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The Ice Crystal Weather Threat to Engines

The Ice Crystal Weather Threat to Engines

Agenda

- Introduction
- Recognition of engine power-loss associated with high-altitude ice crystal weather
- Weather description
- Case study – flight near convection
- Global view of engine events
- Ice particle accretion mechanism in the engine
- Industry activities and challenges
- Summary

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Introduction

- High-altitude ice crystals in convective weather are now recognized to be a cause of engine damage and engine power-loss
- This issue affects multiple models of aircraft and engines
- Over 100 known events
- Leading cause of icing-related power-loss
- Power-loss – engine surge, stall, flameout or rollback
- Blade damage in some events – tip curls and separations

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High-Altitude Ice Crystal Icing

- High-altitude water is likely to be frozen ice particles rather than super-cooled liquid drops
- Previously, the term "icing conditions" has always been used to refer to conditions where super-cooled liquid drops adhere to cold airframe surfaces – typically altitudes 22,000 feet and below
- "Ice crystal icing" does not affect cold airframe surfaces, only some engine surfaces
- Now believed that ice crystal icing can occur deep in the engine where surfaces are warmer than freezing

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Initial Investigations of Engine Events in 2003

A confusing array of pilot reports with seemingly contradictory information initially misled investigators

- Events usually in the vicinity of thunderstorms or convective storms
- No reports of airframe icing, but rain or heavy rain at very cold temperatures led early investigators to conclude rain, not conventional icing as the cause of many events
- A temperature anomaly initially interpreted as a meteorological phenomenon
- Reports of light-to-moderate turbulence, no radar echoes at event location not consistent with flight through convective core
- At that time, only one event at -40°C known where supercooled liquid water is not possible
- A mechanism for ice-particle ice accretion not understood

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High-Altitude Ice Crystal Icing

- One commuter aircraft type suffered engine rollback events at altitudes between 28,000 – 31,000 feet
- Extensive investigation including flight-testing led to the understanding that ice particles were accreting on warm surfaces in the engine core
- Weather instrumentation conclusively established that the condition that led to engine rollback was a high concentration of ice crystals
- Industry icing committee in 2003 compared the commuter aircraft events to the large transport events
- The industry now recognizes that high-altitude large transport engine events are most likely due to ice-particle icing

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Similarities between Commuter and Large Transport Aircraft Events

- High-altitude, cold temperature
- Aircraft in the vicinity of convective clouds/thunderstorms
- Significantly warmer than standard atmosphere
- Visible moisture
- Light-to-moderate turbulence
- Precipitation on heated windscreen, often reported as rain
- Aircraft total air temperature (TAT) probe anomaly
- Lack of observations of significant airframe icing
- No pilot reports of weather radar returns at the event location (only large transport aircraft pilots queried)
- No ice detector response, if installed

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Weather Connected to Engine Ice Crystal Icing Events

- Convective weather containing ice crystals – isolated cumulonimbus or thunderstorms to squall lines and tropical storms
- Deep convective clouds lift high concentrations of water thousands of feet into the atmosphere
- The atmosphere's ability to hold moisture is dependent upon temperature (warmer temperatures = more moisture). Warm, humid surface air is lifted to high altitudes resulting in ice crystals
  - Measurements up to 8 g/m^3. The certification standard for supercooled liquid water for engines is 2 g/m^3
- Ice crystals exist from temperatures near zero to much colder
- Away from the core of the storm, in the anvil, ice particles have been measured to be very tiny – the particle size of baking flour

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Case Study of an Engine Event

- Aircraft on descent into Taipei, weather and TAT anomaly immediately encountered at 38000 ft (-42°C), moderate turbulence, and some lightning in vicinity
- Brief power loss event occurred at 30,000 ft – engines restarted quickly
- Pilot reported heavy rain at -25°C (ambient temperature)
- No radar echoes at the altitude and location of the aircraft
- Ice detector – no response – indicative no super-cooled liquid present
- Rain on windscreen – tied to particles melting, later confirmed to be ice crystals, and described by the pilot to have a unique sound

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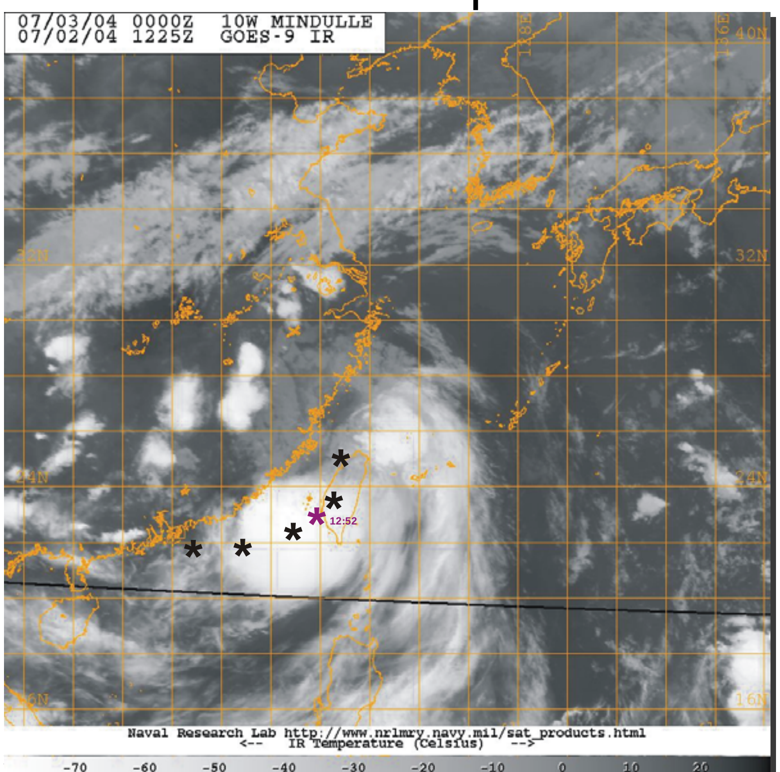
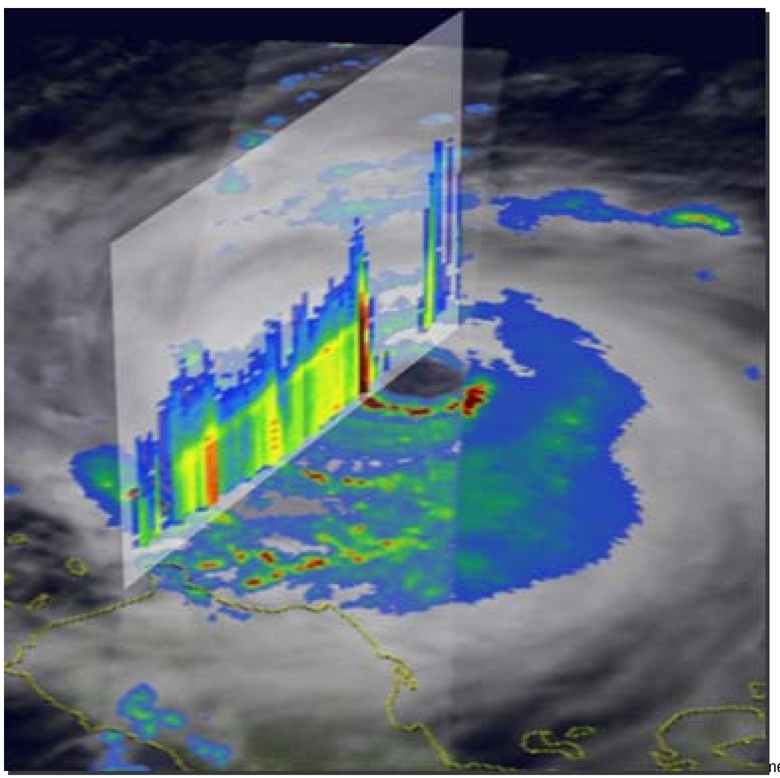
Case Study of an Engine Event

- Figure shows heavy precipitation below aircraft altitude, obvious convection of fully developed typhoon
- Lack of radar echoes on pilot's radar consistent with lack of rain, and with small ice particles at aircraft altitude





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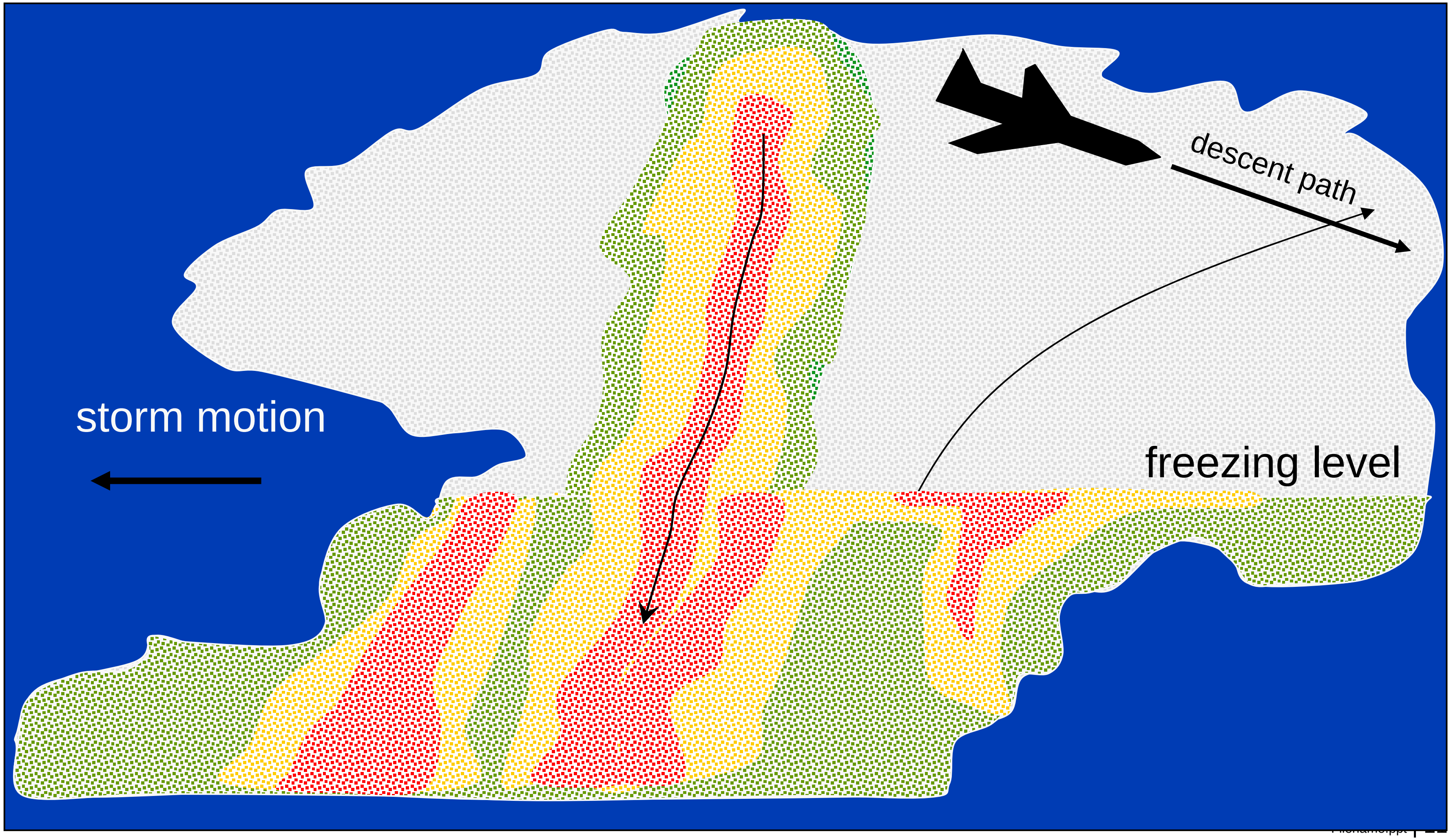
Simplified Diagram of a Cumulonimbus Cloud



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Recommendations for Flight Near Convection

- It is not practical to avoid all ice crystal conditions; crystals may not be detected by aviation radar
- Normal thunderstorm avoidance procedures may help avoid regions of high ice crystal content, however because the principal guide is airborne radar, they may not be sufficient
- These include:
  - Plan a flight path that avoids storm cells by at least 20 nautical miles
  - Fly upwind of the storm
  - Avoid flying over a storm cell. A fully developed thunderstorm can reach altitudes of more than 50,000 feet
  - Even when there are no radar returns, there may be significant moisture in the form of ice crystals at high-altitudes
  - Utilize the radar antenna tilt function to scan the reflectivity of storms ahead. Recognize that heavy rain below likely indicates high concentrations of ice crystals above

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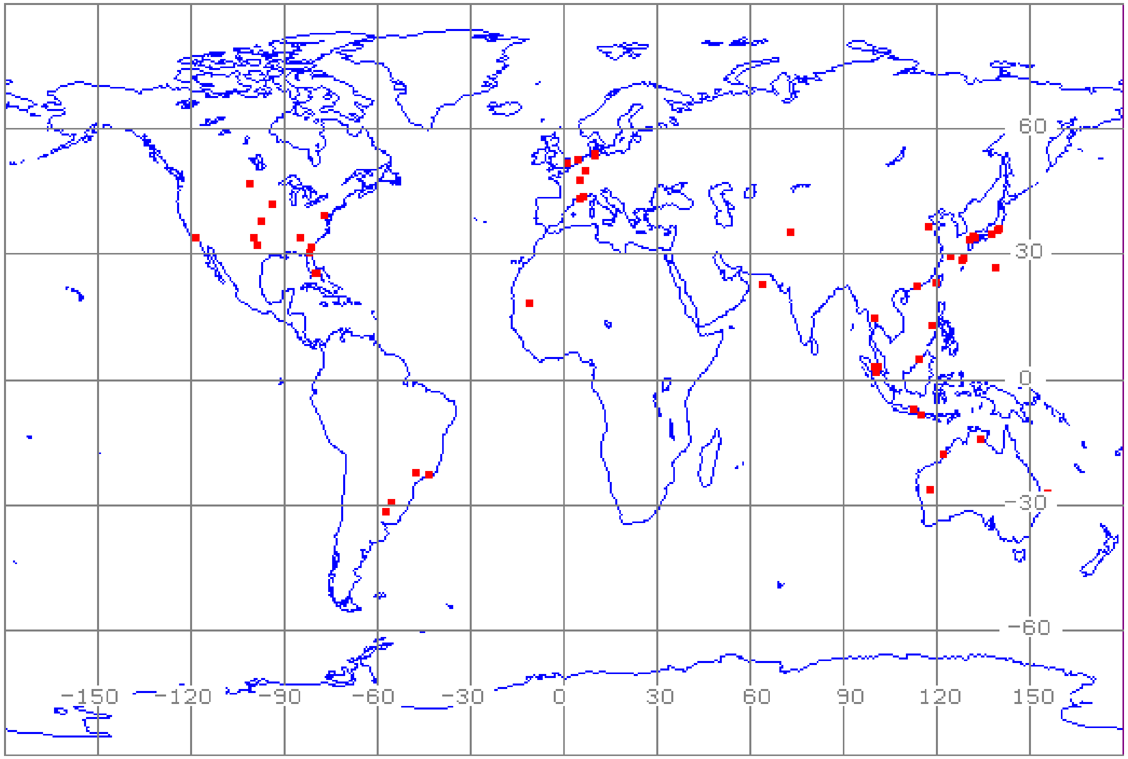
Global View of Engine Powerloss Events

- There is a large concentration of events in the Asia Pacific region – this may be due to the fact that the highest sea surface temperatures are also found in this region



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Ice Crystal Accretion in an Engine

- Frozen ice crystals bounce off cold surfaces; thus airframe icing is not noticed during aircraft operation in high-altitude ice crystals
- The physics of ice crystal accretion in the engine is not completely understood, but the accretion mechanism is thought to be:
  - When ice particles enter the engine, they will reach a zone where temperature is above freezing, at which point some will melt
  - When impinging on an engine surface, the melted particles create a liquid film
  - The liquid film captures incoming ice particles, and heat transfer takes place (captured particles start to melt)
  - Heat is removed from the metal until the freezing point is reached, at which point the liquid film begins to form ice; ice can continue to form so long as liquid is still being supplied
  - This phenomenon means ice accretion can occur well behind the fan in the engine core
- Ice shed from compressor surfaces can cause engine instability such as surge, flameout, or engine damage

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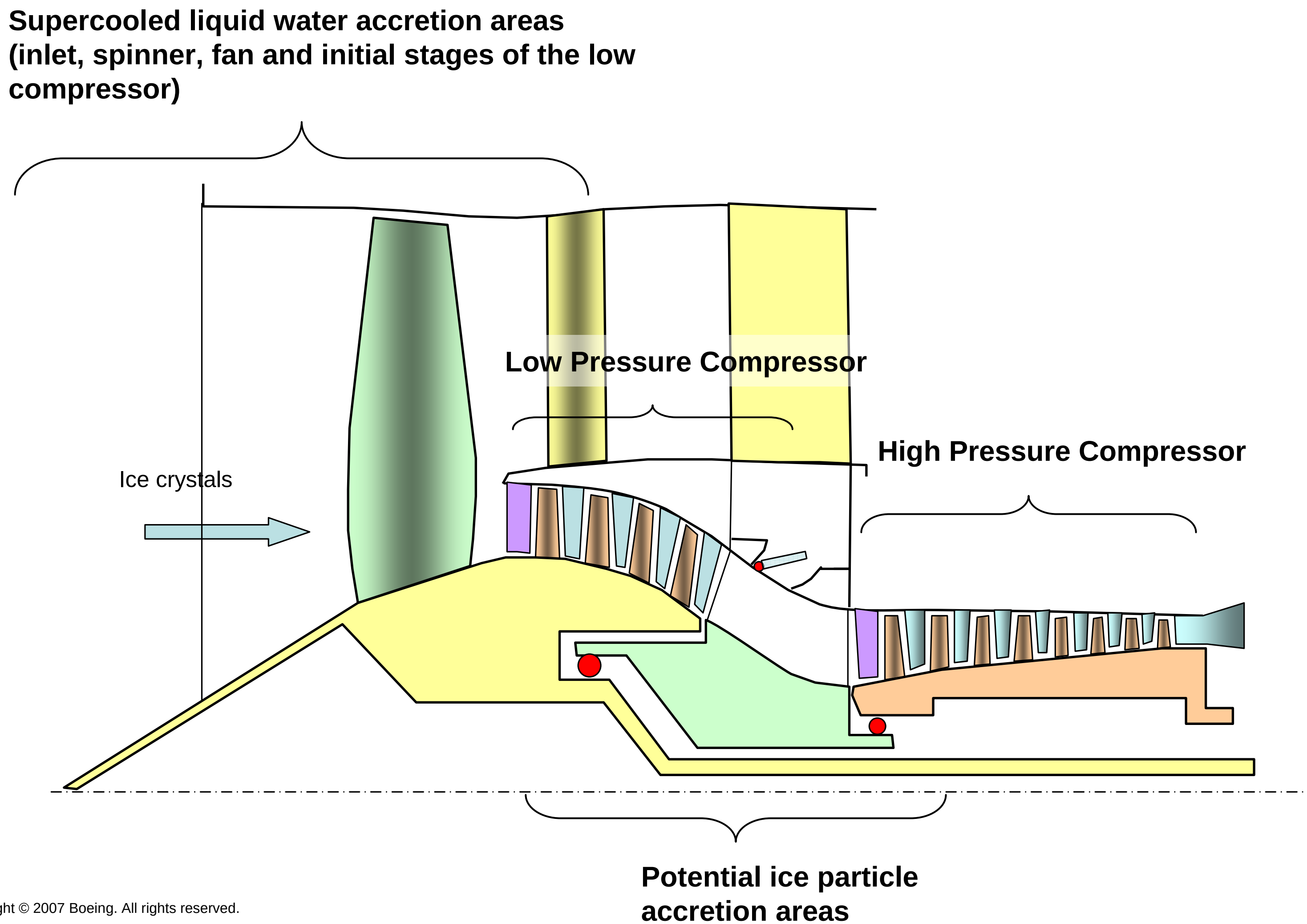
Ice Crystal Accretion in an Engine



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A Different Nature of Engine Ice Crystal Accretion

The difference between ice crystal accretion on a warm engine surface compared to a heated airframe exterior surface, in glaciated conditions (no liquid water)

- To accrete ice in both scenarios, local mixed phase conditions are required: liquid water to create wet surface film, and ice, which attaches to this film, to create the ice shell
- On the airframe surface, the ambient air is below freezing; local mixed phase is created by the melting of ice particles impacting the heated surface; once a shell of ice has accreted, there is no longer liquid on the impingement surface, and ice growth stops (similar to a cold surface in cold air, which does not accrete)
- Inside the engine, when ambient air is above freezing, local mixed phase is created by:
  - Impinging ice particles which melt on contact with the heated surface, and
  - Impinging liquid water droplets, from smaller ice particles melted by the surrounding air
  - We now have a constant source of mixed phase conditions from upstream to fuel the accretion, because mixed phase conditions are generated continuously

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A Different Nature of Engine Ice Crystal Accretion

The difference compared to supercooled liquid water icing

- The potential for much greater concentrations of ice crystals compared to supercooled liquid (8 g/m^3 vs. 2 g/m^3) means ice can accrete on surprisingly warm surfaces. Industry experience has documented over 100^{o}F
- For supercooled liquid, which requires a cold surface on which to accrete, raising the engine power and therefore temperature has the potential to prevent ice from forming
- For engine ice crystal accretion, there is a potential for ice crystal accretion on all static surfaces in the engine at any power setting which produces the right local temperature and water concentration conditions. Changing the power setting may just change the likely ice accretion site
- Ice adhesion and shedding is thought to be different than ice formed from supercooled liquid because of the differences in ice shape and ice adhesion strength influenced by the continuous heat transfer from the air through back of accretion surface, melting the bond of the ice at the surface

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Power-loss Details

- Types of power-loss and engine power recovery
  - Ice shedding induced power-loss - immediate power recovery possible
    - Surge or stall – ice shed causing compressor aerodynamic instability followed in some cases by rotor speed decay
    - Flameout – ice shed causing combustor blow-out
    - Blade damage – ice shed causing bent or broken compressor blades.
  - Ice accretion related power-loss - power recovery when ice is melted
    - Rollback – the build-up of ice on the compressor, blocking airflow. Engine control increases fuel until hitting the fuel flow limit, at which time it commands a return to idle
    - Sensor clogging – the build-up of ice around the sensor, causing anomalous reading. Inlet pressure sensor clogging can cause a falsely high reported power-setting

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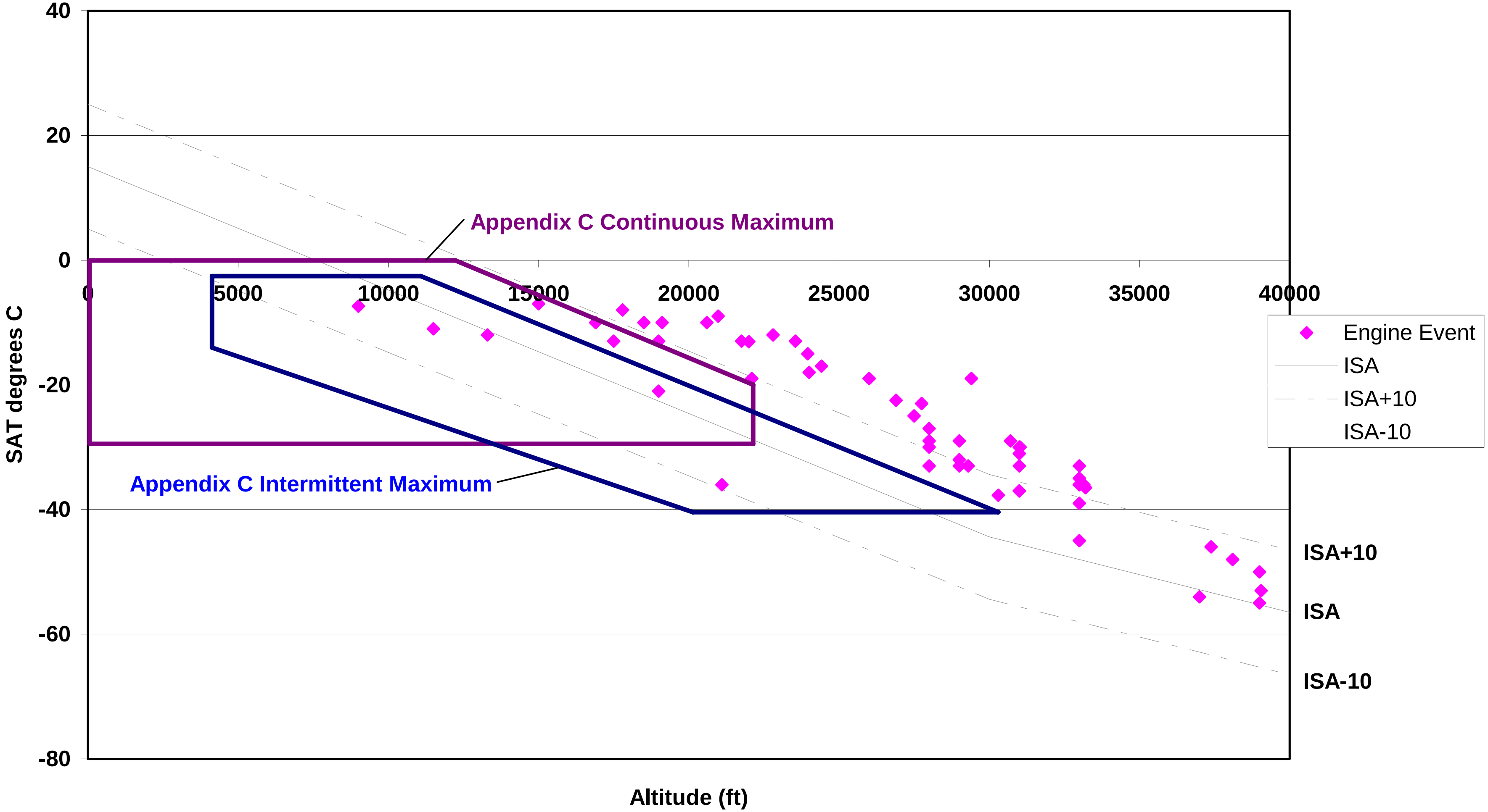
Altitude and Temperature of Engine Power-loss and Damage Events



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Why does it seem like the rate of events is increasing?

- We believe that this icing mechanism has always had the potential of affecting engines, even though it was not recognized
- All of the following may be factors in the apparent increase in rate of engine power-loss events:
  - More flights in geographic areas which are more prone to high ice water content (IWC)
  - Flying closer to convection than previously, due to aircraft congestion
  - More recognition and reporting
- Although a topic on everyone's mind, there is currently no significant evidence to conclude that changing weather patterns are producing higher IWC

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Industry Challenges – Making the Engine More Capable

- Zones of high ice particle concentrations are not easily identifiable by pilots
- High concentrations of ice particles are being penetrated, even those storms being tracked by meteorological agencies
- The most effective solution is to make the engine capable of flight in these conditions
- Experimental data characterizing the ice crystal environment is limited – flight measurements are needed
- Test methods for creating representative crystal environment do not exist
- Facilities for testing engines in these conditions do not exist
- The physics of the ice particle accretion and shedding mechanism is not fully understood

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Industry Committee Activities

- Development of Regulatory Requirements:
  - Created Appendix D to Engine Certification FAR Part 33 – ice crystal envelope – similar to Appendix C, built with theory and experimental data
  - Wrote draft rules for engine compliance in ice crystal environment
- Technology Plan developed to address unknowns:
  - Improved instrumentation to measure atmosphere
  - Flight trials to characterize atmosphere (understand particle size, concentration and extent)
  - Fundamental physics of ice accretion and shedding
  - Test methods and facilities
- Government/Industry partnerships are being developed to fund this work

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Communication

- Most of what we currently understand about the environment associated with engine events is based on pilot reports and flight data
- Previously, pilots did not always connect the engine power-loss at high altitude to the weather
- Through Flight Operations Symposiums and Bulletins, Boeing has begun to get the word out, and as a result is getting more reports of events
- Each new event will be treated as an opportunity to learn more about the weather, flight deck experiences, engine ice accretion mechanisms

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Summary / Conclusions

- Ice crystal icing conditions have been recognized as a hazard to turbofan engines
- Ice can accrete deep in the engine core where temperatures above freezing exist prior to the cloud encounter
- More detailed research on characterizing the atmospheric conditions and on the thermodynamic processes of ice accretion in the engine are needed
- Airline awareness of the potential for ice crystal icing on all airframes may provide additional information which will help Boeing and the industry understand this phenomenon