

Ice Crystal Icing Research at NASA

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Motivation

Engine Ice Crystal Icing events have led to increased need of understanding the mechanisms of engine icing.

NASA Advanced Air Transport Technology (AATT) Project key technology area is to develop engineering model and icing risk assessment tools and improve understanding of the physics of ice crystal icing through fundamental and engine testing.

- Enable analysis of ice crystal icing effects on turbofan engines.
- Provide guidance for safe operation of current and future propulsion systems.

NASA Aeronautics Evaluation and Test Capabilities (AETC) Project investing in the development of the Propulsion Systems Laboratory engine icing capability.

- Understand the differences between PSL Cloud and natural environment ingested in the engine.
- Instrumentation to measure IC Cloud upstream and inside test hardware flow path.
- Characterize PSL Cloud
- Standardize PSL Icing Test Methodology

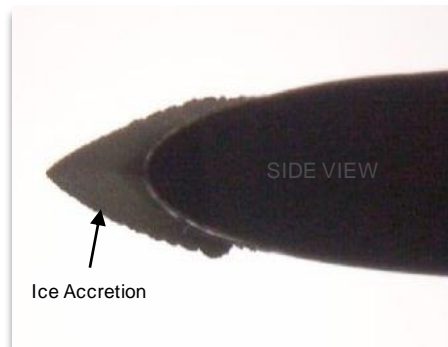
2011 NASA Technical Plan

- Research Areas of Focus:

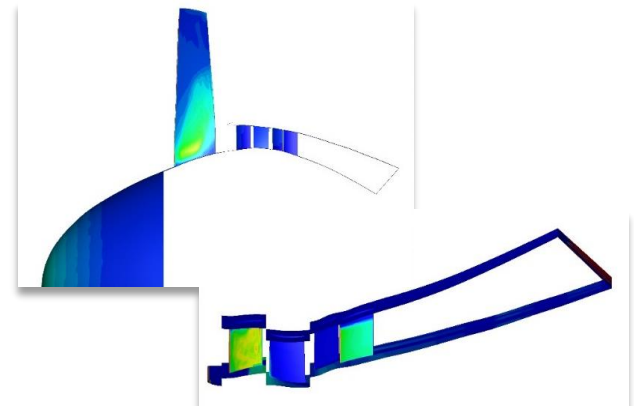
1. Flight Characterization of the High Ice Water Content (HIWC) environment.
2. Classical Research in the area of altitude testing for engine, engine components, and fundamental studies of ice particle aero-thermodynamics.
3. Computational research to simulate engine performance, ice accretion, and engine control methods.



Flight Characterization



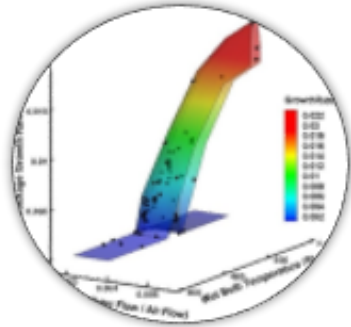
Classical Research



Computational Research

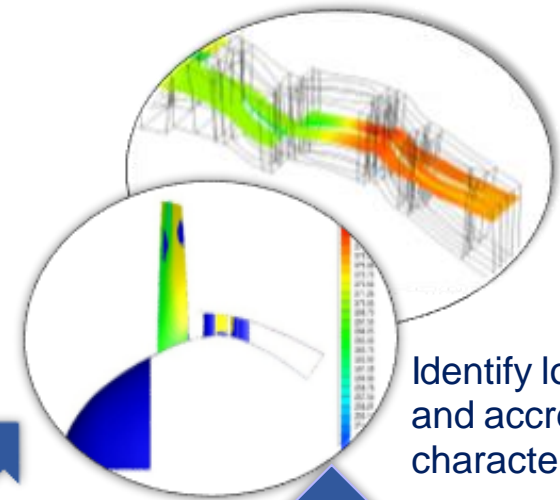
NASA ICI Research Overview

0D/1D Risk Assessment Tools



Identify inlet conditions that will lead to accretion in core flowpath.

3D Risk Assessment Tools



Identify location and accretion characteristics.

Flight Characterization



Understand the underlying physics of ICI accretion and particle breakup

Understand the underlying physics of ICI at the engine system level



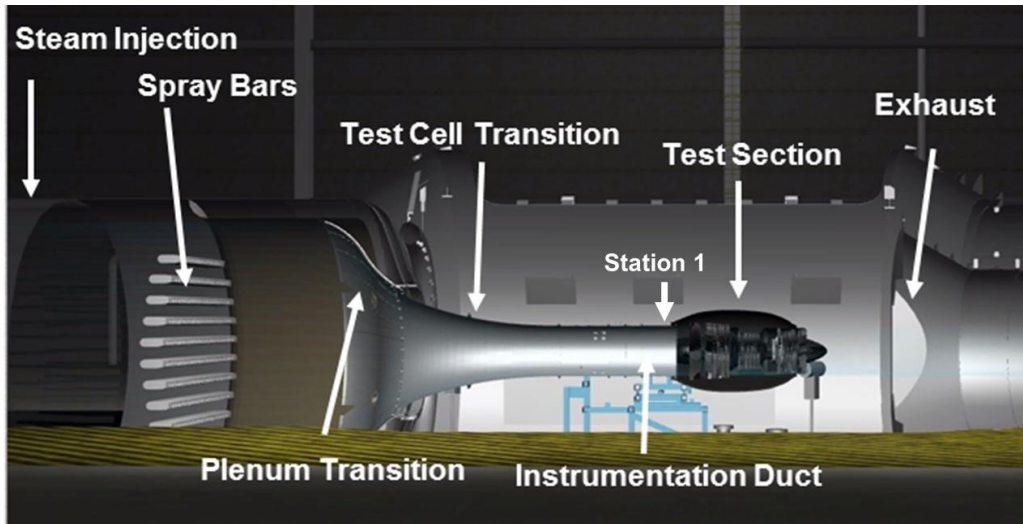
Fundamental Physics



Engine/ Rig Tests

FACILITIES AND CLASSICAL RESEARCH

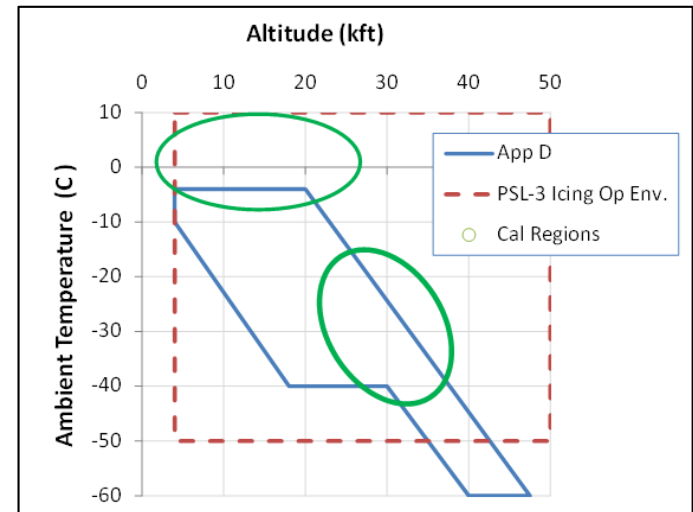
Propulsion Systems Laboratory (PSL)



Specification	Min	Max
Engine / Rig Dia. (in cm)	24 60	72 180
Air Flow Rate (lbm/s kg/s)	10 5	330 150
Altitude, pressure (kft km)	4 1.2	50 15
Total Temp (°F °C)	-60 -50	50 10
Mach Number	0.15	0.80
TWC (g/m ³)	0.5	8.0 *
MVD (um)	15	>100 #

* Evidence that probe under-measured

Particles larger than ~ 90 microns are NOT fully glaciated

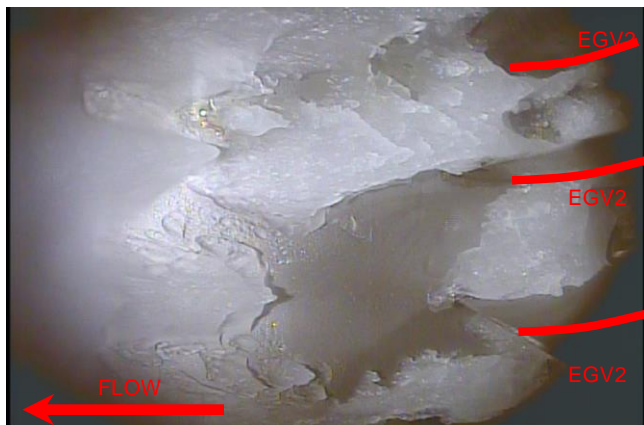


PSL-3 Icing Operating Envelope

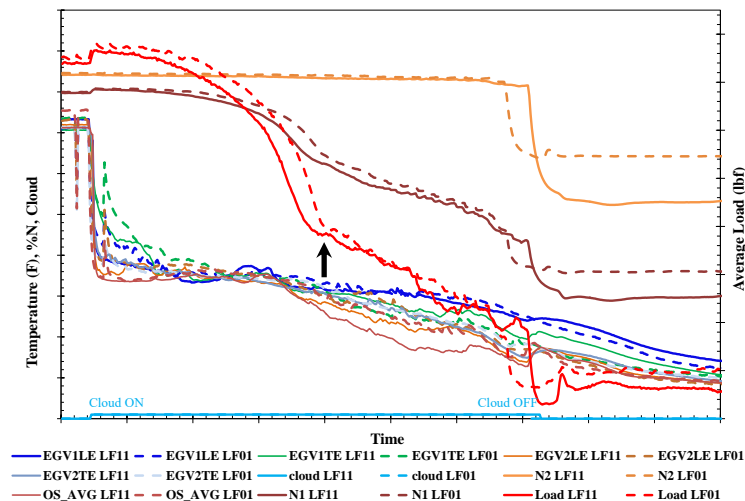
Engine Testing

- Goal: Understand the mechanisms of ICI inside engine core flowpath at relevant flight and environmental conditions.
- Tests conducted on unmodified ALF502R-5
 - Demonstrated Facility Capability (repeatability, Peak TWC simulations, flight descent,...)
 - Made key observations on engine response and accretion during parameter sweeps.
 - Evaluated an approach for altitude scaling.
 - Evaluated measurements techniques
- Future Work:
 - Understand how the fan processes the IC cloud.
 - Develop measurement techniques which can help quantify the icing effects.

Ice Accretion at FLT850



LF11 vs. LF01 Full Rollback



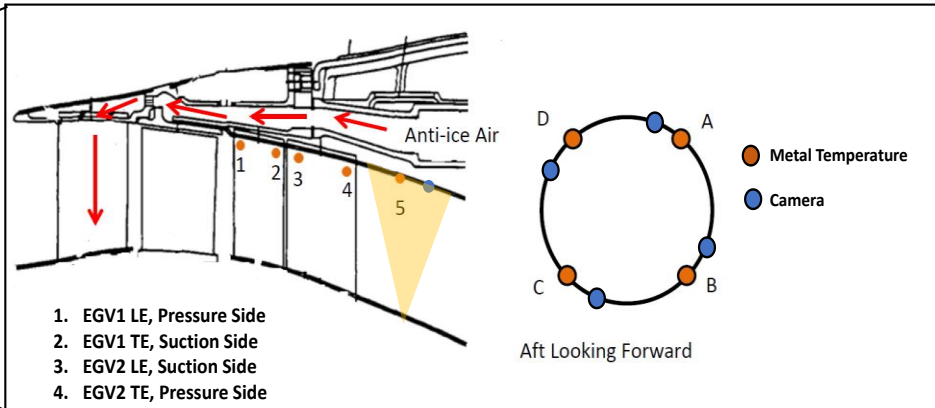
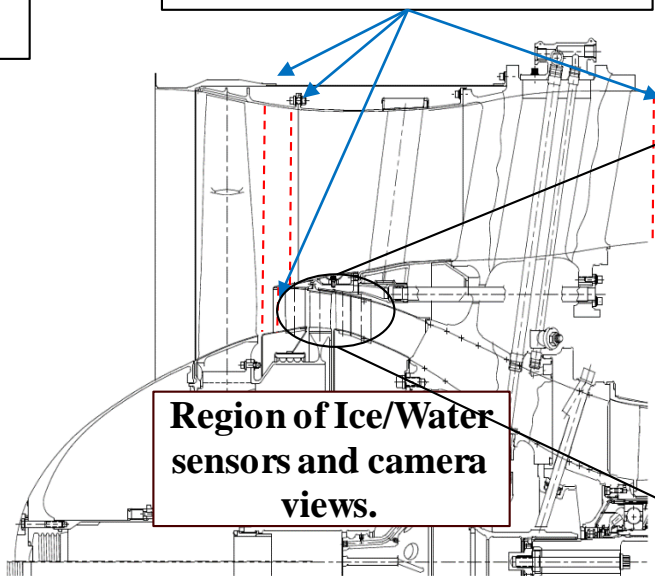
Instrumentation

- Internal Engine Cameras
- NASA Ice/water sensor
- NRC Ultrasound Ice Accretion sensor
- Raman Scattering Probe
- Tomography (inlet)
- Light Extinction Probes

Tomography Plane

Light Extinction Probe Planes

Region of Ice/Water sensors and camera views.

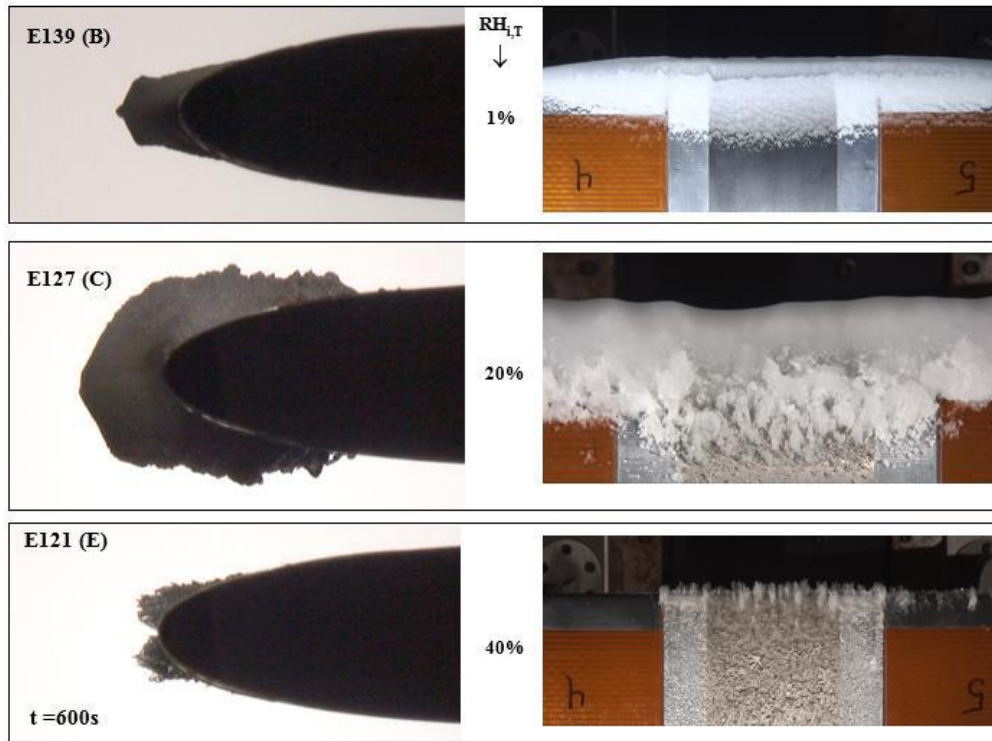


Fundamental Icing Physics Tests

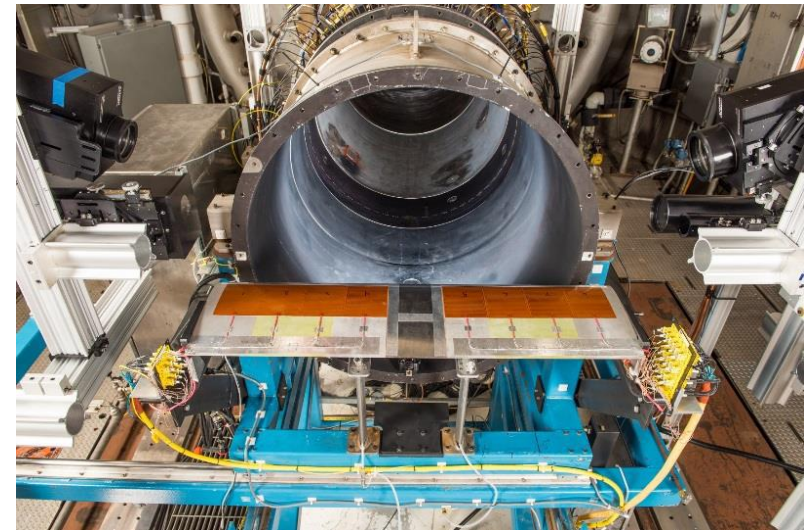
- Goal: Investigate the fundamental physical mechanisms of accretion that occurs in core compressor regions of jet engines when ingesting ice crystals.
- Initial studies at NRC found the importance of local T_{wb} , melt ratio, humidity, and cloud particle size distribution on the accretion process.
- 1D thermodynamic model was developed to simulate the complex interaction of the cloud particles and free stream air.
 - Tool to ensure facility is set-up appropriately to achieve desired conditions at the test section.
- 2016, First Fundamental Test conducted in PSL.
 - Characterized various icing parameters such as water content, particle size distribution, and uniformity.
 - Acquired videos of ice accretions on a NACA 0012 airfoil under mixed-phase cloud conditions.
- Future:
 - Demonstrate the ability to prescribe a particular ice crystal icing condition at the test section
 - Understand the erosion process
 - Focused on tests with more relevant geometry in an effort to generate a more representative ice accretion

Fundamental Icing Physics Tests

Sample of Ice Shapes from FT#1

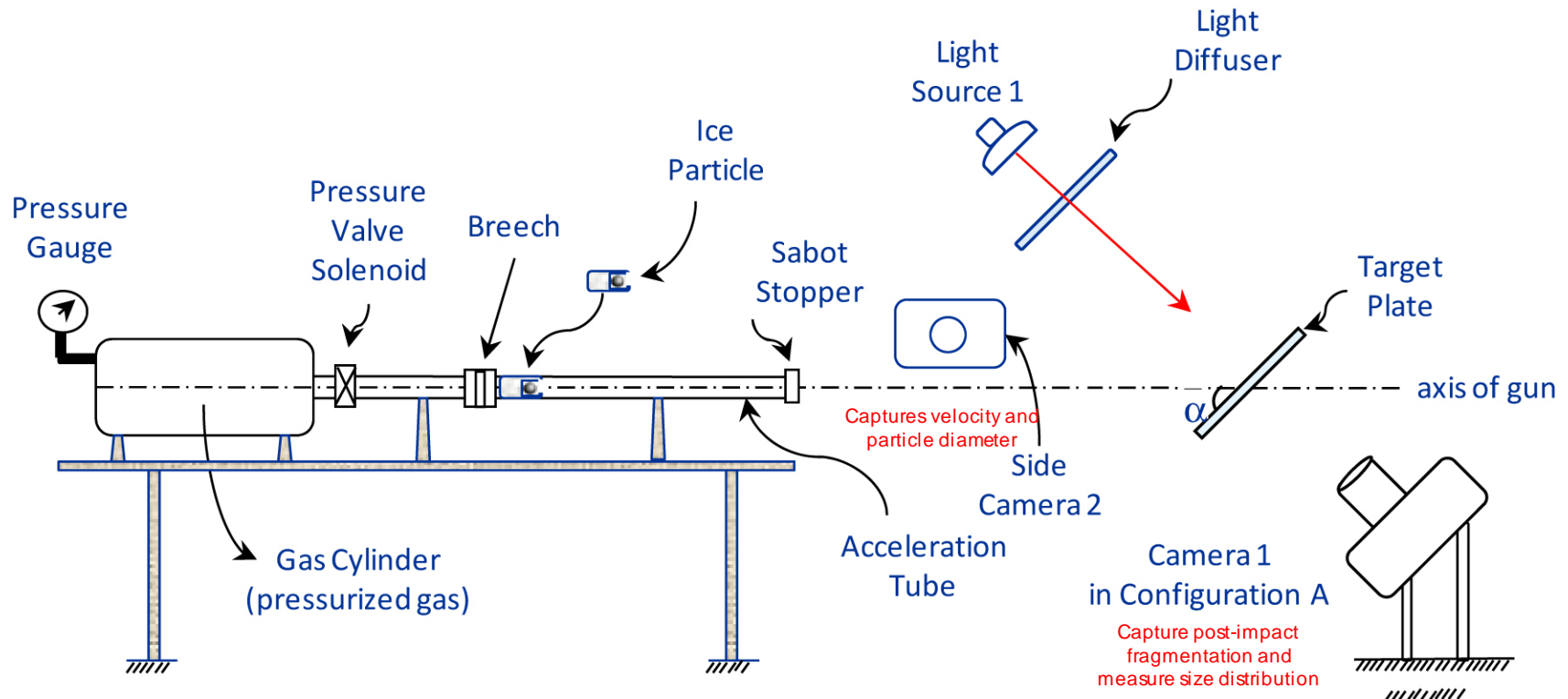


Test Set-up



Ballistics Impact Laboratory

- Ice particles generated by:
 - Dropping calibrated amount of distilled water into liquid nitrogen
 - Compressing ice in a metallic mold.
 - This method ensure particle uniformity

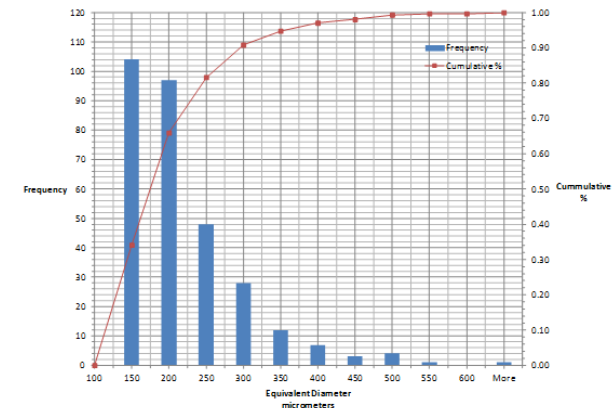
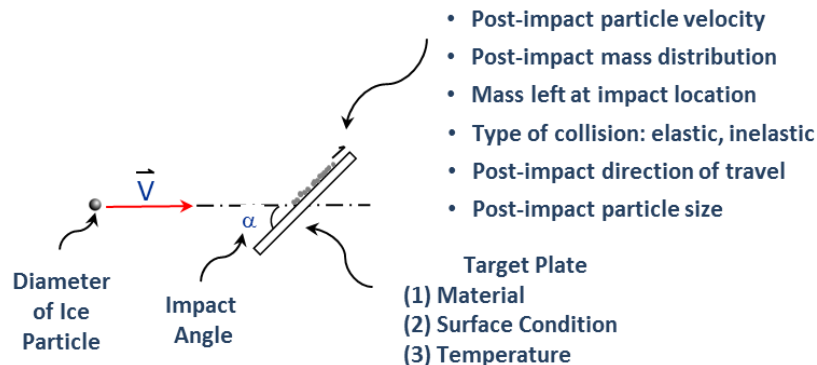


Particle Impact and Break-up Physics

- Goal: Evaluate the impact characteristics of ice crystals on engine components in terms of post-impact: particle size distribution, particle velocity distribution and direction of travel, effect of partial melting of crystals
- In house and collaborative efforts (Penn State NRA)
- Recent efforts studied the effect of particle velocity. High speed images and high speed infrared data were obtained.
- Future Work:
 - Investigate the ability to control the melt ratio of the particle before impact
 - Move towards more complex geometries (i.e. fan blade)



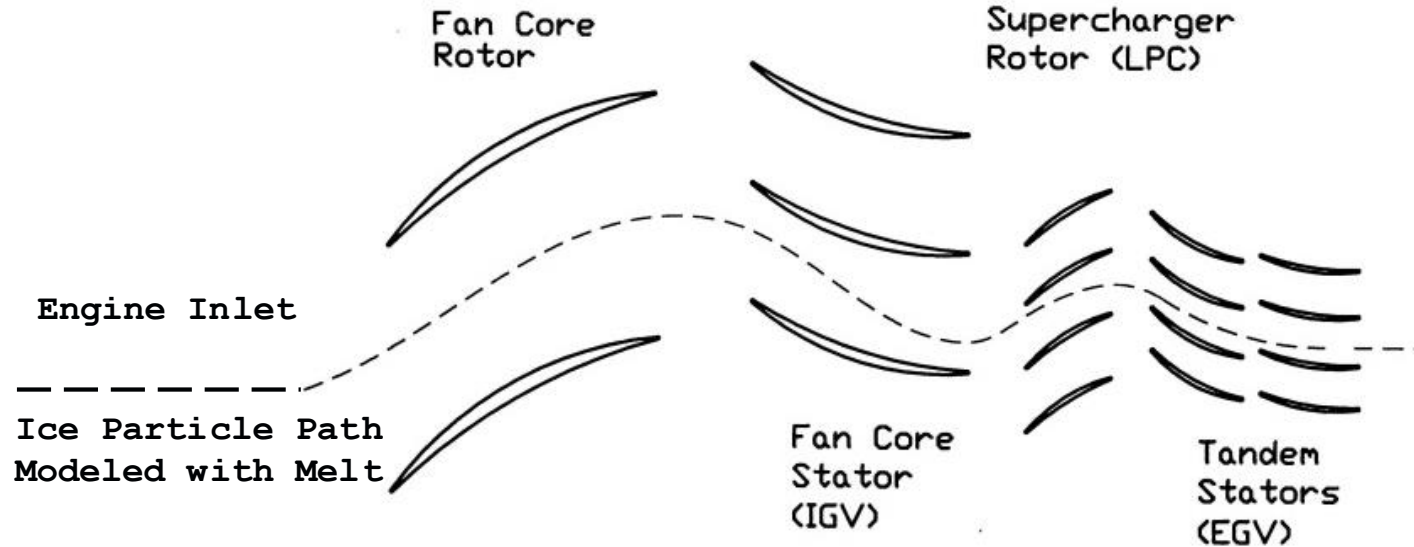
Ice Particle Impact on Flat Target



Fragments Equivalent Diameter Distribution Histogram

COMPUTATIONAL RESEARCH

Particle Path for 0D/1D Analysis



The COMDES - MELT code models the thermodynamic state of the ice particles as they pass through the Inlet, Fan-Core and LPC blading. Includes models for sublimation, particle temperature rise, melting, and evaporation.

Computational Process for Determining the Icing Risk

Turbofan Engine Aerothermodynamic Cycle Code (Engine Customer Deck (CD) or NPSS)

Engine system performance to establish Fan-HPC boundary conditions

Air Flow Rate
LPC Speed: N1
HPC Speed: N2
Engine Inlet Pt and Tt
Fuel Flow Rate

Test Data

Air Flow Rate
LPC Speed: N1
HPC Speed: N2
Engine Inlet Pt and Tt
Fuel Flow Rate
EGV Wall
 P_{static}

COMDES – MELT : Flow and Particle State Analysis of Fan-Core & LPC

- Blade row by blade row compressor aerodynamics.
- **GASPLUS:** Fluid properties of air / water vapor
- **Relative Humidity**
- **Blockage Growth Rate**
- **Static Wet Bulb Temperature**
- **Ice-Water Flow Rate / Air Flow Rate Ratio (IWAR)**
- **Particle Melt Ratio, Enthalpy, Evaporation, Sublimation**

Change Following for Prediction Mode:

- Ambient Temp
- Flight Mach Number
- Fan RPM (N1)

Icing Risk Criteria
"Wedge"

1. Calibration/ Analysis Mode:
Used for further Refinement of Wedge

2. Predication Mode: Identify as potential icing condition

0D/1D Modeling

Goal: Develop in-house tool to predict the engine risk to ice particle ingestion to evaluate the risk of icing.

Recent Work:

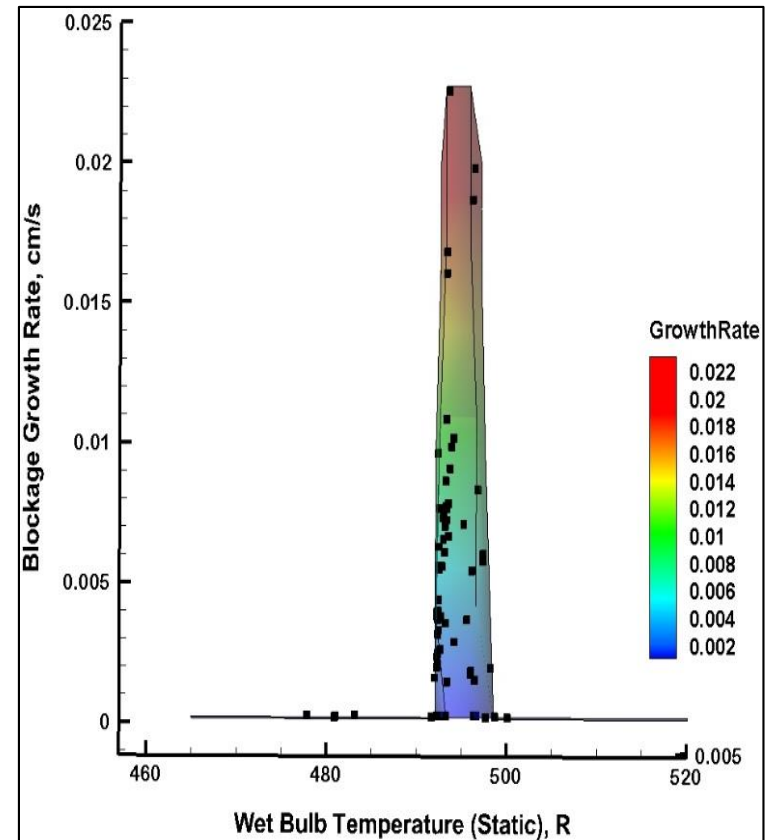
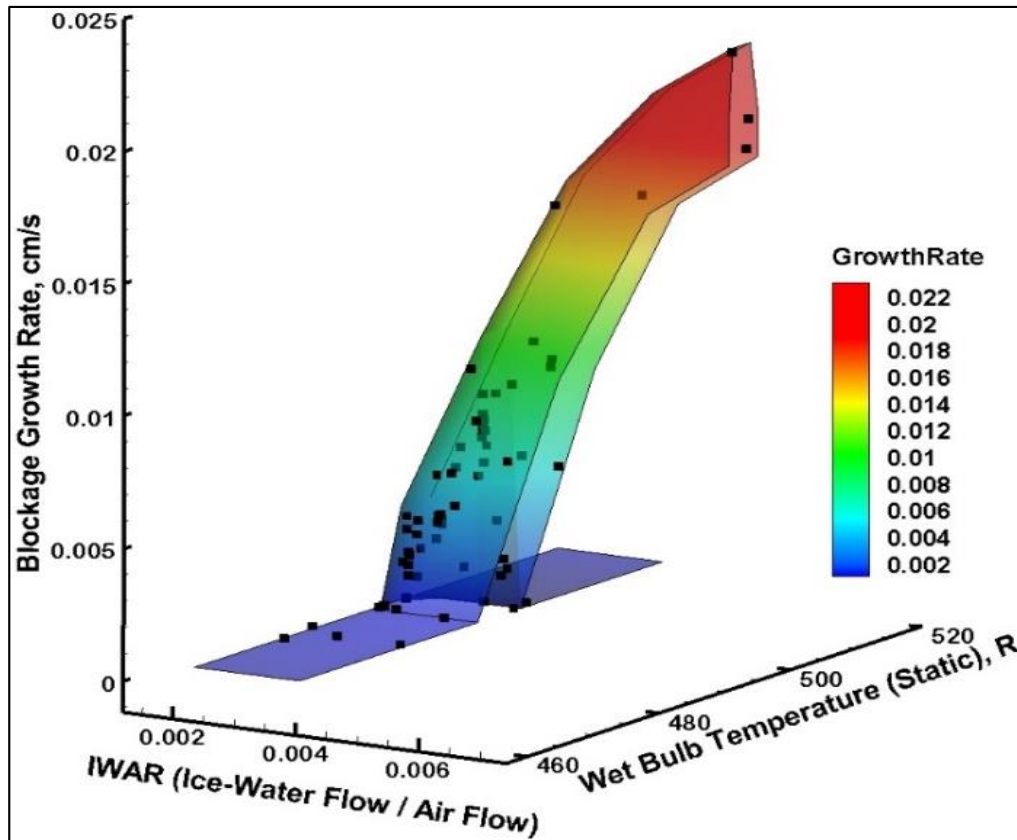
- Estimated the risk of accretion for the ALF502, LF11 engine test points.
 - Pre-test evaluation
 - Guided the formulation of the altitude study test points
 - Post-test evaluation of the test points and defined icing risk criteria
- Relationship between blockage growth rate, ice-water flow rate to air flow rate ratio (IWAR), and static wet bulb temperature was observed and plotted generating an “Icing Wedge”.

Future Work:

- Apply model to new geometries
- Continue to enhance the code

“Icing Wedge” – Risk of Ice Accretion Criteria

- 1.) Static wet bulb temperature is within the range of 492R - 498R
- 2.) IWAR is above 0.002



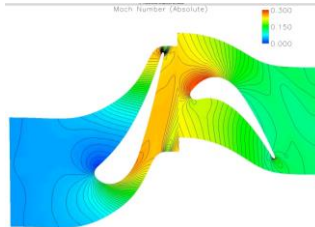
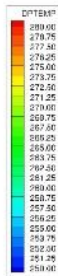
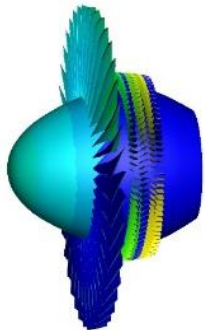
0D/1D Modeling

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High Fidelity Engine Icing Simulations

- Goal: Develop a system of codes that can model the accretion process in current and future engine designs and characterize the accretion risk due to ice crystal ingestion at high altitude.
- Codes:
 - LEWICE: 2D tool that evaluates the freezing process thermodynamics that occur when super-cooled droplets impinge on a body and generate a 2D ice shape.
 - Initial module development (break-up and erosion) which is compared to the Fundamental Test ice shapes.
 - LEWICE3D: 3D tool that predicts the accumulation of ice on three-dimensional aircraft surfaces given the flight and meteorological conditions.
 - Trajectory and accretion analysis.
 - GlennHT: 3D gas turbine flow and convective heat transfer code.
 - Provides flow analysis to LEWICE3D
 - Analysis to calculate heat transfer coefficients.
- Future Direction:
 - Couple GlennHT and LEWICE3D simulations more tightly to allow for effect of ice particles on the air flow and include effects of ice growth on air flow.
 - GlennHT Modifications:
 - Inclusion of real gas effects, accounting for humidity and wet bulb temperature
 - Modelling of tip clearance region
 - Investigating turbulence models to produce accurate heat transfer prediction during the ice accretion process.
 - Develop mechanism to pass heat transfer coefficient distribution to LEWICE3D



Summary

- Focus on experimental efforts that will provide a strong basis of understanding into the fundamental physics of ice accretion and particle behavior
 - Fundamental experimental work will evolve into more relevant and complex geometries to enable three-dimensional model validation
 - PSL full engine and rig tests are desired to continue the development of the facility's capability and computational tools
- Continued development of measurement methods and techniques
- 0D/1D COMDES and LEWICE3D/GlennHT codes are needed to enable the assessment of the icing risk on current and future propulsion designs

Acknowledgements

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