.201(c)(2) need not be demonstrated."

Proposal 12

Amend CS 25.237 Wind velocities to read:

"(a) **__The following applies:**

(1) A 90° cross component of wind velocity, demonstrated to be safe for take-off and landing, must be established for dry runways and must be at least

37 km/h (20 kt) or 0.2 V_{SR0}, whichever is greater, except that it need not exceed 46 km/h (25 kt).

(2) The crosswind component for take-off established without ice accretions is considered valid *with ice accretions*.

(3) The landing crosswind component must be established for:

(i) Non-icing conditions, and

(ii) Icing conditions with the *applicable* "Landing Ice" accretion *specified by CS 25.21(g)*.

(b) *Not required for CS-25."*

Proposal 13

Amend CS.253 High-speed characteristics to read:

"(a) *Speed increase and recovery characteristics*. ....

(b) *Maximum speed for stability characteristics, V_{FC}/M_{FC}.* V_{FC}/M_{FC} is the maximum speed at which the requirements of CS 25.143**(g)**, 25.147(e), 25.175(b)(1), 25.177**(a) through (c)**, and 25.181 must be met with wing-flaps and landing gear retracted. **Except as noted in CS 25.253,** it may not be less than a speed midway between V_{MO}/M_{MO} and V_{DF}/M_{DF}, except that, for altitudes where Mach number is the limiting factor, M_{FC} need not exceed the Mach number at which effective speed warning occurs.

(c) The maximum speed for stability characteristics with the ice accretions *specified by CS 25.21(g)*, at which the requirements of CS 25.143(g), 25.147(e), 25.175(b)(1), 25.177 and 25.181 must be met, is the lower of:

(1) 556 km/h (300 knots) CAS,

(2) $V_{FC,}$ or

(3) A speed at which it is demonstrated that the airframe will be free of ice accretion due to the effects of increased dynamic pressure."

Proposal 14

Amend CS 25.941(c) to read:

"(c) In showing compliance with sub-paragraph (b) of this paragraph, the pilot strength required may not exceed the limits set forth in CS 25.143(**d**) subject to the conditions set forth in sub-paragraphs (**e**) and (**f**) of CS 25.143."

Proposal 15

Amend CS 25.1419 Ice protection to read:

"If certification for flight in icing conditions is desired, the aeroplane must be able to safely operate in the continuous maximum and intermittent maximum icing conditions of Appendix C. To establish **this** ~~that the aeroplane can operate within the continuous maximum and intermittent maximum conditions of Appendix C~~ **–**

(a) An analysis ....

(b) To verify ....

(c) Caution information ....

(d) For turbine engine powered aeroplanes ...."

Proposal 16

Amend Appendix C to CS-25 to read:

"**Part I - Atmospheric Icing Conditions**

(a) *Continuous Maximum Icing. ....*

(b) *Intermittent Maximum Icing. ....*

(c) *Take-off maximum icing*. The maximum intensity of atmospheric icing conditions for take-off (take-off maximum icing) is defined by the cloud liquid water content of 0.35 g/m^3, the mean effective diameter of the cloud droplets of 20 microns, and the ambient air temperature at ground level of -9 degrees C. The take-off maximum icing conditions extend from ground level to a height of 457m (1500 ft) above the level of the take-off surface.

Part II - Airframe Ice Accretions for Showing Compliance with Subpart B

(a) *Ice accretions - General*. CS 25.21(g) states that in the icing conditions of Appendix C the applicable requirements of subpart B must be met (except as specified otherwise). The most critical ice accretion in terms of handling characteristics and/or performance for each flight phase must be determined, taking into consideration the atmospheric conditions of part I of this Appendix, and the flight conditions (e.g. configuration, speed, angle-of-attack, and altitude). The following ice accretions must be determined: (Based on position of group less ALPA in original FTHWG Appendix C report)

(a) *Ice accretions - General*. JAR 25.21(g) states that in the icing conditions of Appendix C the applicable requirements of subpart B must be met (except as specified otherwise). The most critical ice accretion in terms of handling characteristics and/or performance for each flight phase must be determined, taking into consideration the atmospheric conditions of part I of this Appendix, and all flight conditions within the operational limits of the aeroplane (e.g. configuration, configuration changes, speed, angle-of-attack, and altitude). The following ice accretions must be determined: (ALPA's position in original FTHWG Appendix C report)

(1) <u>Take-off Ice</u> is the most critical ice accretion on unprotected surfaces, and any ice accretion on the protected surfaces appropriate to normal ice protection system operation, occurring between lift-off and 122m (400 ft) above the take-off surface, assuming accretion starts at lift-off in the take-off maximum icing conditions of Part I, paragraph (c) of this Appendix.

(2) <u>Final Take-off Ice</u> is the most critical ice accretion on unprotected surfaces, and any ice accretion on the protected surfaces appropriate to normal ice protection system operation, between 122m (400 ft) and 457m (1500 ft) above the take-off surface, assuming accretion starts at lift-off in the take-off maximum icing conditions of Part I, paragraph (c) of this Appendix.

(3) <u>En-route Ice</u> is the critical ice accretion on the unprotected surfaces, and any ice accretion on the protected surfaces appropriate to normal ice protection system operation, during the en-route phase. At the applicant's option, *Holding Ice* may be used in showing compliance with requirements that specify *En-route Ice*.

(4) <u>Holding Ice</u> is the critical ice accretion on the unprotected surfaces, and any ice accretion on the protected surfaces appropriate to normal ice protection system operation, during the holding flight phase.

(5) <u>Landing Ice</u> is normally *Holding Ice*, unless modified by ice protection system operation during the landing phase.

(6) <u>*Sandpaper* Ice</u> is a thin, rough layer of ice.

(b) In order to reduce the number of ice accretions to be considered when demonstrating compliance with the requirements of CS 25.21(g):

(1) The more critical of *Take-off Ice* and *Final Take-off Ice* may be used throughout the take-off phase.

(2) *Holding Ice* may be used for the en-route, holding, approach, landing and go-around flight phases.

(3) *Holding Ice* may also be used for the take-off phase provided it is shown to be more conservative than *Take-off Ice* and *Final Take-off Ice.*

(c) The ice accretion that has the most adverse effect on handling characteristics may be used for performance tests provided any difference in performance is conservatively taken into account.

(d) <u>Ice accretions for the take-off phase</u>. For both unprotected and protected parts, the ice accretion may be determined by calculation, assuming the take-off maximum icing conditions defined in Appendix C, and that:

(1) Aerofoils, control surfaces and, if applicable, propellers are free from frost, snow, or ice at the start of the take-off,

(2) The ice accretion starts at lift-off,

(3) The critical ratio of thrust/power-to-weight,

(4) Failure of the critical engine occurs at V_{EF}, and

(5) Crew activation of the ice protection system is in accordance with an AFM procedure, except that after commencement of the take-off roll no crew action to activate the ice protection system should be assumed to occur until the aeroplane is 122m (400 ft) above the take-off surface.

(e) <u>Ice accretion prior to normal system operation</u>. The ice accretion prior to normal system operation is the ice accretion formed on the unprotected and normally protected surfaces prior to activation and effective operation of any ice protection system in continuous maximum atmospheric icing conditions.

Proposal 17

Renumber AMC 25.119(a) as AMC 25.119 and amend references to CS 25.119(a) accordingly.

Proposal 18

Renumber AMC 25.121(b)(1) as AMC 25.121(b)(1)(i) and amend references to CS 25.121(b)(1) accordingly.

Proposal 19

Renumber AMC 25.125(a)(3) as AMC 25.125(b)(3) and amend references to CS 25.125(a)(3) accordingly.

Proposal 20

Renumber AMC 25.125(b) as AMC 25.125(c) and amend references to CS 25.125(b) accordingly.

Proposal 21

Renumber AMC 25.125(b)(2) as AMC 25.125(c)(2) and amend references to CS 25.125(b)(2) accordingly.

Proposal 22

Renumber AMC 25.143(c) as AMC 25.143(d) and amend references to CS 25.143(c) accordingly.

Proposal 23

Renumber AMCs No 1 and No 2 to CS 25.143(f) as AMCs No 1 and No 2 to CS 25.143(g) and amend references to CS 25.143(f) accordingly, and to CS 25.143(c) as above.

Proposal 24

Renumber AMC 25.143(g) as AMC 25.143(h) and amend references to CS 25.143(g) accordingly.

Proposal 25

Amend the cross-references in paragraphs 4.3(a) and 5.3.1(b) of AMC 25.1329 to refer to CS 25.143(d).

APPENDIX N - FTHWG RECOMMENDATIONS FOR ADVISORY MATERIAL

Note: Bold and italic fonts (and strikeouts) in this Appendix indicate changes relative to previously submitted ACJ 25.21(g) which was initially drafted to address Appendix C icing conditions only. The changes are intended to address Appendix X icing conditions and to consolidate performance and handling quality information that was previously contained in AC 25.1419-1A.

ACJ 25.21(g) Performance and Handling Characteristics in Icing Conditions ~~Contained in Appendix C, Part 25~~ (Acceptable Means of Compliance) (see JAR 25.21(g))

Table of Contents

1 *Purpose*.

1.1 This ACJ describes an acceptable means for showing compliance with the requirements related to performance and handling characteristics of Large Aeroplanes as affected by flight in the icing conditions that are defined in Appendix***es*** C ***and X*** to JAR-25. The means of compliance described in this ACJ is intended to provide guidance to supplement the engineering and operational judgement that should form the basis of any compliance findings relative to handling characteristics and performance in ~~Appendix C~~ icing conditions.

1.2 The guidance information is presented in sections 4 to 6 and three appendices.

1.3 Section 4 explains the various performance and handling requirements in relation to the flight conditions that are relevant for determining the shape and texture of ice accretions for the aeroplane in the atmospheric ***icing*** conditions of JAR-25, Appendix***es*** C ***and X***.

1.4 Section 5 describes acceptable methods and procedures that an applicant may use to show that an aeroplane meets these requirements. Depending on the design features of a specific aeroplane as discussed in Appendix 3 of this ACJ, its similarity to other types or models, and the service history of those types or models, some judgement will often be necessary for determining that any particular method or procedure is adequate for showing compliance with a particular requirement.

1.5 Section 6 provides an acceptable flight test programme where flight testing is selected by the applicant and agreed by the Authority as being the primary means of compliance.

1.6 The three appendices provide additional reference material associated with ice accretion, artificial ice shapes, and aeroplane design features.

2 *Related Requirements.* The following paragraphs of JAR-25 are related to the guidance in this ACJ:

- JAR 25.21 (Proof of compliance)
- JAR 25.103 (Stall speed)
- JAR 25.105 (Takeoff)
- JAR 25.107 (Takeoff speeds)
- JAR 25.111 (Takeoff path)
- JAR 25.119 (Landing climb)

- JAR 25.121 (Climb: One-engine-inoperative)
- JAR 25.123 (En-route flight paths)
- JAR 25.125 (Landing)
- JAR 25.143 (Controllability and Manoeuvrability - General)
- JAR 25.207 (Stall warning)
- JAR 25.237 (Wind velocities)
- JAR 25.253 (High-speed characteristics)
- JAR 25.1309 (Equipment, systems, and installations)
- JAR 25.1419 (Ice protection)
- ***JAR 25.1420 (Supercooled large drop icing conditions)***
- JAR 25.1581 (Aeroplane Flight Manual)
- JAR-25, Appendix C
- ***JAR-25, Appendix X***

3 *Reserved.*

4 *Requirements and Guidance.*

4.1 *General.* This section provides guidance for showing compliance with Subpart B requirements for flight in the icing conditions of Appendix***es*** C ***and X*** to JAR-25.

4.1.1 Operating rules for commercial operation of large aeroplanes (e.g. JAR-OPS 1.345) ***do not allow a take-off to be commenced unless the external surfaces are clear of any deposit (ice or other contaminant) that might adversely affect the performance and/or controllability of the aeroplane except as permitted in the Aeroplane Flight Manual*** ~~require that the aeroplane is free of any significant ice contamination at the beginning of the take-off roll due to application of appropriate ice removal and ice protection procedures during flight preparation on the ground.~~

4.1.2 Appendix***es*** C ***and X*** to JAR-25 define the ice accretions to be used in showing compliance with JAR 25.21(g). Appendix 1 of this ACJ provides details on ice accretions, including accounting for delay in the operation of the ice protection system and consideration of ice detection systems.

4.1.3 Certification experience has shown that it is not necessary to consider ice accumulation on the propeller, induction system or engine components of an inoperative engine for handling qualities substantiation. Similarly, the mass of the ice need not normally be considered.

4.1.4 Flight in icing conditions includes operation of the aeroplane after leaving the icing conditions, but with ice accretion remaining on the critical surfaces of the aeroplane.

4.1.5 Ice contaminated tailplane stall (ICTS) is a phenomenon that occurs due to airflow separation on the lower surface of the tailplane. This can occur if the angle-of-attack of the horizontal tailplane exceeds the stall angle-of-attack, which can be reduced by even small quantities of ice on the tailplane leading edge. The increase in tailplane angle-of-attack can result from aeroplane configuration (e.g., increased flap extension increasing the downwash angle or trim required for the centre-of-gravity position) and flight conditions (e.g., a high approach speed resulting in an increased flap downwash angle, gusts, manoeuvring, or changes to engine power setting). ICTS is characterized by a reduction or loss of pitch control or stability while operating in, or after recently departing from, icing conditions. For aeroplanes with unpowered longitudinal control systems, the pressure differential between the upper and lower surfaces of the stalled tailplane may result in a high elevator hinge moment, forcing the elevator trailing edge down. This elevator hinge moment reversal can be of sufficient magnitude to draw the control column forward with a level of force that is beyond the combined efforts of the flightcrew to overcome. On some aeroplanes, ICTS has been caused by a lateral flow component coming off of the vertical stabilizer, as may occur in sideslip conditions or due to a gust with a lateral component. Aerodynamic effects of reduced tailplane lift should be considered for all aeroplanes, including those with powered controls. Aeroplanes susceptible to this phenomenon are those having a near zero or negative tailplane stall margin with tailplane icing contamination. An acceptable flight test procedure for determining susceptibility to ICTS is presented in paragraph 6.9.3 of this ACJ.

4.1.6 Supercooled large drop icing conditions or runback ice can result in the formation of a ridge of ice aft of the protected area on the wing upper surface, leading to separated airflow over the aileron. Ice induced airflow separation upstream of the aileron can have a significant effect on the aileron hinge moment. Depending on the extent of the separated flow and the flight control system design, ice accretion upstream of the aileron may lead to aileron hinge moment reversal, reduced aileron effectiveness, and aileron control reversal. Although aeroplanes with de-icing boots and unpowered aileron controls are most susceptible to this problem, all aeroplanes should be evaluated for roll control capability in icing conditions. Acceptable flight test procedures for checking roll control capability are presented in paragraphs 6.9.2(e), 6.15, and 6.17.2(e) of this

ACJ and consist of bank-to-bank roll manoeuvres, steady heading sideslips, and stall tests.

4.1.7 JAR 25.21(g) requires that for an aeroplane to be certified for flight in icing conditions, the aeroplane must be able to meet certain performance and handling quality requirements of JAR-25 subpart B while operating in the atmospheric icing environment defined in Appendix C to JAR-25.

4.1.8 JAR 25.21(g) also requires compliance with certain subpart B performance and handling qualities requirements with ice accretions on the aeroplane that are defined in Appendix X to JAR-25. The only subpart B performance requirements that must be met for an encounter with supercooled large drop atmospheric icing conditions beyond those for which the airplane is certified for are: (1) stall speed (JAR 25.103), landing climb (JAR 25.119), and landing (JAR 25.125). Relative to the other performance requirements, it is assumed that the existing requirements for Appendix C ice accretions will provide adequate performance capability to allow a safe exit from all icing conditions after an encounter with supercooled large drop atmospheric icing conditions beyond those for which the airplane is certified.

4.1.9 For Appendix X atmospheric icing conditions, applicants can choose to either: (1) not seek approval for flight in Appendix X conditions; (2) seek approval for flight in only a portion of the Appendix X icing conditions; or (3) seek approval for flight throughout the entire Appendix X atmospheric icing envelope. Applicants may also choose to certify for flight in Appendix X (or a portion of Appendix X) icing conditions in some flight phases and not in others. For any portion of Appendix X for which the aeroplane is not certified for flight, the aeroplane must be capable of encountering those conditions, and then safely exiting all icing conditions.

4.1.10 If the aeroplane is not to be certified for flight throughout the entire atmospheric icing envelope of Appendix X, there must be a means to indicate when the aeroplane has encountered icing conditions beyond those for which it has been certified. See ACJ 25.1419/1420 for guidance on acceptable means of detecting and indicating when the aeroplane has encountered icing conditions beyond those for which it has been certified. Procedures should be provided in the Aeroplane Flight Manual to enable a safe exit from all icing conditions after an encounter with icing conditions beyond those for which the aeroplane is certified.

4.1.11 To certify the aeroplane for operations in Appendix X icing conditions only for certain flight phase(s), the flight phase(s) for which operation is approved should be defined such that a flightcrew can easily determine whether the aeroplane is operating inside or outside of its certified icing envelope. The critical ice accretion or accretions used to show compliance with the applicable Subpart B requirements should cover the range of airplane configurations, operating speeds, angles-of-attack, and engine thrust or power settings that may be

encountered during that phase of flight (not just at the conditions specified in Subpart B requirements), and should include an adequate time in the icing conditions to address operational variabilities. For the ice accretion scenarios defined in paragraph A.1.4.3.3 of Appendix 1 of this AC, the applicable flight phases are: take-off (including the ground roll, take-off and final take-off segments), en-route, holding, and approach/landing (including both the approach and landing segments).

4.1.12 The ice accretions used to show compliance with the applicable subpart B regulations should be consistent with the extent of the desired certification for flight in icing conditions. Appendixes C and X to JAR-25 define the ice accretions, as a function of flight phase, that must be considered for certification approval for flight in those respective icing conditions. In order to reduce the number of ice accretions used for demonstrating compliance, any of the applicable ice accretions (or a composite accretion representing a combination of accretions) may be used to show compliance with a particular Subpart B requirement if that accretion is either the ice accretion identified in the requirement or is shown to be more conservative than the ice accretion identified in the requirement. In addition, the ice accretion that has the most adverse effect on handling characteristics may be used for compliance with the airplane performance requirements if any difference in performance is conservatively taken into account. The ice accretion(s) used to show compliance should consider the speeds, configurations (including configuration changes), angles of attack, power or thrust settings, etc. for the flight phases and icing conditions that they are intended to cover. For example, if certification for flight in the supercooled large drop icing conditions of Appendix X is desired in addition to the icing conditions of Appendix C, compliance with the applicable subpart B requirements may be shown using the most critical of the Appendix C and Appendix X ice accretions.

4.2 *Proof of Compliance (JAR 25.21(g)).*

4.2.1 Demonstration of compliance with certification requirements for flight in icing conditions may be accomplished by any of the means discussed in paragraph 5.1 of this ACJ.

4.2.2 Certification experience has shown that aeroplanes of conventional design do not require additional detailed substantiation of compliance with the requirements of the following paragraphs of JAR-25 for flight in icing conditions or with ice accretions:

25.23,
25.25,
25.27,
25.29,
25.31,
25.231,

25.233,
25.235,
25.253(a) and (b), and
25.255

4.2.3 Where normal operation of the ice protection system results in changing the stall warning system and/or stall identification system activation settings, it is acceptable to establish a procedure to return to the non icing settings when it can be demonstrated that the critical wing surfaces are free of ice accretion.

4.3 *Propeller Speed and Pitch Limits (JAR 25.33).* Certification experience has shown that it may be necessary to impose additional propeller speed limits for operations in icing conditions.

4.4 *Performance - General (JAR 25.101).*

4.4.1 The propulsive power or thrust available for each flight condition must be appropriate to the aeroplane operating limitations and normal procedures for flight in icing conditions. In general, it is acceptable to determine the propulsive power or thrust available by suitable analysis, substantiated when required by appropriate flight tests (e.g. when determining the power or thrust available after 8 seconds for JAR 25.119). The following aspects should be considered:

a. Operation of induction system ice protection.

b. Operation of propeller ice protection.

c. Operation of engine ice protection.

d. Operation of airframe ice protection system.

4.4.2 The following should be considered when determining the change in performance due to flight in icing conditions:

a. Thrust loss due to ice accretion on propulsion system components with normal operation of the ice protection system, including engine induction system and/or engine components, and propeller spinner and blades.

b. The incremental airframe drag due to ice accretion with normal operation of the ice protection system.

c. Changes in operating speeds due to flight in icing conditions.

4.4.3 Certification experience has shown that any increment in drag (or decrement in thrust) due to the effects of ice accumulation on the landing gear, propeller, induction system and engine components may be determined by a suitable analysis.

4.4.4 Apart from the use of appropriate speed adjustments to account for operation in icing conditions, any changes in the procedures established for take-off, balked landing, and missed approaches should be agreed with the Authority.

4.4.5 Performance associated with flight in icing conditions is applicable after exiting icing conditions until the aeroplane critical surfaces are free of ice accretion and the ice protection systems are selected “Off.”

4.5 *Stall speed (JAR 25.103)*. Certification experience has shown that for aeroplanes of conventional design it is not necessary to make a separate determination of the effects of Mach number on stall speeds for the aeroplane with ice accretions.

4.6 *Failure Conditions (JAR 25.1309)*.

4.6.1 The failure modes of the ice protection system and the resulting effects on aeroplane handling and performance should be analysed in accordance with JAR 25.1309. In determining the probability of a failure condition, it should be assumed that the probability of entering ***the atmospheric*** icing conditions ***covered by Appendix C to JAR-25,*** is one. ***As explained in ACJ 25.1419/1420, on an annual basis, the average probability of 1 x*** $\boldsymbol{10^{-2}}$ ***per flight hour may be assumed for encountering Appendix X conditions within a quantitative analysis. This probability should not be reduced based on phase of flight.*** The "Failure Ice" ~~configuration~~ ***accretion*** is defined in Appendix 1, paragraph A1.3.

4.6.2 For probable failure conditions that are not annunciated to the flight crew, the guidance in this ACJ for a normal condition is applicable with the "Failure Ice" configuration.

4.6.3 For probable failure conditions that are annunciated to the flight crew, with an associated procedure that does not require the aeroplane to exit icing conditions, the guidance in this ACJ for a normal condition is applicable with the "Failure Ice" configuration.

4.6.4 For probable failure conditions that are annunciated to the flight crew, with an associated operating procedure that requires the aeroplane to leave the icing conditions as soon as practicable, it should be shown that the aeroplane is capable of continued safe flight and landing with the “Failure Ice" configuration. The operating procedures and related speeds should provide an adequate operating envelope and acceptable performance and handling characteristics to ensure continued safe flight and landing.

4.6.5 For failure conditions that are improbable but not extremely improbable, the analysis and substantiation of continued safe flight and landing, in accordance with JAR 25.1309, should take into consideration whether annunciation of the failure is provided and the associated operating procedures and speeds to be used following the failure condition.

4.7 *Flight-related Systems*. In general, systems aspects are covered by the applicable systems and equipment requirements in other subparts of JAR-25, and associated guidance material. However, certification experience has shown that other flight related systems aspects should be considered when determining compliance with the flight requirements of subpart B. For example, the following aspects may be relevant:

a. The ice protection systems may not anti-ice or de-ice properly at all power or thrust settings. This may result in a minimum power or thrust setting for operation in icing conditions which affects descent and/or approach capability.

b. Ice blockage of control surface gaps and/or freezing of seals causing increased control forces, control restrictions or blockage.

c. Airspeed, altitude and/or angle of attack sensing errors due to ice accretion forward of the sensors (e.g. radome ice). Dynamic pressure ("q") operated feel systems using separate sensors also may be affected.

d. Ice blockage of unprotected inlets and vents that may affect the propulsive thrust available, aerodynamic drag, powerplant control, or flight control.

e. Operation of stall warning and stall identification reset features for flight in icing conditions, including the effects of failure to operate.

f. Operation of icing condition sensors, ice accretion sensors, and automatic or manual activation of ice protection systems.

g. ***Flight guidance and automatic*** flight control systems operation. ***See ACJ 25.1329-XX, "Flight guidance system," for guidance on compliance with § 25.1329 for flight in icing conditions, including stall and maneuverability demonstrations with the airplane under flight guidance system control***.

h. Installed thrust. This includes operation of ice protection systems when establishing acceptable power or thrust setting procedures, control, stability, lapse rates, rotor speed margins, temperature margins, Automatic Reserve Power (ARP) operation, and power or thrust lever angle functions.

4.8 *Aeroplane Flight Manual (JAR 25.1581).*

4.8.1 *Limitations.*

4.8.1.1 Where limitations are required to ensure safe operation in icing conditions, these limitations should be stated in the ***Aeroplane Flight Manual (***AFM***).***

4.8.1.2 Performance limitations should be presented for flight in icing conditions that reflect any effects on lift, drag, thrust, and operating speeds due to operating in icing conditions. These limitations may be presented in the Performance Information Section of the AFM and included as limitations by specific reference in the Limitations Section of the AFM.

4.8.1.3 Any airspeed limitations associated with flight in icing conditions should be presented, such as the minimum airspeed that should be maintained for each normal airplane configuration in icing conditions.

4.8.1.***4*** The Limitations section of the AFM should include, as applicable, a statement similar to the following: “In icing conditions the aeroplane must be operated, and its ice protection systems used, as described in the operating procedures section of this manual. Where specific operational speeds and performance information have been established for such conditions, this information must be used."

4.8.1.5 The “kinds of operation” portion of the AFM Limitations section should include, as applicable, a statement similar to the following, clearly stating the extent of the certification for flight in icing conditions:
“This aircraft has been certified for operations under freezing drizzle or freezing rain icing conditions (as appropriate). If these conditions are anticipated at takeoff [for aeroplanes approved to take off in these conditions,] any relevant limitations or operating procedures for operating on a contaminated runway should also be observed.”

4.8.1.6 For aeroplanes not certified to operate throughout the atmospheric icing envelope of Appendix X for every flight phase, the Limitations section of the AFM should also identify the means for detecting when the certified icing conditions have been exceeded and that intentional flight, including take off and landing, into these conditions is prohibited. A requirement to exit all icing conditions must be included if the uncertified portion of Appendix X is encountered. The statements in the Limitations section should generally be concise with additional information provided in the AFM and Flightcrew Operating Manual (FCOM) procedure sections. See ACJ 25.1419/1420 for guidance on acceptable means for identifying when the icing conditions exceed the icing conditions for which the aeroplane has been certified. Examples of AFM and FCOM wording are provided in Appendix 4 of this AC for some of the possible certification options. (Note: This example

AFM wording only addresses the extent of certification for Appendix X icing conditions. Other limitations and procedural information as noted under paragraphs 4.8.1 and 4.8.2 of this AC should be included as well.)

4.8.2 *Operating Procedures.*

4.8.2.1 AFM operating procedures for flight in icing conditions should include normal operation of the aeroplane including operation of the ice protection system and operation of the aeroplane following ice protection system failures. Any changes in procedures for other aeroplane system failures that affect the capability of the aeroplane to operate in icing conditions should be included.

4.8.2.2 Normal operating procedures provided in the AFM should reflect the procedures used to certify the aeroplane for flight in icing conditions. This includes configurations, speeds, ice protection system operation, power plant and systems operation, for take-off, climb, cruise, descent, holding, go-around, and landing. ***For airplanes not certified for flight in the entire supercooled large drop atmospheric icing conditions defined in Appendix X to JAR-25, procedures should be provided for safely exiting icing conditions that exceed those for which the airplane is certified. Examples of acceptable procedures statements are provided in Appendix 4 of this AC for some of the possible certification options.***

4.8.2.3 Abnormal operating procedures should include the procedures to be followed in the event of annunciated ice protection system failures and suspected unannunciated failures. Any changes to other abnormal procedures contained in the AFM, due to flight in icing conditions, should also be included.

4.8.3 *Performance Information.* Performance information, derived in accordance with subpart B of JAR-25, must be provided in the AFM for all relevant phases of flight.

5 *Acceptable Means of Compliance - General.*

5.1 *General.*

5.1.1 This section describes acceptable methods and procedures that an applicant may use to show that an aeroplane meets the performance and handling requirements of subpart B in the atmospheric ***icing*** conditions of ~~Appendix C to~~ **JAR-25.**

5.1.2 Compliance with JAR 25.21(g) should be shown by one or more of the methods listed in this section.

5.1.3 The compliance process should address all phases of flight, including take-off, climb, cruise, holding, descent, landing, and go-around as appropriate to the aeroplane type, considering its typical operating regime ***and the extent of its certification approval for operation in Appendix X.***

5.1.4 The design features included in Appendix 3 of this ACJ should be considered when determining the extent of the substantiation programme.

5.1.5 Appropriate means for showing compliance include the actions and items listed in Table 1. These are explained in more detail in the following sections of this ACJ.

TABLE 1: Means for Showing Compliance

Flight Testing	Flight testing in dry air using artificial ice shapes or with ice shapes created in natural icing conditions.
Wind Tunnel Testing and Analysis	An analysis of results from wind tunnel tests with artificial or actual ice shapes.
Engineering Simulator Testing and Analysis	An analysis of results from engineering simulator tests.
Engineering Analysis	An analysis which may include the results from executing an agreed computer code.
Ancestor Aeroplane Analysis	An analysis of results from a closely related ancestor aeroplane.

5.1.6 Various factors that affect ice accretion on the airframe with an operative ice protection system and with ice protection system failures are discussed in Appendix 1 of this ACJ.

5.1.7 An acceptable methodology to obtain agreement on the artificial ice shapes is given in Appendix 2 of this ACJ. That appendix also provides the different types of artificial ice shapes to be considered.

5.2 *Flight Testing.*

5.2.1 *General*.

5.2.1.1 The extent of the flight test programme should consider the results obtained with the non-contaminated aeroplane and the design features of the aeroplane as discussed in Appendix 3 of this ACJ.

5.2.1.2 It is not necessary to repeat an extensive performance and flight characteristics test programme on an aeroplane with ice accretion. A suitable programme that is sufficient to demonstrate compliance with the requirements can be established from experience with aeroplanes of similar size, and from review of the ice protection system design, control system design, wing design, horizontal and vertical stabiliser design, performance characteristics, and handling characteristics of the non-contaminated aeroplane. In particular, it is not necessary to investigate all weight and centre of gravity combinations when results from the non-contaminated aeroplane clearly indicate the most critical combination to be tested. It is not necessary to investigate the flight characteristics of the aeroplane at high altitude (i.e. above the upper limit specified in Appendix***es*** C ***and X*** to JAR-25). An acceptable flight test programme is provided in section 6 of this ACJ.

5.2.1.3 Certification experience has shown that tests are usually necessary to evaluate the consequences of ice protection system failures on handling characteristics and performance and to demonstrate continued safe flight and landing.

5.2.2 *Flight Testing Using Approved Artificial Ice Shapes*.

5.2.2.1 The performance and handling tests may be based on flight testing in dry air using artificial ice shapes that have been agreed with the Authority.

5.2.2.2 Additional limited flight tests should be conducted in natural icing conditions, which are discussed in paragraph 5.2.3, below.

5.2.3 *Flight Testing In Natural Icing Conditions.*

5.2.3.1 Where flight testing in natural atmospheric icing conditions is the primary means of compliance, the conditions should be measured and recorded. The tests should ensure good coverage of Appendix***es*** C ***and X (as appropriate for the extent of the certification approval for operation in Appendix X)*** conditions and, in particular, the critical conditions. The conditions for accreting ice (including the icing atmosphere, configuration, speed and duration of exposure) should be agreed with the Authority.

5.2.3.2 Where flight testing with artificial ice shapes is the primary means of compliance, additional limited flight tests should be conducted in natural icing conditions. The objective of these tests is to corroborate the handling characteristics and performance results obtained in flight testing with artificial ice shapes. As such, it is not necessary to measure the atmospheric characteristics (i.e. liquid water content (LWC) and median volumetric diameter (MVD)) of the flight test icing conditions. For some derivative aeroplanes with similar aerodynamic characteristics as the ancestor, it may not be necessary to carry out additional flight test***s*** in natural icing conditions if such tests have been already performed with the ancestor. ***Depending on the extent of certification being sought for flight in the icing conditions of Appendix X and the means for showing compliance with the applicable aeroplane performance and handling characteristics requirements, it may also may not be necessary to conduct flight tests in the natural icing conditions of Appendix X. See ACJ 25.1419/1420 and paragraph 6.21.1.2 of this ACJ for guidance on when flight testing in the natural atmospheric icing conditions of Appendix X is necessary.***

5.3 *Wind Tunnel Testing and Analysis.* Analysis of the results of dry air wind tunnel testing of models with artificial ice shapes, as defined in ***Appendixes C and X*** ~~Part II of Appendix C~~ JAR-25, may be used to substantiate the performance and handling characteristics.

5.4 *Engineering Simulator Testing and Analysis.* The results of an engineering simulator analysis of an aeroplane that includes the effects of the ice accretions as defined in ***Appendixes C and X to*** ~~Part II of Appendix C~~ to JAR-25 may be used to substantiate the handling characteristics. The data used to model the effects of ice accretions for the engineering simulator may be based on results of dry air wind tunnel tests, flight tests, computational analysis, and engineering judgement.

5.5 *Engineering Analysis.* An engineering analysis that includes the effects of the ice accretions as defined in ***Appendixes C and X*** ~~Part II of Appendix C~~ to JAR-25 may be used to substantiate the performance and handling characteristics. The effects of the ice shapes used in this analysis may be determined by an analysis of the results of dry air wind tunnel tests, flight tests, computational analysis, engineering simulator analysis, and engineering judgement.

5.6 *Ancestor Aeroplane Analysis.*

5.6.1 An ancestor aeroplane analysis that includes the effect of the ice accretions as defined in ***Appendixes C and X*** ~~Part II of Appendix C~~ to JAR-25 may be used to substantiate the performance and handling characteristics. This analysis should consider the similarity of the configuration, operating envelope, performance and handling characteristics, and ice protection system of the ancestor aeroplane.

5.6.2 The analysis may include flight test data, dry air wind tunnel test data, icing tunnel test data, engineering simulator analysis, service history, and engineering judgement.

6 *Acceptable Means of Compliance - Flight Test Programme.*

6.1 *General.*

6.1.1 This section provides an acceptable flight test programme where flight testing is selected by the applicant and agreed by the Authority as being the primary means for showing compliance.

6.1.2 Where an alternate means of compliance is proposed for a specific paragraph in this section, it should enable compliance to be shown with at least the same degree of confidence as flight test would provide (see JAR 25.21(a)(1)).

6.1.3 Ice accretions for each flight phase are defined in Appendixes C and X to JAR-25. Additional guidance for determining the applicable ice accretions is provided in Appendix 1 to this ACJ.

6.1.***4*** This test programme is based on the assumption that the applicant will choose to use "Holding Ice" for the majority of the testing ~~on the basis that this is the most conservative shape~~ ***if "Holding Ice" is found to be the most conservative ice shape for all phases of flight.*** ~~Where this is not so, the~~ ***In general, the*** applicant may choose to use ***either*** ~~an~~ ***the specific*** ice ~~shape~~ ***accretion*** appropriate to the particular phase of flight ***and icing conditions for which certification is desired (i.e., Appendix C or Appendix X to JAR-25), or an accretion that is shown to be conservative for the particular application. In addition, the ice accretion that has the most adverse effect on handling characteristics may be used for airplane performance tests provided any difference in performance is conservatively taken into account.***

6.2 *Stall Speed (JAR 25.103).*

6.2.1 The stall speed for intermediate high lift configurations can normally be obtained by interpolation. However if a stall identification system (e.g. stick pusher) firing point is set as a function of the high lift configuration and/or the firing point is reset for icing conditions, or if significant configuration changes occur with extension of trailing edge flaps (such as wing leading edge high-lift device position movement), additional tests may be necessary.

6.2.2 *Acceptable Test Programme*. The following represents an acceptable test programme subject to the provisions outlined above:

a. Forward centre of gravity position appropriate to the configuration.

b. Normal stall test altitude.

c. In the configurations listed below, trim the aeroplane at an initial speed of 1.13 to 1.30 V_{SR}. Decrease speed until an acceptable stall identification is obtained.

i. High lift devices retracted configuration, "Final Take-off Ice."

ii. High lift devices retracted configuration, "En-route Ice."

iii. Holding configuration, "Holding Ice."

iv. Lowest lift take-off configuration, "Holding Ice."

v. Highest lift take-off configuration, "Take-off Ice."

vi. Highest lift landing configuration, "Holding Ice."

6.3 *Accelerate-stop Distance (JAR 25.109).* The effect of any increase in V_1 due to take-off in icing conditions may be determined by a suitable analysis.

6.4 *Take-off Path (JAR 25.111).* If V_{SR} in the configuration defined by JAR 25.121(b) with the “Takeoff Ice" accretion ~~defined in Appendix C to JAR-25~~ exceeds V_{SR} for the same configuration without ice accretions by more than the greater of 3 knots or 3%, the take-off demonstrations should be repeated to substantiate the speed schedule and distances for take-off in icing conditions. The effect of the take-off speed increase, thrust loss, and drag increase on the take-off path may be determined by a suitable analysis.

6.5 *Landing Climb: All-engines-operating (JAR 25.119). Acceptable Test Programme*. The following represents an acceptable test programme:

a. "Holding Ice."

b. Forward centre of gravity position appropriate to the configuration.

c. Highest lift landing configuration, landing climb speed no greater than V_{REF}.

d. Stabilise at the specified speed and conduct 2 climbs or drag polar checks as agreed with the Authority.

6.6 *Climb: One-engine-inoperative (JAR 25.121). Acceptable Test Programme*. The following represents an acceptable test programme:

a. Forward centre of gravity position appropriate to the configuration.

b. In the configurations listed below, stabilise the aeroplane at the specified speed with one engine inoperative (or simulated inoperative if all effects can be taken into account) and conduct 2 climbs in each configuration or drag polar checks substantiated for the asymmetric drag increment as agreed with the Authority.

i. High lift devices retracted configuration, final take-off climb speed, "Final Take-off Ice."

ii. Lowest lift take-off configuration, landing gear retracted, V_2 climb speed, "Take-off Ice."

iii. Approach configuration appropriate to the highest lift landing configuration, landing gear retracted, approach climb speed, "Holding Ice."

6.7 *En-route Flight Path (JAR 25.123)*. *Acceptable Test Programme*. The following represents an acceptable test programme:

a. "En-route Ice."

b. Forward centre of gravity position appropriate to the configuration.

c. En-route configuration and climb speed.

d. Stabilise at the specified speed with one engine inoperative (or simulated inoperative if all effects can be taken into account) and conduct 2 climbs or drag polar checks substantiated for the asymmetric drag increment as agreed with the Authority.

6.8 *Landing (JAR 25.125).* The effect of landing speed increase on the landing distance may be determined by a suitable analysis.

6.9 *Controllability and Manoeuvrability - General (JAR 25.143 and 25.177).*

6.9.1 A qualitative and quantitative evaluation is usually necessary to evaluate the aeroplane's controllability and manoeuvrability. In the case of marginal compliance, or the force limits or stick force per g limits of JAR 25.143 being approached, additional substantiation may be necessary to establish compliance. In general, it is not necessary to consider separately the ice accretion appropriate to take-off and en-route because the "Holding Ice" is usually the most critical.

6.9.2 *General Controllability and Manoeuvrability*. The following represents an acceptable test programme for general controllability and manoeuvrability, subject to the provisions outlined above:

a. "Holding Ice."

b. Medium to light weight, aft centre of gravity position, symmetric fuel loading.

c. In the configurations listed in Table 2, trim at the specified speeds and conduct the following manoeuvres:

~~i. 30° banked turns left and right with rapid reversals;~~

i. Pull up to 1.5g (except that this may be limited to 1.3g at V_{REF}), and pushover to 0.5g (except that the pushover is not required at V_{MO} and V_{FE}); and

ii. Deploy and retract deceleration devices.

TABLE 2: Trim Speeds

Configuration	*Trim Speed*
High lift devices retracted configuration:	• 1.3 V_{SR}, and • V_{MO} or 250 KIAS, whichever is less
Lowest lift takeoff configuration:	• 1.3 V_{SR}, and • V_{FE} or 250 KIAS, whichever is less
Highest lift landing configuration:	• V_{REF}, and • V_{FE} or 250 KIAS, whichever is less.

d. Lowest lift take-off configuration: At the greater of 1.13 V_{SR} or $V_{2\ MIN}$, with one engine inoperative (simulated), conduct 30° banked turns left and right with normal turn reversals and, in wings-level flight, a 5 knot speed decrease and increase.

e. Holding configuration, maximum landing weight, minimum holding speed (highest expected holding angle-of-attack) and highest lift landing configuration, maximum landing weight, forward c.g, V_{REF} (highest expected landing approach angle-of-attack): Trim the aeroplane in level flight, establish a 30° bank level turn. Using a step input of approximately 1/3 full lateral control deflection, roll the aeroplane in the other direction. When the airplane reaches approximately 20° bank in the opposite direction, apply the same lateral control input in the opposite direction. Release input and recover as the

aeroplane passes a wings level attitude. Repeat the test procedure with 2/3 and then full lateral control deflection unless the roll rate is judged to be excessive. It should be possible to readily arrest and reverse the roll rate using only lateral control input, and the lateral control force should not reverse with increasing control deflection.

f. Conduct an approach and go-around with all engines operating using the recommended procedure.

g. Conduct an approach and go-around with one engine inoperative (simulated) using the recommended procedure.

h. Conduct an approach and landing using the recommended procedure. In addition satisfactory controllability should be demonstrated during a landing at V_{REF} minus 5 knots. These tests should be done at heavy weight and forward centre of gravity.

i. Conduct an approach and landing with one engine inoperative (simulated) using the recommended procedure.

6.9.3 *Low g Manoeuvres and Sideslips.* The following represents an acceptable test programme for compliance with controllability requirements in low g manoeuvres and in sideslips.

JAA/FAA/ALPA Position

6.9.3.1 It should be shown that a push force is required throughout a pushover manoeuvre down to zero g or the lowest load obtainable if limited by elevator power. It should be possible to promptly recover from the manoeuvre without exceeding 50 pounds pull control force.

Industry Position

6.9.3.1 For pushover manoeuvres, it should be shown that the aeroplane is controllable down to zero g or the lowest load factor obtainable if limited by elevator power. It should be shown that a push force is required down to 0.5 g load factor, and that it is possible to promptly recover from the manoeuvre without exceeding 50 pounds pull control force.

TC Position

6.9.3.1 For pushover manoeuvres, it should be shown that the aeroplane is controllable down to zero g or the lowest load factor obtainable if limited by elevator power. It should be shown that a push force is required down to 0.25 g load factor, and that it is possible to promptly recover from the manoeuvre without exceeding 50 pounds pull control force.

6.9.3.2 For sideslips, changes in longitudinal control force to maintain speed with increasing sideslip should be progressive, with no reversals or unacceptable discontinuities (see paragraph 6.15.1 of this ACJ).

6.9.3.3 The test manoeuvres described in paragraphs 6.9.3.1 and 6.9.3.2, above, should be conducted using the following configurations and procedures:

a. "Holding Ice." For aeroplanes with unpowered elevators, these tests should also be performed with "Sandpaper Ice."

b. Medium to light weight, the most critical of aft or forward centre of gravity position, symmetric fuel loading.

c. In the configurations listed below, with the aeroplane in trim, or as nearly as possible in trim, at the specified trim speed, perform a continuous manoeuvre (without changing trim) to reach zero g normal load factor or, if limited by elevator control authority, the lowest load factor obtainable at the target speed.

i. Highest lift landing configuration at idle power or thrust, and the more critical of:

- Trim speed 1.23 V_{SR}, target speed not <u>more</u> than 1.23 V_{SR}, or

- Trim speed V_{FE}, target speed not <u>less</u> than V_{FE} - 20 knots.

ii. Highest lift landing configuration at go-around power or thrust, and the more critical of:

- Trim speed 1.23 V_{SR}, target speed not <u>more</u> than 1.23 V_{SR}, or

- Trim speed V_{FE}, target speed not <u>less</u> than V_{FE} - 20 knots.

iii. Conduct steady heading sideslips to full rudder authority, 180 lb. rudder force or full lateral control authority (whichever comes first), with highest lift landing configuration, trim speed 1.23 V_{SR}, and power or thrust for -3° flight path angle.

6.9.4 *Controllability prior to Normal Operation of the Ice Protection System* **and prior to Detection of Appendix X icing conditions.** The following represents an acceptable test programme for compliance with ***the applicable*** controllability requirements ~~with the ice accretion prior to normal operation of the ice protection system~~.

6.9.4.1 Where the ice protection system is activated as described in paragraph A1.2.3.3.a of Appendix 1 of this ACJ, paragraphs 6.9.1, 6.9.2 and 6.9.3 of this ACJ are applicable with the ice accretion prior to normal system operation***. When the primary means of detecting Appendix X icing conditions depends on the flight crew to recognize visual cues of Appendix X icing, paragraphs 6.9.1, 6.9.2 and 6.9.3 of this***

ACJ are also applicable using the ice accretion prior to detection of Appendix X icing conditions.

6.9.4.2 Where the ice protection system is activated as described in paragraphs A1.2.3.3.b,c,d or e of Appendix 1 of this ACJ, it is acceptable to demonstrate adequate controllability with the ice accretion prior to normal system operation, as follows:

a. In the configurations listed below, trim the aeroplane at the specified speed. Conduct pull up to 1.5g and pushover to 0.5g without longitudinal control force reversal.

i. High lift devices retracted configuration (or holding configuration if different), holding speed, power or thrust for level flight.

ii. Landing configuration, V_{REF} for non-icing conditions, power or thrust for landing approach (limit pull up to stall warning).

6.9.4.3 When the primary means of detecting Appendix X icing conditions is an approved ice detection system, controllability prior to detection of Appendix X icing conditions should be assessed using the criteria of paragraph 6.9.4.2 with the ice accretion prior to detection of the Appendix X icing conditions.

6.10 *Longitudinal Control (JAR 25.145).*

6.10.1 No specific quantitative evaluations are required for demonstrating compliance with JAR 25.145(b) and (c). Qualitative evaluations should be combined with the other testing. The results from the non-contaminated aeroplane tests should be reviewed to determine whether there are any cases where there was marginal compliance. If so, these cases should be repeated with ice.

6.10.2 *Acceptable Test Programme*. The following represents an acceptable test programme for compliance with JAR 25.145(a):

a. "Holding ice."

b. Medium to light weight, aft centre of gravity position, symmetric fuel loading.

c. In the configurations listed below, trim the aeroplane at 1.3 V_{SR}. Reduce speed using elevator control to stall warning plus one second and demonstrate prompt recovery to the trim speed using elevator control.

i. High lift devices retracted configuration, maximum continuous power or thrust.

ii. Maximum lift landing configuration, maximum continuous power or thrust.

6.11 *Directional and Lateral Control (JAR 25.147).* Qualitative evaluations should be combined with the other testing. The results from the non-contaminated aeroplane tests should be reviewed to determine whether there are any cases where there was marginal compliance. If so, these cases should be repeated with ice.

6.12 *Trim (JAR 25.161).* Qualitative evaluations should be combined with the other testing. The results from the non-contaminated aeroplane tests should be reviewed to determine whether there are any cases where there was marginal compliance. If so, these cases should be repeated with ice.

6.13 *Stability - General (JAR 25.171).* Qualitative evaluations should be combined with the other testing. Any tendency to change speed when trimmed or requirement for frequent trim inputs should be specifically investigated.

6.14 *Demonstration of Static Longitudinal Stability (JAR 25.175).*

6.14.1 Each of the following cases should be tested. In general, it is not necessary to test the cruise configuration at low speed (JAR 25.175(b)(2)) or the cruise configuration with landing gear extended (JAR 25.175(b)(3)); nor is it necessary to test at high altitude. Although the maximum speed for substantiation of stability characteristics is the lower of 300 knots CAS or V_{FC} (JAR 25.253c), the maximum speed for demonstration can be limited to 280 knots CAS, provided that the stick force gradient can be satisfactorily extrapolated to 300 knots CAS or V_{FC} (e.g. there is no gradient decrease with increasing speed).

6.14.2 *Acceptable Test Programme*. The following represents an acceptable test programme for demonstration of static longitudinal stability:

a. "Holding Ice."

b. High landing weight, aft centre of gravity position, symmetric fuel loading.

c. In the configurations listed below, trim the aeroplane at the specified speed. The power or thrust should be set and stability demonstrated over the speed ranges as stated in JAR 25.175(a) through (d), as applicable.

i. <u>Climb</u>: With high lift devices retracted, trim at 1.3 V_{SR}.

ii. <u>Cruise</u>: With high lift devices retracted, trim at V_{MO} or 250 knots CAS, whichever is lower.

iii. Approach: With the high lift devices in the approach position appropriate to the highest lift landing configuration, trim at 1.3 V_{SR}.

iv. Landing: With the highest lift landing configuration, trim at 1.3V_{SR}.

6.15 *Static Directional and Lateral Stability (JAR 25.177).*

6.15.1 Compliance should be demonstrated using steady heading sideslips to show compliance with directional and lateral stability. The maximum sideslip angles obtained should be recorded and may be used to substantiate a crosswind value for landing (see paragraph 6.19 of this ACJ). ***Directional and lateral control movements and forces must be substantially proportional to the angle of sideslip without snatching (i.e. sudden, sharp oscillations or reversals in control force).***

6.15.2 *Acceptable Test Programme*. The following represents an acceptable test programme for static directional and lateral stability:

a. "Holding Ice."

b. Medium to light weight, aft centre of gravity position, symmetric fuel loading.

c. In the configurations listed below, trim the aeroplane at the specified speed and conduct steady heading sideslips to full rudder authority, 180 lb. rudder pedal force, or full lateral control authority, whichever comes first.

i. High lift devices retracted configuration: Trim at best rate-of-climb speed, but need not be less than 1.3 V_{SR}.

ii. Lowest lift take-off configuration: Trim at the all-engines-operating initial climb speed.

iii. Highest lift landing configuration: Trim at V_{REF}.

6.16 *Dynamic Stability (JAR 25.181).* Provided that there are no marginal compliance aspects with the non-contaminated aeroplane, it is not necessary to demonstrate dynamic stability in specific tests. Qualitative evaluations should be combined with the other testing. Any tendency to sustain oscillations in turbulence or difficulty in achieving precise attitude control should be investigated.

6.17 *Stall Demonstration (JAR 25.201).*

6.17.1 Sufficient stall testing should be conducted to demonstrate that the stall characteristics comply with the requirements. In general, it is not necessary to conduct a stall programme which encompasses all weights, centre of gravity positions (including lateral asymmetry), altitudes, high lift configurations, deceleration device configurations, straight and turning flight stalls, power off and power on stalls. Based on a review of the stall characteristics of the non-contaminated aeroplane, a reduced test matrix can be established. However, additional testing may be necessary if:

- the stall characteristics with ice accretion show a significant difference from the non-contaminated aeroplane,
- testing indicates marginal compliance, or
- a stall identification system (e.g. stick pusher) is required to be reset for icing conditions.

6.17.2 *Acceptable Test Programme*. The following represents an acceptable test programme subject to the provisions outlined above. Turning flight stalls at decelerations greater than 1 knot/sec are not required.

a. "Holding Ice."

b. Medium to light weight, aft centre of gravity position, symmetric fuel loading.

c. Normal stall test altitude.

d. In the configurations listed below, trim the aeroplane at the same initial stall speed factor used for stall speed determination. For power-on stalls, use the power setting as defined in JAR 25.201(a)(2) but with ice accretions on the aeroplane. Decrease speed to stall identification and recover using the same test technique as for the non-contaminated aeroplane.

i. High lift devices retracted configuration: Straight/Power Off, Straight/Power On, Turning/Power Off, Turning/Power On.

ii. Lowest lift take-off configuration: Straight/Power On, Turning/Power Off.

iii. Highest lift take-off configuration: Straight/Power Off, Turning/Power On.

iv. Highest lift landing configuration: Straight/Power Off, Straight/Power On, Turning/Power Off, Turning/Power On.

e. For the configurations listed in paragraph 6.17.2(d)(i) and (iv) (and any other configuration if deemed more critical), in 1 knot/second deceleration rates down to stall warning with wings level and power off, roll the aeroplane left and right up to 10 degrees of bank using lateral control.

6.18 *Stall Warning (JAR 25.207).*

6.18.1 Stall warning should be assessed in conjunction with stall speed testing and stall characteristics testing (JAR 25.103, JAR 25.203 and paragraphs 6.2 and 6.17 of this ACJ, respectively) and in tests with faster entry rates.

6.18.2 *Normal Ice Protection System Operation*. The following represents an acceptable test programme for stall warning in slow down turns of at least 1.5g and at entry rates of at least 2 knot/sec:

a. "Holding Ice."

b. Medium to light weight, aft centre of gravity position, symmetric fuel loading.

c. Normal stall test altitude.

d. In the configurations listed below, trim the aeroplane at 1.3 V_{SR} with the power or thrust necessary to maintain straight level flight. Maintain the trim power or thrust during the test demonstrations. Increase speed as necessary prior to establishing at least 1.5g and a deceleration of at least 2 knot/sec. Decrease speed until 1 sec after stall warning and recover using the same test technique as for the non-contaminated aeroplane.

i. High lift devices retracted configuration;

ii. Lowest lift take-off configuration; and

iii. Highest lift landing configuration.

6.18.3 *Ice Accretion Prior to Normal System Operation* ***and prior to Detection of Appendix X icing conditions (for airplanes not certified for flight throughout the icing conditions of Appendix X)***. The following represent acceptable means for evaluating stall warning margin with the ***applicable*** ice accretion ~~prior to normal operation of the ice protection system.~~

6.18.3.1 Where the ice protection system is activated as described in paragraph A1.2.3.3.a, of Appendix 1 of this ACJ, paragraphs 6.18.1 and 6.18.2 of this ACJ are applicable with the ice accretion prior to normal system operation. ***When the primary means of detecting Appendix X icing conditions depends on the flight crew to recognize visual cues of Appendix X icing, paragraphs 6.18.1 and 6.18.2 of this ACJ are also applicable with the ice accretion existing prior to detection of***

Appendix X icing conditions. For assessing compliance with the ice accretion prior to detection of Appendix X icing conditions, it is assumed that the aeroplane has been in icing conditions long enough for the ice protection system to have been activated. Therefore, any changes to stall warning or stall identification system settings resulting from activation of the ice protection system are assumed to have taken place.

6.18.3.2 Where the ice protection system is activated as described in paragraphs A1.2.3.3.b,c,d or e of Appendix 1 of this ACJ, it is acceptable to demonstrate adequate stall warning with the ice accretion prior to normal system operation, as follows:

a. In the configurations listed below, trim the aeroplane at 1.3 V_{SR}.

i. High lift devices retracted configuration: Straight/Power Off.

i. Landing configuration: Straight/Power Off.

b. At decelerations of up to 1 knot per second, reduce the speed to stall warning plus 1 second, and demonstrate that stalling can be prevented using the same test technique as for the non-contaminated aeroplane, without encountering any adverse characteristics (e.g., a rapid roll-off). As required by JAR 25.207(h)(2)(ii), where stall warning is provided by a different means than for the aeroplane without ice accretion, the stall characteristics must be satisfactory and the delay must be at least 3 seconds.

6.18.3.3 When the primary means of detecting Appendix X icing conditions is an approved ice detection system, the stall warning margin prior to detection of Appendix X icing conditions should be assessed using the criteria of paragraph 6.18.3.2 with the ice accretion prior to detection of the Appendix X icing conditions. For assessing compliance with the ice accretion prior to detection of Appendix X icing conditions, it is assumed that the aeroplane has been in icing conditions long enough for the ice protection system to have been activated. Therefore, any changes to stall warning or stall identification system settings resulting from activation of the ice protection system are assumed to have taken place.

6.19 *Wind Velocities (JAR 25.237).*

6.19.1 Crosswind landings with "Landing Ice" should be evaluated on an opportunity basis.

6.19.2 The results of the steady heading sideslip tests with “Landing Ice” may be used to establish the safe cross wind component. If the flight test data show that the maximum sideslip angle demonstrated is similar to that demonstrated with the non-contaminated aeroplane, and the flight characteristics (e.g. control forces and deflections) are similar, then the non-contaminated aeroplane crosswind component is considered valid.

6.19.3 If the results of the comparison discussed in paragraph 6.19.2, above, are not clearly similar, and in the absence of a more rational analysis, a conservative analysis based on the results of the steady heading sideslip tests may be used to establish the safe crosswind component. The crosswind value may be estimated from:

$$V_{CW} = V_{REF} \times \sin(\text{sideslip angle}) / 1.5$$

where:

V_{CW} is the crosswind component,
V_{REF} is the landing reference speed appropriate to a minimum landing weight, and
sideslip angle is that demonstrated at V_{REF} (see paragraph 6.15 of this ACJ).

6.20 *Vibration and Buffeting (JAR 25.251).*

6.20.1 Qualitative evaluations should be combined with the other testing, including speeds up to the maximum speed obtained in the longitudinal stability tests (see paragraph 6.14 of this ACJ).

6.20.2 It is also necessary to demonstrate that the aeroplane is free from harmful vibration due to residual ice accumulation. This may be done in conjunction with the natural icing tests.

6.20.3 An aeroplane with pneumatic de-icing boots should be evaluated to V_{DF}/M_{DF} with the de-icing boots operating and not operating. It is not necessary to do this demonstration with ice accretion.

6.21 *Natural Icing Conditions.*

6.21.1 *General.*

6.21.1.1 Whether the flight testing has been performed with artificial ice ~~shapes~~ ***accretions*** or in natural icing conditions, additional limited flight testing described in this section should be conducted in ***the*** natural ***atmospheric*** icing conditions ~~of~~ ***specified in Appendix C, and, if necessary, Appendix X to JAR-25.*** Where flight testing with artificial ice ~~shapes~~ ***accretions*** is the primary means for showing compliance, the objective of the tests described in this section is to corroborate the handling characteristics and performance results obtained in flight testing with artificial ice ~~shapes~~ ***accretions. At least a qualitative assessment should be made that the artificial ice accretions are conservative relative to the ice accretions obtained in natural atmospheric icing conditions, and to confirm that ice does not accrete in unexpected places.***

6.21.1.2 ACJ 25.1419/1420 provides guidance on when flight testing in the natural atmospheric icing conditions of Appendix X is necessary.

6.21.1.***3*** It is acceptable for some ice to be shed during the testing due to air loads or wing flexure, etc. However, an attempt should be made to accomplish the test manoeuvres as soon as possible after exiting the icing cloud to minimise the atmospheric influences on ice shedding.

6.21.1.***4*** During any of the manoeuvres specified in paragraph 6.21.2, below, the behaviour of the aeroplane should be consistent with that obtained with artificial ice shapes. There should be no unusual control responses or uncommanded aeroplane motions. Additionally, during the level turns and bank-to-bank rolls, there should be no buffeting or stall warning.

6.21.2 *Ice Accretion/Manoeuvres*.

6.21.2.1 *Holding scenario.*

a. The manoeuvres specified in Table 3, below, should be carried out with the following ice accretions ***defined in Appendix C and, if applicable, Appendix X to JAR-25,*** representative of normal operation of the ice protection system:

i. *On unprotected* ***parts: For the icing conditions defined in Appendix C to JAR-25, a*** thickness of 3 inches on those parts of the aerofoil where the collection efficiency is highest should be the objective. (A thickness of 2 inches is normally a minimum value, unless a lesser value is agreed by the Authority.)

ii. *On protected parts*: The ice accretion thickness should be that resulting from normal operation of the ice protection system.

b. For aeroplanes with control surfaces that may be susceptible to jamming due to ice accretion (e.g. elevator horns exposed to the air flow), the holding speed that is critical with respect to this ice accretion should be used.

TABLE 3: Holding Scenario - Manoeuvres

Configuration	*c.g.*	*Trim speed*	*Manoeuvre*
Flaps up, gear up	Optional (aft range)	Holding	• Level, 40° banked turn, • Bank-to-bank rapid roll, 30° - 30°, • Speedbrake extension, retraction, • Full straight stall.
Flaps in intermediate positions, gear up	Optional (aft range)	1.3 V_{SR}	Deceleration to stall warning.
Landing flaps, gear down	Optional (aft range)	V_{REF}	• Level, 40° banked turn, • Bank-to-bank rapid roll, 30° - 30°, • Speedbrake extension, retraction (if approved), • Full straight stall.

6.21.2.2 *Approach/Landing Scenario.* The manoeuvres specified in Table 4, below, should be carried out with successive accretions in different configurations on unprotected surfaces. Each test condition should be accomplished with the ice accretion that exists at that point. The final ice accretion (Test Condition 3) represents the sum of the amounts that would accrete during a normal descent from holding to landing in icing conditions.

TABLE 4: Approach/Landing Scenario - Manoeuvres

Test Condition	*Ice accretion thickness (*)*	*Configuration*	*c.g.*	*Trim speed*	*Manoeuvre*
_	First 0.5 in.	Flaps up, gear up	Optional (aft range)	Holding	No specific test
1	Additional 0.25 in. (0.75 in. total)	First intermediate flaps, gear up	Optional (aft range)	Holding	• Level 40° banked turn, • Bank-to-bank rapid roll, 30°- 30°, • Speed brake extension and retraction (if approved), • Deceleration to stall warning.
2	Additional 0.25 in. (1.00 in. total)	Further intermediate flaps, gear up (as applicable)	Optional (aft range)	1.3 V_{SR}	• Bank-to-bank rapid roll, 30° - 30°, • Speed brake extension and retraction (if approved), • Deceleration to stall warning.
3	Additional 0.25 in. (1.25 in. total)	Landing flaps, gear down	Optional (aft range)	V_{REF}	• Bank-to-bank rapid roll, 30° - 30°, • Speed brake extension and retraction (if approved), • Bank to 40°, • Full straight stall.

(*) The indicated thickness is that obtained on the parts of the unprotected aerofoil with the highest collection efficiency.

6.21.3 For aeroplanes with unpowered elevator controls, in the absence of an agreed substantiation of the criticality of the artificial ice shape used to demonstrate compliance with the controllability requirement, the pushover test of paragraph 6.9.3 should be repeated with a thin accretion of natural ice.

6.21.4 Existing propeller speed limits or, if required, revised propeller speed limits for flight in icing, should be verified by flight tests in ***the*** natural icing conditions ***of Appendix C, and, if applicable, Appendix X.***

6.22 *Failure Conditions (JAR 25.1309).*

6.22.1 For failure conditions which are annunciated to the flight crew, credit may be taken for the established operating procedures following the failure.

6.22.2 *Acceptable Test Programme*. In addition to a general qualitative evaluation, the following test programme (modified as necessary to reflect the specific operating procedures) should be carried out for the most critical probable failure condition where the associated procedure requires the aeroplane to exit the icing condition:

a. The ice accretion is defined as a combination of the following:

i. On the unprotected surfaces - the “Holding ice” accretion described in paragraph A1.2.1 of this ACJ;

ii. On the normally protected surfaces that are no longer protected - the “Failure ice” accretion described in paragraph A1.3.2 of this AC; and

iii. On the normally protected surfaces that are still functioning following the segmental failure of a cyclical de-ice system – the ice accretion that will form during the rest time of the de-ice system following the critical failure condition.

b. Medium to light weight, aft centre of gravity position, symmetric fuel loading.

c. In the configurations listed below, trim the aeroplane at the specified speed. Conduct 30° banked turns left and right with normal reversals. Conduct pull up to 1.5g and pushover to 0.5g.

i. High lift devices retracted configuration (or holding configuration if different): Holding speed, power or thrust for level flight. In addition, deploy and retract deceleration devices.

ii. Approach configuration: Approach speed, power or thrust for level flight.

iii. Landing configuration: Landing speed, power or thrust for landing approach (limit pull up to 1.3g). In addition, conduct steady heading sideslips to angle of sideslip appropriate to type and landing procedure.

d. In the configurations listed below, trim the aeroplane at estimated 1.3 V_{SR}. Decrease speed to stall warning plus 1 second, and demonstrate prompt recovery using the same test technique as for the non-contaminated aeroplane. Natural stall warning is acceptable for the failure case.

i. High lift devices retracted configuration: Straight/Power Off.

ii. Landing configuration: Straight/Power Off.

e. Conduct an approach and go-around with all engines operating using the recommended procedure.

f. Conduct an approach and landing with all engines operating (unless the one-engine-inoperative condition results in a more critical probable failure condition) using the recommended procedure.

6.22.3 For improbable failure conditions, ***a*** flight test may be required to demonstrate that the effect on safety of flight (as measured by degradation in flight characteristics) is commensurate with the failure probability or to verify the results of analyses and/or wind tunnel tests. The extent of any required flight test should be similar to that described in paragraph 6.22.2, above, or as agreed with the Authority for the specific failure condition.

Appendix 1 - Airframe Ice Accretion

A1.1 *General.* The most critical ice accretion in terms of handling characteristics and/or performance for each flight phase should be determined. The parameters to be considered include:

- the flight conditions (e.g. aeroplane configuration, speed, angle of attack, altitude) and
- the ***atmospheric*** icing conditions ***(i.e., Appendix C or Appendix X to JAR-25) for which certification is desired*** ~~of Appendix C to JAR-25~~ (e.g. temperature, liquid water content, mean effective drop diameter).

A1.1.1 In accordance with JAR 25.1420(a)(1), any aeroplane certified for flight in icing conditions must, as a minimum, be capable of safely operating: (1) in the atmospheric icing conditions of Appendix C to JAR-25, and (2) after encountering the atmospheric icing conditions of Appendix X and subsequently exiting all icing conditions. Therefore, certification for flight in icing conditions must consider at least the following ice accretions: (a) operations in Appendix C icing conditions, and (b) detecting and exiting Appendix X icing conditions. JAR 25.21(g) specifies which subpart B airplane performance and handling characteristics requirements apply for each of these ice accretions.

A1.1.2 In accordance with JAR 25.1420(a)(2), an aeroplane may also be certified for operation in a portion of the atmospheric icing conditions of Appendix X to JAR-25. In that case, the aeroplane must also be capable of operating safely after encountering, and while exiting, the atmospheric icing conditions in the portion of Appendix X for which operation is not approved. Certification for flight in a portion of Appendix X must consider the following ice accretions: (a) operations in Appendix C icing conditions, (b) operations in the Appendix X icing conditions for which approval is sought, and (c) detecting and exiting the Appendix X icing conditions in the portion of Appendix X beyond those for which approval is sought. JAR 25.21(g) specifies which subpart B airplane performance and handling characteristics requirements apply for each of these ice accretions.

A1.1.3 In accordance with JAR 25.1420(a)(3), in addition to certification for flight in Appendix C conditions, an aeroplane may be certified for operation throughout the atmospheric icing conditions of Appendix X to JAR-25. Certification for flight throughout the atmospheric icing conditions of Appendix X must consider the following ice accretions: (a) operations in Appendix C icing conditions, and (b) operations in Appendix X icing conditions. JAR 25.21(g) specifies which subpart B airplane performance and handling characteristics requirements apply for each of these ice accretions.

A1.1.4 In order to reduce the number of ice accretions used for demonstrating compliance, any of the applicable ice accretions (or a composite accretion representing a combination of accretions) may be used to show compliance with

a particular Subpart B requirement if that accretion is either the ice accretion identified in the requirement or is shown to be more conservative than the ice accretion identified in the requirement. In addition, the ice accretion that has the most adverse effect on handling characteristics may be used for compliance with the airplane performance requirements if any difference in performance is conservatively taken into account. The ice accretion(s) used to show compliance should consider the speeds, configurations (including configuration changes), angles of attack, power or thrust settings, etc. for the flight phases and icing conditions that they are intended to cover.

A1.2 *Operative Ice Protection System.*

A1.2.1 *All flight phases except take-off.*

A1.2.1.1 For unprotected parts, the ice accretion to be considered should be determined in accordance with ***Appendixes C and X to JAR-25*** ~~JAR 25.1419.~~

A1.2.1.2 Unprotected parts consist of the unprotected aerofoil leading edges and all unprotected airframe parts on which ice may accrete. The effect of ice accretion on protuberances such as antennae or flap hinge fairings need not normally be investigated. However aeroplanes that are characterised by unusual unprotected airframe protuberances, e.g. fixed landing gear, large engine pylons, or exposed control surface horns or winglets, etc., may experience significant additional effects, which should therefore be taken into consideration.

As provided by FTHWG

A1.2.1.3 For "Holding Ice," certification experience ***for Appendix C icing conditions*** has shown that the amount of ice on the most critical unprotected main aerofoil surface (e.g. wing, horizontal or vertical stabilisers) to be considered need not exceed a pinnacle height of typically 3 inches (75 mm) in a plane in the direction of flight. For other unprotected main surfaces an analysis may be performed to determine the maximum ice accretion associated with this maximum pinnacle height. In the absence of such an acceptable analysis a uniform pinnacle height of 3 inches (75 mm) should be assumed. The shape and texture of the ice are important and should be agreed with the Authority.

As proposed by IPHWG

A1.2.1.3 For unprotected surfaces an analysis may be performed to determine the maximum ice accretion. Assume a 45 minute hold, no reduction for cloud horizontal extent. It is allowable to truncate the pinnacle height of 3 inches (75 mm) if sufficient service history exists on similar ice protection system designs. The shape and texture of the ice are important and should be agreed with the Authority.

Discussion:
This issue has been debated extensively in both the FTHWG and IPHWG without resolution. The FTHWG provided language is essentially unchanged from the draft 25.21(g) materials relative to Appendix C. The FTHWG could not achieve consensus in the time available and elected to leave the language unchanged.

The IPHWG is not in agreement with the draft 25.21(g) materials with respect to using a 3" criterion as the primary means of determining ice shapes. Ice shape size varies with geometry, which can lead to ice shapes less than or greater than the 3" ice shape. The time base criteria allows for differing ice shapes based on geometry, yet retains a consistent level of safety (with respect to exposure time). The proposed language is offered as a compromise in that the 3" criterion can be used if sufficient justification exists. In addition, since this language resides in the advisory materials, alternate methods of compliance are possible provided the same level of safety is achieved.

A1.2.1.4 There is no comparable certification experience to that identified in paragraph A1.2.1.3 for Appendix X icing conditions. See paragraphs A1.4.2.3 and A1.4.3.3 for scenarios that define how to determine the applicable ice accretion for the holding flight phase in Appendix X conditions. The total time in icing conditions in these scenarios should be 45 minutes, and no reduction should be taken for cloud horizontal extent.

A1.2.1.***5*** For protected parts, the ice protection systems are normally assumed to be operative. However, the applicant should consider the effect of ice accretion on the protected surfaces that results from:

a. The rest time of a de-icing cycle. Performance may be established on the basis of a representative intercycle ice accretion for normal operation of the de-icing system (consideration should also be given to the effects of any residual ice accretion that is not shed.) The average drag increment determined over the de-icing cycle may be used for performance calculations.

b. Runback ice which occurs on or downstream of the protected surface.

c. Ice accretion prior to normal operation of the ice protection system (see paragraph A1.2.3, below).

A1.2.2 *Take-off phase.*

A1.2.2.1 For both unprotected and protected parts, the ice accretion identified in ***Appendixes C and X*** ~~Appendix C~~ to JAR-25 for the take-off phase may be determined by calculation, assuming that ~~the Takeoff Maximum icing conditions defined in Appendix C exist, and:~~

- aerofoils, control surfaces and, if applicable, propellers are free from frost, snow, or ice at the start of the take-off;
- the ice accretion starts at lift-off;
- the critical ratio of thrust/power-to-weight;
- failure of the critical engine occurs at V_{EF}; and
- flight crew activation of the ice protection system in accordance with an AFM procedure, except that after commencement of the take-off roll no flight crew action to activate the ice protection system should be assumed to occur until the aeroplane is 400 ft above the take-off surface.

A1.2.2.2 The ice accretions identified in Appendix***es*** C ***and X*** to JAR-25 for the take-off phase are:

- "Take-off ice": The most critical ice accretion between lift-off and 400 ft above the takeoff surface, assuming accretion starts at lift-off in the icing environment.
- "Final Take-off ice": The most critical ice accretion between 400 ft and ***the height at which the transition to the en-route configuration and speed is completed, or*** 1500 ft above the take-off surface, ***whichever is higher,*** assuming accretion starts at lift-off in the icing environment.

A1.2.3 *Ice accretion prior to normal system operation.*

A1.2.3.1 Ice protection systems are normally operated as anti-icing systems (i.e. designed to prevent ice accretion on the protected surface) or de-icing systems (i.e. designed to remove ice from the protected surface). In some cases, systems may be operated as anti-icing or de-icing systems depending on the phase of flight. Operation of ice protection systems can also include a resetting of stall warning and/or stall identification system (e.g. stick pusher) activation thresholds.

A1.2.3.2 The aeroplane Flight Manual contains the operating limitations and operating procedures established by the applicant. Since ice protection systems are normally only operated when icing conditions are encountered or when airframe ice is detected, means of flight crew determination of icing conditions and/or airframe ice should be considered in determining the ice accretion prior to normal system operation. This includes the ice accretion appropriate to the specified means of identification of icing conditions and an additional ice accretion, represented by a time in the ***icing conditions before the ice protection system is activated. In accordance with***

§ 25.21(g)(3), compliance must be shown with ice accretions corresponding to both the Continuous Maximum icing conditions of Appendix ***C and the icing conditions of Appendix X (or to reduce the number of ice accretions tested, the most critical of the two ice accretions if the most critical ice accretion can be determined).*** This additional ice accretion is to account for flight crew delay in either identifying the conditions and activating the ice protection systems (see paragraphs A1.2.3.3(a), (b) and (c) below), or activating the ice protection system following indication from an ice detection system (see paragraph A1.2.3.3 (d) below). In addition the system response time should be considered. System response time is defined as the time interval between activation of the ice protection system and the performance of its intended function (e.g. for a thermal ice protection system, the time to heat the surface and remove the ice).

A1.2.3.3 The means of detecting that the aeroplane is in icing conditions should be the same for all icing conditions for which certification is desired, regardless of whether the icing conditions are within Appendix C or Appendix X.

A1.2.3.***4*** The following examples indicate the ice accretion to be considered on the unprotected and normally protected aerodynamic surfaces:

FTHWG less ALPA Position

a. If activation of normal operation of any ice protection system is dependent on visual recognition of a specified ice accretion on a reference surface (e.g. ice accretion probe, wing leading edge), the ice accretion should not be less than that corresponding to the ice accretion on the reference surface taking into account probable flight crew delays in recognition of the specified ice accretion and operation of the system, determined as follows:

i. the specified accretion, plus

ii. the ice accretion equivalent to thirty seconds of operation in ***icing conditions (***the Continuous Maximum icing conditions of Appendix C, Part I(a) ***and the icing conditions of Appendix X),*** plus

iii. the ice accretion during the system response time.

b. If activation of normal operation of any ice protection system is dependent on visual recognition of the first indication of ice accretion on a reference surface (e.g. ice accretion probe), the ice accretion should not be less than that corresponding to the ice accretion on the reference surface taking into account probable flight crew delays in recognition of the ice accreted and operation of the system, determined as follows:

i. the ice accretion corresponding to first indication on the reference surface, plus

ii. the ice accretion equivalent to thirty seconds of operation in ***icing conditions (***the Continuous Maximum icing conditions of Appendix C, Part I(a) ***and the icing conditions of Appendix X***), plus

iii. the ice accretion during the system response time.

ALPA Position

a. If normal operation of any ice protection system is dependent on visual recognition of ice accretion (e.g. ice accretion probe, wing leading edge), the ice accretion should not be less than that corresponding to the ice accretion on the reference surface taking into account probable flight crew delays in recognition of the specified ice accretion and operation of the system, determined as follows:

i. the specified accretion, plus

ii. the ice accretion equivalent to two minutes of operation in the Continuous Maximum icing conditions of Appendix C, Part I(a), plus

iii. the ice accretion during the system response time.

b. [RESERVED]

c. If activation of normal operation of any ice protection system is dependent upon pilot identification of icing conditions (as defined by an appropriate static or total air temperature and visible moisture conditions), the ice accretion should not be less than that corresponding to the ice accreted during probable crew delays in recognition of icing conditions and operation of the system, determined as follows:

i. the ice accretion equivalent to thirty seconds of operation in ***icing conditions (***the Continuous Maximum icing conditions of Appendix C, Part I(a) ***and the icing conditions of Appendix X),*** plus

ii. the ice accretion during the system response time.

d. If activation of normal operation of any ice protection system is dependent on pilot action following indication from an ice detection system, the ice accretion should not be less than that corresponding to the ice accreted prior to indication from the ice detection system, plus that accreted due to probable flight crew delays in activating the ice protection system and operation of the system, determined as follows:

i. the ice accretion corresponding to the time between entry into the icing conditions and indication from the ice detection system, plus

ii. the ice accretion equivalent to ten seconds of operation in ***icing conditions (***the Continuous Maximum icing conditions of Appendix C, Part I(a***) and the icing conditions of Appendix X),*** plus

iii. the ice accretion during the system response time.

e. If activation of normal operation of any ice protection system is automatic following indication from an ice detection system, the ice accretion should not be less than that corresponding to the ice accreted prior to indication from the ice protection system and operation of the system, determined as follows:

i. the ice accretion on the protected surfaces corresponding to the time between entry into the icing conditions and activation of the system, plus

ii. the ice accretion during the system response time.

A1.3 *Ice Protection System Failure Cases.*

A1.3.1 *Unprotected parts.* The same accretion as in paragraph A1.2.1 is applicable.

A1.3.2 *Protected parts following system failure*. "Failure Ice" is defined as follows:

A1.3.2.1 In the case where the failure condition is not annunciated, the ice accretion on normally protected parts where the ice protection system has failed should be the same as the accretion specified for unprotected parts.

A1.3.2.2 In the case where the failure condition is annunciated and the associated procedure does not require the aeroplane to exit icing conditions, the ice accretion on normally protected parts where the ice protection system has failed should be the same as the accretion specified for unprotected parts.

A1.3.2.3 In the case where the failure condition is annunciated and the associated procedure requires the aeroplane to exit icing conditions as soon as possible, the ice accretion on normally protected parts where the ice protection has failed, should be taken as one-half of the accretion specified for unprotected parts unless another value is agreed by the Authority.

A1.4 Additional Guidance for Appendix X Ice Accretions.

A1.4.1 Pre-detection ice. Pre-detection ice refers to the ice accretion existing at the time the flightcrew becomes aware that they are in Appendix X icing conditions, they have initiated the appropriate action(s) identified by aeroplane Flight Manual limitations or procedures, and any resulting systems changes (e.g., reset of stall warning or stick pusher activation points) are functional.

A1.4.1.1 Both direct entry into Appendix X icing conditions and entry from flight in Appendix C icing conditions should be considered. The aeroplane Flight Manual limitations or procedures may restrict the operating envelope (e.g., speeds, configurations), alter the operation of the ice protection system, change stall warning and stall identification system activation points, or for aeroplanes not certified for flight in those icing conditions, direct the flightcrew to exit all icing conditions.

A1.4.1.2 The time that it takes to detect Appendix X icing conditions that exceed those for which the airplane is certified should be based on the means of detection. Guidance for certification of the detection means is provided in ACJ 25.1419/1420. In general, it is expected that the time to detect exceedance icing conditions may be significantly longer for a detection means that relies on the flightcrew to see and recognize a visual icing cue than for an ice detection system that provides an attention-getting alert to the flightcrew.

A1.4.1.3 Visual detection requires time for accumulation on the reference surface(s) of enough ice to be reliably identified by either pilot in all atmospheric and lighting conditions and consideration of the time between pilot scans of the reference surface(s).

a. The amount of ice for reliable identification is a function of the distinguishing characteristics of the ice (e.g., size, shape, contrast from the surface feature that it is present on), the distance from the pilots (e.g., windshield vs. engine vs. wingtip), and the relative viewing angle (location with respect to the pilots' primary fields of view).

b. Pilot scan time of the reference surface(s) will be influenced by many factors. Some factors include phase of flight, workload, frequency of occurrence of Appendix X conditions, pilot awareness of the possibility of SLD conditions, and ease of seeing the reference surface(s). The infrequency of Appendix X conditions (approximately 1 in 100 to 1 in 1000, on average in all worldwide icing encounters) and the high workload associated with some phases of flight in instrument conditions (e.g. approach and landing) justify using a conservative estimate for the time between pilot scans.

c. In the absence of specific studies or tests validating visual detection times, the following times should be used for visual detection of exceedance icing conditions following accumulation of enough ice to be reliably identified by either pilot in all atmospheric and lighting conditions. For a visual reference located on or immediately outside a cockpit window (e.g., ice accretions on side windows, windshield wipers, or icing probe near the windows) - 3 minutes. For a visual reference located on a wing, wing mounted engine, or wing tip – 5 minutes.

A1.4.2 Ice accretions for encounters with Appendix X beyond those for which the aeroplane is certified to operate.

A1.4.2.1 These ice accretions are to be used to evaluate compliance with the applicable Subpart B requirements for operating safely after encountering Appendix X atmospheric icing conditions for which the aeroplane is not approved, and then safely exiting all icing conditions.

A1.4.2.2 These ice accretions apply when the aeroplane is not certified for flight in any portion of Appendix X atmospheric icing conditions, when the aeroplane is certified for flight in only a portion of Appendix X, and for any flight phase for which the aeroplane is not certified for flight throughout the Appendix X icing envelope.

A1.4.2.3 The following table shows the scenarios to be used for determining the ice accretions for encounters with Appendix X beyond those for which the aeroplane is certified to operate (i.e., detecting and exiting those conditions):

Flight Phase/Condition	***Appendix X Detect-and-Exit Ice Accretion***
Ground Roll	***No accretion***
Take-off	***No accretion***[1]
Final Take-off	***No accretion***[1]
En-route	***En-route Detect-and-Exit Ice*** ***Combination of: (1) Either Appendix C en-route ice or Appendix X en-route ice for which the airplane is approved, whichever is applicable, (2) pre-detection ice, (3) accretion from one standard cloud horizontal extent (17.4 nautical miles) in Appendix X conditions, and (4) accretion from one standard cloud horizontal extent (17.4 nautical miles) in Appendix C continuous maximum icing conditions.***
Holding	***Holding Detect-and-Exit Ice*** ***Combination of: (1) Either Appendix C holding ice or Appendix X holding ice for which the airplane is approved, whichever is applicable, (2) pre-detection ice, (3) accretion from one standard cloud horizontal extent (17.4 nautical miles) in Appendix X conditions, and (4) accretion from one standard cloud horizontal extent (17.4 nautical miles) in Appendix C continuous maximum icing conditions. The total time in icing conditions need not exceed 45 minutes.***

Flight Phase/Condition	***Appendix X Detect-and-Exit Ice Accretion***
Approach	***Approach Detect-and-Exit Ice*** ***The more critical of holding detect-and-exit ice and the combination of: (1) Ice accreted during a descent in the cruise configuration from the maximum vertical extent of the Appendix C maximum continuous or the Appendix X icing environment for which the airplane is approved, whichever is applicable, to 2,000 feet above the landing surface, where transition to the approach configuration is made, (2) pre-detection ice, and (3) ice accreted at 2,000 feet above the landing surface while transiting one standard cloud horizontal extent (17.4 nautical miles) in Appendix X conditions and one standard cloud horizontal extent (17.4 nautical miles) in Appendix C continuous maximum icing conditions.***
Landing	***Landing Detect-and-Exit Ice*** ***The more critical of holding detect-and-exit ice and the combination of: (1) Either Appendix C or Appendix X approach and landing ice for which the airplane is approved, whichever is applicable, (2) pre-detection ice, and (3) ice accreted during an exit manoeuvre beginning with the minimum climb gradient specified in § 25.119 from a height of 200 feet above the landing surface and transiting through one standard cloud horizontal extent (17.4 nautical miles) in Appendix X conditions, and one standard cloud horizontal extent (17.4 nautical miles) in Appendix C continuous maximum icing conditions.*** ***For the purposes of defining the landing detect-and-exit ice shape, the Appendix C approach and landing ice is defined as the ice accreted during a descent in the cruise configuration from the maximum vertical extent of the Appendix C maximum continuous icing environment to 2,000 feet above the landing surface, transitioning to the approach configuration and manoeuvring for 15 minutes at 2,000 feet above the landing surface, a descent from 2,000 feet to 200 feet above the landing surface with a transition to the landing configuration.***

Flight Phase/Condition	***Appendix X Detect-and-Exit Ice Accretion***
Pre-Activation	***Pre-Activation Ice*** ***Ice accreted on the protected and unprotected surfaces during the time it takes for icing conditions (either Appendix C or Appendix X) to be detected, the ice protection system activated, and the ice protection system to become fully effective in performing its intended function.***
Pre-Detection	***Pre-Detection of Appendix X Ice*** ***Ice accreted on the protected and unprotected surfaces during the time it takes to detect and identify Appendix X conditions (based on the method of detection) beyond those for which the aeroplane is certified to operate, and the time for the flight crew to refer to and act on procedures, including coordinating with Air Traffic Control, to exit the icing conditions beyond those for which the aeroplane is certified to operate. A minimum time period of two minutes should be used as the time needed for the flight crew to refer to and act on the procedures to exit the icing conditions after the Appendix X icing conditions are recognized.***
Failure	***Failure Ice*** ***No accretion***[2]

Notes:

[1] ***T/O is not permitted when Appendix X conditions beyond those for which the aeroplane is certified to operate exist in the vicinity of departure airport.***

[2] ***Unnecessary to consider unintentional encounter with Appendix X icing conditions beyond those for which the aeroplane is certified to operate with a failed ice protection system.***

A1.4.3 Ice accretions for encounters with Appendix X atmospheric icing conditions in which the aeroplane is certified to operate.

A1.4.3.1 These ice accretions are to be used to evaluate compliance with the applicable Subpart B requirements for operating safely in the Appendix X atmospheric icing conditions for which the aeroplane is approved.

A1.4.3.2 The ice accretions should include consideration of combinations of Appendix C and Appendix X icing conditions within the scenarios defined in paragraph A4.1.3.3. For example, flight in Appendix X conditions may result in ice accreting, and potentially forming a ridge, behind a protected surface. Once this accretion site has been established, flight in Appendix C icing conditions for the remaining portion of the applicable flight phase scenario may result in a more

critical additional accretion than would occur for continued flight in Appendix X icing conditions.

A1.4.3.3 The following table shows the scenarios to be used for determining the ice accretions for certification for flight in the icing conditions of Appendix X to JAR-25:

Flight Phase/Condition	***Appendix X Ice Accretion***
Ground Roll	***No accretion***
Take-off	***Take-off Ice*** ***Ice accretion occurring between lift-off and 400 feet above the takeoff surface assuming ice accretion starts at lift-off.***
Final Take-off	***Final Take-off Ice*** ***Ice accretion occurring between 400 ft and the height at which the transition to the en-route configuration and speed is completed, or 1500 ft above the take-off surface, whichever is higher, assuming ice accretion starts at lift-off.***
En-route	***En-route Ice*** ***Ice accreted during the en-route phase of flight.***
Holding	***Holding Ice*** ***Ice accreted during a 45 minute hold with no reduction for horizontal cloud extent (i.e., the hold is conducted entirely within the 17.4 nautical mile standard cloud extent).***
Approach	***Approach Ice*** ***Most critical ice accretion of: (1) Ice accreted during a descent in the cruise configuration from the maximum vertical extent of the Appendix X icing environment to 2,000 feet above the landing surface, followed by transition to the approach configuration and manoeuvring for 15 minutes at 2,000 feet above the landing surface; and (2) Holding ice (if the airplane is certified for holding in Appendix X conditions).***

Flight Phase/Condition	***Appendix X Ice Accretion***
Landing	***Landing Ice*** ***Most critical ice accretion of: (1) Approach ice plus descent from 2,000 feet above the landing surface to 200 feet above the landing surface with a transition to the landing configuration, followed by a go-around manoeuvre beginning with the minimum climb gradient specified in § 25.119 from 200 feet to 2,000 feet above the landing surface, holding for 15 minutes at 2,000 feet above the landing surface in the approach configuration, and a descent to the landing surface in the landing configuration; and (2) Holding ice (if the airplane is certified for holding in Appendix X conditions).***
Pre-Activation	***Pre-Activation Ice*** ***Ice accreted during the time for the flightcrew to recognize icing conditions and activate the ice protection system, plus the time for the ice protection system to perform its intended function.***
Pre-Detection	***Pre-Detection Ice*** ***Ice accreted during the time for the flightcrew to detect Appendix X conditions, refer to and initiate procedures, and any time for systems to perform their intended functions (if applicable). Pre-detection ice need not be considered if there are no specific crew actions or systems changes associated with flight in Appendix X conditions.***
Failure	***Failure Ice*** ***Same criteria as for Appendix C, but in Appendix X conditions.***

Appendix 2 - Artificial Ice Shapes

A2.1 *General.*

A2.1.1 The artificial ice shapes used for flight testing should be those which have the most adverse effects on handling characteristics. If analytical data show that other reasonably expected ice shapes could be generated which could produce higher performance decrements, then the ice shape having the most adverse effect on handling characteristics may be used for performance tests provided that any difference in performance can be conservatively taken into account.

A2.1.2 The artificial shapes should be representative of natural icing conditions in terms of location, general shape, thickness and texture. Following determination of the form and surface texture of the ice shape under paragraph A2.2, a surface roughness for the shape should be agreed with the Authority as being representative of natural ice accretion.

A2.1.3 "Sandpaper Ice" is addressed in paragraph A2.3.

A2.2 *Shape and Texture of Artificial Ice*.

A2.2.1 The shape and texture of the artificial ice should be established and substantiated by agreed methods. Common practices include:

- use of computer codes,
- flight in measured natural icing conditions,
- icing wind tunnel tests, and
- flight in a controlled simulated icing cloud (e.g. from an icing tanker).

A2.2.2 In the absence of another agreed definition of texture the following may be used:

A2.2.2.1 For small amounts of ice (for example the amount of ice accreted during a de-icing system rest time), the roughness should be typically:

- roughness height: 1 mm
- particle density: 8 to 10/cm^2

A2.2.2.2 For large amounts of ice (for example on an unprotected, exposed surface), the roughness should be typically:

- roughness height: 3 mm
- particle density: 8 to 10/cm^2

A2.3 *"Sandpaper Ice."*

A2.3.1 "Sandpaper Ice" is the most critical thin, rough layer of ice ***resulting from exposure to the atmospheric icing conditions of Appendix C to JAR-25. Sandpaper Ice is not relevant to the supercooled large drop conditions defined in Appendix X to JAR-25.*** Any representation of "Sandpaper Ice" (e.g. carborundum paper no. 40) should be agreed by the Authority.

A2.3.2 The spanwise and chordwise coverage should be consistent with the areas of ice accretion determined for the conditions of JAR-25, Appendix C except that, for the zero g pushover manoeuvre of paragraph 6.9.3 of this ACJ, the "Sandpaper Ice" may be restricted to the horizontal stabiliser if this can be shown to be conservative.

Appendix 3 - Design Features

A3.1 *Aeroplane Configuration and Ancestry* . An important design feature of an overall aeroplane configuration that can affect performance, controllability and manoeuvrability is its size. In addition, the safety record of the aeroplane's closely-related ancestors may be taken into consideration.

A3.1.1 *Size.* The size of an aeroplane determines the sensitivity of its flight characteristics to ice thickness and roughness. The relative effect of a given ice height (or ice roughness height) decreases as aeroplane size increases.

A3.1.2 *Ancestors.* If a closely related ancestor aeroplane was certified for flight in icing conditions, its safety record may be used to evaluate its general arrangement and systems integration.

A3.2 *Wing*. Design features of a wing that can affect performance, controllability, and manoeuvrability include aerofoil type, leading edge devices and stall protection devices.

A3.2.1 *Aerofoil.* Aerofoils with significant natural laminar flow when non-contaminated may show large changes in lift and drag with ice. Conventional aerofoils operating at high Reynolds numbers make the transition to turbulent flow near the leading edge when non-contaminated, thus reducing the adverse effects of the ice.

A3.2.2 *Leading Edge Device.* The presence of a leading edge device (such as a slat) reduces the percentage decrease in C_{LMAX} due to ice by increasing the overall level of C_L. Gapping the slat may improve the situation further. Leading edge devices can also reduce the loss in angle of attack at stall due to ice.

A3.2.3 *Stall Protection Device.* An aeroplane with an automatic slat-gapping device may generate a greater C_{LMAX} with ice than the certified C_{LMAX} with the slat sealed and a non-contaminated leading edge. This may provide effective protection against degradation in stall performance or characteristics.

A3.2.4 *Lateral Control.* The effectiveness of the lateral control system in icing conditions can be evaluated by comparison with closely related ancestor aeroplanes.

A3.3 *Empennage*. The effects of size and aerofoil type also apply to the horizontal and vertical tails. Other design features include tailplane sizing philosophy, aerofoil design, trimmable stabiliser, and control surface actuation. Since tails are usually not equipped with leading edge devices, the effects of ice on tail aerodynamics are similar to those on a wing with no leading edge devices. However, these effects usually result in changes to aeroplane handling and/or control characteristics rather than degraded performance.

A3.3.1 *Tail Sizing.* The effect on aeroplane handling characteristics depends on the tailplane design philosophy. The tailplane may be designed and sized to provide full functionality in icing conditions without ice protection, or it may be designed with a de-icing or anti-icing system.

A3.3.2 *Horizontal Stabiliser Design.* Cambered aerofoils and trimmable stabilisers may reduce the susceptibility and consequences of elevator hinge moment reversal due to ice-induced tailplane stall.

A3.3.3 *Control Surface Actuation.* Hydraulically powered irreversible elevator controls are not affected by ice-induced aerodynamic hinge moment reversal.

A3.3.4 *Control Surface Size.* For mechanical elevator controls, the size of the surface significantly affects the control force due to an ice-induced aerodynamic hinge moment reversal. Small surfaces are less susceptible to control difficulties for given hinge moment coefficients.

A3.3.5 *Vertical Stabiliser Design.* The effectiveness of the vertical stabiliser in icing conditions can be evaluated by comparison with closely-related ancestor aeroplanes.

A3.4 *Aerodynamic Balancing of Flight Control Surfaces.* The aerodynamic balance of unpowered or boosted reversible flight control surfaces is an important design feature to consider. The design should be carefully evaluated to account for the effects of ice accretion on flight control system hinge moment characteristics. Closely balanced controls may be vulnerable to overbalance in icing. The effect of ice in front of the control surface, or on the surface, may upset the balance of hinge moments leading to either increased positive force gradients or negative force gradients.

A3.4.1 This feature is particularly important with respect to lateral flight control systems when large aileron hinge moments are balanced by equally large hinge moments on the opposite aileron. Any asymmetric disturbance in flow which affects this critical balance can lead to a sudden uncommanded deflection of the control. This auto deflection, in extreme cases, may be to the control stops.

A3.5 *Ice Protection/Detection System*. The ice protection/detection system design philosophy may include design features that reduce the ice accretion on the wing and/or tailplane.

A3.5.1 *Wing Ice Protection/Detection.* An ice detection system that activates a wing de-icing system may ensure that there is no significant ice accretion on wings that are susceptible to performance losses with small amounts of ice.

A3.5.1.1 If the entire wing leading edge is not protected, the part that is protected may be selected to provide good handling characteristics at stall, with an acceptable performance degradation.

A3.5.2 *Tail Ice Protection/Detection.* An ice detection system may activate a tailplane de-icing system on aeroplanes that do not have visible cues for system operation.

A3.5.2.1 An ice protection system on the unshielded aerodynamic balances of aeroplanes with unpowered reversible controls can reduce the risk of ice-induced aerodynamic hinge moment reversal.

Appendix 4 – Examples of Aeroplane Flight Manual limitations and operating procedures for operations in supercooled large drop icing conditions.

A4.1 Approved for Appendix C icing conditions only (no Appendix X)

A4.1.1 AFM Limitations

Intentional flight, including takeoff and landing, into freezing drizzle or freezing rain conditions is prohibited. If freezing drizzle or freezing rain conditions are encountered, or if {insert cue description here}, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.1.2 AFM Operating procedures (normal procedures section)

Freezing drizzle and freezing rain conditions are severe icing conditions for this aeroplane. Intentional flight, including takeoff and landing, into freezing drizzle or freezing rain conditions is prohibited. A flight delay or diversion to an alternate airport is required if these conditions exist at the departure or destination airports.

{insert cue description here} is one indication of severe icing for this aeroplane. If severe icing is encountered, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.1.3 Flightcrew Operating Manual operating procedures

Warning: Severe icing may result from environmental conditions outside of those for which the airplane is certified. Intentional flight into severe icing conditions may result in ice build-up on protected surfaces exceeding the capability of the ice protection system, or may result in ice forming aft of the protected surfaces. This ice may not be shed when using the ice protection systems, and may seriously degrade the performance and controllability of the aeroplane.

Operations in icing conditions were evaluated as part of the certification process for this aeroplane. Freezing drizzle and freezing rain conditions were not evaluated and are considered severe icing conditions for this aeroplane.

Intentional flight, including takeoff and landing, into freezing drizzle or freezing rain conditions is prohibited. A flight delay or diversion to an alternate airport is required if these conditions exist at the departure or destination airports. {insert cue description here}is an indication of severe icing conditions that exceed those

for which the airplane is certified. If severe icing is encountered, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.2 Approved for Appendix C and freezing drizzle conditions of Appendix X (i.e., not approved for freezing rain)

A4.2.1AFM Limitations

Intentional flight, including takeoff and landing, into freezing rain conditions is prohibited. If freezing rain conditions are encountered, or if {insert cue description here}, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.2.2AFM Operating procedures (normal procedures section)

Freezing rain conditions are severe icing conditions for this aeroplane. Intentional flight, including takeoff and landing, into freezing rain conditions is prohibited. A flight delay or diversion to an alternate airport is required if these conditions exist at the departure or destination airports.

{insert cue description here} is one indication of severe icing for this aeroplane. If severe icing is encountered, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.2.3Flightcrew Operating Manual operating procedures

Warning: Severe icing may result from environmental conditions outside of those for which the aeroplane is certified. Intentional flight into severe icing conditions may result in ice build-up on protected surfaces exceeding the capability of the ice protection system, or may result in ice forming aft of the protected surfaces. This ice may not be shed when using the ice protection systems, and may seriously degrade the performance and controllability of the aeroplane.

Operations in icing conditions were evaluated as part of the certification process for this aeroplane. Freezing rain conditions were not evaluated and are considered severe icing conditions for this aeroplane.

Intentional flight, including takeoff and landing, into freezing rain conditions is prohibited. A flight delay or diversion to an alternate airport is required if these

conditions exist at the departure or destination airports. {insert cue description here}is an indication of severe icing conditions that exceed those for which the airplane is certified. If severe icing is encountered, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.3 Approved for Appendix C, and approved for Appendix X except for en route and holding

A4.3.1AFM Limitations

Intentional holding or en route flight into freezing drizzle or freezing rain conditions is prohibited. If freezing drizzle or freezing rain conditions are encountered during a hold (in any aeroplane configuration) or in the en route phase of flight (climb, cruise, or descent with high lift devices and gear retracted), or if {insert cue description here}, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.3.2AFM Operating procedures (normal procedures section)

Freezing drizzle and freezing rain conditions encountered during a hold (in any aeroplane configuration) or in the en route phase of flight (climb, cruise, or descent with high lift devices and gear retracted) are severe icing conditions for this aeroplane. Intentional holding or en route flight into freezing drizzle or freezing rain conditions is prohibited.

{insert cue description here} is one indication of severe icing for this aeroplane. If severe icing is encountered, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.3.3Flightcrew Operating Manual operating procedures

Warning: Severe icing may result from environmental conditions outside of those for which the airplane is certified. Intentional flight into severe icing conditions may result in ice build-up on protected surfaces exceeding the capability of the ice protection system, or may result in ice forming aft of the protected surfaces. This ice may not be shed when using the ice protection systems, and may seriously degrade the performance and controllability of the airplane.

Operations in icing conditions were evaluated as part of the certification process

for this aeroplane. En route (climb, cruise, and descent with high left devices and gear retracted) and holding flight (in any aeroplane configuration) in freezing drizzle and freezing rain conditions were not evaluated and are considered severe icing conditions for this aeroplane.

Intentional holding or en route flight into freezing drizzle or freezing rain conditions is prohibited. {insert cue description here}is an indication of severe icing conditions that exceed those for which the airplane is certified. If severe icing is encountered, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.4 Approved for a portion of Appendix X icing conditions

A4.4.1AFM Limitations

Intentional flight, including takeoff and landing, into {insert pilot usable description here} conditions is prohibited. If {insert pilot usable description here} conditions are encountered, or if {insert cue description here}, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.4.2AFM Operating procedures (normal procedures section)

{insert pilot usable description here} are severe icing conditions for this aeroplane. Intentional flight, including takeoff and landing, into {insert pilot usable description here} conditions is prohibited. A flight delay or diversion to an alternate airport is required if these conditions exist at the departure or destination airports.

{insert cue description here} is one indication of severe icing for this aeroplane. If severe icing is encountered, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Stay clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

A4.4.3 Flightcrew Operating Manual operating procedures

Warning: Severe icing may result from environmental conditions outside of those for which the airplane is certified. Intentional flight into severe icing conditions may result in ice build-up on protected surfaces exceeding the capability of the ice protection system, or may result in ice forming aft of the protected surfaces. This ice may not be shed when using the ice protection systems, and may seriously degrade the performance and controllability of the airplane.

Operations in icing conditions were evaluated as part of the certification process for this aeroplane. {insert pilot usable description here} were not evaluated and are considered severe icing conditions for this aeroplane.

Intentional flight, including takeoff and landing, into {insert pilot usable description here} is prohibited. A flight delay or diversion to an alternate airport is required if these conditions exist at the departure or destination airports. {insert cue description here}is an indication of severe icing conditions that exceed those for which the airplane is certified. If severe icing is encountered, immediately request priority handling from air traffic control to facilitate a route or altitude change to exit all icing conditions. Remain clear of all icing conditions for the remainder of the flight, including landing, unless it can be determined that ice accretions no longer remain on the airframe.

APPENDIX O - ENGINE SUB-GROUP RECOMENDATIONS FOR ADVISORY MATERIALS (REVISION TO AC 20-147)

U.S. Department
of Transportation
Federal Aviation Administration

Advisory Circular

Subject: TURBOJET, TURBOPROP, AND TURBOFAN ENGINE INDUCTION SYSTEM ICING AND ICE INGESTION

Date: 2/02/04
Initiated By: AIR-100

AC No: 20-147
Change:

1. **PURPOSE.** This advisory circular (AC) provides guidance and acceptable methods, but not the only methods, for demonstrating compliance with the applicable engine induction system icing and engine ice ingestion requirements. These requirements are applicable to the Federal Aviation Regulations, parts 23, 25, and 33 of Title 14 of the Code of Federal Regulations (14 CFR parts 23, 25, and 33). The primary purpose of this AC is to prevent inconsistencies when installing a part 33 certified engine in a part 23 or 25 aircraft. The guidance in this AC is not intended to address turboshaft engine installations, or the rotary wing aircraft they are installed on. Due to the complexity that those aircraft and installations pose for icing, AC 20-73, Aircraft Icing Protection, is considered the primary AC for those installations. Further, this AC also provides guidance materials on mixed phase (supercooled liquid drops and ice particles) and ice crystal icing conditions (ice particles only), and a discussion on an acceptable means of demonstrating compliance in such icing conditions. While these guidelines are not mandatory, they are historically based and are derived from extensive Federal Aviation Administration (FAA) and industry experience in determining compliance with the relevant regulations. This AC does take precedence over the engine and engine installation icing guidance in AC 20-73. It is important to note that AC 20-73 does contain useful information on the understanding and characterization of the icing environment. Additionally, AC 23-16, Powerplant Guide for Certification of Part 23 Airplanes, does take precedence over the engine installation guidance provided in this AC, as one method of compliance to part 23 regulations.

2. APPLICABILITY.

a. The guidance provided in this document is directed to engine manufacturers, modifiers, foreign regulatory authorities, FAA engine type certification engineers and their designees.

b. This material is neither mandatory nor regulatory in nature and does not constitute a regulation. It describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations. The FAA will consider other methods of demonstrating compliance that an applicant may elect to present. Terms such as “should,” “shall,” “may,” and “must” are used only in the sense of ensuring applicability of this particular method of compliance when the acceptable method of compliance in this document is used. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. Alternatively, if the FAA becomes aware of circumstances that convince us 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. 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, §§ 25.1093 and 25.1419.

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

4. RELATED READING MATERIAL (Latest Revisions).

a. AC 20-73, Aircraft Ice Protection.

b. AC 33-2B, Aircraft Engine Type Certification Handbook.

c. FAA Report No. FAA-RD-77-78, Engineering Summary of Powerplant Icing Technical Data, July 1977.

d. AC 23-16, Powerplant Guide for Certification of Part 23 Airplanes.

5. BACKGROUND.

a. The induction system icing requirements of parts 33, 23, and 25 are intended to provide protection for anticipated flight into icing conditions with no adverse effect on engine operation or serious loss of power or thrust. Propulsion systems certified under these requirements and operated in accordance with the airplane flight manual, have generally demonstrated safe operation when exposed to natural icing environments. This AC will supersede the engine and induction system icing guidance contained in AC 20-73 and AC 33-2 with regard to turbojet, turboprop and turbofan engine icing and engine installation icing approvals. Bear in mind AC 20-73 does contain additional guidance on turboshaft engines and installations. The test conditions called out in Part 33.68 are intended as standardized engine icing certification test conditions. These standard conditions, in conjunction with any design-specific critical test points, should be used together with any additional conditions that the Administrator determines to be critical. These standard test conditions have been determined, through more than 30 years of certification experience, to provide an adequate and consistent basis for engine icing certification with good service experience. The successful demonstration of the test conditions outlined in the regulation is intended to address many potential engine power conditions, aircraft flight conditions, and environmental conditions that could otherwise prove to be costly and difficult to realistically test. Service experience, now in the hundreds of millions of hours, has also shown a long success record when using these test points to cover unknown environmental or operational factors. Finally, one should be aware that in Appendix C and Appendix X of part 25 and Appendix D of part 33, the environmental threat is considered probable, and therefore likely to occur. In comparison, this occurrence rate is far more probable than the remote threat posed by the rain and hail environmental threat in Appendix B of part 33. Therefore, a direct comparison of guidance between the acceptable test outcomes of the icing certification requirements and the rain and hail certification requirements is not appropriate. Again, it should also be recognized that although Appendix C, Appendix X and Appendix D are the certification standards, it is still possible to have in-service icing conditions that are more severe than the Appendix C, Appendix X and Appendix D conditions. The Appendix C and X conditions were designed to include 99 percent of icing conditions. Evaluation of icing data has indicated that the probability of encountering icing LWC levels outside of Appendix C droplet conditions is on the order of 10-2[1]. The applicant may assume this probability for encountering the large droplet conditions conducive to ice accumulation aft of the airframe's protected areas. It should be considered as an average probability throughout the flight. Often, experience has shown that the actual icing environment in nature can be a combination of conditions, such as a continuous maximum cloud followed by a intermittent maximum cloud followed by a continuous maximum

---

[1] Note that exceedance of Appendix C LWC & MVD and operating below Appendix C temperature simultaneously is on the order of 10-3.

cloud, and so on. While technology efforts need to be completed regarding the analysis and testing requirements for compliance with Appendix D conditions, the allowance for comparative evaluation under the rule enables application of the rule in advance of completing that work.

6. DEFINITIONS. The following are defined for the purpose of this AC

a. Auto-recovery systems. Auto-recovery systems typically include auto-relight systems, stall recovery systems, or any other engine system intended to recover the operability of an engine following a flameout, surge, stall, or a combination of these.

b. Freezing fraction. The fraction of impinging water that freezes on impact

c. Ice formations. Ice formations resulting from the impact of supercooled water droplets on propulsion system surfaces are classified as follows:

(1) Glaze ice. 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 content, and droplet sizes between those that produce rime and glaze ice.

d. 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 through visual means (for example, high-speed camera which should view fan and booster or low pressure compressor (LPC) inlet guide vane components), and engine instrumentation (such as, vibration pickups, temperature probes, speed pickups, and so on).

e. Icing condition. A meteorological condition defined by the following parameters:

(1) Liquid Water Content (LWC). Concentration of liquid water in air, typically expressed in grams of water per 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, i.e. half the water volume is in larger drops and half the volume in smaller drops. (Note: MVD is equivalent to MED of Appendix C for an assumed Langmuir type droplet distribution.)

(3) 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; i.e. half the ice mass is in larger particles and half the ice mass is in smaller particles.

(4) Temperature. The total temperature associated with the icing cloud environment. Appendix C, Appendix X and Appendix D temperatures are static ambient temperatures. When a critical test point analysis is conducted, the local total temperatures at the engine inlet should be considered, based on applying the Appendix C, Appendix X and Appendix D static temperatures and assumed flight Mach number.

f. Power loss instabilities. Engine operating anomalies such as non-recoverable or repeating surge, stall, rollback, or flameout, can result in engine power or thrust cycling.

g. Scoop factor (concentration factor). The ratio of nacelle inlet highlight area (A_H) to the area of the captured air stream tube (A_C) [scoop factor = A_H/A_C]. The highlight area is defined as the area bounded by the leading edge of the nacelle inlet. Scoop factor potentially concentrates liquid water available for ice formation in the inlet and additionally in the low-pressure compressor or engine core as a function of aircraft forward airspeed and engine power condition. The scoop factor affect depends on the droplet diameter, the simulated airspeed and the engine power level as well as the geometry and size of the engine

h. Serious loss of power or thrust. Engine operating anomalies such as non-recoverable or repeating surge, stall, rollback or flameout, which can result in noticeable engine power or thrust loss. The FAA (that is, the Engine and Propeller Directorate, the Transport Airplane Directorate, and the Small Airplane Directorate) expects there will not be a noticeable power or thrust loss. This is especially important when considering that icing encounters are considered a frequent event, and multiple encounters for each flight is a reasonable assumption. The word “noticeable”, as used above, refers to flight crews tactile feel during the event, or the use of typical engine test instrumentation, or flight deck instrumentation (such as, N_1, N_2, vibes, exhaust gas temp).

i. Steady Operation. During icing testing, the engine should demonstrate steady, reliable, and smooth operation while sitting on test point (during multiple build or shed cycles, if ice is accreting), as well as during throttle transients. The term “steadily” is intended to address both stabilized ice accretions and stabilized engine operation. Ice accretions are considered stabilized when either ice is not forming on any engine parts, or the accreting ice has demonstrated a regular shed cycle when viewed by a video camera or instrumentation indication. Engine operation is considered stabilized when the measured engine parameters are not changing, or a regular, repeatable shed cycle has been demonstrated through the recording of measured engine parameters. The applicant should determine what parameters need to be monitored to determine steady operation of the engine during the icing test. 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.

j. Sustained power loss. A permanent reduction in power or thrust at the engine’s primary power set parameter (for example, fan rotor speed, engine pressure ratio). A sustained measurable power loss is considered a “severe power loss” in the context of the icing requirement. Power or thrust losses that are not sustained are temporary in nature and may be related to the effects of ingesting super-cooled water or ice particles, or possibly the effects of ice accumulation or ice shedding. The engine’s momentary response during shedding may be from the thermodynamic engine response to the ice ingestion.

k. Water impingement rate. The rate (gm/Sq. m/min) at which a portion of the surface area of a solid object is impacted by the water droplets in a moving air stream.

l. Descent Idle Engine RPM. The engine RPM for this phase of flight is the altitude- dependent minimum flight idle generally in effect from the top of descent (TOD) to the point at which the approach phase of flight begins (typically defined when flaps are deployed) and idle RPM increases to reflect the flight control requirements during approach.

m. Span. The length of an engine compressor airfoil (rotor or stator) measured from the flowpath ID to the flowpath OD

n. Momentary power loss. A reduction in engine power or thrust associated with a transient event (e.g. ice shedding).

o. Temporary power loss. A reduction in engine power or thrust occurring during an icing encounter due to ice accretion within the flowpath.

p. Maximum continuous. Engine rating required by 14 CFR Part 33.7 (c)(1)(i) and documented in the engine type certificate data sheet, intended as the maximum power for continuous operation.

q. Takeoff power. Engine rating required by 14 CFR Part 33.7 (c)(1)(iii) and documented in the engine type certificate data sheet.

7. DISCUSSION. The induction system icing requirements of §§ 23.1093, 25.1093, and 33.68 are intended to provide protection for flight into icing conditions with no adverse effect on engine operation or sustained loss of power. An icing encounter, including a prolonged encounter, should not be of consequence to the crew, and should not invalidate the engine's compliance with other part 33 requirements (for example, §§ 33.15, 33.19, 33.63, 33.65, 33.75, 33.77, 33.83, 33.89(b), and the like). The engine should have sufficient durability to operate through prolonged or repeated environmental encounters, such as icing, without special operational or maintenance interventions. Operational procedures to assist ice shedding, such as throttle manipulation, should not be relied on, or be required to comply with parts 23, 25, and 33 in-flight icing requirements. It is acceptable to provide engine throttle manipulation (for example, power run-ups to shed ice) instructions to shed accumulated ice during ground operations. These instructions will be used as a recommendation for in-service ground operation, although they would be mandatory if they were utilized during the ground icing compliance demonstration of §§ 33.68(b), 23.1093(b)(2), and 25.1093(b)(2). The applicant should provide instrumentation and video or photographic coverage to supplement test results under §§ 33.68, 23.1093, and 25.1093. The applicant should determine the parameters, which may include both visual and instrumented indications that need to be monitored. The demonstration should include stable build or shed cycles (that is, steady operation) with either no ice buildup or no additional ice buildup on the engine or inlet. Normal engine control system responses during the ice accumulation process (for example, isochronous control response to accreting ice) are considered acceptable as long as there are no power losses. At the conclusion of the test point, during the acceleration to takeoff power, the measured parameters should demonstrate a smooth and steady acceleration characteristic, unless the applicant can provide an acceptable justification for a performance change while on test point (for example, thermodynamic engine response to shed ice ingestion is acceptable). Close coordination is necessary by all parties to ensure that test plans are in reasonable bounds for the anticipated use of the airplane. The body of this AC is arranged in three sections corresponding to the applicable parts (§§ 33.68 and 33.89(b); 33.77; and 23.1093 and 25.1093).

a. Mixed Phase or Ice crystal Icing Conditions. Mixed phase icing conditions occur when supercooled liquid water droplets and ice particles coexist in a cloud, often around the outskirts of a deep convective cloud formation. Ice crystal icing condition exists when all of the liquid water particles in the cloud have frozen into ice particles. In the past, susceptibility of turbine engines to mixed phase or ice crystal conditions has been considered minimal with the possible exception of two design features. They are (1) pronounced inlet bends (such as particle-separator inlets), or inlet flow reversals, where inlet flow can stagnate and accumulate ice, and (2) high solidity, high turning front stage compressor stators that can be susceptible to non-aerodynamic ice buildup on the stator air foils resulting in core airflow blockage. More recently, however, there have been service events due to icing within the engine core stream due to mixed phase/ice crystal conditions. Adverse effects of this type of icing condition on the engine are uncommanded rollback of power or flameout with occasional core hardware damages. The root cause of these events can be traced to ice buildup within the core flow paths of the affected engines. In general, these events occur near convective clouds at ambient temperature warmer than the ISA standard atmosphere and outside of the FAR Part 25 Appendix C and Appendix X icing envelopes. FAR Part 33 Appendix D has been established to include this icing envelope. Malfunctioning of the Total Air Temperature (TAT) probe has been noted during many of these engine icing events and is a known indicator of ice crystals. Ice accumulation within the TAT probe would produce a false signal of air temperature stabilizing at the freezing point. Additionally, there have been cases of icing encounters in mixed phase icing conditions where ice detectors have not detected ice formation. Ice detection systems should be evaluated for these conditions. Guidelines to comply with the certification requirements for mixed phase or ice crystal icing are discussed in this AC.

b. Auto-recovery systems. The use of auto-recovery systems is acceptable for certain engine certification testing. The FAA supports the use of auto-recovery systems, or other protective engine systems or devices, while in service, and allows the use of auto-recovery systems during ice slab ingestion certification testing as defined in § 33.77. Generally, compliance with §§ 33.68 and 33.77 requires a demonstration that no flameout, sustained power loss, surge or stall, or rundown is evident. Although ignition systems have generally been found to be reliable for auto-relight use after certain ice ingestion or accretion induced flameouts (§ 33.77, 25.1093), the auto-relight system should not be relied on during typical icing encounters (§ 33.68). Auto-recovery systems are regarded as only back-up devices, and should not be routinely needed. In addition, auto recovery systems are not considered the primary protection for continued safe engine operation during normal ice sheds or accumulations while operating in typical icing conditions. Details will be provided later in this AC about the use of auto-recovery systems when demonstrating compliance to §§ 33.68 and 33.77.

c. Use of Cloud Extent Factors for § 33.68. In Appendix C, Appendix X and Appendix D, a cloud extent is the distance vertically (vertical extent) or horizontally (horizontal extent) that a cloud extends. Vertical extent is normally measured in feet while horizontal extent is measured in nautical miles. The cloud extent factor is a dimensionless number, which relates the length of a cloud to an average LWC across the cloud. These relationships described within Appendix C, Appendix X and Appendix D should be used in the critical point analysis (CPA) for assessing the probability of occurrence of icing conditions during various aircraft mission and performance analyses. These factors are applicable to airframe flight profiles where the straight-line flight portion of the evaluations may use the cloud extent factor included in Appendix C in Figures 3 and 6, Appendix X in Figure 7 and Appendix D in Figure D-3, as applicable. However, engines and induction systems being evaluated under § 33.68 have historically not been limited to or evaluated against a specific aircraft flight profile when considering icing environments. Instead, under § 33.68, they are evaluated for unlimited operation in icing. It is emphasized that the criteria in Appendix C represent those icing conditions that could result from encounters with supercooled clouds. Other conditions that may contribute to aircraft engine icing conditions include freezing precipitation (that is, rain and drizzle) covered by Appendix X. Ice crystals, and mixed conditions (meaning, mixture of supercooled water droplets and ice crystals) are defined in Appendix D. To account for the differences described above, multiple clouds should be assumed, with an extent factor equal to 1.0, as actual cloud extent is not a consideration for engine operations, particularly in an aircraft hold pattern. This approach will assure unlimited engine and induction system operation within the atmospheric conditions defined by Appendix C, Appendix X and Appendix D, and as experience indicates, in actual icing environments that include Appendix C, Appendix X and Appendix D in its entirety. The cloud horizontal extent factor was not intended to be used to limit the severity of exposure to icing conditions, where it is reasonable to assume the aircraft will be required to operate in that condition (for example, the holding pattern which may require repeated passes through a severe icing environment, or continuously remain in that severe environment). As a general rule, engines and induction systems should be shown to operate continuously in icing without regard to time in icing conditions. The cloud extent factor defined in Appendix D relies primarily on limited data derived from Reference 1. The data covered several geographical regions including eastern Asia where ice crystal-related service events are prevalent.

SECTION 1. INDUCTION SYSTEM ICING (§§ 33.68 and 33.89(b))

8. CRITICAL POINT ANALYSIS (CPA). Compliance with the requirements of § 33.68 includes identifying, through analysis, the critical operating test points for icing within the declared operating envelope of the engine. The CPA should include a range of possible combinations of icing conditions. This range should relate to Appendix C and X of part 25, Appendix D of part 33, aircraft speed range, and engine powers as defined by the engine manufacturer, and prolonged operation in icing (for example, in-flight hold pattern), or repeat icing encounters. The CPA should be validated by empirical test data. This analysis should consider both critical ice accumulation conditions (that is, rime ice and glaze ice), environmental and engine operational effects on accumulation, accretion locations, as well as the most critical engine operating conditions for ice shed and ingestion. Some manufacturers have included within their CPA, a best practice of including conditions that may be outside of Appendix C, Appendix X and Appendix D, that have been identified through service difficulty of other engine models. Often the CPA is supplemented with development test data (for example, wet and dry testing with thermocouple components). The methodology used to calculate ice accretions should account for freezing fraction and pertinent aerodynamic effects. For example, water ingestion into fan inlet and core inlet, water impingement rates for critical surfaces, forward aircraft air speed effects, engine configuration effects such as inter-compressor bleed, and altitude effects such as bypass ratio effects. This should be in conjunction with 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. For anti-iced parts, the critical test point should be determined from energy balance calculations of required heat loads encompassing the range of possible combinations of icing condition and engine power. In instances of low freezing fraction in glaze ice conditions, additional complexities arise from assessing the effects of non-aerodynamic ice formations and their shedding. Federal Aviation Administration (FAA) Report No. FAA-RD-77-78, Engineering Summary of Powerplant Icing Technical Data, provides additional guidance on performing a critical test point icing analysis.

a. Test versus Analysis. The CPA was not meant to replace testing, but instead provides a means to predict other critical test points with equivalent level of safety to replace or supplement the standard certification test points (§ 33.68C) . The FAA maintains this view of the CPA complementing the standard table test points provides an adequate methodology to cover all icing conditions. The FAA recognizes an improvement in the fidelity of analysis tools that are available today. However, based on experience with the various applicants, the FAA believes that the CPA is best utilized as a method to predict the critical icing conditions for a given design, and then use these conditions in conjunction with the standardized certification test points for certification compliance test purposes. It should be noted that FAA concurrence with a type certificate holders generic CPA method does not automatically constitute FAA 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. Some engine manufacturers have had difficulty in consistently achieving the agreed on test points that are necessary for compliance demonstration, due to facility or weather limitations. This difficulty is based on test facility limitations that can be expensive and often impractical to overcome. To directly address this repeated shortfall, the FAA has identified several national and international icing resources for accomplishing § 33.68 compliance testing. These resources include the Air Force's McKinley Climatic Lab (Florida), the Air Force's AEDC (Tennessee), and the Canadian government's NRC (Ottawa), to name a few. There are additional test facilities that are suited for component or model testing.

b. Elements of CPA. The CPA should address, at minimum, the following icing issues:

(1) Ice shed damage. Ice accretion on engine surfaces (for example, blades, vanes, sensors) may eventually shed. The shed ice can subsequently cause engine damage if it impacts an engine surface with sufficient mass and velocity.

(2) Fan module. Acoustic panels, fan rub strips, and fan blade tips are susceptible to ice shed from inlet sensor(s), spinner, and fan blade root. The effects of ice density, hardness, and adhesion strength should be assessed to realistic flight conditions. The ice shed cycle for rotating surfaces, such as fan blades, is strongly influenced by 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 rotor speed at the time of the shed defines the impact threat. In determining the critical conditions for fan module damage, surface temperature, exposure time, and rotor speed are important considerations in addition to more typical parameters, such as icing condition and scoop factor In particular, extended operation in a holding condition in very cold continuous maximum icing conditions will maximize the adhesion of ice on rotating fan components.

(3) Compressor damage. A common damage scenario in turbofan engines, is the accretion of glaze (non-aerodynamic) ice formations on static components (for example, sensors, vanes, and bleed ducts upstream of the compressor) which when it sheds, results in damage. This type of damage generally occurs on the first blade set in the high-pressure compressor (intermediate pressure compressor for three spool engines). Establishing the critical conditions for these glaze ice accretions requires careful consideration as 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 recommended by this AC (that is, flight-idle, 50-percent and 75-percent of maximum continuous or 100-percent maximum continuous).
Any engine damage that results from ice testing should be evaluated against the possibility of multiple occurrences, since icing is a common environmental condition.

(4) 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 the engine to assume new operating conditions (that is, engine component cycle rematch). The engine should be capable of accelerating from minimum flight-idle and ground idle to takeoff power, at any icing condition, without power loss, or instability (surge or stall). Ice sheds should not result in flameout, rollback, or surge. Any anomalous engine behavior should be raised to the cognizant Aircraft Certification Office (ACO) for evaluation and if found acceptable, should be documented in the engine's installation manual. The applicant should consider as part of the CPA both engine accelerations and decelerations relative to operability challenges. Critical test point testing should demonstrate those conditions where minimum operability margin is expected.

(5) Core and Booster ice blockage. Ice accretion on internal engine vanes due to the presence of glaze ice accretions may affect flow capacity and rematch of the engine cycle and should be considered in the CPA. At engine powers that can sustain flight, ice accretion should be reconciled through a demonstration of several ice build shed cycles to demonstrate no adverse operating effects of either the ice builds or sheds.

(6) Sensor fouling. Ice accretion and blockage of control sensors can result in erroneous engine pressure and temperature measurements. A power loss or power loss instability could result if these measurements are used by the engine control systems control law to establish power or thrust ratings, or to schedule other systems required to operate the engine (for example, variable stator vanes). Critical sensors should be designed to operate without accreting ice sufficient to cause an erroneous measurement that would result in an unacceptable operating characteristic. Additionally, ice accretion on upstream sensors can shed and cause engine damage to downstream rotating hardware.

9. TEST POINT(S) SELECTION. Test points selected for supercooled droplet environment must address the FAR Part 25 Appendix C and X icing envelopes. Test points for the mixed phase and ice crystal icing environment must be representative of the meteorological conditions defined in FAR Part 33 Appendix D. Typically, the supercooled droplet test points include those described in the rule and any additional test points identified as part of the CPA. The applicant should consider pertinent service experience as well as the anticipated use of the aircraft when selecting critical icing test points. The following should be considered when constructing an icing test matrix:

a. Section 33.68 Acceptable Means of Compliance. The engine should be capable of operating acceptably under the meteorological conditions of Appendix C and Appendix X over the engine-operating envelope, as described in § 33.68(B), and under conditions of ground fog (§ 33.68(D)). Experience has indicated that testing to the conditions specified in the § 33.68(C) tables have been a successful means of showing compliance, if used in conjunction with the critical conditions determined in the CPA. § 33.68(C) does allow for the elimination of specific standard certification test points if the applicant chooses to run a similar CPA test condition that can be shown to be more severe in terms of ice accretion mass at critical engine locations or to produce an equivalent level of safety. Similar is defined as being at essentially the same level of engine low rotor RPM, the same type of ice accretion (glaze or rime), and for the same or longer period of icing exposure.

Specifically for the icing conditions defined in the Table 33.68-1 of Part 33:

- The LWC for all table points represent ambient icing conditions for an open inlet ground test facility or equivalently within the inlet duct of a direct connect test facility. Consideration of local enrichment for flight effects as would normally be done for a CPA point LWC is not necessary.

- Conditions 1 and 2. Operate the engine steadily (see definitions for “steady operation”) under rime and glaze icing conditions for at least 10 minutes each, typically during separate tests, at maximum continuous (M.C.), 75-percent of M.C., 50-percent of M.C., and for 10 minutes at a flight-idle setting. Each separate test is followed by an acceleration to takeoff power. If ice is still building up at the end of 10 minutes at the three higher power settings, continue running until the engine demonstrates stabilized operation (meaning, stabilized building and shedding is demonstrated or the engine will no longer operate satisfactorily).

- Conditions1 and 2 of Table 33.68-1, are intended to partially cover a widely bounded 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 takeoff during exposure to conditions typical of high altitude where rime ice formations occur, as well as conditions typical of low altitude where glaze ice formations often occur. 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 substantiate engine inlet screens and inlet air passages that might accumulate snow or ice due to restrictions or contours. Also, engines that employ an inlet de-ice system that may have some unheated inlet surfaces may need to be run longer. At 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 high altitude top of descent operation. 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.

- Conditions 3 and 4 (Holding phase). This test, when performed as part of a part 33 demonstration, is intended to be applicable to part 33 engine components. Both the engine (§ 33.68) and aircraft inlet induction system (§§ 23.1093 and 25.1093) should operate safely in an in-flight holding phase without a time limit. The test program for turbofan and turboprop applications should include test points (for example, icing condition and power setting) to address the effects of prolonged exposure in icing conditions typical of in-flight holding patterns. Condition 4 in table 33.68-1 represents a rime icing condition that is typically encountered on transport category airplanes. Condition 3 in table 33.68-1 represents a mixed rime and glaze icing condition that was originally derived from the 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 33.68-1. A 45-minute test exposure followed by acceleration to takeoff power will typically demonstrate several ice shed cycles and should normally be sufficient to assess compliance for the engine.

- For all conditions. Engine operation in these icing conditions should be reliable, uninterrupted, and without any significant adverse effects, and should include the ability to continue in operation and accelerate and decelerate. Some power reduction is acceptable at idle power settings due to the cycle effects of pumping ice and water, but all other operation should be unaffected.

- While at flight-idle engine speed and above, for engines with icing protection systems (including systems for probes), stabilize the engine for at least 2 minutes in the icing atmosphere with these protection systems off, prior to turning on the icing protection system to simulate the delay expected for the pilot to recognize the icing condition. 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 ice protection system demonstration. Where the engine's anti-icing system relies on an ice detector to indicate the presence of icing conditions, delay in anti-ice selection is likely following failure of the detector, and so delayed selection testing should still be demonstrated.

- The engine must operate “steadily” under the tested icing conditions. The term “steadily” is defined in the definitions section and is intended to address both stabilized ice accretion and shed cycles during stabilized engine operation. Ice accretions are considered stabilized when either ice is not forming on any engine parts or the accreting ice has demonstrated a regular shed cycle when viewed by a video camera or instrumentation indication, or both. Engine operation is considered stabilized when the measured engine parameters are not changing, or a regular, repeatable shed cycle has been demonstrated through the recording of measured engine parameters.

- Turboprop engines equipped with an inlet screen: The inlet screen compliance demonstration for icing including any associated shed cycle may be addressed separately from the part 33.68 engine ice compliance testing, but then should be noted in the engine installation manual. If not addressed under part 33.68, compliance could then be demonstrated under the aircraft inlet requirements of 23.1093, 25.1093, 27.1093, or 29.1093. Special attention should be given to these inlet features, including specialized tests or analysis.

- At the conclusion of each steady state icing test point, the engine should be accelerated to takeoff power (throttle movement of 1 second or less) or shedding should be induced by other methods, depending on the critical shed methodology. The throttle 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. The applicant should assess this effect and account for their assessment in their test proposal.

b. <u>Section 33.68(D) – Ground Operation:</u> Section 33.68(D) provides two icing test points that represent a typical freezing fog, a supercooled large droplet (SLD) test point that represents freezing rain or drizzle, and a falling or blowing snow icing encounter during ground operation. The SLD condition is similar to freezing fog in terms of ambient temperature range and LWC levels, but the larger droplets can notably penetrate further back on the surface of the engine spinner with the potential for ice shedding into fan blades. Allowance for analysis as means of compliance offers the option of comparing a new engine design for spinner icing/de-icing characteristics and fan blade robustness to prior engines with good service experience.

The guidance contained in AC 33.2B, with respect to snow ingestion testing, is considered outdated. The ground-fog icing, SLD and falling or blowing snow demonstrations should continue for at least 30 minutes or until stabilized operation (see "steady operation" in the definitions section of this AC) is demonstrated. If this stabilized operation cannot be demonstrated then periodic engine speed run-ups should be demonstrated. These run-ups would then become mandatory in the AFM in icing conditions since they were required to comply with the icing requirements. Service experience has demonstrated compressor damage as a result of exposure to prolonged periods of falling snow during ground operation. Based on review of service events, airports have continued to operate with falling-snow concentrations that result in 0.25 mile or less visibility (about 0.9 gm/m3). While visibility can be a poor indicator of precipitation rate (Rasmussen et al., 1999), the following calculation based upon equivalent rainfall rate gives a similar result. The maximum precipitation rate for moderate snow is 2.5 mm/hr water equivalent. Using a typical fall speed for snow of 0.8 m/s, this translates into a snow concentration of 0.9 g/m3 water equivalent. 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. It should be mentioned that Holdover Time Tables for de-icing fluids are only good for the extreme values of moderate snow which is defined as 2.5 mm/hr (or a visibility of ¼ statute mile). Engine core icing service events in snow conditions support the temperature range of 26 to 32 deg F (-3 to 0 deg C). Within this range, water content in the form of supercooled liquid drops can be considered negligible.. This environment is conducive to ice accretion in mid and rear compressor stages of the engine. Liquid water icing conditions defined in §33.68 adequately evaluate the effects of ice accretion in front sections of the engine. Sections 23.1093(b)(ii) and 25.1093(b)(ii) require that engines must operate satisfactorily in falling and blowing snow throughout the engine power range, within the limitations established for the airplane for such operation.

c. Ground Idle Demonstrations: Operate steadily at ground idle setting for at least 30 minutes under icing conditions of §33.68(D) followed by acceleration to takeoff setting. Since a broad temperature range is provided, the applicant should identify the most critical temperature, as determined by the CPA, and target that range. Turboprop engine inlet screen icing compliance demonstrations may be addressed separately from the part 33.68 engine ice compliance testing, but then should be noted in the engine installation manual. It is recommended that special attention be paid to these inlet features. For large bypass fan engines, shedding at this low speed from static surfaces is not likely at 30 minutes and beyond. For these engines, this test generally establishes the maximum allowable time in the engine operating manual between engine run-ups to shed ice. The AFM should specify the maximum demonstrated time between run-ups. Demonstration that ice sheds from compressor static surfaces during the run-up establishes that the engine can operate continuously (including run-ups, if necessary) at the ground icing condition, as might well occur at an airport where aircraft can be held on the ground several hours in bad weather awaiting takeoff. Alternate run-up procedures that can be shown to provide acceptable engine acceleration to takeoff power are also acceptable.

d. Mixed phase or ice crystal icing: It has been established that mixed phase or ice crystal icing conditions that are hazardous to turbine engines exist around the outskirts (anvil) of a deep convective cloud formation as well as near tropical storms such as monsoons, hurricanes, and typhoons. A compilation of mixed phase/ice crystal icing condition currently available is in Reference 7. This report recommends that ice water content up to 1.2 g/m3 could exist in thunderstorm anvil cloud above 25,000 feet altitude, but also includes information from ADS-4 citing total water concentrations (TWC) in the range of 1 to 5 g/m3 in this range. The ice particles within this cloud can range up to 10 mm, with highest concentrations having a median diameter of less than 200 microns. In order to define compliance requirements, it was necessary to define an extension to the icing envelopes defined in FAR Part 25 Appendix C and Appendix X. FAR Part 33 Appendix D has been created for this purpose. TWC levels in Appendix D are based upon predicted “adiabatic” condensation rates in convective storm updrafts. This has been shown to be a reasonable assumption based on limited field trials. Until a more comprehensive mixed phase and ice crystal icing envelope is defined, Appendix D should be treated as the critical mixed phase/ice crystal icing condition in demonstrating compliance to certification requirements.

10. TEST SETUP CONSIDERATIONS. The Liquid Water Content (LWC) levels defined in Appendix C and Appendix X of Part 25 are intended as supercooled droplet ambient icing conditions. Tests may be conducted with a simulated cloud outside of the inlet that is ingested into the engine. Under such a test environment, the LWC within the inlet ducting may be more or less than the engine inlet LWC concentration if the engine were actually installed in an airplane and flying through those icing conditions at actual airspeeds. This inlet concentration/dilution effect is dependent on droplet size, engine fan speed, and simulated forward airspeed. As an example, operation at idle descent power with simulated forward airspeed that is less than flight speed might require a compensating increase in test level LWC concentration above Appendix C and Appendix X conditions. This increase would be greater for larger supercooled droplet diameters. Engine size is also a variable that affects the difference in LWC inlet concentration between flight conditions and the engine test environment, with the greatest potential compensation requirements being for small engines.

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 that could alter the test parameters (for example, LWC and MVD). The applicant must provide the FAA with substantiation that the required simulated test conditions adequately simulate an installed engine flying through the Appendix C and X conditions. This substantiation can be in the form of direct measurement of LWC within the inlet or by acceptable validated analysis of water droplet trajectories for the test setup. In some cases, LWC may need to be adjusted to address any effects due to the test setup (for example, non-uniformity across the engine face).

Flight-testing in mixed phase or ice crystal icing conditions defined in part 33 Appendix D: Flight-testing is the most accurate method of demonstrating engine operation in this icing condition. Two important considerations in flight testing in mixed phase or ice crystal icing conditions are the measurement of ambient meteorological data and the ability to project the measured engine performance to the critical icing point cited in this AC. To address the latter, a fully instrumented engine with temperature sensors strategically located in the core flow passage is required to collect data during the encounter with this environment. Since the meteorological condition encountered may not be as high as the critical point level, scaling of the measured data would be required to substantiate satisfactory engine operation at the critical point. To support the scaling calculation, an accurate measurement of the ambient meteorological condition is essential. Past engine flight tests in this environment had demonstrated that a combination of liquid water content probe, total water content probe, particle sizing and imaging probe, ice detector and TAT probe is necessary to fully characterize the ambient environment. Onboard real time meteorological data display with GPS positioning capability were also very helpful tools in locating the area where high ice crystal concentration exists. 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 sorties into this hazardous environment.

Simulation of the critical mixed phase/ice crystal icing condition in ground facility: As indicated in Reference 7, facility simulation of mixed phase/ice crystal icing conditions is difficult and not done routinely. It is not known how well any of the various methods that have been used actually simulate the natural environment. A testing standard for this icing condition is not established. Therefore, using ground simulation as a means of demonstrating compliance to the mixed phase/ice crystal icing certification requirement will have to be evaluated on a case-by-case basis.

11. TEST RESULTS AND COMPLIANCE ISSUES. During all icing tests (supercooled droplet, mixed phase or ice crystal icing), the engine should operate without the accumulation of ice, which would adversely affect engine operation (for example, flameout, surge, stall, run-down, high vibrations, slow acceleration or lack of throttle response) or cause a sustained loss of power or thrust. Additionally, the applicant should accurately monitor icing test point conditions either through video surveillance or instrumentation and provide the means to identify the source of ice damage, especially in those instances where test apparatus may shed ice (for example, icing nozzles, special test instrumentation).

a. Sustained loss of power or thrust and power loss instabilities. There should be no sustained power loss while operating at approved ratings in icing conditions. Temporary steady state power losses below the engine power and thrust ratings selected in accordance with § 33.8 can be accepted if it is proven that there is sufficient margin against any power loss instability, such as rollback, surge, stall, high vibes or flameout. Momentary power loss caused by pumping or processing of ice debris through the fan and compressor during the ice shed ingestion process are generally acceptable. If temporary power loss or temporary high vibrations are deemed acceptable to the Administrator, they should be documented in the engine installation manual.

b. Mechanical Damage. There should be no engine damage as a result of § 33.68 icing testing. In some circumstances, some limited damage may be accepted. The acceptance of any damage must fully account for the cumulative damage from repeat encounters, provided the applicant satisfies the following criteria:

(1) Continued in-service use. Any resultant damage should be shown to be acceptable for continued in-service use.

(2) Sustained power losses. There should be no resultant sustained power loss beyond the nominal accepted level considered to be within measurement capability (1.5%);

(3) Temporary power loss. Although not generally acceptable, any resultant temporary steady state power loss, surge or high vibrations, if found acceptable by the Administrator, should be recorded in the installation manual.

(4) Validation basis. Analytical tools used to substantiate the criteria for determining acceptable damage should be shown to have a sufficient validation basis (for example, engine tests, rig tests, service experience) to substantiate the accuracy of results or be shown to yield conservative results.

(5) Disposition of Damage. Disposition of damage to any engine or engine component may not be obtainable solely by comparing the damage against the maintenance manual limits. The cumulative damage for repeated encounters should be evaluated.

(6) Communication of results. The Installation and Operating Manuals required by § 33.5 should provide information describing any resultant engine condition observed during engine certification icing tests. The engine

manufacturer should provide a process to permit disposition of any potential damage that could occur during natural icing flight tests conducted to demonstrate compliance with §§ 23.1093 or 25.1093, if the installing FAA Aircraft Certification Office finds this acceptable. Also, if periodic engine power run-ups are necessary to minimize damage from icing during the ground icing operation demonstration of § 33.68(b), then this run-up must be documented. Documentation must contain a description of the run-up requirements and the required run-up intervals and it must be contained in the operating manual and airworthiness limitations section of the instructions for continued airworthiness (ICA). Any power loss anomalies due to accumulation, shed, runback and the like, and their effects on performance and operation should be documented in the Installation Manual. Both the engine certifying ACO and the installing ACO should carefully consider any high vibrations induced from ice accretions during ice testing. This too should be documented as described above.

c. Engine systems. It is permissible to use engine systems (that is, automatic, engine initiated ice protection systems) to fulfill § 33.68 requirements provided that its operation is not expected to result in crew action. Examples of engine characteristics that may not be transparent to the flight crew are exhaust gas temp fluctuations, or audible surging.

Any engine control system function which may be acceptable and required for engine ice protection certification in part 33 should not create an adverse interaction with other aircraft systems, aircraft handling qualities and performance, and human factors considerations. Any unacceptable interactions with the airplane may result in the engine being deemed un-installable for part 25 operation.

Crew interface, uncommanded thrust changes, thrust setting, asymmetric engine behavior, pilot workload and appropriate flight deck indication and procedures, the effect on airplane handling, pilotability, and human factors are critical issues which must be addressed.

Additionally, any engine system required to show compliance with § 33.68 should meet the following requirements:

(1) System reliability. Demonstrate the capability of the system for reliably sensing the conditions, which enables the function, throughout the operating envelope;

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

(3) Electronic faults. If the system uses electronics, substantiate that the function is not lost due to any single or probable multiple electronic faults;

(4) Other environmental testing. The function should not be affected when the system and any associated electronic systems are exposed to required

operating environments, including high intensity radiated fields (HIRF) and lightning; and

(5) Power requirements. For those systems that are powered solely with a dedicated engine alternator (either directly or using another engine system such as full authority digital electronic/engine control (FADEC)), it should be demonstrated that over the operating envelope, that the function (that is, sensing and performance) is provided at the minimum certified rotor speeds. Minimum certified engine speed is the minimum idle rotor speed achievable anywhere in the icing envelope.

d. Auto-recovery systems. Auto-recovery systems should not be needed during § 33.68 testing since these icing conditions are considered to be within the engine's certified operational envelope. The intent of § 33.68 is to certify engines that will be able to perform and operate reliably in the icing conditions described Appendix C, Appendix X and Appendix D Auto-recovery systems are considered to be back-up devices that are only needed following rare ice ingestion events that result from icing conditions significantly outside Appendix C, Appendix X and Appendix D, and should be communicated to the installing ACO if activation is expected or experienced in these rare occasions. Auto-recovery systems are not the primary protection for continued safe engine operation during normal ice sheds, or accretion while operating in icing conditions described in Appendix C, Appendix X and Appendix D. Therefore, it is acceptable to perform § 33.68 compliance testing with auto-recovery systems enabled, but they should not activate throughout the § 33.68 test sequence. Additionally, continuous ignition should not be selected during § 33.68 compliance testing. To assure non-activation of an enabled auto-recovery system, it may be necessary to display an instrumented signal that monitors auto-recovery system activation. If activation monitoring cannot be accomplished, then disabling of the auto-recovery system may be necessary.

e. Operating 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 §§23.1093(b)(ii), or 25.1093(b)(2), should be communicated to the installer in the Operating Instructions as a requirement, and should 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.

f. Special Considerations for Mixed Phase / Ice Crystals

14-CFR part 33 requirements for the type certification approval of engines operating in an ice crystal environment are located in section 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 paths of the affected engines. Adverse effects of this type of icing condition on the engine include uncommanded rollback of power or flameout as well as compressor stall and core hardware damage. This section provides guidance to applicants for new engine type approvals to address the issue of engine operation in an ice crystal environment defined in Appendix D of Part 33.

Ice crystals have only been recognized as a threat to turbine engines in recent years. In response to this recent recognition, the FAA has worked within a cross-functional industry/governmental group to develop standards to address this threat. During this rule and guidance development process, it is noted that ice crystal tools and test techniques have not yet been developed and validated, thus a phased-in approach has been developed to address this ice crystal issue during the conduct of the engine type certification program.

In the near term, new engines must be shown to address the known field issues in ice crystal environments (core damage and engine flameouts). 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 the new engine cycle and/or design features will result in acceptable engine operation.
Acceptable operation would include the absence of rollback, rundown, stall, flameout, and unacceptable compressor blade damage as described under paragraph (b) of this section.
Additionally, the manufacturer should show progress towards incorporating available technology and be driving towards a thorough substantiation for operation in ice crystals.

Long-term, an acceptable demonstration would include a Critical Point Analysis of an ice crystal environment as defined in Appendix D of Part 33. All engine power levels including in-flight idle operation should be evaluated in these conditions. The critical conditions should 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 used in this analysis should be calibrated by either rig calibration test data or engine test measurements.

Comparative Analysis Guidance

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 must show that the new engine cycle and/or design features will result in acceptable engine operation, when subjected to the ice crystal environment defined in Appendix D of Part 33. This comparative analysis should take into account both suspected susceptible design features as well as mitigating design features.

Susceptible design features could include such features as:

- Stagnation points which could provide an increased accretion potential.
- Exposed core entrance (as opposed to hidden core).
- High turning rates in the inlet, in the booster and core flow path (particularly compound turning elements)
- Protrusions into the core flow path (e.g. bleed door edges and measurement probes)
- Unheated surfaces on booster and front core stages.
- Narrow vane-to-vane circumferential stator spacing leading to a small stator passage hydraulic diameter

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

- Heated surfaces in the fan, booster and forward core compressor stages.
- Elevated rotor speeds.
- Hidden core entrance.
- Low frontal cross-sectional area on flowpath probes.
- Inter-compressor bleed scheduling to remove both the ice crystal media and any up-stream shedding, from the flowpath.
- Circumferential spacing of stators set to enhance tolerance to ice blockage (generally denoted by the hydraulic diameter of the stator passage)
- Core compressor airfoil soft body damage tolerance

(i). Alternate method of compliance by similarity to engines proven safe to operate in mixed phase or ice crystal icing conditions: Although it has been established that mixed phase or ice crystal icing conditions are hazardous to turbine engine operation, severe incident involving this type of meteorological condition is 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 design, similar to those proven engines, is allowed to show compliance by comparative analysis.

Firstly, the baseline (certified) engine should be identified and evidence that this engine is safe to operate in mixed phase or glaciated icing condition should be supplied by the applicant. This evidence can be field service experience or certification test report. Next, the icing pertinent engine features that may influence mixed phase or glaciated ice accretion within the target (certifying) engine should be compared to the baseline engine to establish that the former is less or equally susceptible to icing than the latter.

Lastly, a critical point analysis (CPA) should be performed to show that the operation and flight envelope of the target engine does not make it more susceptible to mixed phase or ice crystal icing than the baseline engine. This analysis should consider both environmental and engine operational effects on accumulation, accretion locations, as well as the most critical engine operating conditions for ice shedding.

If the new engine cycle and/or design features contain innovative design ideas such that a comparative analysis with current engines and specific engine events is not possible, then the applicant should demonstrate that this innovative feature will not be susceptible to the adverse effects of operating in ice crystal environment in a two parts process. Part 1 is to document the physical basis on why this design should result in acceptable operation in ice crystals. Part 2 is to generate physical evidence to substantiate the claims in Part 1. In the near term, before ice crystal tools and test techniques are developed and validated, water particles may be used in lieu of ice crystals in Part 2 of this process. However, data collected with water particles should be corrected to ice crystals

An example of steps that may be used in this process are:
- Part 1
  - Discuss consequences of ice accretion
  - Identify design features that promote tolerance to critical ice accretion
  - Discuss consequences of ice crystals on promotion of ice accretion

-Part 2
  - Identify test article (engine or component)
  - Establish test conditions promoting ice accretion (with allowance for use of liquid water in the near term if testing with ice crystals is not feasible)
  - Evaluate tolerance of new design features over a range of test points

(ii). Compliance Considerations

Engine icing events in atmospheric conditions associated with convective clouds and a mixed phase/ice crystal environment appear to be associated with accretion of ice in regions of the compressor which are further aft than typical for supercooled droplet environments. Understanding of this process is limited, however. It is expected that, as the 'state-of-the-art' progresses in these areas, the applicants can utilize advanced methods to support compliance for engine operation in Mixed Phase/Ice crystal icing conditions.

The accretion process is believed to be a result of ice crystals passing through the front compressor stages until the local atmosphere is conducive to forming a liquid layer on blade surfaces which then allows impinging crystals to melt and accrete on the surface. This is a combination of conductive & convective heat transfer due to melting, evaporation and surface contact. The form of ice can be rime or glaze, this is dictated by local temperature/pressure conditions and thus a function of power setting and ambient atmospheric conditions combined with specific design details. The applicant should use FAR33 Appendix D to define a range of operation to be assessed for potential accretion sites.

(iii). Mixed Phase / Ice Crystals Assessment

Applicant should consider the whole icing envelope, to include cruise, hold and descent power settings in mixed phase / ice crystal conditions defined in Appendix D. There is currently no established critical point analysis in Mixed Phase / Ice crystal icing conditions. To aid the applicant, some possible CPA point selections are illustrated in this section as an example. Some general criteria for selecting points includes:

- Service history suggests selection of points at high ambient temperatures within the Appendix D icing envelope consistent with higher TWC levels . Lower temperatures might push the accretion aft, where there may be a more critical ice accretion site, even with lower TWCs. Hence, both high and low temperatures within the envelope should be evaluated.
- Power levels with internal total air temperature within the core flow path between 0 deg C (32 deg F) and approximately 50 deg (120 deg F) to promote ice crystal melting. Power level adjusts the accretion site forward or aft within the engine.
- High altitude (low air density) to allow greater ice accretion mass prior to shedding from static surfaces.

The operating points for this evaluation are depicted on the Mixed Phase / Ice crystal icing envelope from FAR Part 33 Appendix D in the following two figures. They cover the various flight phases including cruise, idle descent and holding. The water contents shown in Figure 2 represent the level for the standard exposure distance of 17.4 nautical miles and must be adjusted to reflect the expected icing exposure period using the distance scale factor from Appendix D. Service experience suggests that exposure distances in the range of 20 to 80 nautical miles are appropriate.

As noted earlier, ice crystals promote icing at engine sites more rearward and at higher local air temperatures than would exist with only supercooled liquid. These sites also will have higher air loads which can limit ice accretion due to shedding. Hence, as noted in the general criteria, the CPA should consider not only ice accretion, but also the likelihood of ice shedding.

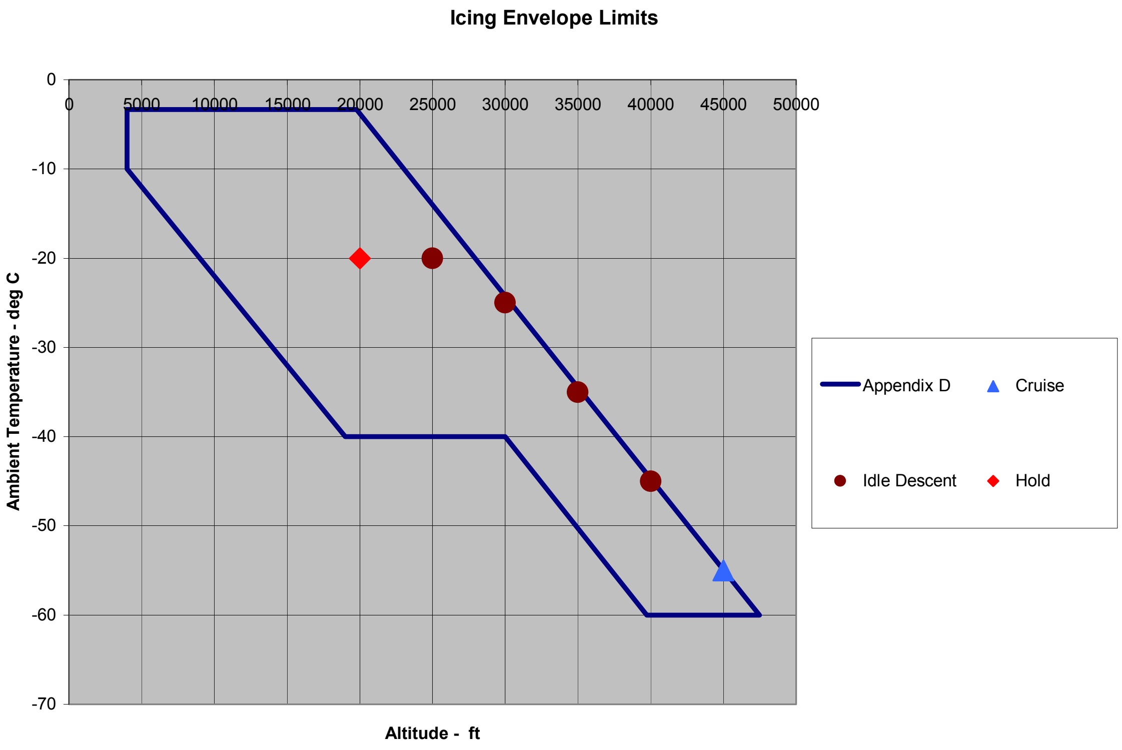


Figure 1. Appendix D Icing Envelope

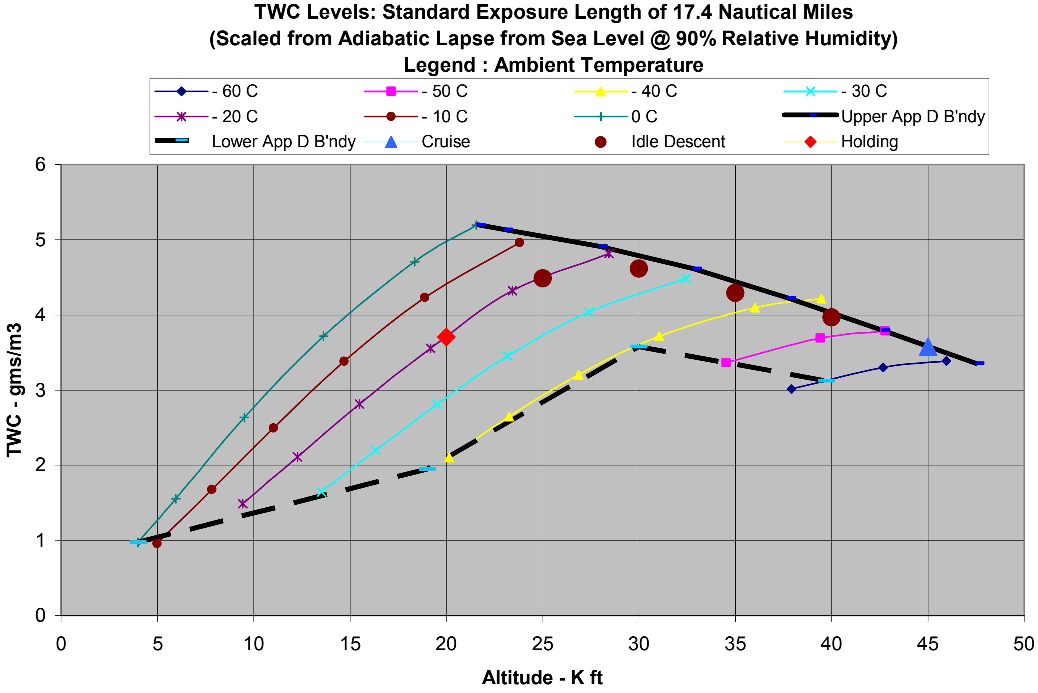


Figure 2. Appendix D Icing Total Water Content

12. <u>APPENDIX X WATER IMPINGEMENT</u>. The water impingement region becomes potentially greater for the large water droplets of Appendix X. This occurs because larger droplets have greater inertia and follow a more ballistic trajectory that is less influenced by local airflow streamlines. A way to illustrate this is through the use of a variable known as the modified inertia parameter. This parameter is a relationship based upon the momentum of droplet, air viscosity and size scale of object (with correction for Reynolds No) and is used to correlate the streamline effect on deflecting a droplet from the object. Such a correlation is depicted in the next figure for several object shapes.

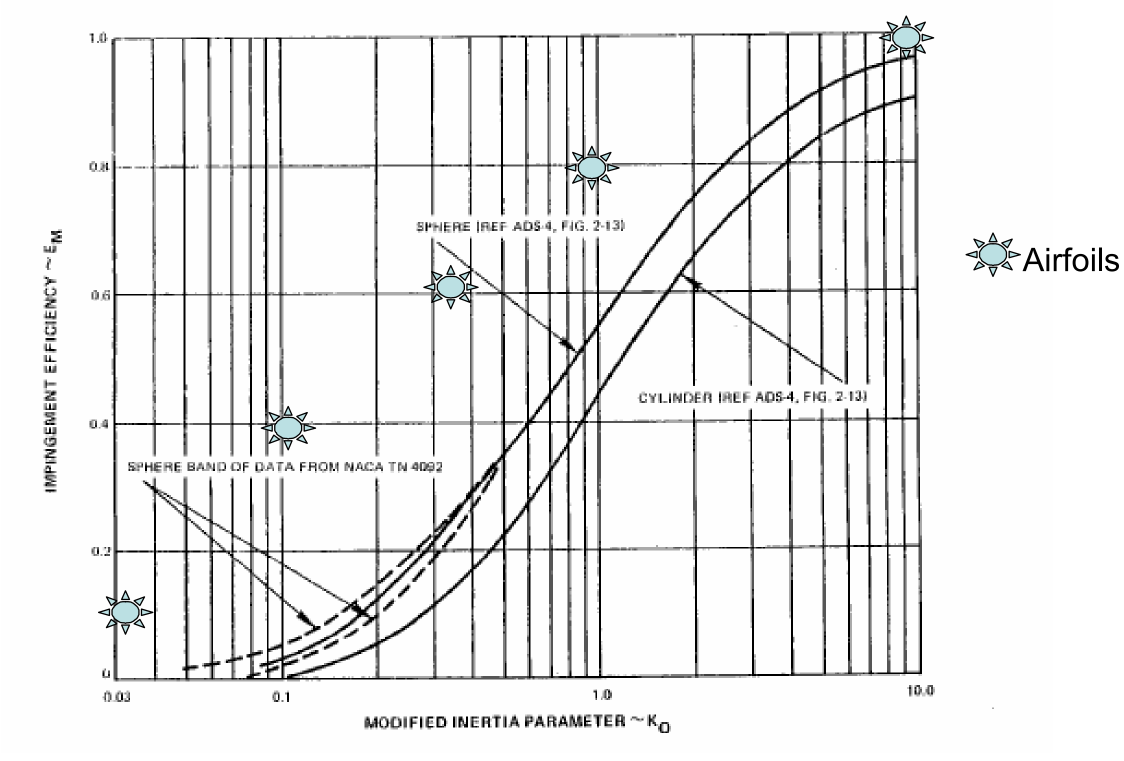


Figure 3. Droplet impingement efficiency for different shapes

The reduction in impingement efficiency below unity from the correlation indicates the degree to which droplets are deflected from the object due to streamlines moving around the object. For most shapes a modified inertial parameter of 10 or greater implies a ballistic path for the droplets. This observation can be used to illustrate the consequences of the larger water droplets defined in Appendix X using the next figure with some target objects of interest denoted to show typical size ranges for larger transport engines. The shaded area covering the Appendix C droplet size range is seen to behave ballistically for small “target” object dimensions typical of engine airfoils, airfoil cascades and probes. Consequently, Appendix X will not alter this local behavior affecting the surface water impingement. For larger targets, however, one would expect greater impingement on surfaces such as the nacelle and engine spinner with the potential for water impingement on regions that are unprotected by surface heating systems that are designed for Appendix C sized droplets.

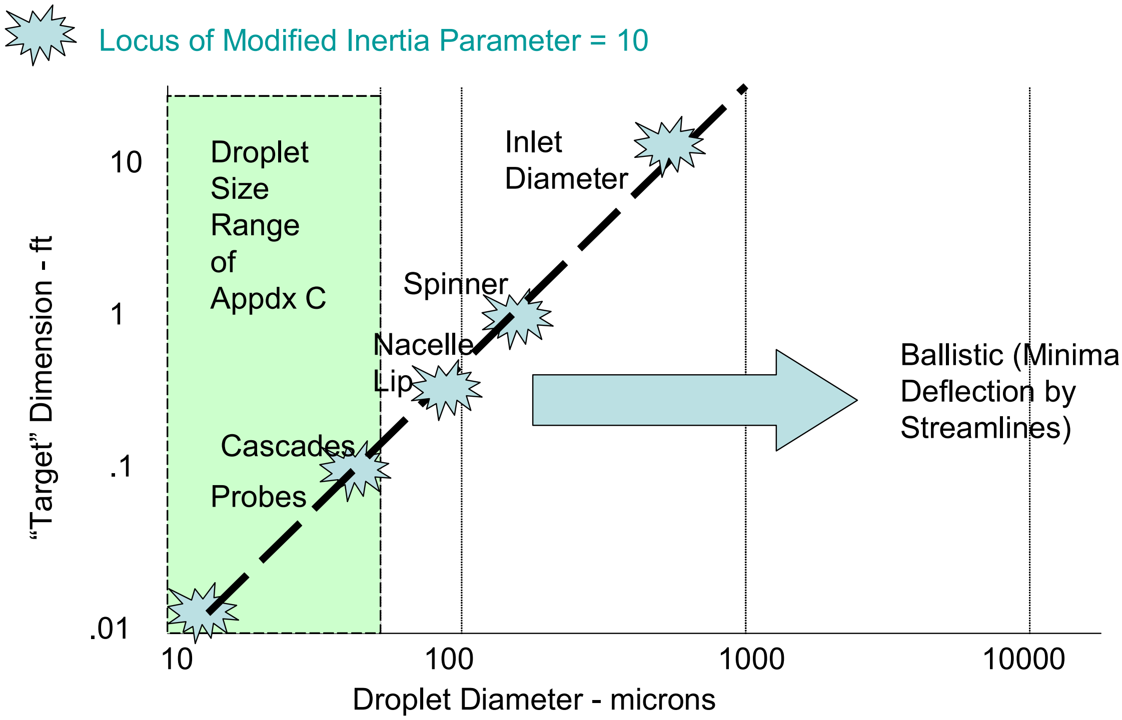


Figure 4. Ballistic boundary as function of target and droplet size

SECTION 2. ICE SLAB INGESTION (§ 33.77)

13. INTENT OF ICE SLAB INGESTION TEST. The intent of the ice slab ingestion test is to demonstrate tolerance to ice ingestion resulting from nacelle surfaces and to establish limits for ice released from other aircraft surfaces in FAR 25 certification. It is intended that the engine manufacturer will conservatively consider the potential installation effects of the engine induction system. Also, there should be close coordination with the installer to ensure that potential airframe ice accumulation sites that can result in ice ingestion by the engine (for example, inboard section of wing for an aft fuselage mounted engine) are either demonstrated under § 33.77 or addressed under §§ 23.901(d)(2), 23.1093, or 25.1093 (see paragraph within this AC). The induction system manufacturer or installer should assess these accumulations in accordance with §§ 23.901(d)(2), 23.1093, or 25.1093 and provide pertinent test variables to the engine manufacturer for incorporation into a test demonstration in accordance with § 33.77. In the case where an application or product inlet has not been selected at the time of engine certification, the engine manufacturer should provide all pertinent inlet assumptions and test data and results in the engine installation manual for use by the future installer. The dimensions of this slab are related to engine size (defined by inlet highlight area) based on earlier certification requirements which showed satisfactory performance in service.

14. COMPLIANCE CONSIDERATIONS. Compliance may be demonstrated by the standard engine ice slab test or by means of a validated analysis procedure that uses equivalent soft body testing. The test demonstration should consider ice slab sizes and trajectories aimed at critical engine locations that are based on the ice accretion and shed characteristics of the induction system that is likely to be installed on the engine. Lacking such specific knowledge, the applicant may select test conditions, which are typical of a condition for a representative installation in-service. The ice slab size, thickness, and density used in § 33.77 compliance demonstration should be assessed for appropriateness against parts 23 and 25 compliance requirements. Minimum ice slab density equivalent to a 0.9 specific gravity should be used unless a different value is considered more appropriate. See AC 20-73 (latest revision), AC 23.1419-2B, and AC 25.1419-1 for more guidance on ice shedding. If it is determined that the ice slab size, thickness, and density are appropriate for the engine installation, then the part 33 test results can often be used by the airframe manufacturer to comply with the natural icing flight test requirements. Execution of the ice slab ingestion test typically involves targeting the slab to the air stream ahead of the fan 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.

a. Validated Analysis with Equivalent Soft Body Tolerance Testing
The alternate compliance method allows use of a validated analysis process in conjunction with appropriate soft body damage testing. If the applicant satisfies the

requirements of this alternate compliance approach, the engine shall be certified for the minimum standard ice slab consistent with the engine inlet area as defined in § 33.77. It is recognized that alternate soft body damage testing may in some circumstances include objects that are larger than the standard ice slab based upon inlet area. Certification for larger than the standard ice slab by this method is currently not allowed. However, it is expected that, as the experience progresses in these areas, the applicants can utilize this method to support compliance for engine operation with larger ice slabs.

Validated Analysis

A validated analysis must contain sufficient elements to show compliance, these elements may include:

– Full fan blade model utilizing latest techniques such as finite element analysis
– Blade material properties for yield and/or failure as appropriate
– Dynamic / time variant capability
– Thrust variance prediction if required to account for blade damage
– Appropriate engine and/or component testing with impact in outer 1/3 span location to anchor results

This model may be used alone, or in conjunction with the results of a certification bird ingestion test to show compliance.

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 & blade speed
- Slab dimensions
- Slab orientation

Any predicted power loss or blade damage (distortion, cracking, tearing) must be assessed against the criteria of paragraph 15(a) below

The following figures help to describe the contribution of these parameters in establishing the threat to the fan blade.

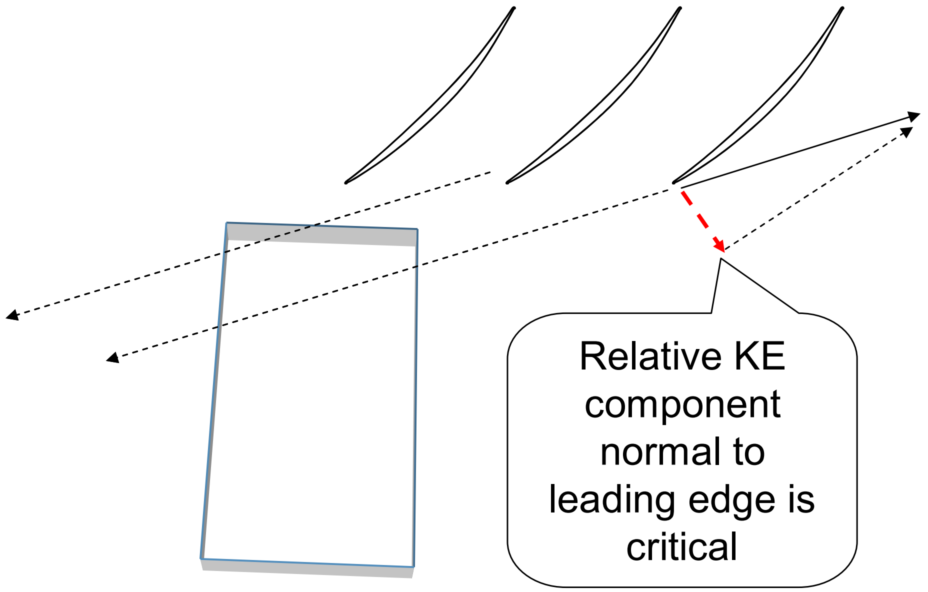


Figure 5. Normal component of Kinetic Energy of ice slab

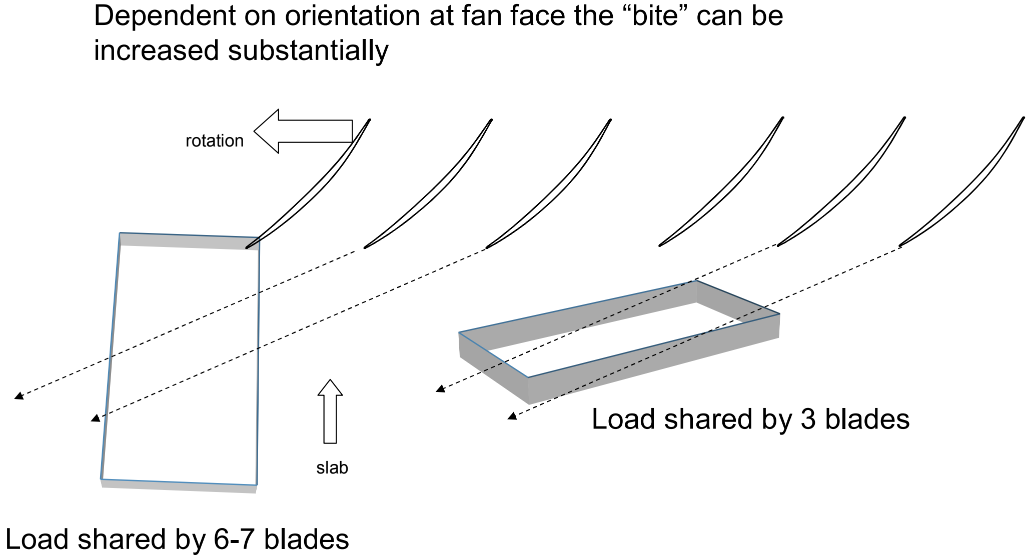


Figure 6. Ice slab orientation effects

The relative kinetic energy of the ice slab shall be determined from an assessment of flight conditions that control the engine rotor speed and the velocity of the ice slab as influenced by the air stream velocity and density at the corresponding "ice slab test point". Engine test results from previous ice slab testing may be provided to support the predicted ice slab velocity.

The analysis shall assume the most critical orientation unless the manufacturer can substantiate that an alternate ice slab orientation is still conservative relative to ice slab testing.

Ice Slab Break Up

The analysis shall utilize the largest slab size consistent with a conservative assessment of slab "break up" that can occur within the air stream ahead of the fan. Historically, the ice slab breaks up into smaller pieces during the ice slab testing. Data derived from a number of tests are included in the next figure. On the basis of the data, the largest ice piece is typically 1/3 to 1/2 the original size. For compliance purposes, the applicant should assume 1/2 of the original slab length unless evidence suggests that this is not conservative relative to ice slab testing.

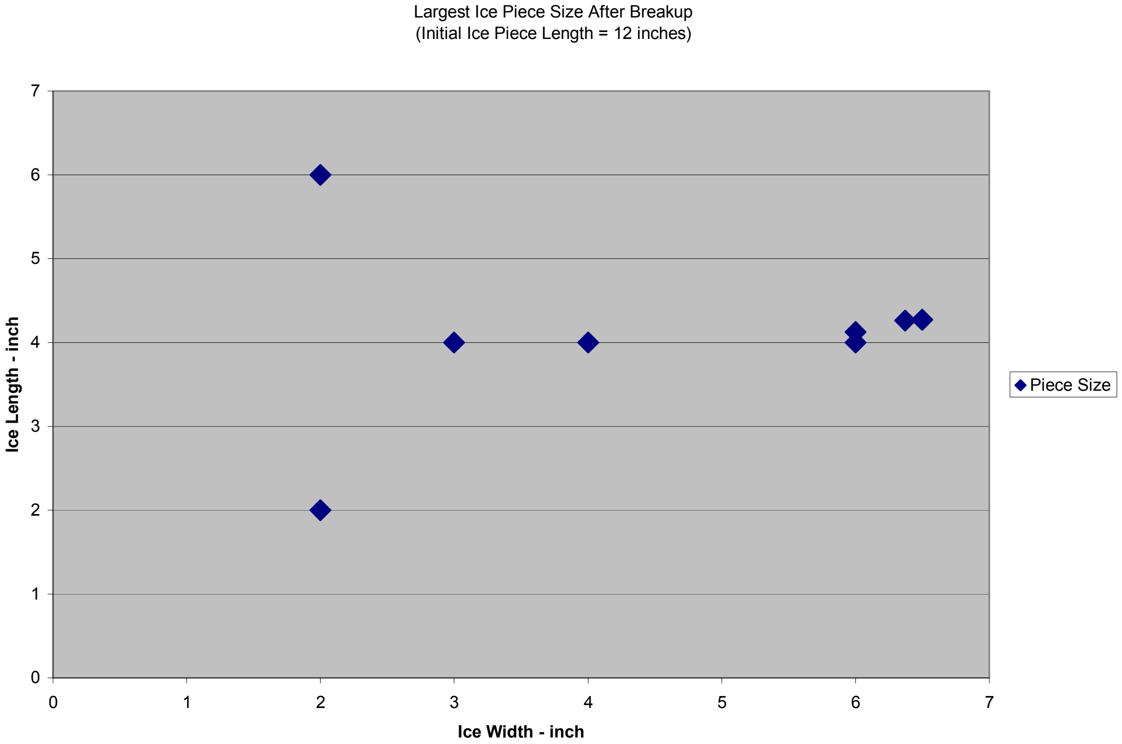


Figure 7. Ice slab breakup experience

15. <u>TEST RESULTS</u>. Section 33.77(c) requires that the ingestion of ice, under the conditions stipulated in § 33.77(e), may not cause a sustained power or thrust loss, or require the engine to be shutdown. The following criteria should be met:

a. Sustained power losses. Any fan blade bending or damage should be assessed against potential sustained power loss. Compliance requires that permanent power loss associated with fan damage from the slab be less than 1.5%. The similarity of fan damage type allows the use of other soft-body testing, such as the medium bird ingestion test, results for compliance with this requirement. If the other soft-body test results in less than 1.5-% permanent power loss and there are no cracks, tears or blade piece breakout due to a bird introduced at the outer 33% of fan diameter, the 33.77 requirement is met. In the event that power loss exceeds 1.5%, the manufacturer must provide a validated analysis that shows consistency with the bird test results and verifies that the ice slab would produce less than the 1.5-% power loss. It is also necessary to demonstrate by test that any cracks, tears or blade piece breakout will not result in “unacceptable sustained power or thrust loss” within 100 cycles (considered sufficient to allow engine operation to the next scheduled “A” check). Further, any damage that results from this test must be documented within the engine installation manual.

b. Engine operability. Damage should not adversely affect engine operability (that is, should not cause surge, flameout, nor prevent transient operation).

c. In-service capability. Damage should not result in a failure or a performance loss that would prevent continued safe operation for a conservative flight cycle scenario (for example, within fly back limits or greater if appropriate testing is done to validate 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 positions).

d. Other anomalies. Damage should not result in any other anomaly (for example, vibration) that may cause the engine to exceed operating or structural limitations.

e. Auto-recovery systems. If during § 33.77 ice slab ingestion testing, an engine does incur a momentary flameout and auto-relight, then normally the acceptance of that test would be predicated on the inclusion of the auto-relight system as being a required part of the engines type design, and an additional dispatch criteria would be required, where the ignition system must be functional (that is, fully operable) prior to each dispatch. The reason for the additional dispatch criteria is to ensure the ignition system’s critical relight function is reliably available during the subsequent flight. The reason for the allowance of auto-recovery systems during § 33.77 certification testing is to account for ice accretion and shedding, as a result of an inadvertent 2-minute delay in actuating the anti-icing system, which is considered to be an abnormal operational result where mild operability effects (for example, momentary flameout and relight) may be accepted.

16. COMMUNICATION OF TEST RESULTS. The installation and operating 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 engines ability to operate at the commanded power setting or rating.

The icing certification report should include information regarding ice slab orientation and trajectories, slab breakup, impact locations, description of any resultant damage, and any 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 to ensure compliance with the delayed activation requirements of §§ 23.1093 or 25.1093.

SECTION 3. INDUCTION SYSTEM ICING PROTECTION (§§ 23.1093 and 25.1093)

Discussion

In recent years, applicants have been using the results of FAR33.77 for compliance with 25.1093 in lieu of a test demonstration of the 2 minute delayed activation of inlet anti-ice. The 33.77 results are also used to show compliance with 25.1093 for other airframe ice sources. This requires close coordination between the engine manufacturer, and the airframer to make sure the 33.77 test covers all the potential ice sources. Further, this close coordination needs to take place as the engine is certified for 33.68 so that the engine can be installed on the airframe – see paragraph 11 (c) of this AC for more definition of potential incompatibilities.

Section 25.1093 (b)(1) Acceptable Means of Compliance

Engine induction systems have historically not been limited to or evaluated against a specific aircraft flight profile when considering icing environments, but instead are evaluated for unlimited operation in icing. The cloud horizontal extent factor was not intended to be used to limit the severity of exposure to icing conditions where it is reasonable to assume the aircraft will be required to operate in that condition. As a general rule, engine induction systems should be shown to operate continuously in icing without regard to time in icing conditions. The only exception would be for low engine power conditions where sustained level flight is not possible. Even then, a conservative approach must be used where multiple horizontal and vertical cloud extents in series are assumed.

The applicant must adequately analyze the performance of the engine inlet anti-ice system and address the potential ingestion hazard to the engine from any predicted ice buildup on the engine inlet, including any runback or lip ice. It must be shown by analysis, and verified by test, that the engine inlet anti-ice system provides adequate protection under all flight operations. The following conditions must be considered. Additional critical points may be identified, depending on the specifics of the airplane/engine design. Bleed crossover points need to be reviewed, if applicable.

If an applicant can show that the inlet anti-ice system performance and the fan blade capability are equivalent to previous certification experience, then certification may be shown by similarity to previous designs.

Inlet Design Point Selection

If the inlet is evaporative under the critical points in continuous maximum icing conditions, and is running wet under intermittent maximum icing conditions, then the design is satisfactory.

Engine inlet anti-ice systems have historically good service experience with systems that run wet, when runback ice is evaluated at the conditions defined in Table A at the ambient conditions that promote maximum runback. Therefore, inlets that are certified for unlimited operation in icing may allow runback ice formation as defined in table A during hold, descent and diversions. Analysis must be used to find the critical accretion conditions for each of the scenarios in Table A and each must be compared individually with the amount of ice the engine has been satisfactorily demonstrated to ingest during engine certification (§ 33.77(c)).

Flight Condition	Descent	Hold	Straight line flight
Icing Design Condition	6500 foot descent in Appendix C continuous maximum, with extent factor = 1, followed by an Appendix C intermittent maximum exposure	45 minute hold, in Appendix C continuous maximum, with an extent factor = 1	45 minute exposure in Appendix C continuous maximum with an extent factor, followed by an Appendix C intermittent maximum exposure

Table A Inlet Lip and Runback Ice

Specifically for the design conditions defined in Table A:

Descent:

If the engine inlet anti-ice system is not fully evaporative during descent in Appendix C continuous maximum conditions, the amount of ice accretion (runback and lip) must be calculated for the continuous maximum and intermittent maximum icing conditions within Appendix C as defined in Table A. Airspeed and scoop factor should be part of this assessment. Ingestion of these calculated quantities of ice runback for that condition (plus lip ice for this condition, if any) must not result in more ice ingestion damage, based on the criteria defined below (size or kinetic energy), than the amount of ice the engine has been satisfactorily demonstrated to ingest during engine certification (§ 33.77(c)).

Holding:

For holding conditions the engine inlet anti-icing system must be capable of safe operation in Appendix C for extended airplane operations. The extended airplane holding condition is defined as 45 minutes at the critical accretion ice conditions for the continuous maximum icing cloud using a horizontal extent factor of one. . If the inlet is evaporative under continuous maximum icing conditions, and 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. 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 defined in Table A. Ingestion of these calculated quantities of ice (total amount of ice: runback and lip for the condition)) must not result in more ice ingestion damage, based on the criteria defined below (size or kinetic energy), than the amount of ice the engine has been satisfactorily demonstrated to ingest during engine certification (§ 33.77(c)).

Straight Line Flight
For straight line flight (cruise, diversion to alternate airport, etc.) the engine inlet anti-icing system must be capable of safe operation in Appendix C for extended airplane operations. The straight line flight evaluation must be investigated including the use of the extent factor. If the inlet is evaporative under continuous maximum icing conditions, and 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 defined in Table A. (continuous maximum exposure followed by an intermittent maximum exposure). Ingestion of these calculated quantities of ice (total amount of ice: runback and lip for the condition)) must not result in more ice ingestion damage, based on the criteria defined below (size or kinetic energy), than the amount of ice the engine has been satisfactorily demonstrated to ingest during engine certification (§ 33.77(c)).

2 Minute Delayed Selection of Inlet Anti-ice Accretion Analysis

Inlet lip ice can form as the result of a 2-minute delayed activation of the engine inlet anti-ice system.

The latest FAR33.77 testing criteria were developed to account for historical means of compliance for the 2-minute delayed selection of inlet anti-ice. Therefore for traditional pitot-style inlets the applicant does not need to consider this scenario if the applicant shows compliance with the FAR33.77 (amendment level defining minimum ice slab size). For inlet designs other than the traditional pitot style inlets, 2 minute delay calculation may be required. The amount of inlet lip ice that forms during the 2-minute delayed activation should be calculated using Appendix C continuous maximum conditions with an 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. Further it may be assumed that 1/3 of the inlet perimeter is ingested as one piece, consistent with the historical approach taken by the engine manufacturers. Since maximum damage to fan would occur at high fan speed, and this critical condition is also when the inlet has the most heat, therefore 2 minutes is a reasonable time to include both pilot reaction to conditions and time to shedding after anti-ice has been selected.

ETOPS
If certification of ETOPS is desired, the applicant must consider the maximum ETOPS diversion scenarios. For example, if a lightweight two-engine diversion at 10,000ft following a cabin depressurization puts the airplane into a region that is susceptible to ice build-up, then ingestion of the calculated quantities of ice must not result in more ice ingestion damage, based on the criteria below (size or kinetic energy) than the amount of ice the engine has been satisfactorily demonstrated to ingest during engine certification (§ 33.77(c)).

17. AIRFRAME ICE SOURCES INCLUDING INLET

It is intended that the engine manufacturer will conservatively consider the potential installation effects of the engine induction system. Also, there should be close coordination with the installer to ensure that potential airframe ice accumulation sites that can result in ice ingestion by the engine (for example, inboard section of wing for an aft fuselage mounted engine) are either demonstrated under § 33.77 or addressed under §§ 23.901(d)(2), 23.1093, or 25.1093 (see paragraph within this AC). The induction system manufacturer or installer should assess these accumulations in accordance with §§ 23.901(d)(2), 23.1093, or 25.1093 and provide pertinent test variables to the engine manufacturer for incorporation into a test demonstration in accordance with § 33.77. In the case where an application or product inlet has not been selected at the time of engine certification, the engine manufacturer should provide all pertinent inlet assumptions and test data and results in the engine installation manual for use by the future installer.
It is normally sufficient to show that the ice from these sites is smaller in size than the FAR 33.77 ice slab. The applicant may also elect to compare the ice on the basis of 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 FAR 33.77 test. Any kinetic energy method must be agreed to by the applicant's Aircraft Certification Office.

Wing Sourced Ice for Aft Mounted Engines

Clear ice may occur on the wing upper surfaces when cold-soaked fuel (due to aircraft prolonged operation at high altitude) is in contact with the fuel tanks' upper surfaces, and the airplane is exposed to conditions of atmospheric moisture (fog, precipitation, and condensation of humid air) at ambient temperatures above freezing. This atmospheric moisture, when in contact with cold wing surfaces, may freeze. Simultaneous ice shedding from both wings of an airplane with aft-mounted engines has resulted in ice ingestion in both engines during takeoff.

In cases where recommended fuel management procedures allow wing fuel tanks to remain basically full until the fuel in fuselage tanks has been consumed, clear ice may form on cold wing surfaces during some operations. Moreover, some past analysis has shown the potential for ice formation on the upper surfaces when the wing tanks are more than 70% full. Therefore, for some operations fuel in the wing tanks could remain above the 70% level for several hours.

Considering only aircraft with aft-mounted engines, equipped with wing mounted ice detection systems, the applicant must demonstrate that any ice mass resulting from cold-soaked fuel undetected by the wing ice detection system is not greater than that used to demonstrate compliance of the engine induction system to 14 CFR §§ 25.1093. Also, it must be demonstrated that shedding of the ice resulting from cold-soaked fuel does not result in hazardous engine operation. Consider that a wing mounted ice detection system advises the presence of clear ice build-up on the upper surface of the wings when the clear ice thickness reaches approximately 0.020 inches. For this example, the worst case to consider would be a 0.020 inch thickness of clear ice sheds from the wing, and the largest clear ice plate area that will be ingested into an engine is the same area as the engine's inlet highlight area.

18. COMPLIANCE WITH APPENDIX D of PART 33

The FAA has conducted mixed phase icing testing on an airfoil, Ref (Q). The results of these tests indicate that for unheated aircraft surfaces, a mixed phase environment results in the same or less ice accretion than the same total water content of supercooled liquid water. The overall power required by the running-wet ice protection system was practically unchanged between all-liquid and mixed-phase conditions. However, in the running-wet mode of operation, the local power density was much higher around the stagnation area in the mixed-phase conditions compared to the purely liquid conditions. This is a result of the power required to offset the heat of fusion necessary to melt the impacting ice particles that either fully or partially stick to the surface.

This may explain why engines with 'pitot' style inlets have not proved to be susceptible to mixed phase icing and the Appendix C compliance methods adequately address these installations for operation in Appendix D of Part 33. Engines designed with reverse flow intakes, or with intakes involving considerable changes in airflow direction, must comply with 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 design that have shown successful service history.

19. COMPLIANCE WITH APPENDIX X of PART 25

In-flight Exposure to Appendix X of Part 25 Conditions:
For engine inlets, an assessment of inlet impingement limits, differing catch efficiency, distribution effects, and water contents for Appendix X should be accomplished.

Ground Taxi Exposure to Appendix X of Part 25 Conditions: Service experience considered for this advisory material indicates that there are engine fan damage events as a result of exposure to SLD during ground taxi operations. For this reason, an additional compliance condition was added to 25.1093 for a 30 minute, idle power exposure to SLD on the ground. Consideration should be given to terminal falling velocity of SLD (freezing rain, freezing drizzle) in assessing the trajectory relative to the protected sections of the inlet. The 100 micron minimum MED was defined as a reasonably achievable test condition given current technology. An applicant choosing to certify by analysis should evaluate the Appendix X drop sizes up to a maximum of 3000 microns particle size to find a critical condition.

20. 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 the accumulation of ice on the engine, inlet system components, or airframe components that would have an adverse affect on engine operation or cause a serious loss of power or thrust. Based on multiple engine natural ice damage and operability events experienced on natural icing flight test and in-service airplanes, the FAA requires natural ice encounters for showing compliance with §§ 23.1093(b)(1) or 25.1093(b)(1). However, for airplanes that are not intended to be certificated for flight in icing conditions, the FAA will accept other methods in lieu of natural icing flight tests, such as analysis, ground testing, dry air flight testing, and similarity, to show compliance to § 23.1093(b)(1). Aside from the benefit of validating the engine inlet icing analysis model, there are several other key issues that the natural ice encounter addresses. These evaluations include: (1) The adequacy of the flight crew procedures for operation in icing conditions, (2) acceptability of tactile inputs to the flight crew as the airplane responds to engine fan blade ice shedding during a variety of airplane operating conditions, (3) performance of the engine vibration indication system as well as other engine indication systems and, (4) confirmation that the powerplant installation as a whole (for example, engine, inlet, anti-ice system) performs satisfactorily while in icing conditions.

a. Identification of ice source. A means should be provided to aid in identifying 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.

b. Icing test point monitoring. The applicant should provide sufficient monitoring of the icing test point condition (that is, LWC, droplet diameter, temperature) against the time to ensure that the icing encounter is representative of the Appendix C and Appendix X certification icing conditions under part 25 or the Appendix D conditions under part 33.

c. Compliance. Compliance with §§ 23.1093 or 25.1093 is required even if flight into icing approval (§§ 23.1419 or 25.1419 compliance) is not obtained. Compliance with the natural ice encounter criteria should be proposed by the applicant and agreed to by the FAA prior to the test. However, typically an adequate test sequence includes three natural fan ice shed cycles at each of the following conditions (with inlet anti-ice turned "on"); descent (flight-idle), holding (power necessary to maintain level flight for a range of anticipated airplane gross weight conditions), and maximum climb, unless a more critical engine power setting exists. These encounters should be conducted at a steady state engine thrust level and although not preferred, sometimes have involved flying through the same icing cloud multiple times (lapping) in order for the fan to accumulate enough ice for a shed cycle to occur. (Caution is emphasized when flying in natural ice conditions.) These fan shed cycles should be due to natural ice accumulation and not induced or forced by throttle excursions or manipulations, or both, during each condition. It has also been allowed for the airplane to exit the icing conditions between each fan shed cycle for the purpose of clearing any other unprotected airplane surfaces from ice. To avoid masking any adverse engine operating conditions during the natural icing encounter, the test engine's ignition system should be selected off during the icing conditions. This may require pulling several airplane circuit breakers to disable the test engine's auto-ignition or recovery system, or both, and caution should be used and all safety precautions exercised. Lastly, based on past experience, it is advisable that the applicants establish and gain concurrence with the FAA for engine damage criteria prior to conducting the natural ice encounter test.

21. FALLING AND BLOWING SNOW. Sections 23.1093(b)(ii) and 25.1093(b)(1) and (2) require that engines must operate satisfactorily in falling and blowing snow throughout the flight power range, and ground idle. The effect of ingesting snow during ground operations can and should be evaluated. The applicant must identify and evaluate the critical temperature for the configuration proposed. A temperature range between 25 and 34 degrees Fahrenheit has been found conducive to the heavy snow environment and to providing the "wet sticky snow" which may accumulate on unheated surfaces (airframe and engine) subject to impingement. Colder temperatures may be critical to some configurations. In these cases, colder exterior surfaces may be bypassed, and the snow crystals may stick to partially heated interior inlet surfaces where melting and refreezing may occur. Service experience has demonstrated compressor damage (see paragraph 8b(3) of this AC) as a result of exposure to prolonged periods of falling snow during ground operation. Based on review of service events, airports have continued to operate with falling-snow concentrations that result in a 0.25 mile or less visibility (about 0.9 gm/m^3, see paragraph 9b of this AC). In-flight service experience has also shown that snow can shed from engine or aircraft accumulation sites and cause severe operability affects on turbine engines. Therefore, all engine inlets, including those with plenum chambers, screens, particle-separators, variable geometry, or any other feature, such as an oil cooler, struts or fairings, which may provide a potential accumulation site for snow should be evaluated. Also, any airframe accumulation sites upstream of the engine inlet should also be considered.

22. 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:

a. Acceptable damage. The extent of damage is equivalent to or less than that incurred and accepted during engine certification testing.

(1) All systems operating normally. The extent of damage is equivalent or less than that incurred and accepted during the § 33.68 tests.

(2) 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 defined in paragraphs 13 and 14 of this AC, should be used. The airframe manufacturer still must consider all potential ice shedding sites (for example, inboard wing and radome). Similar to the accepted compliance of § 33.77 ice slab ingestion tests (outlined in section 2 of this AC), the use of engine auto-ignition and recovery systems are allowed to show compliance with the delayed activation tests of parts 23 or 25, as long as these automatic systems can not be easily turned off by the flight crew (that is, a flight crew that inadvertently forgets to turn on the engine anti-ice protection is also likely not to have selected any other engine protection features such as continuous ignition, prior to entering the inclement weather). It is important to note the difference in anti-iced inlets versus de-iced inlets. De-iced inlets produce a cyclic shedding of ice from the engine inlet into the engine and typically incorporate, as part of their design, an inlet particle-separator that precludes the ingestion of ice into the core of the engine. It should be recognized that an engine auto-recovery system 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 or 25.1093.

b. Damage from testing in non-representative icing conditions. Damage resulting from icing test conditions which fall significantly outside Appendix C, Appendix X or Appendix D icing envelopes, or when the airplane flight test is conducted in an abnormal manner and results in excessive ice shed damage, may be given additional consideration relative to compliance with the provisions of either §§ 23.1093 or 25.1093, and in some cases may be disregarded. An example of abnormal operation could be flying with one engine at idle while the aircraft is operated in level flight.

c. Unacceptable damage. The icing test conditions were representative of in-service encounters and the resultant airframe or engine ice sheds caused damage that exceeds the criteria established in paragraph 11b of this AC.

23. <u>CONCLUDING REMARKS</u>. Although applicants may conduct representative tests under §§ 33.68, 33.77, 23.1093, and 25.1093, flight test events during airplane certification may still occur which appear inconsistent. In all likelihood, those results would not be inconsistent when judged in light of the scope, intent, and limitations of the certification testing. Only through reliable instrumentation and photographic evidence can the icing test disparities be fully understood. Because of the relatively frequent encounters with icing conditions in conjunction with the potential impact on safety, the FAA takes a conservative approach when accepting icing compliance standards.

/s/
David W. Hempe
Manager, Aircraft Engineering Division

References

1. 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 THE EQUATORIAL ZONE by Ian I. McNaughton, B.Sc., Dip. R.T.C.
2. FAA-RD-77-76, ENGINEERING SUMMARY OF POWERPLANT ICING TECHNICAL DATA by G. D. Pfeiffer and G. P. Maier
3. THE ICING OF AN UNHEATED NON-ROTATING CYLINDER IN LIQUID WATER DROPLET-ICE CRYSTAL CLOUDS, E. P. Lozowski, J. R. Stallabrass & P. P. Hearty, National Research Council Canada Report LTR-LT-96, February, 1979.
4. SNOW AND ICE PARTICLE SIZES AND MASS CONCENTRATIONS AT ALTITUDES UP TO 9 KM (30,000 FT), R. K. Jeck, DOT/FAA/AR-97/66, August, 1998.
5. ASSESSMENT OF EFFECTS OF MIXED-PHASE ICING CONDITIONS ON THERMAL ICE PROTECTION SYSTEMS, DOT/FAA/AR-03/48, Kamel Al-KHalil, MAY 2003.
6. FURTHER ICING EXPERIMENTS ON AN UNHEATED NON-ROTATING CYLINDER, LTR-LT-105, J. R. Stallabrass and P. F. Hearty, November 1979.
7. DOT/FAA/AR-98/76 REPORT: "MIXED PHASE ICING CONDITION, A REVIEW", James T Riley.
8. SNOW CONCENTRATION MEASUREMENTS AND CORRELATION WITH VISIBILITY, J. R. Stallabrass, AGARD Conference Proceedings No. 236 *Icing Testing for Aircraft Engines.*
9. THE ESTIMATION OF SNOWFALL RATE USING VISIBILITY , Rasmussen, R.M., J. Vivekanandan, J. Cole, B. Myers, and C. Masters, 1999 : Journal of Applied Meteorology, 38, 1542-1563.

SLD Engineering Tools Development

Project Plan

Work Breakdown Task Descriptions

Mark Potapczuk

Dean Miller

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field

NASA Glenn Research Center
Icing Branch

Revision History

Date	Version	Description	Author
1/3/2002	0.1	Initial version	Mark Potapczuk; Dean Miller; Tom Bond
2/13/2002	0.2	Second draft	Mark Potapczuk; Dean Miller; Tom Bond
3/29/2002	0.3	Third draft	Mark Potapczuk; Dean Miller
4/5/2002	0.4	Fourth draft – combined elements from Mark and Dean	Mark Potapczuk; Dean Miller
11/15/02	0.5	Fifth draft - incorporated feedback from FAA/JAA/TC technical team & NOQ	Mark Potapczuk, Dean Miller
3/18/03	0.6	Sixth draft -incorporated feedback from WSU airframers	Mark Potapczuk, Dean Miller
4/14/03	1.0	Final draft of WBS	Mark Potapczuk, Dean Miller

This document contains the Work Breakdown Structure (WBS) Task Descriptions of the SLD Engineering Tool Development Project. The WBS is current as of the date associated with this document. Since this project is a research effort, not all of the elements of the WBS are known at the outset of the project. As such, the elements and the period of performance associated with each element are the best estimates as of the date of the document. As the project proceeds, the document will be updated to reflect the current planning and elements will be more fully described as well as modified to reflect changes precipitated by the outcome of earlier elements of the project.

Introduction:

The airworthiness authorities (FAA, JAA, Transport Canada) will be releasing a proposed rule in the 2006 timeframe, which concerns the operation of aircraft in an SLD environment aloft. The proposed rule will require aircraft manufacturers to demonstrate that their aircraft can operate safely in an SLD environment for a period of time to facilitate a safe exit from the condition.

It is anticipated that aircraft manufacturers will require the capability to demonstrate compliance with this rule via experimental means (such as icing tunnels, or tankers), and by analytical means (ice prediction codes). Since current icing research facilities and analytical codes were not developed to account for SLD conditions, the capability of these engineering tools need to be upgraded to include SLD conditions.

Given this need, NASA developed an SLD Technology Roadmap to guide the development of an SLD simulation capability in icing research facilities, and analytical codes. The roadmap identified the key technical areas needing development, and provided a logic flow for the required research activities.

An SLD Engineering Tools Development Project Plan (SLD Project Plan) was then developed, based on the SLD Technology Roadmap. This plan was an attempt to translate the SLD Technology Roadmap into a “project” format, by identifying discrete tasks which needed to be accomplished, and then organizing them into a Work Breakdown Structure (WBS).

The SLD Project Plan has been subjected to several stages of review by airworthiness authorities, and international research partners. The result of this review process is the document contained herein. The intent of this document is to list the discrete tasks in a WBS format, provide a brief description or rationale for doing the task, and where possible, associate an organization with the task. Organizations have been associated with tasks if they: 1) indicated an interest in doing a task, or 2) were already actively working in an area.

The association of an organization with a particular task does not constitute a commitment to accomplish the task, only the desire to work on the task. It is expected that once funding and resource allocation issues within each organization have been resolved, organizational commitments can be reflected in this document.

Approach:

The approach used to develop this document was based on FAA review comments, which recognized that it would not be possible to complete all the items in the SLD Technology Roadmap by the 2006 timeframe. Therefore, they stressed the need to focus on a smaller sub-set of highest priority technology items such as: 1) facility capabilities to generate SLD, and 2) scaling for SLD conditions.

Considering this feedback, a reduced scope SLD Engineering Tools Development Project Plan was developed. This was accomplished by assuming the viewpoint of an aircraft manufacturer required to comply with the new SLD airworthiness rule, and then asking ourselves the question: “What are the most important SLD Tool capabilities that need to developed to support compliance activities?” Our response to this question formed the basis for this revised SLD Engineering Tools Development Project Plan.

Four key areas were identified for development in the revised project plan:

1) Simulation of SLD conditions in icing research facilities,
2) Scaling of SLD conditions,
3) Instrumentation to measure SLD conditions
4) Universal SLD simulation methodologies

Further reviews by an FAA/JAA/TC technical team, the Ice Protection Harmonization Working Group, and at an informal meeting with a representative group of aircraft manufacturers lead to further refinements. The notable addition by the manufacturers was support for development of computational tools. They look upon such tools as playing a key role in addressing the issues of certification for SLD conditions and at the same time aiding in keeping costs contained during the certification process. As such, the plan retains elements required for development of such tools.

Scope:

This document contains a Work Breakdown Structure for the revised SLD Engineering Tools Development Project Plan. The intended use for the document is to provide guidance in the identification of research tasks needed for the development of SLD Engineering Tools.

While this document is focused on developing SLD Engineering Tools applicable to ground based and airborne research facilities, WBS tasks have been more completely defined for Icing Wind Tunnels than for Icing Tanker Aircraft. There are two reasons for this; 1) The authors knowledge & experience base in icing does not include the use of tanker aircraft to perform icing simulations, and 2) It is expected that organizations operating icing tankers will want to develop the detailed technical tasks.

Generate/Simulate SLD Icing Conditions

1.1. Develop requirements for SLD simulation

Requirements (or metrics) need to be defined to provide a "target" for SLD simulation in quantified terms. These requirements serve a dual-purpose by providing guidance: 1) about what essential features or characteristics need to be simulated, and 2) about how accurately these characteristics need to be simulated. It is anticipated that these requirements would be developed by means of sensitivity studies, either experimental or computational. *Furthermore, t**hese requirements need to be derived taking into account recommendations from the IPHWG.***

Objective: Identify the metrics that have to be met to assure adequate simulation of the SLD environment from an engineering perspective. These could include LWC range, drop size range and distribution, ice shape similarity, droplet supercooling, and variation of cloud conditions as a function of time. Included in this study is an assessment of how accurately these elements must be simulated to manifest some difference in desired outcome.

1.2. SLD simulation with Icing Wind Tunnel

Two distinct capabilities are needed to replicate SLD conditions in an icing wind tunnel: 1) the capability to generate or reproduce a representative SLD cloud condition (1.2.1) , and 2) the capability to generate a representative SLD ice shape using those cloud conditions (1.2.2).

1.2.1. Reproducing SLD Conditions

This task is focused on developing the capability to generate an SLD icing cloud which is representative of the SLD environment as recommended by the IPHWG Appendix SLD (in document TBD).

1.2.1.1. Assess current capability to produce SLD

Objective: Document what the icing research facility is currently capable of with respect to SLD simulation. Determine whether the current spray system technology is adequate to produce the features of an SLD cloud with respect to the requirements as outlined in Task 1.1. Metrics are icing tunnel cloud size, uniformity, and repeatability. Additional metrics are LWC, and droplet size distribution.

Organization: NASA

1.2.1.2. Develop methods to generate SLD cloud

It may not be possible to exactly match the icing cloud distributions specified by the IPHWG Appendix SLD, with current spray bar technology. Therefore, this task is focused on developing operational methods to utilize existing spraybar technology, and still effectively simulate those IPHWG SLD cloud conditions.

1.2.1.2.1. Investigate and document constant or time varying icing conditions in natural SLD encounters

Objective: Identify the characteristics of a natural cloud that do or don't vary as a function of time during an in-flight icing encounter. These characteristics will be used to guide the development of a simulated encounter in an icing wind tunnel.

Organization: NASA

1.2.1.2.2. Develop cloud sequencing method

Objective: Alter icing conditions during a run to simulate the SLD environment. This could allow for temporal variations in the natural cloud as well as for the differences in droplet distribution between natural and icing wind tunnel clouds.

Organization: NASA

1.2.1.3. Determine residence time for supercooling

Residence time has been defined as the time for heated water droplets emanating from the facility spraybars, to reach static tunnel temperature (which if below 0°C, will be supercooled). Residence time is a function of the distance between the facility spraybars and test article, and varies with tunnel airspeed and water droplet size. To adequately simulate SLD conditions will require that the water droplets in the icing spray cloud be supercooled when they reach the test section or test article. Since it will not be possible to measure the spray cloud temperature in most icing research facilities, an analytical means is needed to determine the range of facility spray conditions which will be supercooled. This task is focused on developing an analytical means to predict the "residence time" required for supercooling, given facility geometry, and tunnel flow conditions

1.2.1.3.1. Evaluate supercooling with droplet thermodynamic codes

Objective: Use droplet thermodynamic codes to determine whether the large droplets are supercooled as they reach the test section of the icing wind tunnel. Develop a chart or series or charts that relate supercooling to drop size, tunnel velocity, and distance from spray bars to test section.

Organizations: QinetiQ, ONERA

1.2.1.3.2. Validation of droplet thermodynamic codes

Objective: Conduct tests in an icing wind tunnel to measure temperature of cloud droplets using measurement methods developed in 3.4.2. Use the results from this task to validate the analytical estimates of supercooling developed in 1.2.1.3.1.

Organization: NASA

1.2.1.4. Document Range of LWC and MVD vs. Appendix SLD

Objective: Map out the range of conditions that can be obtained in the icing wind tunnel and compare those to the range identified for Appendix SLD as recommended by the IPHWG (in document TBD). The intent is to identify areas of overlap, and extent of SLD simulation capability.

Note: Project plan for this task needs to be worked out with icing wind tunnel cloud specialists. Tunnel entries may need to be identified.

Organization: NASA

1.2.1.5. Document drop size distribution vs. Appendix SLD

Objective: To compare the icing wind tunnel SLD droplet size distributions against distributions recommended by IPHWG in Appendix SLD (document TBD). Then document the results of this comparison, which should highlight similarities and differences between the respective drop size spectra.

Note: Project plan for this task needs to be worked out with icing wind tunnel cloud specialists. Tunnel entries may need to be identified.

Organization: NASA

1.2.2. Simulating SLD Shapes

This task is focused on developing the capability to generate SLD ice shapes which are representative of the SLD environment as specified by the IPHWG Appendix SLD in (document TBD).

1.2.2.1. Compare Icing Wind Tunnel shapes to natural shapes

To ensure that SLD ice shapes generated in icing facilities have characteristics that are representative of the SLD environment aloft, natural ice shape databases will be compared with SLD ice shapes generated in icing facilities. This task is focused on compiling the necessary tunnel, and flight ice shape databases for similar SLD icing conditions, and then comparing the two sets of ice shapes.

1.2.2.1.1. Compile database of natural ice shapes

Current SLD ice shape data is not sufficient to assess the level of agreement between natural and simulated SLD ice shapes. The following tasks have been identified to augment the current in-flight ice shape database.

1.2.2.1.1.1. Assess existing database

Objective: Examine the database of documented SLD flight ice shapes and identify the conditions, body geometry, and ice shape geometry for these cases. Further examine the database to determine those cases for which the data is sufficient to allow use as a validation for an icing wind tunnel or code.

Organization: NASA

1.2.2.1.1.2. Acquire new ice shape data

Objective: Obtain ice shape data as well as icing conditions for additional flights. It would be desirable to have constant LWC and drop size conditions during the encounters. Further it would be desirable to augment the current database with respect to icing conditions.

Organization: NASA

1.2.2.1.2. Compile database of tunnel ice shapes

Objective: Create and maintain a database of SLD ice shapes for various body geometries and SLD icing conditions. Be sure to obtain conditions that recreate results of SLD icing flights.

Organization: NASA

1.2.2.1.3. Compare natural and tunnel ice shape databases

Objective: Identify those cases where flight and icing wind tunnel conditions can be compared. Assess adequacy of icing wind tunnel to simulate in-flight SLD ice shapes with respect to requirements. Identify conservative approach for simulation. Use comparison methods developed in 3.5.

Organization: NASA

1.2.2.2. Evaluate repeatabilty of facility for generation of SLD shape

Objective: Conduct tests in icing wind tunnel to quantify repeatability of ice shapes. Correlate with repeatability of spray conditions. Determine if acceptable with respect to requirements. Determine how errors in control of spray bar pressures translate into differences in LWC and drop size. Ideally repeatability of cloud conditions should be less than that which produces a significant change in ice shape.

Organization: NASA

1.2.3. Confirm adequacy of Icing Wind Tunnel to simulate SLD environment

Objective: Compare simulation capabilities developed in 1.2.1 & 1.2.2 to requirements developed in 1.1. Document ability of the icing wind tunnel to simulate the SLD icing cloud and to produce ice shapes representative of those from flight conditions.

1.3. SLD simulation with Ice Prediction Codes

These tasks are focused on modifying ice accretion codes in order to account for icing physics elements which play a role in SLD ice growth that are not currently included in most ice growth models. Most of the tasks are centered on examination of the physical processes considered important for SLD icing and creating the data necessary to allow the development, modification and validation of SLD icing physics models.

This SLD model development activity will address the issues of simulating SLD ice shapes, collection efficiency characteristics, icing impingement limits, and thermal analysis.

1.3.1. Shapes

1.3.1.1. Droplet Dynamics

The larger diameter water droplets of SLD conditions may be more susceptible to deformation and/or break-up due the relatively lower capability of surface tension to maintain the spherical shape and size of the droplet when subjected to the forces present in the flow field surrounding the droplet. Deformation and break-up could impact an SLD ice shape by altering where a droplet impacts or whether it actually does impact on the surface of interest.

1.3.1.1.1. Analysis of droplet dynamics

Objective: Identify those processes that could influence the behavior of super-cooled large droplets as they travel towards the target of interest. This could include the differences experienced by droplets in-flight as compared to those found in an icing wind tunnel

Organization: Iowa State Univ.

1.3.1.1.2. Droplet dynamics experiments

Objective: Determine the range of conditions that may influence the behavior of super-cooled large droplets as they travel towards the target of interest.

Organization: TBD

1.3.1.1.3. Develop droplet dynamics model

Objective: Develop a model for inclusion into ice accretion simulation methods of the dynamics identified in tasks 1.3.1.1.1 and 1.3.1.1.2 that may influence the development of ice during the accretion process.

Organization: TBD

1.3.1.2. Droplet Splashing

Identify droplet splashing parameters (incoming droplet size, outgoing droplet sizes, incoming and outgoing velocities and angles, etc.) and relationships to calculation of mass loss. How much incoming mass splashes and how much of the splashed mass re-impinges or escapes from the surface. This information will then be used to develop droplet splash/mass-loss models for incorporation into CFD ice prediction codes. The desired outcome is accurate prediction of SLD ice shapes.

1.3.1.2.1. NASA Droplet splashing experiment

Objective: Determine how much incoming mass splashes and how much of the splashed mass reimpinges or escapes from the surface.

Organizations: NASA, Wichita State University

1.3.1.2.2. Cranfield droplet splashing contract

This is a CAA sponsored effort to design and build a vertical flow wind tunnel and perform droplet splashing tests.

Objective: Determine the amount of water splashed from the surface during an SLD droplet impact.

Organization: Cranfield University

1.3.1.2.3. Analytical Modeling of Splash/Impact Dynamics

This is the QinetiQ sponsored activity to model the dynamics of the splash/impact process analytically.

Objective: Develop a CFD model which captures the dynamics of droplet impact /splash, and which can be used to estimate mass loss due to splashing.

Organization: University College of London, QinetiQ

1.3.1.2.4. ONERA droplet splashing experiment

This experiment will be conducted at CEPr-PAG icing wind tunnel using DMAE/ONERA Toulouse visualization equipment.

Objective: Study effect of water film properties & surface characteristics on droplet impact/splash dynamics.

Organization: ONERA, CEPr

1.3.1.2.5. Develop droplet splashing model

Objective: Take results of droplet splashing experiments and develop computational algorithms that can be added to existing codes to account for droplet splashing (amount and location of mass loss).

Organizations: NASA, ONERA, QinetiQ

1.3.1.3. Mass Loss

1.3.1.3.1. Ice mass measurements on airfoils

Objective: Develop a database for validation of mass loss algorithms used in codes. Used to help determine whether splashing plays a significant role in the SLD ice accretion process. This task is analysis and reporting of already completed tests.

Organizations: NASA, QinetiQ

1.3.1.3.2. Water runback mass measurements

Objective: Develop a first order estimate of mass loss due to splashing by measuring the amount of water mass that remains on the surface

Organization: QinetiQ

1.3.1.4. Ice Sliding

Questions about ice sliding first arose in 1996, during a series of exploratory SLD icing tests conducted in the NASA IRT. There were occasions where surface ice accretions were observed to slide back, and refreeze at a new chordwise location, farther aft on the airfoil. This task is intended to determine whether ice sliding is a legitimate phenomena associated with SLD icing, and whether it needs to be modeled with ice prediction codes.

1.3.1.4.1. Review previous test efforts

Objective: Examine the videotapes from previous tests and determine which ones had ice sliding occur.

Organizations: NASA, QinetiQ

1.3.1.4.2. Assess need for further work

Objective: Determine if there is enough evidence to warrant further investigation.

Organizations: NASA, QinetiQ

1.3.2. Icing Impingement Limit

Definition of this task will be deferred until the requirements for icing impingement limit simulation is determined in Task 1.1 The tasks identified under this element of the WBS should provide capabilities to allow evaluation of distribution effects on ice shapes. These were identified by the manufacturers as important for evaluation of impact on ice protection system design and in determination of aerodynamic impact. Particularly they are interested in reducing the over-conservatism in simulation of SLD ice shapes.

1.3.3. Collection Efficiency

1.3.3.1. Influence of droplet splashing on collection efficiency measurements

Objective: Quantify the influence of droplet splashing on current collection efficiency measurement methods.

Organization: WSU, FAA, NASA

1.3.3.2. Clean geometry SLD collection efficiency study

Objective: Measure collection efficiency on several representative aircraft component geometries under SLD conditions.

Organization: WSU, FAA, NASA

1.3.3.3. SLD Ice Shape Collection Efficiency Study

Objective: Measure collection efficiency for several sequences of ice shapes on a single airfoil under SLD conditions. The intent is to evaluate how collection efficiency changes as ice shapes develop and to provide validation data for simulation codes.

Organizations: WSU, FAA, NASA

1.3.4. Thermal Analysis

The intent of this work area is to identify and evaluate any features associated with thermal ice protection simulation in SLD conditions that differ from Appendix C conditions.

1.3.4.1. SLD Runback Ice

Objective: Document characteristics of SLD runback ice shapes obtained from operation of a thermal ice protection system in SLD icing conditions. Evaluate the potential effects of runback ice (e.g. - with respect to aircraft performance, control surface operation, etc).

Organizations: NASA, Cessna

1.3.5. SLD Model Development

The creation of updated capabilities for SLD modeling in current ice accretion software. The development effort shall conform to industry standards set for design, implementation, version control and documentation used for public release of validated software.

1.3.5.1. Development of proposed SLD model

Objective: Design of icing models for SLD ice accretion incorporating results of experimental activities outlined in sections 1.3.1 through 1.3.4

Organization: NASA, ONERA, QinetiQ

1.3.5.2. Implementation

Objective: Creation and/or modification of software needed to add models of SLD behavior to existing ice accretion prediction software.

Organization: NASA, ONERA, QinetiQ

1.3.5.3. Validation Testing

Objective: Comparison of computational results to existing database of SLD ice shapes. Evaluation of ice shape comparisons using quantitative measures delineated in NASA CR 208690, “Validation Report for LEWICE 2.0”.

Organization: NASA, ONERA, QinetiQ

1.3.5.4. Documentation

Objective: Preparation of appropriate technical documents to describe new software capabilities and to document the validation process.

Organization: NASA, ONERA, QinetiQ

1.4. SLD In-Flight Simulation with Tankers

Except for any modifications to allow for the unique capabilities of tanker systems, these tasks should be similar in nature to those required to simulate SLD in icing wind tunnels. It is expected that the organizations proposing to simulate the SLD environment with icing tankers, would provide more detail for work in this area.

1.4.1. Reproducing SLD Conditions

Objective: Develop the capability to generate an SLD icing cloud which is representative of the SLD environment as recommended by the IPHWG Appendix SLD (in document TBD).

Organizations: Raytheon, Cessna

1.4.1.1. Assess current capability to produce SLD

Objective: Document what the icing tanker facility is currently capable of with respect to SLD simulation. Determine whether the current spray system technology is adequate to produce the features of an SLD cloud with respect to the requirements as outlined in Task 1.1. Metrics are icing tunnel cloud size, uniformity, and repeatability. Additional metrics are LWC, and droplet size distribution.

Organizations: Raytheon, Cessna

1.4.1.2. Develop capability to generate SLD cloud

Objective: Develop capability to generate SLD conditions with tanker aircraft spray system. This task remains to be defined in more detail.

Organizations: Raytheon, Cessna

1.4.1.3. Determine residence time for supercooling

Residence time has been defined as the time for heated water droplets emanating from the tanker spraybars, to reach static or ambient temperature (which if below 0°C, will be supercooled). This task is focused on developing the capability to analytically predict "residence time" for tanker aircraft spray clouds.

1.4.1.3.1. Develop analytical capability to predict supercooling

Objective: Adapt existing droplet thermodynamics codes or methods (validated for use in icing wind tunnels in 1.2.1.3.2) for use with tanker aircraft spray systems.

Organizations: Raytheon, Cessna

1.4.1.3.2. Evaluate supercooling with droplet thermodynamic codes

Objective: Use droplet thermodynamic codes to determine whether the large droplets from the tanker spray cloud are supercooled as they reach the test aircraft. Develop a chart or series or charts that relate supercooling to drop size, aircraft velocity, and distance from spray bars to aircraft under test.

Organizations: Raytheon, Cessna

1.4.2. Simulating SLD Shapes

Objective: Develop the capability to generate SLD ice shapes which are representative of the SLD environment as specified by the IPHWG Appendix SLD in (document TBD).

Organizations: Raytheon,Cessna

1.4.3. Confirm adequacy of tanker to simulate SLD environment

Objective: Compare simulation capabilities developed in 1.4.1 & 1.4.2 to requirements developed in 1.1.

Organizations: Raytheon, Cessna

2. Scaling

2.1. Assess current scaling methods for use with SLD

2.1.1. Scaling requirements

Objective: Determine what level of accuracy is required for scaling methods to be considered successful. How well do current scaling capabilities aid in providing models that can be used to evaluate characteristics such as impingement/icing limits and aerodynamic parameters.

Organizations: TBD

2.1.2. Perform SLD scaling experiments

Objective: Use current scaling laws for SLD conditions to determine if the methods currently employed for App. C conditions can be used for SLD.

Organizations: NASA

2.1.3. Water film scaling studies

Objective: Determine the scaling methods needed to insure that surface water films can scale over the range of drop sizes that include App. C and SLD.

Organizations: INTA, NASA

2.1.4. Summary report

Objective: Write and publish a report on scaling methods for SLD. Identify what methods may be unique for SLD conditions, if any. Provide guidance for engineers performing icing tests under scaled conditions.

Organization: NASA

2.2. Incorporate new findings into scaling methods

Objective: Update scaling methods as more information is obtained from continued scaling tests.

Organization: NASA

3. Instrumentation

The tasks undertaken in the previous two sections as well as the general process of testing under SLD conditions requires the use of accurate measurement devices for quantities such as water droplet size, liquid water content, temperature, and velocity. Instruments to perform these measurements are currently available for Appendix C icing conditions. It is the intent of this element of the project plan to identify the requirements for such instruments with respect to SLD conditions and to assess the abilities of current instruments to satisfy those requirements.

3.1. Requirements

3.1.1. Sensitivity studies of ice shapes to measurement parameters

Objective: Perform computational studies using LEWICE to determine the sensitivitiy of ice shapes to changes in cloud parameters such as LWC, drop size, velocity, temperature, etc.

This work is related to the activities identified in Task 1.1 and thus there should be some connection between these two tasks.

Organization: NASA

3.1.2. Survey users on instrumentation requirements

This task is undertaken in order to obtain a sense of what the icing community thinks is required for accurate determination of quantities of interest for icing simulation.

3.1.2.1. Identify user requirements

Objective: Survey users to determine what they need from icing measurements in terms of accuracy and repeatability.

Organization: NASA, FAA

3.1.2.2. Evaluate user requirements

Objective: Identify if instrumentation used for certification purposes have differing requirements from those used for research. If so, quantify the differences.

Organizations NASA, FAA

3.1.2.3. Document user requirements

Objective: Summarize and document results of user survey.

Organizations NASA, FAA

3.1.3. Define operational requirements of instruments

Objective: Identify what additional requirements must be satisfied for appropriate operation of the icing instruments of interest.

Each instrument has additional requirements with respect to how it is set up and operated in order to assure maximum performance. These requirements should be identified and agreed to by the community at large in order to assure uniform reliability by those using such instruments. These requirements should be published in order to promote "best practices" by the community.

Organization: NASA

3.2. LWC

3.2.1. Instrumentation assessment

Objective: Perform a study to determine what are the current capabilities of LWC measurement instruments. Compare capabilities to requirements identified in Task 3.1

Organization: NASA

3.2.2. Reference Measurement Devices

Current icing cloud LWC measurement methods have limitations and varying undefined uncertainties which are affected by air flow velocity, air flow turbulence, absolute water content level, water drop size, and drop size distribution. These performance issues lead to discrepancies when similar devices are tested in different icing facilities. A reference LWC measurement device is needed to eliminate the ambiguity due to these performance issues. This task is focused on developing a device, which provides a well-defined measurement of LWC in order to calibrate other existing LWC devices.

3.2.2.1. LWC measurement based on slotted airfoil

Objective: Develop LWC measurement device based on direct collection of water droplets and measurement of the collected mass.

Organization: NASA

3.2.2.2. LWC measurement based on iso-kinetic probe (method1)

Objective: Develop an LWC measurement device based on direct collection of water droplets and measurement of their mass. Principle for collection and measurement is different than that used in Task 3.2.2.1

Organizations: WSU, FAA

3.2.2.3. LWC measurement based on iso-kinetic probe (method 2)

Objective: Develop an LWC measurement device based on iso-kinetic sampling, evaporation of cloud water, and measurement of resulting humidity. Principle for collection and measurement is different than that used in Task 3.2.2.1, and has some features different from Task 3.2.2.2.

Organization: Cranfield University

3.2.3. Correlate other instruments to reference

Objective: Once a reference LWC measurement device is developed, compare results to other LWC devices and create correlations to adjust readings of other devices.

Organization: NASA

3.3. Drop Size

3.3.1. Instrumentation assessment

Objective: Conduct a study to determine what measurement devices are currently available for measurement of drop size and drop size distribution. Determine whether devices are suitable for use with SLD conditions.

Organization: NASA

3.3.2. Evaluate performance of candidate instruments through comparative testing

Objective: Conduct a series of tests with the candidate systems identified in Task 3.3.1 to examine their capabilities over the range of conditions specified in Task 1.1

Organization: TBD

3.3.3. Identify appropriate usage of candidate instruments based on Task 3.3.2

Objective: Based on the results of testing in Task 3.3.2, recommend appropriate usage of the candidate instruments.

Organization: TBD

3.4. Cloud Temperature

3.4.1. Instrumentation assessment

Objective: Examine what devices are currently available for measurement of cloud water droplet temperature.

Organization: NASA

3.4.2. Develop selected method / device - (TBD depending on selected device)

Objective: If it is determined from Task 3.4.1 that there is a need for a new device or measurement method, then a plan for development will have to be created.

Organization: TBD

3.5. Ice Shape

3.5.1. Examine requirements for SLD ice shape measurement

Objective: Determine whether there are different measurements required to characterize SLD ice shapes. Identify those measurements and establish comparison criteria.

Organization: NASA

3.5.2. Develop new measurement method

Objective: Based on the findings of task 3.5.1, develop measurement technique for unique SLD ice shape features. This task will only be undertaken if deemed necessary.

Organization: TBD

3.6. Humidity

3.6.1. Instrumentation assessment

3.6.1.1. Define capabilities of current humidity measurements

Objective: Identify devices used to make humidity measurements currently and whether their current installation is appropriate for accurate assessment of humidity as defined in Task 3.1

Organization: TBD

3.6.1.2. Compare current capabilities to requirements identified in Task 3.1

Objective: Report on what can and can't be determined from current humidity measurements. Make recommendations for improvements, if necessary.

Organization: TBD

4. Develop a universal methodology for SLD icing simulation

Icing research facilities will have different capabilities and limitations relative to simulating the SLD environment. Therefore, methods developed under tasks 1 thru 3 of this document should be generalized to provide guidance to other icing research facilities. The intent is provide a "template" for development of SLD simulation methods, which can be adapted to the unique requirements of each facility.

4.1. Assess capabilities of all icing facilities

Objective: Report on known icing facilities based on information that can be provided by owners. This report should be based on characteristics of the facilities needed for generation of SLD conditions.

Organization: NASA, TBD

4.2. Compare facilities to modeling requirements

Objective: Report on the potential for each facility to be able to produce SLD conditions based on the findings of Task 4.1 and the requirements identified in Task 1.1

Organization: NASA, TBD

4.3. Identify methods that can be commonly used

Objective: Based on the SLD simulation methods developed in Task 1.2, determine practices that are not unique to the IRT and describe in terms that could be put into practice by any facility.

Organization: NASA, TBD

4.4. Document practices required for simulation

Objective: Report on the measurements and methods used to allow simulation of SLD environment in the IRT.

Organization: NASA, TBD

Mixed-Phase/Glaciated Icing

Technology Plan

Table of Contents

Introduction

This report describes propulsion systems icing related research recommended by the Aviation Rulemaking Advisor Committee's (ARAC) joint Engine and Power Plant Installation Harmonization Working Groups (hereafter referred to as EHWG), and the ARAC Transport Airplanes and Engines Issues Group (TAEIG), to the FAA for more effective compliance with proposed 14 Code of Federal Regulations (14 CFR) part 33 regulatory requirements for safe operation and performance of turbofan engines and propellers in high ice water content environments. These high ice water content environments exist in mixed-phase (supercooled liquid drops (SLD) and ice particles) and glaciated (ice particles only) conditions. The proposed engine icing rulemaking was developed by the EHWG, in support of the Ice Protection Harmonization Working Group (IPHWG), in response to Task 2 assigned to the IPHWG by the ARAC.

For reference, IPHWG Task 2 is as follows:

> "Review National Transportation Safety Board recommendations A-96-54, A-96-56, and A-96-58, and advances in ice protection state-of-the-art. In light of this review, define an icing environment that includes supercooled large droplets (SLD), and devise requirements to assess the ability of aircraft to safely operate either for the period of time to exit or to operate without restriction in SLD aloft, in SLD at or near the surface, and in mixed phase conditions if such conditions are determined to be more hazardous than the liquid phase icing environment containing supercooled water droplets. Consider the effects of icing requirement changes on 14 CFR part 25 and part 33 and revise the regulations if necessary. In addition, consider the need for a regulation that requires installation of a means to discriminate between conditions within and outside the certification envelope."

The IPHWG requested the EHWG to assess safe operation of aircraft propulsion systems in SLD, mixed-phase, and glaciated icing conditions. The EHWG examined data on engine icing events and determined that high ice water content environments in mixed-phase, glaciated, and SLD conditions posed hazards for safe operation of aircraft propulsions systems.

The EHWG drafted proposed rules addressing 14 CFR part 25 aircraft turbofan engine installation icing and propeller requirements and Part 33 turbofan engine icing requirements. Included was a proposed Appendix D to 14 CFR part 33 defining high ice water content environments in mixed phase and glaciated conditions. The group also drafted new certification advisory material for the proposed rulemaking. The proposed rules and advisory material were included in the Task 2 IPHWG Report that was submitted to the ARAC TAEIG during September 2005.

The EHWG regards the proposed Appendix D to Part 33 as defining an initial assessment of the high ice water content environments in mixed phase and glaciated conditions for engine certification purposes. It concluded during the derivation of Appendix D that there is a need for more extensive and accurate meteorological data to characterize these environments.

The EHWG group also determined that test and simulation techniques for engine testing in high ice water content environments in mixed phase and glaciated conditions needs development. The proposed AC materials relative to engine certifications acknowledge that necessary tools and test techniques have not yet been developed and/or validated. As a result, a phased-in approach was proposed. In the near term, new engines must be shown to address ice particle issues through comparative analysis relative to engines with known field events. Long term, the advisory material recommends the use of a Critical Point Analysis (CPA) of the high ice water content environment as proposed in Appendix D of Part 33. The critical conditions would be demonstrated through a combination of testing and validated analysis.

Due to the interim status of testing and analytical tools for engine icing in high ice water content environments, continued development of these tools was recommended by the EHWG to improve confidence for both design and certification. The IPHWG included this recommendation in its submittal of the proposed IPHWG Task 2 rulemaking to the TAEIG, which in turn strongly endorsed the recommendation to the FAA.

This document provides a technology plan, with a roadmap and work break down structure for technology development required to produce mature technology for more effective design and certification of engines for high ice water content environments. It is expected that the plan will be modified by the EHWG as the research is carried out and results are obtained. Thus the plan provides an effective programs determining and establishing the resources required for more effective compliance with the proposed engine icing rulemaking.

Four primary research tasks are identified:

- Task 1. Instrumentation development and evaluation for high ice water content
- Task 2. Flight test research for characterization of high ice water content environments.
- Task 3. Experimental testing in support of ice accretion model development and validation for high ice water content environments.
- Task 4. Test Facilities Requirements for demonstrating engine compliance with Appendix D requirements.

Task 1 is essential to the successful execution of Task 2, and is also needed for Tasks 3 and 4. It is essential to Task 2 because the instrumentation that has been used for characterization of mixed-phase and glaciated conditions in the past (mainly in stratiform clouds) is not considered to be adequate for the high ice water content environments judged to represent significant safety hazard to propellers and turbofan engine operability and performance. Task 1 is needed for Tasks 3 and 4 because both of the latter involve the simulation of high ice water content environments in icing tunnels and facilities, and it will be necessary to measure the conditions to a sufficient level of accuracy for the purposes of the testing. Just as current instrumentation is not adequate to measure the atmospheric environment to be simulated, it is not adequate to determine the quality of facility simulations of that environment.

Task 2 recognizes the provisional nature of the proposed Appendix D and has as it goal the development and analysis of data so as to confidently produce a revised Appendix D with improved accuracy and applicability.

Task 3 describes experimental work necessary to address the limitations of tools available to the manufacturer to conduct CPA assessments within the proposed Appendix D to 14 CFR part 33. The focus of this task is testing to provide data and other information for engine manufacturers to develop the necessary tools for successful CPA.

Task 4 concerns the development/modification of facilities that can provide an adequate simulation of high ice water content environments for engine testing for design and certification for the proposed new regulations. The environment simulated will be that described in Appendix D to Part 33 (modified as necessary in accordance with the results of Task 2). Instrumentation from Task 1 will be used to measure the conditions in the facility and assess their adequacy in simulating Appendix D to Part 33. Testing is such a facility can be used for validation of the CPA tools developed under Task 3.

The discussion of Tasks 1 and 2 is much more extensive than that of Tasks 3 and 4. This does not reflect the relative importance of the tasks, but simply that the planning for Tasks 1 and 2 is at a much more advanced stage.

The discussion of Task 3 is exceptionally brief, reflecting a lack of a common understanding of how ice accretes within engine cores in high ice water content environments, and of how best to formulate an experimental approach intended to provide the information needed to model the process. This is the reason that Task 3 recognizes a need for an industry workshop to discuss how best to proceed. A Technology Roadmap by Task for this plan is presented in Appendix I. The Work Breakdown Structure (WBS) associated with the plan is presented in Appendix II. A tentative schedule, assuming availability of sufficient resources, is presented in Appendix III. Of significant note, the National Research Council of Canada (NRC) has authorized a two year research program that directly addresses goals of Task 4 and to a limited extent, Task 3. Details of that program are provided in Appendix IV. Finally, the NASA Glenn Research Center (GRC) is conducting a technical and cost assessment of modification of the direct connect engine altitude simulation Facility at Propulsion Systems Laboratory (PSL) to conduct altitude testing of engines under glaciated conditions. Information concerning the PSL and possible modification can be found in Appendix V. The proposed modification has the potential for a major contribution to Tasks 3 and 4.

The tasks described in this document require the cooperation of research organizations and industry and the availability of substantial resources. Some resources have been identified, for the most part focusing on Task 1. However, extensive resources must be provided to carry out the work described in this document. If this is not possible, then prioritization of the tasks will be required and effective compliance with the proposed rulemaking will be hampered.

Task 1. Instrumentation Development and Evaluation for High Ice Water Content

The proposed 14 CFR part 33, Appendix D, describes an ice water environment standard for engine certification purposes. The proposed Appendix D to 14 CFR part 33 is based upon theoretical estimates of maximum ice water content made by J.W. Strapp of Environment Canada and total water content measurements reported in 1959 by I. I. McNaughtan[1]. Because the proposed Appendix D lacks substantive microphysical measurements of high-altitude convective clouds, the EHWG recommended that more extensive and accurate meteorological measurements be made near convective storm clouds. This includes tropical storms and convective complexes that can cover large horizontal distances. This plan defines evaluation and improvement of instrumentation designed to measure the cloud ice water content (IWC) and associated parameters for planned icing flight programs, including the programs described under Task 2. The limitations of current flight instrumentation will be discussed in detail in later sections.

Mason et al.[2] have considered past measurements and reports of the properties of deep convective clouds, and observations from an abridged engine event database, to formulate the hypothesis that events occur in very high IWC regions of deep convective clouds, where the supercooled liquid water content (LWC) was either absent or in a much smaller proportion than ice water content (IWC). In this Technology plan, this is referred to as the Appendix D environment. An assessment of available cloud microphysical data in deep convective clouds reveals that the most of the total water content (TWC) measurements were made in the late 1950s[1], but those measurements involved non-ideal sampling with several corrections factors[1,3] .The accuracy of those results can no longer be confirmed. The EHWG recommended that further measurements of the Appendix D environment be made with modern instrumentation to provide confidence in the adequacy of the proposed Appendix D to industry and regulators. It is expected such measurements would be made in the altitude range of 15000-45000 feet, and at temperatures between 0 and –50 C. The event database and climatological studies suggest that measurements be made in the inter-tropical convergence zone (south of approximate latitude 20° N), perhaps in southeast Asia or northern Australia. Adiabatic IWC calculations, and the uncertainty associated with potential errors in past measurements noted above, suggest that it is prudent to design instrumentation to operate up to a maximum IWC of approximately 9 gm^{-3}. The most recent information suggests that Median Mass Diameter (MMD), the diameter at which half the ice particle mass resides below and half above, will be lower than about 200 μm in high IWC situations. Due to the high altitude, it is likely that the aircraft will operate at airspeeds higher than the design limits of much current instrumentation.

Primary measurements required for an Appendix D characterization are altitude, temperature, geographical position, total water content (TWC), IWC, LWC (including statistics on water content variation with distance), and ice particle size. A number of other supporting measurements, such as cloud particle imagery, winds and turbulence, icing rate, visibility, and radar reflectivity are recommended. Other ancillary data sets related to observations made by pilots during engine events, such as sound and appearance of precipitation on the windscreen, and the visual impressions of airframe icing, should be included in plans for future Appendix D characterization.

There is very little experience in making aircraft cloud microphysical measurements in such clouds with modern instrumentation. Past cloud measurements from the atmospheric physics community have focused on benign liquid cloud or mixed phase clouds with low to moderate IWC, and have usually been performed at low true airspeeds. Few of these measurements have been made in deep convective clouds. Based on the few that have been performed, current instrumentation is inadequate to meet the requirements of the Appendix D environment, in terms of accuracy and reliability [4,5]. Further testing, modification, and implementation of new cloud microphysical measurement technology are required. Although a proposed new instrumentation suite must cover measurement of liquid, mixed phase, and glaciated clouds, this plan emphasizes the needs for improvements of measurements of high IWC and MMD in a glaciated environment. This is because Appendix D conditions are expected to be mostly glaciated, and because of the very large technology challenge required to solve all of the known measurement issues. Secondary emphasis is placed on improving separate measurements of the liquid and ice components in mixed-phase cloud. Research is also required to determine if the Rosemount Ice Detector (RID) can provide unambiguous detection of supercooled LWC in the Appendix D environment.

Ice Water Content (IWC) Measurements:

The limited amount of information in the literature on the microphysical properties of deep convective clouds (Black and Hallett [6], Strapp et al.[4], Lawson et al.[7], Stith et al.[8]) suggests that the regions above the freezing level are dominated by vast expanses of glaciated anvils. Also, supercooled liquid water is uncommon away from the core updraft area and is usually not found in significant amounts at temperatures colder than about –10 C. McNaughtan[1] made the seminal measurements of deep convective cloud that are used by industry today for compliance. These measurements were made with a total water content (TWC) measurement system[3] that would have collected both liquid and ice particles, but based on the probability of glaciated cloud noted above, were most likely the equivalent of IWC measurements in most cases. Although McNaughtan's pioneering technical achievements are laudable, several correction factors were applied for the non-isokinetic sampling, and for the location of the instrumentation on the top of the fuselage[1,3], a location that is known to be problematic for sampling. The EHWG has determined that the accuracy of these measurements is no longer traceable. This Technology Plan recommends replicating the measurements made by McNaughtan, but with more modern instrumentation and optimized instrumentation locations for accurate sampling the cloud environment.

The following describes current techniques for measuring IWC, technical issues *(T*)* associated with these measurement techniques, and the strategy for improving IWC measurements.

IWC measurement techniques, and technical issues (T*):

(a) Direct capture and weighing of an ice particle sample in a manner similar to McNaugtan[2] using an inlet exposed to the airflow.

Such a system measures TWC, and an independent measurement is required to determine the liquid water content (LWC) in mixed-phase conditions. McNaughtan[1] used a heated pitot-style inlet system[3] that melted ice particles, the liquid combining with any supercooled liquid present. Captured water was then weighed for a known period.

> (T1) Such a system is non-isokinetic, and may therefore underestimate small particle mass. Time resolution is poor, and sampling is labour-intensive.

(b) Derivation of IWC from particle number concentration spectrum measurements:

Prior to the mid-90s, IWC and ice particle representative size estimates from cloud physics research aircraft studies (e.g. Jeck [9] , Lawson et al. [7]) were accomplished primarily by analyzing data from laser optical array probes (OAPs) that are known to have large errors for particle sizes smaller than about 100 μm (Joe and List[10], Korolev et al.[11], Baumgardner and Korolev [12], Korolev et al. [13], Reuter and Bakan [14], Strapp et al. [15]). It should be noted at the outset that this technique has really only been used in glaciated clouds, due to the difficulties in separating ice particle from water droplets in mixed-phase clouds, as discussed in detail in a later section. Ice mass is calculated by first determining a particle-concentration-versus diameter spectrum, and then applying mass-diameter relationships for various particle types that are available in the cloud physics literature (e.g. Zikmunda and Vali [16], Locatelli and Hobbs [17], Heymsfield [18]).

> (T2) This type of IWC estimation has been reported to have errors as high as a factor of 5 (Plank et al. [19]), but a factor of two is more commonly discussed outside the scientific literature. Errors are first due to the uncertainties in the application of mass-diameter relationships for classical ice crystals (e.g. hexagonal plates, columns etc.) to aircraft measurements in natural clouds, where ice particles are more commonly found to be irregular rather than classical in shape (e.g. Korolev et al.[20]). The mass of crystals may also be heavily dependent on the amount of riming on the particles, information not provided by imaging OAPs. Secondly, measurements near thunderstorm cores and in a hurricane (Strapp et al. [4], Abraham et al. [21]) suggest that a significant fraction, and in some cases perhaps the majority of the ice mass may be concentrated at sizes below 100 μm. Therefore this basic uncertainty of a factor of 2-5 may be worse for thunderstorm core regions, because of the importance of the poorly measured ice particle sizes below 100 μm. Due to the complexity of assessing the errors in this method, this type of IWC mass measurement will not be used as a primary estimate for a future Appendix D flight measurement program, but will be used for comparison and backup only.

(c) TWC and IWC from hot-wire measurement devices:

In the mid 90s, new estimates of LWC and TWC became available due to the introduction of the Nevzorov hot-wire probe (Korolev et al. [22]) to many research aircraft in North America. The data from this probe have been reported extensively in a number of articles describing the mixed-phase environment. IWC is obtained by subtracting the LWC from the TWC measurement. The advantage of a bulk measurement probe such as a hot wire device is the much simpler derivation of IWC, and potentially lower associated errors. The currently available hot-wire TWC devices include the Nevzorov LWC/TWC system, the Science Engineering Associates TWC and TWC/LWC multiwire systems, the DRI T-probe, and the DMT TWC option on several of their OAP probes.

(T3) Recent visualization studies have suggested the possibility of significant IWC underestimation by hot wires due to particle fragment loss and bouncing after impact. Pooling of melted ice particles, and subsequent loss of this melted water by particle impacts and perhaps aerodynamic effects is another factor (Emery et al.[23], Strapp et al.[5]). IWC measurements from different hot wire geometries vary by more than a factor of two in wind tunnel testing with ice particles produced by shaved ice blocks (Strapp et al.[5]). Further testing is required to optimize sensor geometry to minimize particle loss and maximize evaporation efficiency.

(T4) Some hot-wire designs may not be able to survive the hostile Appendix D environment without modifications (Strapp et al. [4]), due to physical destruction of the hot wire elements by ice particle erosion and large particle strikes.

(T5) The high IWC content target (9 gm^{-3} at 200 ms^{-1}) for Appendix D characterization is beyond the limit of all of the currently available hot wire devices. For example, the SEA TWC and Nevzorov LWC/TWC hot-wire devices are currently designed for a maximum of about 5 gm^{-3} at 100 ms^{-1}.

(d) TWC by Evaporation Techniques:

A number of devices operate on the principle of ingesting cloud particles (LWC and TWC), evaporating the particles, and then measuring the humidity enhancement due to the evaporated hydrometeors. Only those devices that are possible candidates for airborne use in a high IWC environment are considered here. The UK Met Office evaporator (Brown [24]) ingests and exhausts air through an evaporation chamber. The increase of the humidity after evaporation is a direct measurement of the TWC. This device has not specifically been designed to sample isokinetically, but it may be possible to modify it to do so. The Cranfield University isokinetic TWC sampling system similarly ingests and evaporates particles, and then exhausts the sample. This system is currently in the prototype stage, and has not been specifically designed for ice particle measurement. Again, the increase of the humidity after evaporation is a direct measurement of the TWC. The disadvantage of these flow-through devices is that they measure the total vapor of evaporated hydrometeors plus the background water vapor, and thus require an independent measurement of ambient water vapor in cloud. The Counterflow Virtual Impactor (Noone at al.[25]) recently commercialized by Droplet Measurement Technologies, measures TWC by ingesting and evaporating ice and water particles into a chamber fed with dry air, thereby eliminating the need for an independent measurement of water vapor in cloud. The disadvantage of this latter device is that it is non-isokinetic. Some of the technical issues are further discussed below:

(T6) It is likely that the both UK Met Office evaporator and the Counterflow Virtual Impactor will saturate well below the maximum target IWC of 9 gm^{-3} at 200 ms^{-1} for Appendix D measurement. The CVI has been designed to operate up to a maximum of about 2.5 gm^{-3} at 200 ms^{-1}.

(T7) It is necessary to characterize flow-through evaporators to ensure that there is full evaporation of hydrometeors before the humidity measurement section. This is particularly important due to the high maximum target value for the Appendix-D environment.

(T8) Due to the fact that the CVI is non-isokinetic, there is a minimum particle size (typically 10-20 μm) that will be measured by the probe that is a function air density and airspeed. If Appendix-D ice particle mass is concentrated at small sizes, the CVI may therefore underestimate TWC.

(e) Other general technical issues for IWC measurement:

(T9) None of the existing commercially available IWC measurement systems is likely to be robust enough for the Appendix D environment, or able to cover the entire range of IWC required for measurement of the Appendix D environment.

(T10) The accuracy of all of the devices noted above is currently unknown. Ice particle simulations in wind tunnels are currently not well developed, and no accurate reference method exists for evaluating instrument performance.

IWC Measurement Strategy:

Due to the lack of knowledge on the accuracy and reliability of the current IWC instrumentation, a series of technical performance studies will be performed on current instrumentation, certain modifications will be implemented, and some new development will be pursued. Wind tunnel testing will be performed to attempt to determine final accuracy, followed by flight-testing to confirm some of the wind tunnel findings in natural cloud conditions. Details are contained in the following strategy items *(S*)*.

(S1) Since the various technologies likely have different performance characteristics, it is prudent to design an instrumentation package with multiple IWC measurement devices. Appendix D airborne measurements will likely be made with a combination of hot-wire and evaporative devices, with optical particle probe derived IWC as a backup. Before testing is completed, it is unclear exactly how this combination of probes may be used. For example, the Counterflow Virtual Impactor may provide the most accurate measurements up to about 2.5 gm^{-3} (200 ms^{-1}), but cannot be extended to higher values, so modifications to a hot-wire device may be necessary to cover the

2.5-9 gm^{-3} range. A new TWC device development (see S3) may alternatively cover the high IWC range. Redundant measurements on research aircraft also provide backup in case of probe failures.

(S2) In order to widen the measurement ranges of the various currently available IWC measurement devices, and to improve their overall IWC measurement efficiency, it is proposed to work with the various manufacturers to make special modifications to their devices to optimize their performance for the Appendix D environment. Maximum IWC limits will be increased where possible. Sensor designs will be modified to minimize particle bouncing and other types of hydrometeor loss. Wound hot-wires will be modified, and solid-wire sensors will be investigated to ensure that sensors are more resilient to ice particle erosion and large particle strikes (addresses T3, T4, T5, T9)

(S3) Since none of the existing commercially available technologies covers the entire range of the IWC values expected for Appendix D, and each system has some undesirable characteristics, it is also proposed to develop a new TWC system specifically for these measurements. The Cranfield University isokinetic TWC device, still in the prototype stage, has many of the desirable attributes, and may be a suitable candidate for an Appendix-D specific redesign (addresses T9)

(S5) Initial wind tunnel testing of all candidate TWC devices will be performed in liquid conditions, the simplest test for a TWC device, at the NASA IRT and the Cox and Co. LeClerc tunnel (Al-Khalil et al.[26], Emery et al. [23]). Relatively accurate LWC reference standards are available, and any important shortcomings of any of the techniques will be recognized.

(S6) Glaciated cloud testing will be performed at relatively low speed (< 90 ms^{-1}) at the Cox and Co. LeClerc tunnel. This tunnel produces simulated ice particles by shaving blocks of ice, and has a relatively large sample section that will accommodate all of the instruments currently under consideration. The possible range of IWC test values at this tunnel is estimated to be 0.2-3.0 gm^{-3} (increased to 5.0 gm^{-3} if LWC is added) at 90 ms^{-1}, considerably less than the target test extreme of 9 gm^{-3} at 200 ms^{-1} for the Appendix D environment.

(S7) It will be necessary to identify other wind tunnel facilities to perform high-speed and high-IWC glaciated cloud testing. In order to reach the airspeeds of 200 ms^{-1}, it may be necessary to work in tunnels with smaller test sections that may only accommodate a subset of the full complement of instruments. This activity may be limited by the available facilities.

(S8) Since there is no reference standard for measuring IWC in icing wind tunnels, as there is for LWC (blade or icing cylinder), probe accuracy estimates may need to be inferred from inter-comparisons of the different probes under the same glaciated and liquid conditions. However, there is some hope that an absolute IWC reference can be derived from simple estimates of the amount of ice delivered into the tunnel and measurements of the ice plume dimensions and isopleths of concentration. It may be necessary to work in open rather than closed-circuit tunnels in order to perform this absolute comparison, due to the complication of ice particle recirculation in the case of the former (addresses T10)

(S9) Since ice particles are produced artificially in all tunnels proposed above, and may not accurately reflect the shapes and densities of natural cloud particles, it is expected that flight testing will be needed to test the performance and accuracies of the various probes under natural conditions. Piggyback opportunities will be pursued to install subsets of the planned instrumentation on 'target-of-opportunity' research aircraft involved in already-funded cloud investigations, particularly those similar to the Appendix D environment. In addition, some dedicated test programs will be implemented on the specific aircraft to be used for the Appendix D characterization flights in advance of the major data collection flights (see Flight-Test Section). This strategy applies not only to IWC instrumentation, but also all key instrumentation planned for the Appendix D environment measurements (Table 1).

(S10) Special care must also be taken in identifying suitable locations for the sampling of IWC from the aircraft, because of the concentration gradients that are expected from flow effects and ice particle debris around the aircraft skin. For example, McNaughtan[1] estimated an enhancement factor of 1.5 from free stream values with their pitot-style Ice Concentration Meter located ~1.5m behind the windshield and about 27 cm above the top fuselage. King [27] pointed out that a shadow zone is created by flow effects over the top of the fuselage for certain particle sizes, suggesting that sampling distances of the order of 1 m are required above the top of the fuselage to ensure proper measurements. This latter analysis considered only the trajectories of free-stream particles around the fuselage, and not ice particles impacting and deflecting from the fuselage. Nevertheless, these studies point out the potential errors due to poor choices of sampling location.

Measurements of Particle Spectra and Representative Particle Size in Glaciated Cloud.

The EHWG requires information on the representative size of ice particles in Appendix D conditions. In the case of liquid water droplet spectra, the median volume diameter (MVD) has been commonly used as such a representative size. The Median Mass Diameter (MMD) is the ice-particle analog to the MVD, defining the diameter where half of the ice mass resides at smaller sizes, and half at larger. The diameter of a typical non-spherical ice particle can be defined using a number of techniques, the most common of which is probably the use of the maximum length of the particle parallel to the photodiode array. There are significant challenges in measuring liquid water droplet MVD accurately, and these challenges become greater for the ice particle MMD. Several probes are required to measure the entire range of ice particles from tens of microns to centimeter sizes, and certain size regions of these probes can be problematic. The performance of conventional airborne cloud probes is inadequate for the Appendix D Environment.

Technical Issues:

(T11) The severity of the proposed 14 CFR part 33, Appendix D, high IWC environment, and the relatively high airspeed (~200 ms^{-1}) at which it will be sampled, causes multiple problems for conventional OAP and light scattering probes (Strapp et al.[4]). These include rolloff in the small particle response at high airspeed, and ingestion of ice particles into the optical pathways resulting in complete loss of data.

(T12) Measurements below 100 μm are especially difficult for ice particles. OAPs have poor accuracy due to digitization, out-of-focus particles, response time, and sample volume uncertainty (Joe and List[10], Korolev et al.[11,13], Baumgardner and Korolev [12], Reuter and Bakan [14], Strapp et al. [15]). Light scattering probes such as the PMS Forward Scattering Spectrometer Probe (FSSP), that measure in the size range of 2-100 μm, are designed for water droplet measurements, and their response to ice particles is not fully understood. Gayet et al.[28] have concluded that FSSP measurements of ice particles in glaciated clouds may be reasonable if the particles are small (see T13). Korolev et al.[29] have shown that ice particles are typically more spherical at smaller sizes, and thus more similar to water droplets, so there is some reason to believe that the FSSP could provide reasonable measurements if particles are small.

(T13) Both the OAP and light scattering probes have been shown to be somewhat sensitive to breakup of large particles on the forward edges of the probe, leading to multiple small fragments of ice particle debris in the particle spectrum measurements (Gardiner and Hallett [30], Field et al.[31], Korolev et al.[32]). When large particles are present, this may lead to an excessive measurement of small particles and perhaps an absence of large particles. Some software techniques can eliminate the artifact particles using interarrival time (particle spacing) measurements (e.g. Field et al. [31]). Within the family of OAP and FSSP probes, only the two-dimensional (2D) OAP probes measure interarrival time. Special modifications are required for the other probes.

(T14) Assuming that an accurate ice particle size spectrum can be measured given the shortcomings noted above, to measure MMD one must convert the ice particle number concentration spectrum into a mass spectrum. See (T2) above for a discussion on the uncertainties in determining mass spectra from particle probe data. It is likely that the errors in MMD are much smaller than those for integrated mass (IWC), however the uncertainty in unknown.

Accurate measurement of ice particles smaller than 100 μm may be a critical issue for accurate estimations of MMD. If IWC mass were concentrated above 100 μm, OAP probes alone would provide a reasonable measurement, subject to uncertainties in mass-diameter conversions noted above. The Lawson et al.[7] review of thunderstorm anvil properties concluded that ice particle size was concentrated at approximately 2 mm, but this study only considered IWC particle sizes from OAP probes, and thus would have underestimated the mass of any sub-100 μm ice particles. Some of their data used only an OAP probe with a minimum detection size of 300 μm. More recent measurements by Strapp et al.[4] and Abraham et al.[21] using OAP probes, and a FSSP probe to estimate ice particle mass below 100 μm, have suggested that the mass of ice particles near the centers of cumulonimbus clouds and in hurricanes is concentrated at surprisingly small sizes, with MMDs of approximately 40 μm and 185 μm respectively. Due to the FSSP and OAP particle breakup issue noted above (T13), it is possible that these MMD estimates are artificially low due to artifacts. However, current estimates in the literature suggest that FSSP total number concentration may be augmented only by a factor of 2 or 3 by breakup, and it is therefore unlikely that it could account for the very large small ice concentrations and small MMDs observed during the recent studies. The future effort to characterize the Appendix D environment must resolve this small particle measurement controversy, and the instrument reliability issues noted above. The following section outlines the strategy for addressing these technical issues:

Strategy:

(S11) It is recommended that several new probes with sealed optics and better time response be purchased, to circumvent problems with probe time response and ice particle ingestion (DMT Cloud Droplet Spectrometer, SPEC 2D-S[33]). It is also planned to modify existing FSSP and OAP probes to seal the optics and contain the electronics in dry air, to keep optical paths clear and reduce condensation (addresses T11 above).

(S12) Purchase of the new 2D-S, with high-speed response capable of 10 μm resolution at 200 ms^{-1}, will improve the accuracy of ice particle measurements below 100 μm, and possibly eliminate the need to use a scattering probe for ice particle size measurements in the sub-100 μm size range. This instrument images particles with two orthogonal lasers, and the intersection area of the two lasers will provide a constant depth of field region for particles larger than about 20 μm. Conventional OAPs have a constant depth-of-field area only for particles larger than about 100 μm (Korolev et al.[13]). A constant depth-of-field is a key attribute for more accurate OAP measurements (Strapp et al.[15]). The overlap region of the two lasers will also provide a small sample volume centered between the two arms of the probe, which will be less prone to measurement of artifacts from particle breakups on the probe tips (addresses T12 and T13 above).

(S13) Scattering probe measurements will continue to be explored for the measurement of sub-100 μm size ice particles. The modification of the FSSP and DMT CDP probes to measure inter-arrival times, so as to allow rejection of particle breakup artifacts, will be investigated. The modification of an FSSP as a 'Fast FSSP' (Brenguier et al.[34]) will also be investigated. In addition to providing inter-arrival times, this modification will also provide information on particle measurement coincidences, a problem that leads to oversizing and undercounting. Such information may be used in correction algorithms that are important at high airspeeds and concentrations. The Small Ice Detector (SID-2), an upgrade to the SID-1 described by Hirst et al.[35], is a scattering probe specifically designed to measure the size, spacing, and sphericity of particles in the sub-50 μm size range, thereby providing valuable individual particle phase information. This probe will also be investigated as a potential new probe for Appendix-D measurements (addresses T12 and T13).

(S14) An alternative ice particle representative size estimate will be implemented as an independent measurement to help resolve the potential controversy over the expected small MMD estimates in the Appendix D environment. Korolev et al.[36,37]

have suggested the use of 'effective diameter'(D_e) as a more easily measured representative particle size. D_e is defined as the ratio of the third moment (volume) to the second moment (area) of a particle size distribution. This can also be shown to be directly calculable from two bulk parameters, the TWC and the extinction. TWC is measured using a hot wire or evaporative device, as discussed in the previous section. Extinction is measured with an optical probe (extinction meter) that transmits light to a reflector, and then back to a receiver. Extinction is then deduced from the reduction in the light received versus transmitted (e.g. Korolev et al.[36]). Due to the relatively long path length of this measurement (~5 m), this measurement will be almost immune to large-particle breakups, because such breakups would only populate a very small fraction of the total path length close to the aircraft skin. Assuming then that an accurate TWC device will be developed before Appendix D characterization flights, these two bulk parameters would provide a completely independent estimate of a representative size D_e, that can then be compared to the MMD derived from particle number concentration spectra. Although some differences are expected in these two measurements due to their definitions, it is nevertheless expected that the comparison will provide critical information to help resolve the issue of whether the Appendix D environment is characterized by MMDs of several millimeters (Lawson et al.[6]), or typically less than 200 μm, as suggested by Strapp et al.[4] and Abraham et al.[21] (addresses T14).

(S15) Wind tunnel testing will be performed at the NASA IRT to evaluate the response of the 2D-S probe in liquid conditions for particles < 100 μm. These spectra will be compared to conventional OAP, FSSP probes, and Phase Doppler particle analyzers, to evaluate the enhanced performance of the 2D-S. Spectra defined solely by the 'stereo' overlap region will be investigated to determine if this feature provides a more accurate spectrum estimate. If possible, these tests will be repeated at the Cox and Co. LeClerc icing wind tunnel using shaved ice to simulate ice particle conditions.

Measurements of Mixed-Phase Clouds.

The accuracy of LWC and MVD measurements in liquid-only clouds has been established in a series of wind tunnel studies, and is considered acceptable for most applications (King et al.[38], Biter el al.[39], Strapp et al.[40]). The separate measurement of LWC and IWC, ice particle and liquid particle distributions, and liquid MVD and ice MMD in deep convective *mixed-phase* clouds may prove to be a technical challenge beyond the reach of this several-year Technology Plan. However, it is fortunate that the Appendix D measurements are anticipated to be in largely glaciated conditions, negating the need to completely solve the mixed-phase measurement problem at this time. The accurate assessment of cloud glaciation will therefore be of particular importance, and will require special development efforts. A more detailed discussion of the technical issues follows.

Technical Issues:

(T15) Cylindrical hot-wire probes designed to measure LWC suffer from false response to ice crystals (Cober et al.[41], Korolev et al.[22]) that may be as high as 40% of the IWC in deep convective clouds (Strapp et al.[4]). They therefore cannot be used directly to infer LWC without proper understanding of and correction for this false response. Evaporators measure TWC, and therefore cannot isolate the liquid component unless in liquid-only cloud.

(T16) Conventional scattering probes designed to measure liquid droplets (e.g. FSSP) also respond to ice particles, and cannot be used to infer droplet spectra in mixed phase clouds unless ice particle concentrations are low (Cober et al.[41]). All past measurements in Appendix D conditions reveal that high ice particle concentrations can be expected, so the FSSP response will be dominated by ice particles. Any liquid component in the FSSP will be indistinguishable from the ice particle component. Imaging OAPs can distinguish spheres from non-spheres, and thus possibly water droplets from ice particles, but only above a threshold size determined by the pixel resolution and the number of pixels required to discriminate a sphere from common ice particle shapes. This is typically of the order of 125 μm for conventional probes. Since any liquid water content is expected to be in sub-50 μm size range, conventional optical array probes lack the image resolution to distinguish liquid droplets from ice particles.

(T17) In some past studies (Strapp et al.[4], Abraham et al.[21], Cober et al.[41]), the Rosemount Ice Detector (RID) has been used to directly indicate the absence of riming on the aircraft surfaces, and therefore indirectly indicate the lack of significant amounts of supercooled LWC in Appendix-D type clouds. This indication is subject to a minimum RID detection threshold which is dependent on aircraft speed, and was estimated by Strapp et al.[4] at ~ 0.03-0.06 gm^{-3} for their measurements at ~200 ms^{-1} (see also Mazin et al.[42]). More recent unpublished tunnel experiments have pointed out that significant erosion of ice shapes may result from the impact of ice particles. This leads to the speculation that the RID may be similarly facing erosion due to ice particle impacts, and a lack of RID response may not be a reliable indicator of the absence of supercooled LWC. Although this effect appears to be insignificant in past measurements in mid-latitude mixed-phase cloud studies at airspeeds around 100 ms^{-1}, this may not be the case in very high IWC situations sampled at twice the speed. There is very little information on the subject.

Strategy:

(S16) The various cylindrical hot wire devices will be tested at the Cox and Co. LeClerc wind tunnel to characterize their false LWC response to ice particles, up to a maximum speed of ~90 ms^{-1}. Since the effect may be airspeed dependent, further testing in any high-speed tunnel identified in (S7) will be necessary to reach the expected Appendix D flight program airspeed (~ 200 ms^{-1}). Instrument flight testing described in (S9) will also be important to verify that false response relationships derived from tunnel measurements are also valid for natural clouds. Korolev and Strapp[43] have described a technique for isolation of LWC and IWC from hot wire measurements if the false response of the LWC probe to ice particles is known (addresses T15).

(S17) The Phase Doppler probe, an alternative water droplet spectrum measurement, will be investigated for use on aircraft. Particle size (nominally 2-120 μm) is derived using diffraction fringe spacing, a much different technology than used in conventional airborne scattering and optical array probes. One of the stated but unverified features of this probe is the rejection of non-spherical particles, a potentially very important addition to an Appendix-D measurement program. Subject to the issue of whether small ice crystals are spherical, this feature could lead to a direct isolation of the liquid component in mixed-phase conditions. The probe could therefore help in answering the very important questions as to whether a cloud is truly glaciated, an issue that may not be simply answered by RID measurements (see T17). Due to the fact that the probe measures inter-arrival time and particle velocity, and has a relatively small sample volume centered between two horizontally aligned arms, it is a particularly good probe for the elimination of any artifacts due to ice particle breakup on probe tips (see T13). Wind tunnel tests are planned at the NASA IRT, and possibly the Cox and Co. LeClerc icing wind tunnel, to test these features in liquid, mixed phase, and glaciated conditions. Due to the potentially great importance of this sphericity identification feature, Phase Doppler airborne testing is also being planned, and the probe has been added as a tentative addition to the Appendix D instrumentation complement (Table 1); (addresses issues T13, T16 and T17).

(S18) The Small Ice Detector[35] (SID–2) is a new probe that also measures the size, spacing, and sphericity of particles in the sub-50 μm size range, and will be investigated for use in an Appendix-D flight program (see S13). As in the case of the Phase Doppler probe, it could potentially provide segregated spherical and non-spherical particle spectra in mixed-phase clouds, and help verify RID measurements of glaciation. Since this probe has only recently become available, and has not been as extensively tested as the Phase Doppler Probe, it is proposed to monitor the research use of this probe with the possible thought of later wind tunnel and flight testing under this Technology Plan (addresses issues T13, T16, T17).

(S19) The implementation of the SPEC 2D-S probe (see S12) may allow spherical shape recognition at high airspeed from particles of about ~50 μm and larger. This may be verified in liquid and glaciated conditions in wind tunnels (e.g. S6, S7, S15) if time and resources permit.

(S20) It is recommended that an inlet system be designed for the aircraft to decelerate air and particles before being sampled by the RID. The purpose of this decelerator is to decrease the potential of ice particles to erode any ice that has accumulated on the RID vibrating rod. Due to the potential complexity of such a system, modeling will be performed to simulate the deceleration and trajectories of particles in the decelerator, and the potential evaporation of IWC and LWC due to adiabatic temperature and pressure rises. A decelerated airspeed of about 50 ms^{-1} is currently being targeted, due to the subjective impression that erosion is not a significant problem at 100 ms^{-1} or below. If modeling efforts predict a successful design, an airborne unit will be designed. Wind tunnel testing will be performed in low and high-speed tunnels (e.g. S6, S7) to assess the behavior of the RID under liquid-only, mixed-phase, and glaciated conditions, both with and without the decelerator (addresses T17).

Proposed Instrumentation Suite:

Table 1 contains a list of the instruments proposed for future measurement of the Appendix D environment. New probes chosen specifically for this environment are highlighted. A number of conventional probes are included for comparison to previous data sets. Many must be modified to survive in the hostile Appendix D environment. IWC will be measured with a combination of hot wire probes and evaporators, and a new isokinetic IWC measurement device will be developed specifically for the Appendix D environment in an attempt to measure the highest expected IWC values. The expected lack of supercooled LWC in these clouds must be carefully documented, and it is proposed that Rosemount Ice Detector measurements be made both at aircraft speed, and in a decelerator developed for this purpose to minimize erosion due to ice particle impacts. The Phase Doppler probe is an important addition for mixed-phase measurements, due to its potential phase-discrimination capability for small particles, and because it may also help to independently establish the amount of supercooled LWC in these clouds. The Nevzorov extinction probe will provide key measurements to assist in the resolution of the issue of whether high concentration measurements of small ice particles are artifacts that lead to erroneously low MMD values in Appendix D conditions. By providing another bulk parameter that is essentially immune from particle breakup issues that complicate measurements of small particles by particle spectrometers, an alternative representative size derived from extinction and TWC, rather than MMD from particle spectrometers, may help resolve whether particle mass is concentrated at the sub-200 μm sizes as reported in some recent studies.

Important information on the properties of clouds has been inferred from pilot reports during in-service engine events (Mason et al.[2]). For example, the observation of a Total Air Temperature (TAT) probe anomaly, the apparent observation and sound of precipitation on the windscreen, the observations or ice accretion (or lack thereof) on the airframe and engine inlet, the Rosemount Ice Detector information when available, and the information from the pilot's radar have all provided common features that have contributed to the initial formulation of the Appendix D environment. It is therefore important to replicate many of these common observations during future Appendix D flights, both to establish commonality between in-service events and future characterization flights, and to help understand the pilot observations and perhaps formulate further pilot cues. Accordingly, it is proposed to record the pilot's radar and install a much more sensitive vertically pointing Ka band research radar. Video cameras are proposed to monitor ice accretion on the airframe, and visual apparent impact of precipitation on the windscreen. It is also proposed that a small icing rod be mounted on the fuselage above the windscreen so as to be visible by the pilot or copilot, to provide close-in observations of the nature of any ice buildup.

The proposed instrumentation list also deliberately contains a certain amount of redundancy. With the implementation of the newer technologies, the inclusion of the older technologies will provide a bridge to past data sets. In spite of best efforts to assess some of these technologies in advance of a field program, it is still likely that new instrument idiosyncrasies will be discovered under real Appendix D conditions. Multiple measurements of the same parameter will be valuable in the further assessment of instrument accuracy and in identifying periods of bad data. Finally, instruments fail much more frequently on aircraft than they do in the laboratory, and redundancy during expensive flight operations is prudent.

Table 1: Proposed Instrumentation Suite for aircraft measurements of the Appendix D Environment

Atmospheric State Parameter Instrumentation:

- TAT probe (standard probe sensitive to TAT freezing)
- TAT probe (new design to mitigate TAT freezing)
- LICOR water vapor mixing ratio probe (reverse flow)
- Chilled mirror dewpoint sensor
- Standard static pressure and airspeed sensors
- Wind and gust measurement system
- GPS position

Bulk Microphysics Probes for LWC, TWC, and IWC:

- PMS King LWC hot-wire probe[7]
- Science Engineering LWC hot-wire probe[7] (standard 2 mm solid wire[1])
- Nevzorov LWC/TWC hot-wire probe[7] (standard[2] and/or modified[3]
- Science Engineering TWC hot-wire probe[7] (modified solid wire[3])
- or Science Engineering multi-wire system[7]
- Counterflow Virtual Impactor for TWC/IWC (new[4])
- Isokinetic evaporator for TWC/IWC (new[4])

Cloud Spectrometers

- PMS FSSP probes (5-95 um), normally for liquid cloud spectra[5]
- PMS FSSP probe (2-47 μm), modified as Fast FSSP[5]
- DMT mini cloud droplet spectrometer (2-50 μm)(new[6])
- PMS 2D2-C probe (35-1120 um), imaging at 35 um res. [5]
- PMS 2DC-grey probe (35-2240 um), imaging at 35 um res. [5]
- PMS 2D-P probe (200 – 6400 μm), imaging at 200 μm res. [5]
- SPEC 2DS probe (10 – 1280 μm), imaging at 10 μm res. [5]
- DMT CIP probe (25-1600 um), imaging at 25 um res., (new[6])
- Phase Doppler probe (2-120 μm) (source unidentified[6])

Others Important Microphysics Instruments:

- Nevzorov extinction probe
- Rosemount Ice detector
- Second Rosemount Ice Detector, modified with a decelerator to mitigate erosion.

Remote Sensing Measurements:

- Ka band radar, upward and downward fixed antennae
- Recording of pilot's forward scanning radar.

Visible Cues:

- Video cameras to monitor ice buildup on key surfaces (wing, engine inlet)
- Video camera to monitor visual appearance of windscreen
- Icing rod close to pilot or co-pilot

[1] More robust sensor design than King for harsh Appendix D environment
[2] possibly more robust sensor design for harsh Appendix D environment
[3] new sensor designs for efficient trapping of ice particles, best choice from Cox and Co. testing
[4] New purchase for Appendix D measurement
[5] Modified for the harsh environment of Appendix D
[6] already suitable for harsh environment of Appendix D
[7] Modified to extend saturation limit for high airspeed and IWC

Task 2. Flight test research and modeling for characterization of high ice water content environments.

Flight-Testing:

Flight tests will be conducted with the objective to collect sufficient atmospheric data near thunderstorm cores to establish the levels of TWC and IWC to verify or revise the proposed Appendix D envelope. A primary product of this characterization effort is to develop plots of TWC versus distance scale for establishing future compliance. Additionally, an envelope of altitude versus temperature and median mass diameter relationships will be pursued.

In order to achieve this goal, an aircraft suitable for flights into the harsh environment and with the capacity for carrying the instruments listed in Table 1 needs to be identified. One such airplane is the NASA S-3B Viking Icing Research Aircraft. Designed as a carrier-based, military aircraft, it is capable of withstanding high G-loads and has abundant control authority that is likely needed in the proximity of thunderstorms. The NASA S-3 also has existing hard points on the wing pylons for mounting the specialized instruments and the electrical power generation capacity to operate the extensive suite of equipment. Lastly, the S-3's ceiling, range and endurance are sufficient to fly to where the storms are located, conduct the flight profiles for Appendix D, and return to base.

Any research aircraft used for the high IWC environment will need to undergo modification to incorporate the new and improved instrumentation that will be developed in Task 1. In selecting mounting locations for the instruments, the design should include considerations of structural loads, data and power cable accessibility, and air-flow quality at the sensor location. NASA is currently studying these design considerations for the S-3 to include the suite of instruments listed in Table 1. Conceptually, two clusters of drop/precipitation spectrometers and water content probes will be mounted to the wing pylons. The clusters will contain up to five major particle probes each. Additional spectrometers may be mounted at separate wing station locations. An upward/downward looking radar will be installed to enable the flight crew to locate regions of intense rain below the airplane, and to document the storm structure for future analysis. Finally, a satellite telephone system will be installed to enable required communication with and provide data to the research team / ground support. All modifications to the aircraft will be reviewed and approved through the NASA safety process.

Prior to conducting the intense high IWC field campaign overseas, a series of initial flight tests and a trial campaign are needed to verify instrumentation function in the actual environment and refine the overall test plan and flight profiles needed to accomplish the characterization goal.

To check instrumentation functionality in real clouds and at high true airspeeds, initial flight tests will be conducted out of Cleveland into cirrus or very cold stratus clouds. Although these conditions will not be high in IWC, the issues of speed and particle resolution can be addressed. To further ascertain instrument measurement capabilities, additional flights will be made into tropical storms off the east coast of Canada or Northeast US in the fall time frame. Previous flight research by Environment Canada with the National Research Counsel of Canada's Convair 580 into these types of storms indicates that they contain high IWC and little lightning. The NASA S-3, equipped as described above, could be based in Cleveland and on call for when the appropriate storm occurs. Environment Canada's Hurricane Desk may provide meteorology support for the test. It is anticipated that flights into two of these storms could be sufficient to verify instrumentation function. A flight test plan will be developed for this initial series of flight tests.

After instrumentation function is ensured through the initial testing described above, a trial field campaign into an Appendix D tropical environment is proposed to test the mature instrument package, collect useful data in the Appendix D environment, and develop lessons-learned to refine test plans prior to a more distant campaign based in the inter-tropical convergence zone of Asia or in Australia. Previous flight test experience by British Aerospace suggests that Costa Rica would be a good basing location for the trial campaign, providing easy access to relatively frequent and predictable deep tropical convection similar to that which has caused many engine events. This would enable time-efficient operations relatively close to the USA. Other base options will be explored and reviewed on the basis of deployment costs, logistics issues, distance to storm paths, and frequency of storms. Meteorological support for this is yet to be determined.

After the trial campaign is completed, a "full-up" field campaign in northern Australia or Southeast Asia region will be conducted to gather data to characterize the high IWC conditions for Appendix D. This region of the world experiences the highest sea surface temperatures - a factor that fuels deep convection and high TWC. Additionally, this region was used to generate most of the currently used database from the 1950's, and is where a large number of recent events have taken place.

In developing the test plan, consideration for basing locations will be made using an engine event database (Mason et al. [2]) , and by studying deployment costs, logistic issues, distance to storm paths, and frequency of storms. To better understand the regional weather patterns and storms, it is anticipated that a relationship with a local meteorological agency will be developed, whose contribution it will be to provide climatologolical studies to support test plan development, and provide forecast and nowcast support to the flight operations. Local airlines may be asked to provide local support such as information on flight experiences with engine events. Developing these relationships will be a key factor in developing the operations test plan and will be critical to the success of the field campaign. The operations test plan with hazard analyses will be developed in partnership with the participating organizations.

The conduct of the flights is anticipated as follows:

- Work with severe weather experts with local expertise to forecast and nowcast suitable deep convective storms
    - Forecast and identify tropical storms and/or Cbs and Cb complexes from standard modeling and forecast activities, and from satellite and radar measurements
- Launch test aircraft towards identified storm region.
    - Develop a flight plan based on best information before flight
    - Update flight crew on storm position using SATCOM on aircraft to upload latest radar and satellite images
- Simulate the typical flight profiles in which incidents have occurred:
    - Fly in the anvil region of thunderstorms and tropical storms

  - Fly in low reflectivity regions adjacent to high reflectivity regions at altitude
  - Fly above expected regions of high radar reflectivity (heavy rain) below the freezing level, as per ground radar network and onboard cloud radar
  - Sampling strategy to be determined from trial campaign; possibly fly constant-altitude straight legs of varying length across the anvil region
  - Altitude range of interest : ~15,000 – 35,000 feet or higher
  - Temperature range of interest : 0 to –50 C
- Return to base and recycle aircraft and instrumentation for next flight.

Hazards analyses will be performed for the initial flight-testing, the first phase Appendix D flights in Costa Rica, and for the operations plan for the main field phase in Australia/Southeast Asia. These analyses will identify the hazard for flight and other aspects of the operation in each case, describe the causes of each hazard, and put controls in place to reduce the severity and/or probability of the hazard. The analysis will be reviewed and approved by the NASA safety committees. Additional reviews may be required by participating organizations.

Use of Cloud Resolving Models:

A future Appendix D aircraft research program will be costly, and will return a limited number of hours in cloud, and thus a limited data set. For example, the original tropical cloud measurements collected in the 1950s by the RAE[1] in order to characterize flight in the ice crystal environment were complied from a total of 101 flight sorties, culminating in a total of 44 hours of in-cloud measurements. Data were collected over three years at three different locations, and it is likely that in excess of 300 flight hours were consumed in the effort. In spite of this extensive effort, the volume of data provided is probably not sufficient to provide some desirable analysis products such as statistics of the 99% percentile TWC subcategorized according to altitude or temperature. The future Appendix D flight program will face the same problems related to collection of a suitable data set, and may not even have sufficient budget to mount such a 300-hour program. A potential solution to this problem is the use of Cloud Resolving Models (CRMs) to extend the quantity of these measurements and to possibly augment aircraft measurements. CRMs are used by the atmospheric science community to study the dynamics and microphysics of cloud systems on scales that allow the identification of individual clouds, in simulations ranging from tornadoes in severe summer convection to heavy snow in winter synoptic situations. The CRM can be used to study the formation, evolution, and dissipation stages of cloud systems, and some impressive and enlightening visualizations of cloud system evolution have been produced. CRMs have also been used by the satellite community to train algorithms used to infer cloud properties from satellite-measured radiances. For example, Tassa et al.[44] describe the use of several CRMs to provide a simulated tropical and mid-latitude cloud data base for algorithm development. The spatial resolution of the CRM is typically better than 1 km, although increased resolution is done at the expense of model domain. Still, it is expected that a domain of several hundred kilometers could be encompassed with such resolution, enough to cover most convective clouds and complexes. In order to cover the domain of possibly more than 500 Km for a tropical storm, a lower resolution (~5-10 Km) use of Numerical Weather Prediction (NWP) models might be required.

Both CRM and NWP models produce high-resolution 3-dimensional fields of winds, temperatures, humidity, and cloud microphysical parameters such as LWC and IWC that in some cases are even categorized into different precipitation types. The microphysical algorithms for cloud LWC and IWC apportionment in these models are quite complicated, and are generally unvalidated. However, since we expect the Appendix D clouds to be for the most part glaciated above the freezing level, the use of the model output of TWC should circumvent most of this complication by eliminating one of the key uncertainties, the phase conversion from liquid water to ice particles. The simulations of a CRM are highly variable in space and time, and are produced from an initial estimate of the state of the atmosphere that cannot be determined to nearly the same resolution. For this and other reasons, a CRM simulation at any particular time cannot be expected to recreate actual observations, especially on the small scale. However a CRM does often recreate the major features observed in a storm. More importantly, since the model does obey the laws of physics and does not create or destroy water mass, it may recreate the storm in a statistical sense, so that statistics derived for the cloud lifetime for a parameter such as TWC may accurately reflect true statistics. The great advantage of a computer-produced 3-dimensional field of TWC is that it can be examined statistically in many different ways, and can provide sub-categories of statistics such as TWC versus distance as a function of altitude or temperature. In contrast, an aircraft flight will provide only limited coverage of a cloud during a specific period in its lifetime, and may be biased in its area coverage due to operational issues.

A key aspect of the use of the CRM is the validation of the TWC statistics it produces. The Appendix D flight program would provide an ideal data set with which to validate the model TWC estimates. If and when the CRM can be determined to provide accurate statistics of TWC, it can then be subsequently used to extend the flight test program data by providing more extensive statistics of data collected during the flight program, but could also be used for later simulations at different locations and times of year to extend the data set to a near-global perspective.

It is therefore proposed as part of the Technology Plan to investigate the use of cloud resolving models to augment measurements from the Appendix D flight program. As a first step, a survey of currently available simulations will be performed with the hope of providing some preliminary model-derived case-specific TWC statistics. This exercise would provide some experience in the use of the model for this purpose, and identify any issues before proceeding to its use in the Appendix D flight program. The model would then be run for the entire duration of the flight program, filling in simulations for cases not sampled by the aircraft, as well as providing data to compare to those collected during flight operations. These latter studies would be used to determine the validity of the model TWC statistics. If this approach is successful, a full extension of the simulations for near global and temporal coverage could be investigated and pursued if economically feasible.

The CRM community is mainly based in universities and government meteorological agencies. In addition to the opportunity to test and improve their CRMs with expensive and high-quality aircraft measurements that could rarely be afforded otherwise, it is expected that the CRM community may be interested in evaluating the prognostic capabilities of their models, possibly even for forecasting Appendix D conditions to improve the safety of their local commercial air traffic. It is therefore proposed that a quid-pro-quo partnership with a university or government meteorological bureau with expertise in local severe weather be explored. In addition to providing a potential CRM partner, this collaboration will also be important in securing local forecast support and access to the real-time data that will be required to mount a safe and scientifically effective flight program. The CRM data may in fact provide important forecast information in the planning of flights.

Task 3. Experimental testing in support of ice accretion model development and validation for high ice water content environments.

Validated mixed phase / ice crystal accretion analytical tools are required by the manufacturer to conduct critical point analysis (CPA) assessments for 14 CFR part 33 Appendix D. The focus of this task is testing to provide data and other information for engine manufacturers in their efforts to construct the necessary ice accretion models and tools for certification of new engines in Mixed Phase/Glaciated icing conditions. The data base provided by these tests is envisioned to support the industry efforts for developing and validating the required ice crystal analytical tools.

Some initial assessment of the contribution of ice crystals to ice accretion on gas turbine engine airfoils (Ref. 50, 51, 52) suggests that there are numerous areas requiring research activity. The following listing addresses some of the basic issues requiring investigation:

1. The ice crystal melting process
2. Ice Crystal “sticking” and “bouncing/splashing” mechanisms
3. Ice crystal contribution to ice accretion thermodynamics
4. Ice adhesion/shedding and erosion associated with ice crystals

Candidates for testing under Task 3 include (but are not limited to) the following:

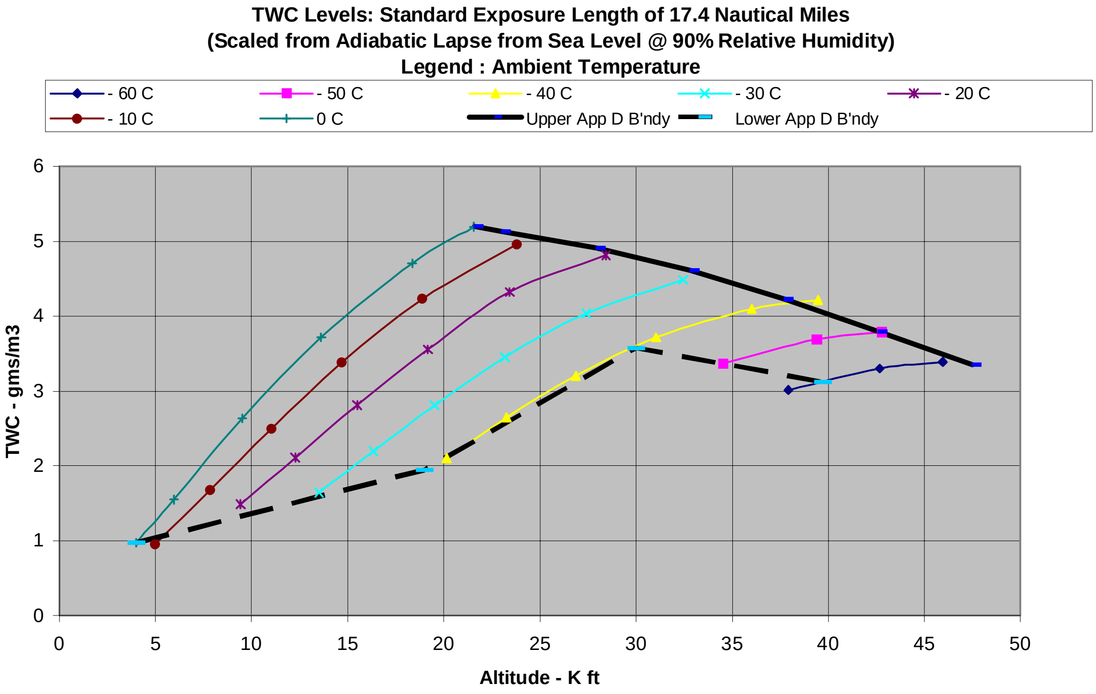
- A test evaluation of the ice melting associated with the contact with internal engine surfaces that are above 32 deg F (0 deg C). It is envisioned that heated plates might be used in an icing wind tunnel to evaluate melting for a range of ice crystal sizes.
- Ice accretion testing and evaluation of actual compressor airfoil cascades. All liquid, mixed phase and all ice crystal (with heated plates to melt ice crystals ahead of cascade) tests might be appropriate to establish a data base for validation.
- Testing at reduced pressure (to simulate altitude) to provide ice shedding information.
- Testing with ice crystals to quantify bouncing/splashing, sticking and erosion contributions to the final ice accretion mass.
- Testing in a warm air temperature environment combined with cold liquid and ice crystals
- Ultimately, engine testing in a controlled ice crystal environment for comparison with analysis for full validation.

There is a need to for an industry workshop as a first step in detailing and prioritizing the testing that will be required to address these issues. This workshop is being planned for the first quarter of 2006.

Task 4. Test Facilities Requirements for demonstrating engine compliance with Appendix D requirements.

Test Facility Water Flow Requirements

The amount of water (in the form of ice crystals) needed for typical sea level (free jet) and altitude (direct connect) facilities is based upon 14 CFR part 33 Appendix D conditions. (*Note that a sea level test facility can also be configured as a direct connect facility.)* The following figure from Appendix D illustrates the ambient total water content (TWC) for a standard icing cloud exposure length of 17.4 nautical miles.



Historically, simulation of supercooled liquid flight icing encounters in an engine test facility primarily requires accounting for flight effects (altitude and Mach No) on water droplet temperature and inlet concentration. The engine manufacturer makes use of ice accretion models and analysis for a critical point analysis to evaluate the icing threat to various engine components and defines them in terms of freezing fraction, accreted ice mass and consequences of ice shedding. These same models then define any required changes to the LWC, air temperature and test time to achieve similar results in the test facility. Supercooled water droplets are readily produced by water spray nozzles in the same size range as natural conditions (MMD ~15 - 50 µm). Ice crystals, however, occur naturally in many different shapes and potentially larger sizes than can be easily produced by artificial means. The large size of ice crystals can also contribute to even stronger inlet TWC concentration effects than with supercooled liquid droplets. Ice shavers have been used successfully for creating limited quantities of ice crystals in representative sizes, but a more convenient method for artificially producing ice crystals would also make use of spray nozzles. However, the ice crystals produced are typically smaller than in nature. Engine testing with ice crystals generated by this manner, either at sea level or in an altitude test facility, must therefore be appraised with regard to differences in ice particle size and velocity relative to flight conditions. The effort also includes atmospheric and heat transfer scaling evaluation to assure consistency between engine test facilities and flight operation.

Ice Shavers

Ice shavers utilize large ice blocks that are fed at a determined rate through a mechanical shaver that consisted of multiple rotating blades. The shaved ice is then introduced into the icing tunnel air stream via a blower. Some key advantages of ice shavers include:

- Particles are larger (Median Mass Diameter - MMD ~ 185 μm)
- Particles are fully frozen as they are produced.
- The ice particles produced using this technique are usually irregular in shape
- Technology is currently available

The main drawback of ice shavers is size and expense of facilities needed to produce large enough quantities of ice crystals for engine testing.

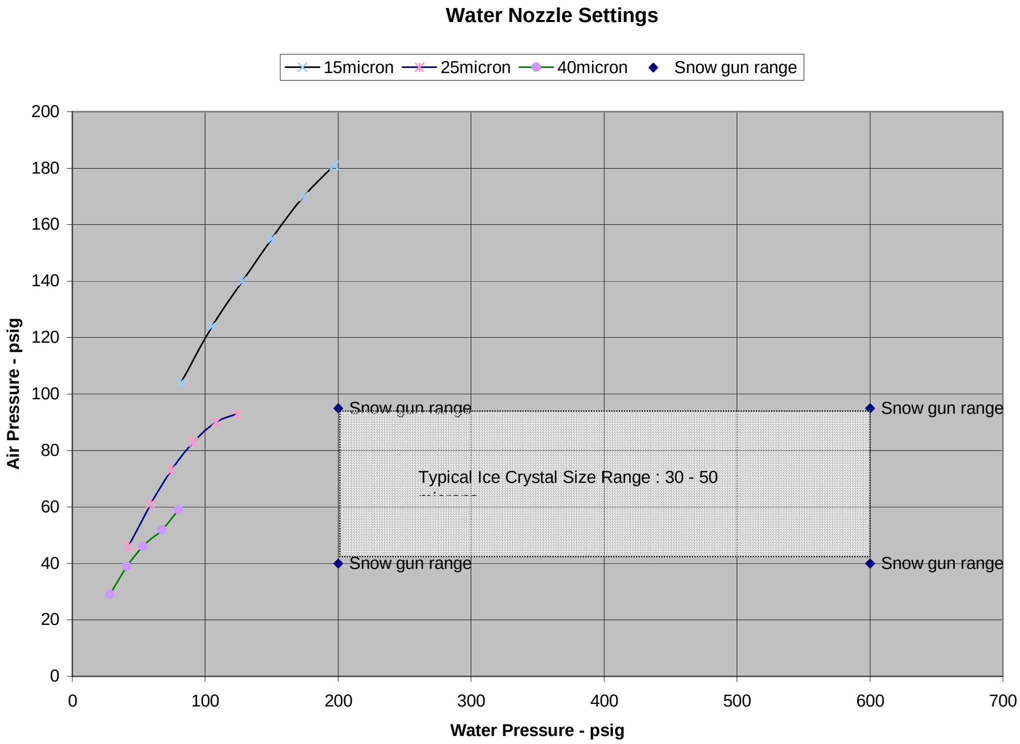
Snow Nozzles

Snow nozzles differ from water fog (supercooled liquid test) nozzles in the fundamental means of atomization. The former rely on water pressure to accelerate/swirl the water for atomization, while fog nozzles internally mix high velocity air with water for this purpose. Snow nozzles are typically combined with an air source for the manufacture of artificial snow at ski areas as either “snow guns” or “snow fans”. Air flow use in snow guns is mainly for the purpose of “casting” the small water droplets out to the target area, typically as an arc to allow sufficient time for ice crystallization to take place (~several seconds in the quiescent atmosphere). Snow fans are an assembly of many small nozzles located on the periphery of a tube with a single larger volume air supply.

Ice Crystal Coalescence

The figure shown below provides a comparison of operating pressures and water droplet/ice crystal sizes for typical supercooled liquid testing and for commercially available snow guns. All of the droplet diameter specifications are at the nozzle discharge. Ice particles generated using the snow gun are small (MMD ~30-50 μm) in comparison with naturally occurring ice crystals (MMD >200 μm) and require some residency time in the air stream to coalesce into larger sizes. By virtue of ice crystals colliding during the travel away from the gun, there is a potential for coalescence into particles with larger dimensions (MMD ~100 μm) prior to impacting the test model. A newer technology low pressure snow gun is designed to intensify the external mixing and can achieve crystallization more rapidly and hence may accelerate the growth to still larger diameters via the coalescence process.

Based on the air velocity forward of the engine, the time interval required for crystallization in quiescent air would imply distances of several hundred feet between the nozzle and the engine for typical engine ground test installations. Direct injection of the discharge from a snow gun into an inlet duct may require similar duct lengths for low power testing and potentially longer ducting for higher power. Results with a snow gun reported in Reference 47, however, show promise for the use of snow nozzles for engine testing. In that report, larger ice crystal sizes (MMD ~150 microns) were obtained within a realistic distance by utilizing a secondary icing tunnel test section that was further downstream from the snow gun location.



Ice Particle Trajectory

In addition to technology requirements associated with creating a sufficient quantity of representative ice crystal sizes for engine testing, there is a need for research focused toward a calibrated model of the interaction of ice crystals with the engine inlet air stream in flight and in the test facility. The trajectory path of potentially larger ice crystals of irregular shape versus smaller ice particles of more uniform shape must be accounted for in establishing icing certification test conditions.

To achieve this end, technology requirements include the characterization of ice crystal size distributions and degree of wetness from snow nozzles as well as the ice crystal growth via coalescence downstream of the nozzle. Additionally, ice crystal mass to surface area relations for natural ice crystals and those produced with ice shavers and snow nozzles must be characterized to support trajectory assessments of the ice crystal velocity adjustments to surrounding air flow. These factors are part of the requirement for adjusting test facility conditions to achieve similar ice accretion and shedding effects as in the flight environment.

Internal Engine Instrumentation

In an ice crystal environment, ice may accrete on compressor stages downstream of the first compressor stator. Direct visibility of these locations is not possible with frontal view cameras currently used during icing certification testing. Therefore, an effort is required to investigate the adaptation and use of other means for viewing/measuring the ice accretion and shedding within the engine.

Equivalent Liquid Water Tests

As experience is gained in the modeling and assessment of engine operation with ice crystals, representative icing test conditions using only liquid supercooled water may be needed. Use of a set of super-cooled liquid test conditions by manufacturers as an alternative to ice crystal testing may be possible. Estimating the success of being able to specify such an option is difficult. It is an opportunity to be explored once validated analyses of ice crystals are developed.

References

1. McNaughtan, I.I.,"The Analysis of Measurements of Free Ice and Ice/Water Concentrations in the Atmosphere of the Equatorial Zone," *Royal Aircraft Establishment (Farnborough) Technical Note No. : Mech. Eng. 283,* 1959.
2. Mason, J.G., J.W. Strapp, and P. Chow, "The Ice Particle Threat to Engines in Flight,"*44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada*, 9-12 January 2006, AIAA-2006-0206.
3. McNaughtan, I.I, and F.J. Bigg, "Development and Calibration of the Pitot Type Ice Concentration Meter," *Royal Aircraft Establishment (Farnborough) Technical Note No: Mech. Eng. 281*, Feb. 1959
4. Strapp, J.W., P. Chow, M. Maltby, A.D. Bezer, A. Korolev, I. Stomberg, and J. Hallett, "Cloud Microphysical Measurements in Thunderstorm Outflow Regions during Allied/BAe 1997 Flight Trials," *37th AIAA Aerospace Sciences Meeting and Exhibit , Reno, NV.* , Jan. 11-14, 1999, AIAA 99-0498

5. Strapp, J.W., L. E. Lilie, E. Emery and D. Miller, "Preliminary Comparison of Ice Water Content as Measured by Hot Wire Instruments of Varying Configuration," *43rd AIAA Aerospace Sciences Meeting, Reno, Nevada*, 11-13 January 2005, AIAA-2005-0860
6. Black, R. and J. Hallett, "Observations of the Ice Distributions in Hurricanes," *J. Atmos. Sci., Vol. 43*, 1986, pp. 802-822
7. Lawson, R.P., Angus, L.J., and Heymsfield, A..J., "Cloud Particle Measurements in Thunderstorm anvils and Possible Threat to Aviation," *J. Aircraft*, *Vol. 35, No. 1*, 1998, pp. 113-121.
8. Stith, J. L., J. E. Dye, A. Bansemer, A. Heymsfield, C. Grainger, W.W. Petersen, and R. Berticelli, "Microphysical Observations of Tropical Clouds," *J. Appl. Meteor., Vol. 41*, 2002, pp. 97-117.
9. Jeck, R.K., "Snow And Ice Particle Sizes And Mass Concentrations At Altitudes Up To 9 Km (30,000 ft)," DOT/FAA/AR-97/66, August, 1998.
10. Joe, P. and R. List, "Testing and Performance of Two-Dimensional Optical Array Spectrometers with Greyscale," *J. Atmos. Oceanic Technol., Vol.* 4, 1987, pp.139-150.
11. Korolev, A.V., S.V. Kuznetsov, Y.E. Makarov, and V.S. Novikov, "Evaluation of Measurements of Particle Size and Sample Area from Optical Array Probes," *J. Atmos. Oceanic Technol.*, Vol. 8, 1991, pp. 514-522.
12. Baumgardner, D., and A. Korolev, "Airspeed Corrections for Optical Array Probe Sample Volumes," *J. Atmos. Oceanic Technol., Vol. 14*, 1997, pp. 1224-1129.
13. Korolev, A.V., J.W. Strapp, and G.A. Isaac, "Evaluation of the Accuracy of PMS Optical Array Probes," *J. Atmos. Oceanic Technol., Vol. 15*, 1998, pp. 708-720.
14. Reuter, A., and S. Bakan, "Improvements of Cloud Particle Sizing with a 2D-grey Probe," *J. Atmos. Oceanic Technol., Vol. 15*, 1998, pp. 1196-1203.
15. Strapp, J.W., F. Albers, A. Reuter, A.V. Korolev, U. Maixner, E. Rashke, and Z. Vukovic, "Laboratory Measurements of the Response of a PMS OAP-2DC," *J. Atmos. Oceanic Technol., Vol. 18*, 2001, pp. 1150-1170.
16. Zikmunda, J. and B. Vali, "Fall Patterns and Fall Velocities of Rimed Ice Crystals," *J. Atmos. Sci.*, Vol. 29, 1972, pp 1334-1347.
17. Locatelli, J.D., and P.V. Hobbs, "Fallspeeds and Masses of Solid Precipitation Particles," *J. Geophys. Res*., Vol. 79, 1974, pp. 2185-2197.
18. Heymsfield, A., "Ice Crystal Terminal Velocities," *J. Atmos. Sci.*, Vol. 29, 1972, pp. 1348-1357
19. Plank, V.G., R.O. Berthel, and A.A. Barnes Jr., "An Improved Method for Obtaining Water Content Values of Ice Hydrometeors from Aircraft and Radar Data," J. Appl. Meteor., Vol. 19, 1980, pp. 1293-1299.
20. Korolev, A., G.A. Isaac, and J. Hallett, "Ice Particle Habits in Stratiform Clouds," *Q. J. Roy. Meteor. Soc.*, Vol. 128, 2000, pp. 2873-2902.
21. Abraham, J., J. W. Strapp, C. Fogarty, and M. Wolde, "Extratropical Transition of Hurricane Michael", *Bull. Amer. Met. Soc*., Vol. 85, 2004, pp. 1323-1339.

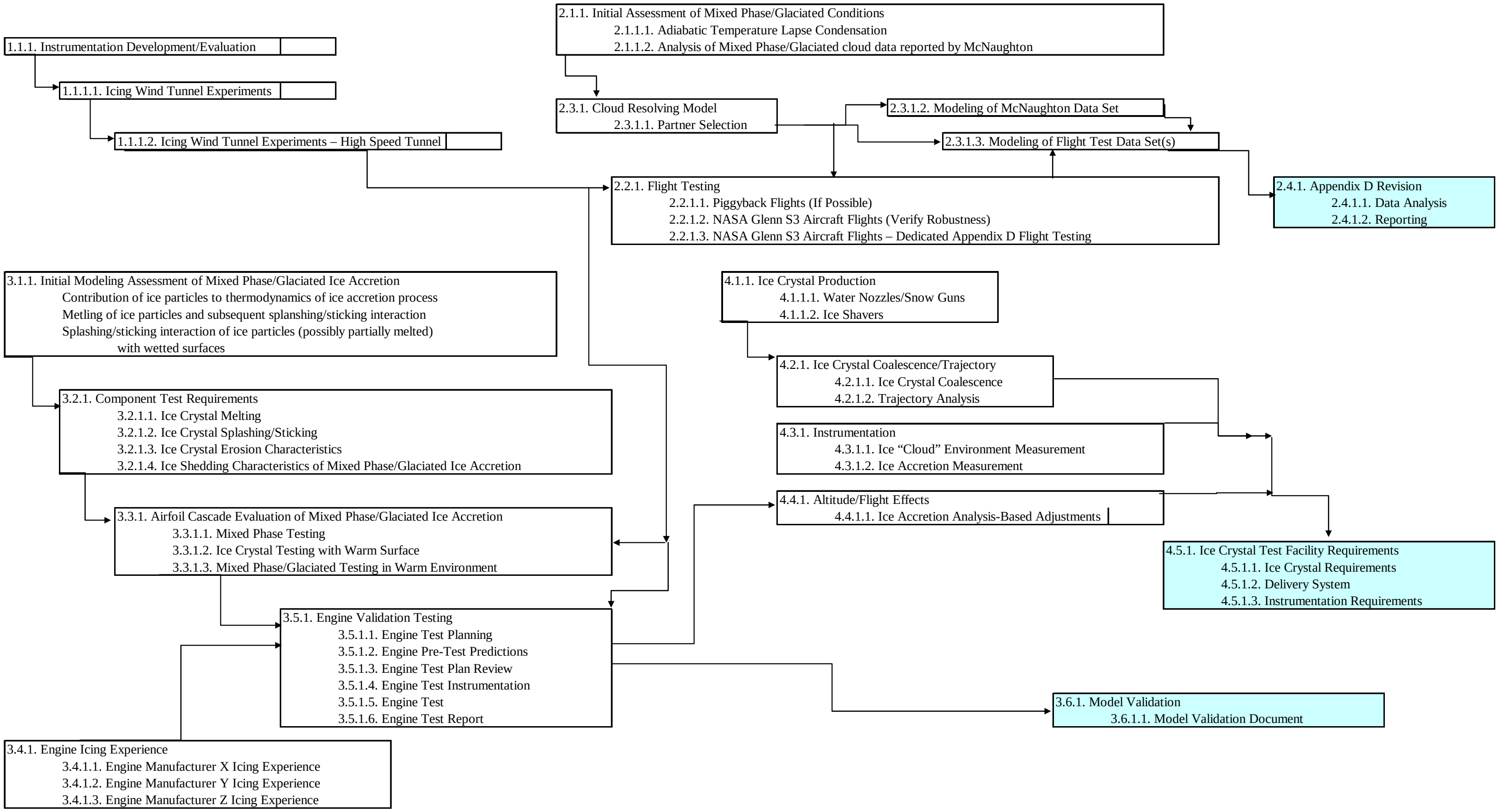
22. Korolev, A.V., J.W. Strapp, G.A. Isaac And A.N. Nevzorov, "The Nevzorov Airborne Hot-Wire Lwc-Twc Probe: Principle Of Operation And Performance Characteristics," *J. Atmos. Oceanic Technol.,* Vol. 15, 1998, pp. 1495-1510.
23. Emery, E., Miller, D., Plaskon, S., Strapp, J.W., And Lilie, L.E., "Ice Particle Impact On Cloud Water Content Instrumentation," *42nd Aiaa Aerospace Sciences Meeting And Exhibit*, Jan. 2004, AIAA-2004-0731.
24. Brown, P.A., "Measurements Of The Ice Water Content In Cirrus Using An Evaporative Technique," *J. Atmos. Oceanic Technol.,*Vol. 2, 1993, pp. 340-352
25. Noone, K.B., K.J. Noone, J. Heintzenberg, J. Strom, and J.A. Ogren, "In Situ Observations Using The Counterflow Virtual Impactor," *J. Atmos. Oceanic Technol*., Vol. 10, 1993, pp. 294-303.
26. Al-Khalil, K., E. Irani, and D. Miller, "Mixed-Phase Icing Simulation and Testing At The Cox Icing Wind Tunnel," *41st AIAA Aerospace Sciences Meeting And Exhibit*, Jan. 2003, AIAA-2003-0903.
27. King, W.D., "Airflow and Particle Trajectories Around Aircraft Fuselages. I: Theory," *J Atmos. and Oceanic Technol*., Vol. 1, 1984, pp. 5-13
28. Gayet, J., G. Febvre And H. Larsen, "The Reliability of the PMS FSSP in the Presence of Small Ice Crystals," *J. Atmos. Oceanic Technol.*, Vol. 13, 1996, pp. 1300-1310
29. Korolev, A.V, And G.A. Isaac, "Roundness And Aspect Ratio Of Particles In Ice Cloud," *J. Atmos. Sci.*, Vol. 60, 2003, pp. 1795-1808
30. Gardiner, B. A. and J. Hallett, "Degradation of in-cloud Forward Scattering Probe Measurements in the Presences of Ice Crystals," *J. Atmos. and Oceanic. Technol., Vol. 2*, 1985, pp. 171-180.
31. Field, P.R., R. Wood, P.R.A. Brown, P.H. Kaye, E. Hirst, R. Greenaway, and J.A. Smith, "Ice Particle Interarrival Times Measured with a Fast FSSP," *J. Atmos. and Oceanic Technol., Vol. 20*, 2003, pp. 249-261.
32. Korolev. A., and G.A. Isaac, "Shattering during Sampling by OAPs and HVPS. Part I: Snow Particles," *J. Atmos. and Oceanic Technol.*, Vol. 22, 2005, pp. 528-542.
33. Lawson, R. P., D. O'Connor, P. Zmarzly, K. Weaver, B. A. Baker, Q. Mo, and H. Jonsson, "The 2D-S (Stereo) Probe: Design and Preliminary Tests of a New Airborne, High Speed, High-Resolution Particle Imaging Probe," *J. of Atmos. Oceanic Technol.*, In Press, 2006.
34. Brenguier, J.L., T. Bourrianne, A. Coehlo, J. Isbert, R. Peytavi, D. Trevarin, and P. Weschler, "Improvement of Droplet Size Distribution Measurements with the Fast FSSP," *J. Atmos. Oceanic Technol.*, Vol. 15, 1998, pp. 1077-1090.
35. Hirst, E., P.H. Kaye, R.S. Greenaway, P. Field, and D.W. Johnson, "Discrimination of Micrometer-Sized Ice and Super-Cooled Droplets in Mixed-Phase Cloud,". Atmos. Env., Vol. 36, 2001, pp. 33-27.
36. Korolev, A.V., G.A. Isaac, I.P. Mazin, and H.W. Barker, "Microphysical Properties of Continental Clouds from In Situ Measurements," *Quart. J. Roy., Meteor. Soc*., Vol. 127, No. 576, 2001, pp. 2117-2151
37. Korolev, A.V., G.A. Isaac, J.W. Strapp, and A.N. Nevzorov, "In situ measurements of effective diameter and effective droplet number concentration," *J. Geophys. Res*., Vol. 104, 1999, pp. 3993-4003.
38. King , W.D., J.E. Dye, J.W. Strapp, D. Baumgardner, and D. Huffman, "Icing Wind Tunnel Tests On The CSIRO Liquid Water Probe," *J. Atmos. Oceanic Technol.*, Vol. 2, 1985, pp. 340-352
39. Biter, C.J., J.E. Dye, D. Huffman, And W.D. King, "The Drop-Size Response Of The CSIRO Liquid Water Probe," *J. Atmos. Oceanic Technol.*, Vol. 4, 1987, pp. 359-367.
40. Strapp, J.W., J. Oldenburg, R. Ide, L. Lilie, S. Bacic, Z, Vukovic, M. Oleskiw, D. Miller, E. Emery, And G. Leone, "Wind Tunnel Measurements Of The Response Of Hot-Wire Liquid Water Content Instruments To Large Droplets," *J. Atmos. And Oceanic Technol.*, Vol. 20, 2002, pp. 791-806.
41. Cober, S.G., Isaac, G.A. Korolev, A.V. And Strapp, J.W., "Assessing Cloud Phase Conditions", *J. Appl. Meteor*., Vol. 40, 2001, pp. 1967-1983
42. Mazin, I. P., A. V. Korolev, A. Heymsfield, G. A. Isaac, And S. G. Cober, "Thermodynamics Of Icing Cylinder For Measurements Of Liquid Water Content In Supercooled Clouds," *J. Atmos. Oceanic Technol.*, Vol. 18, 2001, pp. 543-558.

43. Korolev, A.V., and J.W. Strapp, "Accuracy of Measurements of Cloud Ice Water Content by the Nevzorov Probe," *40th AIAA Aerospace Sciences Meeting and Exhibit*, Jan. 2002, AIAA-2002-0679.

44. Tassa, A., S. Dietrich, S. Di Michele, S. Pinori, and A. Mugnai, "The EURAINSAT Cloud Radiative Data Set,", *EURAINSAT Tech. Report. 1*, 2003, 32 pages.
45. Pfeiffer, G.D., and G. P. Maier, "Engineering Summary Of Powerplant Icing Technical Data," Report FAA-RD-77-76.
46. Lozowski, E.P., J. R. Stallabrass, and P. P. Hearty, "The Icing Of An Unheated Non-Rotating Cylinder In Liquid Water Droplet-Ice Crystal Clouds," National Research Council Canada Report LTR-LT-96, February, 1979.
47. Al-Khalil, Kamel, "Assessment Of Effects Of Mixed-Phase Icing Conditions On Thermal Ice Protection Systems," DOT/FAA/AR-03/48, May 2003.
48. Stallabrass, J.R., and P. F. Hearty, "Further Icing Experiments On An Unheated Non-Rotating Cylinder," National Research Council Canada Report LTR-LT-105, November 1979.
49. Riley, J.T., "Mixed Phase Icing Condition, A Review," Report No. DOT/FAA/AR-98/76.
50. Mazzawy, R.S., "TSIICE : Engine Icing Code User's Manual," FAATC Contract Report, 2005
51. Mazzawy, R.S., "TSIICE – Modeling Of Mixed Phase Ice Accretion : Comparison With Icing Tunnel Data," FAATC Contract Report, 2005
52. Tibbals, T. , "On Internal Engine Component Icing", Proceedings of the FAA Specialists" Workshop on Mixed-Phase and Glaciated Conditions, Dec. 2-3, 1998, Pages 333-335

Appendix I. Technology Roadmaps by Task

Task 1. - Instrumentation development and evaluation for high ice water content
Task 2. - Flight test research for characterization of high ice water content environments.
Task 3. - Experimental testing in support of ice accretion model development and validation for high ice water content environments.
Task 4. - Test Facilities Requirements for demonstrating engine compliance with Appendix D requirements.



Appendix II. Work Breakdown Structures by Task

This document contains the Work Breakdown Structure (WBS) Task Descriptions of the Mixed Phase/Glaciated Technology Project. The WBS is current as of the date associated with this document. Since this project is a research effort, not all of the elements of the WBS are known. The elements and the period of performance associated with each element are the best estimates. As the project proceeds, this document will be updated to reflect the current planning and elements will be more fully described as well as modified to reflect changes precipitated by the outcome of earlier elements of the project.

Task 1. - Instrumentation development and evaluation for high ice water content
Task 2. - Flight test research for characterization of high ice water content environments.
Task 3. - Experimental testing in support of ice accretion model development and validation for high ice water content environments.
Task 4. - Test Facilities Requirements for demonstrating engine compliance with Appendix D requirements.

Note regarding listed Organizations- listed are ones for whom there is reasonably firm information that they will be involved, but others may well be involved as well.

Task 1. - Instrumentation development and evaluation for high ice water content

This task is devoted to the development of accurate and robust instrumentation for the purpose of supporting flight testing in the Mixed Phase/Glaciated cloud environment (Task 2). Such instrumentation would also be required for measurement of test conditions during component testing required for model development/validation (Task 3) and in facilities for certification testing of new engines (Task 4).

1.1.1. Instrumentation

This task is to develop instrumentation for use on aircraft flight tests to measure Mixed Phase/Glaciated water content

1.1.1.1 Purchase of new instrumentation

Objective: to make strategic purchases of airborne cloud measurement instrumentation to ensure more reliable and accurate measurements in the Appendix D environment.
Organizations: Environment Canada, NASA Glenn Research Center

1.1.1.2 Development of new IWC device and aircraft decelerator

Objective: to develop a new IWC sensor specifically for the Appendix D environment, and a decelerator to improve glaciation measurement
Organizations: Environment Canada, NASA Glenn Research Center, Cranfield University, FAA

1.1.1.3 Modifications of cloud measurement equipment for Appendix D flight environment

Objective: to make modifications to existing cloud measurement equipment so that they cover a more representative range of IWC, and can more adequately survive the hostile Appendix D flight environment
Organizations: Environment Canada, NASA Glenn Research Center, Cranfield University, FAA

1.1.1.4. Icing Wind Tunnel Experiments (instrumentation evaluation)

Objective: Evaluate the accuracy and robustness of candidate probes for use in a Mixed Phase/Glaciated cloud environment.
Organization: Environment Canada, FAA, NASA Glenn Research Center, Cox & Co. Inc

1.1.1.5. Icing Wind Tunnel Experiments – High Speed Tunnel (instrument evaluation)

Objective: Evaluate the accuracy and robustness of candidate probes for use in a Mixed Phase/Glaciated cloud environment, at representative flight speeds
Organization: Environment Canada, FAA, NASA Glenn Research Center, National Research Council, TBD

1.2.1. Flight Testing

This task utilizes available flight testing opportunities to proof test the instrumentation in the flight environment. It is synonymous with the initial flight-testing under Task 2.

1.2.1.1. Piggyback Flights

Objective: Verify the robustness of instrumentation in actual Mixed Phase/Glaciated flight conditions, using already-funded research aircraft programs to test instrumentation in advance of a future dedicated Appendix D flight characterization program.
Organization: EC, NASA, FAA

Task 2. - Flight test research for characterization of high ice water content environments.

This task is focused on defining the Mixed Phase/Glaciated icing environment in convective storms for the purpose of validation/enhancement of the icing envelope as recommended by the IPHWG (FAR Part 33 Appendix D).

2.1.1. Initial Assessment of Mixed Phase/Glaciated Conditions

This task makes use of the limited existing flight data to characterize an Mixed Phase/Glaciated icing convective storm cloud environment.

2.1.1.1. Adiabatic IWC estimates
Objective: Assess the condensation associated with an adiabatic temperature lapse with altitude to estimate upper limits for ice water content (IWC) in convective storm updraft regions at different altitudes and ambient temperatures.
Organization: Environment Canada, FAA

2.1.1.2. Analysis of Mixed Phase/Glaciated cloud data reported in 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 the Equatorial Zone”, by Ian I. McNaughtan, B.Sc., Dip. R.T.C.
Objective: Define the TWC for standard cloud length and the distance scale factor for initial definition of Appendix D Mixed Phase/Glaciated icing envelope.
Organization: Environment Canada, FAA

2.2.1. Flight Testing

This task utilizes piggyback (if possible) and dedicated aircraft flight testing in the vicinity of convective storms to measure Mixed Phase/Glaciated icing water content. (Note. “Piggyback” flights refer to research flights in collaboration with other organizations whose primary purpose is not the measurement of atmospheric icing environments but rather other scientific activity, such as “weather satellite validation.” Funding for such research has been greatly reduced in recent years so there may not be any opportunity for piggyback flights.)

2.2.1.1. Piggyback Flights
Objective: Verify the robustness of instrumentation in actual Mixed Phase/Glaciated flight conditions, using already-funded research aircraft programs to test instrumentation in advance of a future dedicated Appendix D flight characterization program.
Organization: Environment Canada, NASA, FAA

2.2.1.2. NASA Glenn S3 Aircraft Flights
Objective: Obtain or expand a limited initial data set in advance of a dedicated flight test program, , and do initial full flight program testing of instrumentation and test methodologies under a real Appendix D environment
Organization: NASA, Environment Canada

2.2.1.3. NASA Glenn S3 Aircraft Flights – Dedicated Appendix D Flight Testing

Objective: Obtain and compile the required data sets to characterize the Mixed Phase/Glaciated icing environment.
Organization: NASA, Environment Canada

2.3.1. Cloud Resolving Model

This task will expand the effective data set through use of cloud resolving model, and evaluate the use of models to predict regions of hazard to engines. (Note. A cloud resolving model (CRM) is a numerical model that resolves cloud-scale (and mesoscale) circulations in either two or three spatial dimensions, and attempts to mathematically simulate cloud microphysical properties such as TWC. CRM's have been widely used in cloud system research to investigate the formation, maintenance, structure, and dissipation of cloud systems.)

2.3.1.1. Partner Selection
Objective: Establish working relationship with organization having the required cloud resolving model expertise.
Organization: Environment Canada, FAA

2.3.1.2. Modeling of existing engine data base events
Objective: Make use of cloud resolving model to derive initial cloud TWC statistics, and compare to statistical results from the McNaughtan data set.
Organization: FAA, Environment Canada, TBD

2.3.1.3. Modeling validation during the Flight Test Data Program during Appendix D flight program
Objective: Make use of cloud resolving model to make simulations of clouds that are part of the Appendix D field program. Use airborne data to validate model. Compare statistics from airborne program to those from same CRM simulations.
Organization: FAA, Environment Canada, TBD

2.3.1.4 Further Expansion of Flight test Data Set
Objective: If flight program and CRM statistics compare favorably, to expand the Appendix D flight program statistics to further cases, other locations and seasons using CRM simulations.
Organization: FAA, Environment Canada, TBD

2.4.1. Appendix D Revision

This task utilizes the data gathered during flight testing and supplemented with the cloud resolving model to revise Appendix D.

2.4.1.1. Data Analysis
Objective: Compile the flight data in a form suitable for comparison with Appendix D.
Organization: FAA, Environment Canada, TBD

2.4.1.2. Reporting
Objective: Document the Mixed Phase/Glaciated icing environment from the data analysis and recommend necessary revisions to Appendix D
Organization: FAA, Environment Canada, TBD

Task 3. - Experimental testing in support of ice accretion model development and validation for high ice water content environments.

This task is focused on developing ice accretion analysis tools for the Mixed Phase/Glaciated icing environment. It builds upon insight gained from preliminary modeling studies done under the guidance of the IPHWG. This modeling effort made use of a "first generation" code (TSIICE) that was assembled for the purpose of assessing requirements for engine certification rule changes. *It should be emphasized that this task is not focused on the development of that particular code.* Rather, it is intended to provide data and other information for engine manufacturers in their efforts to construct the necessary ice accretion models for certification of new engines in Mixed Phase/Glaciated icing conditions.

3.1.1. Initial Modeling Assessment of Mixed Phase/Glaciated Ice Accretion

Initial modeling has been conducted in support of the IPHWG/EHWG, and is embodied in the engine icing analysis code TSIICE. This code was previously validated for engine ice accretion analysis associated with supercooled liquid water droplets. It was modified during the IPHWG/EHWG rule making study effort to gain insight into the requirements for modeling ice accretion in a Mixed Phase/Glaciated icing convective storm cloud environment. Modifications included the incorporation of preliminary modeling of the contribution of ice particles to the thermodynamics of the ice accretion process on engine airfoils, of melting of ice crystals and their subsequent splashing/sticking interaction with wetted surfaces of engine airfoils, comparison with mixed phase testing conducted in the NRC and Cox icing wind tunnels. In addition, both internal and external documentation of the code and a user interface were developed. (References 50,51)

3.2.1. Component Test Requirements

This task is to describe component testing for the evaluation of the elements of ice accretion required for the analysis of an engine in a Mixed Phase/Glaciated environment. NASA Glenn must be a partner in this work, since the use of their imaging equipment will be crucial to getting the needed data. Also, the involvement of MSC will probably be needed for the measurement of the environment of the test.

3.2.1.1. Ice Crystal Melting
Objective: Evaluate the melting process associated with interaction of ice crystals with a warm surface, including effects of ice crystal size and velocity.
Organization: FAA, NASA Glenn, MSC, Cox & Co. Inc or TBD

3.2.1.2. Ice Crystal Splashing/Sticking
Objective: Evaluate the ice crystal splashing of liquid and sticking to wetted surfaces for a range of icing tunnel temperature and velocity. Focus on the net mass of water remaining on the surface for potential ice accretion.
Organization: FAA, NASA Glenn, MSC, Cox & Co. Inc or TBD

3.2.1.3. Ice Crystal Erosion Characteristics
Objective: Evaluate the contribution of ice crystal erosion of accreted ice in the determination of resultant ice accretion mass.
Organization: FAA, NASA Glenn, MSC, Cox & Co. Inc or TBD

3.2.1.4. Ice Shedding Characteristics of Mixed Phase/Glaciated Ice Accretion
Objective: Evaluate any effect of ice crystals on the adhesion properties of accreted ice.
Organization: FAA, NASA Glenn, MSC, Cox & Co. Inc or TBD

3.3.1. Airfoil Cascade Evaluation of Mixed Phase/Glaciated Ice Accretion

The purpose of this task is to evaluate ice accretion on a cascade of representative size engine airfoils at conditions similar to those within an engine. NASA Glenn must be a partner in this work, since the use of their imaging equipment will be crucial to getting the needed data. Also, the involvement of MSC will probably be needed for the measurement of the environment of the test.

3.3.1.1. Mixed Phase Testing
Objective: Evaluate the ice accretion for a range of LWC and TWC to establish data base for model validation
Organization: FAA, NASA Glenn, MSC, Cox & Co. Inc or TBD

3.3.1.2. Ice Crystal Testing with Warm Surface
Objective: Evaluate the ice accretion resulting from a fully glaciated (no LWC) environment that becomes partially melted by contact with warm surface forward of the cascade, again to provide a data base for model evaluation.
Organization: FAA, NASA Glenn, MSC, Cox & Co. Inc or TBD

3.3.1.3. Mixed Phase/Glaciated Testing in Warm Environment
Objective: Evaluate the ice accretion resulting from the introduction of pre-formed ice crystals (e.g. from ice shaver) into a cascade (or series of cascades) with wind tunnel temperature similar to that of critical icing locations of an engine (70 – 90 deg F) operating in a Mixed Phase/Glaciated environment.
Organization: FAA, NASA Glenn, MSC, Cox & Co. Inc or TBD

3.4.1. Engine Icing Experience

The purpose of this task is to elicit any available information that can be determined and shared regarding engine ice accretion in a Mixed Phase/Glaciated environment.

3.4.1.1. Engine Manufacturer X Icing Experience
Objective: The voluntary sharing of information within the industry (potentially can be expedited by providing use of an engine icing analysis code as a means of protecting engine manufacturer proprietary tools.)
Organization: FAA, TBD Engine Manufacturer

3.4.1.2. Engine Manufacturer Y Icing Experience
Objective: The voluntary sharing of information within the industry (potentially can be expedited by providing use of an engine icing analysis code as a means of protecting engine manufacturer proprietary tools.)
Organization: FAA, TBD Engine Manufacturer

3.4.1.3. Engine Manufacturer Z Icing Experience
Objective: The voluntary sharing of information within the industry (potentially can be expedited by providing use of an engine icing analysis code as a means of protecting engine manufacturer proprietary tools.)
Organization: FAA, TBD Engine Manufacturer

3.5.1. Engine Validation Testing

The purpose of this task is to conduct a dedicated engine test program in a Mixed Phase/Glaciated environment to provide a data base for icing analysis validation.

3.5.1.1. Engine Test Planning
Objective: Lay out the necessary elements of the test plan, including schedule, instrumentation, pre-test modeling predictions and test plan review.
Organization: FAA, IPHWG

3.5.1.1 Engine Pre-Test Predictions
Objective: Forecast ice accretion characteristics and critical icing sites to assist in the test planning and location of instrumentation.
Organization: FAA, TBD

3.5.1.2 Engine Test Plan Review
Objective: Industry review of the test plan.
Organization: FAA, IPHWG

3.5.1.3 Engine Test Instrumentation
Objective: Provide the necessary instrumentation to monitor icing conditions and to view ice accretion at various sites within the engine.
Organization: FAA, MSC, TBD

3.5.1.4 Engine Test
Objective: Execute the test program.
Organization: FAA, TBD

3.5.1.4. Engine Test Report
Objective: Report the results of the test program, encompassing the data in digital form and a format mutually acceptable to the engine manufacturers.
Organization: FAA, IPHWG, TBD

3.6.1. Model Validation

The purpose of this task is to provide a summary document outlining the process for ice accretion model validation, including the various data bases derived from this task.

3.6.1.1. Model Validation Document
Objective: Publish summary document of results for use by engine manufacturers to validate mixed phase/glaciated icing models
Organization: FAA, IPHWG, TBD

Task 4. - Test Facilities Requirements for demonstrating engine compliance with Appendix D requirements.

This task is focused on defining the test facility requirements for creating the necessary Mixed Phase/Glaciated icing environment for demonstrating engine compliance with safe operation in FAR Part 33 Appendix D. It is anticipated that close coordination with NASA programs devoted to test facility requirements for SLD compliance testing will be mutually beneficial.

4.1.1. Ice Crystal Production
This task assesses the different means for producing ice crystals in an engine test facility.

4.1.1.1. Water Nozzles/Snow Guns
Objective: Assess the characteristics of ice crystals produced by water nozzles/snow guns and the facility requirements for achieving desired ice particle size, etc.
Organization: FAA, NRC, TBD

4.1.1.2. Ice Shavers
Objective: Assess the characteristics of ice crystals produced by ice shavers and the facility requirements for achieving desired ice particle volume flow rate
Organization: FAA, NRC, TBD

4.2.1. Ice Crystal Coalescence/Trajectory
This task is to investigate the coalescence and trajectory of ice crystals during engine compliance testing relative to the flight environment.

4.2.1.1. Ice Crystal Coalescence
Objective: Assess the coalescence process and ice crystal growth associated with water nozzles/snow guns and distance required for required ice crystal size
Organization: FAA, NRC, TBD

4.2.1.2. Trajectory Analysis
Objective: Assess the mass/surface area characteristics of ice crystals produced by water nozzles/snow guns and ice shavers relative to naturally occurring ice crystals and their effect on ice particle trajectory in flight and in the test facility environment.
Organization: FAA, NRC, TBD

4.3.1. Instrumentation
This task is to establish instrumentation for use during engine compliance testing

4.3.1.1. Ice “Cloud” Environment Measurement
Objective: Recommend selection of instrumentation for measuring the artificial ice crystal cloud in engine compliance testing
Organization: FAA, TBD

4.3.1.2. Ice Accretion Measurement

Objective: Recommend best types of instrumentation for measuring ice accretion at internal engine locations.
Organization: FAA, TBD

4.4.1. Altitude Effects

This task is to establish any special requirements for sea level engine compliance testing to account for altitude effects of the real icing environment.

4.4.1.1. Ice Accretion Analysis-Based Adjustments

Objective: Make use of validated ice accretion code modeling of sea level test environment in comparison with the flight environment to establish methodology for adjusting the compliance test conditions.
Organization: FAA, TBD

4.5.1. Ice Crystal Test Facility Requirements

This task is to document the test facility requirements for ice crystal testing.

4.5.1.1. Ice Crystal Requirements

Objective: Document the details necessary for assuring that artificially produced ice crystals are acceptable for compliance testing
Organization: FAA, TBD

4.5.1.2. Delivery System

Objective: Document the details of acceptable ice crystal delivery system characteristics
Organization: FAA, TBD

4.5.1.3. Instrumentation Requirements

Objective: Document requirements for instrumentation requirements for assessing icing conditions and ice accretion within engine
Organization: FAA, TBD

Appendix III. Schedule

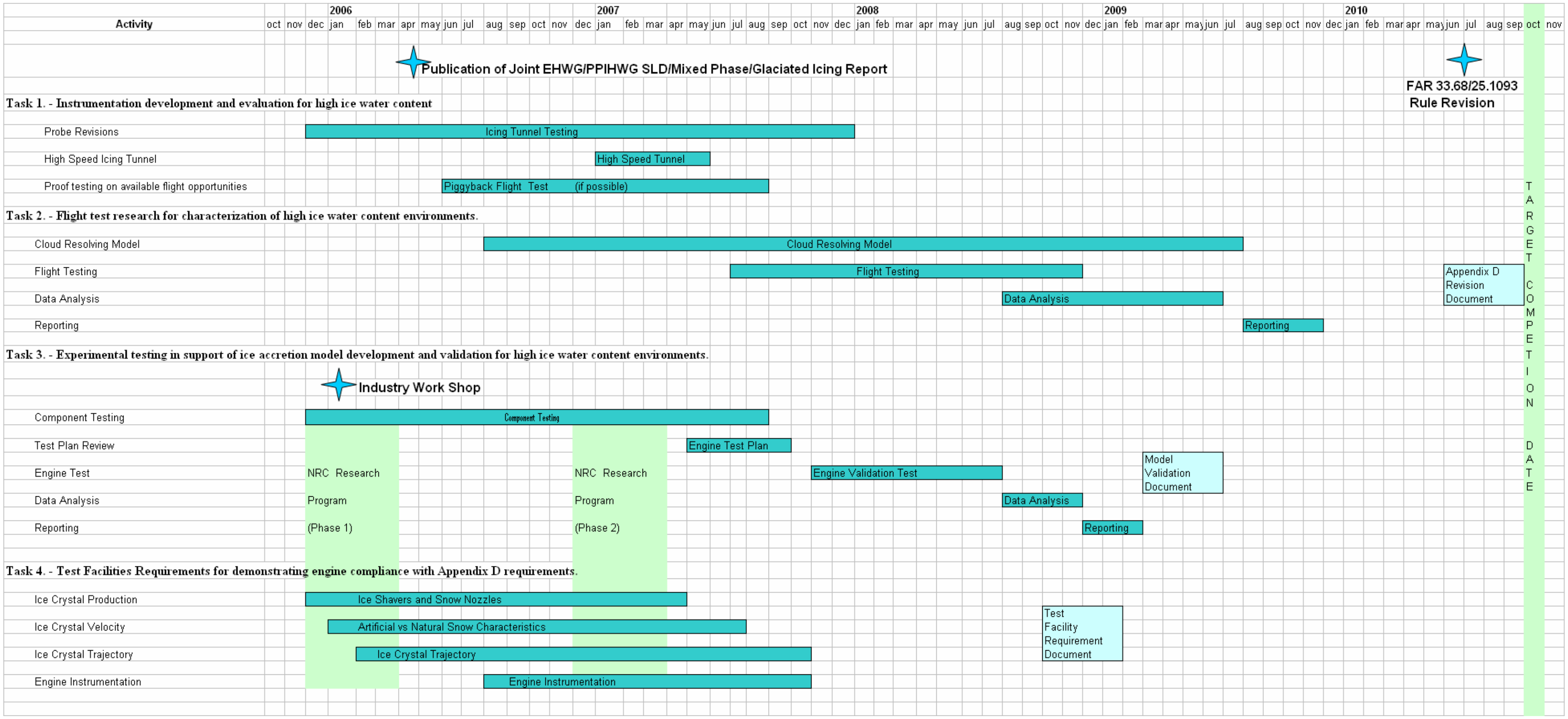
Required completion dates of the tasks:

Task 1 and 2 of this roadmap address the need to refine and validate the mixed phase/glaciated icing envelope currently depicted in the proposed Part 33.68 Appendix D. Task 3 and 4, on the other hand, address the methodology and means of demonstrating compliance to the new rule. Industry recommendations for the completion dates for these tasks are aligned with the time when these specific needs are required. It is recommended that Task 1 should be treated as a short term project with a goal of producing accurate ice crystal measurement devices in 2 to 3 years time. Task 2 should be treated as a long term continuous project aiming to produce an accurate representation of the mixed phase/glaciated icing envelope in 10 years. Task 3 and 4 are both short term projects. Task 3 should produce enough fundamental data to assist the analysis tool development by the time the proposed mixed phase/glaciated icing certification requirement becomes law. This is estimated to be approximately 3 years after the publication of the joint EHWG/PPIHWG SLD/Mixed Phase/Glaciated Icing report which is scheduled for the second quarter of 2006. The information generated in Task 3 could be used in comparative studies that the proposed rule allows in near term immediately after it becomes effective. Eventually the proposed rule requires engine testing which Task 4 addresses. Therefore, the completion date of Task 4 should not be longer than 5 years after the effective date of the new regulation.

Embedded Excel Workbook containing schedule appears below. A copy of the schedule is also provided on the following page.

C:\Documents and
Settings\Trebor Syste

This schedule reflects estimates of duration span of task activities and relative timing.



Appendix IV. Ice Crystal Research Program At NRC

Background

The Gas Turbine Laboratory at the National Research Council of Canada has historically performed icing certification testing on gas turbine engines since 1947. Starting in the late 1950's, the Laboratory began using ice crystal generating equipment to simulate conditions in high altitude clouds. The use of ice crystals as part of the gas turbine engine certification process continued for nearly twenty years until demand for ice crystals diminished and the equipment was eventually mothballed.

In 2004, NRC realized that there was renewed interest in ice crystal ingestion testing as part of changing certification requirements. A decision was made to resurrect the ice crystal generating equipment, and incorporate several improvements to automate the production and injection process and develop better measurement techniques.

In April 2005, a two-year project was approved to develop ice crystal generating capabilities and to address the following objectives:

a) investigate various methods of producing ice crystals, using shavers, crushers, spray nozzles, and natural snow,
b) determine the maximum realistic achievable concentrations for the airflow and feed rates for small and medium sized engines currently tested at NRC,
c) determine the best obtainable uniformity and particle size distribution,
d) compare the behavior of artificially created ice crystals to that of natural ice crystals or snow,
e) develop a fully operational system capable of performing an ice crystal certification test on a gas turbine engine up to the 10,000 pound thrust class.

Project Definition

During the two-year project, the objectives for the first year are to address the ice crystal production methods, evaluate the uniformity and distribution limits and compare the behavior characteristics of artificial versus natural crystals in one of the NRC icing tunnels.

In the first year of the project the first goal is to evaluate several methods for producing artificial ice crystals, such as shaving using various blade geometries, atomizing nozzles, and crushing devices. In addition, a method to produce natural crystals from natural snow will be investigated. The purpose of this exercise is to determine the types of ice crystal sizes and shapes that can be produced and their relationship to cutter shape, blade speed, feed rate, and ice and ambient temperature. For atomizing nozzles, the goal is to determine the maximum ice crystal size possible from a variety of different nozzle geometries.

The second goal is to evaluate the particle size distribution and uniformity across the tunnel cross-section for a variety of concentrations and velocities. An objective of this

test sequence will be to determine whether the larger ice crystals tend migrate to the bottom of the tunnel. Several mitigating solutions to prevent fall-out will be tested.
The third goal is to compare the behavior of the artificial crystals versus the natural crystals. This test will be carried out using a set of aerodynamically contoured shapes or passages placed in the ice crystal-seeded flow field, to compare the accumulation rates for the various types of crystals. The test shapes will accommodate a partial heating capability to determine at what temperature the crystals begin to melt and when a rapid buildup of crystals occurs. These tests will be performed over a variety of temperature conditions for both the ambient air and the ice crystals.

The second year of the project is designed to take the lessons learned from first year and apply them to a fully functional ice crystal generating system to feed the icing certification tunnel in NRC Test Cell #5, for testing turbofan engines up to 10,000 pounds of thrust.
The objectives in this phase of the project are to implement an automated feed system, entering the tunnel in the plane of the current icing spray nozzles, and to incorporate an on-line measurement system to determine ice crystal concentration and calibrate ice crystal size distribution. A demonstration engine will be setup to direct connect to the icing tunnel to determine system operability, and to investigate ice crystal melting phenomena.

Tunnel Facilities

To perform the ice crystal studies, NRC will use two non-recirculating icing tunnels. The first is a small pilot tunnel, which has two test sections, one with an 18 inch diameter and one with a 10 inch diameter. The velocity in the 10 inch section is 250 ft/s. The tunnel has a built-in axial drive fan, and plexiglass viewing windows. The tunnel is mounted on a trailer and is therefore completely portable, and is moved outdoors for testing. The second tunnel, located in Test Cell #5, has a 60 inch inlet with 48 spray nozzles, which converges down to a 33 inch test section with large Lexan viewing windows. The tunnel is driven by a compressed air ejector, capable of producing a test section velocity of approximately Mach 0.5.

Demonstration Engine

NRC has a 3000 pound thrust turbojet engine which will be instrumented to measure compressor stage temperatures and incorporate small viewing ports to monitor capture probes inserted into several compressor stages. The objective is to shed some light on the conditions that spawn rapid ice crystal build-up within the compressor.

Instrumentation

For the initial stages of the project, the objective is to investigate only qualitative and bulk properties of the ice crystal flow within the tunnels. For this purpose, oil slide techniques, and high-speed video equipment will be used. Ice mass injected, time and tunnel air flow rates will be measured. Through consultation with Environment Canada, it is hoped that specialized instrumentation can be borrowed or purchased to allow specific measurements of total ice water and mixed phase concentrations, as well as, ice particle sizing.

Reports

At least two separate reports will be published on the results of this two-year project. The first will describe the results of the initial component testing, comparing various methods of producing the ice crystals, and the differences between artificial and natural crystal behavior. The second will outline the results of the full scale ice crystal facility and the use of the demonstration engine to determine ice crystal behavior at different stages within the compressor.

Appendix V. NASA GRC Propulsion Systems Laboratory Proposal

This proposal is in the form of a presentation provided in the following file:

C:\Documents and
Settings\Trebor Syste

A hard copy of the file is also attached below.

Icing Capability Studies

for

NASA's
Propulsion Systems Laboratory (PSL)

PSL - Facility Capability

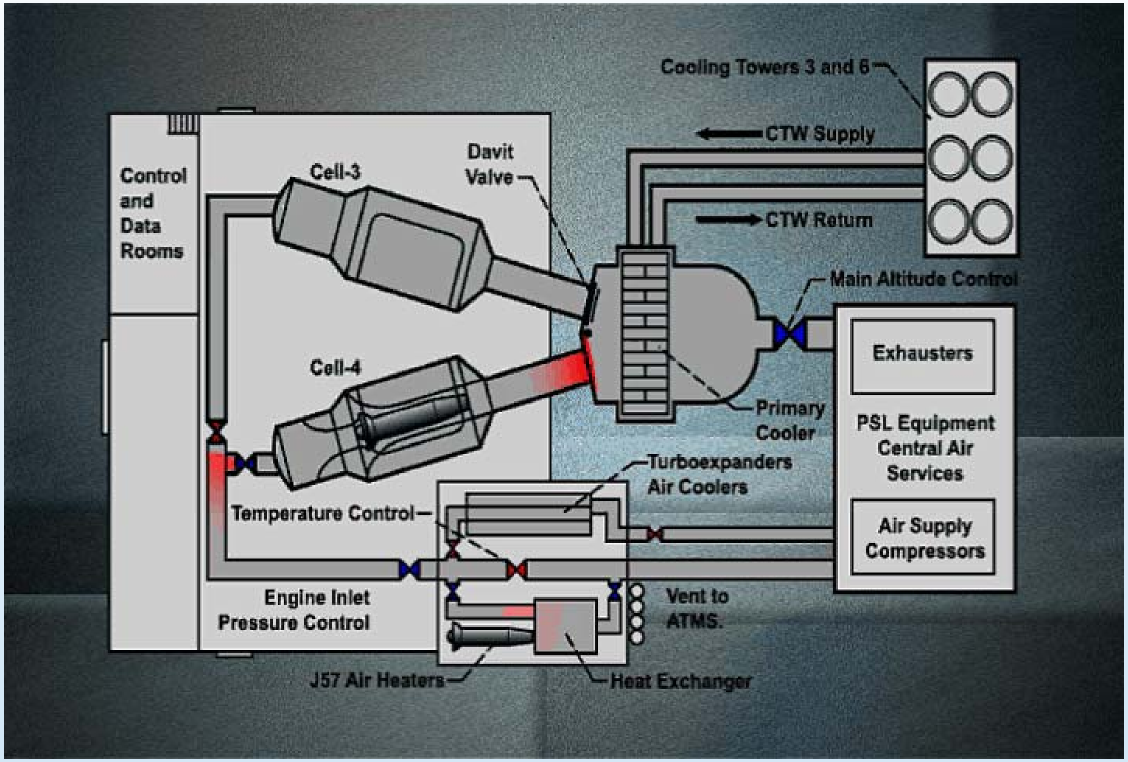
The Nation's Premier Direct Connect Altitude Simulation Facility for Full-Scale Gas Turbine Engine and Propulsion System Research

- **Two test sections share common inlet and exhaust**
- **Continuous Operation at high air flow rates**

  Altitude 90,000 ft (-90 deg F)

  PSL-3 Mach 3.0 (600 deg F)

  PSL-4 Mach 4.0 (1200 deg F)
- **Multi-axis thrust measurement**
- **Real time, high speed data acquisition and display**
- **Infrastructure for secure test requirement**



PSL - Facility Capability

NASA's only ground-based, full-scale engine test capability designed for research to provide detailed information on the performance and operability of engines and propulsion systems at extreme conditions over the entire flight envelope, which can only be obtained through altitude-simulated ground based testing.

Test Chamber Dimensions: **24 Feet Diameter, 38 Feet in Length**

Ambient Air
480 lbm/sec @ 55 psig
380 lbm/sec @ 150 psig
100 lbm/sec @ 450 psig

Vitiated Heated Air
50 lbm/sec @ 50 psig & 2670 deg F [Mach~6.0]

Cold Air
330 lbm/sec @ 10 psig & -40 deg F
30 lbm/sec @ 10 psig & -90 deg F

Non-vitiated Heated Air
39 lbm/sec @ 465 psia & 1200 deg F
(alternate conditions)
25 lbm/sec at 180 psia & 1375 deg F
10 lbm/sec at 425 psia & 1100 deg F
73 lbm/sec at 425 psia & 450 deg F

Altitude Exhaust Capabilities
Sea level @ 750 lbm/sec
90,000 ft @ 18 lbm/sec

PSL - Facility Support Systems

Support Services:

- GH2, two independent (manifolded) systems with 2.0 & 2.5 in. supply lines
- GO2 with 3.0 inch supply line
- Natural gas and Steam systems
- Two 25,000 gallons liquid fuel system with infrastructure for heating
- Hydraulic support systems (3000 – 5000 psig)
- 40, 150, & 450 psig continuous cooling air, 2400 psig single trailer system
- Two sources of cooling tower water, and potable water systems
- GN2 with .50 inch supply line

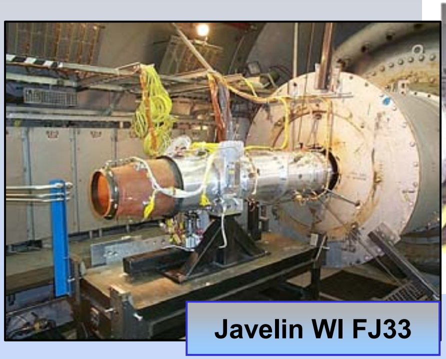
Measurement Systems:

- Six component thrust system: axial/lateral/vertical @ 50K lbf, 2oK lbf, and 30K lbf
- Infrared imaging system
- Schlieren system
- Gas sampling/measurement system

Data Acquisition/Recording/Display Systems:

- 1600 channels steady state data acquisition/display system
- 256 channels high speed digital data acquisition/display system
- 64 channel dynamic digital tape system (20k samples/sec/channel)
- 52 channel analog system

Commercial Development


Javelin WI FJ33


PW 545

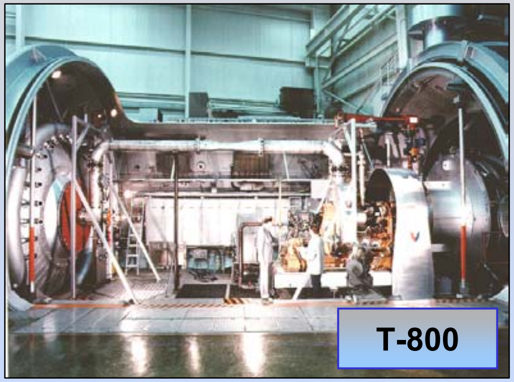
High Altitude Subsonic Performance

- Smaller turbofan engines
- Altitudes of 60K – 75K feet
- Unmanned aerial vehicles (UAV) and other special applications

Small Engines

- General Aviation and Business Jets
- 700 lbf thrust class engines

National Defense


T-800

Turbo shaft Engine Testing

- Performance and controls with power absorption
- Inlet Distortion (temp./pressure) caused by rotor downwash and munitions deployment
- **Joint Strike Fighter**
- Primary expertise in complex systems research
- Typical size 30K lbf thrust class, including F119 and F110 engine
- Nozzle-Engine Integration and Development

Recent Engine Icing Issues

- Ground simulation for new icing conditions regulations - the Aviation Rulemaking Advisory Committee (ARAC) tasked working groups to examine new certification requirements for SLD and mixed phase icing conditions
  - Ice Protection and Engine Harmonization Working Groups tasked to look at SLD and Mixed Phase icing conditions for airframe and propulsion systems
    - EHWG found mixed phase/glaciated ice (ice crystal) to be of concern to engine operations (series of recent events highlighted problem)
    - Need to develop means of compliance
- New R&D in engine CFD requires test and validation
- Engine manufacturers are closing their facilities and have expressed an interest in other engine icing facility options, especially for ice crystal testing

PSL - Icing Capability Study

- Motivation
  - NASA Glenn Research Center (GRC) is the agency's air-breathing propulsion center
  - Icing Branch researchers and Icing Research Tunnel operations engineers and technical staff represent world class experience in aircraft icing
  - PSL is uniquely suited to operate small and medium sized engines at varying altitudes and inlet conditions
  - GRC has the necessary, existing infrastructure to add icing conditions testing

PSL - Icing Capability Study

- Current Status (1/2)
  - In 1997, a preliminary concept was developed for an induction engine icing capability for PSL
    - 36” diameter exit nozzle, free-jet design
    - Nozzles based on IRT designs
    - Fully modular design
  - Current efforts focus on review of upcoming requirements and the development of the requirements for a new PSL system
    - Targeting basic certification requirements - Appendix C, Supercooled Large Droplet (SLD) - Appendix X, and ice crystal - Appendix D environmental conditions
    - Working with ARAC Harmonization Working Groups and industry to understand future needs

PSL - Icing Capability Study

- Current Status (2/2)
  - Over the last 1 1/2 years, an effort underway by NASA, MSC, FAA, NRC, and Cox & Co. to address:
    - Instrumentation development for ice particle water content measurement and particle sizing for use on research aircraft and in ground facilities
    - Ice particle ground simulation development with accurate, repeatable ice content
  - NASA recently initiated new task (Fall 2005) to review & update icing conditions test requirements for PSL
    - Facility icing performance requirements, including development of ice particle generation system

NASA has initiated a new Agency-wide aeronautics planning activity - working to coordinate facility enhancement strategies with new program requirements

PSL - Icing Capability Study

- Conclusion
  - NASA GRC anticipates the need for an altitude engine icing test capability
    - PSL is uniquely positioned to develop icing conditions simulation for propulsion system ground testing
    - A facility enhancement at PSL would be required
  - There is an opportunity for NASA to work with regulatory agencies, airframe and engine manufacturers, and other research organizations to develop and service future propulsion icing needs
    - Current effort to develop ground facility ice particle and mixed phase simulation capabilities and instrumentation for measuring these conditions is underway: NASA, FAA, Meteorological Service of Canada, National Research Council Canada, and Cox and Company, Inc.

Contact Information

Gary A. Klann
PSL Facility Manager
NASA Glenn Research Center
(216) 433 – 5715

gary.a.klann@grc.nasa.gov

http://facilities.grc.nasa.gov

Ice Particle Instrumentation & Testing

Instrumentation Performance Issues

- IWC measurement
- Ice particle measurement
- Ice erosion mitigation

Ice Water Content Measurement

Issue

- Existing TWC probes appear to under-estimate IWC

Resolution Strategy

- Test new and upgraded TWC probes in glaciated conditions
- Test alternate technologies such as airborne evaporators

Plan

- Current tests at Cox and IRT icing tunnels (May, Sept., & Nov. 2005, additional entries scheduled in both for 2006) characterize TWC probe and evaporator response
- Consider more test entries in Cox tunnel in 2006, to evaluate any instrument modifications identified in 2005 tests

Ice Particle Measurement

Issue

- S-3 operational speed beyond existing particle sizing probe speed limits (100 mps)
- Shattering of ice particles

Resolution Strategy

- Quantify limitations of operating existing probes at S-3 speeds
- Evaluate capability of newer probes (e.g.- mini-FSSP, SPEC 2DS)
- Evaluate probe modifications to mitigate shattering

Plan

- Determine if can extend existing probe(s) operational speed
- Test selected probes in IRT (Sept 2005, TBD 2006) to get initial assessment of airspeed response
- Test selected probes on NRC Convair (winter 2005-2006) in mixed phase conditions
- Test selected probes under controlled glaciated conditions in Cox tunnel (TBD 2006)

Ice Erosion Mitigation (for Ice Detection)

Issue

- Need proper functioning of ice detector to determine when super-cooled liquid present
- Ice particles will erode accreted ice on sensor adversely affecting detector operation

Resolution Strategy

- Consider developing a decelerator (Strapp concept)

Plan

- Define requirements
- Design & fab decelerator
- Test under controlled glaciated conditions (Cox, TBD 2006)
- Evaluate response and if necessary modify design
- Re-test under controlled glaciated conditions (Cox, TBD 2006)

Ground Facility Simulation

- Ice particle generation
- Cloud simulation methods
- Simulation issues

Ice Particle Generation

Working with Cox and Company, Inc. (Cox), history:

- Development of the mixed phase simulation in the Cox tunnel was initiated in 1997 to meet some customers requirements
- The developments were later funded by NASA Glenn through SBIR Phase-I and Phase-II:
  - Phase-I (Dec 1998 - June 1999)
  - Phase-II (Nov 1999 - Nov 2001)
- Cox continued to improve this simulation capability based on tunnel customers needs
- Cox was funded by NASA Glenn for indoor simulation of mixed-phase and snow icing conditions (1999-2001)
- Developments were conducted at Cox (static chamber and Icing Wind Tunnel):
  - Snow gun (air atomization of water particles)
  - Ice shaver (particles from frozen ice blocks)
- Snow gun tested in the NASA IRT (May 2001)
- Snow gun and ice shaver were tested and are in current use and continued development at the Cox icing wind tunnel

Slide information courtesy of Cox

Cloud Simulation Methods (1/3)

Development Work at Cox

Supercooled:
  - Tunnel base spray bars, NASA MOD-1 nozzles

- Glaciated:
  - Snow Gun:
    - Air assisted atomization and freeze-out of water particles
  - Ice Shaver
    - Mechanically shave frozen ice blocks

- Mixed:
  - Supercooled + Ice Shaver
  - Supercooled + Snow gun

Cloud Simulation Methods (2/3)

Development Work at Cox

Ice Shaver Particle Simulation - Current Design

- Up to about 4 lb/min of shaved ice
- 100% freezing fraction
- Maximum IWC = 2.2 g/m3@ 200 mph with a runtime of ~8 minutes (Cox TS-1)
- Ice coverage of approximately 18 x 24 inch ellipse in TS-1
- Mixed Phase possible by parallel super cooled spray
- MVD range: about 130 to 200 microns

Cloud Simulation Methods (3/3)

Development Work at Cox

Ice Shaver Particle Simulation - Large Capacity Design

- Currently in development
- Up to about 82 lb/minute of shaved ice
- Maximum IWC ≥11 g/m3 @ TAS = 200 mph (Cox Main Test Section; TS-1)
- Run time dependent on final feed mechanism
- Ice coverage of approximately 27 x 36 inch in TS-1

Simulation Issues

- Simulation fidelity
  - Document the ice particle characteristics (particle size, ice water content, uniformity, and repeatability)
  - Attempt to determine the true IWC in the Cox tunnel by doing a mass closure experiment knowing the ice ejected into the tunnel and the tunnel IWC plume profile
  - Confirm previous results, and get new results with an independent measurement (evaporator) as a sanity check
- Performance improvements
  - Attempt to work at lower IWC values; this will require working with the ice shaver, better control of ice shaver, and measurements of more ice shaver parameters.

Backup Slides

PSL - Cold Temperature Ops

GRC existing 10 psi refrigerated-air system at PSL

Turbo-expanders

- 3- units dedicated to PSL (TE 3, 4, 5)
- Installed in 1978; upgraded in 2003
- Dyno loaded; energy is dissipated to CTW
- Each delivers 133#/sec at -90 °F
- New unit in design; installation in FY06

Rotoflow Turbo-expander #3

Introduction To The SLD Technology Roadmap

Dean Miller
Mark Potapczuk

presented at the
SLD Engineering Tool Development Workshop
Wichita, Kansas
October 20, 2004

Outline

- Background
- SLD Technology Roadmap
- Evolution of SLD Engineering Tool Project Plan
- Summary Of SLD Engineering Tool Research
- Concluding Remarks

Why Develop SLD Engineering Tools?

- A draft regulation affecting aircraft operations in SLD icing conditions is expected to be released
- Aircraft manufacturers must be able to design for SLD icing conditions and provide “proof of performance” to certification authorities
- This requires the capability to simulate SLD icing conditions and have SLD engineering tools, analytical and experimental methods, that provide means of compliance (along with the possibility that natural icing flight testing may be required)
  - icing tunnels
  - icing tankers
  - analytical codes
- Current engineering tool capabilities are inadequate to support SLD certification

SLD Tool Development – International In Scope

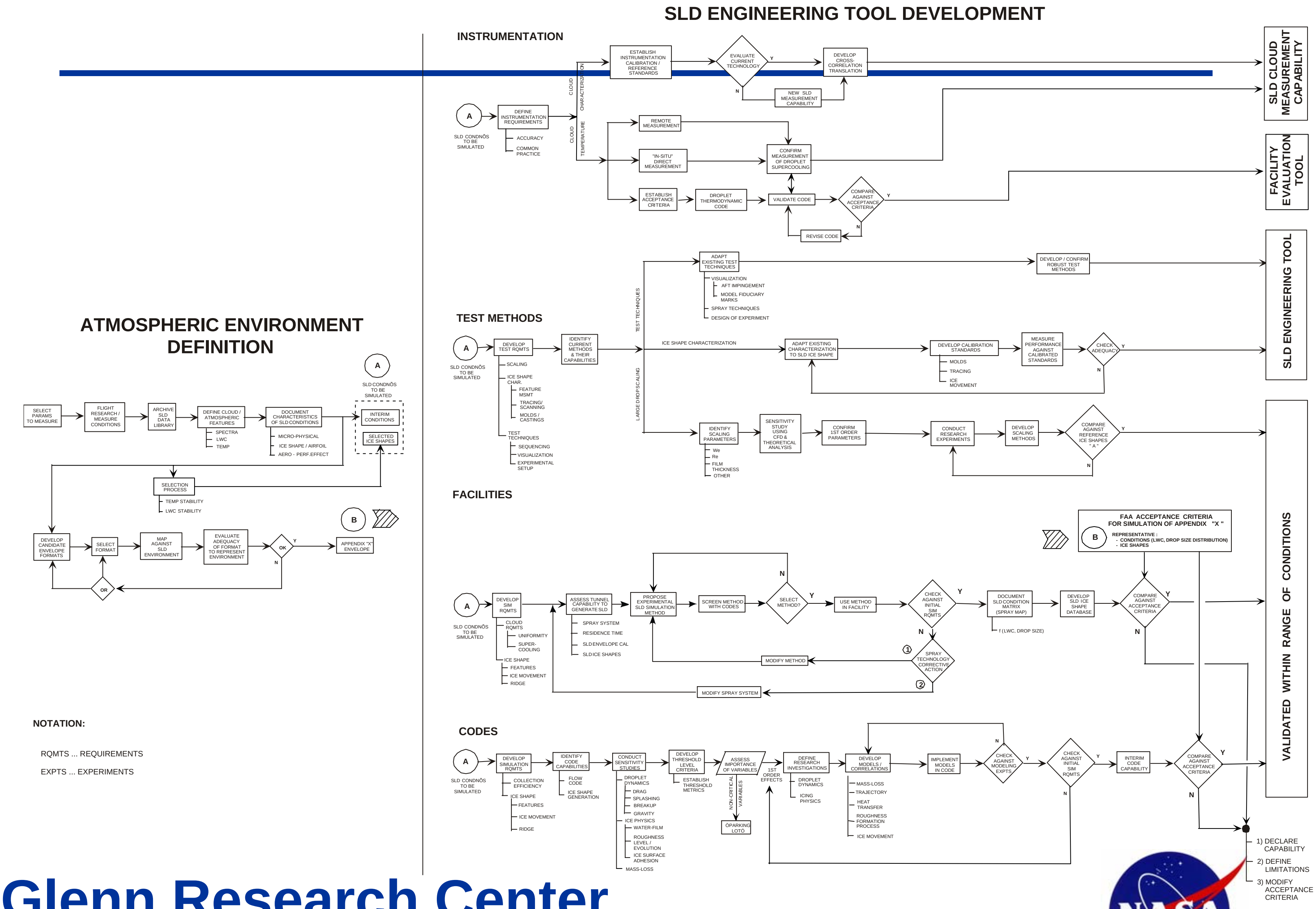
CePR (France)	**Research Organizations**
INTA (Spain)	
NASA (US)	
ONERA (France)	
QinetiQ (UK)	
CIRA (Italy)	
CAA (UK)	**Airworthiness Authorities**
FAA (US)	
Cranfield University (UK)	**Universities**
Univ. College Of London (UK)	
University Of Illinois (US)	
Wichita State University (US)	
BAE Systems (UK)	**Industry**
Airbus (UK)	
ATS (UK)	

- **An Ad Hoc group of international icing researchers formed a partnership to develop SLD engineering tools**
  - **Composed of national and private research organizations and academic institutions**
  - **The U.S., British, and French started collaborative discussions for partnering and have identified and implemented research tasks**
    - **Semi-annual meetings since 2000**
- **Group has expanded to include other organizations with expertise and resources**

SLD Technology Roadmap

- Development of SLD engineering tools was recognized to be a very complex effort
  - **Fundamental and applied research required**
  - **Many inter-related tasks (w/ time dependencies)**
  - **Different, but inter-connected technical elements**
- NASA and it's international partners developed an SLD Technology Roadmap
  - **To provide a comprehensive plan**
  - **Identify overall process for resolving issues**
  - **Identify inter-relationships between technical tasks**
  - **Provide a documented guideline for developing SLD tools**

SLD TECHNOLOGY ROADMAP



ATMOSPHERIC ENVIRONMENT DEFINITION

SELECT PARAMS TO MEASURE
FLIGHT RESEARCH / MEASURE CONDITIONS
ARCHIVE SLD DATA LIBRARY
DEFINE CLOUD / ATMOSPHERIC FEATURES
- SPECTRA
- LWC
- TEMP

DOCUMENT CHARACTERISTICS OF SLD CONDITIONS
- MICRO-PHYSICAL
- ICE SHAPE / AIRFOIL
- AERO - PERF.EFFECT

A
SLD CONDNÕS TO BE SIMULATED
INTERIM CONDITIONS
SELECTED ICE SHAPES
SELECTION PROCESS
- TEMP STABILITY
- LWC STABILITY

B
DEVELOP CANDIDATE ENVELOPE FORMATS
SELECT FORMAT
MAP AGAINST SLD ENVIRONMENT
EVALUATE ADEQUACY OF FORMAT TO REPRESENT ENVIRONMENT
OK
Y
N
OR
APPENDIX "X" ENVELOPE

SLD ENGINEERING TOOL DEVELOPMENT

INSTRUMENTATION

A
SLD CONDNÕS TO BE SIMULATED
DEFINE INSTRUMENTATION REQUIREMENTS
- ACCURACY
- COMMON PRACTICE

CLOUD CHARACTERIZATION
CLOUD TEMPERATURE
ESTABLISH INSTRUMENTATION CALIBRATION / REFERENCE STANDARDS
EVALUATE CURRENT TECHNOLOGY
Y
N
NEW SLD MEASUREMENT CAPABILITY
DEVELOP CROSS-CORRELATION TRANSLATION
REMOTE MEASUREMENT
"IN-SITU" DIRECT MEASUREMENT
CONFIRM MEASUREMENT OF DROPLET SUPERCOOLING
ESTABLISH ACCEPTANCE CRITERIA
DROPLET THERMODYNAMIC CODE
VALIDATE CODE
COMPARE AGAINST ACCEPTANCE CRITERIA
Y
N
REVISE CODE

SLD CLOUD MEASUREMENT CAPABILITY

FACILITY EVALUATION TOOL

TEST METHODS

A
SLD CONDNÕS TO BE SIMULATED
DEVELOP TEST RQMTS
- SCALING
- ICE SHAPE CHAR.
  - FEATURE MSMT
  - TRACING/ SCANNING
  - MOLDS / CASTINGS
- TEST TECHNIQUES
  - SEQUENCING
  - VISUALIZATION
  - EXPERIMENTAL SETUP

IDENTIFY CURRENT METHODS & THEIR CAPABILITIES
TEST TECHNIQUES
ADAPT EXISTING TEST TECHNIQUES
- VISUALIZATION
  - AFT IMPINGEMENT
  - MODEL FIDUCIARY MARKS
- SPRAY TECHNIQUES
- DESIGN OF EXPERIMENT

DEVELOP / CONFIRM ROBUST TEST METHODS
ICE SHAPE CHARACTERIZATION
ADAPT EXISTING CHARACTERIZATION TO SLD ICE SHAPE
DEVELOP CALIBRATION STANDARDS
- MOLDS
- TRACING
- ICE MOVEMENT

MEASURE PERFORMANCE AGAINST CALIBRATED STANDARDS
CHECK ADEQUACY
Y
N
LARGE DROP SCALING
IDENTIFY SCALING PARAMETERS
- We
- Re
- FILM THICKNESS
- OTHER

SENSITIVITY STUDY USING CFD & THEORETICAL ANALYSIS
CONFIRM 1ST ORDER PARAMETERS
CONDUCT RESEARCH EXPERIMENTS
DEVELOP SCALING METHODS
COMPARE AGAINST REFERENCE ICE SHAPES " A "
Y
N

SLD ENGINEERING TOOL

FACILITIES

A
SLD CONDNÕS TO BE SIMULATED
DEVELOP SIM RQMTS
- CLOUD RQMTS
  - UNIFORMITY
  - SUPER-COOLING
- ICE SHAPE
  - FEATURES
  - ICE MOVEMENT
  - RIDGE

ASSESS TUNNEL CAPABILITY TO GENERATE SLD
- SPRAY SYSTEM
- RESIDENCE TIME
- SLD ENVELOPE CAL
- SLD ICE SHAPES

PROPOSE EXPERIMENTAL SLD SIMULATION METHOD
SCREEN METHOD WITH CODES
SELECT METHOD?
Y
N
USE METHOD IN FACILITY
CHECK AGAINST INITIAL SIM RQMTS
Y
N
SPRAY TECHNOLOGY CORRECTIVE ACTION
①
②
MODIFY METHOD
MODIFY SPRAY SYSTEM
DOCUMENT SLD CONDITION MATRIX (SPRAY MAP)
- f (LWC, DROP SIZE)

DEVELOP SLD ICE SHAPE DATABASE
COMPARE AGAINST ACCEPTANCE CRITERIA
Y
N

B
FAA ACCEPTANCE CRITERIA FOR SIMULATION OF APPENDIX "X "
REPRESENTATIVE :
- **CONDITIONS (LWC, DROP SIZE DISTRIBUTION)**
- **ICE SHAPES**

VALIDATED WITHIN RANGE OF CONDITIONS

CODES

A
SLD CONDNÕS TO BE SIMULATED
DEVELOP SIMULATION RQMTS
- COLLECTION EFFICIENCY
- ICE SHAPE
  - FEATURES
  - ICE MOVEMENT
  - RIDGE

IDENTIFY CODE CAPABILITIES
- FLOW CODE
- ICE SHAPE GENERATION

CONDUCT SENSITIVITY STUDIES
- DROPLET DYNAMICS
  - DRAG
  - SPLASHING
  - BREAKUP
  - GRAVITY
- ICE PHYSICS
  - WATER-FILM
  - ROUGHNESS LEVEL / EVOLUTION
  - ICE SURFACE ADHESION
- MASS-LOSS

DEVELOP THRESHOLD LEVEL CRITERIA
- ESTABLISH THRESHOLD METRICS

ASSESS IMPORTANCE OF VARIABLES
NON-CRITICAL VARIABLES
ÒPARKING LOTÓ
1ST ORDER EFFECTS
DEFINE RESEARCH INVESTIGATIONS
- DROPLET DYNAMICS
- ICING PHYSICS

DEVELOP MODELS / CORRELATIONS
- MASS-LOSS
- TRAJECTORY
- HEAT TRANSFER
- ROUGHNESS FORMATION PROCESS
- ICE MOVEMENT

IMPLEMENT MODELS IN CODE
CHECK AGAINST MODELING EXPTS
Y
N
CHECK AGAINST INITIAL SIM RQMTS
Y
N
INTERIM CODE CAPABILITY
COMPARE AGAINST ACCEPTANCE CRITERIA
Y
N
- 1) DECLARE CAPABILITY
- 2) DEFINE LIMITATIONS
- 3) MODIFY ACCEPTANCE CRITERIA

NOTATION:

RQMTS ... REQUIREMENTS
EXPTS ... EXPERIMENTS

SLD Tool Project Plan Evolution

- It was desired to take the ideas embodied in the roadmap and turn them into a project plan that included the following elements
  - **Adjustments for priorities**
  - **Task identification**
  - **Resource identification**
  - **Milestones and deliverables**

- A draft SLD Engineering Tool Project Plan & WBS was developed and presented for comments to the FAA & international partners
  - **The draft SLD Tool Project Plan contained a Gantt chart (schedule / ROM resource allocation estimates)**
  - **The WBS associated with this Project Plan was a text document with a numerical index of tasks, each corresponding to tasks in the Project Plan**

SLD Tool Project Plan Evolution

- **The feedback from these meetings was as follows:**
  - The SLD Roadmap was comprehensive
  - To implement the entire Roadmap might extend beyond 2006
  - Some research tasks could be viewed as longer term objectives and of lower priority
  - Viewed from a certification perspective, some tasks were deemed higher priority than others

- **Ability to simulate SLD in facilities (tunnels, tankers)**
- **Ability to scale SLD conditions**

SLD Tool Project Plan Evolution

This review process led to modification of the draft project plan into the following 4 primary technical areas:

- **SLD Simulation Capability … simulate SLD conditions and generate SLD ice shapes with facilities and codes**
- **Scaling Capability … scale SLD icing conditions based on facility or test article constraints**
- **Instrumentation Capability … accurately measure SLD icing conditions**
- **Universal Methodology … translate SLD simulation methodologies developed using NASA IRT into a “generic” form which could potentially be adapted by other icing research facilities**

SLD Tool Project Plan Evolution

- In this form the project plan has undergone further review by
  - FAA/JAA/TC Technical Team
  - Ice Protection Harmonization Working Group
  - Aircraft Manufacturers in Wichita Kansas
- The SLD Engineering Tools Project Plan has been updated to the current version 1.0 based on comments received from these reviews
- In this form it has been used to guide the implementation of research tasks to support the development of SLD Engineering Tools

Project Plan WBS Primary Elements

1.0
Simulation

- **Reproduction of SLD conditions in facilities**
- **Generation of SLD ice shapes in facilities**
- **Prediction of ice shapes with codes**

2.0
Scaling

- **Scaling methods for use in SLD icing conditions**
  - testing subscale models
  - scale desired test conditions within facility capabilities

3.0
Instrumentation

- **Measurement capability to quantify attributes of SLD icing conditions**
  - cloud conditions
  - ice shape features

4.0
Universal Methodology

- **Capture technology / methods and document in form which can be customized for adaptation to other icing facilities and organizations**

Element 1: Simulation

SLD Requirements

1.1
Dev SLD Rqmts

1.2
SLD simulation With Tunnel

1.2.1 Reproducing SLD Condns — **1.2.2** Simulating SLD Ice Shapes — **1.2.3** Confirm Tunnel Simulation

1.3
SLD simulation With Codes

1.3.1 Icing Physics — **1.3.2** Impingement Limit — **1.3.3** Collection Efficiency — **1.3.4** Thermal Analysis — **1.3.5** Develop Models

1.4
SLD Simulation With Tankers

1.4.1 Reproducing SLD Condns — **1.4.2** Simulating SLD Ice Shapes — **1.4.3** Confirm Tanker Simulation

SLD Requirements

BACKGROUND

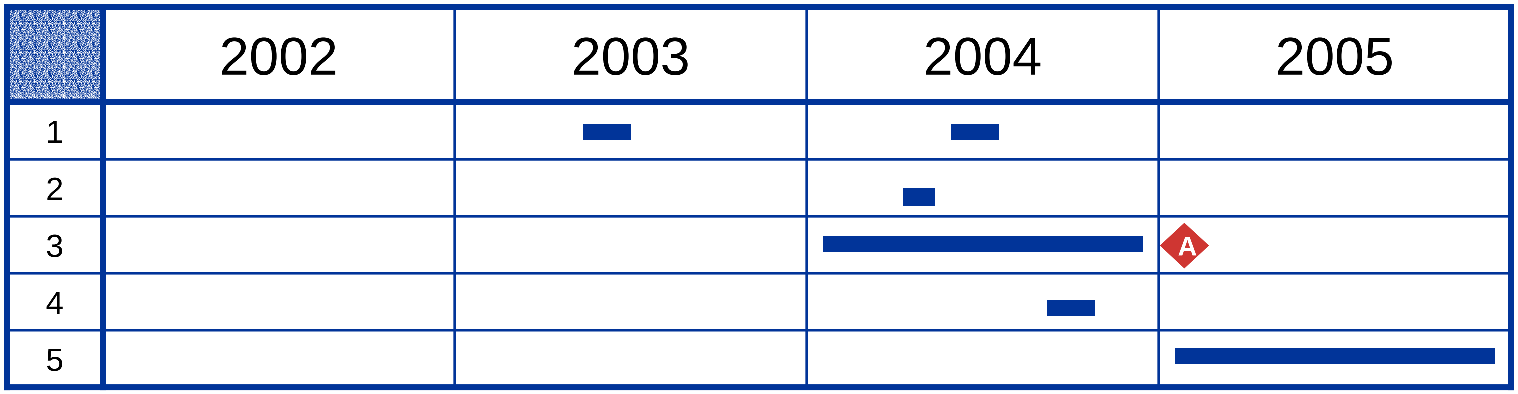
- Requirements (or metrics) need to be defined to provide a "target" for SLD simulation in quantified terms
  - essential features or characteristics need to be simulated
  - how accurately characteristics need to be simulated
- It is anticipated that these requirements would be developed by means of sensitivity studies, either experimental or computational
- Requirements would take into account recommendations from the IPHWG on Appendix SLD

OBJECTIVES:

- Identify the metrics that have to be met to assure adequate simulation of the SLD environment from an engineering perspective
- Provide assessment of how accurately these elements must be simulated

SLD Requirements

Goal – **Identify the metrics / accuracy that have to be met to assure adequate simulation of the SLD environment from an engineering perspective**



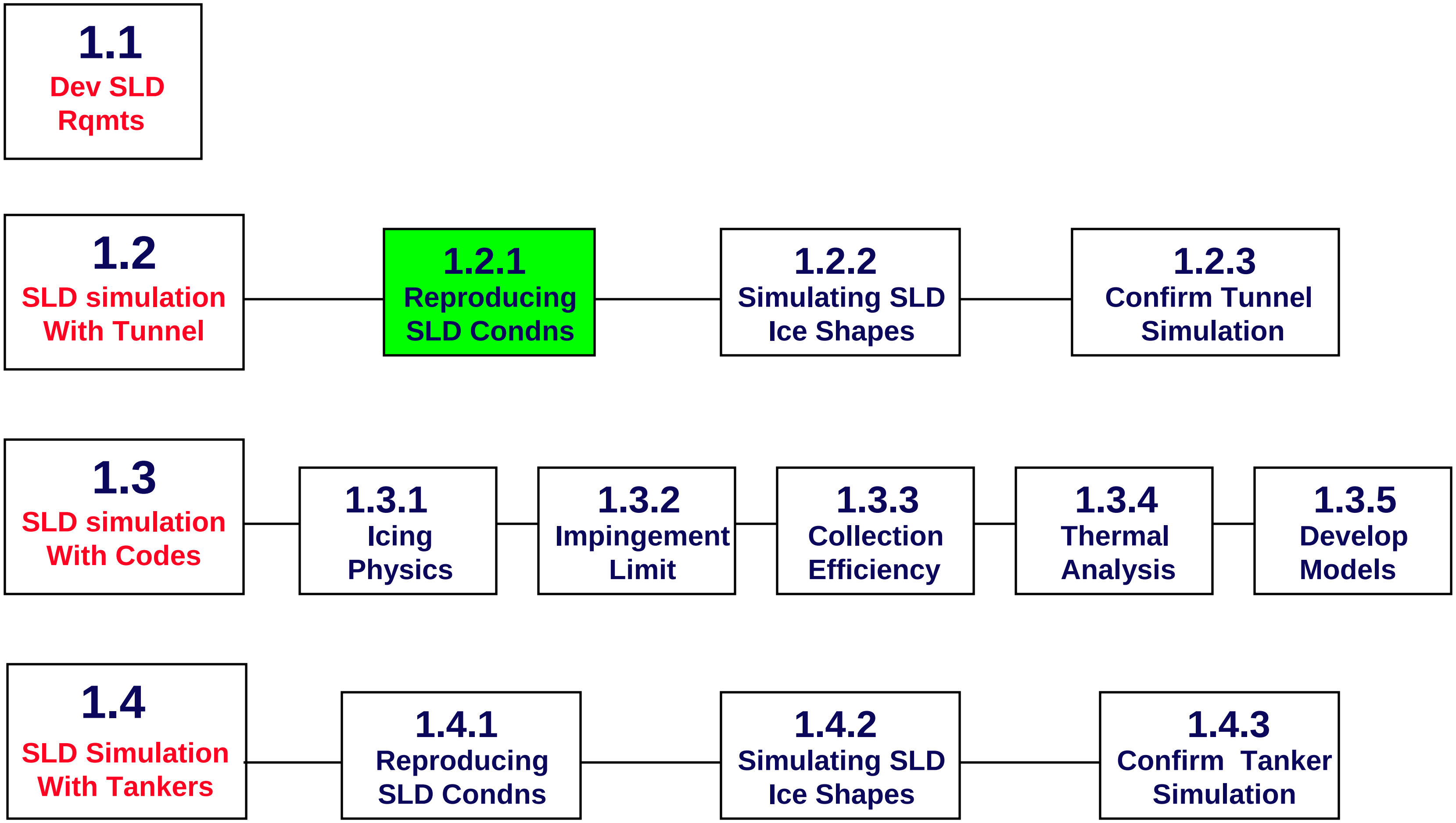
TASKS

- **1 – SLD sensitivity tests (LWC, MVD, temp)**
- **2 - SLD instrumentation workshop**
- **3 - Develop draft SLD rqmts doc**
- **4 - User feedback at SLD tools workshop**
- **5 - Update and refine SLD requirements**

MILESTONES

◆ A **Definition of SLD requirements (version 1)**

Reproducing SLD Conditions in the IRT



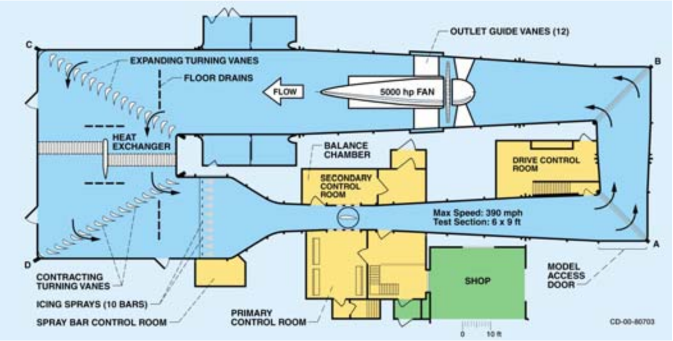
1.1 Dev SLD Rqmts

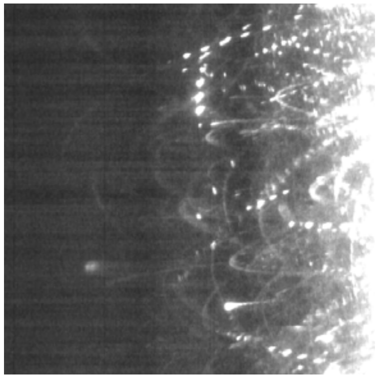
1.2 SLD simulation With Tunnel — **1.2.1** Reproducing SLD Condns — **1.2.2** Simulating SLD Ice Shapes — **1.2.3** Confirm Tunnel Simulation

1.3 SLD simulation With Codes — **1.3.1** Icing Physics — **1.3.2** Impingement Limit — **1.3.3** Collection Efficiency — **1.3.4** Thermal Analysis — **1.3.5** Develop Models

1.4 SLD Simulation With Tankers — **1.4.1** Reproducing SLD Condns — **1.4.2** Simulating SLD Ice Shapes — **1.4.3** Confirm Tanker Simulation

Reproducing SLD Conditions in the IRT



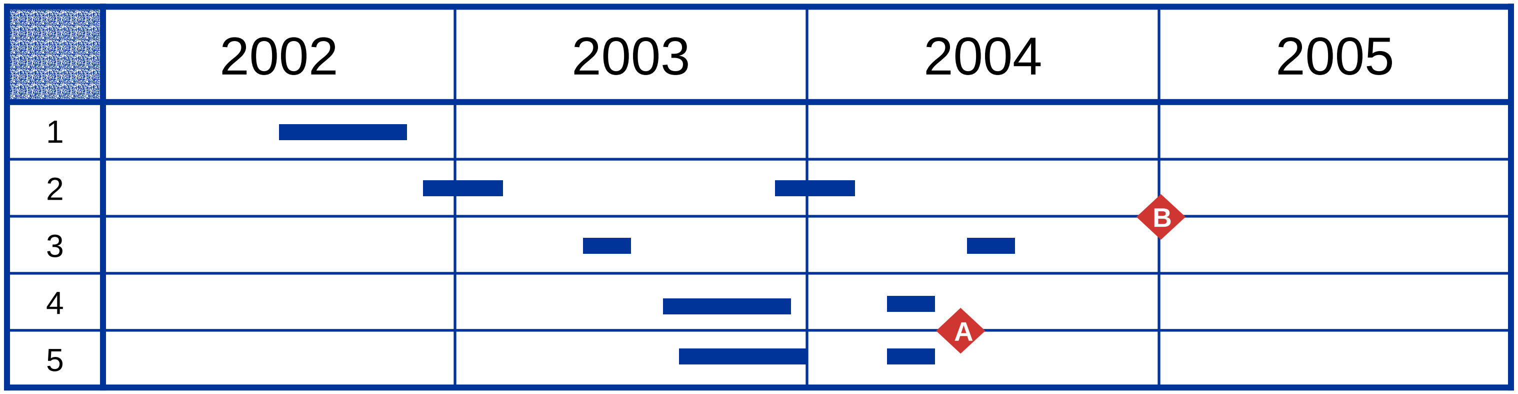


Background

- Determine the characteristics of SLD icing conditions that must be reproduced in a ground based icing facility.
- Identify the range of SLD conditions that can be produced using the current capabilities of the IRT.
- Develop methods for reproducing characteristics of in-flight SLD icing conditions that cannot be simulated currently.
- Document those characteristics that cannot be reproduced in the facility in its current configuration.

Reproducing SLD Conditions in the IRT

Goal - Develop methods for simulating natural SLD conditions in the IRT



Tasks

1 - Assess current capability to produce SLD

2 - Investigate and document constant or time varying icing conditions in natural SLD encounters

3 - Develop SLD cloud simulation method

4 - Document Range of LWC and MVD vs. Appendix X

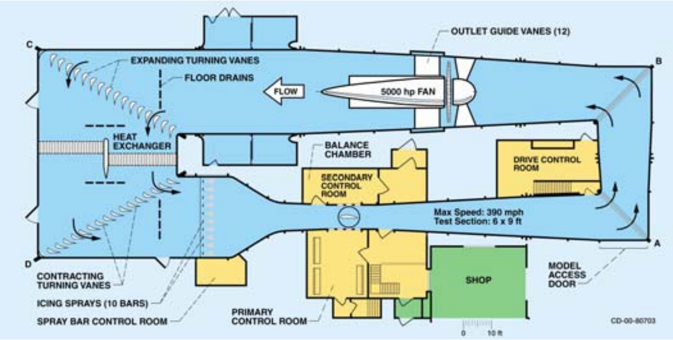
5 - Document drop size distribution vs. Appendix X

Milestones

A - IRT SLD conditions capabilities documented

B - Interim SLD simulation method available

Assess Current Capability to Produce SLD



Location: Glenn Research Center

Principle Investigator: Robert Ide

Objective:

- SLD Calibration of NASA Icing Research Tunnel

Status:

- Drop size calibration is complete MVD: 50 to 220 μm
- Have defined LWC/MVD for airspeeds of 100 to 250 knot
- LWC uniformity needs improvement for large MVD's
- Need to improve LWC measurement confidence
  - Currently using the icing blade for SLD LWC calibration

Develop SLD Cloud Simulation Method

Location: Glenn Research Center

Principle Investigators: Dean Miller, Mark Potapczuk, Robert Ide, & John Oldenburg

Objective:

- Attempt to generate a Bi-Modal SLD spray cloud in an icing tunnel

Approach:

- Sequentially spray a small drop (20 µm MVD) condition, then a large drop (130 µm MVD) condition
  - Maintain freezing fraction for both conditions
  - Vary order / time of spray conditions
  - Generate a "sequenced" ice shape
  - Document ice shape with ice tracings and photographs
- Compare "sequenced" SLD ice shape to ice shape generated from "non-sequenced" 20 µm MVD or 130 µm MVD icing spray

Status:

- Initial test completed, results being analyzed, further testing this summer

Simulating SLD Shapes in the IRT

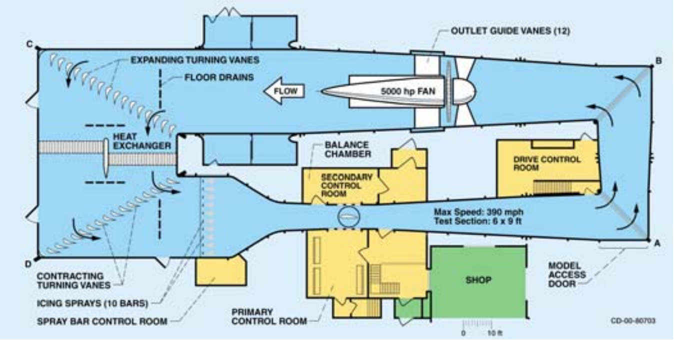
1.1 Dev SLD Rqmts

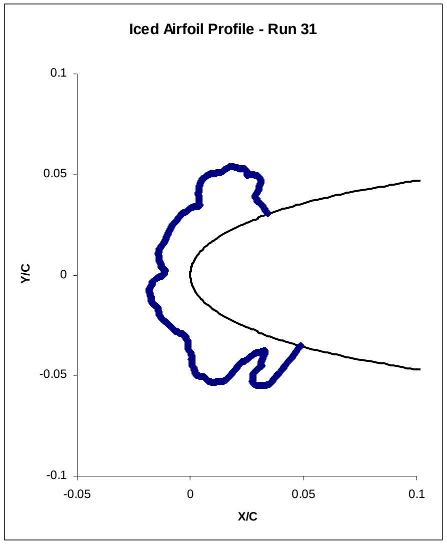
1.2 SLD simulation With Tunnel — **1.2.1** Reproducing SLD Condns — 🟩 **1.2.2** Simulating SLD Ice Shapes — **1.2.3** Confirm Tunnel Simulation

1.3 SLD simulation With Codes — **1.3.1** Icing Physics — **1.3.2** Impingement Limit — **1.3.3** Collection Efficiency — **1.3.4** Thermal Analysis — **1.3.5** Develop Models

1.4 SLD Simulation With Tankers — **1.4.1** Reproducing SLD Condns — **1.4.2** Simulating SLD Ice Shapes — **1.4.3** Confirm Tanker Simulation

Simulating SLD Shapes in the IRT



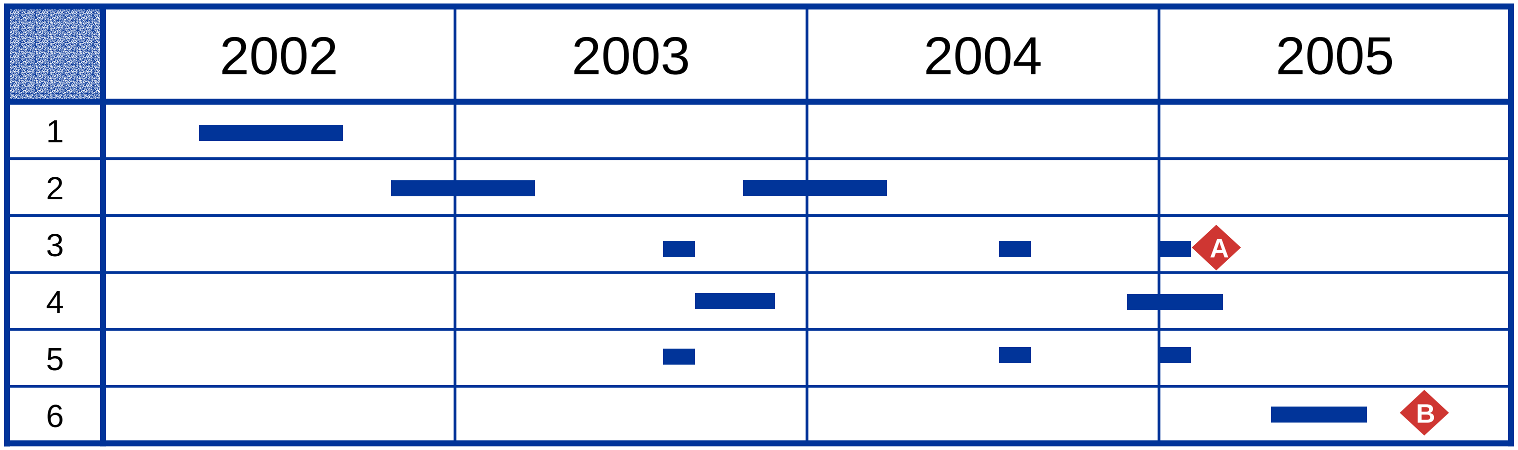


Background

- Develop test procedures for the IRT that create SLD ice shapes similar to those found in flight using the SLD icing cloud simulation methods developed in the previous section.
- Document these procedures for use in other facilities
- Develop a database of SLD ice shapes using these test procedures

Simulating SLD Shapes in the IRT

Goal - Develop methods for reproducing natural SLD ice shapes in the IRT



Tasks

1 - Assess existing natural SLD ice shape database

2 - Acquire new ice shape data

3 - Compile database of tunnel ice shapes

4 - Compare natural and tunnel ice shape databases

5 - Evaluate repeatability of facility for generation of SLD shape

6 - Confirm adequacy of Icing Wind Tunnel to simulate SLD environment

Milestones

A - Initial SLD ice shape database available

B - Interim SLD simulation capability available in IRT

Acquire Ice Shape Data

Location: Glenn Research Center
Principle Investigator: Tom Ratvasky

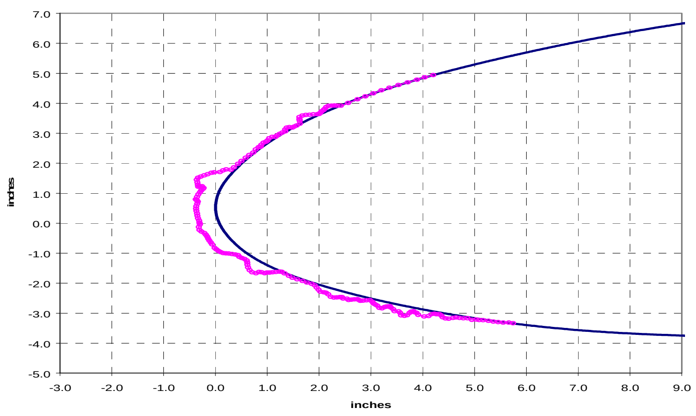
Objectives:

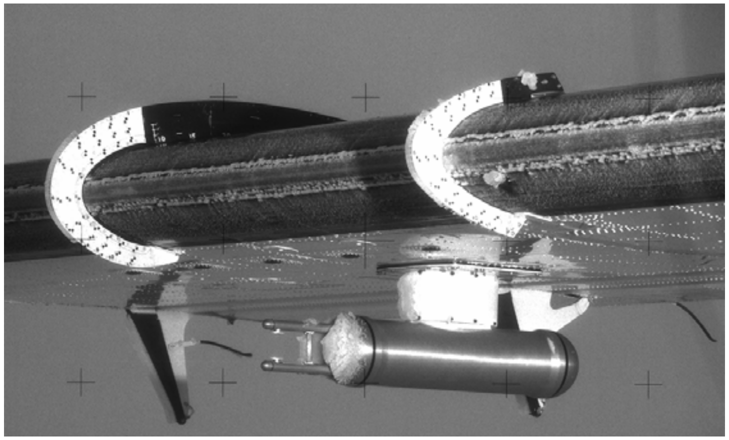
- Acquire additional SLD flight ice shapes, add to database
- Fly Twin Otter into SLD conditions
- Allow ice to build on wing, and photograph resulting ice accretion with stereo camera system

Status:

- Data analyzed from winter icing research flights, acquire more during winter of 2004-2005

Flight No.9768 ; Flight Date: 12/11/97; Time: 15:05:51; Span= 18





Compile Database of Tunnel Ice Shapes

Location: Glenn Research Center

Principle Investigators: Judy Van Zante

Objective:

- Create a database of ice shape profiles on several airfoil geometries for use in code validation

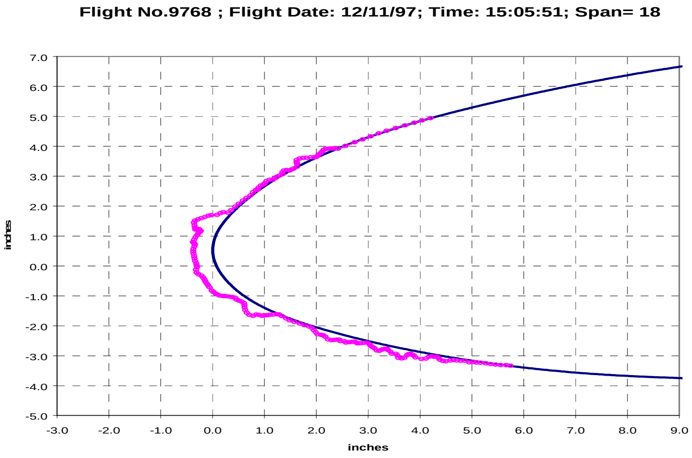
Approach:

- Use the SLD ice shape simulation method developed under this project
- Accumulate ice shape profile data, ice mass measurements, and 3D ice shape data
- Document results in a publicly available database

Status:

- Two test entries planned for Fall ’04 and Winter ’05

Compare Natural and Tunnel Ice Shape Databases



<u>Location:</u> Glenn Research Center

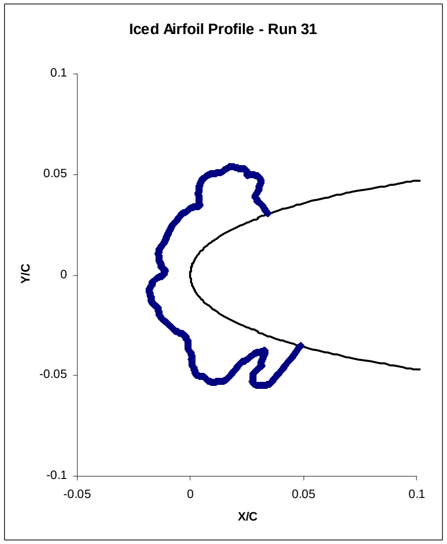
<u>Principle Investigators:</u> Mark Potapczuk and Dean Miller

<u>Objective:</u>

- **Compare ice shape data from in-flight with 'equivalent' tunnel ice shapes; identify areas of agreement and disagreement**

<u>Approach</u>:

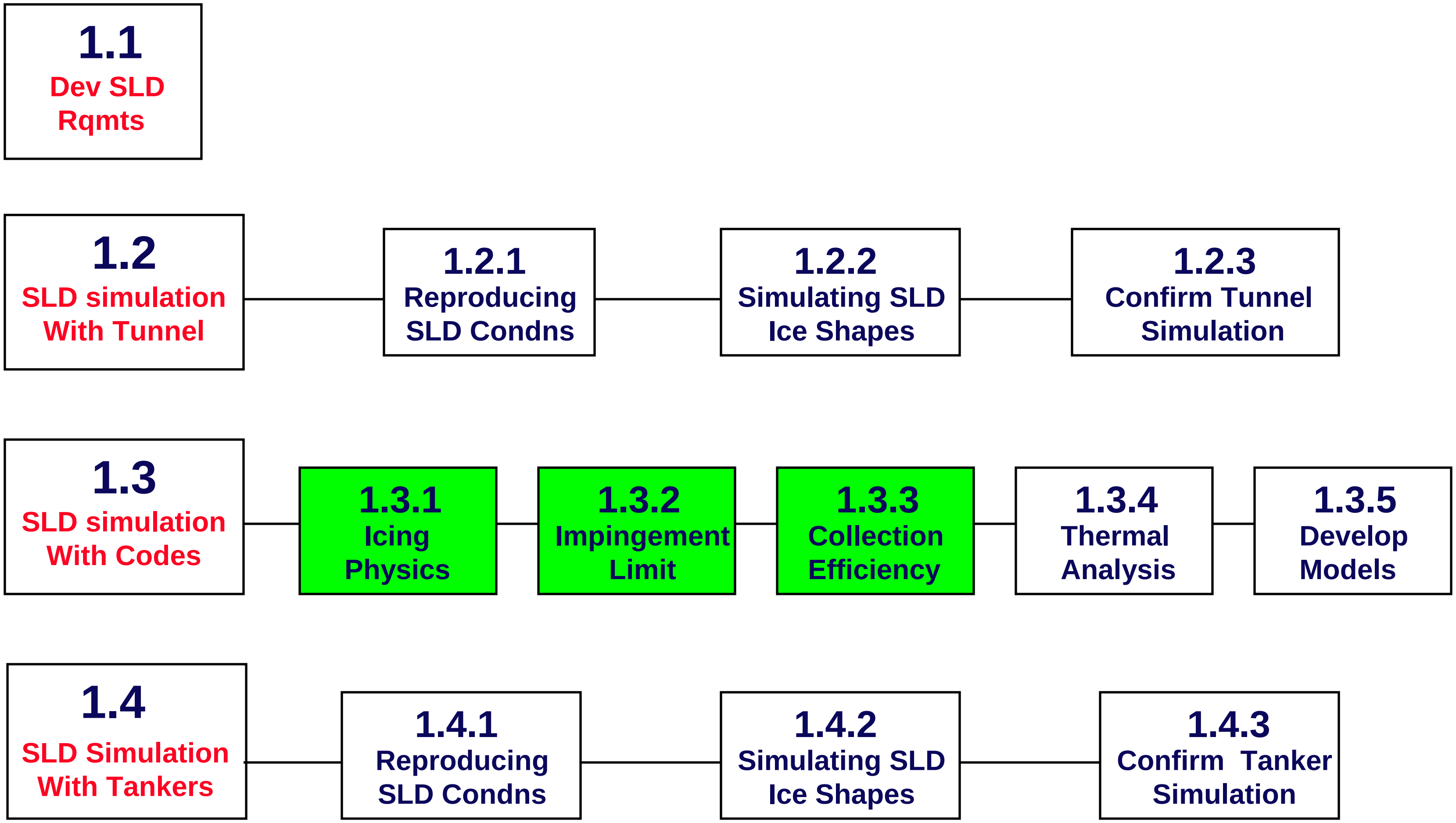
- **Compare tracings using measurements of ice shape area, ice horn location and size, thickness at stagnation point, etc.**
- **If sufficient data is available, identify cloud conditions least likely to be reproduced accurately in the tunnel**



<u>Status:</u>

- **Some flight test data available**
- **Tunnel data to be available by January '05**
- **Comparison measurement methods needed**

Simulating SLD Shapes in the IRT



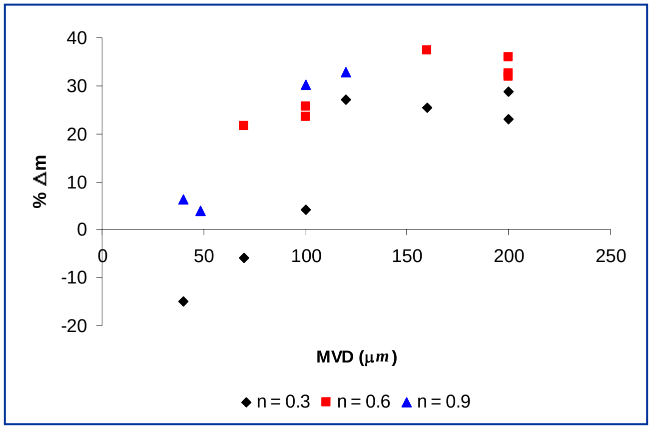
1.1 Dev SLD Rqmts

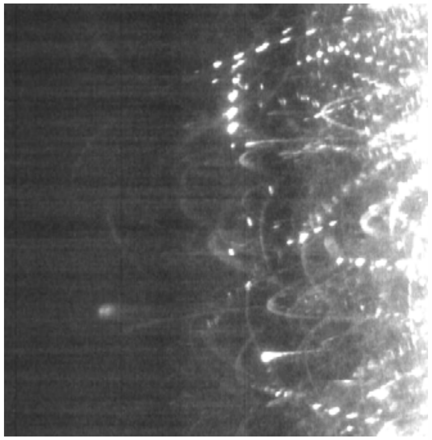
1.2 SLD simulation With Tunnel — **1.2.1** Reproducing SLD Condns — **1.2.2** Simulating SLD Ice Shapes — **1.2.3** Confirm Tunnel Simulation

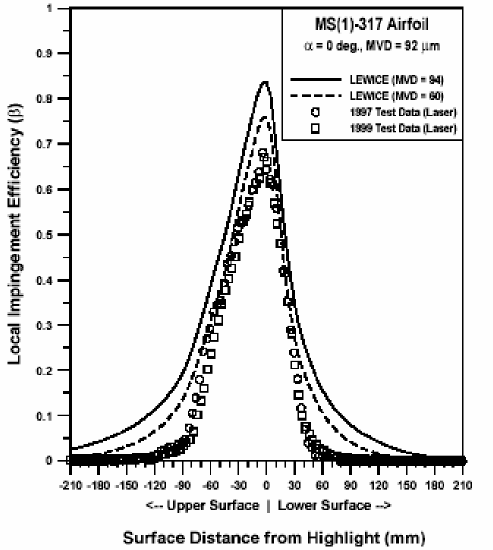
1.3 SLD simulation With Codes — 🟩 **1.3.1** Icing Physics — 🟩 **1.3.2** Impingement Limit — 🟩 **1.3.3** Collection Efficiency — **1.3.4** Thermal Analysis — **1.3.5** Develop Models

1.4 SLD Simulation With Tankers — **1.4.1** Reproducing SLD Condns — **1.4.2** Simulating SLD Ice Shapes — **1.4.3** Confirm Tanker Simulation

SLD Icing Physics





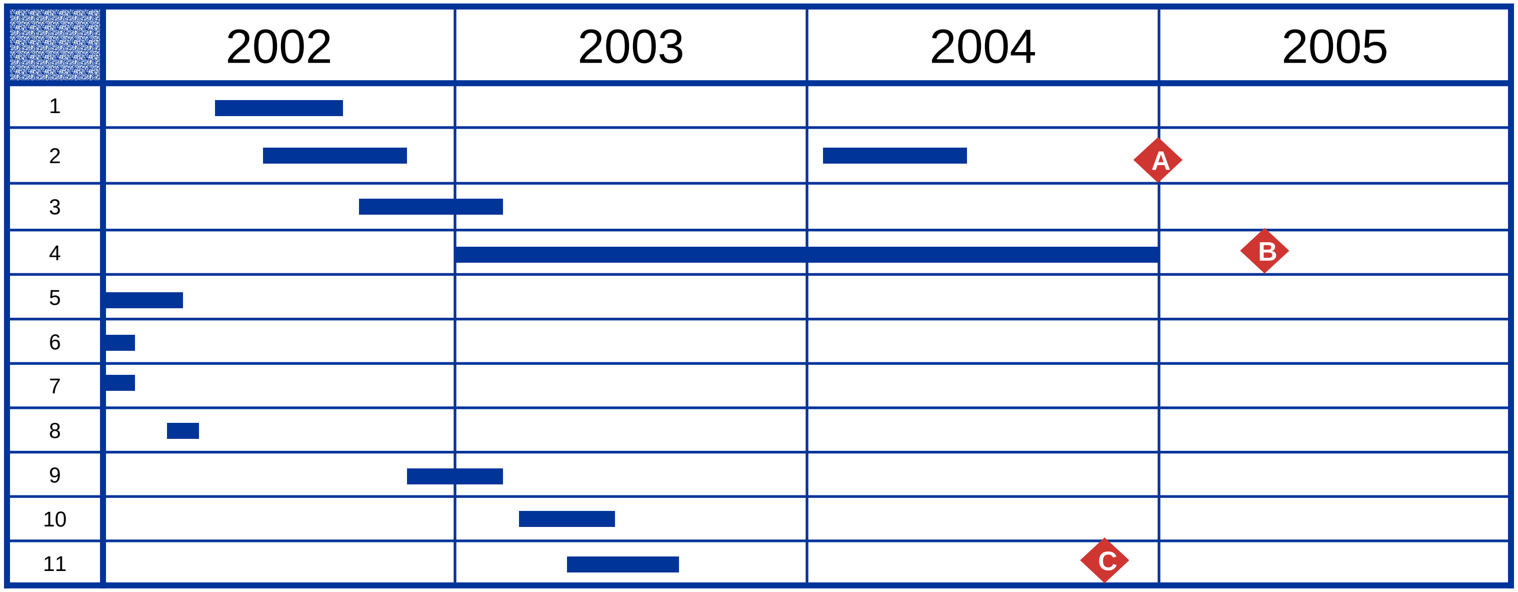


Background

Identify the physical processes of ice accretion that are impacted by the presence of super-cooled large droplets. Quantify the important physical characteristics of the identified processes. Develop a database of information for development of models to be used in simulation software.

SLD Icing Physics

Goal – Investigate and characterize the physical processes governing SLD accretion behavior



Tasks

1 - LEWICE simulation of droplet break-up

2 - WSU droplet break-up analysis

3 - NASA Droplet splashing experiment

4 - Cranfield droplet splashing contract

5 - Ice mass measurements on airfoils

6 - Water runback mass measurements

7 - Review previous ice sliding test efforts

8 - Assess need for further ice sliding work

9 - Influence of droplet splashing on β

10 - Clean geometry SLD β study

11 - SLD ice shape β study

Milestones

A - Understanding of droplet break-up

B - Understanding of droplet splashing

C - Collection efficiency database for code validation

LEWICE simulation of droplet break-up

Location: Glenn Research Center

Principle Investigators: William Wright

Objective

- Identify potential conditions that may lead to droplet break-up

Approach

- Use LEWICE to determine when the conditions for droplet break-up may be present for a typical airfoil

Status

- Calculations have been performed icing conditions that could lead to possible droplet break-up have been identified

WSU droplet break-up analysis

Location: Wichita State University

Principle Investigator: Jason Tan & Michael Papadakis

Objective:

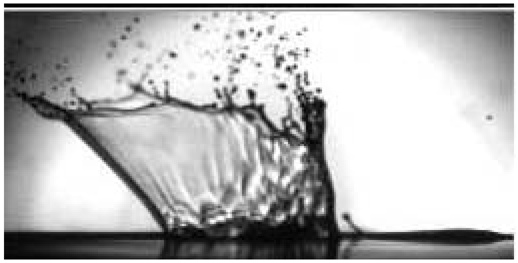
- Identify droplet dynamic issues relevant to SLD icing
  - Droplet deformation & breakup prior to impact
  - Droplet splash/deposition/bounce
  - Near-wall effects
  - Supercooling large droplets
  - LWC measurement of large MVD spray cloud

- AIAA paper # 2003-392

Cranfield Droplet Splashing Contract

Location - Cranfield University

Principle Investigators - David Hammond, NASA, WSU



Objective

- Characterize large droplet impact / splash
  - Quantify the incoming/splashed drop size, velocity, and angle
  - Measure the mass resulting from the splash process

Approach

- Use a low turbulence vertical tunnel to accelerate droplets of known size toward a target plate having a controlled water film
- Quantify drop size, velocity, angle of impact splash with high speed imaging methods
- Correlate droplet impact/splash parameters with mass splashed from target plate water film

Status

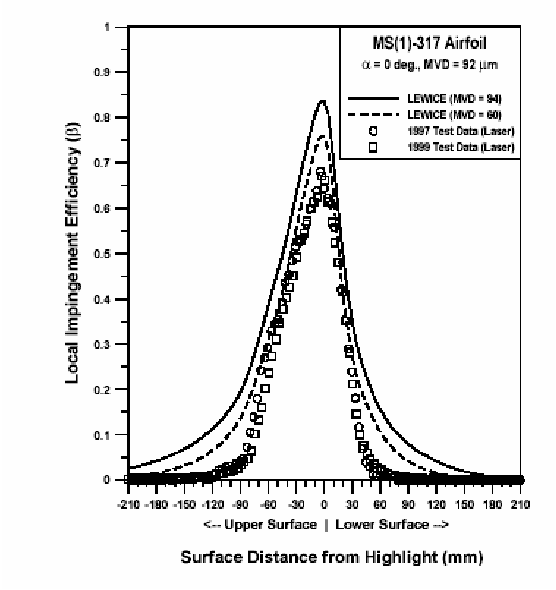
- First test completed in summer of 2004
- Data being analyzed for AIAA 2005 paper

Clean Geometry SLD β Study

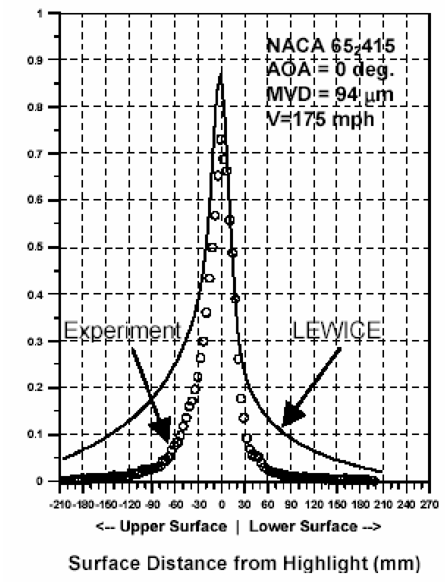
Location: NASA Glenn Icing Research Tunnel

Principle Investigator: Michael Papadakis

Objective: Measure collection efficiency in SLD



SLD impingement on an MS-317 airfoil (LEWICE vs. experiment)



SLD impingement on a NACA 65$_2$415 airfoil (LEWICE vs. experiment)

SLD Ice Shape β Study

Location: NASA Glenn Icing Research Tunnel (US)

Principle Investigator: Michael Papadakis

Objective:

Measure collection efficiency in airfoils with existing ice shapes

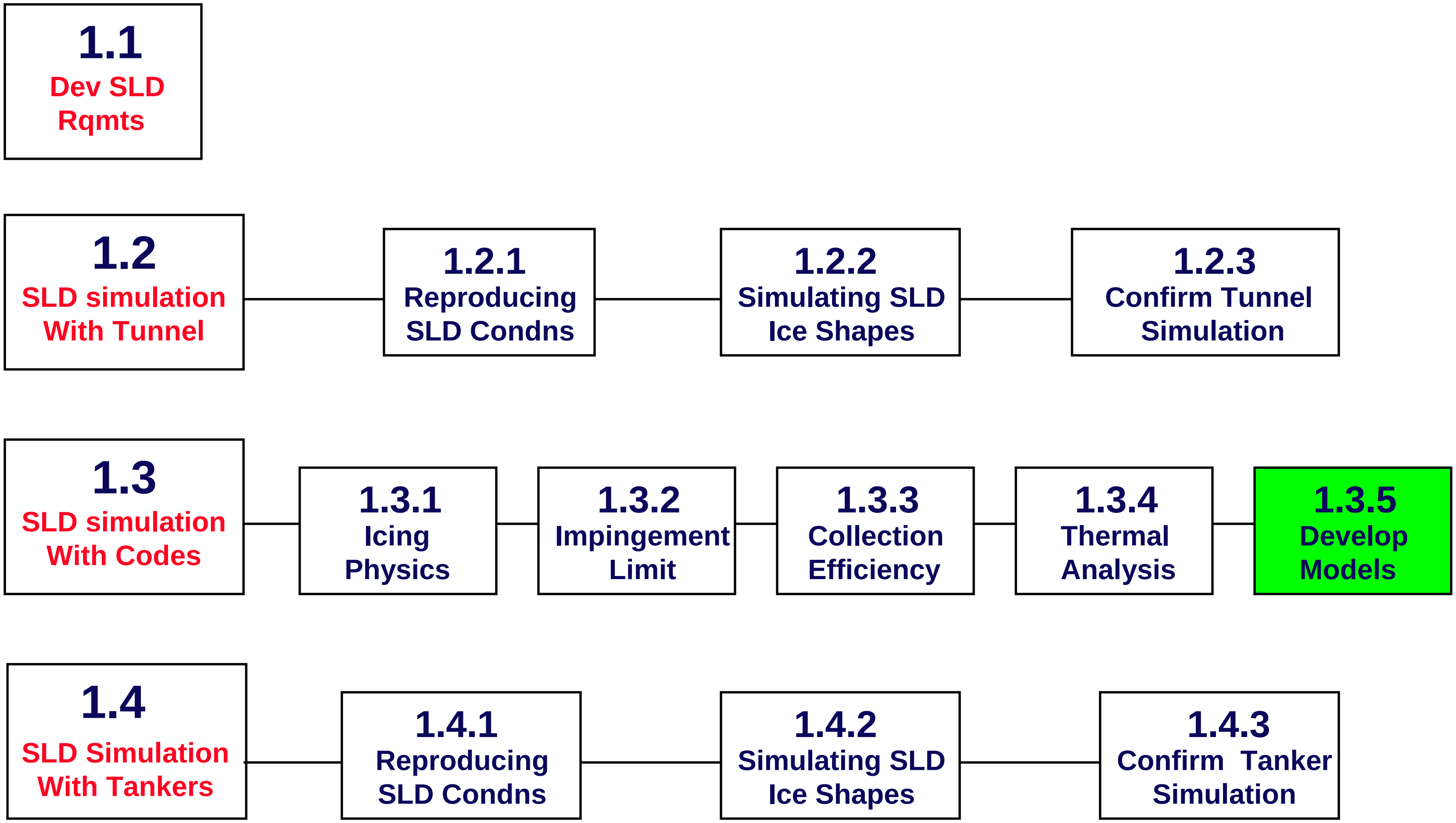
Approach:

Use existing blotter strip method for collection efficiency measurement on ice shape models

Status:

Initial testing completed. Report to become available soon

Develop SLD Models



1.1
Dev SLD Rqmts

1.2
SLD simulation With Tunnel

1.2.1
Reproducing SLD Condns

1.2.2
Simulating SLD Ice Shapes

1.2.3
Confirm Tunnel Simulation

1.3
SLD simulation With Codes

1.3.1
Icing Physics

1.3.2
Impingement Limit

1.3.3
Collection Efficiency

1.3.4
Thermal Analysis

1.3.5
Develop Models

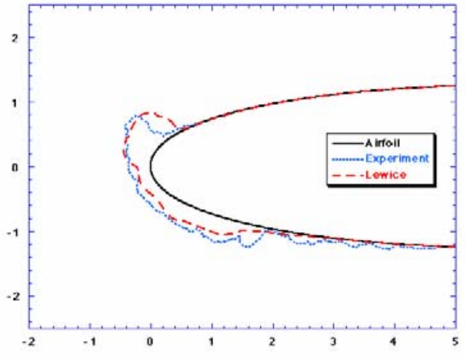
1.4
SLD Simulation With Tankers

1.4.1
Reproducing SLD Condns

1.4.2
Simulating SLD Ice Shapes

1.4.3
Confirm Tanker Simulation

Develop SLD Models

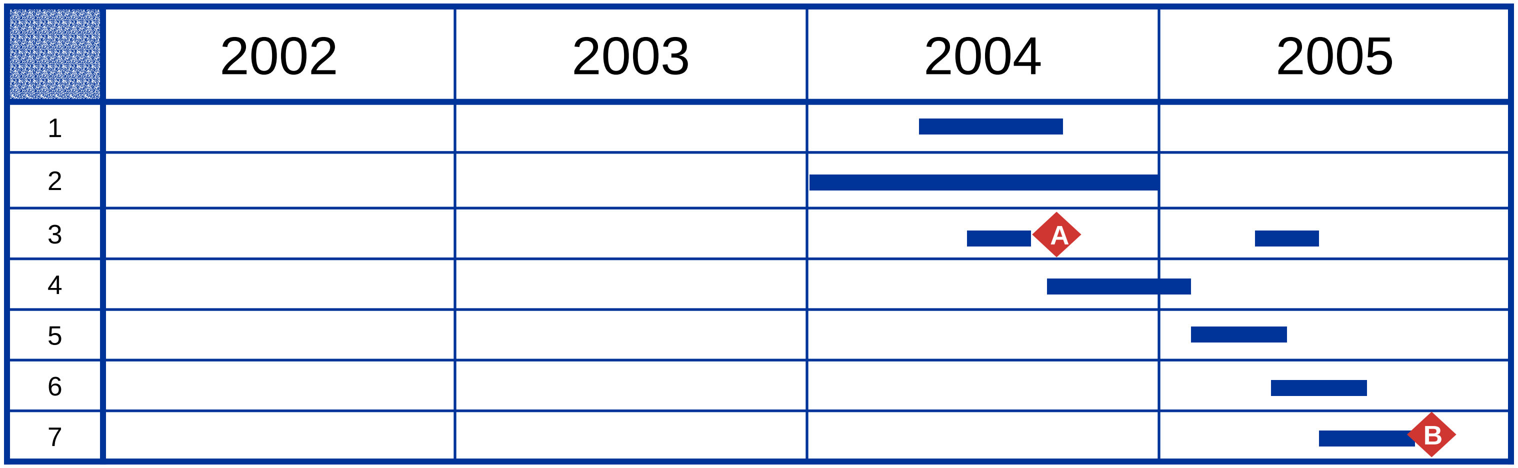


Background

Develop an interim model for SLD ice growth that can be added to LEWICE. Develop a framework for introduction of updated SLD icing physics into models as they become available.

Develop SLD Models

Goal - Develop an interim model for SLD ice growth that can be added to LEWICE



Tasks

1 - Develop droplet dynamics model

2 - Develop droplet splashing model

3 - Compare LEWICE model to mass loss data

4 - Development of a proposed SLD model

5 - Model implementation

6 - Validation testing

7 - Documentation

Milestones

A - Initial evaluation of LEWICE SLD capability

B - Interim SLD simulation capability available in LEWICE

Develop droplet dynamics model

Location: Glenn Research Center

Principle Investigator: William Wright

Objective

- **Allow SLD droplet break-up to influence ice shape development**

Approach

- **Incorporate droplet dynamics model into LEWICE and investigate influence on ice shape development**

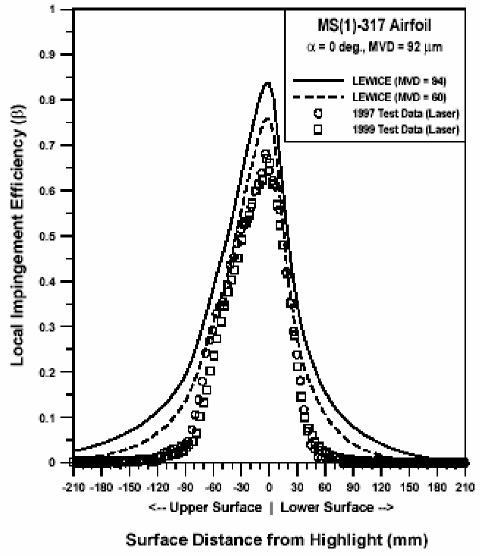
Status

- **Model has been incorporated into LEWICE 3.0**
- **Thorough testing of model needs to be conducted**
- **Upgrades to model can be included as more break-up testing and modeling is conducted**

Develop droplet splashing model

Location: Glenn Research Center

Principle Investigator: William Wright



Objective

- Allow SLD droplet splashing to influence ice shape development

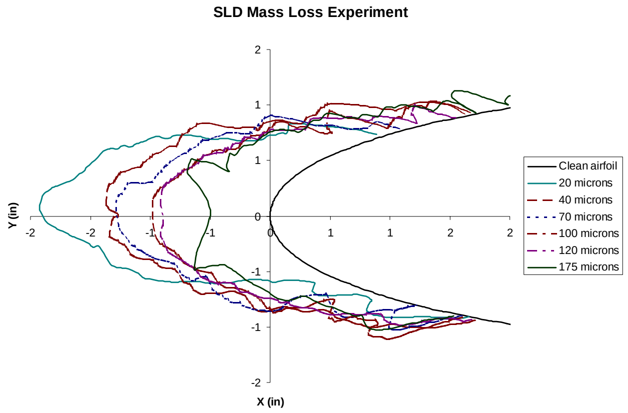
Approach

- Incorporate droplet splashing model into LEWICE and investigate influence on ice shape development

Status

- Model has been incorporated into LEWICE 3.0
- Thorough testing of model needs to be conducted
- Upgrades to model can be included as more splashing testing and modeling is conducted

Compare LEWICE model to mass loss data



Location: Glenn Research Center

Principle Investigator: William Wright, Mark Potapczuk

Objective

- Identify strengths and weaknesses of SLD model

Approach

- Run LEWICE for conditions used in development of SLD ice shape database and compare ice shapes

Status

- Some initial comparisons have been conducted
- Further comparisons will be made as experimental data becomes available

Development of a proposed SLD model

Location: All Group Members

Principle Investigator: SLD Engineering Tool Development Working Group

Objective

- **Develop an interim SLD model into ice accretion codes**

Approach

- **Evaluate the work performed in earlier tasks and identify those elements that should be included in an SLD model**

Status

- To be initiated

SLD Model Validation

Location: All Group Member

Principle Investigator: Ad-hoc Group

Objective

- Insure interim SLD model provides accurate simulation of SLD ice accretion

Approach

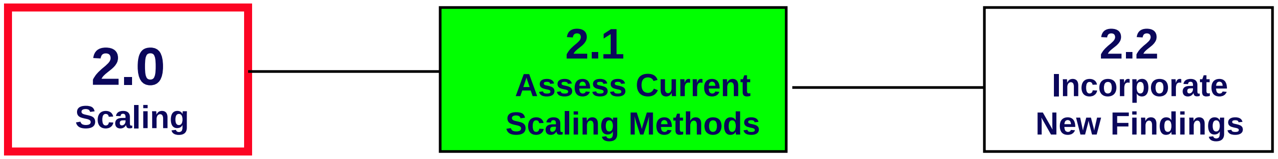
- Compare ice shapes from simulation to data from SLD database
- Compare ice weight from simulation to data from SLD database
- Compare collection efficiency calculations to data

Status

- To be initiated

Element 2: Scaling

Assess Current Scaling Methods



2.0
Scaling

2.1
Assess Current Scaling Methods

2.2
Incorporate New Findings

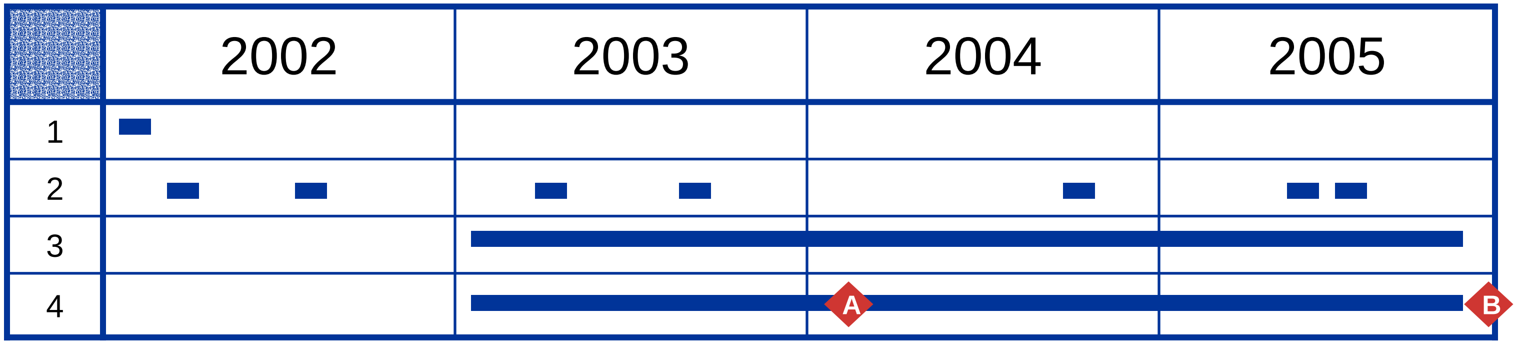
Scaling Capability

BACKGROUND:

- Various scaling methods have been developed for Appendix C icing conditions
- It is not known if these same methods can be utilized in SLD conditions
- Tests need to be conducted to verify the use of scaling methods in SLD

Scaling Capability

Goal - Assess scaling methods for use in SLD conditions



TASKS

1 - Define SLD conditions for scaling tests

2 - Conduct scaling experiments in the IRT

3 - Conduct scaling experiments at INTA

4 - Develop summary reports

MILESTONES

◆ A Interim report on APP C scaling methods

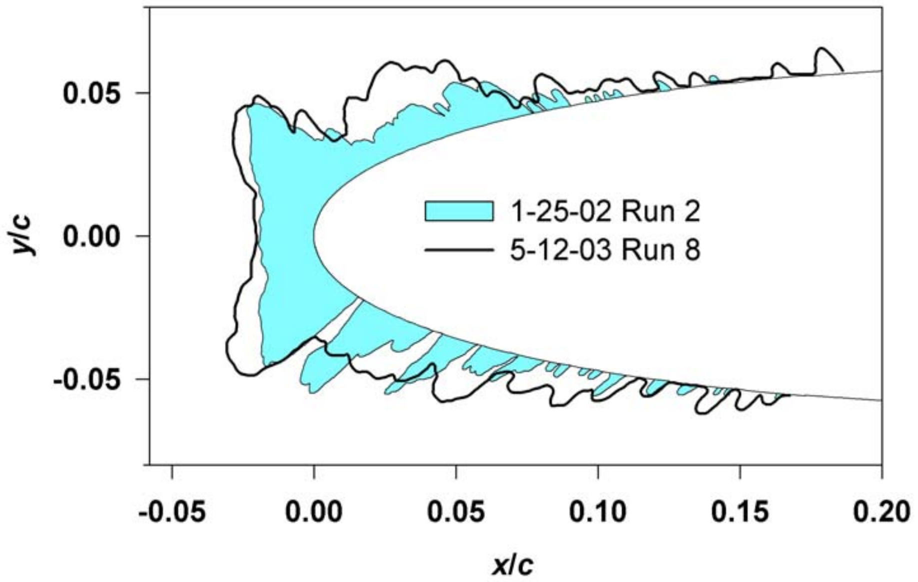
◆ B Preliminary documentation of recommended SLD scaling methods

Scaling Research Task

Location: Glenn Icing Research Tunnel (US)

Principle Investigators: Dave Anderson & Paul Tsao`

	c, in	t_{st}, °F	V, kt	MVD, μm	LWC, g/m³	τ, min	β_0, %	$\beta_0 A_c$	n_0	We_L, 10^6
🟦	36.0	5	100	160	1.50	9.7	95	1.6	0.43	1.2
—	10.5	11	200	40	1.00	2.4	93	1.8	0.40	1.4



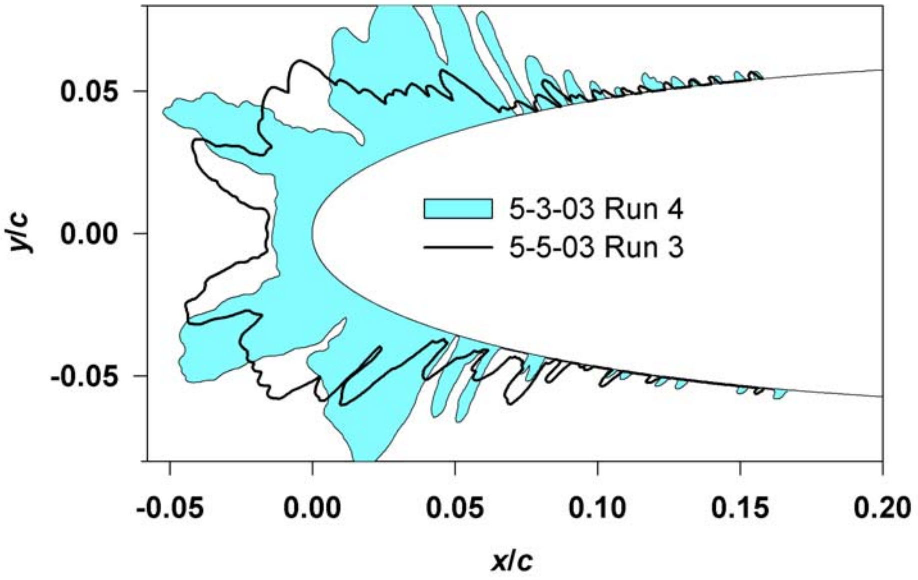
Scaling to App C from MVD’s as great as 160μm demonstrated

Scaling Research Task (con’t)

Location: Glenn Icing Research Tunnel (US)

Principle Investigators: Dave Anderson & Paul Tsao`

	c, in	t_{st}, °F	V, kt	MVD, μm	LWC, g/m^3	τ, min	β_0, %	$\beta_0 A_c$	n_0	We_L, 10^6
🟦	36.0	11	200	200	0.55	14.7	97	1.8	0.40	4.7
—	36.0	5	200	160	0.83	9.7	97	1.8	0.40	4.7



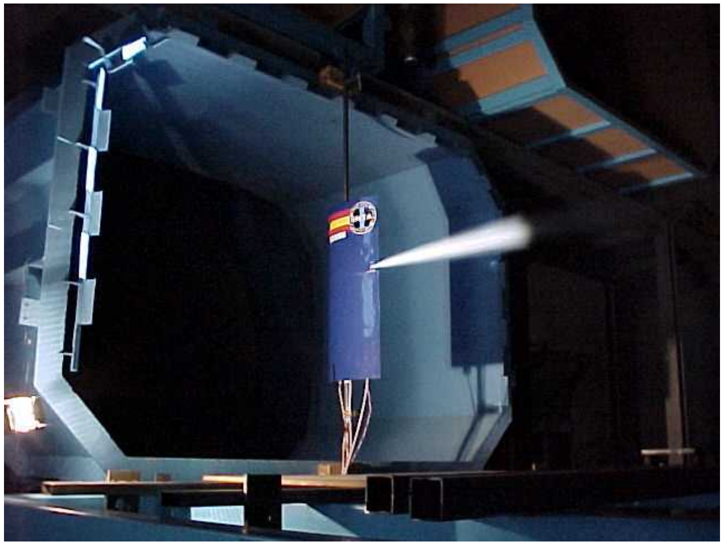
Dramatic changes in ice shape for MVD > 160μm are under study

Scaling Research Task

Location: INTA flow lab/wind tunnel (Spain)

Principle Investigator: Alejandro Feo

Objective: Water film thickness scaling effects



- Develop two spray systems: the first will simulate Appendix C drop sizes and *LWC*'s; the second to simulate SLD conditions
- Measure the water film thickness for these conditions and correlate the film thickness with non-dimensional parameters such as the Weber and Reynolds numbers
- Film-thickness probe installed in a rounded shape to represent airfoil
- Initial testing with this probe at Appendix C conditions has started

Summary Reports

Location: NASA Glenn, Ohio Aerospace Institute

Principle Investigators: Dave Anderson & Paul Tsao`

Objectives:
- Develop report on scaling methods for SLD
- Identify what if any methods are unique to SLD
- Provide guidance to engineers performing icing tests in SLD conditions

Approach:
- Summarize results from SLD scaling tests
- Note any differences between SLD and Appendix C scaling methods (as outlined in Appendix C scaling manual)
- Document recommended methods for scaling in SLD conditions

Status:
- Preliminary manual on Appendix C scaling methods to be released in 2004
- SLD scaling method summary report TBD (probably late 2005)

Element 3: Instrumentation

Instrumentation Requirements

3.0 Instrumentation

3.1 Rqmts

3.2 LWC

3.3 Droplet Size

3.4 Cloud Temp

3.5 Ice Shape

3.6 Humidity

LWC Sensitivity Study

Location: Glenn Icing Research Tunnel (US)
Principle Investigators: Dean Miller, Mark Potapczuk

OBJECTIVE:

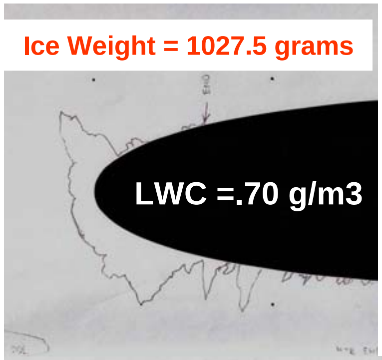
- Determine the variation in icing cloud parameters (e.g. – LWC) necessary to produce a measurable change in resulting ice accumulation

APPROACH:

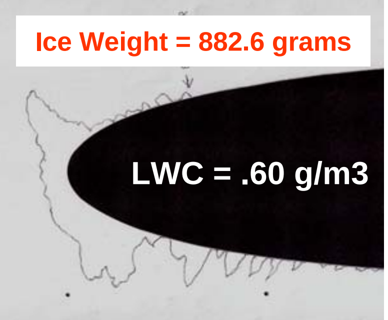
- Identify nominal SLD icing conditions
  - Freezing fractions of 0.3 and 0.7
- Determine the variant conditions (i.e. the amount of variation from the nominal for a given icing cloud parameter)
- Measure and compare ice shape parameters for nominal and variant conditions (Geometric parameters/Ice mass)

STATUS:

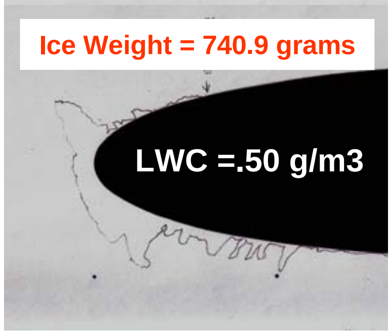
- Data being analyzed
- Results to be reported in AIAA 2005 paper


Ice Weight = 1027.5 grams

LWC =.70 g/m3


Ice Weight = 882.6 grams

LWC = .60 g/m3


Ice Weight = 740.9 grams

LWC =.50 g/m3

MVD Sensitivity Study

Location: Glenn Icing Research Tunnel (US)
Principle Investigators: Dean Miller, Mark Potapczuk

OBJECTIVE:

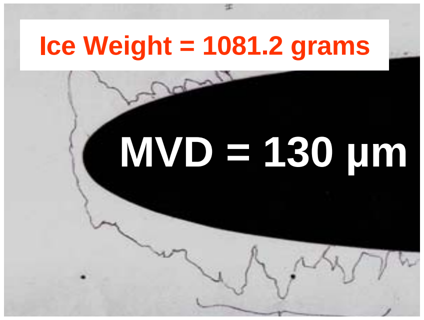
- Determine the variation in icing cloud parameters (e.g. – MVD) necessary to produce a measurable change in resulting ice accumulation

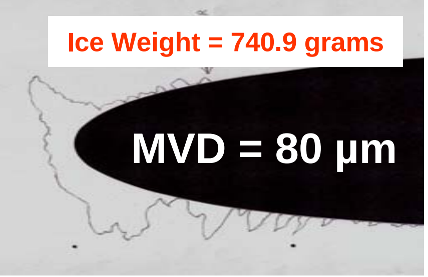
APPROACH:

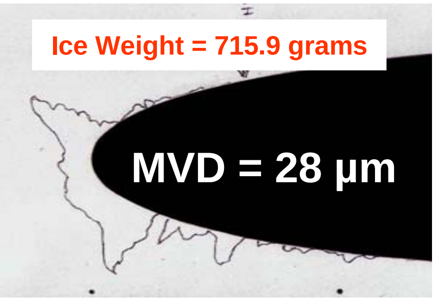
- Identify nominal SLD icing conditions
  - Freezing fractions of 0.3 and 0.7
- Determine the variant conditions (i.e. the amount of variation from the nominal for a given icing cloud parameter)
- Measure and compare ice shape parameters for nominal and variant conditions (Geometric parameters/Ice mass)

STATUS:

- Data being analyzed







Instrumentation Workshop

Location: **Ohio Aerospace Institute** **Date:** **May 12-13, 2004**

Principle Contact: **Dean Miller**

PURPOSE: To evaluate the progress made toward measuring cloud water content and drop size measurement capability in SLD conditions, and to determine what remaining technical issues need to be resolved before this instrumentation can be used to support SLD certification activities beginning in 2006.

OBJECTIVES:

- To review the current state of the art in cloud water content and particle sizing instrumentation with respect to the measurement of SLD icing conditions
- To identify instrumentation issues affecting the measurement of drop size and liquid water content which would adversely affect the use of this instrumentation in SLD certification activities
- To identify the highest priority instrumentation issues which need to be resolved prior to 2006
- To identify a general approach for resolving the highest priority issues

LWC Measurement

3.0 Instrumen-tation

3.1 Rqmts

3.2 LWC

3.3 Droplet Size

3.4 Cloud Temp

3.5 Ice Shape

3.6 Humidity

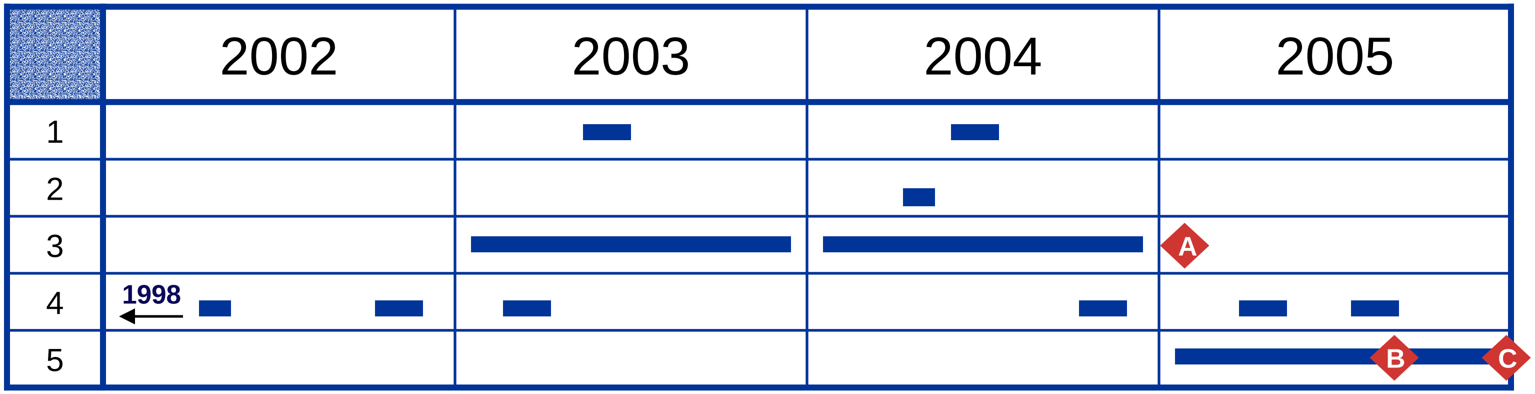
LWC Measurement Capability

BACKGROUND:

- **LWC is a critical measurement needed to describe SLD icing conditions (in ground based research facilities and flight research)**
- **There are issues that affect the accuracy and comparability of LWC instruments in SLD icing conditions**
  - **Under-reading of LWC sensors in SLD conditions**
  - **Variation in LWC measurements obtained with different LWC instruments under similar conditions**
- **A more accurate and consistent LWC measurement capability is needed to support SLD certification activities**

LWC Measurement Capability

Goal - Develop capability to accurately and consistently measure LWC in SLD conditions



TASKS

1 - Estimate effect of LWC error on ice shape

2 - SLD instrumentation workshop

3 – Development of “reference” LWC device

4 - Conduct cross-comparison tests in SLD

5 - Develop LWC correlation matrix

MILESTONES

- A Proto-type Reference LWC probe
- B International Instrumentation Workshop
- C LWC cross-comparison matrix available

LWC Reference Probe

Location: Wichita State University
Principle Investigators: Jason Tan & Michael Papadakis

Objectives:

- Develop a reference LWC probe
  - Provide a more accurate measurement of LWC
  - Serve as a “primary” LWC standard
  - Reference / calibrate other LWC probes to this device
  - Provide quantified / traceable accuracy

Status:

- Phase I probe completed
  - Iso-kinetic capture of 92% in laboratory environment

- Phase II Probe development to begin in 2005
  - FAA Grant
  - Absolute humidity sensor to be added
  - Future plans to test in warm icing tunnel spray cloud

LWC Cross Comparison

Location: Various Icing Research Tunnels

Principle Investigators: NASA, MSC, NRC, CIRA

OBJECTIVES: Quantify differences in water content probe response to SLD icing conditions

APPROACH:

- Conduct experimental tests in icing research facility over range of MVD, and LWC (including SLD conditions)
  - Measure cloud water content with existing LWC/TWC probes
  - Measure cloud water content with LWC “reference” probe
- Compare LWC/TWC probe responses to LWC “reference” probe
- Inter-compare LWC/TWC probe responses
- Evaluate differences in device response
  - Relative to references (LWC reference probe, icing blade)
  - Relative to each other device

STATUS:

- Comparison tests conducted in NRC & IRT between 1998 and 2003
- Obtained somewhat differing results for Nevzorov & King responses
- Tests planned in NRC AIWT for fall 2004, and NASA IRT in 2005 to resolve issues

Drop Size Measurement

3.0 Instrumen-tation

3.1 Rqmts

3.2 LWC

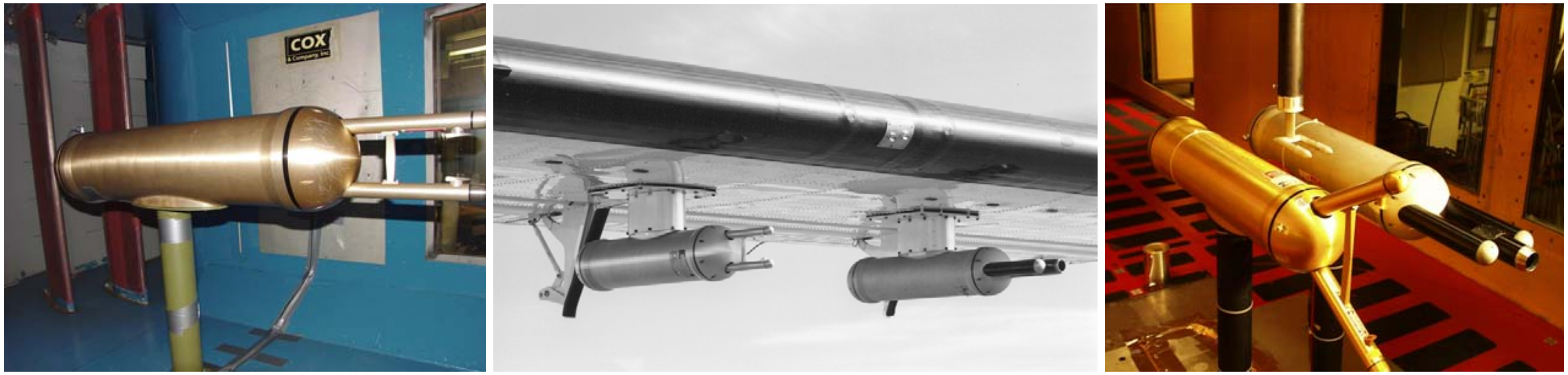
3.3 Droplet Size

3.4 Cloud Temp

3.5 Ice Shape

3.6 Humidity

Drop Size Measurement Capability

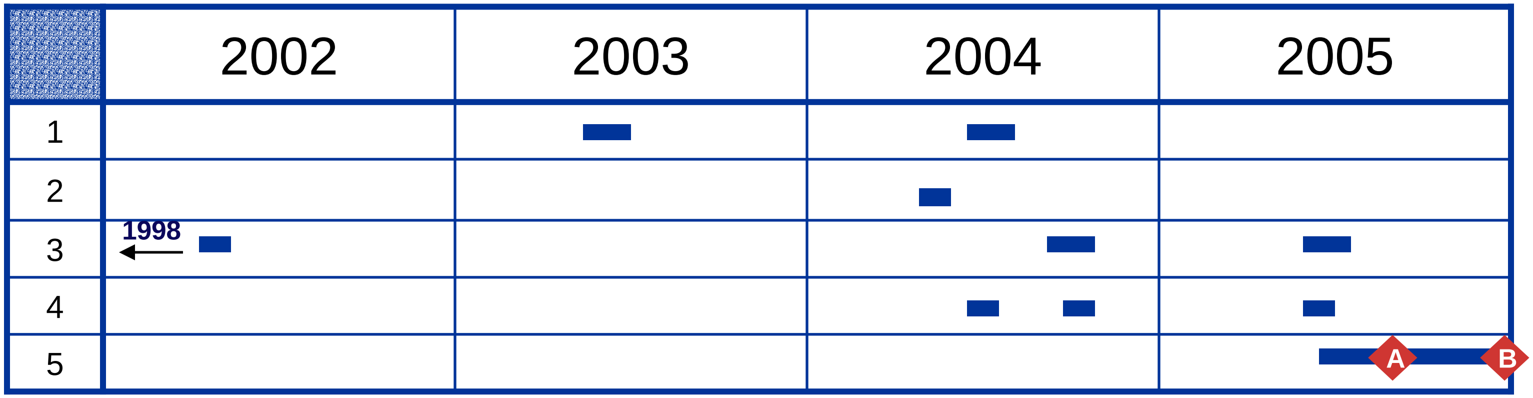


BACKGROUND:

- Drop size distribution is an important measurement parameter needed to describe SLD icing conditions (in ground based research facilities and flight research)
- Though various particle sizing instruments are currently available to measure SLD conditions, there are some issues affecting he development of an SLD drop size spectrum which need to be resolved:
  - Accurate sizing of water drops by FSSP in icing tunnels where particle concentrations are very high (co-incidence over-sizing problem)
  - Inaccurate sizing in 50-150 µm range where FSSP's and OAP spectra overlap
- Also, a set of recommended measurement specifications needs to be defined, to facilitate the selection of particle sizing instrumentation for SLD certification testing

Drop Size Measurement Capability

Goal - Develop drop size measurement capability in SLD conditions



TASKS

1 - Estimate effect of MVD error on ice shape

2 - SLD instrumentation workshop

3 – Conduct cross comparison tests

4 - Test / evaluate drop size probes (PDPA, Malvern, …) to resolve FSSP coincidence & 50-150 um issues

5 - Develop list of instrumentation specifications to guide selection of drop size instruments

MILESTONES

A - International Instrumentation Workshop

B - Recommended drop size measurement specifications available

Drop Size Cross Comparison

Location: Various Icing Research Tunnels

Principle Investigators: NASA, MSC, NRC, CIRA

OBJECTIVE: Quantify differences in drop size probe measurement in SLD icing conditions

APPROACH:

- Conduct experimental tests in icing research facility over range of MVD, and LWC (including SLD conditions)
  - Measure drop distribution with existing LWC/TWC probes
- Inter-compare drop size distributions from various probe
  - Concentration
  - Integrated spectrum LWC (combined small & large drop probes)
- Evaluate differences in drop size probe results

STATUS:

- Comparison tests conducted in NRC AIWT & NASA IRT between 1998 and 2003, some issues affecting SLD drop spectrum need to be resolved
- Faulty estimates of FSSP concentration/size in high concentrations of small particles (coincidence over-sizing)
- Mis-sizing of droplets in the 50-150um size range

PDPA/Malvern Testing

Location: Various Icing Research Tunnels

Principle Investigators: NASA, CIRA, MSC, NRC

OBJECTIVE: Develop confidence in PDPA and Malvern as alternate drop sizing instrument to FSSP in icing cloud environments having high concentrations of small particles (resolve FSSP coincidence over-sizing issue)

APPROACH:

- Conduct tests in icing research tunnels
- Compare / contrast PDPA, Malvern sizing response in Appendix C and SLD conditions
- Develop more experience and confidence with PDPA & Malvern to support SLD certification testing

STATUS:

- MSC/NRC PDPA/Malvern tests planned for Oct 2004 in NRC AIWT
- PDPA Tests planned in NASA IRT for 2004
- CIRA PDPA comparison tests at CIRA? (TBD)

Drop Size Instrument Recommendations

Location: Various Icing Research Tunnels

Principle Investigators: NASA, CIRA, MSC, NRC

OBJECTIVE: Develop recommendations for selecting drop size instruments to measure SLD conditions

APPROACH:

- Identify capabilities of current drop sizing instruments
- Identify requirements for drop size measurement in various environments
  - Icing tunnel
  - Natural flight
  - Icing tanker
- Compare instrument capabilities with requirements for each environment
- Develop list of recommended instruments for each environment

STATUS:

- George Isaac has drafted some preliminary recommendations in paper presented at FAA/SAE conference (Chicago 2003)

Element 4: Universal Methodology

Universal Methodology

4.0
Universal Methodology

4.1
Assess Capabilities

4.2
Compare Facilities

4.3
Identify Common Methods

4.4
Document Practices

- **Icing research facilities will have different capabilities and limitations relative to simulating the SLD environment.**

- **Therefore, methods developed under tasks 1.0 thru 3.0 of this WBS should be generalized to provide guidance to other icing research facilities.**

- **The intent is provide a "template" for development of SLD simulation methods, which can be adapted to the unique requirements of each facility.**

Pratt & Whitney
400 Main Street
East Hartford, CT 06108

Pratt & Whitney
A United Technologies Company

June 29, 2009

Federal Aviation Administration
800 Independence Avenue, SW
Washington, D.C. 20591

Attention: Ms. Margaret Gilligan, Associate Administrator for Aviation Safety

Subject: ARAC Recommendation, Ice Protection HWG Phase IV review of Task 2

References: 1. ARAC Tasking, Federal Register, December 8, 1997
2. ARAC TAEIG letter to FAA, IPHWG task 2 recommendation, March 7, 2005

Dear Peggy,

The Transport Airplane and Engine Issues Group and the Ice Protection Harmonization Working Group are pleased to submit the attached Phase IV review of IPHWG Task 2 (Reference 1 tasking and Reference 2 ARAC recommendation). The IPHWG report was approved by TAEIG for transmittal to the FAA at our June 11, 2009 meeting.

Also attached are a letter from Boeing expressing concerns about some aspects of the proposed guidance material and a letter from Cessna regarding the Boeing concerns.

Sincerely yours,

Craig R. Bolt

C. R. Bolt
Assistant Chair, TAEIG

Copy: Mike Kaszycki – FAA-NWR
Jim Hoppins – Cessna
James Wilborn – FAA-NWR
Ralen Gao – FAA-Washington, D.C. – Office of Rulemaking

Acknowledgement Letter

U.S. Department
of Transportation
**Federal Aviation
Administration**

800 Independence Ave., S.W.
Washington, D.C. 20591

August 14, 2009

Mr. Craig R. Bolt
Assistant Chair, Aviation Rulemaking
Advisory Committee
Pratt & Whitney
400 Main Street, Mail Stop 162-14
East Hartford, CT 06108

Dear Mr. Bolt:

This is in reply to your June 29, 2009 letter. Your letter transmitted to the FAA the ARAC Rulemaking Advisory Committee's (ARAC) recommendation regarding Phase IV review of Task 2. The Phase IV review was requested due to the immature state of large drop icing simulation and compliance methods at the time of Task 2 report submittal. I understand that members of the Ice Protection Harmonization Working Group (IPHWG) reached consensus and the report was approved unanimously by the Transport Airplane and Engine Issues Group (TAEIG).

I wish to thank the ARAC, particularly the members associated with TAEIG and its IPHWG that provided resources to develop the report and recommendation. The report will be placed on the ARAC website at:
http://www.faa.gov/regulations_policies/rulemaking/committees/arac/.

We consider your submittal of the IPHWG report as completion of Phase IV review Task 2 from our December 8, 1997 tasking statement. We will keep the committee apprised of the agency's efforts on this recommendation through the FAA report at future ARAC meetings.

Sincerely,

/S/

Pamela Hamilton-Powell
Director, Office of Rulemaking

Recommendation

AIRBUS

Mr. Craig R. Bolt
Assistant Chair
Advisory Committee on
Transport Airplane & Engines Issues Group (TAEIG)

Pratt & Whitney
400 Main Street
East Hartford, CT 06108

FROM
Rolf Greiner
DATE
07 July 2009
PHONE
+ 49 (0)40 7437 3392
FAX
+ 49 (0)40 7437 3983
E-MAIL
Rolf.Greiner@airbus.com
OUR REFERENCE
EAIX-073/07/09
YOUR REFERENCE

TAEIG Meeting 11 June 2009; IPHWG Task 2 Report;
BOEING Concerns on proposed SLD Rule; AIRBUS Opinion

Dear Mr. Bolt:

Airbus fully supports the important work performed by the IPHWG and as a member of this body would like to provide its opinion on the concerns expressed by Boeing during the 11th June 2009 Transport Airplane and Engine Issues Group (TAEIG). Boeing's concerns relate to the implications of the proposed Supercooled Large Droplet (SLD) rule and the related guidance material for component certification. Airbus agrees with Boeing's conclusions which in summary are:

- FAA and IPHWG to consider revising component regulations and/or guidance material
- FAA and IPHWG to clarify component guidance material for detect & exit applicants to clarify what is required for compliance
- FAA and IPHWG to enhance guidance material for component regulations
- FAA and IPHWG to mitigate the lack of engineering tools & consequences of conservative analytical methodologies for example: allow service history as MOC for windshield heating so long as maximum possible/practical heat is provided
- FAA and IPHWG to re-evaluate cert compliance cost estimates for component rules for regulatory evaluation
- NASA (and/or other research bodies) to develop increased engineering tool capability for systems component MOC
- NASA (and/or other research bodies) to conduct flight validation of engineering tools
- NASA (and/or other research bodies) to lead effort to develop facility or other means of evaluating FZRA accretion

AN EADS COMPANY

BANK ACCOUNTS:
DEUTSCHE BANK AG, HAMBURG
ACC. 024850000, BANK CODE 200 700 00
SWIFT/BIC DEUTDEHH
IBAN DE62200700000024850000
DRESDNER BANK AG, HAMBURG
ACC. 0915859500, BANK CODE 200 800 00
SWIFT/BIC DRESDEFF200
IBAN DE27200800000915859500
HYPOVEREINSBANK AG, HAMBURG
ACC. 223941, BANK CODE 200 300 00
SWIFT/BIC HYVEDEMM300
IBAN DE84200300000000223941

AIRBUS OPERATIONS GMBH
LEGAL DOMICILE: HAMBURG
REGISTRATION COURT:
AMTSGERICHT HAMBURG
COMMERCIAL REGISTER HRB 43527
CHAIRMAN OF SUPERVISORY BOARD:
DR. THOMAS ENDERS
BOARD OF MANAGEMENT:
DR. GERALD WEBER, CHAIRMAN & CEO
JOACHIM SAUER
HARALD WILHELM

POSTAL ADDRESS:
P.O. BOX 95 01 09
21111 HAMBURG
GERMANY
PHONE +49 (0) 40 7 43-70
FAX +49 (0) 40 7 43 44 22
OFFICES:
KREETSLAG 10
21129 HAMBURG
GERMANY

EA01901E/1-08/03

- NASA (and/or other research bodies) Provide schedule for tool development per a technology roadmap

Airbus believes that acting upon these recommendations will lead to a more accurate and consistent application of the rule and therefore will be beneficial to both applicants and airworthiness authorities alike.

Boeing has developed these recommendations as a results of performing an assessment of the implications of the new SLD rule by conservatively applying existing widely available icing analysis tools, as recommended by the proposed guidance material.. The analysis is the first detailed attempt to assess the feasibility of certifying aircraft components to the new rule and guidance material and shows significant impacts to the engine inlet ice protection system, radome ice accretion and windshield heating system. The guidance material and lack of validated simulation tools may also lead to an extensive SLD flight test program. Boeing's results confirm the Airbus' fears that the conservative application of existing tools, currently used for traditional Appendix C certification demonstrations, leads to unrealistic design constraints that are not justified by the good in-service experience of aircraft like those produced by Boeing and Airbus.

Although some impacts of the new rule were anticipated the scale of the impacts predicted by Boeing are in some ways surprising. This reinforces the need for further development of the simulation tools and indicates that a reassessment of the guidance material for aircraft component certification in SLDs is needed.

In our opinion, the use of Boeing's assessment results will undoubtedly lead to a more consistent application of the SLD rule. Boeing have expressed regret for providing concerns late in the rule-making process and Airbus share those regrets but feel that it is better for all stakeholders if these issues are dealt with now rather than later in the process.

Airbus remains committed to supporting the development of the new icing rules and values the opportunity to be involved in the process. If there are any questions on the information contained herein please do not hesitate to contact us.

Sincerely,

Rolf G

Rolf GREINER
AIRBUS Representative in TAEIG
Regulations Manager
Regulations & Policies - Product Integrity - EAIX

Cessna
A **Textron** Company

17 June 2009

IN REPLY, REFER TO:
L390-09-2469

Aerospace Industries Association
1000 Wilson Boulevard, Suite 1700
Arlington, VA 22209-3928

ATTENTION: Ms. Ranee Carr

SUBJECT: **Comments to AIA on Boeing’s Icing TAEIG presentation.**

Dear Ms. Carr,

This letter is being transmitted electronically; the original will be kept in the Cessna Airworthiness files for permanent storage unless otherwise requested. Cessna Engineering staff has reviewed the TAEIG presentation made by Boeing and has the following comments:

Cessna Aircraft Company is supportive of an effort to increase clarity of the SLD rules and guidance materials, but recommends that Boeing's concerns be further reviewed within Ice Protection Harmonization Working Group (IPHWG).

Cessna Aircraft Company is grateful for the opportunity to comment, and respectfully requests that the comments be considered during discussion of the presentation material.

We thank you for your consideration of our comments. Cessna appreciates the AIA’s leadership in this effort. If you require additional information or have any questions, please do not hesitate to contact Neale Eyler at telephone number 316-517-7488, facsimile number 316-206- 7258, or email neyler@cessna.textron.com.

Sincerely,

for
Vasant Gondhalekar
Director of Engineering
CESSNA AIRCRAFT COMPANY

Cc: Jim Hoppins, Engineer Principal

18 March 2009

IN REPLY, REFER TO
L374-44-09-001

Mr. Craig R. Bolt
Assistant Chair
Advisory Committee on Transport Airplane & Engines Issues Group (TAEIG)
Pratt & Whitney
400 Main Street
East Hartford, CT 06108

Ref: L374-44-05-003, dated 19 September 2005 (Submittal of Task 2, Rev. n/c)
L374-44-05-004, dated 23 December 2005 (Submittal of Task 2, Rev. A)

Dear Mr. Bolt:

This letter is provided for closure of the Phase IV review of IPHWG Task 2. The Phase IV review was requested due to the immature state of large drop icing simulation and compliance methods at the time of Task 2 report submittal (references above). The Phase IV review consisted of a review of current status of simulation and compliance methods, as well as a review of the preliminary Regulatory Evaluation. There are still concerns regarding the maturity state, and as such interim guidance materials are recommended.

Airframe Icing Simulation & Compliance Methods

The analytical and simulation techniques for predicting large drop ice accumulations have matured since the original Task 2 report was submitted (Dec 2005). However, there are still significant challenges in simulating large drop accretions and, consequently, in showing compliance to all aspects of the rule.

In addition, the FAA has drafted a proposed rule that modifies the rule applicability from application to all Part 25 aircraft to a subset of aircraft with a maximum takeoff weights of less than 60,000 lbs, or the use of reversible flight controls (regardless of weight). Consequently, the rule is primarily applicable to smaller Part 25 aircraft such as business jets and regional commuter aircraft. Many of these aircraft are expected to be certified on a “detect and exit” basis with respect to the large drop environment.

The interim materials were drafted with a focus on how to show compliance for these “detect and exit” aircraft, as well as for aspects of the rule package with which all airplanes must comply, using currently available simulation methods. The intent is that these materials would be appended to the draft advisory materials proposed in the IPHWG Task 2 report (Appendix K).

When operated on a “detect and exit” basis, affected aircraft will have limited exposures and limited accumulations due to the large droplet conditions. The IPHWG determined that the use of existing simulation methods alone may be an acceptable means of compliance when used in a conservative manner as discussed in the interim guidance. The IPHWG recommends that these compliance methods may provide sufficient accuracy to certify aircraft operated in this manner without requiring flight tests in natural freezing drizzle and freezing rain conditions. However, the IPHWG acknowledges that the tool maturity is not sufficient to support unrestricted operations (including unrestricted in a portion of the large drop environment) without certification flight tests in natural freezing drizzle and freezing rain conditions.

Some manufacturers have concerns that the applicability provisions will not be accepted by all certifying authorities. If the applicability provisions of the FAA draft rule are not accepted by international authorities, the means of compliance for the larger aircraft to operate unrestricted, as indicated above, will require flight tests in natural large drop conditions. Per current understanding, this rulemaking project is not on the EASA work list at this time. As such, there is still considerable uncertainty with respect to harmonization of the applicability provisions of the rule.

Given the current state of funding for icing research, the ability to continue to mature the simulation methods will be limited. As such, the interim methods of compliance may be required for the foreseeable future.

Engine/Engine Installation Compliance Methods

The proposed standards for SLD and mixed phase icing conditions effects on engines were developed when industry, EASA, Transport Canada, and the FAA combined together as an engine and engine installation subgroup under the Ice Protection Harmonization Working Group. A thorough review of service experience in conjunction with meteorological data was used to develop propulsion rules and guidance material for these weather conditions.

For Propulsion systems, SLD is addressed in proposed rule changes for 14 CFR Part 33, sections 33.68 and 33.77, and 14 CFR Part 25, section 25.1093. Mixed phase and ice crystal conditions are addressed in proposed rule changes for 14 CFR Part 33, section 33.68, and 14 CFR Part 25, section 25.1093. Engine and engine installation certification to Appendix X of part 25 and Appendix D of part 33 require that the plane operate safely throughout these icing envelopes. The subgroup reached a consensus on a proposed revision to AC 20-147.

It contains acceptable compliance methods that rely on similarity analysis for mixed phase and ice crystal conditions. The proposed text change to § 25.903 is consistent with the current § 25.903, and allows flexibility for installation of pre § 33.68 certification basis engines into new aircraft applications at the FAA's discretion. For 14 CFR 33 engine rules, the JAA/EASA is expected to maintain equivalency to FAA rules, and not direct similarity. This equivalency allows for all manufacturers to continue their equivalent methods of compliance demonstrations. In the future the subgroup anticipates the guidance material will be updated as industry and authorities advance in their understanding of mixed phase and ice crystal conditions and as engineering tools for compliance with the proposed rules are improved.

Flight Test Compliance Methods

The 14 CFR 25 Subpart B Flight recommendations were not altered as part of this review. Compliance methods are largely based on flight tests with simulated ice shapes to evaluate the performance and handling quality effects. The maturity concerns are with respect to creation of the simulated ice shapes and not with the flight evaluation requirements.

Regulatory Evaluation

The IPHWG reviewed a draft copy of the APO regulatory analysis and provided comments and recommendations. A summary of open comments is provided by attachment.

Recommendation

While the final outcome of the APO analysis is still in work, the technical aspects of the interim materials have agreement within the IPHWG and are recommended for approval by TAEIG for transmittal to the FAA for rulemaking.

Sincerely,

J R H

Jim Hoppins
Co-Chair Ice Protection
Harmonization Working Group

Attachments:

A. Results of IPHWG review of draft regulatory evaluation

B. Interim guidance materials to be added to AC 25-XX
(IPHWG Task 2 report, Appendix K)

Results of IPHWG Review of Draft Regulatory Evaluation

A draft summary of the regulatory evaluation was provided to the IPHWG for review. The following recommendations were provided:

- The development of the affected fleet included aircraft that would not be affected by the rule, due to maximum takeoff weights exceeding 60,000 lbs. Recommendations were made with respect to categorizing aircraft based on the MTOW, usage and the use of reversible flight controls.
- IPHWG members provided input to improve the accuracy of the delivery numbers for affected aircraft.
- There were concerns that only looking at new type certificates as a basis for applicable aircraft (with increased certification costs) would not accurately address potential certification efforts driven by the changed product rule (§21.101).
- All of the applicable events in the regulatory analysis were considered as catastrophic events. However, two of the events in the analysis resulted in aircraft damage, but did not result in fatalities. The rationale for inclusion of these events on a catastrophic basis is unclear.
- Some IPHWG members do not concur that the Cessna 560 Eagle River event is applicable to the cost and benefit analysis. Icing was indicated in this event but was not cited as the probable cause. A consensus was not reached on the removal of the event from the cost and benefit analysis.
- The estimated passenger loading for small Part 25 aircraft was estimated based on the maximum number of seats certified. The majority of small Part 25 aircraft are delivered with executive seating arrangements which reduce the passenger load. Recommendations were provided.
- The IPHWG has concerns that the Taiwanese study used as a basis for estimating a reduction of passenger demand following a catastrophic event may not accurately indicate the US market. Statistics for the US are available from the DOT Bureau of Transportation Services which maintains records for “passenger enplanements” available through the internet. A brief review by IPHWG indicated seasonal variation of enplanements that would be difficult to attribute to the cited effect of reduced passenger demand following a catastrophic event. Further review is recommended.
- Recurrent costs for SLD ice detectors were not included in the analysis. IPHWG recommendation was to assume 50% of the aircraft would use SLD ice detectors and 50% would use visual cues.
- The use of the 2006 GA Survey to determine the annual flight hours for smaller airplanes (393 hours) affected by the rule may be biased by the smaller single engine aircraft within the GA fleet. Many of the applicable small Part 25 aircraft are operated under a fractional share basis and accumulate significantly greater hours than an individual operating a single engine piston aircraft.
- It is not clear how US manufactured aircraft versus non-US manufactured aircraft are being accounted for in the international impact statement. The fleet definitions contain a mix of both types.
- Additional detail level comments have been provided to the economist through the IPHWG FAA representative for resolution.

Appendix to AC 25.XX

Capabilities of Engineering Tools for Compliance with the Appendix X Requirements of Part 25

1. Assessment of Engineering Tool Capabilities

This appendix is the result of an ARAC Ice Protection Harmonization Working Group (IPHWG) 2009 evaluation of the engineering tool capabilities with respect to the prediction of Appendix X ice accretions and icing effects. The intent of this appendix is to provide interim guidance on the use of the tools.

Table 1 provides a graphical assessment of the capabilities of engineering icing tools. The capability of each tool for the various applications is classified as either Green, Yellow, or Red, as described in the Legend. As discussed in the main body of the AC, reliance upon the available simulation methods combined with engineering judgment will be required for finding compliance to the Appendix X requirements of Part 25. Even though a simulation tool type is classified as Green, an applicant must ensure that the specific tool is appropriate for their application and is used in a conservative manner, including critical-case icing conditions. General and specific concerns that should be considered are discussed later in this appendix. Section 2 of this appendix provides guidance on the tools, capabilities, and best practices for tool use with respect to Appendix X conditions. Section 3 discusses means of compliance for specific airplane components. Sections 4-6 discuss means of compliance for each of the three certification options of §25.1420. Section 7 discusses means of compliance for air data sensors and windshields (§§25.1323, 25.1325, and 25.773). Section 8 defines standard roughness levels.

Table 1 illustrates the current state of simulation capabilities. It is expected that capabilities will improve in the future. Applicants and research agencies are encouraged to develop and validate the engineering tools currently classified as Yellow and Red.

Interim Guidance Materials

		Unprotected Areas				Protected Areas					Detection Methods			Air Data Sensors	
		Wing	Tail	Radome	Non-lifting Surfaces (antenna, inlets, external modifications)	Thermal (protected area)	Thermal (Aft of protected area)	Mechanical (protected area)	Mechanical (aft of protected area)	Fluid Freezing Point Depressant	Visual Cues (Reference Surface)	Instrument (position or installation effects)	Instrument (performance)	Instrument (position or installation effects)	Instrument (performance)
FZDZ MVD < 40µm	**Icing Tunnels**	🟩	🟩	🟧 *	🟩	🟩	🟩	🟩	🟩	🟩	🟩 🟨 *	🟩 🟧 *	🟩	🟩 🟧 *	🟩
	Codes	🟩	🟩	🟨	🟩 🟧 **	🟩	🟧	🟧	🟧	🟩	🟩 🟨 **	🟩	🟧 **	🟩	🟧
	Tankers	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
FZDZ MVD > 40µm	**Icing Tunnels**	🟩	🟩	🟧 *	🟩	🟩	🟩	🟨	🟨	🟩	🟩 🟨 *	🟩 🟧 *	🟩	🟩 🟧 *	🟩
	Codes	🟩	🟩	🟨	🟩 🟧 **	🟩	🟧	🟧	🟧	🟩	🟩 🟨 **	🟩	🟧 **	🟩	🟧
	Tankers	🟧	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
FZRA MVD < 40µm	**Icing Tunnels**	🟨	🟨	🟧 *	🟨	🟨	🟨	🟨	🟨	🟩	🟧	🟧	🟧	🟧	🟧
	Codes	🟨	🟨	🟧 **	🟨 🟧 **	🟨	🟧	🟧	🟧	🟨	🟨	🟩	🟧	🟩	🟧
	Tankers	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
FZRA MVD > 40µm	**Icing Tunnels**	🟧	🟧	🟧 *	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Codes	🟨	🟨	🟧 **	🟨 🟧 **	🟨	🟧	🟧	🟧	🟨	🟨	🟩	🟧	🟩	🟧
	Tankers	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

LEGEND Updated FEB 2009

🟩	The capability exists today and is suitable to be an element of a means of compliance, or is readily achievable based on current experience
🟨	The capability is possible, but has not been demonstrated, or there is limited or no validation.
🟧	The capability is unknown, or does not currently exist
*	It may be possible to test small scale installation effects, but large scale installations are not currently feasible
**	Current 2D capabilities exist with large droplet effects, but limitations exist in the use of 3D codes for simulation of Appendix X effects

Table 1 - Assessment of Appendix X Engineering Tool Capabilities

This evaluation of tool capabilities is predominantly based upon NASA LEWICE codes (2D and 3D), the NASA Icing Research Tunnel facilities, and existing icing tanker information such as SAE ARP 5904, *Airborne Icing Tankers*. International icing simulations codes and facilities were considered where information was available. The US Air Force icing tanker that was used for SLD investigations during the 1990's on some commercial airplanes is currently not operational and its capabilities were not assessed.

The main body of the AC states that flight testing in natural Appendix X icing conditions should not be necessary if at least two methods of predicting Appendix X ice accretions are shown to provide similar results. The intent of this guidance is that at least two different methods (for example, icing tunnels and CFD codes) will be used to impart some level of data validation. The intent is not meant to allow as a basis for a finding of compliance the use of two different CFD codes that would give similar results. Table 1 illustrates that for some Appendix X conditions, few of the engineering tools are classified as Green or Yellow for use as a means of compliance. For example, radomes have no engineering tools classified as Green for use as a means of compliance. In other cases, such as areas aft of protected areas, there is only one simulation tool that is classified as Green.

In freezing rain (FZRA), there are very few engineering tools classified as Green, indicating that the primary method for showing compliance available at this time appears to be natural icing flight testing. In some cases, engineering judgment may allow other methods of compliance, even though not validated, when used in a fashion similar to that recommended for freezing drizzle (FZDZ). However, until the engineering tools become more mature, flight tests in natural Appendix X icing conditions will likely be necessary to achieve the confidence necessary for certification of airplanes for unrestricted flight in Appendix X or a portion of Appendix X conditions (i.e., compliance with 25.1420(a)(3) or 25.1420(a)(2)).

For airplanes certificated to detect Appendix X icing conditions and safely exit all icing conditions (i.e., compliance with § 25.1420(a)(1)), it may be acceptable to use one tool alone, even if Yellow or Red, without natural icing flight tests, provided that the one tool is used in a conservative manner. In cases where there are two Green tools available, the applicant should use both tools to verify results, as discussed in the main body of the AC.

Test cases may be reduced through the use of conservative test methods and critical-point analyses. However, validation of the test methods should be accomplished until confidence is provided

2. Capabilities & Limitations of Engineering Tools and SLD Measurement Instrumentation

2.1. Icing Tunnel Appendix X Simulations

Tunnels that have independent pressures at the nozzles may be able to produce the Appendix X bi-modal distributions. A tunnel that uses a single pressure source for spray bars cannot simultaneously produce the large and small droplet distributions defined in Appendix X. However, NASA developed a technique called “sequencing” that alternates large and small droplet sprays to simulate Appendix X.

The following should be considered when icing tunnels are used as an element of the means of compliance:

- Scale effects must be considered relative to tunnel blockage effects for all tests.
- For FZDZ MVD<40μm, the cloud drop distributions are similar in the IRT to existing Appendix C calibrations

- If there are concerns with the bi-modal distribution affecting the performance of ice protection systems, sequencing has been demonstrated in the freezing drizzle regime for an unprotected surface. This technique approximates the droplet distributions found in natural conditions (insert reference # for NASA sequencing paper). This technique results in rougher textures than Appendix C ice shapes.
    - Unprotected shapes are generally picked to be critical from the perspective of producing the largest disruption to the airflow. Consequently, details on the impingement limit characteristics may not be essential. However, sequencing may be necessary if standard sprays[1] do not produce the droplet distribution appropriate for simulation of the conditions desired. For example, in cases where the impingement limit characteristics are important, sequencing may be necessary.
    - In general, sequencing produces rougher textures than a standard spray.
    - Sequencing may not be appropriate for thermal systems since the mass flux of incoming water is not the same for the small and large droplet sprays.
    - If sequencing is used on deicing systems, the ratio of sequencing time to shed cycles should be evaluated to ensure that sequencing does not inappropriately affect the ice shape.

Hybrid airfoil design methods have been used in icing wind tunnels for experimental testing of subscale airfoils with full-scale leading edges to determine leading edge ice shapes for large-chord airfoil sections[2,3]. These techniques have been used successfully for Appendix C icing conditions. Adapting these techniques to icing tests for SLD conditions requires an evaluation of areas of impingement interest and analysis of the flow-field to determine if scale conditions aft of the leading edge can be met regarding compromises in design variables on circulation, velocity distribution and impingement characteristics. Although it is anticipated that this approach would be applicable for SLD conditions, the hybrid airfoil design technique for SLD conditions has not been tested and validated to date.

2.2. Computational Fluid Dynamic Tools

Computational fluid dynamic (CFD) tools are used extensively in certification for Appendix C conditions. CFD tools can provide valuable information on impingement limits, icing limits, ice size, shape, and thickness for Appendix X conditions. Some

---

[1] The phrase "standard spray" method refers to using the IRT nozzles in off-design conditions to generate larger drops for SLD conditions.

[2] Saeed, Farooq, Selig, Michael S. and Bragg, Michael B., "Design of Subscale Airfoils with Full-Scale Leading Edges for Ice Accretion Testing," Journal of Aircraft, Vol. 34, No.1, 1997.

[3] Saeed, Farooq, Selig, Michael S., Bragg Michael B., and Addy, Harold E. Jr., "Experimental Validation of the Hybrid Airfoil Design Procedure for Full-Scale Ice Accretion Simulation," AIAA Paper No. 98-0199, Reno, NV, January 12-15, 1998.

validation of collection efficiency and ice shapes has been accomplished for FZDZ; there have been no validation exercises for FZRA.

CFD tools have been devised to simulate ice accretion for SLD conditions and the behavior of various types of ice protection systems. Aside from the protected surfaces, these CFD tools can account for the possibility of SLD ice impingement beyond the ice protection system limits, as well as for possible water runback. No current CFD method can identify the breakup of water into rivulets, roughness formation, or ice sliding that may occur under these circumstances. As such, analysis of the regions behind ice protection systems requires some combination of CFD results, empirical data and test results (if available), and engineering judgment. This usually consists of determining the extent of possible ice formation using some criteria from the computational analysis, such as ice extent, impingement limits, or some minimum ice thickness level. The resulting ice shape would consist of a simulation of any intercycle or residual ice on the protected region combined with the simulation of the ice formed aft of the protected region. This result is then combined with guidance on ice roughness levels, such as described elsewhere in this document, to produce a rough ice region that can be evaluated in wind tunnel testing or flight tests.

Information can be calculated for drop trajectories for evaluating sensor locations and potential visual cues.

Many non-lifting surfaces require the use of 3D codes. At the current time, many 3D codes do not have large droplet effects (such as splashing and break-up). Even without large droplet effects, 3D codes can offer information on impingement limits. Although 3D codes may have physical models and correlations that can support analysis of large droplet icing, the capabilities to perform 3D SLD CFD have not yet been evaluated. There are codes that may have this potential, but no guidance can be offered at this time regarding their use.

Some codes have limited capabilities with short-chord geometries (e.g., antennas or struts) for Appendix C icing conditions. These limitations are expected to be similar for large drop icing and are typically addressed using empirical methods or icing tunnels. However, for non-lifting surfaces, conservative assessments may be acceptable, such as assuming the full frontal area, a collection efficiency of one, and approximating the shapes appropriate for the temperature (glaze, rime, etc.).

2.3. Icing Tankers

Icing tankers have been used extensively by some manufacturers for Appendix C icing certifications. Icing tankers typically have limited plume size and have been used primarily for localized icing effects, such as ice shedding and assessing the thermal performance of anti-ice systems.

Current tankers do have some limited capabilities to produce freezing drizzle sized drops but cannot produce the distribution effects. Current tankers do not produce freezing rain distributions and the feasibility of producing such conditions is likely limited by drop break-up (due to deceleration effects) and the ability to sub-cool the large drops within a workable flight envelope. Additionally, drop sorting effects are likely due to higher fall rates of large drops within an Appendix X distribution.

2.4. Instrumentation

When making in-situ measurements of Appendix X conditions, it is important to note that technology to make such measurements is rapidly changing. It is essential to consult experts in all phases of the measurement program, including those aware of the latest problems and strengths of each probe. Instrumentation should be used that is suited to the task and it must be mounted in appropriate locations on the aircraft, where the measurements are not affected by the airflow. For certification purposes, the instrumentation must be calibrated. An often-overlooked aspect of a measurement program is the necessity to calibrate the instrumentation at least once during a measurement campaign. Appropriate software and analysis techniques are also essential because complicated algorithms are often necessary in the analysis.

Instruments are required to measure particle concentrations as a function of size over the complete size range, 2 µm to at least 1,500 µm, including cloud droplets and precipitation drops. This may require more than one probe. Liquid water content (LWC) and ice water content (IWC) measurements obtained by integration of 2D images from spectral measurements generally have larger errors than those obtained from probes specifically designed to make such measurements. Consequently, it is recommended that probes designed to measure LWC and, if necessary, IWC directly be used, recognizing that some hot-wire devices detect larger drops (>50µm) with reduced efficiency. Mixed-phase clouds can occur frequently, so it is necessary to be able to discriminate between ice and liquid particles, especially for sizes larger than 50µm, so that ice particles are not incorrectly identified as supercooled large drops. For detect and exit airplanes (§25.1420(a)(1)), measurement of IWC directly may not be necessary; however, for airplanes using natural icing SLD flight tests to certify for a portion of Appendix X (§25.1420(a)(2)) or for unrestricted operations (§25.1420(a)(3)), IWC needs to be determined to assess the SLD conditions.

3. Component Evaluations

3.1. Lifting Surfaces

This paragraph is applicable for anti-icing systems aft of protected area and deicing Systems both on and aft of protected area.

For detect and exit airplanes (§25.1420(a)(1)) in freezing drizzle conditions, icing tunnels alone may be used as a means for developing ice shapes, provided that the model appropriately represents the airfoil beyond the FZDZ icing limit. Roughness may be evaluated in icing tunnel testing and replicated on the ice shapes for flight testing. The standard spray[1] method should be used for anti-icing systems because of the varying mass flux of incoming water associated with sequencing. For deicing systems, it is acceptable to use the standard spray or sequencing technique.

3.2. Radomes

Most radomes are too large to fit into existing icing wind tunnels. Additionally, computational analysis of radomes typically would require 3D codes. Many 3D codes do not have large droplet effects, although some codes may have this potential. (However, all 3D codes do have capabilities with respect to impingement limits.) Consequently, freezing drizzle ice shapes cannot be simulated. Radome ice shapes have been developed in the past using analysis and observed ice shapes from Appendix C flight tests (typically holding ice shapes).

For detect and exit airplanes (§25.1420(a)(1)) in freezing drizzle conditions, one method of compliance would be to modify Appendix C ice shapes to account for the larger impingement regions produced in FZDZ as predicted by the 3D codes. CFD codes maybe used to predict the ice thickness. The ice roughness should be in accordance with paragraph 8 of this Appendix. The radome ice should reflect the total mass associated with the icing exposures for §25.1420(a)(1) airplanes, which are defined in Part II of Appendix X .

3.3. Non-Lifting Surfaces (Antennas, Enhanced Vision Cameras, Struts, Auxiliary Inlets)

For non-lifting surfaces that do not require the use of 3D codes, 2D codes in combination with icing tunnels are available as means of compliance. However, many non-lifting surfaces require the use of 3D codes. At the current time, many 3D codes do not have large droplet effects, although some codes may have this potential.

For detect and exit airplanes (§25.1420(a)(1)), if the non-lifting surface is not critical from an engine ingestion or airframe damage perspective, 3D codes may provide sufficient information for compliance. However, for more critical surfaces, until 3D codes have large droplet effects which have been validated, icing tunnels alone may be used as a means for developing ice shapes.

3.4. Ice Detection Methods

Different types of ice detection require assessment of their capabilities in large droplet conditions, based upon their sensing technology. Magnetostrictive-type ice detectors may experience increased response time in large droplet exposures due to water shedding off of sensing surfaces from splashing and aerodynamic forces, particularly near freezing. This physical behavior may also occur with other types of probes.

While CFD can determine whether the large drops impact the ice detection surface, available CFD codes cannot accurately predict aerodynamic forces that cause drop shedding, or freezing fraction effects which may delay freezing. Therefore, the use of CFD alone for showing that ice detectors function in large drop conditions is not acceptable. When possible, the position installation effects should be evaluated using a combination of codes and icing tunnels. Devices mounted on smaller surfaces could be assessed in an icing tunnel. However, if the device is mounted on the fuselage and tunnel blockage effects would preclude a meaningful icing tunnel test, then CFD codes that adequately predict the shadowing and concentration effects may be used to verify that the equipment is properly located.

3.4.1. Activation of Ice Protection Systems (§25.1419(e))

3.4.1.1. Primary Visual Cues with Advisory Ice Detection Systems

The magnetostrictive type ice detectors can be used as an advisory system since the pre-detection ice accretions are based on the primary means (visual) and are therefore not dependent on the instrument response time. It is acceptable to assume that crew recognition times based upon visual cues will be similar to those for Appendix C conditions defined in AC 25-25.

3.4.1.2. Primary Ice Detection Systems

Due to the lack of engineering tools for FZRA, certification of ice detectors or icing conditions detectors will require validation in natural large droplet conditions, unless ground testing with both FZDZ and FZRA drops representative of Appendix X distributions and temperatures can be substantiated.

3.4.2. Detection for Exit (§25.1420(a)(1))

Certification of visual cues for detect and exit airplanes is discussed in paragraph 4 of this appendix.

Due to the lack of engineering tools for FZRA, certification of ice detection systems for detecting Appendix X conditions will require validation in natural large droplet conditions, unless ground testing with both FZDZ and FZRA drops representative of Appendix X distributions and temperatures can be substantiated.

3.5. Air Data Sensors

3.5.1. Air Data Sensor Position Installation Effects

When possible, the position installation effects should be evaluated using a combination of codes and icing tunnels. Devices mounted on smaller surfaces could be assessed in an icing tunnel. However, if the device is mounted on the fuselage and tunnel blockage effects would preclude a meaningful icing tunnel test, then codes that adequately predict the shadowing and concentration effects are acceptable as the only method for compliance with installation location requirements.

3.5.2. Air Data Sensor Performance Effects

Icing tunnels alone may be used as a means of compliance for determining the performance of air data sensors for compliance with the Appendix X icing requirements of §§25.1323, 25.1325, and 25.13XX. For sensors that have collection efficiencies approaching one, if performance has been shown in FZDZ conditions, then the use of a qualitative analysis based upon water-catch ratios may be used for extrapolation to FZRA conditions.

For air data sensors, test cases may be reduced if the Appendix C or mixed-phase or ice crystal conditions are shown to be more critical than the SLD environment. However, validation of the test methods should be accomplished until confidence is provided. In some cases, such as wing leading-edge-mounted lift transducers, icing tunnel tests may be necessary.

4. Certification for Detect and Exit - §25.1420(a)(1)

4.1. Detect and Exit FZDZ<40µm

FZDZ conditions with an MVD less than 40µm are similar to existing Appendix C distributions with the exception of a small percentage of the mass in drops larger than typical Appendix C. As a result, many of the current Appendix C simulation methods can support compliance. The small percentage of large drops in this distribution can affect the impingement limits and increase the water catch.

If visual cues are used for compliance with §25.1420(a)(1)(i), it may be possible to use codes in combination with icing tunnels to verify the visual cues. Visual cues should not be based on only one engineering method; a second, correlating method should be used.

4.2. Detect and Exit FZDZ>40μm

Where the capabilities of the tools available for FZDZ>40μm are the same as for FZDZ<40μm, the applicant may use similar means of compliance that are adjusted for the FZDZ>40μm icing conditions. The tool capabilities are different for mechanical deicing system protected areas and areas aft of the protected areas.

Other concerns:

- The icing tunnels are classified as Yellow in the FZDZ >40μm regime because use of the tunnels appears feasible but has not been demonstrated. Icing tunnel tests alone are acceptable for the development of ice shapes for deicing system protected areas and areas aft of the mechanically protected areas. Sequencing or standard distributions are acceptable, but the ratio of sequencing time to shed cycles should be examined.

4.3. Detect and Exit Freezing Rain (MVD<40μm & MVD>40μm)

The capabilities of the tools for FZRA are limited. For simulation of accretions on unprotected surfaces and aft of protected areas, CFD codes may be used to determine the difference in impingement region between freezing rain and freezing drizzle. The increase in impingement area can then be simulated using a standard roughness in that region. For areas where a ridge of ice may form, a simulated ridge may be developed using a height developed analytically based upon local water catch. Ridge location could be developed from freezing drizzle icing tunnel tests, and the height would be modified based upon the ratio of local water catch (determined with CFD) between freezing drizzle and freezing rain.

Other concerns:

- Thermal Ice Protection Systems – Analyses to assess the water catch and melting/evaporation rates are acceptable to determine the capabilities of thermal systems in FZRA, provided that the analyses are based upon the validated results of the system capabilities performed for Appendix C and FZDZ. Any additional ice that may form on runback ice shapes in freezing rain should be accounted for by analysis of the runback volume. Potential roughness effects ahead of the runback should be addressed.

- Mechanical Ice Protection Systems – It is acceptable to use the same pre-activation and intercycle and residual ice shapes as for FZDZ. The limits of accretion should be determined using CFD tools.

- Validation of Visual Cues – Use of qualitative analysis that the visual cues used for FZDZ will function in FZRA conditions is acceptable.

5. Certification for a Portion of Appendix X - §25.1420(a)(2)

Current technology does not support distinguishing between FZDZ and FZRA in flight. Due to this concern, airplanes should not be certificated for compliance with §25.1420(a)(2) based upon the boundaries between FZDZ and FZRA. Certification to §25.1420(a)(2) is discussed in the main body of the AC; however, there are concerns about the ability of applicants to define ice shapes which distinguish between the approved portions and the unapproved portions with the current simulation tools. As such, certification for a portion of Appendix X will be challenging and would require close coordination with certifying authorities.

Certification for a portion of Appendix X that considers phase of flight (e.g., takeoff, holding), as discussed in main AC paragraph 8(b), may be feasible. Any method of certification for a portion of Appendix X should be included as part of the certification planning and will require approval from the cognizant certifying authority.

In cases where only one engineering tool or none have been validated as capable of simulating FZDZ or FZRA, the means of compliance should include flight tests in measured Appendix X icing conditions to verify ice accretions.

6. Certification for Unrestricted Operations - §25.1420(a)(3)

The use of the simulation tools as described for detect and exit airplanes may be used for airplanes certificated in accordance with §25.1420(a)(3). However, in cases where only one engineering tool or none have been validated as capable of simulating FZDZ or FZRA, the means of compliance should include flight tests in measured Appendix X icing conditions to verify ice accretions.

7. Compliance with §§25.1323, 25.1325, and 25.773

7.1. Compliance with §§25.1323, 25.1325 and 25.773 for Appendix C and Appendix X Conditions

The exposures to Appendix C and Appendix X conditions should consider holding operations consistent with the applicable Holding Ice definition contained in Part II of those appendices.

7.2. Compliance with §25.1323 for Mixed-Phase and Ice Crystal Conditions

The exposures to mixed-phase and ice crystal conditions should consider the horizontal extents defined in the rule.

8. Standard Roughness Levels for Appendix X Ice Shapes

Ice shapes for Subpart B testing are typically based upon icing tunnel tests or CFD computations or both. Current CFD programs do not provide roughness information. Roughness levels and aft extent of roughness for Appendix X ice shapes should be determined from icing tunnels or tanker testing, if the capabilities exist. However, when the empirical capabilities do not exist, the roughness levels (or equivalents) as defined in Table 2 may be used. Note that roughness levels for Appendix C ice shapes are discussed in AC 25-25.

Ice Type	Roughness Height (mm)	Particle Density	Notes
FZDZ & FZRA, thin accretions; thickness < 3mm (0.12 inch)	1.5 to 2 mm (0.06 to 0.08 inch) or 16 to 20 grit sandpaper	Particles density to cover 50% to 70% of total area	Use to simulate pre-detection, initial accretions, or roughness on computed ice shapes
FZDZ thickness > 3 mm (0.12 inch)	3 to 6 mm (0.12 to 0.24 inch) Mean particle size ~4.5mm		Intercycle, residual, unprotected surfaces
FZRA thickness ≥ 3 mm (0.12 inch) and ≤ 6 mm (0.24 inch)			
FZRA thickness ≥ 6 mm (0.24 inch)	6 to 8 mm (0.24 to 0.31 inch) Mean particle size ~7 mm		

Notes:

1. The simulated roughness elements should approximate roughness elements observed in icing tunnels or natural icing. Smooth and spherical elements should not be used because they may result in non-conservative aerodynamic results.
2. For computed ice shapes, the roughness simulation should be extended aft to the limits of predicted accretion (where the ice accretion thickness is calculated as 0.015").

Table 2 - Appendix X Standard Roughness