NASA Icing Update

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SAE AC-9C COMMITTEE MEETING

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Note

- This update focuses on work that was not presented at the SAE Icing Conference in Vienna.
- A list of NASA papers and presentations from the conference was included in the Spring 2023 AC-9C meeting minutes.

Advanced Air Mobility Icing Research

PROBLEM Advanced Air Mobility (AAM) introduces many novel electric vertical take-off and landing (eVTOL) aircraft designs that must demonstrate safe flight in icing inadvertent encounter with potential flight-in-icing certification on the horizon. Icing engineering tools and methods for means of compliance are fairly mature for existing legacy aircraft but there are no accepted icing engineering tools specifically developed for AAM class vehicles.

OBJECTIVE Develop experimental and computational icing simulation capabilities for eVTOL vehicles.

APPROACH

- Acquire **experimental ice shapes** on non-proprietary propeller/rotor geometries for code validation and development.
- Establish **best practices** and **scaling methodologies** for conducting icing tests on rotating geometries.
- Acquire **experimental shedding data** to support development of ice shedding prediction capabilities.

ACCOMPLISHMENTS Successfully completed testing of a generic eVTOL propeller in the Icing Research Tunnel during March of 2023. Acquired ice shapes, propeller performance degradation, and high-speed images of shedding events. Results and analysis to be published at AIAA Aviation Forum 2024.

AAM Rotor Test Stand

MOTOR FEATURES

- Power: 45 hp (cont.), 80 hp (peak)
- Torque: 38 ft-lbf (cont.), 74 ft-lbf (peak)

PROPELLER AND BLADES

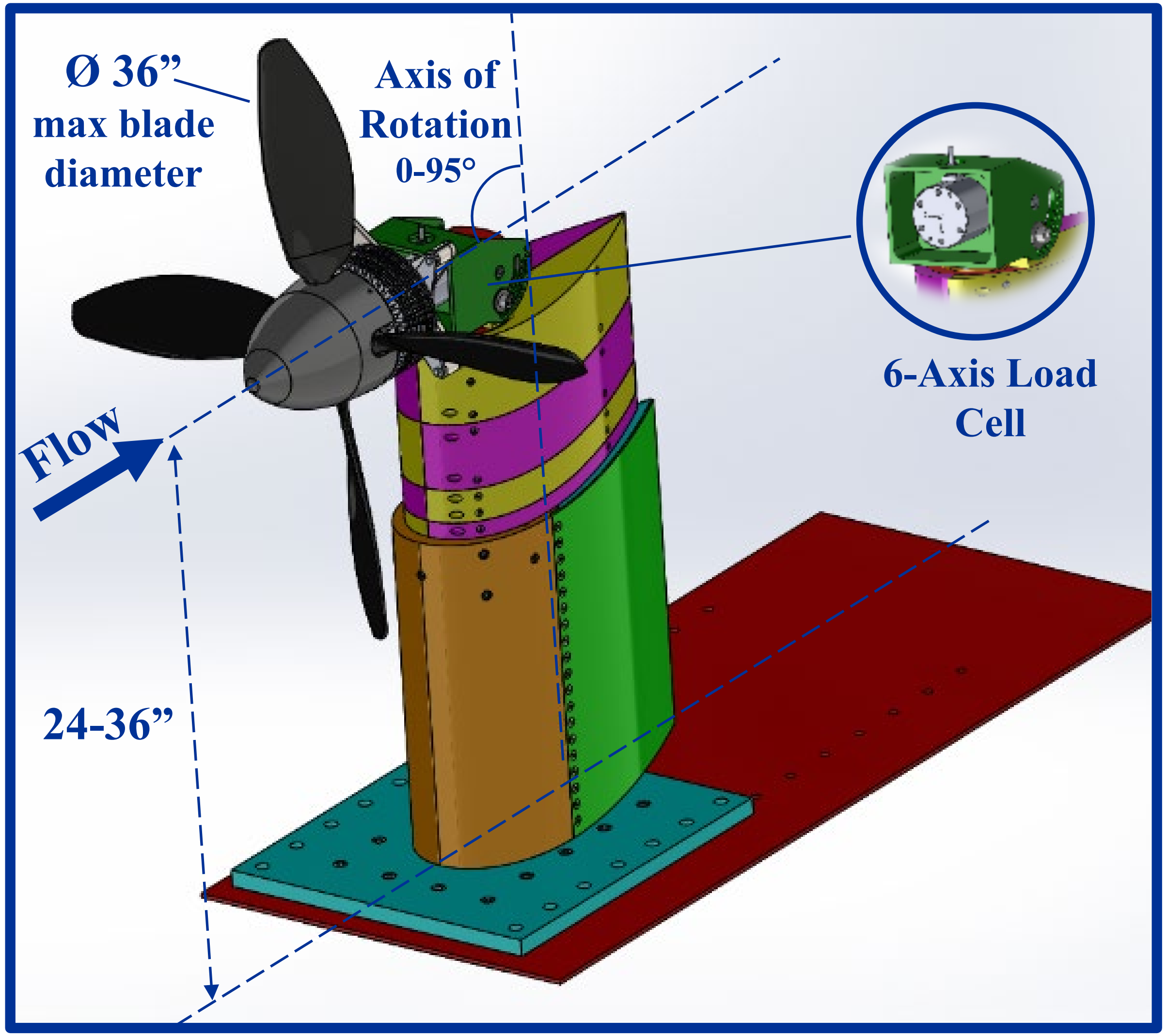
- Fixed-pitch propeller, with 4 blades.
- NASA GRC acoustics branch advised blade design.
- Blade composed of NACA 0012 airfoils
- Composite manufactured by Mejzlik Propellers

TEST STAND FEATURES

- Adjustable axis of rotation for non-axial flow
- 6-axis load cell for torque and thrust measurements

MEASUREMENT CAPABILITIES

- 3D ice shape documentation
- Ice mass measurements
- High speed imaging for capturing ice shedding events
- Light strobing for real-time ice growth monitoring
- Torque and thrust measurements
- Motor current and voltage measurements



AAM Rotor Icing Evaluation Study (ARIES) 1

ARIES I: March 20th – 31st (10 days), 2023

Operating Conditions Tested

Blade Diameters (in)	Tunnel Speeds (knots)	Tip Speeds (Mach)	Advance Ratios
24, 28, 36	87 - 130	0.20 - 0.31	2.3 – 2.7

Cloud Conditions Tested

MVD (μm)	LWC (g/m^3)	Total Temp. (˚C)
15, 30, 80	0.55, 0.65, 1.20	-3 to -15

Data Acquired

- Blade Ice Scans (32)
- Spinner Ice Scans (3)
- Spinner and Blade Ice Mass
- Motor Power Consumption
- High Speed Video of Shedding Events (11)

A portion of the ARIES I team.

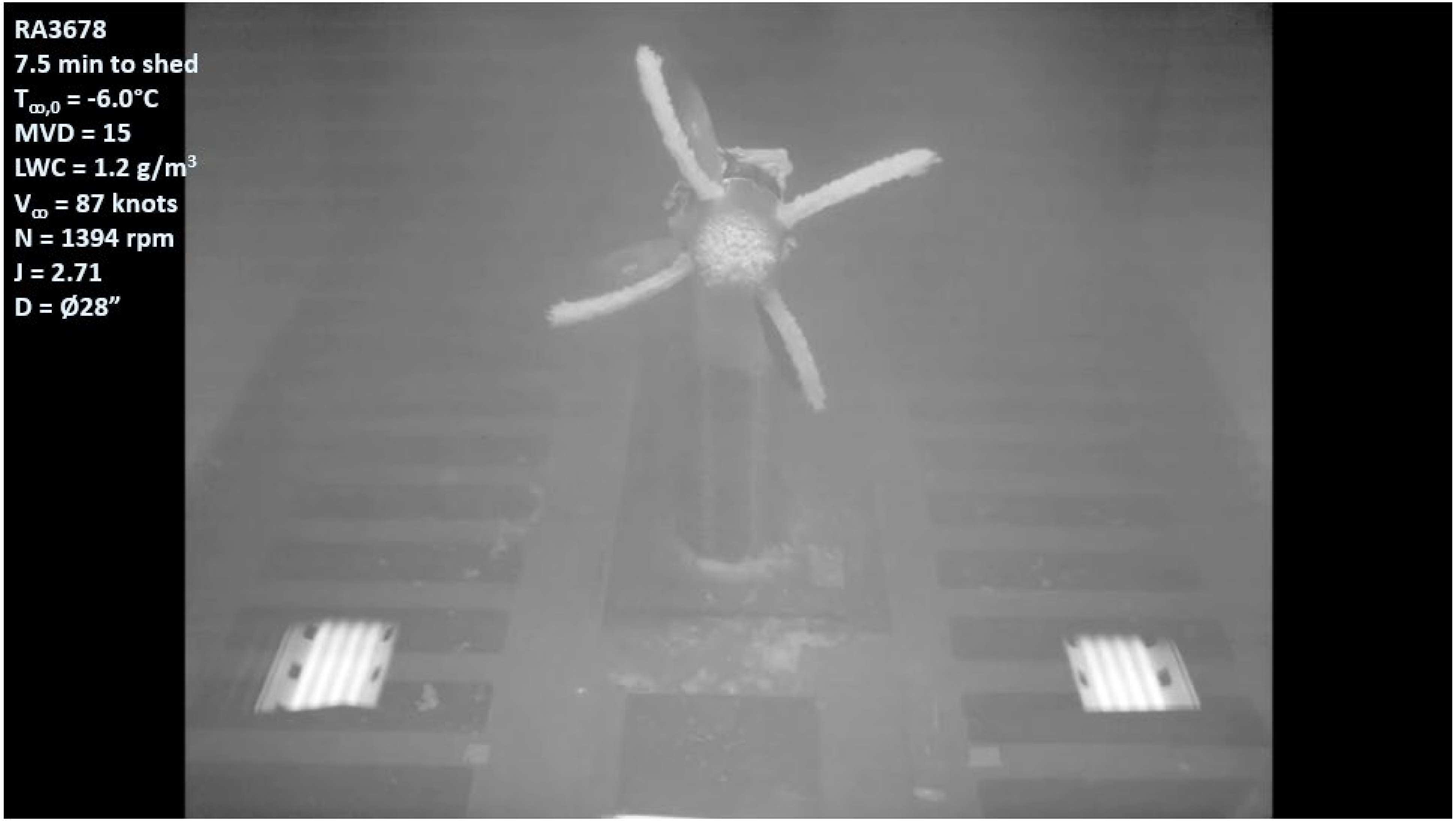
Propeller Size Comparison

Diameter = Ø24”

Ø28”

Ø36”

Ice Shedding Example (video)



Effect of Exposure Time on Rime Ice

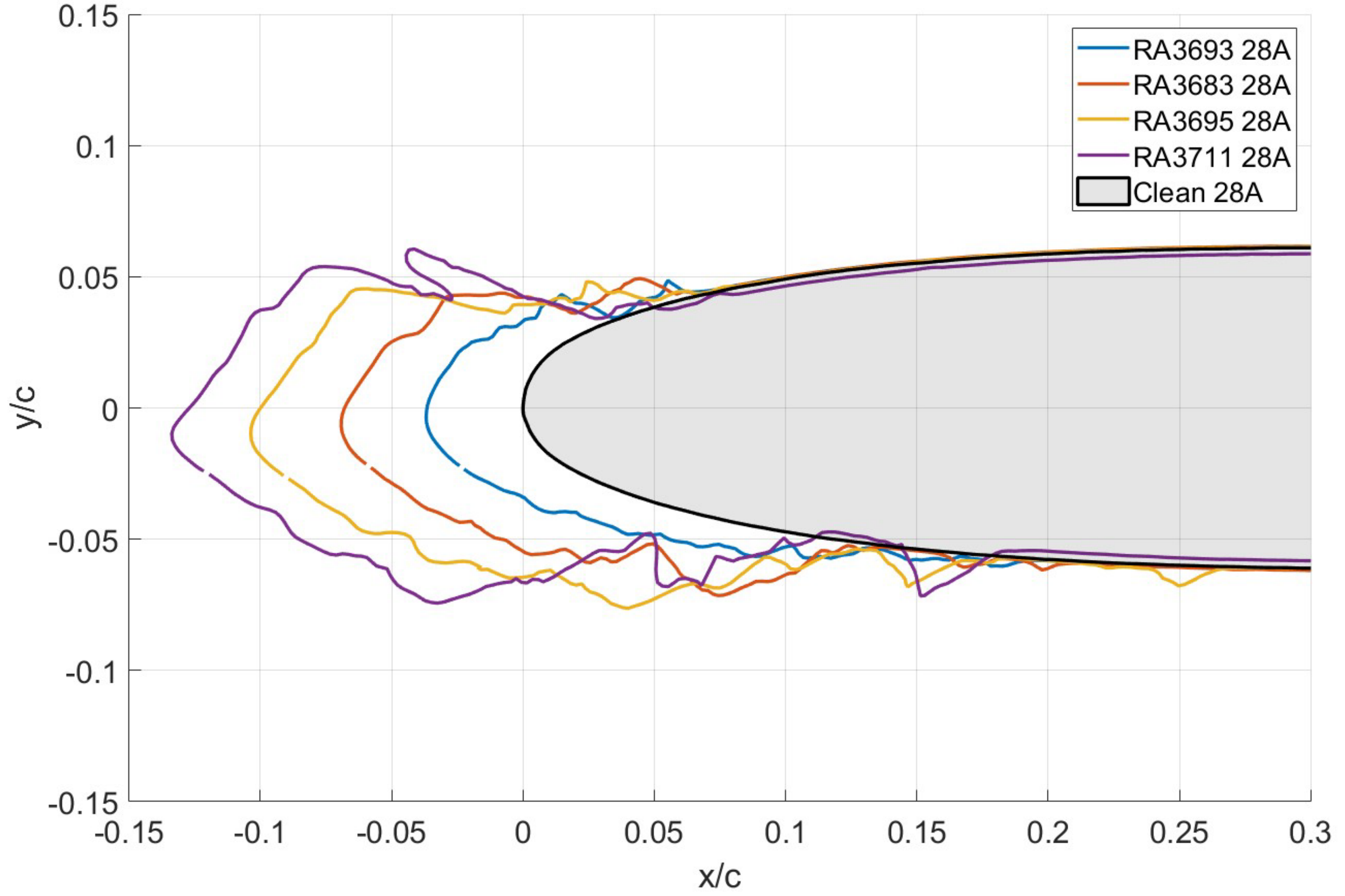
1.5 min

3.0 min

4.5 min

6.0 min

Exp. Time for Rime Ice (@ 0.75R)



Tunnel Conditions

Branch ID	V∞ (knots)	MVD (µm)	LWC (g/m³)	T∞,0 (°C)
RA3693 RA3683 RA3695 RA3711	87	15	0.55	-15

Operating Conditions

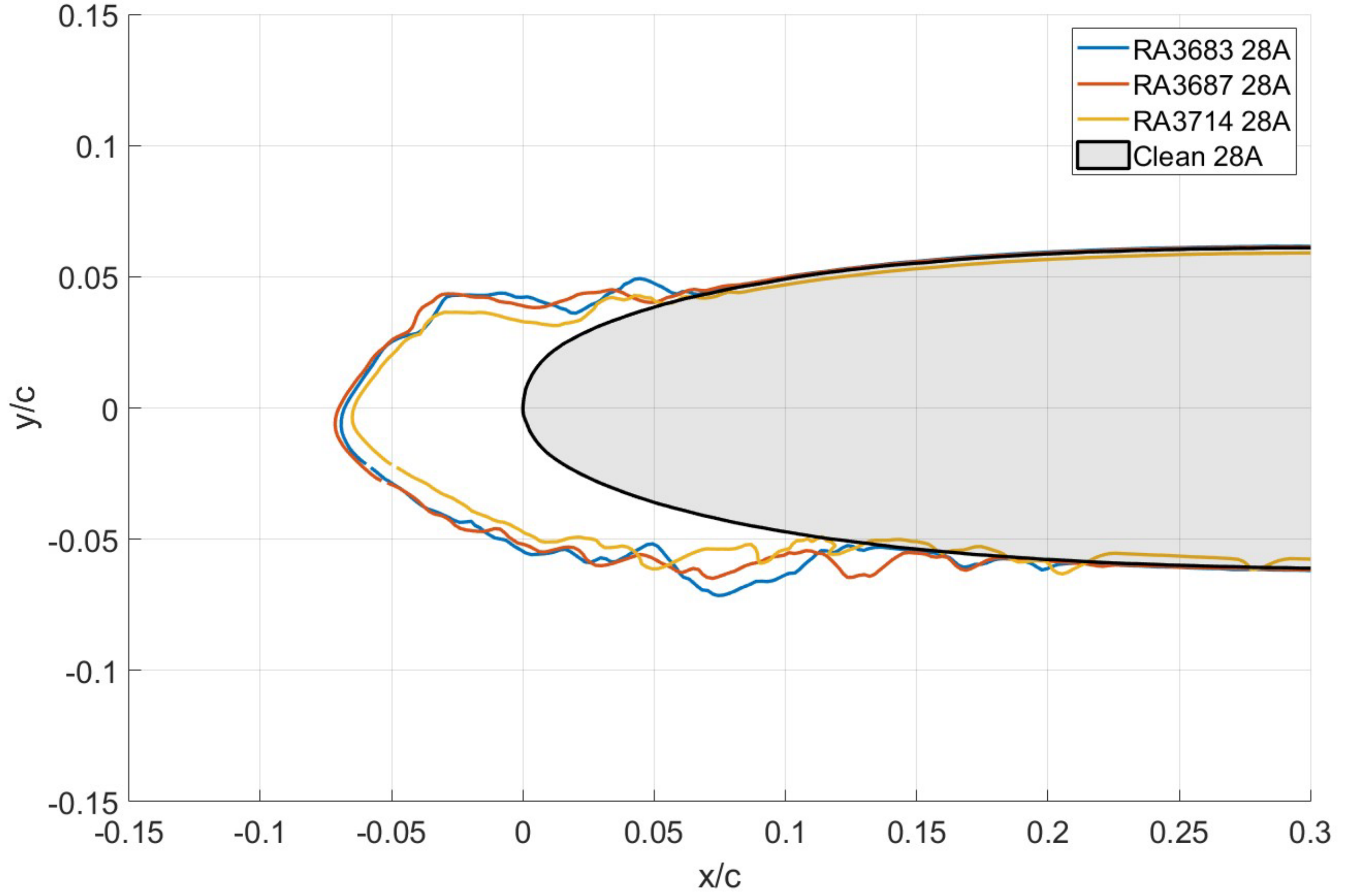
Branch ID	D (in)	N (rpm)	J (~)	α (°)	M_{tip} (Mach)
RA3693 RA3683 RA3695 RA3711	28	1516	2.49	4.5	0.21

Icing Scaling Parameters + Ice Mass

Branch ID	Time (min)	n_0 (~)	β_0 (~)	A_{C_LED} (~)	Blade Ice Mass (g)	Spinner Ice Mass (g)
RA3693	1.5	1	0.88	0.30	4.2	5.1
RA3683	3.0	1	0.88	0.60	9.0	10.6
RA3695	4.5	1	0.88	0.90	10.7*	15.9
RA3711	6.0	1	0.88	1.20	21	21.5

*RA3695 shed towards the tip of the blade resulting in the lower-than-expected ice mass.

Repeatability for Rime Ice (@ 0.75R)



Tunnel Conditions

Branch ID	V∞ (knots)	MVD (μm)	LWC (g/m³)	T∞,0 (°C)
RA3683 RA3687 RA3714	87	15	0.55	-15

Operating Conditions

Branch ID	D (in)	n (rpm)	J (~)	α (°)	M_{tip} (Mach)
RA3683 RA3687 RA3714	28	1516	2.49	4.5	0.21

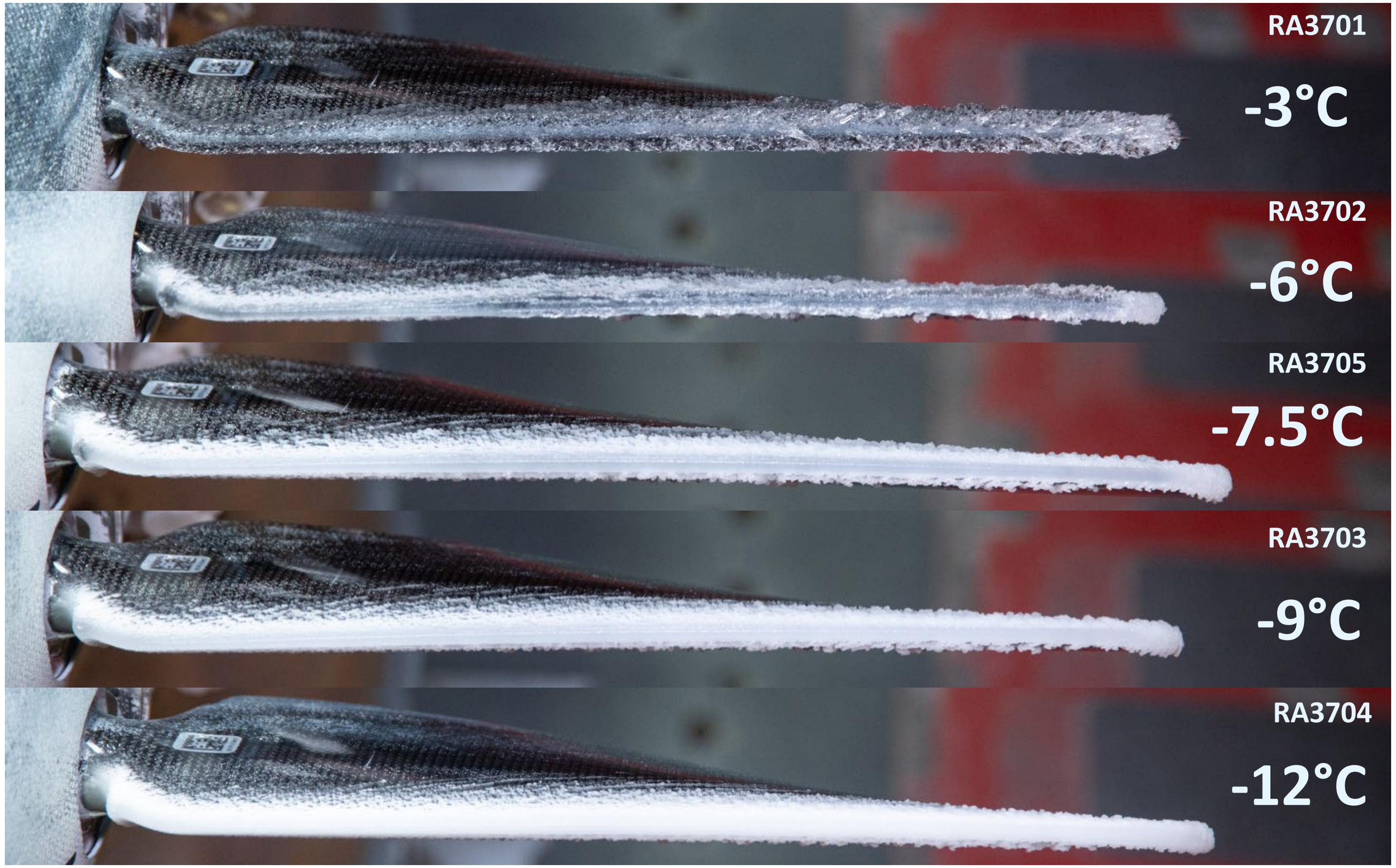
Icing Scaling Parameters + Ice Mass

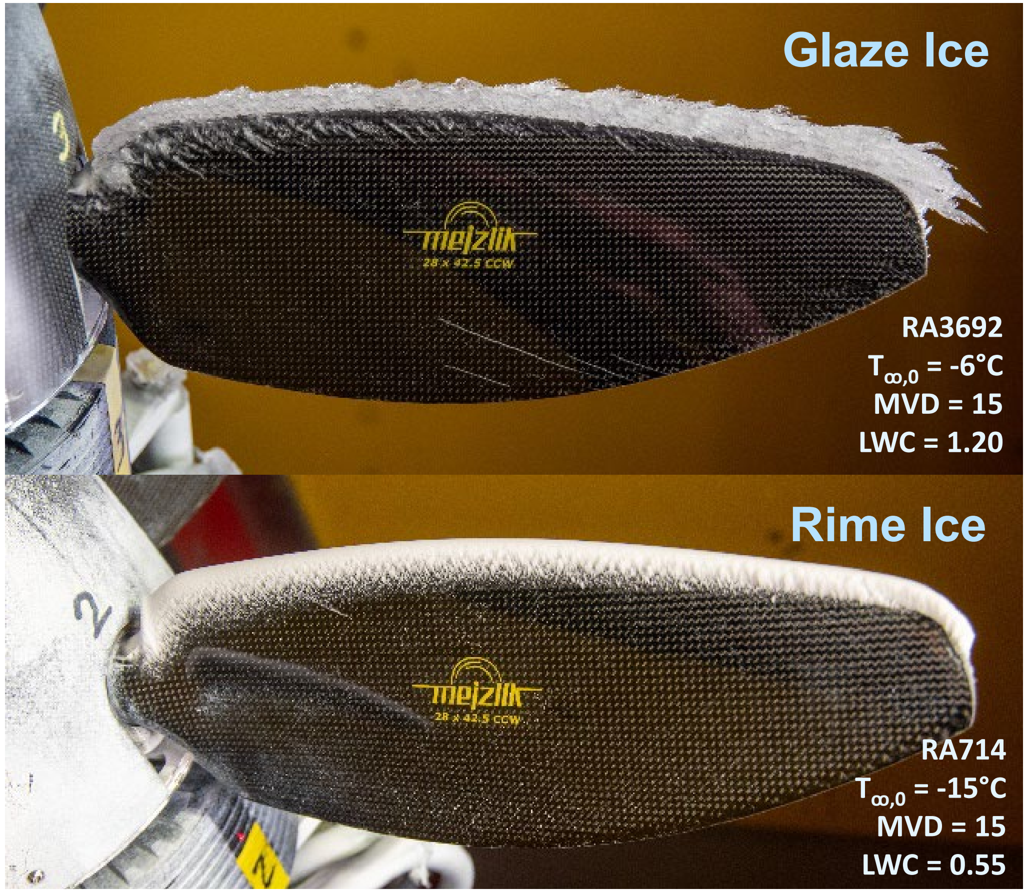
Branch ID	Time (min)	n_0 (~)	β_0 (~)	A_{C_LED} (~)	Blade Ice Mass (g)	Spinner Ice Mass (g)
RA3683	3.0	1	0.88	0.60	9.0	10.6
RA3687	3.0	1	0.88	0.60	8.5	10.3
RA3714	3.0	1	0.88	0.60	9.8	10.8

Note: RA3683 and RA3687 were taken at the start and end of the same night, respectively. RA3714 was taken several days later.

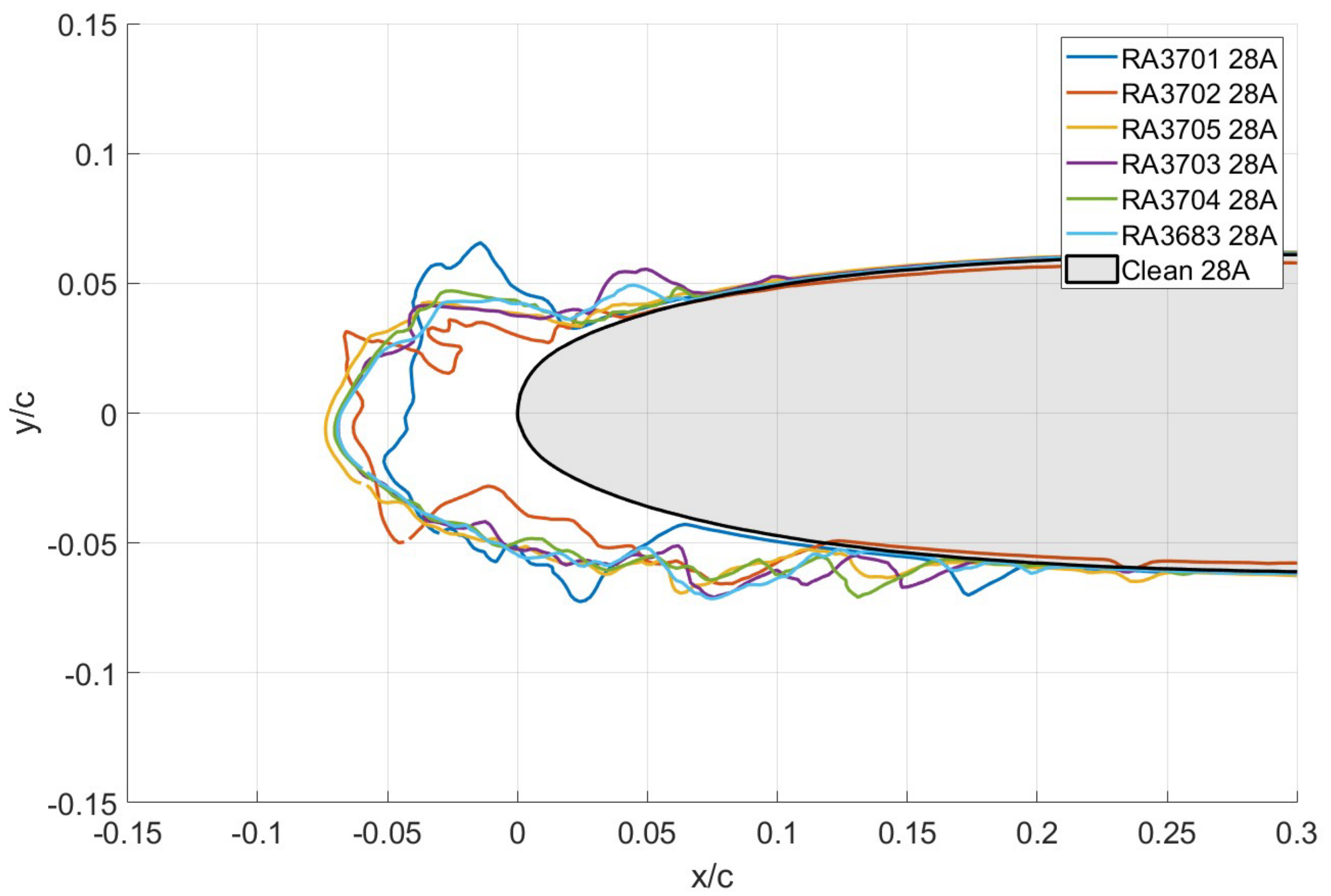
Effect of Total Air Temperature

Total Temperature ($T_{\infty,0}$) Sweep at MVD = 15µm and LWC = 0.55 g/m^3





Temperature Effect (@ 0.75R)



Tunnel Conditions

Branch ID	V∞ (knots)	MVD (μm)	LWC (g/m³)	T∞,0 (°C)
RA3701	87	15	0.55	-3.0
RA3702	87	15	0.55	-6.0
RA3705	87	15	0.55	-7.5
RA3703	87	15	0.55	-9.0
RA3704	87	15	0.55	-12.0
RA3683	87	15	0.55	-15.0

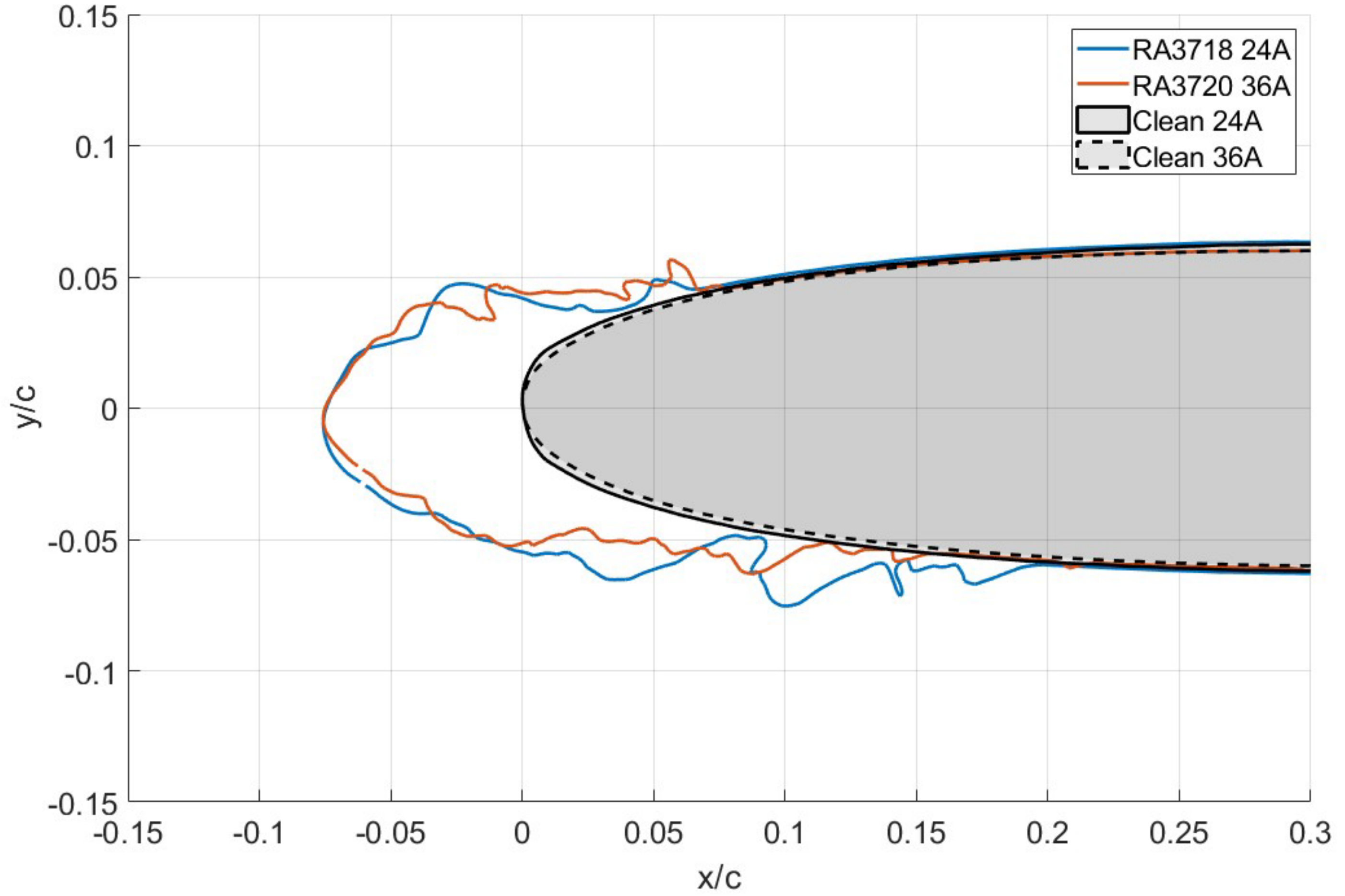
Operating Conditions

Branch ID	D (in)	n (rpm)	J (~)	α (°)	M_{tip} (Mach)
“	28	1516	2.49	4.5	0.21

Icing Scaling Parameters + Ice Mass

Branch ID	Time (min)	n_0 (~)	β_0 (~)	A_{C_LED} (~)	Blade Ice Mass (g)	Spinner Ice Mass (g)
RA3701	3.0	0.53	0.88	0.60	7.0	8.4
RA3702	3.0	1.0	0.88	0.60	8.3	9.3
RA3705	3.0	1.0	0.88	0.60	9.7	10.1
RA3703	3.0	1.0	0.88	0.60	8.7	9.8
RA3704	3.0	1.0	0.88	0.60	9.1	9.8
RA3683	3.0	1.0	0.88	0.60	9.0	10.6

Scaling for Propeller Size AND Speed (@ 0.75R)



Tunnel Conditions

Branch ID	V∞ (knots)	MVD (µm)	LWC (g/m³)	T∞,0 (°C)
RA3718	87	15	0.55	-15
RA3720	110	15	0.55	-15

Operating Conditions

Branch ID	D (in)	n (rpm)	J (~)	α (°)	M_{tip} (Mach)
RA3718	24	1766	2.49	4.5	0.21
RA3720	36	1504	2.47	4.5	0.27

Icing Scaling Parameters + Ice Mass

Branch ID	Time (min)	n_0 (~)	β_0 (~)	A_{C_LED} (~)	Blade Ice Mass (g)	Spinner Ice Mass (g)
RA3718	2.6	1.0	0.89	0.61	6.0	8.9
RA3720	3.0	1.0	0.87	0.60	15.8	17.0

Propeller Icing Test Summary

- A 10-day IRT test was completed in March 2023.
- A clean performance map was acquired for each propeller diameter prior to icing tests
- A total of 45 icing runs were to performed for parametric variations in icing conditions
  - Effect of icing cloud parameters on ice accretion at constant propeller RPM
  - Effect of icing on propeller torque (estimated through motor current)
  - Preliminary study of icing conditions scaling for propeller tests.
  - Data for GlennICE development and validation
- Data analysis is ongoing with paper to be prepared and presented at AIAA Aviation Forum, 29 July – 2 August, 2024, Las Vegas.

IRT Capability Utilization Assessment

Background

- NASA study commissioned by the Aerosciences Evaluation and Test Capabilities (AETC) Portfolio
  - AETC manages 12 large facilities at NASA including IRT and PSL
- AETC ensures the strategic availability and ease of access of a minimum critical suite of aerosciences ground test assets that are necessary to meet the long-term needs of the United States.
- AETC plans to conduct similar studies of its other major facilities.

Schedule

- May 15, 2022: Kick-off Meeting
- February 8, 2023: Final report to AETC
- March 9, 2023: Final Report to NASA Aeronautics Testing Advisory Board

IRT Capability Utilization Assessment

Objective

- Assess NASA and national capabilities and needs for icing ground testing.

Approach

- Gather data to assess the following capability attributes:
  - NASA and external test demand forecasts link to specific program/customer test requirements
  - Uniqueness and costs with respect to alternate ground test capabilities
  - Assessment of the state of icing computational tools or CFD as well as Certification by Analysis (CbA) efforts that could impact future ground test needs
  - Facility condition of the IRT
  - Cost of IRT ownership including AETC and institutional support
- Requested external stakeholder feedback at Fall 2022 AC-9C meeting in Belfast.

History as a Predictor of the Future

- Statement from John H. Enders, Head of Aviation Safety Research at NASA Headquarters. Presented at the Icing Specialists Workshop, July 19-21, 1978 (Taken from NASA CP-2086).

> *“The recent renewal of interest in flight icing may be surprising to many, but it probably should have been expected. Our experience with safety and operating problems research has been that problems are “solved” for a time, and then, as aircraft designs and operating practices change, these problems re-emerge and call for renewed effort, often in terms of a finer-scale resolution than was offered earlier.”*

- 45 years later, NASA remains focused on advanced configurations bound by significantly increased aircraft performance and certification requirements (“*finer-scale resolution*”).




Significance of Icing Research

- NASA Aeronautics and external stakeholders are investing in new technologies:
  - Transonic Truss Braced Wing
  - Advanced Air Mobility
  - Small Core Engine Technology
- New icing regulations are a risk to these technologies entering the market
  - Regulations introduced in 2007 and 2015
- Icing research is needed to mitigate the risk of certification challenges and help enable Certification by Analysis in the future.

This is validated by the recent Analysis of Alternatives study on Icing (see NASA TM-2022000696)

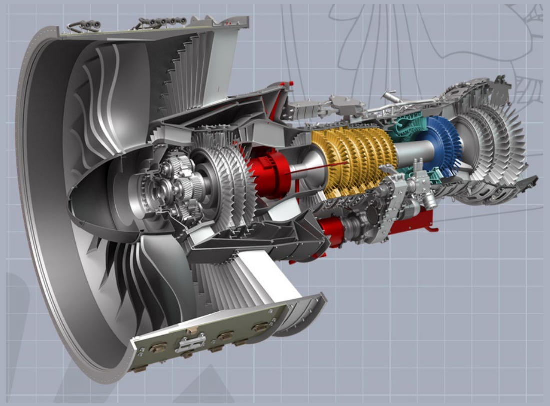
External Stakeholder Feedback

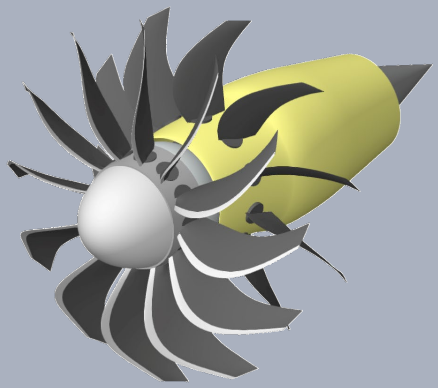
- Received detailed feedback from 11 companies and the FAA.
- Emphasized the unique capabilities of IRT for icing testing, especially within United States.
- Needs-based evidence for the importance of ground test capability for research and certification (not everything can be done with computer codes!).
- Good data on possible near-term need for IRT testing.
- Many suggestions for potential new capabilities—see next slide.
  - An initial screening of these suggestions has been performed to determine relative feasibility and cost.
  - Plan is to pursue the most feasible and least cost items first and build-out from there.

Potential New Capabilities—Consolidated

- Tunnel / Facility
  - Turntable improvements including force balance capability.
  - Ability to test aircraft deicing/anti-icing fluids.
  - Ability to dynamically adjust and measure ice protection system energy input.
  - Ability to test fans/rotors (add drive system capability).
  - Ability to perform icing tests in the diffuser (larger diameter rotors/propellers).
- Cloud
  - Lower liquid water content.
  - Improve SLD cloud to better match App. O.
  - Improve ice crystal cloud capabilities.
  - Add falling and blowing snow capabilities.
- Instrumentation / Diagnostics
  - Improved (faster/more efficient) method for 3D scanning of ice shapes.
  - In-situ measurements of cloud LWC and phase and particle temperature.

Efficient Quiet Integrated Propulsor (EQuIP)





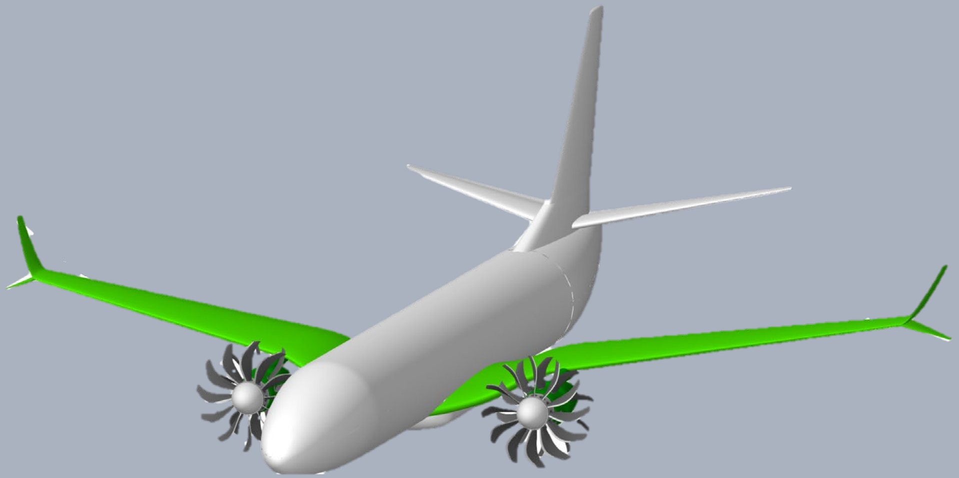
Icing Work Areas:

- Fan Icing
  - 3D rotational icing simulation
  - Ice shedding simulation
  - Requirements for engine fan icing test rig
- Ice Crystal Icing (ICI)
  - Simulation tools / SIDRM analysis
  - IC capability development for IRT / AIT

New Tech Challenge (FY24-FY27)

Overall EQuiP Goals
Predict, model, and assess…next-gen propulsors
…while reducing risk* for use on…aircraft in 2030s

* Icing work in EQuiP seeks to reduce risk by raising TRL of engine icing simulation tools



EQuIP Icing Research Tasks (FY24-FY27)

- 3D Rotating Icing Simulation
  - Develop and assess GlennICE for next generation propulsors and airframe
  - Initial studies will utilize recently acquired propeller icing data.
  - Add mixing plane capability for rotating and fixed components.
- Ice Shedding
  - Develop numerical methodology to estimate onset and mass of shed ice using fracture mechanics-based approach.
- Rotating System Icing Experiment Development
  - Gather requirements for rotating system test in IRT.
  - Perform feasibility studies

Rotating System Icing Experiment Development

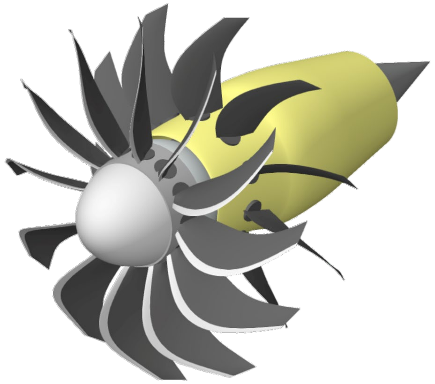
Develop requirements and feasibility for icing experiments in IRT for code validation.

- Currently no rotating driven system capability in IRT.
- No in-house IRT icing tests have been performed in this operational regime

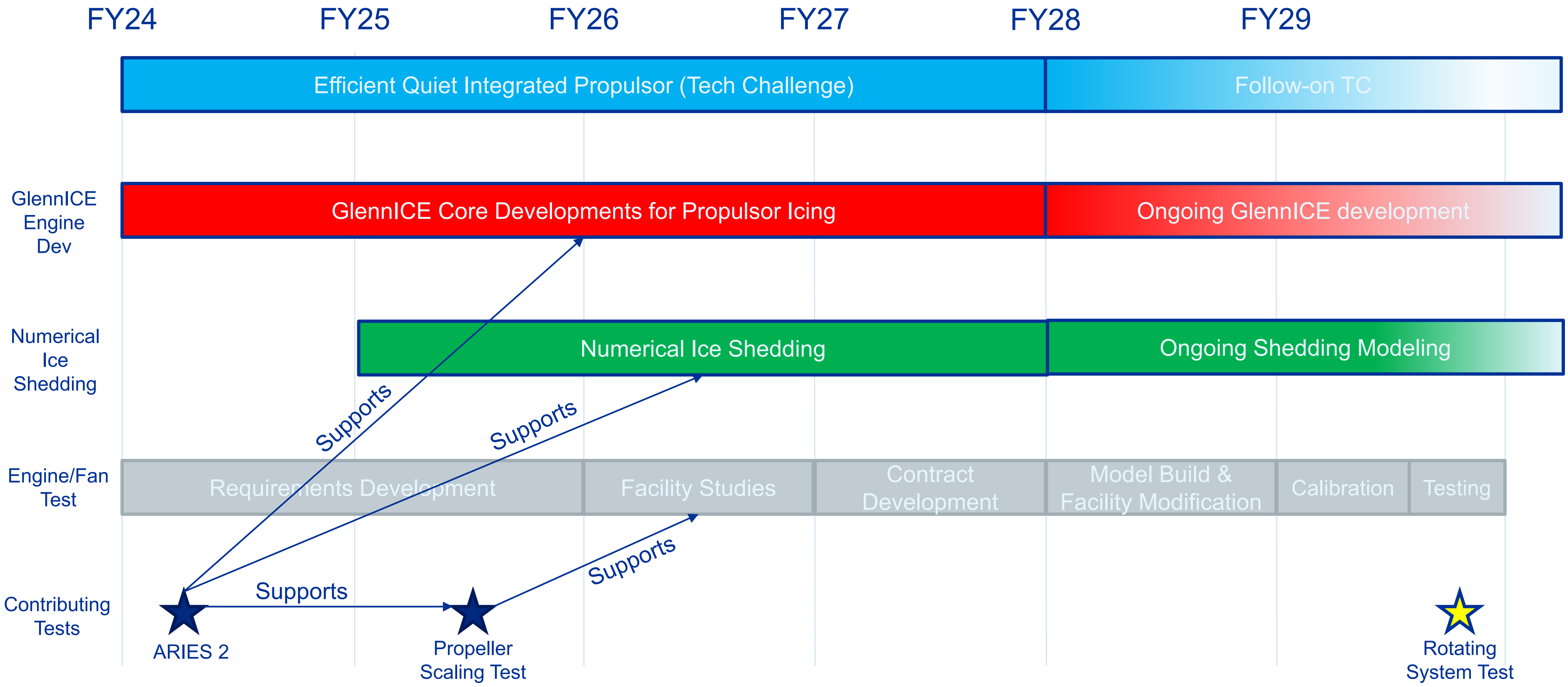
Path forward:

- ~2 years of stakeholder needs and requirements analysis
  - Scientific requirements
  - Operational Requirements
  - Technical Requirements
- Feasibility studies
  - Propulsor-in-tunnel CFD simulations
  - Cost
  - Integration
- Rotor scaling test to understand the impacts of scaling down an engine fan
  - Leveraging data from the recent propeller icing test campaign
- Targeting a driven rig propulsor test in FY28/29

Seeking collaboration opportunities for this effort



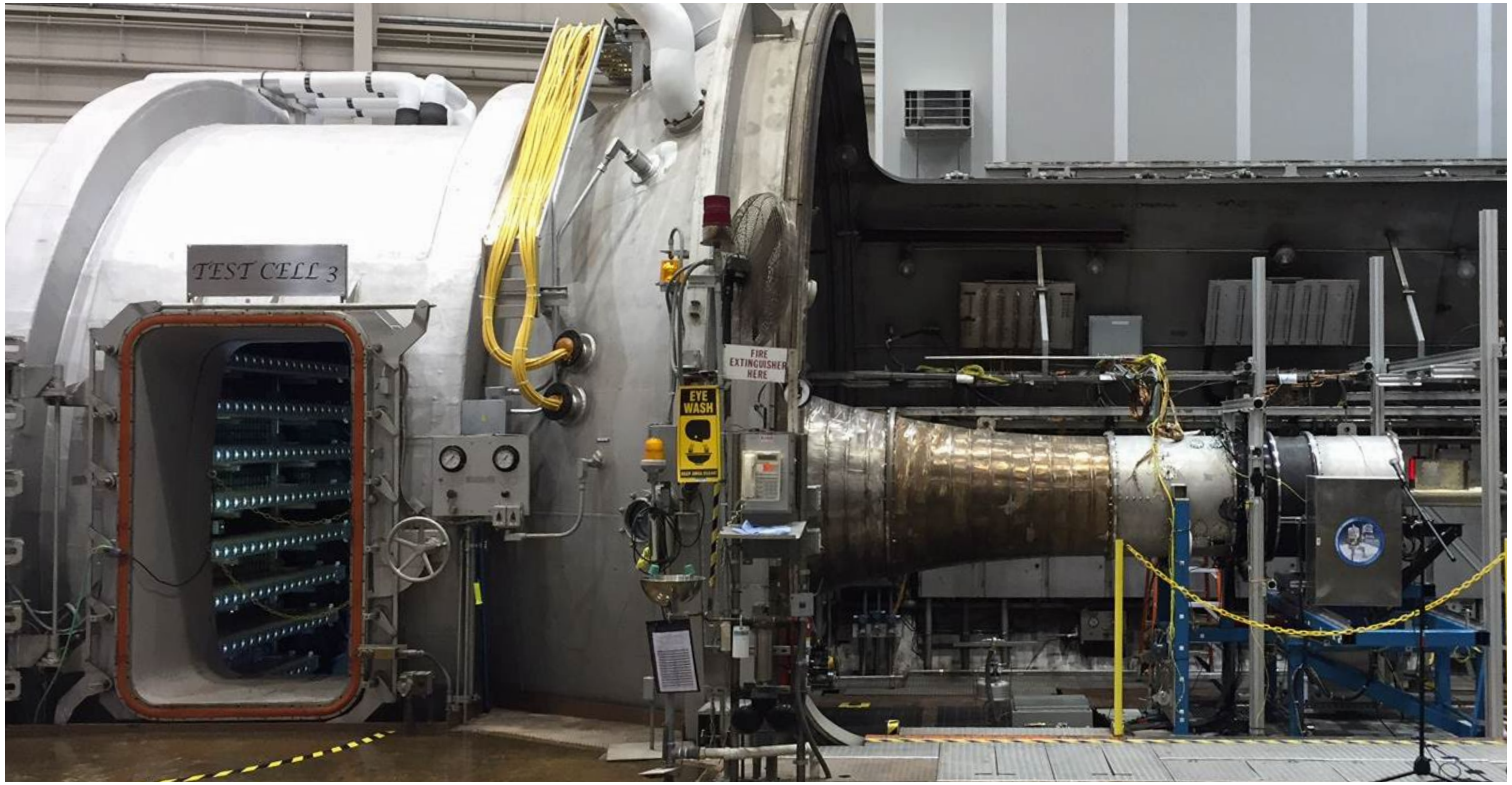
EQuIP Icing Notional Timeline



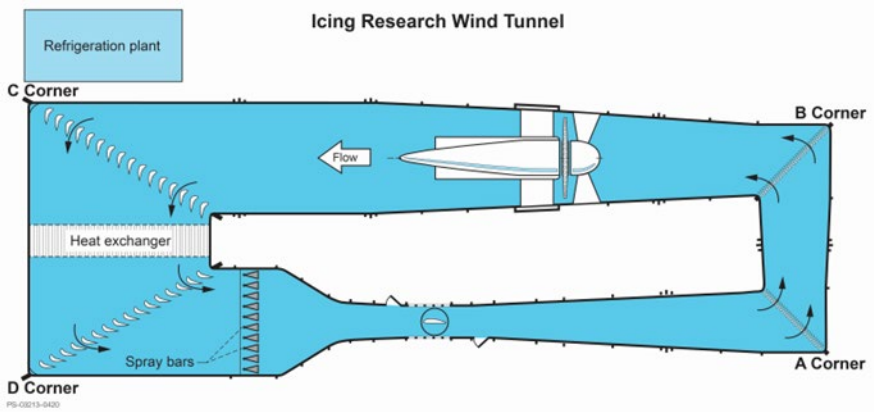
Propulsion Systems Laboratory Status

Engine altitude test stand with ice crystal & supercooled liquid clouds.

- Plan to re-install the Icing System in 2025 for App D/P & App C calibration.
- Test an ASME nozzle or, ideally, an Engine in 2026.
- NASA is looking to collaborate with an Engine OEM to test an engine in lieu of the ASME nozzle.



Icing Research Tunnel Status



Maintenance and projects performed in past months:

- Roof repair on building
- New pumps in water room
- New water storage tank

Currently undergoing 5-year calibration (per ARP-5905)

- Last calibration completed in 2019
  - Sooner than 5 year (technically should be 2024) but since many maintenance projects took place during summer shutdown, made sense to come back up with a full calibration
- Cloud uniformity testing completed
  - Investigated current spray patterns and optimized as needed
  - Standard-nozzle spraying patter remained the same (as it has since 2011)
  - Made a few changes to the Mod1 nozzle patter to smooth out some high/low spots
    - Number of nozzles reduced from 103 to 101
- Aero/Thermal check calibration completed
  - Center-line rake to measure total and static pressures and flow angularity
  - Temperature uniformity with RTD array (check-cal configuration)
- To be completed: drop size measurements, water content, and ice shape repeatability
  - Expect to be finished by mid-December