ICE CRYSTAL ICING THREAT TO ENGINES

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Check this box if presentation contains "no technical data"

Summarize the export classifications of all slides in this presentation as instructed below:

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<th>Instructions: Box 1 and one (1) of boxes 2-5 must be completed</th>
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ICE CRYSTAL ICING - AGENDA

Background

Engine Ice Ingestion

Regulatory Framework

Regulatory Working Groups

Next Steps

Conclusions
ICE CRYSTAL ICING - AGENDA

LET'S GET STARTED

Background

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Encounters with ice crystals at high-altitude now recognized to be responsible for engine damage / power loss as well as potential aircraft hazard.

Convective clouds lift supercooled liquid water droplets thousands of feet into the atmosphere.

Ice crystals form due to collision/agglomeration of supercooled droplets:

- Over 100 known events on multiple aircraft & engine models
- Events generally reported either during cruise or descent phase
- Air France AF447 accident attributed to obstruction of aircraft Pitot probes by ice crystals at FL350
High-altitude and cold temperature
Events usually in vicinity of convective clouds or thunderstorms
Warmer conditions than ISA

Typically between ISA+10°C to ISA+20°C

Reports of no airframe icing, only visible moisture

Perception of rain on the windshield

Light to moderate turbulence
Primarily affects turbofan engines

Aircraft/Engine total air temperature probe discrepancy
ICE CRYSTAL ICING - BACKGROUND

COLORS CORRESPOND AIRPLANE RADAR RETURNS FOR PRECIPITATION

COMET MetEd program: education/training resources about meteorology, weather forecasting, and related geoscience topics.

Ref: “Avoiding Convective Weather and Ice Crystal Engine Events”, Boeing article from Matthew L. Grzych
**Conventional Icing:**
Super-cooled liquid water droplets
Freeze upon contact with engine parts with below-freezing surface temperatures forming rime or glaze ice
Typically at altitudes below 28,000 ft
LWC < 2 g/m³

**Ice Crystal Icing:**
Solid ice particles bounce on cold surfaces
Ice accretion occurs deep within engine where surfaces are warmer than freezing
Typically at altitudes above 28,000 ft
IWC as high as 9 g/m³
ICE CRYSTAL ICING - BACKGROUND

Most ICI events are outside of the FAR 25 Appendix C icing envelope and generally at warmer conditions than ISA

Figure extracted from: Mason, J., and al., “The Ice Particle Threat to Engines in Flight”, AIAA 2006-206, January 2006, Reno, Nevada
Aircraft traffic/congestion forces more flights in geographic areas that are prone to ice crystal conditions:

- More events conducive to engine power loss or mechanical damage.

Ref: CAAC Review on Ice Crystal Icing, Boeing Presentation from Melissa Bravin, 2017
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ICE ACCRETION INSIDE AN ENGINE

**Supercooled droplet icing**: Accretion on the front of the engine like on the nosecone, fan, and first stages of the LPC

**Ice crystal icing**: Accretion deep inside the engine like on the final stages of the LPC, LPBOV, and initial stages of the HPC

Ice crystal accretion can occur on engine core surfaces where temperature is much higher than freezing.
When ice crystal particles enter the engine inlet:

- Ice particles entering engine core will reach warm environment where some ice crystals start to melt leading to mixed phase composition (liquid water + ice)
- Melted particles impinge on warm engine surfaces (compressor walls & airfoils), leading to mixture of liquid water & ice on the warm surfaces (slush-like)
- Slushy composition ideal for capturing incoming ice crystals on core surfaces, increasing amount of slush within core
- Heat extracted from core surfaces until the freezing point is achieved & liquid portion on the wall solidifies
Engine manufacturers use heated or unheated inlet probes for measurements of:

– Pressure
– Temperature, or
– Both (integrated PT/TT probe)

Heated probes typically efficient for:

– For preventing ice accretion in supercooled droplet conditions, but
– Vulnerable to probe blockage in ice crystal conditions

Unheated probes are susceptible to:

– Supercooled droplet icing conditions, but
– Less vulnerable to blockage in ice crystal environments

Engine operation anomalies occur when ice crystals block an engine air data probe:

• Engine power rollback and lack of throttle response
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Aircraft & engine icing certification bases included:

AWM 533.68 Induction System Icing
AWM 52x.1093 Induction System Icing Protections
FAR 25 Appendix C icing envelope:
  - Supercooled LWC
  - Continuous Maximum & Intermittent Maximum clouds
Mean Effective Diameter from 0 to 50 microns (liquid water droplets)
Ambient air temperature from 0 to -30°C
Altitude from 0 to 28,000 ft
ICING CERTIFICATION – POST-2015

ATR-72 accident in 1994 (Roselawn Ill.):

- Atmospheric conditions exceeded those of FAR 25 Appendix C

- NTSB issued safety recommendations to FAA

- FAA tasked ARAC committee to define Supercooled Large Droplet (SLD) and ice crystal & mixed phase conditions

- **Ice Protection Harmonization Working Group** (IPHWG) issued a draft report in September 2005 based on recommendations from **Engine Harmonization Working Group** (EHWG) proposed draft rules for engine compliance in SLD and ice crystal conditions
ICING CERTIFICATION – POST-2015

FAA issued NPRM 10-10 in 2010: Airplane and Engine Certification Requirements in Supercooled Large Drop, Mixed Phase and Ice Crystal Icing Conditions.

FAA amendment 33-34 published November 2014 (eff. January 2015) included requirements on Ice Crystal, SLD, & Mixed phase conditions:

- 14 CFR 33.68 extensively revised
- 14 CFR 2x.1093 revised
- Appendix D introduced – defines ice crystal environmental parameters
- Appendix O introduced – defines SLD environmental parameters
Appendix D envelope is based on the ICI engine events

Peak TWC levels are based on theoretical adiabatic lift calculations
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ICING WORKING GROUPS

EHWG → Engine Harmonization Working Group
IPHWG → Ice Protection Harmonization Working Group
ICC → Ice Crystal Consortium
EIWG → Engine Icing Working Group
HAIC → High Altitude Ice Crystal
New ARAC Ice Crystal Working Group

ARAC → Aviation Rulemaking Advisory Committee
Objective:
To understand of high-altitude ice crystals and their potential interactions with jet engine-powered aircraft by conducting fundamental research via a joint program controlled and funded by the Consortium signatories.

Members:
Industry: Boeing, Airbus, P&W, Honeywell, GE, Rolls-Royce, Snecma, and Textron Aviation
Research centers: NRCC and NASA

Tests to understand ICI physics:
Cascade geometry & EGV rig at NRC
Honeywell ALF502 at NASA PSL-3
(ALF502 engine experienced multiple ice crystal events in service)

Unique collaboration among industry & research institutions to address safety issue.
ICE CRYSTAL CONSORTIUM WORKING GROUP

Test data from NRC cascade, EGV rig test data, and results from Honeywell ALF502 at PSL (Propulsion Systems Laboratory) allows engine companies to develop ICI analytical tools.

ALF502 testing was able to reproduce in-service rollback events.

Ref: AIAA-2016-3892

ALF502 tests at NASA PSL

Ice accretion on the LPC outer wall

Ref: AIAA-2017-4085

Figure 9.—LF11 ice accretion at called rollback

Ice accretion location on the ALF502 LPC outer wall

Ref: AIAA-2017-4085
ENGINE ICING WORKING GROUP

Objective: Propose recommendations for engine icing regulatory compliance

Composed of industry members (similar members as ICC) + FAA, TCCA, EASA

Affiliated with the Aerospace Industries Association (AIA)

Status: working group is active

Example of WG activities:
- Provided comments to AIA on the FAA NPRM 10-10 (Completed)
- Defined Ground Icing threat at cold temperatures (Completed)
Example of WG activities specifically for Ice Crystals (continued):

• Developed Means of Compliance for engine inlet probes (Completed)

• Formed four subgroups to provide recommendations to FAA for improved MoC:
  1) Ground tests
  2) Simulated altitude tests
  3) Analytical tools
  4) Susceptible features

• Report to be provided by early 2019.
Flight characterization of the ice crystal environment through International efforts

Flight characterization campaigns:
2014 → Darwin, Australia
2015 → Cayenne, French Guyana
NEW ARAC ICE CRYSTAL WORKING GROUP TASK

Formed in October 2018:
WG activities begin in January 2019.

Review ice crystal data from flight characterization campaigns

Evaluate published Appendix D ice crystal envelope against new data from ice crystal flight campaigns (Darwin, Australia; Cayenne, French Guyana):
- Appendix D may not be representative of natural ice crystal environments

Identify areas where FAA & EASA ICI regulations/guidance not harmonized:
- Example: TWC levels for engine probe substantiation are higher for EASA than FAA

Propose changes to increase harmonization
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CURRENT AND FUTURE MOC ON ICE CRYSTAL ICING

- Until ice crystal tools & test techniques have been developed & validated, engine manufacturers may use **comparative analysis** as Means of Compliance (MOC) for new engine models:
  - Compare with features of already certified engine models with safe service experience
- Based on FAA feedback, ICI MoC using comparative analysis appears to be not sufficient:
  - In some cases new engine models are demonstrating less tolerance to ICI than previous designs in service, showing need to enhance current MoC
- If analytical tools are used to demonstrate IC compliance, FAA requires a validation of the tools
- Acceptable demonstration will include Critical Point Analysis (CPA) of ice crystal environment as depicted in Appendix D of part 33:
  - The severity analysis should consider both environmental & engine operational effects on accumulation, accretion locations, as well as ice shedding
P&WC AND P&WA JOINT EFFORT ON ICI

Common Objectives:

Develop ice crystal analytical models & validate against data from NRCC cascade ice crystal testing

Validate model accuracy for engine components

Develop methodology for CPA for ice crystal certification

Example of CFD-mixed phase crystal on a generic airfoil
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SUMMARY/CONCLUSIONS

• Ice Crystal Icing (ICI) recognized as environmental threat to turbofan engines.
• ICI occurs deep inside the engine core where wall temperatures above freezing exist prior entering the cloud.
  – Also probes can be susceptible to ICI
• FAA Amendment 33-34 icing requirements include Ice crystal, SLD, & Mixed phase environments
• Working Groups such as ICC and EIWG active:
  – to understand ICI physics
  – to propose MoCs.
• Future engine certification will require enhanced MoC relative to comparative analysis that is currently used