NASA Icing Update

Presentation (virtual) to the:
Ice Crystal Consortium (ICC)
November 9, 2022

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NASA Glenn Research Center

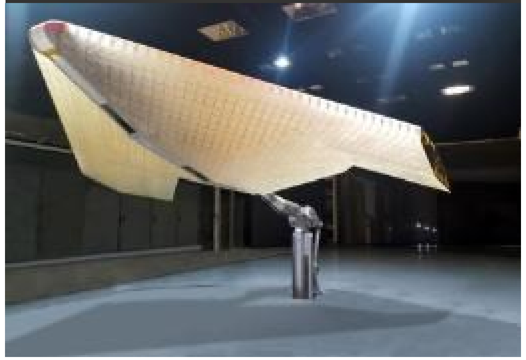
Agenda

- Introduction / Background
- Facility Update
  - Propulsion Systems Lab
  - Icing Research Tunnel
  - Adaptive Icing Tunnel
- Experiment Update:
  - Simulated Inter-compressor Duct Research Model (SIDRM)
- Simulation & Experimental Tools

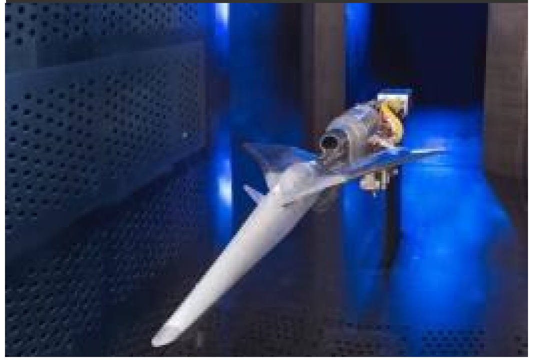
Icing Work across NASA Aero Projects

Advanced Air Vehicles Program

Transformative Aeronautics Concepts Program



Aerosciences Evaluation and Test Capabilities Portfolio



AAVP Projects

Advance Air Transport Tech (AATT)

- **Vehicle System Integration (VSI)***
- **Power & Propulsion (P&P) ***

Commercial Supersonic Tech (CST)

Hi-Rate Composite Aircraft Mfg. (HiCAM)

Hybrid Thermally Efficient Core (HyTEC)

Hypersonic Tech (HT)

Revolutionary Vertical Lift Tech (RVLT) *

TACP Projects

Convergent Aeronautics Solutions (CAS)*

Transformational Tools and Tech (TTT)*

- **Reduced Life Cycle Cost (RLCC)***

University Innovation (UI)

AETC Portfolio Office

Portfolio Facilities with Icing

- **Icing Research Tunnel (IRT)**
- **Propulsion Systems Lab (PSL)**

Operations

Maintenance

Capabilities Improvement*

Data Systems and Security

Computational Fluid Dynamics and Test Integration

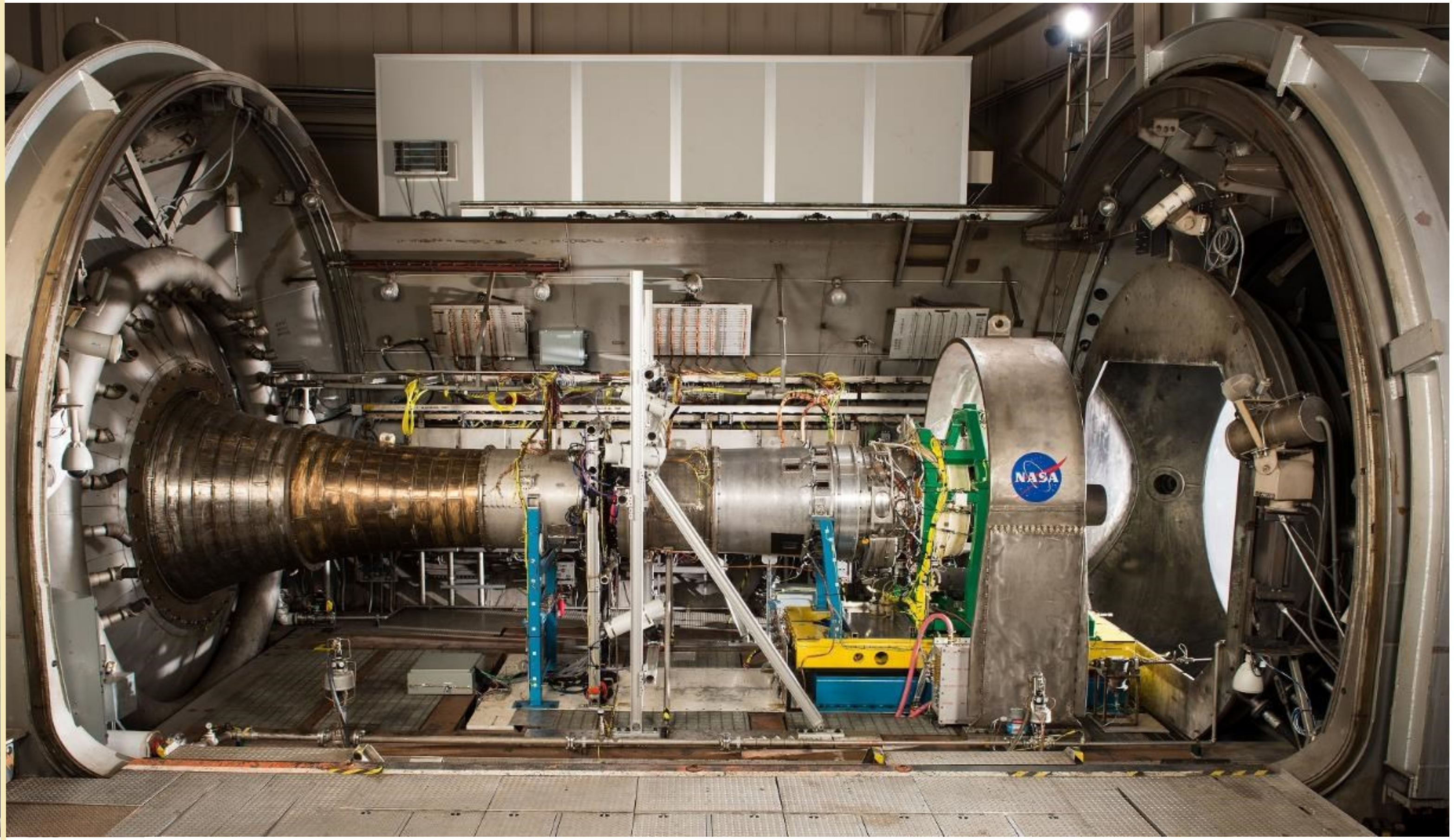
* Icing work currently in these projects / subprojects

PSL Update

POC: Judy Van Zante
Mike Oliver, Rick Bozak

PSL: Propulsion Systems Lab

Engine Test Stand with Altitude and Ice Crystal Capability



Plenum with Spray Bars, $\Phi = 18$-ft

Bulkhead w/ NASA-owned contraction duct (to $\Phi = 3$-ft)

Engine

PSL Ranges for Engine or Driven Rig

Conditions:

Duct Geometry Dia: 24 to 84 in

Pressure Altitude: 4 to 40 kft

Mach: 0.15 to 0.8

Air Mass Flow Rate: 50 to 330 lbm/s

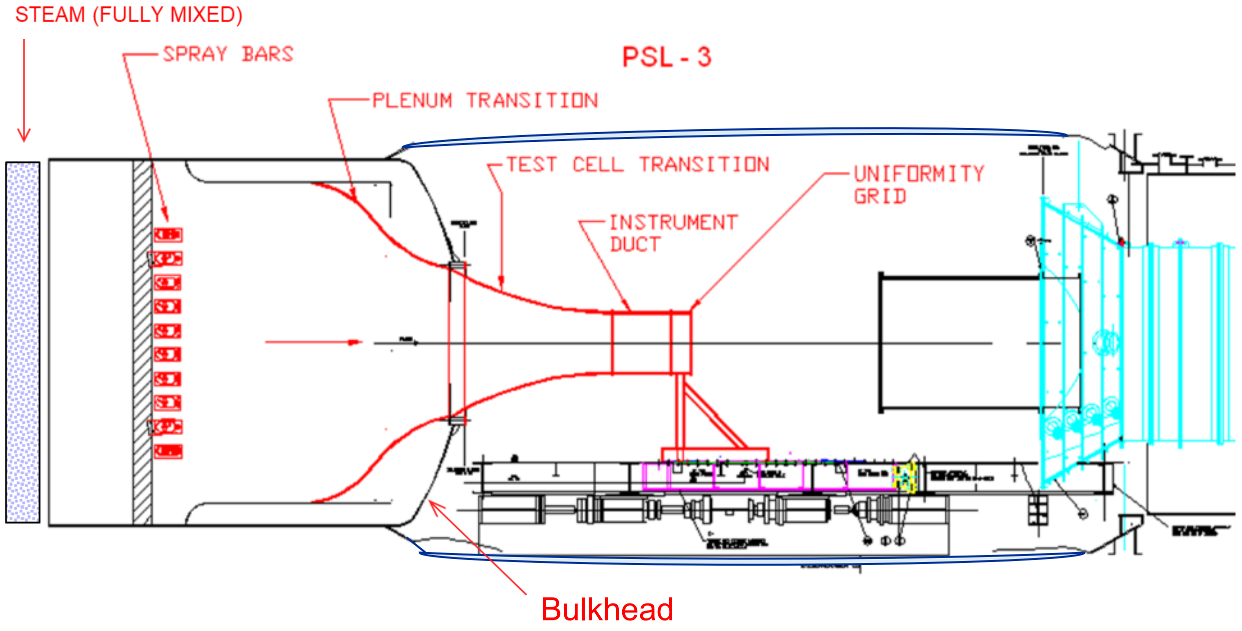
Temperature: -50 to +50 F

Relative Humidity: 3 to 50%

User supplies:

Static Pres, static Temp, Mach No. & Mass Flow Rate at plane of interest.

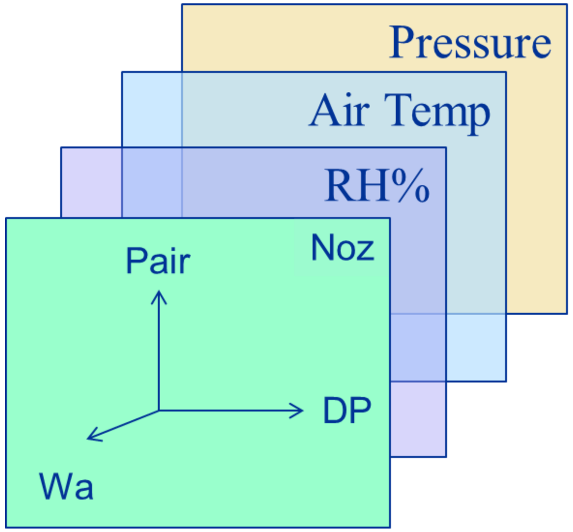
TWC, MVD ranges



36-in duct calibration configuration

Ice Crystal & Icing Cloud

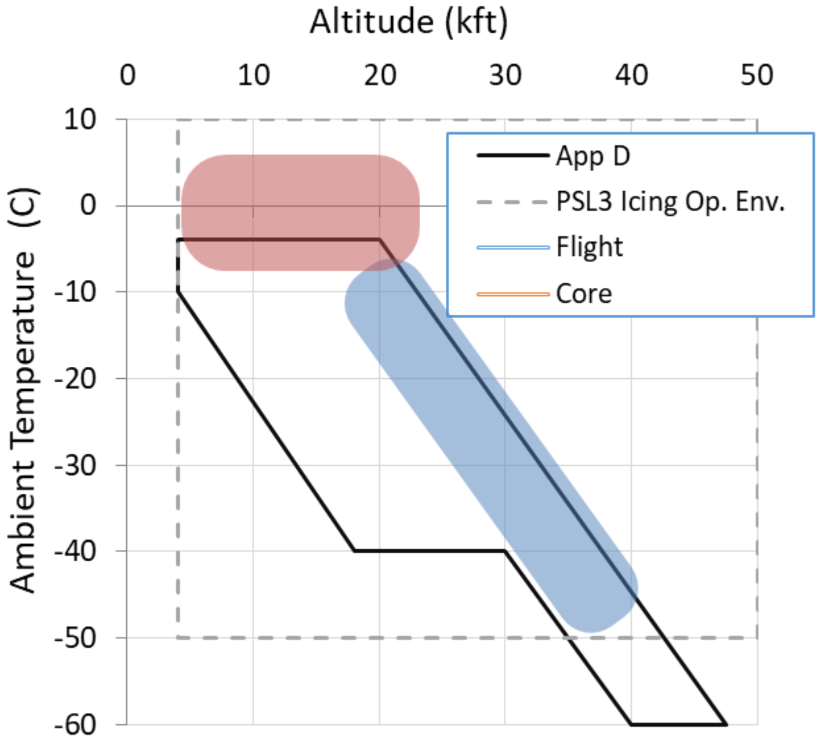
NASA will calibrate TWC and MVD for test-specific ranges in App D, App C & App O.



Most calibrations to date have been in the 36-in duct.

Two atmospheric conditions have been simulated: Flight and Core Flow Path.

App D Cal Regimes to date



Cloud Calibration Plan

- Investigate ability to produce IC with DI water.
- Investigate new IC characterization instrumentation.
- Calibrate IC cloud in "flight" environment (higher altitude, tropical day)
- Calibrate cloud in "core" flow path conditions (lower altitude, Twb near 0C)
- Calibrate SCL cloud for fan testing

Nomenclature

DI	De-ionized
IC	Ice Crystal
SCL	Supercooled Liquid
Twb	Wet Bulb Temp.

PSL Plans – Icing

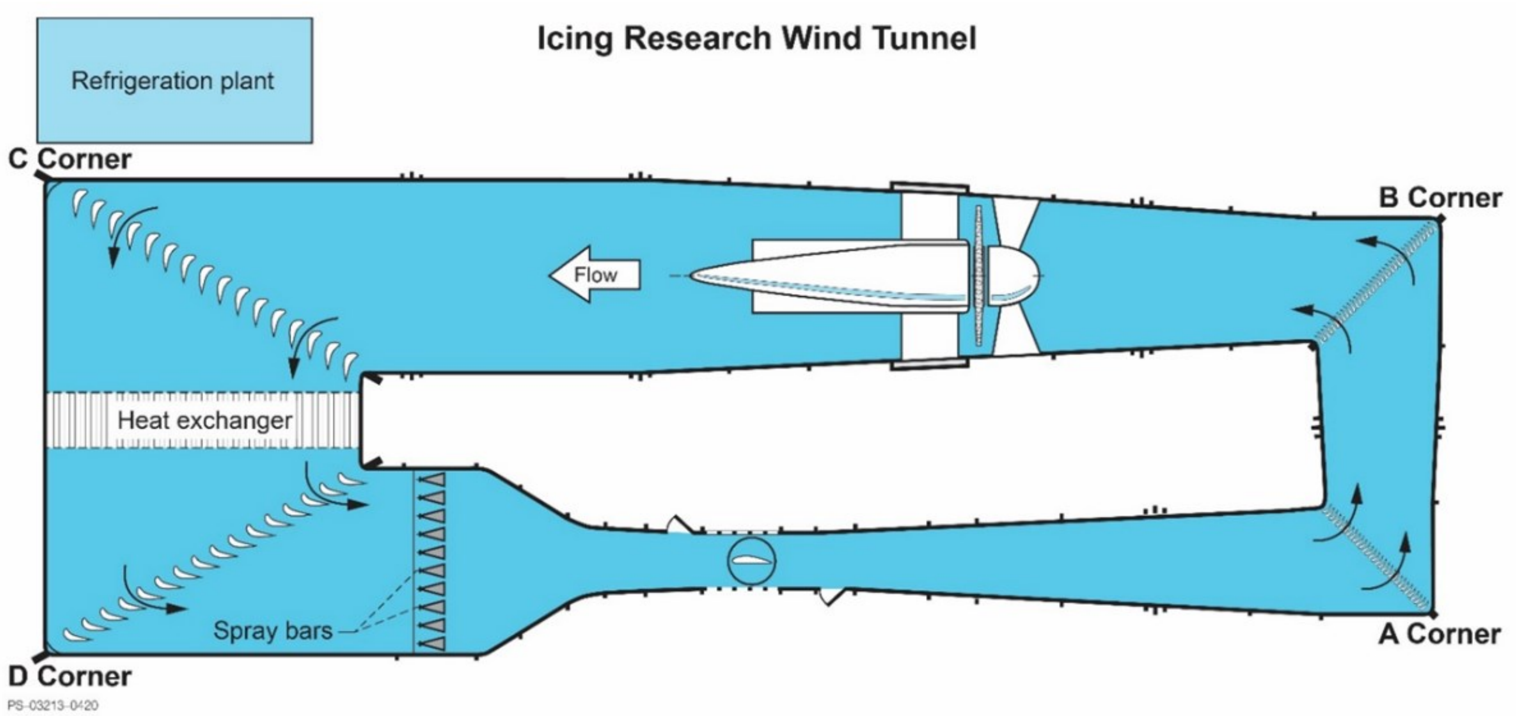
- Proposed Icing Plans
  - Re-install icing spray bars
  - Conduct a cloud calibration
  - Collaborate with an engine manufacturer to expand and validate capabilities

- Proposed Future Goals: Expand Icing Test Capabilities
  - Free Jet Icing Capability
  - Impact of alternative ducting (e.g. turboshaft)
  - Transient testing, including snap accels

IRT Update

POC: Emily Timko

IRT: Icing Research Tunnel



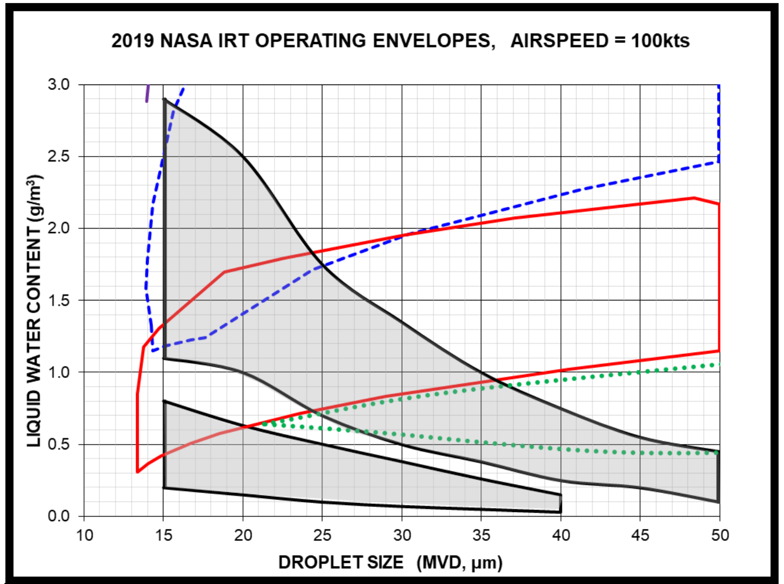
- Test section size: 6 ft. x 9 ft. (1.8 m x 2.7 m)
- LWC & MVD calibration measurements are made in the center of the test section
- LWC uniformity: ±10% for central 4 ft x 6 ft
- Calibrated test section airspeed: 50 –300 kts
- Air temperature: -35ºC static to +15ºC total
- Calibrated MVD range: 14 –270 µm
- Calibrated LWC range: 0.17 –4.0 g/m^3 (function of airspeed)
- Two types of spray nozzles:
  - Standards = higher water flow rate
  - Mod1 = lower water flow rate

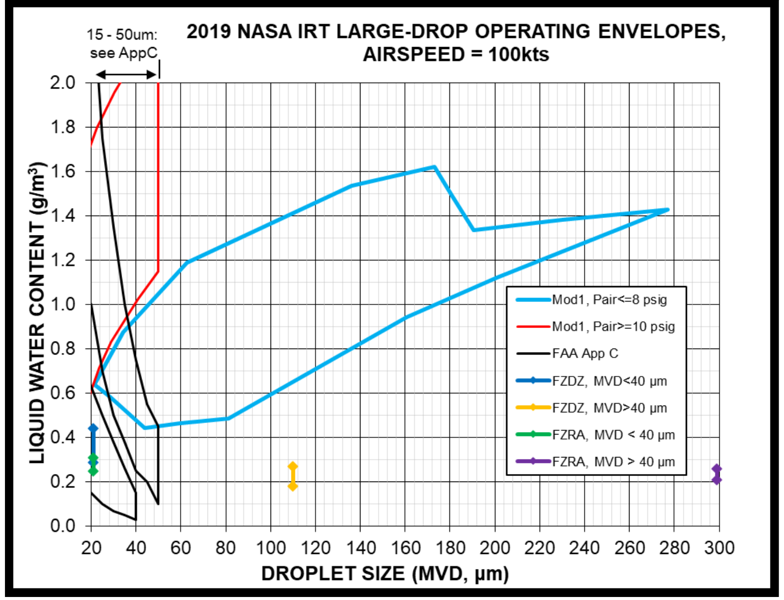
IRT Calibration

- SAE's ARP5905 "Calibration and Acceptance of Icing Wind Tunnels"
- 5-year calibration interval
- Check calibrations every 6 months
- Interim calibration 1 year after full calibration
- Full calibration performed in 2019

Calibration report available upon request

- Calibration done for Appendix C and Appendix O





Potential Ice Crystal Capabilities

- Increasing demand
  - Researchers, outside customers, facility engineers
- Efforts have begun
  - Phase repeatability analysis
  - Characterization focused on specific research tests
  - Test entries on schedule to evaluate uniformity, ice water content, and particle sizes
- Ice Crystal Cloud Challenges
  - How to develop uniformity
  - Particle size instrumentation for smaller, frozen particles
  - Recirculation of accumulated ice particles
- Facility Challenges
  - Spraybar air and water supply can only be "not heated"
    - Technology and development to be able to cool the supply
    - Unheated supplies also result in frozen nozzles
  - Ice crystals left in tunnel loop
    - Quantifying recirculation effects

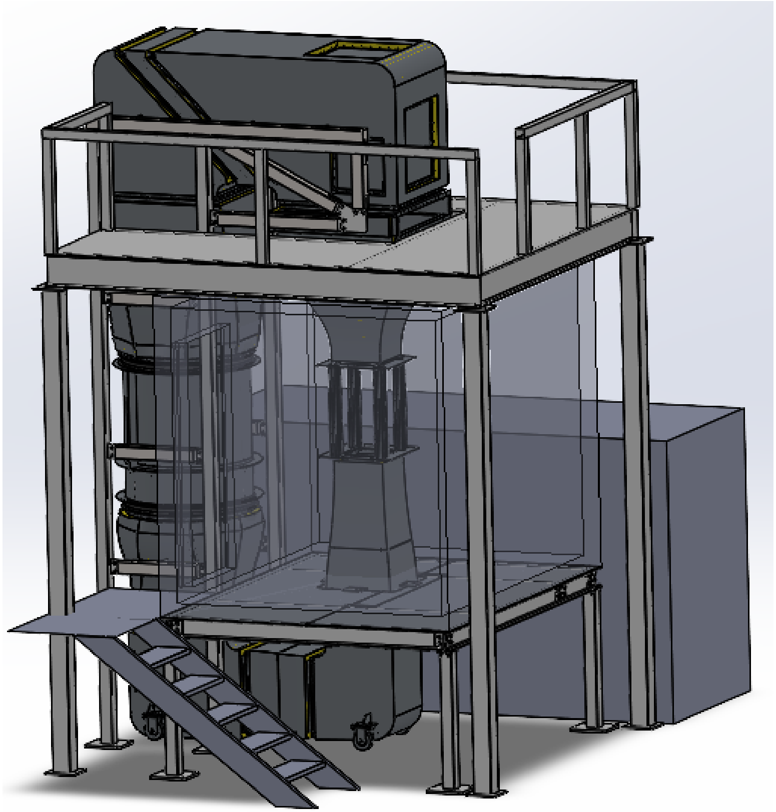
Adaptive Icing Tunnel (AIT)

POC: Ru-Ching Chen

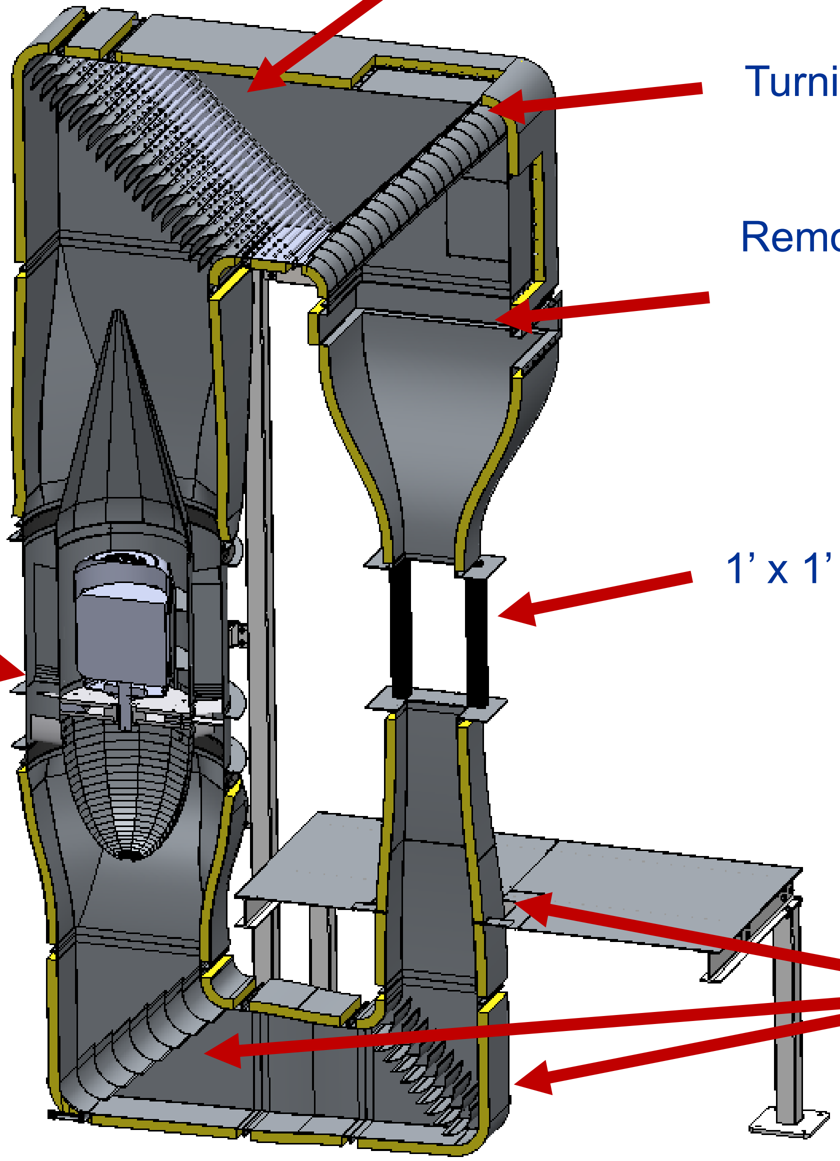
What is the Adaptive Icing Tunnel (AIT)

- 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
- Planning for supercooled water and ice crystal capability
- Scheduled for installation in FY23 followed by tunnel characterization

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



Adaptive Icing Tunnel Cross Section



Removable Heat Exchanger

Turning vanes

Removable spray bar

1’ x 1’ x 2’ Test Section

Fan blades accessible via Panel

Removable corners and diffuser

Simulated Inter-compressor Duct Research Model (SIDRM)

Project Sponsor: AATT P&P

POC: Tadas Bartkus

IRT Ice Crystal Cloud Characterization and SIDRM Icing Tests

Problem

Turbofan power-loss or damage events attributed to ice crystals. 3D computational engine icing tools, such as GlennICE, require validation data.

Objective

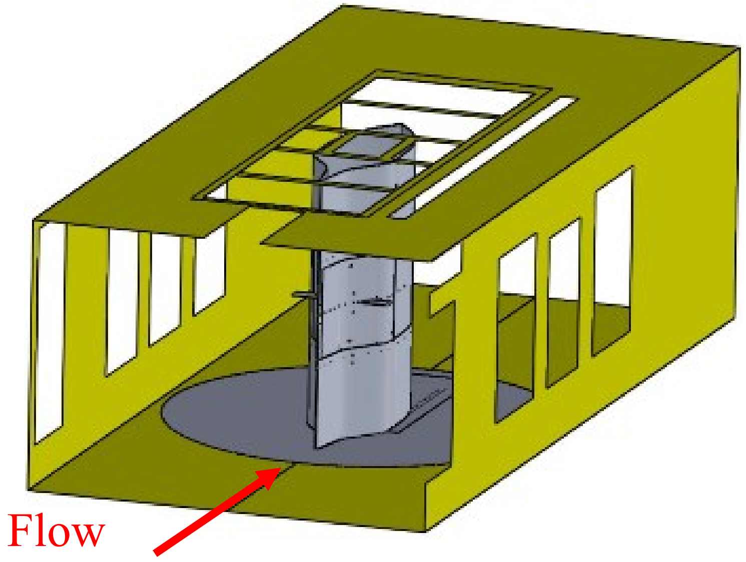
Develop a test article - the Simulated Inter-compressor Duct Research Model (SIDRM) – representative of a compressor strut-duct interface. Generate and measure supercooled liquid and ice crystal icing accretions under well characterized conditions to develop and validate 3D icing tools.

Approach

1. Identify and characterize ice crystal clouds in Icing Research Tunnel (IRT).
2. Supercooled liquid water testing
3. Ice crystal test testing using a heated surface.

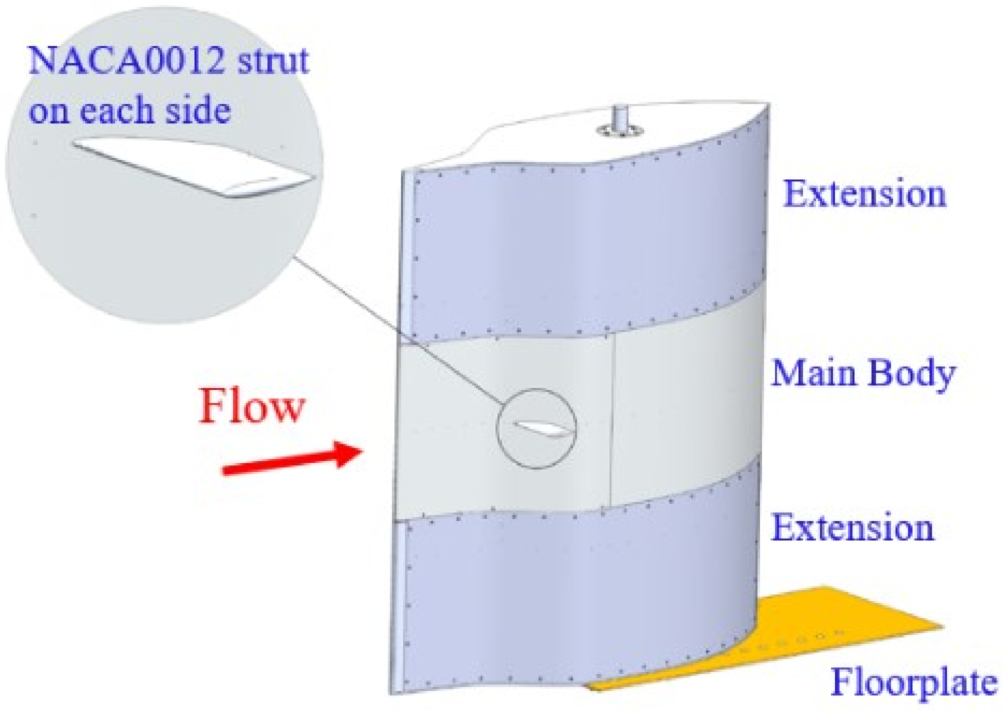
Significance

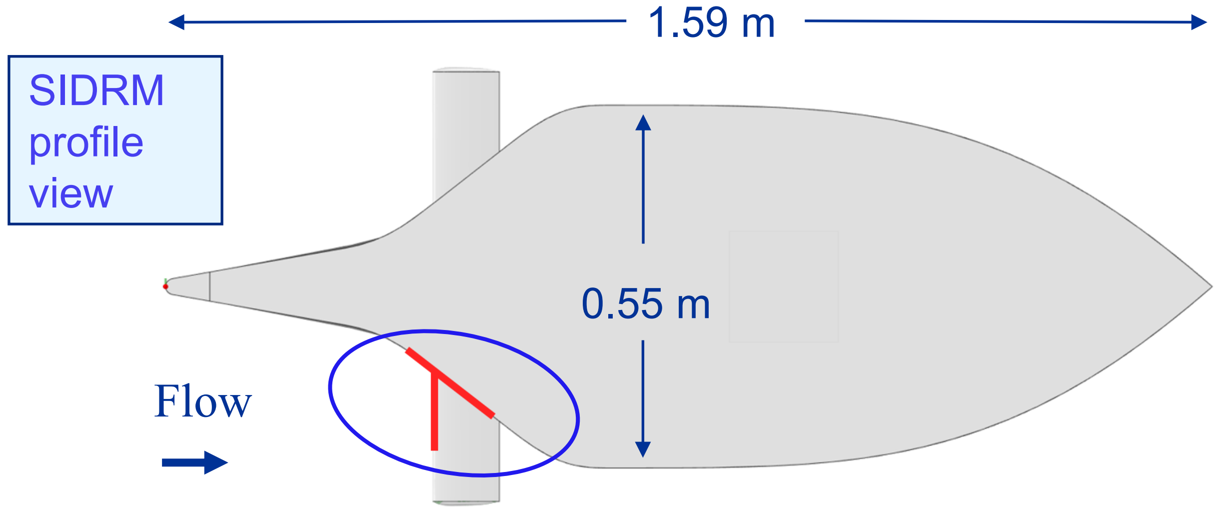
These tests represent the first time that ice accretions were measured on a 3D test article at IRT. Using an open geometry configuration, these tests recreated ice crystal icing features characteristic of those seen in previous engine icing tests.

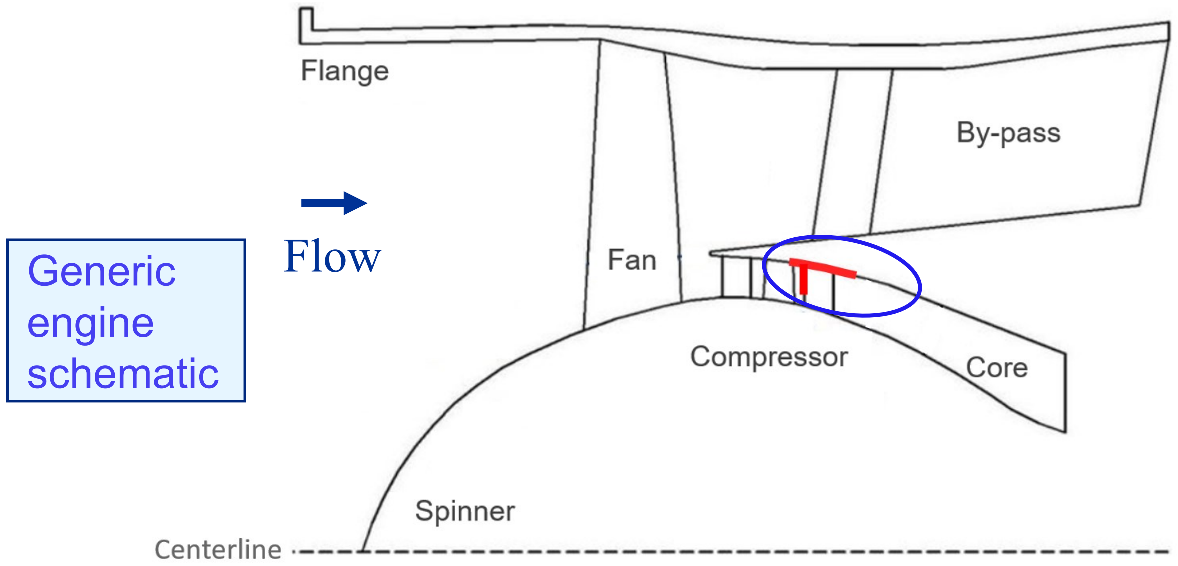


SIDRM vertical orientation in IRT tunnel with multiple viewing windows

SIDRM Test Article







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

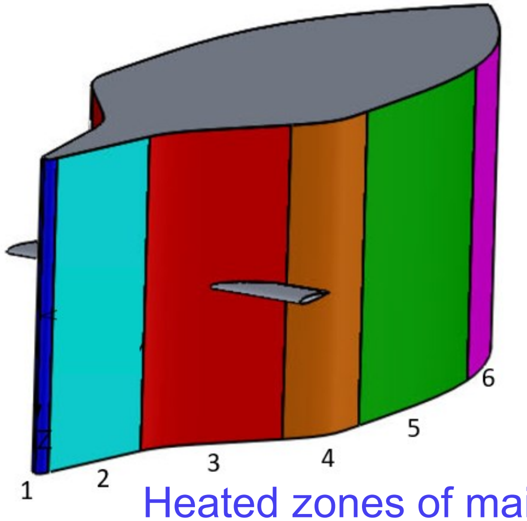
Primary Instruments and Measurements

SIDRM Built-In Instruments

- 64 Pressure taps
- 43 Thermocouples
- 11 Heat flux gauges
- 6 Independently controlled heater zones (main body)

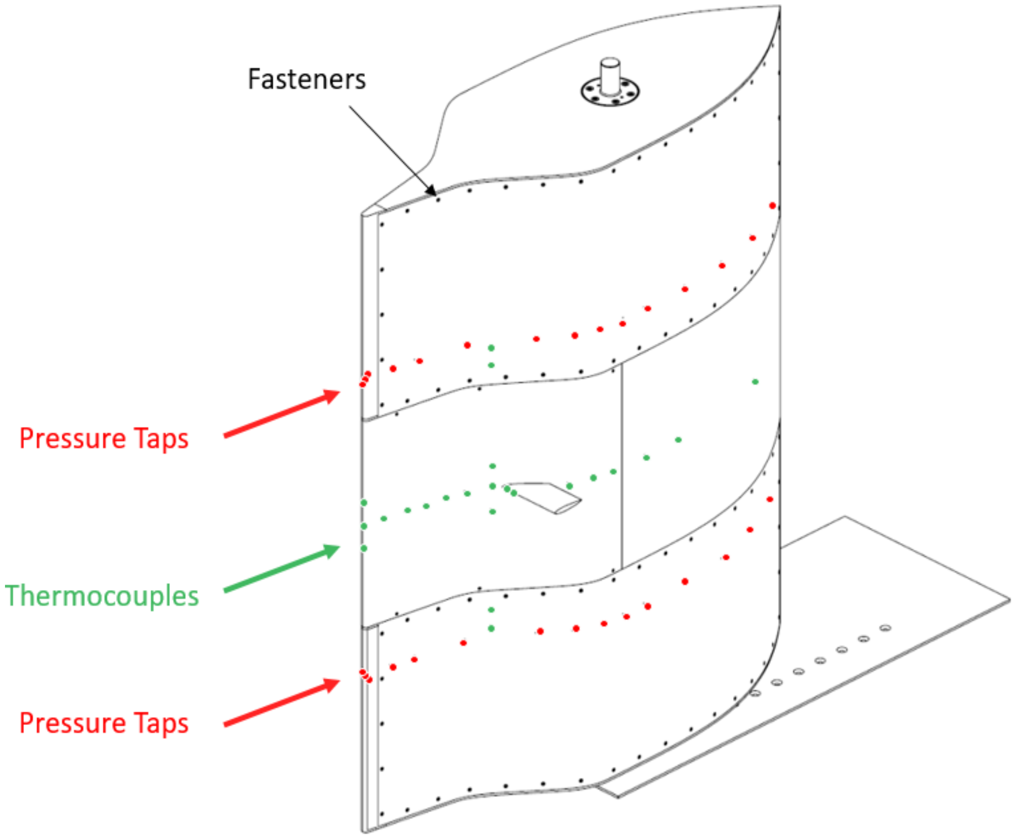
External Instruments

- 3D laser scanner
- Scale to weigh accreted ice mass
- Video and digital cameras



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

Heated zones of main body



View of TCs and pressure taps

SIDRM Supercooled Liquid Icing and Ice Crystal Icing Tests

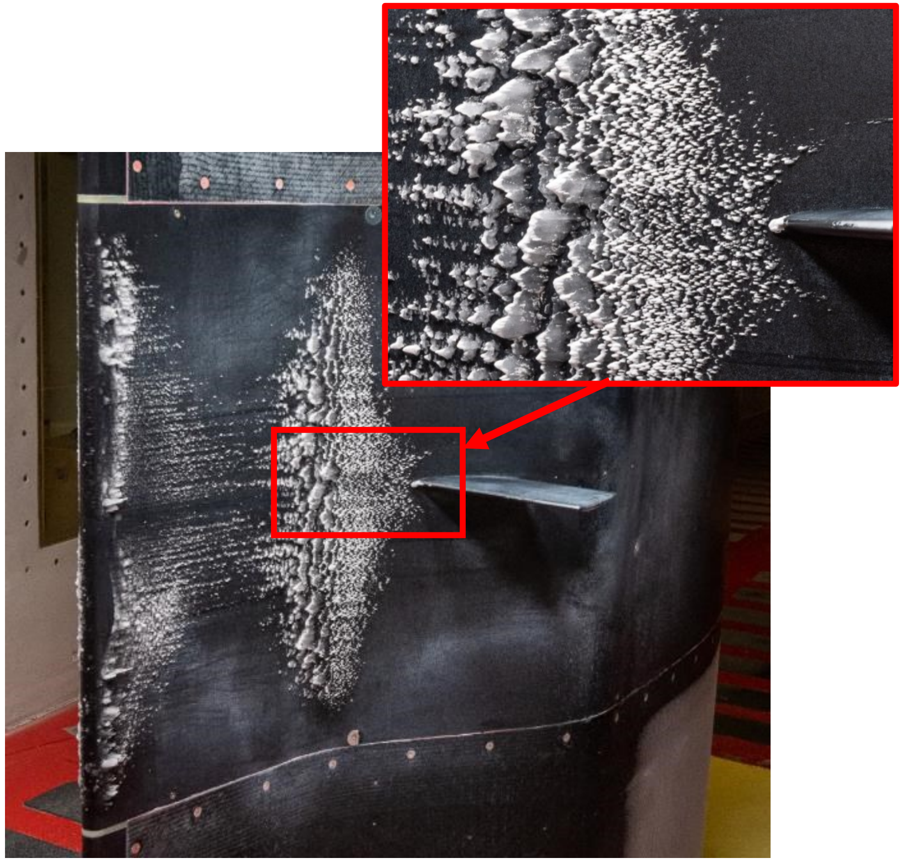
Results

In 2022, characterized numerous ice crystal cloud conditions at IRT and 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. 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



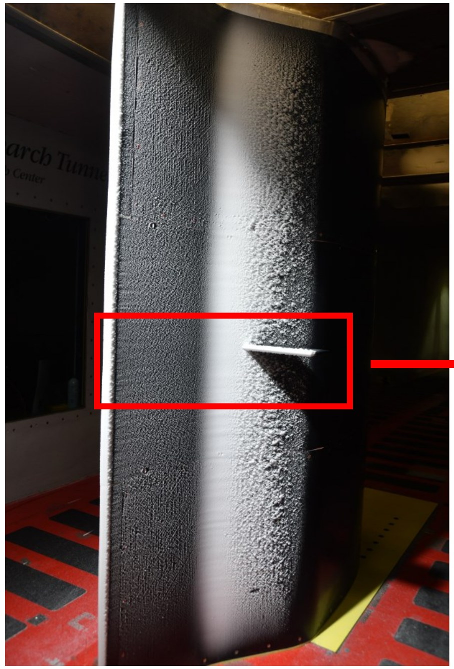
Ice crystal icing utilizing SIDRM's heated panels with zoomed in view of "sharkteeth"

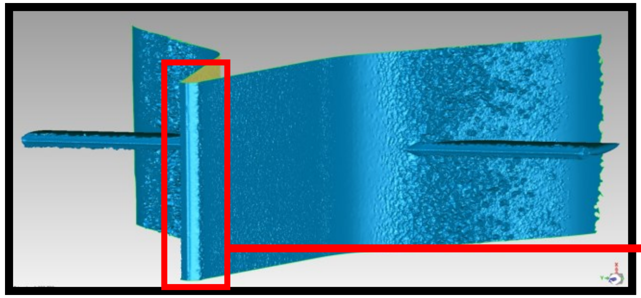
https://arc.aiaa.org/doi/abs/10.2514/6.2022-3700
https://ntrs.nasa.gov/citations/20220006460

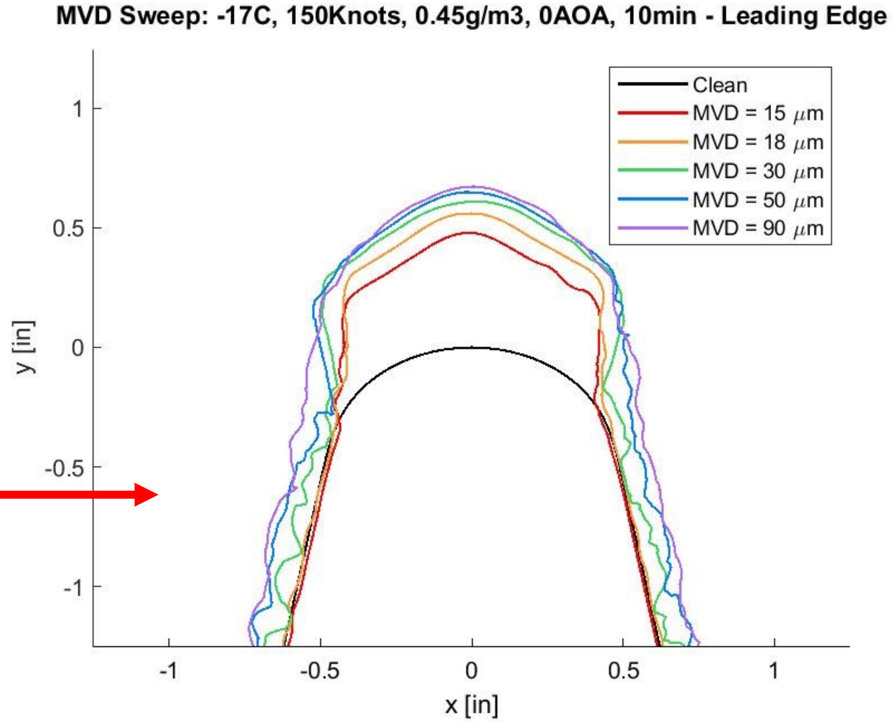
Supercooled Liquid Icing Analysis

- Ice mass weighed – center 8” span
- 3D laser scan – center 10” span
- Identify parameters and interpret the physics that influence accretion size, location, and quality.

Date	Cobra Reading (#)	Icing Branch ID (#)	Spray Duration (min)	TOTAL AIR TEMP (Deg. C)	AIR SPEED (Knots)	AOA (Deg)	MVD (microns)	LWC (g/m^3)	Both Struts Ice mass (g)	Main Body Ice mass (g)
2/22/2022	104	UG3513	10.0	-17.0	150	0	15	0.45	66	172
2/22/2022	105	UG3514	10.0	-17.0	150	0	18	0.45	70	221
2/23/2022	109	UG3518	10.0	-17.0	150	0	30	0.45	79	407
2/22/2022	106	UG3515	10.0	-17.0	150	0	50	0.45	79	548
2/22/2022	107	UG3516	10.0	-17.0	150	0	90	0.45	83	781







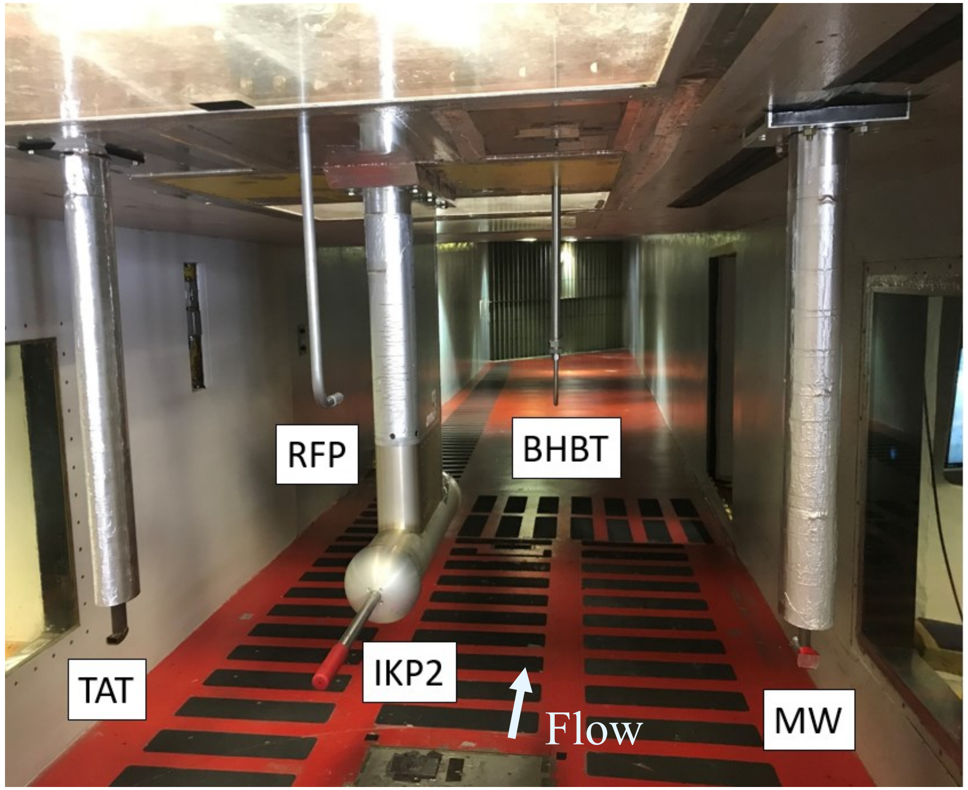
Centerline cross sections at the SIDRM leading edge

Ice Crystal Cloud Characterization at IRT

- Ice crystal generation is not well characterized at IRT
- Well characterized cloud needed to properly model resulting icing data
- Objective: Identify glaciated conditions and characterize IC cloud using following instrument suite
- 13 days of testing identified and characterized 12 conditions
- Ice crystal cloud envelope limited to colder (T0 < -15 ^{O}C), and smaller diameter (MVD < 43 µm).
- Repeated tests and recirculation important

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

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



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

NASA Computational Tools

Project Sponsors: AATT/P&P & VSI, TTT/RLCC

POC: Christopher Porter

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.
- https://software.nasa.gov/software/LEW-18573-1

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.
- https://software.nasa.gov/software/LEW-19433-1

COMDES-MELT: A Turbofan Engine Icing Risk Analysis Tool

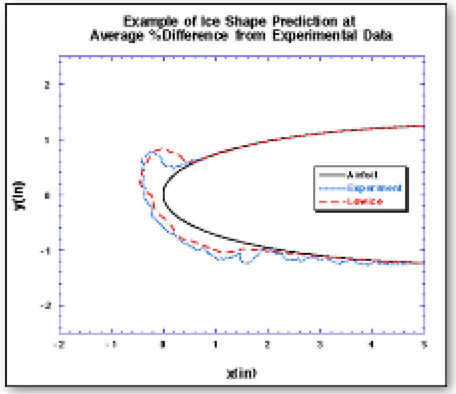
- Mean-line compressor analysis code coupled with an ice crystal thermodynamic state code.
- https://software.nasa.gov/software/LEW-20027-1

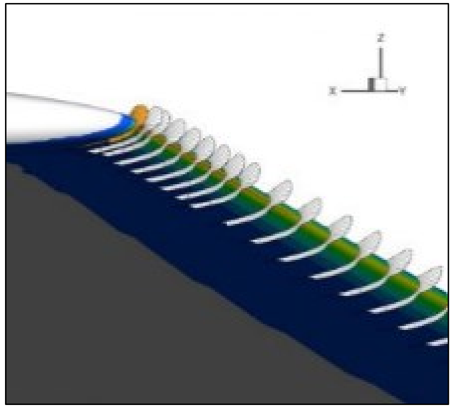
TADICE

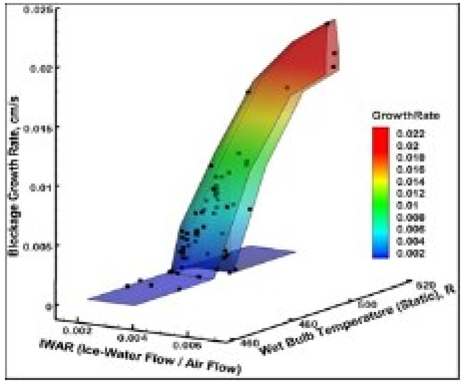
- One dimensional (1D) numerical model simulates icing wind tunnels by modeling the thermodynamic interactions between the water/ice particles of an icing cloud and the flowing air.
- https://software.nasa.gov/software/LEW-19874-1

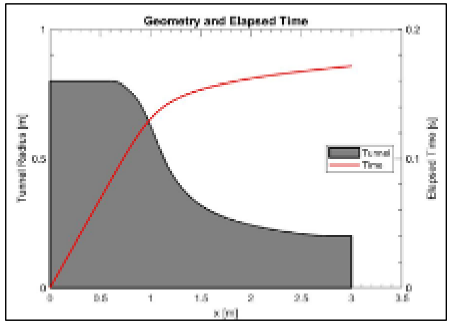
Multiscale Modeling

- A seedling effort investigating multiscale modeling for icephobic research.









GlennICE

Version Timeline

0.1	0.2	1.0	1.1	1.2	2.0	2.1	2.2	3.0	3.1	3.2	4.0	4.1	4.2	5.0	5.1	5.2	6.0	6.1	6.2
2/20	6/20	10/20	2/21	6/21	10/21	2/22	6/22	10/22	2/23	6/23	10/23	2/24	6/24	10/24	2/25	6/25	10/25	2/26	6/26

External Icing

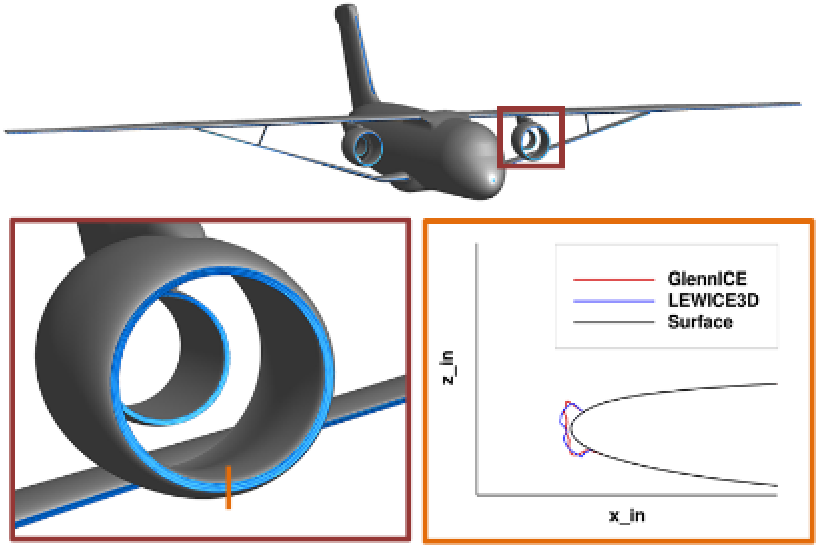
- Quasi-3D (LEWICE3D) → Full 3D (GlennICE)
- Utilize modern programming practices and capabilities.

Rotating Icing (Super Cooled)

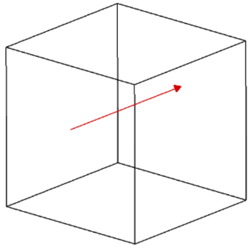
- Introduce rotating reference frames (Engine Fan and Propellors).
- Handle periodic boundary conditions/mixing planes.
- Handle runback in rotating reference frame.

Internal Icing (Ice Crystal)

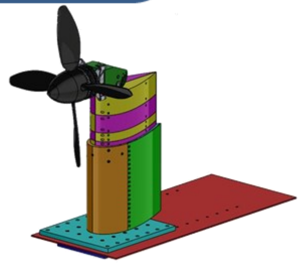
- Introduce ice crystals and related physics
- Address multiphase runback and icing.



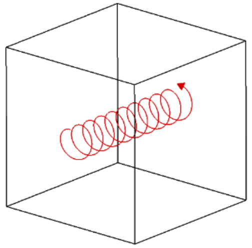
A full 3D GlennICE simulation of an ice accretion due to a 15 μm cloud on the TTBW. Insets depict the accretion on the engine inlet, with the line plot including a comparison to the legacy quasi-3D icing software, LEWICE3D.



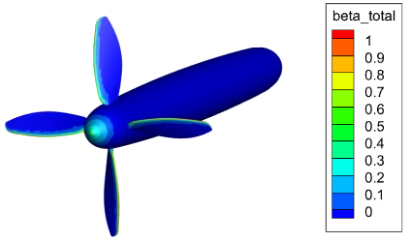
Non-Rotating Reference Frame



AAM test stand



Rotating Reference Frame



GlennICE simulation of the AAM test stand.

Depiction of the differences in trajectory representation in a rotating and non-rotating reference frame (left). Demonstration of the rotating reference frame additions on the Advance Air Mobility (AAM) test stand geometry (right).