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# Current Perspectives on Jet Engine Power Loss in Ice Crystal Conditions: Engine Icing

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Matt Grzych, Boeing
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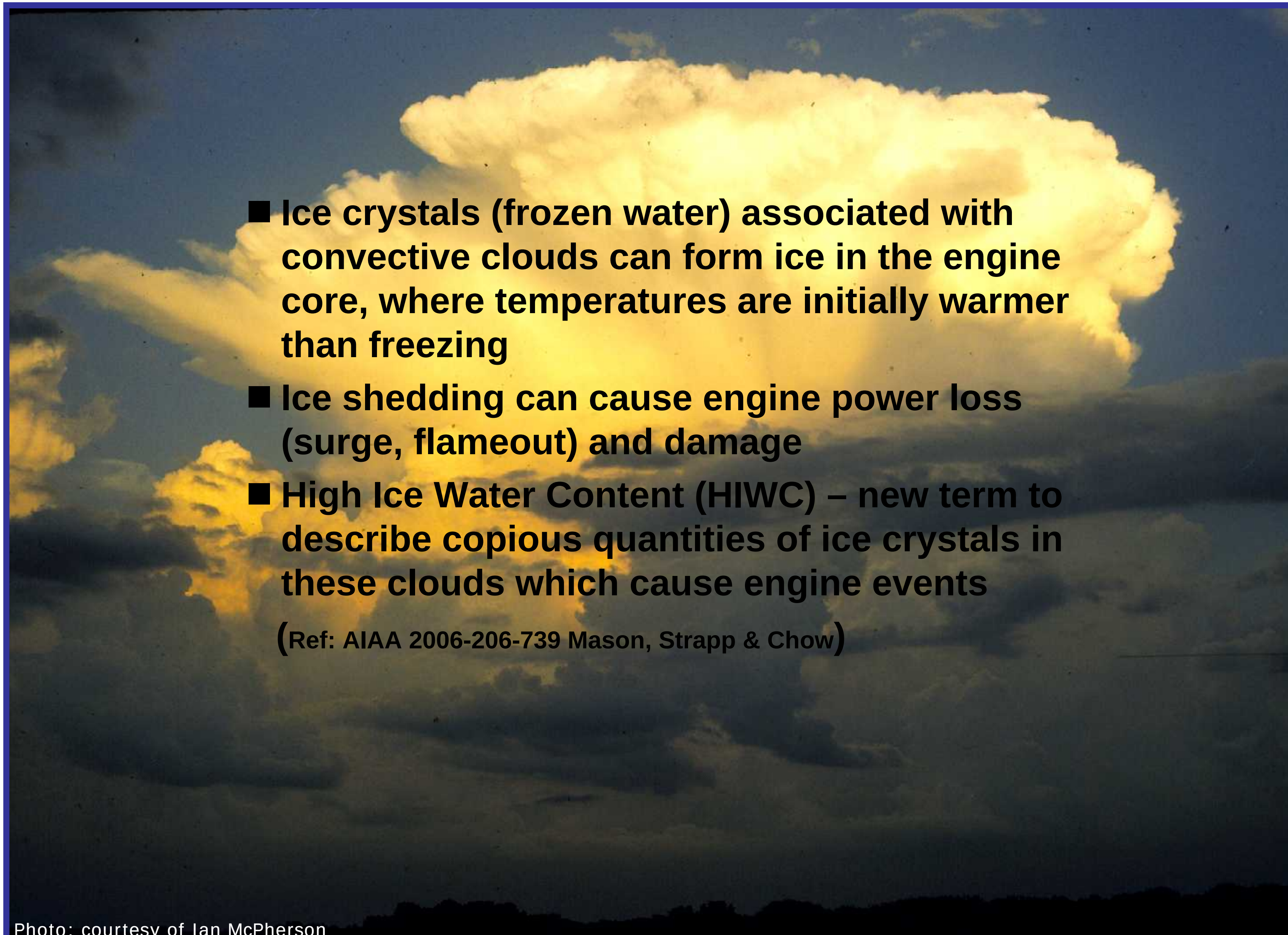
# Ice Crystal Icing - Definition



- Ice crystals (frozen water) associated with convective clouds can form ice in the engine core, where temperatures are initially warmer than freezing
- Ice shedding can cause engine power loss (surge, flameout) and damage
- High Ice Water Content (HIWC) – new term to describe copious quantities of ice crystals in these clouds which cause engine events

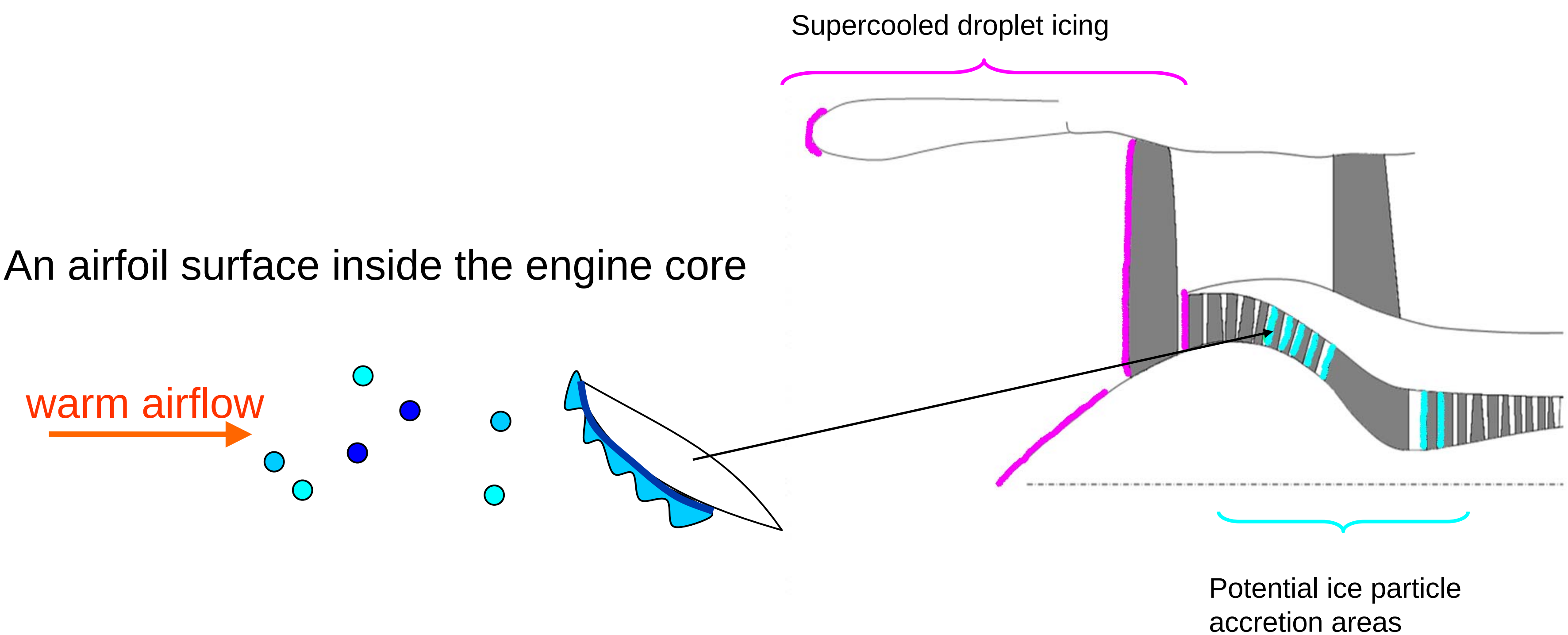
(Ref: AIAA 2006-206-739 Mason, Strapp & Chow)

Photo: courtesy of Ian McPherson

# What is Ice Crystal Icing?

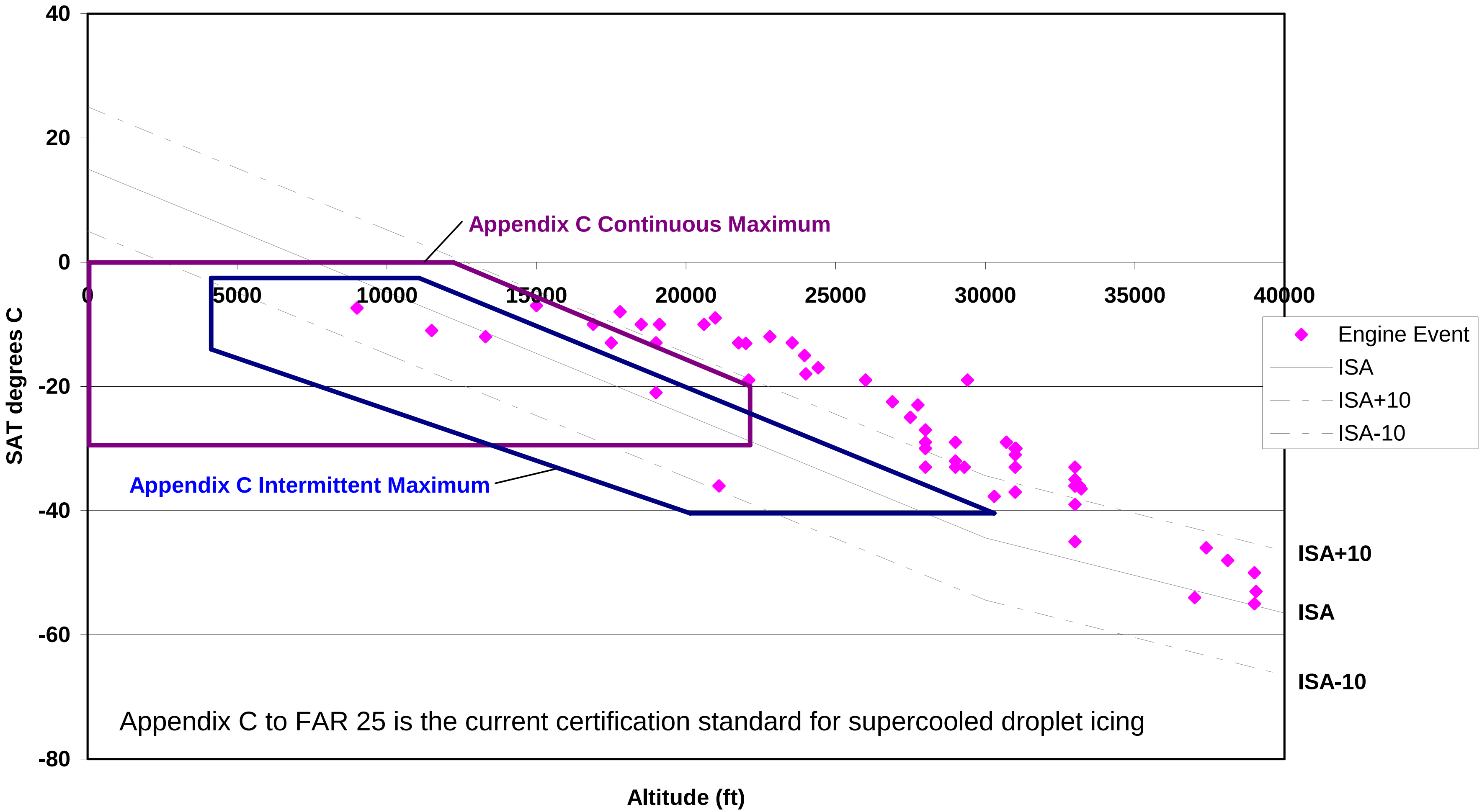
*Ice Crystals Encounter Heated Engine Surfaces and Form Ice*

- **Frozen ice crystals impinging on a warm surface in the engine**
- **Some crystals melt, creating local mixed phase conditions**
- **Crystals impinging on wetted surface stick, cool the surface to 0C**
- **Ice begins to form**
- **At high altitude, ice can form deep in the engine core**



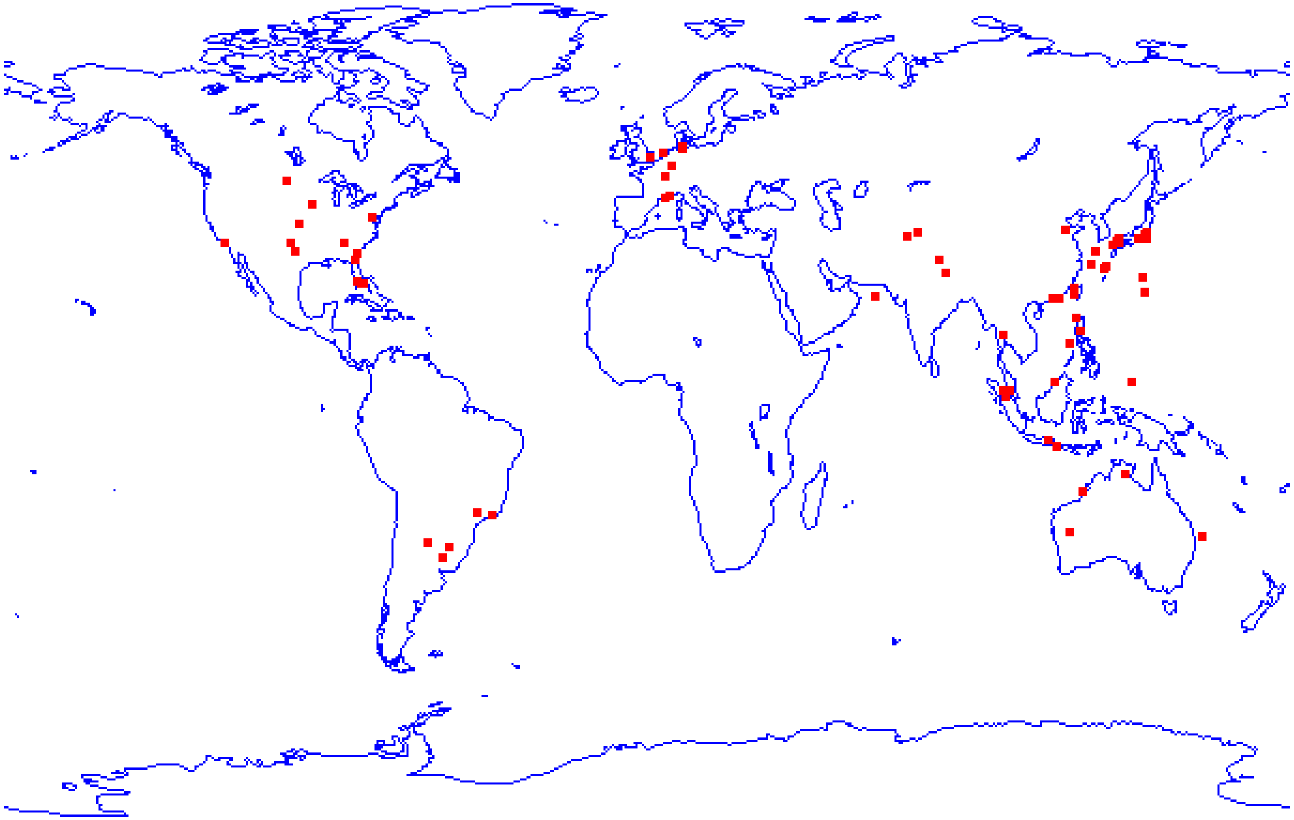
# Environmental Conditions

*Altitude and Temperature of Engine Power Loss and Damage Events*



# Global View of Engine Power Loss Events

- **60% 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**



# Scope of the Ice Crystal Icing Problem

- **Affects multiple models of aircraft and engines**

  **(Large transport aircraft and small jet aircraft)**
- **Over 100 power loss events – approximately 1 every 4 months**
- **Typically 1 in 4 engine power loss events involves multiple engines – large transport events have always restarted**
- **Approximately 60 damage events, typically compressor blade tip curl, rarely multiple engines damaged**
- **Affects new and old engine designs, new and old engines**
- **Data mostly comes from in-service events – pilot reports and digital flight data**
- **The industry is just beginning to understand this icing phenomenon**

# Types of Power Loss Events

| ***Powerloss Type*** | ***Description*** | ***Cockpit Effect*** |
|---|---|---|
| Surge/Stall | Ice shed into compressor drives engine to surge, then stall causes rotor speeds to decay and reducing airflow while combustor remains lit | Thrust loss and High EGT |
| Flameout | Ice shed into the combustor quenches the flame | Thrust loss and all parameters dropping |
| Engine Damage | Engine compressor blades become damaged as shed ice impacts them | Typically no effect at time of initial damage, damaged blades may fail later causing vibration or engine stall |

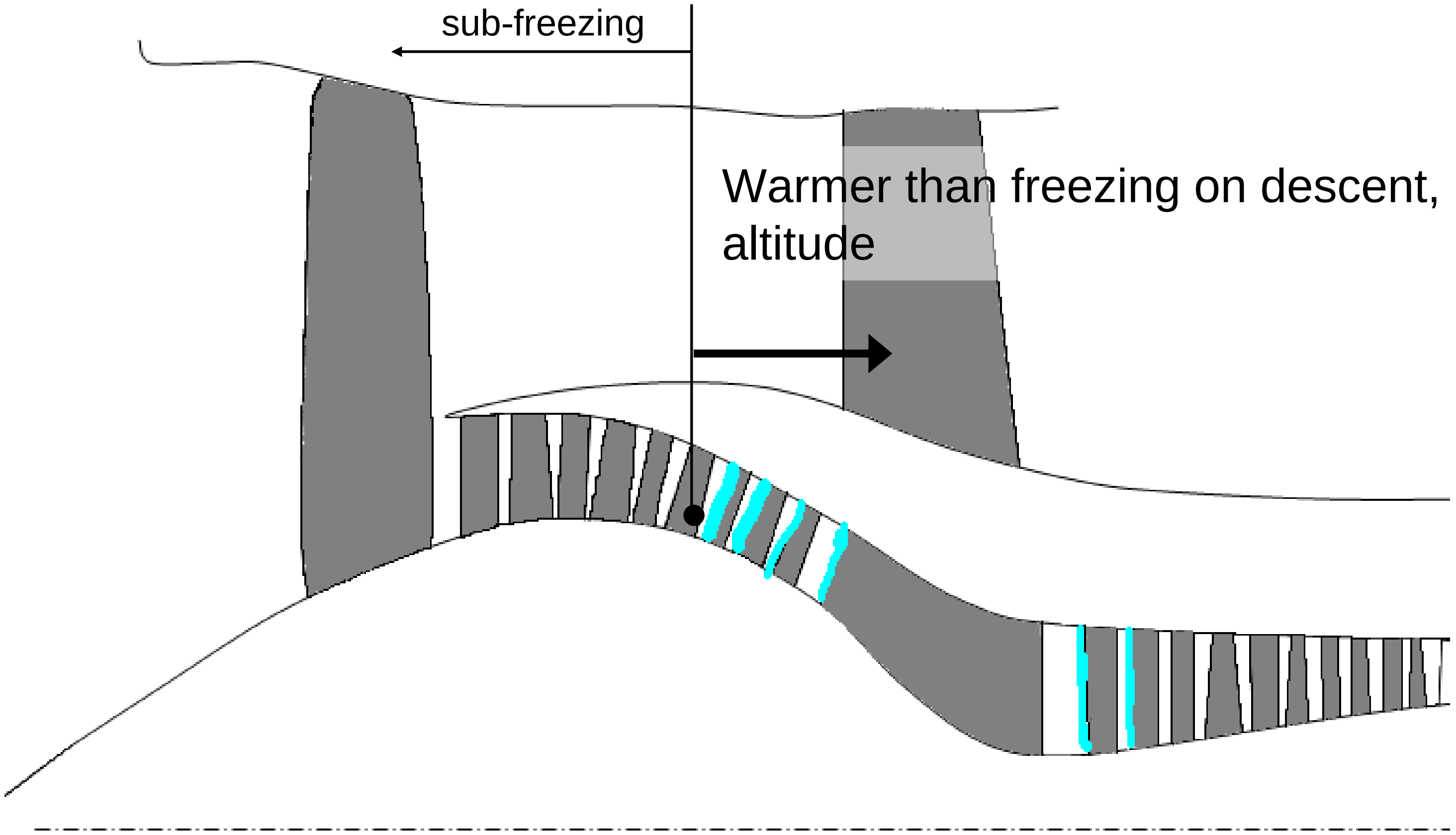
- **Each engine appears to have a different manifestation of ice crystal icing**
- **Flight crew recognition and recommended action depends on the event**
- **There is no single solution for all events**

# Location of Ice Crystal Ice Formation

- **From aircraft flight recorder data it is not evident exactly when and under what conditions the ice is forming**
- **In large turbofan engines, power loss occurs when ice sheds, not during ice formation**
- **Often, the engine throttle is not steady during the accretion conditions**
- **Some clues to ice accretion location:**
  - **Current industry experience: ice has formed on engine surfaces ranging from >0°C to 38°C (100°F)**
  - **Damage likely from ice shed from location immediately upstream**

# Location of Ice Crystal Ice Formation

*Pinpointing Location of Ice Formation in the Engine*



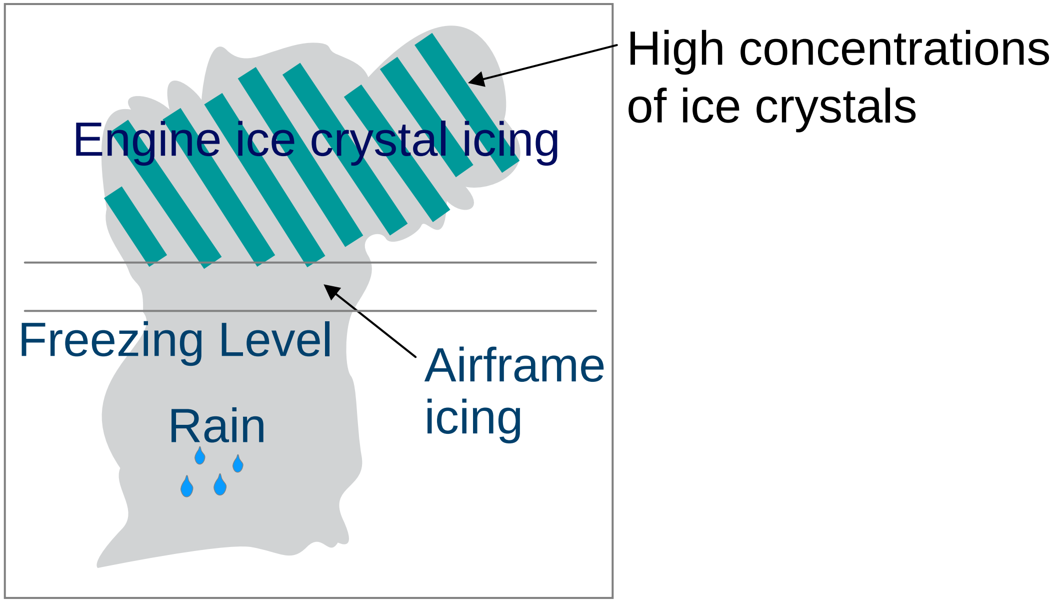
# Pilot Reports Provide Valuable Insight

*Events often occur in conditions the pilots consider benign*

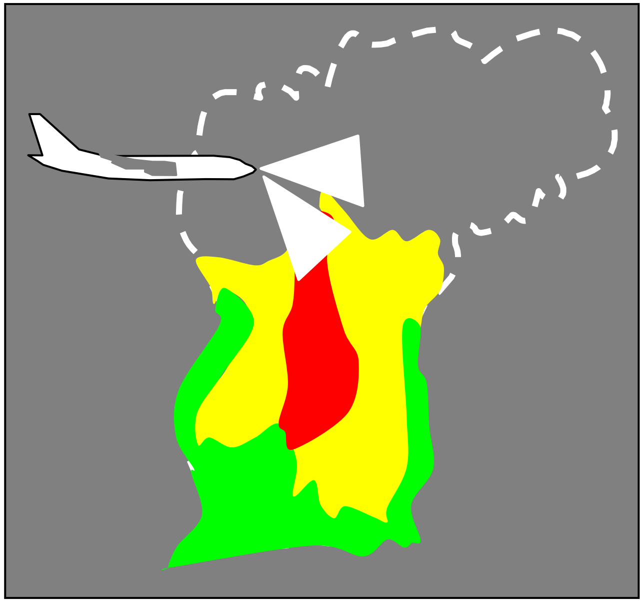
- **Events occur with little or no reflectivity at flight level – ice particles are very small & poor reflectors of radar energy**
- **While avoiding weather radar returns – not flying through heavy storm cores**
- **Low to moderate turbulence – low updraft velocities**
- **No airframe ice – ice particles hitting airframe do not accrete**
- **Pilots often report heavy rain – ice particles melting on the heated windscreen give the appearance of rain**
- **Pilots are following standard practices regarding thunderstorm avoidance – the conditions where engine power loss events are occurring have not traditionally been considered a weather concern**

# Pilot Recognition of HIWC is a Process of Deduction

- **Flying in cloud above the freezing level in convective weather**
- **Aircraft may already be avoiding flight-level weather radar returns**
- **Aircraft is near the deepest part of the cloud (cloud tops can reach the tropopause)**
- **Heavy rain is present** *below* **the aircraft, producing yellow and red returns, but few or no returns** *at flight level*
- **Using 'tilt feature' on radar should identify heavy rain below – a good indicator that dense ice crystals may exist above**




**Convective Cloud**

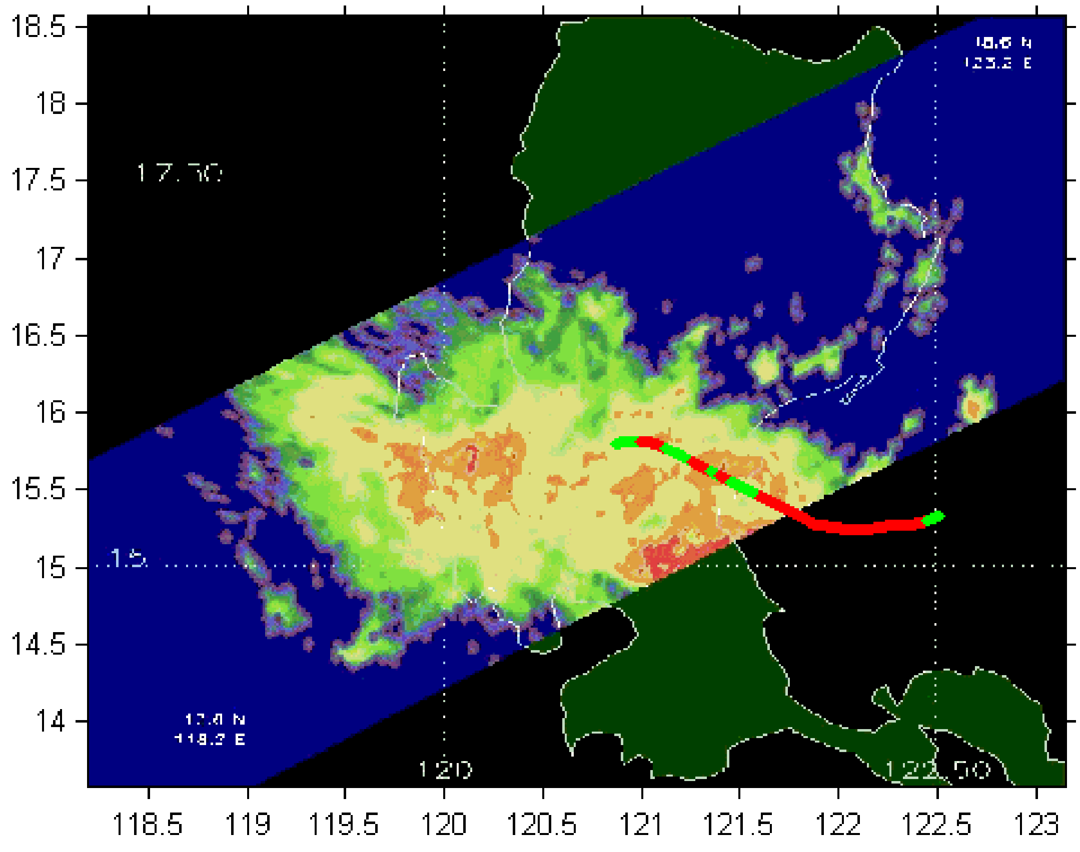


**Radar Representation of Convective Cloud**

# Event Analysis – Where does HIWC occur?

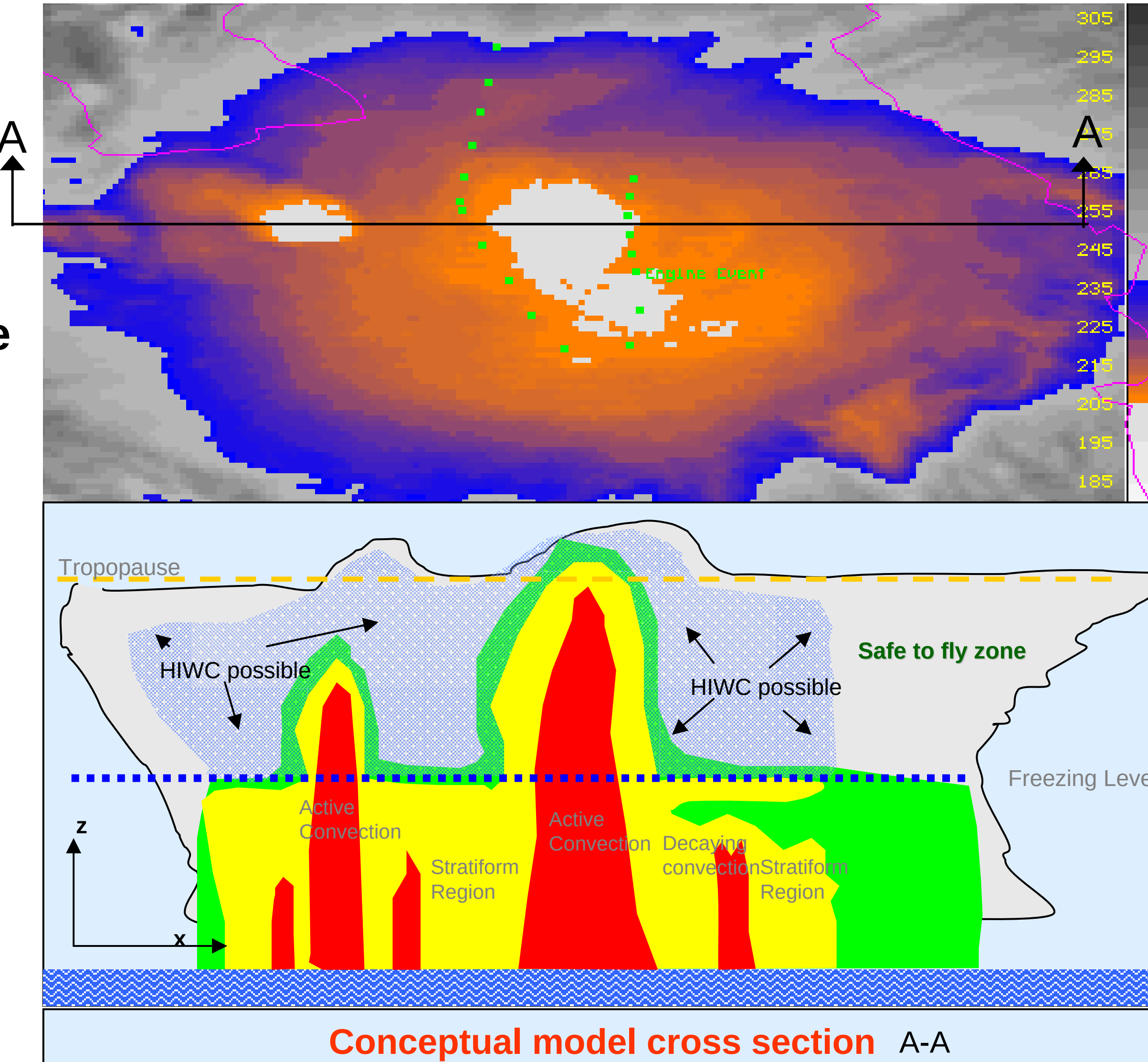
*Boeing has conducted in-depth analyses of 50 events*

- **Goal: to understand *where*, and in *what types* of cloud high ice water content occurs**
- **Three areas of focus:**
  1. **Meteorological: satellite images, ground based radar, convective environment**
  2. **Pilot reports: proximity to radar returns, reports of rain, turbulence**
  3. **Total Temperature Sensor Anomaly**



# A Conceptual Model of HIWC Regions

- **Developed from event database with ground based radar data**
- **Radar data has revealed that reflectivity typically exceeds 30dbz below the aircraft at the time of the engine power loss**



# Industry Progress - Regulations

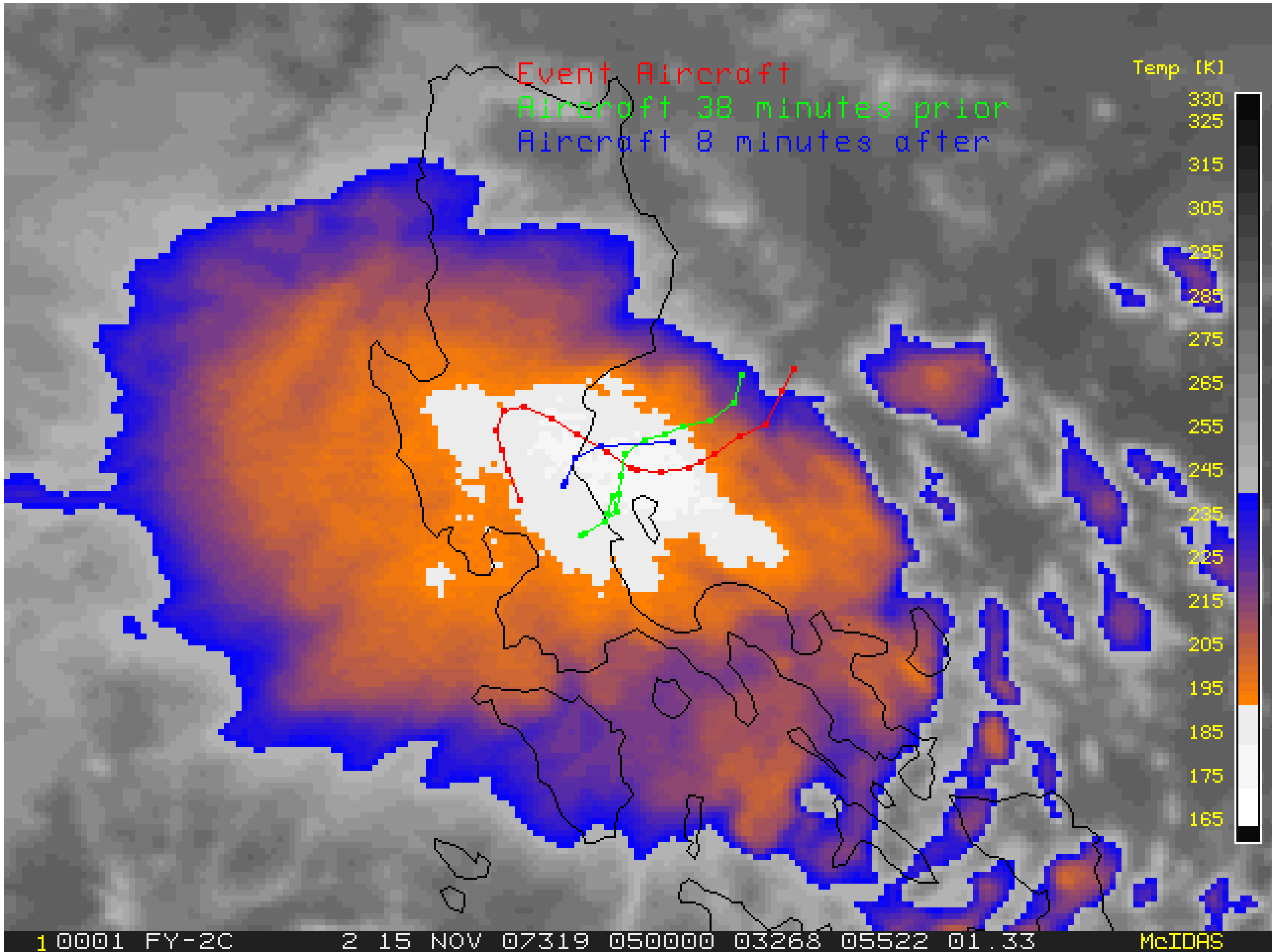
*Industry Committee Activities*

- **Development of Regulatory Requirements:**
  - **Created Appendix D, an interim icing envelope for Engine Certification FAR Part 33 – similar to Appendix C, built with theory and experimental data**
    **(SAE 2007-01-3377 Mazzawy & Strapp)**
  - **Developed draft rules for engine and powerplant certification - part of Supercooled Large Droplet package expected to be published as FAA Notice of Proposed Rulemaking (NPRM) 1st quarter 2010**
  - **Means of compliance by similarity proposed until technology needs are completed**

# Future Compliance with Federal Aviation Regulations

*Event Analysis Provides Information for Future Engine Testing in Ice Crystals*

- Compliance with the regulations in future will mean conducting engine tests
- Currently specific test points do not exist – need to reflect real life encounters
- Event data analysis can help formulate test conditions
- How long do we expose the engine to HIWC?
- Can the aircraft be exposed during holding?



# Industry Progress – Research Needs

*Industry Committee Activities*

- **Technology Plan developed to address unknowns:**
  1. **Improved instrumentation to measure atmosphere**
  2. **Flight trials to characterize atmosphere (understand particle size, concentration and extent)**
  3. **Fundamental physics of ice accretion and shedding**
  4. **Test methods and facilities**
- **Government/Industry partnerships are being created to fund this work**

# Fundamental Physics of Ice Accretion and Shedding - Progress

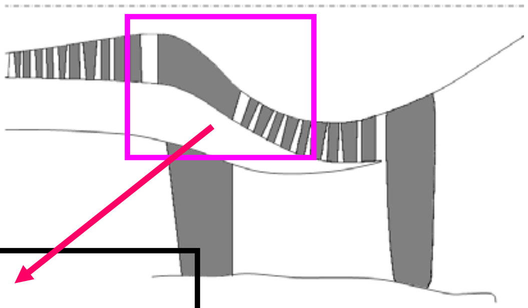
*Technology Plan Item 3 - Successful Rig test*

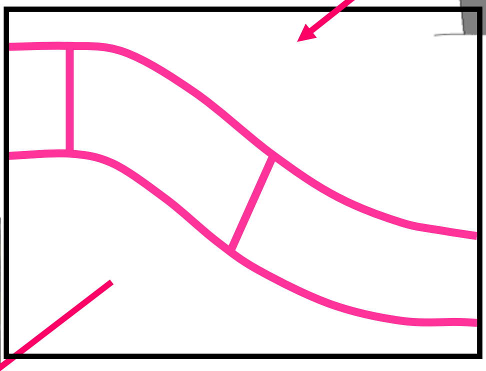
- **Boeing and National Research Council of Canada partnered for the first successful rig-based simulation of engine-like conditions January 2009**
- **Objectives:**

1. **Modeled mixed phase ice accretion in both above freezing and below freezing airflow**
2. **Explored accretion characteristics of various combinations of LWC (liquid water content) and IWC (ice water content)**
3. **Determined the influence of surface temperature on accretion and the adhesion of the accreted ice**
4. **Observed the response of embedded metal thermocouples**
5. **Obtained data to understand the process of the ice crystals impacting the surface and the initiation of accretion**

# Technology Plan Item 3 - Successful Rig Test

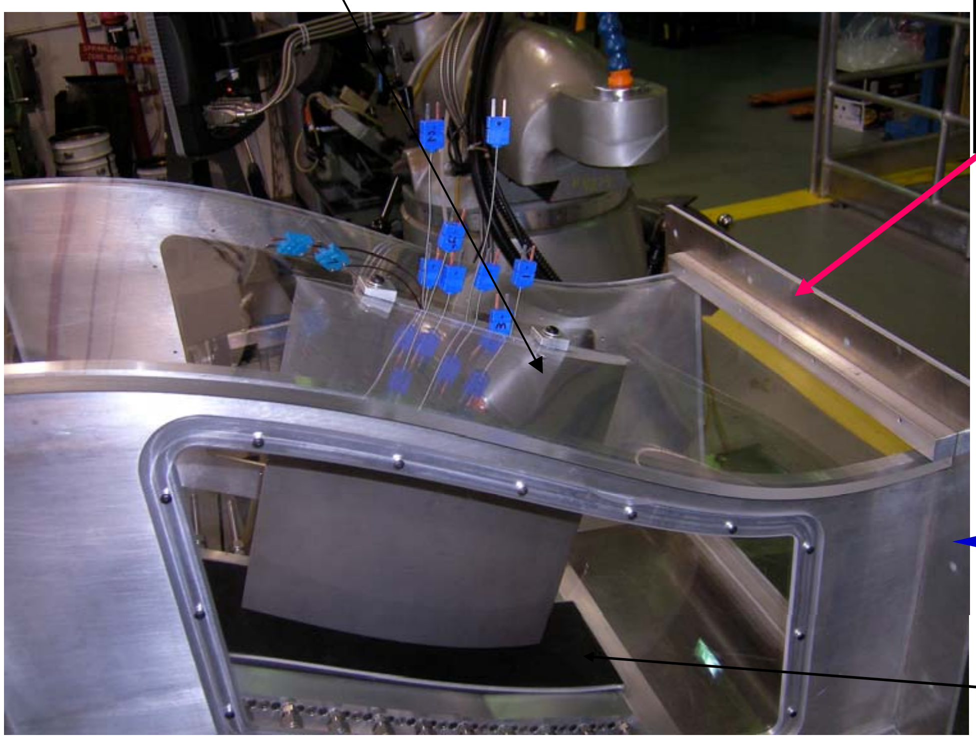
*Simulation of the s-shaped duct between the low and high compressors*





Geometry to simulate engine s-shaped duct with fan frame

Metal surface thermocouples on leading edge of airfoil



***Warm air, frozen ice particles***

Independently heat controlled endwall

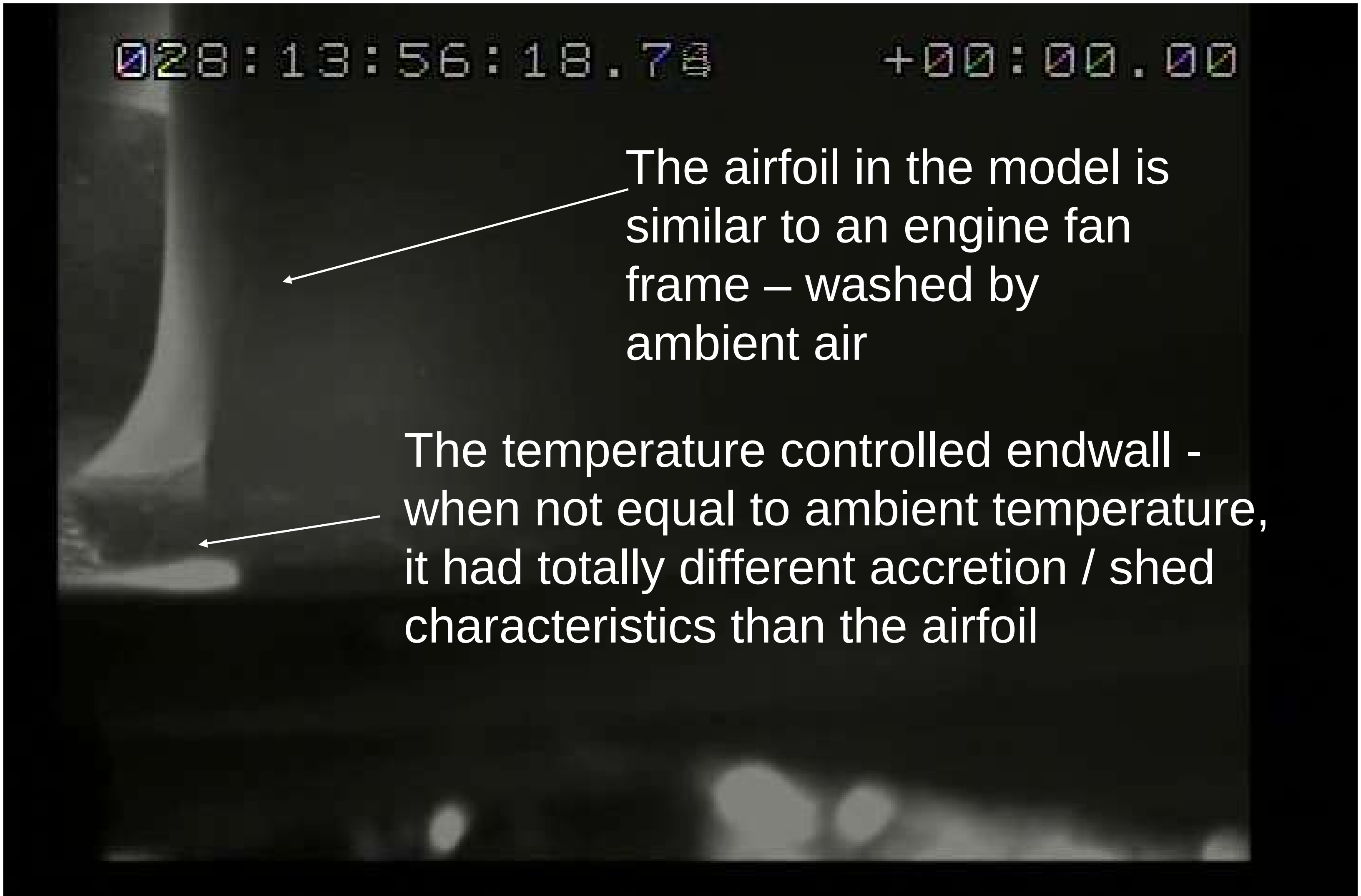
# Rig Simulation of Icing in Engine Environment

*General Test Results*

- Local mixed phase conditions must be present
- Surface temperature reduction to freezing (0ºC) for ice formation
- Observed ice forming on endwall and stagnation points

# Rig Simulation of Icing in Engine Environment

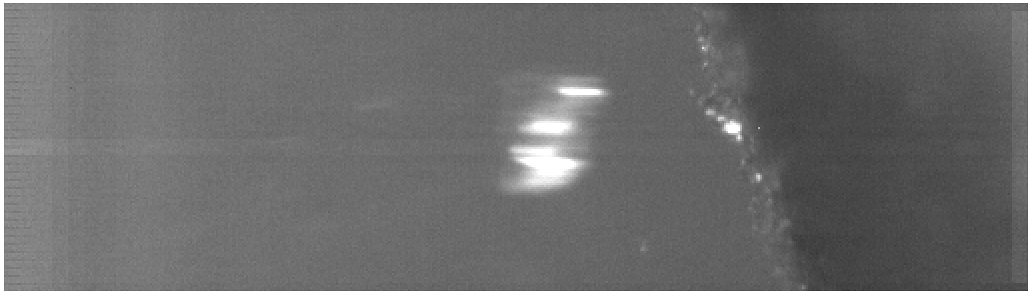
*Two Different Scenarios for Ice Crystal Accretion and Shedding*

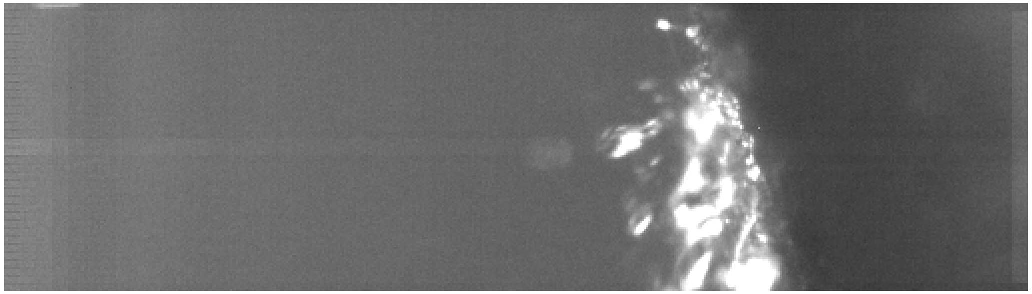


# Phantom Camera Images of Ice Impact

*Single ice particle impacting leading edge taken with NASA's phantom camera*

- **Investigated:**
  - **onset of ice accretion**
  - **how/whether particles bounce/break on the surface**
  - **where incoming water goes – splash or stick to surface**
  - **how much liquid is present on the surface, and does it splash**
  - **amount of melting of incoming particle**

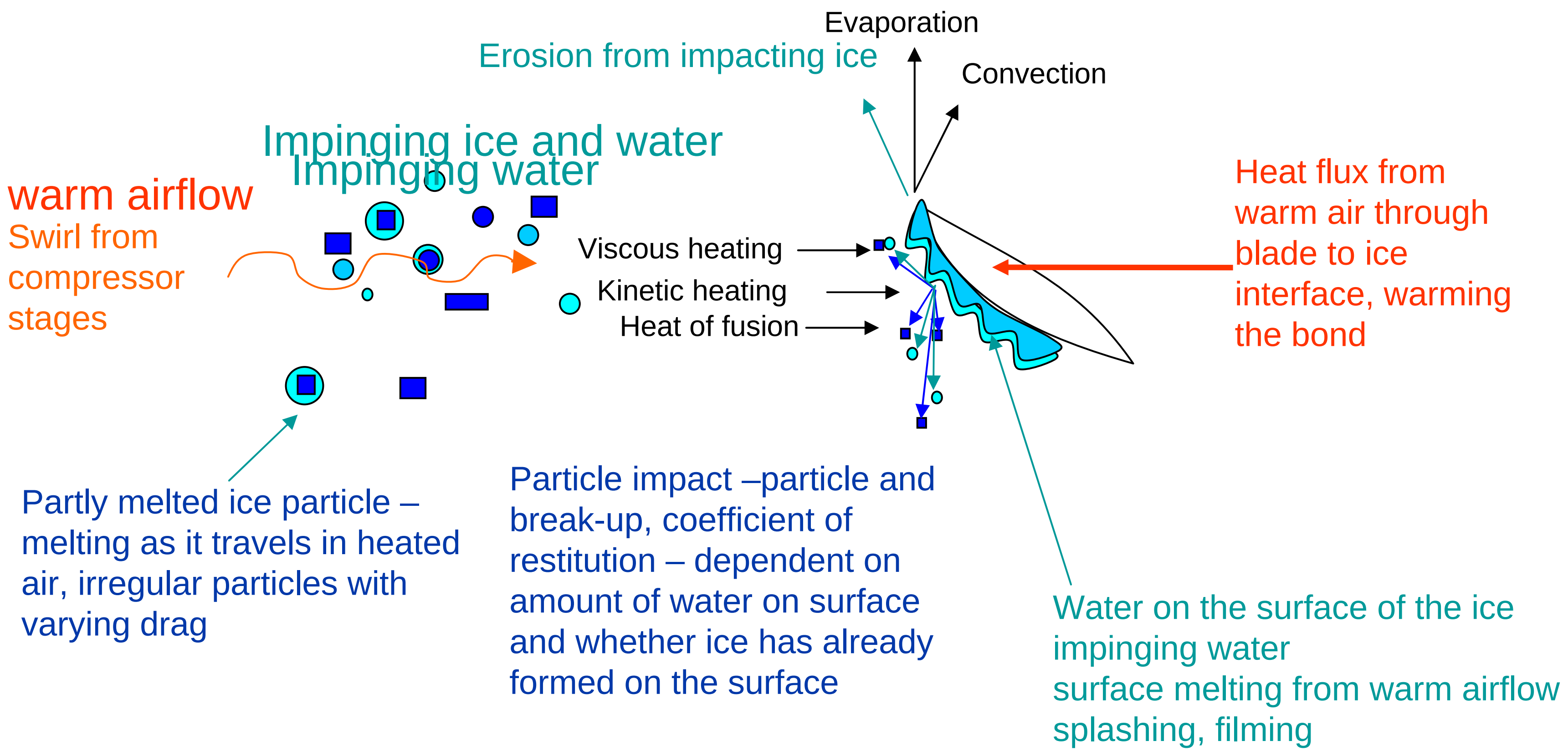




# Overview of Results

- **Although a simplified model, the rig produced results consistent with some of our predictions about the ice crystal accretion process**
- **It is the first time that we have a controlled experiment showing that accretion is possible on surfaces warmer than freezing, as measured by thermocouples**
- **The high speed camera provided insight into the mechanism of initial accretion, and build-up**
- **The experimental data is still being evaluated, and is expected to provide guidance for developing the next set of rig tests**
- **Further testing of this nature will be needed to develop parameterizations for all the elements of the icing process**

# Complex Heat Transfer Problem – Some of the Elements




Black text represents elements of supercooled droplet accretion

# Next Steps in Fundamental Physics Research

*Technology Plan – Progress on Item 3 Fundamental Physics*

- **2nd Boeing/NRC Collaborative Rig Test May 2009 – airfoil at an angle of attack**
- **Ice Crystal Icing Consortium - cascade test in 2009 (macroscopic processes)**
- **Collaborative test on flat plate (microscopic processes of particle bouncing, breakup & splashing)**

# Conclusions

- **Ice crystal icing conditions continue to cause turbofan engines power loss and damage events**
- **Event analysis allows us to provide better information to pilots for weather recognition**
- **Data on location of events with respect to reflectivity in the cloud will be valuable to future flight programs and definition of future engine tests**
- **Progress is being made towards understanding of the physics of ice crystal accretion and shedding in the engine**
- **There are still many challenges**