Introduction to Aircraft Icing

and NASA's Approach to Understanding It

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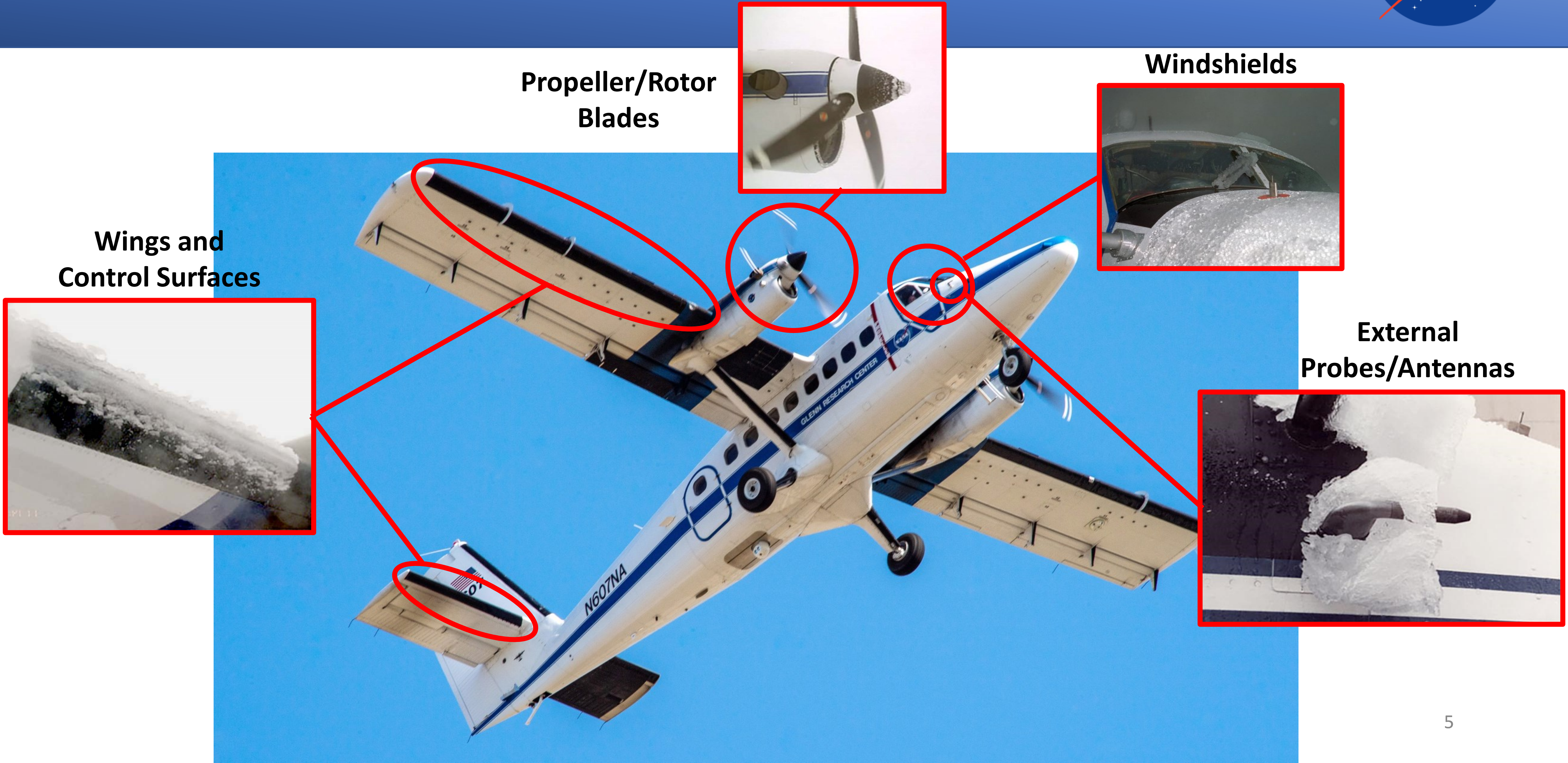
Overview

- What is Aircraft Icing?
- Types of icing
  - Airframe icing (supercooled liquid)
    - Introductory icing physics
  - Engine icing (ice crystal)
  - Rotorcraft icing
- NASA's Approach to Understanding
  - Flight Tests
  - Wind tunnel Tests
  - Computational Tools
- The Future of Aviation and Icing

What Is Icing And Why Is NASA Studying It?

What is Icing?

What is Aircraft Icing?



Why NASA studies aircraft icing

- **Challenges**
  - Aircraft icing can be a safety hazard
  - Meteorological conditions that result in aircraft icing will always be present
  - It is expensive for any single entity to study it and provide solutions.
  - Newer icing regulations will have large impacts on new airframes and propulsion systems design, cost, and certification

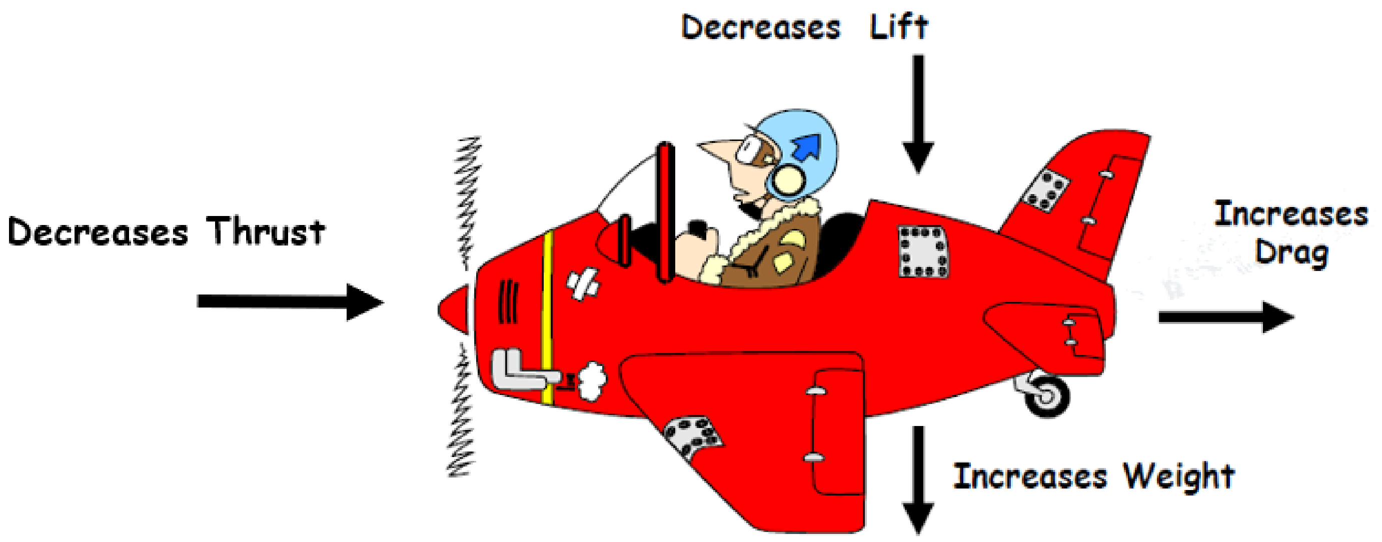
- **Needs**
  - Mitigate icing safety risks
  - Reduce amount of expensive/dangerous icing flight testing
  - Improve computational icing tools to aid certification
  - Provide publicly available data to validate tools
  - Develop technologies like icephobics, low power and weight Ice Protection Systems

- **NASA's role**
  - An agency that can provide publicly available models and validating datasets
  - Mature testing facilities
  - Decades of institutional icing knowledge
  - **Community enduring need is** for NASA to continue performing foundational icing physics studies in the public to improve current capabilities

Airframe Icing - Supercooled Liquid Icing

Impact on Aerodynamic Performance

- **What factors affect airframe icing?**
  - Water in the cloud (not ice)
  - Temperature
  - Size of the water droplets
  - Type of clouds
  - Airfoil geometry
  - Airspeed
  - Time the aircraft is in icing condition
- **What does ice do to an aircraft?**

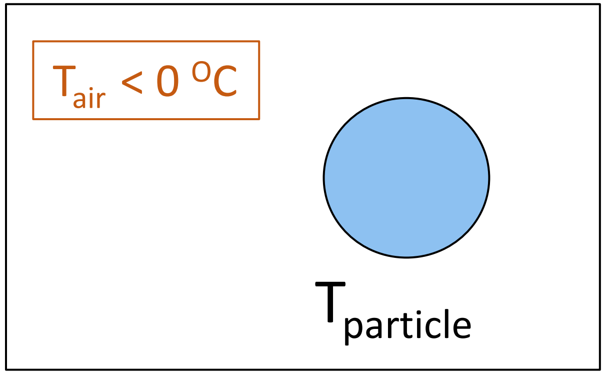


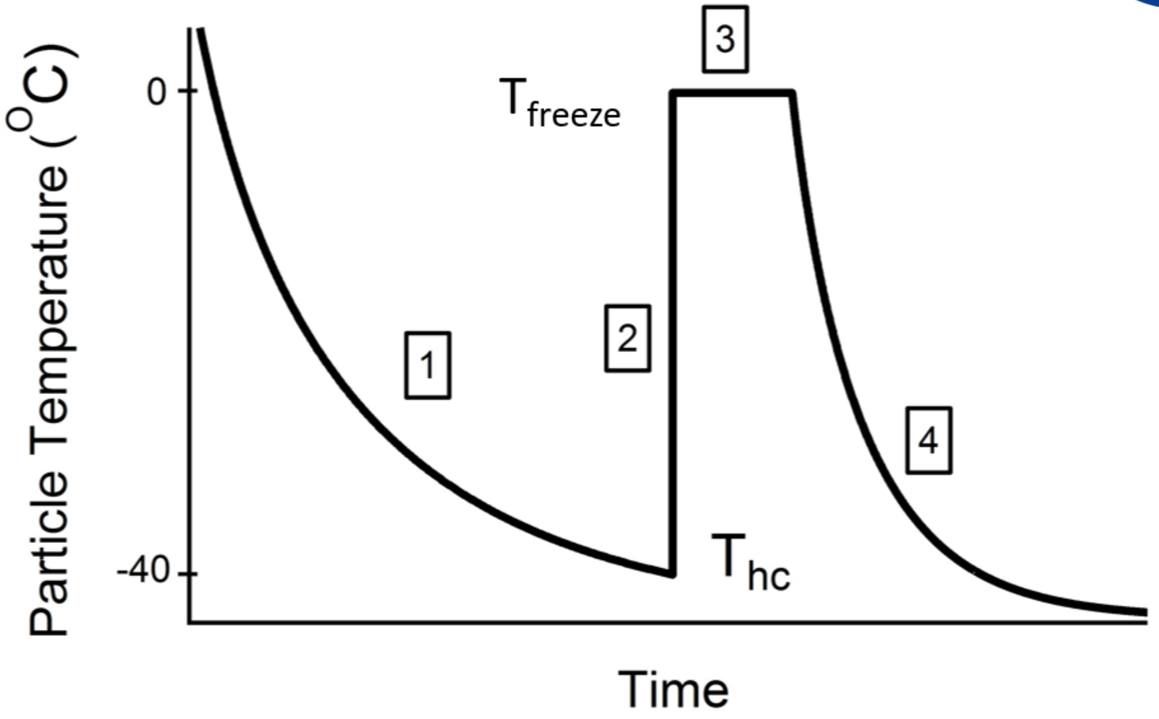
Where to find supercooled liquid icing clouds

Cumulus – Large Drops

Stratus – Small Drops

Physics of Supercooled Liquid Water





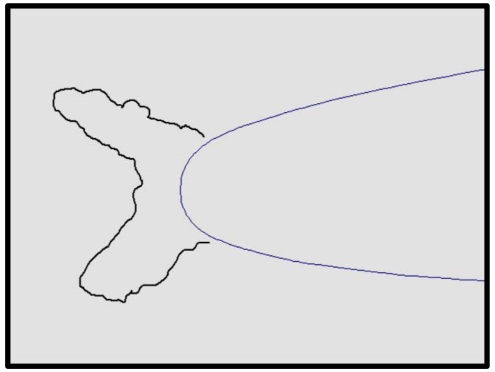
1. Sensible cooling of liquid water to below the equilibrium freezing temperature (T_{freeze} = 0 ^{O}C) until homogeneous/heterogeneous crystallization temperature (T_{hc}) is reached. T_{hc} dependent on droplet impurity content.
2. Latent heat release of supercooled water where rapid crystallization of a particle occurs, along with an increase in particle temperature. The particle will partially freeze and reach its equilibrium freezing temperature of 0 ^{O}C.
3. Latent freezing where heat is transferred from the partially frozen particle at a constant temperature of 0 ^{O}C until it has completely frozen.
4. Sensible cooling of the solid ice particle until the temperature is reduced to the wet-bulb temperature.

Glaze vs Rime Icing (Video)

Glaze

Clear/translucent

Ice shapes protrude from the leading edge

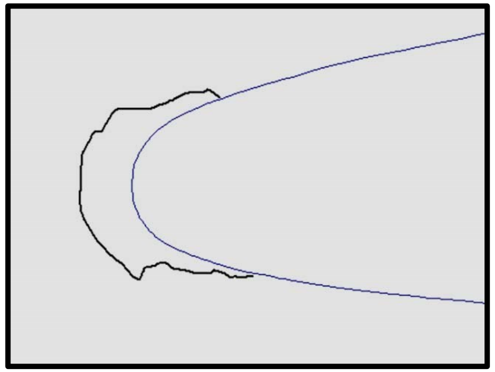


T = -2 to -10 ^{O}C

Rime

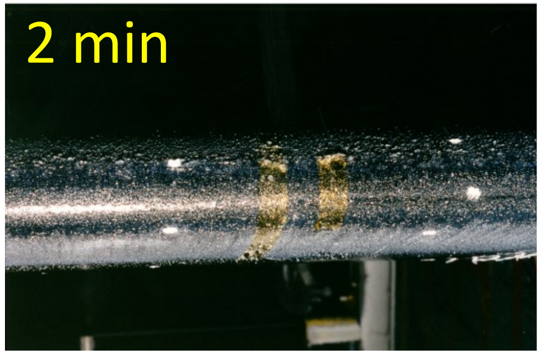
Opaque

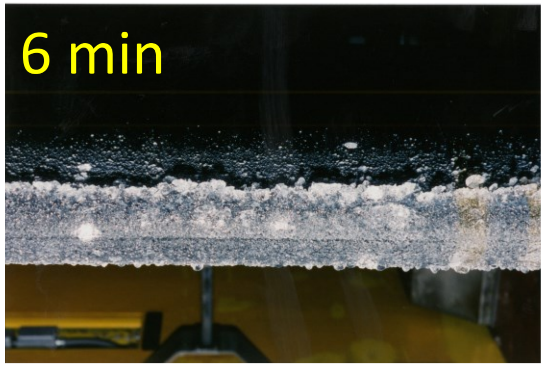
Streamlined ice shapes

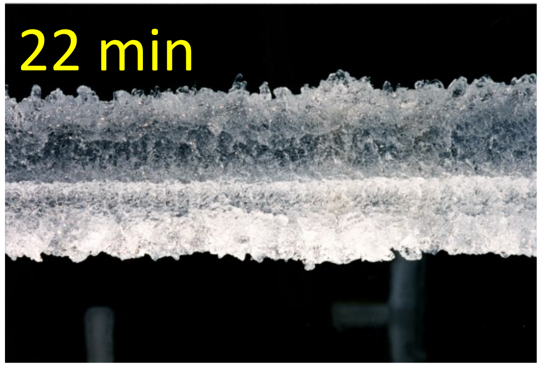


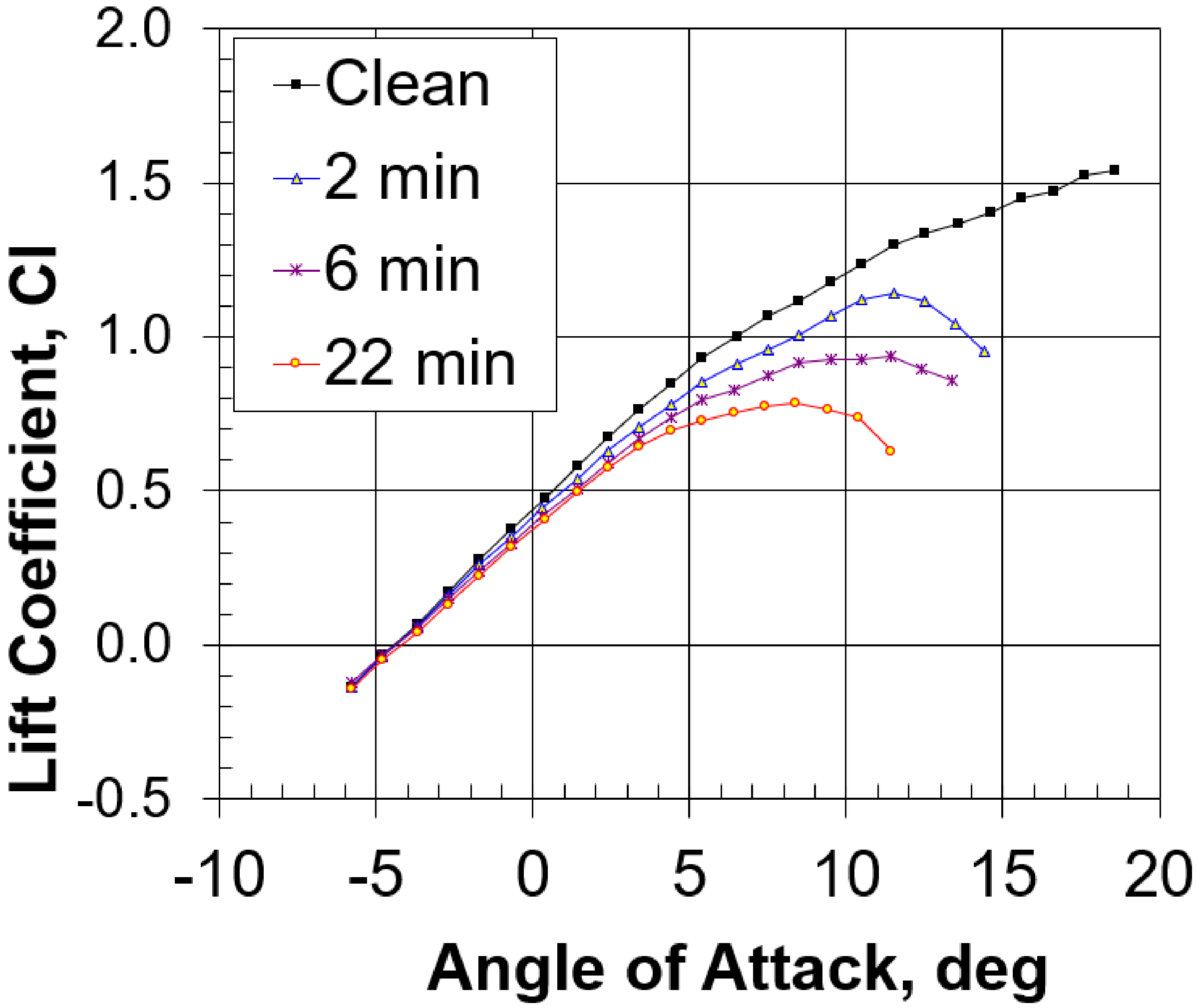
T < -10 ^{O}C

Impact on Aerodynamic Performance

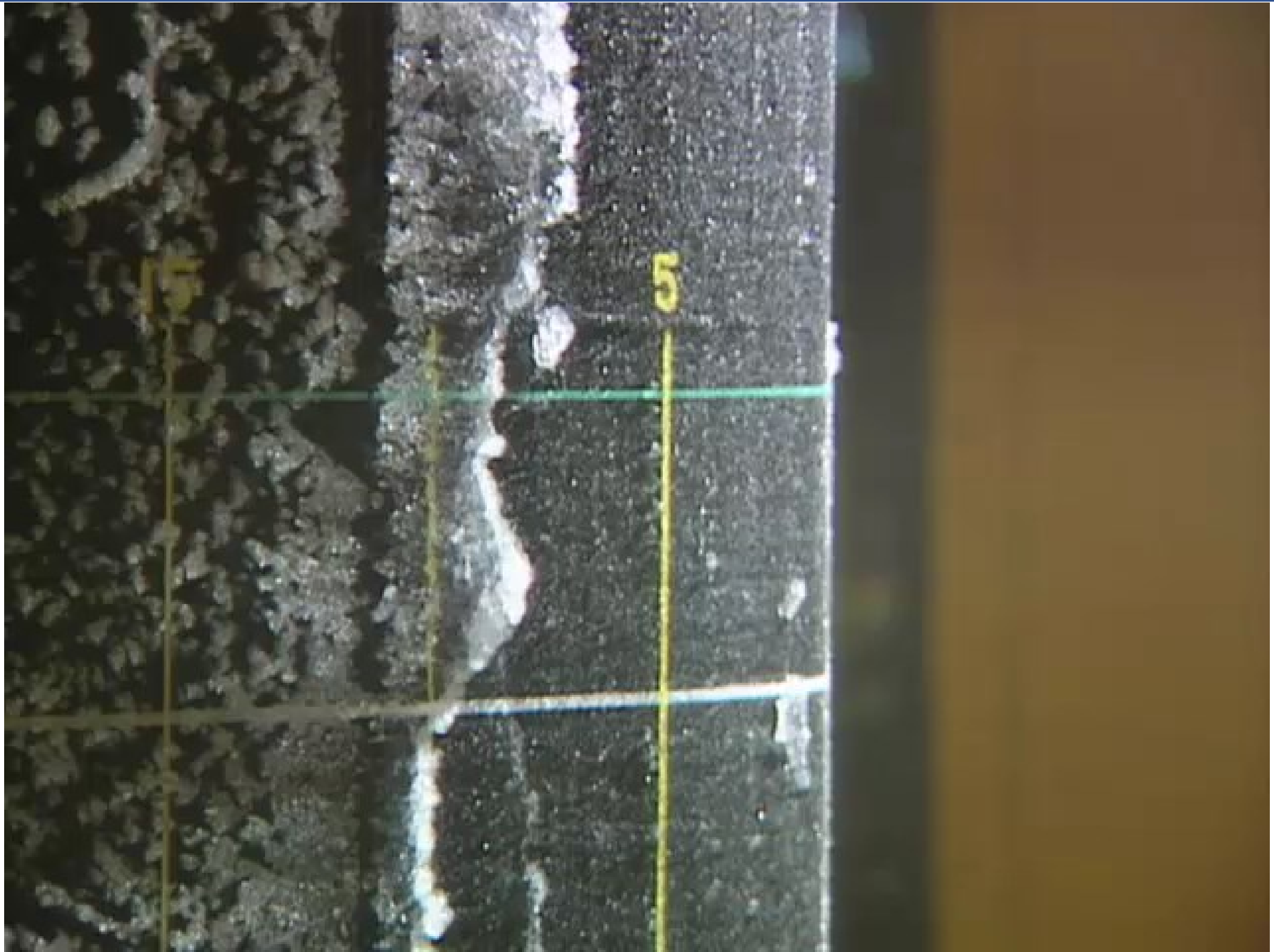








Deicing Boot (Video)



Meteorological Requirements for Icing

Aircraft icing requires two conditions to occur:

1. **Temperatures near or below freezing**
    - Icing is more frequent when the static air temperature (SAT) is between +2°C and -20°C.
2. **Existence of water droplets**
    - Liquid water must be present in the air for ice accretion to occur.
    - Water in the form of vapor, snow, or ice will generally not stick to an airplane's external surface and contributes little to the overall ice buildup.
    - If there is sufficient liquid water in the air to pose an icing threat, it will generally be visible in the form of a cloud or liquid precipitation.

Meteorological Conditions that Influence Icing Severity

The main meteorological conditions that influence icing severity include ***temperature***, ***liquid water content (LWC)***, and ***droplet size***.

Temperature

- Temperature effects both severity and type of icing.
- Most icing occurs between 0°C and -20°C. Icing is not severe below -40°C because this is the temperature droplets freeze without an icing nuclei.

Liquid Water Content (LWC)

- Defined as the density of liquid water in a cloud expressed in grams of water per cubic meter (g/m^3)
- In general, the higher the LWC, the greater the icing severity.

Continued…

Meteorological Conditions that Influence Icing Severity

Droplet Size

- Droplet diameter is usually expressed in microns (µm) and represented by an average value called **Median Volumetric Diameter (MVD)**.
- Droplet size affects the collection of water drops on the surface of the aircraft; **smaller drops tend to impact near the leading edge of a wing whereas larger droplets can impact farther aft.**

Non-meteorological Factors that Influence Icing Severity

Airspeed and **collecting surface geometry** are important non-meteorological factors that influence icing type and severity.

Airspeed

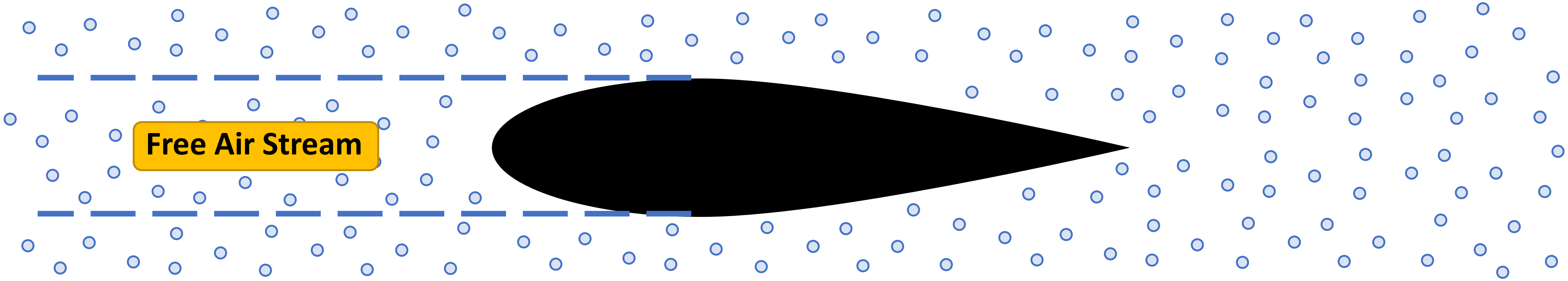
- The higher the airspeed, the higher the rate of ice accumulation.
- Airspeed also determines where ice collects on a surface; higher airspeeds allows for more droplets to impinge farther aft on an airfoil.

Collecting Surface Geometry

- Often described by the radius of curvature of the leading edge.
- Surfaces with smaller radiuses of curvature have greater collection efficiency's and thus collect more droplets.

Collection Efficiency (β)

Not all water droplets in the free air stream will strike the airframe. Droplets with small inertial forces will closely follow the streamlines and avoid striking the airframe.



The ratio of the water mass striking the airframe to the water mass in the free airstream is known as the **Collection Efficiency (β)**.

- *As collection efficiency increases, so will the rate of ice accretion.*

Collection Efficiency (β)

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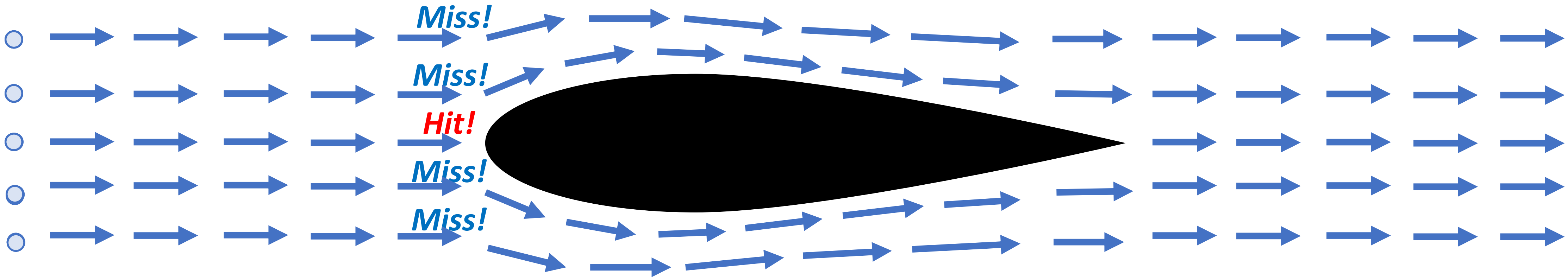

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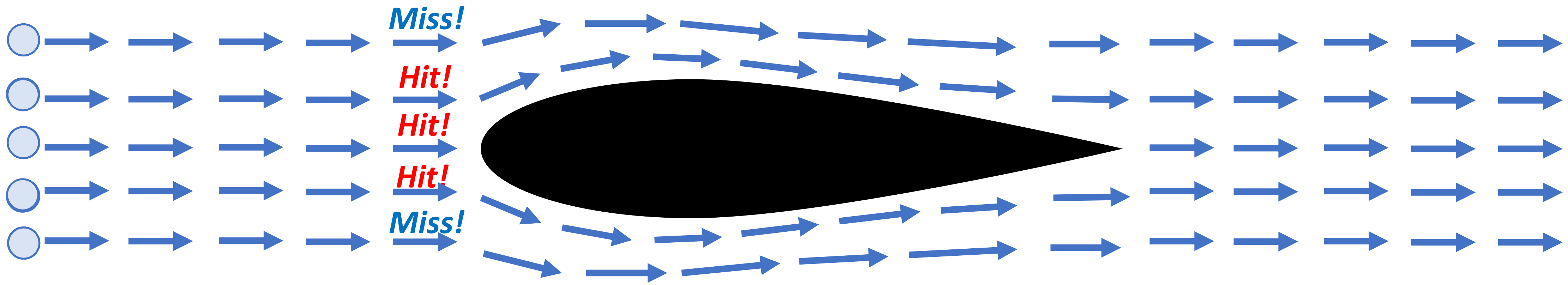
Collection Efficiency (β)

Collection Efficiency (β) is influenced by:

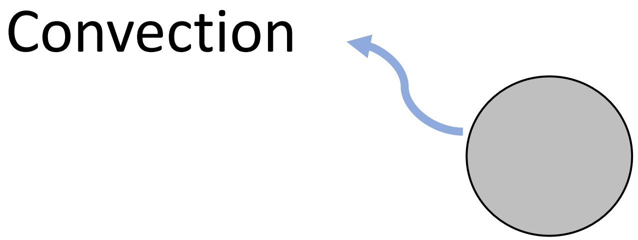
- **Airspeed** (increase in airspeed = increase in β)
- **Droplet Size** (increase in droplet size = increase in β)
- **Collecting Surface Geometry** (smaller radius of curvature = increase in β)



Due to having greater inertia, droplets with higher mass and/or velocity are more ballistic and more likely to strike the object.

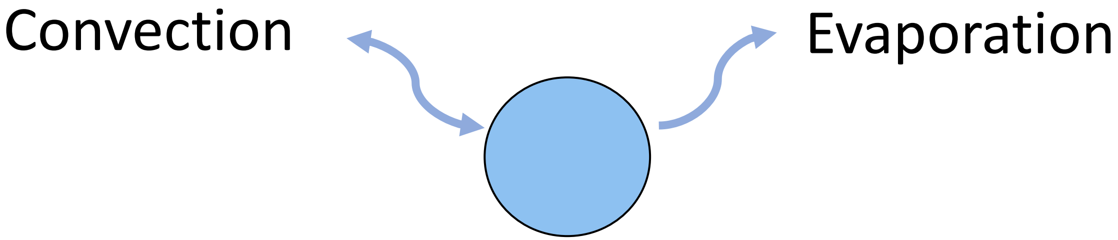
Dry-Bulb Temperature vs Wet-Bulb Temperature

Metal ball



$T_{SS} = T_{DB} = f(T_{air})$

Water droplet (small)



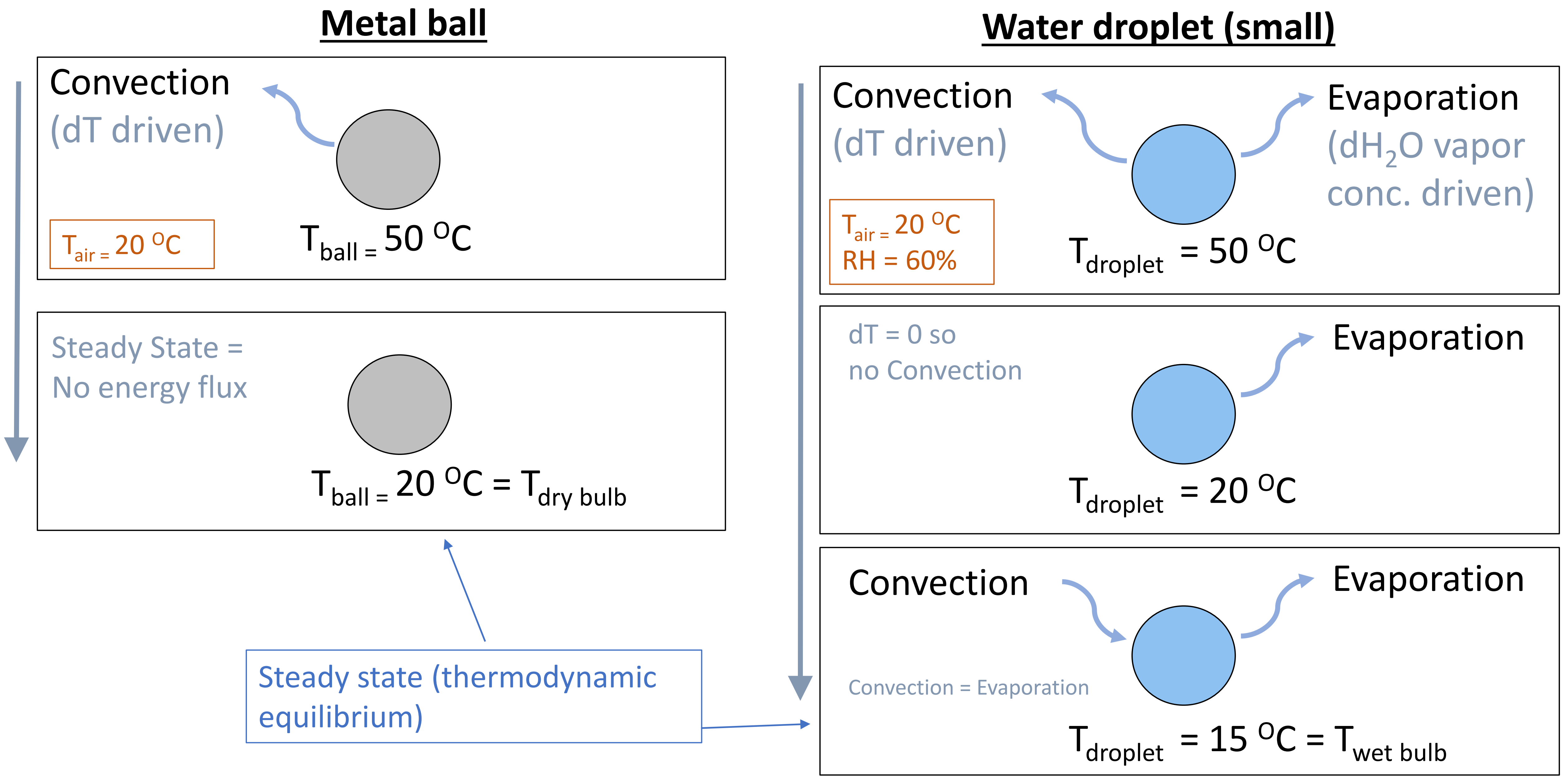
$T_{SS} = T_{WB} = f(T_{air}, RH, P)$

T_{SS} = Steady State Temperature, T_{DB} = dry bulb temperature, T_{WB} = wet bulb temperature

If RH = 100% → No evaporation → $T_{WB} = T_{DB}$

If RH < 100% → Evaporation → $T_{WB} < T_{DB}$

Dry-Bulb Temperature vs Wet-Bulb Temperature

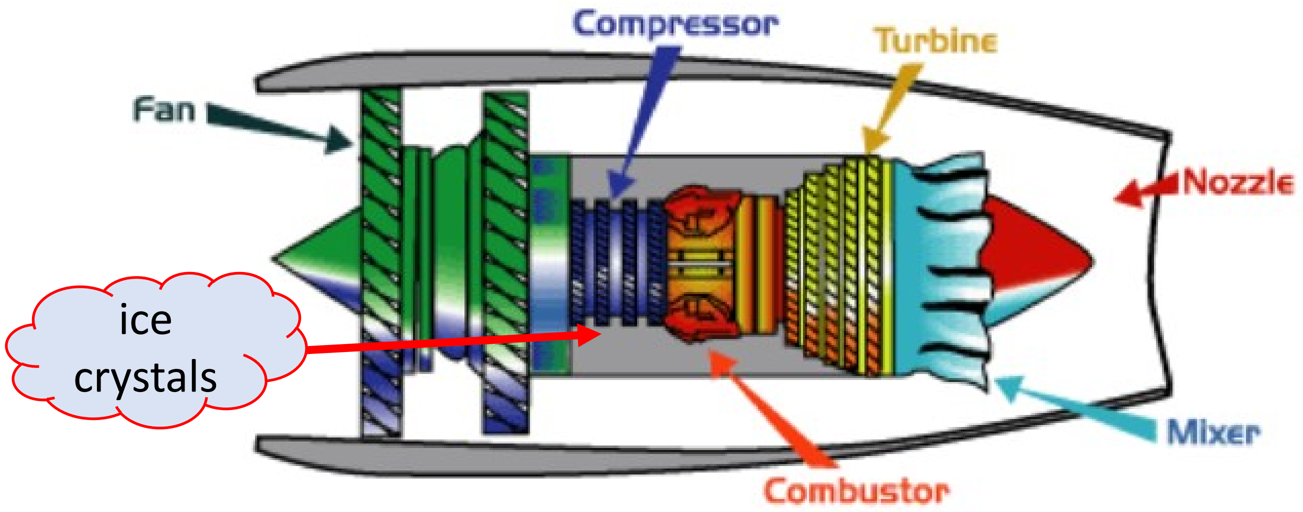


Engine Icing – Ice Crystal Icing

Where to find ice crystals

High Clouds – Ice Crystals

Engine Cross-Section



Generic Engine Compression System

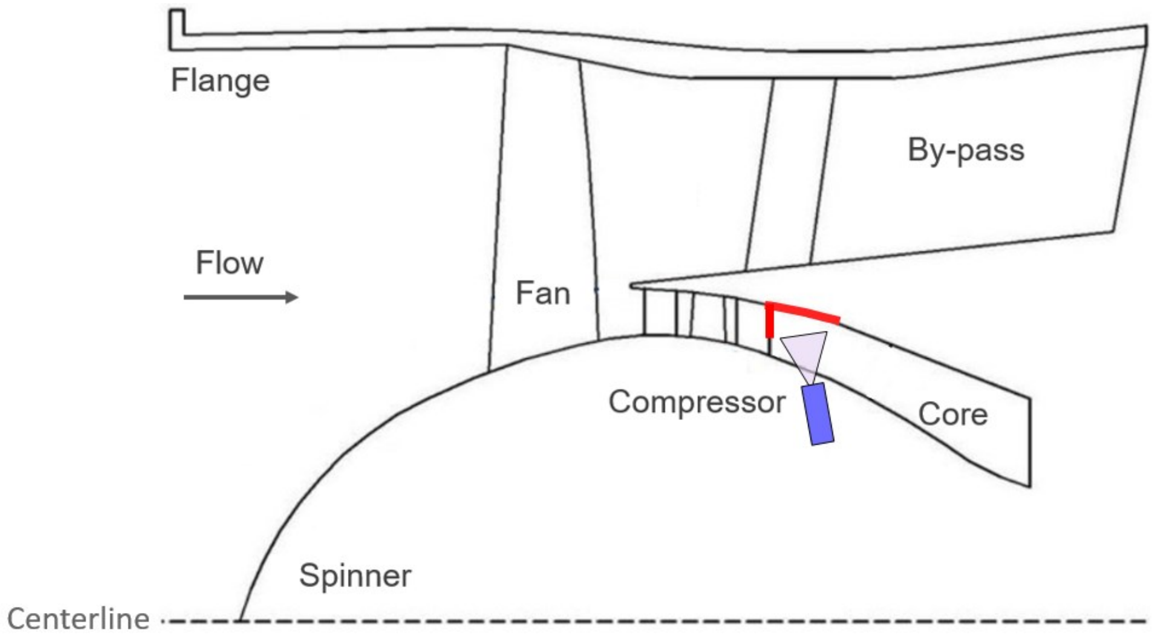
174 reported jet engine icing events worldwide and documented in Boeing database as of January 2019

Bravin, SAE Technical Paper 2019-01-1964

Engine Icing (Video)

Engine Icing Tests

Generic engine schematic



Honeywell ALF02 LF11 Engine icing test

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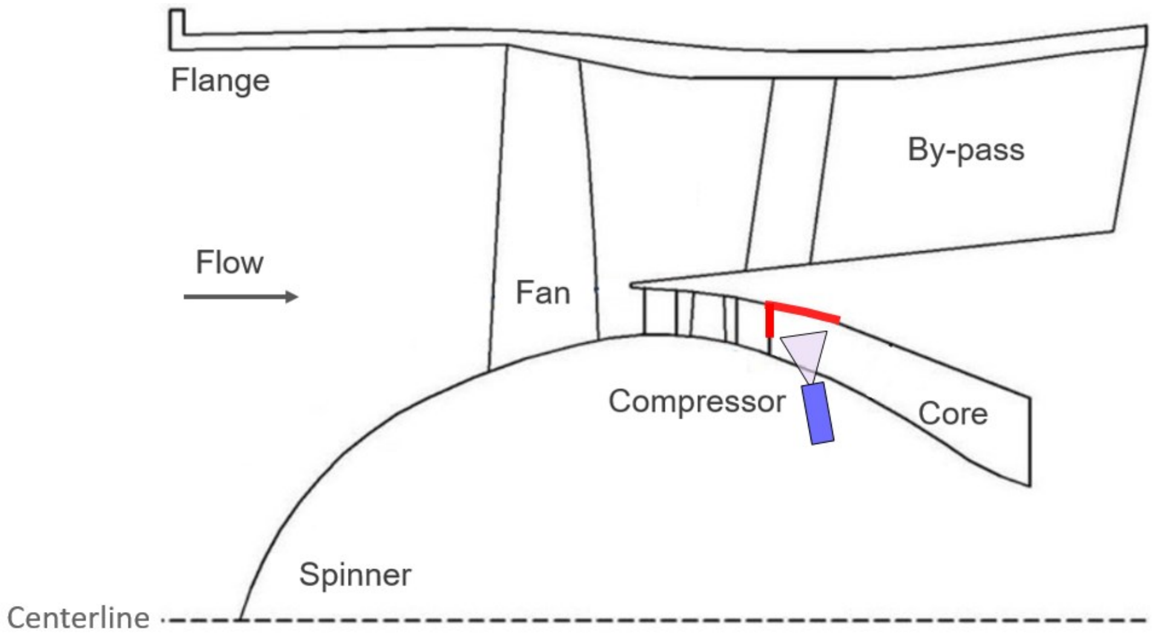
Engine Icing Tests (video)

Generic engine schematic



Honeywell ALF02 LF11 Engine icing test

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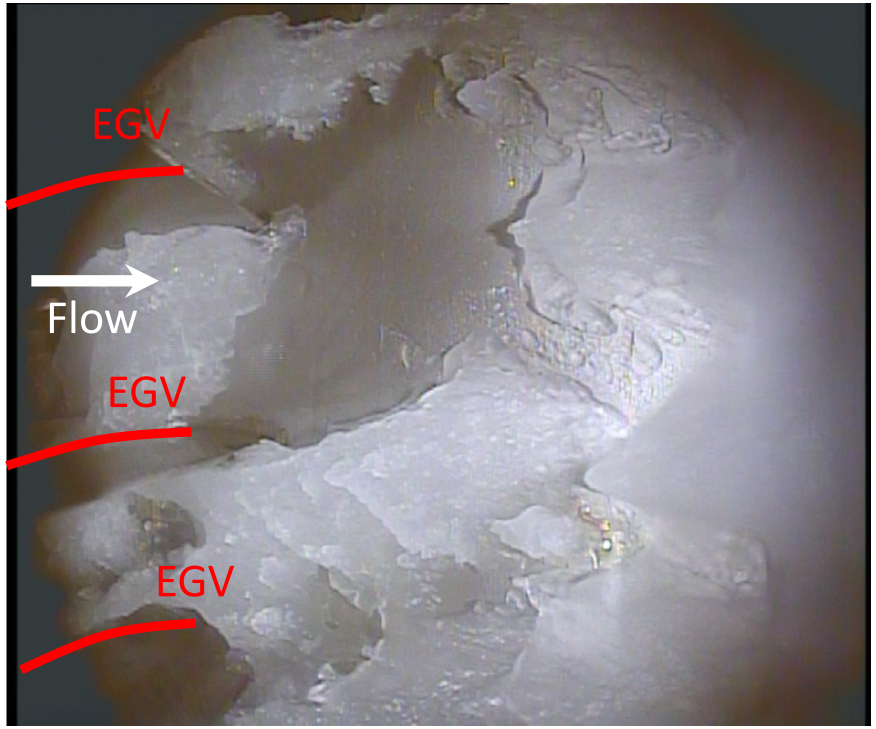
Engine Icing Tests

Goal: Understand the mechanisms of ice crystal icing inside engine core flow path

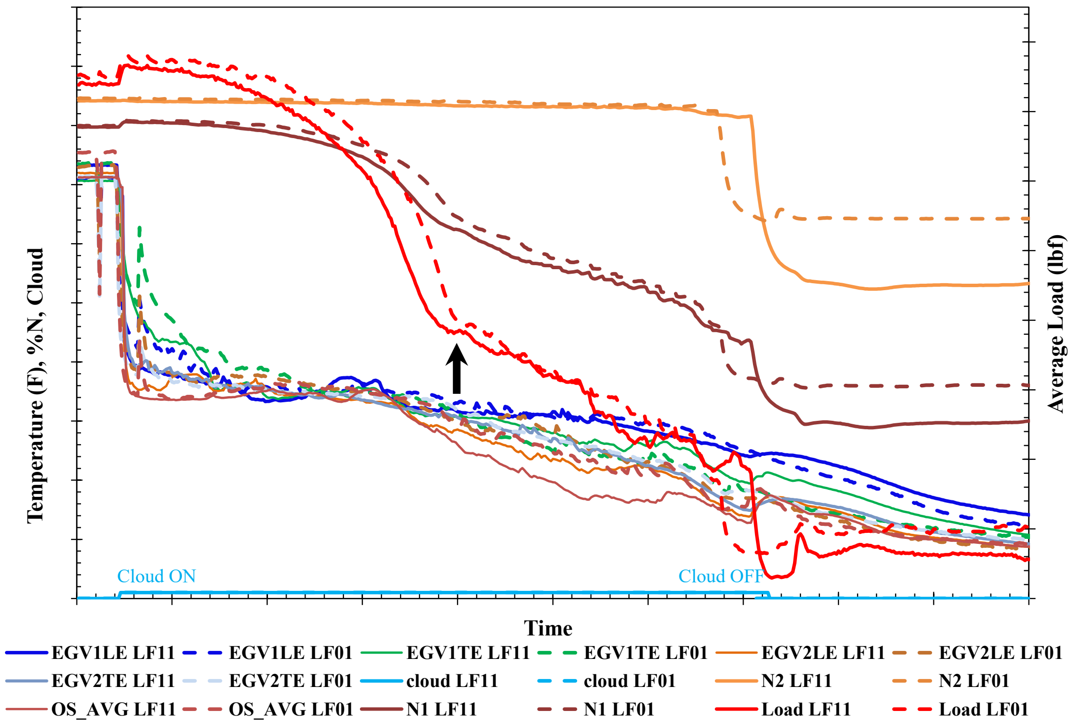
Engine icing tests provide valuable data but…

- **Difficult to instrument jet engine with probes and cameras**
- **Difficult to quantify accreted ice mass**

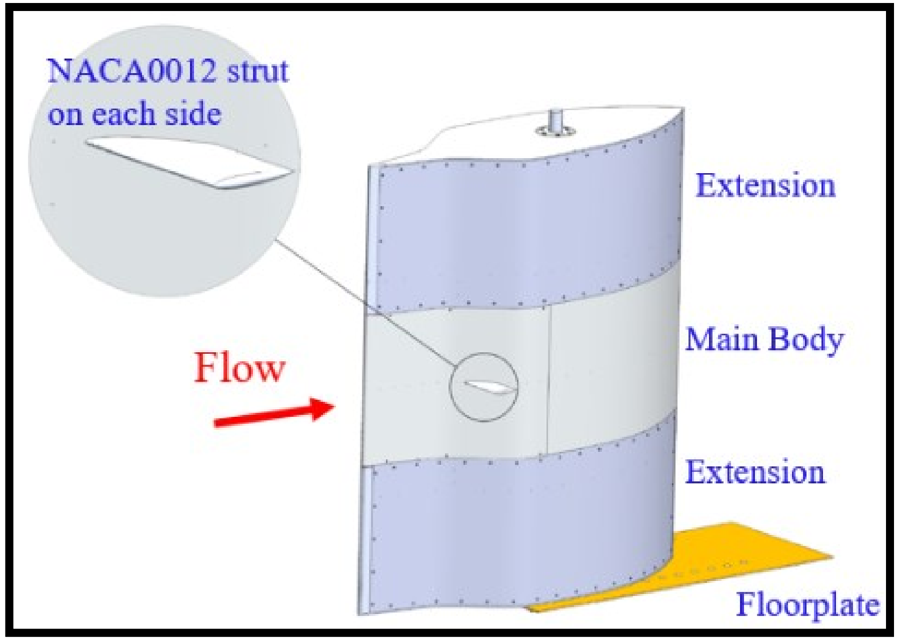
Ice Accretion in the Engine



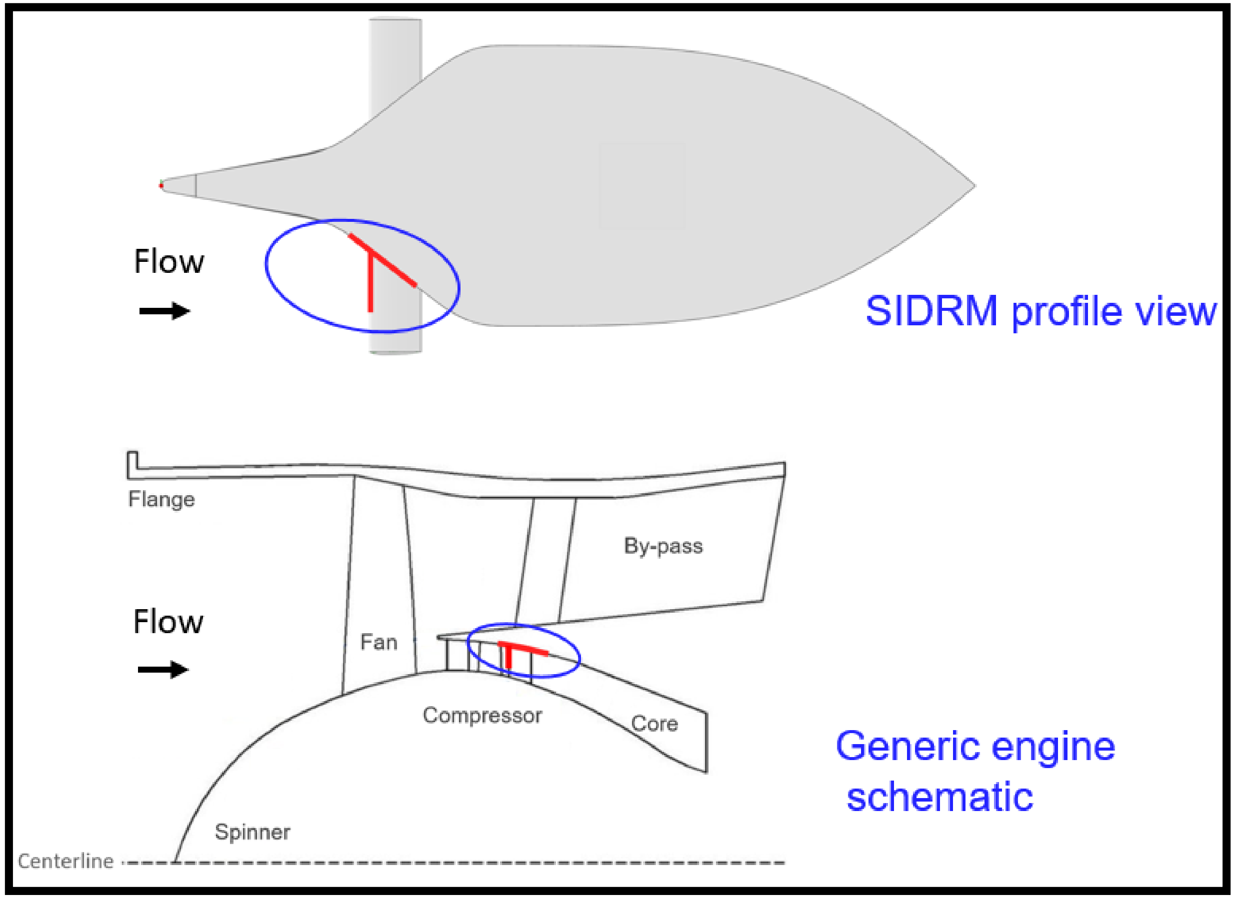
Typical Performance Data

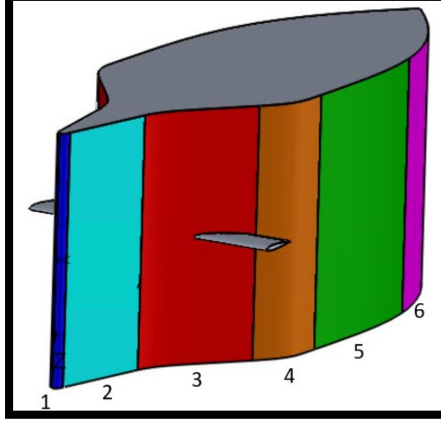


Component-level Icing Test with SIDRM Test Article



SIDRM = Simulated Inter-compressor Duct Research Model





Zone	Surface Heat Flux (W/in^2)
1	60
2	20
3	20
4	20
5	20
6	20

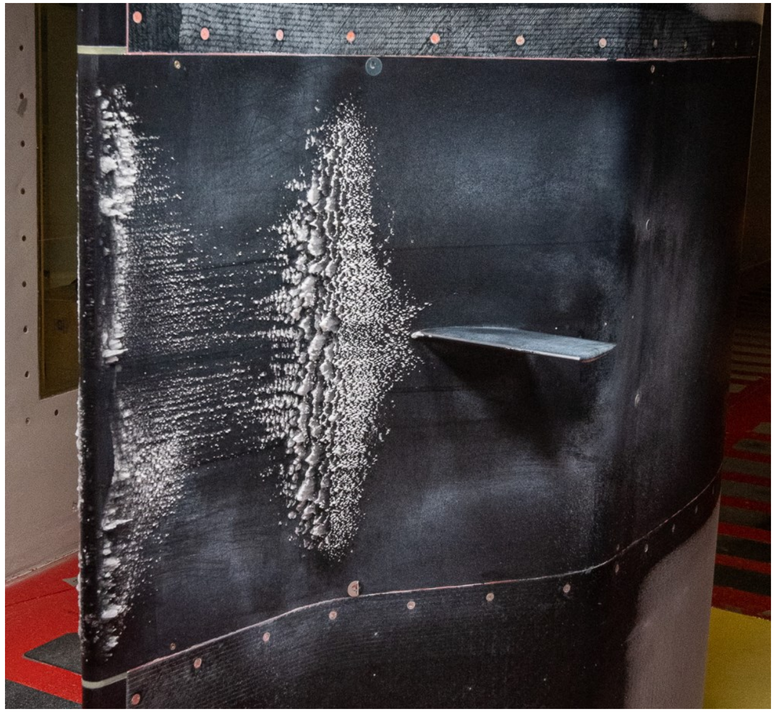
Thin film
surface heaters

Ice Crystal Icing Tests with SIDRM Test Article

Results
In 2022, conducted 61 icing tests, providing validation data for 3D computational icing tools.

Significance
These tests represent the first time that ice accretions were measured on a 3D test article at IRT. It also marks at first time that ice crystal ice accretions were generated utilizing heated surfaces. Using an open geometry configuration, these tests recreated ice crystal icing features characteristic of those seen in previous engine icing tests.

Supercooled liquid ice accretion on SIDRM



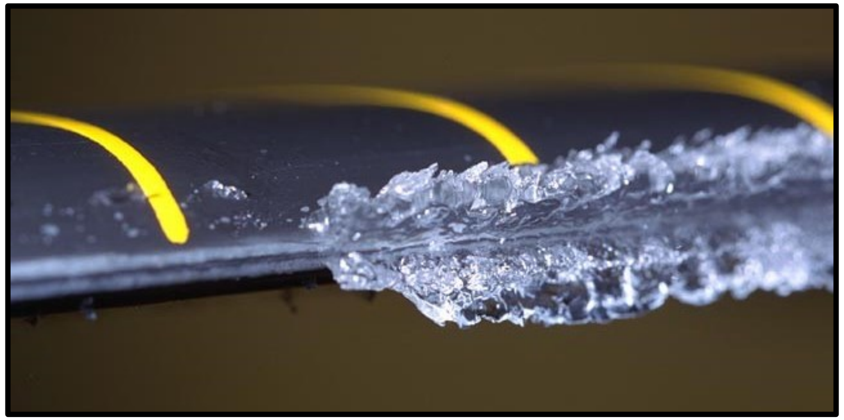
Ice crystal icing utilizing SIDRM's heated panels

https://arc.aiaa.org/doi/abs/10.2514/6.2022-3700
https://ntrs.nasa.gov/citations/20220006460

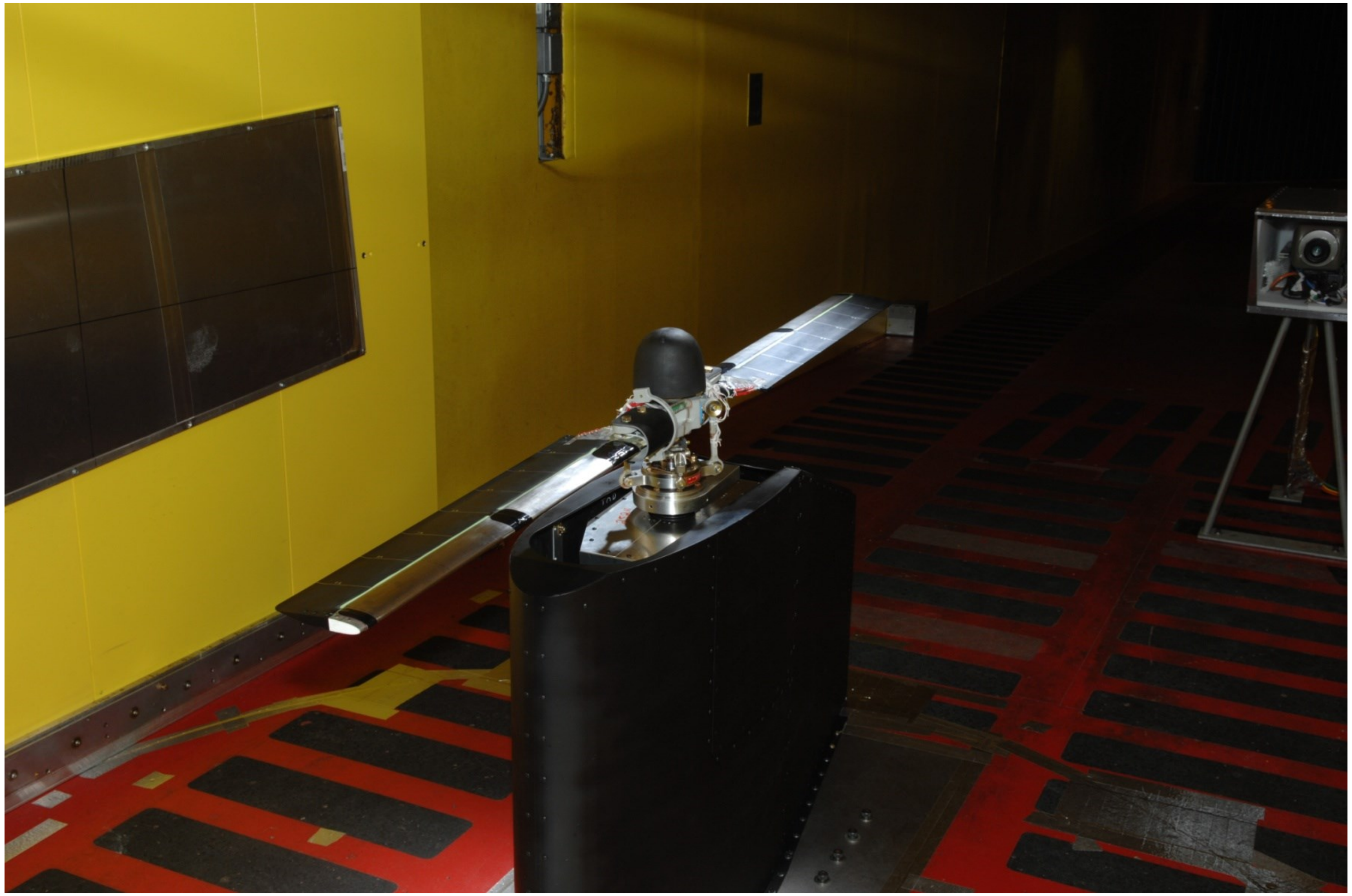
Rotorcraft Icing

Rotorcraft Icing

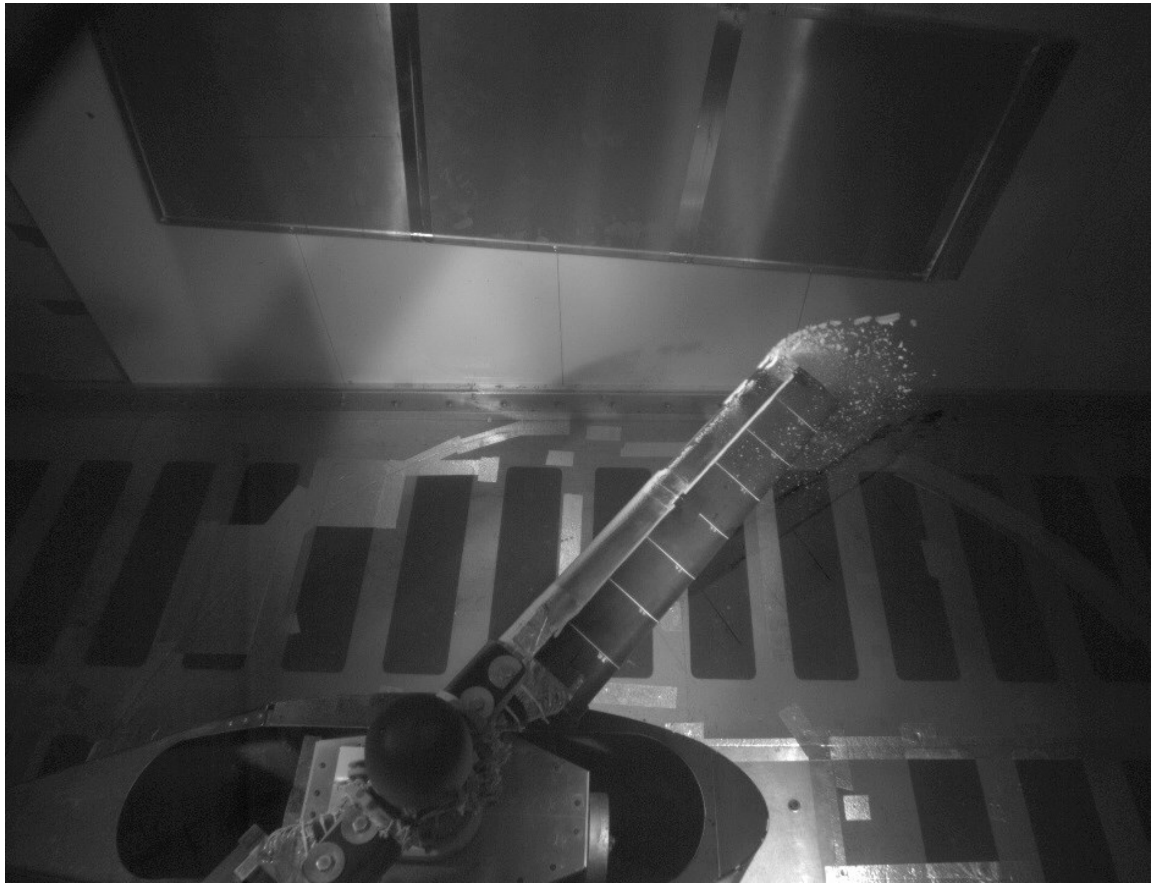
- **Rotorcraft are often required by mission objectives to operate in icing conditions for prolonged periods of time.**
  - Military Operations
  - Search and Rescue
  - Urgent Transportation
  - Operate at lower altitudes
- **Current certification process is time consuming and expensive.**
  - Flight campaigns in natural icing conditions
  - Simulated icing conditions using a tanker
- **Conventional electrothermal deicing systems can be unreliable and consume a lot of power.**
- **Severe vibration or damage can occur due to ice shedding from rotor blades.**

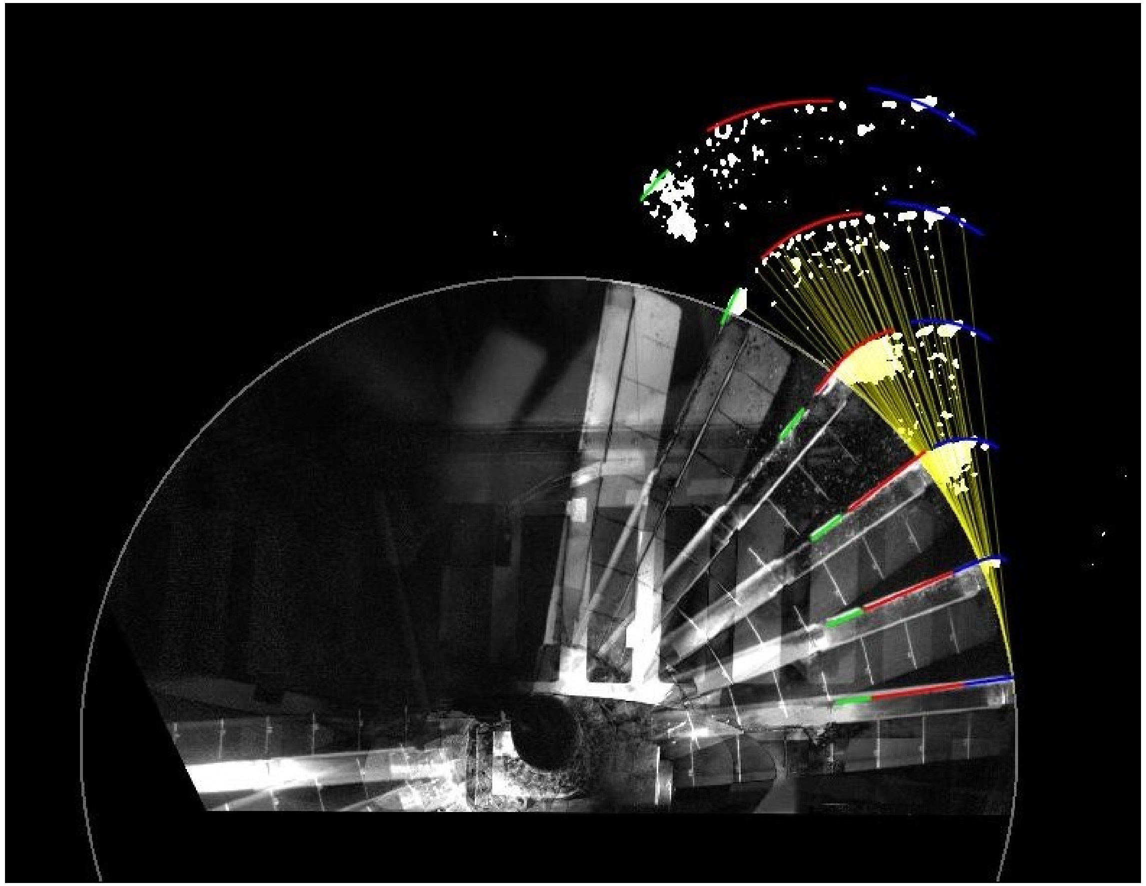


Rotorcraft Icing Studies



Rotor Ice Shedding





Characterization of Low Ice Adhesion Materials

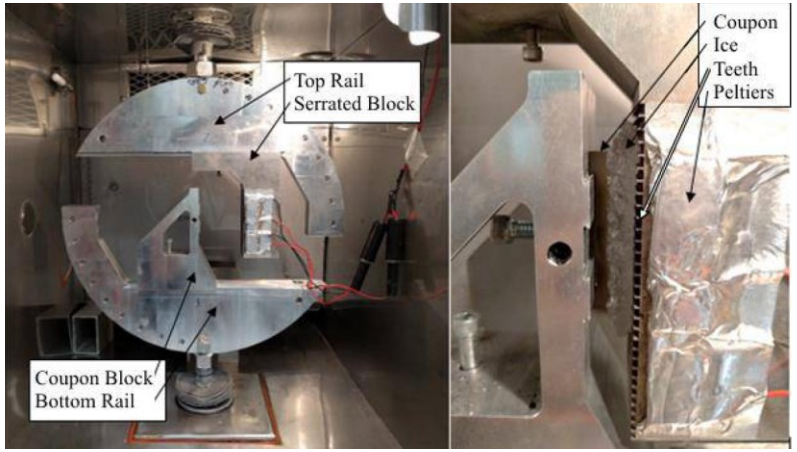
PROBLEM In order to develop effective ice-resistant coatings for aircraft, we must first have a consistent, reliable method for quantifying adhesion strength of accreted ice.

OBJECTIVE Design, fabricate and demonstrate robust, efficient adhesion test method(s) which can be used in our facilities.

APPROACH Utilize various test methods: Centrifugal test, lap joint method.

ACCOMPLISHMENTS Determined factors driving the ice adhesion strength are icing cloud conditions and stress concentrations.

SIGNIFICANCE Evaluate coatings. Develop adhesion strength database. Exploring the effect(s) of grain structure on ice adhesion.



Ice adhesion shear test using lap joint rig

Shear test sample and accreted ice grain structure

Centrifuge shear test and ice coupon on centrifuge arm

NASA’s Approach to Understanding Icing

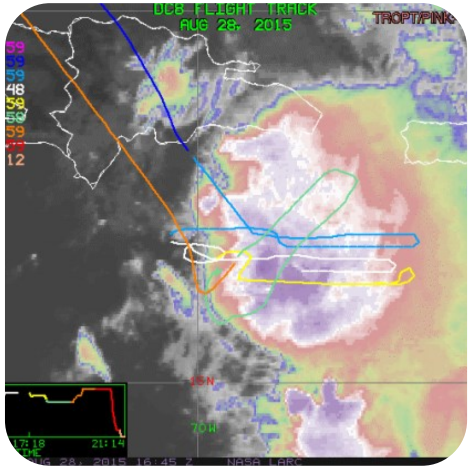
NASA's Approach to Understanding Icing

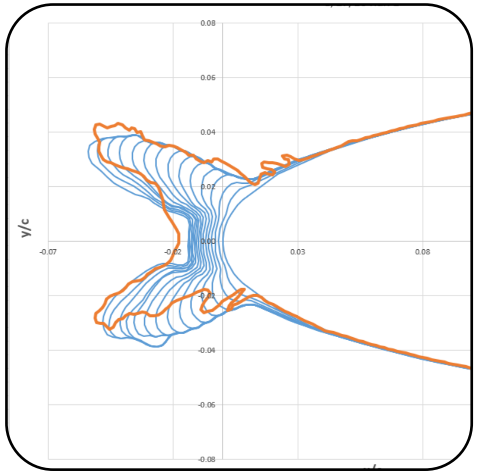
Wind Tunnel Tests

Simulate the Environment

Flight Tests

Understand the Environment





Computational Tools

Model the Environment

Icing Flight Tests

High Ice Water Content Flight Test Campaign

Problem
- Turbofan engine power-loss or damage events have been attributed to the ingestion of ice crystals.

Objective
- Measure ice crystal cloud properties in high-aerosol environment to determine globally representative and data-driven engine certification envelope limits.

Approach
- NASA's DC-8, instrumented with icing cloud and aerosol sampling instruments, was flown at high altitudes through deep convective clouds and below clouds to measure the aerosols that interacted with cloud and ice crystals.

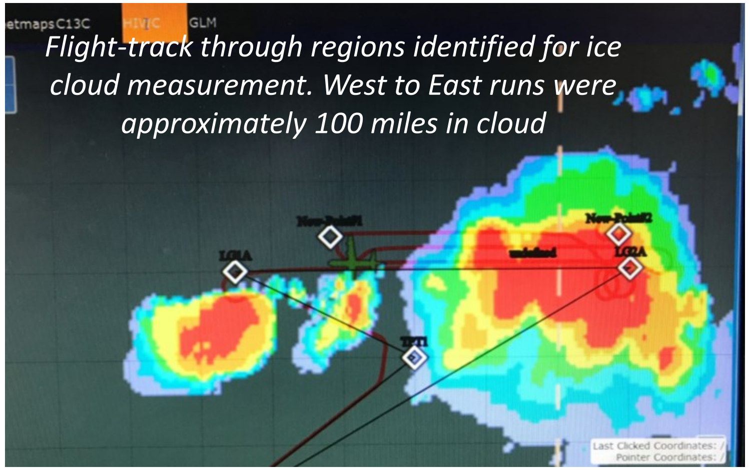
- Radar development to identify and avoid hazardous icing conditions

Results
- Research flight campaign conducted with over 60 flight-hours of data collected.

Significance
- Once the data is analyzed, the regulations for ice crystal icing certification will be assessed and updated for engine certification and operability.

- Measured conditions in Nature used to recreate icing conditions in ground-based icing wind tunnels

Early morning takeoff. Inset shows icing instruments on DC-8 wing pylon



Flight-track through regions identified for ice cloud measurement. West to East runs were approximately 100 miles in cloud

Icing Wind Tunnel Facilities:

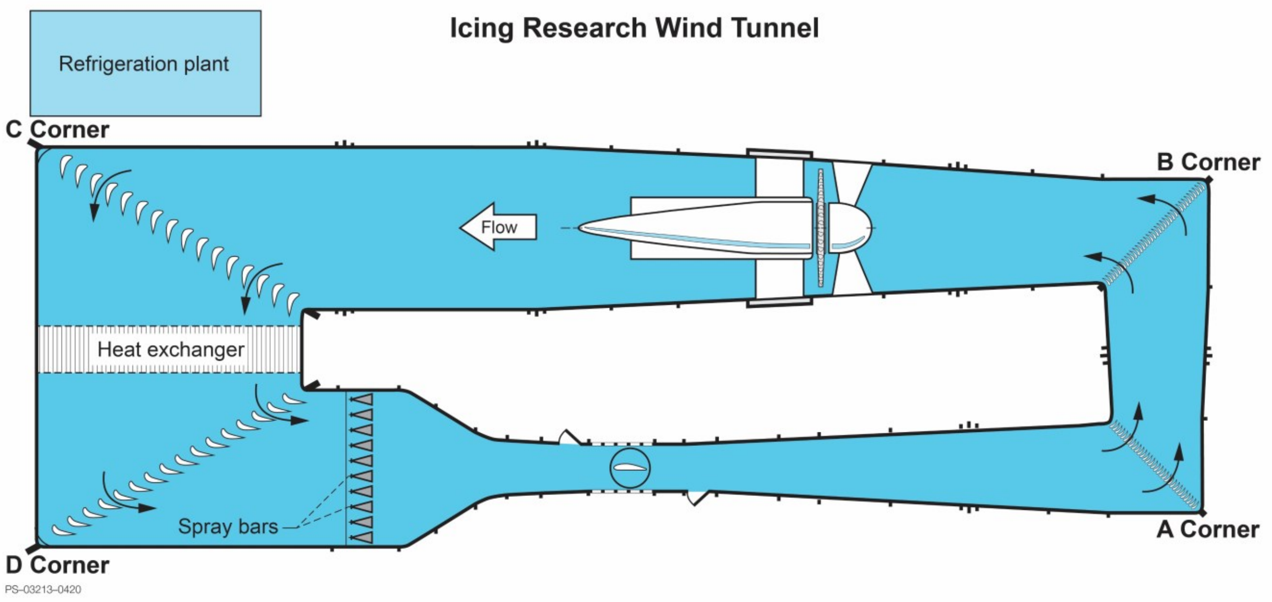
Icing Research Tunnel

Propulsions Systems Laboratory

Adaptive Icing Tunnel

Icing Research Tunnel (IRT)

Icing Research Tunnel



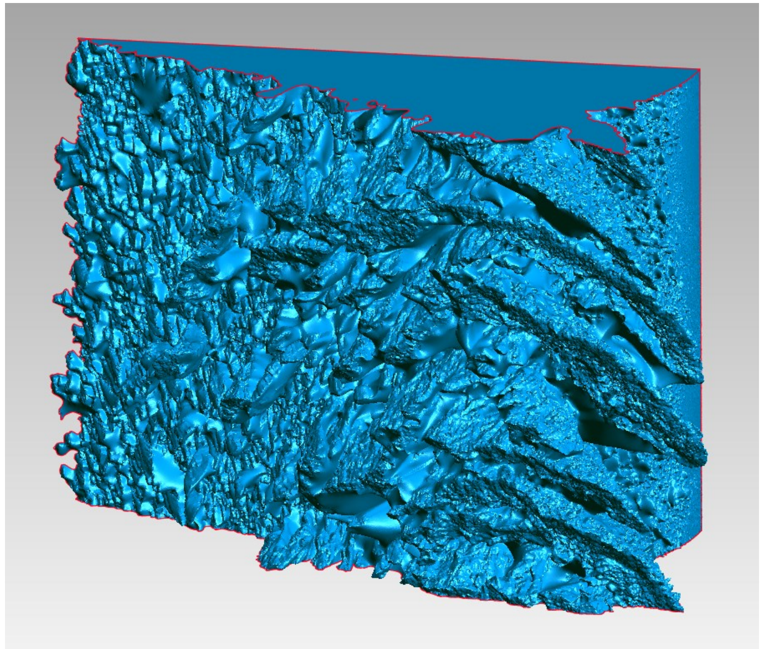
Icing Research Tunnel Quick Facts	
Test Section	6 ft tall by 9 ft wide by 20 ft long
Airspeeds	50 to 300 knots
Temperatures	As low as -35°C
Droplet Size	15 to 275 microns
Water Content	0.15 to 4.0 g/m^3

IRT Test Section

Icing Research Tunnel (IRT)

Spray Bars
(Video)

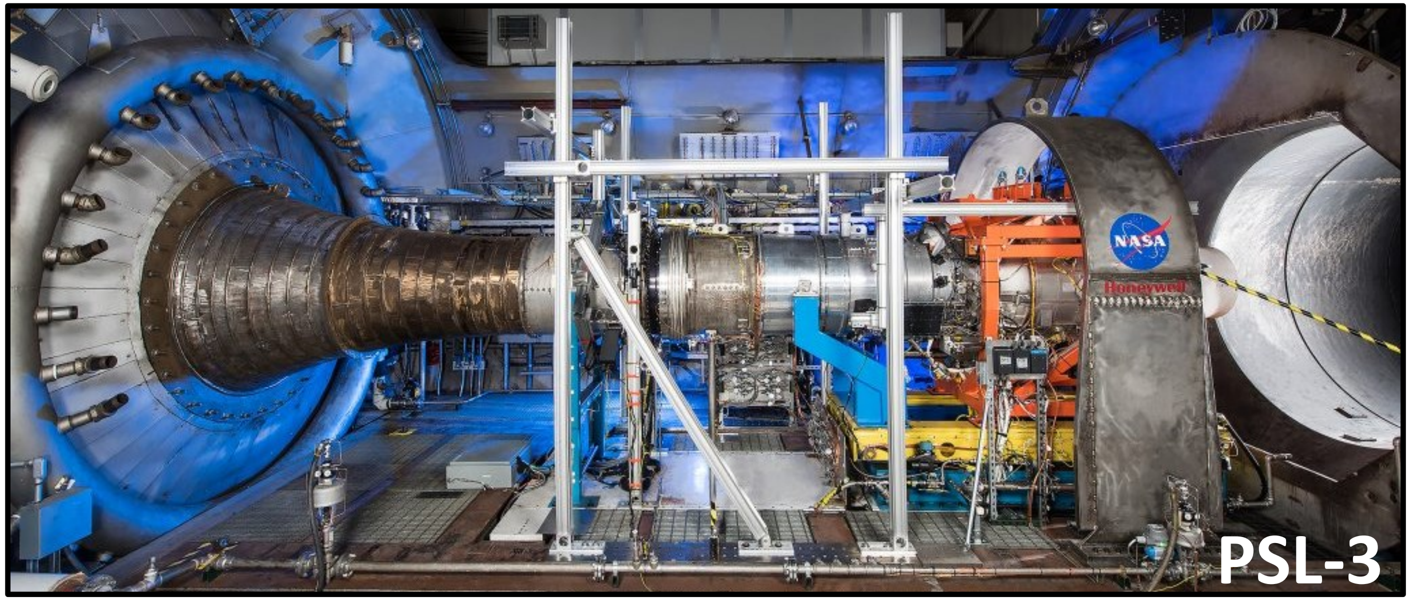
Laser Scanner Technology

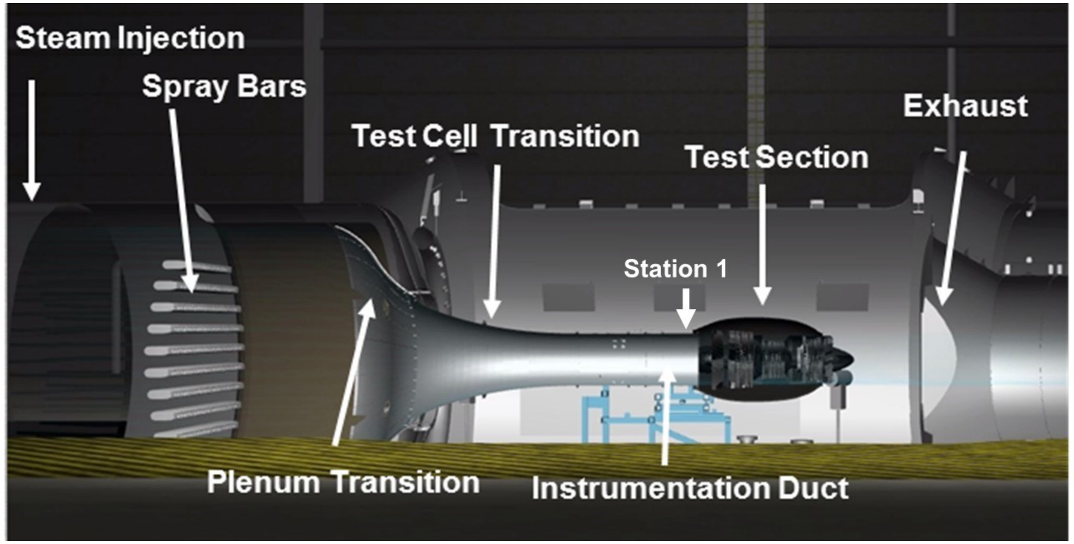


Document ice accretion geometry with high fidelity

Propulsion Systems Laboratory (PSL)

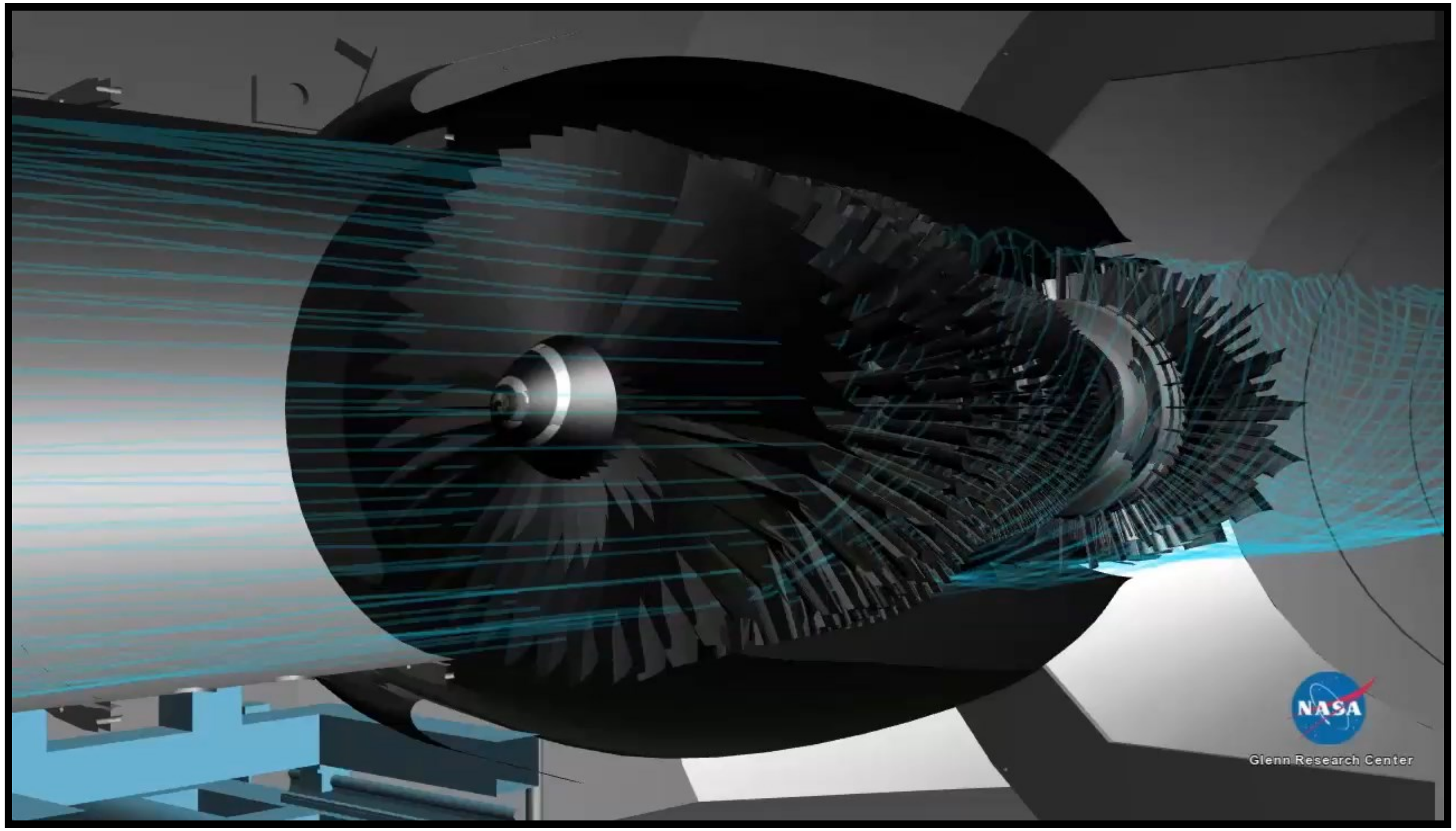
Propulsion Systems Laboratory (PSL)





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/m³)	0.5	8.0
Particle Size - MVD (um)	15	>100

Propulsion Systems Laboratory (Video – 1 min)

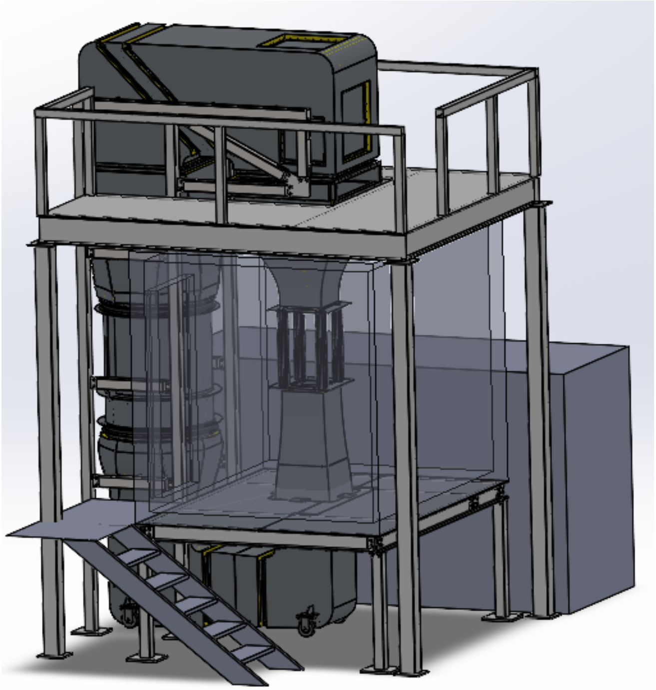


Adaptive Icing Tunnel (AIT)

What is the Adaptive Icing Tunnel (AIT)

- Closed loop, vertical refrigerated icing wind tunnel
- Test section:
  - 1’ x 1’ cross section
  - 2’ long
  - Flow speeds of ~210 knots (~110 m/s)
  - Temperatures as cold as -20°C
- Walk-in freezer surrounding test section
- Scheduled for installation in FY23 followed by tunnel characterization

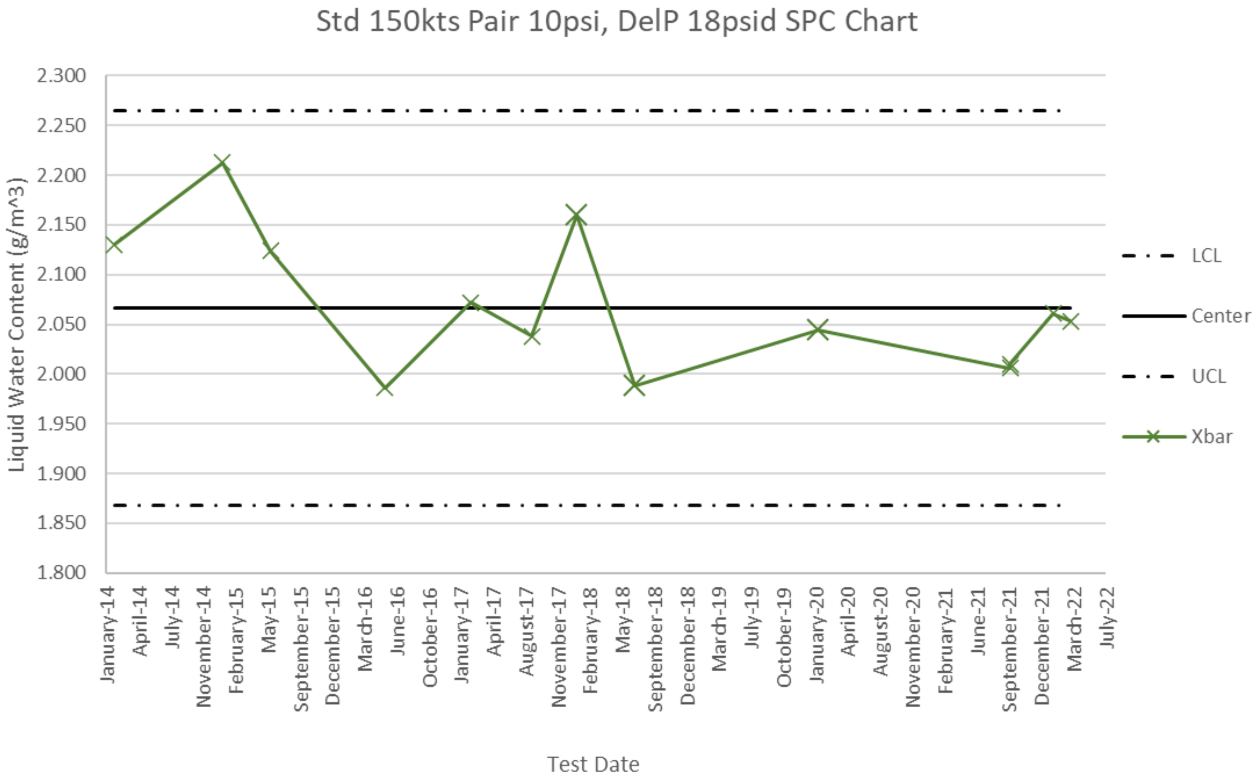
Lower-cost capability for instrument evaluation and proof-of-concept testing.



Icing Tunnel Cloud Measurement and Calibration

IRT Calibration and Maintenance

- SAE's ARP5905 "Calibration and Acceptance of Icing Wind Tunnels"
- Regular calibrations
- Interim and full calibrations
- Statistical Analysis and Statistical Process Control



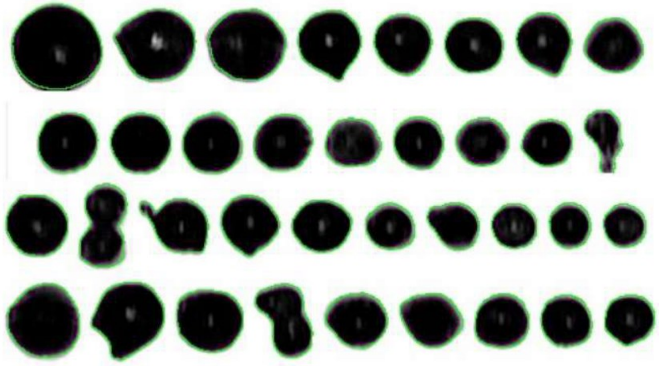
Calibration Instrumentation

- Uniformity
  - 6ft x 6ft grid, extends floor to ceiling, mesh elements spaced every 6 in, digital calipers used on vertical elements to measure ice thickness

- Liquid Water Content
  - Multi-Element Sensor ("Multi-Wire"), Science Engineering Associates, Inc., 3 sensing elements of different size, designed for response of varying conditions
  - Icing Blade, 1/8" x 6" x ¾" stainless steel blade used to confirm accuracy of MW

Calibration Instrumentation

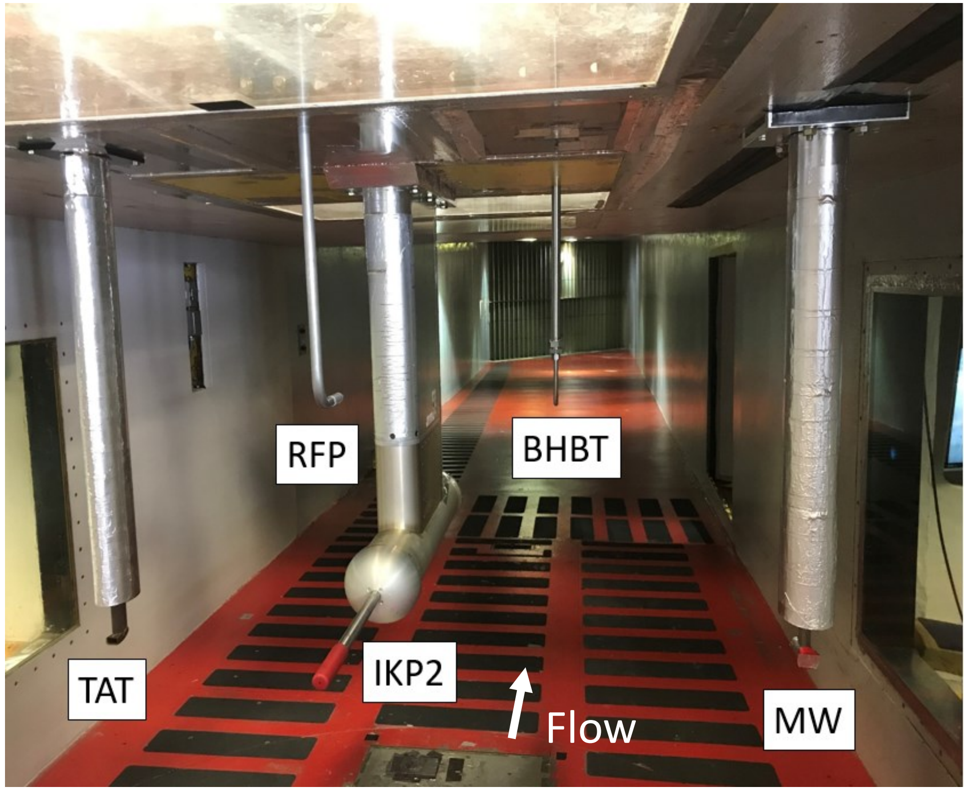
- Drop Size
  - Cloud Droplet Probe (CDP), 2-50 um
  - Optical Array Probe, OAP-230X, 15-450 um
  - Optical Array Probe, OAP-230Y, 50-1525 um
  - Drop size distributions from the CDP are combined with the OAP-230X and OAP-230Y to calculate the particle size distribution



Particle size measurements

Cloud Characterization Instrumentation

Test Section Instrument	Measurement
Multiwire (MW)	Melt ratio & recirculation
Isokinetic Probe 2 (IKP2)	Total water content & recirculation
Rearward Facing Probe (RFP)	Air temperature and humidity
Particle Imaging – Ice Crystal probe	Particle size distribution
Particle Tracking Velocimetry probe	Particle velocity
TAT probe (TAT)	Air temperature
Ice Detector probe	Glaciation (liquid presence)
Background Humidity Bent Tube probe (BHBT)	Humidity
Light Extinction Probe	Recirculation

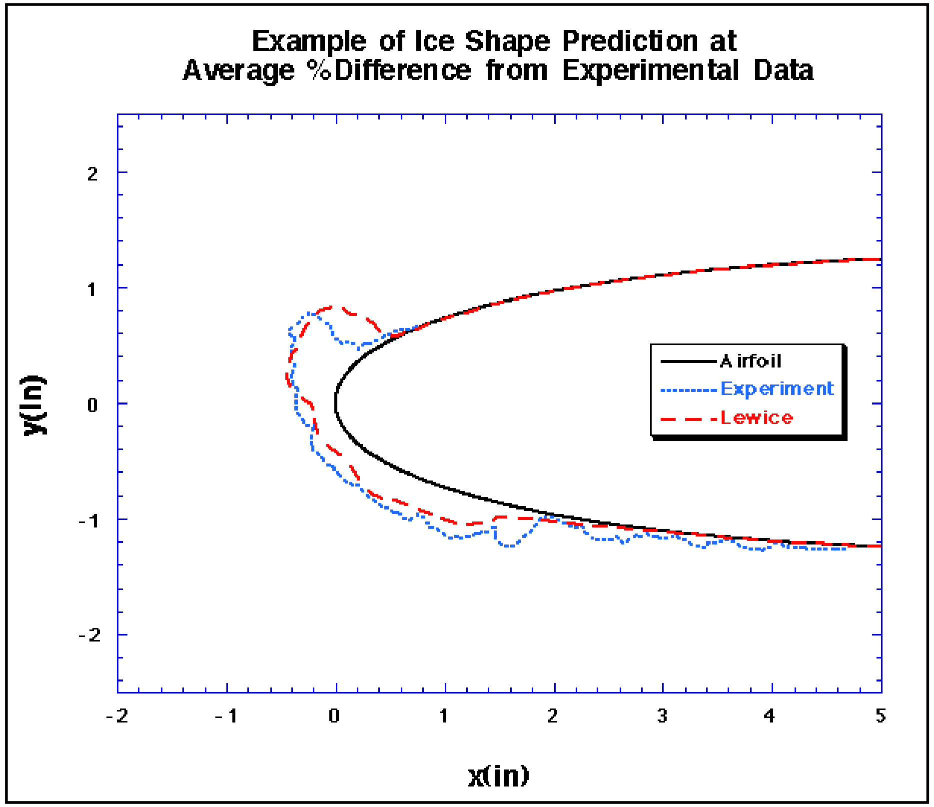


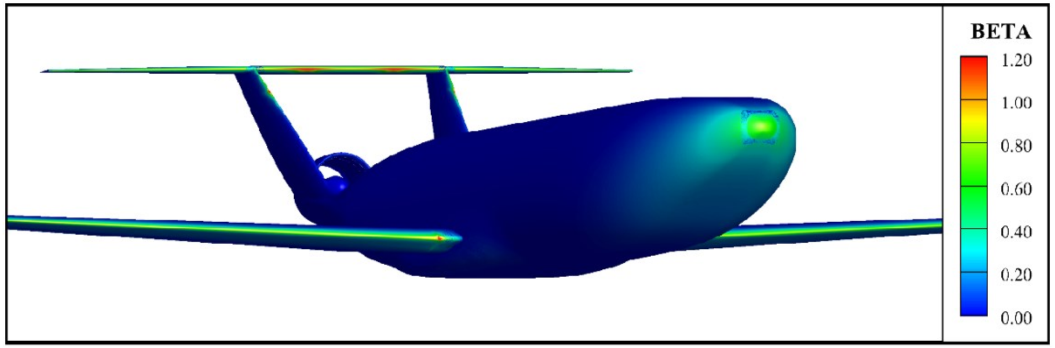
Various probes installed in the NASA IRT test section during Ice crystal cloud characterization tests in Feb 2022

NASA Computational Icing Tools

Icing Computational Tools

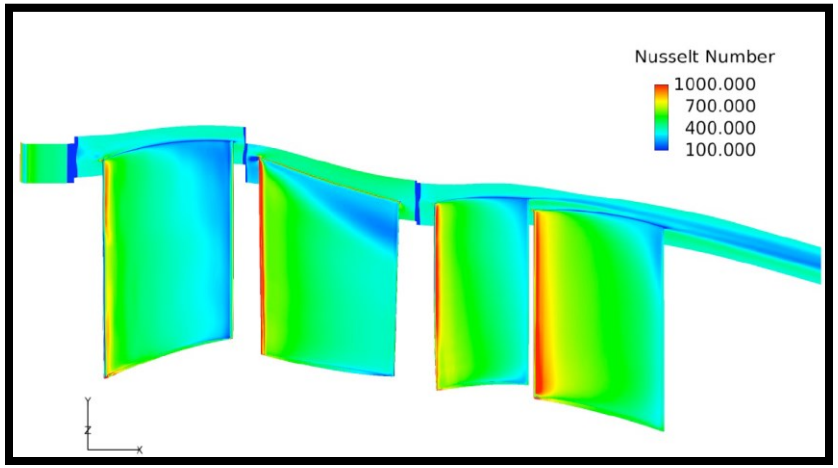
Goal: Develop a system of codes that can model the accretion process in current and future engine and airframe designs and characterize the accretion risk





Sample Output

- Ice shape geometry
- Collection efficiencies
- Heat transfer values
- Surface Temperatures



NASA Icing Tools

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.

LEWICE3D

- Quasi-3D tool that computes the trajectories and impingement in 3D but uses a strip-theory assumption to compute the mass/energy balance and ice growth on user specified cut planes.

COMDES-MELT: A Turbofan Engine Icing Risk Analysis Tool

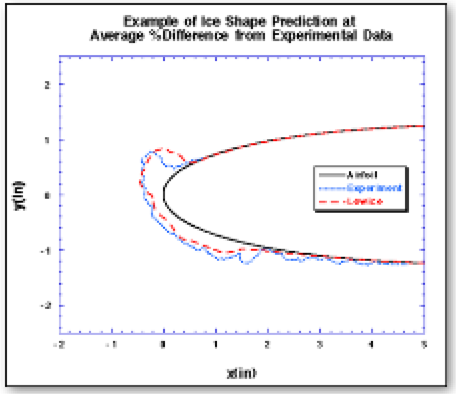
- Mean-line compressor analysis code coupled with an ice crystal thermodynamic state code.

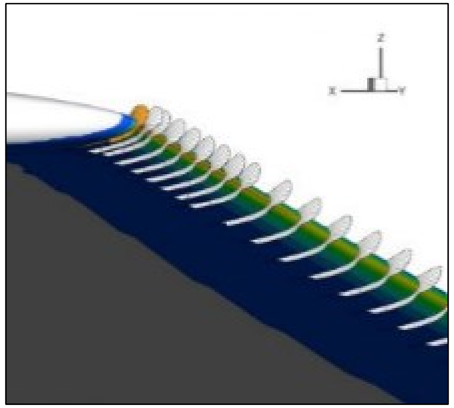
TADICE

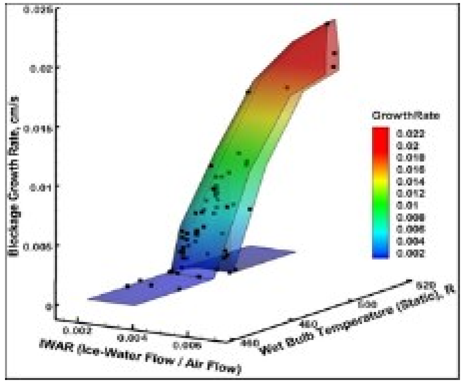
- One dimensional (1D) numerical model simulates icing wind tunnels by modeling the thermodynamic interactions between the water/ice particles of an icing cloud and the flowing air.

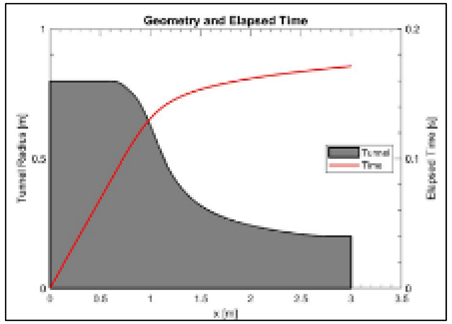
GlennICE

- 3D ice accretion simulation; multi time step. Currently the most supported icing code.









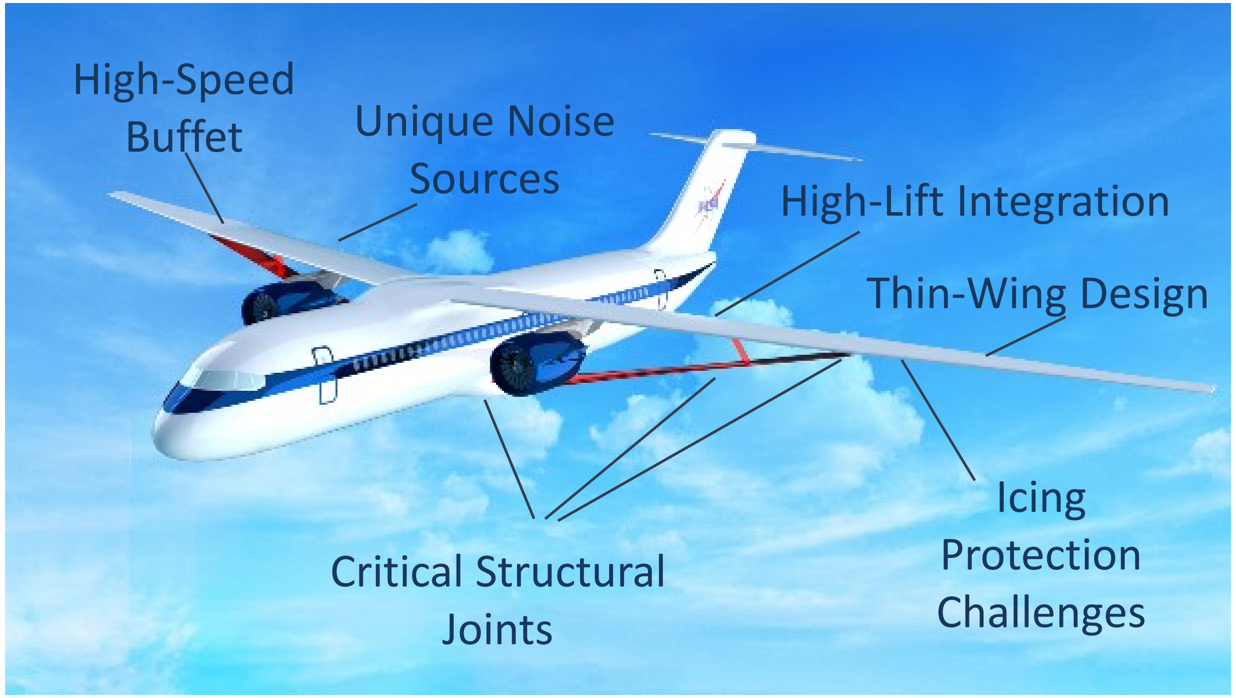
The Future of Aviation and Icing

Transonic Truss-Braced Wing

High aspect wing ratio can enable fuel burn benefit of 5-10%

Key Icing Objectives:

- Provide a validated capability to determine the impact of ice accumulation on the Transonic Truss Braced Wing aircraft
- Reduce conservatism while maintaining safe operation in an icing encounter
- Identify potential impact of ice protection system on fuel burn objective
- Develop of potential materials that are both durable and icephobic



Advanced Air Mobility (AAM)

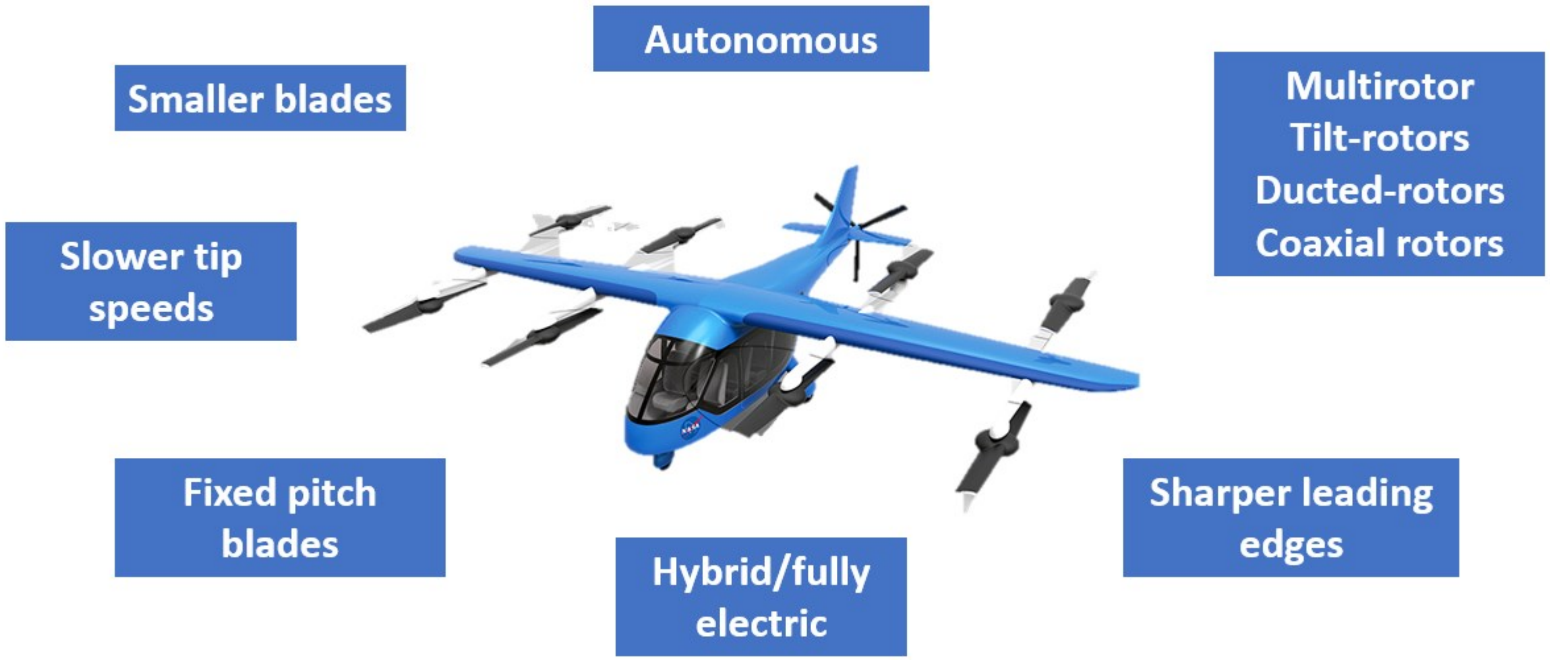
NASA's Vision for Advanced Air Mobility

Advanced Air Mobility (AAM): An air transportation system that moves people and cargo between places previously not served or underserved by aviation.

Why AAM?

- Decreased surface traffic congestion
- Fast and reliable transportation

What makes AAM unique from traditional rotorcraft?



Planned AAM Icing Tests

Problem

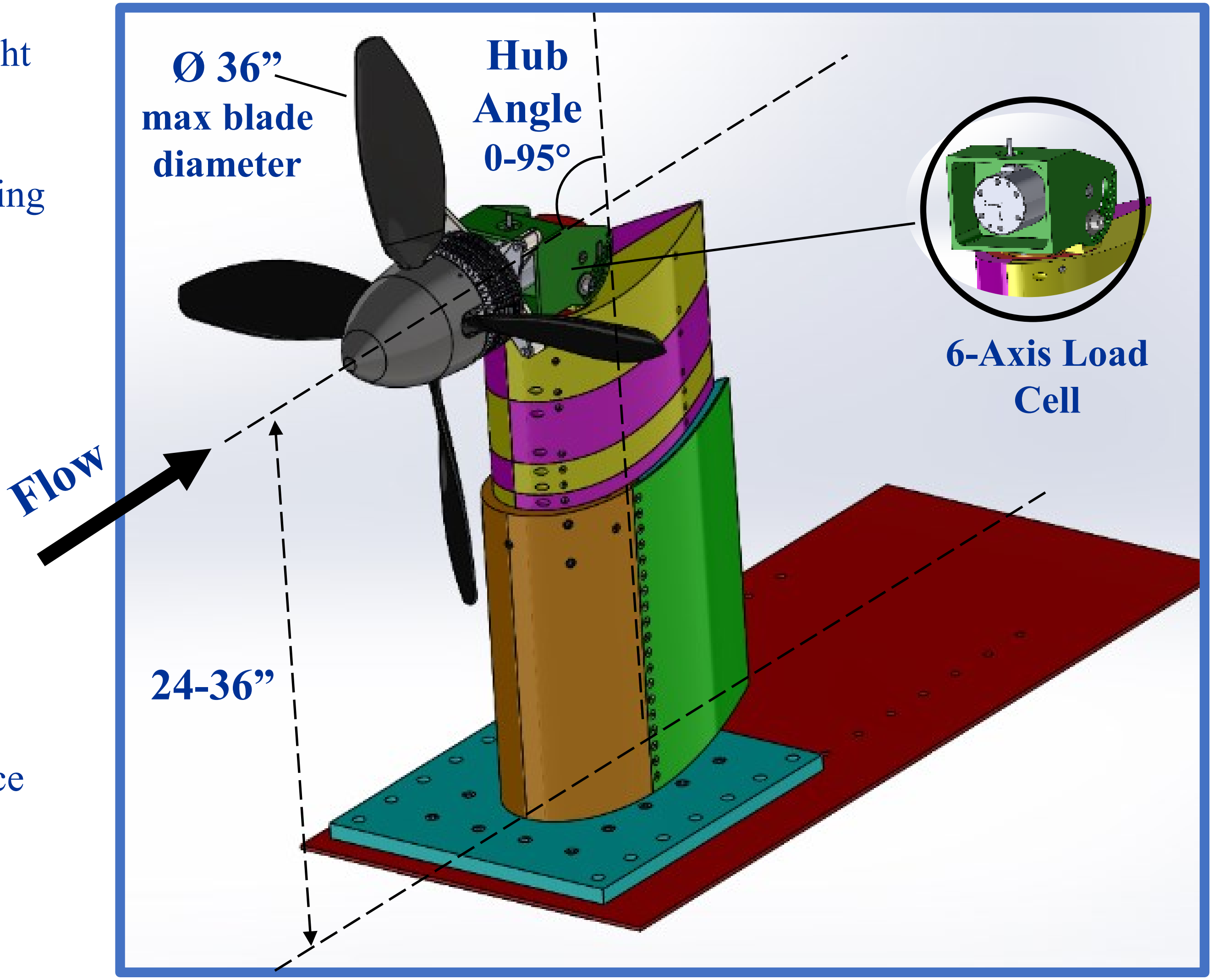
- AAM vehicles will need to be certified for safe flight in icing conditions. Icing engineering tools and methods for means of compliance are mature for existing legacy aircraft but there are no accepted icing engineering tools specifically developed for AAM class vehicles.

Objective

- Develop an experimental and computational icing simulation capability for AAM vehicles.

Experimental Test Plans

- Simulate an Advanced Air Mobility representative rotor in forward flight conditions in the IRT
- Acquire rotor performance data in icing conditions
- Characterize ice accretion on rotor (3D ice scans, ice mass measurements)



AAM Rotor Test Stand

Thank You