Aircraft Icing
Supercooled Large Droplets, Mixed Phase Icing, Appendix O, Appendix P

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Outline

- Background
- Review of accident and incident lessons
- Existing CS-25 certification specifications for operation in icing conditions
- CS-25 rule change proposal
- Appendix O – SLD icing conditions
- Appendix P – Mixed phase and ice crystal icing envelope (deep convective clouds)
- Ice accretion simulation in mixed phase conditions
Background

- It has been evidenced that the **icing environment** used for certification of large airplanes and turbine engines needs to be **expanded** in order to improve the level of safety when operating in icing conditions.
- On 31 October 1994, near Roselawn, Indiana-USA, an accident involving an Avions de Transport Régional ATR 72 occurred in icing conditions believed to include **freezing drizzle drops**.
Background

- Indeed, the accident investigation led to the conclusion that freezing drizzle conditions created a **ridge of ice** on the wings’ upper surface **aft of the de-icing boots** and forward of the ailerons.

- It was further concluded that the ridge of ice resulted in an uncommanded roll of the airplane. The atmospheric condition (freezing drizzle) that may have contributed to the accident is **outside the existing CS-25 Appendix C icing envelope** that is used for certification of large airplanes.
Background

• Another atmospheric icing condition which airplanes may experience and that is outside of the Appendix C icing envelope is freezing rain. These kinds of icing conditions constitute an icing environment known as Supercooled Large Drops (SLD).
Background

• Since at least the early 1990s, commercial aircraft have encountered several in-service events (probe blockage, engine rollbacks and flameouts ...) while flying at high altitudes in tropical regions.

• Information gathered on over 100 weather related engine power loss events has permitted to conclude that aircraft flying through areas of high Ice Water Content (IWC) are subject to a specific type of weather induced incidents.

• High water content is often found in deep convective clouds present in the warm tropical regions. These clouds can contain deep updraft cores that transport low-level air high into the atmosphere, during which water vapor is continually condensed as the temperature drops.

• In doing so, these updraft cores may produce localized regions where very high concentration of ice crystals can be encountered and where ice particles may also be found simultaneously with supercooled droplets (mixed phase icing conditions).
Background

• Service experience of different engine types installed on CS-25 aircraft has also identified the potential for a multiple engine failure during take-off, after prolonged ground operation in freezing fog. A multiple engine failure during take-off would compromise safe flight and landing.

• Moreover, falling and blowing snow is a weather condition, which needs to be considered for the powerplants and essential Auxiliary Power Units (APUs) of transport airplanes.

• Although snow conditions can be encountered on the ground or in flight, there is little evidence that snow can cause adverse effects in flight on turbojet and turbofan engines with traditional Pitot style inlets where protection against icing conditions is provided.

• However, service history has shown that in-flight snow (and mixed phase) conditions have caused power interruptions on some turbine engines and APUs.
Therefore, an **Aviation Rulemaking Advisory Committee (ARAC)** was tasked by the **Federal Aviation Administration (FAA)** in December 1997, through its **Ice Protection Harmonization Working Group (IPHWG)**, to perform the following actions:

- Define an icing environment that includes **SLDs**;
- Consider the need to define a **mixed phase icing** environment (supercooled liquid and ice crystals);
- Devise requirements to assess the ability of an airplane to either safely operate without restrictions in these conditions or safely operate until it can exit these conditions;
- Study the effects icing equipment changes could have on regulations on “Pilot compartment view”, “Airspeed indicating system” and “Static pressure systems”;
- Consider the need for a regulation on ice protection for angle of attack probes.
### Accidents in severe icing conditions including SLD

<table>
<thead>
<tr>
<th>Date</th>
<th>Type of aeroplane</th>
<th>Location</th>
<th>Fatalities</th>
<th>Injuries</th>
<th>Hull loss of the aeroplane</th>
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<tbody>
<tr>
<td>29 April 1993</td>
<td>EMB-120</td>
<td>Pine Bluff, USA</td>
<td>0</td>
<td>13 minor</td>
<td>Yes</td>
</tr>
<tr>
<td>31 October 1994</td>
<td>ATR-72</td>
<td>Roselawn, USA</td>
<td>68</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>30 December 1995</td>
<td>Cessna 560</td>
<td>Eagle River, USA</td>
<td>2</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>09 January 1997</td>
<td>EMB-120</td>
<td>Monroe, USA</td>
<td>29</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>19 March 2001</td>
<td>EMB-120</td>
<td>Orlando, USA</td>
<td>0</td>
<td>0</td>
<td>Severe damage</td>
</tr>
<tr>
<td>21 December 2002</td>
<td>ATR-72</td>
<td>Pengu island, Taiwan</td>
<td>2</td>
<td>0</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Review of accidents and incidents lessons

- IPHWG found accidents and incidents that are believed to have occurred in **icing conditions that are not addressed in Appendix C**.
- These icing conditions resulted in **flight crews losing control of the aircraft** and in some cases **engine power loss**.
- The review found **hull losses and fatalities associated with SLD conditions but not for ice crystal and mixed phase conditions**.
- However, there have been a number of **engine power loss events reports during the last two decades, which occurred in presence of ice crystals and mixed phase**. Some of them involved multi-engine power loss.
- Incident history also reveals that temporary loss of or erroneous airspeed indications in severe icing conditions (in deep convection).
  - Static ports are not prone to icing because they are flush mounted,
  - Pitot or pitot-static probes are prone to icing.
Existing CS-25 certification specifications for operation in icing conditions

- CS-25 provides a set of requirements involving protection systems and airplane operation principles.
- CS 25.1419 (Ice protection) requires the aeroplane to be able to “safely operate in the continuous maximum and intermittent maximum icing conditions of Appendix C”.
- Minimum performance and handling qualities, as well as to detect airframe icing and to operate ice protection systems are also required in these icing conditions.
Existing CS-25 certification specifications for operation in icing conditions

• These specifications can be found in:
  – CS 25.21: Proof of compliance,
  – CS 25.103: Stall speed,
  – CS 25.105: Take-off,
  – CS 25.107: Take-off speeds,
  – CS 25.111: Take-off flight path,
  – CS 25.119: Climb: all engines operating,
  – CS 25.121: Climb: one engine inoperative,
  – CS 25.125: Landing,
  – CS 25.143: Controllability and maneuvrability,
  – CS 25.207: Stall warning,
  – CS 25.237: Wind velocity,
Existing CS-25 certification specifications for operation in icing conditions

- These specifications can be found in:
  - CS 25.1093(b): Turbine engines air intake system de-icing and anti-icing,
  - CS 25.1093(b)(1): Turbine engine safe operation throughout Appendix C icing conditions,
  - CS 25.1093(b)(2): Defines test conditions in order to demonstrate the safe operation of the powerplant systems in freezing fog conditions at idle on ground.
CS-25 rule change proposal

• It is proposed to amend CS-25 to better protect large airplanes certified for flight in icing conditions.
• The new icing environment would include Supercooled Large Drops (Appendix O), Mixed Phase and Ice Crystals (Appendix P).
• It is also proposed to update the requirements for turbine engine air intake system protection (updated freezing fog conditions and new falling and blowing snow conditions).
• In connection with this proposal an amendment of CS-E to update turbine engine certification is proposed.
Appendix O – SLD icing conditions

• Supercooled Large Droplets develop as falling snow encounters a layer of warm air deep enough for the snow to completely melt and become rain/drizzle.

• As the drops continue to fall, they pass through a thin layer of cold air just above the surface and cools to a temperature below freezing.

• When the supercooled drops strike the frozen ground (power lines, or tree branches), they instantly freeze, forming a thin film of ice, hence freezing rain.
Appendix O – SLD icing conditions

- Drop becomes supercooled when crossing the thin layer of cold air close to the ground and freezes upon impact with cold surfaces.
- Freezing rain and freezing drizzle are most commonly found in a narrow band on the **cold side of a warm front**, where surface temperatures are at or just below freezing.
Appendix O – SLD icing conditions

• Description of 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 O continuous maximum (stratiform clouds) icing conditions.

• For Appendix O, SLD icing conditions consist of freezing drizzle and freezing rain occurring in and/or below stratiform clouds.
Appendix O – SLD icing conditions

- Freezing Drizzle (Conditions with maximum drop diameters from 100 μm to 500 μm):
  - Pressure altitude range: 0 to 6706 m (22000 feet),
  - Maximum vertical extent: 3656 m (12000 feet),
  - Horizontal extent: standard distance of 32.2 km (17.4 nautical miles),
  - Total liquid water content.
Appendix O, Freezing Drizzle, LWC

![Graph showing the relationship between Ambient Temperature (°C) and Liquid Water Content (g m⁻³) for Freezing Drizzle with MVD < 40 microns and MVD > 40 microns.]
Appendix O, Freezing Drizzle, droplet diameter distribution

Freezing Drizzle MVD < 40 microns

Freezing Drizzle MVD > 40 microns
Appendix O, Freezing Drizzle, altitude and temperature
Appendix O – SLD icing conditions

• Freezing Rain (Conditions with maximum drop diameters greater than 500 μm):
  – Pressure altitude range: 0 to 3656 m (12000 ft) MSL,
  – Maximum vertical extent: 2134 m (7000 ft),
  – Horizontal extent: standard distance of 32.2 km (17.4 nautical miles),
  – Total liquid water content.
Appendix O, Freezing Rain, LWC
Appendix O, Freezing Rain, droplet diameter distribution

Freezing Rain MVD < 40 microns

Freezing Rain MVD > 40 microns
Appendix O, Freezing Rain, altitude and temperature

![Graph showing the relationship between ambient temperature and pressure altitude. The graph is a straight line indicating a linear relationship.](image-url)
Appendix O, Horizontal Extent, Drizzle and Freezing Rain
Appendix P – Mixed phase and ice crystal icing envelope (deep convective clouds)

• High water content is often found in deep convective clouds present in the warm tropical regions around the globe.

• These clouds can contain deep updraft cores that transport low-level air high into the atmosphere, during which water vapour is continually condensed as the temperature drops.

• In doing so, these updraft cores may produce localized regions where very high concentration of ice particles, or ice crystals, can be encountered. Such conditions are called glaciated icing conditions.

• These ice particles can also be found simultaneously with supercooled droplets. Such conditions are called mixed phase icing conditions.
Appendix P – Mixed phase and ice crystal icing envelope (deep convective clouds)

• Ice particles are mainly encountered in high levels of atmosphere (above the freezing level estimated at approximately 20000ft for a standard atmosphere).

• This means that ice particles are present in:
  – high altitude clouds (cirrus, cirrostratus, cirrocumulus),
  – aircraft contrails (condensation trails – artificial cirrus clouds),
  – deep convective complexes (anvils of thunderstorms, tropical storms...)

![Diagram of high ice water content](image-url)
Appendix P – Mixed phase and ice crystal icing envelope (deep convective clouds)

- Defines the ice crystal and mixed phase icing environment requiring any flight instrument external probe (mostly pitot probe) to operate normally.
- Within the envelope, total water content (TWC) has been determined based upon adiabatic lapse rate (1°C/100 m) defined by the convective rise of 90% relative humidity air from sea level to higher altitudes and scaled by a factor of 0.65 (in order to obtain maximum probable or 99 % values instead of maximum values) to a standard cloud length of 17.4 nm.
Appendix P – Mixed phase and ice crystal icing envelope

Figure 1 – Convective cloud ice crystal envelope
Appendix P – Mixed phase and ice crystal icing envelope
Appendix P icing envelope

![Icing Envelope Limits Graph]

- Ambient Temperature - deg C
- Altitude - ft

- Appendix D
- Cruise
- Idle Descent
- Hold
Appendix P icing envelope
Appendix P – Supercooled liquid portion of TWC

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

• The TWC can be treated as completely glaciated (ice crystal) except:

<table>
<thead>
<tr>
<th>Temperature range - deg C</th>
<th>Horizontal cloud length</th>
<th>LWC - g/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to -20</td>
<td>≤92.6 km (50 nautical miles)</td>
<td>≤1.0</td>
</tr>
<tr>
<td>0 to -20</td>
<td>Indefinite</td>
<td>≤0.5</td>
</tr>
<tr>
<td>&lt; -20</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>
Appendix P – Exposure length influence on TWC

![Graph showing the relationship between Total Water Content (TWC) and Horizontal Extent - Nautical Miles. The graph indicates a decreasing trend as the horizontal extent increases.]
Appendix P – Glaciated Conditions

- In service occurrences show that several Pitot Icing events in Glaciated Conditions above 30,000 ft are outside of the Appendix P domain in terms of altitude and outside air temperature.
- A reported event occurred at -70° C.
- Testing may not be possible at such a low temperature due to simulation tool limitations.
- However, presence of ice crystals has been observed and it is anticipated that an extrapolation of existing data at higher temperature should allow assessing the predicted performance of the probe heating down to this minimum temperature.
Appendix P – Glaciated Conditions

• The standard cloud of 17.4 nm and the associated average TWC concentration values provided by Appendix P may not provide the most conservative conditions for Flight Instrument External Probes testing.

• The “maximum” or “peak” TWC concentration values should be considered instead of the 17.4 nm values provided by Appendix P. They correspond to 17.4 nm values multiplied by a factor of 1.538=1/0.65.
Appendix P – Max concentration values (TWC) Glaciated conditions
Appendix P – Mixed phase Conditions

• In service occurrences show several Pitot Icing events in Mixed Phase Conditions, between 20 000 - 30 000 ft are outside of the Appendix P domain in terms of altitude and outside air temperature.

• The 2.6 nm TWC concentration values should be considered instead of the 17.4 nm values provided by Appendix P. They correspond to 17.4 nm values multiplied by a factor of 1.175.
Appendix P – Max concentration values (TWC) Mixed Phase conditions
Appendix P – Ice particles

• There are several methods for generating ice particles used in testing which produce a wide range of particle sizes.
• Some methods for generating ice particles result in irregular shapes which are difficult to quantify in terms of mean particle diameter.
• The heat requirements for mixed phase icing are driven primarily by the quantity of ice collected in the probe rather than the size of ice particles.
Appendix P – Ice particles

• Particles in the range of 50-1000 microns tend towards ballistic trajectories with collection efficiencies approaching one on conventional pitot probes.

• Past experience shows that an ice crystal **MMD size of 150 microns** is the more **practical size** to be tested in a wind tunnel.

• For mixed phase conditions, it should be tested together with supercooled droplet MVD size of 20 microns.
Ice accretion simulation in mixed phase conditions

- Since frozen ice crystals bounce off cold solid surfaces, for observing ice growth on a surface in glaciated icing conditions, the airflow environment, or the accreting site itself, has to be warm (above freezing) to allow ice crystals to partially stick after impact. For engine the following scenario, as proposed by Mason et al, is generally assumed:
  - The warm airflow inside the engine melts some of the ice crystals.
  - When droplets and partially melted ice particles impact a solid surface, a water film can be created on the surface.
  - The water film captures incoming ice particles long enough for heat transfer to take place.
  - Heat is extracted from the surface until the freezing point is reached, and ice begins to form.
  - After this point, it is contended that further impingement of liquid and ice particles on the surface would accrete and shedding could occur.
Ice accretion simulation in mixed phase conditions

Compared to the case of supercooled droplet icing conditions, major modifications have to be introduced as far as the modeling of ice-crystal and mixed-phase ice accretion is concerned:

• Since ice crystal accretion is supposed to mainly occur in a warm environment, it is mandatory to consider melting of the ice particles, evaporation / sublimation and heat exchange with the air flow along their trajectory.

• Ice crystals being non-spherical, the influence of their shape must be taken into account in the expression of the heat and mass exchange coefficients and also in the expression of the force exerted by the air on the particles.

• Since ice particles (or partially melted ice particles) may bounce, shatter and partially stick when they impinge on a dry or a wetted surface, an impingement model must be introduced which takes into account the influence of the wall temperature, film thickness and particle liquid water mass fraction on the outcome of the impact.
Ice accretion simulation in mixed phase conditions

- Re-emitted particles must also be accounted for since they may re-impinge downwind in the engine core.
- As shown by experimental results, erosion effects may have a strong influence and must also be considered in the impingement model.
- Since the film thickness has an influence on the probability for a crystal to stick (or partially stick) after the impact, it is necessary to introduce a model for being able to compute the local water film thickness on the wall.
- The presence of ice particles (or partially melted ice particles) in the mix must also be taken into account in the mass and energy balance equations which are used for computing the local ice accretion rate.
References

• EASA, Notice of Proposed Amendment (NPA) 2011-03
• EASA, Notice of Proposed Amendment (NPA) 2012-22
• EASA, Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes, CS-25, Amendment 16.