

NASA Icing Simulation Information



Mary Wadel & Christopher Porter/NASA Glenn Research Center
Icing Branch & Advanced Air Transport Technologies Project (AATT)
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Outline

- Icing Simulation Evaluation
- Swept-Wing Icing and Aerodynamics
- NASA Ice Accretion Simulation Tools



Icing Simulation Evaluation – Research Elements

The Road to Simulation by Analysis

- Current Capabilities
 - The Icing Environment
 - Experimental Capabilities
 - Computational Capabilities
- Development of Rigorous Evaluation Metrics
- Initial Assessment of Simulation Tools



Current Capabilities

The Icing Environment

An aircraft encounter with icing conditions can occur during all aspects of aircraft operations including ground-based operations, take-off, cruise, hold, approach, and landing. Icing encounters can have quite different characteristics for each of these operational states. Aircraft and engine manufacturers, OEMs, and operators are all concerned with assessing the impact of operations in icing conditions on their businesses. Short of actual flight or ground operations in icing, each of these industry segments uses simulation methods, experimental or computational, to develop their strategies for coping with an icing encounter and meeting the requirements of certification authorities for such encounters.

NASA and the FAA have collaborated over the years to increase the communities understanding of the icing threat as well as to develop means for assessing it's impact on aircraft design and operations. Much of the work has focused on determining the characteristics of the icing environment and this work has led to the creation of so-called 'certification envelopes' which are embodied in Federal Regulations.



Current Capabilities

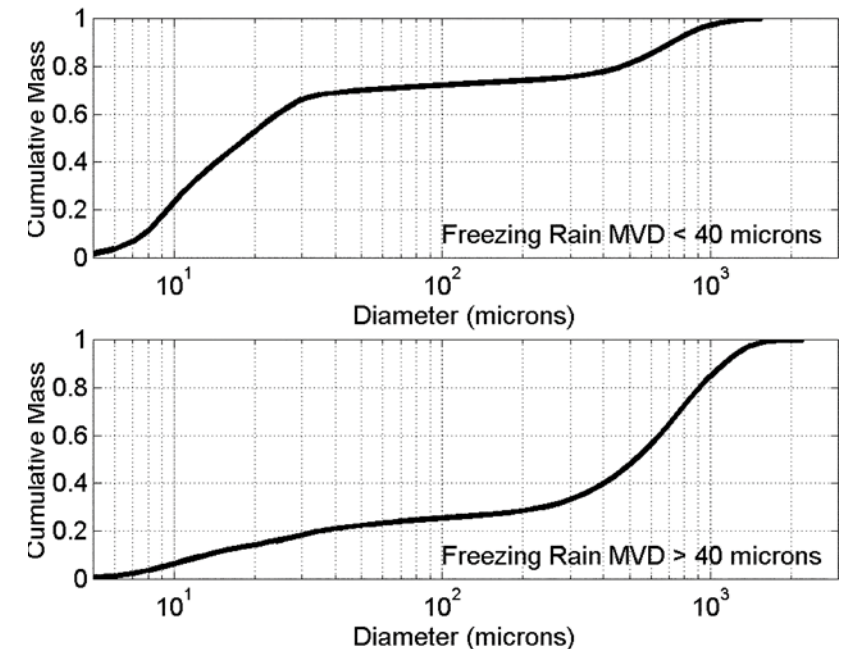
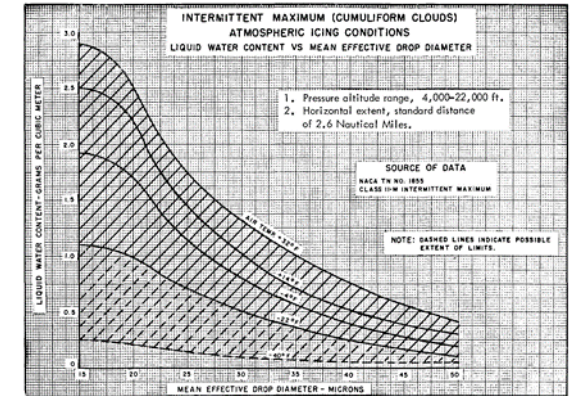
The Icing Environment

These regulations include:

- Title 14, Part 23, Subpart B, §23.2165 - Performance and flight characteristics requirements for flight in icing conditions.
- Title 14, Part 23, Subpart B, §23.2415 - Powerplant ice protection.
- Title 14, Part 23, Subpart B, §23.2540 - Flight in icing conditions.
- Title 14, Part 25, Subpart F, §25.1403 - Wing icing detection lights.
- Title 14, Part 25, Subpart F, §25.1419 - Ice protection.
- Title 14, Part 25, Subpart F, §25.1420 - Supercooled large drop icing conditions.

- Title 14, Part 25, Appendix C
 - Part I—Atmospheric Icing Conditions
 - Part II—Airframe Ice Accretions for Showing Compliance With Subpart B.

- Title 14, Part 25, Appendix O - Supercooled Large Drop Icing Conditions
 - Part I—Meteorology
 - Part II—Airframe Ice Accretions For Showing Compliance With Subpart B Of This Part



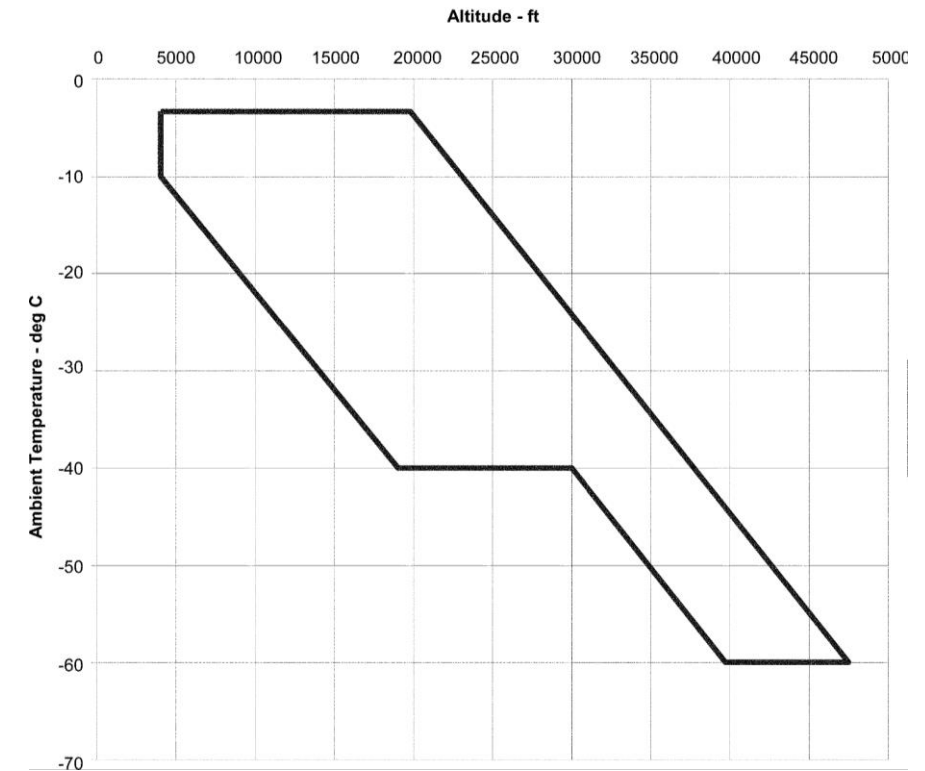


Current Capabilities

The Icing Environment

These regulations include:

- Title 14, Part 27, Subpart F, §27.1419 - Ice protection.
- Title 14, Part 27, Subpart F, §29.1419 - Ice protection.
- Title 14, Part 29, Appendix C - Icing Certification.
- Title 14, Part 33, Subpart E, §33.68 - Induction system icing.
- Title 14, Part 33, Appendix D - Mixed Phase and Ice Crystal Icing Envelope (Deep Convective Clouds).
- Title 14, Part 121, Subpart U (Dispatching and Flight Release Rules), §121.629 - Operation in icing conditions.
 - ~ Over 100 other regulations including the word icing ~



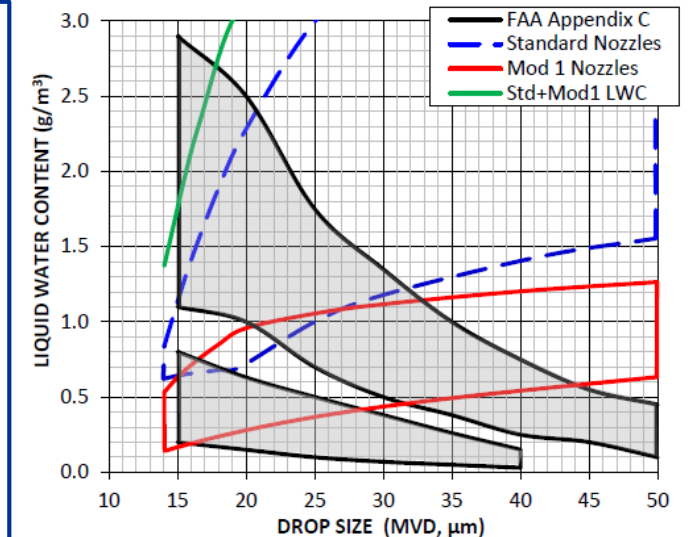
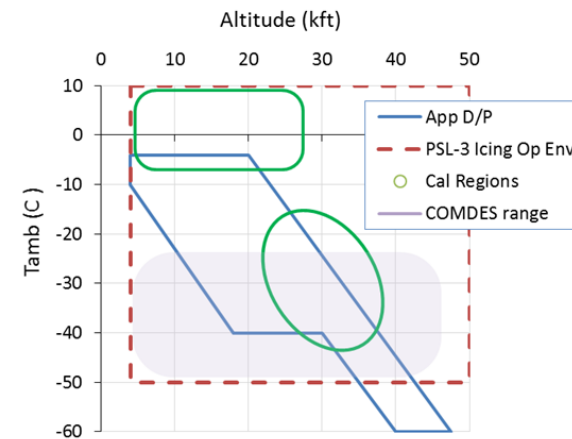
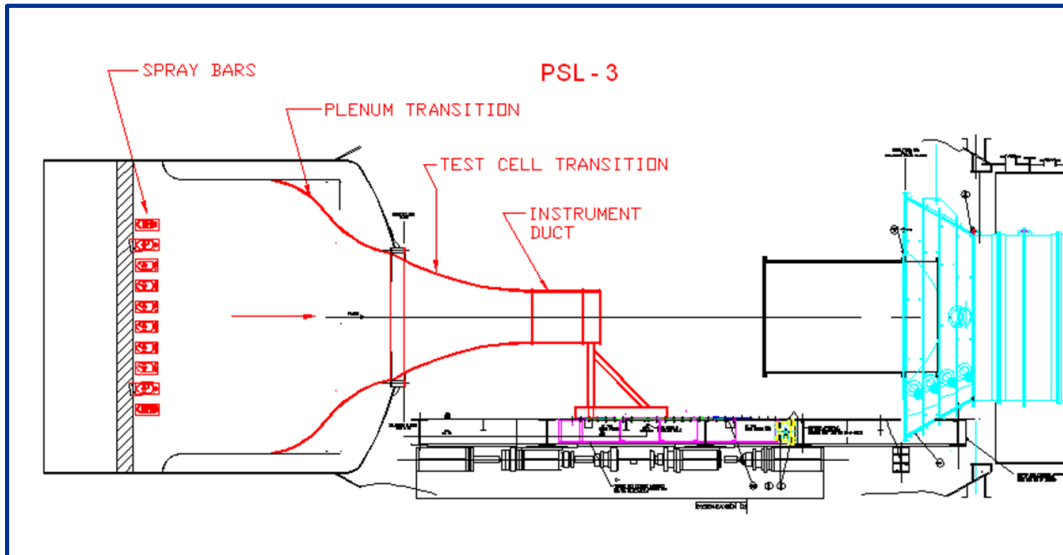
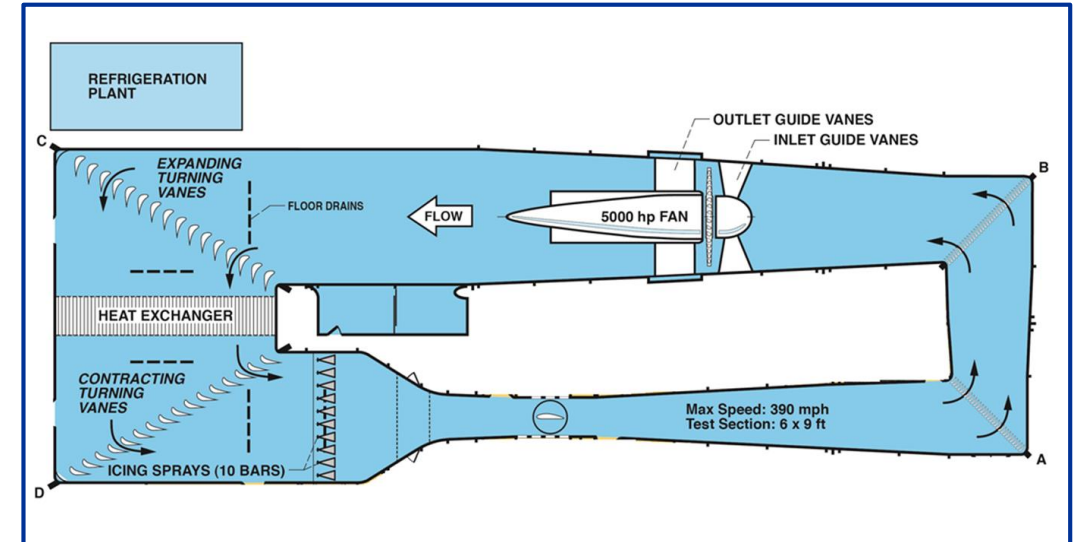


Current Capabilities

Experimental Capabilities

There are two major facilities at NASA that can simulate elements of the atmospheric icing environment

- The Icing Research Tunnel (IRT)
 - ✓ Appendix C
 - ✓ Appendix O
- The Propulsion Systems Laboratory (PSL)
 - ✓ Appendix D/P





Current Capabilities

Computational Capabilities

NASA has developed several tools that can be used for icing simulation

➤ LEWICE

- ✓ 2D ice accretion simulation; multi time step
- ✓ Fast and easy to use
- ✓ Can reproduce Appendix C and O conditions

➤ LEWICE3D

- ✓ 3D ice accretion simulation; single time step
- ✓ Used in conjunction with a large group of 3D CFD tools
- ✓ Can reproduce Appendix C and O conditions and elements of Appendix D

➤ GlennICE

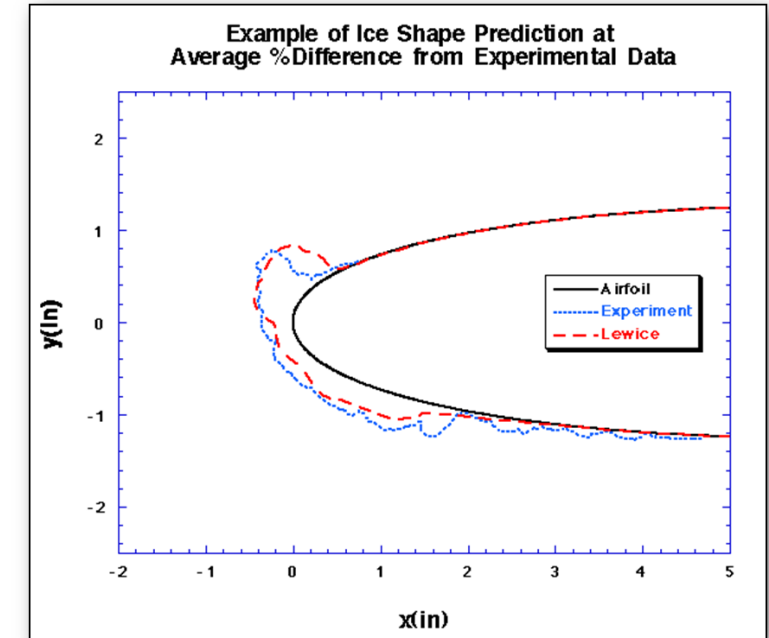
- ✓ Currently under development
- ✓ 3D ice accretion simulation; multi time step
- ✓ Planned to reproduce Appendix C, O, and D conditions

➤ COMDES

- ✓ One dimensional tool for prediction of ice crystal icing possibility in engines

➤ TADICE

- ✓ One dimensional simulation of icing conditions within engine flow path





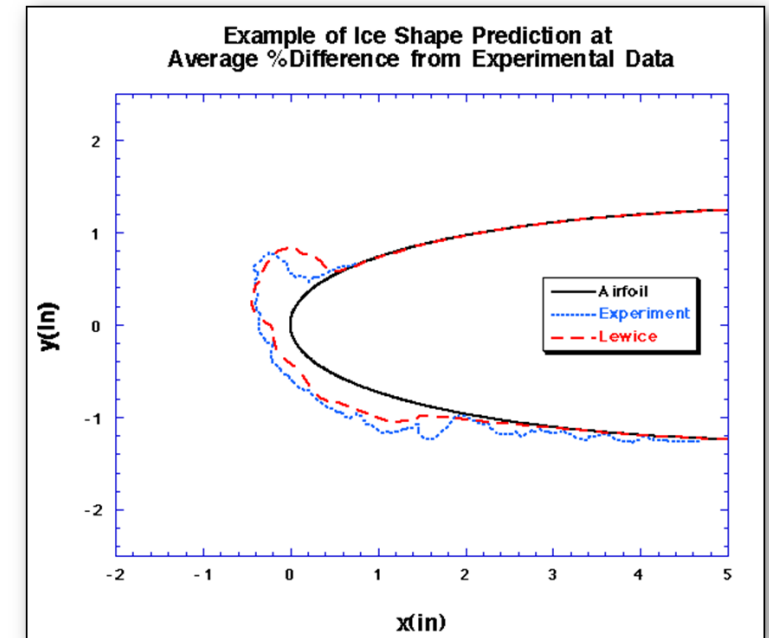
Development of Rigorous Evaluation Metrics

How good is good enough?

NASA has created a significant database of information for comparison of experimental and computational ice shapes. Additionally, NASA has also created, along with several research partners, a database of aerodynamic data, icing physics experiments, and flight test data for evaluating of our simulation methods, whether experimental or computational.

Development of evaluation metrics

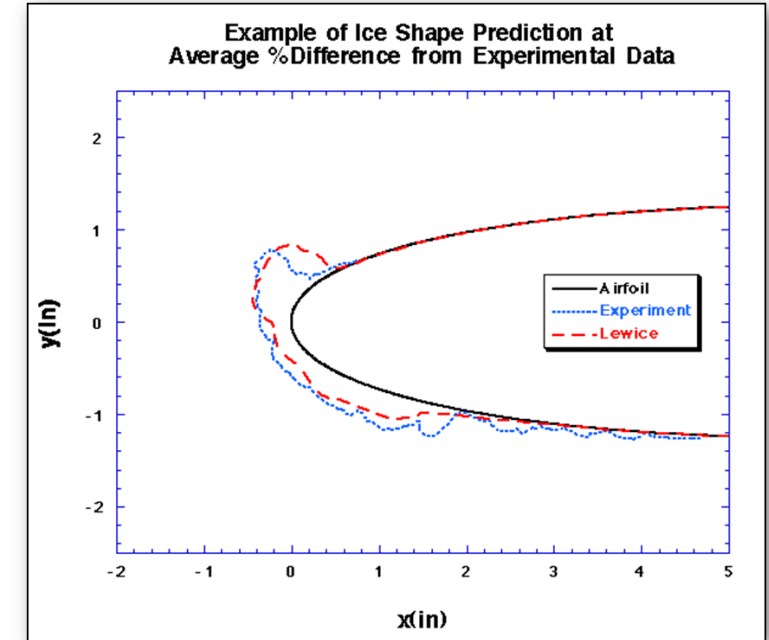
- What are the outcomes of an icing simulation that must be obtained?
 - Ice shapes
 - Performance degradation data
 - Ice protection system performance
 - Others?
- How are these to be evaluated?
 - Comparison to flight data; what is available?
 - Accuracy
 - Range of Icing Conditions
 - What additional data is needed?





Initial Assessment of Simulation Tools

- Establish simulation goals
- Identify what simulations can be performed at this time
- Identify gaps in capability
- Develop evaluation metrics for the simulations that can be performed
- Develop plan for examining simulation capabilities by comparison of results to metrics
- Develop recommendation for further development





NASA/FAA/ONERA Swept-Wing Icing and Aerodynamics

- NASA Background and Motivation
- Project Overview
- Schedule and Status
- Goals and Objectives
- Research Roadmap
- Research Phases I-VII Description and Status
- Research Timeline FY18-19
- Research Products and Accomplishments to Date



NASA—Background

- NASA has supported icing research, design and certification efforts through the development of icing simulation tools and experimental databases.
- The NASA LEWICE (2D) icing code has achieved acceptance in icing engineering analysis and certification based upon thousands of validation cases acquired over many years, mostly from the NASA Icing Research Tunnel.
- This achievement is combined with closely related research to develop an aerodynamic understanding of icing effects on airfoils.
- Similar validation is currently needed to achieve acceptance of LEWICE3D.

Why Are We Here?

- Development and use of 3D icing simulation tools.
- Lack of ice accretion and aerodynamic data for large-scale, swept wing geometries.
- Aerodynamic understanding important for evaluating efficacy of 3D icing simulation tools.
- Multi-faceted research effort.





NASA Motivation

- Common features of NASA's advanced air transport concepts are large-scale, three-dimensional lifting surfaces; integrated, embedded engines; boundary-layer ingestion (BLI) and locations of high local sweep angles.





Icing Hazards Workshop

January 28-29, 2015 at NASA GRC

- Identified gaps in current icing research and suggestions for advanced aircraft concepts, including:
 - Icing tool development
 - Modernize LEWICE3D; completely re-write.
 - More focus on 3D, full-aircraft simulations.
 - Modern computational methods for certification by analysis.
 - Swept-wing icing simulation and importance of scallop ice.
 - Runback icing simulation.
 - Incorporation of icing in advanced aircraft design
 - Configuration design constraints for icing.
 - New concepts are contamination intolerant.
 - BLI technologies are incompatible with current ice protection systems.
 - Icing impact on active flow control devices.
 - Icing impact on active control for aeroelasticity.



Summary of Motivation

- NASA advanced airplane concepts present significant challenges for LEWICE3D.
- This research is directed at understanding the limitations and required improvements for successful icing simulation directed toward NASA advanced airplane concepts.
- This research is required in order to develop advanced engineering tools to support “Certification by Analysis.”
 - Need for validation databases.
- Additional work is necessary to address freezing drizzle and freezing rain conditions that are beyond the scope of the current effort, but are significant with respect to icing design and certification efforts.



Partnership Acknowledgements

Sponsor Organizations:

- NASA—Advanced Air Transport Technology Project
- FAA
- ONERA

Supporting Organizations:

- Boeing
- University of Illinois
- University of Virginia
- University of Washington



Swept-Wing Goal and Objectives

Overall Goal

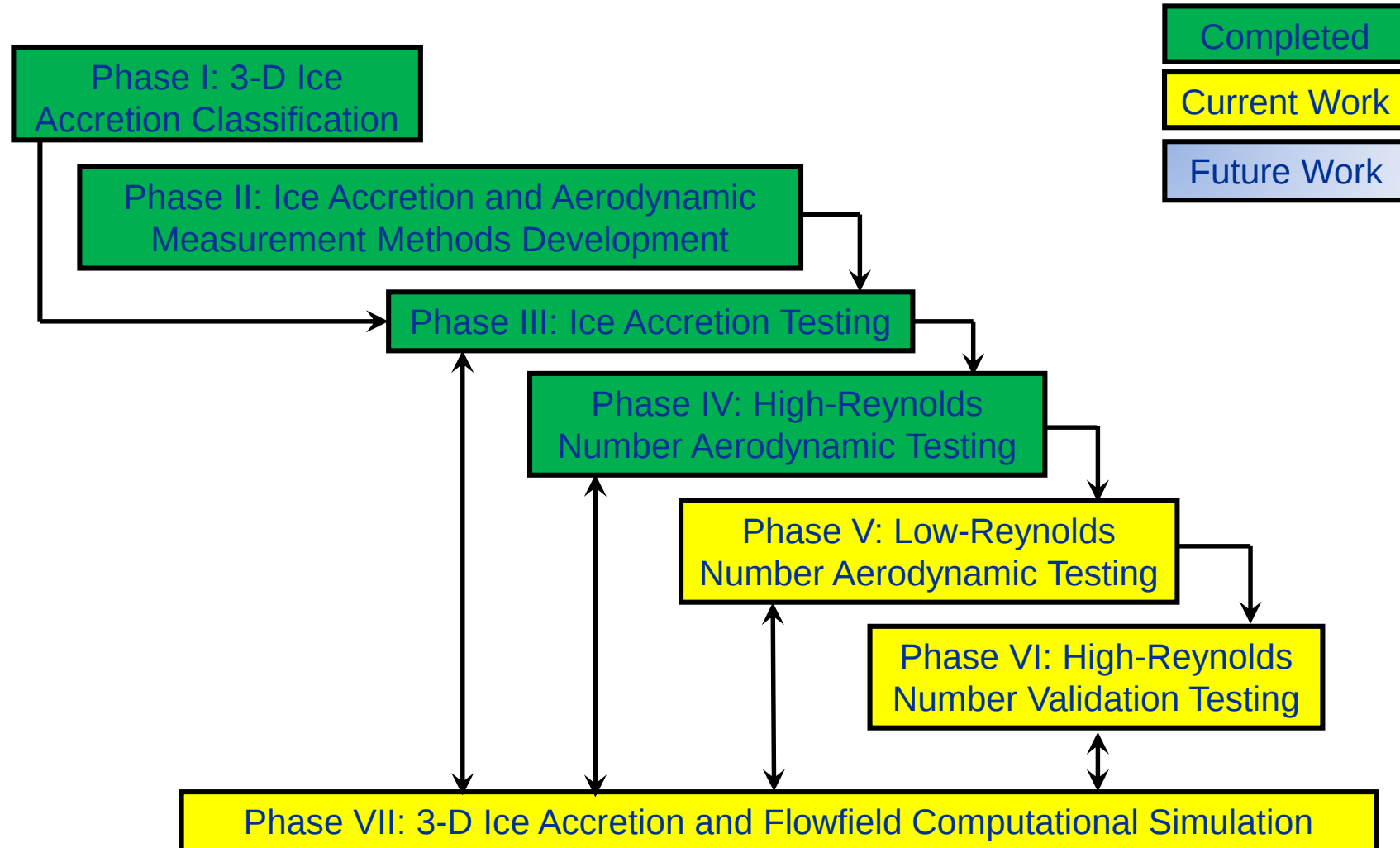
- Improve the fidelity of experimental and computational simulation methods for swept-wing ice accretion formation and resulting aerodynamic effect.

Objectives

- Generate a database of 3D ice-accretion geometry for icing-code development and validation; and for aerodynamic testing.
- Develop a systematic understanding of the aerodynamic effect of icing on swept-wings including: Reynolds and Mach number effects, important flowfield physics and fundamental differences from 2D.
- Determine the level of geometric fidelity required for accurate aerodynamic simulation of swept-wing icing effects.



Research Roadmap





Phase I: Ice-Shape Classification

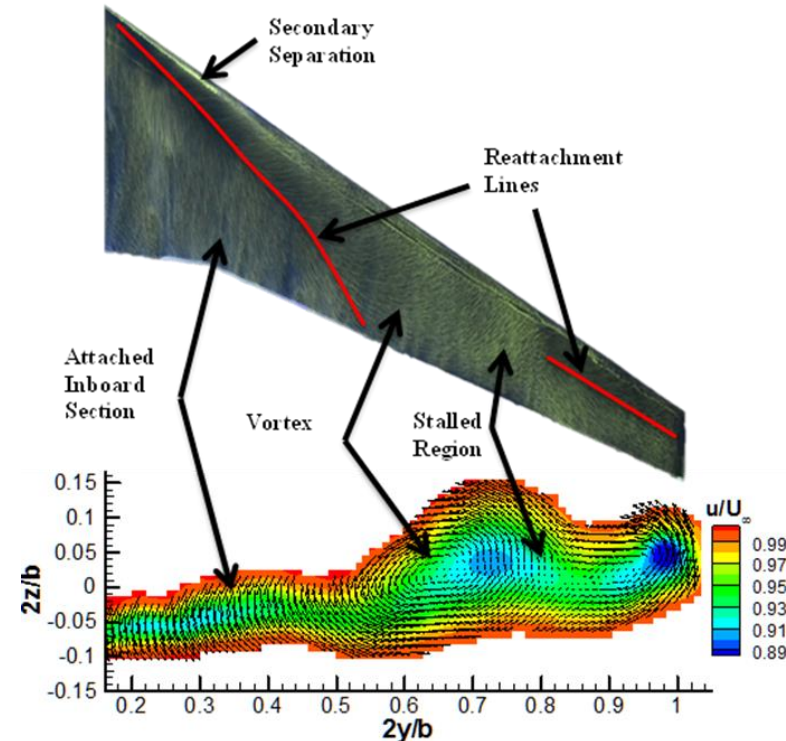
Define ice shapes based on their aerodynamic characteristics.

- Roughness
- Streamwise ice
- Horn ice
- Spanwise-ridge ice



Phase II: Measurement Methods Development

- Common Research Model selected as the baseline, full-scale, reference geometry for the swept-wing configuration.
- Applied and validated existing 3D laser scanning methods to measure highly 3D ice accretion.
- Applied existing 3D wake survey methods to iced swept wings.

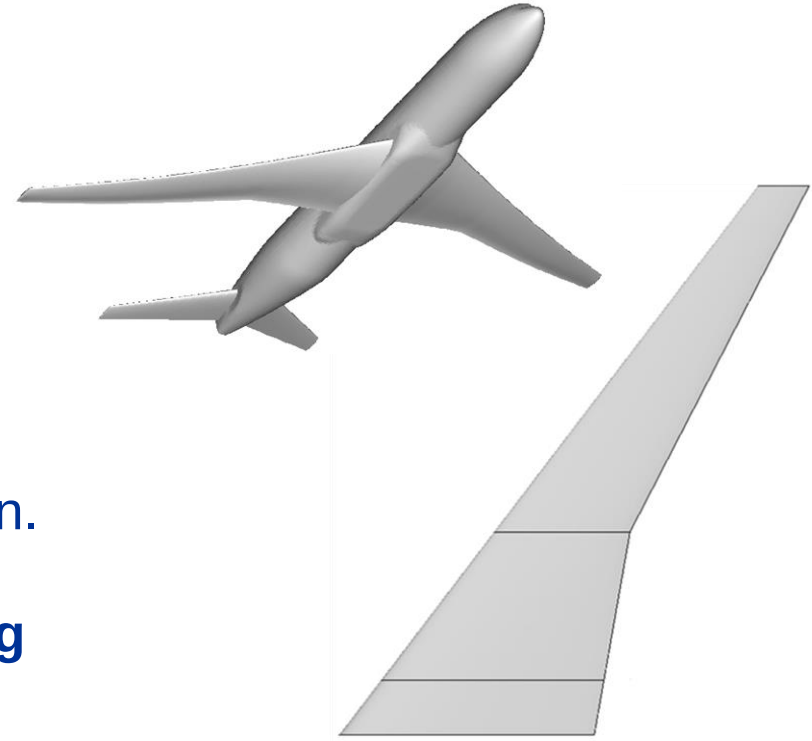




Phase II: Baseline Swept-Wing Model

Common Research Model (CRM)

- Commercial transport class configuration developed by Boeing with support from NASA.
- Contemporary transonic supercritical wing design.
- Publically available and otherwise unrestricted for world-wide distribution.
- **A 65% scale CRM was selected as the full-scale, reference swept-wing geometry for this research.**



Airplane	Span (ft)	MAC (ft)	Area (ft ²)	Aspect Ratio	Taper Ratio	Sweep, c/4 (deg.)
CRM65	125.3	15.0	1,745	9.0	0.28	35
Airbus A320	112.0	14.1	1,320	9.5	0.21	25
Boeing 737-800	112.6	13.0	1,341	9.5	0.16	25
Boeing 757-200	124.8	16.7	1,847	7.8	0.21	25



Phase III: Ice Accretion Testing

Objective

- Generate a database of ice-accretion geometry for large-scale, swept wings.

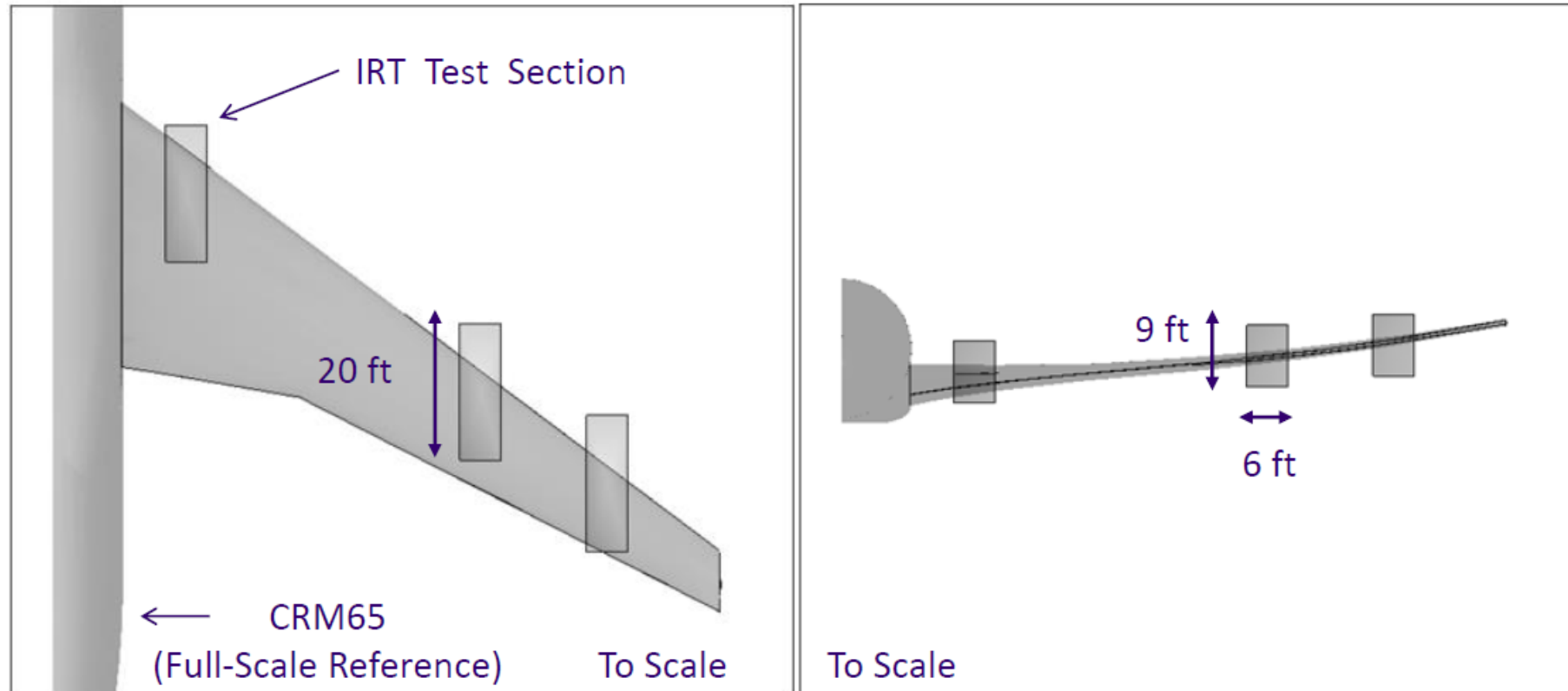
Approach

- Use the CRM65 as the baseline or reference swept-wing geometry.
- Identify three spanwise stations of interest—Inboard, Midspan and Outboard.
- Design hybrid or truncated wing-section models for IRT test section.
- Conduct ice-accretion testing in IRT.
- Measure ice geometry with 3D scanning technique.

Phase III: Ice Accretion Testing

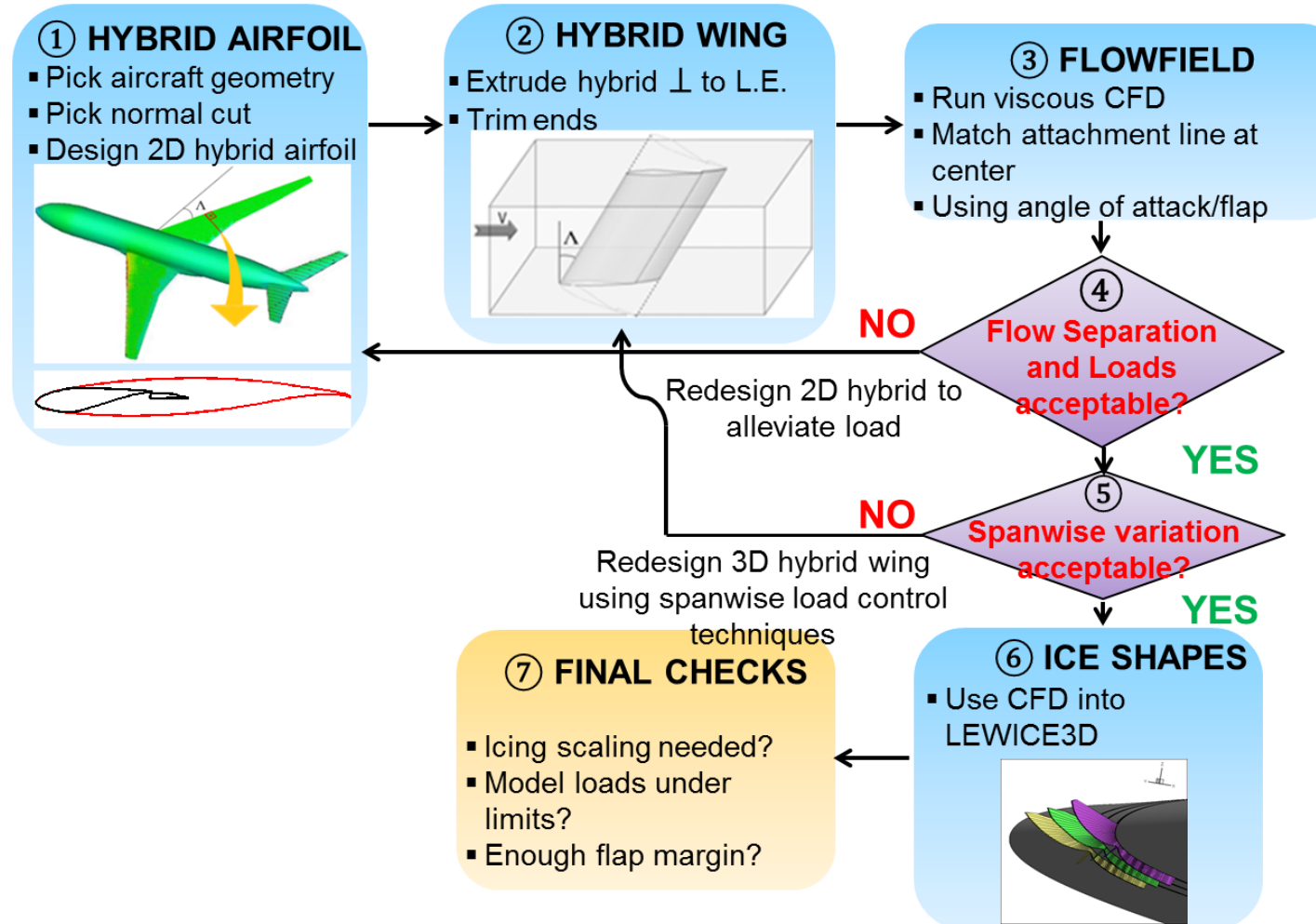
Challenges

- In icing, size does matter...but
- CRM65 too large for any icing wind tunnel



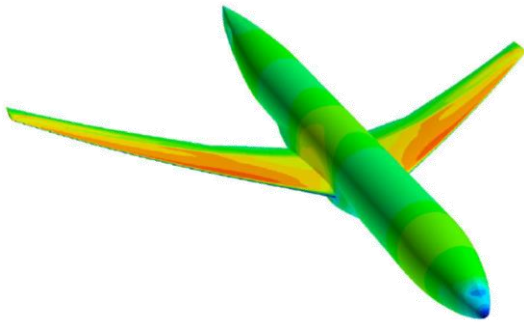
Phase III: Ice Accretion Testing

Hybrid model design process in 3D

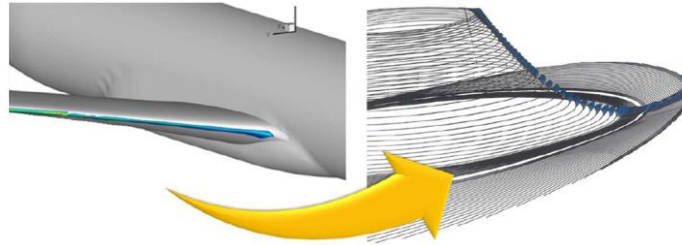


Phase III: Ice Accretion Testing

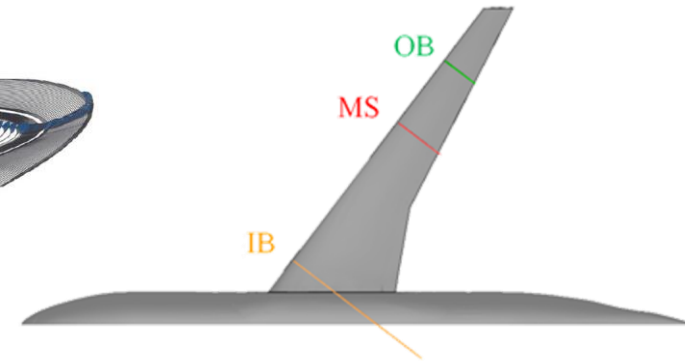
Clean Flight
Baseline (CFB)
OVERFLOW



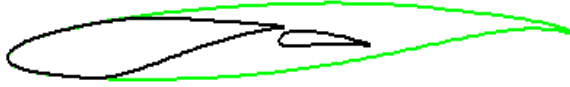
Iced Flight Baseline (IFB)
LEWICE3D



Select wing stations for
hybrid model design



- Design hybrid models to generate full-scale ice accretion.

Inboard, 20% Semispan Scale Factor = 2.25	Midspan, 64% Semispan Scale Factor = 2	Outboard, 83% Semispan Scale Factor = 1.5
		

Phase III: Ice Accretion Testing

- Ice-accretion testing was conducted at NASA Icing Research Tunnel (IRT) that simulates flight through an icing cloud at pressure-altitudes near sea level.
- IRT test section is 6 ft high by 9 ft wide by 20 ft long.
- Models were installed vertically from floor-to-ceiling with small gaps to provide clearance for angle of attack and flap angle changes.

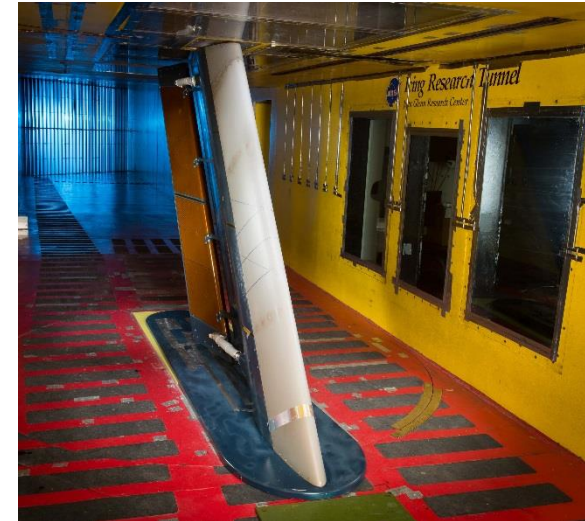
Inboard Model



Midspan Model



Outboard Model



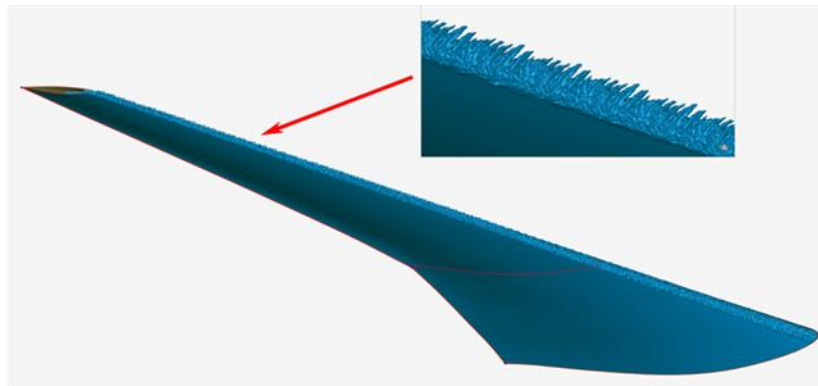
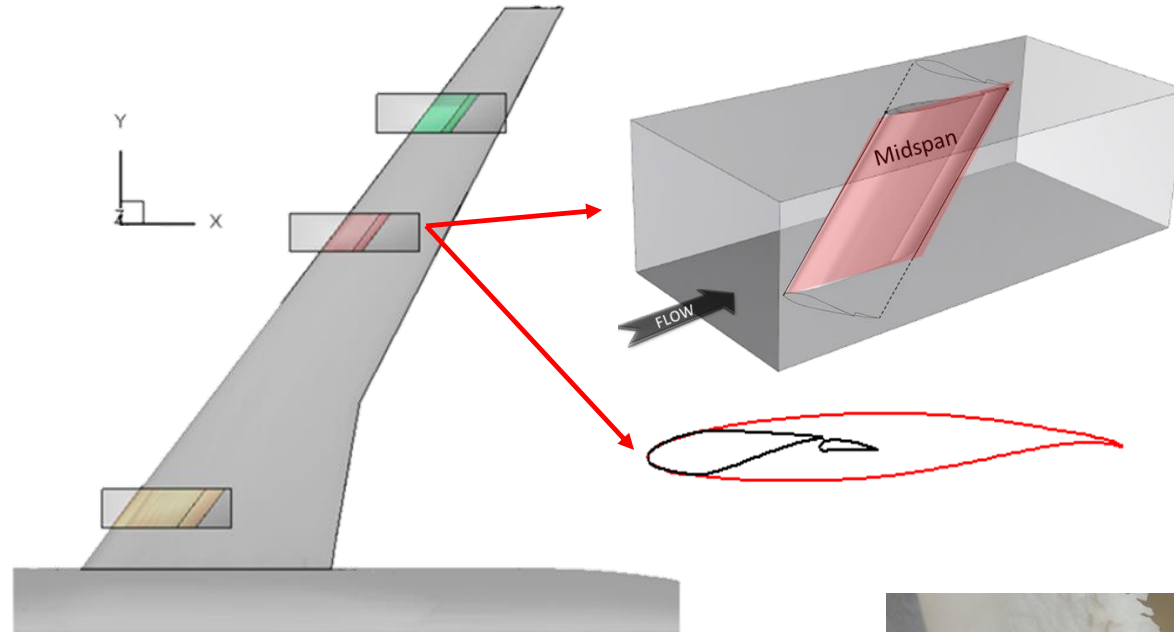
Phase III: Ice Accretion Testing

Identical Condition Run on Each Model

Run	AoA deg.	TAS Knots	Total Temp deg. C	Static Temp deg. C	MVD μm	LWC g/m ³	Exp. Time min.
TG2411	3.7	130	-6.3	-8.5	25	1.0	29
TH2450	3.7	130	-6.3	-8.5	25	1.0	29
TI2461	3.7	130	-6.3	-8.5	25	1.0	29



Approach for Aerodynamic Testing





Phase IV: High-Reynolds Number Aerodynamic Testing

Objective

- Determine the aerodynamic effect of artificial ice shapes of varying geometric fidelity on the CRM65 wing.

Approach

- Conduct aerodynamic testing at ONERA F1 pressurized wind tunnel.
- Utilize a 13.3% scale model of the CRM65 semispan wing for the ONERA F1 11.5 ft x 14.8 ft test section.
- Perform aerodynamic testing over a range of Reynolds and Mach numbers up to $Re = 12 \times 10^6$ and $M = 0.34$.
- Test a series of full-span artificial ice shapes of varying geometric fidelity using the 3-D scan geometries from the IRT tests of the 20%, 64% and 83% semispan stations of the CRM65 wing.



Phase IV: High-Reynolds Number Aerodynamic Testing

Status

- 10-day test campaign completed in May 2017.
- A total of 15 configurations were tested including:
 - Clean wing
 - Two boundary-layer trip sets
 - Effect of mini-tufts
 - 12 artificial ice shape configurations
 - Repeat configurations
- Detailed presentation of experimental methods and results scheduled for tomorrow.





Phase V: Low-Reynolds Number Aerodynamic Testing

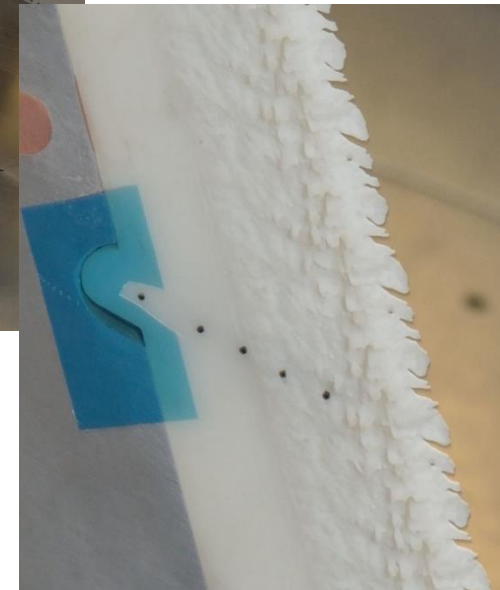
- Test campaigns completed in August 2014, March 2016, and June 2016.
- 8.9% scale CRM65 was built for the Wichita State University 7 ft. x 10 ft. size wind tunnel.
- Aerodynamic performance and 3D wake surveys up to $Re = 2.4 \times 10^6$ and $M = 0.27$.
- Scale models of the artificial ice shapes used in the ONERA F1 tests.
- Quantify the differences 8.9% scale model and 13.3% scale model.
- Investigate sensitivity to ice features.





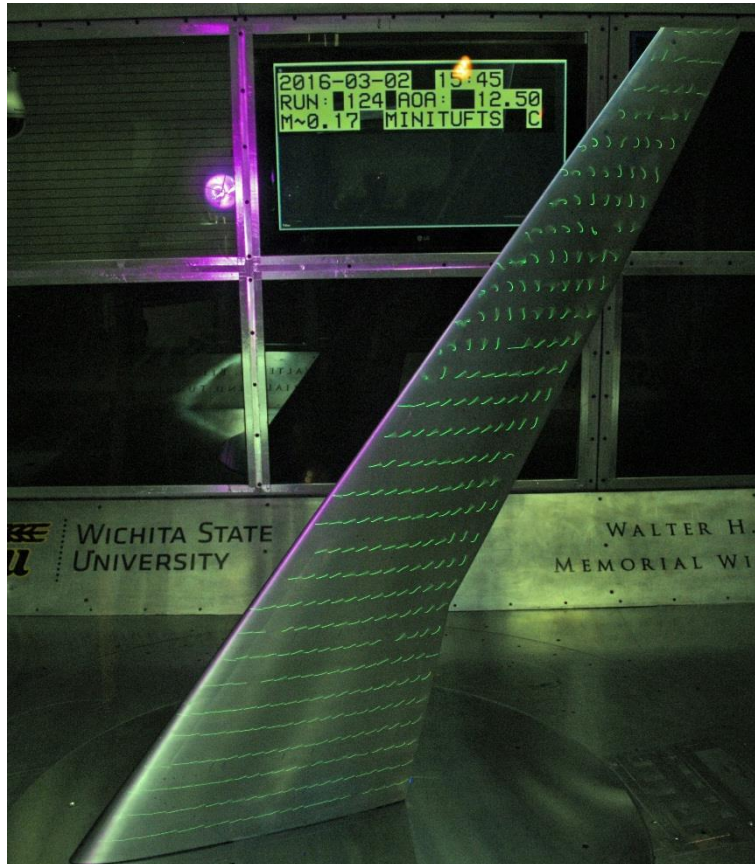
Phase V: Low-Reynolds Number Aerodynamic Testing

- First test campaign Feb. 29-Mar. 8, 2016
 - 10 different ice-shape configurations were tested.
 - Fluorescent mini-tuft flow visualization was recorded for clean and iced-wing configurations.
 - Surface-oil flow visualizations were performed for selected iced-wing configurations.
 - Preliminary assessment of wake survey capability was performed.
- Second test campaign May 16-June 3, 2016
 - Acquire performance data for additional artificial ice shapes along with 5-hole-probe wake surveys.
- More details to be presented tomorrow.



Phase V: Low-Reynolds Number Aerodynamic Testing

- Mini-tuft and surface-oil flow visualization for high-fidelity, 3D streamwise ice shape at $M = 0.17$.



Phase VI: High-Re Validation Testing

- Identify critical ice shape configurations from Phase V.
- Build and test these configurations in ONERA F1 pressurized wind tunnel.
- Test campaign scheduled for September 2018.
- Quantify the differences in aerodynamic performance and key flowfield features between the 13.3% model scale and 8.9% model scale tests.





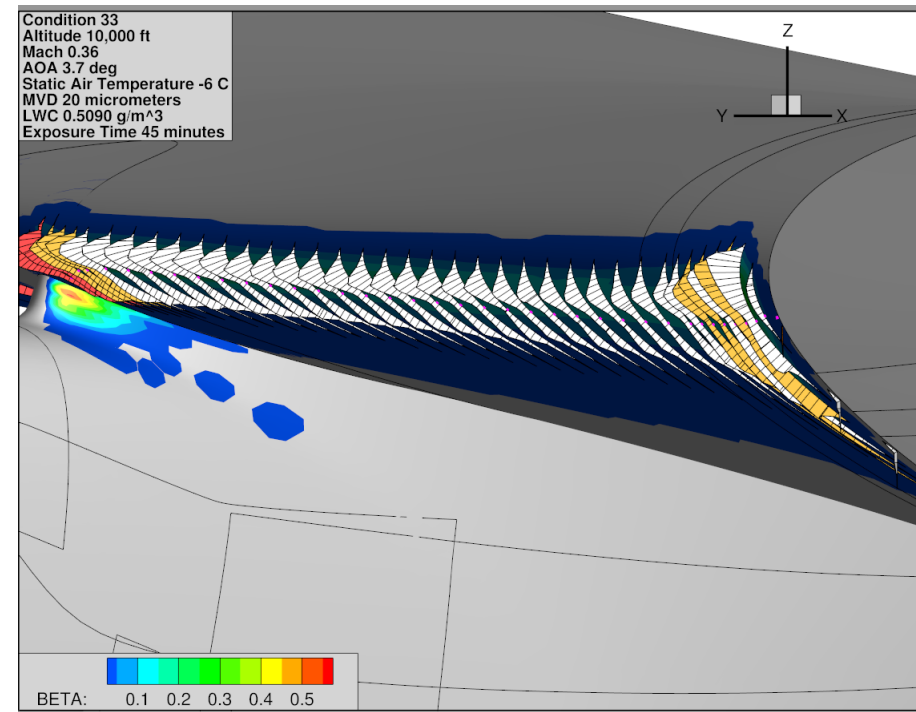
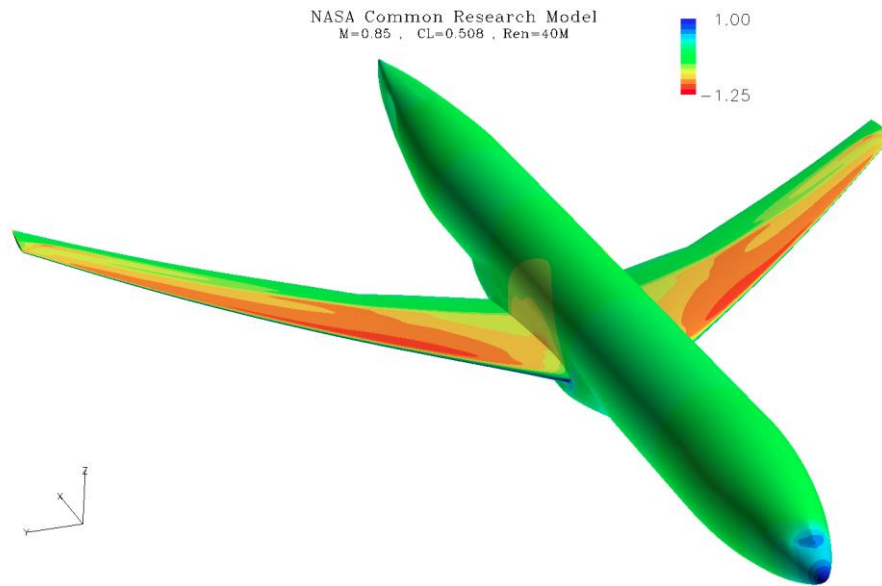
Phase VII: 3-D Ice Accretion and Flowfield Computational Simulation

Computational simulations are organized into three main areas:

- Hybrid model design process—using 3D RANS CFD combined with LEWICE3D.
- Post-IRT-test CFD simulations of CRM models as installed in the IRT, using RANS and hybrid schemes.
 - LEWICE3D simulations of IRT conditions.
 - Ice-shape comparison presented in today's meeting
- CFD simulations of clean and iced semispan wing for comparison with aerodynamic wind-tunnel test results.
 - Status and plans will be discussed on Thursday.

Phase VII: 3-D Ice Accretion and Flowfield Computational Simulation

Hybrid model design process—flight baseline simulations, subsequently used as the reference for the hybrid model design.





Research Timeline FY18-19

Phase V Low-Reynolds Number Aerodynamic Testing

- Third and final test campaign at WSU Beech wind tunnel scheduled for February 2018.
- List of artificial ice shape configurations will be discussed tomorrow.

Phase VI High-Reynolds Number Aerodynamic Testing

- Second and final test campaign at ONERA F1 wind tunnel scheduled for September 2018.
- Current NASA/ONERA international agreement set to end in May 2018.
- An extension to the agreement is being pursued to include final joint-reporting activities in FY19.

Phase VII Icing and Flowfield Computational Simulation

- Anticipate completion of some iced-swept-wing CFD simulations for comparison to experimental database.



Research Products and Accomplishments to Date

- Three-dimensional scanning methods for measuring IRT ice accretion geometry.
 - Now used in some “production” tests by outside customers.
 - Transitioned to GRC’s Imaging Technology Center.
- Hybrid-model design methods for conducting icing-tunnel tests of large-scale swept wings.
 - Based upon the use of 3D CFD and icing simulation tools.
- Database of swept-wing ice accretion geometry for large-scale swept wings.
 - Evaluate current status of icing simulation tools that were used to design the hybrid models in the first place.
- Methods to interpolate and extrapolate 3D ice accretion geometry along the full-span of a swept wing.
 - Develop artificial ice shapes for aerodynamic testing.



Research Products and Accomplishments to Date

- Database of low- to high-Reynolds number aerodynamic data for swept-wing ice accretion.
 - An understanding of Reynolds and Mach number effects for the CRM65 wing with ice accretion.
- An understanding of the geometric fidelity required for accurate aerodynamic simulation of swept-wing ice accretion.
- A substantiated low-cost, low-Reynolds number test capability for evaluation of performance characteristics and aerodynamics of iced-swept-wing geometries.
- Aerodynamic wake survey methods successfully extended to iced swept wings.
 - Used to achieve better understanding of flowfield based origins of performance degradations.

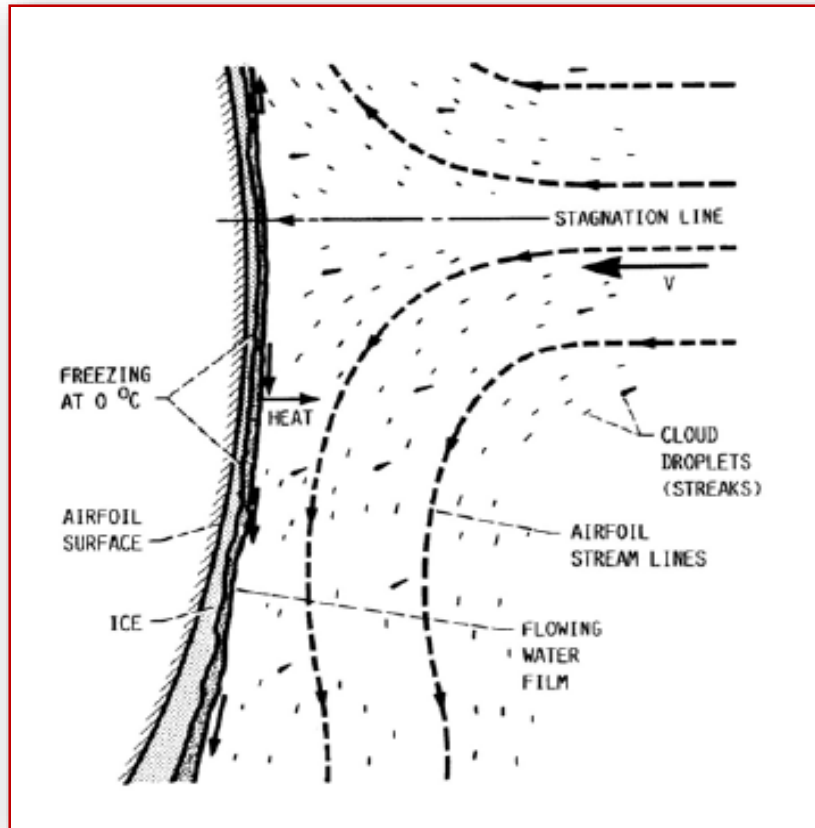


Status and Plans for NASA Ice Accretion Simulation Tools

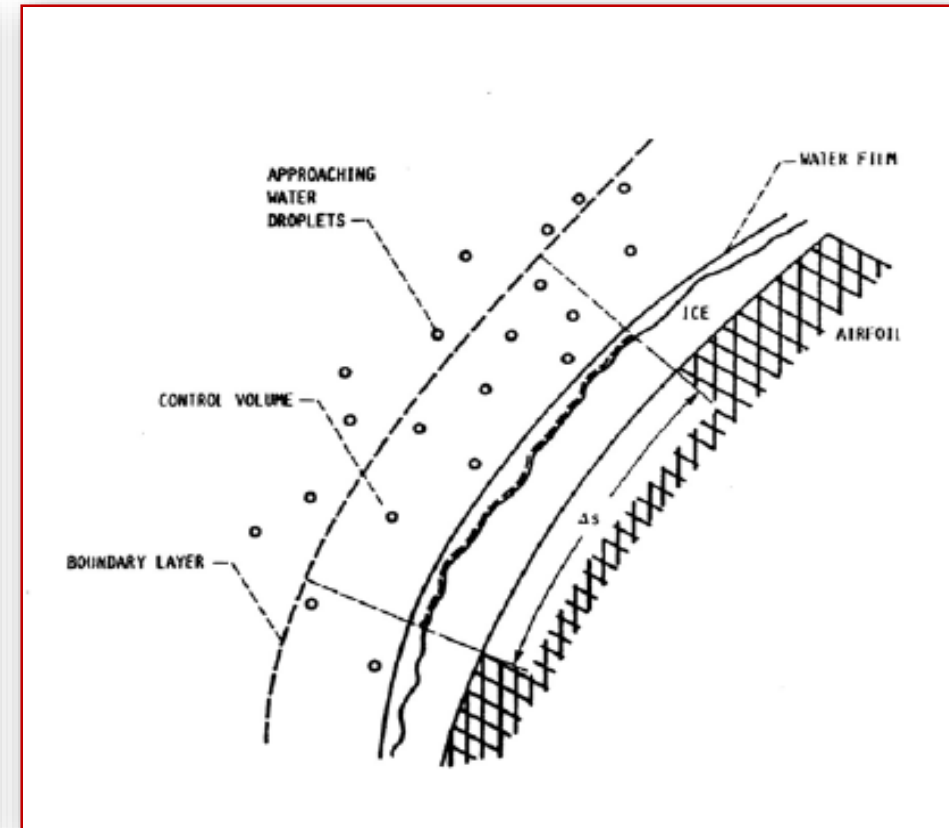
- Background
- Current Tools
 - LEWICE – 2D ice accretion simulation
 - LEWICE3D – quasi 3D ice accretion simulation
- Current and Future Development
 - GlennICE – Full 3D ice accretion simulation
- Icing Physics Research for Model Development
- Verification and Validation

Background

Airframe Icing



Physical aspects of icing problem



Control volume approach used in
LEWICE software



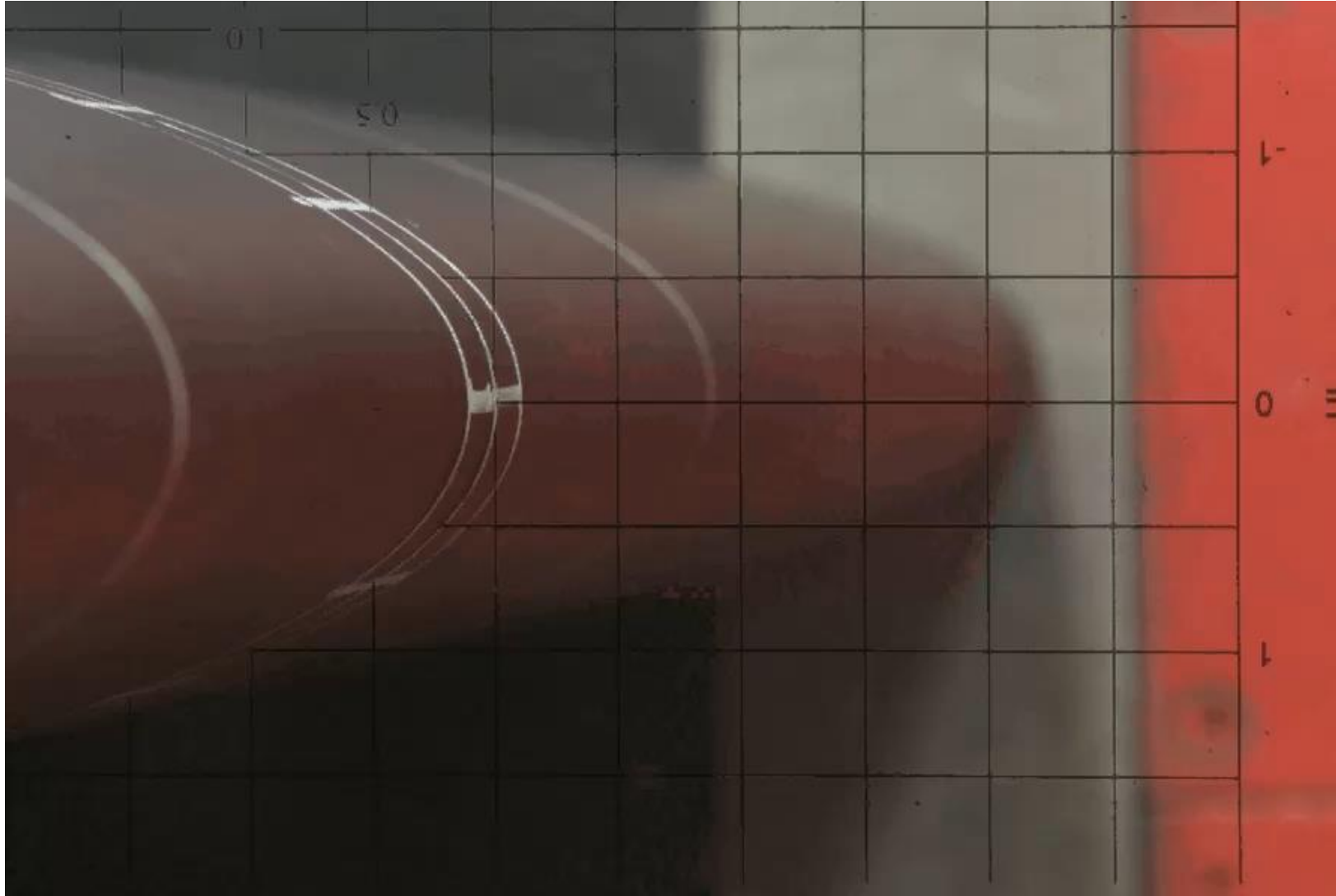
Background

Airframe Icing



Background

Airframe Icing



Background

Engine Icing





Background

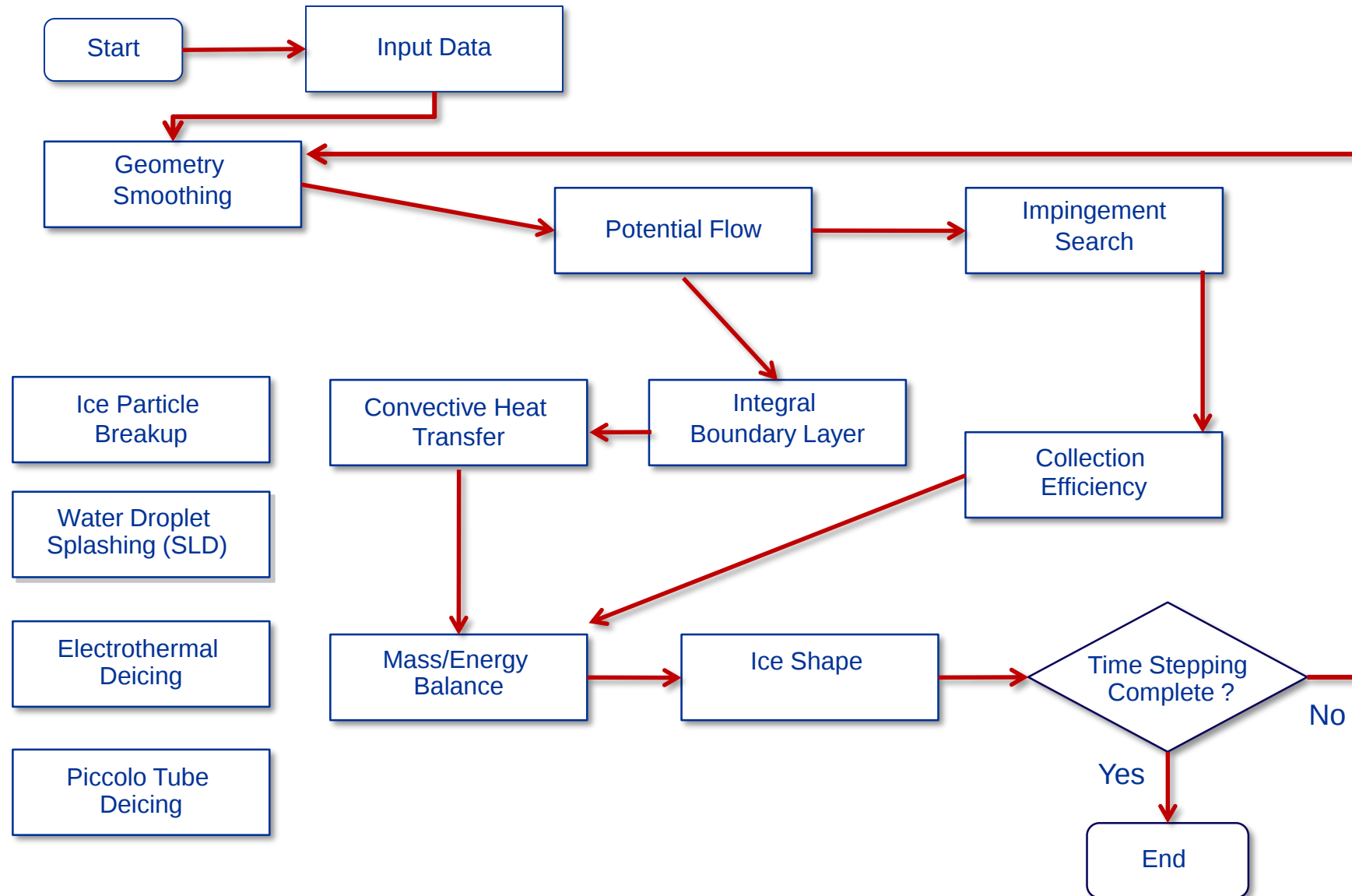
Ice Accretion Computational Simulation

- Focus of code development efforts since 1983 has been airframe icing; engine icing development is more recent
- Has led to the development of both LEWICE and LEWICE3D
 - ✓ Used throughout the industry
 - ✓ Considered the gold standard to which other codes are compared
 - ✓ Well validated by comparison to literally thousands of experimental ice shapes
- Still room for improvement
 - ✓ Full 3D ice shape simulation
 - ✓ Modeling of scalloped or “lobster tail” ice shapes
 - ✓ Full range of SLD simulation; we can do part of freezing drizzle and we need to do freezing rain conditions
- “How good is good enough?”
 - ✓ Using aerodynamic degradation and ice shape fidelity as metrics for addressing that question



Current Tools

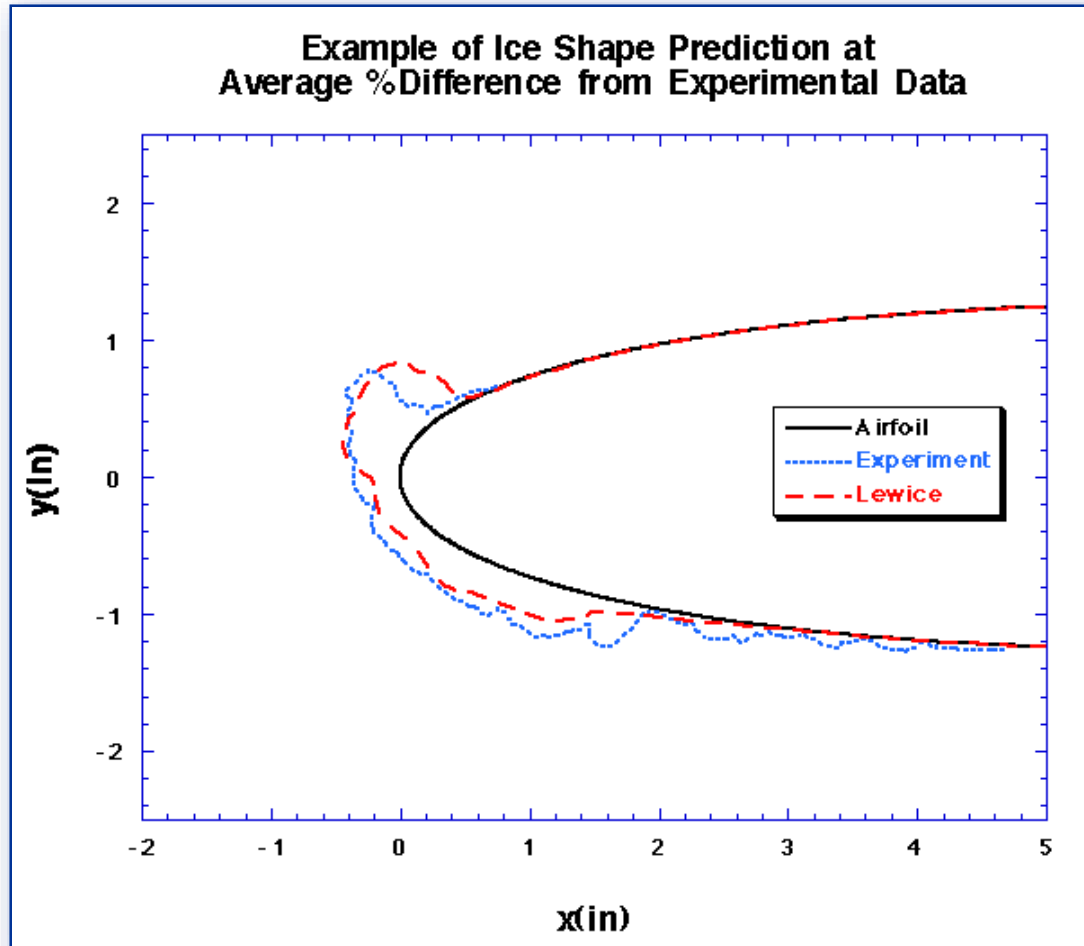
LEWICE Flow Diagram





Current Tools

LEWICE for Airframe Icing



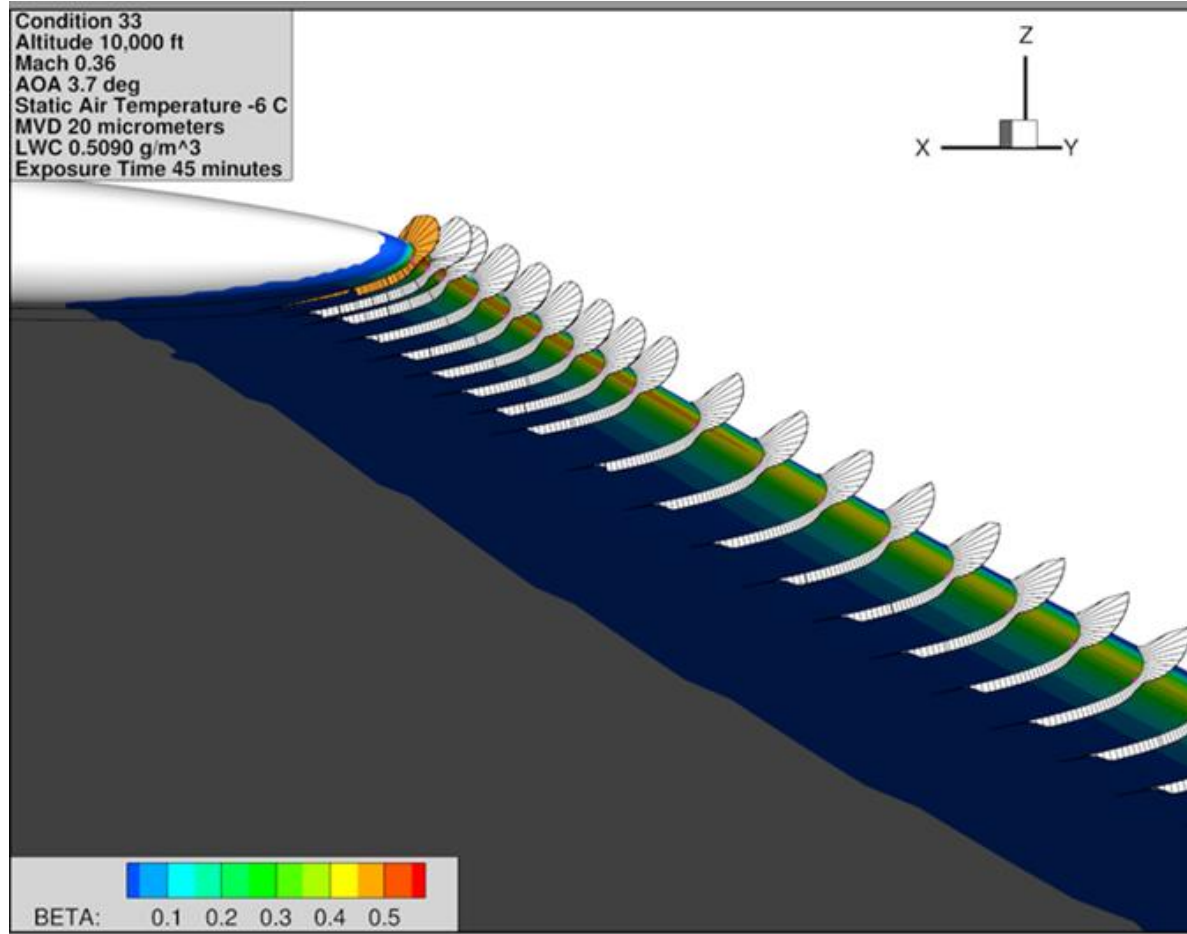
Output:

- Ice shape geometry
- Collection efficiency on the surface
- Freezing fraction along the ice surface
- Heat transfer values along the surface
- Temperatures along the surface

This is a typical result.

Current Tools

LEWICE3D for Airframe Icing



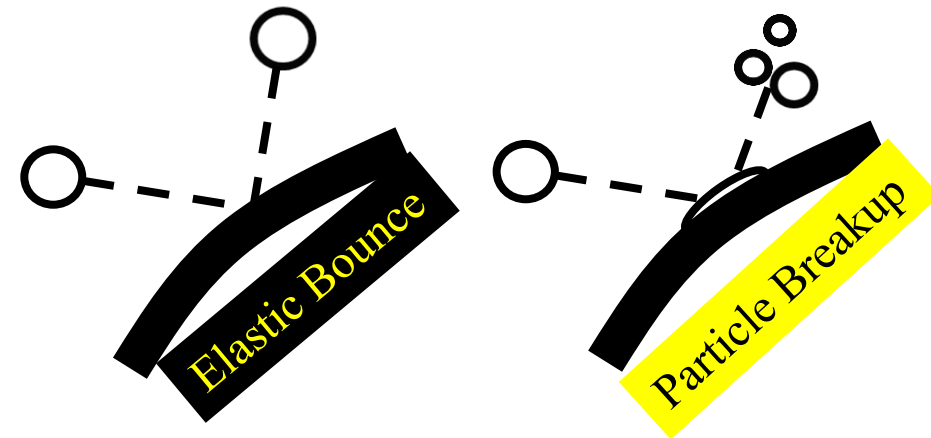
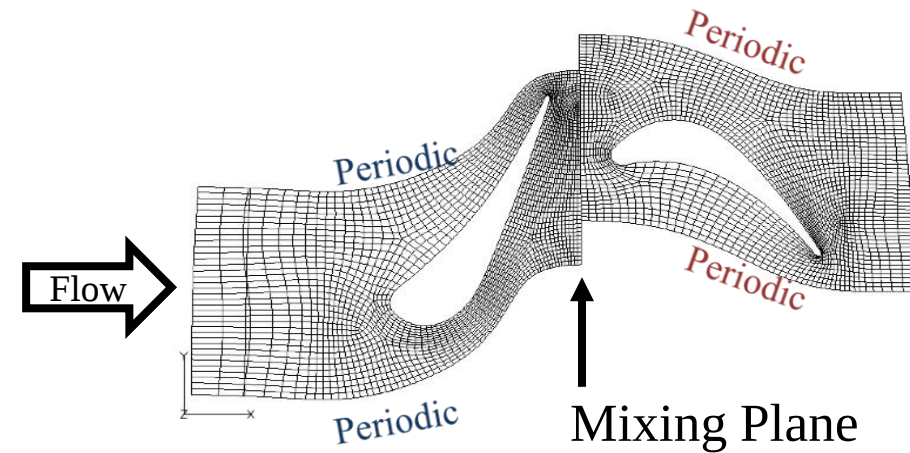
Output:

- Collection efficiency on the entire surface
- Ice shape geometry along cut lines or streamlines
- Freezing fraction along the ice surfaces
- Heat transfer values along the ice surfaces
- Temperatures along the ice surfaces

Current Tools

LEWICE3D for Engine Icing

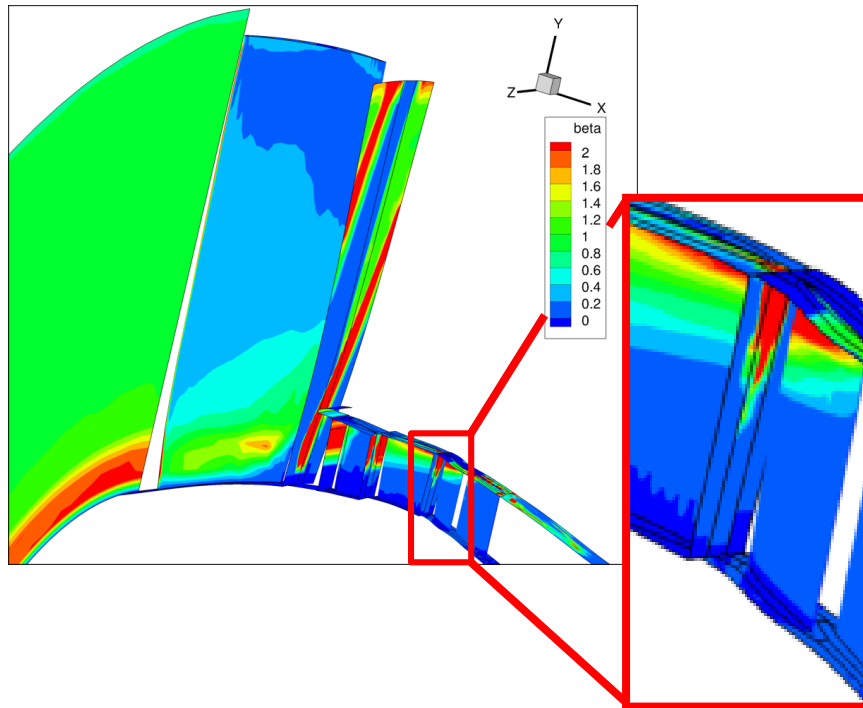
- Accepts a flow solution then extracts icing related parameters
 - Solution is made up of multiple zones, some rotating and some stationary
 - Periodic conditions are imposed in the pitchwise direction
 - A mixing plane approximation is employed between rotating and stationary zones
- Particles are tracked as they pass through the zones
- A surface parameter (IREBOUND) can be set to control how particles act upon impact
 - Choices include
 - Sticking
 - Elastic Rebound
 - Super-Cooled Large Droplet model
 - Particle Breakup
- Cuts can be extracted for ice growth simulation
- General 3D ice growth is not supported



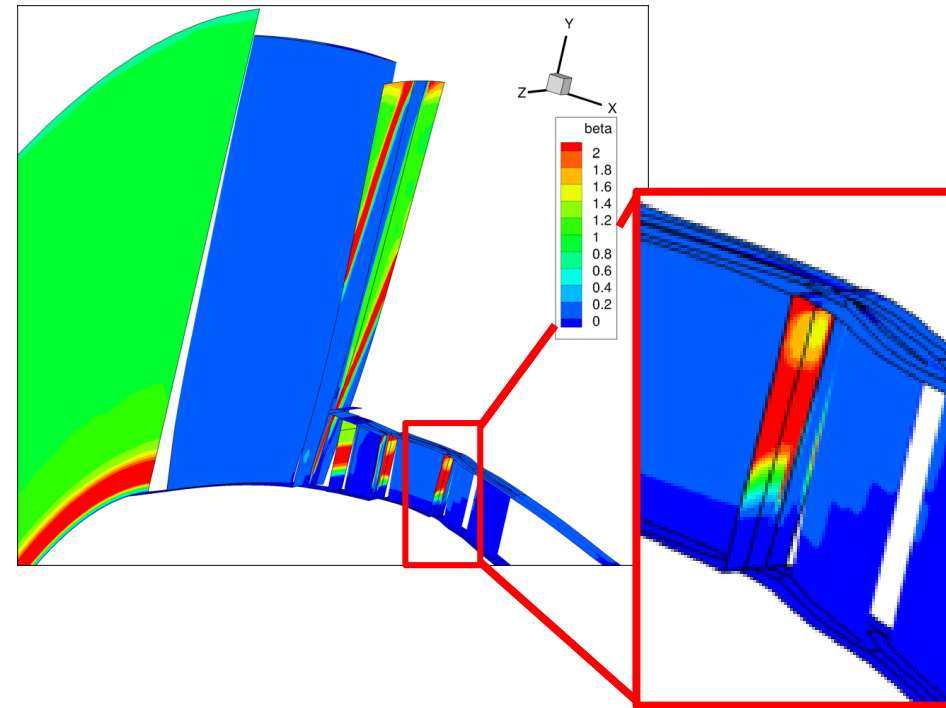
Current Tools

LEWICE3D for Engine Icing

Elastic Bounce, 20 micron at Inlet



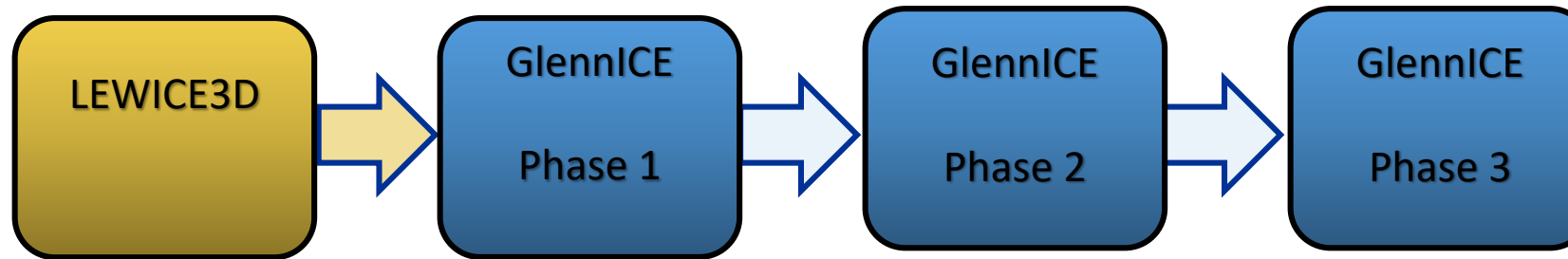
Particle Breakup, 20 micron at Inlet





Current and Future Plans

GlennICE



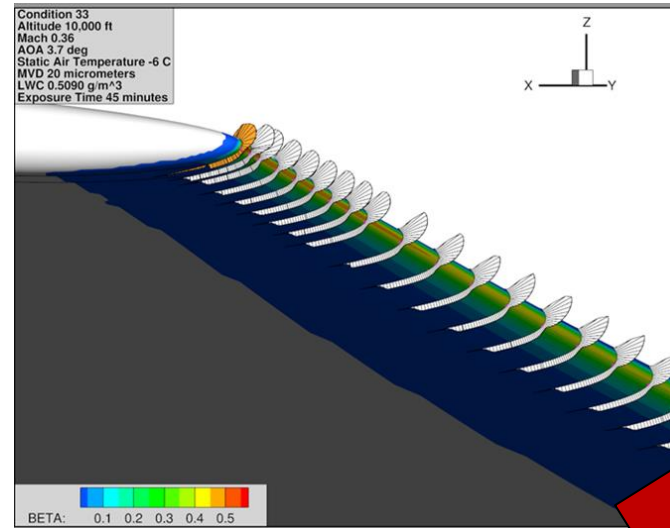
- GlennICE is focused on providing a computational tool for external and internal Appendix C, D, & O icing analysis.
- This full functionality will be implemented in three feature releases.

Current and Future Plans

GlennICE

Phase 1 Goals

- Quasi 3D → Full 3D
- Runback
- Ice Growth
- Multi-Timestep Capability
 - From CFD
 - Ice Roughness Model



Current and Future Plans

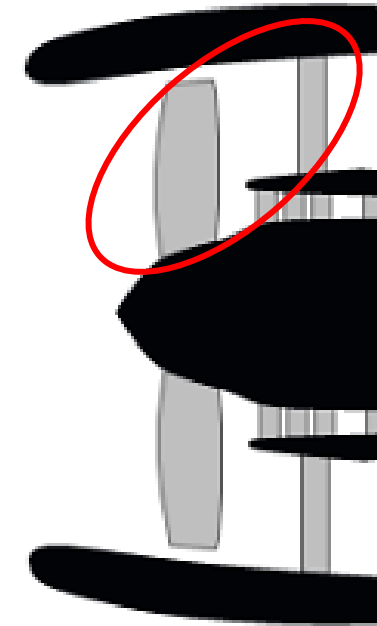
GlennICE

Phase 2 Goals

- Turbomachinery Simulations in Appendix C and O Icing Conditions
- Full 3D ice growth on rotating surfaces

Expected Outcome

- Physics are very analogous to airframe icing.
- Should produce good ice shapes out of the box.
- May need some splashing model work.





Current and Future Plans

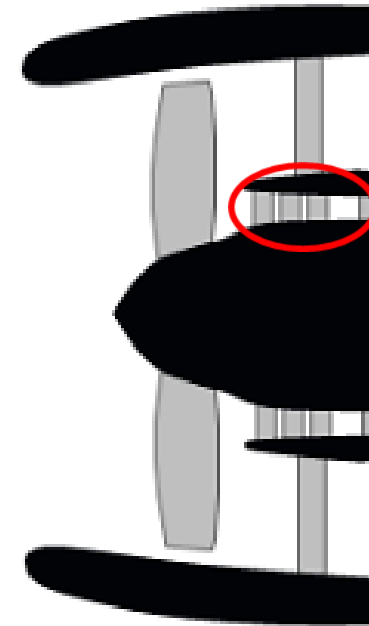
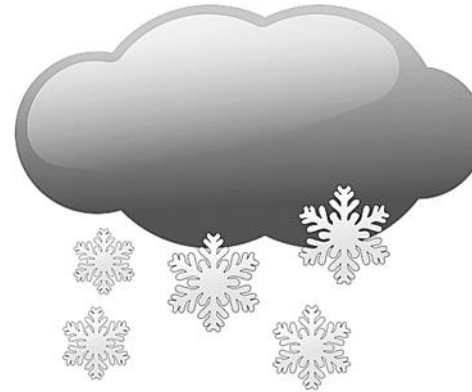
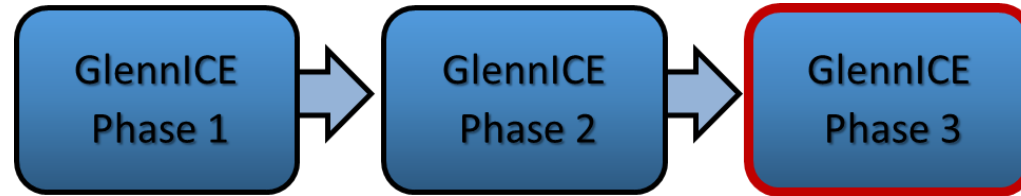
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Phase 3 Goals

- Appendix D
- Improved Ice Crystal Mechanics
 - Breakup
 - Melting
 - Evaporative Cooling

Expected Outcome

- Predicting Core Icing Risk
- Liquid Water Impingement Location
- Wet-Bulb Temperature
- Major advances needed for ice shape/shedding.
- Ice growth rate is achievable.





Icing Physics Research for Model Development

Facilities

- Icing Research Tunnel (IRT)
- Propulsion Systems Laboratory (PSL)
- Test rigs
 - DRIFT tunnel for instrumentation testing and single drop measurements
 - VIST tunnel for boundary layer scale testing; i.e. roughness and heat transfer studies

Icing Physics

- Supercooled water drop and ice particle studies
 - Particle/drop trajectories
 - Thermodynamics
 - Splashing
 - Break-up
- Ice surface roughness and heat transfer
- Ice growth mechanisms
- Ice adhesion and shedding



Verification and Validation

Ice Shapes

- Thousands of hand tracings of ice on airfoils
- Recent development of 3D laser tracing technique has enabled creation of an expanding database of full 3D shapes
- Photographic data of engine ice shapes has just begun to be collected; current methods do not enable tracing or scanning
- Software has been developed to quantitatively compare experimental to computational ice shapes via examination of geometric features
- LEWICE has been compared to thousands of ice shapes and the differences between computation and experiment are at the same level as experimental repeatability
- LEWICE3D has been compared to a more limited database

Collection Efficiency

- LEWICE and LEWICE3D have compared well to measured collection efficiency measurements; This database is not as extensive as that for ice shapes

